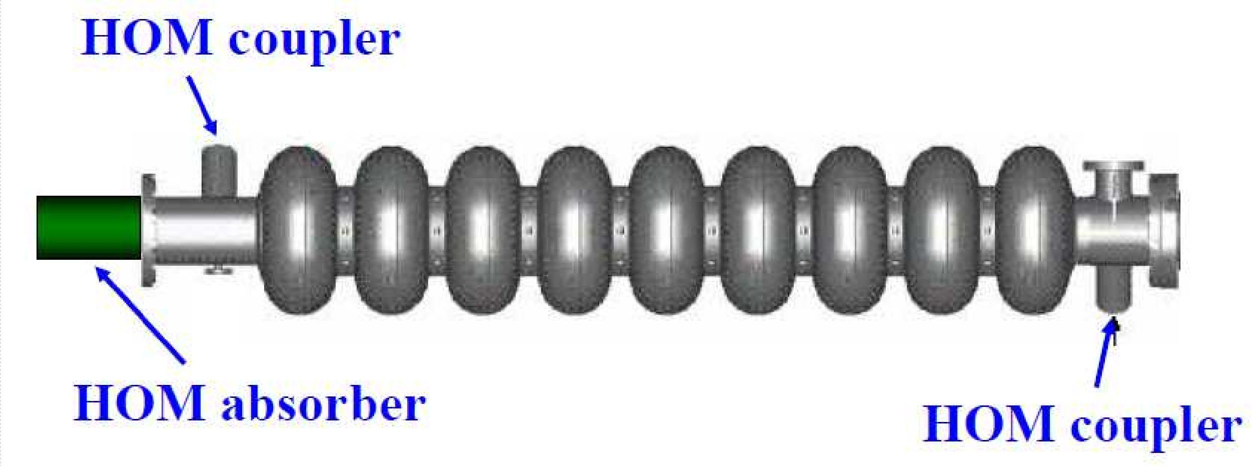
S. Belomestnykh

Superconducting RF for storage rings, ERLs, and linac-based FELs:

- Lecture 10 ***HOM dampers***

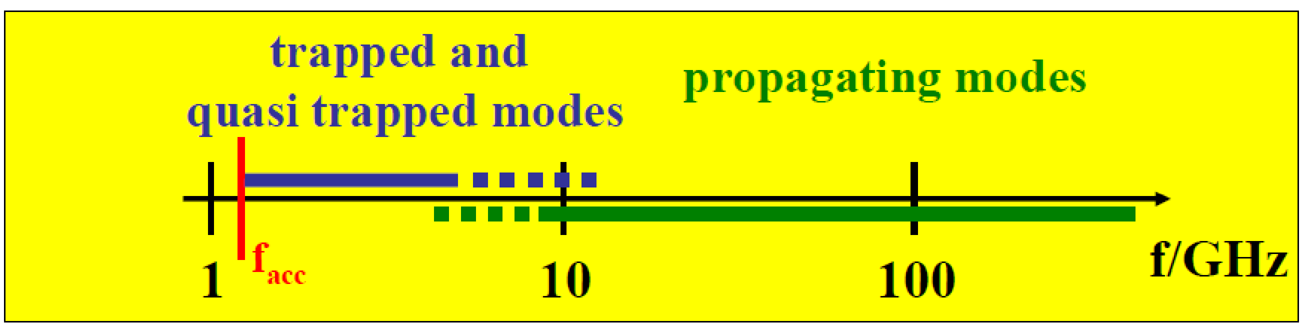
HOM dampers

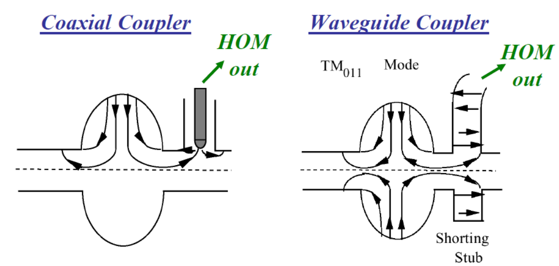
- Extremely low RF losses that make SC cavities so attractive in the first place are a handicap when we consider higher-order modes (HOMs).
- The parasitic interaction of a beam with HOMs can cause additional cryogenic loss, excite multi-bunch instabilities (longitudinal and transverse in storage rings, BBU in linacs and ERLs), lead to emittance growth and bunch-to-bunch energy spread.
- Depending on accelerator type, different levels of damping HOM's quality factors is required: from $10^2 \ldots 10^3$ for storage rings to $10^4 \ldots 10^5$ for some linacs.
- To keep the impedance of HOMs under control, special HOM dampers are usually attached to the beam tubes of SC cavities.



HOM damper types

- From an RF engineer point of view an HOM damper is nothing more than a RF/microwave absorber at the and of a transmission line coupled to the SC cavity via either an aperture or a coupling circuit consisting of lumped elements.
- There are designs using different transmission lines and coupling circuits: beam pipe HOM absorbers (beam pipe ≡ circular waveguide), rectangular waveguide HOM couplers, radial and coaxial line HOM couplers, and loop HOM couplers to a coaxial line.
- Waveguide couplers have a cut-off frequency and therefore do not need a filter to reject the fundamental RF frequency. Thus they are inherently more broad band.
- The cavity beam pipe is frequently opened more to facilitate propagation of the lowest frequency HOMs toward the absorber. The absorber is a section of the beam pipe with a layer of microwave absorbing material (ferrite or ceramics).
- Coaxial and radial lines can transmit TEM waves (hence no cut-off) and therefore HOM couplers based on these lines need special means to reject the fundamental RF. Coaxial loop couplers are more compact than other types and can be tuned to frequencies of trapped modes.



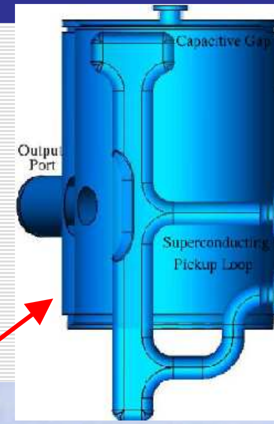


Rejection filter suppresses coupling to the accelerating mode.

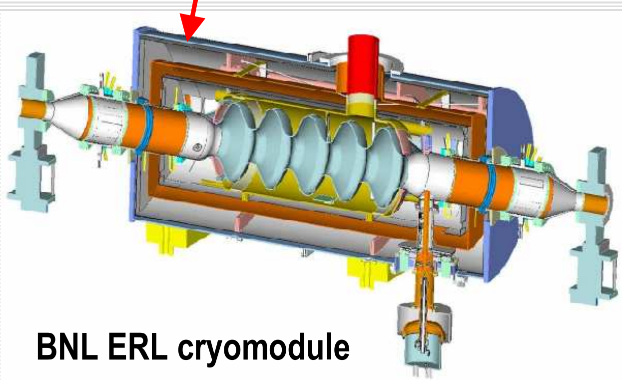
Waveguide cutoff suppresses coupling to the accelerating mode.

