BESSY
Berliner Elektronenspeicherring-Gesellschaft
für Synchrotronstrahlung m.b.H.

CW Superconducting RF for Future Linac-Based Light Sources

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Leibniz Gemeinschaft

Overview: CW superconducting RF for light sources

- The past & present: History of CW superconducting RF, some installations in light sources
- The future: New proposals for linac-based light sources
- Implications for CW SRF systems & resulting challenges

  Some examples

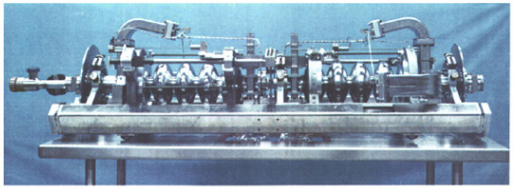
  - Dynamic losses & cryogenics
  - Microphonic detuning
  - Higher-order modes

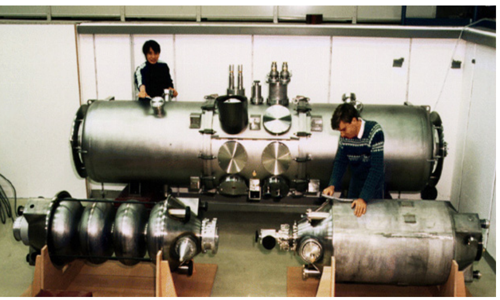
  Some of the things that won't be covered, but should be!

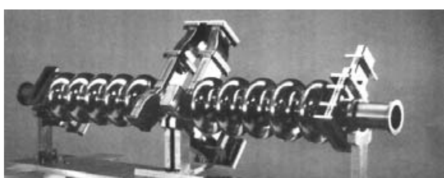
  - RF control
  - Input couplers
  - RF system
  - ERL Injectors in detail (including guns!)
  - Transfer of technology to industry
  - …

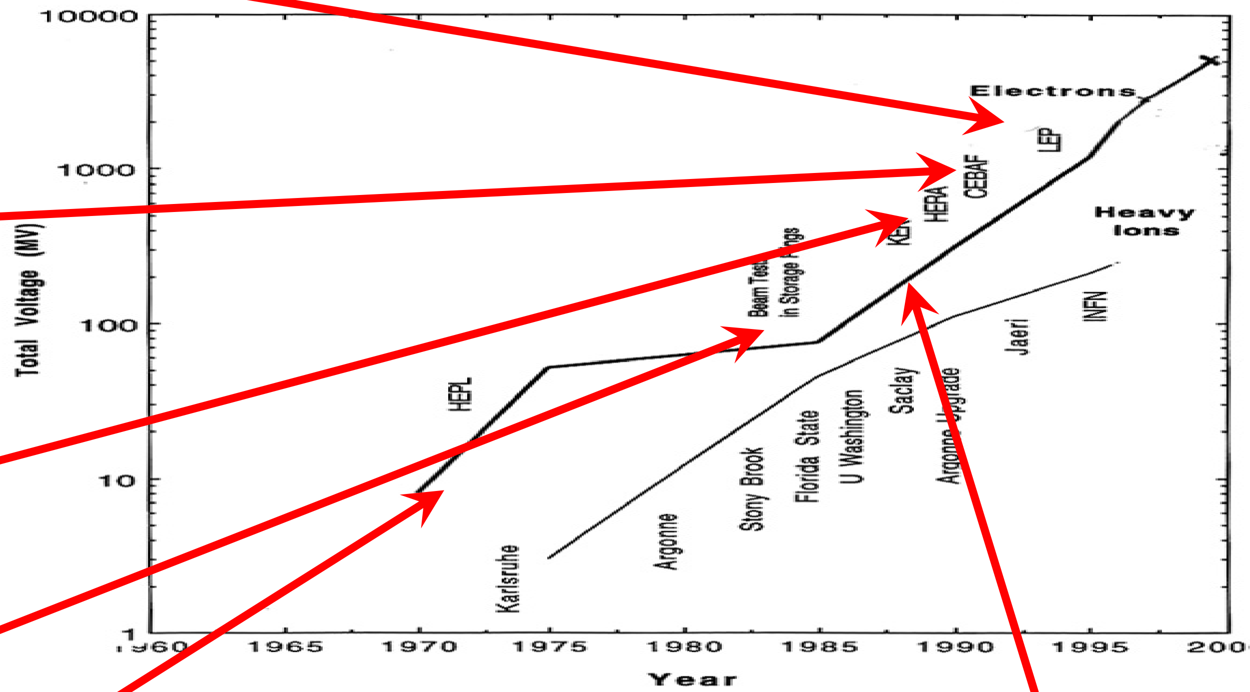
Note: No claim is made that this review is complete. Rather this is aimed to give a "flavor" of the subject with some examples.

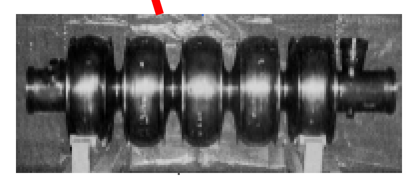
Superconducting rf technology throughout the ages











