RF SUPERCONDUCTIVITY 2010

Science, Technology and Applications

Cornell Laboratory
for Accelerator-based Sciences
and Education (CLASSE)

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RF - SUPERCONDUCTIVITY - 2010

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OVERVIEW

The aim of this brochure is to summarize the status of the science, technology and applications of superconducting RF (SRF), and to discuss exciting prospects for the future. The rapid growth of this technology has alerted the world accelerator community and its supporting agencies to the importance of SRF for frontier instruments in high energy, nuclear, and astrophysics, as well as in the materials and life sciences. Newcomers to the field may also benefit from the introductory material.

SRF cavities excel in applications requiring continuous wave (CW) or long-pulse high voltage. Since ohmic loss in the cavity walls increases as the square of the accelerating voltage, copper cavities become uneconomical when the demand for high CW voltage grows with particle energy. Here superconductivity comes to the rescue. The surface resistance of a superconductor is five orders of magnitude less than that of copper. The quality factor (Q_0) of a superconducting resonator is typically in the billions. (The quality factor determines the number of oscillation cycles before the resonator stored energy dissipates.) After accounting for the refrigerator power needed to provide the liquid helium operating temperature, a net gain factor of several hundred remains in the overall cooling power for superconducting over copper cavities of the best shapes.

The presence of RF accelerating structures in the beam line also has a disruptive effect, limiting beam quality in aspects such as energy spread, beam emittance, beam halo, and maximum current. With capability to provide higher voltage, SRF systems can be shorter and impose less beam disruption. By virtue of low wall losses, an SRF cavity design can also afford a large beam hole, which further reduces beam disruption.

For low velocity, heavy ion accelerators, a similar advantage of superconducting resonators is that a high CW voltage can be obtained in a short structure. The accelerator to boost ion energies can be formed as an array of independently phased resonators, making it possible to accelerate a variety of ion species and charge states with different velocities through the same structures. An independently phased array forms a system which provides a high degree of operational flexibility, and tolerates variations in the performance of individual cavities. Superconducting boosters show excellent beam properties. Because of their intrinsic modularity, there is also the flexibility to increase the output energy by adding higher velocity sections at the output, or to extend the mass range by adding lower velocity resonators at the input.

RF superconductivity has become an important technology for accelerators at the energy and luminosity frontiers as well as at the cutting edge of low and medium energy nuclear physics, nuclear astro-physics, and basic materials science. SRF cavities are now routinely accelerating electron, proton and heavy ion beams in a variety of frontier accelerators.

In the late 1990's the energy of LEP at CERN was doubled with 500 meters of superconducting cavities built by sputtering a micron thin film of niobium on copper. CEBAF at Jefferson Lab has been operating for more than a decade with more than 150 meters of SRF cavities, the largest number in operation at one facility. Jefferson Lab is developing high gradient cavities and cryomodules to upgrade CEBAF's energy from 6.5 GeV to 12 GeV. Doubling the beam energy is an important priority for advancing understanding of the strong force and its manifestation in gluonic matter.

High current, high luminosity electron-positron storage rings have been operating with SRF cavities for copious production of C and B quarks at CESR in the US, KEK-B in Japan and BEPC in China.

Electron storage rings as light sources have an enormous impact on materials and biological science. SRF accelerating systems have upgraded storage ring light sources, such as CHESS at Cornell, and the Taiwan Light Source. The Canadian Light Source DIAMOND in UK, Shangai Light Source in China, and SOLEIL in France are operating routinely with SRF. The Swiss Light Source and ELETTRA in Treiste have installed third harmonic superconducting cavities to improve beam lifetime and stability.

SRF linac based Free Electron Lasers (FEL) provide tunable, coherent radiation over a wide range of wavelengths. The Jefferson lab FEL generates 14 kW of CW laser power in the infra-red, with energy recovery by recirculating nearly one MW of beam power. This is an important milestone toward Energy Recovery Linacs for future light sources, and electron beam cooling applications. Other FELs have operated at JAERI in Japan and ELBE in Germany. FLASH at DESY in Germany is a short wavelength FEL based on the SASE principle delivering 6 nm wavelength light. Its SRF linac uses more than 60 one-meter long cavities to accelerate a one GeV electron beam.

The first high intensity proton accelerator is operating at the Spallation Neutron Source (SNS), Oak Ridge National Laboratory. Neutron scattering is an important tool for materials, chemistry and life science. With a beam energy above 1 GeV, SNS provides one megawatt of beam power on target to produce a neutron flux comparable to the average flux of the Grenoble reactor, the largest neutron science facility.

OVERVIEW - Continued

As a natural outcome of the LEP Nb-Cu technology, superconducting cavities meet the voltage and high current demands of the Large Hadron Collider (LHC) at CERN to run 7 TeV proton beams with currents approaching one amp.

In the low-β arena, ATLAS at Argonne and ALPI at Legnaro have been operating for several decades for heavy-ion, nuclear and atomic physics research. TRIUMF in Canada has expanded its radioactive beam facility (ISAC) by adding a superconducting heavy ion-linac to supply more than 40 MV. Heavy ion linacs in New Delhi and Mumbai have come on line. Among other fundamental questions, radioactive beams provide basic insight into the origin of the heavy elements in supernovae. Radio-Isotope Beams (RIB) facilities are under construction with the SPIRAL2 project at GANIL in France, and at the ReAccelerator at MSU in the US. More than 250 superconducting low-β resonators are operating around the world.

In all more than one kilometer of superconducting cavities have been installed in accelerators world-wide providing more than 7 GV of acceleration. Superconducting cavities support beam currents above one ampere in continuous operation, delivering up to 380 kW beam power through individual cavity units.

There is more good news. Steady advances in SRF science and technology are responsible for spectacular increases in performance since the large installations at CEBAF and CERN in the 1990's. Improved understanding and invention of treatments have raised bare cavity gradients from 5-10 MV/m typical of the early 1990's to 25 - 35 MV/m in 2010. Q_0 values at high gradients approach 10^{10}. Cryomodules with eight cavities have operated above 20 MV/m at the FLASH laser facility. High performance cavities demand excellent control of niobium material properties, purity, surface smoothness, and surface cleanliness in cavity preparation and assembly. New cavity geometries are underway to optimize the accelerating voltage available from the highest surface fields.

These advances in cavity performance have spurred new accelerators, some already under construction and some in planning. With many exciting prospects on the horizon, the world SRF community has expanded to include many new laboratories where extensive SRF facilities have been installed.

The largest application underway is a 16 GeV superconducting linac for the European XFEL at DESY. It will be based on nearly 700 niobium cavities operating at 22 MV/m gradient. When completed in 2016 it will provide Angstrom wavelength X-ray beams of unprecedented brilliance.

A new Facility for Rare Isotope Beams (FRIB) is underway at MSU in the US to allow the study of exotic isotopes related to stellar evolution and the formation of elements in the cosmos. FRIB will be based on more than 330 low-β resonators, more than doubling the number presently in operation.

A variety of innovative linac-based light sources are under study, for FELs and energy recovery linacs (ERL) to deliver orders of magnitude higher brightness and optical beam quality. High intensity beams for ERLs have spurred explorations for electron cooling applications and for electron-ion colliders, for example to upgrade Relativistic Heavy Ion Collider (RHIC).

High intensity proton linacs will likely fulfill future needs in a variety of arenas: upgrading injector chains of proton accelerators at Fermilab's Tevatron and CERN's LHC, heavy-ion radioactive beams for nuclear physics, medical therapy, industrial applications, higher intensity spallation neutron sources, transmutation applications for treatment of radioactive nuclear waste, nuclear energy production using thorium fuel, high intensity neutrino beam lines, high intensity muon sources for muon storage rings based neutrino factories, and eventually a multi-TeV energy scale muon collider.

A major future application for high gradient niobium cavities is likely to be the International Linear Collider (ILC), a TeV Energy Superconducting Linear Accelerator. To achieve TeV energy will require 16 km of superconducting cavities operating at gradients of 31.5 MV per meter. Future ILC energy upgrades toward 1 TeV will benefit from even higher gradients, pushing niobium towards its ultimate potential of 55 MV/m, and opening the door for new materials with gradient potentials of 100 MV/m.

There is now excellent prognosis for reaching 40 MV/m with niobium cavities. Many 9-cell, one meter long niobium structures have demonstrated 40 MV/m performance in qualification tests. Research continues to push towards the theoretical limit of 55 MV/m.

Although the most successful cavities are based on niobium, exploratory work has been carried out on other materials. Nb_3Sn is the most promising candidate with the potential of 100 MV/m gradients. Basic research is needed to verify that potential and development necessary to harness it.

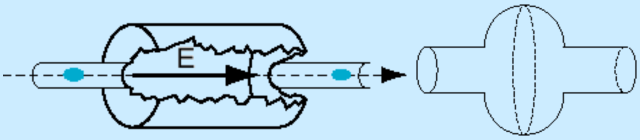
New techniques for cavity fabrication are emerging, such as spinning and hydro-forming multicell structures from tubes or sheets. If successful, these approaches will help reduce the cost.

SUPERCONDUCTING CAVITY RESONATORS

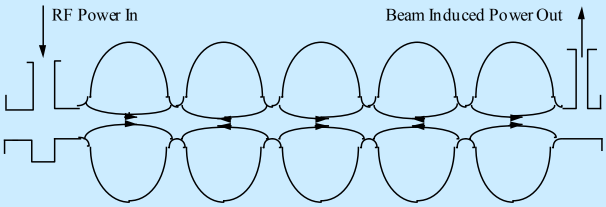
A key component of the modern particle accelerator is the electromagnetic cavity resonator that imparts energy to the charged particles. The resonant frequency is usually between 100 MHz and 3000 MHz depending on the trade-offs for each specific application. Traditionally accelerating cavities are made from copper. One of the main incentives for using superconducting cavities is that the dissipation in the walls of the structure is many orders of magnitude lower than for a copper wall, which brings special benefits for accelerators that operate in a continuous wave (CW) mode or at a high duty factor (e.g. > 1 per cent). Superconducting cavities economically provide high CW operating fields. Another important benefit is that superconducting cavities can have a larger beam aperture than copper cavities which reduces the beam-cavity interactions, allowing higher beam quality, higher beam current or less activation of the walls of the structure from beam losses.

Structure Geometry

There are several distinct types of cavities, depending on the velocity of the charged particles accelerated. The first category is for particles that move at nearly the speed of light, such as electrons in a linear accelerator or a storage ring. Here the structure evolves from the simple pill-box shape cavity resonating in the fundamental (TM_{010}) mode. Beam tubes are added and the cylindrical wall is rounded to avoid the multipacting limitation (discussed later).

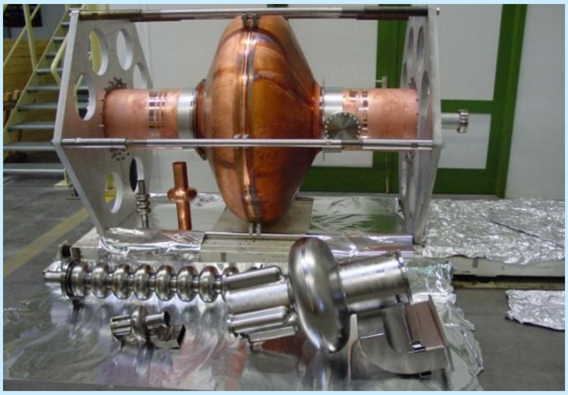


Speed-of-Light-Structures



Accelerating structure for velocity-of-light particles. The resonant frequency is typically between 350 and 3000 MHz. The cell length is half a wavelength ($\lambda/2$). From cell to cell there is a π phase shift in the axial electric field for the accelerating mode. Charged particles traverse each half-wavelength gap in half an RF period. As a result they see an electric field pointing in the same direction for continuous acceleration. Ports outside the cell region are for input power couplers and higher order mode power output couplers.

Photograph of a 9-cell, 1300 MHz, one-meter long accelerating structure with one input power coupling port at one end, and one HOM coupler at each end. It is used at FLASH and will be used in the European XFEL.



A variety of superconducting cavities for accelerating velocity-of-light particles. In the foreground (left) is the 9-cell cavity and (right) a CESR 500 MHz cavity together with a 1/3-scale version of the latter. In the background the large 200 MHz Nb-Cu cavity dominates. With a few micron layer of niobium sputtered on the inside, the cavity was developed by a Cornell/CERN collaboration for future muon accelerators and the neutrino factory.

Medium Velocity Structures

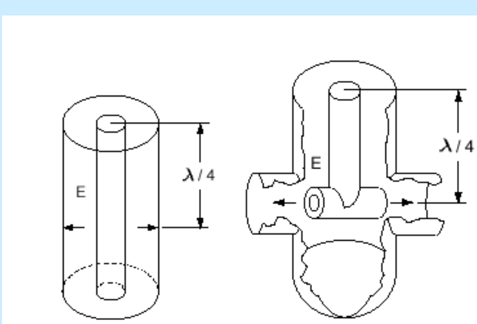
Medium velocity structures with β = *v/c* between 0.5 and 1 are used for protons with energies less than one GeV as well as for low-velocity ions. The structures are either foreshortened speed-of-light structures or spoke resonators.

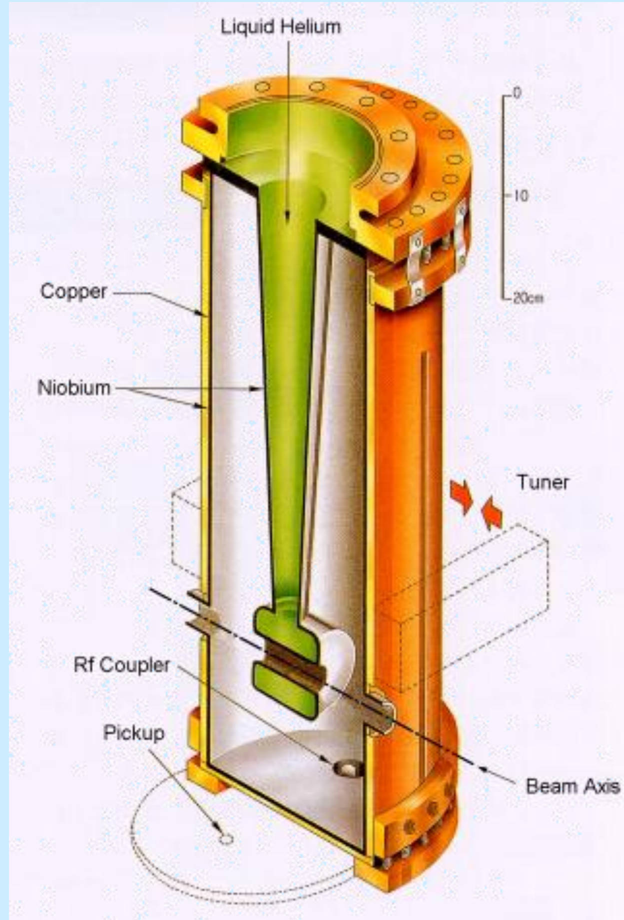
β= 0.47, 800 MHz, 6-cell elliptical-cell (JLAB/MSU)

345 MHz, β = 0.4, double-spoke resonator (ANL) The presence of a spoke through a TM cavity makes the structure both compact and rigid, allowing low frequencies.

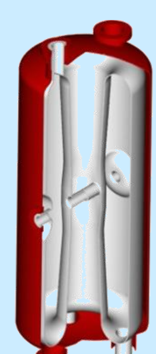
Low Velocity Structures

The low-velocity structure is for particles moving at a small fraction (e.g. 0.01 to 0.3) of the speed of light, such as the heavy ions emerging from a Van de Graff accelerator or an Electron Cyclotron Resonance (ECR) ion source. The structure evolves from a shorted transmission line either quarter-wavelength or half-wavelength long.





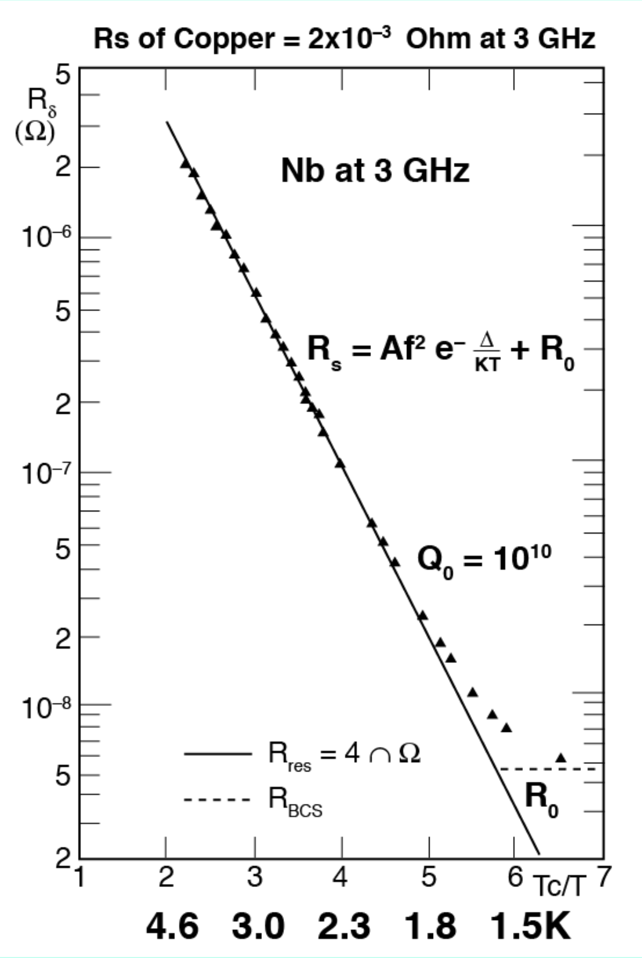
For the Quarter-Wave Resonators, suitable for β between 0.01 to 0.2, a coaxial transmission line a quarter wavelength long, resonates in the *TEM* mode. A drift tube is suspended from the end of the hollow center conductor. The structure has two accelerating cells between the ends of the drift tube and beam hole openings located in the outer conductor of the coax. For low velocity acceleration, the structure period is $\beta\lambda/2$. Since β is small, the desire to get reasonable accelerating voltages per structure period leads to large wavelengths and low frequencies, e.g. 100 - 200 MHz. The wavelength also sets the height of the quarter-wave resonator. The RF frequency choice generally increases with particle velocity.



For the Half-Wave Resonator, suitable for β about 0.2, a coaxial transmission line, half wavelength long, resonates in the TEM mode. A drift tube is located in the middle of the hollow center conductor. The structure has two accelerating cells between the ends of the drift tube and beam hole openings located in the outer conductor of the coax. The structure period is $\beta\lambda/2$.

THE MIRACLE OF SUPERCONDUCTIVITY

The remarkable properties of superconductivity arise from the condensation of electrons into Cooper pairs which move without friction; hence the zero resistance. What causes the condensation? There is an attractive force between electrons of opposite spin that arises from interaction between the electrons and the lattice, popularly visualized as the "mattress effect." At $T = 0\ K$, all charge carriers condense into Cooper pairs. At higher temperatures, pairs break up. The fraction of unpaired carriers increases exponentially with temperature, as $e^{-\Delta/kT}$, until none of the carriers are paired above T_c. Here 2Δ is the energy gap of the superconductor, the energy needed to break up pairs. In this simplified picture, known as the London two-fluid model, when a DC field turns on, pairs carry all the current, shielding the applied field from normal electrons. Electrical resistance vanishes. For RF currents, dissipation does occur for all $T > 0\ K$, albeit very small compared to the normal conducting state. While Cooper pairs move without friction, they do have inertial mass. For high frequency currents to flow, forces must be applied to bring about alternating directions of flow. Hence an AC electric field will be present in the skin layer. It will continually accelerate and decelerate the normal carriers, leading to dissipation, proportional to the square of the RF frequency and dropping exponentially with temperature as the electrons freeze out into Cooper pairs. The two fluid model provides a simple explanation for the quadratic frequency and the exponential temperature dependence of the RF surface resistance. The power dissipated is proportional to the internal electric field (proportional to the RF frequency) and to the "normal" component of the current. The latter being proportional to the interior electric field, gives another factor proportional to the frequency. The "normal" component of the current also depends on the number of carriers thermally excited across the gap, and is given by the Boltzmann factor, $e^{-\Delta/kT}$.



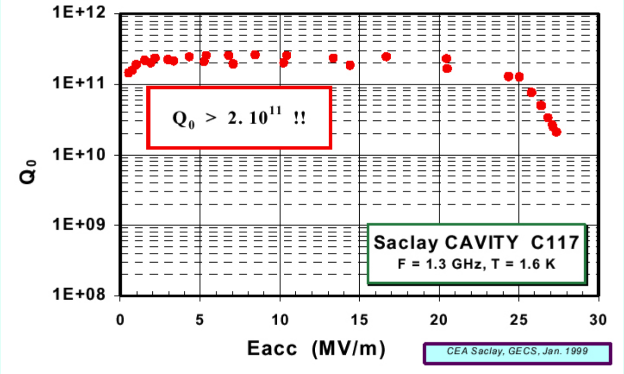
Surface resistance (Rs) vs. Temperature of niobium at 3 GHz, showing the exponential drop due to the energy gap.

The two fluid model provides a simple explanation for the exponential fall of the RF surface resistance. The operating temperature of a superconducting cavity is usually chosen so that the temperature dependent part of the surface resistance drops to an economically tolerable value. Below 2 K the observed resistance departs from the exponential and saturates at a residual resistance of 5 - 10 nΩ. Several factors, such as impurities on the surface or the ambient DC magnetic field influence the residual resistance.

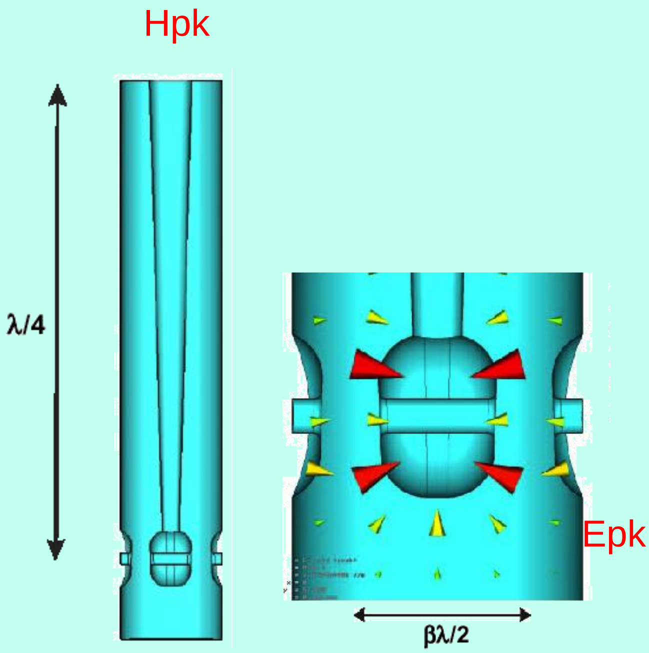
Q vs. E Curves

The two most salient characteristics of an accelerating cavity are its average accelerating field, E_{acc}, and the quality factor Q_0. The quality is related to the surface resistance R_s via a geometry factor, G.

$$Q = \frac{G}{R_s}$$



In some of the best performing cavities, Q values of 10^{11} have been reached in 1.3 GHz single cell test cavities at 1.6 K and accelerating fields of 25 MV/m. The corresponding energy decay time is of the order of 10 seconds!



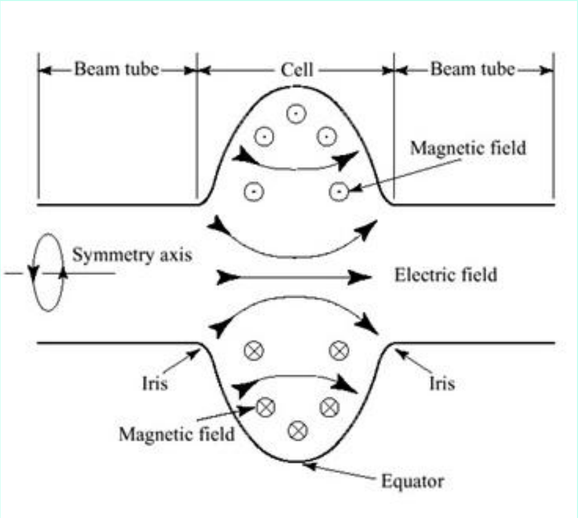
Peak field locations for the Quarter-Wave resonator.

Peak Surface Fields Determine Performance

The accelerating field is proportional to the peak surface electric field (E_{pk}), as well as the peak surface magnetic surface field (H_{pk}). Besides the phenomenally low RF surface resistance, other important aspects are the maximum values of these surface fields that can be tolerated without increasing the microwave surface resistance substantially, or without causing a breakdown of superconductivity. The ultimate limit is set by the RF critical magnetic field, theoretically equal to the superheating critical magnetic field, H_{sh}. For the most commonly used superconductor, niobium, H_{sh} is about 0.23 tesla, which translates to a maximum accelerating field of 50 MV/m for a typical $\beta = 1$ niobium structure, and roughly 30 MV/m for a $\beta < 1$ niobium structure.

The peak surface to accelerating field ratios is significantly higher in the low-velocity structures. For a gradient of 1 MV/m, the peak electric field typically ranges from 4 to 6 MV/m (compared to 2 to 2.6 MV/m for $\beta = 1$ structures) and the peak magnetic field ranges from 60 to 200 Oe (compared to 40 to 47 Oe for β = 1 structures).

Improved geometry structures will be discussed later which provide higher accelerating fields for the same surface fields.



A single cell cavity shows electric and magnetic field lines for the accelerating mode as well as the location of the peak fields.

ATTRACTIVE FEATURES OF SRF

The strongest incentive to use superconducting cavities is for accelerators that operate in a continuous wave (CW) mode, or at a high duty factor (>1%). For CW operation, the power dissipation in the walls of a structure built from normal conducting material (such as copper) is substantial. Therefore the typical CW operating field for a copper cavity is kept below 1 MV/m. The microwave surface resistance of a superconductor is typically 5 orders of magnitude lower than that of copper, and therefore the Q_0 is five orders of magnitude higher. The real gain of a superconducting cavity is, however, not as spectacular, since the few watts per meter of RF power are dissipated at liquid helium temperature. The efficiency of the refrigerator must be taken into account. This is typically 0.003 for 4.2 K operation and half that 2 K. Even after taking into account the refrigerator efficiency there is a net reduction factor of several hundred in AC power relative to normal conducting RF.

For applications demanding high CW voltage, such as storage rings, the advantage of superconducting cavities becomes clear. Since the dissipated power increases with the square of the operating field, superconducting cavities can economically provide the large needed voltage. For example, in the late 1990's LEP (the Large Electron Positron Collider at CERN) required more than 3 GV to double its energy from 50 GeV to 104 GeV per beam. If copper cavities were used, both the capital cost of the klystrons and the AC power operating cost would have become prohibitive at the higher accelerating field. Several MW/m of AC power are required to operate a copper cavity at 5 MV/m. There are practical limits to dissipating such high power in the walls of a copper cavity. When more than 100 kW is dissipated in a 500 MHz copper cell, the surface temperatures exceeds 100 C, causing vacuum degradation, stresses and metal fatigue due to thermal expansion.

Apart from the general advantages of reduced RF capital and operating costs, superconductivity offers certain special advantages that stem from the low cavity wall losses. Because of the phenomenally low power dissipation at high accelerating field, one can afford to make the beam hole of a superconducting cavity much larger than for a normal conducting cavity. The large beam hole substantially reduces the beam cavity interaction, allowing better beam quality and higher beam current for improving the precision and reaction rates of physics experiments.

In considering SRF applications, the gradient and aperture advantages must be balanced against the added cost and technology of the refrigerator and cryogen distribution system, as well as the demands for clean surface preparation. Another factor to bear in mind is that the “useful length” to “active length” ratio ranges from 50 - 75% due to the filling factor of cavities in the cryostat as well as to the need for other accelerator components (such as higher mode couplers) in the beam line.

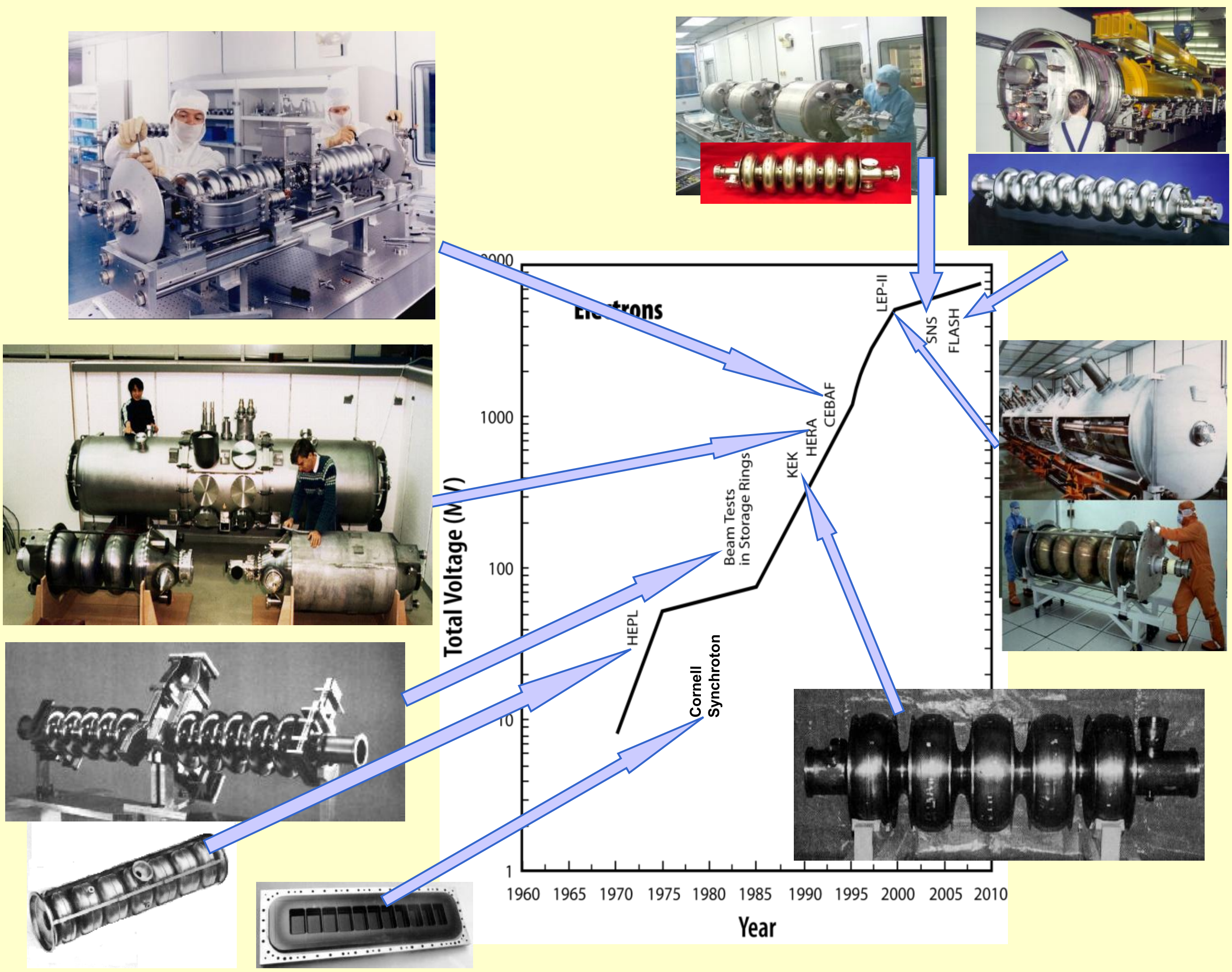
Finally, niobium-based superconducting cavities reach the fundamental limit of the the RF critical magnetic field at about 50 MV/m accelerating. For low (< 0.1%) duty factor operation, copper cavities take the advantage. Copper cavities can produce high accelerating fields (50 - 100 MV/m), but only for microseconds. The peak RF power needed to reach such fields also becomes enormous (> 100 MW per meter).

STORAGE RINGS AND LINACS - A SUCCESS STORY

Large scale application of superconducting cavities to electron and proton accelerators is established at many laboratories around the world. These facilities provide high energy electron and positron beams for elementary particle physics research, medium energy electron beams for nuclear physics research, high quality electron beams for free electron lasers, and high intensity proton beams for neutron source.

A "Livingston Plot" for RF Superconductivity

Total Installation > 1000 m, > 7 GV

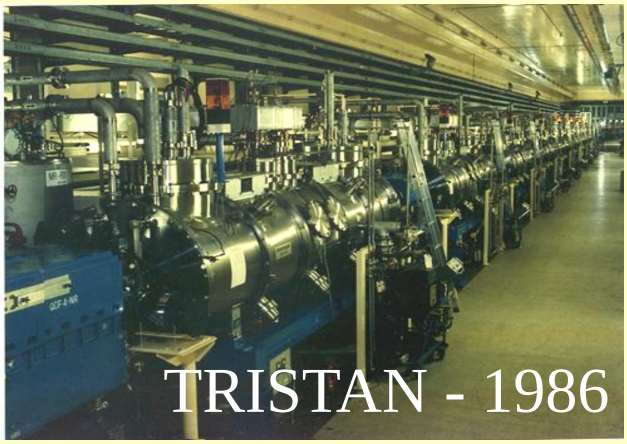


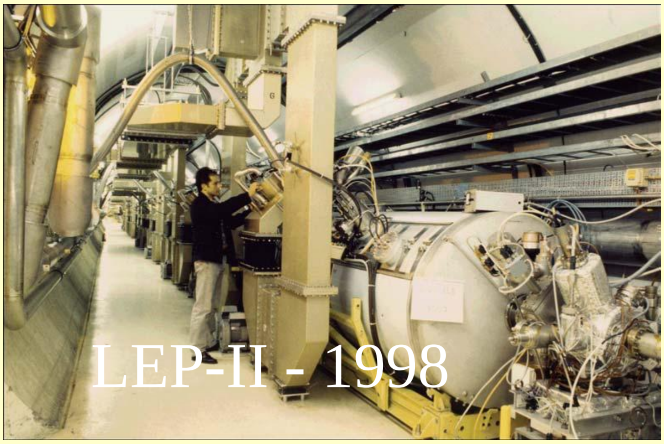
SRF FACILITIES AT THE ENERGY FRONTIER

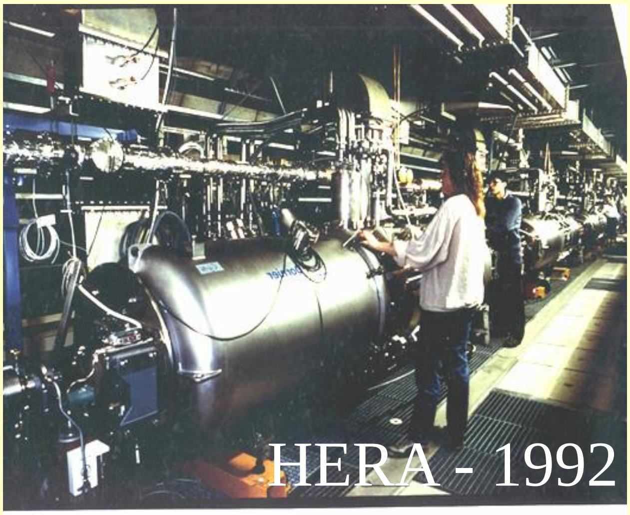
To study the fundamental properties of matter, high-energy physics laboratories built colliding beam storage rings of steadily increasing energies. Electrons in storage rings lose energy in the form of synchrotron radiation. Because the energy loss increases as the fourth power of the beam energy, the electron and positron storage rings needed high CW gradient superconducting cavities.