HOM extraction/damping

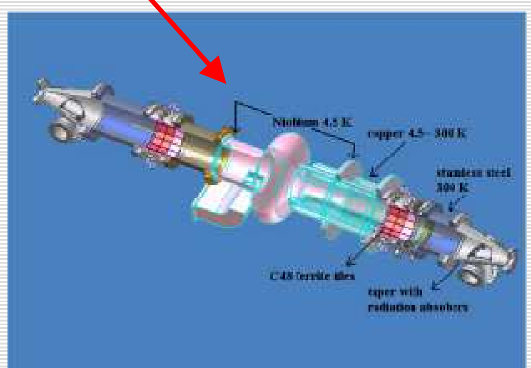
- Loop couplers (several per cavity for different modes/orientations)
- Waveguide dampers
- Beam pipe absorbers (ferrite or ceramic)



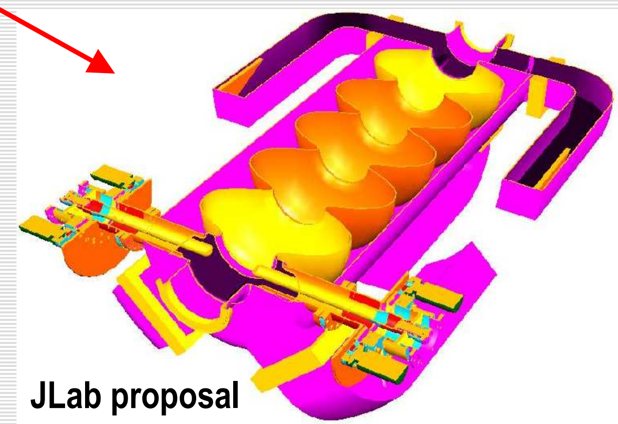
TESLA cavity loop coupler



BNL ERL cryomodule



B-cell beam line components (TLS)

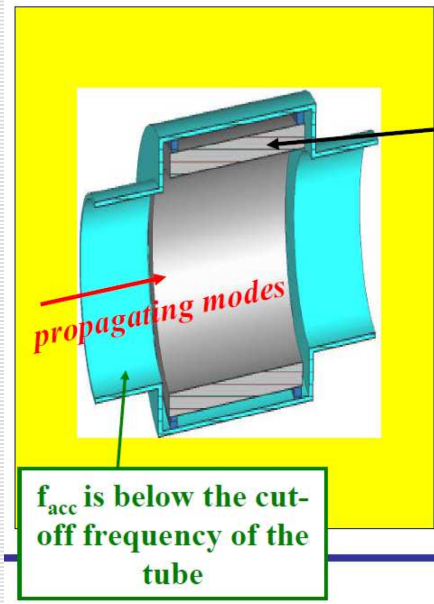


JLab proposal

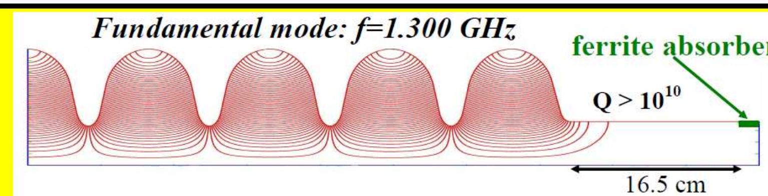
Beam pipe absorbers

BEAM PIPE HOM ABSORBERS

- Originally developed at Cornell and KEK for very high average power absorption.
- Widely used in high-current storage rings, where they operate at RT outside the cryomodule.
- Achieved $Q_{HOM} \approx 10^2 \ldots 10^3$ in single-cell storage ring cavities.
- Cornell developed an HOM load operating at 80 K for ERL cavities with dissipating capacity of ~200 W.
- KEK is also developing beam pipe HOM loads for ERL.
- DESY developed a beam pipe absorber for XFEL to compliment loop HOM couplers.
- Dampers of this type are probably the most efficient, BUT their main disadvantage for linacs is that they occupy real estate along the beam axis and thus reduce the fill factor.



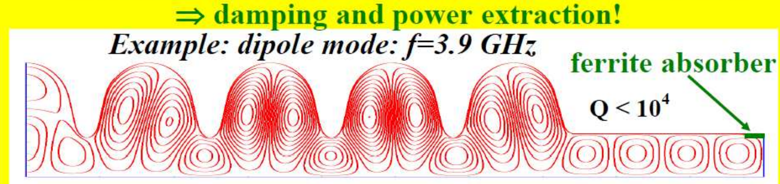
- High frequency modes propagate out the beam pipe.
- RF absorbing material can damp these modes.
- Dissipated power will be intercepted by cooling (water, GHe, LN_2).
- Candidate absorber materials:
  - ferrites (used in CESR HOM load)
  - $Zr_{10}CB_5$ CERADYNE (used for CEBAF HOM load)
  - Mo in AL_2O_3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



- Low field at absorber
  ⇒ no significant damping of the fundamental mode

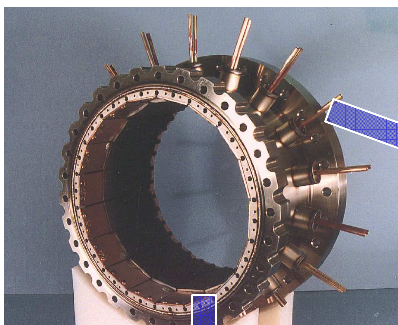
but:

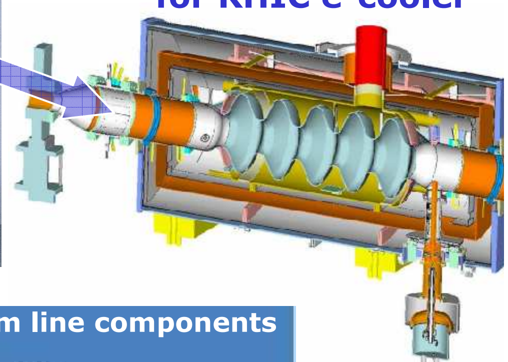
- Propagating modes have higher fields at the absorber
  ⇒ damping and power extraction!



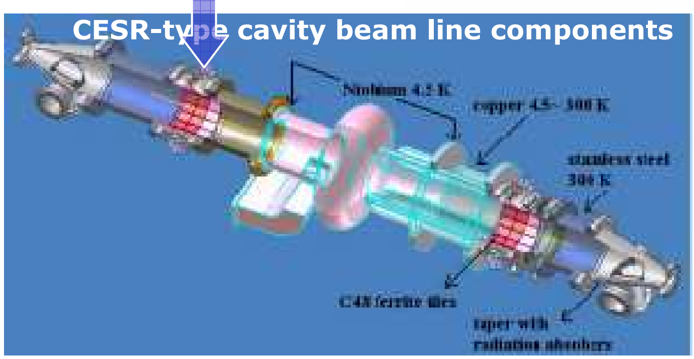
Cornell beam pipe absorbers

- CESR HOM loads
- Ferrite tiles are soldered to water-cooled Elkonite plates, which in turn are mounted inside a stainless steel shell
- CESR-type HOM loads are used at CESR, TLS, CLS, Diamond, SSRF, and BNL e-cooler for RHIC
- Absorbed up to 5.7 kW in operation