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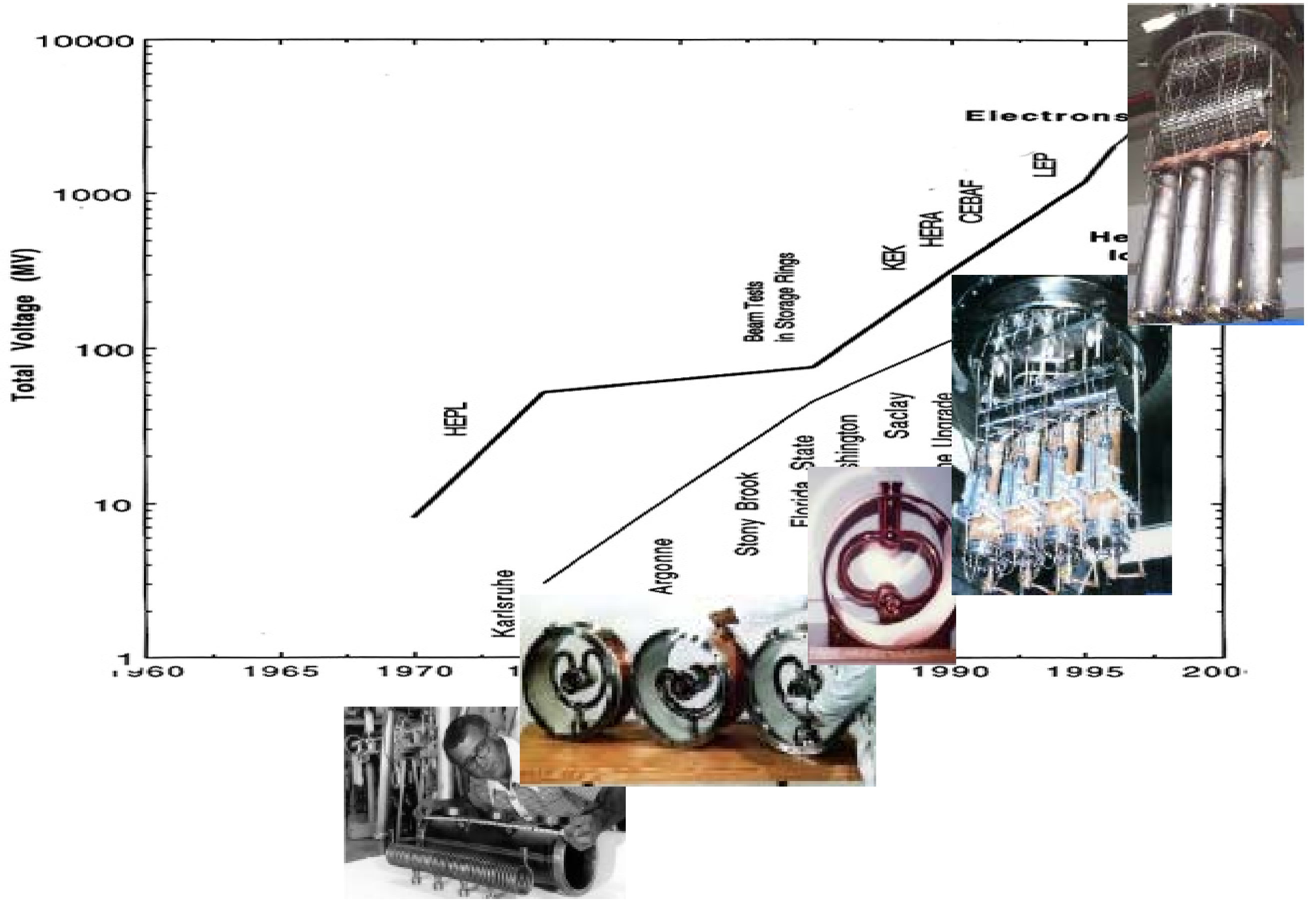
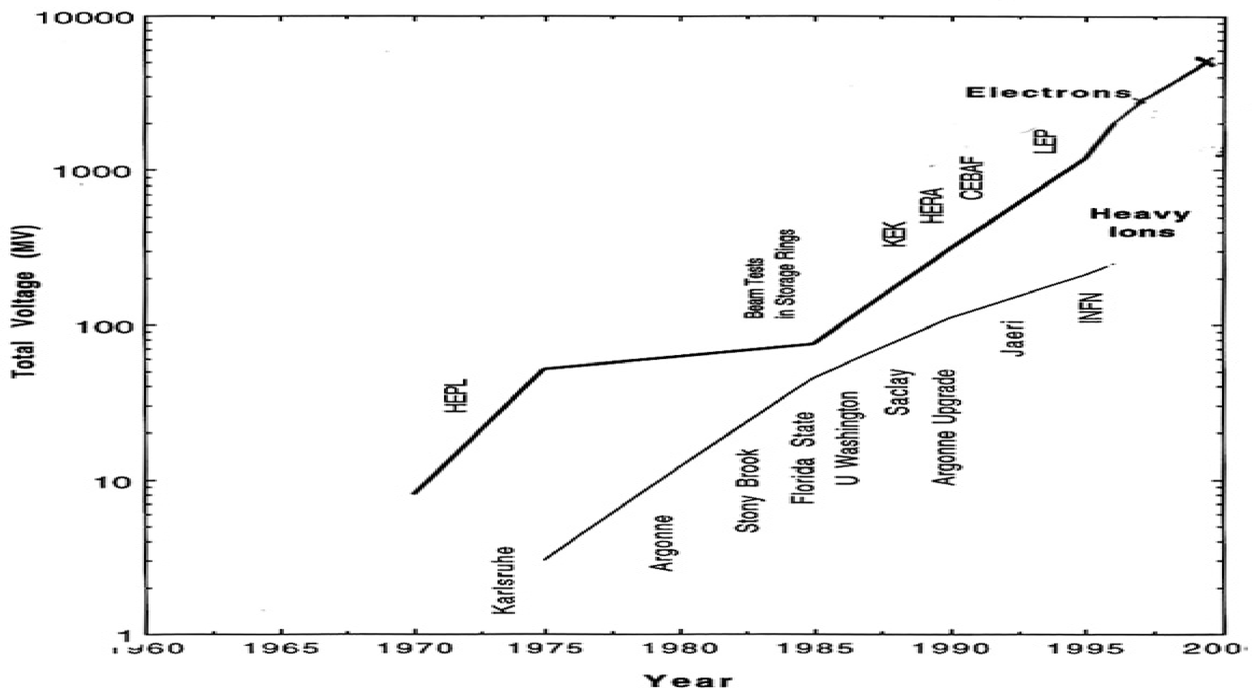


Total >1000 meters, > 5 GV

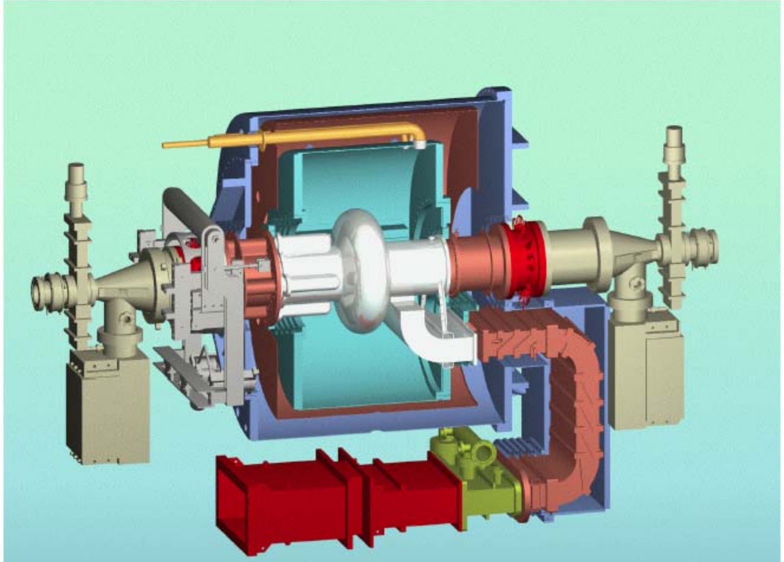


- Superconducting technology is a mature & tested technology
- In the past has been used primarily for particle physics & nuclear physics
- Ready for extensive use in light sources

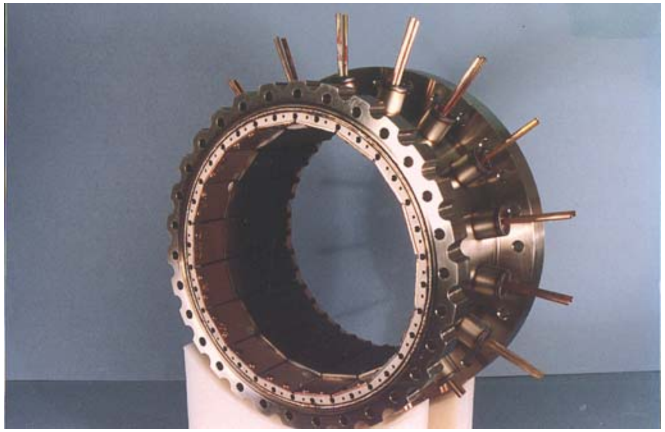
Existing CW Superconducting Technology for Light Sources

Cornell 500 MHz System:

- Installed and successfully demonstrated in CESR-B, 2nd generation light source (>500 mA)
- One key feature: heavy HOM damping → "monomode cavity"



Cornell 500-MHz SRF Cavity

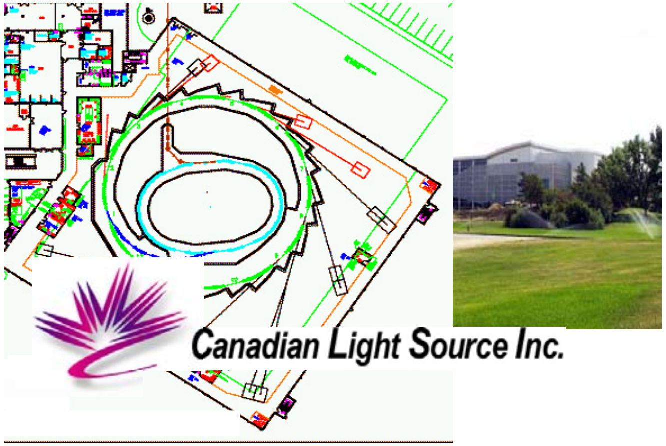


Existing CW Superconducting Technology for Light Sources

Cornell 500 MHz System:

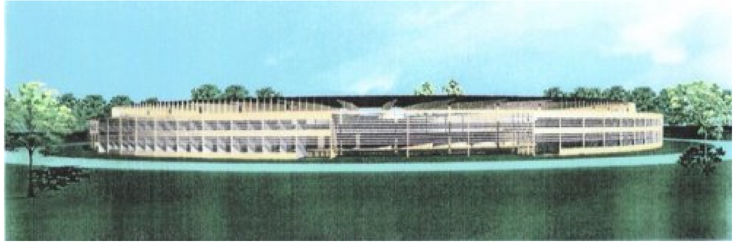
- Very successful operation in CESR
- Has been adopted by a number of 3rd generation light sources:
  - Diamond, 500 mA
  - Canadian Light Source, 300 mA
  - SRRC-Taiwan Light Source, 500 mA

