Lecture 21

5. RF Systems and Particle Acceleration

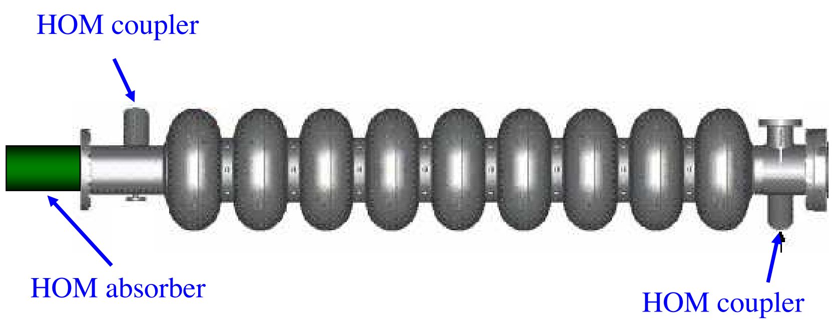
- **5.2 Accelerating RF Cavities**
  - **5.2.5 Higher-Order-Modes**
  - **5.2.6 SRF primer**
- **5.3 RF power sources**

HOMs

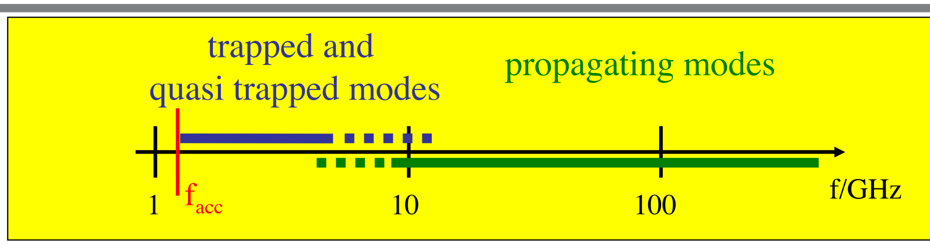
- Higher order modes
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

Solution (for SC Cavities): HOM Couplers and Absorbers

The parasitic e-m fields can be kept below the threshold by means of HOM couplers and HOM absorbers, usually attached to the beam tubes of a s.c. cavity.



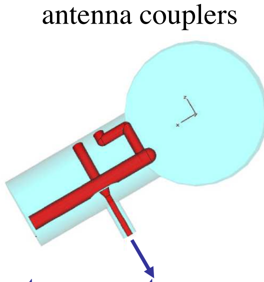
Higher-Order-Mode Couplers and Absorbers



HOM couplers

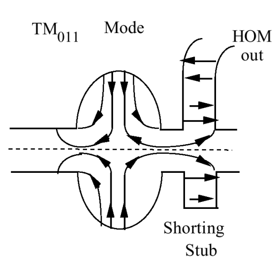
HOM beam-pipe absorber

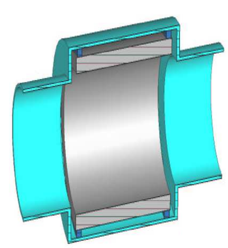
antenna couplers



to room temperature load

waveguide couplers





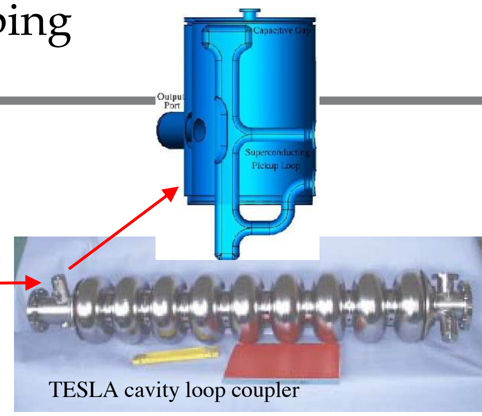
absorber between cavities at temperature level with good cryogenic-efficiency

The frequency where the HOMs start to propagate depends on the beam tube diameter: $\omega_c \propto 1/\text{diameter}$!

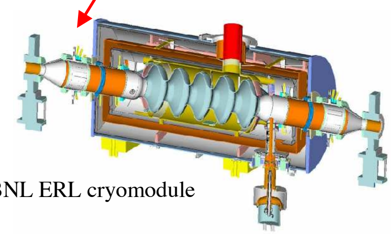
HOM Extraction/Damping Schemes

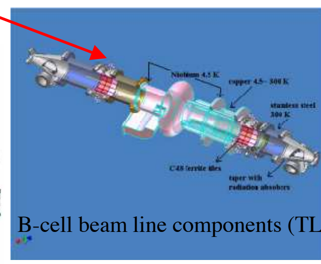
Several approaches are used:

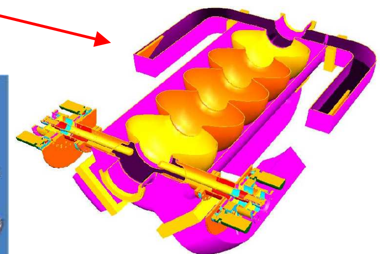
- Loop couplers (several per cavity for different modes/orientations)
- Waveguide dampers
- Beam pipe absorbers (ferrite or ceramic)



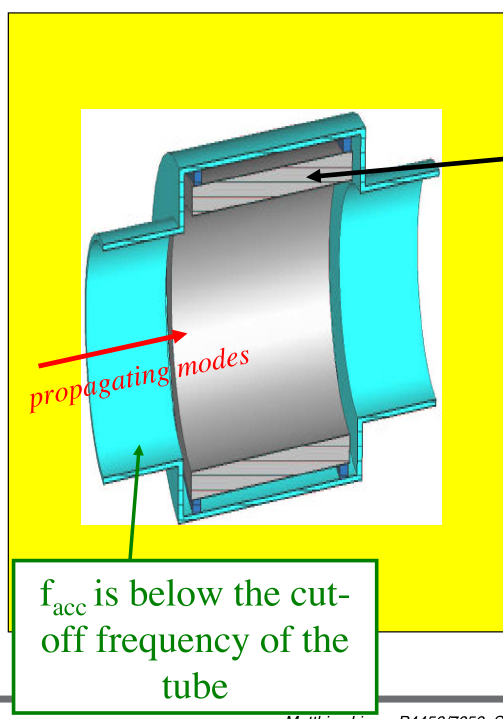
TESLA cavity loop coupler


BNL ERL cryomodule


B-cell beam line components (TLS)

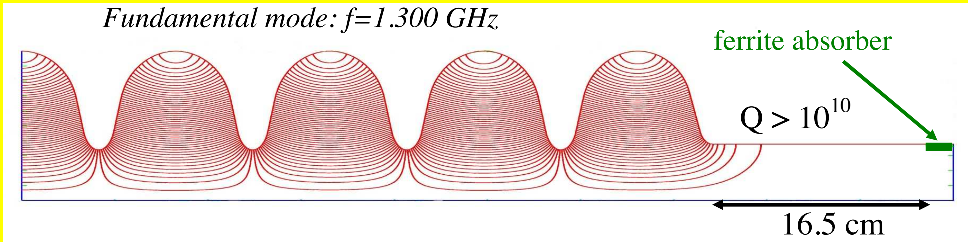

JLab proposal

Broadband Beam Pipe RF Absorber



- High frequency modes propagate out the beam pipe.
- RF absorbing material can damp these modes.
- Dissipated power will be intercepted by cooling (water, He, LN_2).
- Candidate absorber materials:
  - ferrites (used in CESR HOM load)
  - $Zr_{10}CB_5$ CERADYNE (used for CEBAF HOM load)
  - Mo in AL_2O_3
  - …

Broadband RF Absorber



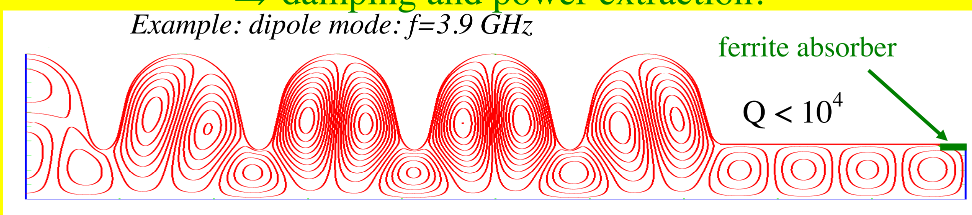
•Low field at absorber

⇒ no significant damping of the fundamental mode

but:

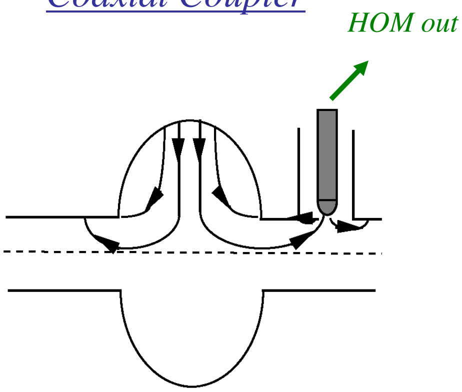
• Propagating modes have higher fields at the absorber

⇒ damping and power extraction!



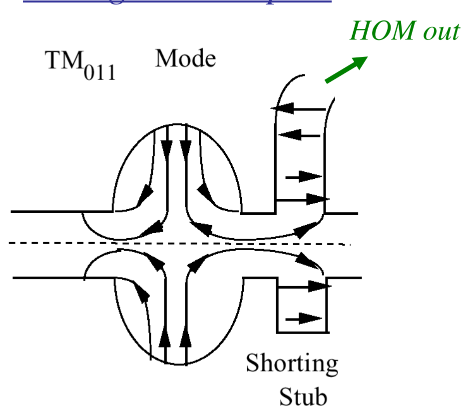
Higher-Order-Mode Couplers

Coaxial Coupler



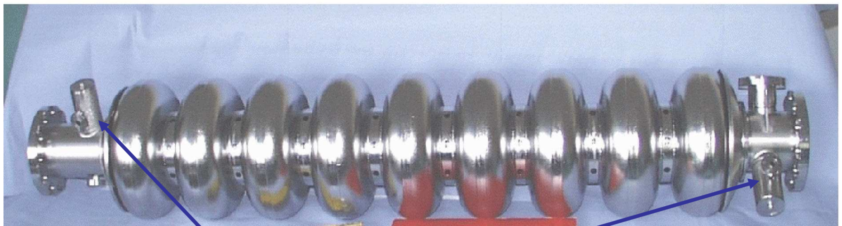
Rejection filter suppresses coupling to the accelerating mode.

Waveguide Coupler

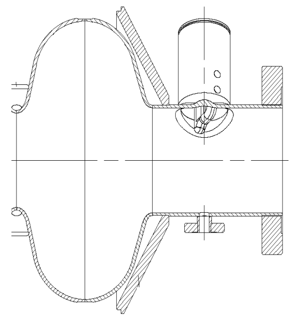


Waveguide cutoff suppresses coupling to the accelerating mode.

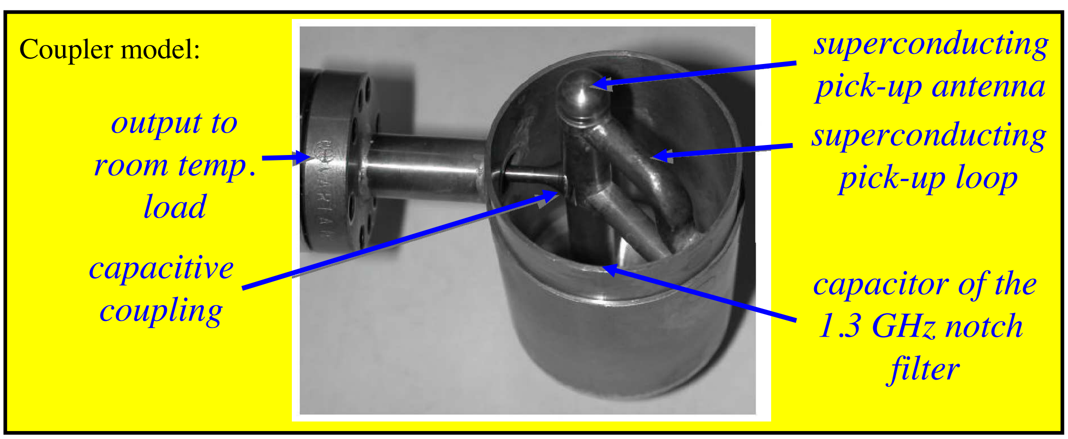
TTF HOM Loop Coupler (1)



HOM coupler at each side
of the cavity close to end cell
to damp HOMs



HOM Loop-Couplers

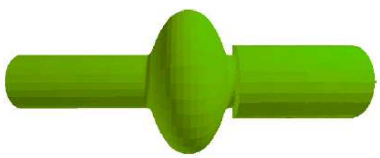


- Important to reduce Q of non-propagating dipole modes.
- Can only handle a few 10 W.
- Will work up to a few GHz but not above.
- Cooling / heating from fundamental mode issue in cw cavity operation.

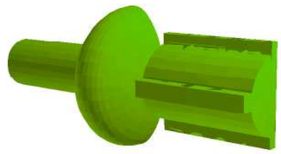
Methods for HOM Damping

Methods of broad-band HOM damping:

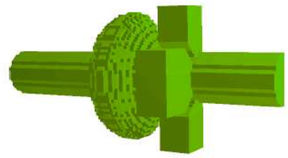
Strong HOM damping has been shown in single-cell cavities, e.g. Cornell and B-factory storage rings. Studies show these methods can be applied to multi-cell cavities. Options include multiple coaxial antennas, beam pipe loads, waveguide loads.



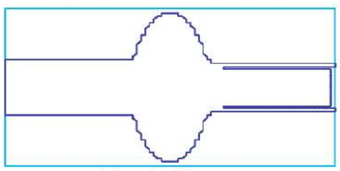
Enlarged beam pipe.
(KEK, BNL, Cornell ERL)



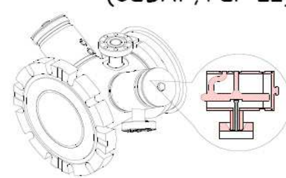
Fluted beam pipe.
(Cornell, CESR)



Waveguide dampers
(CEBAF, PEP-II)



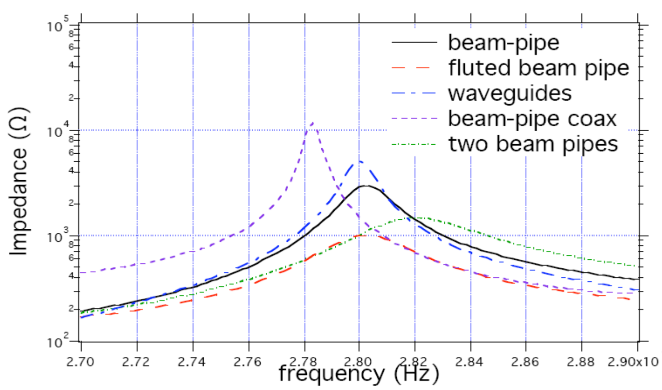
Coaxial/radial beam pipe
(KEK, JAERI)



Multiple coaxial loops
(DESY, CERN)

from Bob Rimmer

Methods for HOM Damping: Effectiveness



TM_{011} mode with various damping schemes.