The colliding beams facilities that used SRF were TRISTAN at KEK in Japan, LEP at CERN in Switzerland, and the electron-proton collider HERA at DESY in Germany. These facilities are now de-commissioned to make way for other accelerators.

Accelerator Installations


TRISTAN - 1986


LEP-II - 1998


HERA - 1992

Two Largest Installations

At the frontiers of nuclear and elementary particle science, CEBAF at Jefferson Lab in the USA, and LEP-II at CERN in Europe have been the two largest SRF installations.

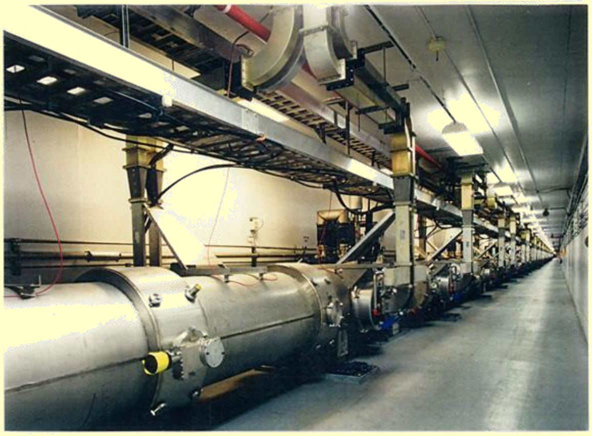
CEBAF improves the basic understanding of nuclear matter, by elucidating the quark and gluon structure of protons and neutrons. It operates with polarized electrons for more than 5000 hours per year. Some of the salient Nuclear Physics advances have been: detailed mapping of neutron charge structure, detailed mapping of the proton electro-magnetic structure, and the absence of strange quarks in the proton.

Construction finished in 1993 with installation of 380 cavities. Originally designed for 4 GeV, CEBAF achieved a beam energy of 6.5 GeV in five recirculating passes with a CW beam current of 200 μA. Over a period of a few years, CEBAF upgraded their in-line accelerating gradient from the design value of 5 MV/m to more than 7 MV/m. By 2010 they accumulated more than four cryomodule-centuries of automated operation. In 2003, Hurricane Isabel severely tested the robustness of CEBAF. After a 3.5 day region-wide power outage, CEBAF restarted its physics program within six weeks, losing just one percent of their cavities due to vacuum.

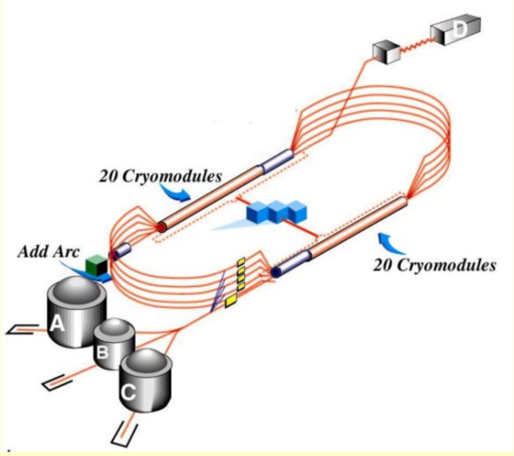
LEP-II installed a total of 465 meters of superconducting RF cavities to provide more than 3.6 GV reaching the highest energy electron-positron collisions: 208 GeV in the Center-of-Mass before LEP-II shut down for installation of the LHC. At the higher energy, LEP-II confirmed the existence of the W meson (one of the carriers of the weak force) and measured its mass with high accuracy.

At the Cutting Edge of Nuclear Physics

Superconducting cavities offer special advantages to electron accelerators for nuclear physics in the 1 to 10 GeV range: high average current, low peak current, continuous beam, and excellent beam quality. For precise measurement of small electromagnetic cross sections and for coincidence detection of reaction particles, a CW beam with high average beam current (100-200 μA) is paramount. In addition, the beam must have a high quality for adequate resolution of closely spaced nuclear states, low energy spread and low transverse emittance to reduce background arising from the beam halo. Because of the highly stable operation possible with a CW superconducting linac, the RF phase and amplitude are controlled very precisely, yielding a very low energy spread. In CW operation, the desired average beam current is possible with a low peak current. Also, the interaction of the beam with the cavity and the vacuum chamber is weak and the small emittance of the beam can be preserved through the linac.

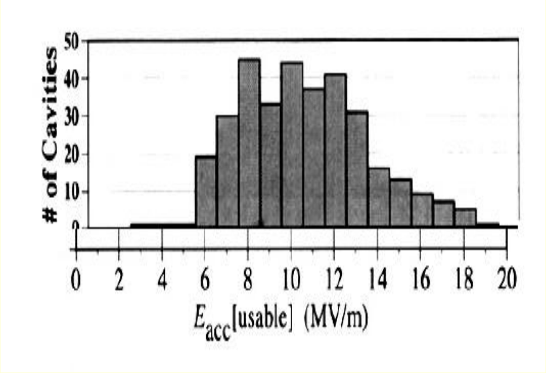


SOUTH LINAC CRYOMODULES



CEBAF is the largest SRF accelerator in operation in 2010. It has two 0.6 GeV linacs in the North and South tunnels, with 20 cryomodules each, and another 2¼ cryomodules in the injector making a total of 42¼ cryomodules. Each cryomodule has eight 5-cell cavities, making a total of 338 cavities. Having operated for more than 15 years it has accumulated more than 6 cryomodule-centuries of operating experience.

CEBAF 5-cell cavities operate at 1497 MHz with an active length of 50 cm each There are eight cavities per cryomodule The cavity design chosen for CEBAF was based on a Cornell design developed for storage rings. It met gradient and Q_0 requirements, damped higher-order modes well, and was proven in a beam test at CESR.

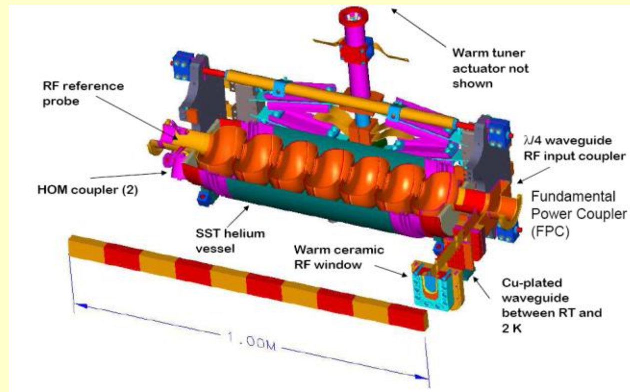


Usable gradients for CEBAF cavities at first installation. Most of the 42 cryomodules have been kept permanently cold since 1995. From October 2000 through June of 2001, CEBAF delivered more than 4500 beam hours for physics. SRF cavity related faults accounted for less than 0.5% down time. Cavity gradients are being steadily upgraded by re-processing from 7 to 15 MV/m.

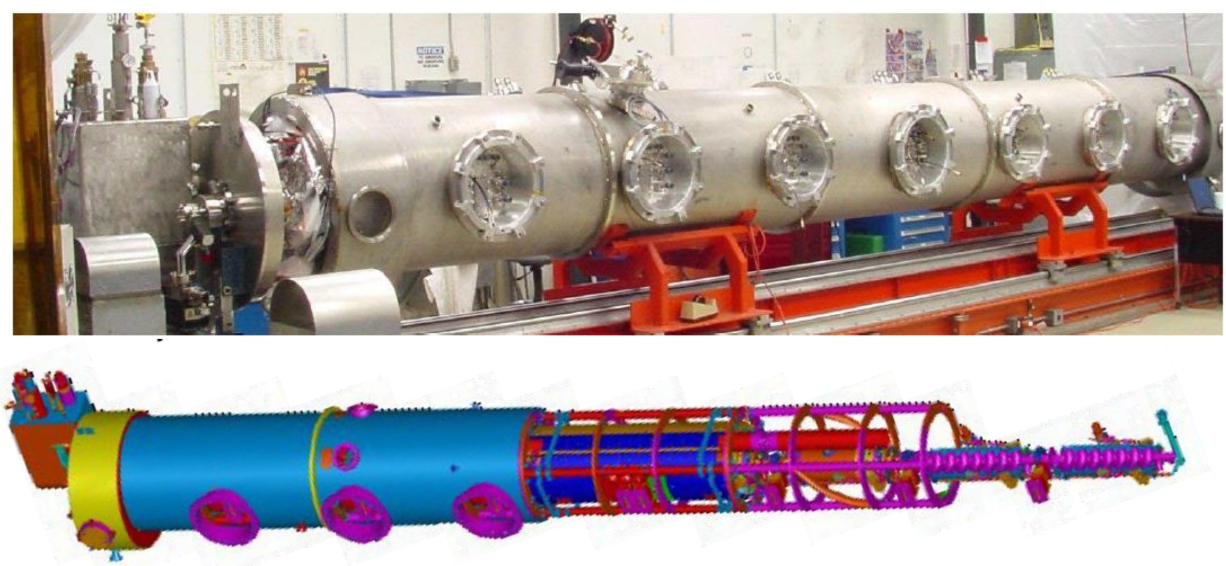
CEBAF Energy Upgrade

CEBAF will upgrade its energy from 6.5 to 12 GeV by adding 0.5 GV in each of its two linacs, so that each linac will deliver 1.1 GeV. The beam power will remain unchanged at one MW. Doubling the beam energy is an important priority for advancing understanding of the strong force and its manifestation in gluonic matter. The plan is to install a total of 10 new 100 MV cryomodules with 7-cell cavities operating at 18 MV/m. This should be compared to the original 30 MV per CEBAF cryomodule with original cavities operating at 7.5 MV/m. The size of the cryoplant will be doubled to provide 10 kW total at about 2 K .

CEBAF upgrade 7-cell cavity has the Low-Loss shape to reduce dynamic heat load and stiffeners for operational stability.

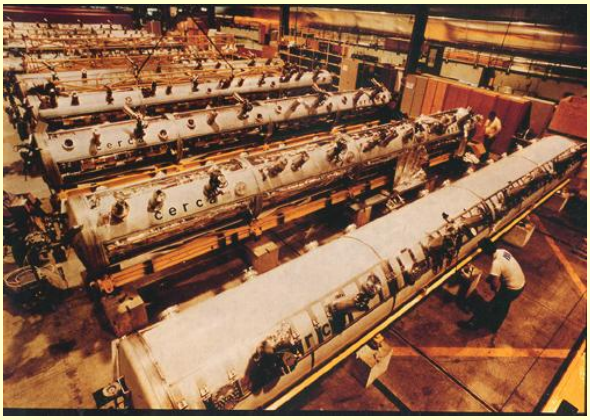


The CEBAF Upgrade cavity package, coaxial HOM couplers outside the He vessel, waveguide fundamental power coupler, and scissors type tuner.



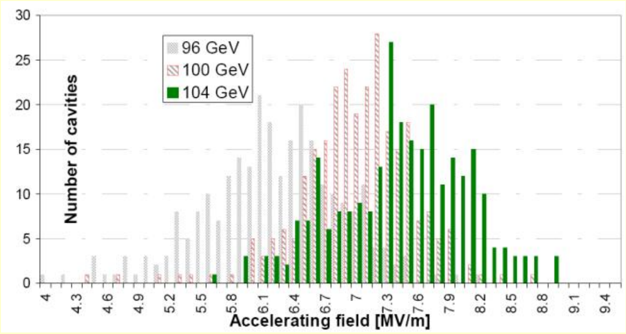
CEBAF Upgrade Cryomodule

350 MHz Nb/Cu Cavities for LEP-II



350 MHz Nb-Cu 4-cell cavities and cryomodules. More than 270 cavities were installed. Nb-Cu cavities will play an important role for low frequency cavities (100 – 350 MHz) , such as those needed for a future neutrino factory, or muon collider

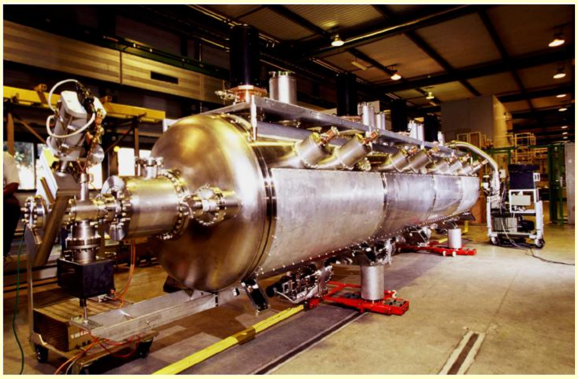
Instead of using bulk sheet niobium cavities, CERN adopted a unique approach for LEP-II : to sputter a thin film of niobium on to a copper cavity for thermal stability to avoid quench. The average in-line performance was 6 MV/m. During operation, LEP-II upgraded performance from 6 to 7 MV/m. During 1999 and 2000, the RF system was pushed to its absolute maximum limits for physics. By mid-2000 maximum total RF voltages of well over 3600 MV could be sustained, corresponding to average gradients approaching 7.2 MV/m. This level of performance was achieved by the very successful high-field conditioning with both pulsed and continuous RF. Slightly degraded cavities could generally be recovered and pushed gradually up to their maximum performance. LEP accumulated more than 4 cryomodule-centuries of operating experience.



Steady improvement in LEP-II cavity gradients

LHC, the New Frontier

With 14 TeV in the CM, the LHC will keep pace with the historical rate of energy growth. Built in the same tunnel as LEP, the LHC will collide 7 TeV high current proton beams, a significant push on the energy frontier beyond the Fermilab Tevatron. The luminosity goal for the LHC is 1000 times higher than the Tevatron. The LHC hopes to test several ideas that extend the Standard Model of Elementary Particles. One is the Higgs mechanism to explain the origin of mass. If the Higgs particle exists it would have a mass between 150 GeV and 1 TeV. Other ideas, such as supersymmetry, which provide candidate particles for "dark matter," and extra-dimensions could be some of the new discoveries that impact the frontiers of cosmology.



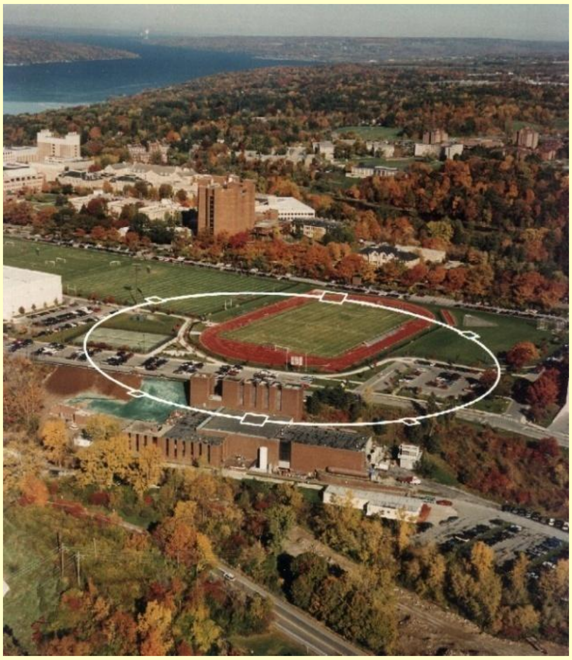
Superconducting cavities and cryomodules installed in the LHC, operating at an initial 7 TeV CM energy. At 400 MHz, 16 Nb-Cu cavities in 4 cryomodules provide 16 MV per beam and can deliver about 180 kW of beam power when needed. SRF cavities will help resolve the issue of transient beam loading by virtue of their low impedance and high cell voltage.

SRF at the Luminosity Frontier

High luminosity, electron-positron colliders gain important advantages from superconducting cavities. Ampere size beam currents are stored in a very large number of bunches, spaced very closely together. The high current and the tight bunch spacing make control of multibunch instabilities a serious issue. Since superconducting cavities economically provide higher CW gradients than copper cavities, the needed voltage can be provided by fewer cells, which means reduced beam-cavity interaction and reduced multibunch instabilities. Similar benefits arise for high current storage ring synchrotron radiation light sources.

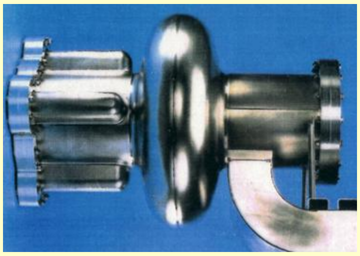
The high luminosity machines with SRF cavities are: CESR in the US, KEK-B in Japan, and the Beijing Electron Positron Collider in China. These colliders operate(d) for copious production of C- and B-quark mesons. From 1980 - 2000, the decays of B quarks at CESR provided a wealth of data to test the Standard Model of fundamental particle physics. Running with 4 SRF cavities, the availability of CESR between 1998 - 2003, was between 84 - 95% of the scheduled operating time. Over the same period CESR's beam current increased from 300 to 780 mA..

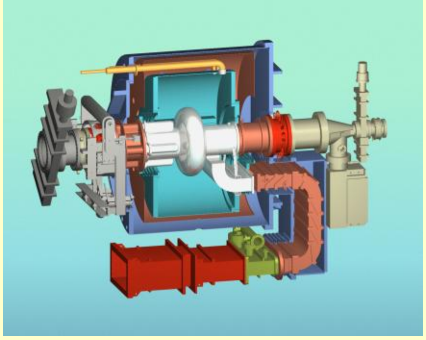
Peak luminosity	1.3×10^{33} $cm^{-2}s^{-1}$
Beam current	0.78 A
RF voltage with beam	1.85 MV/cavity (1.6 – 2)
Q_0	1×10^9 at 2 MV 0.3 – 1 $\times10^9$ at 2.7 MV
Max. power transferred to beam	300 kW/cavity (360 kW forward power)
HOM power	5.7 kW/cavity at 0.75 A



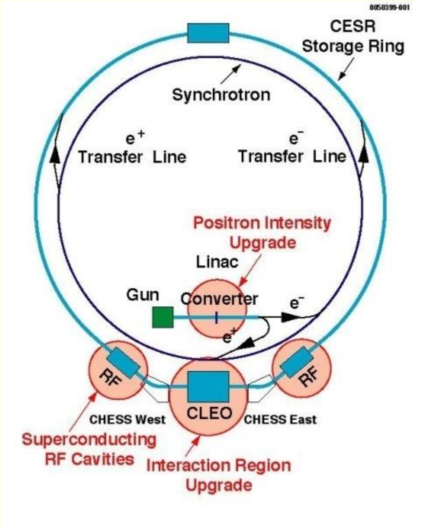
Highlights:

- **1994: Beam test, first demonstration of high current operation**
- **1997: First SRF cavity installed in CESR for routine operation**
- **1999: First storage ring to run entirely on SRF cavities**





CESR cavity and cryomodule.



CESR Storage Ring, site and layout.

KEK-B Factory

One of the outstanding problems of elementary particle physics is the very small asymmetry between the properties of matter and antimatter. Theory suggests that it is this slight imbalance in nature's otherwise symmetric order that led, during the first moments after the big bang, to the now observed predominance of matter over antimatter in the universe. The asymmetry is related to a phenomenon known as charge-parity (CP) violation. CP violation has now been observed in the B-meson system at the B-factories. Continued studies of CP violation will help to establish the complete mechanism. KEK-B is now the highest luminosity collider in history.

Peak luminosity	1.0567×10^{34} $cm^{-2}s^{-1}$
Beam current	1.1 A
RF voltage with beam	1.2 – 2.0 MV/cavity
Q_0	1 – 2 $\times 10^9$ at 2 MV 0.3 – 1 $\times 10^9$ at 2.5 MV
Max. power transferred to beam	380 kW/cavity
HOM power	10 kW/cavity at 1.1 A

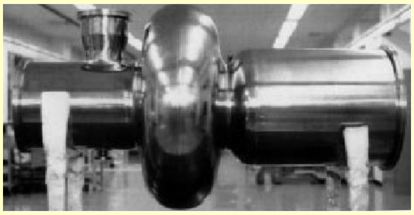
Highlights

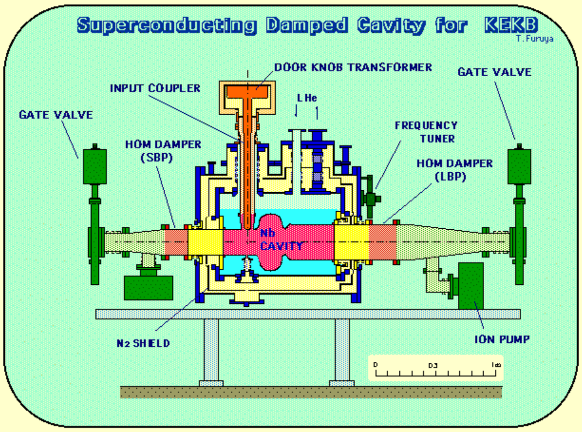
1996 Beam test in TRISTAN Accumulation Ring

1998 First four accelerating cavities installed in KEK-B, High Energy Ring

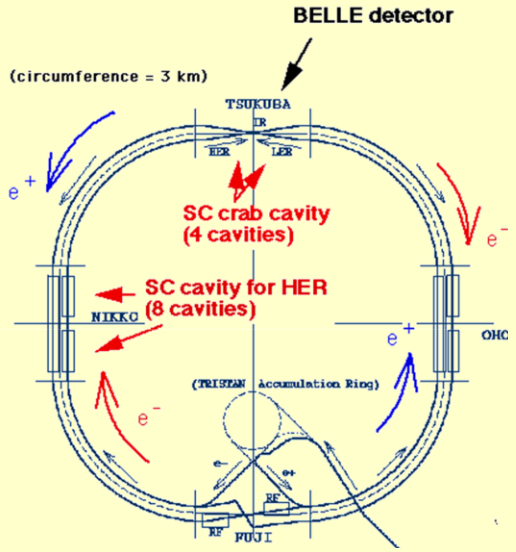
2000 Four more cavities added

2009 KEKB breaks world luminosity record with luminosity of 1.96 x 10^{34}/cm^2/sec using the Crab Cavities.





KEK-B cavity and cryomodule.

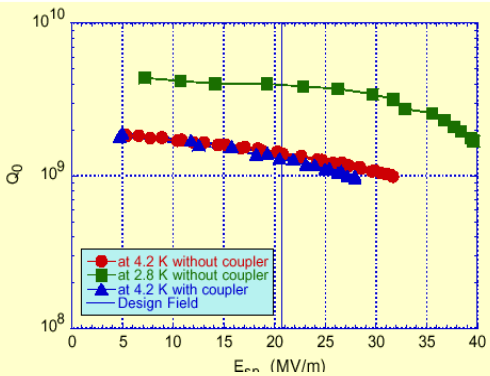


KEK-B storage ring site and layout.

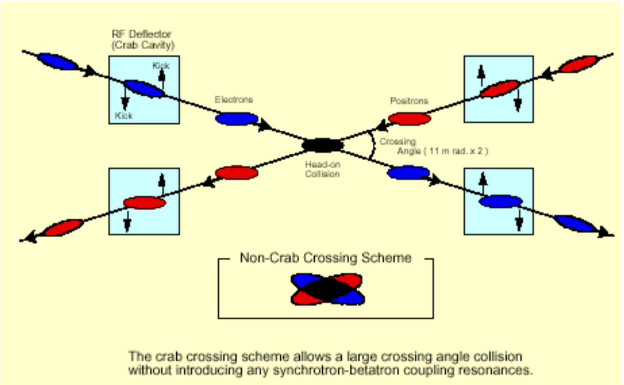
KEK-B Crab Cavities for Luminosity Upgrades

At KEK-B, two beams intersect at a finite angle (11 mrad). The angle crossing simplifies beam optics at collision and reduces background, but hurts luminosity because of the reduced geometrical overlap. To raise luminosity, rf deflectors called crab cavities tilt the bunches to head-on collision. The tilted motion of the bunches resembles the crawling motion of crabs; hence the name. The fields in the crab cavity installed near the collision point kick the heads and the tails of the bunches in opposite directions, starting an oscillation which results in a head-on collision at the interaction point. After collision, another set of crab cavities kick the bunches back to their original direction to re-enter the ring. Thus four crab cavities are generally required for a crab crossing. As a more economical first option, KEK adopted a modified crabbing scheme with just one crab cavity in each ring. The electron and positron bunches kicked by crab cavities wiggle around the ring and make a crab crossing at the collision point to reach a KEKB world luminosity record with luminosity of 1.96 x 10^{34}/cm^2/sec

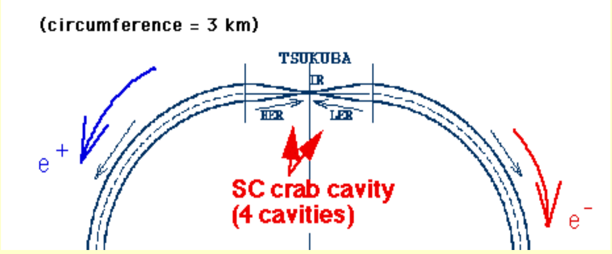
The crab cavity is 1m by 0.5m in cross -section.



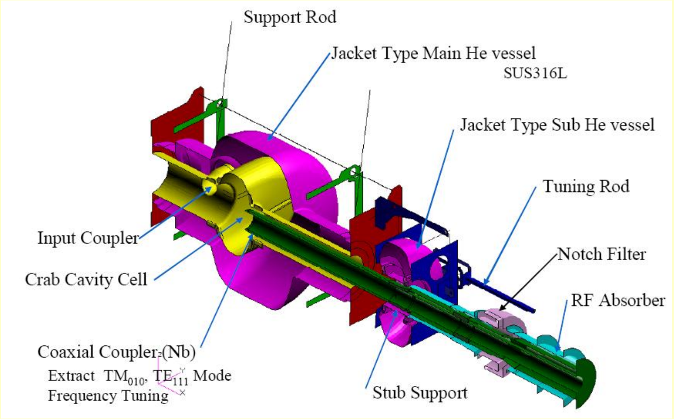
Performance of 500 MHz crab cavity The design kick is 1.44 MV, corresponding to peak surface fields of 21 MV/m and 60 mT.



The crab crossing scheme tilts the bunches to provide head-on collisions.



KEK-B collision point.

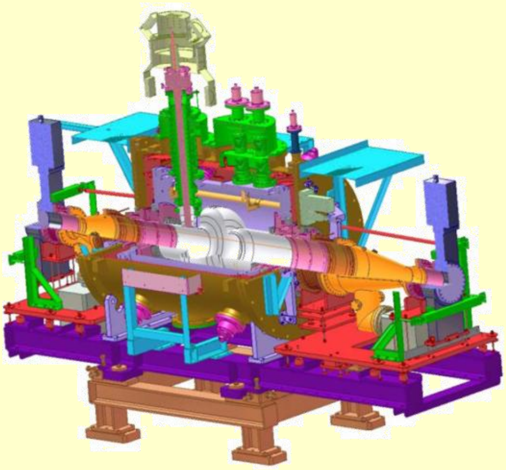


3D layout of the crab cavity in its helium vessel .

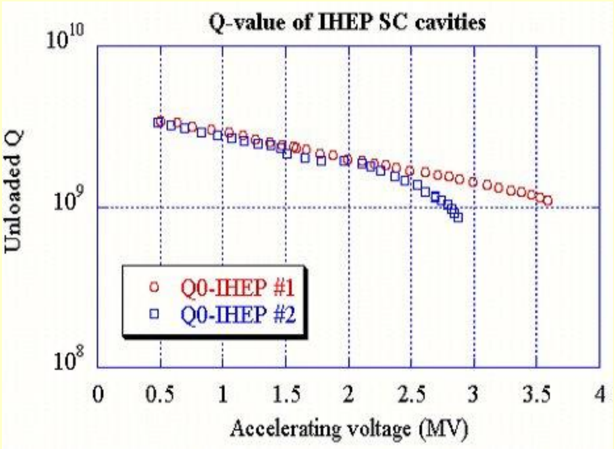
BEPC-II Beijing Electron Positron Collider

The Beijing Electron Positron Collider BEPC-II at the Institute of High Energy Physics (IHEP) in Beijing upgraded their beam energy from 1.55GeV to 1.89 GeV to run in the charm-quark regime. The luminosity of BEPC-II has reached to 2.3×10^{32} cgs units, with beam currents of 550 mA for both electrons and positrons. The detector has accumulated a large data set of more than 100 million ψ(2S) events for the excited state of the charmed quark mesons.

Inside the BEPC-II e+e- Storage Ring Collider.



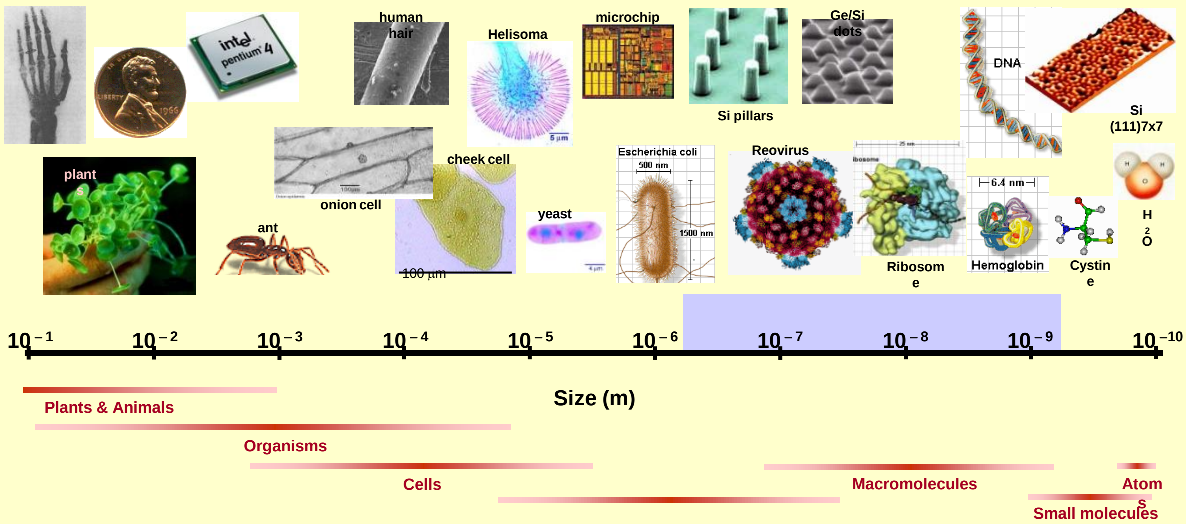
KEK-B module for BEPC-II .



Vertical test results at KEK for two BEPC cavities.

BEPC adopted the KEK-B module with a slight modification to adjust rf frequency from 508 to 500 MHz. Cavity performance in vertical tests is shown. Two cryomodules produced by KEK with industry exceeded 2 MV during horizontal tests.

STORAGE RING LIGHT SOURCES AND THE EVOLUTION OF IMAGING SCIENCE



Growth in Scientific Applications As X-Ray Wavelengths Get Shorter

Electron storage rings as x-radiation sources are having an enormous impact on materials and biological science. Molecular and electronic structure determination, elemental analysis, imaging and microtomography, are among the many applications. World-wide growth in storage-ring based synchrotron radiation (SR) sources has been phenomenal, from just a few machines in the late 1960’s to roughly 70 machines now either built or in advanced stages of development.

At CESR, CHESS has been operating as a prolific light source for two decades. After replacing the CESR copper RF system of 20 cells by a superconducting RF system with 4 cells, the beam current could be increased from 300 mA to 750 mA, and accordingly the SR flux.

CESR-based superconducting cavity systems have upgraded the Taiwan Light Source. The Canadian Light Source (CLS), the DIAMOND light source in England and the Shangai Light Source in China have installed CESR-based superconducting systems built by industry. Three CESR type single cell SRF cavities of ACCEL are working steadily on the SSRF storage ring providing 3-6MV accelerating voltage and transferring up to 600kW RF power to the stored beam.

A Saclay-CERN collaboration developed a 350 MHz Nb-Cu SRF system for SOLEIL and ESRF in France. BEPC in China is using SRF based on the the KEK-B system.

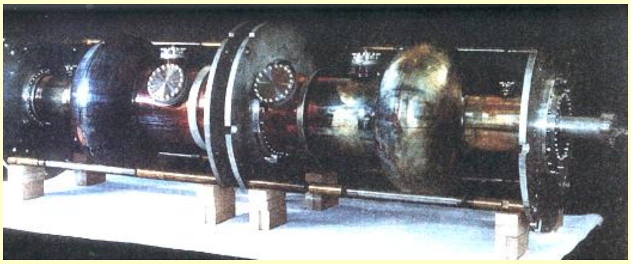
Storage Ring Light Sources

Cornell LEPP has transferred the technology of CESR cavities to industry which is providing turnkey systems for major storage ring light sources around the world.