Diamond Site

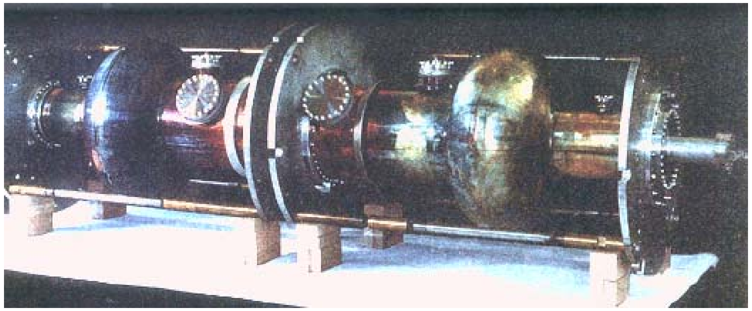


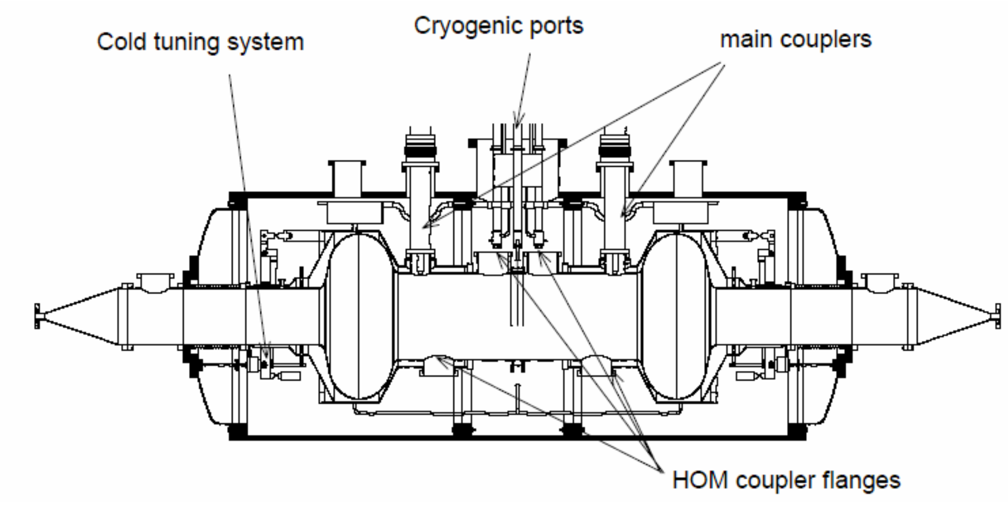
Soleil

- Two single-cell copper-Nb cavities in one cryomodule
- 352 MHz
- 2.5 GeV, 500 mA



Niobium on copper technology





Soleil 352-MHz system

Big Advantage: Turn-key systems are now available from Industry

- Even laboratories that do not (initially) have SRF expertise can get in on the act and concentrate on other things

Existing CW Superconducting Technology for Light Sources

Some advantages over normal-conducting technology:

- CW operation at fairly high gradients (10 MV/m) → save space
- High wall-plug-to-beam power conversion efficiency → especially enticing for ERLs
- Can transfer a lot of RF-power to the beam (100's of kW) → ERL injectors
- Large beam aperature → low impedance for low emittance beams (FELs)
- Easy HOM damping → high BBU threshold → ERLs

→ Attractive for CW, high-current future light sources which deliver small-emittance, low-energy spread beams.

Some disadvantages (of the 500/352 MHz systems):

- Low fill factor → not suited for linacs
- Cryogenic losses up to 100 W for one cavity → not suited for linacs
- Medium CW fields → not suited for linacs
- HOM-damping designed for long (storage-ring) bunches → needs to be examined for SASE and short-bunch light sources
- → MUST ADAPT TECHNOLOGY FOR FUTURE (LINAC-BASED) LIGHT SOURCES

The past & present: Superconducting linac-based light sources

	Frequency (MHz)	Energy (MeV)	Current (mA)	Wavelength (μm)	Type
JAERI Japan	500	16	5.2-40	20-30	ERL
ELBE Germany	1300	12-40	1 mA	2-10	FEL
SCA, Stanford USA	1300	40-50	0.15	1-2	FEL,ERL
DALINAC Germany	3000	40-50	0.06	2.5-7	FEL, ERL
JLAB USA	1500	45-80	5-10	1-6	FEL, ERL
VUV-FEL Germany	1300	500	mA (pulsed)	0.1-0.2	SASE-FEL

- Beam ernergy is moderate and beam current is typically < 10 mA. Most produce IR radiation Exception is VUV-FEL, but this is pulsed

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- Beam ernergy is moderate and beam current is typically < 10 mA. Most produce IR radiation Exception is VUV-FEL, but this is pulsed
- Can use this technology as the baseline for future machines

The future: Newly proposed CW linac-based light sources

	Frequency (MHz)	Energy (GeV)	Current (mA)	Wavelength	Type
Cornell ERL USA	1300	5-7	100	X ray 10's keV	ERL
4GLS UK	1300?	0.600	100	VUV, X ray	ERL, FEL
LUX, LBNL USA	1300 (1500?)	2.5	40	VUV, X ray	Recirculator
BESSY FEL Germany	1300	2.3	0.075	VUV, X ray	FEL
JLAB 100 kW USA	750/1500	0.045-0.080	1000	IR	ERL, FEL
KEK ERL Japan	1300	5	100	X ray	ERL
European XFEL	1300	20	1-10	X ray	SASE-FEL

Generally

- Beam energy in the GeV range

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Generally

- Beam energy in the GeV range
- Current in the 100 mA range

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Generally

- Beam energy in the GeV range
- Current in the 100 mA range
- Frequency tends to be L-Band (TESLA/CEBAF technology)

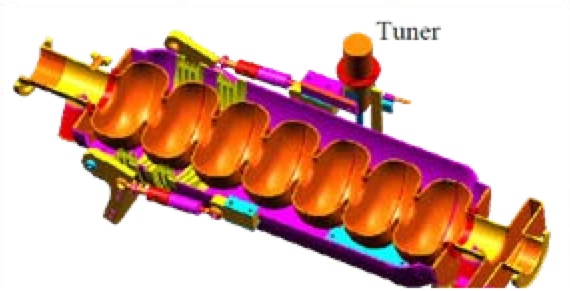
Linac requirements of future CW light sources

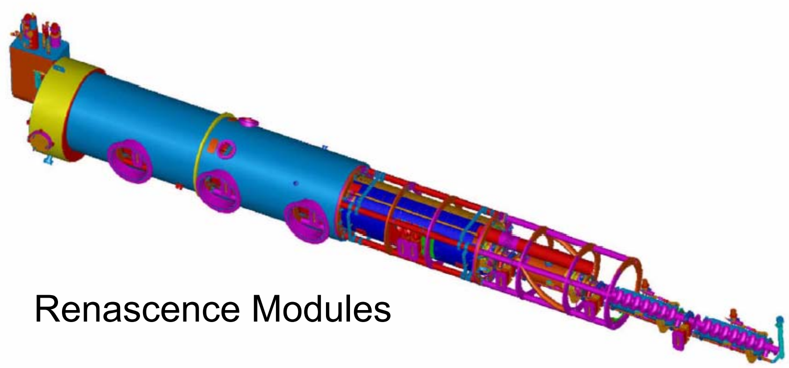
- Energies in the 0.1’s GeV to 10’s GeV
  - → Fairly high gradients (15-20 MV/m) and high fill factor to limit length
  - → Highest quality factor to limit the cryogenic load
- Beam currents up to 100’s mA
- Bunch lengths down into the fs range
  - → Strong HOM damping *up to high frequencies* for beam stability and to limit cryogenic load
- Emittances in the 1 μm range
- Energy spread around 10^{-4}
- Bunch jitter below 100 fs
  - → Tight RF control (amplitude & phase) of the gun, injector and linac
- For ERLs
  - → Injector must transfer high-power to the beam without disrupting it (emittance preservation)

Existing linac technology for light sources

CEBAF cryomodules and upgrades

- Use 5-cell 1.5-GHz Nb cavities
- 380 cavities, installed in early 90’s
- Operated at < 10 MV/m
- Now developing a new upgrade module for low-loss operation at 20 MV/m
- Designed for CW operation