	Freq. MHz	Q_{ext}	R* ( )	R/Q ( )
b-pipe	2803	252	3001	11.9
flutes	2803	137	1010	7.3
w-guide	2800	353	5040	14.3
bp-coax	2783	725	11879	16.4
2xbp	2822	121	1481	12.2

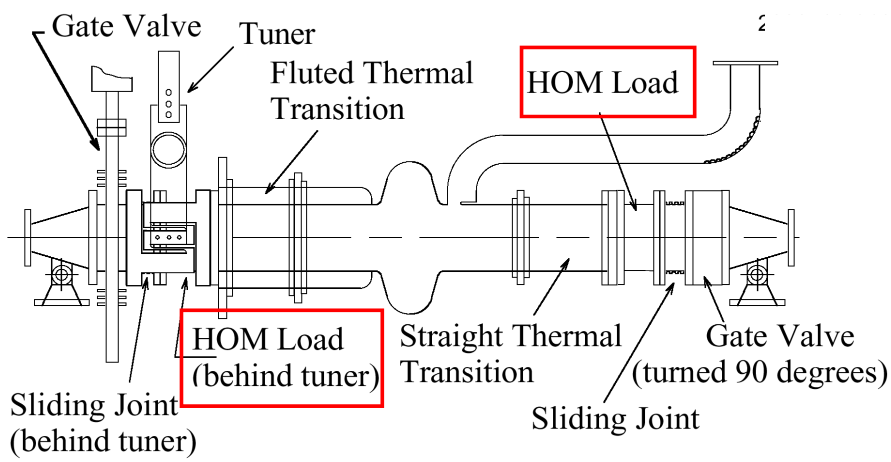
*$R=V^2/2P$

from Bob Rimmer

HOMs

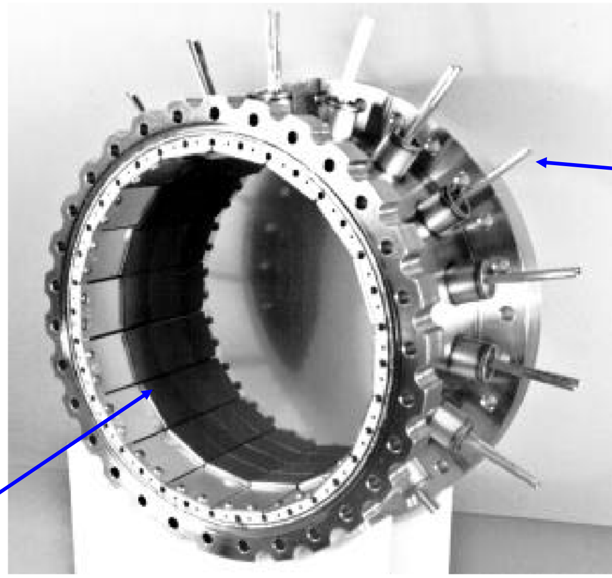
- Higher order modes
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

Example 1: CESR HOM Ferrite Absorber (1)



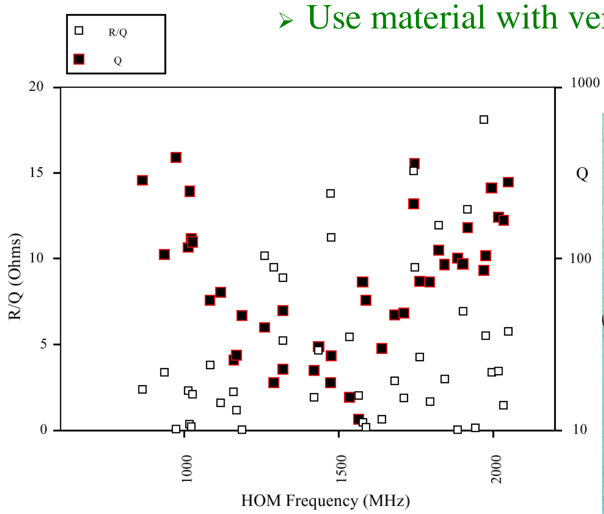
- Flute beam pipe ⇒ guide out the first two deflecting modes.
- Total HOM power: several kW!
- $Q_{ext} < 10^3$

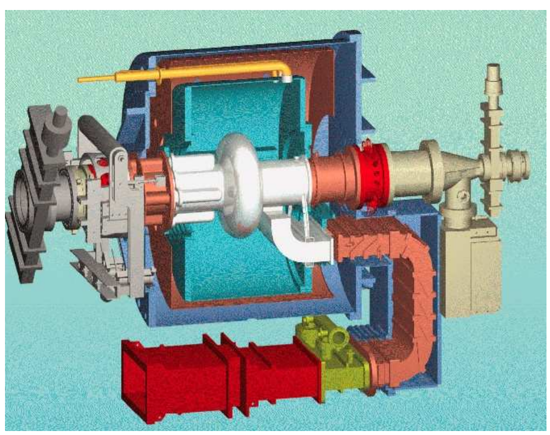
CESR HOM Ferrite Absorber (2)



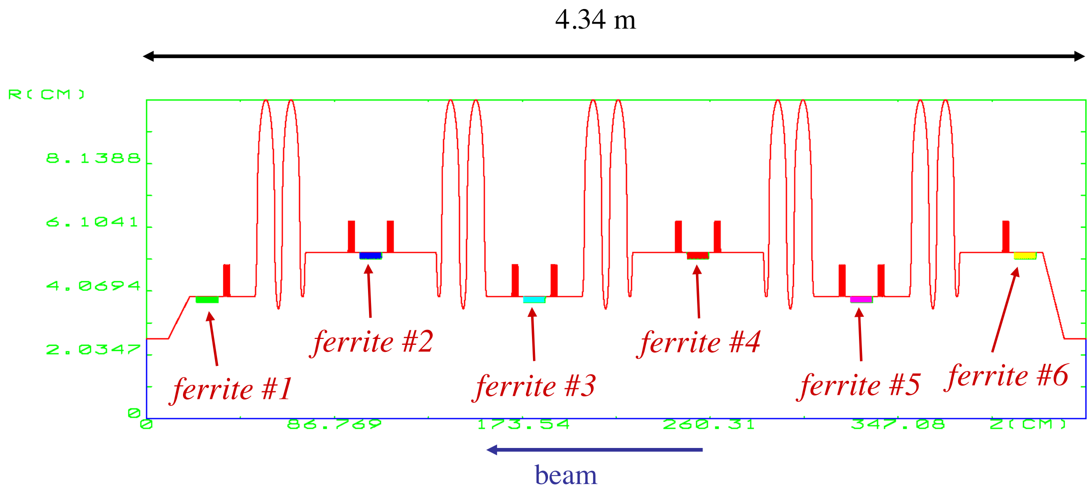
CESR HOM Ferrite Absorber (3)

- Use a single cell (no reflection by irises between cells)
- Open beam tubes so that all modes propagate out the beam tubes!
- Use material with very high RF losses.





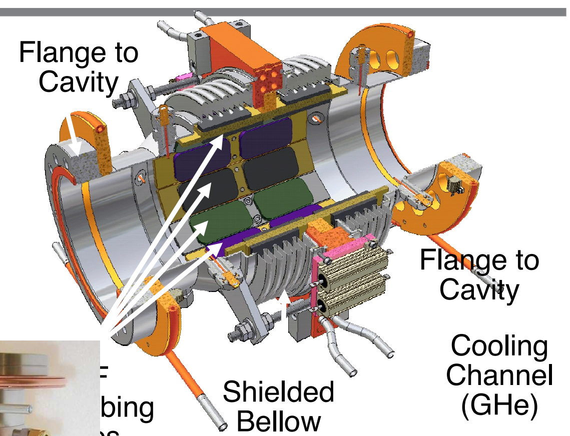
Example 2: The Cornell ERL Injector

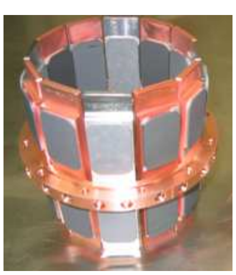


HOM damping concept: Make all TM monopole and all dipole modes propagating by increasing the beam tube diameter (as in CESR).

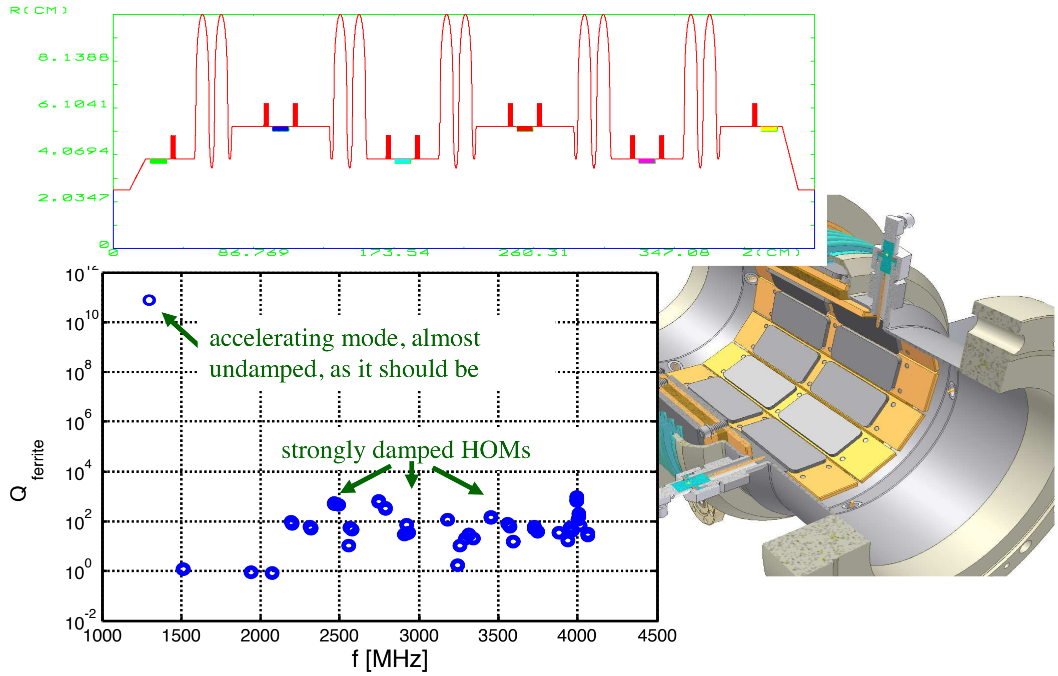
Cornell ERL Beam Line HOM Loads

Power per load	**26 W (200 W max)**
HOM frequencies	**1.4 – 100 GHz**
Operating temp.	**80 K**
Coolant	**He Gas**
RF absorbing tiles	**TT2, Co2Z, Ceralloy**

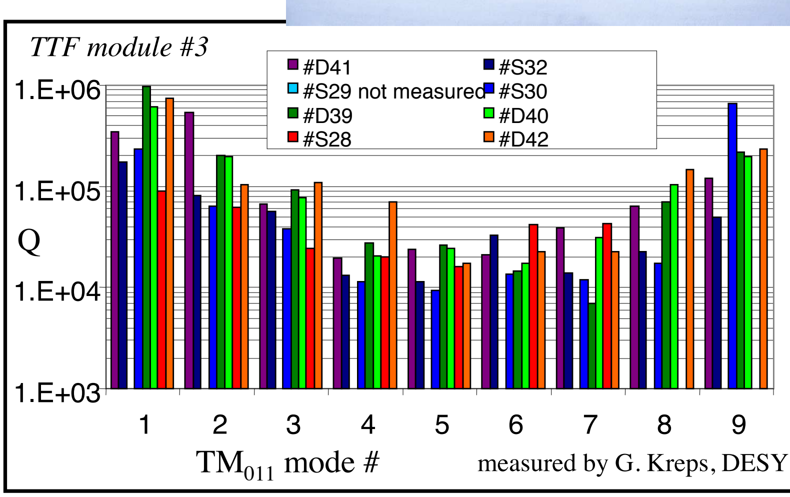




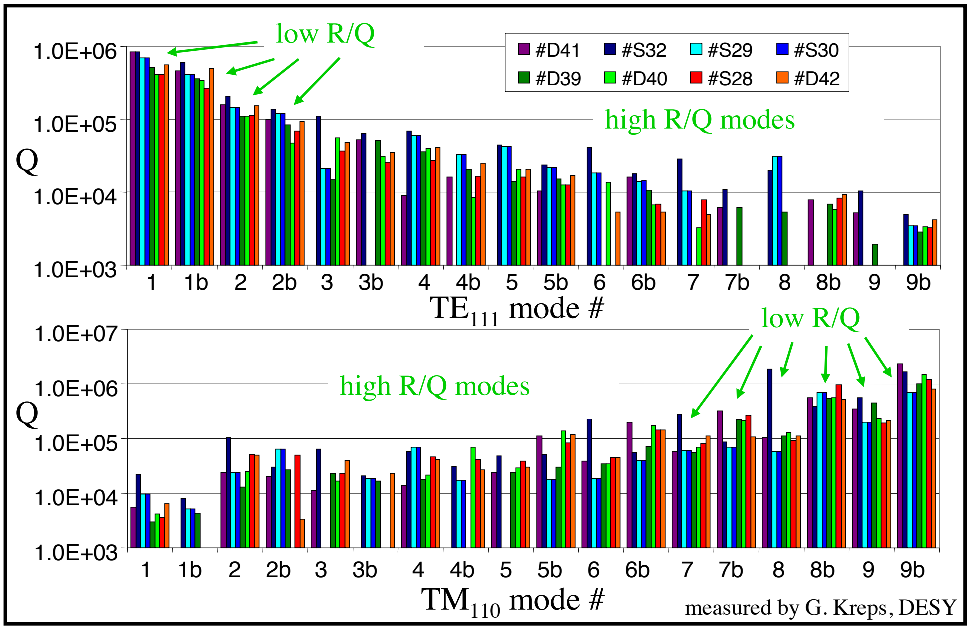
Cornell ERL Beam Line HOM Loads: Damping Calculations



