UVA Course on Accelerator Physics

SRF FOR ACCELERATORS

- APPLICATIONS-

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Two Main Classes of Structures and Accelerators

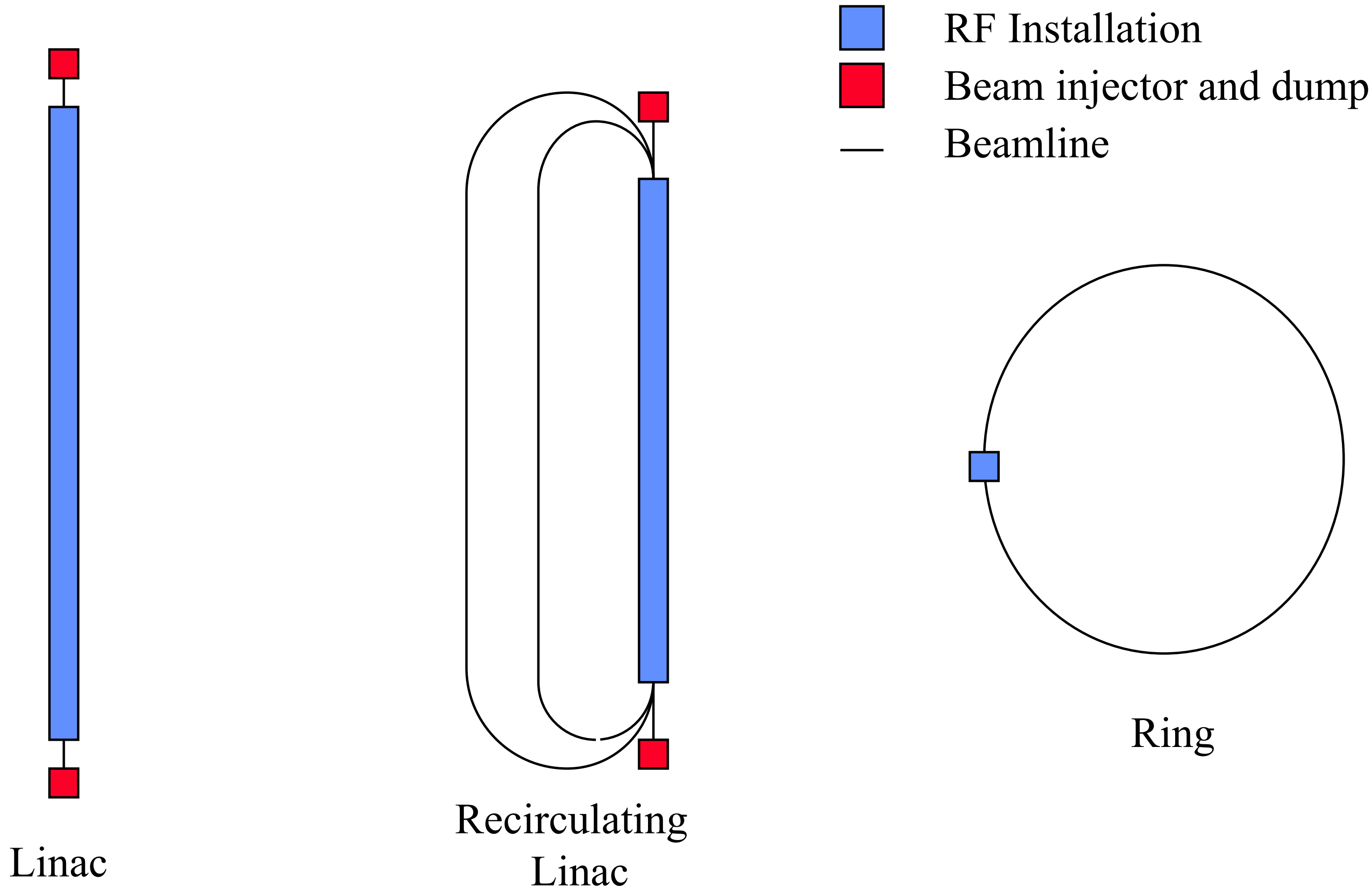
- **Low and medium velocity**
  - **Proton and ion accelerators**

