RF - SUPERCONDUCTIVITY - 2004

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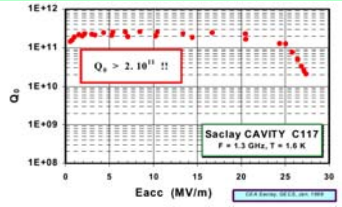

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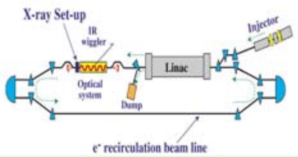

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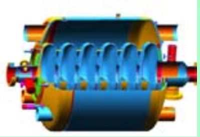

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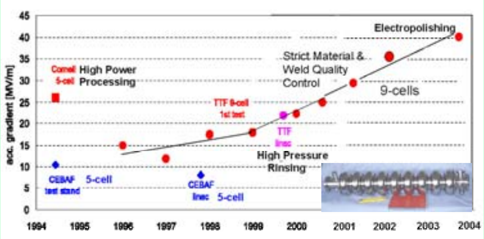

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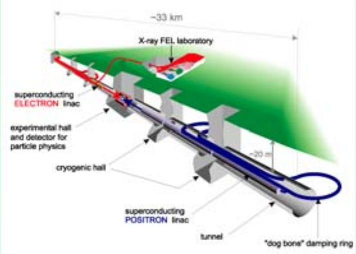

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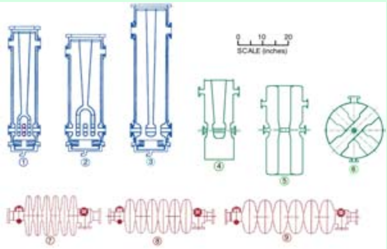

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OVERVIEW

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 should alert the world accelerator community and its supporting agencies to the importance of SRF for upcoming applications in high energy, nuclear, and astro physics, 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.

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

RF superconductivity has become an important technology for accelerators at the energy and luminosity frontiers as well as at the cutting edge of nuclear physics and basic materials science. Nearly one kilometer of superconducting cavities have been installed in electron accelerators around the world and have provided more than 5 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. The two largest installations at CEBAF and LEP-II have served their accelerators well. There is more good news. Steady advances in SRF science and technology are responsible for a spectacular increase in performance level since the large installations of the 1990's.

There has been much progress in understanding the gradient and Q_0 limitations of bulk niobium cavities. Improved understanding and invention of treatments have raised gradients from 5-10 MV/m typical of the early 1990's to 25 - 35 MV/m in 2004. Q_0 values at high gradients approach 10^{10}. High performance demands excellent control of niobium material properties, purity, surface smoothness, and surface cleanliness. Sputtered niobium on copper (Nb/Cu) has served LEP exceedingly well.

New applications of niobum and Nb/Cu cavities are forthcoming for high energy and high luminosity electron-positron colliders, proton-proton colliders, storage ring light sources, free-electron lasers, linac based light sources, energy recovery linacs (ERL), intense proton linacs for neutrons sources, muon storage rings for neutrino sources, and eventually high energy muon colliders. With exciting prospects on the horizon, the world SRF community has expanded to many laboratories where extensive SRF facilities have been installed.

The largest of these applications will be a 20 GeV linac for the European XFEL at DESY. A major future application is likely to be for TESLA, a TeV Energy Superconducting Linear Accelerator. To achieve TeV energy will require 30 km of superconducting cavities operating at gradients of 35 MV per meter. Preparing for TESLA, the achievable gradient of cavities has more than doubled over the last decade. These advances have spurred new accelerators now under construction and planning. For basic materials sciences, SNS switched to superconducting technology in 2000. TESLA technology will drive a linac-based free electron laser to provide Angstrom wavelength X-ray beams of unprecedented brilliance. ERL studies are flowering around the world. Designs for the nuclear astrophysics Rare Isotope Accelerator are able to call on techniques that deliver high performance cavities.

There is now excellent prognosis for reaching 40 MV/m. Research continues to push performance towards the theoretical limit of 50 MV/m. Future improvements in Nb/Cu cavities will prove especially beneficial to muon storage ring applications where the low RF frequency (200 MHz) makes for very large cavities.

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 of future facilities.

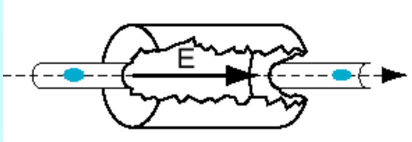
While many years of operation at major accelerators demonstrates that SRF is a robust technology. the existing infrastructure developed at many laboratories prepares SRF to launch major initiatives.

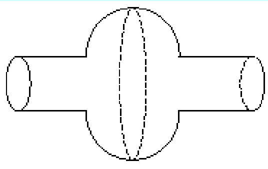
SUPERCONDUCTING CAVITY RESONATORS

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.

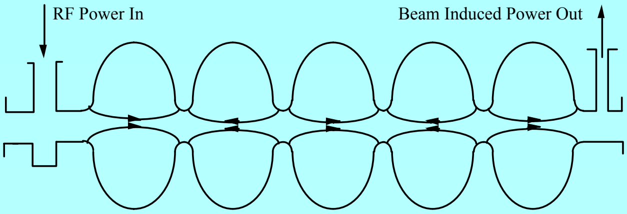
Structure Geometry

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).



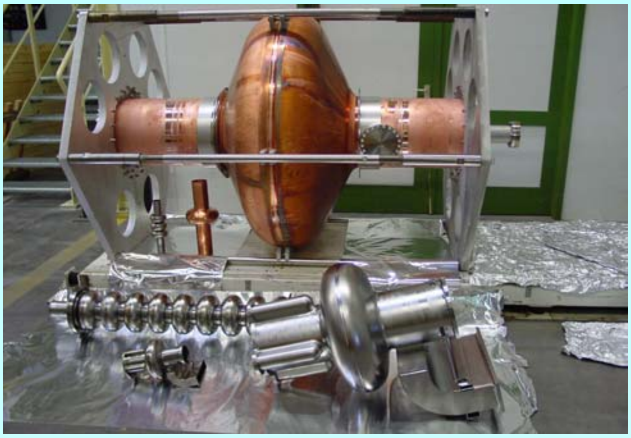


Speed-of-Light-Structures



An accelerating structure for velocity-of-light particles. The resonant frequency is typically between 350 MHz 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 accelerating 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.

Prototype 1500 MHz, 7-cell cavity for CEBAF upgrade



A variety of superconducting cavities for accelerating velocity-of-light particles. In the foreground (left) is the DESY 9-cell TESLA cavity and (right) a CESR 500 MHz cavity together with a small scale version of the latter. In the background the large 200 MHz Nb-Cu cavity dominates. It was developed by a Cornell/CERN collaboration for future muon accelerators and the neutrino factory.

Medium Velocity Structures

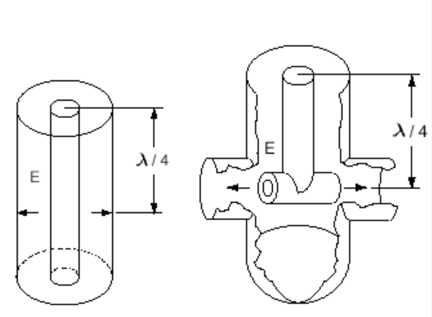
Medium velocity structures with β = v/c between 0.5 and 1 are used for protons with energies less than one GeV as well as for ions. These are either foreshortened speed-of-light structures or spoke resonators.

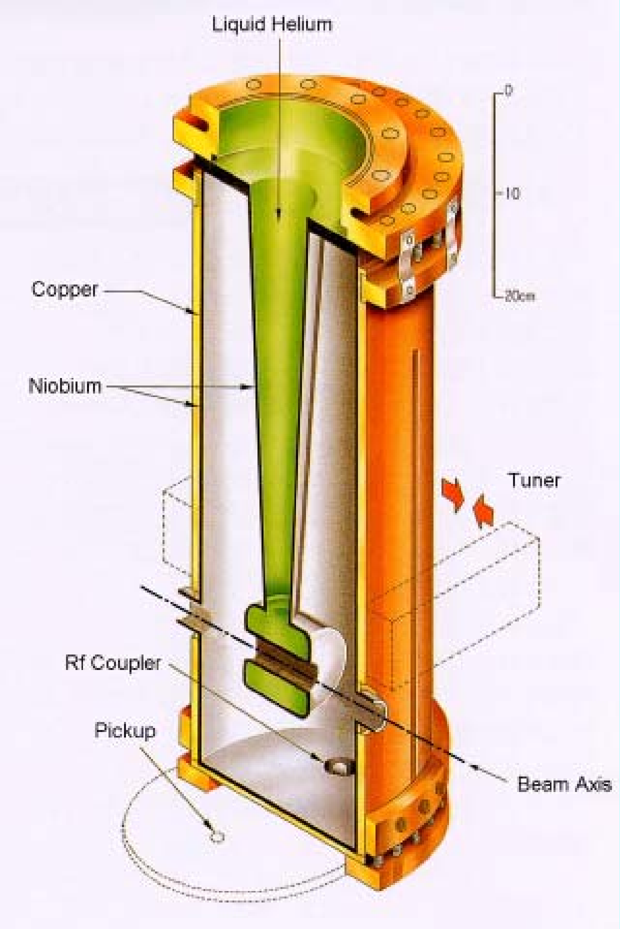
β= 0.47, 800 MHz, 6-cell elliptical-cell (JLAB/MSU)

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

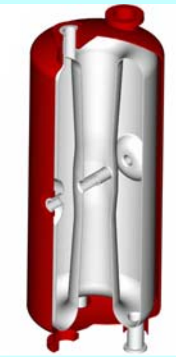
Low Velocity Structures

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.





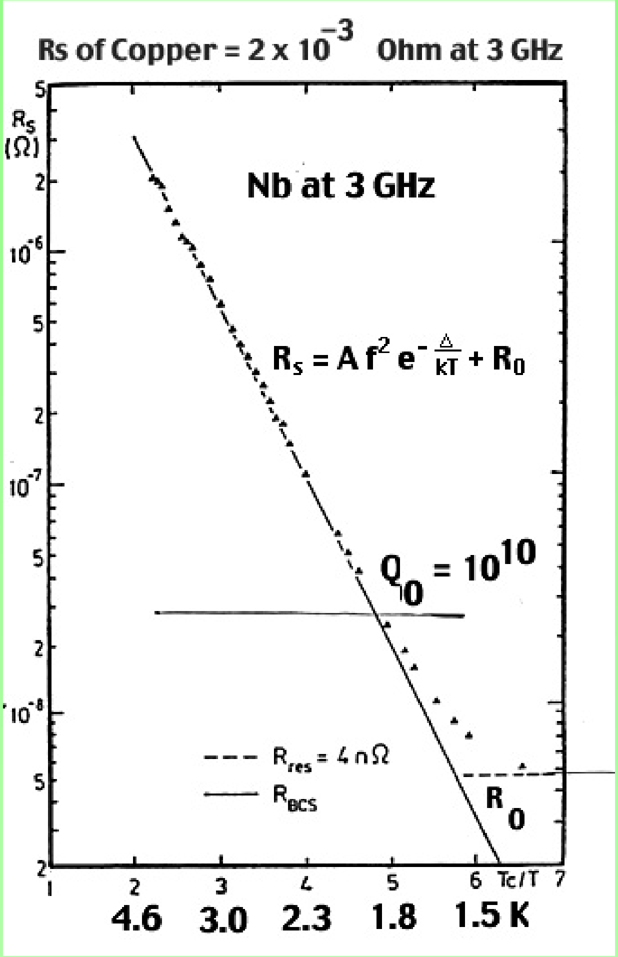
For the Quarter-Wave Resonators, suitable for β between 0.01 to 0.2, a coaxial transmission line a quarter wavelength long, resonates in the TEM mode. A drift tube is suspended from the end of the hollow center conductor. The structure has two accelerating cells between the ends of the drift tube and beam hole openings located in the outer conductor of the coax. For low velocity acceleration, the structure period is βλ/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 βλ/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 "normal" component of the current, 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, $e^{-\Delta/kT}$.



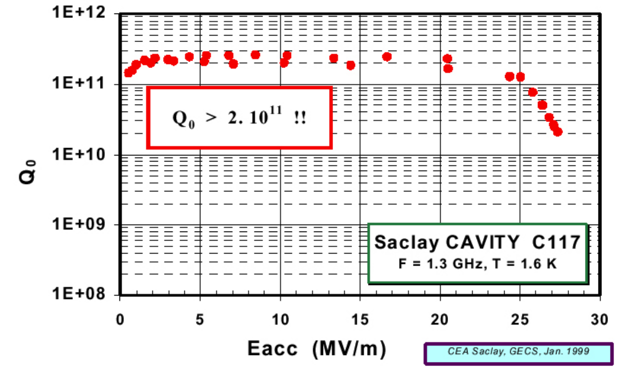
Surface resistance vs. Temperature of niobium at 3 GHz showing the exponential drop due to the energy gap.

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.

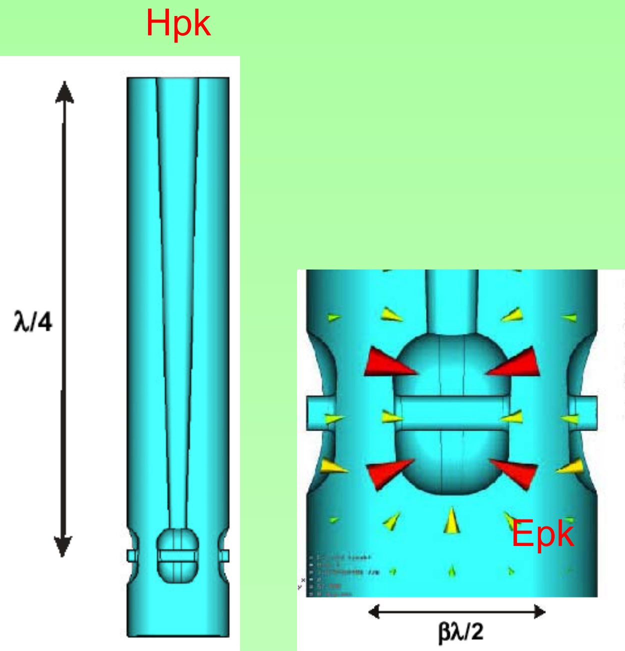
Q vs. E Curves

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!

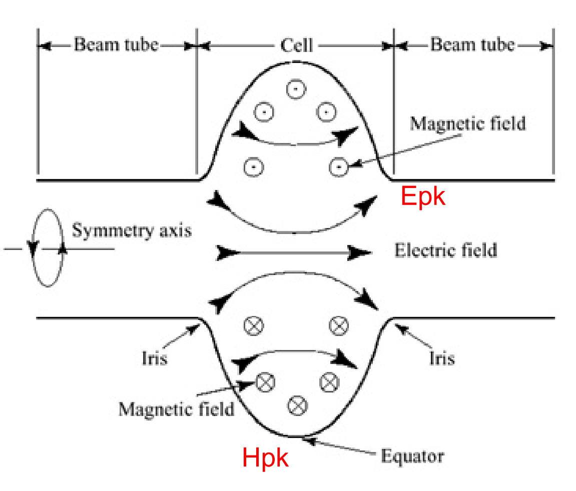


Peak field locations for the Quarter-Wave resonator

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 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 $\beta = 1$ structures).



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 increasing the energy of 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, LEP 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 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 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).

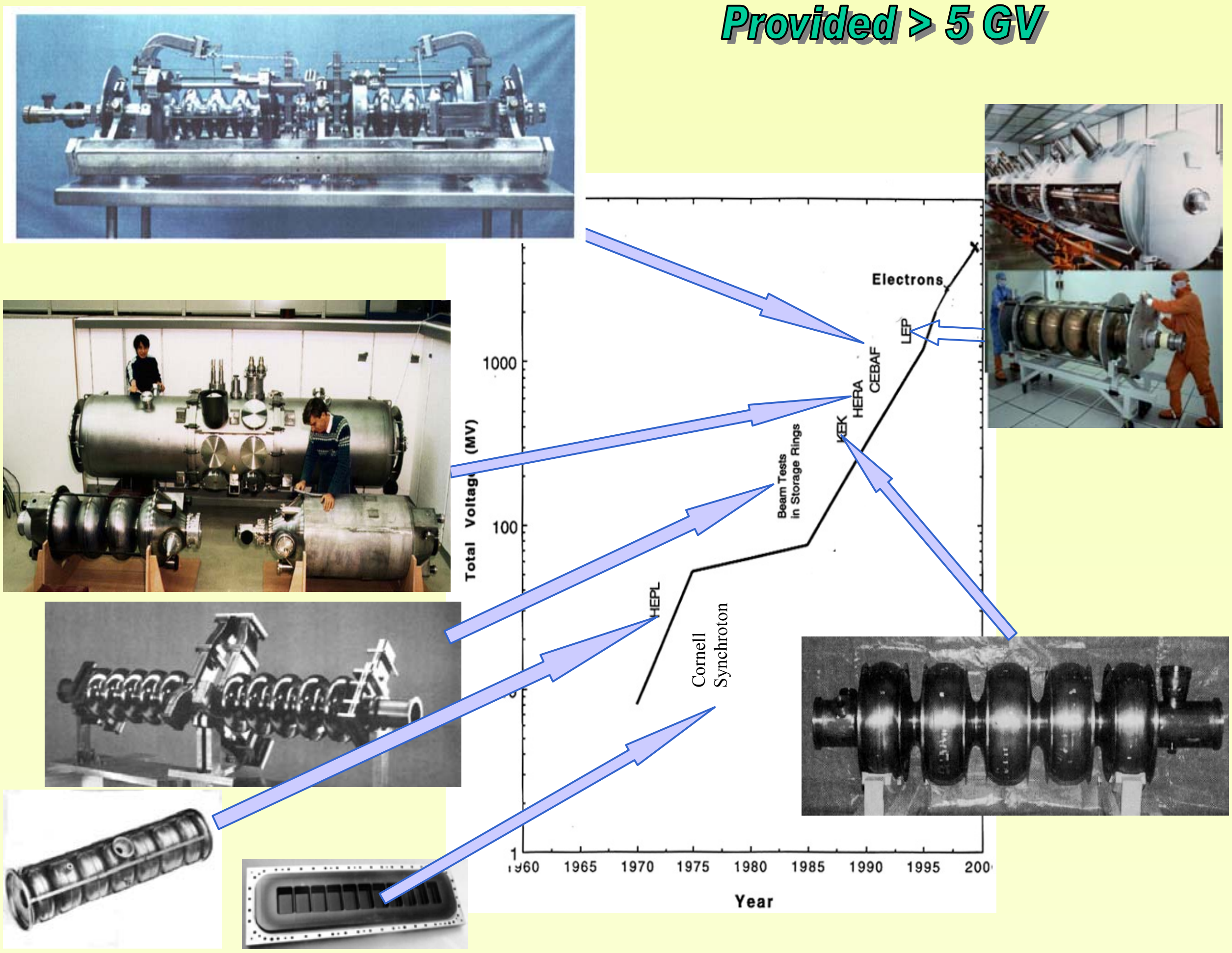
STORAGE RINGS AND LINACS - A SUCCESS STORY

Large scale application of superconducting cavities to electron accelerators is now 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, and high quality electron beams for free electron lasers.

A "Livingston Plot" for RF Superconductivity

Total Installation > 1000 m

Provided > 5 GV

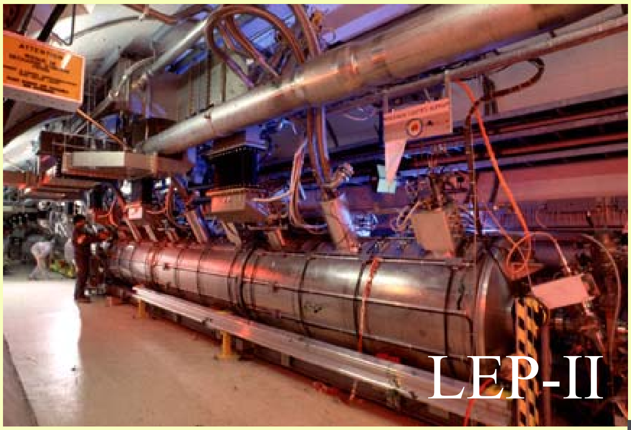


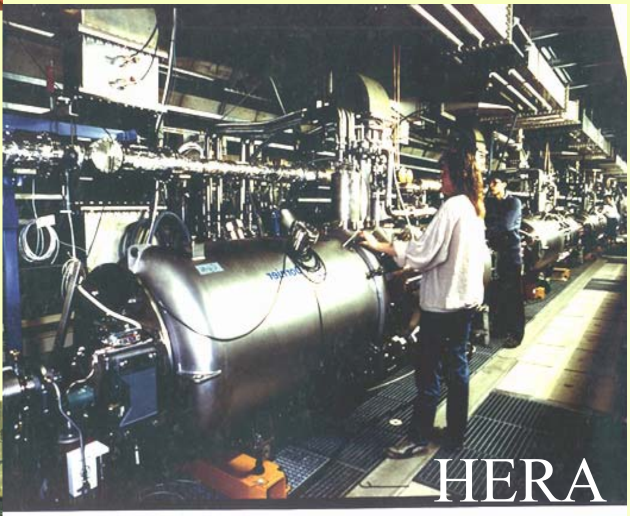
SRF Facilities at the Energy Frontier

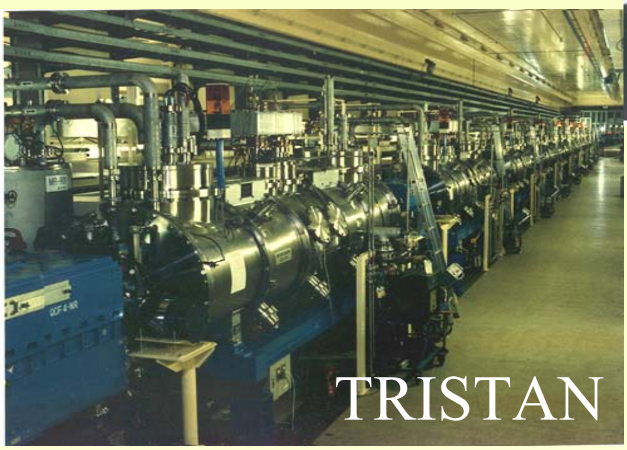
To study the fundamental properties of matter, high-energy physicists have built colliding beam storage rings of steadily increasing energies. Electrons in storage rings lose energy in the form of synchrotron radiation. Because the energy loss increases as the fourth power of the beam energy, the electron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

The colliding beams facilities that use(d) SRF are (were) TRISTAN at KEK in Japan, LEP at CERN in Switzerland, and the electron-proton collider HERA at DESY in Germany.

Accelerator Installations







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.

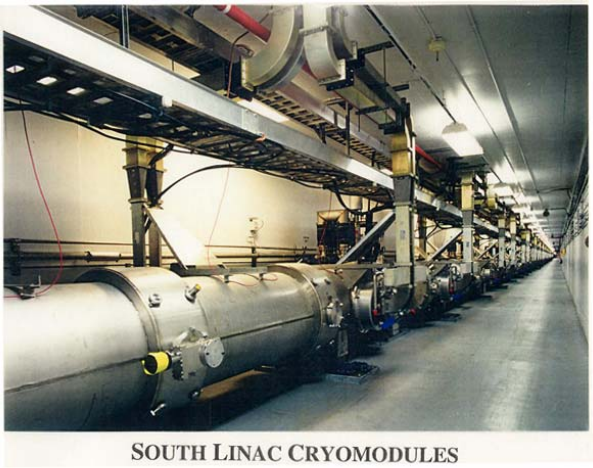
CEBAF improves the basic understanding of nuclear matter, by elucidating the quark and gluon structure of protons and neutrons. It now operates with polarized electrons for more than 5000 hours per year. Some of the salient Nuclear Physics advances have been: detailed mapping of neutron charge structure,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

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 now they have accumulated more than 2000 cavity-years 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.

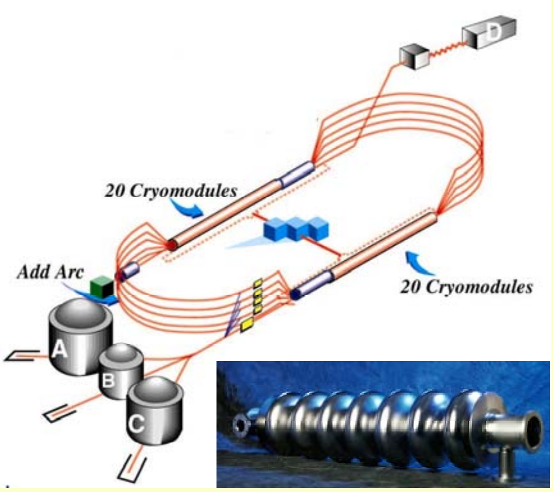
LEP-II installed a total of 465 meters of superconducting RF cavities to provide more than 3.6 GV reaching the highest energy electron-positron collisions: 208 GeV in the Center-of-Mass before LEP-II shut down for installation of the LHC. At the higher energy, LEP-II confirmed the existence of the W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

At the Cutting Edge of Nuclear Physics

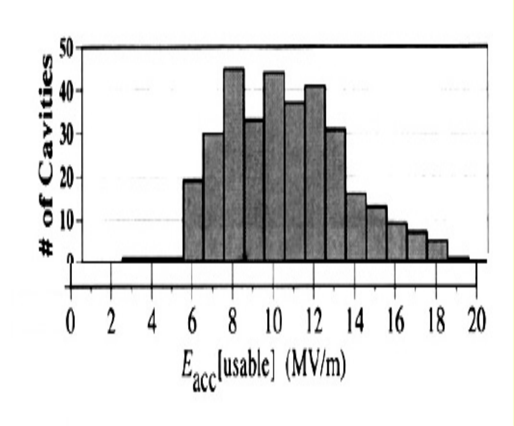
Superconducting cavities offer special advantages to electron accelerators for nuclear physics in the 1 to 10 GeV range: high average current, low peak current, continuous beam, and excellent beam quality. For precise measurement of small electromagnetic cross sections and for coincidence detection of 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.