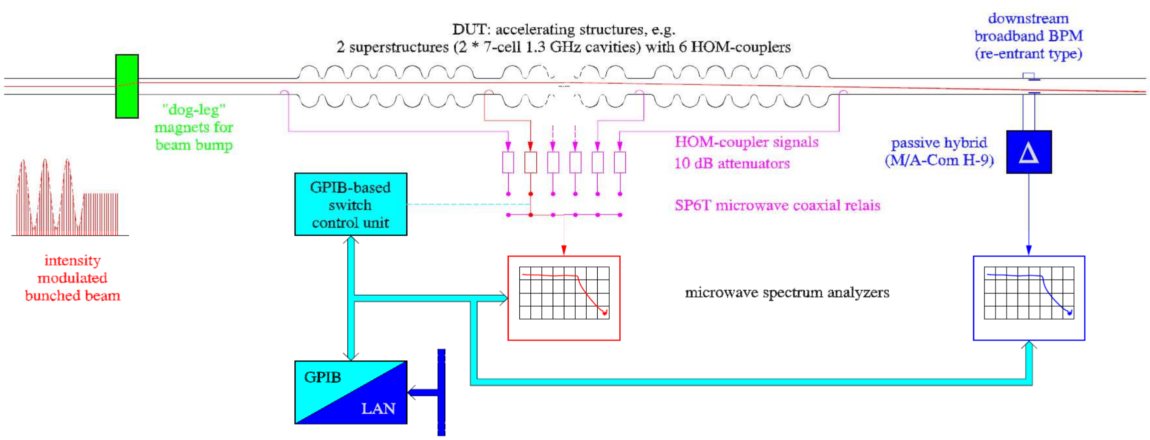
Example 3: ILC Cavity with HOM Loop Couplers



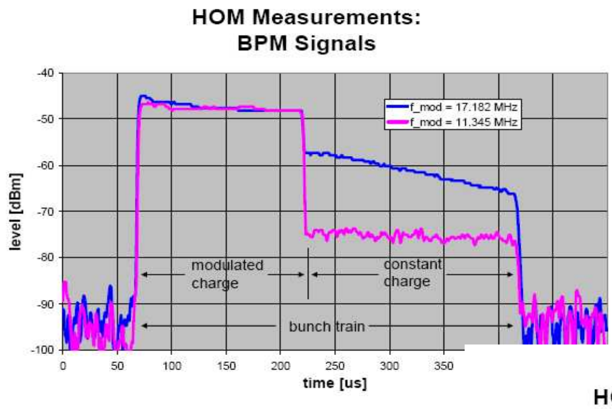
TTF HOM Coupler:
Measured Damping of Dipole Modes

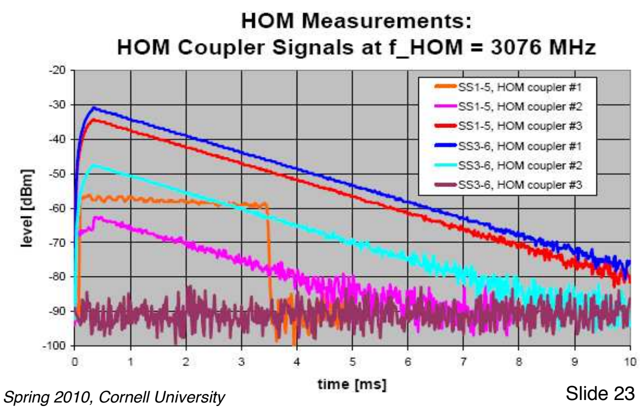


Experimental Setup for Beam Based HOM Measurements at TTF/FLASH

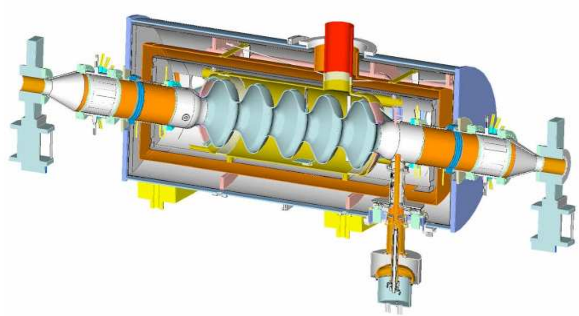


Beam Based HOM Measurements at TTF/FLASH

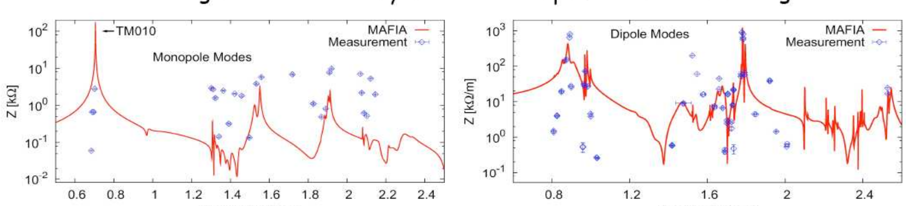




Example 4: BNL ERL Cavity



BNL high current ERL cryomodule concept for electron cooling



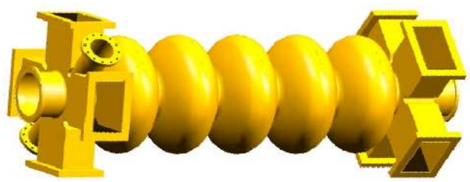
Calculated and Measured HOM spectra. (See Rama Calaga's talk, this working group)

Example 5: TJNAF 1A Cryomodule Design

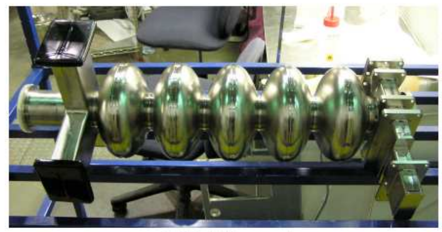
FEL Ampere-class module draft specs.

Voltage	100-120 MV
Length	~10m
Frequency	750 MHz
Beam Aperture	>3"
BBU Threshold	>1A
HOM Q's	<10^4

JLab FEL proposal:

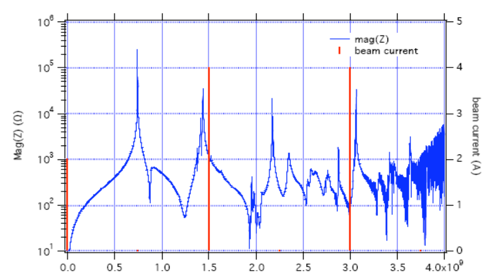


5-cell waveguide damped cavity

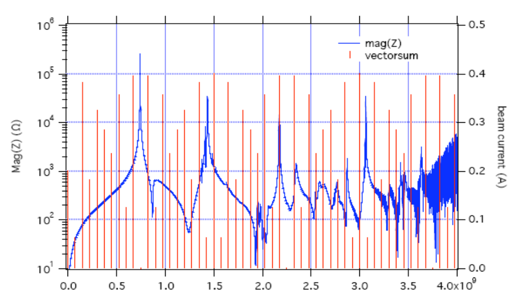


CEBAF cavity

TJNAF 1A Cryomodule Design



Beam spectrum, 750 MHz, 1A 2 pass, 50.2m path length (~22 kW below cutoff)



Beam spectrum, 75 MHz, 100mA 2 pass, 50.2m path length (>5 kW below cutoff?)

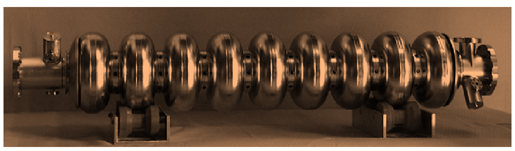
5.2.6 SRF primer

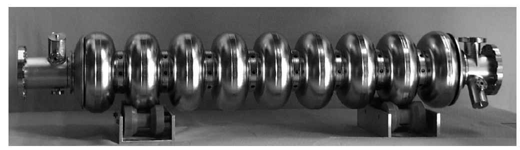
- Why superconducting cavities?

Power dissipated into the wall: $P_{diss} = \frac{1}{2} R_s \int_S \left|\vec{H}\right|^2 ds = \frac{V_{acc}^2}{R/Q \cdot G} R_S$

Example:
- Accelerating voltage: let's take only 1 MV
- Constant R/Q (depends on cell shape): 1000 Ω
- Geometry constant: 270 Ω
- Surface resistance: $R_{s,copper}$ = 10 mΩ, $R_{s,Nb}$ = 10 nΩ

$\Rightarrow P_{diss,copper} = 37$ kW $P_{diss,Nb} = 37$ mW





Minimizing Losses

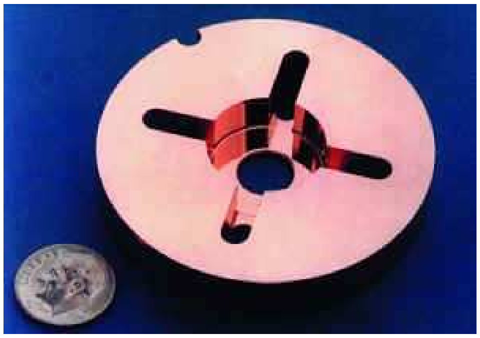
Minimize surface resistance!
⇒ Superconducting cavities.
mΩ (copper) ⇒ nΩ

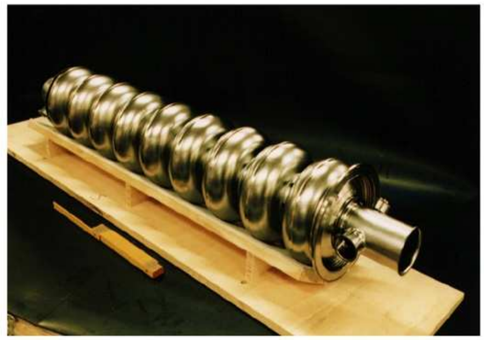
$$P_{diss} = \frac{1}{2} R_s \int_S \left|\vec{H}\right|^2 ds = \frac{V_{acc}^2}{R/Q \cdot G} R_S$$

~~Depend only on cavity geometry.~~
~~⇒ Maximize for copper cavities.~~

Less important for SRF cavities!

RF Cavities for Linacs: NC vs SC





- one cell from NLC
- normal conducting cavity
- copper
- 11.4 GHz
- water cooled

- TESLA
- superconducting cavity
- niobium
- 1.3 GHz
- 2 K (LHe)

Fundamental differences due to difference in wall losses.

Superconducting Cavities: Advantages

- Can operate at a higher voltage in cw operation or long pulse operation because of low losses.
- Power consumption is less. ⇒ Operating cost savings, better conversion of ac power to beam power.
- Power dissipation is not the primary concern! Can tailor design to a given accelerator application.

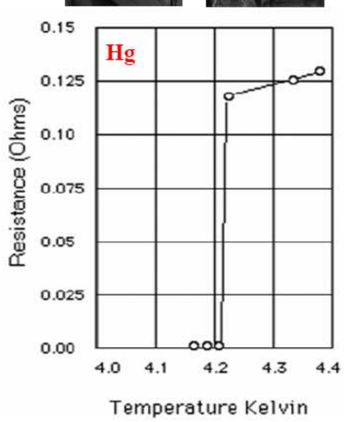
Superconducting Cavities: Advantages (cont.)

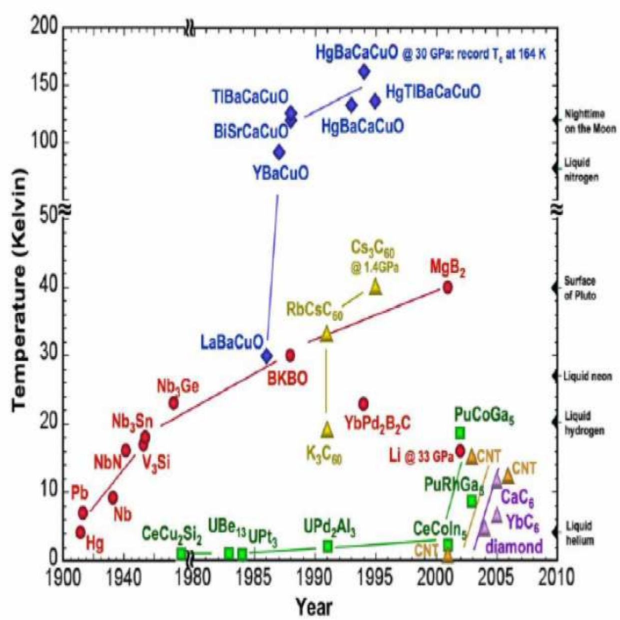
➢ Freedom to adapt design better to the accelerator requirements allows, for example, the beam-tube and the cell iris size to be increased:

- Reduces the interaction of the beam with the cavity. (scales as iris radius$^{2 \text{ to } 3}$) ⇒ The beam quality is better preserved. Important for, e.g., FELs.
- HOMs are removed more easily. Better beam stability. ⇒ More current accelerated. Important for, e.g., B-factories.
- Reduce the amount of beam scraping. ⇒ Less activation in, e.g., proton machines. Important for, e.g., SNS, Neutrino factory.
- Allows more coupling between cells in multicell structures. ⇒ Better energy exchange between cells. Important for e.g., high-energy machines.