Renascence Modules

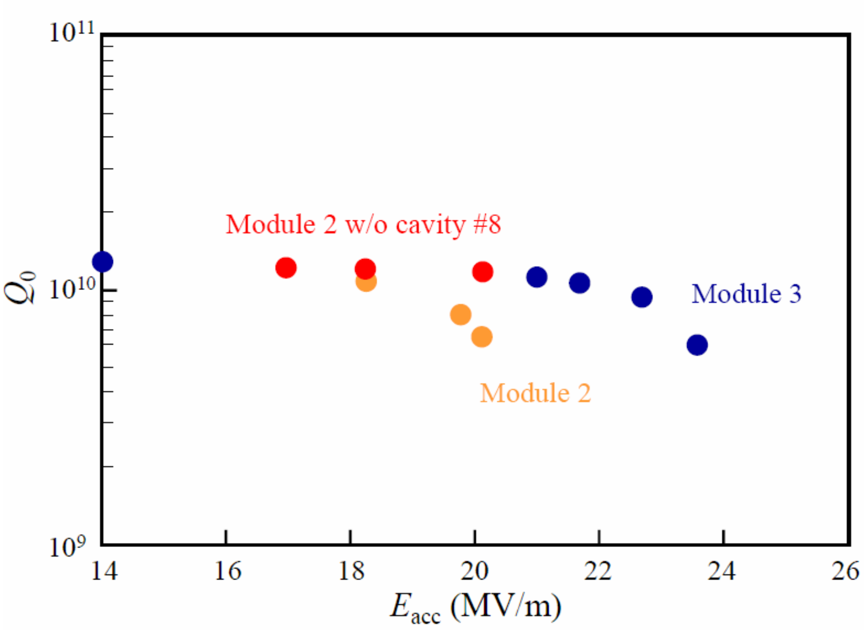

CEBAF

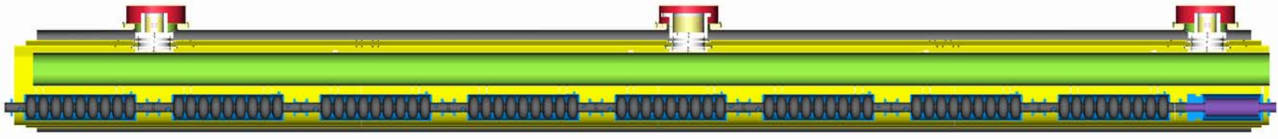

CEBAF Cavities

Existing linac technology for light sources

TESLA-type modules

- Operating in VUV FEL, planned for XFEL
- Use 9-cell 1.3 GHz Nb cavities
- Typically operated at > 15 MV/m,
- **Designed for pulsed operation**





Future technology for CW linac-based light sources

Either type of system can serve as a baseline for future light-source linac development

For example:

- TESLA technology is being modified for
  - BESSY FEL
  - Cornell ERL
  - 4GLS
  - Arc-en-Ciel
  - LUX (?)
  - …
- CEBAF technology serves as a baseline for
  - JLAB IR FEL
  - LUX (?)
  - More to come?

What do we need to modify?

Technology challenges for CW linac operation

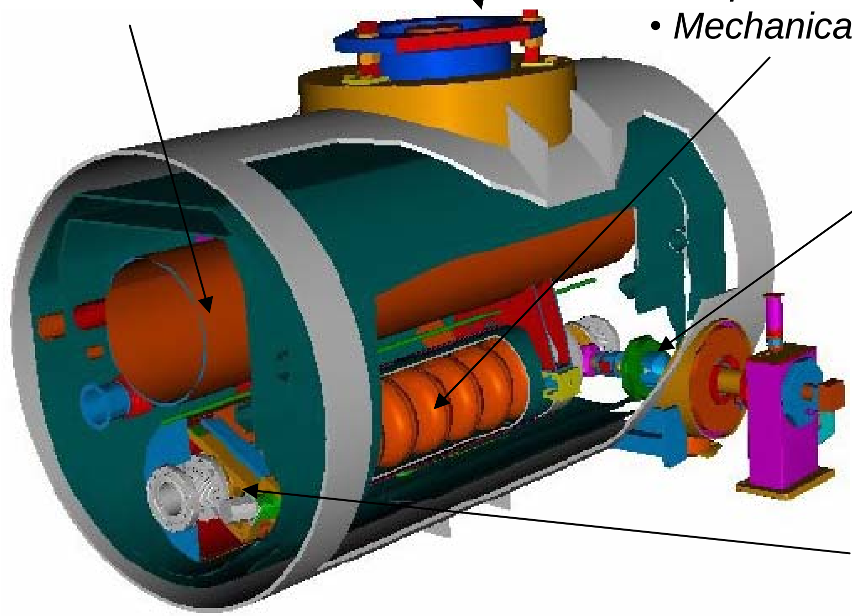
Cryostat design
- *Magnetic shielding*
- *Low microphonics*
- Cost & Transportability

HOM Dampers
- *Strong damping of high-frequency modes*
- Impact on the beam?

Cryogenics
- *CW loads*
- *Bath temperature*
- *LHe distribution in module/linac*
- *Pressure stability*

Cavities
- *Frequency*
- *Shape*
- *Number of cells*
- *Preparation*
- *Mechanical stiffness*

Input couplers
- Adjustibility?
- Peak-power capability
- Average-power (SW) capability



RF Control
- Exacting amplitude & phase control
- Flexibility and programmability

RF Sources
- Efficient
- Low cost
- Reliable
- Up to > 100 kW CW

Cavity tuner
- Reliable
- Design to minimize microphonics
- *Active microphonic compensation*

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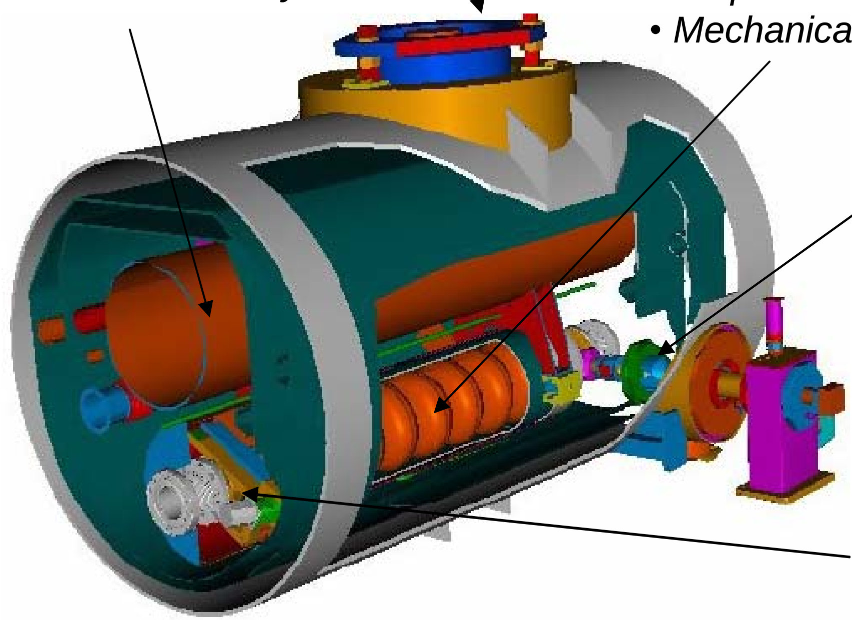

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Dynamic (cryogenic) losses

Dynamic Losses

Example: 5 GeV ERL linac operating at 20 MV/m

- Assume CEBAF (5-cell) cavities will be used → need 500 Cavities
- Dynamic losses per cavity: 20.7 W (for Q = 10^{10} @2 K)

→ Dynamic losses for the linac > 10.4 kW > 4 x XFEL design!