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.

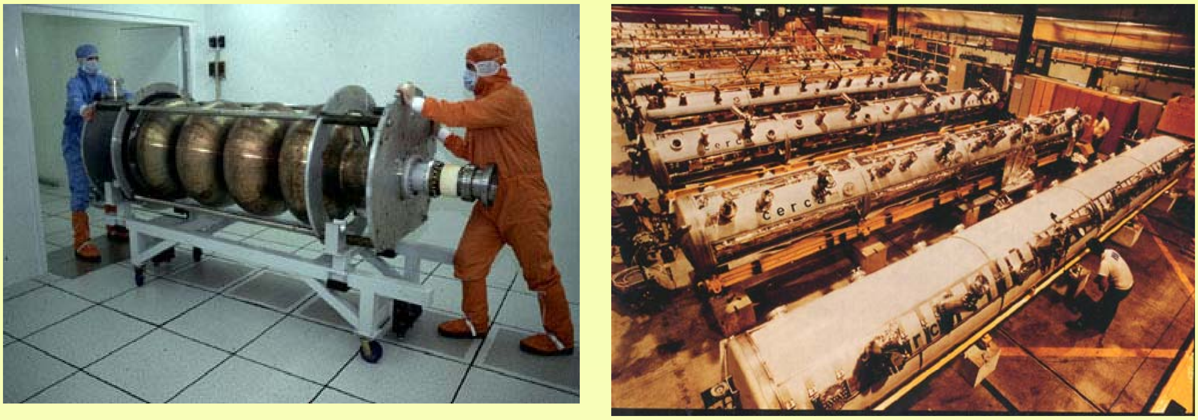


CEBAF is developing new higher gradient cavities and cryomodules to upgrade their energy to 12 GeV. Doubling the beam energy is an important priority for advancing understanding of the strong force and its manifestation in gluonic matter.



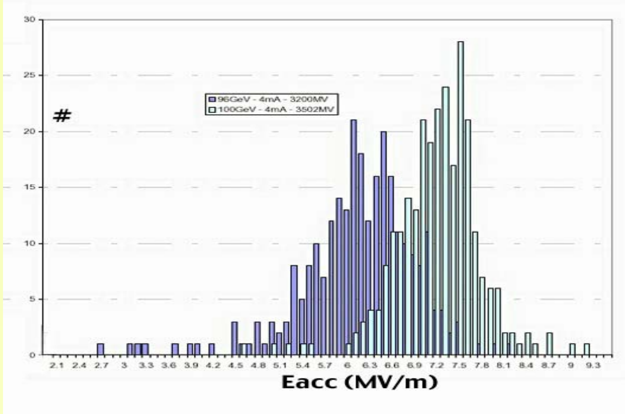
Usable gradients for CEBAF cavities. Most of the 42 cryomodules have been kept permanently cold since 1995. From October 2000 through June of 2001, CEBAF delivered more than 4500 beam hours for physics. SRF cavity related faults accounted for less than 0.5% down time.

350 MHz Nb/Cu Cavities for LEP-II



LEP-II 350 MHz Nb-Cu cavities and cryomodules

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. LEP-II upgraded the in-line performance of their niobium-on-copper (Nb/Cu) cavities from 6 to 7 MV/m, During 1999 and 2000, the RF system in LEP-II 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 by pushing gradually back to maximum.



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," could be some of the new discoveries that impact the frontiers of cosmology.

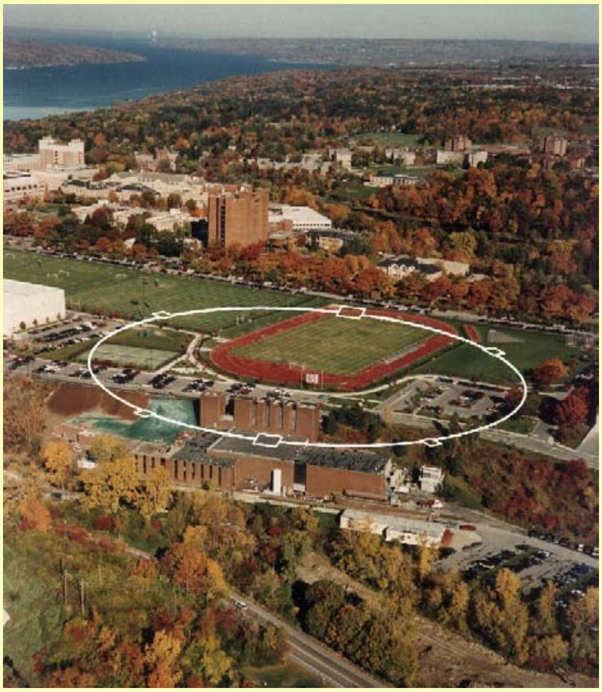
Superconducting cavities and cryomodules are ready for LHC. At 400 MHz, 16 Nb-Cu cavities in 4 cryomodules will provide 16 MV per beam and deliver about 180 kW of beam power. SC cavities will help resolve the issue of transient beam loading by virtue of their low impedance and high cell voltage.

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.

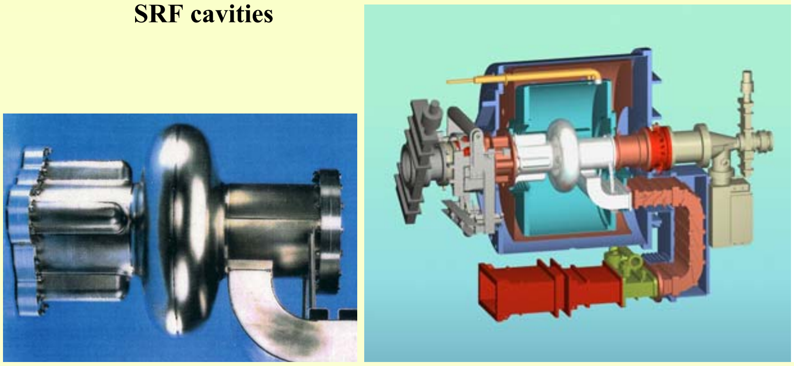
The high luminosity machines with SRF cavities are: CESR in the US, and the KEK-B in Japan, both operating for copious production of C- and B-quark mesons. From 1980 - 2000, the decays of B quarks at CESR provided a wealth of data to test the Standard Model. Running with 4 SRF cavities, the availability 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

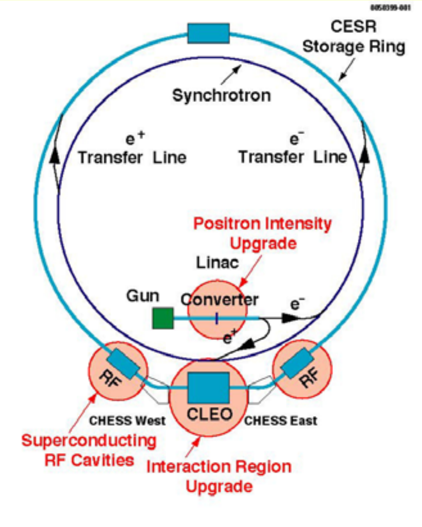


Highlights:

- **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



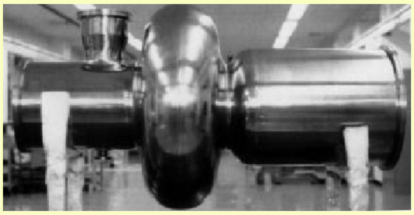
CESR Storage Ring

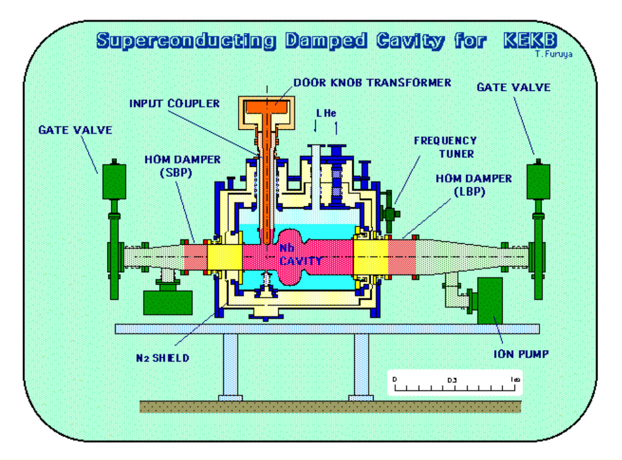
KEK-B Factory

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.

Highlights:

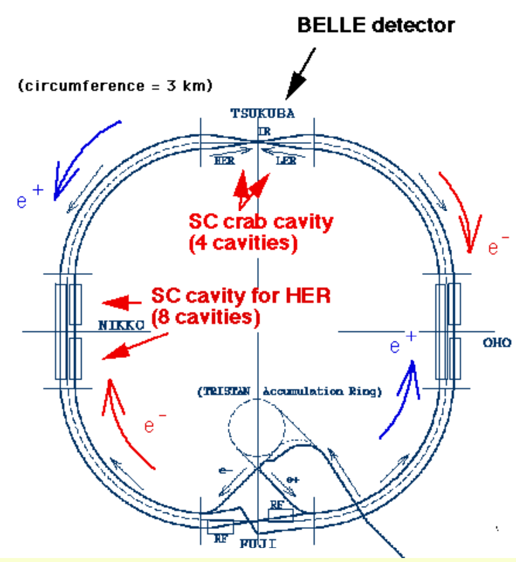
- **1996:** **Beam test in the TRISTAN AR**
- **1998:** **First four SRF cavity installed in KEKB HER**
- **2000:** **Four more cavities added**





KEK-B cavity and cryomodule

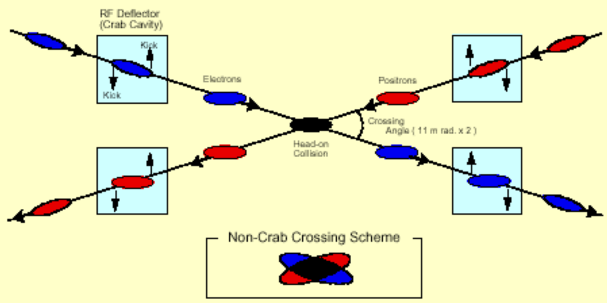
Peak luminosity	1.0567×10^{34} cm^{-2}s^{-1}
Beam current	1.1 A
RF voltage with beam	1.2 – 2.0 MV/cavity
Q_0	1 – 2 $\times 10^9$ at 2 MV 0.3 – 1 $\times 10^9$ at 2.5 MV
Max. power transferred to beam	380 kW/cavity
HOM power	10 kW/cavity at 1.1 A



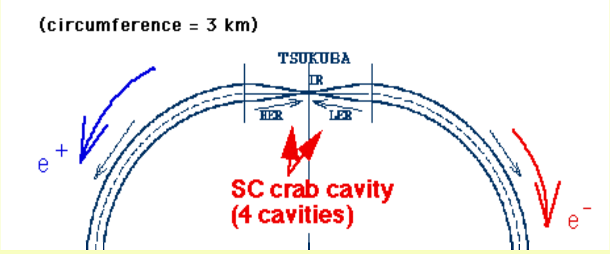
KEK-B storage ring

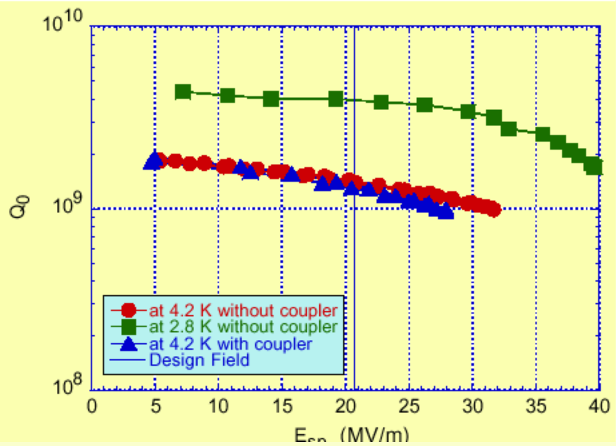
KEK-B Crab Cavities for Luminosity Upgrade

At KEK-B two beams intersect with a finite angle. The crossing arrangement reduces background and simplifies beam optics at the colliding region, but hurts luminosity because of the geometrical effect, and can give rise to a synchrotron-betatron instability at higher currents. To circumvent these effects, RF deflectors called crab cavities are under development to tilt the bunches and bring them into a head-on collision. The tilted motion of the bunches after deflection resembles the crawling motion of crabs; hence the name “crab crossing"



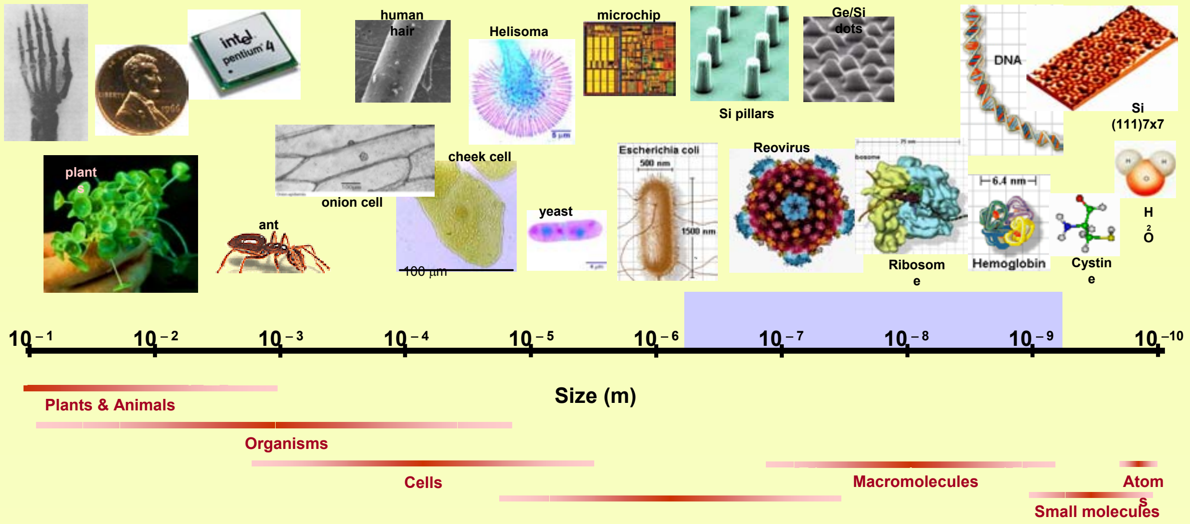
The crab crossing scheme allows a large crossing angle collision without introducing any synchrotron-betatron coupling resonances.





Peformance of the prototype 500 MHz crab cavity

STORAGE RING LIGHT SOURCES AND THE EVOLUTION OF IMAGING SCIENCE



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.

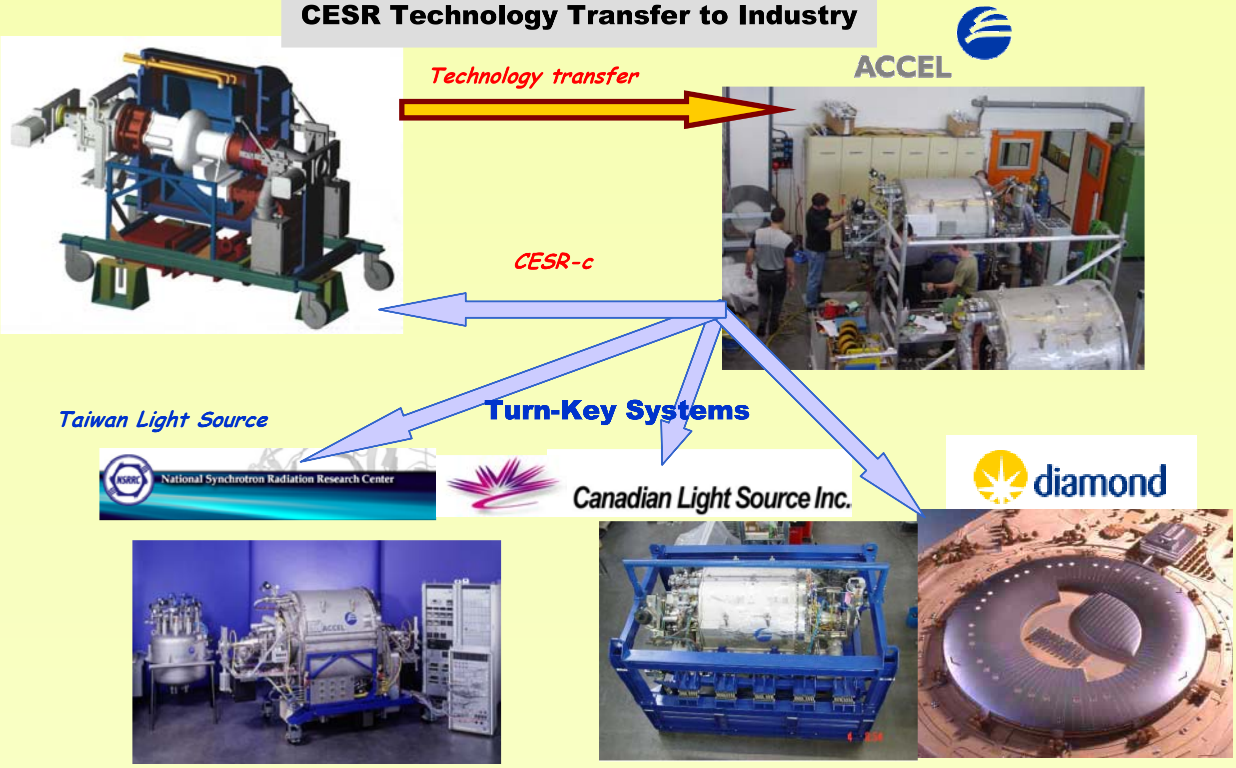
At CESR, CHESS has been operating as a prolific light source for two decades. After replacing the CESR copper RF system of 20 cells by a superconducting RF system with 4 cells, the beam current could be increased from 300 mA to 750 mA, and accordingly the SR flux.

CESR-based superconducting cavity systems will upgrade the Taiwan Light Source. The Canadian Light Source (CLS), the DIAMOND light source in England will also install similar superconducting systems. A Saclay-CERN collaboration developed a 350 MHz Nb-Cu SRF system for SOLEIL in France. BEPC in China and the Shangai Light Source envision using SRF based on the the KEK-B system.

Storage Ring Light Sources

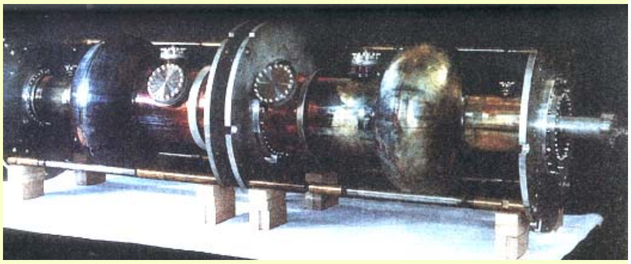
Cornell LEPP has transferred the technology of CESR cavities to industry which is providing turnkey systems for major storage ring light sources around the world.

CESR Technology Transfer to Industry



SOLEIL

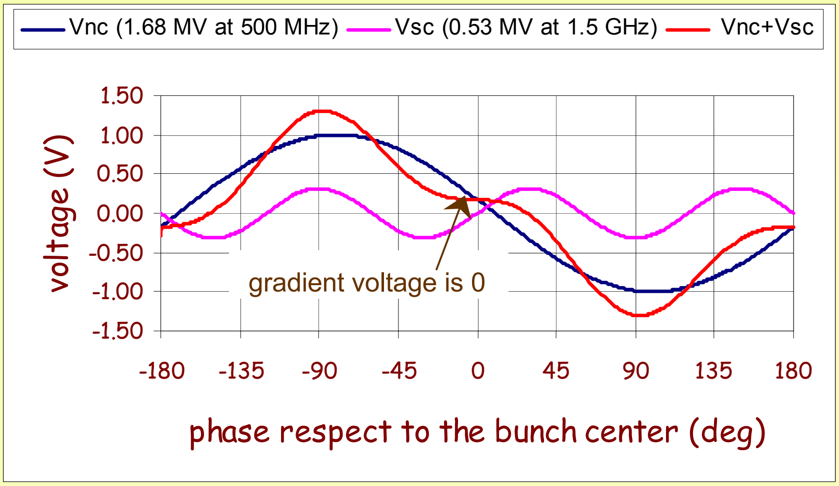
A 2.75 GeV, 500 mA Light Source



Nb/Cu single-cell HOM damped 352 MHz cavities, designed and built by a Saclay/CERN, collaboration were high power tested at ESRF to Eacc of 7 MV/m and transferred 360 kW to 170 mA beam.

Third Harmonic Passive Cavities

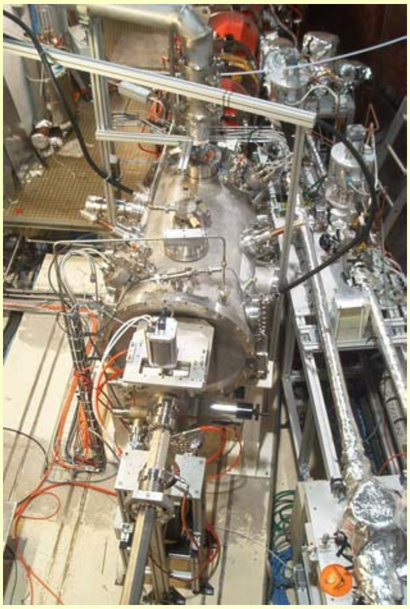
A 3rd harmonic (1.5 GHz) RF system allows bunch lengthening, decrease of charge density & increase of beam lifetime. Landau damping allows suppression of coupled bunch instabilities. After installation, both SLS and ELETTRA gained a factor of 3 on bunch lengthening and more than a factor of 2 on beam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



Prototype 3rd harmonic Cavity Built at CERN

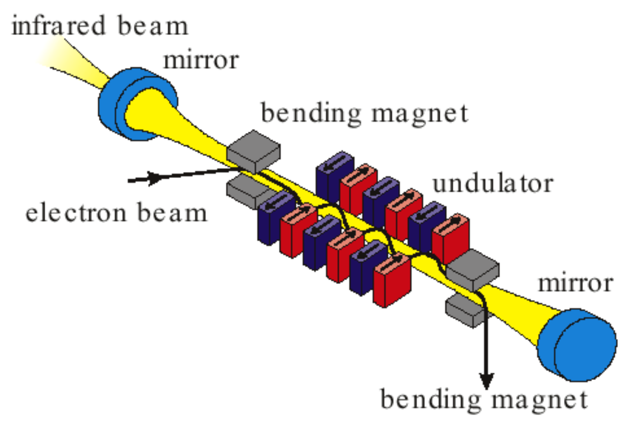
In 2004 BESSY will use a 1/3 scale model of the CESR cavity

SLS Cryomodules



ELETTRA Cryomodule

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.

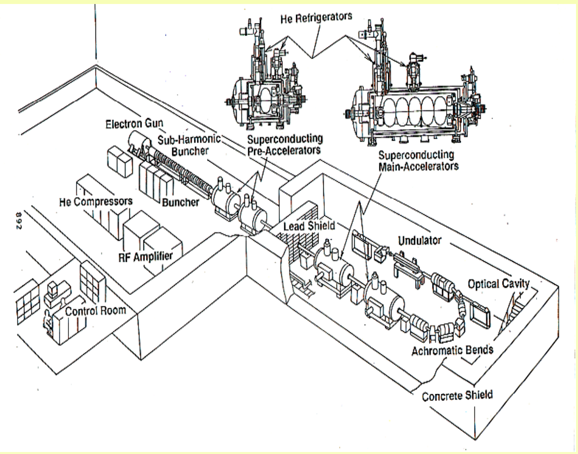
FELs offer many desirable characteristics over conventional lasers: wavelength tunability, high average power, and high efficiency of conversion of AC to laser power. High peak power and high average power infrared and ultraviolet FELs serve as valuable research tools in solid state physics, chemistry, 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 nearly 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.