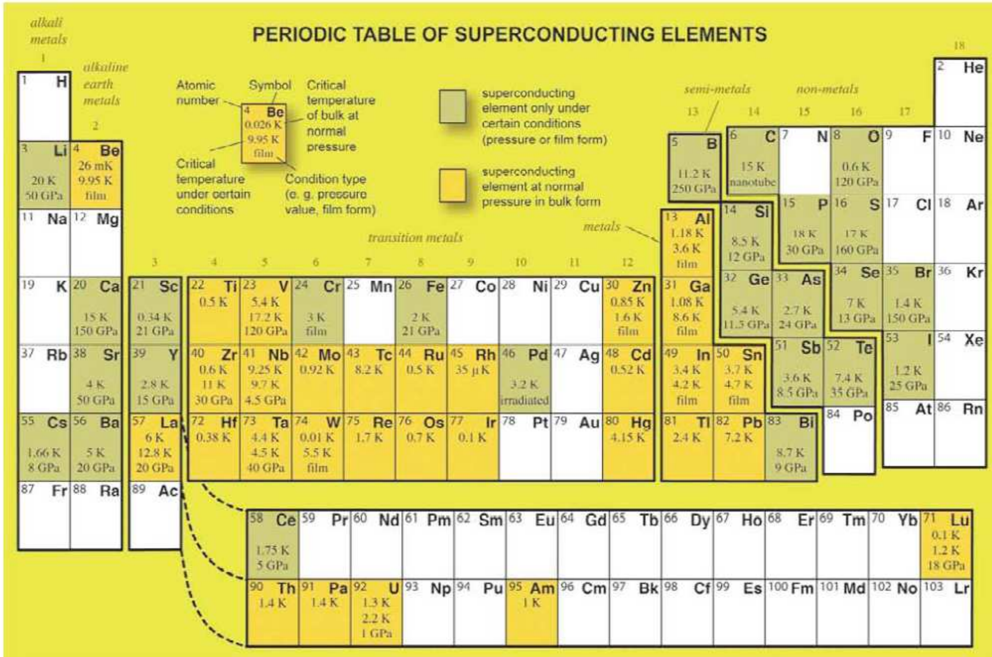
Discovery of superconductivity

Discovered in 1911 by Heike Kamerlingh Onnes and Giles Holst after Onnes was able to liquify helium in 1908. Nobel prize in 1913





Superconducting elements



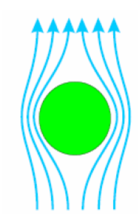
Superconducting state

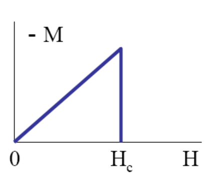
- **The superconducting state is characterized by the critical temperature T_c and field H_c**

$$H_c(T) = H_c(0)\cdot\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

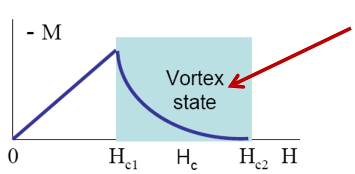
- **The external field is expelled from a superconductor if $H_{ext} < H_c$ for Type I superconductors.**
- **For Type II superconductors the external field will partially penetrate for $H_{ext} > H_{c1}$ and will completely penetrate at H_{c2}**

Superconductor in Meissner state = ideal diamagnetic

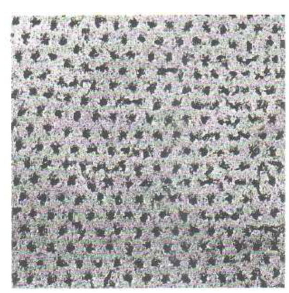




Complete Meissner effect in type-I superconductors



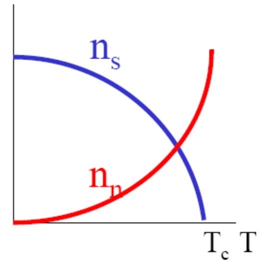
High-field partial Meissner effect in type-II superconductors



- Type-I: Meissner state B = H + M = 0 for H < H_c; normal state at H > H_c
- Type-II: Meissner state B = H + M = 0 for H < H_{c1}; partial flux penetration for H_{c1} < H < H_{c2}; normal state for H > H_{c2}

London equations (1935)

- Two-fluid model: coexisting SC and N "liquids" with the densities $n_s(T) + n_n(T) = n$.
- Electric field E accelerates only the SC component, the N component is short circuited.
- Second Newton law for the SC component: $m d\mathbf{v}_s/dt = e\mathbf{E}$ yields the **first London equation:**



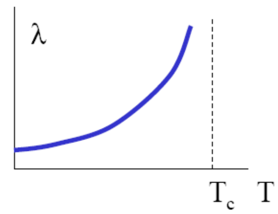
$d\mathbf{J}_s/dt = (e^2 n_s/m)\mathbf{E}$ ⟷ $\mathbf{J} = \sigma\mathbf{E}$

(ballistic electron flow in SC) (viscous electron flow in metals)

- Using the Maxwell equations, $\nabla\times\mathbf{E} = -\mu_0\partial_t\mathbf{H}$ and $\nabla\times\mathbf{H} = \mathbf{J}_s$ we obtain the **second London equation:**

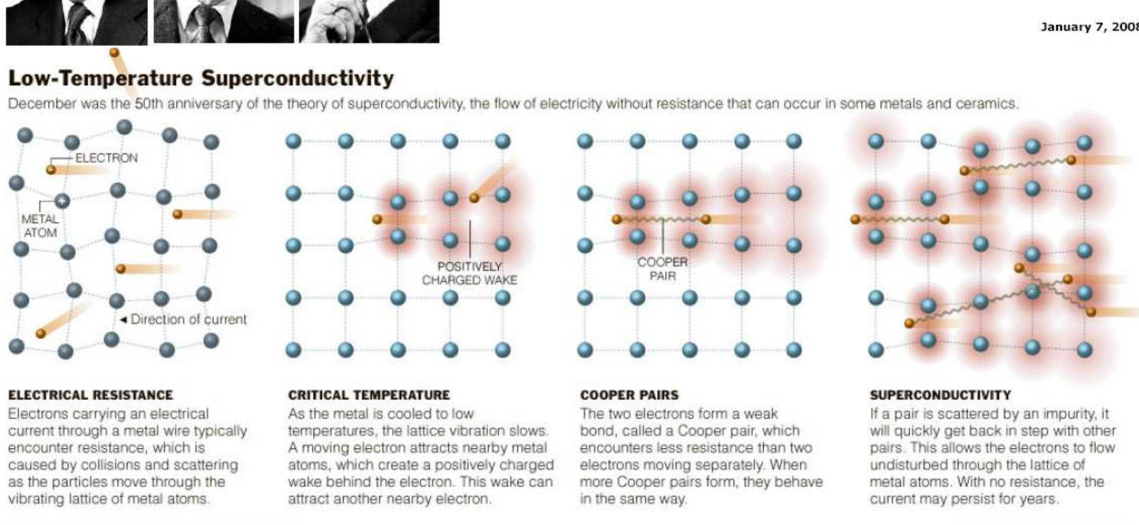
$$\lambda^2\nabla\mathbf{H} - \mathbf{H} = 0$$

- London penetration depth: $\lambda = \left(\dfrac{m}{e^2 n_s(T)\mu_0}\right)^{1/2}$



50+ years of BCS theory

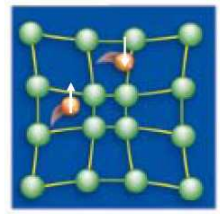
Bardeen-Cooper-Schrieffer (BCS) theory (1957). Nobel prize in 1972



BCS theory

- **Attraction** between electrons with antiparallel momenta **k** and spins due to exchange of lattice vibration quanta (phonons)
- Instability of the normal Fermi surface due to bound states of electron (Cooper) pairs
- Bose condensation of overlapping Cooper pairs in a coherent superconducting state.
- Scattering on electrons does not cause the electric resistance because it would break the Cooper pair

The strong overlap of many Cooper pairs results in the macroscopic phase coherence



What is the phase coherence?

Incoherent (normal) crowd: each electron for itself

Phase-coherent (superconducting) condensate of electrons

GL theory

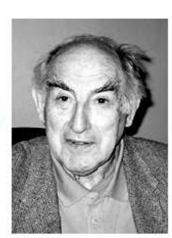
- the linear London equations

$$\frac{\partial \vec{J}_s}{\partial t} = -\frac{\vec{E}}{\lambda^2 \mu_0}, \qquad \lambda^2 \nabla^2 \vec{H} - \vec{H} = 0$$

along with the Maxwell equations describe the electrdynamics of SC at all T if:

- J_s is much smaller than the depairing current density J_d
- the superfluid density n_s is unaffected by current

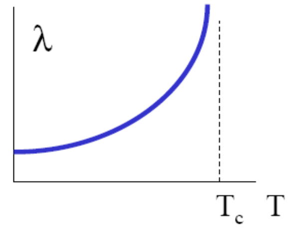
- Generalization of the London equations to **nonlinear** problems
- Phenomenological **Ginzburg-Landau** theory **(1950, Nobel prize 2003)** was developed before the microscopic BCS theory (1957).
- GL theory is one of the most widely used theories



Fundamental lengths and GL parameter

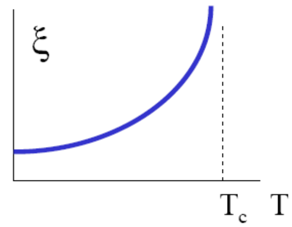
- **Magnetic London penetration depth:**

$$\lambda(T) = \left(\frac{m\beta}{2e^2\mu_0\alpha_0}\right)^{1/2}\sqrt{\frac{T_c}{T_c - T}}$$



- **Coherence length – a new scale of spatial variation of the superfluid density $n_s(r)$ or superconducting gap $\Delta(r)$:**

$$\xi(T) = \left(\frac{\hbar^2}{4m\alpha_0}\right)^{1/2}\sqrt{\frac{T_c}{T_c - T}}$$

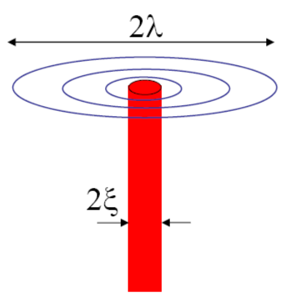


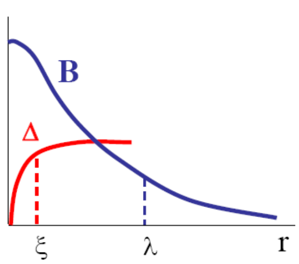
- **The GL parameter $\kappa = \lambda/\xi$ is independent of T.**
- **Critical field $H_c(T)$ in terms of λ and ξ:**

$$B_c(T) = \frac{\phi_0}{2\sqrt{2}\pi\xi(T)\lambda(T)}$$

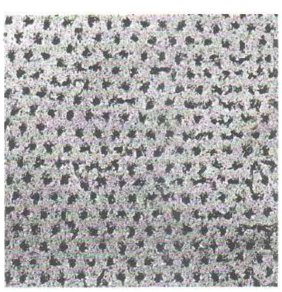
Vortex state between H_{c1} and H_{c2}

Single vortex line





- Small core region $r < \xi$ where $\Delta(r)$ is suppressed
- Region of circulating supercurrents, $r < \lambda$.
- Each vortex carries the flux quantum ϕ_0



Important lengths and fields

- Coherence length ξ and magnetic (London) penetration depth λ

$$B_{c1} = \frac{\phi_0}{2\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right), \qquad B_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}, \qquad B_{c2} = \frac{\phi_0}{2\pi\xi^2}$$

Type-II superconductors: $\lambda/\xi > 1/\sqrt{2}$: For clean Nb, $\lambda \approx 40$ nm, $\xi \approx 38$ nm

What happens if an AC field is applied?

Two fluid model considers both superconducting and normal conducting components:

- At $0 < T < T_c$ not all electrons are bonded into Cooper pairs. The density of *unpaired,* "normal" electrons is given by the Boltzman factor

$$n_{\text{normal}} \propto \exp\left(-\frac{\Delta}{k_B T}\right)$$

where 2Δ is the energy gap around Fermi level between the ground state and the excited state.

- Cooper pairs move without resistance, and thus dissipate no power. In DC case the lossless Cooper pairs short out the field, hence the normal electrons are not accelerated and the SC is lossless even for $T > 0$ K.
- The Cooper pairs do nonetheless have an inertial mass, and thus they cannot follow an AC electromagnetic fields instantly and do not shield it perfectly. A residual EM field remains and acts on the unpaired electrons as well, therefore causing power dissipation.
- We expect the surface resistance to drop exponentially below T_c.
- For the nearly-free electron model

$$\mathbf{j} = \sigma \mathbf{E} = \frac{n_n e^2 \tau}{m} \mathbf{E}$$

where τ is the average time between collisions.

- Between scattering events the electrons gain velocity $\Delta \mathbf{v} = \frac{-e\mathbf{E}\tau}{m}$

Current in two-fluid model

- To calculate the surface impedance of a superconductor, one must take into account the "superconducting" electrons n_s in the two-fluid model
- There is no scattering, thus $\mathbf{j}_s = -n_s e \mathbf{v}$ and one can get the first London equation

$$m\frac{\partial \mathbf{v}}{\partial t} = -e\mathbf{E} \quad \Rightarrow \quad \frac{\partial \mathbf{j}_s}{\partial t} = \frac{n_s e^2}{m}\mathbf{E}$$

- In an RF field one gets

$$\mathbf{j}_s = -i\frac{n_s e^2}{m\omega}\mathbf{E} = -i\sigma_s \mathbf{E} \quad \text{or} \quad \mathbf{j}_s = \frac{-i}{\omega \mu_0 \lambda_L^2}\mathbf{E}$$

- Notice that the effective scattering time for a superconductor is the RF period divided by 2π.
- The total current is simply a sum of currents due to two "fluids":

$$\mathbf{j} = \mathbf{j}_n + \mathbf{j}_s = (\sigma_n - i\sigma_s)\mathbf{E}$$

- Thus one can apply the same treatment to a superconductor as was used for a normal conductor before with the substitution of the newly obtained conductivity.