CESR Technology Transfer to Industry

SOLEIL

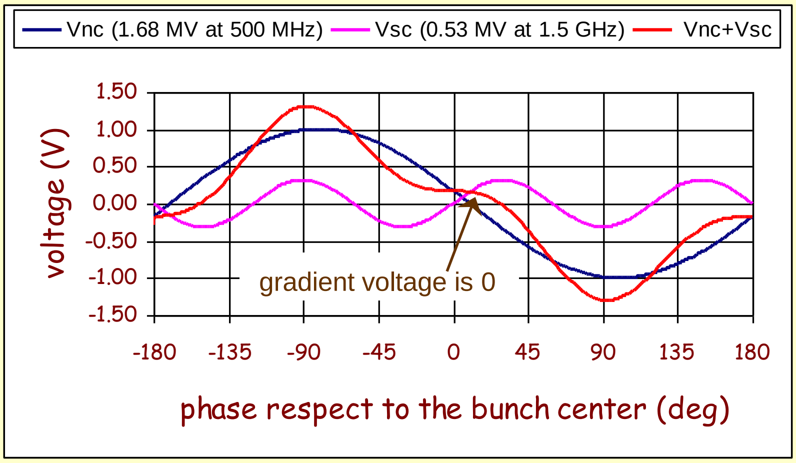
A 2.75 GeV, 500 mA Light Source



A pair of Nb/Cu single-cell HOM damped 352 MHz cavities, designed and built by a Saclay/CERN collaboration for SOLEIL and ESRF. The module (on the right) was high power tested at ESRF to Eacc of 7 MV/m and transferred 360 kW to 170 mA beam. Two modules have been installed and operated in SOLEIL to 300 mA beam current.

Third Harmonic Passive Cavities

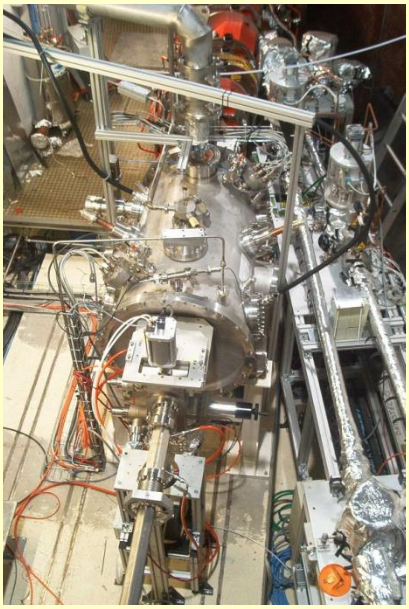
A 3rd harmonic (1.5 GHz) RF system in a storage ring allows bunch lengthening, decrease of charge density & increase of beam lifetime. Landau damping allows suppression of coupled bunch instabilities. After installation, both SLS and ELETTRA gained a factor of 3 on bunch lengthening and more than a factor of 2 on beam life-time.



Prototype 3rd harmonic Cavity Built at CERN, Sputter coated with niobium.

BESSY will use a 1/3 scale model of the CESR cavity.

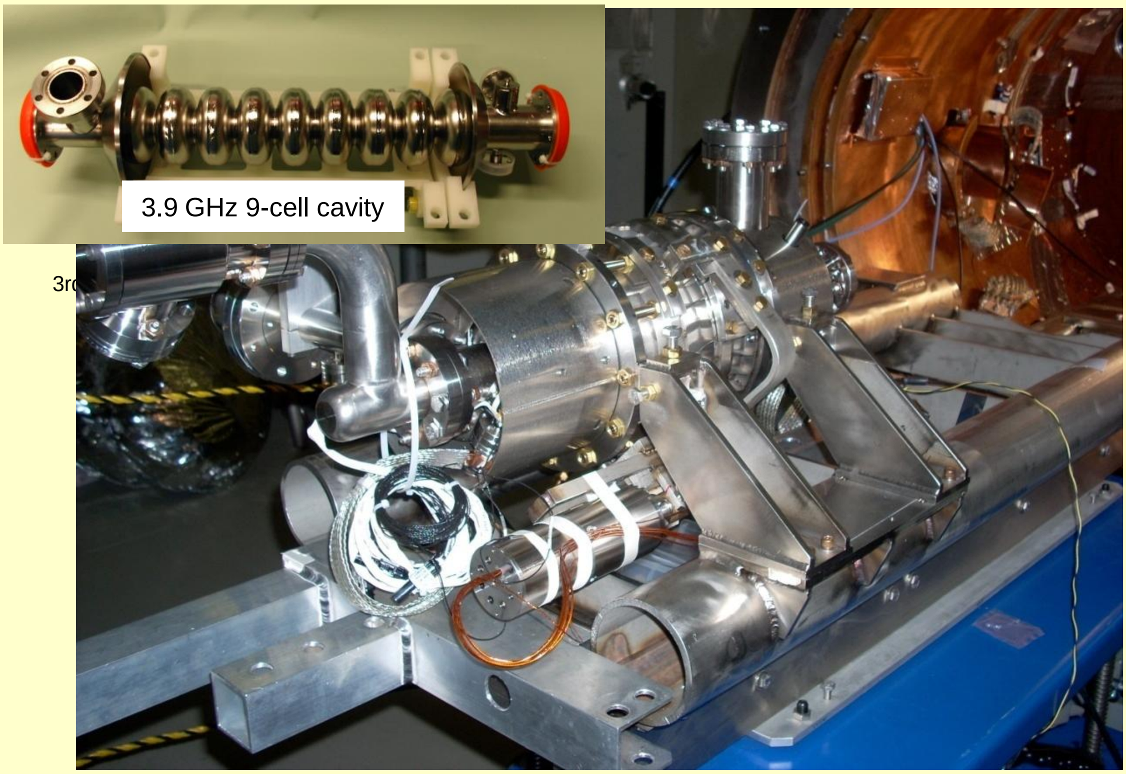
SLS Cryomodules.



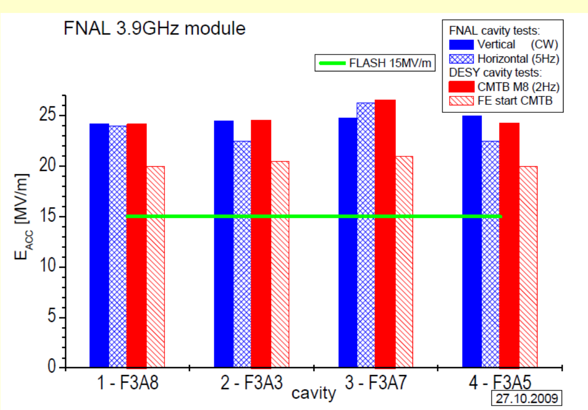
ELETTRA Cryomodule.

Third Harmonic Cavities for FLASH and XFEL

A 3rd harmonic RF system can be used in a linac for linearizing the RF wave-form to improve longitudinal beam emittance. FLASH at DESY plans to use a 3.9 GHz system to linearize the acceleration provided by the 1.3 GHz cavities. Fermilab built the cavities, cavity package and cryomodule of four 9-cell, 3.9 GHz cavities. The module ran in the horizontal test bed at DESY to 24 MV/m and helped reduce the shortest wavelength at FLASH from 6.5 nm to 4.5 nm.



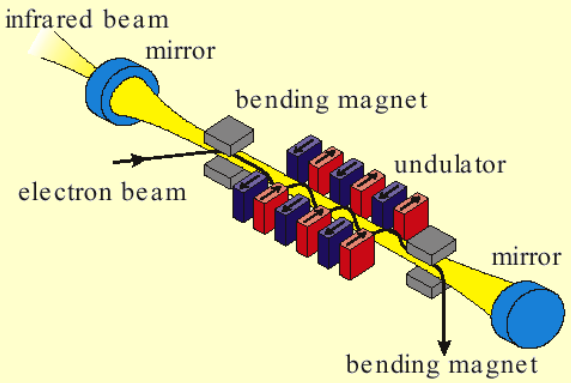
3.9 GHz cavity package showing 9-cell cavity in its helium-vessel, tuner, support and alignment, ready to be installed in a horizontal test cryostat at Fermilab .



Performance results comparison for vertical test, horizontal test at FNAL, and cryomodule test at DESY.

Clean Room assembly of four cavity package units at Fermilab.

FREE ELECTRON LASERS



Free Electron Lasers (FELs) are sources of tunable, coherent radiation at wavelengths covering a wide range from mm to the vacuum UV and soft X-rays. An FEL consists of an electron accelerator and a "wiggler" magnet. The magnetic field of the wiggler causes the electrons to oscillate transversely and radiate. These waves bunch the electrons causing them to radiate coherently near a resonant wavelength. In the oscillator configuration, the laser light reflects back and forth between the mirrors, gaining strength on each pass through the wiggler.

To achieve lasing, it is necessary to focus the electron beam inside the laser beam so that there is adequate spatial overlap between the two beams. Therefore good beam quality (i.e., low energy spread and low emittance) is essential for FEL operation. Linacs in general and SRF linacs in particular can deliver beams, which satisfy these requirements. The injector determines the emittance and energy spread. Sub-ps bunches are possible, whereas in storage rings typical rms bunch lengths are not shorter than about 10 ps. High-gradient, low impedance SRF structures allow the preservation of exceptional beam quality required for short wavelength FELs. Linacs can ensure exceptional amplitude and phase stability of the RF fields, at the 10^{-5} level (as for CEBAF) thereby ensuring minimum contribution to the energy spread.

Linacs demonstrate operational flexibility; changes in beam energy, bunch length, pulse patterns are all possible. SRF-driven FELs have reached unprecedented values wavelength and average output power.

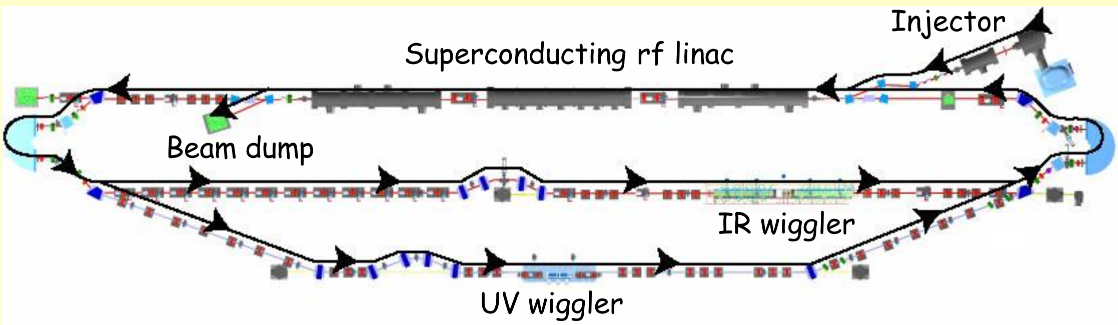
FELs offer many desirable characteristics over conventional lasers: wavelength tunability, high average power, and high efficiency of conversion of AC to laser power. High peak power and high average power infrared and ultraviolet FELs serve as valuable research tools in solid state physics, chemistry, biology and medicine. They offer a variety of applications in high-power microwaves, materials processing, surface processing, micro-machining, surgery, and defense.

The first FEL beam was demonstrated more than two decades ago with a 50-MeV beam from the SCA at Stanford. The SCA experiment at 1.6 micron wavelength converted more than 1% of beam energy to laser energy and made the first demonstration of energy recovery. Decelerating a 50-MeV beam to 5 MeV by recirculating through the linac at the appropriate phase required only 10% of the power in the recovery mode.

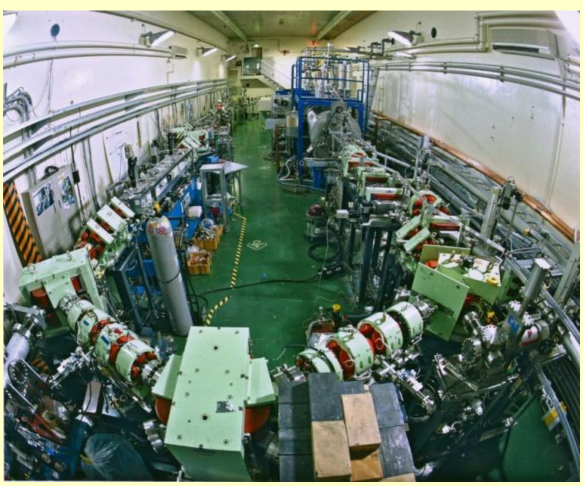
At the Stanford Picosecond FEL Center, the linac provided a 200 μA electron beam of high quality at energies from 15 MeV to 45 MeV. The beam drives FELs covering wavelengths from 3-13 μm and 15-65 μm. Experiments include infrared near-field spectroscopy of single living cells and synchronous pumping of an external optical cavity. The pico-second pulse train is suited to fast time domain studies, such as vibrational dynamics in condensed matter systems.

High Average Power FELs

The Jefferson Lab IR FEL has lased in the 1-6 μm wavelength range and reached average output power of 14 kW at 1.6 microns, the highest CW average power ever to be achieved. JLab runs in the energy recovery mode with more than 99.8% efficiency. More than 1.3 MW beam power was energy recovered with a beam of 9.1 mA at 150 MeV. This is an important milestone toward high beam power ERLs of the future Users pursue ultra-fast phenomena in condensed matter, atomic physics, chemistry and life sciences, as well as applications in micro-machining and ablation.

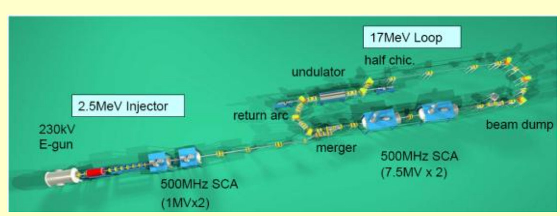


Layout of the Jlab IR FEL with UV upgrade. The FEL runs in the energy recovery mode. It comprises a 10 MeV injector, a linac consisting of three Jefferson Lab cryomodules generating a total of 80 to 160 MeV of energy gain, and a recirculator.



Main Accelerator Vault of JAEA (formerly JAERI) FEL.

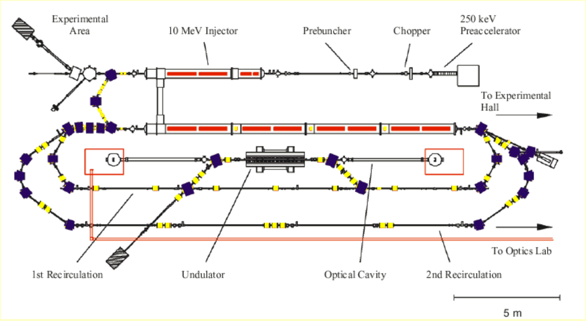
A 500 MHz superconducting linear accelerator at the Japan Atomic Energy Agency (JAEA) FEL provided quasi-CW far infrared laser of 1 ms long macro-pulse at 10 Hz repetition rate. The FEL is based on a 500 MHz SRF system with four cavities operating at *Eacc* = 5 MV/m (4.2K). The 17 MeV linac operates in a pulsed mode (1% duty factor) with a beam power of about 140 kW in the energy recovery mode. It lases between 1 and 22 mm with a laser power of 700 watts at 22 μm.



The JAEA FEL runs with 500 MHz superconducting cavities .

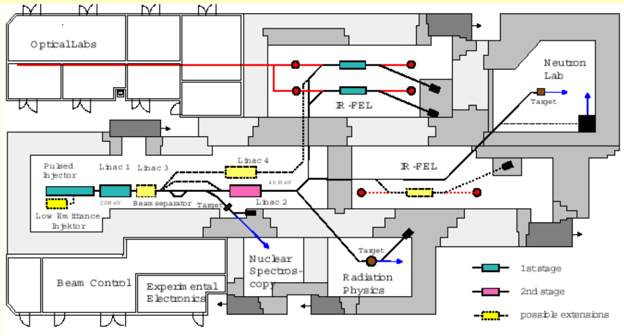
FELs in Europe

The S-DALINAC at Darmstadt drives an FEL with a CW recirculating linac operating at 3 GHz using 20-cell SRF cavities accelerating a 50 MeV beam. When diverted through a wiggler and mirror section, lasing takes place at 7.0 microns The radiation is used for experiments on the ablation of soft tissue. In the future, FEL efficiency will be increased by dynamic tapering of the undulator.

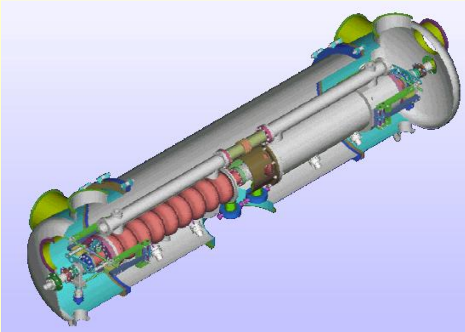


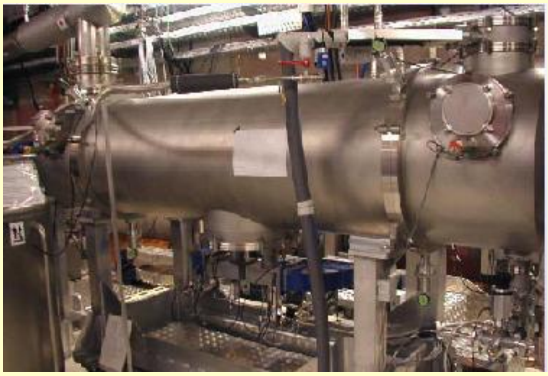
Layout of the S-Dalinac.

The radiation source ELBE at Rossendorf runs a superconducting 1300 MHz linear accelerator using TTF cavities that accelerate one mA electron beam to energies of 12 - 40 MeV. Two undulators allow access to a wide range of wavelengths. Two FELs operate in the mid and far infra-red. The facility also provides different beams for neutron production, positron production, bremstrahlung and x-radiation.



Beam Line layout of the ELBE Facility.

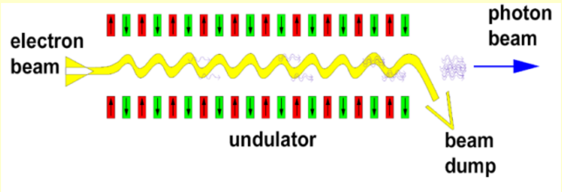




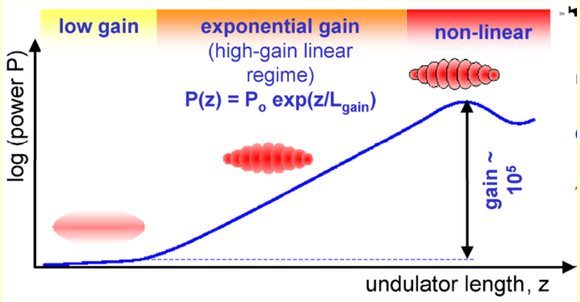
Rossendorf Cryostat, with two 9-cell cavities based on TELSA technology.

SASE: Self Amplification of Spontaneous Emission

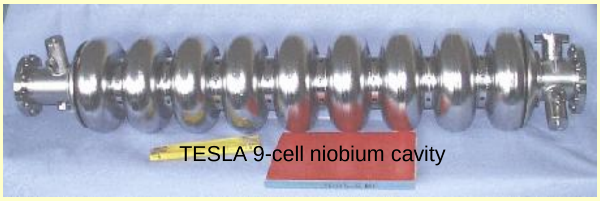
At ultra short wavelengths, less than 100 nm, mirrors are not available for FELs. In this case, coherent bunching of the electron beam develops in a single-pass through a long wiggler. As the bunch interacts with the undulator field, micro bunches develop which emit coherently. In the "high gain mode" the radiation field amplitude grows exponentially with distance along the undulator. The power increases as the square of the number of particles per bunch. This process is called Self-Amplified-Spontaneous-Emission (SASE). SASE FELs are the most attractive candidates for extremely high brilliance coherent light with wavelength in the angstrom regime.



The SASE principle : A short bunch of high intensity interacts with the undulator field of a long wiggler.

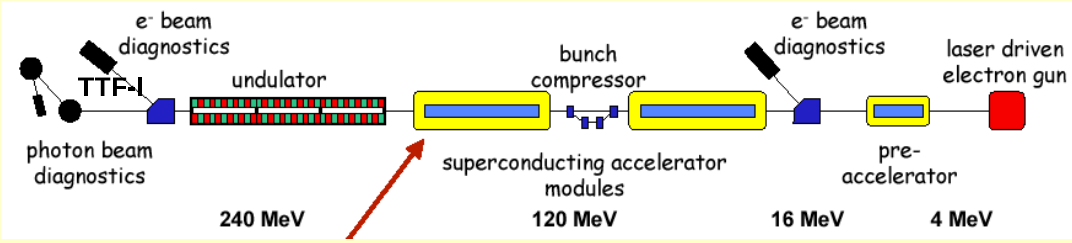


Micro bunches develop emitting photons coherently. The gain in power is exponential with undulator length until it reaches saturation at full bunching.



9-cell, 1.3 GHz niobium cavity

The TTF Linac operated 7 days per week, 24 hours per day. Approximately 50% time was allocated to FEL operation including a large percentage of user time.



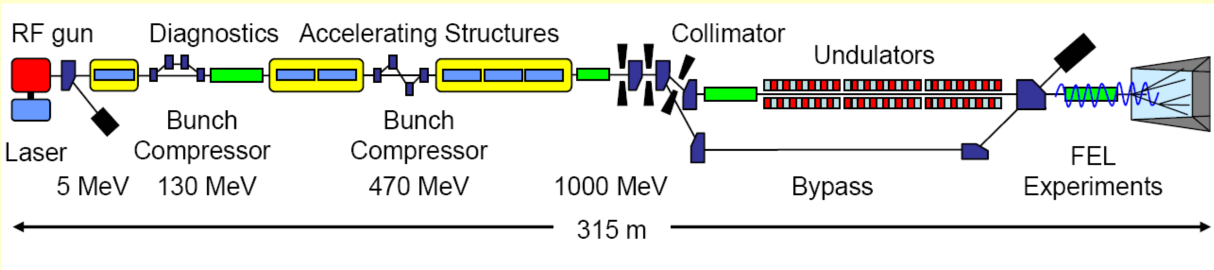
The first phase of the Tesla-Test-Facility (TTF).

The Tesla Test Facility (TTF) at DESY served a dual purpose. (1) To demonstrate a high gradient SRF linac to prepare for the future TeV energy Superconducting Linear Collider to complement the LHC. (2) To advance the science of SASE while providing UV to x-ray beams to a user facility. TTF has lased over a wavelength range from 80 nm to 180 nm, corresponding to a beam energy between 181 and 272 MeV, to demonstrate SASE saturation at the wavelength of 98 nm. Over 13,000 hours of operation, the average availability was 84%.

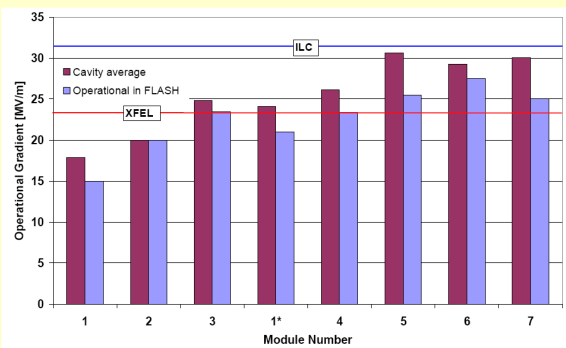
Inside the TTF- Linac.

Evolution of SASE FELs at DESY

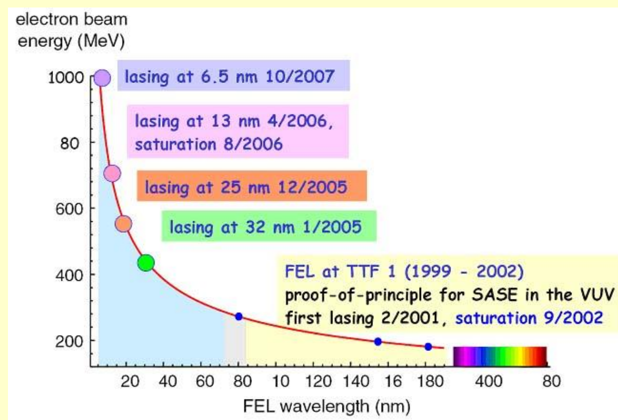
TTF has been upgraded to one GeV and re-named FLASH. A total of six modules installed have 48 cavities, some operating above 20 MV/m. An additional bunch compressor and an improved injector allow 2.5 kA peak current and a normalized emittance of 2 mm mrad. Lasing has been achieved near the expected minimum wavelength of 6 nm, with the use of a 30 m undulator.



FLASH: One GeV linac for SASE FEL to 6.6 nm.



Evolution of cryomodule gradients over installation history. The bar chart compares linac and cavity acceptance test results. The average degradation is a few MV/m. Module 6 has only cavities prepared by the latest techniques of electropolishing and baking.



Evolution of TTF wavelength and beam energy.

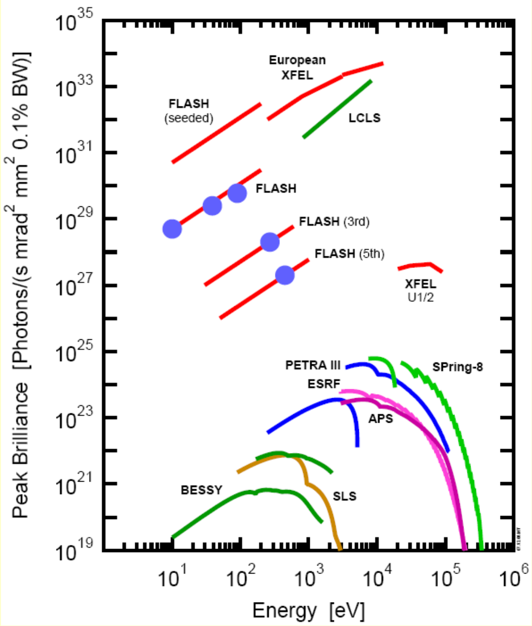
The successful completion of the first and second phases of the test facility demonstrated that superconducting 9-cell Nb cavities can reliably perform at 25 MV/m, as demonstrated by the results of modules 5, 6, and 7. A large fraction of these cavities were prepared by advanced methods of electropolishing and baking to demonstrate higher gradients. TTF/FLASH has proven to be an important test-bed for future SRF based accelerators.

Inside the FLASH Linac.

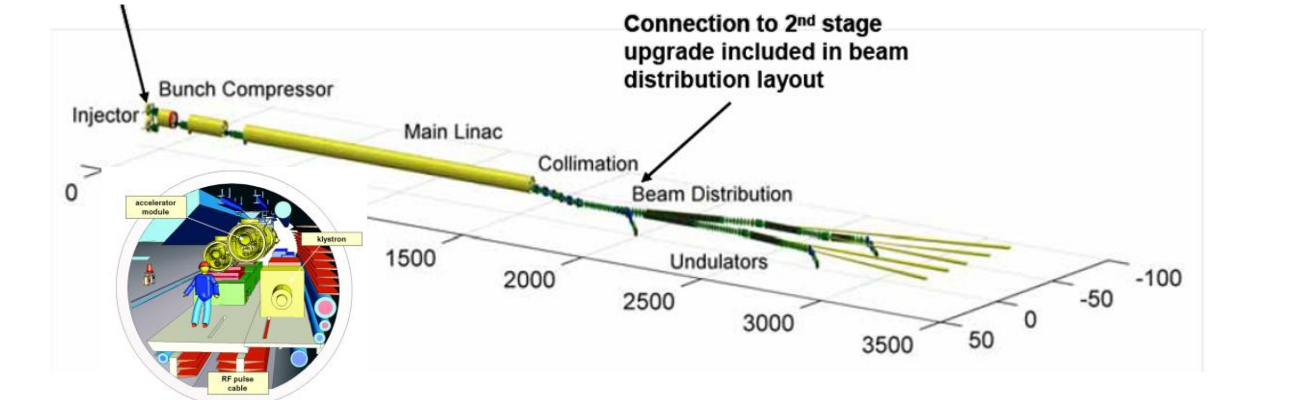
European X-Ray FEL

X-rays from storage ring based light sources, have played a crucial role in the study of structural and electronic properties of matter on an atomic scale for many decades. An exponentially increasing number of biological structures have been solved and deposited with the protein data bank. The growth trend is bound to continue, but there remain many challenges in structural biology, especially resolving systems that are difficult to crystallize.

Linear accelerator driven FELs using the SASE principle provide a promising approach to produce x-radiation with unprecedented quality, as well as a path for extension to the angstrom wavelength regime. With the ultra-high brilliance, coherence and ultra-short (10 - 100 fs) pulse length from FEL X-ray sources, the research will enter a new era, impacting the full span of materials and biological sciences. The femtosecond time scale opens the possibility for novel time exposure experiments in biological, chemical and physical processes to investigate structural changes. Ultimately it will become possible to acquire holographic snapshots with atomic resolution in space and time on the scale of chemical bond formation and breaking. The first high brilliance X-ray laser facility (LCLS) is operating, using 20 GeV electrons from the existing SLAC normal conducting 2.86 GHz linac.



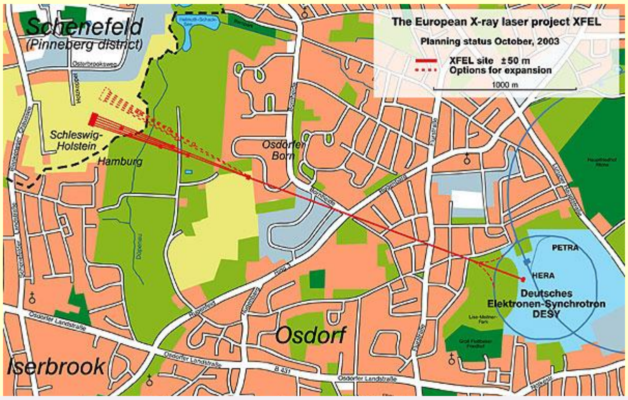
Comparison of the peak brilliance of the SASE light sources with 3rd generation storage ring light sources, showing ultimate gains of ten orders of magnitude.

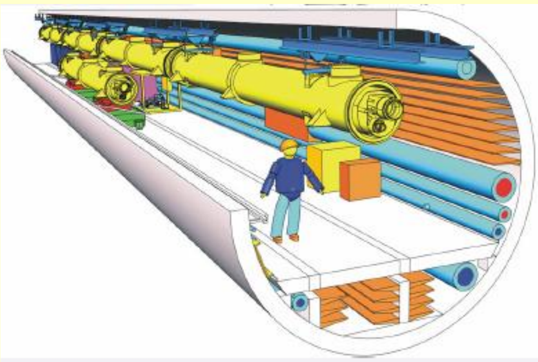


Layout of the European XFEL driven by a 20 GeV superconducting linac

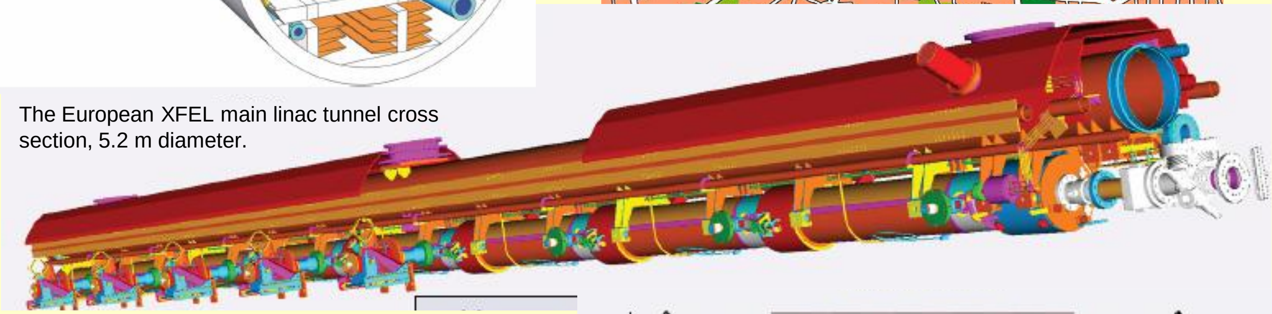
At the European XFEL under construction at DESY in Hamburg, Germany, a superconducting driver linac, modeled after the FLASH linac at DESY, will deliver short bunches ($\sigma_z = 25\ \mu m$) at maximum energy of 14.5 GeV to long undulators for SASE light generation. The nominal charge will be 1 nC and the intra-pulse repetition frequency will be 5 MHz. Operation in the short bunch-length regime presents considerable technical and beam dynamics challenges. The X-ray pulses will have a duration in the range of 10 to a few 100 femtosecond, with a peak power of tens of GW. The linac will be housed in a tunnel 15 to 30 m underground. The klystrons are in the tunnel and connected to the modulators in an easily accessible surface building on the DESY site by the high voltage pulse cables. The European XFEL main linac tunnel cross section, 5.2 m diameter tunnel. The accelerator modules will be suspended from the ceiling.

Layout of the European XFEL on the Hamburg site, showing the location of the DESY accelerators in the East

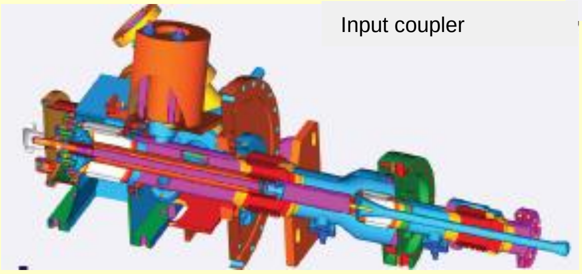




The European XFEL main linac tunnel cross section, 5.2 m diameter.



9-cell cavity, 800 needed.



Input coupler

HOM coupler

The main linac will have twelve meter long accelerator modules with 8 superconducting cavities each, grouped into about 20 rf stations. The linac will be housed in a tunnel 15 to 30 m underground. The required klystron power per station is about 5 MW,

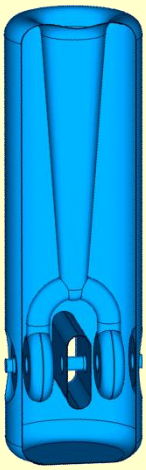
In total there will be about 800 cavities operating at a gradient of about 23 MV/m (for the Main Linac) and housed in 80 modules with about 25 RF stations. Industrialization of linac components will be one of the key tasks towards construction of future large accelerators such as the XFEL and the ILC.

Cavity string assembly in clean room at DESY.