Consequences

- Very expensive refrigeration plant (capital + operating!) → Cost driver
- Big footprint for refrigeration plant
- Heat exhaustion issues: E.g., TESLA modules were not designed for these loads and instabilities may occur

Solution

- *Maximize the cavity quality & design for high shunt impedance*
- + Design cryomodule and linac layout to handle the higher heat loads

For CW operation highest attainable fields are not important. Highest attainable *Q*'s a around 20 MV/m are absolutely critical (contrast this with pulsed ILC operation)

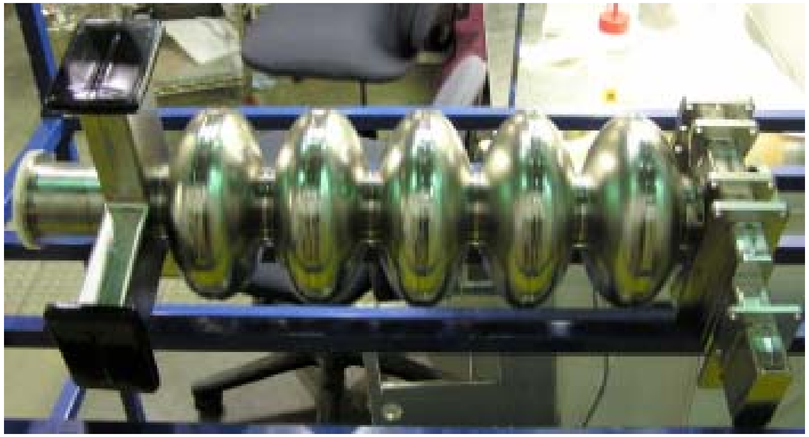
How do we reduce the dynamic losses

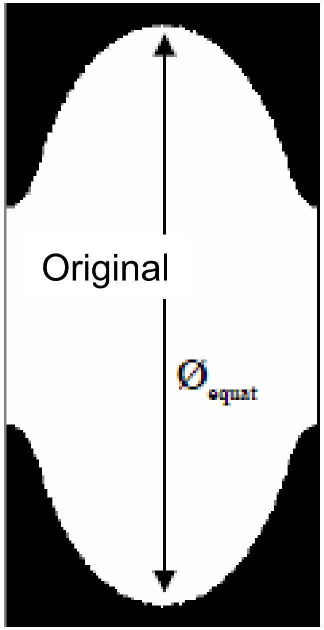
- **Design**: Design your cavity properly for low losses (shape, frequency, magnetic shielding)
- **Preparation**: Prepare your cavity VERY cleanly to avoid anomalous losses (especially field emission)
- **Operating parameters**: Choose your operating bath temperature and field level properly

How do we design the cavity to minimize the dynamic losses?

- Modify the shape of the cavity to increase shunt impedance & Geometry factor: → *E.g. at JLAB: Low-Loss Design*

Reduces losses by 27 % over original design saving 2.8 kW cryopower for our example!!





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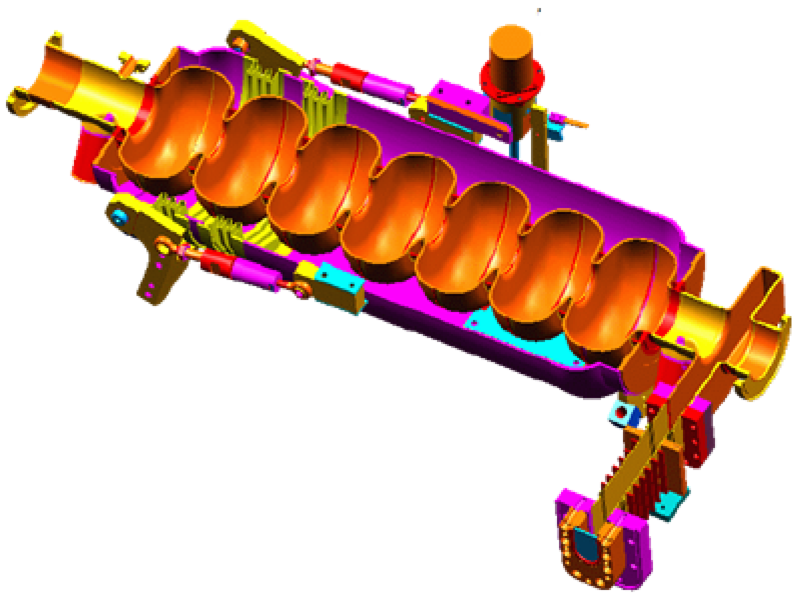
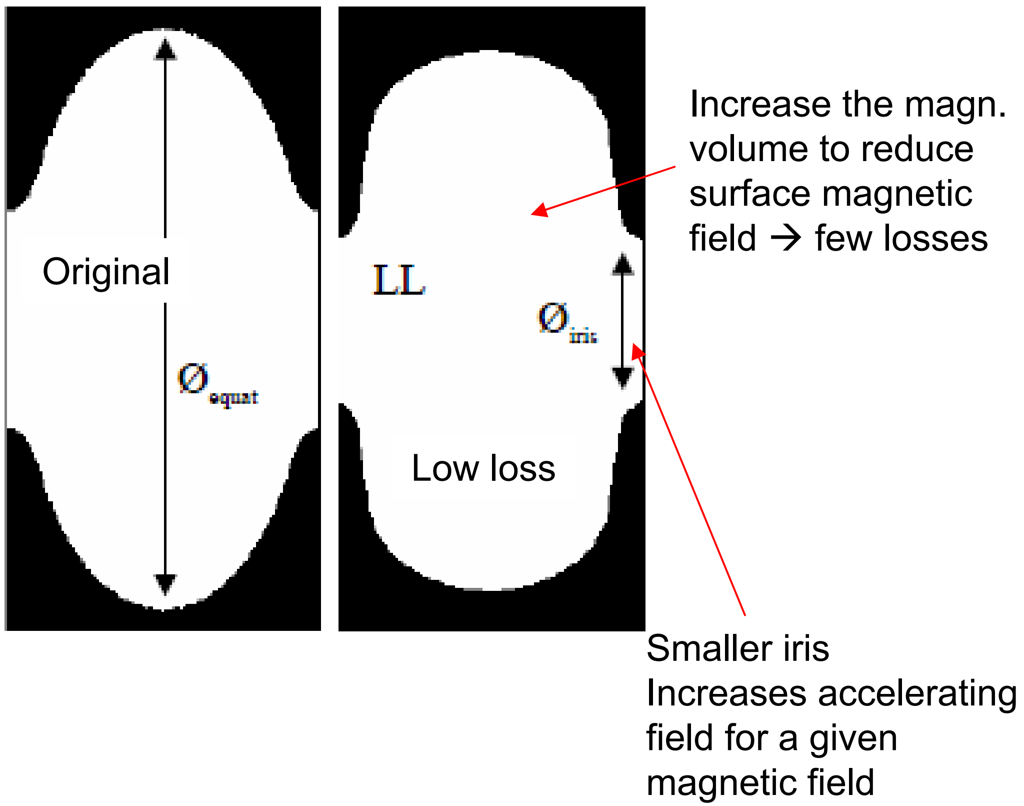
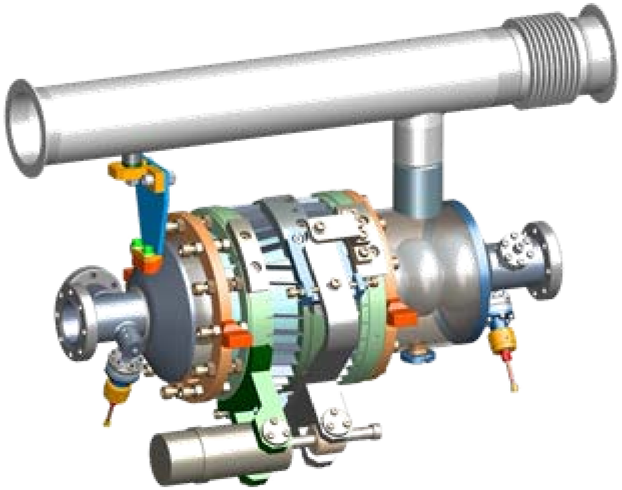




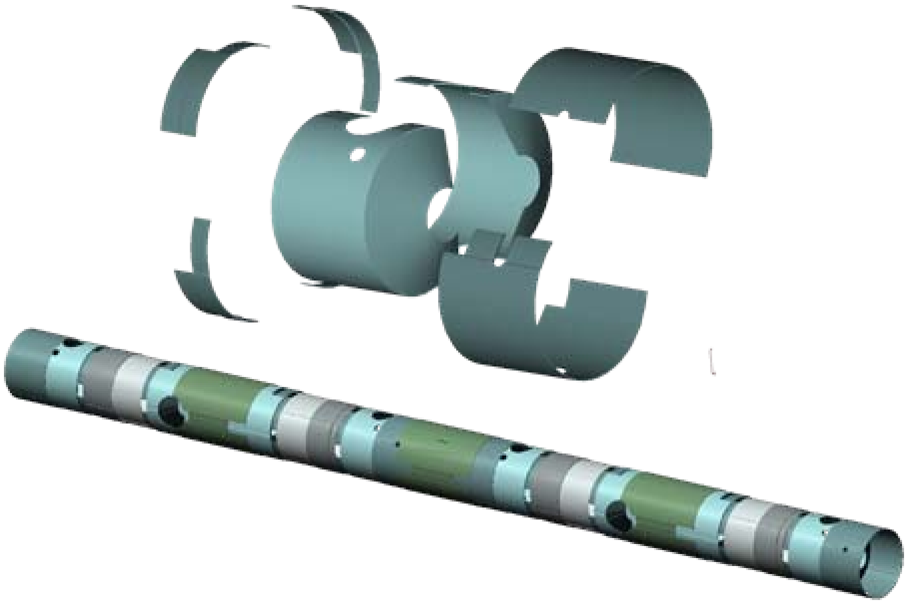
Reducing the dynamic losses

Impact of magnetic shielding

- Flux trapped in the cavity during cooldown results in losses (3.5 nOhm/μT)
  - → Magnetic field sets upper limit on attainable *Q*
- E.g., 2 μT → 7 nOhm → Q = 3.9 x 10^{10}
  - → Our example: Dynamic losses = 2 kW due to magnetic field alone!!!
- *Measurements in operating accelerator modules needed to determine effectiveness of shields*
- Fully enclosed designs needed + Must use materials that work well in the cold.