Surface impedance of superconductors

- The surface impedance

$$Z_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}(1+i) \Rightarrow \sqrt{\frac{\omega\mu_0}{2(\sigma_n - i\sigma_s)}}(1+i)$$

- The penetration depth

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}} \Rightarrow \frac{1}{\sqrt{\pi f \mu_0(\sigma_n - i\sigma_s)}}$$

- Note that $1/\omega$ is of the order of 100 ps whereas the relaxation time for normal conducting electrons if of the order of 10 fs. Also, $n_s >> n_n$ for $T << T_c$, hence $\sigma_n << \sigma_s$.
- Then

$$\delta \approx (1+i)\lambda_L \left(1 + i\frac{\sigma_n}{2\sigma_s}\right) \quad \text{and} \quad H_y = H_0 e^{-x/\lambda_L} e^{-ix\sigma_n/2\sigma_s\lambda_L}$$

- The fields decay rapidly, but now over the London penetration depth, which is much shorter than the skin depth of a normal conductor.
- For the impedance we get

$$Z_s \approx \sqrt{\frac{\omega\mu_0}{\sigma_s}}\left(\frac{\sigma_n}{2\sigma_s} + i\right) \qquad X_s = \omega\mu_0\lambda_L \qquad R_s = \frac{1}{2}\sigma_n\omega^2\mu_0\lambda_L^3$$

BCS surface resistivity

- Surface impedance

$$Z_s \approx \sqrt{\frac{\omega\mu_0}{\sigma_s}}\left(\frac{\sigma_n}{2\sigma_s} + i\right) \qquad X_s = \omega\mu_0\lambda_L \qquad R_s = \frac{1}{2}\sigma_n\omega^2\mu_0\lambda_L^3$$

- One can easily show that $X_s >> R_s \rightarrow$ the superconductor is mostly reactive.
- The surface resistivity is proportional to the conductivity of the normal fluid! That is if the normal-state resistivity is low, the superconductor is more lossy. Analogy: a parallel circuit of a resistor and a reactive element driven by a current source. Observation: lower Q for cavities made of higher purity Nb.
- Calculation of surface resistivity must take into account numerous parameters. Mattis and Bardeen developed theory based on BCS, which predicts

$$R_{BCS} = A\frac{\omega^2}{T} e^{-\left(\frac{\Delta}{k_B T_c}\right)\frac{T_c}{T}},$$

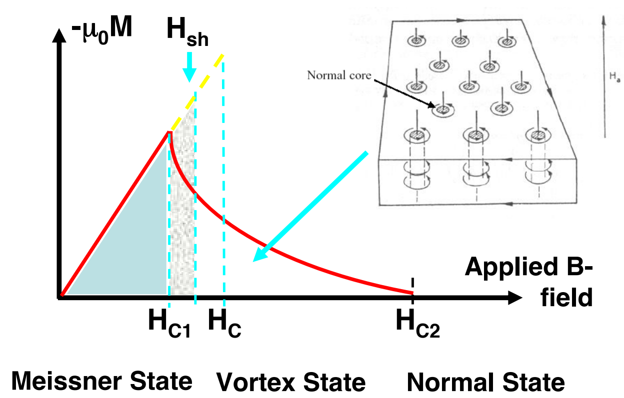
  where A is the material constant.
- While for low frequencies (≤ 500 MHz) it may be efficient to operate at 4.2 K (liquid helium at atmospheric pressure), higher frequency structures favor lower operating temperatures (typically superfluid LHe at 2 K, below the lambda point, 2.172 K).
- Approximate expression for Nb:

$$R_{BCS} \approx 2\times10^{-4}\left(\frac{f[\text{MHz}]}{1500}\right)^2 \frac{1}{T} e^{\left(\frac{-17.67}{T}\right)} [\text{Ohm}]$$

Critical Magnetic Field

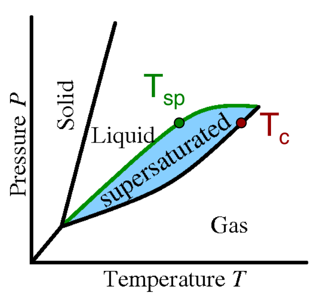
- Critical magnetic RF field limits maximum achievable field in a SRF cavity.
- But: What is the critical RF field?
- Niobium: Weak type II superconductor
- Measured: Meissner state can persist meta-stably above H_{c1} in RF fields (superheating field H_{sh})

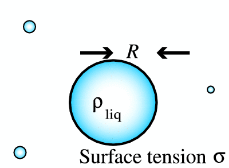
Type II Superconductor



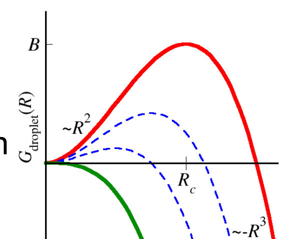
Metastability and Nucleation

Example of metastability: Raindrops: the Liquid-Gas Transition





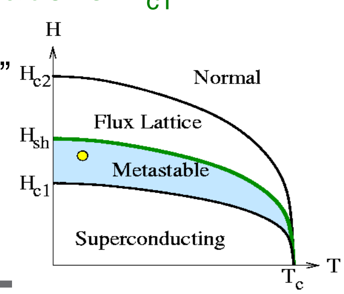
Metastable
energy barrier B
droplet nucleation
R^2 surface tension cost
R^3 bulk energy gain



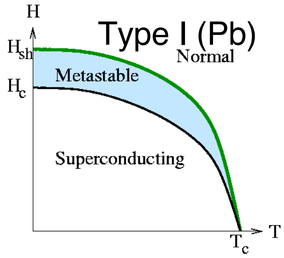
Gas phase metastable for $T_c > T > T_{sp}$, spinodal temperature

Superconductors: Flux penetration delayed above H_{c1}:

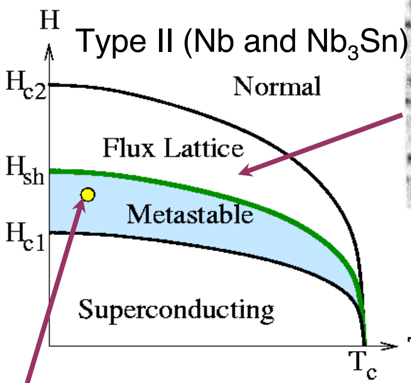
-> Flux penetration only above the "Superheating" Field > H_{c1} (like 110% humidity)

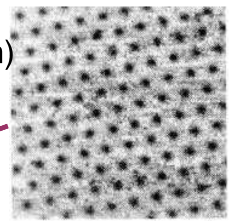


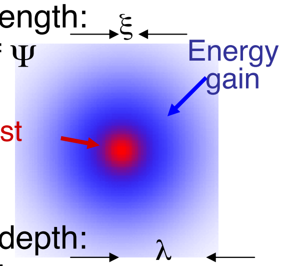
Superconductors and magnetic fields



What's the superheating field?





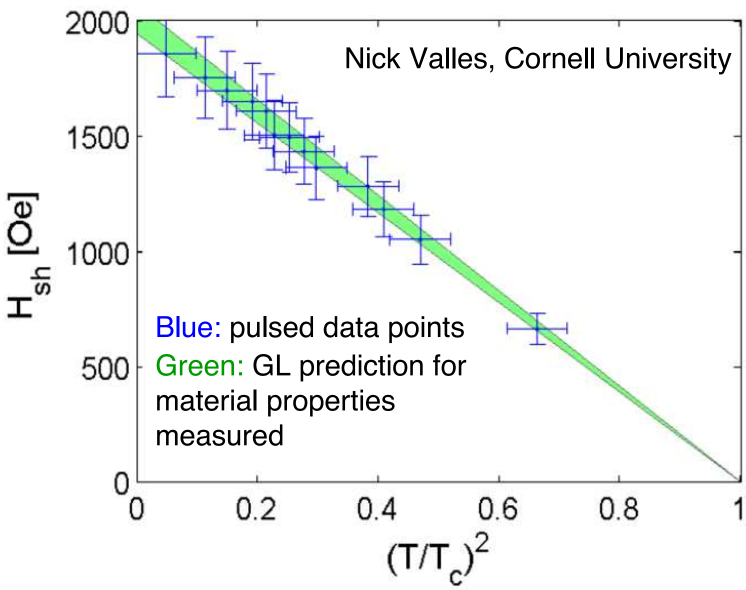


Type II superconductors

- $\lambda > \xi$
- Magnetic flux lattice $H > H_{c1}$

RF cavity operating conditions already above H_{c1}

Our result: H_{sh}(T) of Niobium with $\kappa = 3.5$



- Within ± 10% error bars:

$$H_{sh} \propto \left[1-\left(\frac{T}{T_c}\right)^2\right]$$

down to 1.6 K

- Slop is in very good agreement with prediction from GL theory for material properties measured (κ= 3.5)

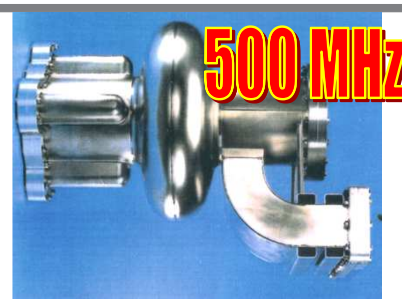
Why Nb?

	Type	T_c	H_{c1}	H_c	H_{c2}	Fabrication
	-	K	Oe	Oe	Oe	-
Nb	II	9.25	1700	2060	4000	bulk, film
Pb	I	7.20	-	803	-	electroplating
Nb_3Sn*	II	18.1	380	5200	~25000	film
MgB_2	II	39.0	300	4290		film
Hg	I	4.15	-	411/339	-	-
Ta	I	4.47	-	829	-	-
In	I	3.41	-	281.5	-	-

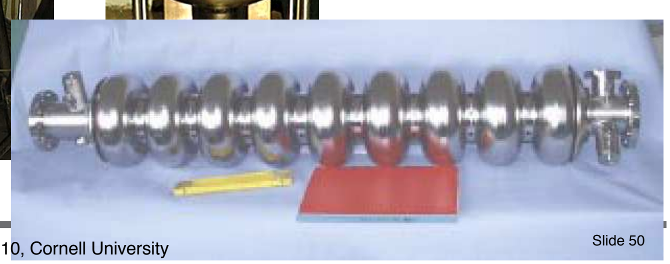
) Other compounds with the same β-tungsten or A15 structure are under investigation as well.

- High critical temperature (cavities with High-T_c sputter coatings on copper have shown much inferior performance in comparison to niobium cavities) → lower RF losses → smaller heat load on refrigeration system.
- High RF critical field, which of the order of H_c. Strong flux pinning associated with high H_{c2} is undesirable as it is coupled with losses due to hysteresis. Hence a 'soft' superconductor must be used.
- Good formability is desirable for ease of cavity fabrication. Alternative is a thin superconducting film on a copper substrate.
- Pure niobium is the best candidate, although its critical temperature Tc is only 9.25 K, and the superheating field about 200 mT. Nb_3Sn with a critical temperature of 18.1 K looks more favorable at first sight, however the gradients achieved in Nb_3Sn coated niobium cavities so far were always below 15 MV/m, probably due to grain boundary effects in the Nb_3Sn layer. For this reason niobium is the current preferred superconducting material.

Real SRF Cavities



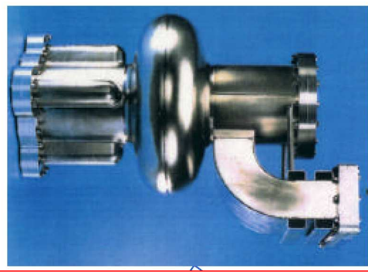
1300 MHz

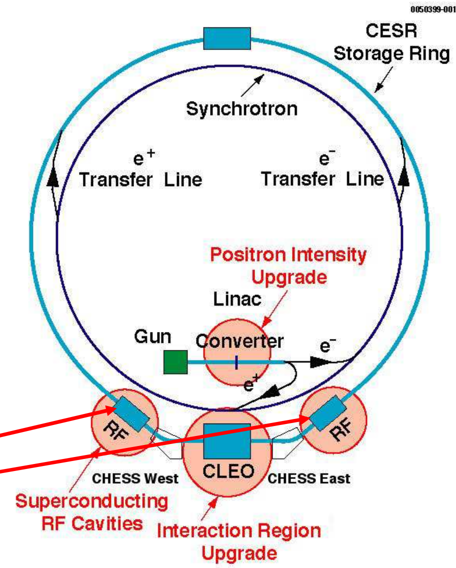


SRF Cavities at Cornell: CESR

Example: CESR

Challenge is to store high currents stably (ampere) rather than achieve very high energy

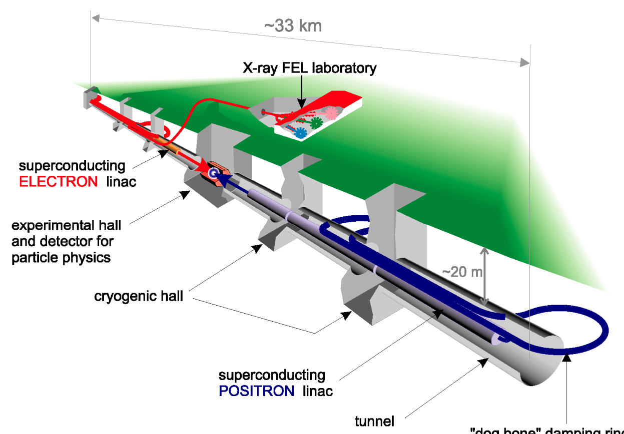




SRF Cavities: Engine for Accelerators

Example: ILC

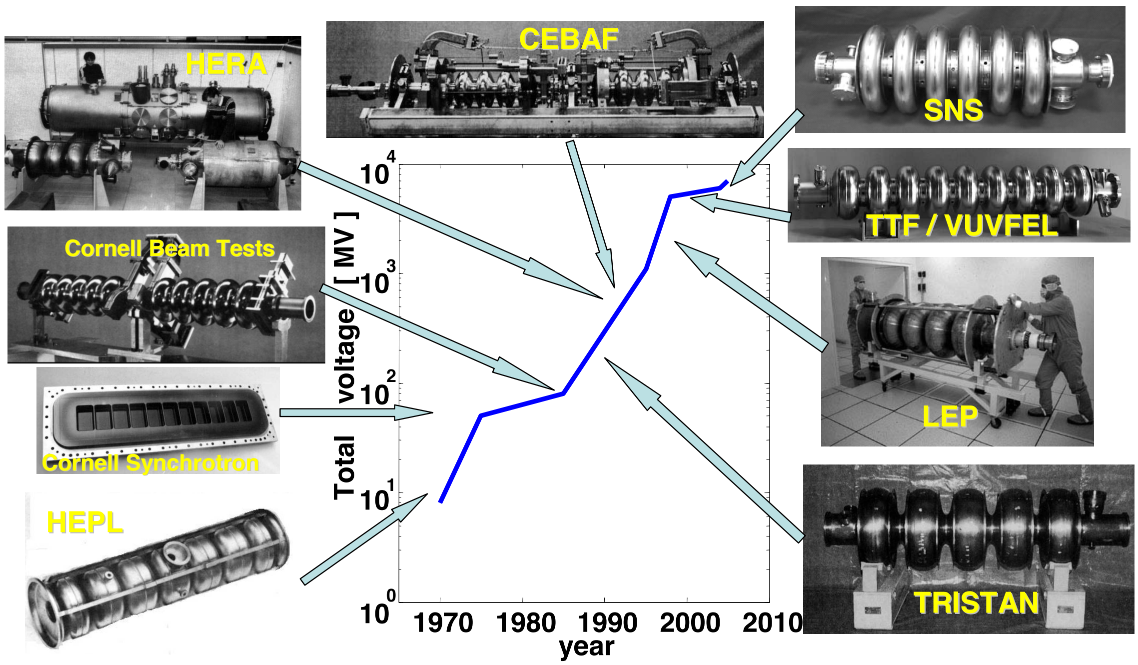
Challenge is to reach very high energy while maintaining good beam quality!