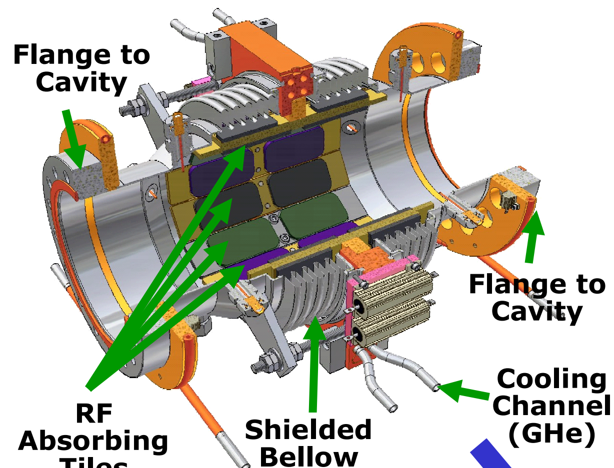


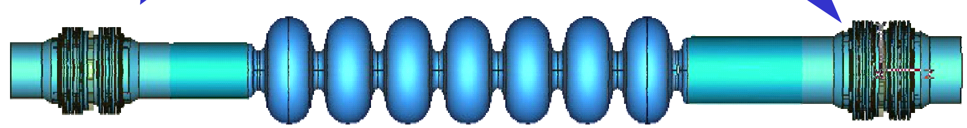


BNL cryomodule for RHIC e-cooler



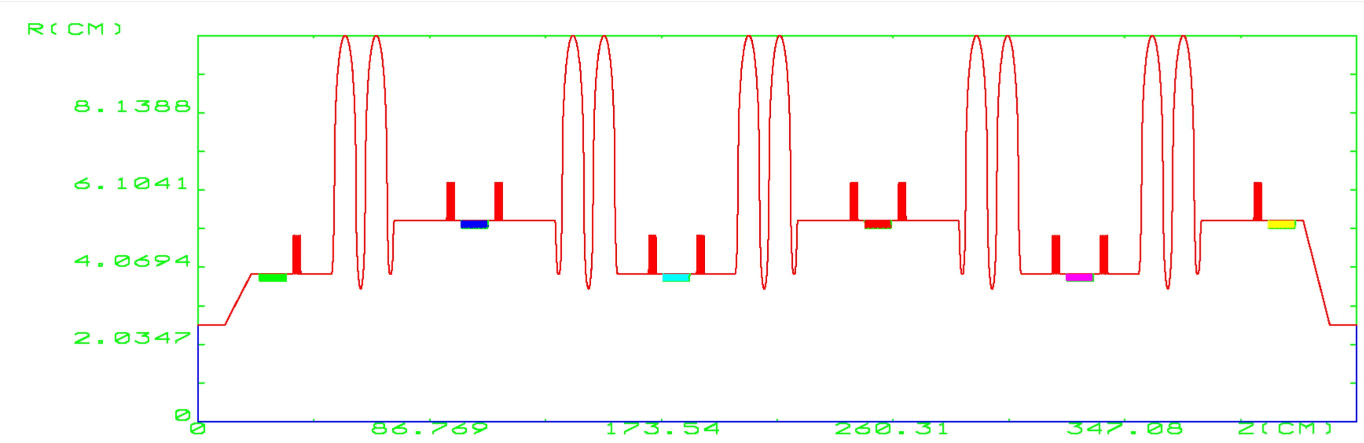
- ERL cavity HOM loads
- Use combination of two different ferrites and lossy ceramics to cover frequency range > 40 GHz
- Operate at 80 K, cooled by cold He gas
- Dissipating capacity of ~200 W