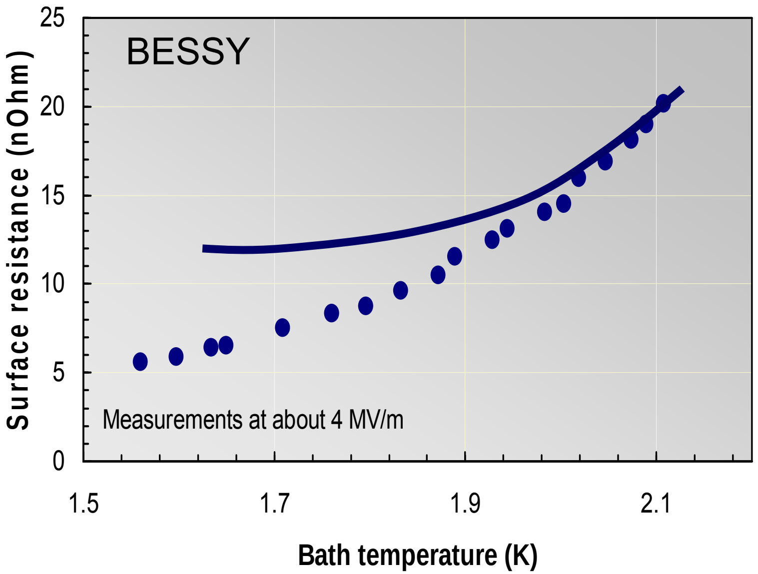
3.9 GHz cavity development at Fermilab



Another "knob" is the helium bath temperature

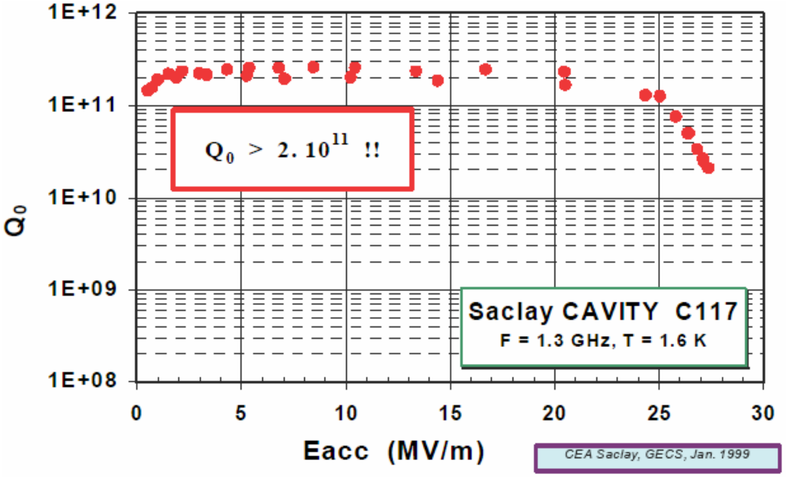
- BCS losses reduce exponential with T_b.
- Lower temperature → less refrigeration power

  provided residual & anomalous losses (e.g., due to magn. field & field emission) are small!
- Refrigeration plant must be configured to handle to the lower temp (additional cold compressors)



Ideal cavity performance

- "Perfect" Q curves have been achieved
- Now need to learn how to obtain these in a real module
- Dynamic load = 388 W for 5 GeV linac in this dream



Microphonics

Microphonics

Microphonic detuning of the cavities is a VERY important issue! Why?

- Bandwidth of cavities inversely proportional to the cavity losses
- Storage ring cavities, e.g., CESR: 500 mA, 6 MV/m, 70 deg → Beam loading = 308 kW
  - → Optimal bandwidth for match = 4.3 kHz
- ERL, effective beam loading is 0 (except injector)
  - → Optimal bandwidth for match is theoretically 0.1 Hz!
  - → Mechanical detuning of the cavity can shift resonance by many bandwidths.

How much microphonic detuning should we expect?

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

Consequences of Microphonics

Field stability

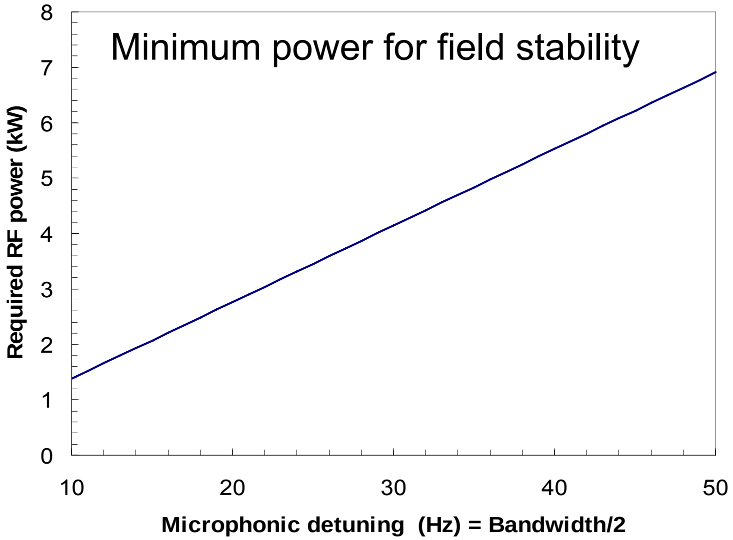
- Detuning by 1 bandwidth = 45 deg phase shift

  → Energy jitter from bunch to bunch

  → Timing jitter from bunch to bunch if bunch compression/dispersive sections present.

  → Energy spread

  → Tight (high-gain) RF control needed



RF system layout

- Require significant additional RF power to stabilize the field

  → Thermal issues (e.g., coupler)

  → Wall-plug power consumption

  → Dimensioning of the RF system, Type of RF system

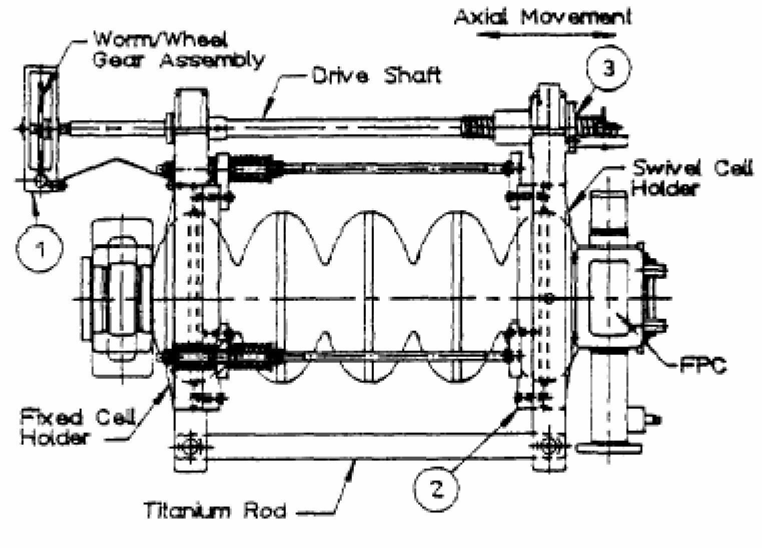
  - No microphonics: 50 W solid-state amplifier!!
  - 50 Hz microphonics: 7 kW klystron

  → **linac cost driver**

Must know mechanical dynamics of the module & helium system to specify the RF system

How does one limit microphonics?