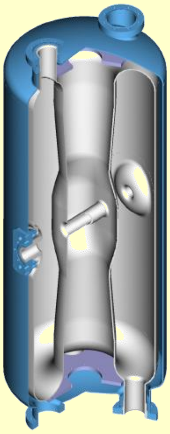
LOW AND MEDIUM VELOCITY STRUCTURES

Heavy-ion and proton accelerators must efficiently accelerate particles whose velocity changes along the accelerator. They must also be able to accelerate a variety of ions with different velocity profiles. Several structure geometries are therefore needed, each of which must be optimized for a particular velocity range. A major advantage of superconducting resonators is that a CW high voltage can be obtained in a short structure. The linac to boost ion energies can therefore be formed as an array of independently phased resonators, making it possible to vary the velocity profile of the machine. The superconducting booster is capable of accelerating a variety of ion species and charge states. An independently phased array forms a system which provides a high degree of operational flexibility and tolerates variations in the performance of individual cavities. Superconducting boosters show excellent transverse and longitudinal phase space properties, and excel in beam transmission and timing characteristics. Because of their intrinsic modularity, there is also the flexibility to increase the output energy by adding higher beta sections at the output, or to extend the mass range by adding lower β resonators at the input.

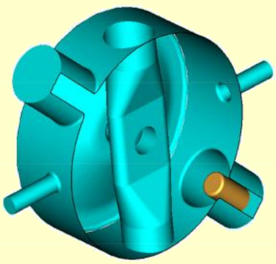
The Quarter-Wave resonator derives from transmission-line like elements and therefore belongs to the TEM resonator class. A coaxial line, $\lambda/2$ in length, when shorted at both ends forms a resonator with maximum electric field at $\lambda/4$. One or several field-free drift tubes hang from the center conductor in the maximum electric field region. The typical height is about one meter. The inner conductor, which is made from niobium, is hollow and filled with liquid helium. With a typical frequency of 100 - 200 MHz, 4.2 K operation is usual. Mechanical stability and phase stability are important issues, particularly for the lowest velocities and for small beam loading.



57.5 MHz QWR-based structures .02 < β < <0.14



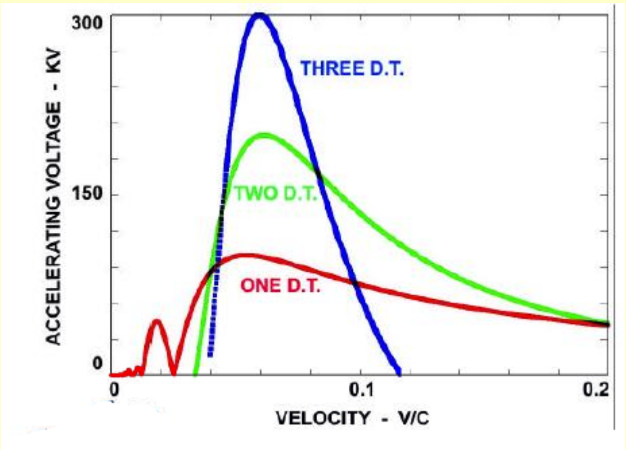
172.5 MHz, β = 0.14 Half Wave Resonator



LANL 350 MHz 2-gap Spoke resonator, β=0.175

The peak surface to accelerating field ratios are significantly higher in the low-velocity structures. For a gradient of 1 MV/m, the peak electric field typically ranges from 4 to 6 MV/m (compared to 2 to 2.6 MV/m for $\beta = 1$ structures) and the peak magnetic field ranges from 60 to 200 Oe (compared to 40 to 47 Oe for $\beta = 1$ structures).

Low-velocity structures also show multipacting which can be processed in a few hours.



Non-relativistic ion beams require a broad velocity acceptance. The more drift tubes (D.T.) in a structure the more the total voltage gain, but at the cost of a smaller velocity range.

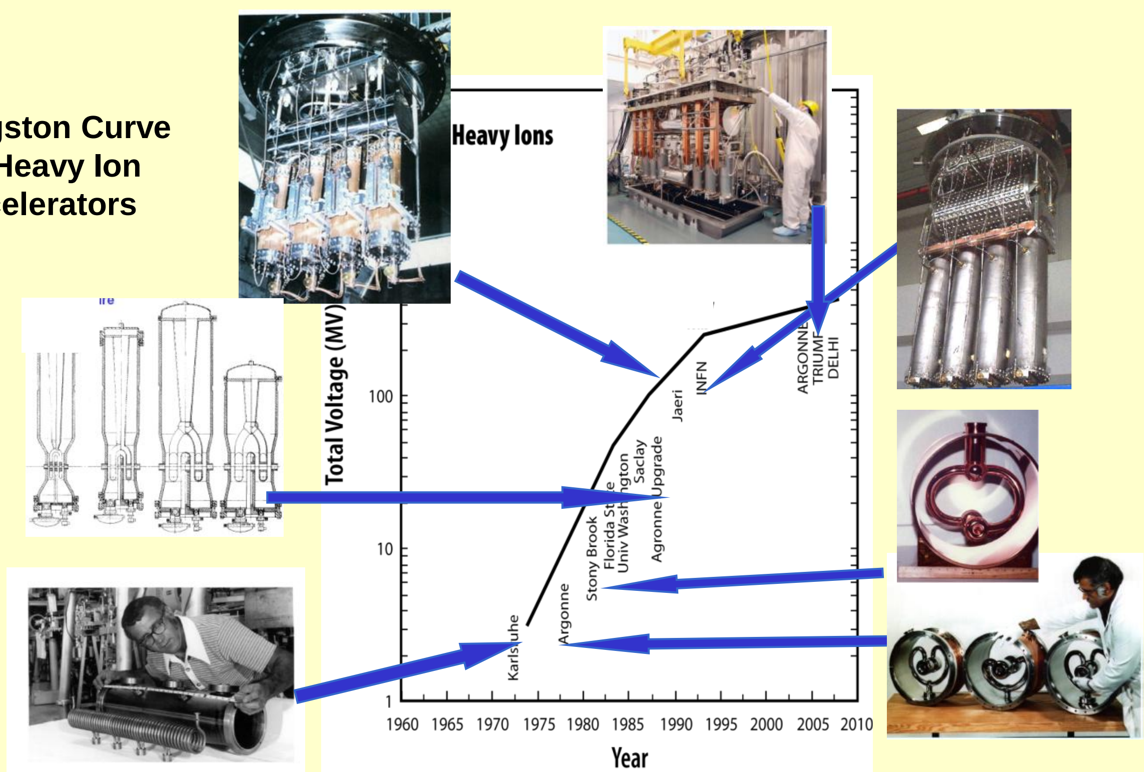
NUCLEAR SCIENCE WITH SUPERCONDUCTING HEAVY-ION ACCELERATORS

Superconducting linacs providing precision beams of heavy ions have consistently been one of the most successful applications. Heavy ions, from helium to uranium, are accelerated to energies from a few to 20 MeV/nucleon and used to bombard other nuclei. Above 5 MeV/nucleon, ions have sufficient energy to overcome the Coulomb barrier and penetrate the nucleus. The collisions cause energy, mass, and angular momentum to be transferred between the projectile and target nuclei, enabling structure research on the evolution of nuclear shape as a function of excitation energy and other aspects, such as spin.

At Argonne, ATLAS has been operating for more than 25 years as a national user facility for heavy-ion nuclear and atomic physics research, logging over 100,000 beam-on-target hours of operation, A major upgrade has been to replace the combination of negative ion source and tandem accelerator by an Electron Cyclotron Resonance (ECR) source and a new superconducting injector linac. A series of superconducting resonators span β values between 0.009 and 0.037. ECR ion sources have provided the Nuclear Science program with beams of virtually all stable isotopes at ever increasing intensities. A further Energy Upgrade project has increased ion beam energies by 30-40%.

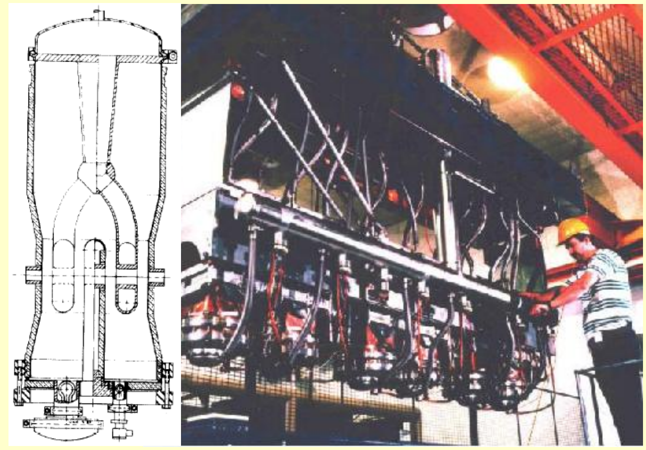
Besides the pioneer accelerators at Argonne and Stony Brook, eight heavy-ion accelerator facilities which have operated, or are still operating, utilized over 270 resonators made of niobium or lead-on-copper. These facilities are (were) located at the University of Washington, Florida State University, Kansas State University, CEA Saclay (France), JAERI (Tokai, Japan), and INFN (Legnaro, Italy), Australian National University. These accelerators provide beams with mass up to 100 atomic units and energies up to 25 MeV per nucleon. New heavy-ion accelerator facilities utilizing superconducting structures are under construction at, Sao Paolo (Brazil), New Delhi and Bombay.

Livingston Curve for Heavy Ion Accelerators



ATLAS (USA) and ALPI (ITALY)

Inside ATLAS at Argonne, in operation since 1978.

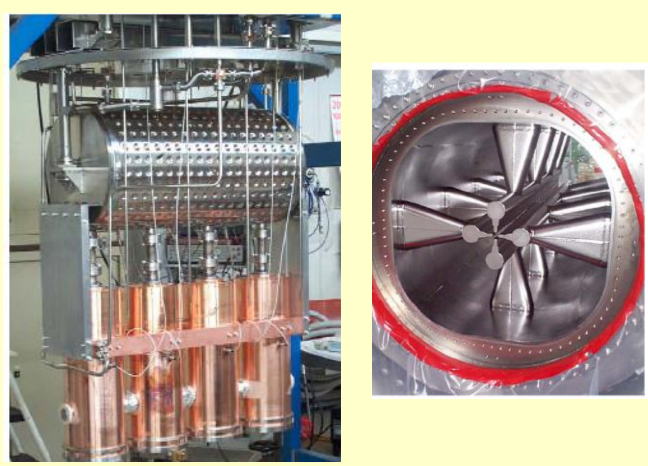


ATLAS Injector Cryomodule with inter-digital structures for particle velocities from 0.01c to 0.05 c (shown on left).

Energy upgrade cryomodule in the ATLAS tunnel.

ATLAS energy upgrade cryomodule with seven $\beta = 0.15$ structures (shown on left). The average accelerating gradient is 11.7 MV/m.

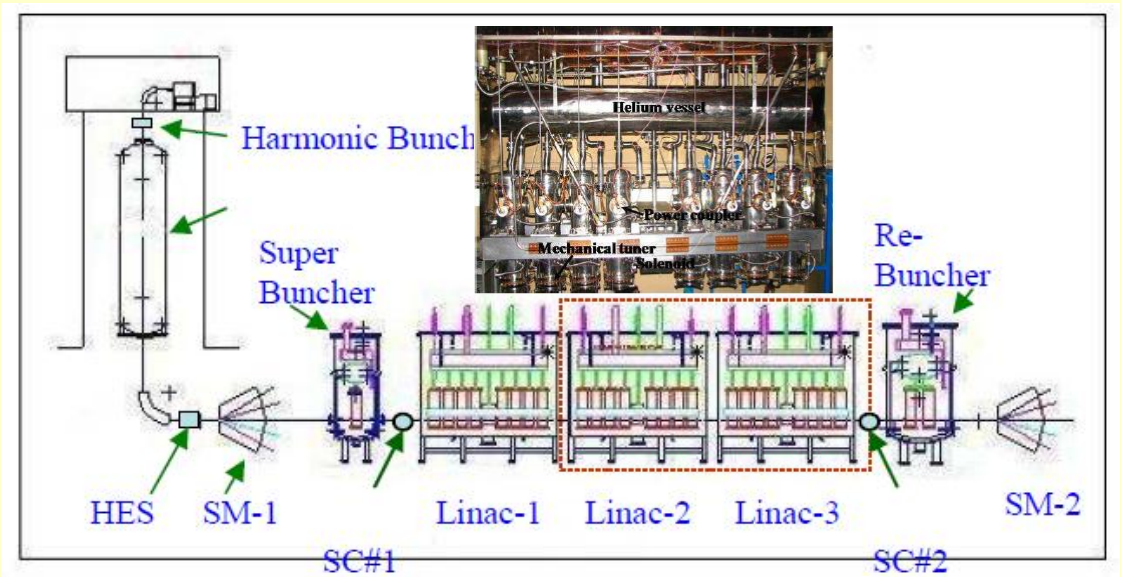
Inside ALPI at INFN Legnaro. ALPI has been in operation since 1994. In all, 64 QWR at 160 MHz are in the main beam line delivering a total of 49 MV. 44 cavities are medium β (0.11) and 8 are high β (0.13). 12 low β (0.055) resonators at 80 MHz are made from solid Nb. Both Nb and Nb-Cu resonators reached 6 to 8 MV/m at 7 watts in vertical tests.



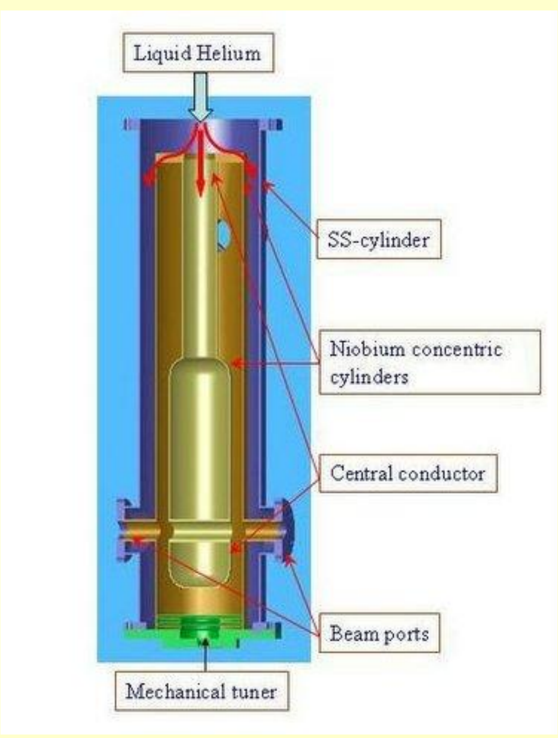
160 MHz medium beta PIAVE injector cryostat with Nb-Cu sputtered resonators. PIAVE extends the mass range of beams up to Uranium reaching 6 MeV/u of energy. In the very low β range from 0.01 to 0.05, the superconducting RFQ offers low power consumption for cw operation. Two structures delivered 4.7 MV in 2.13 m in PIAVE.

HEAVY- ION ACCELERATOR IN NEW DELHI, INDIA

A Superconducting linac booster is in operation for increasing the energy of heavy ions from the Pelletron at the Inter-University Accelerator Centre (IUAC), New Delhi. The linac requires 27 QWRs, of which 13 were built in collaboration with Argonne National Lab, and the rest in Delhi after a full suite of new SRF infrastructure was installed. The QWR is made of bulk Niobium operating at 97 MHz and optimized for β= 0.08. One module with eight cavities has been operated with beam.



Pelletron & Linac Booster at the Inter-University Accelerator Centre, New Delhi, India.



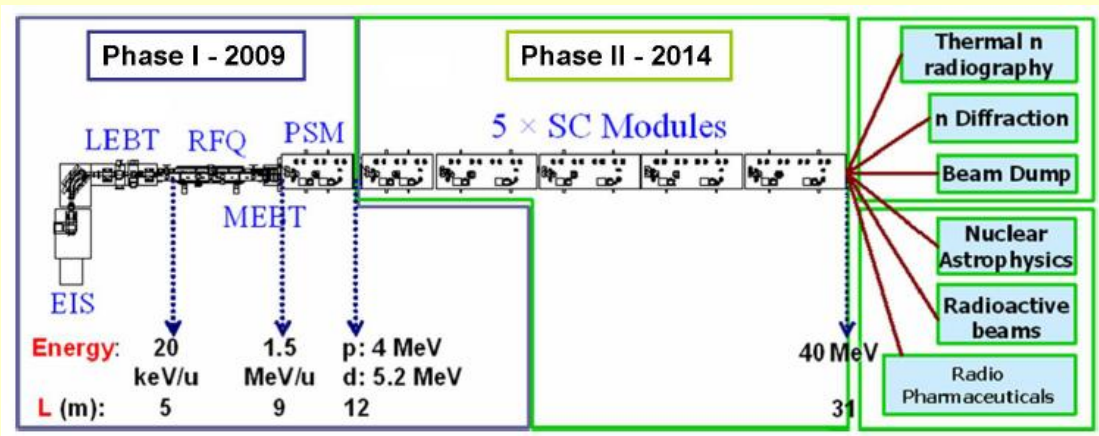
Design of the QWR for the Delhi booster at 97 MHz with β= 0.08.

Completed resonator made from solid Nb and electron beam welding.

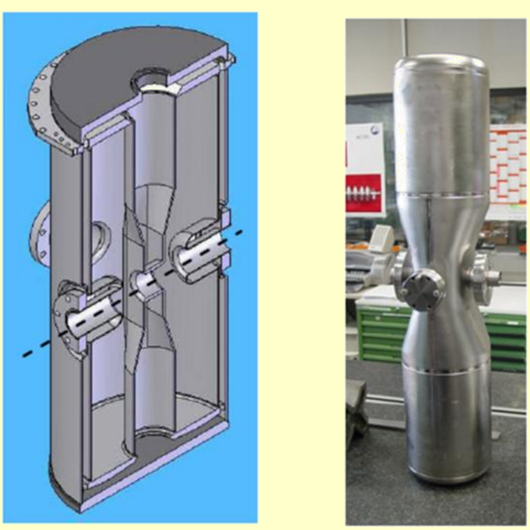
Linac for Protons and Deuterons in Israel

The SOREQ Institute in Yafne Israel has launched the SARAF project to install a linac for protons and deuterons to energies of 1.5 MeV/u as an alternative to cyclotrons. The energy will be variable from 5 - 40 MeV, and the CW maximum current 4 mA. It will have 48 Half-Wave Resonators at 176 MHz built by industry. The applications will be radioisotope production for medical use, nuclear physics, nuclear astrophysics and neutron physics. The design is based on two families, one with optimized $\beta = 0.09$, and the second with $\beta = 0.15$.

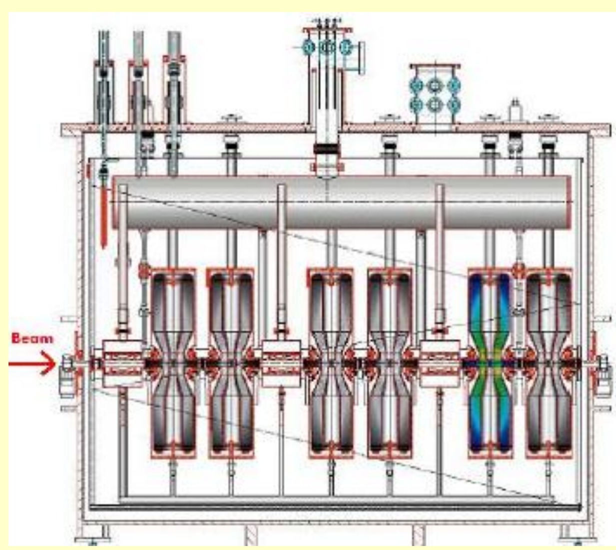
In the first phase, protons/deuterons starting from an ECR ion source, followed by 176 MHz RFQ will be accelerated to about 7 MeV by six half-wave $\beta = 0.09$ resonators. Resonators built in series production at ACCEL reached surface fields of 28 – 30 MV/m (*Epk/Ea* ~ 3) at 10 W dissipation.



SC linac for Medical Isotope Production in Israel.



(Left) 3D schematic of a Half-Wave resonator (HWR). (Right) 176 MHz, $\beta = 0.09$ HWR built for SARAF by ACCEL. The resonator height is 85 cm.

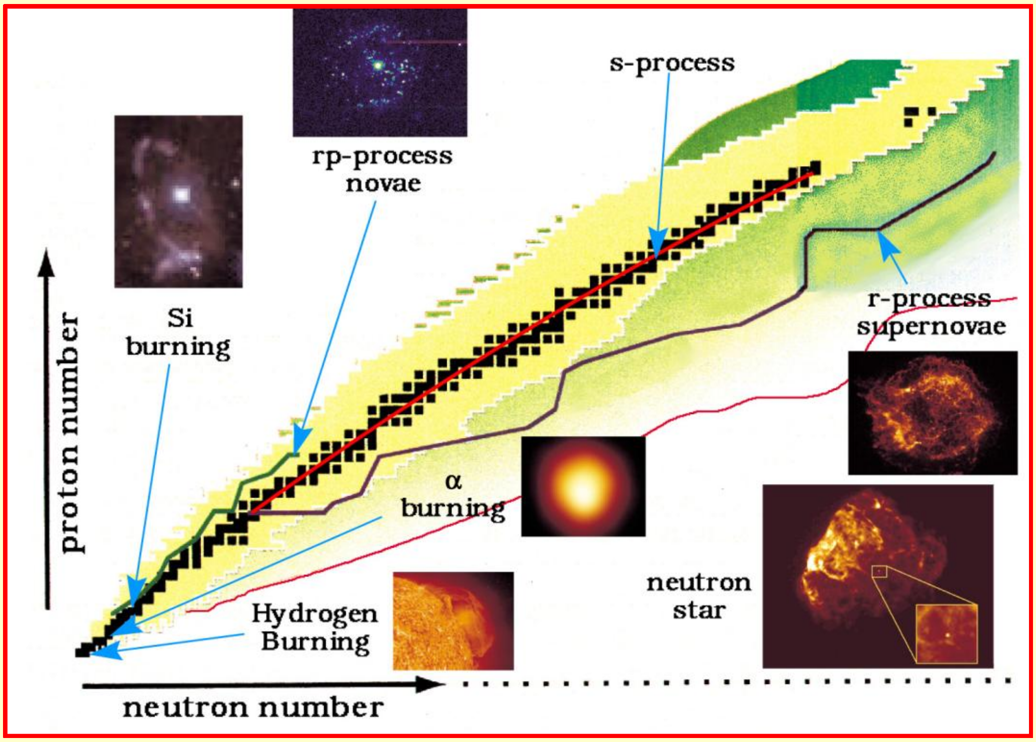


SARAF prototype module (PSM) with six HWR with $\beta = 0.09$ for Phase I.

NUCLEAR ASTROPHYSICS: RARE ISOTOPE BEAMS (RIB)

Several heavy ion accelerator facilities are preparing superconducting linacs to accelerate Rare Isotope Beams (RIBs) up to energies of at least 6.5 MeV per nucleon. Among other fundamental questions, experiments with the radioactive beams will provide basic insight into the origin of the heavy elements in supernovae. Through data on neutron rich weakly bound nuclei RIBs will promote further understanding of nuclear many body science.

As with most heavy ion boosters, the choice of short superconducting cavities, exhibiting wide velocity acceptance allows optimization of the output energy for each ion species by adjusting individual rf phases. Beam loading is an important consideration in the driver linacs and beam halo must be understood and controlled.



Proton-Neutron plot of stable and un-stable nuclei.

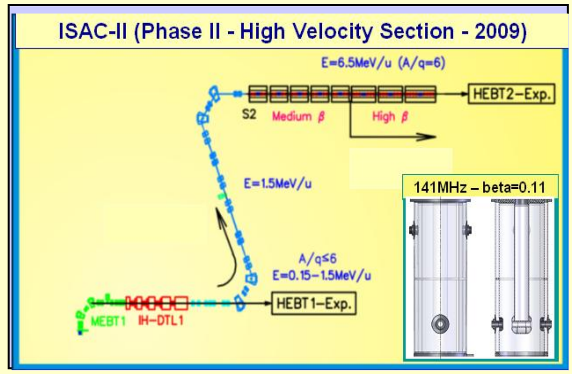
ISAC – II RIB at TRIUMF in Canada

TRIUMF in Canada is operating an Isotope Separation On Line (ISOL) facility based radioactive beam facility, ISAC, supplying both low-energy (60 kV, mass *A* = 238) and high energy (0.15-1.5 MeV/u, *A* = 30) experimental areas with exotic beams.

To extend the final energy to at least 6.5 MeV/u and mass range up to 150, TRIUMF is installing ISAC-II in two phases. The expansion adds a superconducting heavy ion linac supplying a total of 42.7 MV of acceleration. The linac will have three cavity geometries, all bulk niobium, two-gap quarter wave resonators with β values of 0.057, 0.071 and 0.11 and rf frequencies of 106.1 and 141.4 MHz respectively. The installation has been grouped into three stages.

In the first stage, there are twenty bulk niobium quarter wave cavities at 106MHz housed in five cryomodules, with four cavities per cryomodule. Each cryomodule is also equipped with a single superconducting solenoid of up to 9T in close proximity to the cavities. The cavities operate at 106MHz and produce an effective acceleration of >1.1MV for a cavity power of 7W at 4.2K. The average operating gradient corresponds to a peak surface field of 30-35MV/m and is significantly above the performance at other heavy ion linacs operating in CW mode.

ISAC-II Facility at TRIUMF.



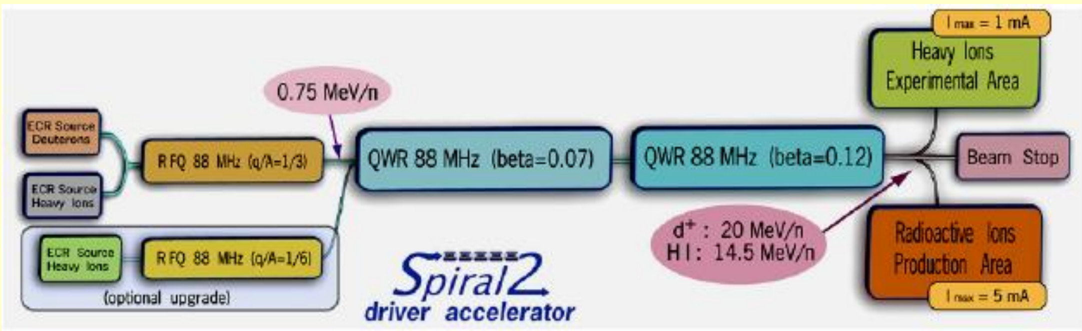
In the second stage (installation in 2010) another twenty cavities at β =*0.11* (141MHz) will raise the final energy to 6.5 MeV/u, doubling the voltage gain of ISAC-II. The cavities will be housed in three cryomodules with six cavities in each of the first two modules and eight cavities in the third. Each cryomodule has one superconducting solenoid symmetrically placed in the cryomodule. Production of the cavities is with a Canadian company, PAVAC Industries of Richmond, B.C.

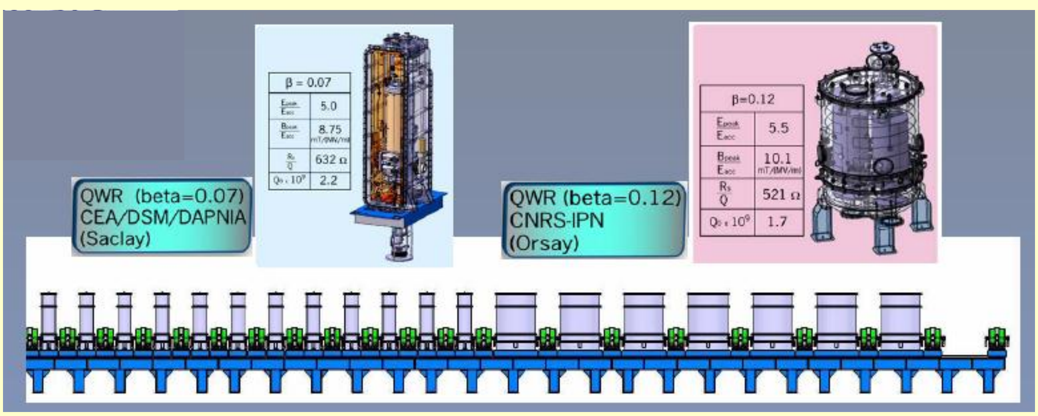
First cryomodule for Phase II.

Spiral - II RIB at GANIL in France

The GANIL facility in Caen, France is one of the major Rare Ion Beam (RIB) and stable ion beam facilities for nuclear physics, astrophysics and interdisciplinary research in Europe. It uses a cascade of three cyclotrons to accelerate the primary heavy ion beam The SPIRAL-2 upgrade is based on a high power, superconducting linac, which will deliver a high-intensity, 40 MeV deuteron beam as well as a variety of heavy-ion beams with mass-to-charge ratio of 3 and energy up to 14.5 MeV/nucleon.

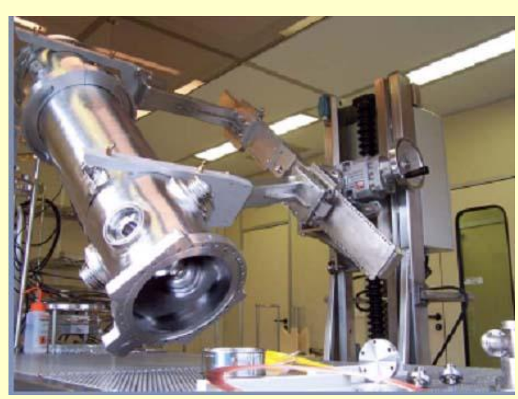
Acceleration is planned with twenty-six 88 MHz, quarter wave resonators, divided into two beta families (β=0.07 and β = 0.12). The low beta cavities and cryomodules (single resonator) will be developed at CEA-Saclay, while the high beta ones (two resonators per module) at IPN-Orsay. Prototypes of each cavity type have been built, prepared and tested in vertical cryostats.   The resonators have demonstrated gradients of 9 and 11 MV/m in qualifying tests. The first operation is scheduled for 2012.





Layout of two types of QWR.

High beta cryomodule by Orsay.



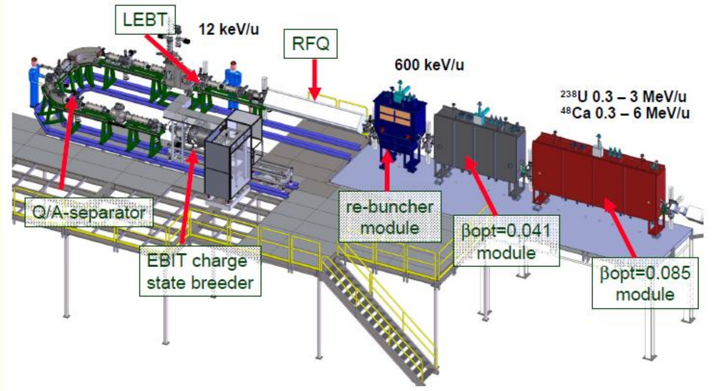
Low beta resonator by Saclay for Spiral-II.

NSCL RIB , Michigan State University (USA)

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is constructing a reaccelerated beam facility, ReA3, to provide unique low-energy rare isotope beams by stopping fast rare isotopes in gas stopping systems and reaccelerating them in a compact linac to provide opportunities for experiments ranging from low energy Coulomb excitation to high energy studies of astrophysical reactions. Beams from ReA3 will range in energy from 0.3 to 6 MeV/u: the maximum energy is 3 MeV/u for heavy nuclei such as uranium, and 6 MeV/u for ions with A<50, The superconducting linac will use quarter-wave resonators with β of 0.041 and 0.085, together with superconducting solenoid magnets for transverse focusing and dipole coils for alignment error corrections. A total of three cryomodules consisting of fifteen 80.5 MHz QWR SRF cavities will be used.

In rf tests, the 0.041β QWR exceeded a surface field of 50 MV/m at 4.2 K compared to the design field of 16.5 MV/m. The 0.085β QWR exceeded 30 MV/m compared to the design field of 20 MV/m. A prototype cryomodule has been designed and fabricated. The module consists of an 80.5 MHz, 0.085β, QWR cavity, a 322 MHz, 0.285β HWR cavity, a superconducting dipole solenoid and quadrupole.

A second stage is the planned as an extension of the ReA3 linac to a maximum energy of 12 MeV/u for uranium and up to about 20 MeV/u for lighter nuclei, called ReA12. This upgrade is an essential part of the FRIB project. The ReA12 upgrade will require three additional cryomodules with *βopt=0.085* cavities identical to the third cryomodule of ReA3.

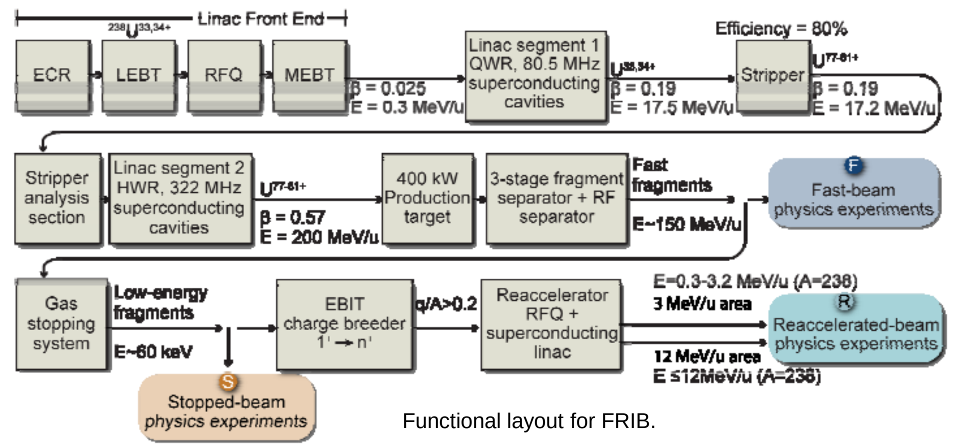


A prototype cryomodule housing a quarter-wave and a half-wave structure along with focusing magnets.

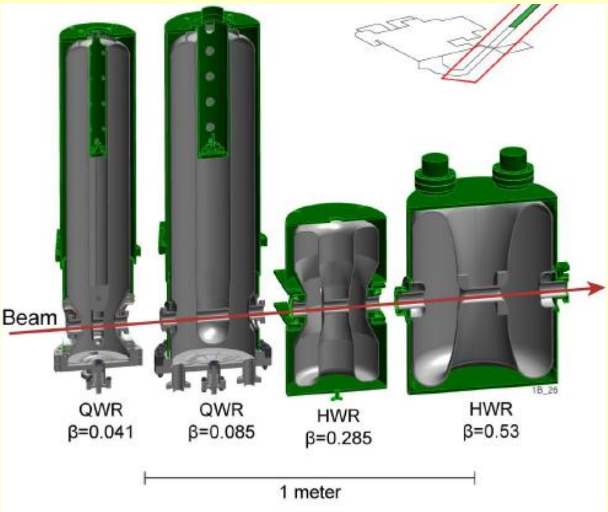
Quarter wave resonator designs for ReAccelerator3.