- **High velocity**
  - **Electron accelerators**

Electron Accelerators

- Factories and storage rings
- Recirculating linacs – CEBAF
- Free electron lasers
- Linear colliders
- Linac – ring colliders, electron cooling
- Muon colliders
- Neutrino factories

Recirculating Linacs



Features of Recirculating Linacs and Storage Rings

Linacs

Emittance dominated by source emittance and emittance growth down linac

Beam Polarization "easily" produced at the source, switched, and preserved

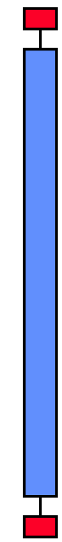
Total transit time is quite short

Beam is easily extracted.

Utilizing source control, flexible bunch patterns possible

Long undulators are a natural addition

Bunch durations can be SMALL



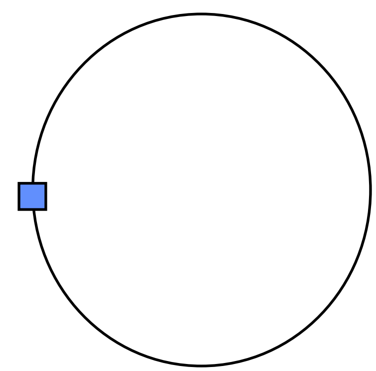
Storage Rings

Up to now, the stored average current is much larger

Very efficient use of accelerating voltage

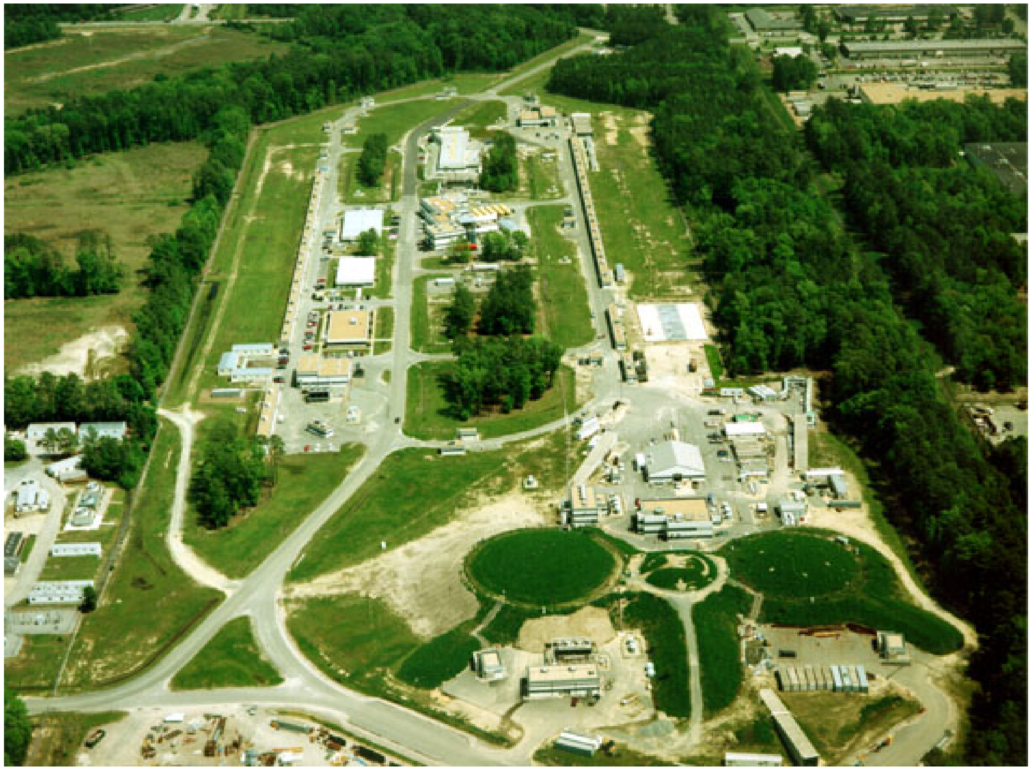
Technology well developed and mature (+ or -)