>20,000 cavities!

500 GeV cm energy

A rapid Growth in SRF Application



A Science makes Science

- SRF for high-energy-physics:
  - TRISTAN, HERA, CESR, LEP, SPS, KEK-B
- SRF for nuclear science:
  - CEBAF, ATLAS, SBSL, Florida State U., PIAVE, JAERI, New Delhi, CEN Saclay, Australian National U., U. Of Washington, …
- SRF for neutron sources:
  - SNS
- SRF for Free-Electron-Lasers:
  - DESY VUV-FEL, TJANF IR-FEL, ELBE, …
- SRF for storage ring light sources:
  - CHESS, Diamond, Canadian LS, Taiwan LS

History of SRF for Accelerators (I)
From a nice technology …

- 1965, Stanford U.: R&D on superconducting cavities starts
- 1968, Cornell: R&D on superconducting cavities starts
- 1975, Cornell Electron Synchrotron: First SRF cavity in a high-energy-physics accelerator
- 1982, CESR: First test of a SRF cavity in a high-energy-physics storage ring.
- 1990, Cornell: First TESLA (International Linear Collider, ILC) workshop
- 1993, Cornell : First ILC multi-cell cavity passes 25 MV/m (TESLA design gradient)

… to the dominating choice of accelerating structure

- 1990 to present, Tristan, CESR, HERA, LEP, KEK-B, …: High-energy-physics accelerators use SRF
- 1994, CEBAF: Operation starts with 310 cavities. Cavity design and R&D by Cornell
- 1999, CESR: First storage ring runs entirely on SRF cavities.
- 2000 to present: Storage ring light sources are using the CESR SRF cryostat design (Taiwan, Canada, England, China)
- 2004: International Technology Recommendation Panel recommends cold SRF technology for International Linear Collider (ILC)
- 2005: First cavity passes 50 MV/m (Cavity design and production by Cornell)

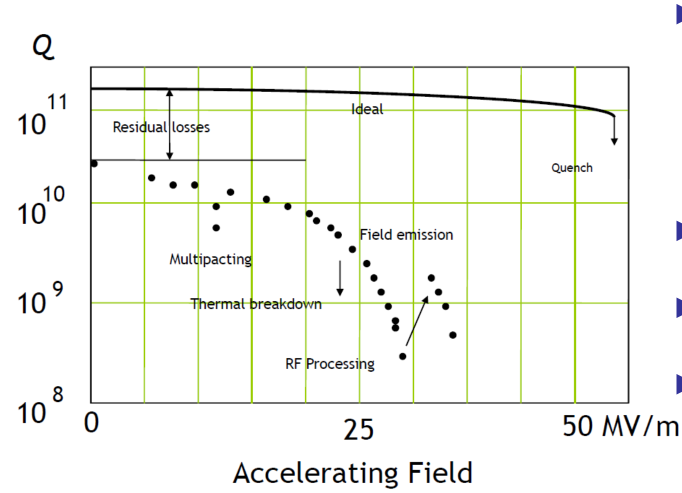
Evolution of SRF Cavity Field Gradients

1975	1985	1990	1995	2005
3 MV/m	6 MV/m	15 MV/m	25 MV/m	>40 MV/m

Limitation:	Electron multiplication	Thermal breakdown	Electron field emission	High field Q-reduction
Solution:	Improved cavity shape	High-purity Nb	High-pressure rinsing	Electropolishing, high and low temperature baking, …

⇨ **Cornell has been prominent in overcoming all these limitations**

Q vs *E*: real world



- It is customary to characterize performance of superconducting cavities by plotting dependence of their quality factor on either electric field (accelerating or peak surface) or peak magnetic field.
- *Q* vs *E* plots is a "signature" of cavity performance.
- At low temperatures measured *Q* is lower than predicted by BCS theory.
- There are several mechanisms responsible for additional losses. Some of them are well understood and preventable, some are still under investigation.

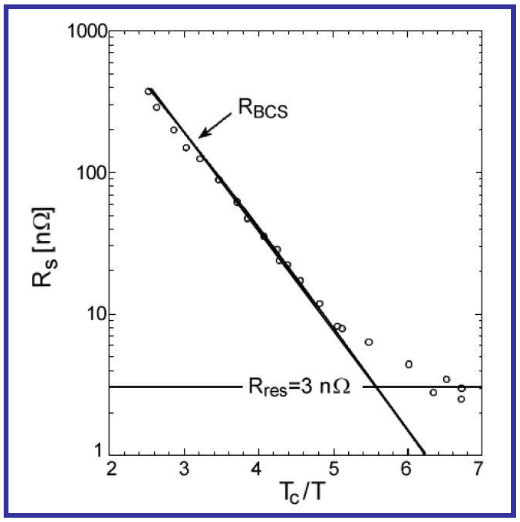
Residual surface resistivity

- At low temperatures the measured surface resistivity is larger than predicted by theory:

$$R_s = R_{BCS}(T) + R_{res}$$

where R_{res} is the temperature independent residual resistivity. It can be as low as 1 nOhm, but typically is ~10 nOhm.

- Characteristics:
  - no strong temperature dependence
  - no clear frequency dependence
  - can be localized
  - not always reproducible
- Causes for this are:
  - magnetic flux trapped in at cooldown
  - dielectric surface contaminations (chemical residues, dust, adsorbates)
  - NC defects & inclusions
  - surface imperfections
  - hydrogen precipitates



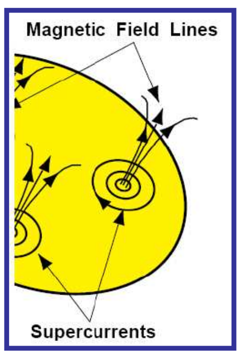
Trapped magnetic flux

- Ideally, if the external magnetic fiels is less than H_{c1}, the DC flux will be expelled due to Meissner effect. In reality, there are lattice defects and other inhomogeneities, where the flux lines may be "pinned" and trapped within material.
- The resulting contribution to the residual resistance is

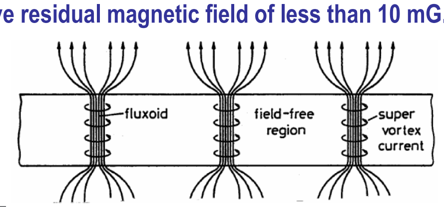
$$R_{mag} = \frac{H_{ext}}{2H_{c2}} R_n$$

- For high purity (RRR=300) Nb one gets

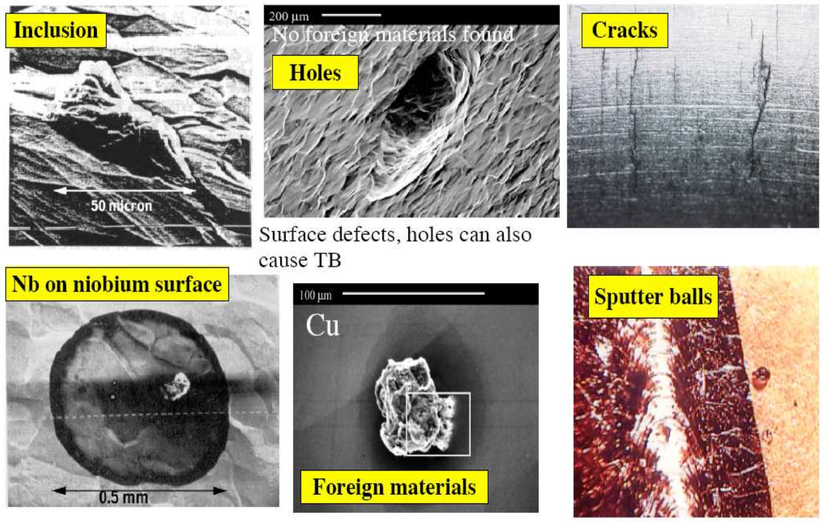
$$R_{mag} = 0.3(n\Omega) H_{ext}(mOe)\sqrt{f(GHz)}$$



- Earth's field is 0.5 G, which produces residual resistivity of 150 nOhm at 1 GHz and $Q_0 < 2\times10^9$
- Hence one needs magnetic shielding around the cavity to reach quality factor in the 10^{10} range.
- Usually the goal is to have residual magnetic field of less than 10 mG.



Examples of surface defects and contamination

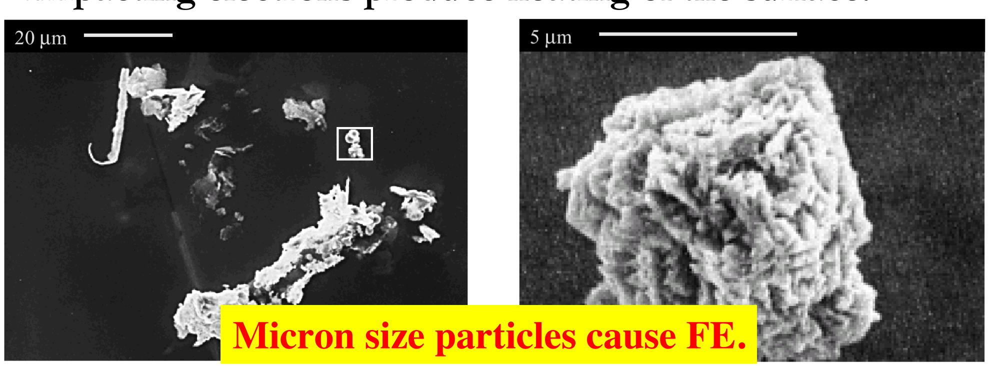


Surface defects can cause:

- Enhanced residual losses
- Premature quench
- Field emission

Electron Field Emission

- Emission of e^- from cavity surface in high (GV/m!) E-fields.
- All emission is associated with (conducting) microscopic particles.
- Sharp features of particles cause electric field enhancement
- Acceleration of electrons drains cavity energy.
- Impacting electrons produce heating of the surface.



Field Emission: Solutions (I)

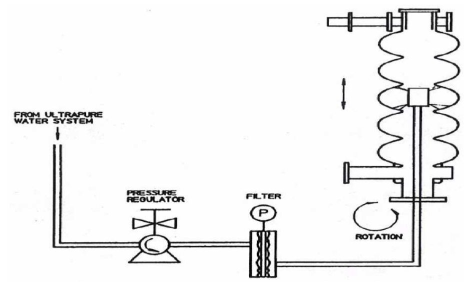
- ***Buffered Chemical Polishing (BCP):***

  ➢ **Etching removes damaged surface layer (100 μm)**

BCP = HF + HNO_3 + H_3PO_4

- ***High Pressure Water Rinsing (HPR):***

  ➢ **Rinsing of cavities with up to 1000 psi ultra-pure water jets removes many particles.**



Field Emission: Solutions (II)

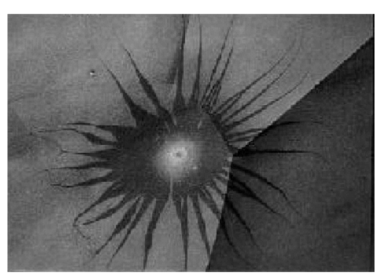
- ***Clean Room Technology:***

  ➢ **All cavities and vacuum components are cleaned and assembled in clean rooms.**

- ***High-Power Processing:***

  ➢ **In some cases applying of high power can cause the destruction of field emitters and improve the cavity performance.**

  ⇨ **Reduction of field emission after the cavity is installed in the accelerator**

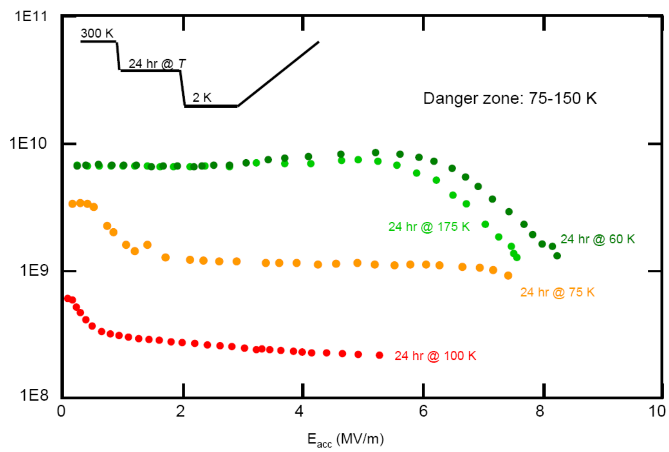


Q disease

The hydrogen dissolved in bulk niobium can under certain conditions during cooldown precipitate as a lossy hydride at the niobium surface. It has poor superconducting properties: Tc = 2.8 K and Hc = 60 Oe. This is known as the "Q-disease". At temperatures above 150 K very high concentration of hydrogen is required to form the hydride phase (10^3 – 10^4 ppm). However, in the temperature range from 75 to 150 K the required hydrogen concentrations drops to as low as 2 wt ppm while its diffusion rate remains significant. This is the danger zone.