FRIB: A New Accelerator Facility for the Production of Rare Isotope Beams -- Michigan State University (USA)

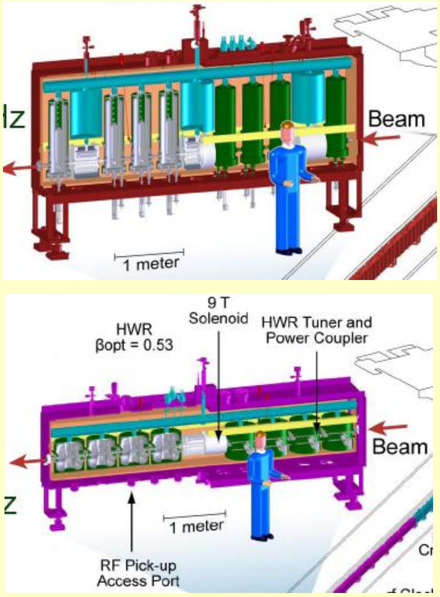
One of its highest recommendations of The Long Range Plan for Nuclear Science is the construction of a Facility for Rare Isotope Beams (FRIB) for the study of nuclear structure, nuclear reactions, and nuclear astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, and provide an understanding of matter in the crust of neutron stars. It will permit sensitive tests of the fundamental symmetries of nature. In addition, FRIB will provide a source of rare isotopes for medicine with new and improved applications. A superconducting heavy-ion driver linac will be used to provide stable beams of >200 MeV/u at beam powers up to 400 kW that will be used to produce rare isotopes. After stripping, Segment 2 of the driver linac will accelerate up to five charge states to energies of at least 200 MeV/u for uranium with a beam power of 400 kW. Linac Segment 2 will use two types (*βopt* = 0.285 and 0.53) of Half Wave Resonators (HWRs) operating at a frequency of 322 MHz. In all, there will be a total of 335 resonators in 45 cryomodules. This will be the world's largest heavy ion accelerator.



Functional layout for FRIB.



Resonator geometries for FRIB. There will be 335 of these resonators in two linacs.



Cryomodule layouts for the QWR and HWR resonators. There will be 45 cryomodules in all.

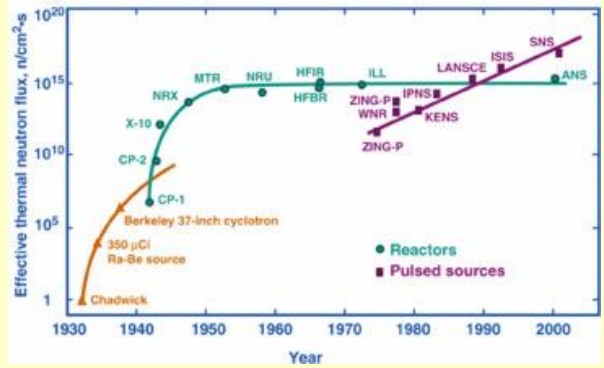
ACCELERATOR-BASED NEUTRON SOURCES

Neutron scattering is an important tool for material science, chemistry and life science. For example, neutron scattering studies have played a major role in elucidating the structure of high temperature superconductors. It is possible to sensitively detect the presence of light oxygen atoms among heavy neighboring atoms of Cu and Y. In polymers, hydrogen atoms can be located precisely with neutrons, but not with x-rays. Neutrons are also used to probe structure, dynamics, and properties of magnetic materials. Since the penetration of neutrons is relatively deep, it is possible to study strain distribution in bulk materials, such as welded sections.

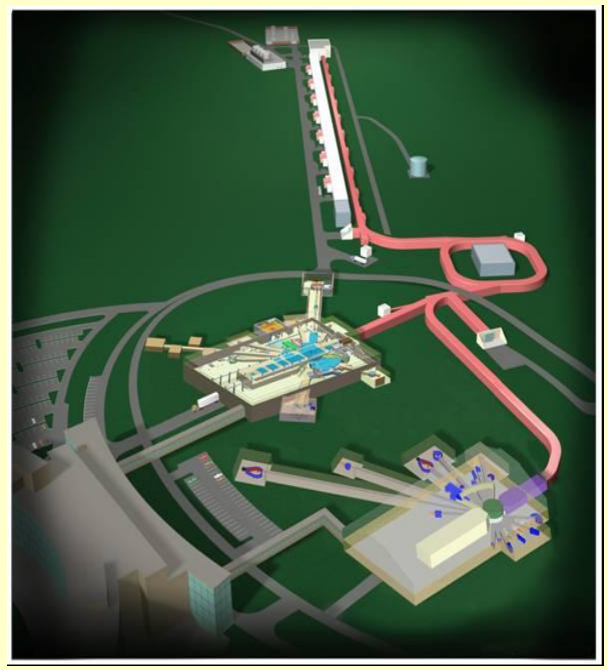
To increase the capability for such studies, higher neutron flux is desired. For many years, nuclear reactors were the main rich source of neutrons. Since neutrons emerging from reactors must be slowed down in a hydrogen-rich moderator to useful energies, a large fraction is lost in the moderator. A serious obstacle to advanced reactor based sources is environmental unpopularity, adding to the large inventory of fissile material already built up. Therefore there is a very strong incentive to push accelerator-based neutron sources.

Although lower in flux, accelerator-based pulsed neutron sources have begun to compete with reactors. High energy (1-GeV) protons produce neutrons by hitting a heavy metal target and exciting nuclei to energies where neutrons are “evaporated" in a process referred to as spallation.

Accelerator based neutron sources provide high peak intensity and very short (ms) pulses at rep rates of the order of 50 Hz. The advantage of short pulses is it that becomes possible to use time-of-flight measurements to determine the incident neutron energy, eliminating the need for monochromatization and the accompanying waste of neutrons.



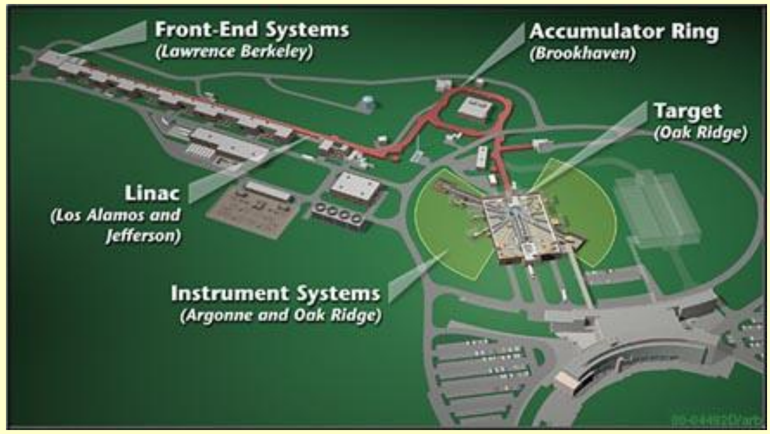
The highest intensity accelerator-based neutron sources in operation today are LANSCE at Los Alamos and ISIS at Rutherford Lab. The SNS at Oak Ridge National Lab is the first advanced pulsed spallation source with 1.4 MW of beam power at the target, upgradable to 5 MW. 6 Partner Labs: ANL, BNL, JLAB, LANL, LBNL, ORNL built SNS at ORNL in Oak Ridge Tennessee.

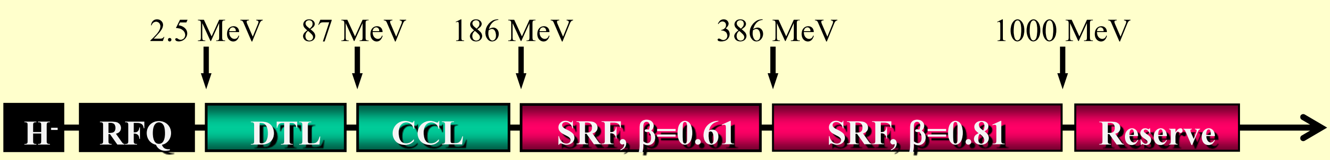


Layout for SNS and upgrade plans.

SNS : First High Intensity Superconducting Proton Linac

A 1.4 MW proton linac from 200 MeV to 1000 MeV, based on 804 MHz superconducting cavities, drives SNS at Oak Ridge National Laboratory in Tennessee. As one of the partner labs, JLAB was responsible for SRF design and construction. There are a total of 81 (one meter-long) cavities operating at 804 MHz. 11 medium-beta cryomodules have three cavities each, and 12 high-beta cryomodules have four cavities each. Performance at design specifications of 15 MV/m has been achieved for most of the cryomodules at SNS. The beam energy of 1000 MeV and beam power of 1 MW has been achieved.





Accelerator layout

Medium beta cavity

High beta cavity

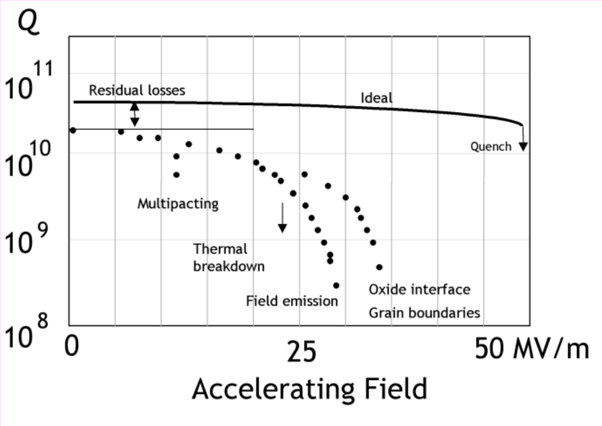
Cavity and helium-vessel string in clean room.

23 Cryomodules installed and operating at SNS.

BASIC RESEARCH IN SRF

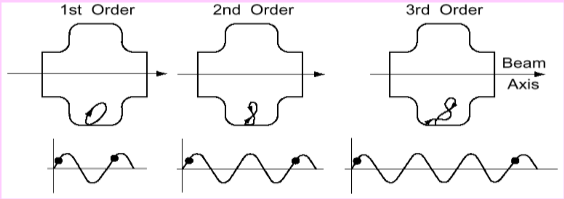
The operating gradient of cavities in accelerators today range from 5 to 20 MV/m, depending largely on when in the development history of SRF these cavities were installed. The history of advances in superconducting cavities shows that cavity performance has improved steadily over time as research penetrated gradient and *Q* limiting mechanisms, gleaned understanding, and developed techniques to overcome limits. Today, full-scale structures reach gradients of 25 - 40 MV/m in laboratory tests and in off-line cryomodules. Therefore future accelerators can anticipate to capitalize on these advances in the near future.

For the far future, gradients of 40 – 50 MV/m may become accessible based on results from single cell cavities which exceed accelerating fields of 50 MV/m, not far from the theoretical limit imposed by the RF critical field.



Ideally we would expect the cavity *Q* to remain constant (at the BCS predicted value) as the field increases, until the quench field. However, as surface electric and magnetic fields rise, several effects set in to drop the *Q*. These are multipacting, thermal breakdown, medium field slope, field emission, and high field *Q*-drop. Most of these effects are now understood and solutions invented.

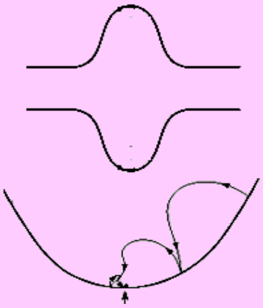
Multipacting and Its Cure



High Field ***Low Field***

In the early stages of SRF development, prior to 1980, a major performance limitation was ``multipacting.'' 1.3 GHz structures were limited to about 3 - 4 MV/m.

Multipacting is a resonant process in which an electron avalanche builds up within a small region of the cavity surface due to a confluence of several circumstances. Electrons in the high magnetic field region of the cavity travel in quasi-circular orbits returning to near the point of emission at about the same phase of the RF period as for their emission. The energy gain of 30 – 100 eV from the electric field in the region is sufficient to generate secondary electrons. With the invention of the round-wall cavity shape, multipacting is no longer a significant problem for velocity-of-light structures. The essential idea is to gradually curve the outer wall of the cavity. Electrons travel to the equator of the cavity where the electric fields are sufficiently low to stop regeneration.

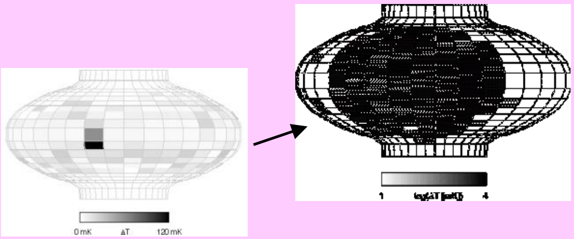


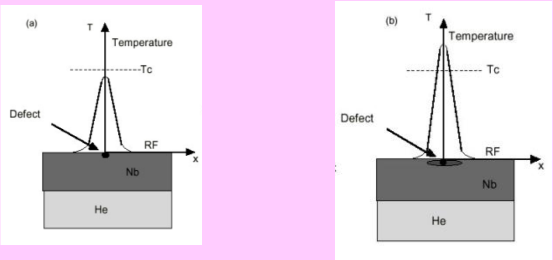
The spherical or elliptical shaped cavity eliminates multipacting.

Thermal Breakdown

Even after elimination of multipacting in the 1980's, gradients improved to only about 5 MV/m because of the thermal breakdown limits of superconductivity.

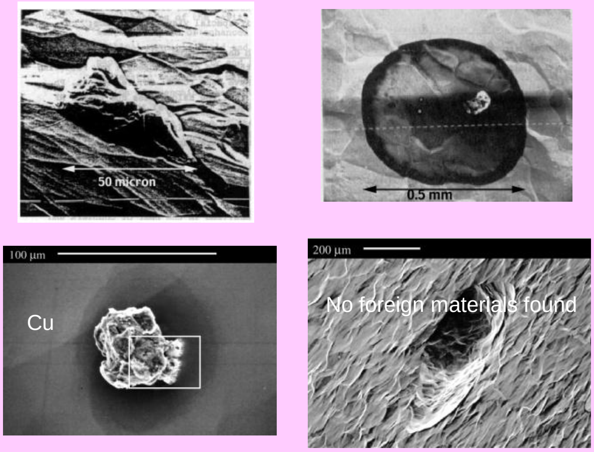
Nevertheless many applications were possible and cavities were installed in several accelerators. Well below the critical field, RF heating originates at sub-millimeter-size regions of high RF loss, called defects. When the temperature of the good superconductor outside the defect exceeds the superconducting transition temperature, T_c, RF losses increase, and large regions become normal conducting. Because the cavity field falls abruptly, we refer to the rapid loss of stored energy as a "quench."



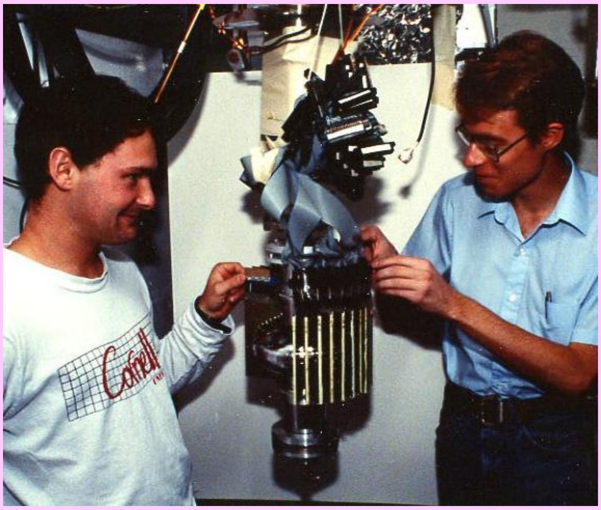


(Above) Temperature maps of a single cell cavity show spot heating as a precursor to large region of the cavity becoming normal conducting when the quench develops.

(Below) Calculated temperature rise in the vicinity of a defect. When the temperature of the good niobium just outside the defect rises above Tc, the defect grows unstably and so does the power deposited. This is called the quench.



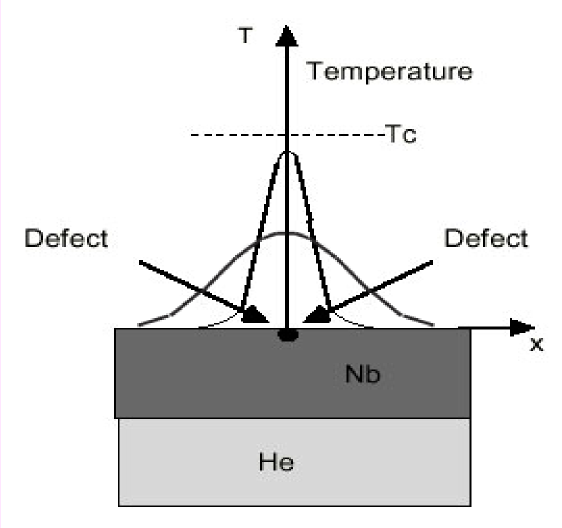
Typical examples of quench-producing defects located by temperature mapping and imaged by SEM are: chemical stains, foreign metal inclusions, pits with sharp edges, metal burrs from scratches, voids or delaminated regions of Nb, weld beads and other types of welding mistakes. 0.1 to 1 mm size defects cause thermal breakdown.



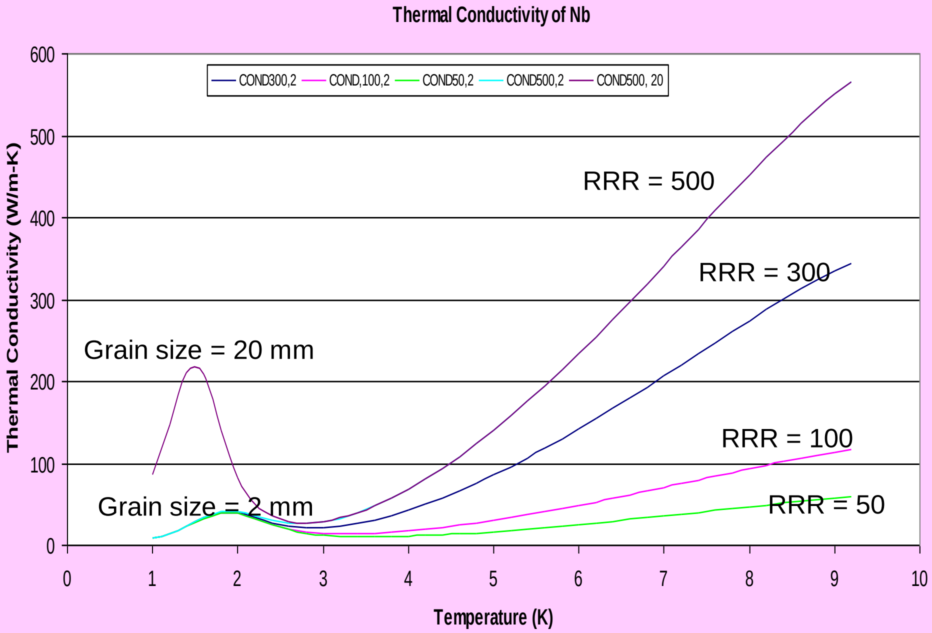
Temperature mapping system for a single cell cavity.

Overcoming Thermal Breakdown

An obvious approach to avoid quench is to prepare the niobium material with great care to keep it free from defects. Performance gains can be expected from searching the starting niobium sheet for defects by the eddy-current scanning method. However, it is impossible to ensure that there will be no defects, especially in large area cavities, or when dealing with hundreds of cavities, or perhaps 20,000 cavities for a future linear collider. The best insurance against thermal breakdown is to raise the thermal conductivity of the niobium by raising the RRR, which is a measure of niobium purity. Then defects can tolerate more power before driving the neighboring superconductor into the normal state.



As the thermal conductivity improves, the defect and the niobium around it stay below the transition temperature. It becomes possible to raise the field further.



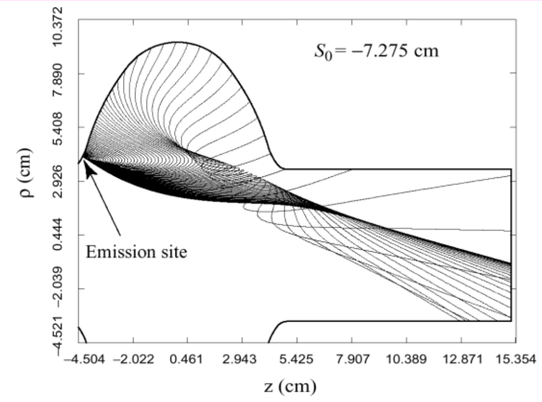
Temperature dependence of thermal conductivity for niobium of various purities, as characterized by the RRR. The thermal conductivity of niobium decreases rapidly with temperature below T_c, because electrons, the dominant heat carriers, rapidly freeze out into Cooper pairs. Below 2 K there is a phonon conductivity peak which increases sharply with grain size. The phonon peak does not help stabilize defects against quench because the temperature around the defect is well above 2K.

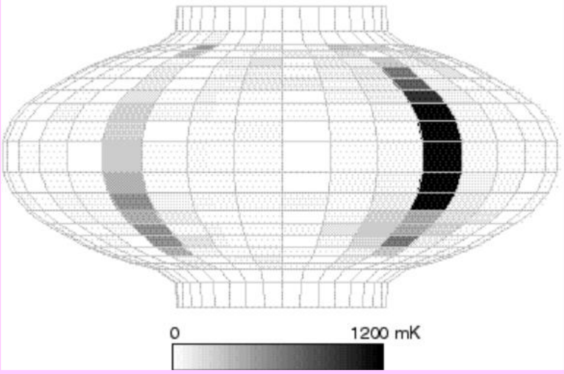
The most effective approach to increasing Nb thermal conductivity is to remove interstitial impurities, chiefly oxygen, nitrogen, carbon and hydrogen, which pose the highest electron scattering mechanism. These impurities are volatile only near the melting temperature of niobium. Therefore the best purification method is to improve the electron beam melting technique and the conditions for refining the starting ingot at the niobium producing plant.

Field Emission

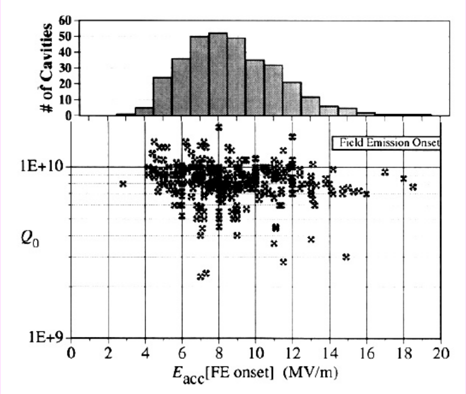
After thermal breakdown came under control in the 1990's, field emission took over as the dominant limitation. Field emission is a generic problem for high voltage devices. SRF cavities are particularly sensitive because losses from other sources are low. As a result, the SRF community has devoted considerable resources to understanding the origins of field emission, and paid a great deal of attention to avoiding field emission and dealing with residual emission. At the onset of field emission, the Q_0 of a niobium cavity typically starts to fall steeply because of exponentially increasing electron currents emerging from the surface.

The temperature mapping diagnostic technique for superconducting cavities shows that emission always arises from particular spots, called ``emitters," usually located in high electric field regions. The emerging electrons travel in the RF fields of the cavity and impact the surface. Since the power deposited by impacting electrons depends on their trajectory as well as on the intrinsic properties of the emitter, the pattern of temperature rise as a function of position along a given meridian contains implicit information about the location and characteristics of the emission source. By tracking the heating patterns with thermometers, it is possible locate the emitters and analyze their emission properties.

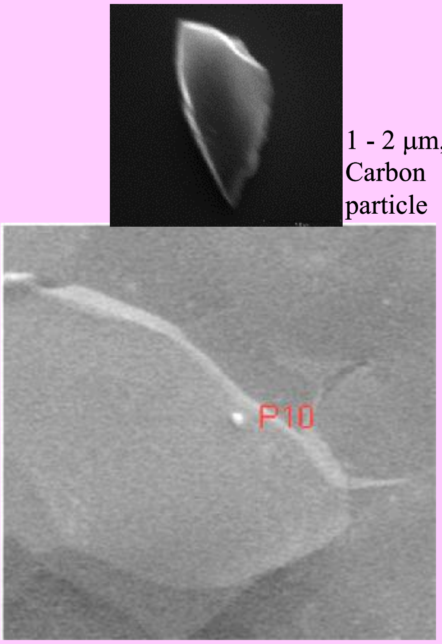




Temperature map showing a longitudinal heating profiles due to field emission.



Distribution of gradients and Q_0 at the onset of field emission for more than 300 CEBAF cavities tested in the early 1990's. The average gradient is 8:7 MV/m.



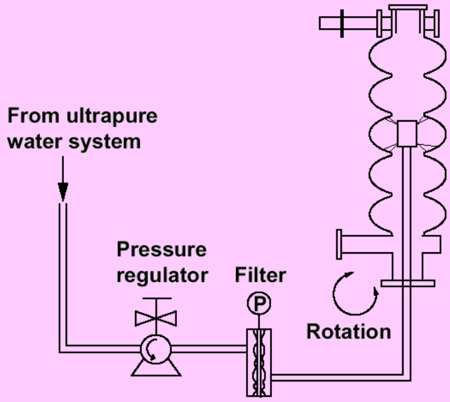
1 - 2 μm, Carbon particle

Typical field emitter, carbon micro-particle.

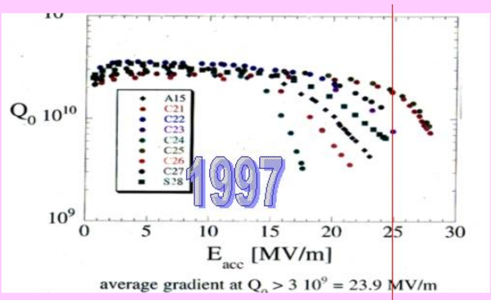
Overcoming Field Emission

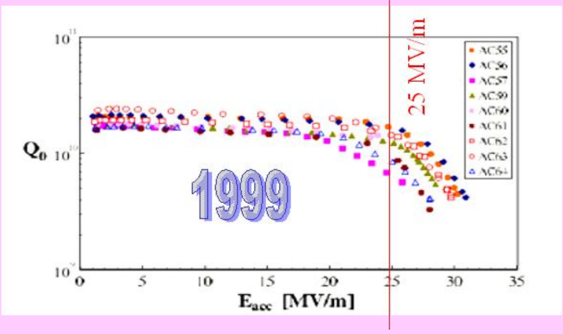
Field emitter studies showed that increased vigilance in cleanliness during final surface preparation and assembly procedures is important to keep particulate contamination and associated emission under control. Sensitized by these results, new approaches - in particular high pressure water rinsing and class-100 clean room assembly - have been adopted to strive for high levels of cleanliness in cavity surface preparation, leading to fewer emission sites and better cavity performance.

Clean room preparation at DESY.



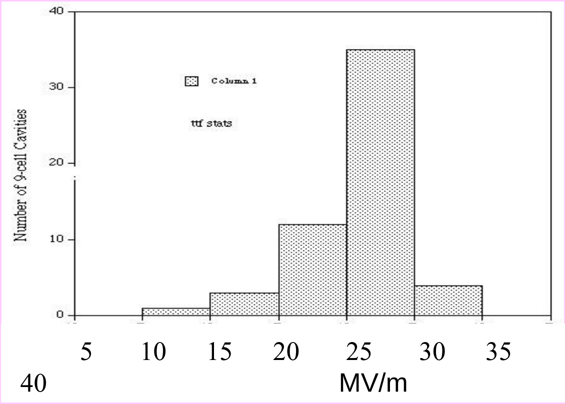
A jet of ultra pure water dislodges surface contaminants that normally resist removal with conventional rinsing procedures. The benefits of HPR in reducing field emission are well demonstrated in tests with multicell cavities that reach accelerating fields of 35 MV/m at DESY.





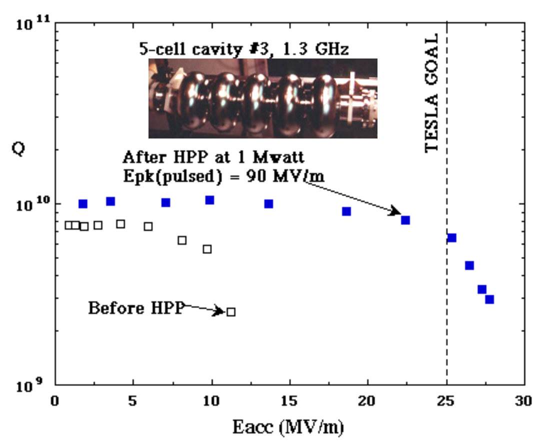
Steady Improvement in Gradients

As field emission came under control in the late 1990's due to high pressure water rinsing and clean room assembly, gradients of 9-cell cavities improved steadily, as shown for 9-cell cavities between 1997 and 1999. By 2000, gradients consistently reached 25 - 30 MV/m.



High Power Processing

The super-cleanliness approach can reduce field emission substantially. But in large-area structures there is always a probability of dust falling into the cavity upon installation of power-coupling devices or during the installation of a cavity into the accelerator. There exists a technique to eliminate emitters in-situ. Called high pulse power processing (HPP), the technique springs from the observation that application of sufficiently high electric fields destroys emitters. The essential idea is to raise the RF power level so as to raise the surface electric field at the emitter, even if for a very short time (μs). The power level, pulse length, and input coupling need to be arranged to reach the high electric field. An important additional benefit is that HPP can recover cavities that may be accidentally contaminated, e.g., in a vacuum mishap.

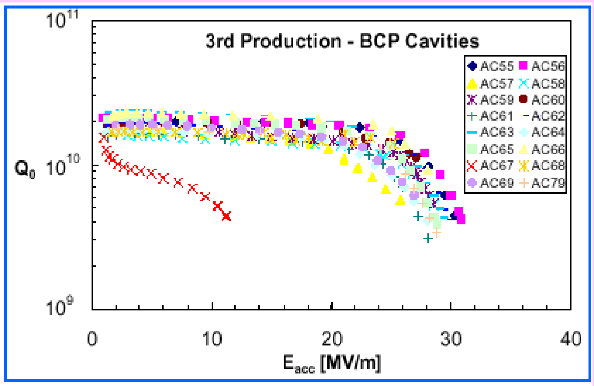


An example of ``before-and-after'' HPP. Here a cavity contaminated down to 10 MV/m improves with HPP to 28 MV/m.

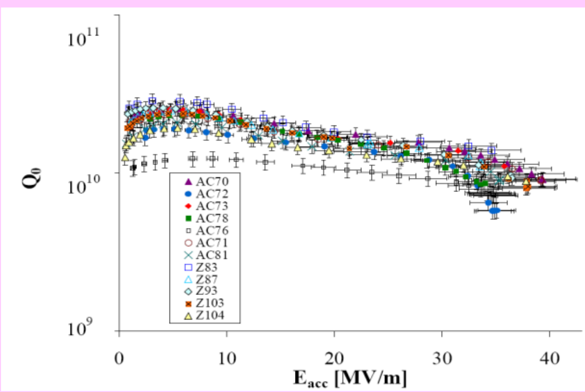
SEM micrographs of a field emission site located with thermometry in a 3 GHz cavity and subsequently found to process with RF power. (Left) A dark starburst feature surrounding the central crater. Auger measurements show the starburst region to be cleaner (less carbon and fluorine) presumably from the ion bombardment during the spark which occurs during RF breakdown. (Right) Expanded view of crater showing mostly molten niobium with traces of molten copper. Presumably the original field emission site was a copper micro-particle.

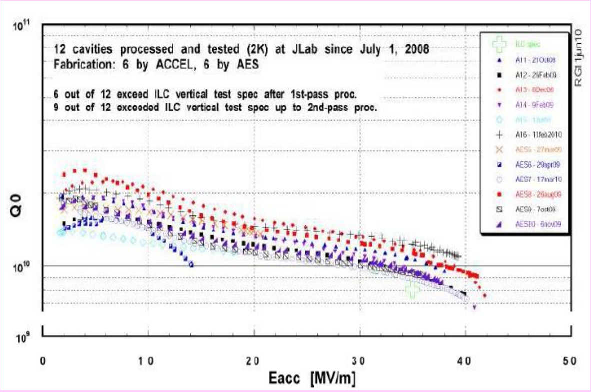
The Final Push

Even when there is no field emission (as judged by the absence of x-rays) the *Q* starts to drop above accelerating fields of 20 MV/m. Temperature maps show losses take place in high magnetic field regions of the cavity. For want of a better term, the phenomenon carries the label “high-field *Q*-drop.”



Performance of 9-cell cavities at DESY prepared by chemical etching, limited by high-field Q-drop.





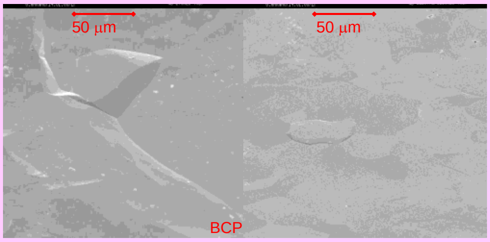
Performance of twenty-four 9-cell electropolished and baked (120C) cavities at DESY and JLAB reach 40 MV/m with no Q-drop.

Methods to bring the high-field Q-drop under control in hand. These are electropolishing to produce a smooth surface and 100 – 120 C baking for 48 hours to heal the surface dislocations which increase flux flow losses.

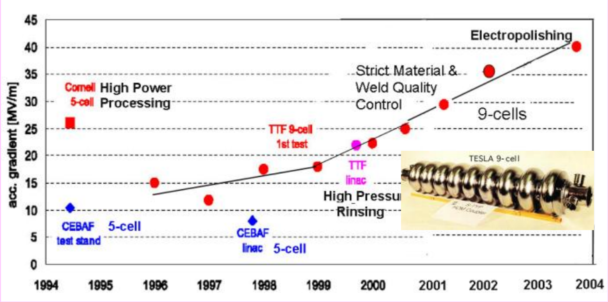
The prevailing mechanism for the high field *Q*-drop is that above a local rf critical field rf flux enters the surface, and flux flow produces rf losses. Dislocations or dissolved oxygen impurities lower the local critical field for flux entry. Smoothening the surface raises the onset field slightly, while 120 C baking heals the dislocations and diffuses mobile excess impurities, such as oxygen to have the most beneficial effect on *Q*-drop.