There's nothing you can do about synchrotron radiation damping

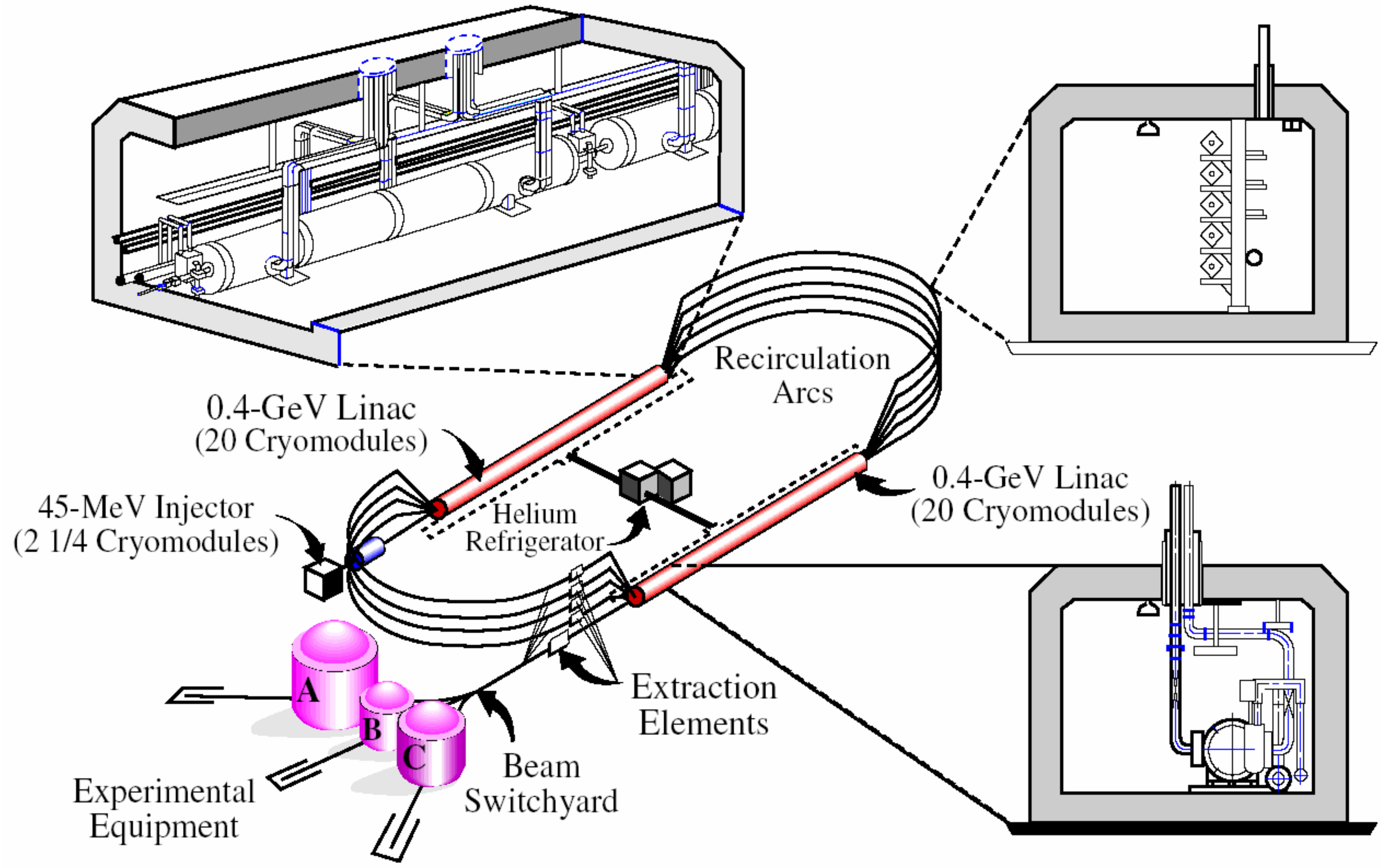


The CEBAF at Jefferson Lab

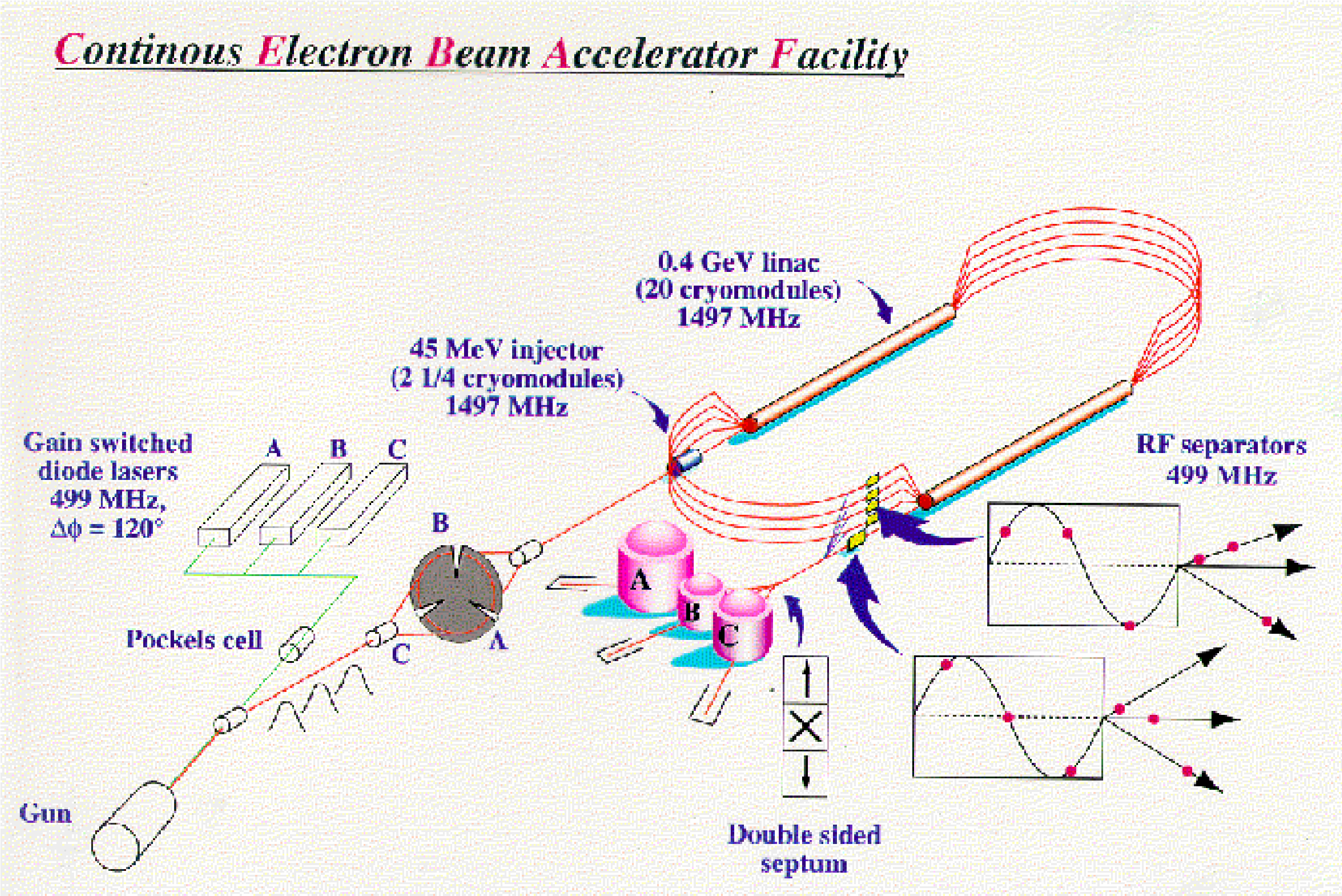
- Most radical innovations (had not been done before on the scale of CEBAF):
  - choice of srf technology
  - use of multipass beam recirculation
- Until LEP II came into operation, CEBAF was the world's largest implementation of srf technology.