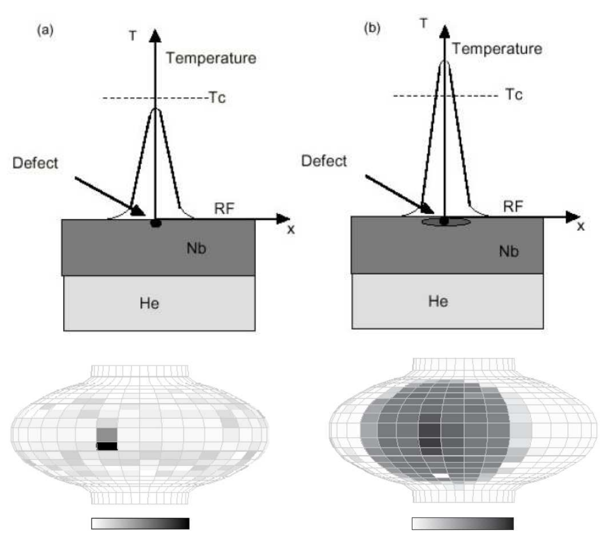
Mitigation:

- rapid cooldown through the danger temperature zone;
- degassing hydrogen by heating the Nb cavity in vacuum of better than 10^{-6} Torr at 600°C for 10 hrs or at 800°C for 1 to 2 hrs.;
- keep the acid temperature below 15°C during chemical etching to minimize hydrogen absorption in the niobium

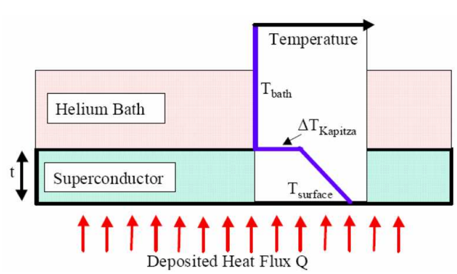


Thermal breakdown

- If there is a localized heating, the temperature of the "hot spot" will increase with field. At a certain field H becomes larger then Hsh(T), causing transition to the normal conducting state and a thermal runaway and the filed collapses (loss of superconductivity or quench).



► Note: The thermal conductivity, the superheating field and the surface resistance of Nb are temperature dependent!

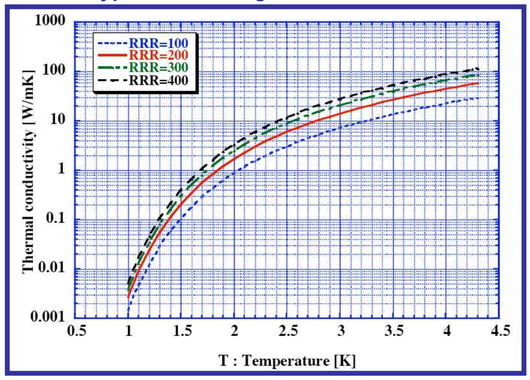


RRR

- Residual Resistivity Ratio (RRR) is a measure of material purity and is defined as the ratio of the resistivity at 273 K (or at 300 K) to that at 4.2 K in normal state.
- High purity materials have better thermal conductivity, hence better handling of RF losses.
- The ideal RRR of niobium due to phonon scattering is 35,000. Typical "reactor grade" Nb has RRR ≈ 30. Nb sheets used in cavity fabrication have RRR ≥ 200.

$$\lambda(4.2K) \approx 0.25 \cdot RRR \quad [W/(m \cdot K)]$$

$$RRR = \left(\sum_i f_i / r_i \right)^{-1}$$



where the f_i denote the fractional contents of impurity i (measured in weight ppm) and the r_i the corresponding resistivity coefficients which are listed in the following table.

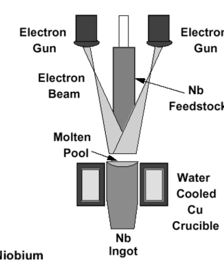
Table II Weight factor r_i of some impurities (see equation (4))

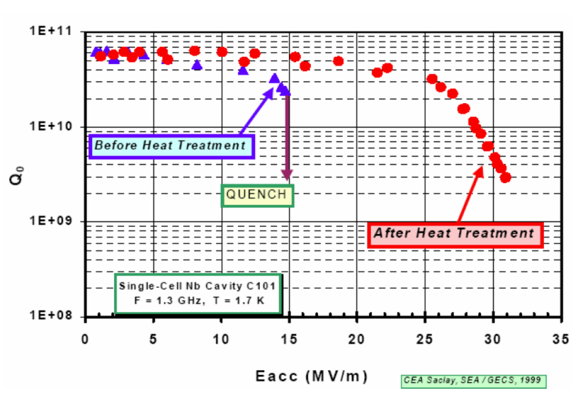
Impurity atom i	N	O	C	H	Ta
r_i in 10^4 wt. ppm	0.44	0.58	0.47	0.36	111

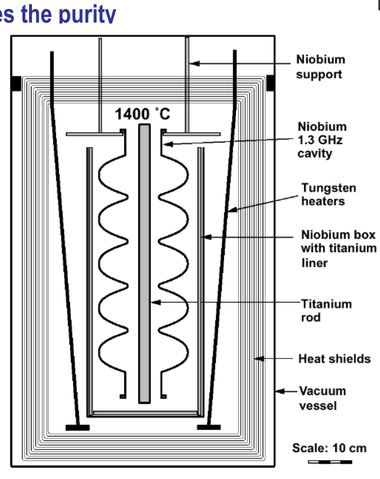
Improving thermal conductivity

There are several ways to improve material purity of Nb:

- Industry can produce high Nb purity by e-beam melting in a vacuum furnace. RRR = 300 – 400 Nb is available.
- Cavities can be post-purified in a vacuum furnace by heating to ~ 1400°C, evaporating Ti on cavity surface (use titanium as getter to capture impurities), upon cooldown etching away the titanium. This doubles the purity (RRR ~ 600 if originally RRR = 300).

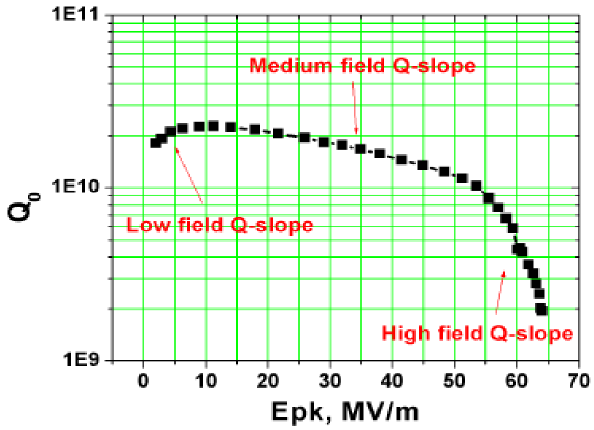






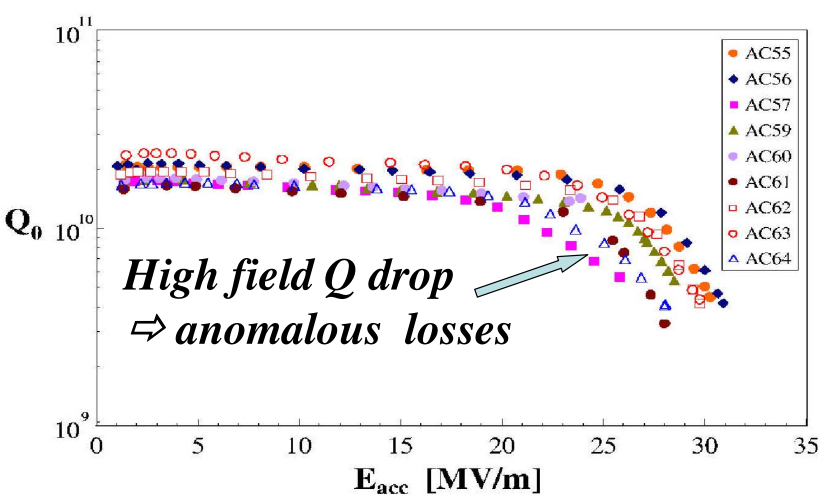
Q-slopes

- The observed *Q* of a niobium cavity shows several “interesting“ features with increasing field.
- As there is still no commonly accepted explanation of physics behind each of the *Q*-slopes
- In the low-field region *Q* surprisingly increases. This does not present any limitation of cavity performance. Mild baking generally enhances the low-field *Q*-slope.
- At medium fields Q gradually decreases, a common feature of all Nb cavities. This is generally attributed to a combination of surface heating and “nonlinear” BCS resistance. Mild baking (100 – 120°C for 48 hrs) usually decreases this *Q*-slope.
- Finally, there is a strong *Q*-drop at the highest fields. This is still highly active area of basic SRF research. Mild baking helps under certain conditions.
- Eventually superconductivity quenches due to a thermal instability at defects or due to exceeding.



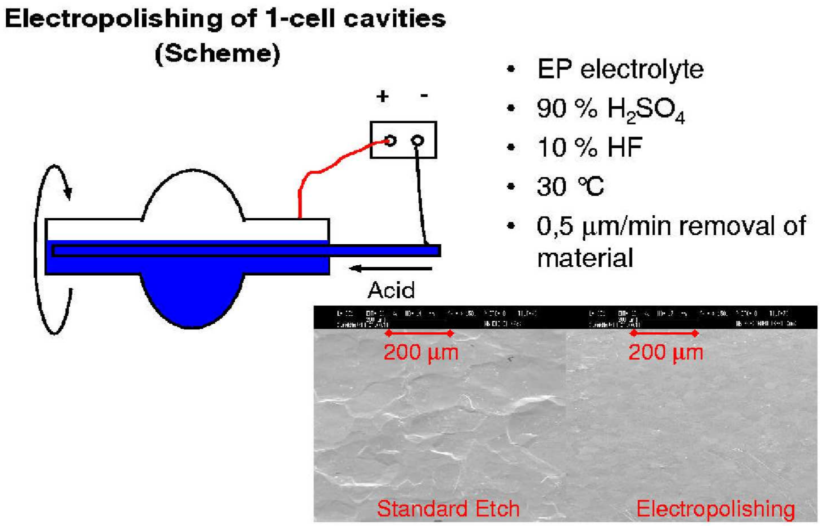
High Field Q-Slope

- High field Q-slope without field-emission!
- Effect not 100% clear yet…



High Field Q-Reduction: Solution

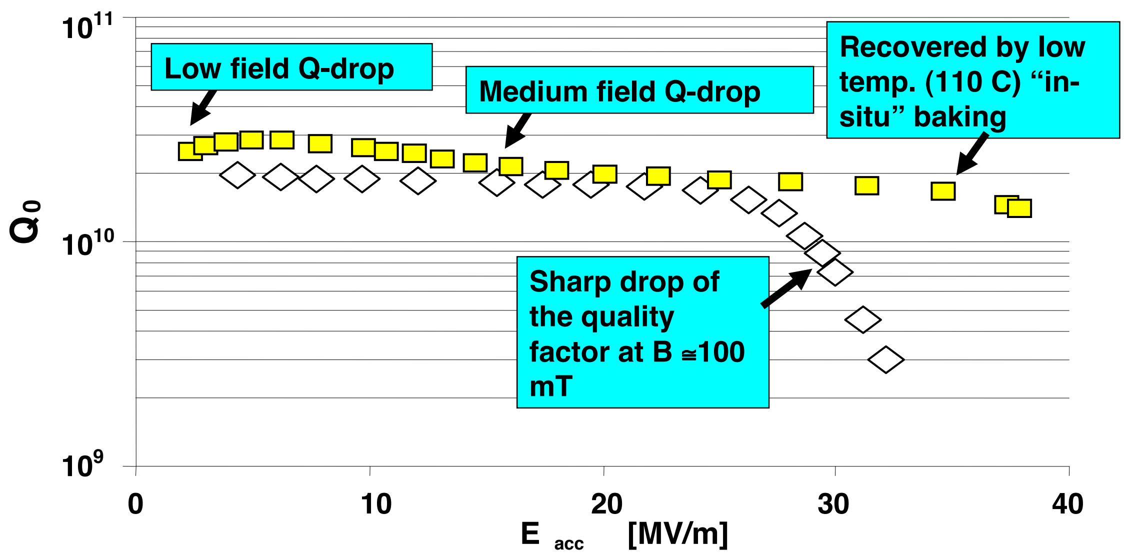
- *Electropolishing of cavities*



- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 µm/min removal of material

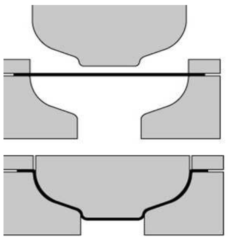
- *Low temperature (110 C) "in-situ" baking*

State of the Art Cavity Performance

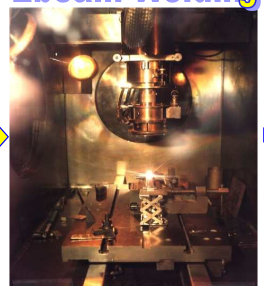


Getting highest fields: A Recipe

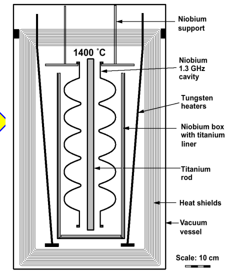
Stamping



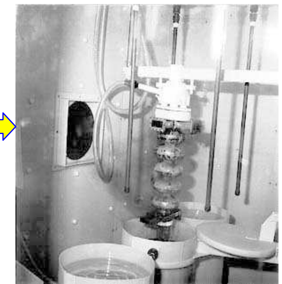
Ebeam Welding



High T bake



Chemical Etching



High Pressure Rinsing

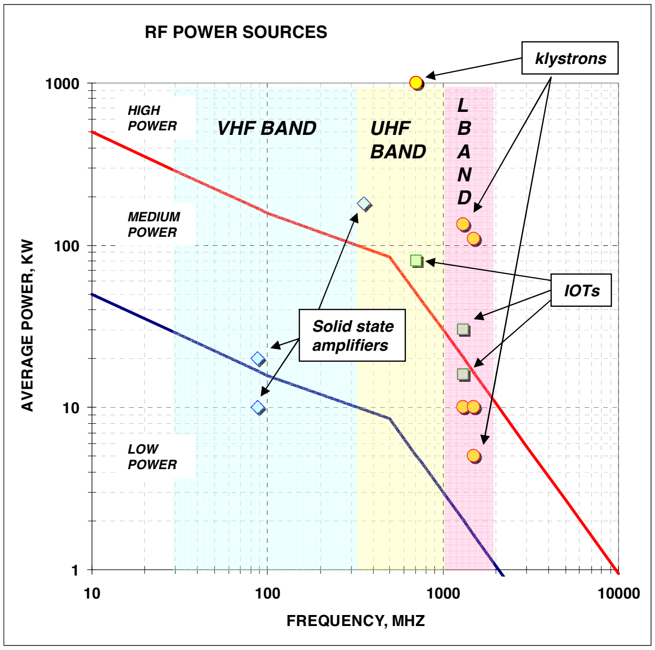
Mounting in Clean Room

110C bake

5.3 RF power sources

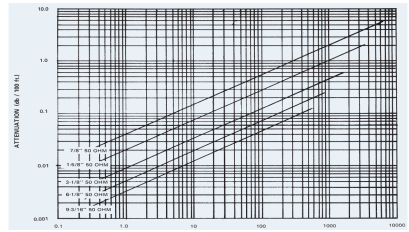
- Overview
- Klystrons
- IOTs
- Solid state amplifiers
- …