For electropolished and baked cavities, the *Q*-drop begins around 25 - 27 MV/m, ending with a quench between 30 - 35 MV/m. This is a substantial improvement over the typical *Q*-drop onset field of 20 MV/m for a rough Nb surface prepared by standard chemical etching, followed by quench at 25 - 30 MV/m.

Gradients up to 42 MV/m without significant Q-drop have been reached with 9-cells at several laboratories using EP plus 120 C baking.



Comparison of a niobium surface prepared by (left) standard chemical polishing and (right) electropolishing.

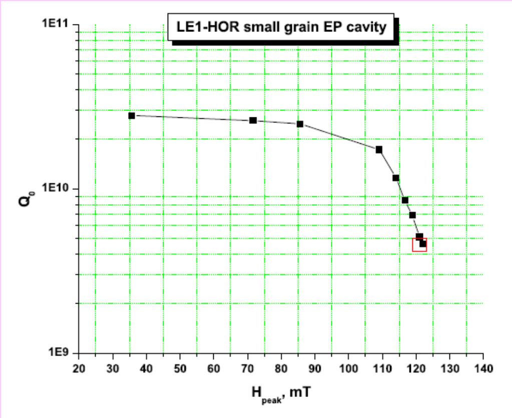


Steady progress in 9-cell gradients over one decade.

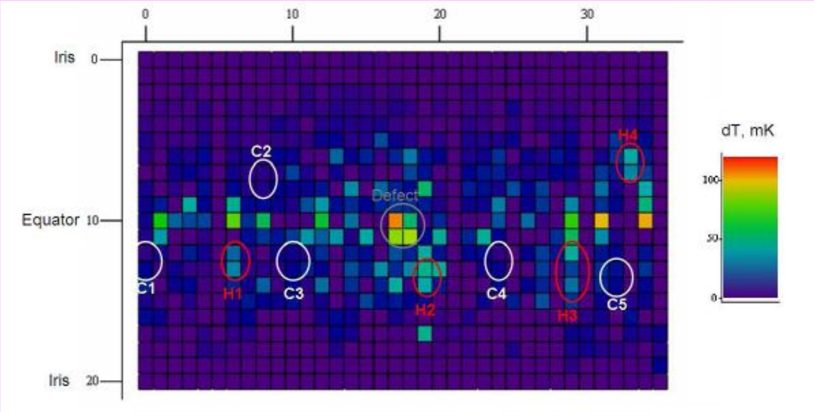
The Wonders of Thermometry and Coupled Surface Analysis

All through the development of superconducting cavities and gradient advances temperature mapping and coupled surface analyses have proved powerful tools to understand cavity performance limits and improve preparation to overcome the limits. Previous examples come from thermal breakdown and field emisison. A case in point is the high field Q-drop cured by baking at 120 C.

When selected hot and cold regions are extracted from the cavity and analyzed with Electron Back Scattered Diffraction, the hot samples show a high density of dislocations compared to the cold sample.



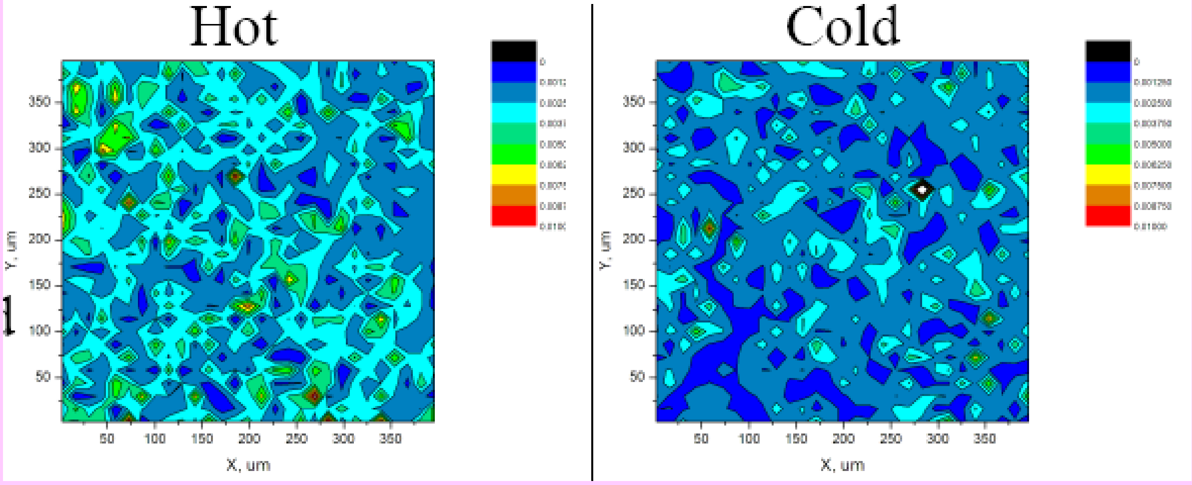
Electropolished single cell 1.3 GHz cavity with high field Q-drop.



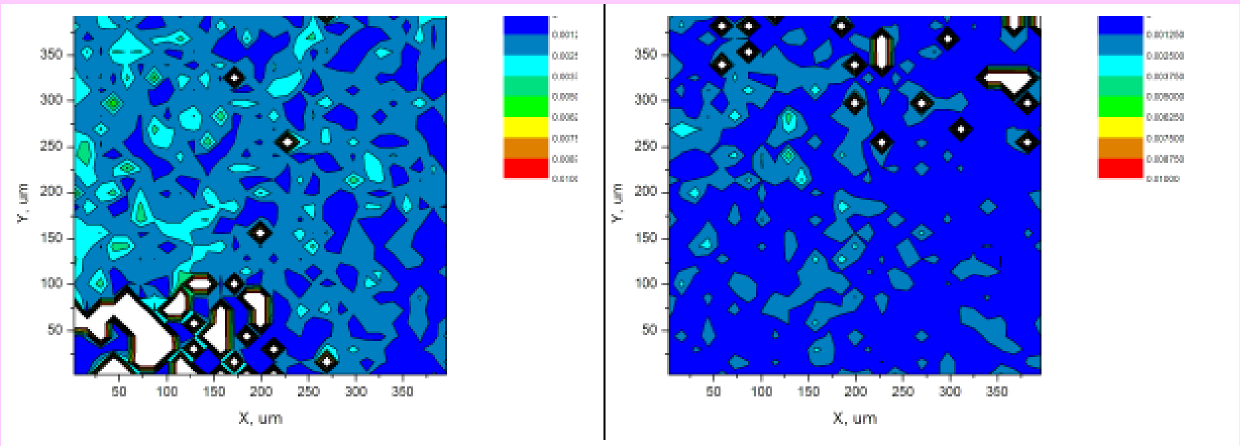
Temperature map of a single cell cavity with high field Q-drop shows regions of strong heating (hot spots) and regions of weak heating (cold spots) in the high magnetic field.

A Model for the High Field Q-Drop

Electron Back Scattered Diffraction reveals areas of local crystal misorientation due to the presence of dislocation clusters. The EBSD images are analyzed for dislocation density. The current model of the high field Q-drop is that the dislocation clusters lower the rf critical field by providing sites for flux entry. Flux flow is responsible for rf losses. The baking effect is explained by reduction of dislocation density.



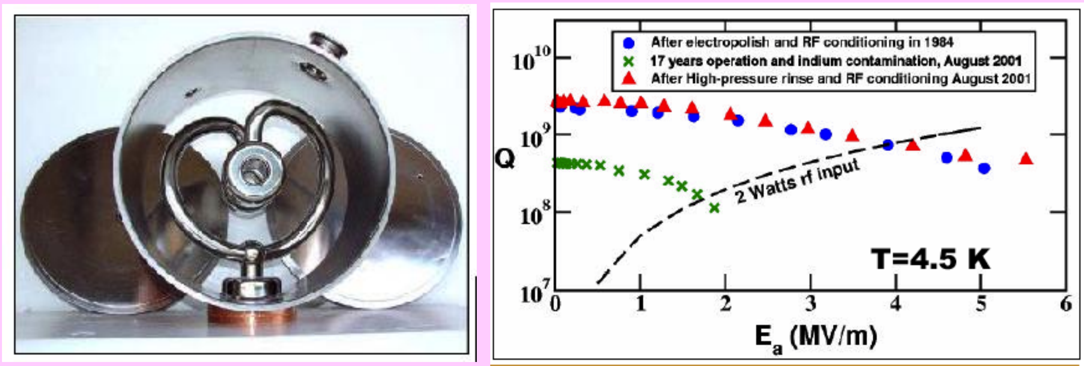
The hot samples show a high density of dislocations compared to the cold sample.



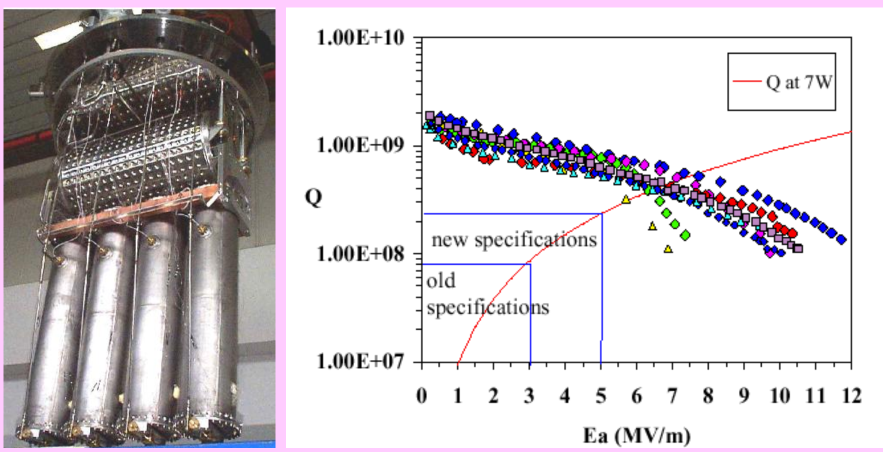
Baking at 120 C for 48 hours significantly reduces the dislocation density of both the hot and cold samples.

Performance of Low-Velocity Structures

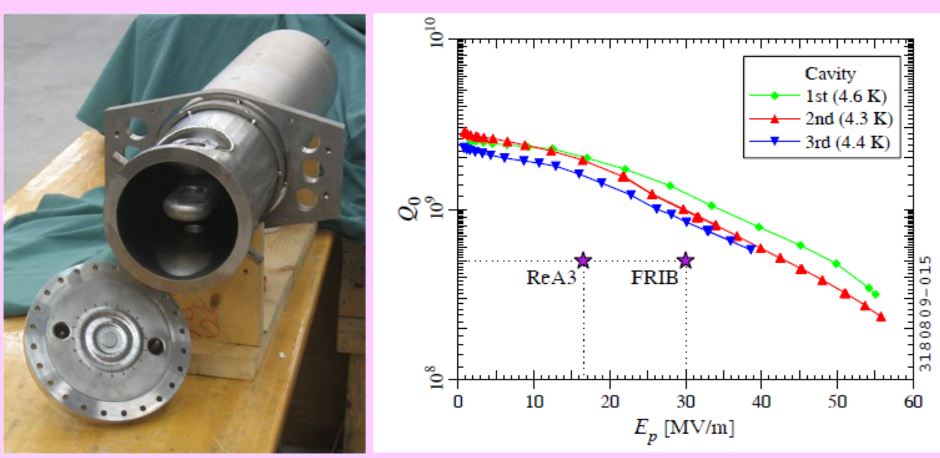
Advances in materials and surface processing techniques have improved performance of low and medium beta resonators. Gradients above 10 MV/m are now possible.



Argonne Split Ring Resonator, Frequency = 97 MHz, E_{pk} = 4.8 Eacc , H_{pk} = 183 Oe/MV/m. Performance improved substantially after high pressure rinsing.



INFN Injector PIAVE 80 MHz Quarter-Wave Resonators beta = 0.05.

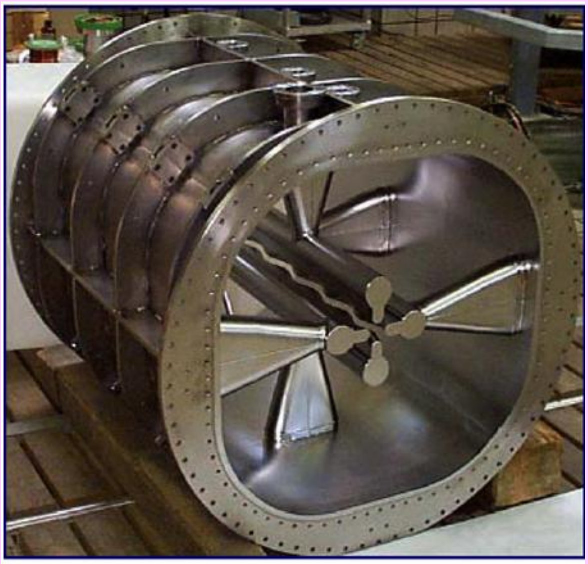


MSU, Quarter Waver Resonator, β = 0.041, 80.5 MHz.

The First Superconducting RFQ

Radiofrequency quadrupoles (RFQs) have been used since decades for the acceleration of low velocity ions. They combine the strong electric focusing provided by the RF quadrupole with effective acceleration by the modulation of the vanes. These are machined to provide a longitudinal electric field component synchronous with ion bunches. RFQ structures are ideal for very low ion velocities β = v/c < 0.01. They are typically normal conducting, spanning a frequency range 50 - 400 MHz, and providing a 100 - 200 kV voltage difference between vanes with a quality factor Q~10^4 . Normal conducting RFQ power consumption usually limits their duty cycle to values < 20%. The superconducting RFQ offers lower power consumption (Q~10^8 - 10^9) and CW operation. A significantly higher vane voltage than in the normal conducting case is beyond present development.

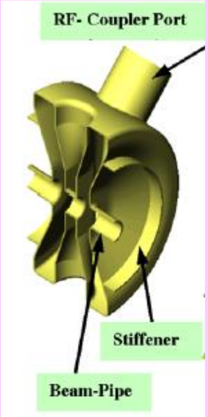
INFN at Legnaro successfully tested the first superconducting RFQ at 80 MHz. With 12 cells, an aperture of 1.5 cm it reached the design voltage of 280 kV at a surface field of 25 MV/m.



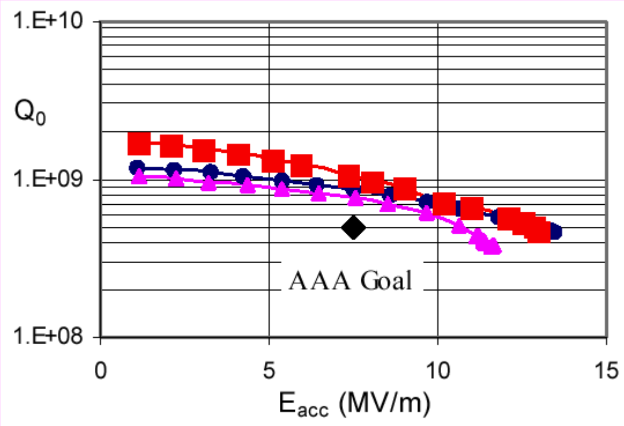
Superconducting RFQ for Injector PIAVE at INFN.

Medium Velocity Structures

Medium velocity structures with β between 0.5 to 0.8 can be foreshortened speed-of-light TM type structures or multi-gap spoke TEM type resonators. TEM structures exhibit a higher accelerating field for a given power loss than TM structures, and also have a smaller diameter at a given frequency. They are mechanically quite stable and show a larger velocity acceptance than multicelll elliptical cavities. Choosing a lower frequency opens the option of 4.2 K operation. On the other hand TM structures have lower E_{pk} and H_{pk} and have larger apertures.



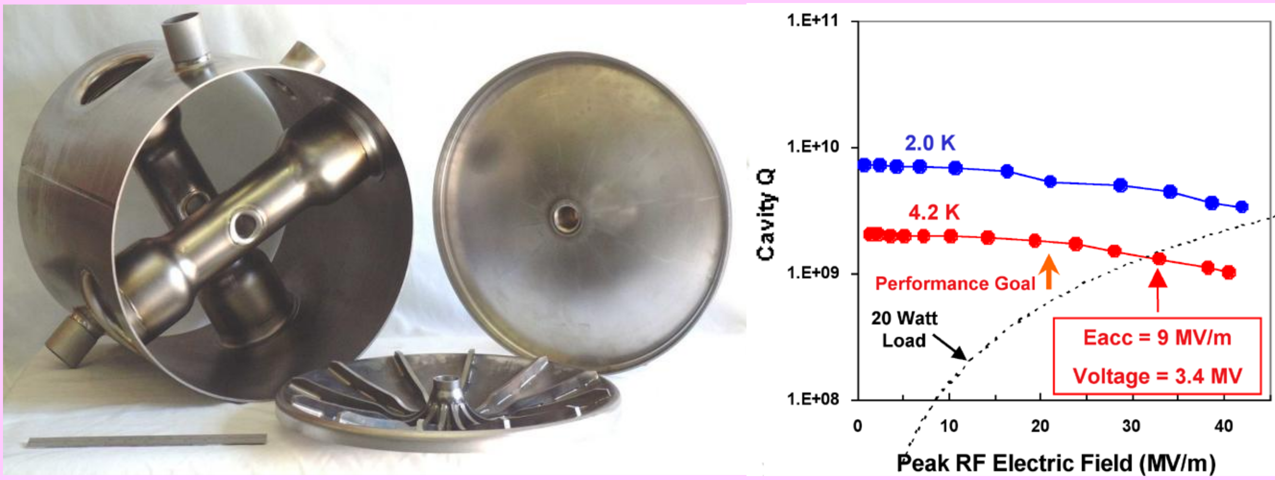
LANL, β = 0.175, 175 MHz, single spoke, 2-gap cavity.



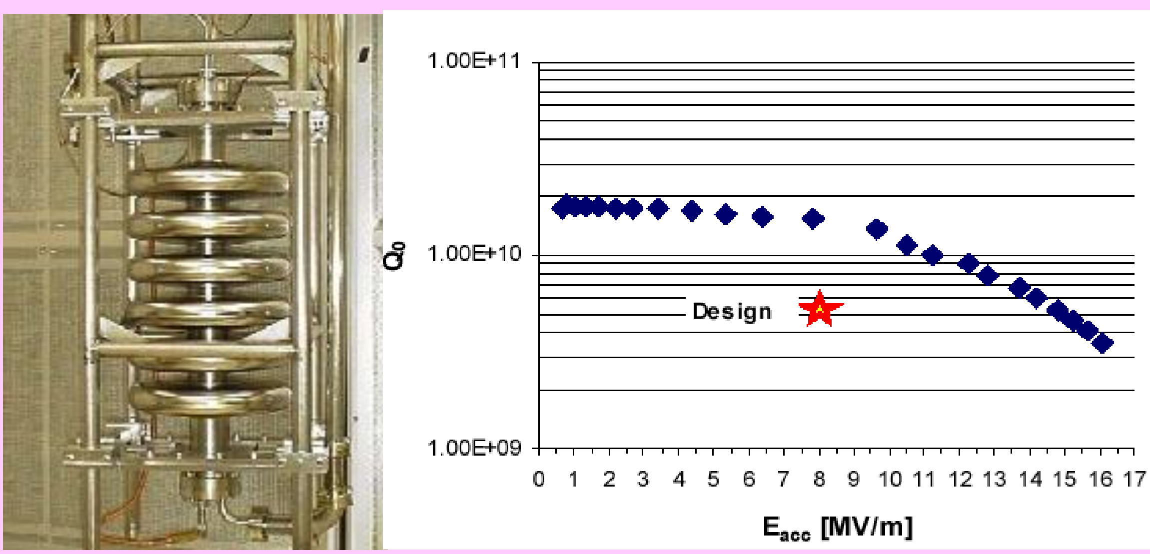
Performance of the LANL spoke cavity.

Performance of Medium Velocity Structures

A comparison of the performance of medium beta spoke and elliptical cavities



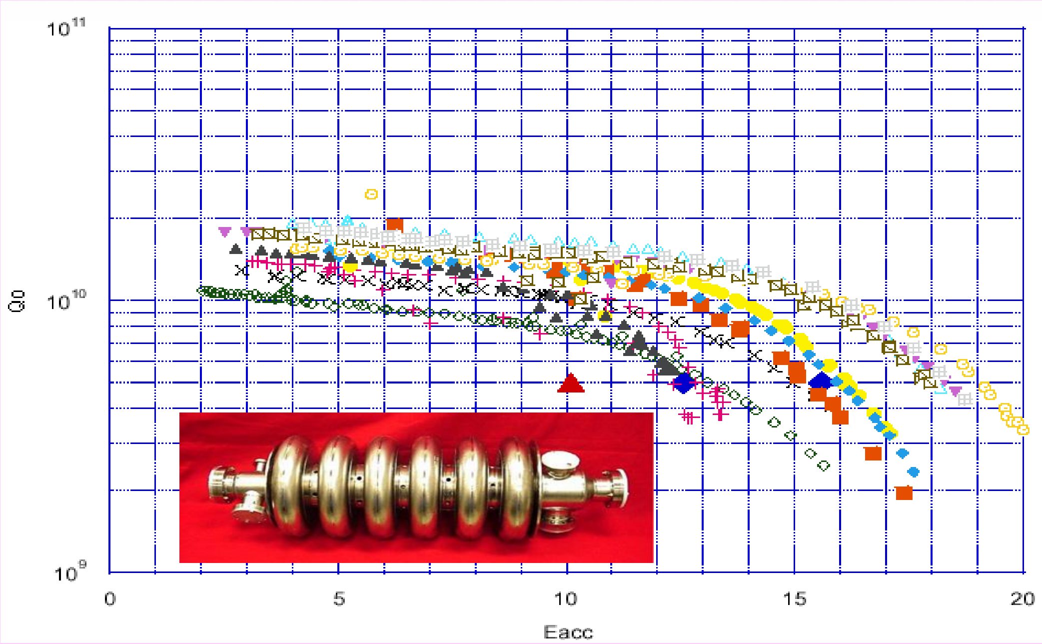
Argonne, 345 MHz , β = 0.4, double Spoke Resonator.



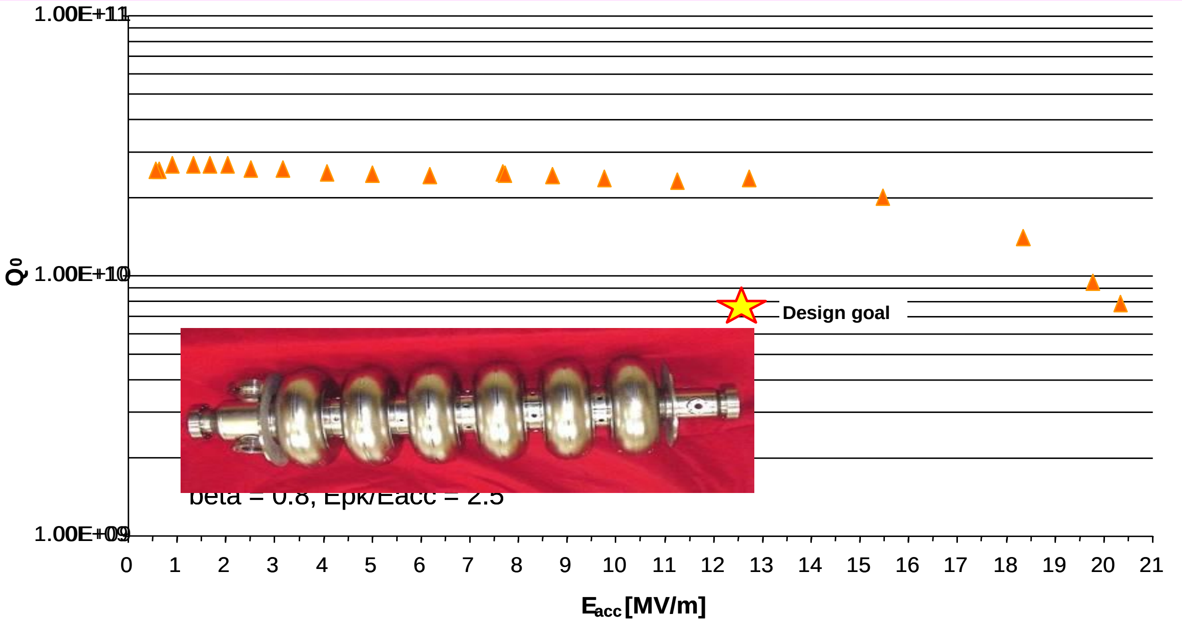
MSU, β = 0.49, 805 MHz, e-beam welded and tested at JLAB.

Performance of Medium and High Velocity Structures for SNS

Peak surface electric fields in medium beta elliptical structures are now in the range of 50 - 70 MV/m, comparable to 9-cell structures for XFEL.



β = 0.61, 805 MHz, Epk/Eacc = 3.5, tested at JLAB.

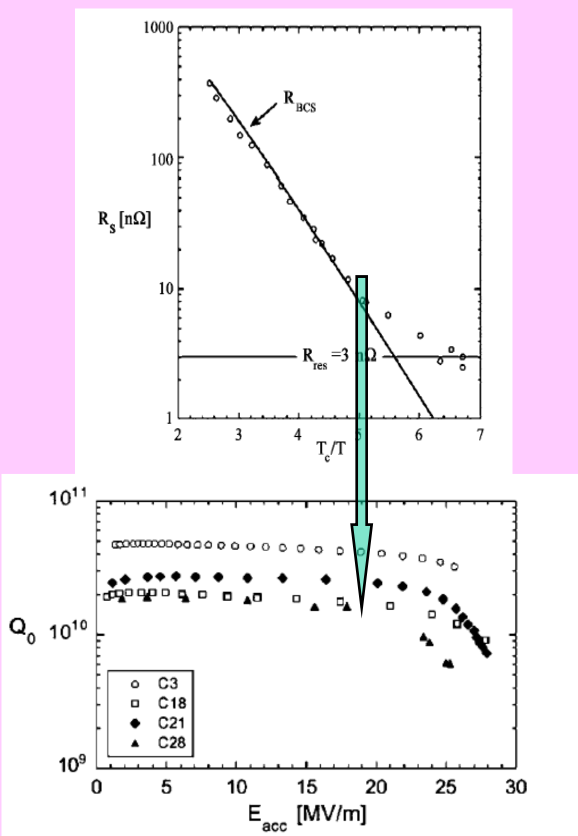


β = 0.8, 805 MHz, Epk/Eacc = 2.5, tested at JLAB.

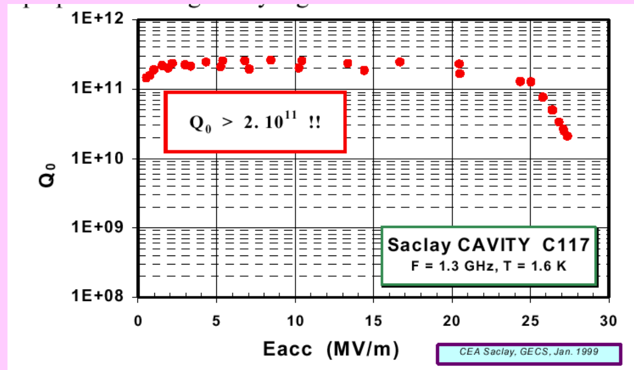
RAISING THE CEILING

High Q

At 1300 MHz and 2 K operation, the BCS contribution to the surface resistance is still important, limiting the Q to 2×10^{10}. At 1.8 K, the theoretical Q is 6×10^{10} and rises to above 10^{11} at 1.7 K. Single cell cavities have already demonstrated Q's above 10^{11}. But much development is needed to transfer this accomplishment to multicells and to reach comparably high Q's in cryomodules and in operation. If such high Qs are achieved it would permit CW operation at high gradient, important for high performance in Energy Recovery Linac based applications. Progress continues for high Q.

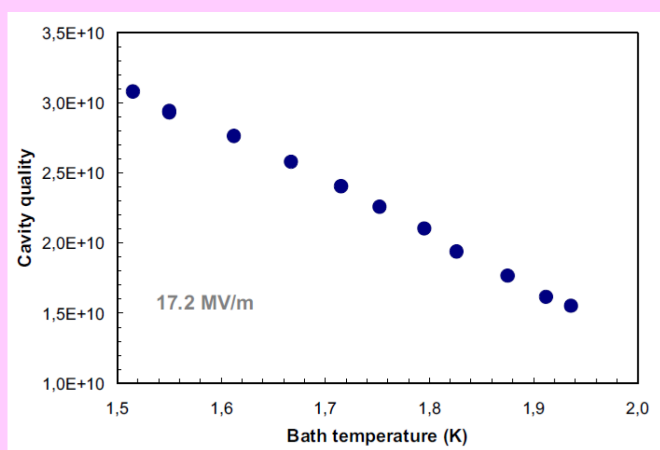


At 2 K, the BCS component of the surface resistance dominates the Q of 2×10^{10} so that lowering the temperature to 1.8 K improves Q to 5×10^{10}.



The world-record Q value is 2×10^{11} for a single cell 1.3 GHz cavity at 1.6 K and an ambient magnetic field less than 5 mGuass.

BESSY Cryomodule for testing 9-cell cavities equipped with coupler and tuner.

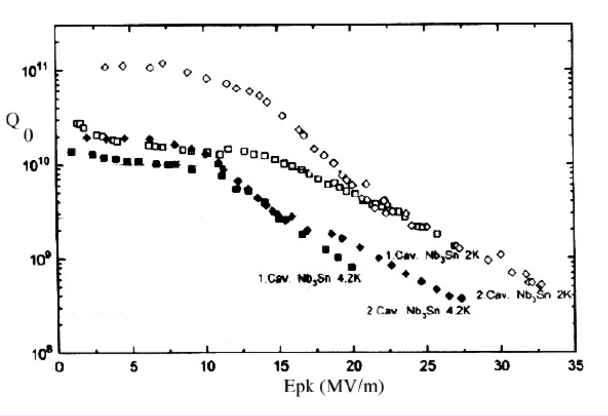


High Q values for a 9-cell cavity measured in the BESSY test cryomodule.

Alternate Materials

Nb_3Sn

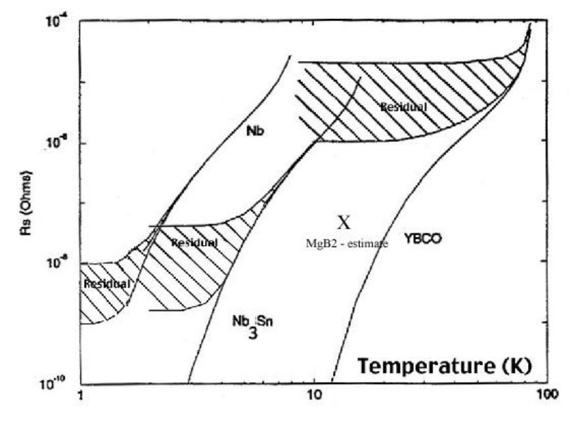
The realm of superconducting compounds has been much less explored because of technical complexities that govern compound formation. In looking at candidates, such as Nb_3Sn, NbN, and the new high-temperature superconductors (HTS), it is important to select a material for which the desired compound phase is stable over a broad composition range. With these criteria, Nb_3Sn proves the most attractive candidate for the next stage of development. It is more tolerant to variations in fabrication conditions to achieve the desired single phase over a large surface area. With a T_c of 18 K, the theoretical maximum magnetic field is twice that of Nb. Therefore the accelerating field is potential is near 100 MV/m. Gradients above 50 MV/m at Qs of 10^{11} would open the road to multi-TeV superconducting linear colliders in the far future. However, the highest RF magnetic field reached to date is 890 Oe, corresponding to an accelerating gradient of about 20 MV/m, still far below the ultimate potential. Much research and development is needed, but the gains would be immensely rewarding.



Performance of the best Nb_3Sn Cavity.

High Temperature Superconductors

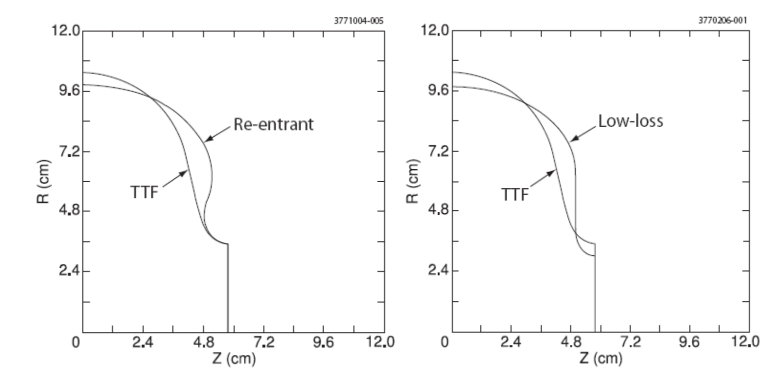
The intrinsic properties of HTS are very different from the familiar superconductors. The coherence lengths are very short: 17 Å within the copper-oxygen planes and 3 Å perpendicular to the planes, respectively. There is also a large anisotropy of the magnetic and electrical properties between the c-axis and the ab-planes, with superior behavior when the current is in the ab-plane. Besides proper orientation, fabrication of good material poses many challenges. For example, it is essential to have the right stoichiometry and oxygen content. Because of the short coherence length, transport properties are extremely sensitive to minute defects, such as grain boundaries and their associated imperfections. Decoupling of superconducting grains is believed to occur because the coherence lengths approach the scale of the grain boundary thickness, forming only weak links between individual grains. At present performance levels, HTS films are attractive for low field, passive electronic applications involving planar devices, such as multipole band-pass filters or compact delay lines, but not yet for high field accelerator applications.



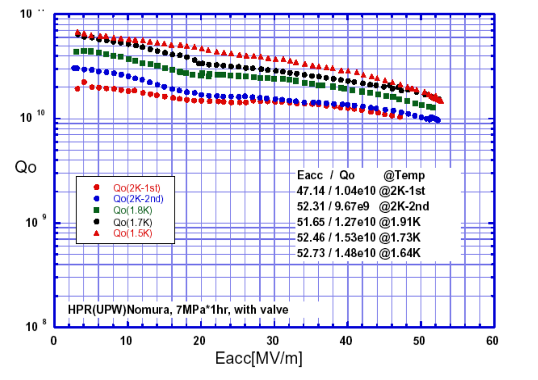
A comparison of superconductors Nb, Nb_3Sn YBCO and MgB_2 at 1 GHz.