CEBAF Accelerator Layout



CEBAF Accelerator Layout

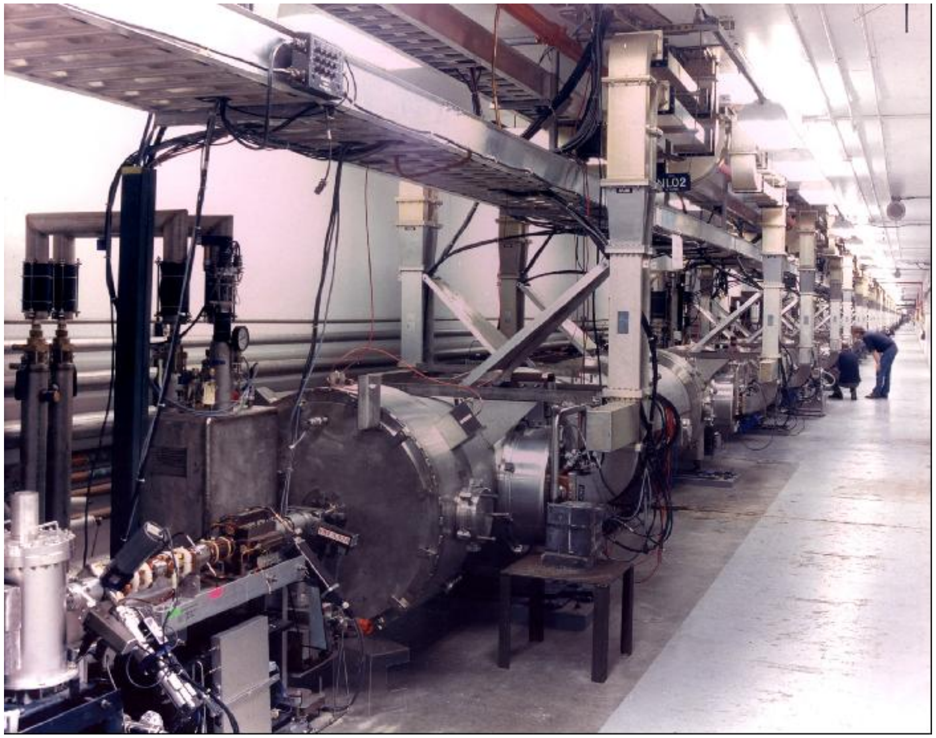


Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

CEBAF Beam Parameters

Beam energy	6 GeV
Beam current	A: 100 μA, B: 10-200 nA, C: 100 μA
Normalized rms emittance	1 mm mrad
Repetition rate	500 MHz/Hall
Charge per bunch	≤ 0.2 pC
Extracted energy spread	< 10^{-4}
Beam sizes (transverse)	< 100 microns
Beam size (longitudinal)	100 microns (330 fsec)
Beam angle spread	< 0.1/γ

CEBAF Accelerator



CEBAF Cavities

Energy Recovering Linacs

- Energy recovery is the process by which the energy invested in accelerating a beam is returned to the rf cavities by decelerating the same beam
- There have been several energy recovery experiments to date
  - Stanford SCA/FEL
  - Los Alamos FEL
  - CEBAF front end
- Same-cell energy recovery with cw beam current up to 5 mA and energy up to 50 MeV has been demonstrated at the Jefferson Lab IR FEL. Energy recovery is used routinely for the operation of the FEL as a user facility

Features of Energy Recovery

- With the exception of the injector, the required rf power is nearly independent of beam current
  - Increased overall system efficiency
  - Reduced rf capital cost