High/medium/low RF power



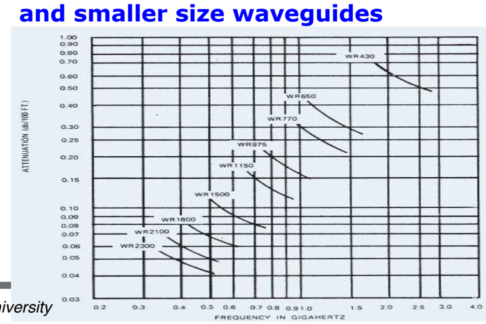
***VHF to UHF frequencies*:**

Coaxial transmission lines, losses increase as √f



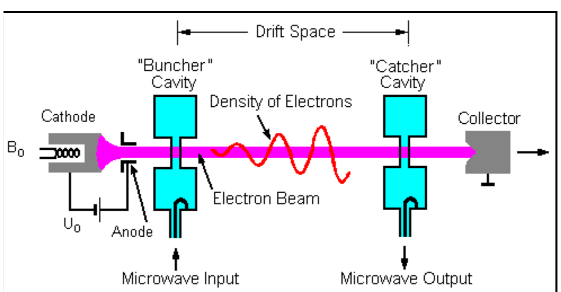
***UHF and higher*:**

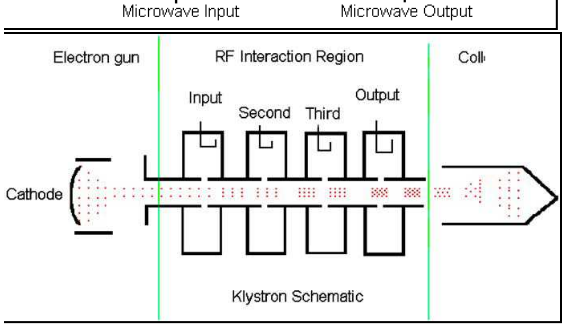
Waveguides, losses increase as ~f^3/2 as in addition to skin depth decrease one has to use smaller and smaller size waveguides



RF power generation options

Klystron

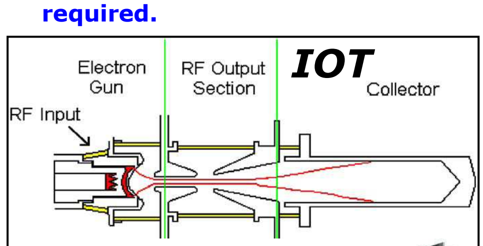


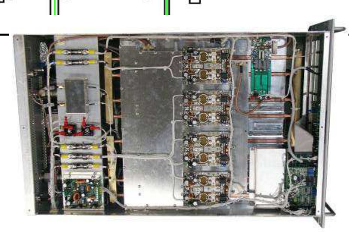


RF power generation at higher frequencies is still dominated by vacuum tubes: klystrons and, with the success in broadcast applications, IOTs.

At lower frequencies tetrodes were traditionally used, but recent progress in solid state technology will make it the technology of choice in VHF and UHF bands, except when very high power is required.

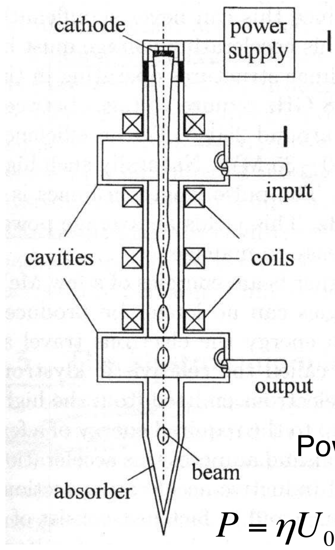
IOT





Solid state

The Klystron



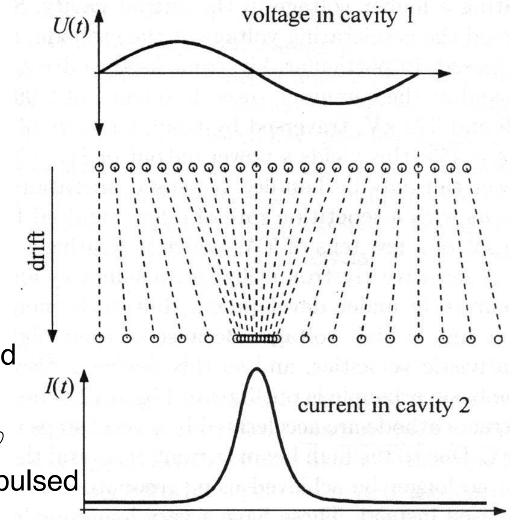
I up to > 10A

Power < 1.5MW

Power < 40MW pulsed

$$P = \eta U_0 I_{\text{beam}} \ , \quad \eta \le 65\%$$

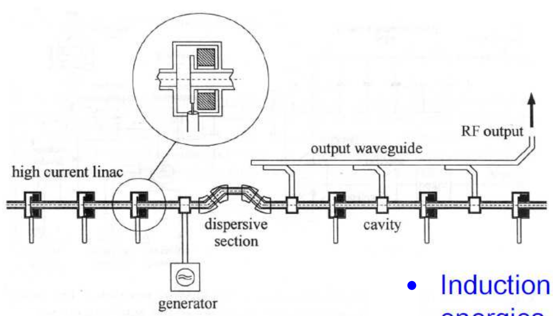
Time of flight bunching

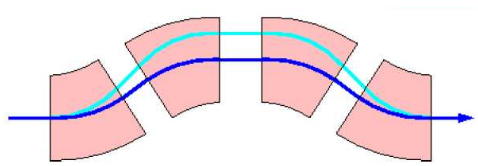


- DC acceleration to several 10kV, 100kV pulsed
- Energy modulation with a cavity
- Time of flight density modulation
- Excitation of a cavity with output coupler

Only works for non-relativistic electrons

Relativistic Klystron

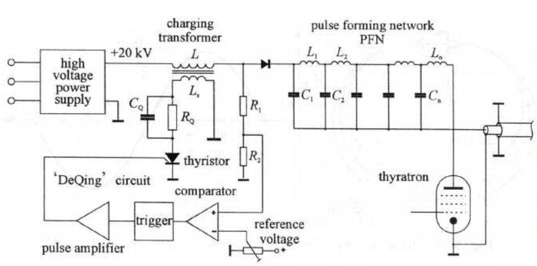




Bunch compressor with dispersion.

- E a few MeV
- I a few 1000A

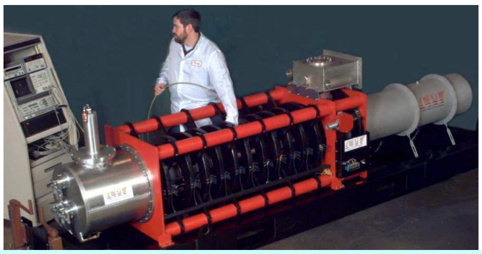
- Induction linac for high currents and low energies.
- A high current low energy beam creates the RF power for a low current high energy beam.



A modulator pulses the Klystron in with the required repetition rate.
DeQing circuit precisely defines the voltage.

Klystrons

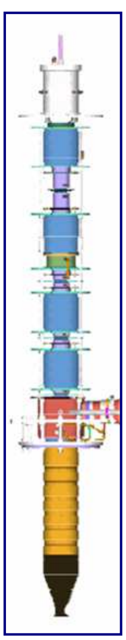
VLK7811W
- **Specifications**
  - 5 kW CW
  - 11.6 kV @ 1.33 A
  - 32.4% efficiency (min)
  - 38 dB gain
  - 4 cavity design
  - Coaxial output
  - Permanent magnet focusing
  - Potted gun



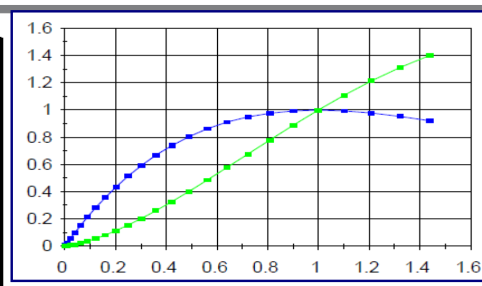
Parameters of *VKP-7952B* klystron (CPI):
- ❑ beam voltage 92 kV @ 17.1 A
- ❑ full power collector
- ❑ max. output power 1000 kW
- ❑ efficiency 65%
- ❑ gain >40 dB
- ❑ bandwidth ±0.7 MHz @ 1 dB

VKL7966A
- 110 kWatts
- 33.5 kV @ 6.5 A
- 1497 MHz
- -1dB Bandwidth 14 MHz
- Saturated Gain 55.5 dB
- Efficiency 51 %

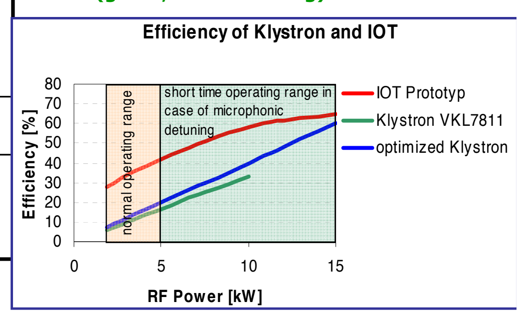
RF power: klystron vs IOT



Klystron	IOT
Electron bunches are formed by velocity modulation from the cavities translated into density modulation in the drift spaces	Density modulation directly from cathode
Several bunching cavities, optional mod anode	Control grid
High gain (> 40 dB): low power drive amplifier	Low gain (~22 dB): high power drive amplifier (expensive)
High efficiency in saturation, which drops rapidly at reduced power	Higher efficiency, which does not drop quickly at reduced power: highly linear device
Longer, expensive device	Shorter, less expensive tube
Can be designed for very high power operation	Output power is limited though R&D for high power tubes are under way

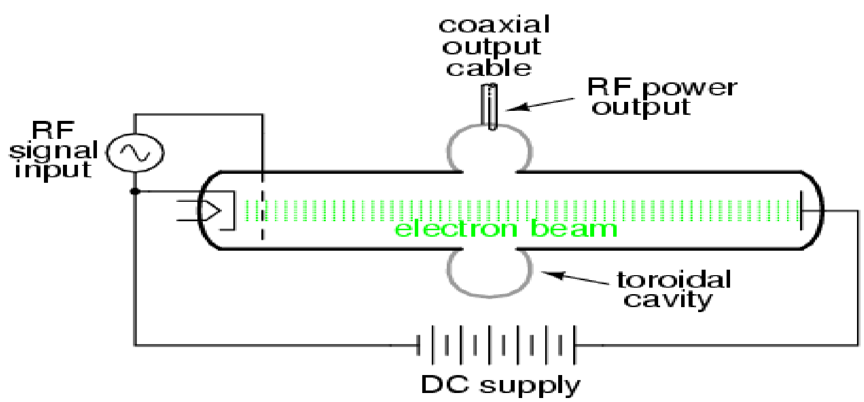


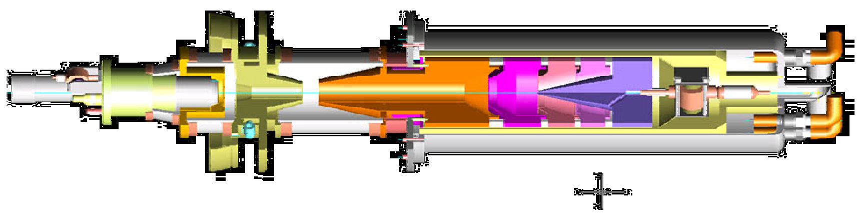
Normalized characteristics of output power (vertical axis) vs. drive power (horizontal axis) for klystrons (blue, saturating) and IOTs (green, not saturating).



Inductive-Output Tubes (IOTs)

The inductive output tube (IOT)





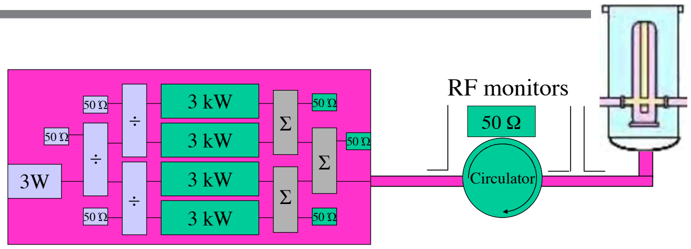
Inductive-Output Tubes (IOTs)

- IOTs have a cathode with a control grid 0.1 mm in front of it like a triode.
- They then use high voltage DC and a magnetic lens to focus a modulated high energy electron beam through a small drift tube like a klystron. This drift tube prevents backflow of electromagnetic radiation.
- The bunched electron beam passes through a resonant cavity, equivalent to the output cavity of a klystron. The electron bunches excite the cavity, and the electromagnetic energy of the beam is extracted by a coaxial transmission line.

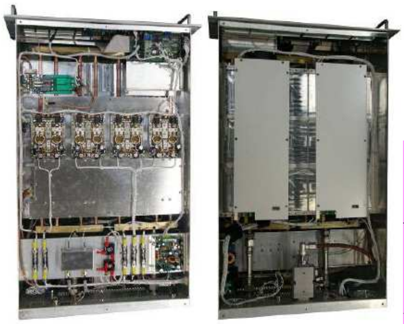
Frequency	1.3GHz
Output Power	16kW
Beam Voltage	<28kV
Efficiency	>60%
Gain	>20dB
Class of operation	B or AB

CPI
- **CW or pulse operation**
- **35kW CW or 80 kW pulse**
-

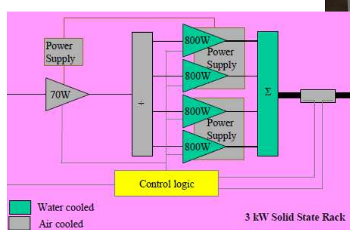
Solid State Amplifier: Example SPIRAL-2 RF system



10 kW amplifier architecture. Circulators and dummy load are outside the amplifier cabinet, at high power level. Green elements are water cooled.



Two 10 kW amplifiers.



SOLEIL solid state HPA

180 kW CW solid state amplifier for SOLEIL storage ring based light source (France)

- **352 MHz**
- **very reliable and stable operation**
- **efficiency ~50%**