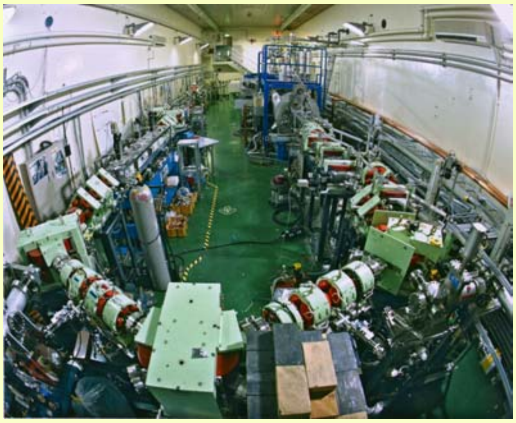
At the Stanford Picosecond FEL Center, the linac continues to provide a 200 μA electron beam of high quality at energies from 15 MeV to 45 MeV. The beam drives FELs covering wavelengths from 3-13 μm and 15-65 μm. Experiments include infrared near-field spectroscopy of single living cells and synchronous 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

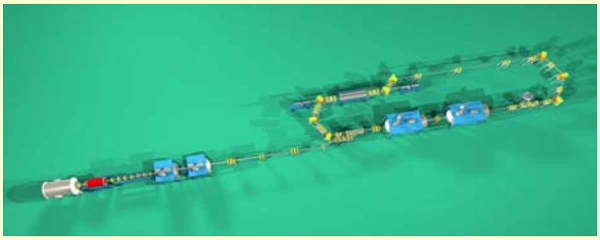
The Jefferson Lab IR FEL has lased in the 1-6 μm wavelength range and reached average output power of 2.1 kW, the highest CW average power ever to be achieved. Users pursue ultra-fast phenomena in condensed matter, atomic physics, chemistry and life sciences, as well as applications in micro-machining and ablation.



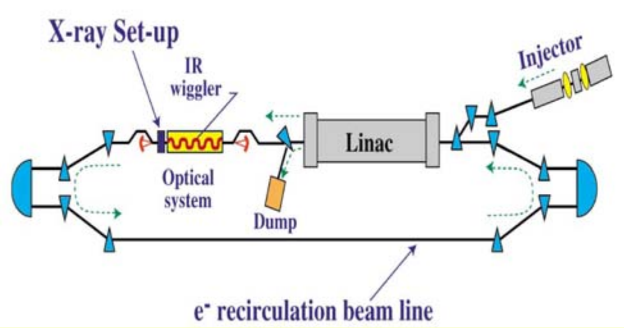
A 500 MHz superconducting linear accelerator drives the JAERI-FEL facility to provide quasi-CW far infrared laser of 1 ms long macro-pulse at 10 Hz repetition rate. Recently they demonstrated an extraction efficiency of 6%.



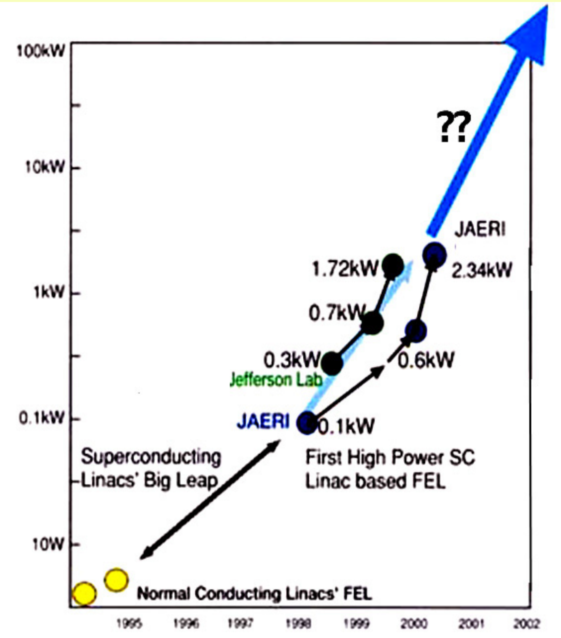
Main Accelerator Vault of JAERI FEL



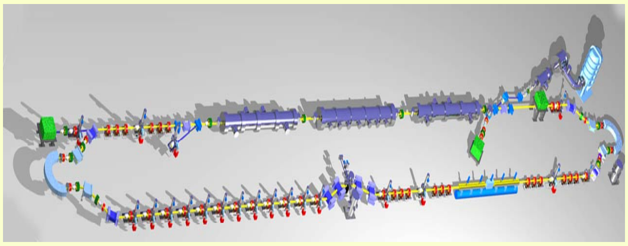
JAERI 10 kW Upgrade Plan



With 5 mA average current, the JLAB FEL demonstrated energy recovery with more than 99.8% efficiency. This is an important milestone toward high beam power Energy Recovery Linacs of the future.



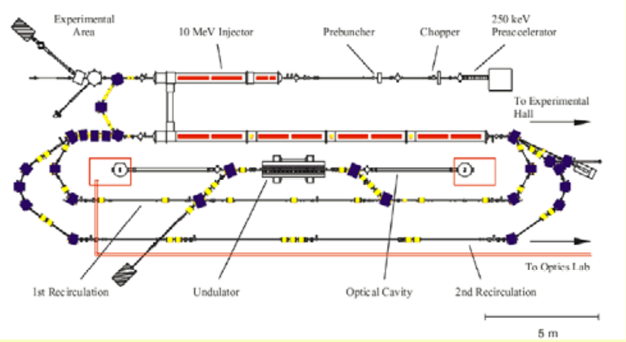
Growth of average FEL power output



In 2004, JLAB is commissioning a 10 kW IR FEL upgrade. At design, it will energy recover a 145 MeV, 10 mA beam through 3 cryomodules.

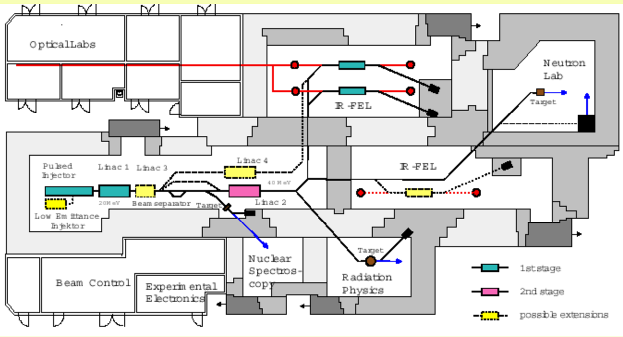
FELs in Europe

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 2.5 and 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.

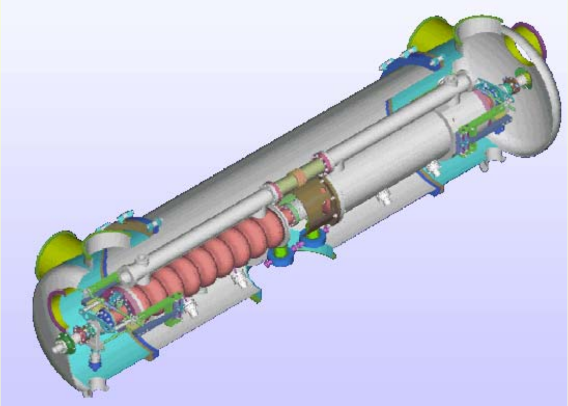


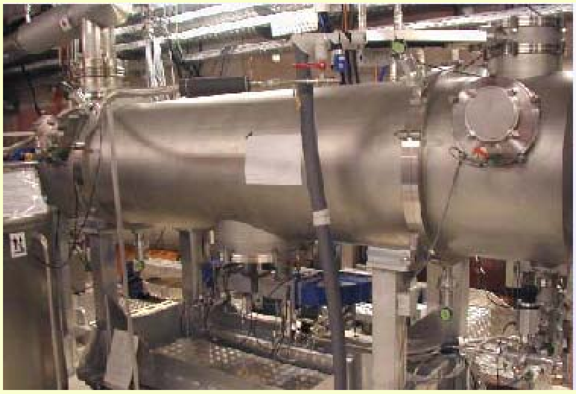
Layout of the S-Dalinac

The radiation source ELBE at Rossendorf is installing a superconducting 1300 MHz linear accelerator using TESLA cavities that will accelerate a one mA electron beam to energies of 12 - 40 MeV. Two undulators will allow access to a wide range of wavelengths. One module is already in operation.



Beam Line layout of the ELBE Facility

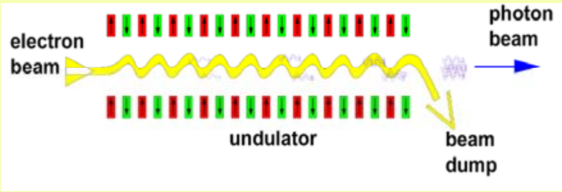


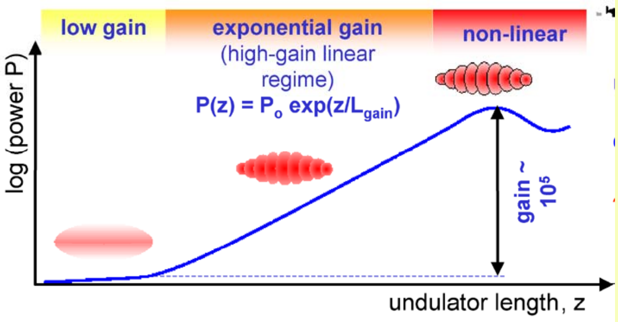


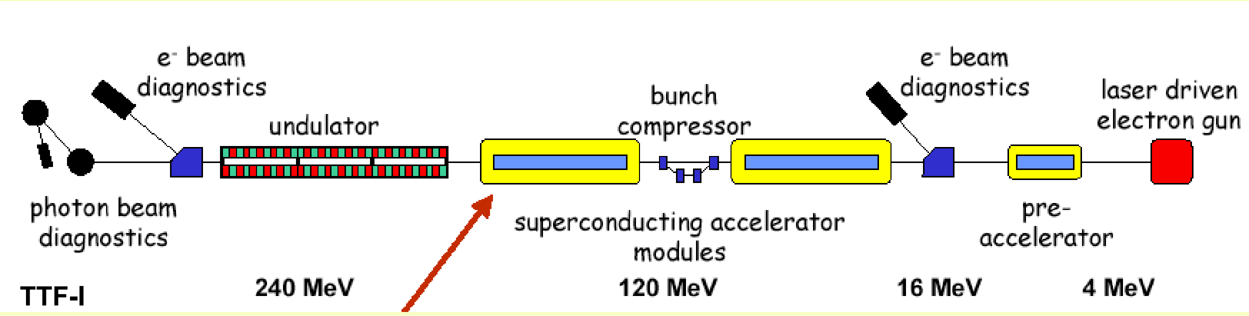
Rossendorf Cryostat, based on TESLA cavities

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.





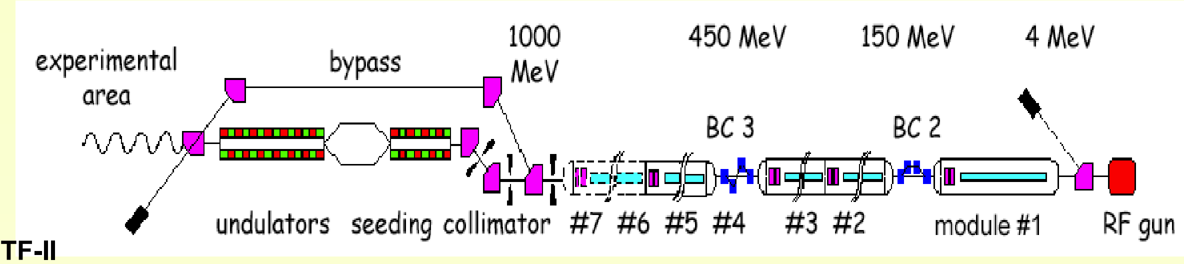


TTF-I

The TESLA Test Facility (TTF-FEL) at DESY 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.

An upgrade to one GeV is underway. The installation of an additional bunch compressor and an improved injector will allow 2500 A peak current and normalized emittance of 2 mm mrad. The expected minimum wavelength is 6 nm, with the use of a 30 m undulator.

TESLA 9-cell niobium cavity

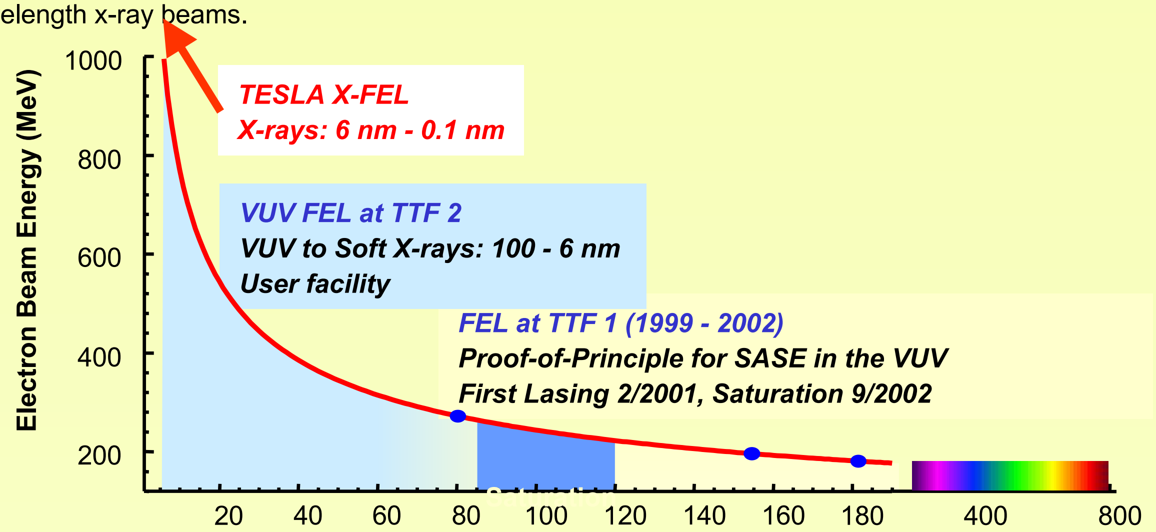


TTF-II

Evolution of SASE FELs at TTF

The Tesla Test Facility (TTF) at DESY has a dual purpose. (1) To demonstrate a high gradient SRF linac to prepare for TESLA, the future TeV energy Superconducting Linear Collider needed to complement the LHC. (2) To advance the science of SASE while providing UV to x-ray beams to a user facility.

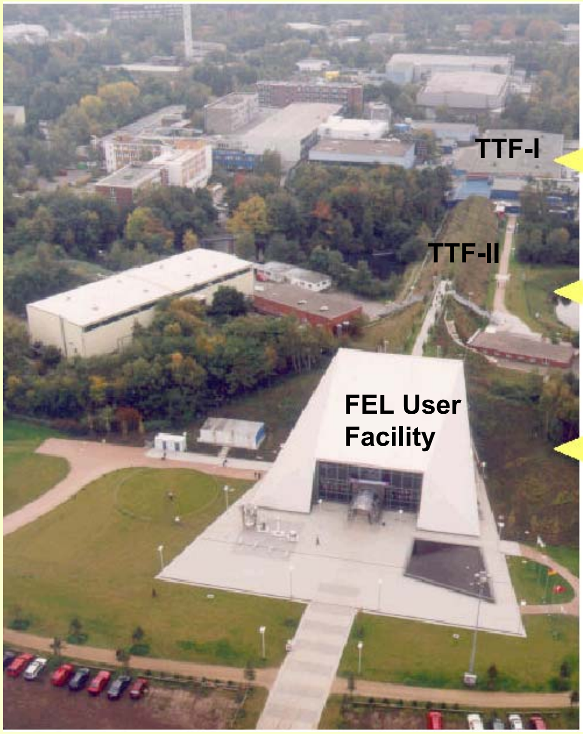
The TTF Linac was operated 7 days per week, at 24 hours per day. Approximately 50% of the time was allocated to FEL operation including a large percentage of user time. The FEL requires very stable beam conditions. In its different set-ups, approximately 13,000 hours beam time were achieved since 1997. After successful completion of Phase I at 250 MeV, installation is proceeding to upgrade the linac to one GeV. Eventually a 20 GeV linac using TESLA technology will be built to produce angstrom wavelength x-ray beams.



TESLA X-FEL
X-rays: 6 nm - 0.1 nm

VUV FEL at TTF 2
VUV to Soft X-rays: 100 - 6 nm
User facility

FEL at TTF 1 (1999 - 2002)
Proof-of-Principle for SASE in the VUV
First Lasing 2/2001, Saturation 9/2002

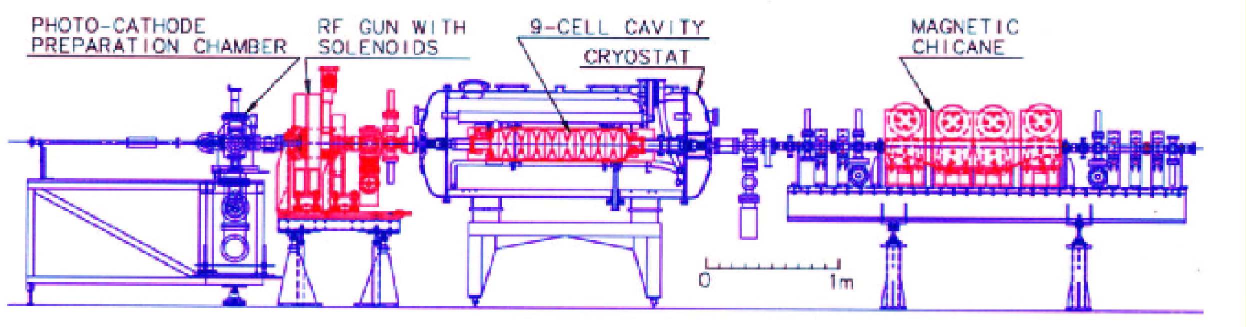


Inside the TTF-I Linac

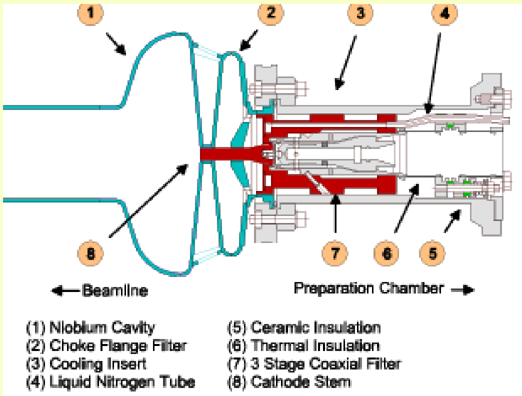
High Brightness Photo-Injectors

The electron source is a crucial area of needed development for FEL and ERL light sources, as well as for the superconducting linear collider.

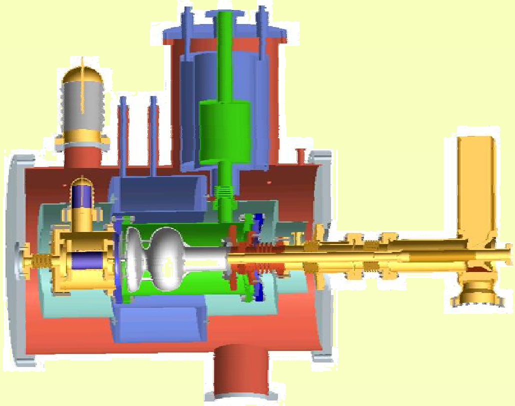
A Fermilab based collaboration NICADD is developing a multipurpose pulsed Photoinjector Facility based on TESLA linac technology. A 9-cell cavity cryomodule has operated at 15 MV/m.



Inside the Fermilab Photo-Injector Facility



At Rossendorf, a photo-injector based on an SRF cavity has operated successfully.

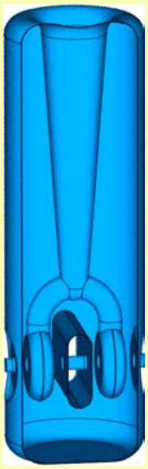


Beijing Photo-Injector. With the collaboration of DESY, Beijing University, is developing a 70 kV DC-SC photo-cathode injector and a superconducting accelerator module with two TESLA 9-cell cavities. The electron beam energy is 20~35 MeV and the current is about 1mA, CW. The first section is a 1.5 cell cavity operating at 15 MV/m. At 60 pC bunch charge, the transverse emittance is 12.5 μrad.

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.

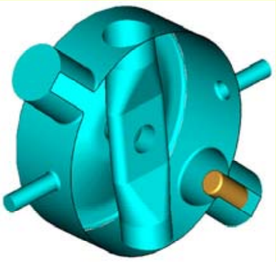
The Quarter-Wave resonator derives from transmission-line like elements and therefore belongs to the TEM resonator class. A coaxial line, $\lambda/2$ in length, when shorted at both ends forms a resonator with maximum electric field at $\lambda/4$. One or several field-free drift tubes hang from the 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

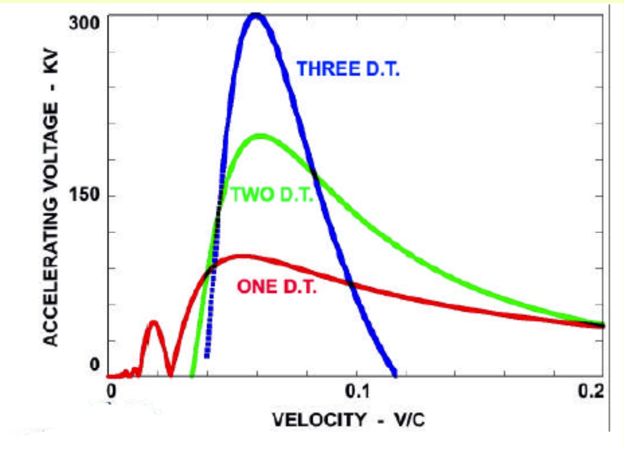
172.5 MHz,β =0.14 Half Wave Resonator

LANL 350 MHz 2-gap Spoke, 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 β = 1 structures) and the peak magnetic field ranges from 60 to 200 Oe (compared to 40 to 47 Oe for β = 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 in a structure the more the total voltage gain, but at the cost of a smaller velocity range.

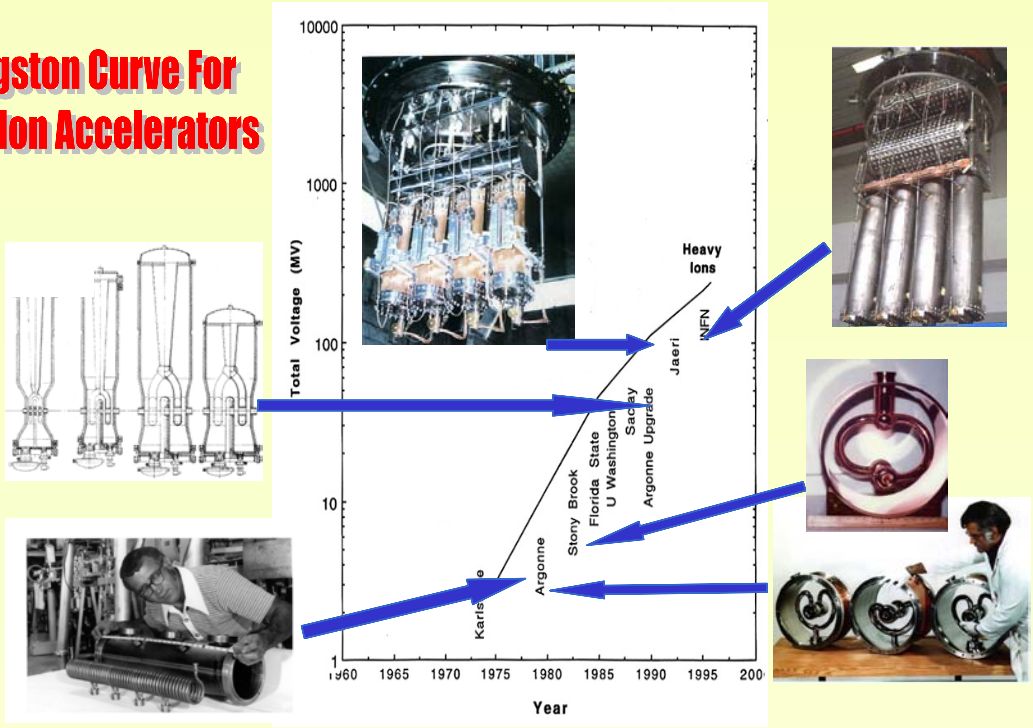
NUCLEAR SCIENCE WITH SUPERCONDUCTING HEAVY-ION ACCELERATORS

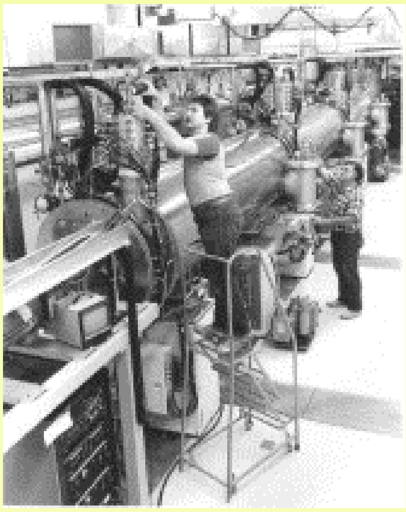
Superconducting linacs providing precision beams of heavy ions have consistently been one of the most successful applications. Heavy ions, from helium to uranium, are accelerated to energies from a few to 20 MeV/nucleon and used to bombard other nuclei. Above 5 MeV/nucleon, ions have sufficient energy 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.