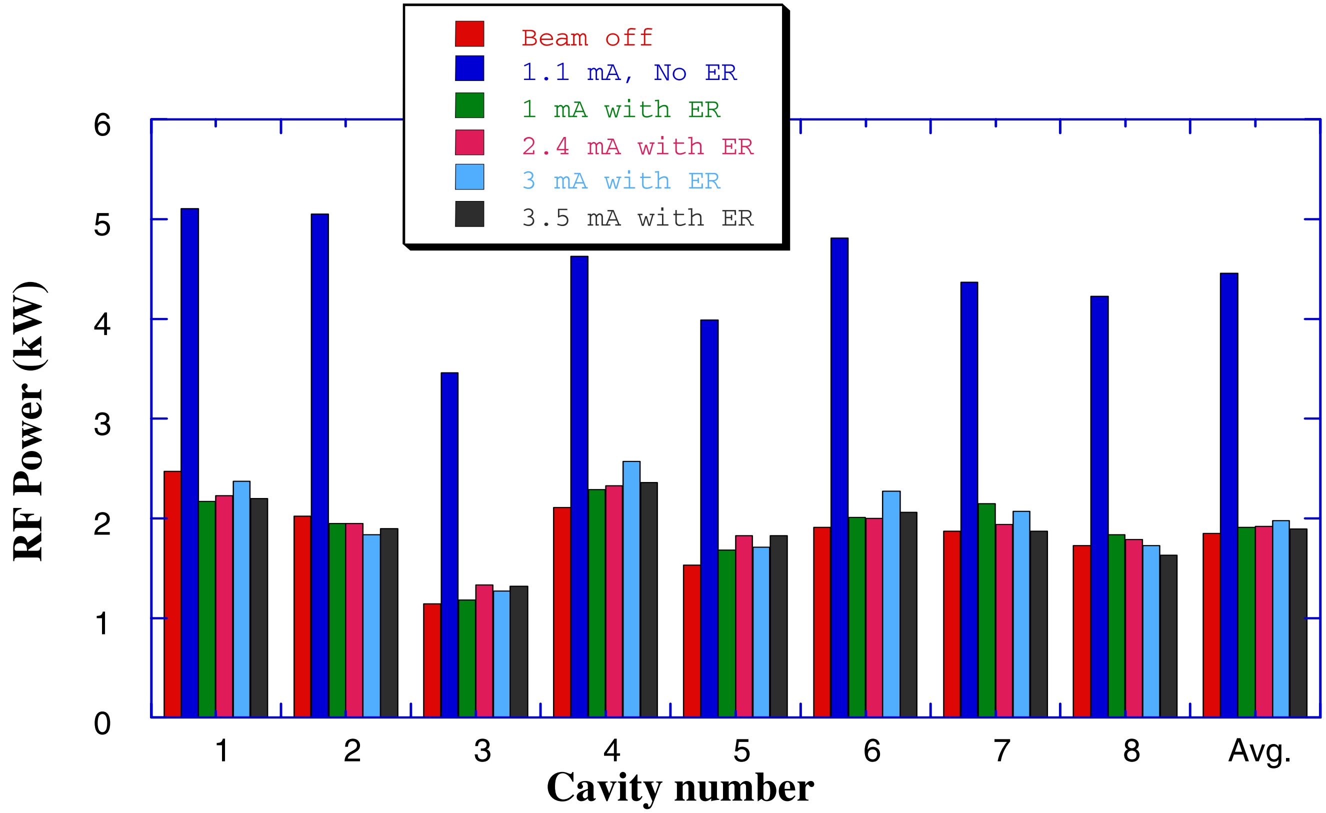
- The electron beam power to be disposed of at beam dumps is reduced by ratio of E_{max}/E_{inj}
  - Thermal design of beam dumps is simplified
  - If the beam is dumped below the neutron production threshold, then the induced radioactivity (shielding problem) will be reduced