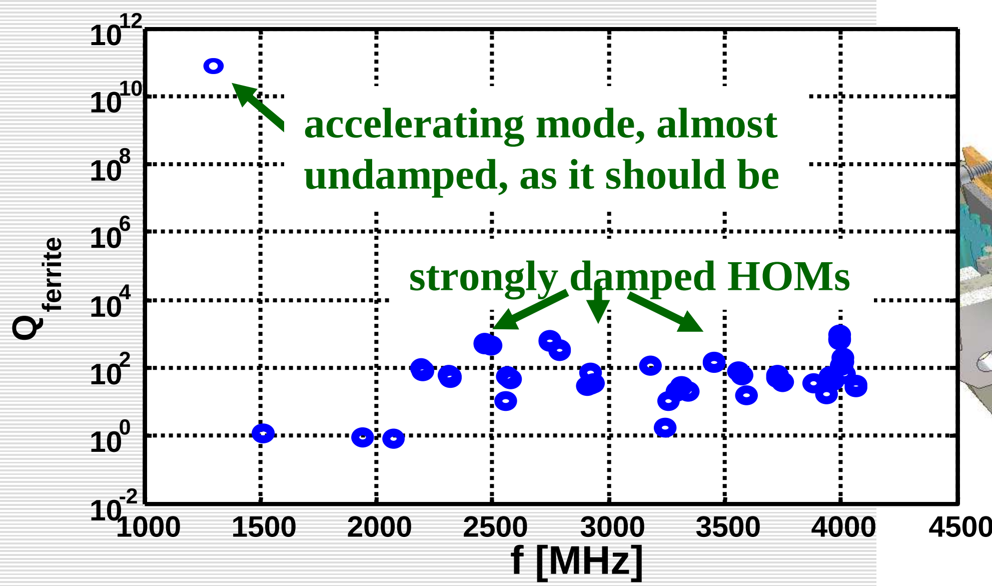


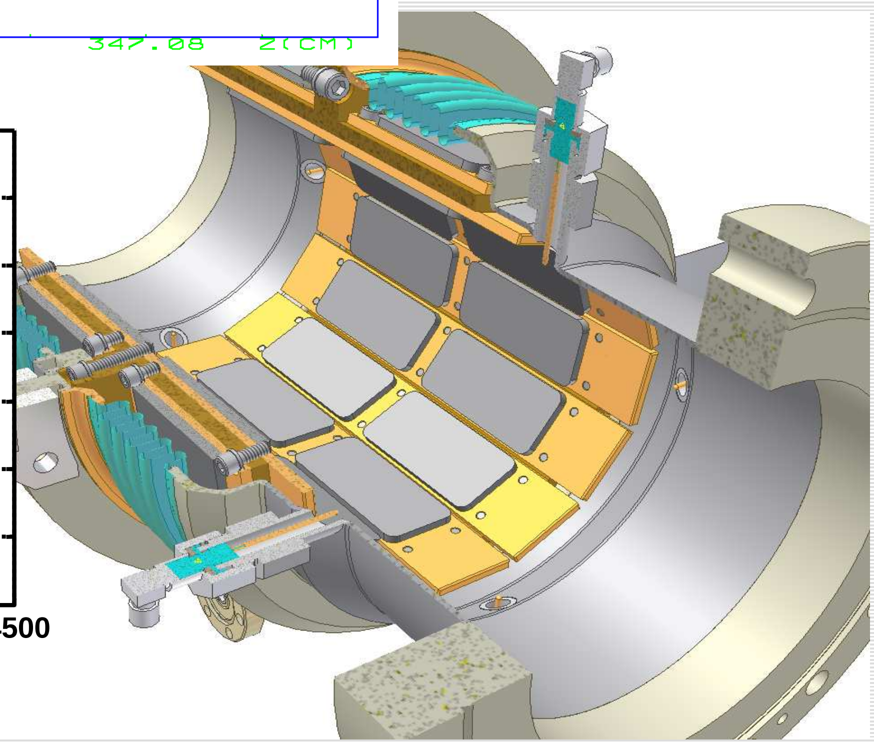


Cornell ERL cavity

HOM extraction/damping in Cornell ERL injector



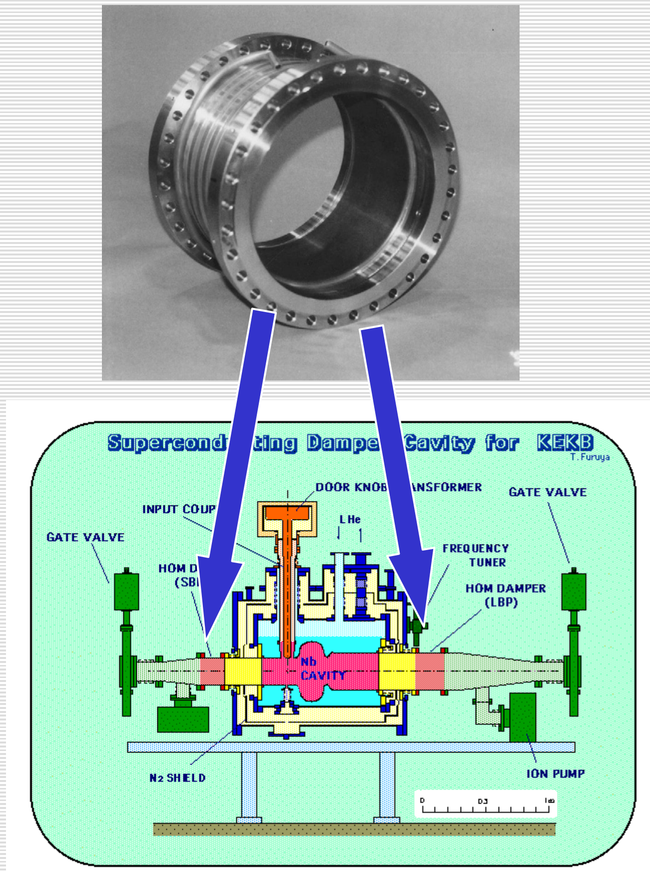




Beam pipe absorbers; KEKB

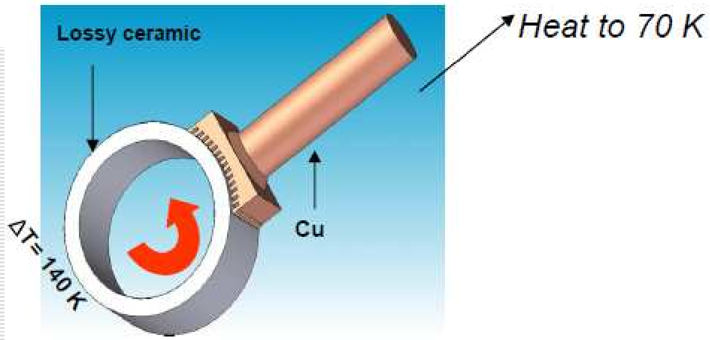
KEKB HOM absorbers

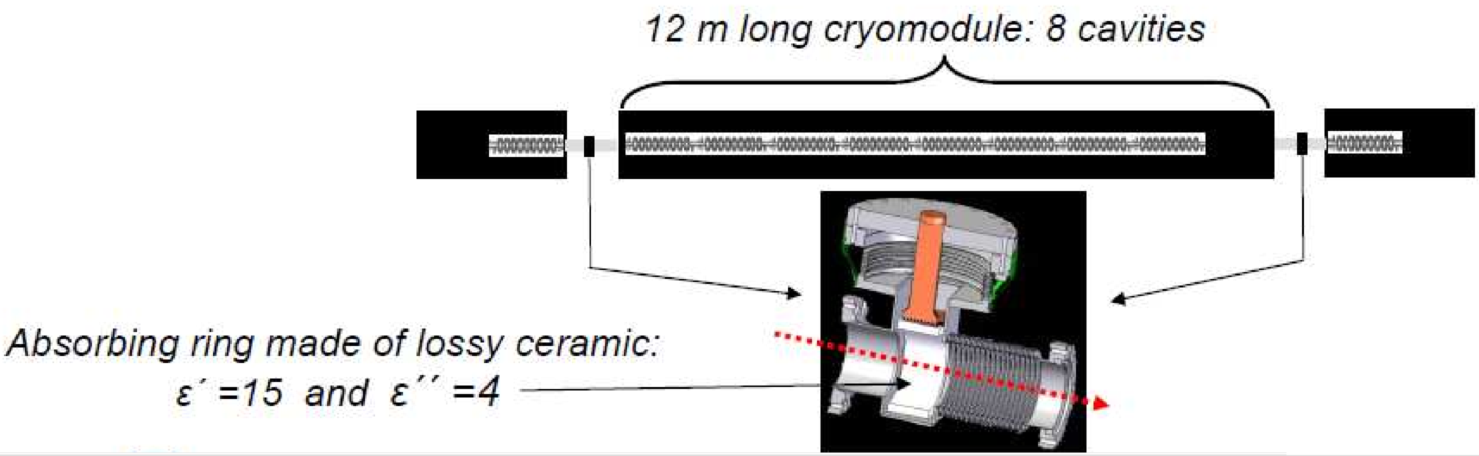
- Ferrite is bonded to copper plated steel housing using HIP process
- Absorbers of this design are used at KEKB and BEPC-II
- Designed to for 5 kW absorption, reached 16 kW in operation



XFEL beam pipe absorber

- Needed to cover the high frequency part of the HOM spectrum
- Absorbers will be installed between 8-cavity cryomodules
- 5.4 W of microwave power per lossy ceramic ring during nominal operation of XFEL
- Capable to dissipate up to 100 W

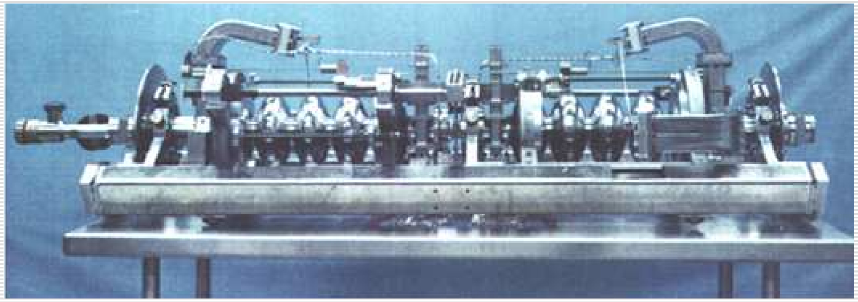




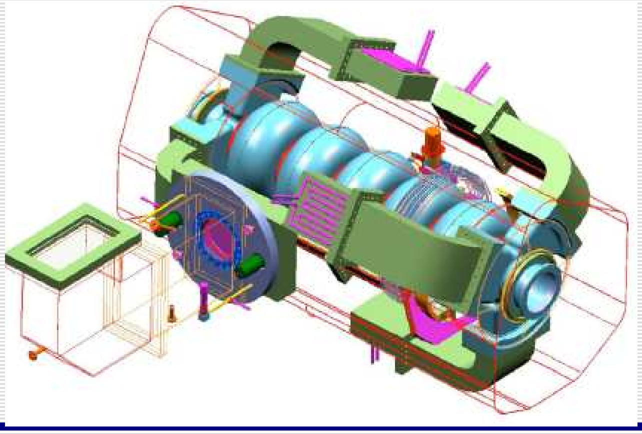
Rectangular waveguide HOM couplers

- Used in CEBAF and JLab FEL SC linacs
- New designs are being developed primarily at Jefferson Lab
- Proposed for JLab's Ampere-class cryomodule (748.5 MHz) and "100 mA" cryomodule (1497 MHz)
- While can provide very efficient damping in broad frequency range and don't compromise the fill factor, waveguides significantly complicate the cavity and cryomodule design