Exploring New Cavity Geometries to Raise Gradients

Several laboratories are exploring ways to beat the fundamental critical magnetic field limit by designing structures with lower surface peak magnetic fields for the same accelerating field. The JLAB design increases the area of the magnetic field region and reduces the beam aperture of the TTF design to keep E_{pk} the same. KEK is pursuing a slight variant of the Low Loss design, named ICHIRO. The Cornell approach keeps the large beam aperture to minimize wakes, but makes the shape re-entrant to reduce the peak magnetic field. Both the low-loss and re-entrant approaches reduce H_{pk} by about 10%, but the Cornell approach increases E_{pk} by 20%. The rationale is that H_{pk} presents a hard limit whereas E_{pk} enhances field emission which can be overcome by techniques such as high pressure rinsing and high power processing.



Comparison of cell profiles (a) TTF and Re-entrant shapes (b) TTF and Low-loss shapes.



Single-cell re-entrant and low-loss cavities reach Eacc = 50 MV/m.

JLAB upgrade 7-cell Low-Loss cavity for lowering H_{pk}.

KEK ICHIRO (Low-Loss) 9-cell cavity for lowering H_{pk}.

Cornell 9-cell re-entrant cavity for lowering H_{pk}.

New Fabrication Techniques

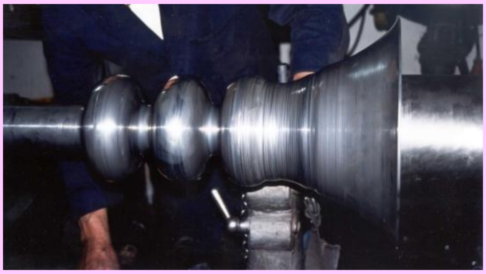
Spinning

The most common fabrication method for cavities from sheet niobium is to deep draw or spin half-cells. After forming and trim machining, the parts are electron beam welded together under a good vacuum. The weld parameters must be chosen to give a smooth bead on the rf side by using a defocused or rastered electron beam.

New techniques for cavity fabrication are emerging, such as spinning and hydroforming multicell structures from tubes or sheets. If successful these approaches will help reduce the cost of future facilities.

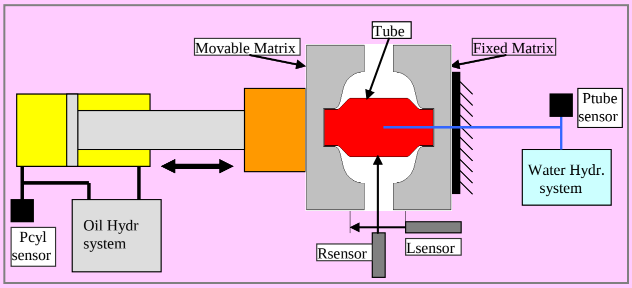
First Spun 9-cell Nb cavity.

Spinning from a disk at INFN.



Spinning from a tube at INFN.

Hydroforming



Principle of hydroforming .

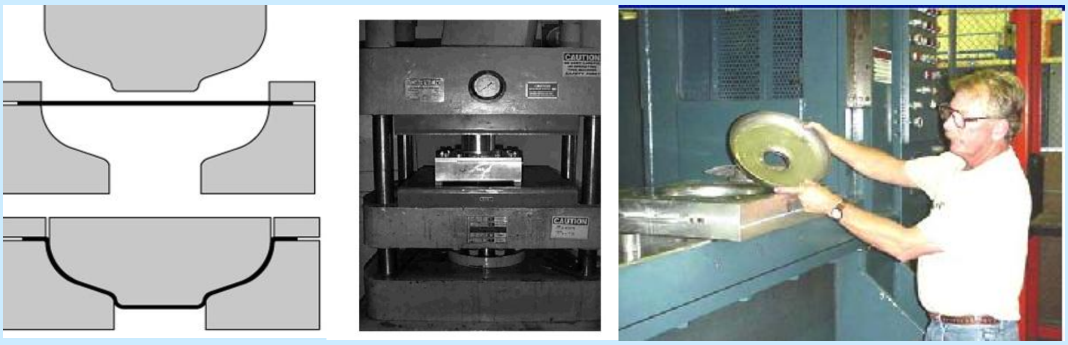
Equipment for hydroforming by DESY.

Two and three cell cavities hydroformed at DESY.

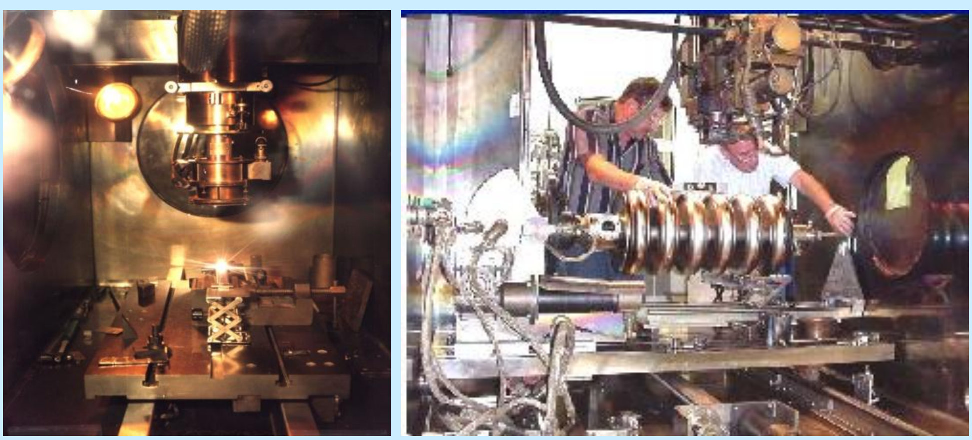
GLOBAL FACILITIES FOR SRF ACCELERATORS

Velocity-of-Light Structures

Extensive SRF infrastructure exists worldwide for cavity fabrication, surface treatment, clean assembly, cold testing, and cryomodule assembly. Major facilities for electron accelerators are available at DESY, CERN, INFN, Saclay, KEK, JLAB, Cornell, Fermilab and at several industries. Cavity production facilities include hydraulic presses for deep drawing cavity half-cells, digital control milling machines for precise trim machining, and large electron beam welders.



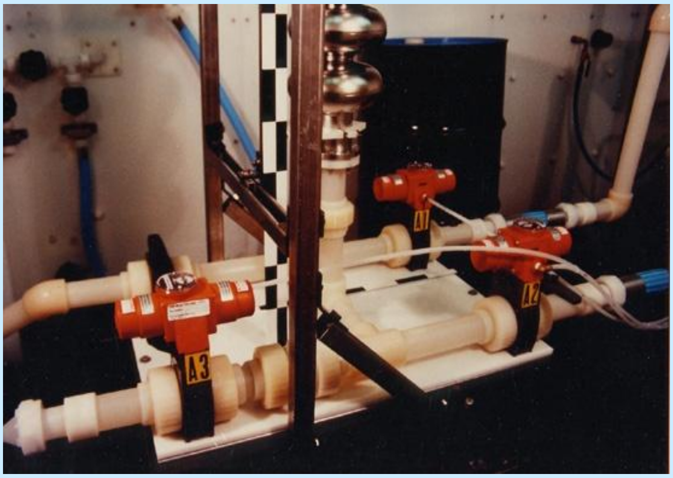
Deep drawing half cells at Cornell and JLAB.



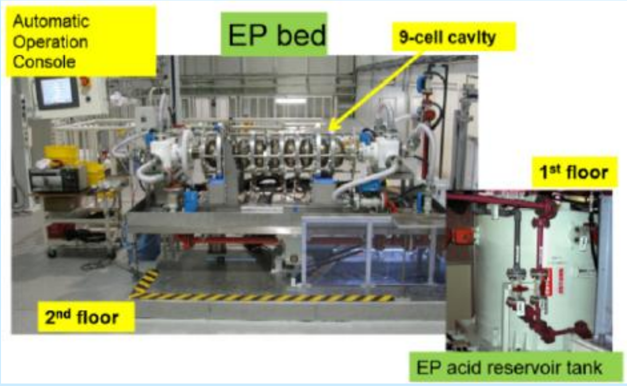
Electron beam welding at Cornell and JLAB.

9-cell cavity fabrication and mechanical quality control at DESY.

Cleaning Facilities Include Open and Closed Cavity Etching Systems, Electropolishing Set-ups




Chemical etching faciltiies at Cornell and DESY.

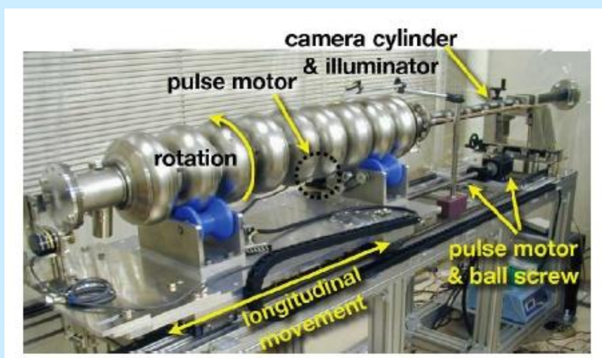


Electro-polishing at KEK and DESY.

Argonne/Fermilab Electropolishing facility.

Cornell Vertical Electropolishing Facility.

High Pressure Rinsing at JLAB, Cornell and KEK.

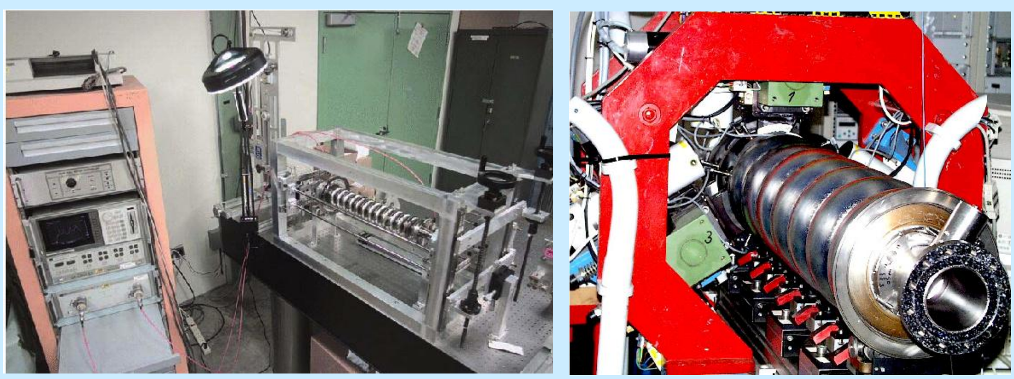


Internal cavity inspection system at KEK with CCD camera.

DESY tuning system.

UHV furnaces purify cavities. Test setups include radiation shielded pits and bunkers, cryostats, and cryostat inserts, multi-hundred watt CW RF power sources and MW class pulsed klystrons for high power operation and high pulsed power processing.

Furnace treatment at Jlab and DESY.



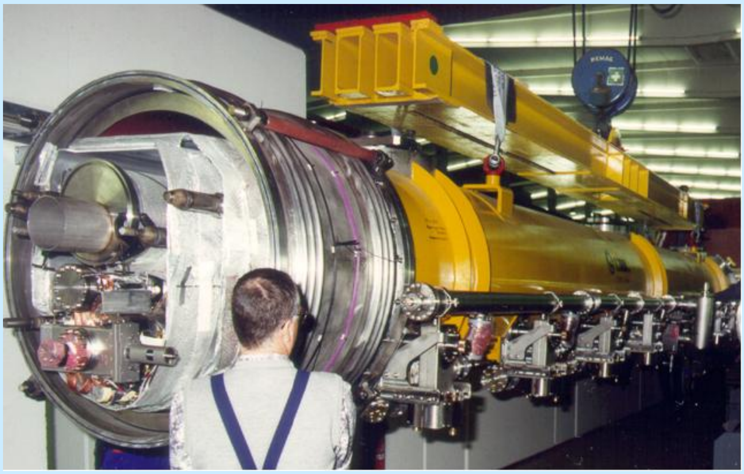
Tuning at Fermilab and DESY.

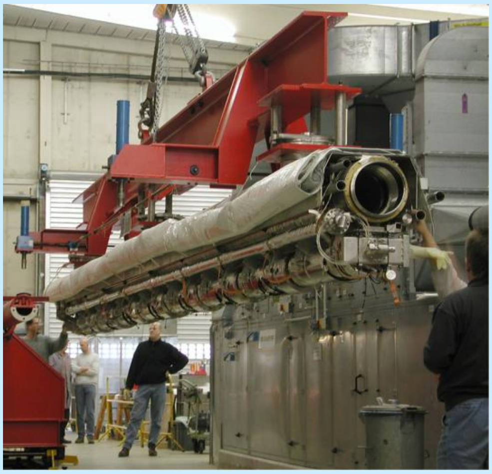
Vertical Cavity Testing at JLAB and Cornell.

There are large Class 10 - 100 clean rooms for cavity assembly and cavity-string assembly. These facilities have been used to build cavities and cryomodules for TRISTAN, HERA, CEBAF LEP-II, CESR, KEK-B, FELs, SNS, TESLA TEST FACILITY and the ERL injector cryomodule.

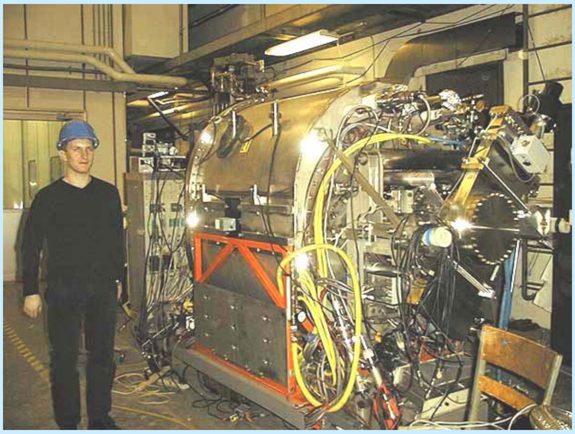
ERL-injector cavity string assembly at Cornell.

Cryomodule assembly at JLAB.





Cryomodule assembly at DESY.



ERL injector and CESR Cryomodule assembly at Cornell.

Cryomodule assembled at FNAL with DESY assistance.

KEK Cryomodule test facility in tunnel.

Cavity string assembly in clean room at KEK.

Major Facilities for Low and Medium Velocity Structures

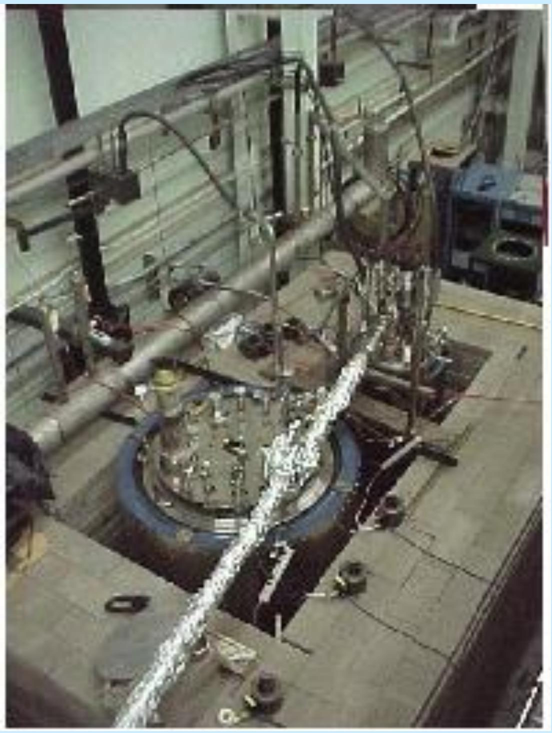
Extensive SRF infrastructure exists worldwide for cavity fabrication, surface treatment, clean assembly, cold testing, and final cryomodule assembly before accelerator installation. Major facilities for low velocity accelerators are available at INFN, ANL, Michigan State University, Los Alamos National Lab and TRIUMF in Canada. Argonne has fabricated structures for many laboratories around the world: JAERI, Florida State U, Kansas State U, Brazil and New Delhi.


Resonator Fabrication at ANL.


Chemical Treatment at MSU and high pressure rinsing at Los Alamos.

Clean room assembly at MSU and vertical test cryostats at Los Alamos.

Shielded test caves for vertical cavity tests at MSU and Los Alamos.



FUTURE APPLICATIONS- LIGHT SOURCES

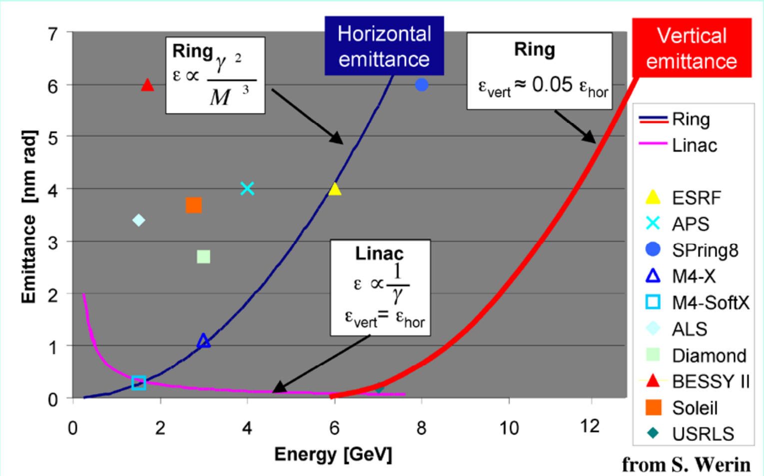
Synchrotron radiation (SR) has proven to be immensely important for the physical, biological, and engineering sciences. The demand for SR continues to grow, with new uses opening all the time. Currently, most major SR sources are based on storage rings. The characteristics of x-ray produced by a SR source are limited by the qualities of electron beams used to produce the SR. Beam emittance, bunch profile and energy spread in a storage ring are determined by an equilibrium between radiation damping and quantum fluctuations with the emission of SR. In existing 3 rd generation rings, such as ESRF and APS, beam characteristics are approaching limits. Although improvements are possible with better designs, storage ring technology will eventually reach a point of diminishing returns and future improvements will come at enormous cost with larger rings.

For the next generation of light sources it is desirable to have (1) Low electron beam emittance in order increase the brilliance and coherence of SR; (2) Very short electron bunches to enable fast time-resolved experiments; (3) Round, small cross-sectional area bunches with sharp edges to enable micro-beams, that improve through-put on the x-ray optics and that pass through long narrow-gap undulators; (4) A SR output which does not decay over time.

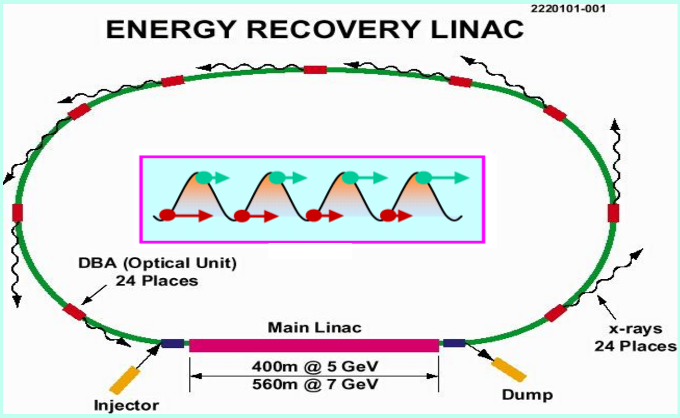
Energy Recovery Linacs

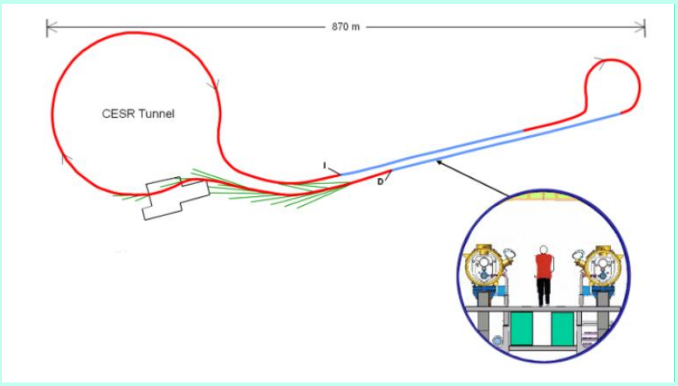
The Energy Recovery Linac (ERL) takes a different approach to producing high quality beams. Electrons are not stored, so constraints of beam equilibrium never become a limit. Photo-injectors can achieve bunches with emittances, shapes, and length which are superior in important ways to bunches in storage rings. A CW superconducting linac accelerates bunches to high energy while preserving the salient beam characteristics. For long pulses or CW operation, SRF linacs have a clear advantage over storage rings. High-gradient, low-impedance SRF structures allow the preservation of the exceptional beam quality produced by the injector. Linacs can ensure exceptional amplitude and phase stability of the RF fields, at the 10^{-5} level. Linacs in general demonstrate operational flexibility; changes in beam energy, bunch length, and pulse patterns. After acceleration, by the linac, superior high energy bunches pass though undulators to produce SR beams with unprecedented characteristics.

The problem is that the beam currents required for high radiation flux carry enormous power. For example, a 5 GeV, 100 mA electron beam carries 500 MW of beam power!



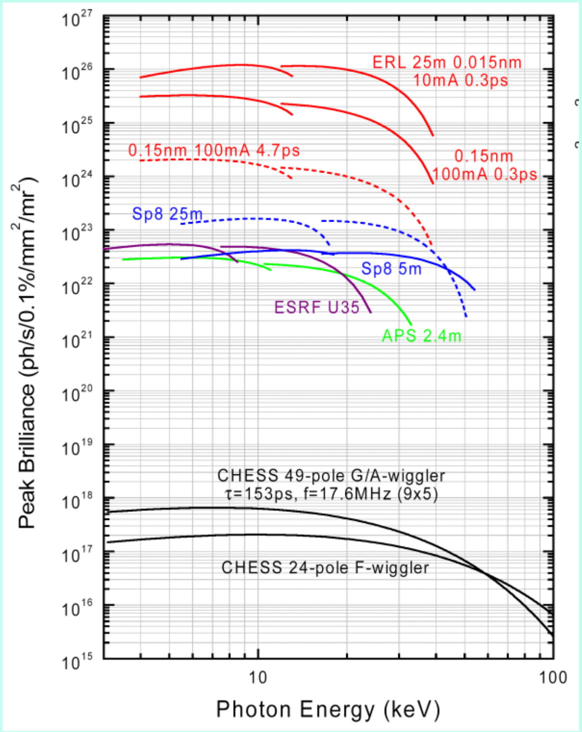
A comparison of vertical and horizontal emittances for rings and linacs.





Possible layout for a 5 GeV Cornell ERL based on the CESR ring, under study.

Higher Peak Brilliance



Therefore, it is not economically feasible to simply dump the electrons after acceleration. A storage ring keeps the power costs down by reusing the energetic electrons many times. ERLs resolve the power dilemma by reusing the beam energy. After producing SR, the electrons in an ERL re-enter the linac, but 180º out of accelerating phase. The bunches then decelerate and yield their energy back to the electromagnetic field in the linac. When bunches emerge from the linac with the low injector energy (minus SR losses), a weak bending magnet deflects them into a beam dump. The energy recovered by the linac accelerates new electrons. For the best stability, CW operation is a must.

Ultimately, ERLs promise efficiencies approaching those of storage rings, while maintaining beam quality characteristics of linacs: superior emittance and energy spread, and sub-picosecond bunches. The ERL has the advantage that beam quality is limited by the photo-injector, rather than the machine as a whole.

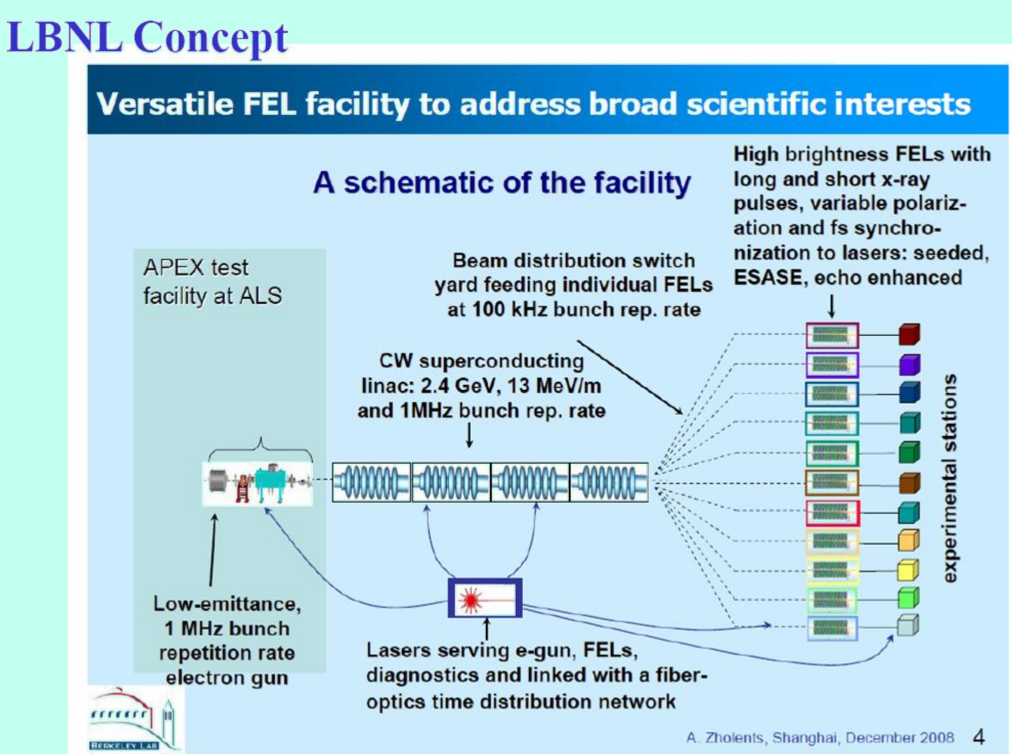
Cornell is proposing a synchrotron radiation light source as an extension to the CESR ring. The ERL will be driven by an energy recovering SRF linac operating at an energy of 5 GeV and an average current of 100 mA. While offering average photon flux comparable to storage rings, the proper parameters of an ERL can lead to higher peak brilliance, shorter pulses and a higher coherent fraction. The Cornell ERL will need 350 cavities and 60 cryomodules. KEK is proposing a similar 2.5 – 5 GeV ERL.

Jefferson Lab and Japan Atomic Energy Agency used superconducting cavities to demonstrate energy recovery for low energy (50 and 17MeV) and low current (5mA) beams. More than 1.3 MW beam power was energy recovered with a beam of 9.1 mA at 150 MeV. These laboratories showed they could save most of the energy required for beam acceleration up to a beam power of about one MW. A one GeV experiment in CEBAF also demonstrated recovery at high beam energy.

Free Electron Lasers

The next generation light sources will need to deliver orders of magnitude higher brightness and optical beam quality through multi-particle coherence, smaller source emittance, shorter bunch lengths and high average currents. The demands for high beam quality can be met using low emittance injectors and CW SRF-based linear accelerators. For modest average current, but high bunch charge and low emittance beams, a single pass linac with a Free Electron Laser (FEL) configuration is favorable. Typical parameters are a few GeV, for nm wavelength x-rays, ~1 nC per bunch, and bunch repetition rates in the 100 kHz to 1 MHz range. The energy required for high-power FELs is in the range of 100 MeV for infra-red (IR) to less than 1 GeV for ultra-violet (UV). Both ERL and single-pass configurations benefit from the efficient operation and large beam apertures afforded by CW SRF cavities

The oscillator configuration for FEL is generally limited in wavelength to ~160 nm by the availability of mirrors. For UV and X ray lasers long undulators provide single-pass amplification via SASE. The light spectrum and pulse shape is made more reproducible with a seed laser. High-Gain-Harmonic Generation (HGHG) is proposed for “upconversion” to shorter wavelengths. With a very short pulse (< 100 fs) seed laser (e.g. Ti:Sa), the external seed overlaps the bunch and modulates the energy in a short undulator. A dispersive chicane converts this to a spatial modulation with higher-harmonic content. A second undulator, tuned to a harmonic, then generates coherent radiation that seeds the next stage. The cascade repeats until the desired wavelength (down to 1.25 nm) is reached. The modulated part of the bunch radiates coherently at a harmonic of the seed laser (limited to about n ≤ 5). The seed laser rather than the electron bunch determines the properties of the output photon pulses, yielding reproducible “clean” pulses both temporally and spectrally. Several beam lines can be separately seeded providing high flexibility for a range of users. There are several studies, such as the LBNL described below, in progress for future one-pass FELs to provide VUV to X-rays as reviewed in. Many concepts are based on the high gradient SRF technology developed at TTF for the XFEL and the ILC

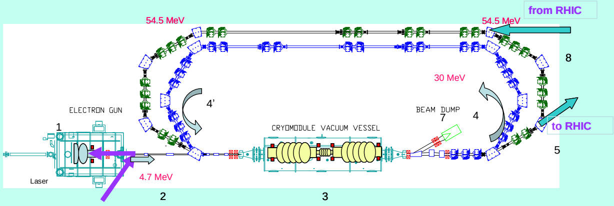


ERLs for Nuclear Physics

Electron Cooling and Electron-Ion Colliders

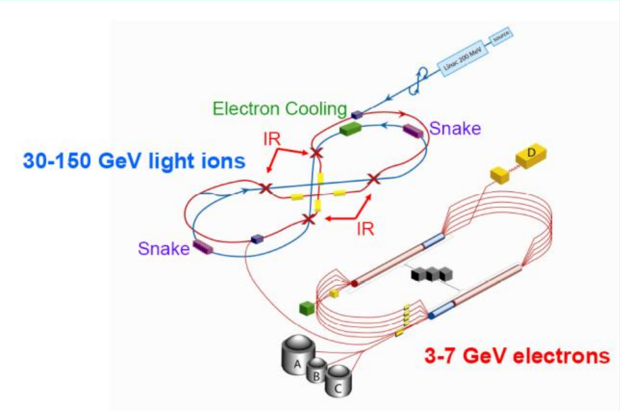
Over the past two decades, nuclear science has made great strides in mapping hadronic structure. Crucial questions remain: What is the quark-gluon structure of the proton and neutron? How do quarks and gluons evolve into hadrons? What is the quark-gluon origin of nuclear binding? High-luminosity electron-ion colliders are under exploration as a powerful new microscopes to probe nuclear structure. The potential benefits of ERLs have spurred explorations world-wide for electron cooling applications and for electron-ion colliders.

RHIC-II is a luminosity upgrade to RHIC (Relativistic Heavy Ion Collider) via a high power electron beam with energy recovery. Electrons with a high bunch charge (5 nC) and a relatively low emittance (3 μm) are introduced into the ion beam. Energy exchange between ions and electrons decreases the longitudinal and transverse emittances of the ion beam. A module with two five cell 704 MHz cavities is proposed to accelerate the electron beam from the gun at about 5 MeV to 54 MeV in a two pass ERL



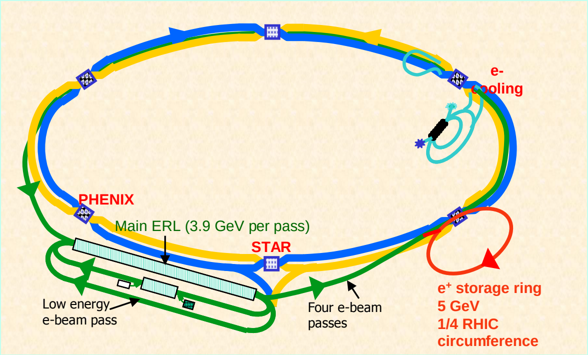
ERL for electron cooling the RHIC beam.

For the future, a high-energy, high luminosity electron-ion collider, eRHIC, will provide 3-20 GeV polarized electrons to collide with high energy polarized protons, gold ions and polarized ^{3}He ions. A 4 GeV electron accelerator with a five pass ERL will provide 20 GeV electrons with high polarization (> 80%). The electron current required will be 0.25 A at 10 – 20 nC bunch charge. The linac will be based on a 703.75MHz, 5-cell cavity under development.



The Electron-Light-Ion Collider (eLIC) concept developed by Jlab.

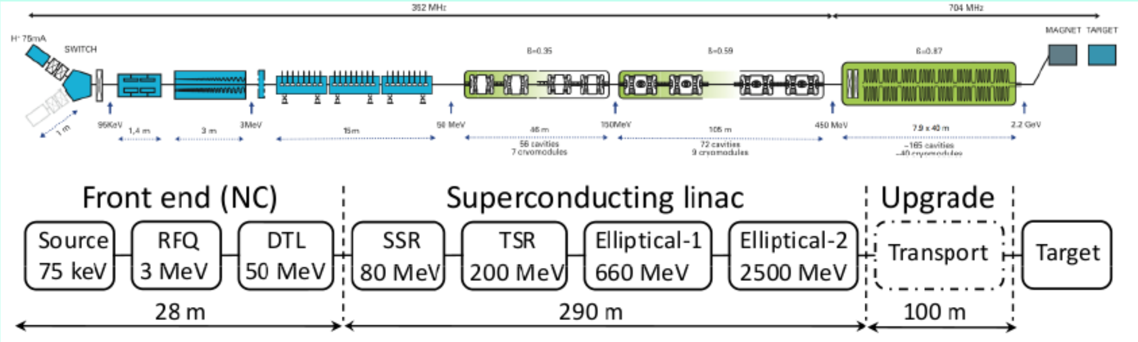
The Electron-Light-Ion Collider (eLIC) concept at JLAB is a hybrid between ring-ring and linac-ring. It stores the electron beam for ~100 turns in a circulator ring (CR). The potential advantages are: less electron beam disruption than for a ring-ring option and 100 x less average linac current, thus reducing demands on the electron source.



ERL for electron-ion collider.