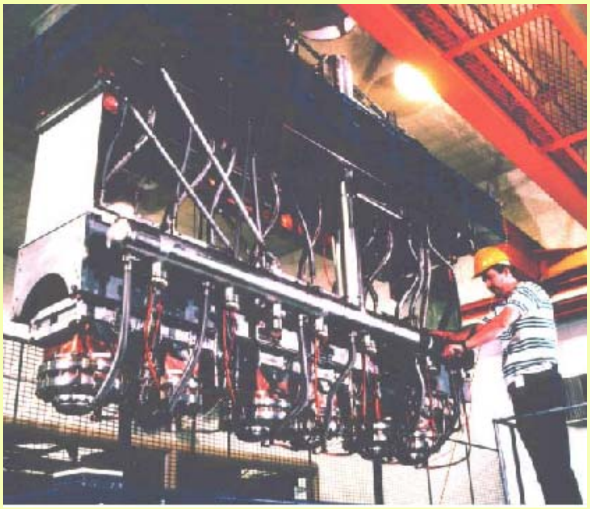
Besides the pioneer accelerators at Argonne and Stony Brook, eight heavy-ion accelerator facilities have operated or are still operating, utilizing over 270 resonators made of niobium or lead-on-copper. These facilities are (were) located at the University of Washington, Florida State University, Kansas 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





Inside ATLAS at Argonne. ATLAS has been in operation as a national user facility since 1978. It operates for more than 5000 hours per year.



ATLAS Injector Cryomodule

Inside ALPI at INFN Legnaro. ALPI has been in operation since 1994. 30 QWR Nb/Cu are in the beam line operating at about 4 MV/m at 7 watts dissipation. 12 Nb resonators are also in the beam line and operate at 6 MV/m with 7 watt dissipation. Typical beam time was between 3700 hours and 5000 hours from 1999 – 2000, with 25% of the time using the SC booster, since many experiments desired lower energies.

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.

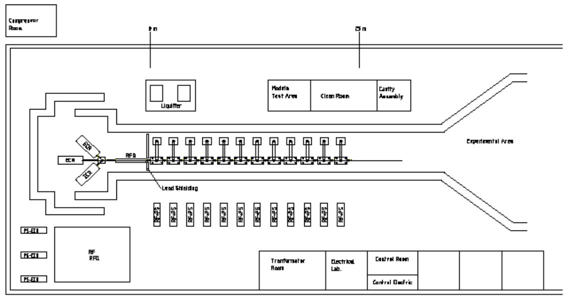


Figure 1: General layout

SC linac for Medical Isotope Production in Israel

Medical Isotope Production

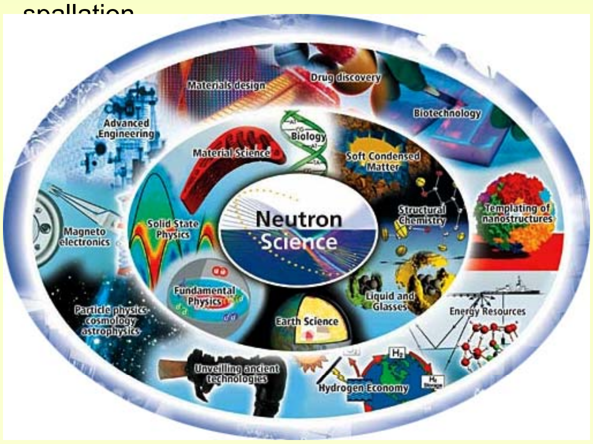
In Israel, SOREQ, NRC is installing a linac for protons and deuterons as an alternative to cyclotrons. The final energy will be 40 MeV and the CW current 4 mA. It will have 48 Half-Wave Resonators at 176 MHz to be built by industry. The main application of the SARAF project will be radioisotopes production for medical use. Operation is expected to start in 2008.

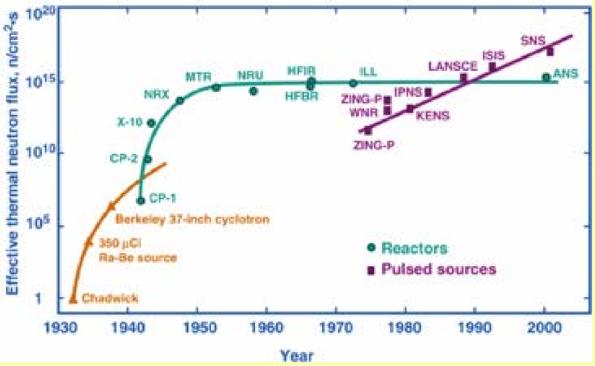
ACCELERATOR-BASED NEUTRON SOURCES

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 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





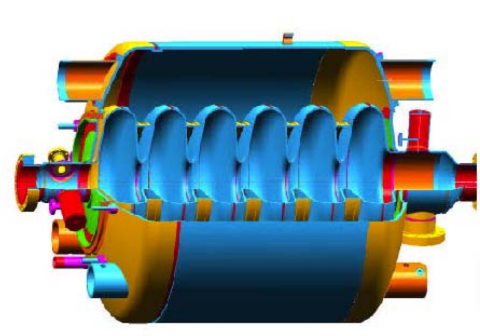
Accelerator based neutron sources provide high peak intensity and very short (μs) pulses at rep rates of the order of 50 Hz. The advantage of short pulses is it that becomes possible to use time-of-flight measurements to determine the incident neutron energy, eliminating the need for monochromatization 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 flux of these pulsed sources is still a factor of 30 below what reactors can provide.

The SNS at Oak Ridge National Lab will be an advanced pulsed spallation source with 1 - 2 MW of beam power at the target, upgradable to 5 MW. This would correspond to the average flux of the highest flux reactor at Grenoble.

6 Partner Labs: ANL, BNL, JLAB, LANL, LBNL, ORNL are building SNS

SNS: First High Intensity Superconducting Proton Linac

A 1.4 MW proton linac from 200 MeV to 1000 MeV,based on 800 MHz superconducting cavities, will drive SNS. As one of the partner labs, JLAB is responsible for SRF design and construction. There will be a total of 81 (one meter-long) cavites operating at 804 MHz. 11 medium-beta cryomodules have three cavities each and 12 high-beta cryomodules will have four cavities each. Performance above design specifications has been achieved for the bare cavities and first cryomodules.



Cavity and helium-vessel

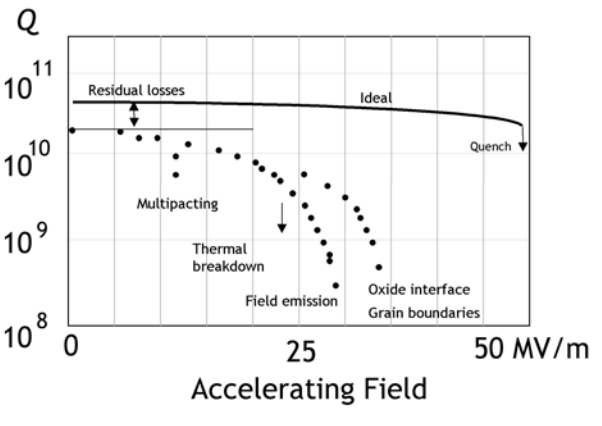
6 cryomodules installed at SNS

Cavity and helium-vessel string

Cold Mass

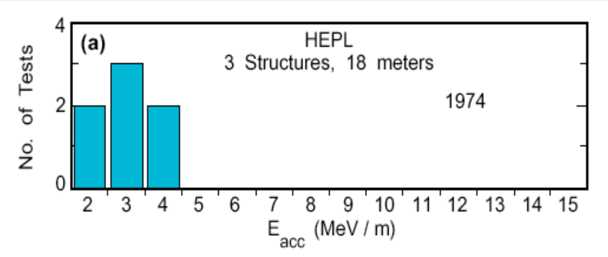
BASIC RESEARCH IN SRF

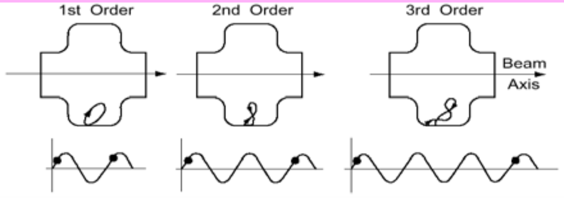
Ideally we would expect the cavity Q to remain constant (at the BCS predicted value) as the field increases, until the quench field. However, as surface electric and magnetic fields rise, several effects set in to drop the Q. The history of advances in superconducting cavities shows that cavity performance improved steadily over time as research penetrated gradient and Q limiting mechanisms, gleaned understanding, and developed techniques to overcome limits. Today, single cell cavities exceed accelerating fields of 40 MV/m, not far from the theoretical limit imposed by the RF critical field. Full-scale structures reach gradients of 35 MV/m.



Multipacting and Its Cure

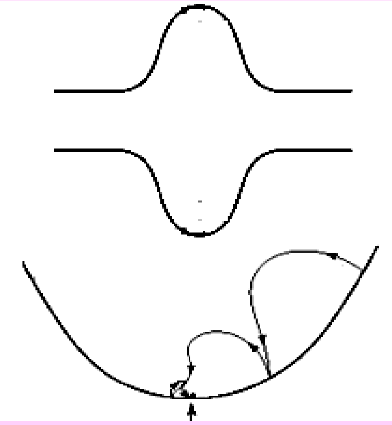
In the early stages of SRF development, a major performance limitation was ``multipacting.'' 1.3 GHz structures were limited to about 3 - 4 MV/m.





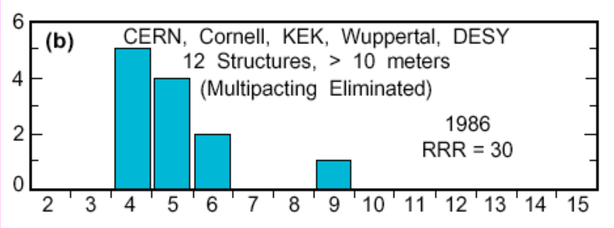
High Field ***Low Field***

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 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 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.

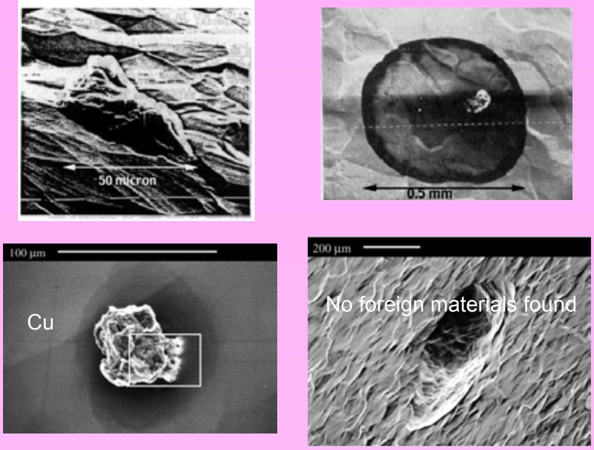


The spherical shape cavity eliminates multipacting

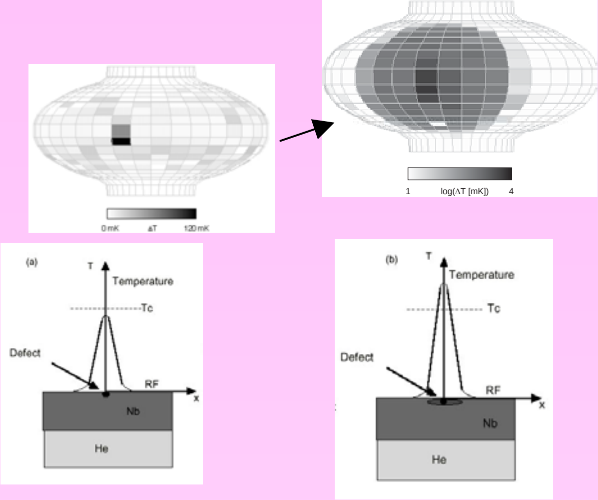
Thermal Breakdown



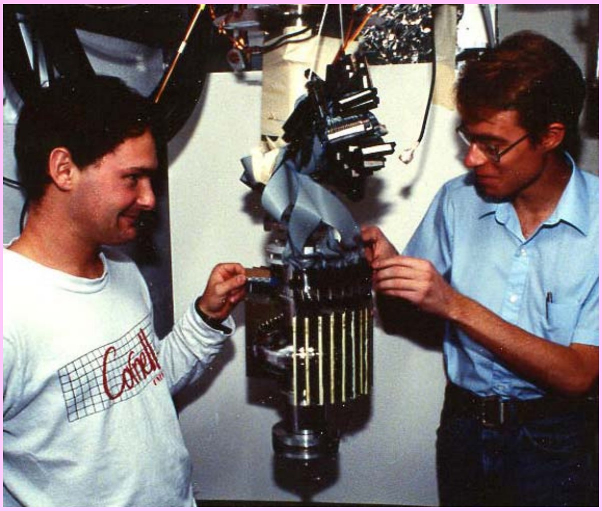
Even after elimination of multipacting in the 1980's, gradients improved to only about 5 MV/m because of the thermal breakdown limits of superconductivity. Nevertheless many applications were possible and cavities installed in several accelerators. Well below the critical field, RF heating can originate 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 field falls abruptly, we refer to the rapid loss of stored energy as a "quench."



Typical examples of 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, and welding mistakes. 0.1 to 1 mm size defects cause thermal breakdown.



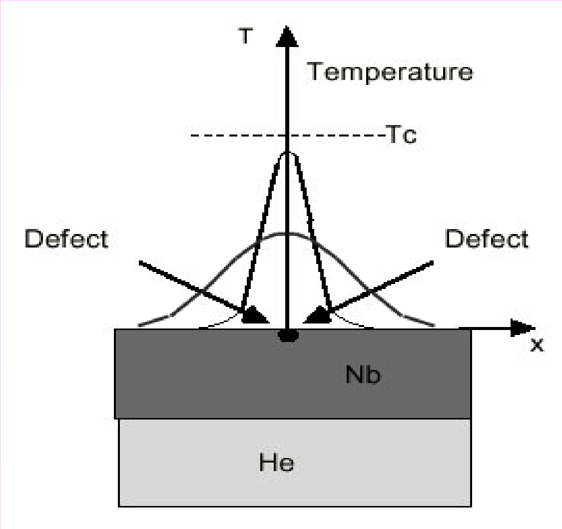
Temperature maps of a single cell cavity show spot heating as a precursor to large region of the cavity becoming normal conducting when the quench develops.



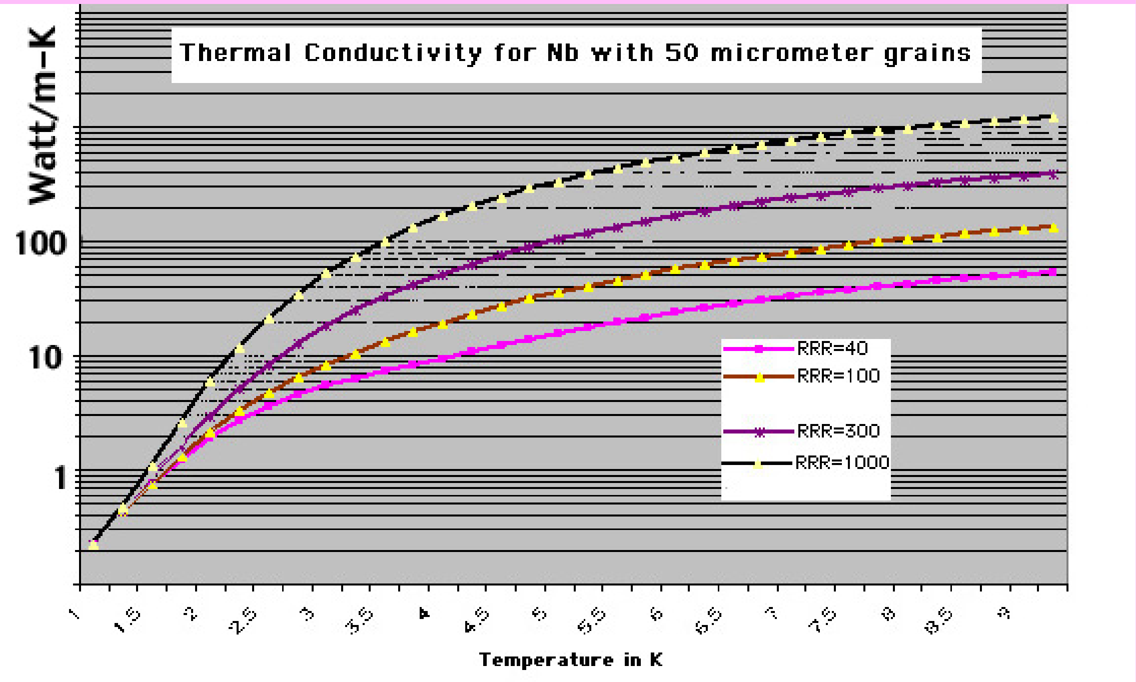
Temperature mapping system for a single cell cavity.

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. 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.

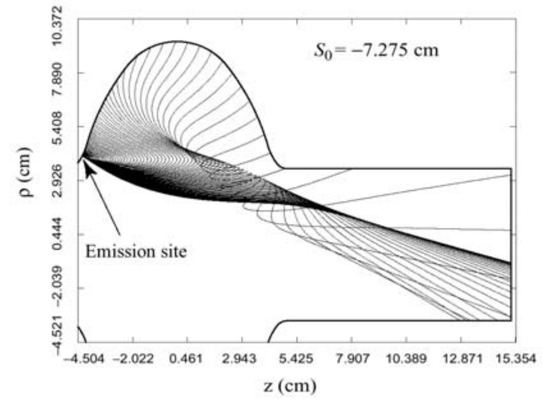


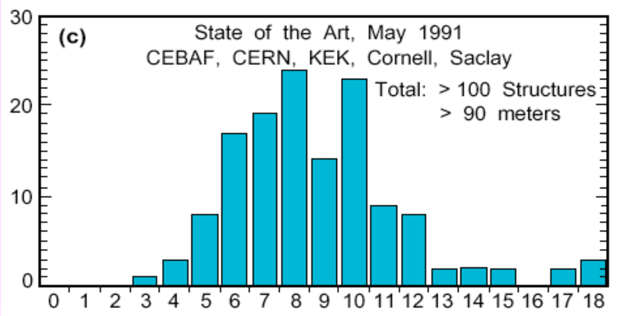
Temperature dependence of thermal conductivity for niobium of various purities, as characterized by the RRR. The thermal conductivity of niobium decreases rapidly with temperature below T_c, because electrons, the dominant heat carriers, rapidly freeze out into Cooper pairs.

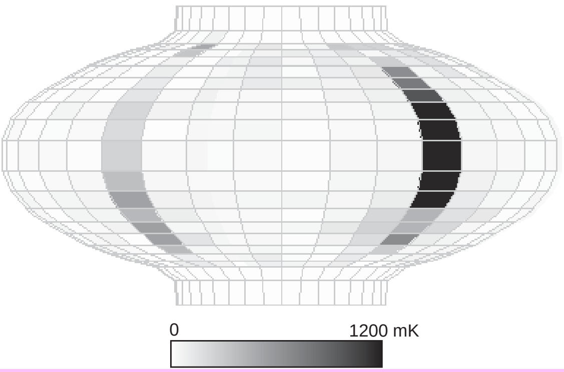
The most effective approach to increasing Nb thermal conductivity is to remove interstitial impurities, chiefly oxygen, nitrogen, carbon and hydrogen, which pose the highest electron scattering mechanism. These impurities are volatile only near the melting temperature of niobium. Therefore the best purification 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 to field emission 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.

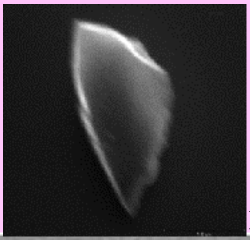




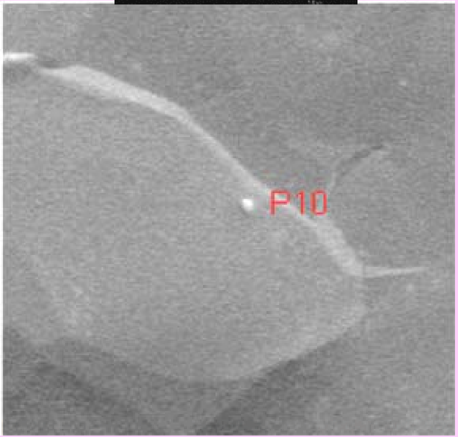


Temperature map showing a longitudinal heating profiles due to field emission.

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.



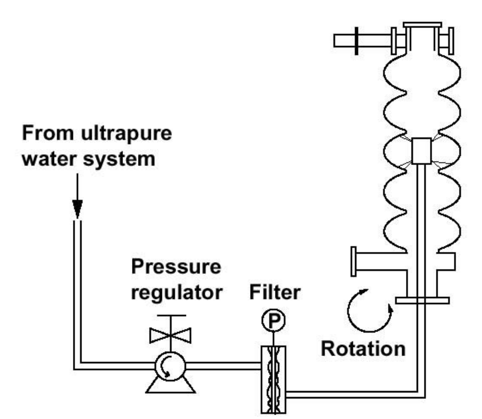
1 - 2 µm,
Carbon
particle



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 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.



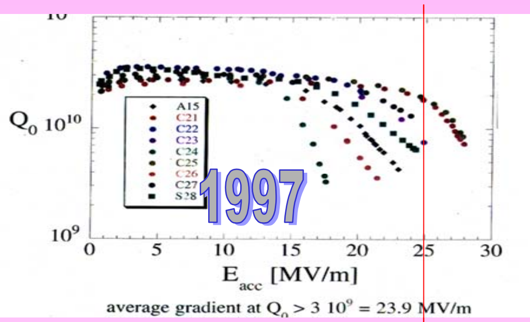
A jet of ultra pure water dislodges surface contaminants that normally resist removal with conventional rinsing procedures. The benefits of HPR in reducing field emission are well demonstrated in tests with multicell cavities that reach accelerating fields of 35 MV/m at DESY.

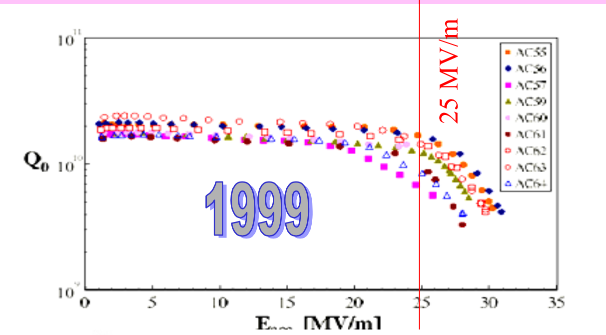
Steady Improvement in Gradients

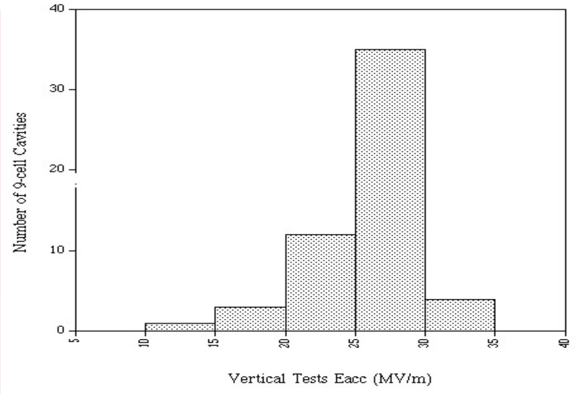
As field emission came under control in the late 1990's, gradients of 9-cell cavities consistently reached 25 - 30 MV/m. →

Class 100 Cleanliness

Clean room preparation at DESY

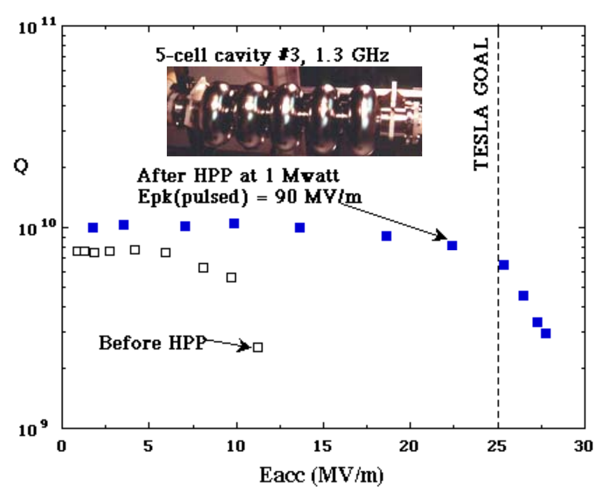






High Power Processing

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 high fields destroys emitters. The essential idea is to apply high RF power so as to raise the surface electric field at the emitter as high as possible, even if for a very short time (ms). Accordingly, the power level, pulse length, and coupling need to be arranged. An important benefit is that HPP can recover cavities that may be accidentally contaminated, e.g., in a vacuum mishap.