CEBAF: WG absorbers at 2 K

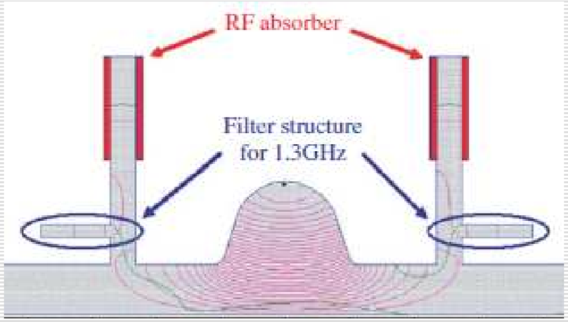


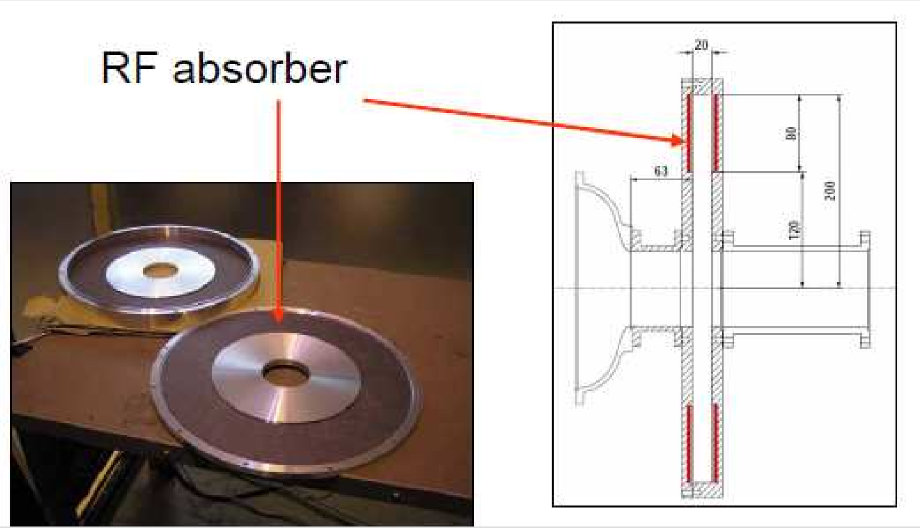
Ampere-class cryomodule: WG absorbers at RT



Radial line HOM coupler

- Proposed at KEK for ERL L-band linacs
- Derived from Shintake's choke-modde cavity and proposal by Koseki at al.
- Can provide very efficient damping in broad frequency range and don't compromise the fill factor, BUT radial lines complicate the cavity and cryomodule design, need filter structure to reject fundamental mode





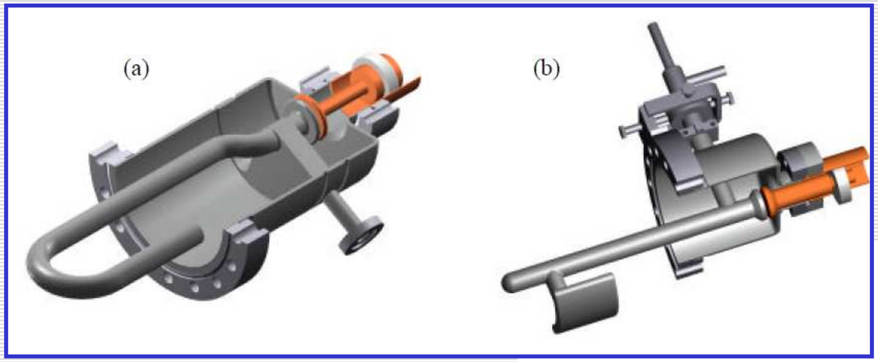
Loop HOM coupler

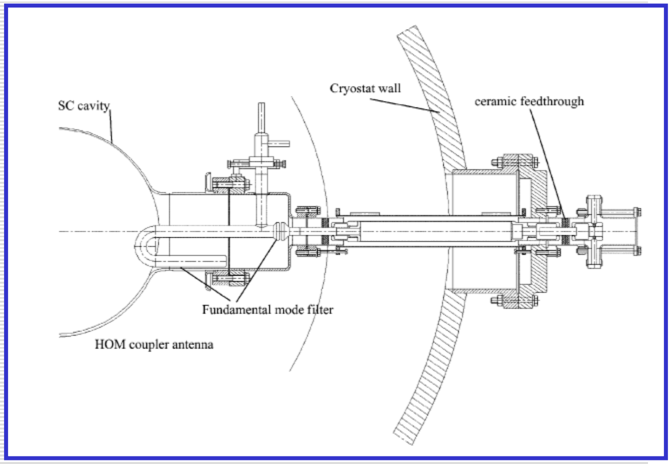
COAXIAL LOOP HOM COUPLERS

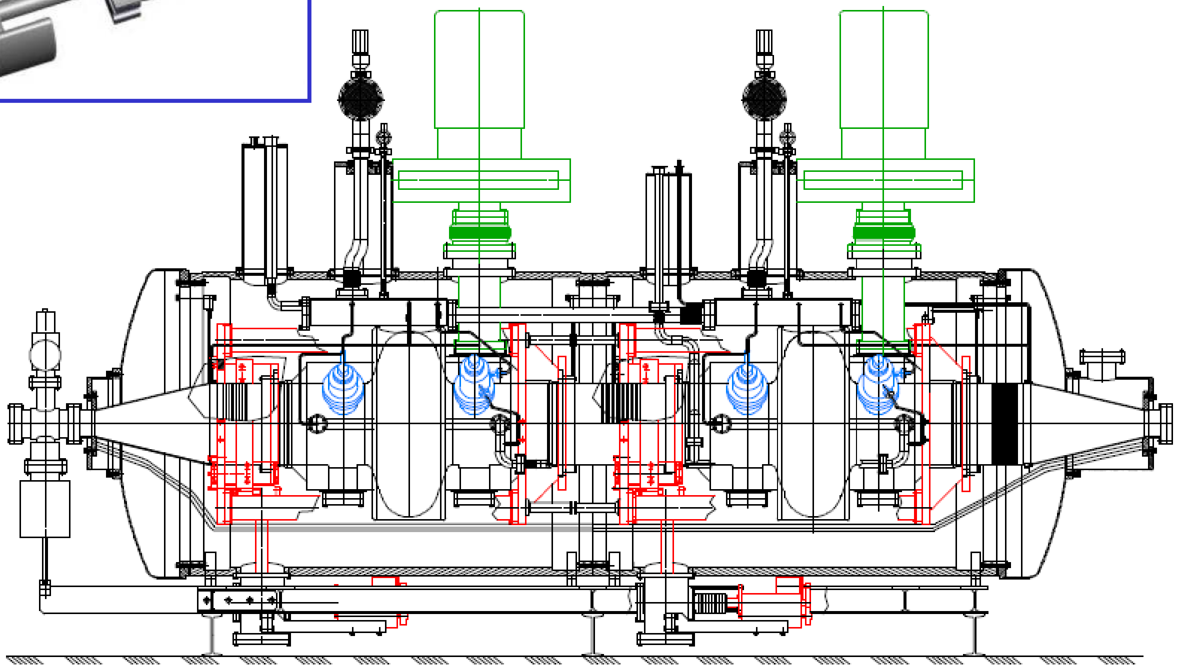
- Couplers of this type were proposed and developed for HERA and LEP in mid-80's
- LEP-type couplers were later adapted for SOLEIL, LHC, and Super-3HC cryomodules at SLS and ELETTRA
- TESLA HOM couplers are derived from HERA couplers with a simplified RF design due to more moderate damping specs ($Q_{HOM} \sim 10^5$)
- Later scaled for use at SNS (805 MHz), Fermilab (3.9 GHz) and 12 GeV CEBAF upgrade (1.5 GHz) cryomodules though there were some difficulties
- Dampers of this can provide strong damping dependent on a particular RF design
- Their main disadvantage is fundamental RF rejection filters, which must be carefully tuned
- Nevertheless, SNS experience indicates that loop couplers are sufficient for a spallation source application

LEP/LHC couplers

- LEP2 cavities had two "hook" type couplers, where the hook was filled with liquid helium for cooling
- The notch filter can be adjusted after installation
- In addition to LEP2 dipole mode couplers, LHC cavities have broadband couplers