Multi-Mission High Intensity Proton Linacs

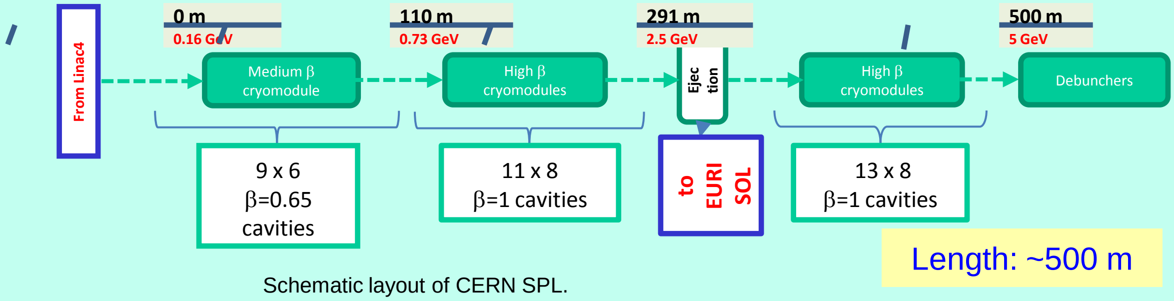
High intensity proton linacs will likely fulfill future needs in a variety of arenas: upgrading the injector chains of proton colliders, such as the Fermilab Tevatron and the CERN accelerator complex including the LHC, heavy-ion radioactive beams for nuclear physics, medical therapy, industrial applications, high intensity spallation neutron sources, transmutation applications for treatment of radioactive nuclear waste, nuclear energy production using thorium fuel, high intensity neutrino beam lines, neutrino factories, and muon colliders for frontier High Energy Physics. In a generic definition, a High Intensity Proton Accelerator delivers proton beams of several mA, at an energy between 50 and 3000 MeV. Challenges are the presence of high beam power, space-charge dominated, non-relativistic beams with halo formation. Accelerating structures need development for nearly every beta value. Typical requirements are low beam losses (<1 W/m) to avoid excess activation, high reliability and, in nuclear reactor cases, absence of long (> 0.3s) beam interruptions.



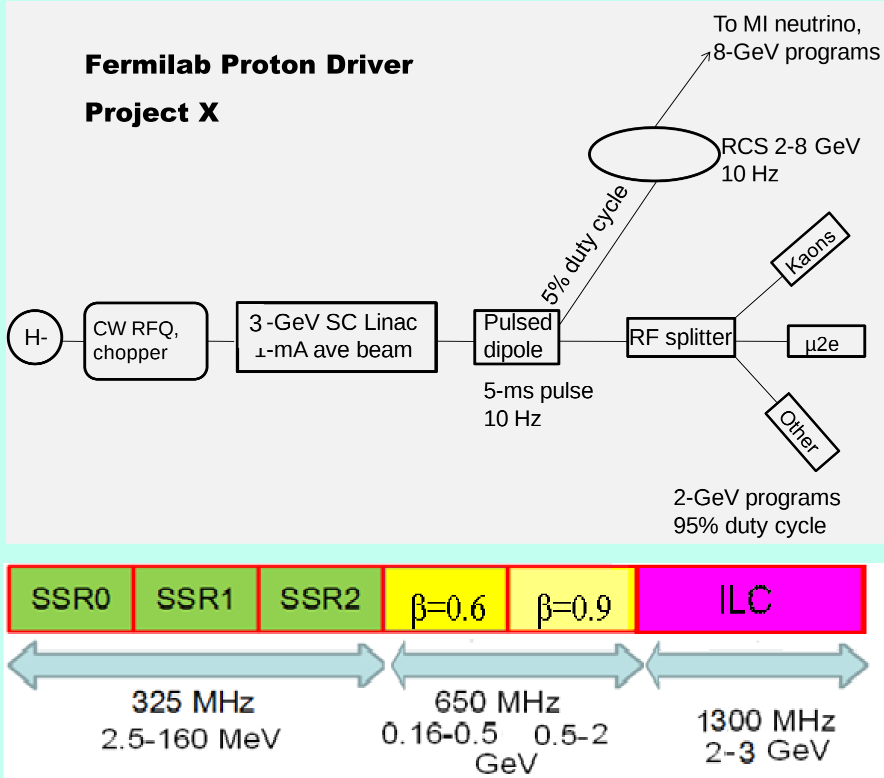
Schematic layout of ESS (European Spallation Source).

Although cyclotrons could reach the desired performance with a few mA, only SRF linacs are competitive for high average currents (e.g. 100 mA) and CW operation. The generic layout is similar to the SNS layout. This includes a normal conducting injector and an RFQ ($\beta \leq 0.1$), a low- and intermediate-energy section ($0.1 \leq \beta \leq 0.5$) containing the normal to superconducting transition, and a superconducting high energy section. The optimum transition energy to superconducting depends on the linac parameters (beam current, time structure, and reliability requirements). Short, low-beta superconducting cavities offer advantages of wide velocity acceptance, acceleration of different mass/charge beams (e.g. protons and deuterons) and a more cavity-fault tolerant linac with small loss in total voltage in case of individual cavity failures. A large number of accelerating gaps in a single structure (typical for normal conducting cases) cannot be completely utilized at low velocity due to rf defocusing. This favors short low-β structures, the strong feature for SRF. Quarter-wave resonators and two-gap spoke cavities are typical below $\beta = 0.5$. Elliptical multicell cavities are the candidates for $\beta \geq 0.5$. Efficiency, gradient and aperture are larger in superconducting cavities than in normal conducting ones.

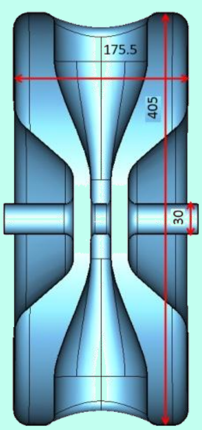
There are a large number of accelerators under study: the Fermilab Proton Driver (now called Project X), the CERN SRF Proton Linac (SPL), the European Spallation Source (ESS) and a variety of transmutation demonstration accelerators in Europe and Asia.



Schematic layout of CERN SPL.

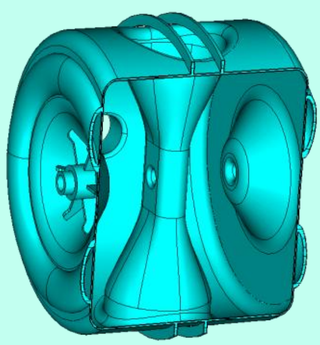


Schematic layout for the Fermilab Project X (formerly Proton Driver) SSR is single spoke resonator. ILC section has nearly ILC compatible cavities.

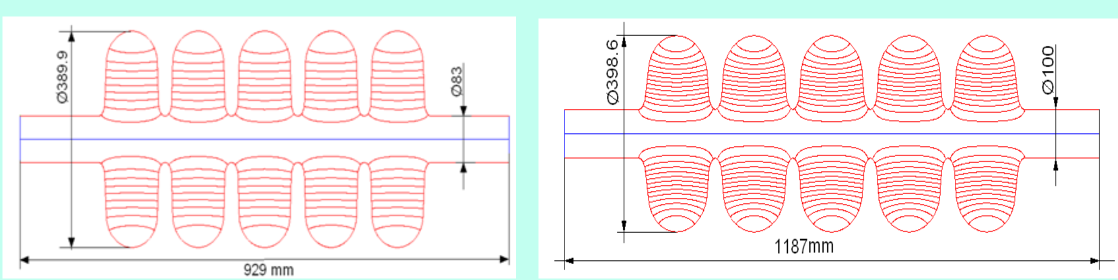


SSR0

SSR1



SSR2



650 MHz, 5-cell cavities, beta = 0.6 and 0.9.

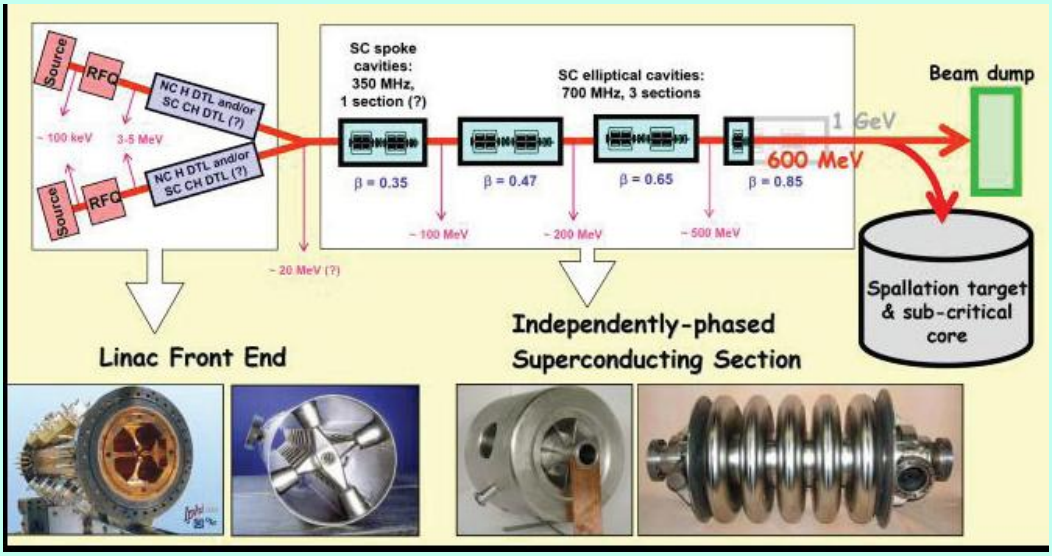
Transmutation Applications

Over the last 50 years, nuclear power and nuclear materials production have produced a large quantity of radioactive wastes, a stockpile which continues to grow while 17% of the world electricity supply continues to rely on nuclear energy. The safe disposal of this waste is a technical problem. To store the highly concentrated wastes in a geological repository is fraught with dangers because of the 10,000-year life-time of some of the radioactive waste products. This danger may be reduced if the long-lived species can be transmuted to isotopes with short life. In Accelerator Based Transmutation of Waste (ATW), spallation neutrons transmute long-lived actinide isotopes and fission products to stable isotopes, or to isotopes that decay to stable products over 100 years instead of 10000 years. No additional transuranic waste is produced. This approach can lessen the technical problems of storing long-lived high level radioactive waste. In an optimistic design, a single accelerator can burn the waste from ten 1 GW reactors, while providing enough power to run itself.

For a 5 - 10 MW proton beam, a superconducting linac significantly lowers the total linac AC power requirement. The SC linac would employ independently controlled RF modules with redundancy, allowing close adjustment of RF phases and amplitudes of RF modules to compensate for faults of individual cavities, klystrons, or focusing magnets. The SRF cavitiesl have a large bore radius that relaxes alignment and steering tolerances, as well as reducing beam loss.

A European consortium is studying XADS, a 10 mA CW, 600 MeV (tunable) proton linac based on SC cavity technology developed in earlier national projects (ASH, IPHI, TRASCO, ESS, and CONCERT) JPARK in Japan is developing a 200 MeV SC section to upgrade energy for future ADS applications

The Korean Multi-purpose Accelerator Complex KOMAC at KAERI is studying a one GeV 20 mA linac for waste transmutation, medical therapy and industrial applications. There is a smilar Indian ADS program at Center for Accelerator Techonology (CAT) in Indore.



European ADS.

FUTURE APPLICATIONS: HIGH ENERGY

Linear Colliders

Particle accelerators have a broad impact on many areas of science and technology. Advances in materials sciences, nuclear science, elementary particle science are paced by advances in accelerator science and technology. Further advances in accelerators will lead to significantly improved capabilities opening new opportunities in physical and life sciences.

Understanding the basic features of energy, matter, and space-time remain the focus of elementary particle physics. Dominant questions are: what is the origin of mass; what is the mechanism of electro-weak symmetry breaking; is super-symmetry a feature of our universe; what is the nature of dark matter and dark energy; can four dimensions describe the universe; can the fundamental interactions be completely unified? Answering some of these questions will require accelerators with energies beyond our current capabilities. Both hadron and electron machines will continue to play important roles.

To complement the LHC, the CM energy for the next lepton collider will have to be in the range of one TeV, a factor of five over LEP-II. In the past, however, the energy steps for lepton colliders have been smaller, because the needed technologies are only mastered in incremental stages. According to the above arguments, the widespread consensus which has emerged is that the next lepton collider should have an initial center-of-mass energy of 500 GeV and luminosity in excess of 1034 (cgs units). It should eventually be capable of reaching one TeV. The initial collider would have the potential for discovery of the much-anticipated Higgs particle and its connection to the origin of mass.

It will also provide well-controlled experimental conditions for precise measurements to elucidate why the electromagnetic and weak forces are so different in nature and strength.

At the TeV energy scale, storage rings become un-affordable as lepton colliders because energy losses from synchrotron radiation increase with the fourth power of the beam energy. Hence the circumference, RF power, and cost of a circular machine increase with the square of the energy. On the other hand, for a linear collider, the length and RF power scale linearly with energy for a fixed gradient.

In 2004 the International Technology Recommendation panel selected the low frequency (1.3 GHz) superconducting approach to the linear collider over the high frequency (11.4 GHz) normal conducting path. One of the reasons was the higher conversion efficiency of wall-plug power to beam power.

One of the attractive features of the superconducting option is that the peak RF power/m is very low compared to the normal conducting option. For pulsed operation, it is possible to fill the cavity slowly (ms), which means modest peak powers (< 400 kW/m instead of 100 MW/m). Superconductivity also makes affordable low RF frequency (1.3 GHz) structures. The resultant large aperture (0.27 times the wavelength) yields substantially low short- and long-range wakefields, fighting the main enemies of high luminosity.

A main challenge for the SRF technology is to reproducibly obtain 35 MV/m gradient cavities and 31.5 MV/m in operation.

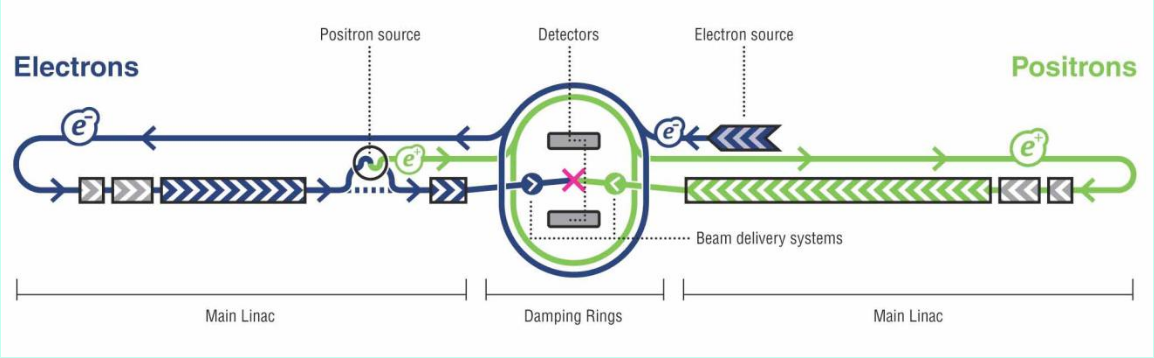
Evolution of the Superconducting Linear Collider

The first international workshop on the superconducting linear collider was held at Cornell in 1990. At the time the name TESLA was adopted for TeV Energy Superconducting Linear Accelerator. Participants at the workshop developed a preliminary baseline parameter set. The international collaboration grew by early 2004 to encompass 55 laboratories in 12 countries. Over the evolution of the design, there have been several international workshops during which the strategies and trade-offs emerged. The resulting parameter set is based on 16 km active length superconducting cavities to operate at an initial accelerating gradient of 31.5 MV/m at a Q_0 near 10^{10}.

When DESY adopted the TESLA Test Facility (TTF) project in 1992, the design continued to evolve under its auspices together with the design for the XFEL and test accelerator TTF, which was later re-nmaed FLASH.

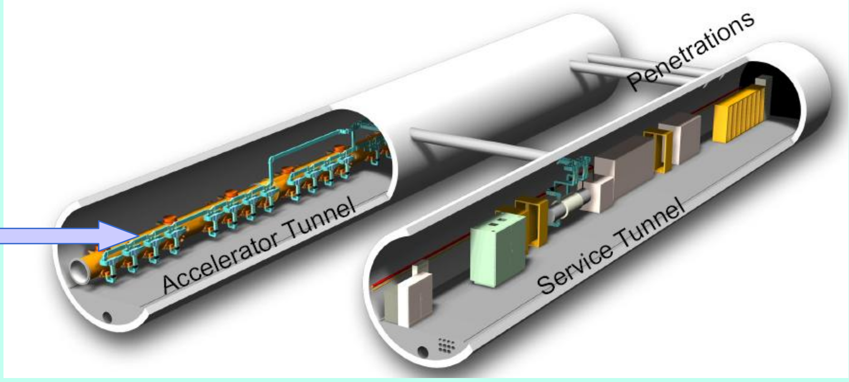
After the ITRP decision in 2004 the International Linear Collider (ILC) has been organized and driven by the Global Design Effort (GDE), a consortium of international laboratories interested in the linear collider and in acquiring the superconducting rf technology for future accelerators in general.

The ILC layout shows the major components of a linear collider. Electron and positron sources produce the beam. The large beam power demands a copious source of positrons. Damping rings reduce the beam emittances by synchrotron radiation. Bunch compressors reduce the bunch length. The main linacs must accelerate electrons and positrons to the desired energy without significantly degrading the emittances from the damping rings. The final focus system demagnifies the beam size for final collision.



0.5 TeV International Linear Collider, 33 km in overall length.

9-cell cavity and cryomodule for ILC.

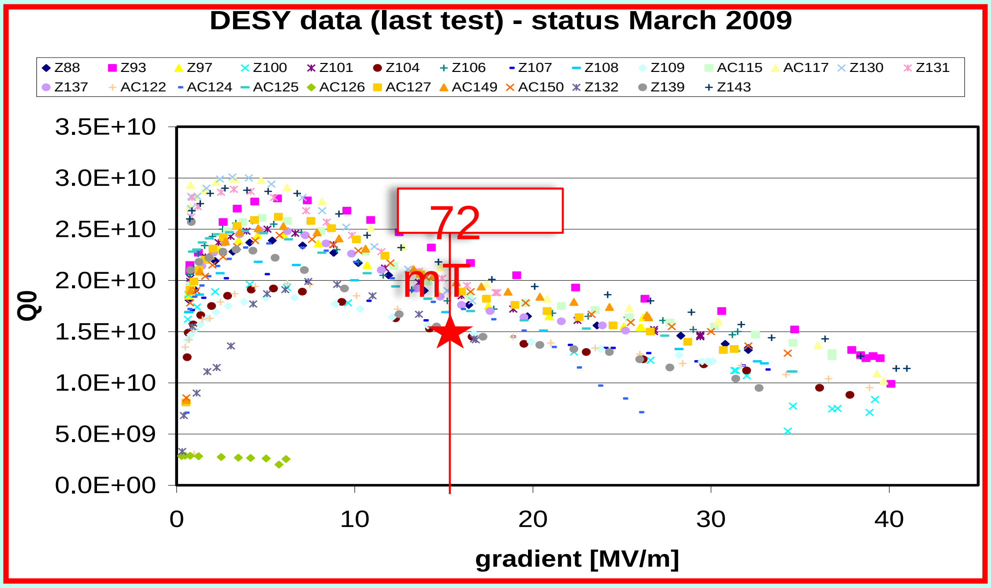


Two tunnel layout for the ILC, one for the accelerator and second for the RF sources and other services.

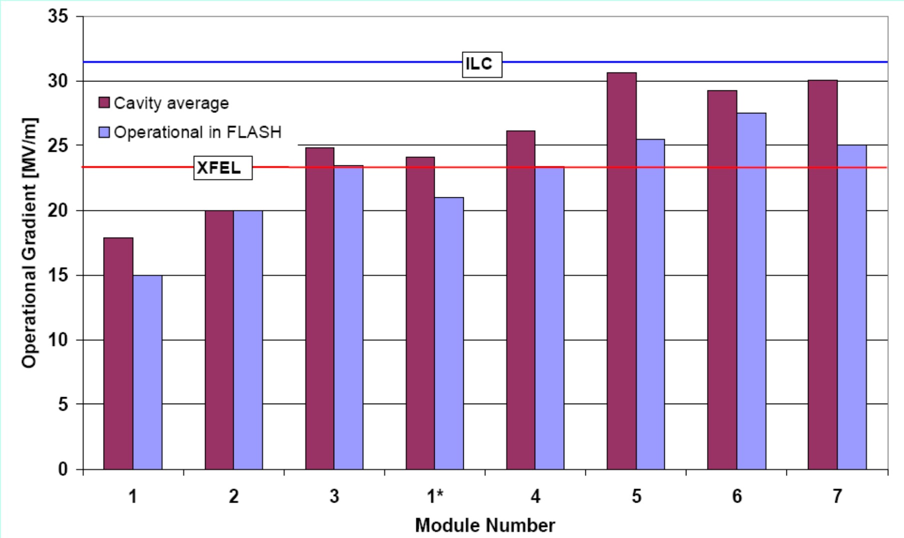
Performance Advances for ILC

The ILC collaboration has made significant advances during the past decade to improve niobium purity and surface processing techniques, allowing cavity gradients to rise to reach 25 - 35 MV/m by the year 2010. More than two hundred 9-cell structures have been produced by several industries. Steady rise in 9-cell cavity gradients has been due to material and process improvements, such as high pressure rinsing, eddy current screening of starting niobium sheets, electro-polishing, and mild baking.

The 500 GeV collider will need 1700 cryomodules housing 16,000 niobium structures. Many cryomodules have been assembled between and tested in TTF-1, TTF-II (now FLASH). The average gradient has been rising steadily. Several individual 9-cell cavities in the best of these cryomodules have been operated at 35 – 37 MV/m. With nearly 700 cavities, and 90 cryomodules, the XFEL project in Hamburg will provide a solid basis for the large-scale application of SRF cavities to the ILC.



Distribution of 9-cell cavity performance from two vendors (measured at DESY).



Steady advance in cryomodule gradients at DESY.

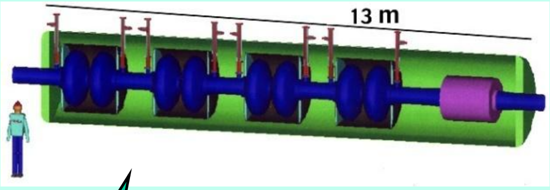
Neutrino Factories, A First Step to Muon Colliders

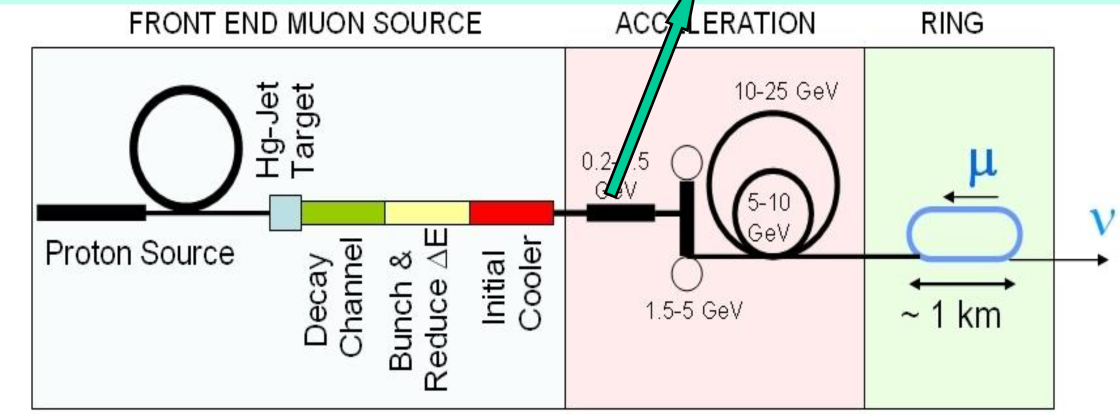
Electron-positron colliders beyond 2 TeV CM energy are likely to be limited by background from beamstrahlung, and proton colliders beyond 14 TeV CM are likely to be limited by the sheer size of the multi-hundred km circumference. Being 200 times more massive than electrons, muons do not suffer from beamstrahlung limits. A 3 TeV muon collider is likely to fit on a site such as Fermilab. But muons are unstable. Problems from muon decay are the heat load, large detector background and neutrino radiation hazards. The last adversity can be turned into the fortune of an intense neutrino source.

As a first step, the Muon Collaboration is studying a Muon Storage Ring based Neutrino Factory. Atmospheric neutrino, solar neutrino and short baseline accelerator experiments show that neutrinos have a small but finite mass. According to theory, neutrinos with mass should oscillate in flavor, which opens up exciting fields of neutrino flavor physics, such as the search for CP violation in neutrino interactions. This symmetry breaking may be the correct explanation for the mystery of matter-antimatter a-symmmetry in the universe. The goal of the neutrino factory would be to provide 3 x 10^{20} muon decays per year.

Acceleration of a muon beam is challenging because of the large phase space and short muon lifetime. The need for very large beam acceptances drives the design to a low RF frequency of 200 MHz. To minimize muon loss from decay, the highest possible gradient is necessary. At gradients of 15 MV/m SRF reduces the peak RF power by virtue of long fill times made affordable by superconductivity. SRF cavities also provide a large aperture that helps preserve beam quality and beam stability.

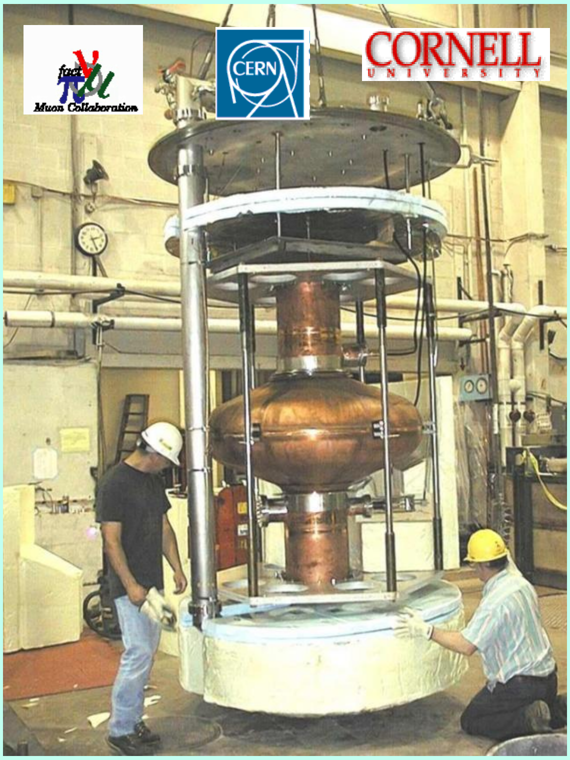
The muon acceleration system starts with a linac from about 200 MeV to 1.5 GeV followed by a 4-pass recirculating linac to the final energy of 25 GeV. Some designs call for a final energy of 50 GeV with a second recirculating linac. A pre-accelerator linac is necessary in the first stage because the beam is not relativistic and phase slippage in a recirculating linac would reduce acceleration efficiency.





A generic neutrino factory from proton source to muon production, followed by cooling and acceleration.The demands on muon cooling are much reduced over that for a collider. In the final storage ring, muons decay to produce the desired intense neutrino beam.

A 200 MHz Nb-Cu Cavity for Muon Acceleration

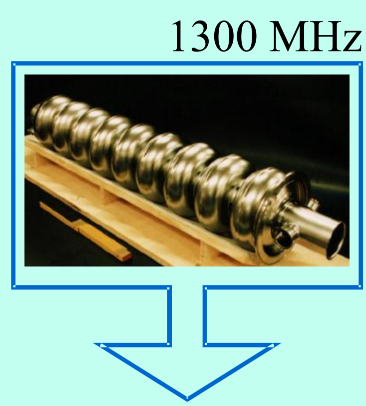


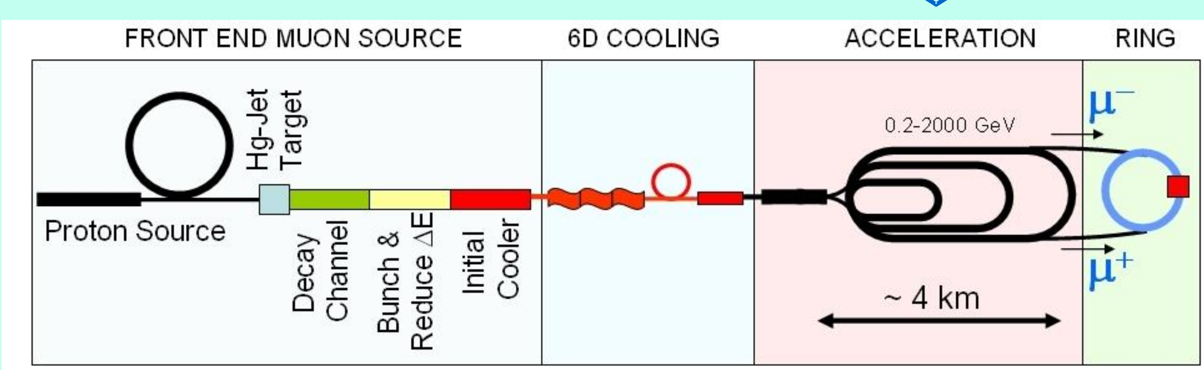
A CERN-Cornell collaboration designed, fabricated and tested a 200 MHz single cell Nb-Cu cavity. In the first such unit, an accelerating field of 10 MV/m was reached at a Q near 10^9. The neutrino factory and the muon collder call for several hundred meters of 200 MHz cavities to provide gradients of 15 MV/m. Nb-Cu is the technology of choice driven by the cost concern. The success of 400 MHz LHC cavities in reaching comparable gradients is encouraging.

Muon Colliders

A muon collider concept has been put forward for 4 TeV CM at a luminosity of 3 x10^{34} cgs units Many aspects of the system are still in need of substantial exploration, in particular the cooling the muons. After cooling and pre-acceleration, the beam will be accelerated to full energy using a cascade of superconducting recirculators that would accelerate the beam in stages. The RF frequency would increase as the bunch length decreases. An early stage of acceleration would be based on 200 MHz superconducting cavities under development for the neutrino factory. The final stage would be based on several km of 1.3-GHz ILC-type superconducting cavities operating in the pulsed mode with 1% duty factor and a gradient of 20 MV/m.

The path to a multi-TeV muon collider is filled with many challenges. A time scale shorter than 20 years seems unlikely. For comparison, the ILC effort was started around 1988, and is still many years towards completion, if it moves forward.

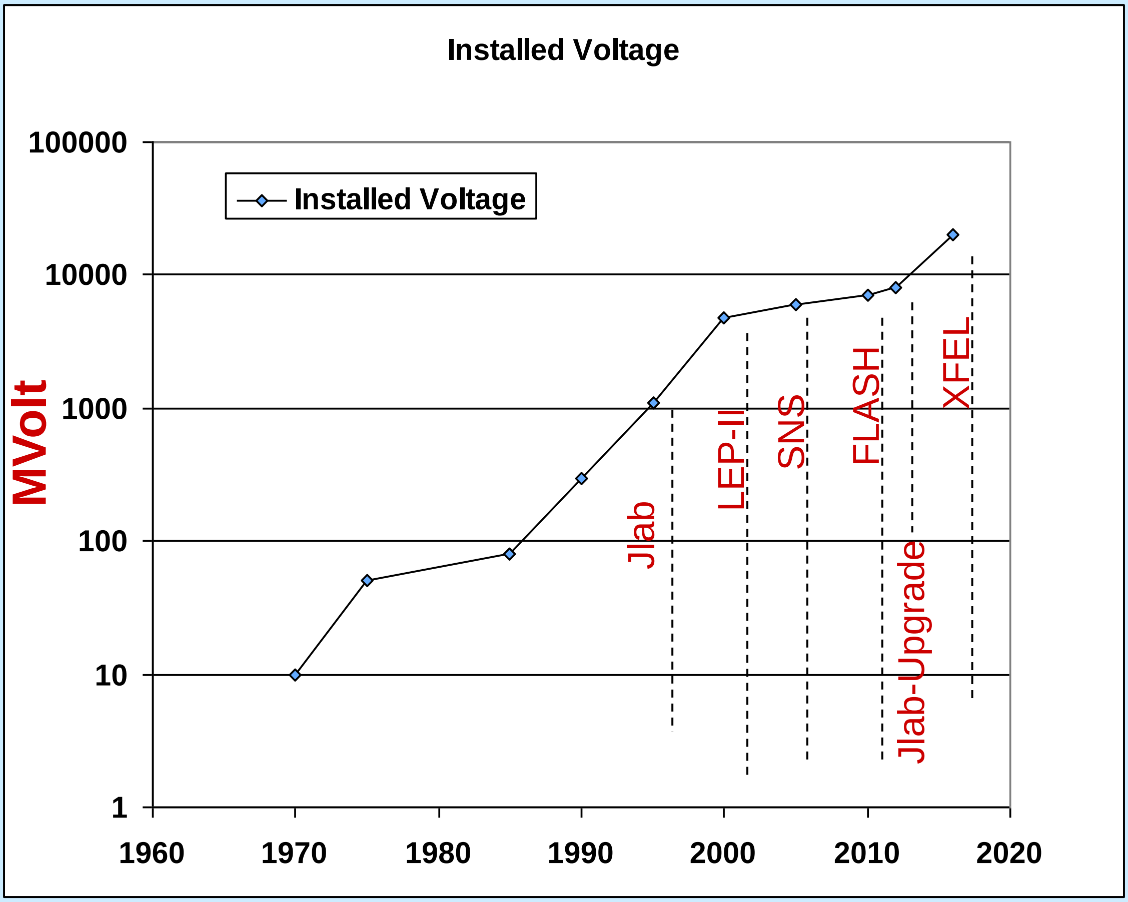




Generic layout for a 4 TeV Muon collider for the far future.

CONCLUDING REMARKS

Total Voltage Installed (Near Future)



Year

Superconducting cavities have been operating routinely in a variety of accelerators with a range of demanding applications. With the success of completed projects, niobium cavities have become an enabling technology offering upgrade paths for existing facilities, and pushing frontier accelerators for nuclear physics, high energy physics, materials and life sciences. With continued progress in basic understanding of superconductivity, the performance of cavities has steadily improved to approach theoretical capabilities. Besides offering exciting options for traditional applications, superconducting cavities are branching out into new applications to light sources, neutron sources and high intensity proton sources to fulfill a variety of needs. The total installed voltage for these projects is on the path to grow to from 7 GeV to near 20 GeV.

The most ambitious application for niobium cavities is the superconducting linear collider for high energy physics. If LHC results warrant the launch of the ILC, the total voltage will grow to above 500 GeV.

We can remain confident that the RF superconductivity community has both the creativity and determination to face the upcoming challenges and successfully realize these exciting prospects.

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