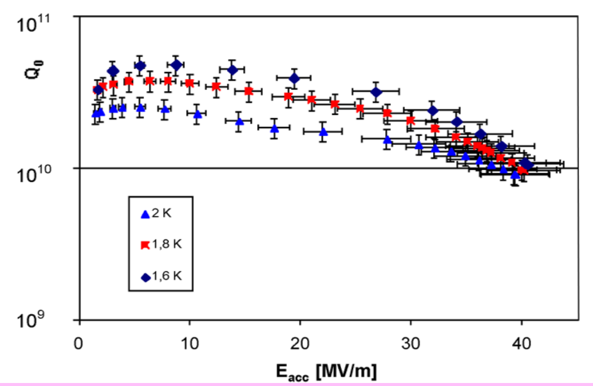


An example of ``before-and-after" HPP. Here a cavity contaminated down to 10 MV/m improves with HPP to 28 MV/m.

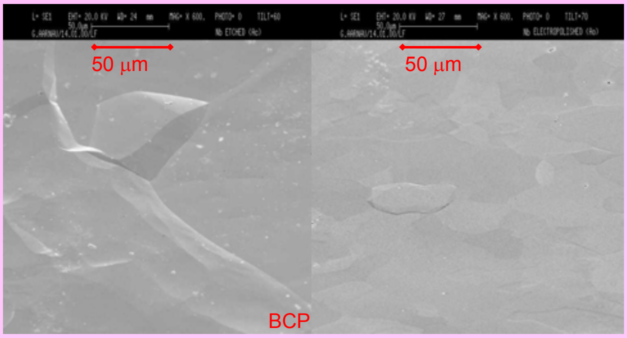
SEM micrographs of a field emission site located with thermometry in a 3 GHz cavity and subsequently found to process with RF power. (Left) A dark starburst feature surrounding the central crater. Auger measurements show the starburst region to be cleaner (less carbon and fluorine) presumably from the 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-slope.” Methods to bring it under control are in hand. These are electropolishing and 100 C baking.



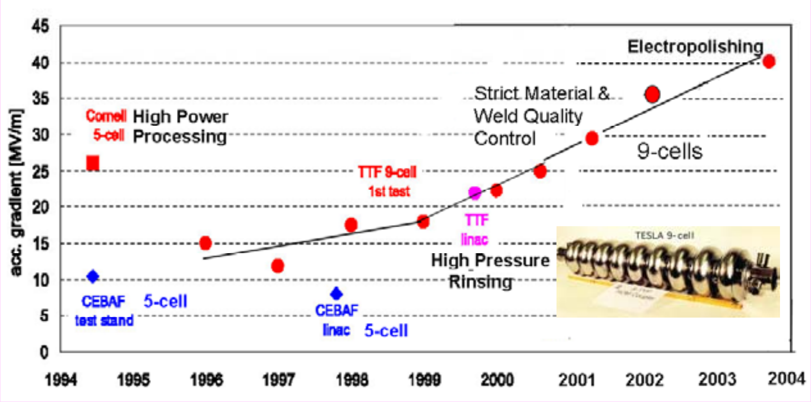
Nine-cell electropolished and baked (100C) cavities at DESY reach 40 MV/m.



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

One mechanism proposed is magnetic field enhancement at surface microstructures, such as grain boundaries. Standard etching produces grain boundary steps of about 5 microns, which give rise to field enhancements of about 100%. According to the “roughness model,” the Q-slope begins when the steepest grain boundary edges exceed the RF critical field due to geometric field enhancement. As more and more edges quench with increasing field, the Q drops further. Eventually thermal breakdown occurs when the heat flux at the He interface exceeds the critical flux at the Nb-He interface. The Q-slope arises primarily from the normal conducting resistance of the quenched grain boundary edges. Any treatment that increases smoothness reduces the Q-slope. There is now substantial evidence that electropolishing produces smoother surfaces and raises the onset field level of the Q-slope as well as the final quench field.

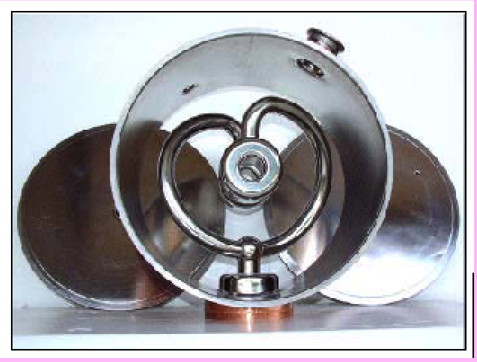
The roughness model remains open because mild baking (50 hours, near 100 C) improves the high field Q-slope of both CP and EP prepared cavities. It is unlikely that such baking will modify the local geometry. For electropolished and baked cavities, the Q-slope begins around 25 - 27 MV/m, ending with a quench between 30 - 35 MV/m. This is a substantial improvement over the typical Q-slope onset field of 20 MV/m for a Nb surface prepared by standard chemical etching, followed by quench at 25 - 30 MV/m. Accelerating fields up to 40 MV/m without significant Q-slope have also been reached in single cell cavities at several laboratories using EP plus baking. In early 2004, a 9-cell cavity reached Eacc = 40 MV/m.

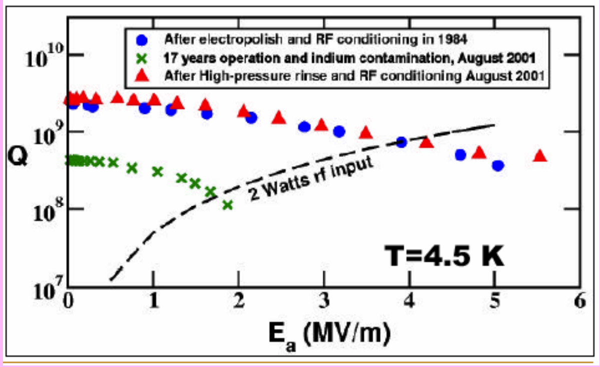


Steady progress in 9-cell cavity gradients over one decade.

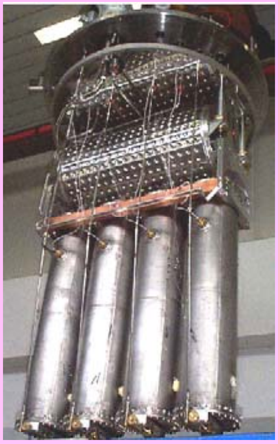
Performance of Low Velocity Structures

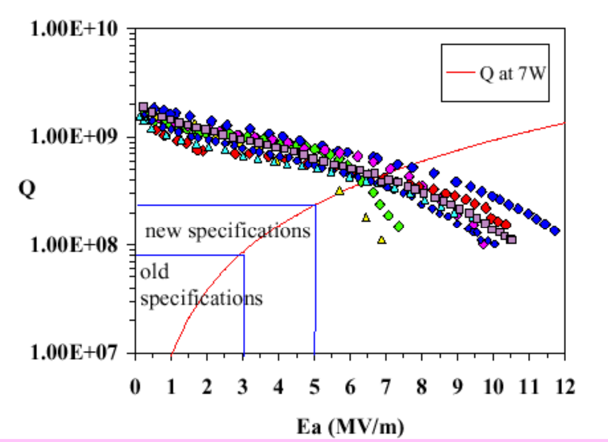
Advances in materials and surface processing techniques have improved performance of low and medium beta resonators. Gradients of 10 MV/m are now possible.



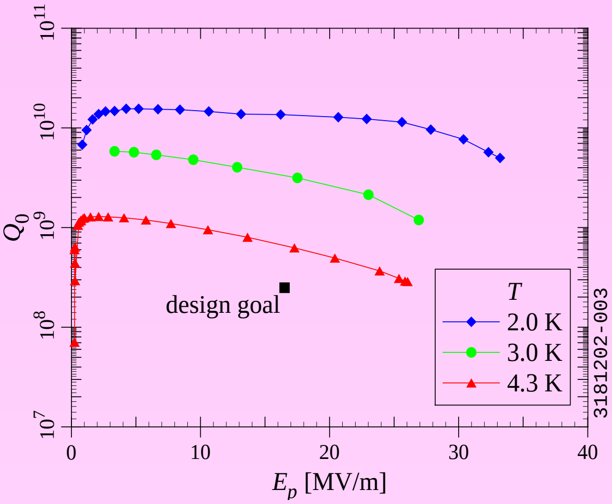


Argonne Split Ring Resonator, Frequency = 97 MHz, E_{pk} = 4.8 Eacc , H_{pk} = 183 Oe/MV/m





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

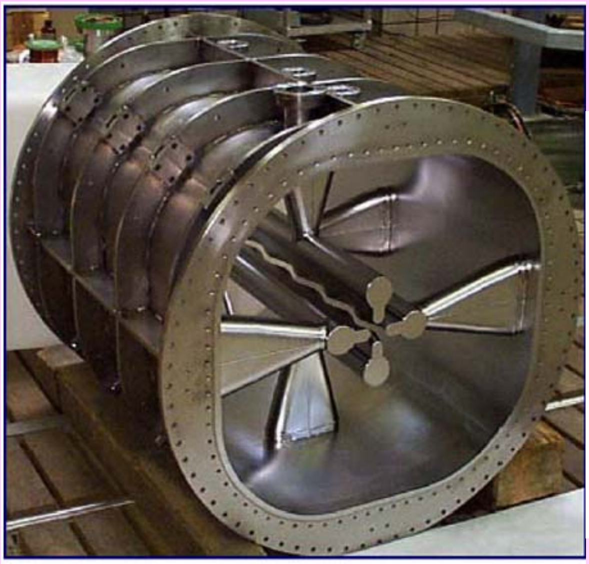


MSU, half-wave resonator, beta = 0.285, 322 MHz

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 $\beta = v/c < 0.01$. 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 $Q \sim 10^4$. Normal conducting RFQ power consumption usually limits their duty cycle to values < 20%. The superconducting RFQ offers lower power consumption ($Q \sim 10^8$ - 10^9) and CW operation. A significantly higher vane voltage than in the normal conducting case is beyond present development.

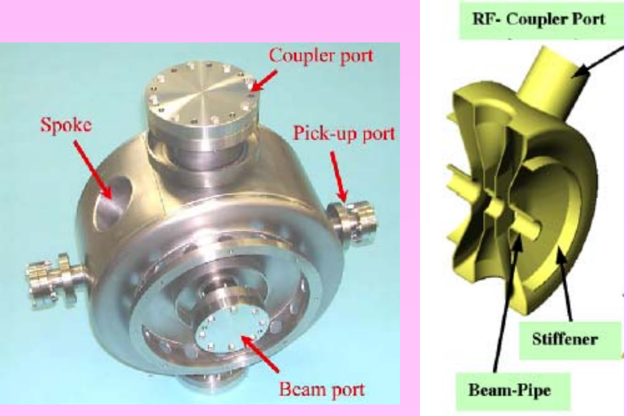
INFN at Legnaro successfully tested the first superconducting RFQ at 80 MHz. With 12 cells, an aperture of 1.5 cm it reached the design voltage of 280 kV at a surface field of 25 MV/m.



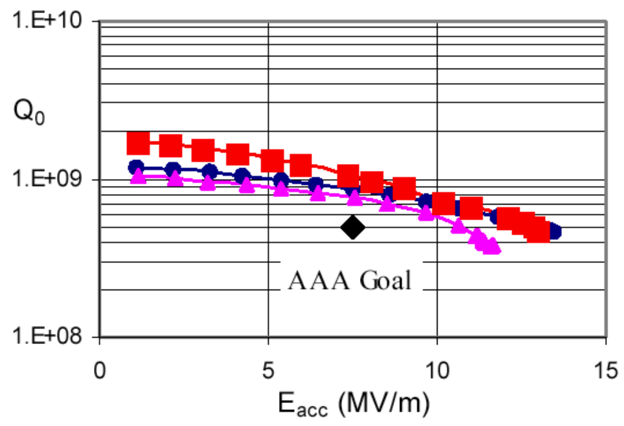
Superconducting RFQ for Injector PIAVE at INFN

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.



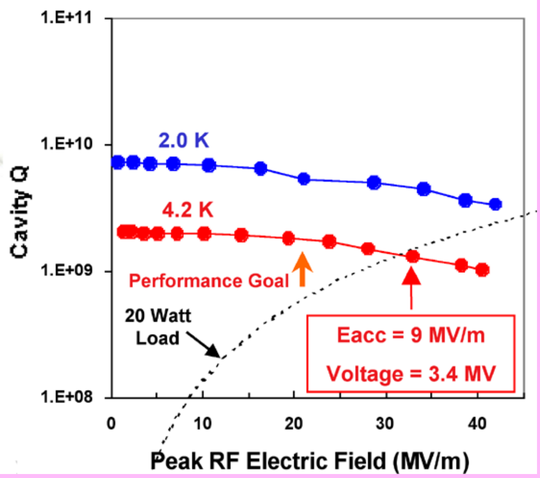
LANL, β = 0.175, 175 MHz, single spoke, 2-gap cavity



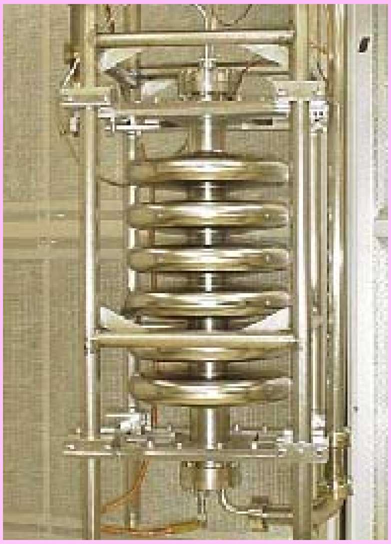
Performance of the LANL spoke cavity

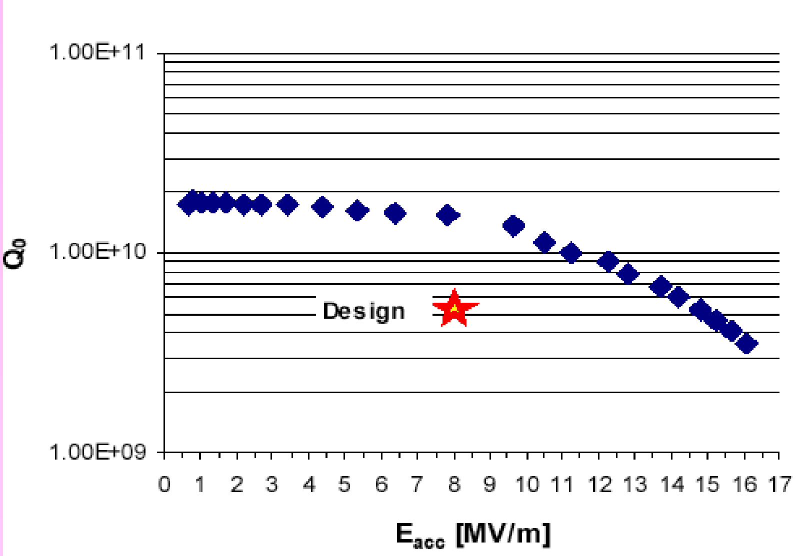
Performance of Medium Velocity Structures

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



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

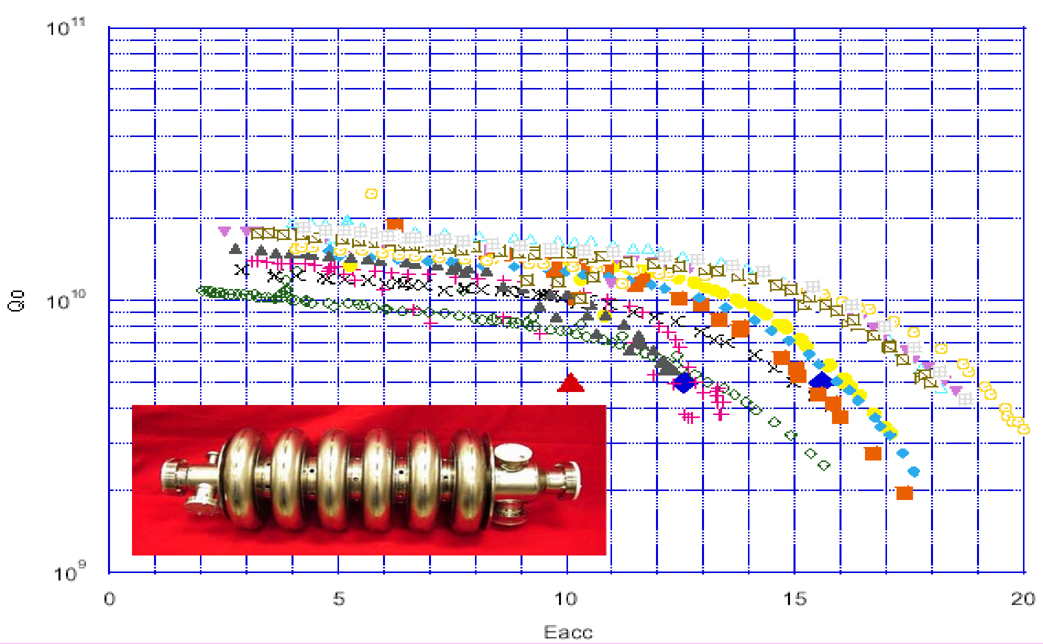




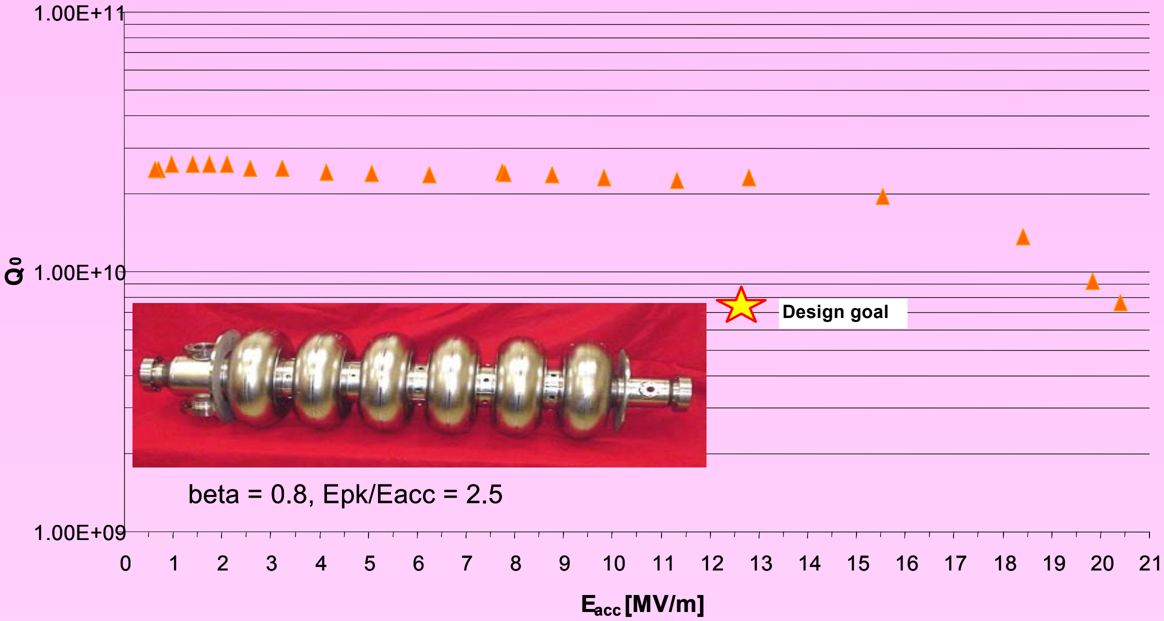
MSU, β = 0.49, 805 MHz, e-beam welded and tested at JLAB

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 TESLA structures.



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

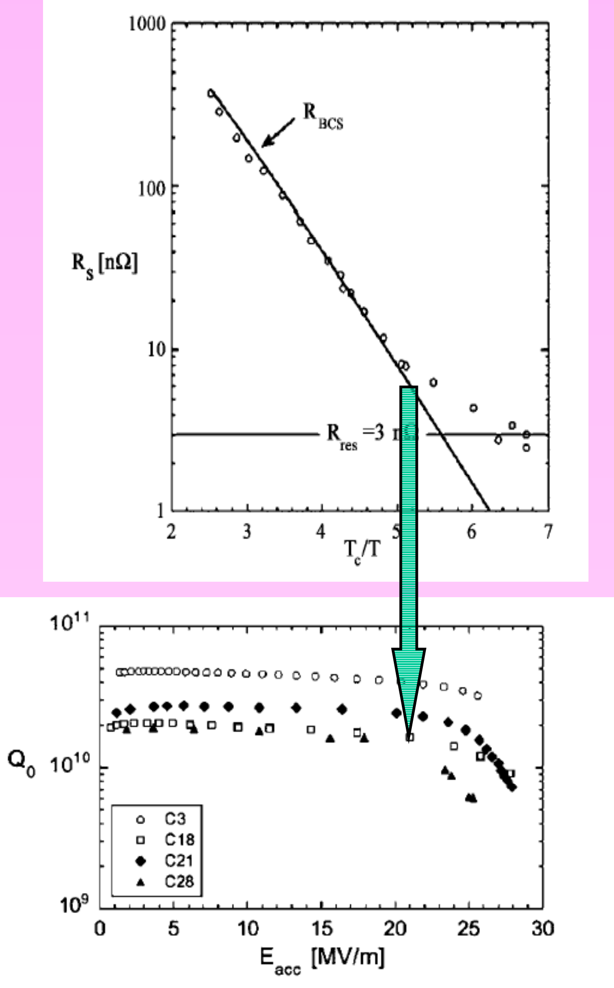


β = 0.8, 805 MHz, Epk/Eacc = 2.5, tested at JLAB

RAISING THE CEILING

Ultra-High Q

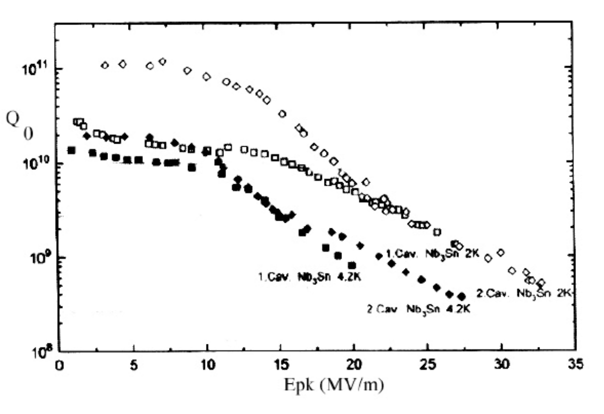
At 1300 MHz and 2 K operation, the BCS contribution to the surface resistance is still important, limiting the Q to 2×10^{10}. At 1.8 K, the theoretical Q is 6×10^{10} and rises to above 10^{11} at 1.7 K. Single cell cavities have already demonstrated Q's above 10^{11}. But much development is needed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



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}

Alternate Materials

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

Nb-Cu

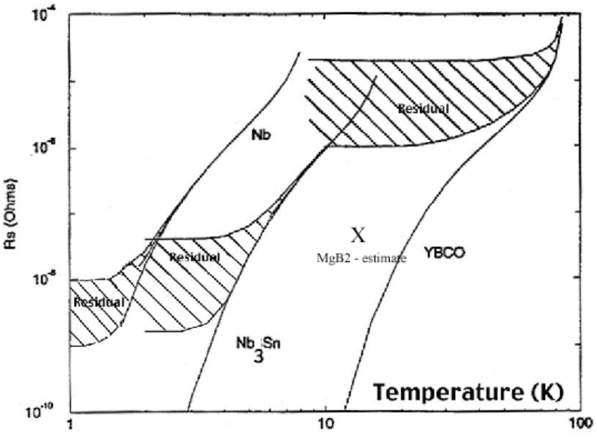
Niobium has been used extensivley as a superconducting thin film on a copper substrate cavity. The chief motivation for using niobium-coated copper (Nb/Cu) cavities is to provide increased stability against thermal breakdown, by virtue of the higher thermal conductivity of copper. The cost saving of niobium material is another potential advantage, significant for large-size (350 MHz) cavities, as for LEP-II, or 200 MHz cavities for future neutrino factories or muon colliders. A serious problem with Nb films is that the surface resistance starts to increase exponentially with field. The cause is not yet fully understood. Possible causes are impurities in the film and surface roughness. The highest accelerating field reached at 1500 MHz is 20 MV/m. By comparison, single cell sheet metal Nb cavities have now reached E_{acc} = 40 MV/m. But the enormous potential of thermal stability and cost reduction make Nb/Cu worthwhile to pursue for future accelerators. Research must continue to understand the cause of the Q-slope and thereby defeat it.

At present, the base copper cavity is made by the same methods as the sheet metal niobium cavities i.e., forming half-cells by spinning, trim machining, cleaning, electropolishing, electron beam welding. For the future, techniques for hydroforming the base copper multicell cavity from a single tube are being explored. This avoids the expensive electron-beam welding procedures, leading to further cost reduction.