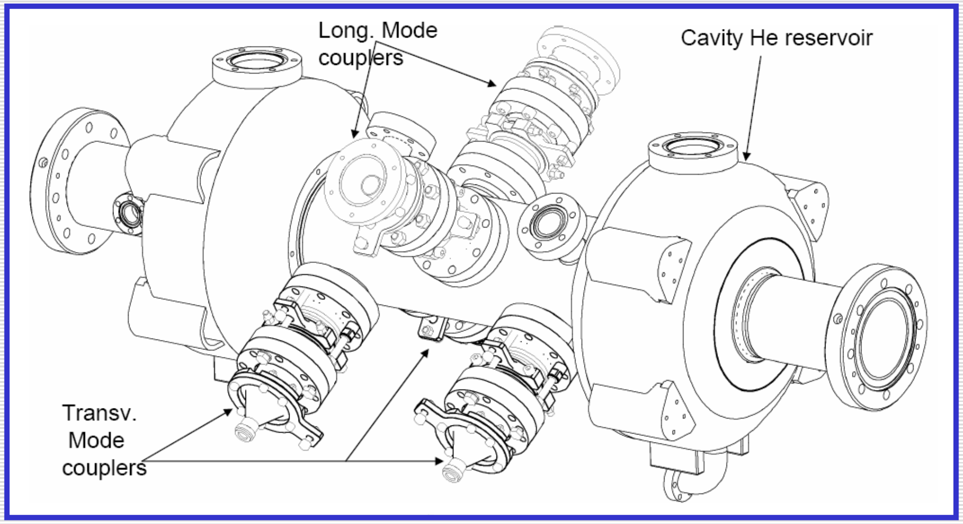


SOLEIL/Super-3HC couplers

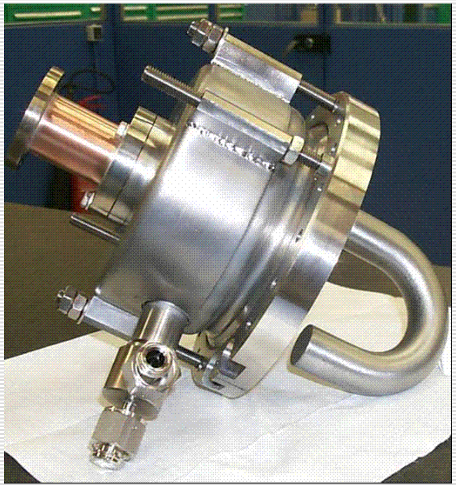
- Two types of HOM couplers: for dipole and monopole modes
- Much higher coupling factor than in LEP or TESLA cavities

What the beam sees passing through the SOLEIL module

Super-3HC cryomodule with HOM couplers

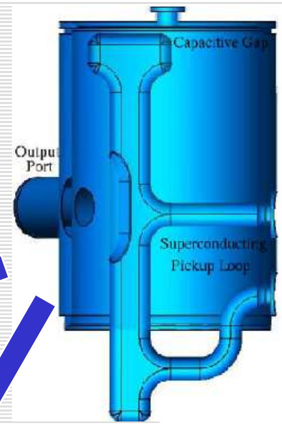


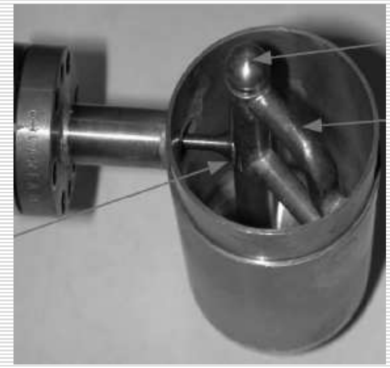
SOLEIL HOM coupler

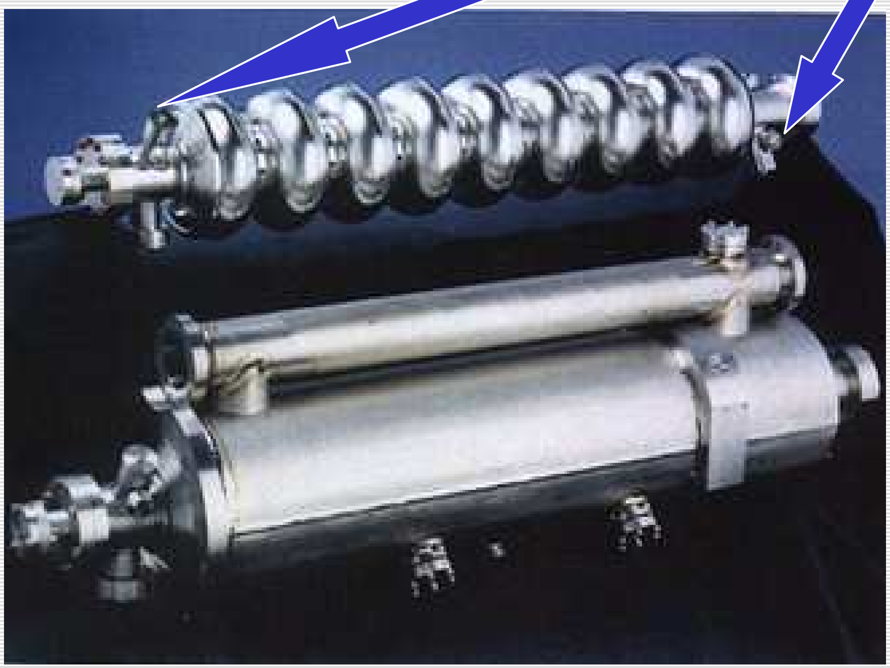


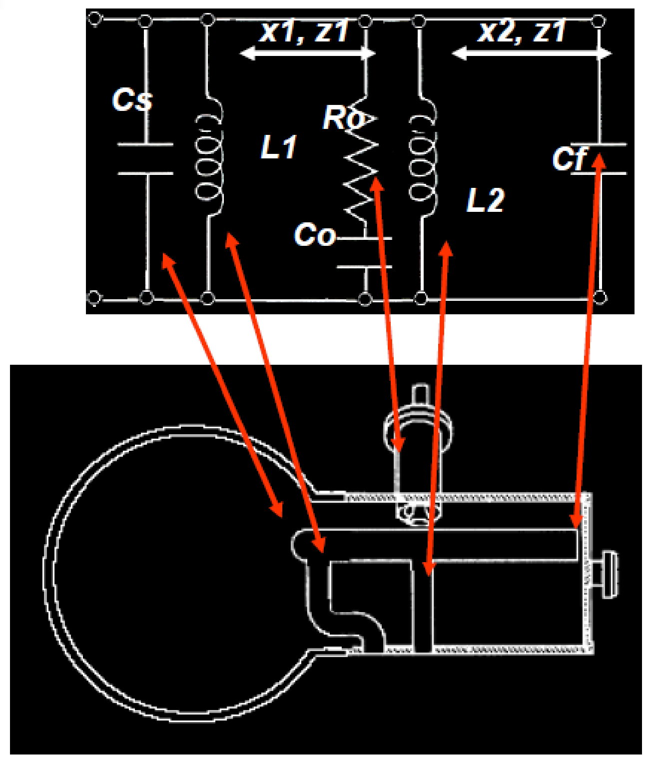
TESLA HOM couplers

- Simplified version of HERA HOM couplers: less damping required
- Locating outside helium vessel is possible because of negligibly small heating (1% duty factor)
- Successfully used on all TESLA-type cavities in pulsed mode