- Ensure stable helium system, low pressure fluctuations (0.01 mbar)
- Design the cryostat not to transmit mechanical vibration to the cavity
- Ensure your system is stiff and mechanical resonances are at high frequencies



CEBAF

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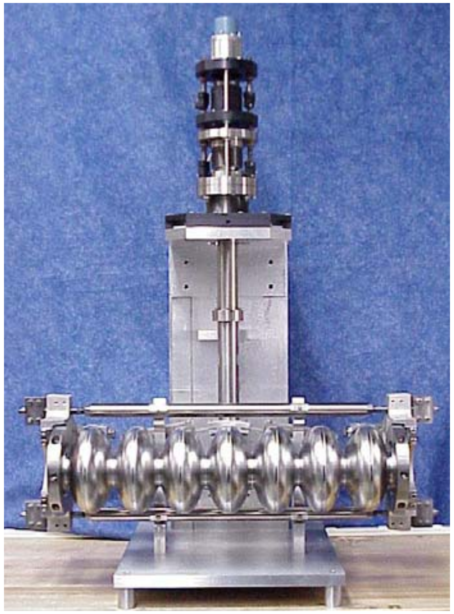

CEBAF upgrade

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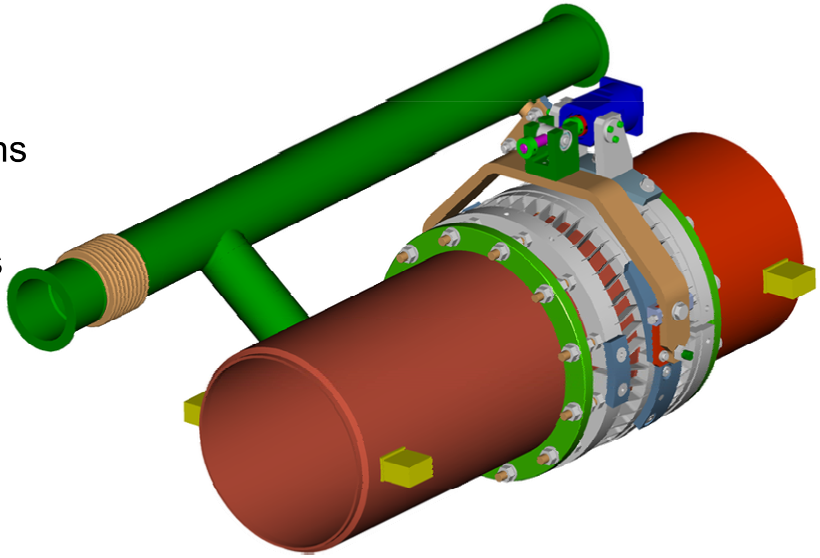
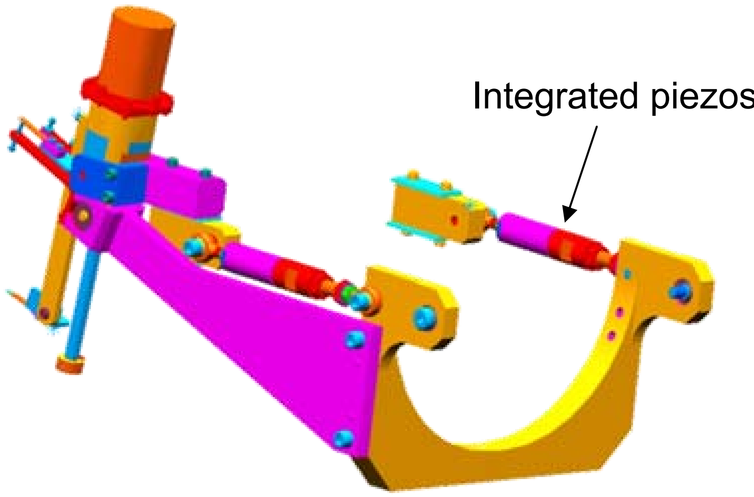


TESLA blade tuner

How does one limit microphonics?

- Ensure stable helium system, low pressure fluctuations (0.01 mbar)
- Design the cryostat not to transmit mechanical vibrations to the cavity
- Ensure your system is stiff and mechanical resonances are at high frequencies
- Active control with the tuner. Originally developed for LF detuning in pulsed machines
- Low-microphonic modules exist, e.g., ELBE. But no one really knows what features are beneficial

→ **A lot can be gained by further studies here (may not be sexy, but you get the chance to save the budget!)**



CEBAF Renascence

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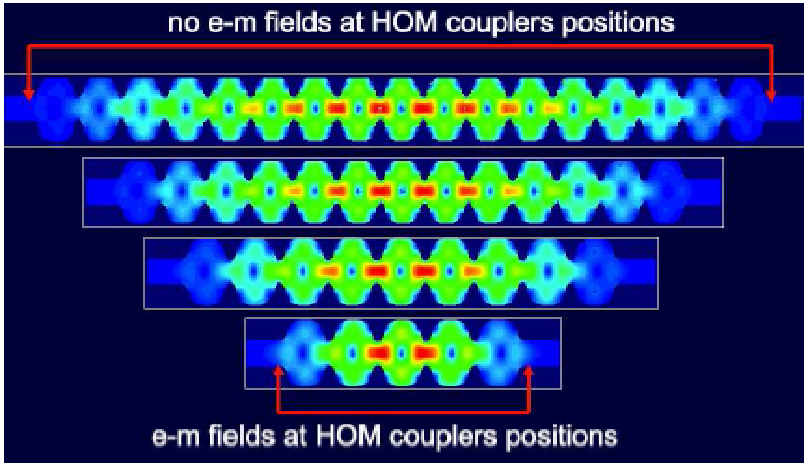
Higher order modes

Many future light sources are ERLs which run at 100+ mA!

- Average HOM power is given by: $P_{avg} = k_{||} I_b Q_b$
- Given our example ERL with Q_b = 77 pC and I_b = 100 mA **x 2**, $\boldsymbol{P_{avg}}$ **= 104 W/cavity** > dynamic losses!
- Dipole modes cause instabilities: BBU threshold scales as $1/(R/Q \times Q_L)$
- Frequency spectrum extends up to 100 GHz

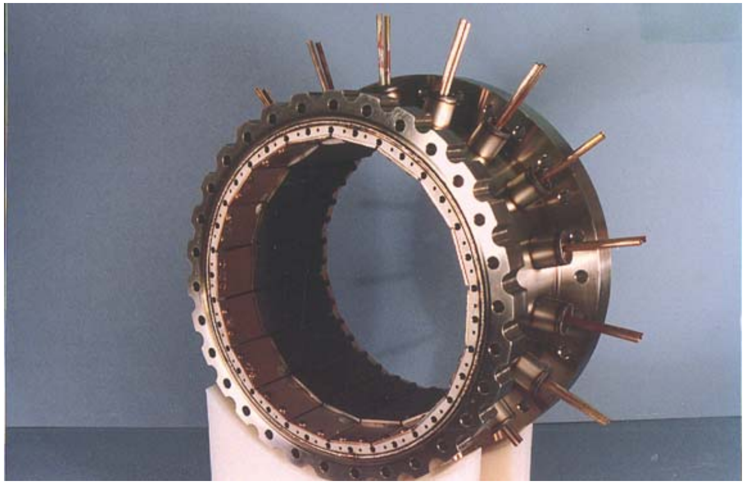
- **How to avoid the problem of HOMs**
- **Generate few HOMs** in the first place
  → cavity design (low frequency, large iris)
  → lower loss factor
- **Enable easy HOM extraction** from the cavity (few cells, large beam tubes)
- **Damp heavily** extracted HOMs (efficient loads)
  → lowers Q_L