CERN Nb-Cu Cavity at 350 MHz

High Temperature Superconductors

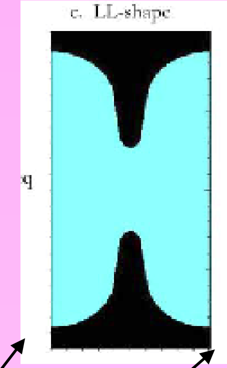
The intrinsic properties of HTS are very different from the familiar superconductors. The coherence lengths are very short: 17 Å within the copper-oxygen planes and 3 Å perpendicular to the planes, respectively. There is also a large anisotropy of the magnetic and electrical properties between the c-axis 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.



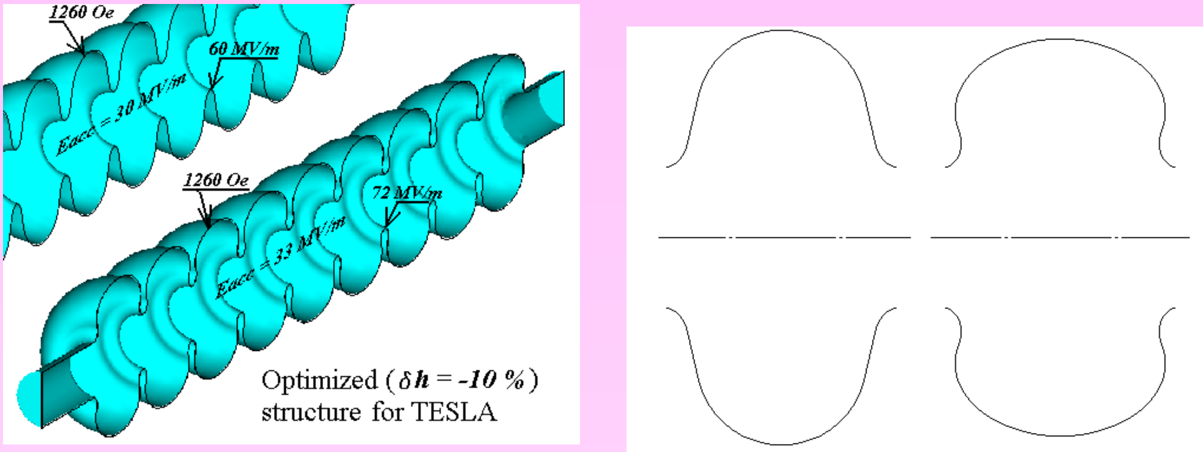
A comparison of superconductors Nb, Nb_3Sn YBCO and MgB_2 at 1 GHz

Exploring New Cavity Geometries

Cornell and JLAB are exploring ways to beat the magnetic field limit by designing structures with lower surface peak magnetic fields. The JLAB design increases the area of the magnetic field region and reduces the beam aperture of the TESLA design to keep E_{pk} the same. The Cornell design keeps the large aperture of the TESLA design to minimize wakes, but makes the shape re-entrant to reduce the peak magnetic field. Both 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.



JLAB design for lowering H_{pk}



Cornell design 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 by using a defocused or rastered electron beam.

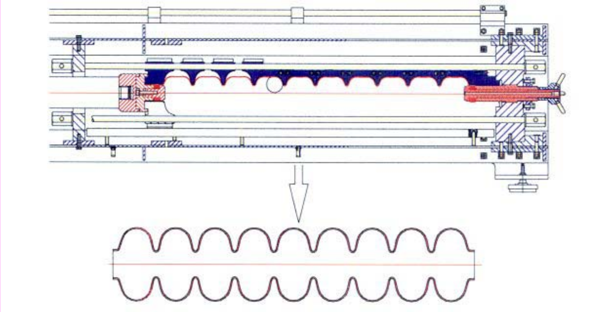
New techniques for cavity fabrication are emerging, such as spinning and hydroforming multicell structures from tubes or sheets. If successful these approaches will help reduce the cost of future facilities.

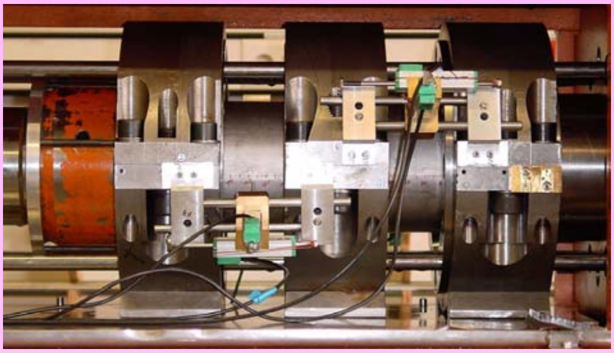
First Spun 9-cell Nb cavity

Spinning from a disk at INFN

Spinning from a tube at INFN

Hydoforming





Hydroforming by DESY

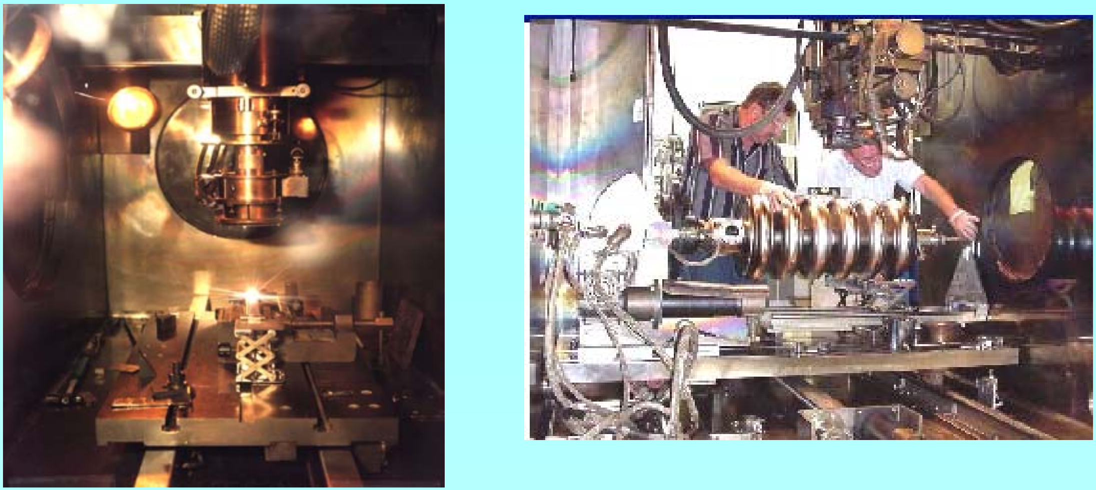
Two and three cell cavities hydroformed at DESY

GLOBAL FACILITIES FOR SRF ACCELERATORS

Velocity-of-Light Structures

Extensive SRF infrastructure exists worldwide for cavity fabrication, surface treatment, clean assembly, cold testing, and final cryomodule assembly before accelerator installation. 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.

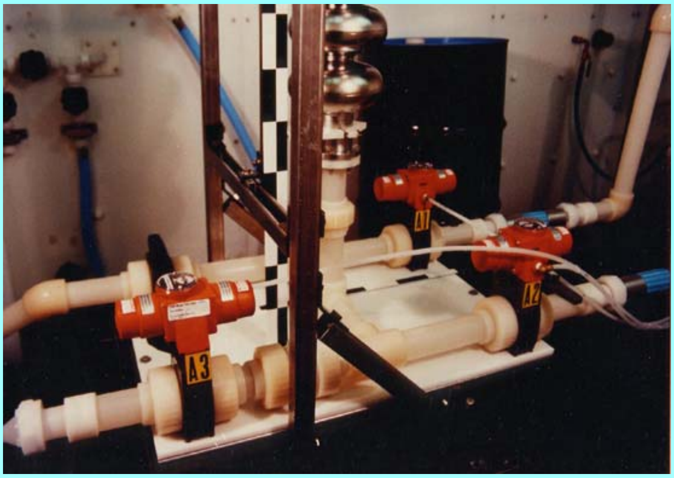
Deep drawing half cells at Cornell and JLAB



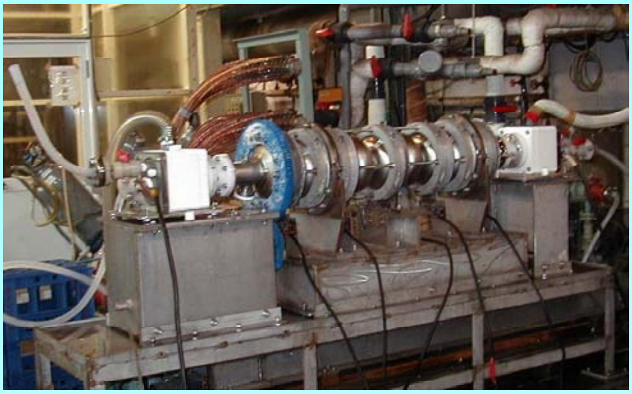
Electron beam welding at Cornell and JLAB

TESLA cavity fabrication and quality control at DESY

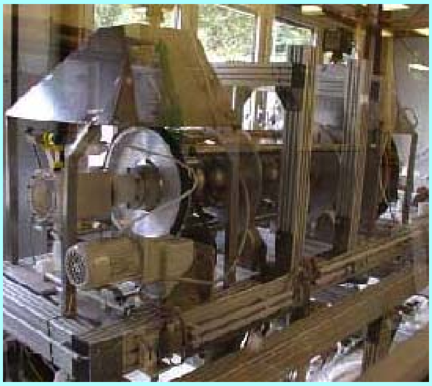
Cleaning facilities include open and closed cavity etching systems, electropolishing set-ups, high purity dust free water systems, and high pressure (100 atmospheres) water rinsing.



Chemical treatment at Cornell and DESY



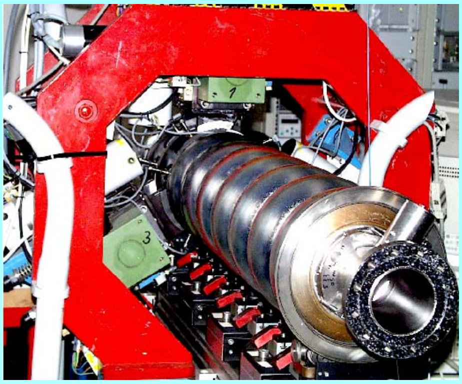
Electro-polising at KEK and DESY



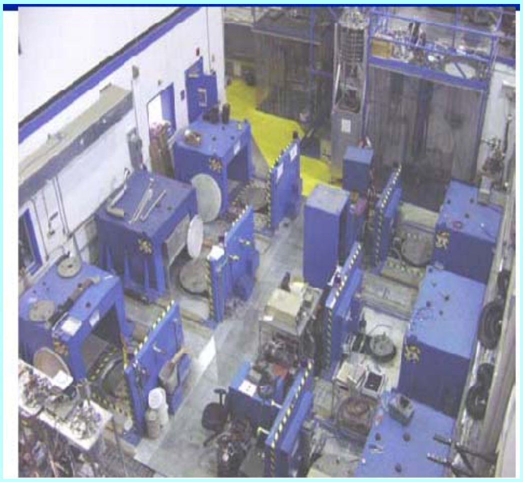
High Pressure Rinsing at JLAB and Cornell

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



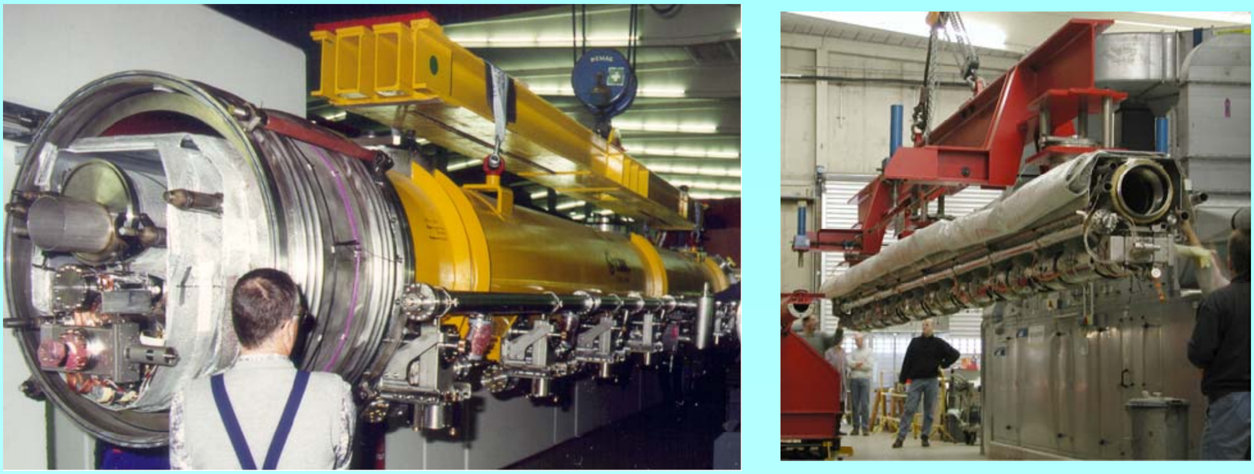
Tuning at Fermilab and DESY



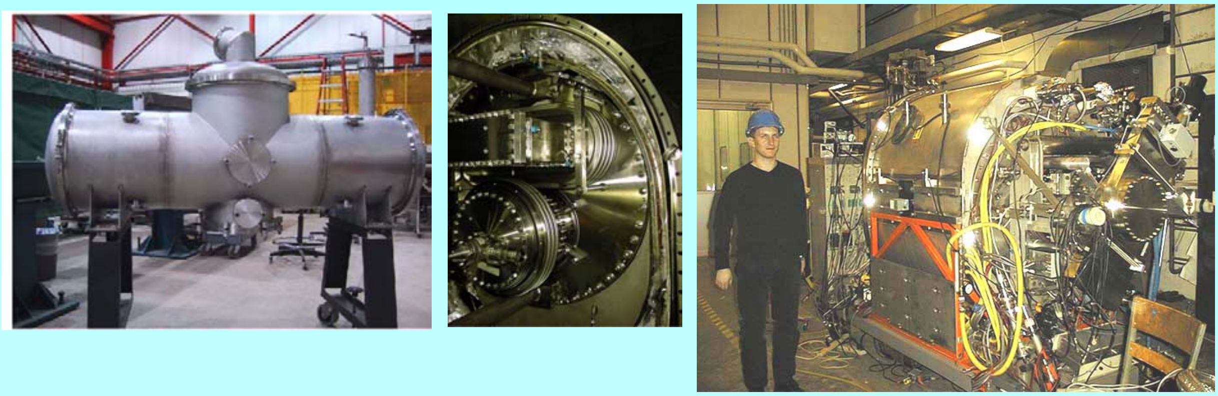
Vertical Cavity Testing at JLAB and Cornell

There are large Class 10 - 100 clean rooms for cavity 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 and the TESLA TEST FACILITY.

Cryomodule assembly at JLAB



Cryomodule assembly at DESY



Cryomodule assembly at FNAL and Cornell

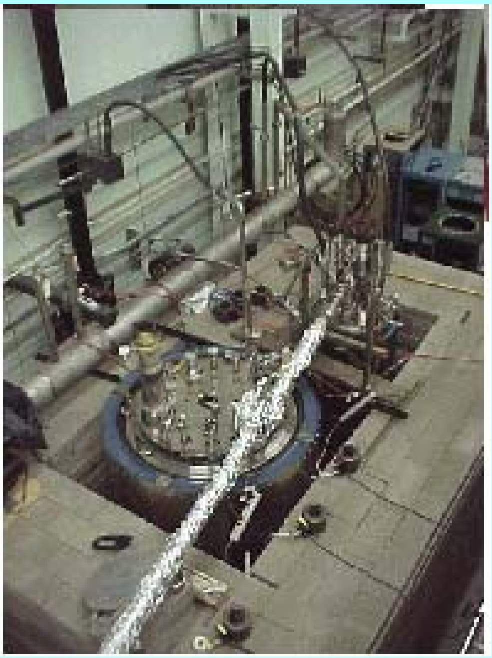
Major Facilities for Low and Medium Velocity Structures

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, and Los Alamos National Lab. 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 at MSU and Los Alamos

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.

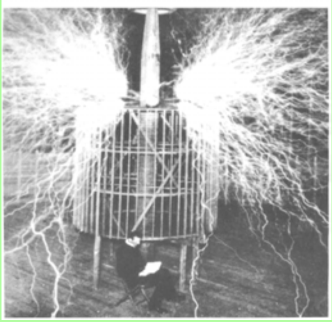
Understanding the basic features of energy, matter, and space-time remain the focus of elementary particle physics. Dominant questions are: what is the origin of mass; what is the mechanism of electro-weak symmetry breaking; is supersymmetry a feature of our universe; what is the nature of dark matter 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 10^{34} (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.

One of the two mature approaches to the linear collider is TESLA, which stands for TeV Energy Superconducting Linear Accelerator. (It is appropriately named after Nikola Tesla whose ambition was to establish high voltages with his famous spark coils.) The competing approach is the high frequency normal conducting approach developed by the SLAC/KEK collaboration and called NLC/JLC.

TESLA Evolution



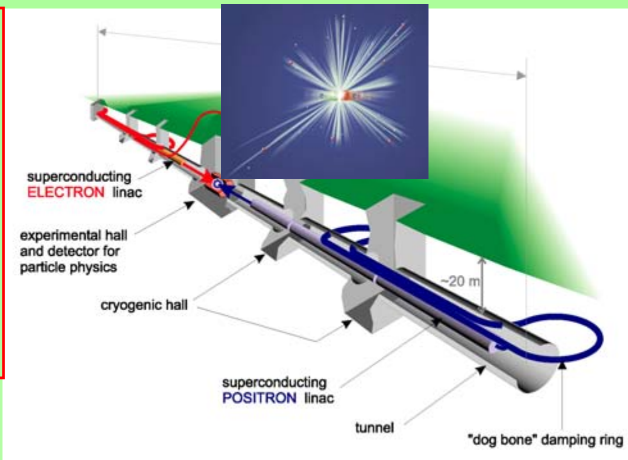
Tesla, the scientist

PROCEEDINGS OF 1990

The First International
TESLA Workshop
CORNELL

Held at Cornell University
July 23-26, 1990

The first international TESLA workshop was held at Cornell in 1990 where participants developed a preliminary baseline parameter set. The international collaboration has grown by early 2004 to encompass 55 laboratories in 12 countries. Over the evolution of the design parameters for this accelerator, there have been several international workshops on TESLA during which the strategies and trade-offs have emerged. The resulting parameter set is based on 20 km active length superconducting cavities to operate at an initial accelerating gradient of 25 MV/m at a Q_0 of 10^{10}. Since DESY adopted the TESLA Test Facility (TTF) project, the design has continued to evolve under its auspices since 1992.



The TESLA layout shows the major components of a linear collider. Electron and positron sources produce the beam. For TESLA, the large beam power demands a more 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.

TESLA

CIEMAT- Spain
(Madrid)

Yerevan Physics Institute

DSM/DAPNIA, Saclay
IN2P3/IPN, Orsay
IN2P3/LAL, Orsay

INFN, Frascati
INFN, Legnaro
INFN, Milano
Univ.Roma II

BINP, Novosibirsk
BINP, Protvino
IHEP, Protvino
INR, Troitsk
JINR Dubna
MEPhI, Moscow
ITEP, Moscow

Paul Scherrer Institut, Villingen

IHEP, BeijingTsinghua University

BESSY, Berlin
DESY, Hamburg
Frankfurt University
FZ Karlsruhe
GKSS Research Centre
Hahn-Meitner-Institut Berlin
Hamburg University
Max Born Institute, Berlin
Rostock University
RWTH, Aachen
TU, Berlin
TU, Darmstadt
TU, Dresden
Wuppertal University

APS/Argonne, Chicago, IL
Cornell University, Ithaca, NY
Fermilab, Batavia, IL
Thomas Jefferson National Laboratory, Newport News, VA
UCLA Dep.of Physics, Los Angeles, LA

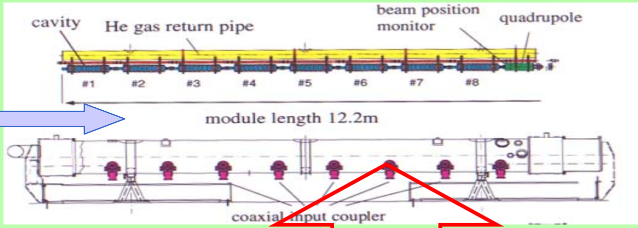
Institute of Physics, Helsinki

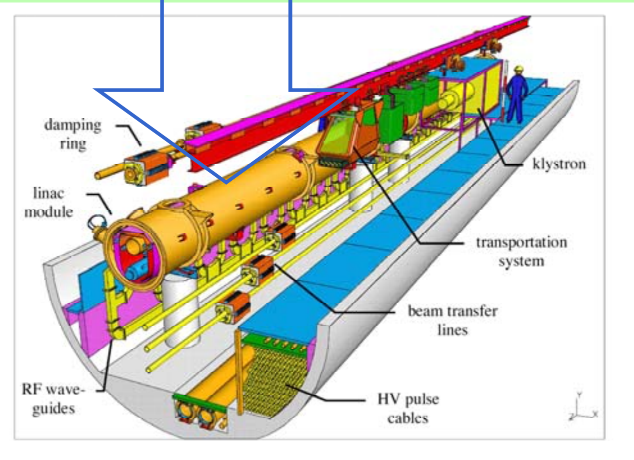
CCLRC, Daresbury & Rutherford Appleton

DMCS Technical University, Lodz Faculty of Physics Warsaw University
High Pressure Reaserch Center "UNIPRESS" PAS, Warsaw
Inst. of Nuclear Physics, Cracow
Inst. of Physics Polish Acad. of Science, Warsaw
ISE Technical University, Warsaw
Polish Atomic Energy Agency, Warsaw
Soltan Inst. for Nuclear Studies, Otwock-Swierk
Univ. of Mining & Metallurgy, Cracow

TESLA : Principal Features

One of the most attractive features of TESLA is that the peak RF power/m is very low compared to the normal conducting option. Since RF dissipation in the structure walls is miniscule, only the beam power needs to be supplied. For pulsed operation, it is possible to fill the cavity slowly (ms), which means modest peak powers (< 250 kW/m). With respect to the need for high luminosity, a crucial advantage that emerges from superconductivity is the affordability of low RF frequency (1.3 GHz) structures. For the same length of accelerating structure, and the same accelerating voltage, the RF energy stored in a structure increases as the square of the wavelength; but the large amount of structure stored energy becomes affordable because the dissipation is low. The resultant large aperture (0.27 times the wavelength) yields the pleasant consequence of substantially low short- and long-range wakefields, fighting the main enemies of high luminosity. When the cavity walls are close to the beam (as for high frequency structures), the wakefields increase, making tolerances tight and emittance dilution effects strong. Low losses also permit a long RF pulse length, so there can be a long time between bunch passages. This offers the possibility to measure individual bunch position variations, and to make corrections to subsequent bunches. Such corrections could be made at the end of the linac, or a few times along the linac.





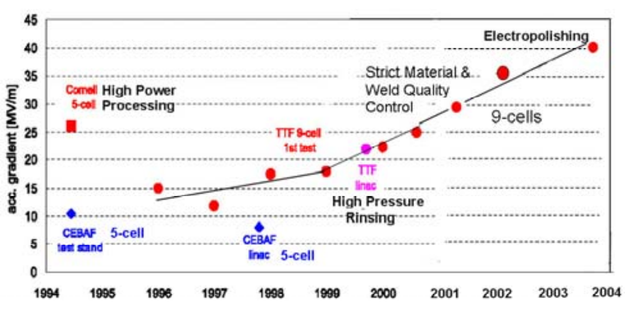
TELSA Cryomodule in the Tunnel (Concept)

Feature	TESLA 1.3 GHz
Structure length (cm)	104
(loaded) accelerating gradient [MV/m]	24 (35*)
Number of structures	20592
Two-Linac length [km]	30
RF pulse length [μs]	1370
Cycle rate [Hz]	5
RF power/structure [MW] - all for beam	0.25
Efficiency (Beam power/AC Power [%])	23.8

*Gradient for the one TeV upgrade

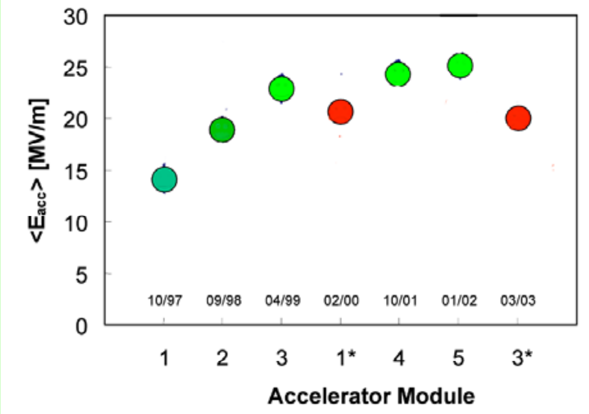
Steady Performance Advances for TESLA

The TESLA collaboration has made significant advances during the past decade to improve niobium purity and surface processing, allowing cavity gradients to rise from 5-10 MV/m typical in the early 1990's to reach 25 - 30 MV/m by the year 2000. More than a hundred 9-cell structures have been produced by industry. Over the last two years, the use of electropolishing and mild baking (100 C) techniques have yielded CW gradients between 35 - 40 MV/m in five units, to meet the one TeV upgrade requirement. Electropolishing eliminates micron-size steps at grain boundaries believed responsible for a Q-drop above 20 MV/m.