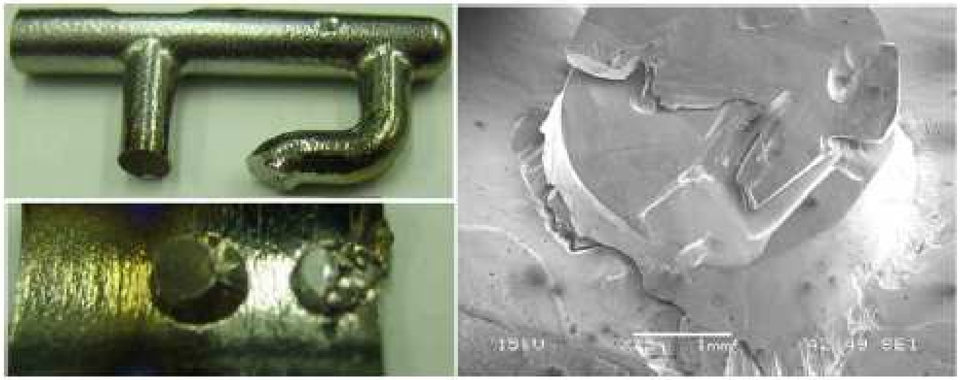




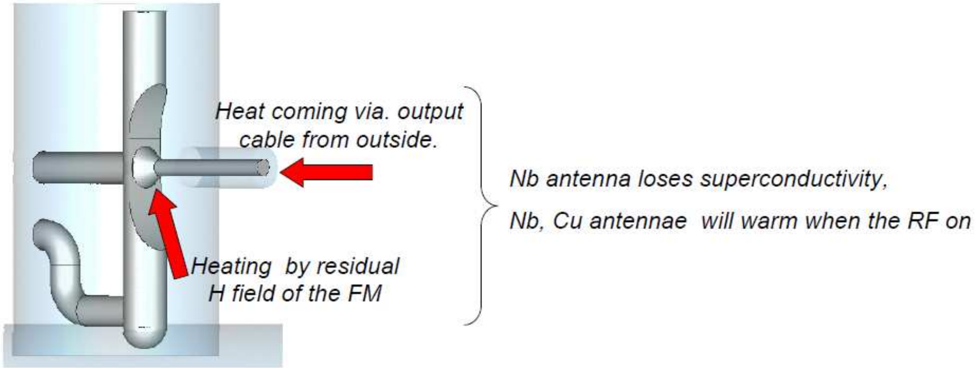


"Bumps in the road"

- Fermilab: multipacting damage to HOM couplers on 3.9 GHz cavities (MP → overheating → fracture) → redesigned to shift MP levels above operating gradients



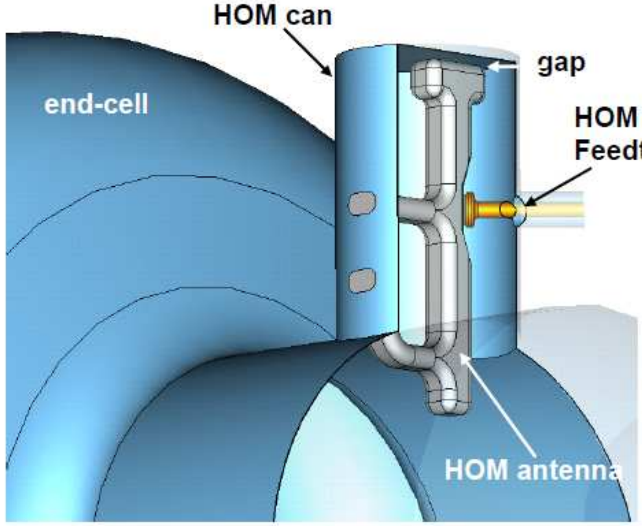
- CW operation (12 GeV CEBAF upgrade): heating of the output antenna by the residual magnetic field of the fundamental mode → redesigned to improve heat removal and reduce residual field pick up



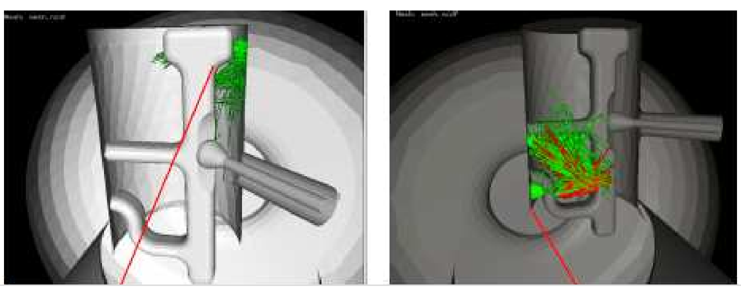
SNS experience

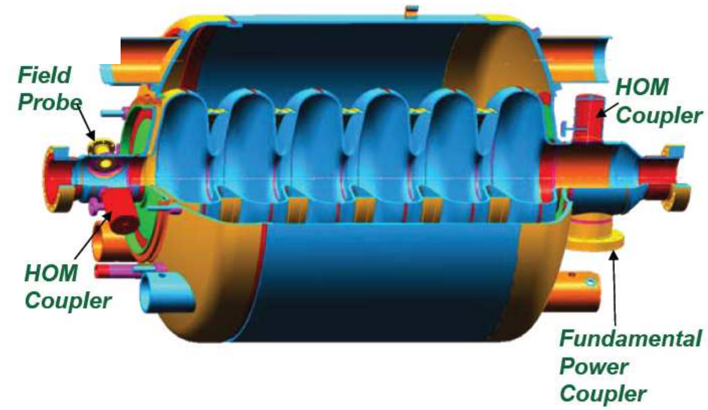
- **Two cryomodules are removed form the linac**
- **One showed large coupling of the fundamental RF power to HOM port. Removed feedthroughs, blank-off, and detuned HOM notch frequency. This cryomodule has been back in service with good performance.**
- **Second cryomodule: found 3 places having leaks at HOM feedthroughs. Removed feedthroughs, blank-off, and detuned. Will be back in service soon.**

- HOM couplers added as extra safety against longitudinal instabilities
- Some HOM feed-throughs have been damaged or show abnormal transmission curves
- Exact cause of anomalies not completely known, but conservatively turned off of run at limited gradients