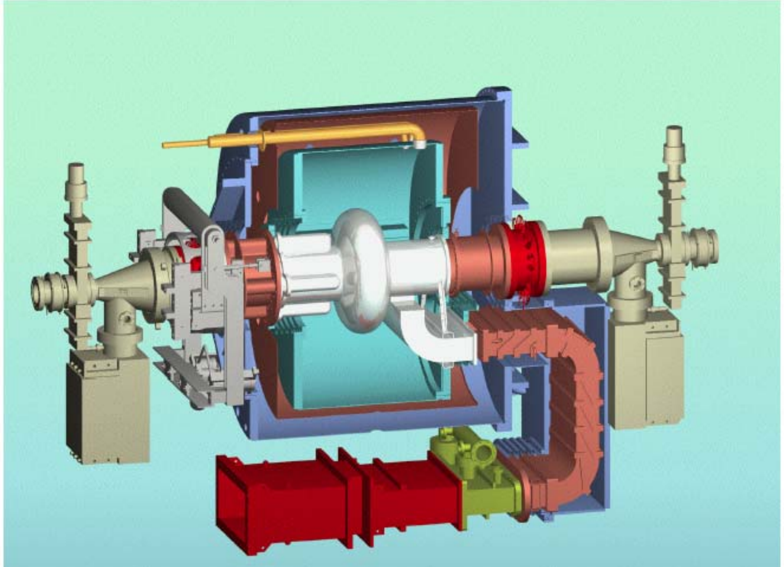


Designing HOM-free cavities

Much information can be had from existing storage-ring cavities

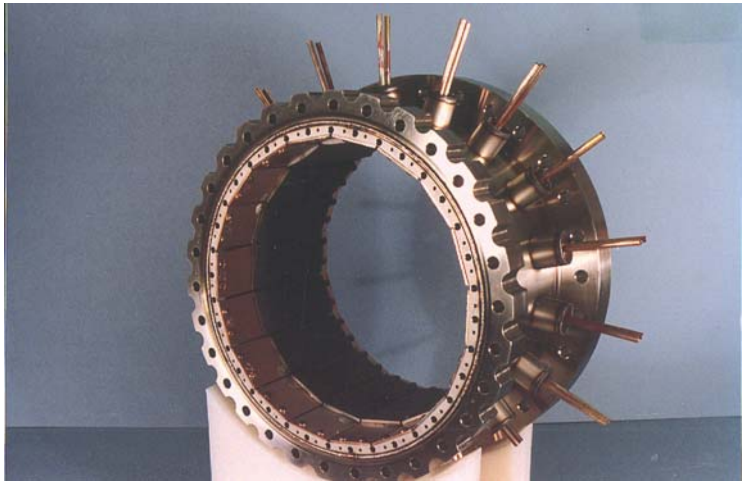
- Storage-ring SRF systems routinely accelerate 500 mA of current, BBU and HOM power is a big issue
- Tend to be low frequency (500 MHz)
- Have a large beam tube → excite fewer HOMs, extract them more easily
- Few cells to not trap HOMs at the center
- Strong absorber to damp all HOMs for very low *Q* values



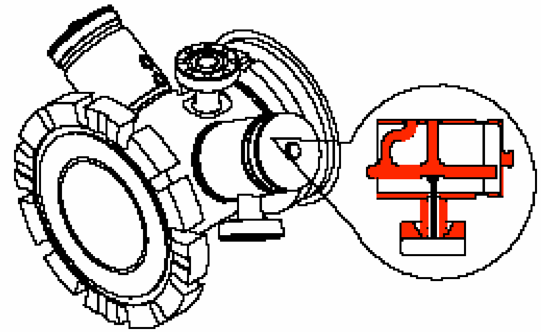


500 MHz Cornell system

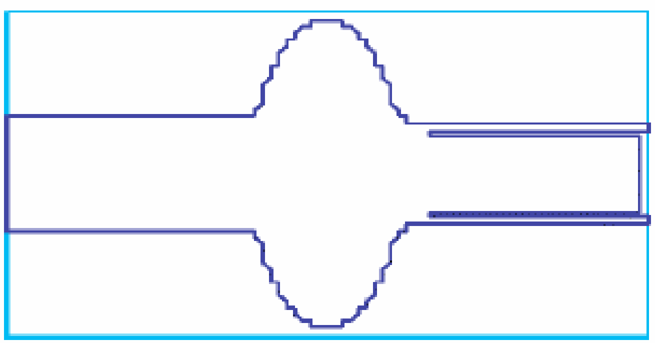
HOM absorber designs



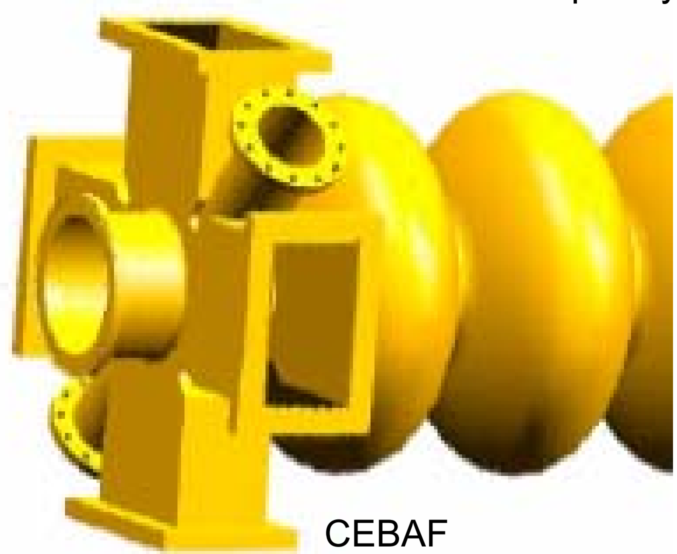
Cornell, KEK B-factories



Multiple coaxial loops
(DESY, CERN)
Lower frequency, low power



Coaxial/radial beam pipe
(KEK, JAERI)

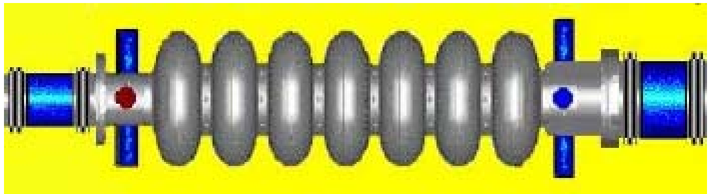


CEBAF

Cavities for future light sources

Solutions

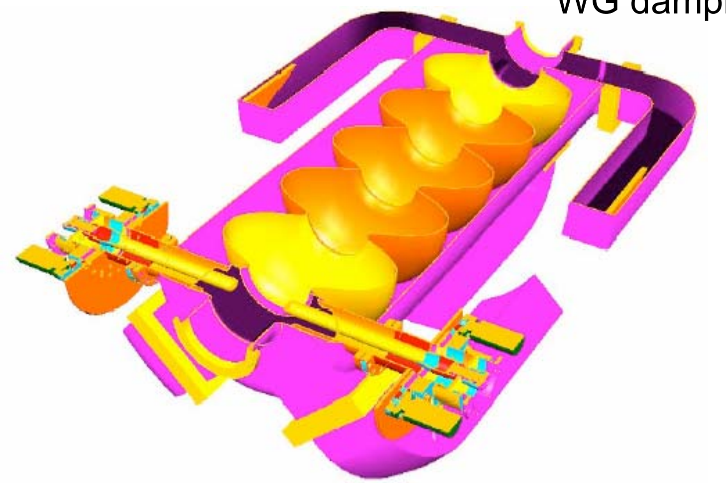
BESSY FEL: < 75 µA
„Standard TESLA technology“
Loop couplers



Cornell ERL: 100 mA
Modified TESLA technology, 7 cells
Ferrites + Loop couplers

Coaxial dampers

WG damping



JLAB 750 MHz injector cavities: 1 A

Putting everything together

- Superconducting RF has come of age and is a mature and reliable technology
- Not surprisingly, many future (linac-based) projects are based on superconducting RF
- There is much existing technology to choose from!
- None of this is perfect “as is”, but it provides a good starting point
- Many of the challenges arise because we …
    - … want to operate CW
    - … want fairly high energies
    - … must have a linac
    - … want much more current and energy recover
    - … want much shorter bunches (mm to sub mm)
    - … want super beam quality

Conclusions

As a result we …

- … must change the cavity designs
- … **must minimize the dynamic losses**
- … **must minimize the microphonics**
- … must change the cryostat layout
- … must re-examine the cryogenic system
- … must improve the HOM-power extraction
- … must develop RF sources, modify couplers and LLRF control
- … must develop the tuner systems
- … must transfer the technology to industry
- …

There is much to do, but the goals are clear and technical solutions are in sight!

No radical (exotic) changes are needed.

→ From a linac point-of-view, construction of the new CW light sources can begin in the “near” (= few years) future