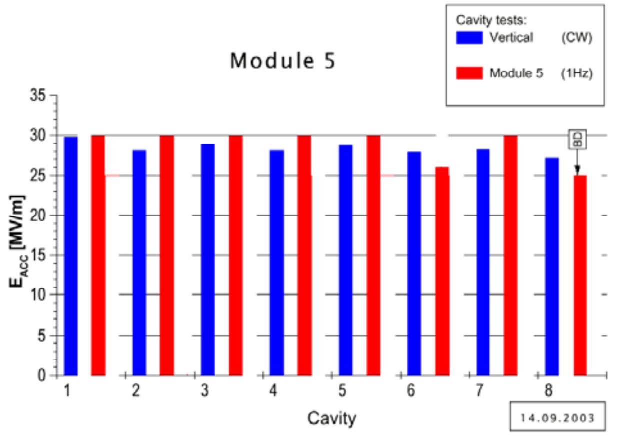


Steady rise in 9-cell cavity gradients due to material and process improvements, such as high pressure rinsing, eddy current screening of starting niobium sheets, electropolishing, and mild baking.

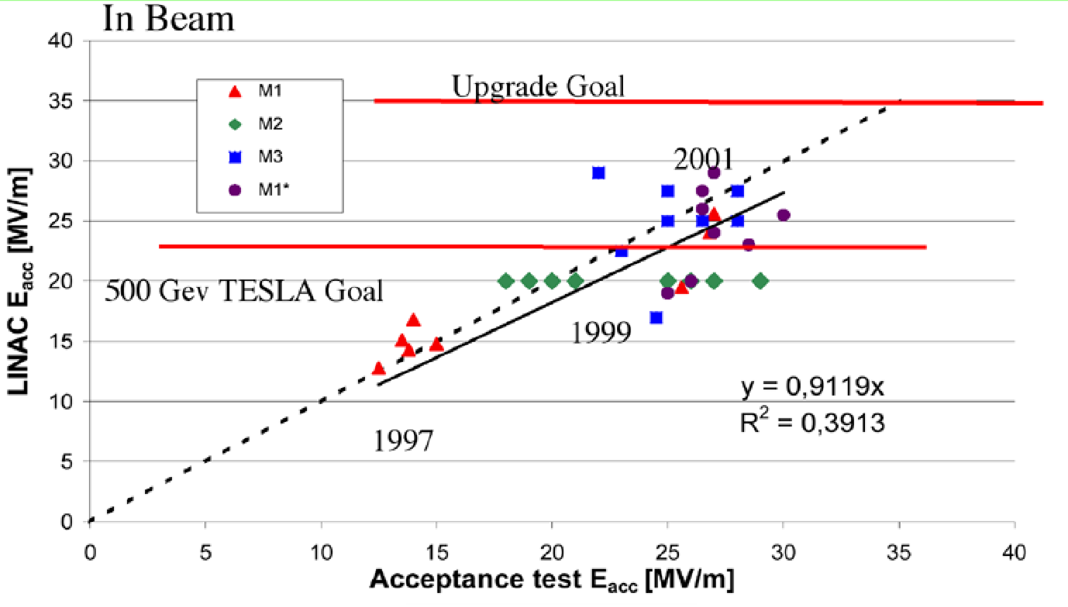
The 500 GeV collider will need 1700 cryomodules housing 20,000 niobium structures. Seven cryomodules have been assembled between 1997 and 2003 and tested in TTF-I and TTF-II. All cavities were prepared by standard chemical etching, since electropolishing was under investigation at the time.



As assembly techniques and cavity gradients improve, cryomodule performance has been rising steadily with time. Note: module 1* had lower results due to an accidental contact of an input coupler antenna, and module 3* had a batch of (immediately available) lower gradient cavities installed from the start.



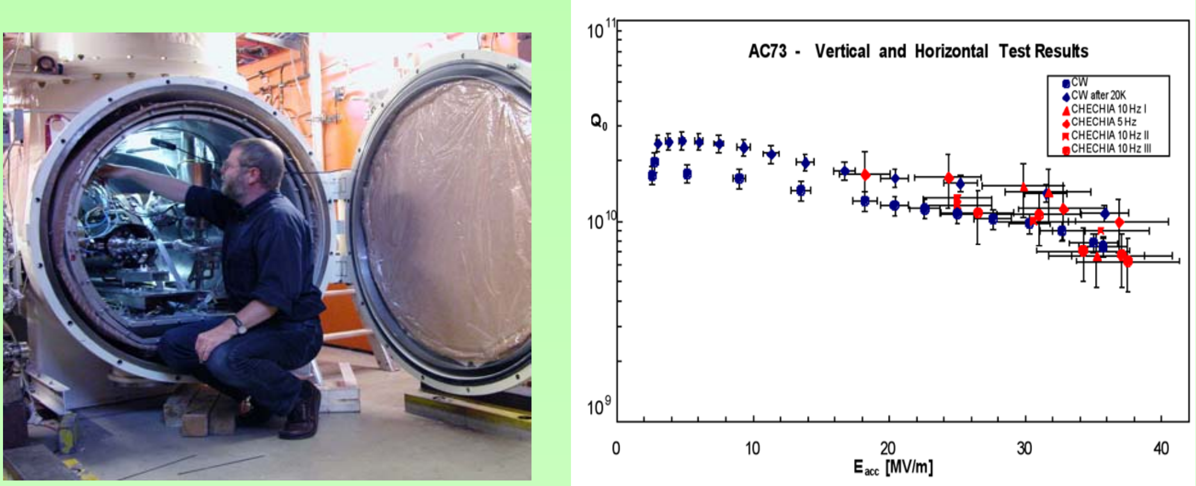
Powering individual cavities in the most recent module 5, six cavities reached 30 MV/m at 1 Hz rep rate. Module tests will resume in March 04 after installation of TTF-II is complete.



Beam tests have been carried out in TTF-I for a total 13,000 hours. Among three modules completed, the best accelerated beam at 22.7 MV/m. More than ten structures (in different modules) operated above 25 MV/m. During 2004, the plan is to test several more fully equipped cavities in their horizontal test cryomodule, and to accelerate beam through one or more cavities operating at 35 MV/m.

Electropolished Cavities in Cryomodules

Among the electropolished and baked cavities, a 9-cell unit equipped with input couplers, higher order mode (HOM) couplers and tuners has been operated inside a single-cavity test cryomodule (called CHECHIA) with a high power klystron to reach gradients between 35 - 37 MV/m. The cavity operated stably for more than 1100 hours at 35 MV/m at a Q value of 7×10^9. Operation was without quench or trips originating from the cavity-coupler system. There was no field emission below 35 MV/m as judged from the absence of x-radiation. Tests on a second cavity have reached 35 MV/m at a Q of 6×10^9 with no x-rays detected at 34 MV/m.



Individual 9-cell cavity cryomodule and test results

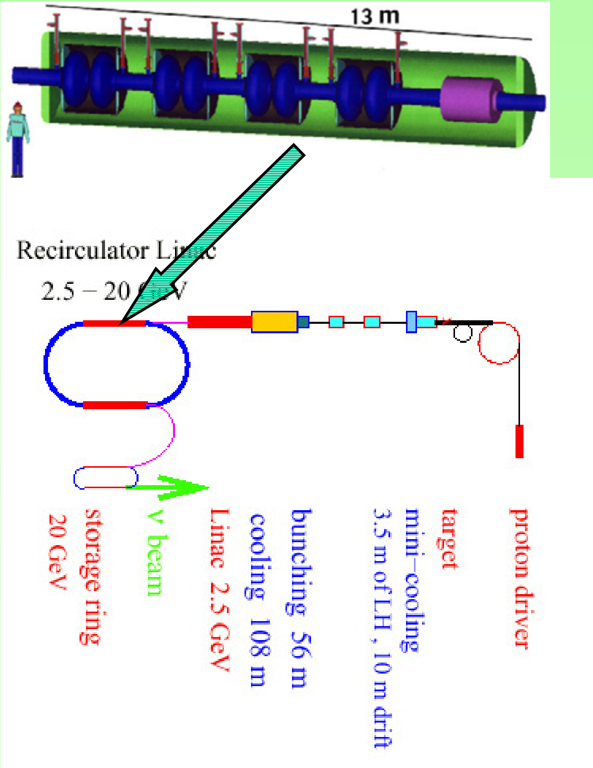
Neutrino Factories, A First Step to Muon Colliders

Interest in the Muon Colliders is growing. Electron-positron colliders beyond 2 TeV CM energy are likely to 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 interested in building a Muon Storage Ring based Neutrino Factory. Atmospheric neutrino, solar neutrino and short baseline accelerator experiments have accumulated evidence to 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. 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 2.5 GeV followed by a 4-pass recirculating linac to the final energy of 20 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.

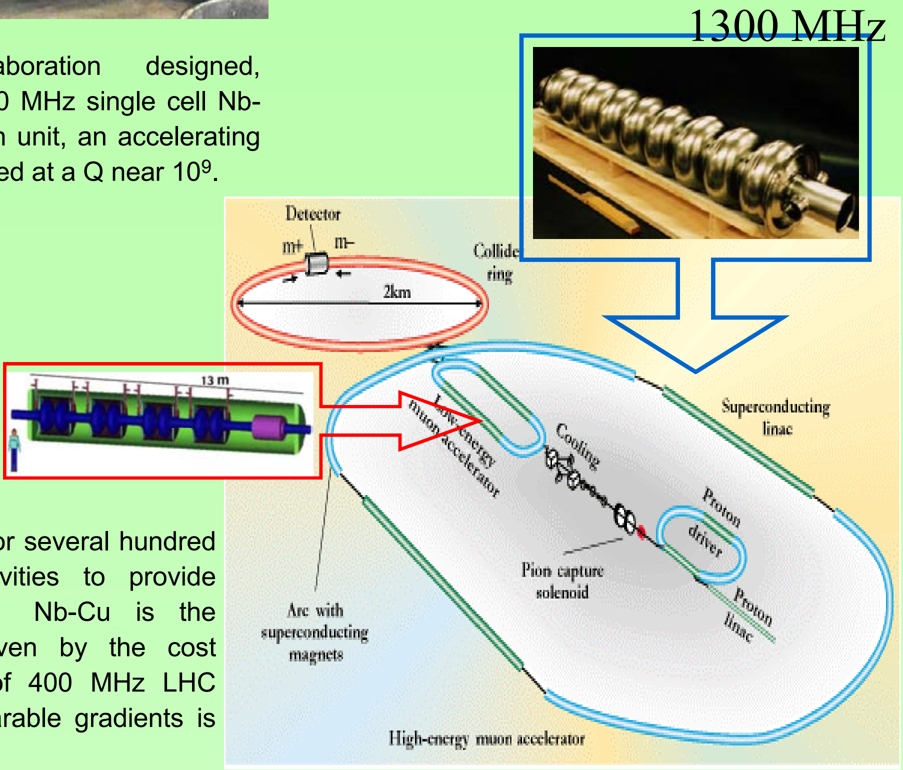
A 200 MHz Nb-Cu Cavity for Muon Acceleration

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 calls 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, such as 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 could 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 TESLA-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 TESLA effort was started around 1988, and is still many years towards completion, if chosen.



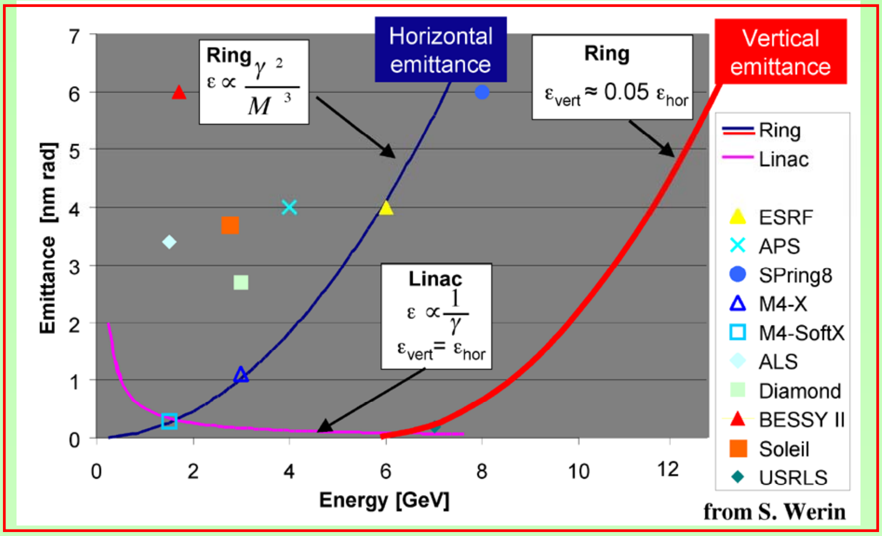
FUTURE LIGHT SOURCES

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 near limits. Although some improvement is possible, storage ring technology is at the 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

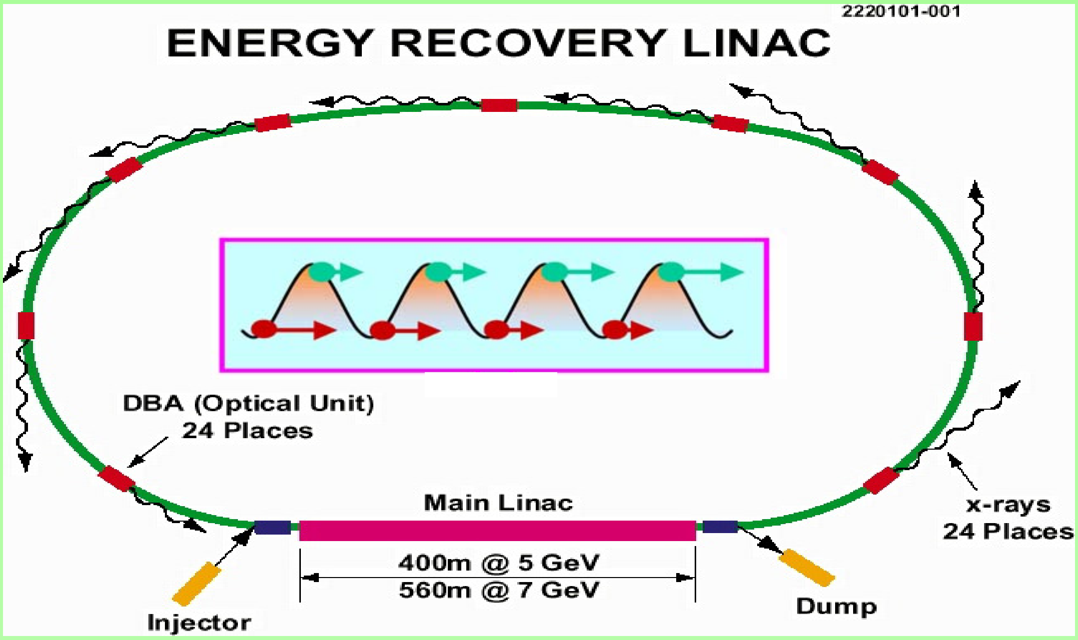
The Energy Recovery Linac (ERL) takes a different approach to producing high quality beams. Electrons are not stored, so constraints of beam equilibrium never become a limit. Photo-injectors can achieve bunches with emittances, shapes, and length which are superior in important ways to bunches in storage 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!



from S. Werin

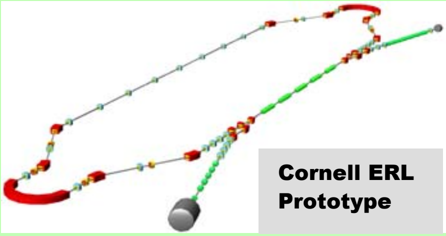
A comparison of vertical and horizontal emittances for rings and linacs.



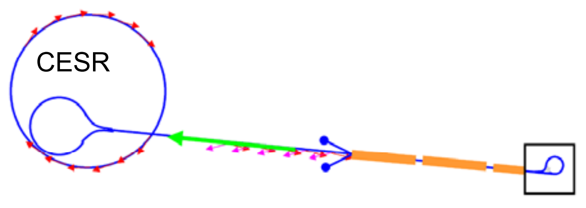
Therefore, it is economically unfeasible to simply dump the electrons after acceleration. A storage ring keeps the power costs down by reusing the energetic electrons many times. ERLs resolve the power dilemma by reusing the beam energy. After producing SR, the electrons in an ERL re-enter the linac, 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.

A Cornell/JLab collaboration has proposed a synchrotron radiation light source driven by an energy recovering SRF linac operating at an energy of 5-7 GeV and an average current of 100 mA. While offering average photon flux comparable to storage rings, the panels on the next page show that proper parameters of an ERL can lead to higher peak brilliance, shorter pulses and a higher coherent fraction.

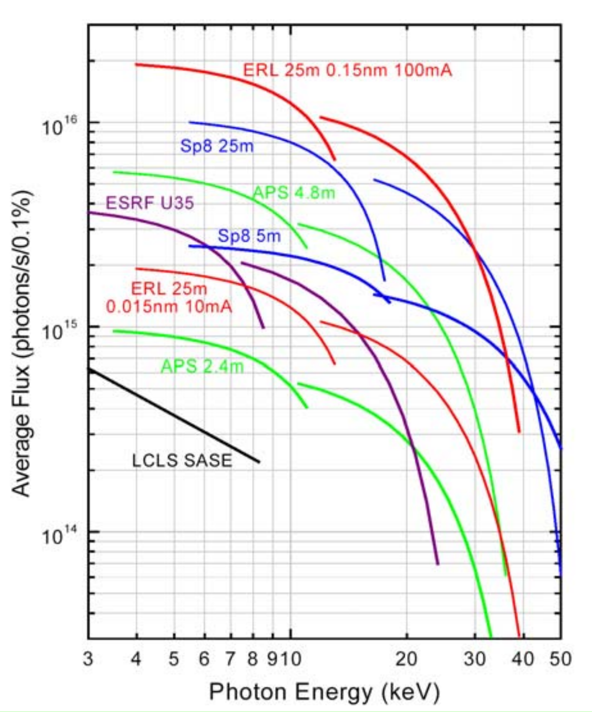


To address many important accelerator physics issues of the injector and the main linac, there is a proposal for a small scale prototype ERL at 100 MeV and 100 mA.

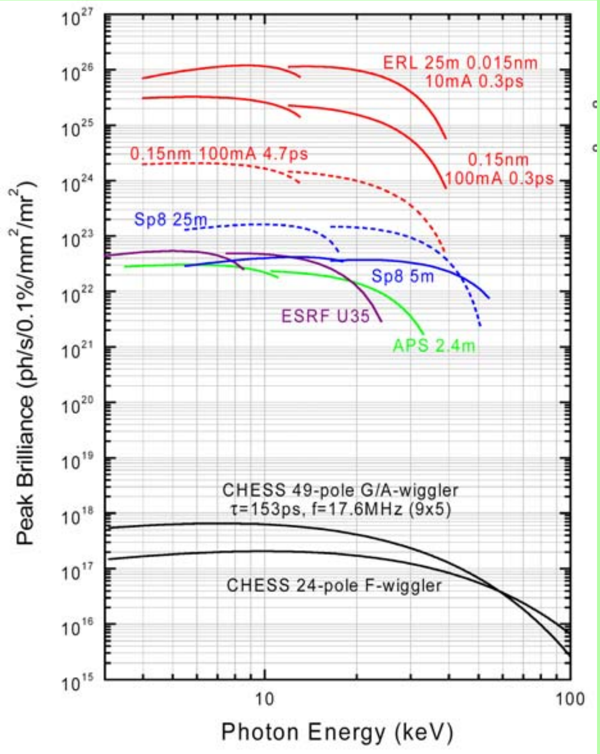


Possible layout for a 5 GeV Cornell ERL based on the CESR ring, under study.

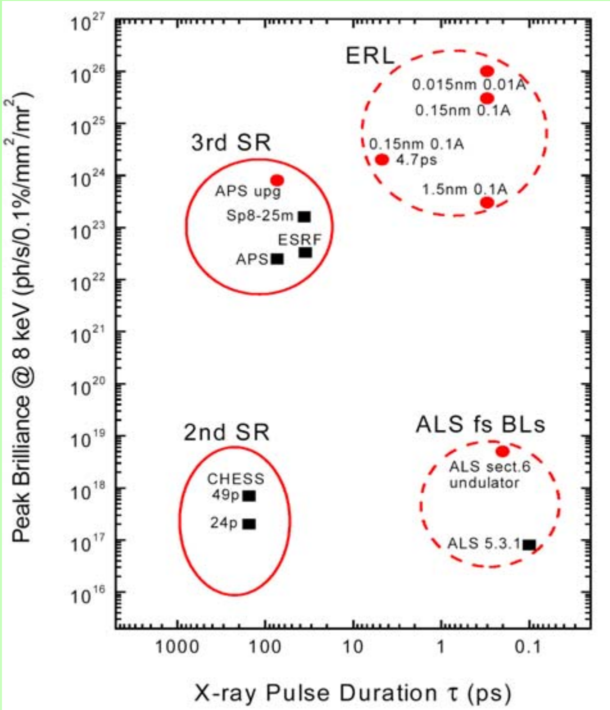
Flux Comparable to Rings



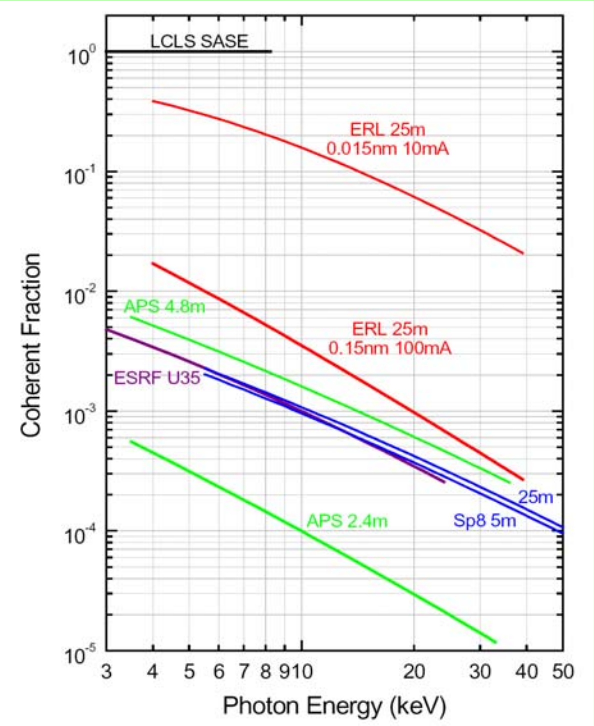
Higher Peak Brilliance



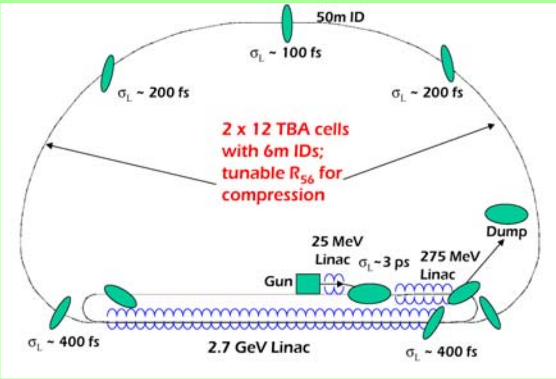
Shorter Pulses at Higher Brilliance



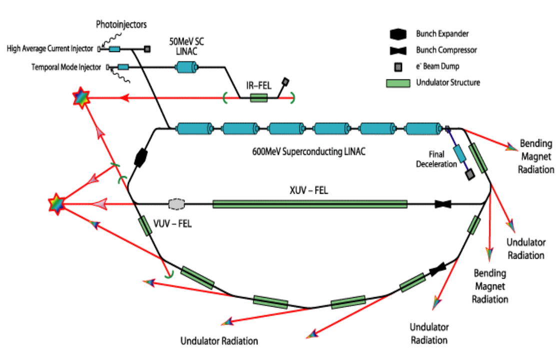
Higher Coherent Fraction



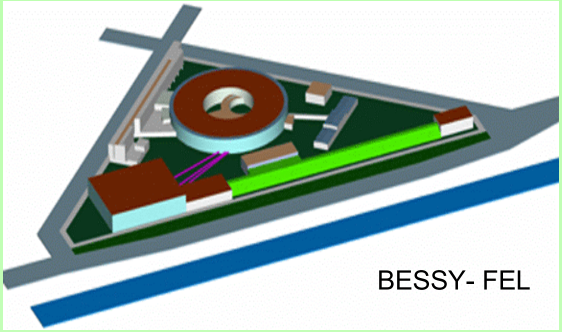
SRF Linac-Based Light Sources



BNL-PERL

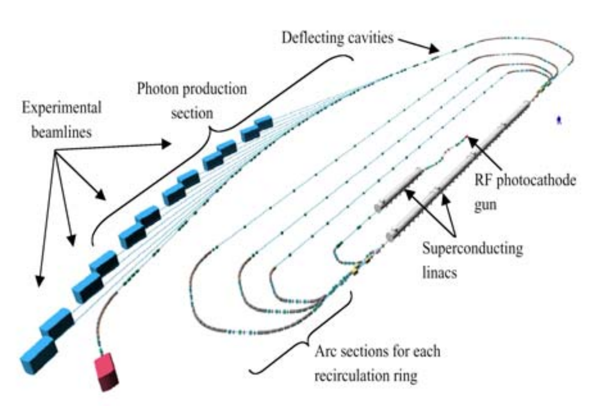


Daresbury 4GLS

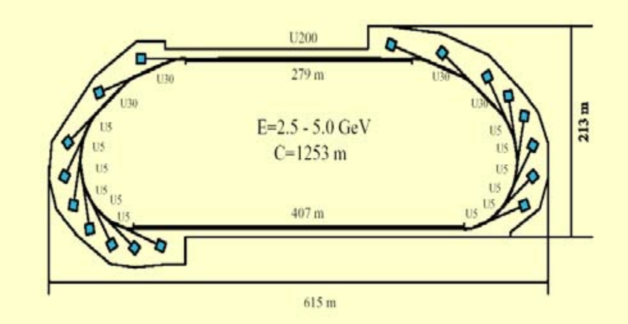


BESSY- FEL

Brookhaven National Laboratory is exploring the PERL Light Source, driven by a 1300 MHz, 3 GeV SRF linac. The average current is 200 mA with 150 pC per bunch at 1.3 GHz repetition rate. Lawrence Berkeley National Lab is developing the LUX concept to produce femtosecond x-ray pulses with high flux, and repetition rate matched to the requirements of structural dynamics experiments.