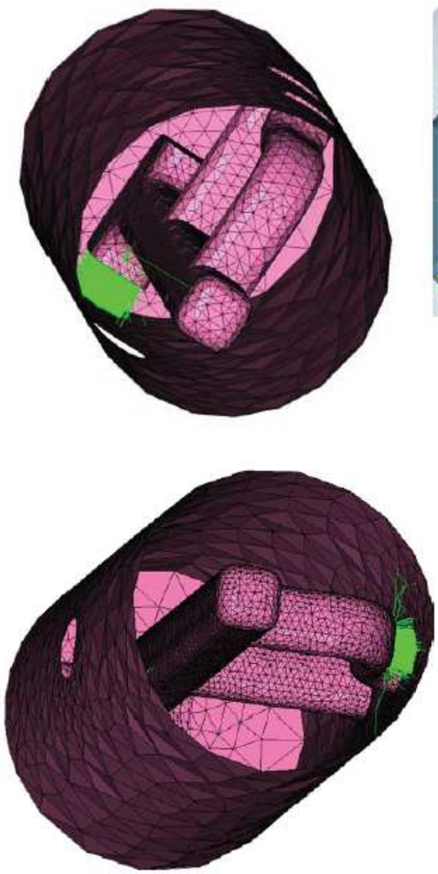
Multipacting in HOM2

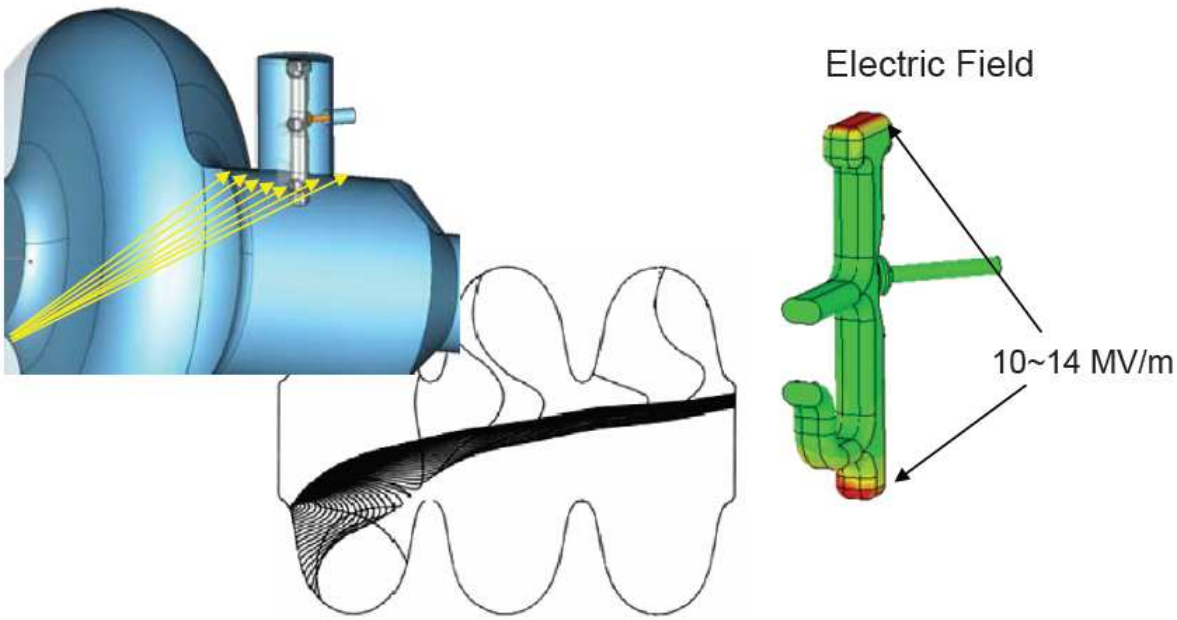




SNS experience (2)

Electron activities → damage HOM coupler

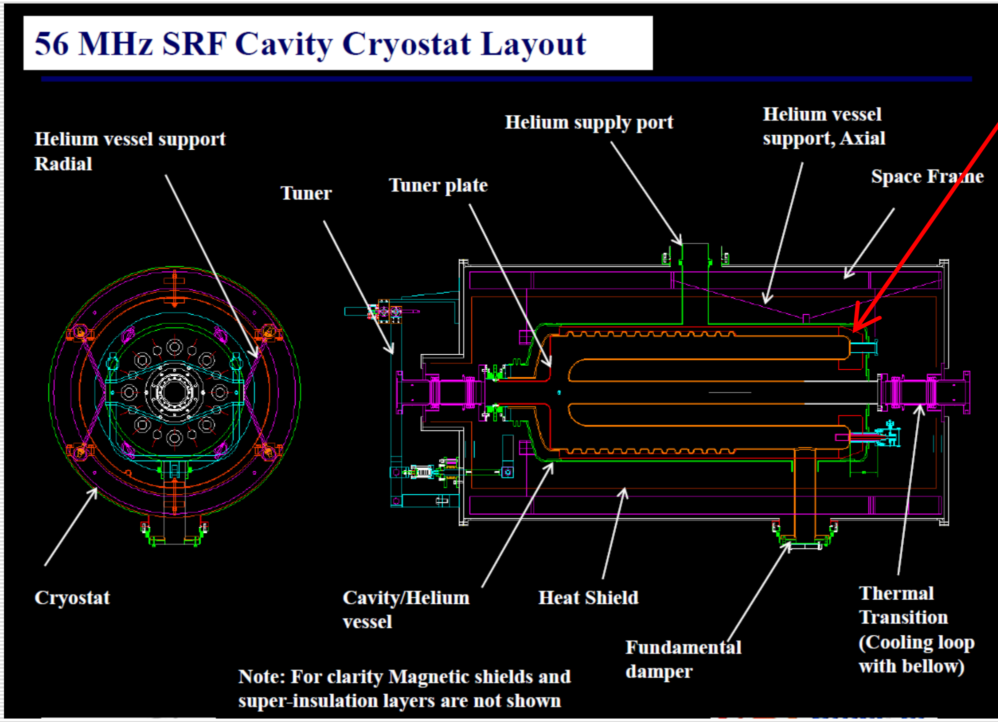


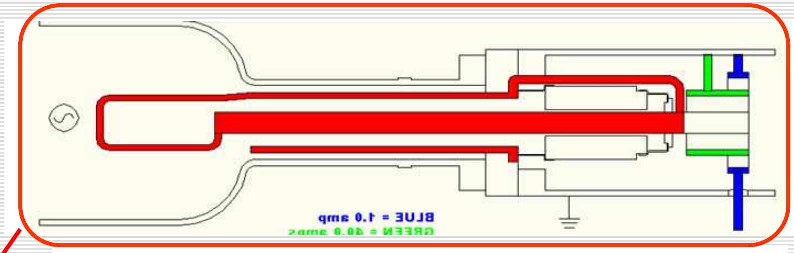


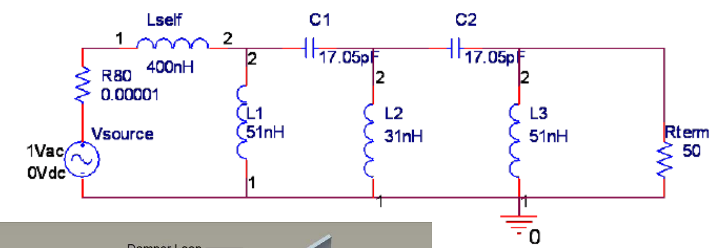
Any electron activity
→Destroy standing wave pattern
(or notching characteristics)
→Large fundamental power coupling
→Feedthrough/transmission line damage
→Irreversible

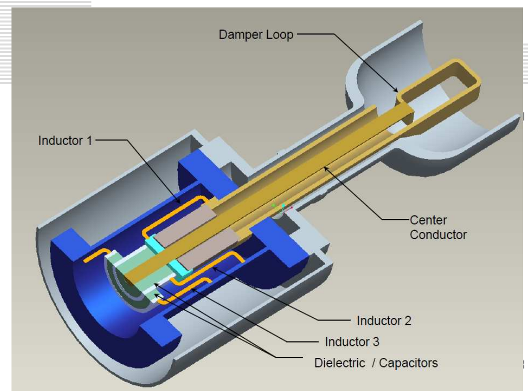
Loop HOM coupler for RHIC 56 MHz SC cavity at BNL

- HOM couplers are located in a high magnetic field region of SC cavity, which was a taboo until recently

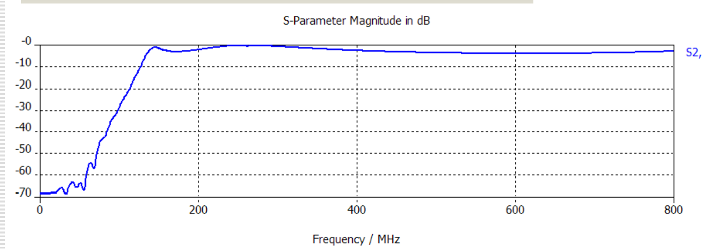








A new compact HOM filter has been designed and under fabrication.
→ Allows a current path through the first inductor which enables the cooling path much simpler.



-60 dB rejection At 56 MHz

What have we learned?

- Extremely low RF losses is a handicap when we consider HOMs.
- Special HOM dampers are utilized to keep HOM impedance under control.
- Though many designs have been developed over years, this field is still quite open as new SRF accelerator project make HOM damping requirements more and more demanding.
- When adapting somebody else's design, one must be aware of possible "bumps in the road".

✪ We will discuss the cavity fabrication techniques, preparation and testing in the next lecture.