LUX-LBL

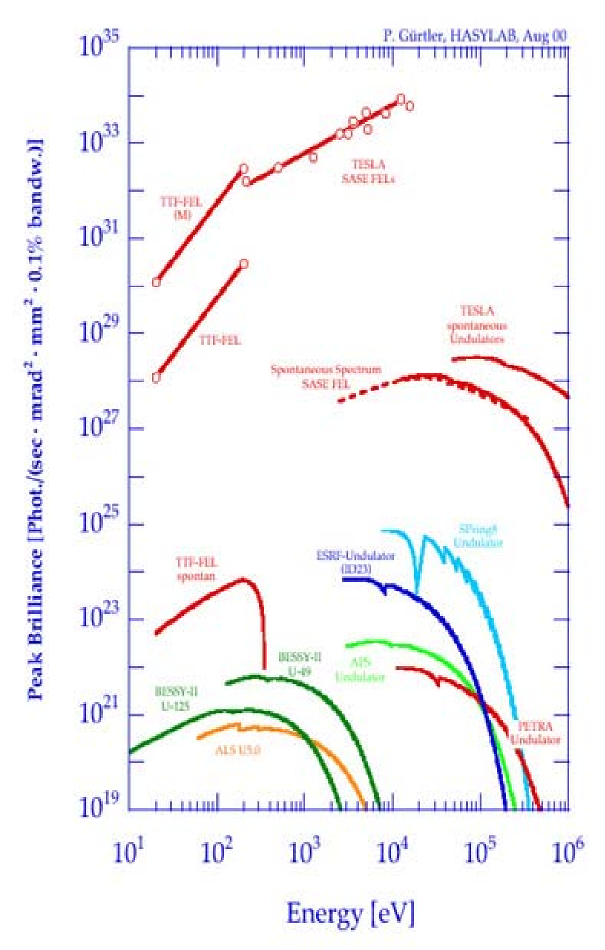


KEK-ERL

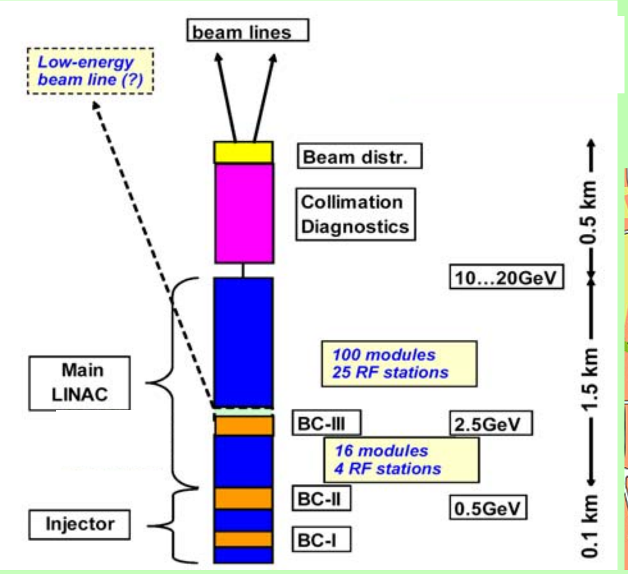
The 2.5 - 3 GeV LUX machine is based on a 1300 MHz SRF 4-pass recirculating linac for acceleration (and deceleration) of electrons (average current 10uA) produced by a high-brightness photocathode RF gun, at a bunch repetition rate of approximately 10 kHz. Daresbury (UK) has funding to build a prototype for its 4GLS project, a 600 MeV, 100 mA energy recovery linac driving a suite of light sources to generate radiation in the 3 - 500 eV range (IR to XUV). KEK is considering a 2.5 - 5 GeV, 100 mA ERL light source along the design of the Cornell ERL. BESSY in Berlin proposes the construction of a single-pass FEL for photon energies from 20 eV to 1 keV corresponding to wavelengths between 63 and 1.2 nm. Many FEL/ERL concepts are based on an evolution of TESLA high gradient technology.

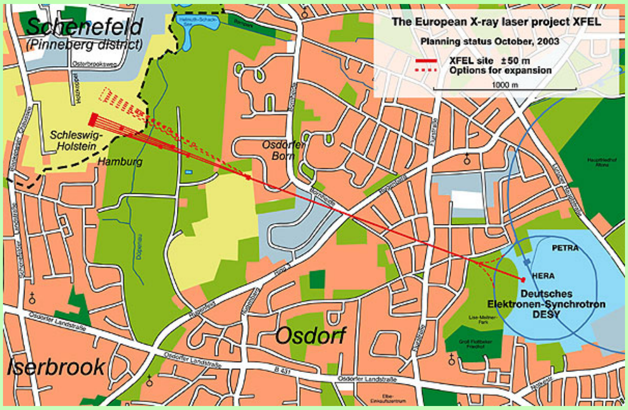
X-Ray FELs

Two large programs for X-ray FELs with the capability of reaching the 1 Å wavelength range are approved: LCLS at SLAC in the USA and the TESLA XFEL at DESY in Germany. The X-ray pulses they will produce will have a duration in the range of 10 to a few 100 femtosecond, and a peak power of tens of GW. The brilliance, coherence and femtosecond timing regime open a wide range of novel experiments not possible with the present radiation sources. These include: investigation of structural changes on ultra short time scales, the nonlinear interaction of X-rays and matter, and multi-photon processes in atoms and molecules. Some of the most fascinating applications of X-ray FELs come from the life sciences. At the present time, an exponentially increasing number of biological structures are solved and deposited at the protein data bank. In all likelihood this trend will continue. However, there remain many challenges in structural biology, including resolving systems that are difficult to crystallize. The possibilities of X-FELs would impact the full span of the materials and biological sciences.



The promise of x-ray FELs





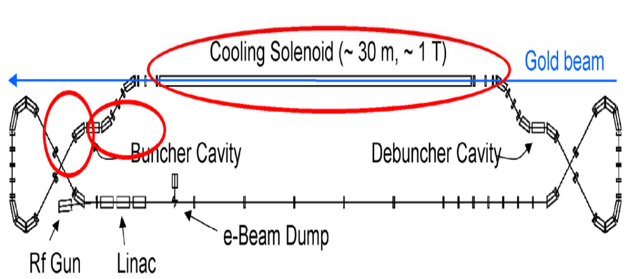
The DESY xray FEL

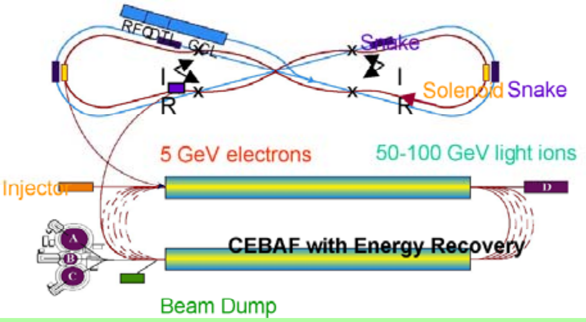
ERLs for Nuclear Physics

Electron Cooling and Electron-Ion Colliders

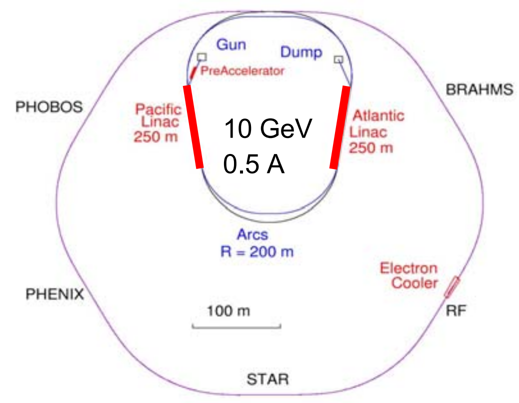
Over the past two decades, nuclear science has made great strides in mapping hadronic structure. Some crucial questions remain: What is the quark-gluon structure of the proton and neutron? How do quarks and gluons evolve into hadrons? What is the quark-gluon origin of nuclear binding? High-luminosity 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 (100-300 mA, 600 MeV) with energy recovery. The anticipated increase in average luminosity is 9 times for Au-Au (100 GeV/u) and 3 times for p - p (at 250 GeV/u).





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.

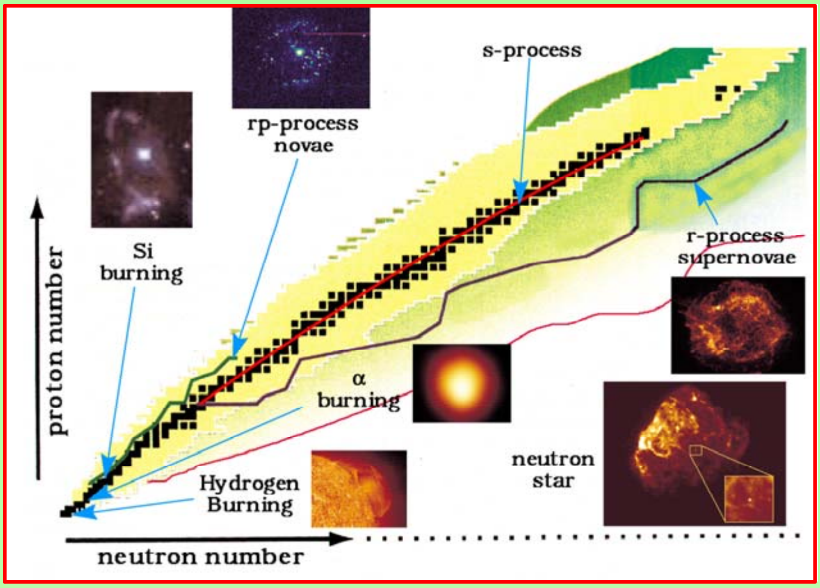


Energy recovering linac-on-ring scenarios for electron-ion colliders are under study as alternatives to ring-ring scenarios. Such designs push the envelope of energy recovery in various fronts. To collide with RHIC and provide a center-of-mass energy between 20-45 GeV (with an energy asymmetry of ~10) there would be 3 GeV polarized electrons on ions with 30 GeV/nucleon and 5 GeV electrons on 100 GeV/nucleon ions for many species. The CW luminosity goal is 2x HERA.

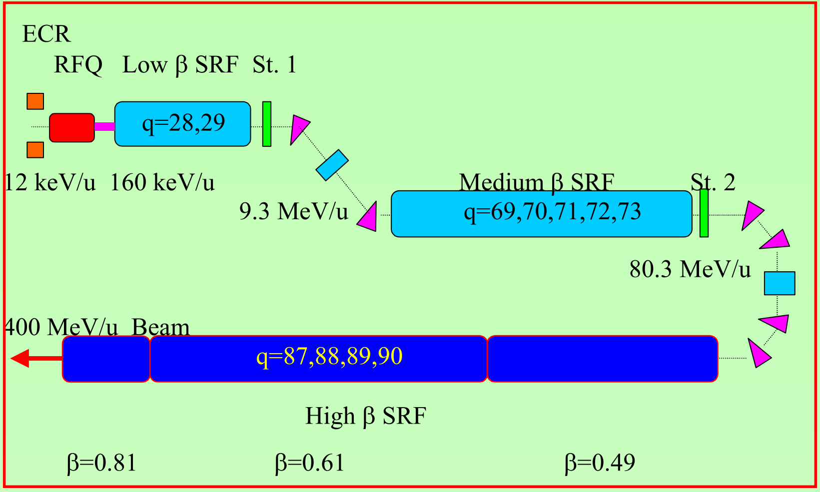
FUTURE APPLICATIONS : IONS AND PROTONS

Nuclear Astrophysics : Rare Isotope Accelerator

The highest priority for a major new facility in the Long Range Plan of the US Nuclear Science Advisory Committee is the Rare Isotope Accelerator, RIA. Among other fundamental questions, RIA will provide basic insight into the origin of the elements. Through understanding the “r process,” RIA will allow understanding of the origin of the heavy elements. Through data on neutron rich weakly bound nuclei RIA will promote further understanding of nuclear many body science.

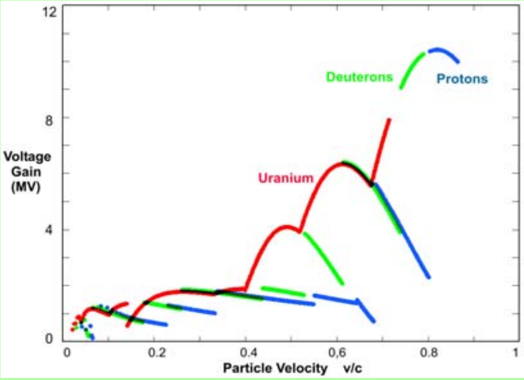


There will be two major sections to RIA, a superconducting multi-ion multi charge-state driver linac spanning nearly the entire range of masses from protons to uranium and particle velocities, $0.02 < \beta < 0.84$, and a superconducting post accelerator of efficient acceleration and transmission of multi charge-state rare isotopes. The 1.4 GeV driver linac will deliver several hundred kilowatts of beam onto production targets at energies of 400 MeV/nucleon for uranium and more than 900 MeV for protons. The highly flexible driver linac can provide a variety of beams to utilize combinations of projectile fragmentation, target fragmentation, fission, and spallation and produce a broad assortment of short-lived unstable isotopes. Compared to existing facilities GSI, GANIL SPIRAL II, and RIKEN RIBF, the isotope reach and intensities will be much higher with RIA. In Europe, SPES and EURISOL are RIA type facilities also under study. EURISOL is a 3rd generation rare isotope facility, with 1 GeV, 5 ma proton driver and a 100 MeV/u heavy ion re-accelerator. SPES is a smaller scale model for EURISOL.

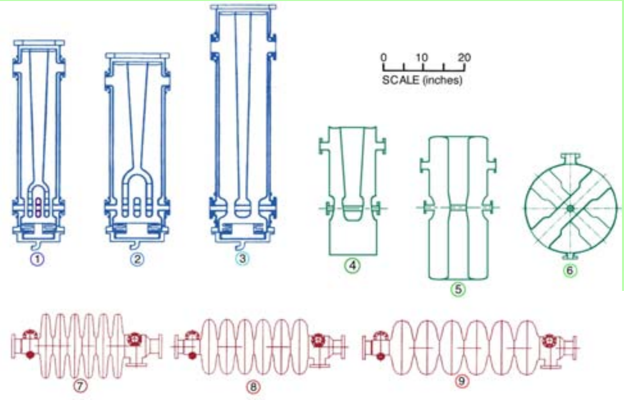


Possible RIA Layout: Electron Cyclotron Resonance (ECR) ion sources feeding an RFQ will be used as input to a stable beam linac with the ECR performance providing one of the facilities intensity limitations (MSU).

Possible Driver Linac Cavity Array



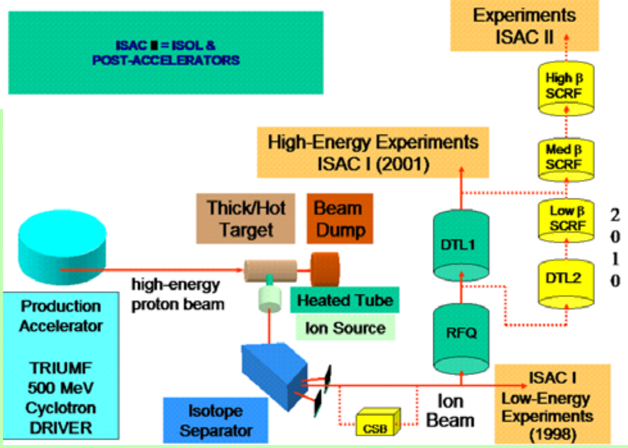
“Cavity-Walk”(voltage gain per cavity) for the Baseline RIA Driver Design



The SRF-based linac will use superconducting structures suitable for particle velocities ranging from a few percent to about 70% the speed of light. High Q’s and gradients are needed to reduce capital and operating costs. Of these nine types, the first four closely resemble existing cavities which were developed for, and have been operating for many years in several existing SC heavy ion linacs. The lower beta (<0.5) structures utilize quarter-wave, half-wave and spoke resonators. The last two cavity types, the 805 MHz β =0.61 and β = 0.81 six-cell cavities, are presently being developed at JLAB for the SNS project. Multiple spoke resonators could also be used in the medium beta sections.

Anticipating RIA, ISAC-II

TRIUMF in Canada is presently operating an ISOL based radioactive beam facility, ISAC, supplying both low-energy (60 kV, A 238) and high energy (0.15-1.5 MeV/u, A 30) experimental areas with exotic beams. They have recently been funded to proceed with a second stage, ISAC-II, to extend the final energy to at least 6.5 MeV/u and mass range up to 150. The expansion includes the addition of a superconducting heavy ion linac supplying 42.7 MV of acceleration. The linac will consist of three cavity geometries, all quarter wave bulk niobium in design, with design β values of 0.042, 0.072 and 0.105 and RF frequencies of 70.7, 106.1 and 141.4 MHz respectively. They have designed, fabricated and tested a medium beta prototype cavity in a collaboration with INFN-LNL with an achieved gradient of 6.7 MV/m @7W dissipated power at 4.5K.

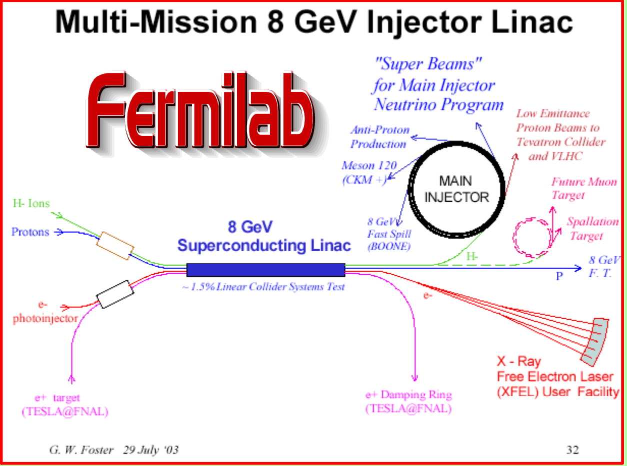


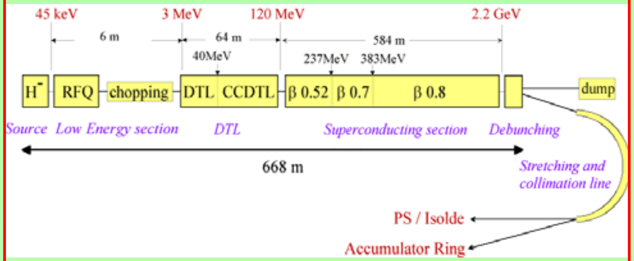
Multi-Mission High Intensity Proton Linacs

Future spallation neutron sources, neutrino factories and muon colliders place a heavy emphasis on developments in high intensity proton linac and relevant superconducting accelerator technologies. Fermilab, CERN and Brookhaven are studying high intensity proton linacs for multi purposes.

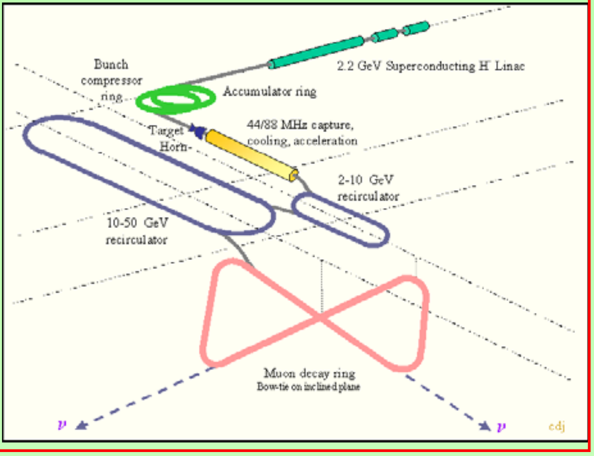
The Fermilab 8 GeV superconducting linac could supply the Main Injector to produce super beams for the neutrino program and intense beams for anti-proton production, or the linac could directly produce muons and spallation neutrons. Alternatively the linac could be used for electrons and for an x-ray FEL.

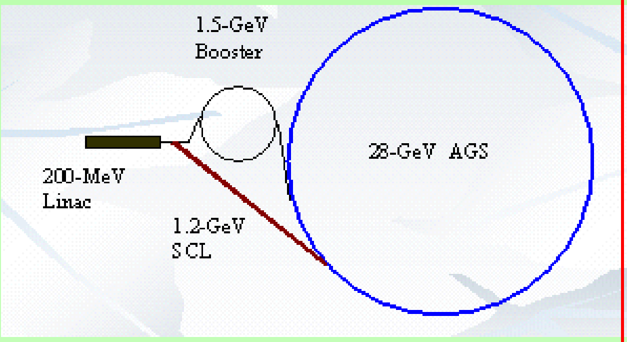
CERN is studying a multi-Purpose SC proton linac (SPL) for a super neutrino beam, a possible neutrino factory, as well as to upgrade the injector chain for the LHC, and to produce heavy ion radioactive beams for nuclear physics.



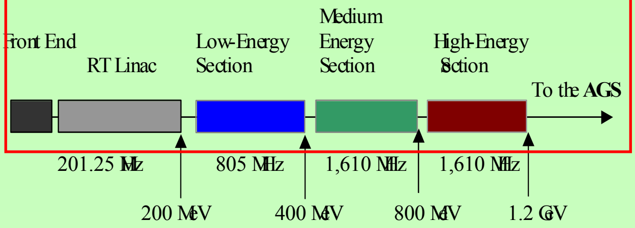


CERN





BNL



Using SNS cavity technology at twice the frequency, the 1.2-GeV SCL for the 1-MW AGS upgrade at BNL aims to increase the AGS beam power by a factor of 10 in order to produce intense neutrino beams and for other applications.

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.

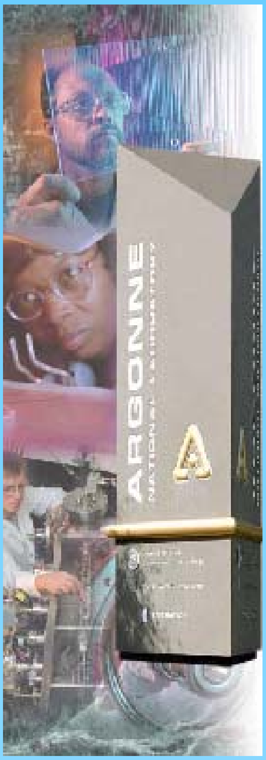
For a 5 - 10 MW proton beam, a superconducting linac significantly lowers the total linac AC power requirement. For example, Los Alamos is studying the Acceleration Demonstration Test Facility consisting of a 600-MeV linac at 13 mA. A SC linac would need 23 MW of AC power as compared to 80 MW needed for a warm linac. 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 cavities will have larger 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.

Concluding Remarks

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. The most ambitious application for niobium cavities is the superconducting linear collider for high energy physics. 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. 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.



TESLA

DESY

NSCL

SNS
SPALLATION NEUTRON SOURCE

fact
Muon Collaboration

CERN

CORNELL UNIVERSITY LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

～宇宙と物質の
起源と構造を探る～
KEK

Jefferson Lab

cea
DAPNIA

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LNL INFN

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