Three Main Challenges of Energy Recovery

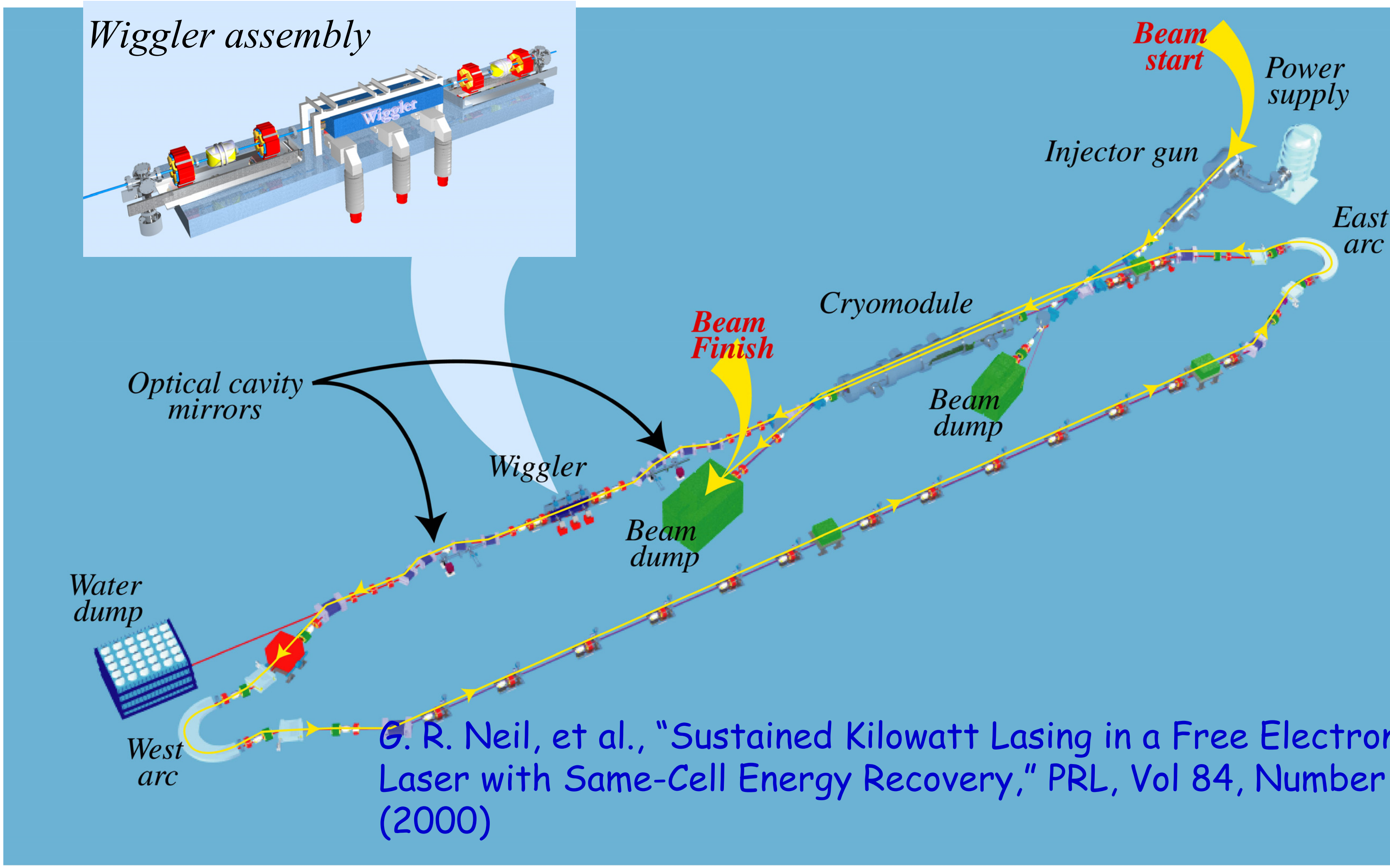
- Generation and preservation of low emittance, high average current beams
- Accelerator transport
- High current effects in superconducting rf

Demonstration of Energy Recovery

With energy recovery the required linac rf power is ~ 16 kW, nearly independent of beam current. It rises to ~ 36 kW with no recovery at 1.1 mA

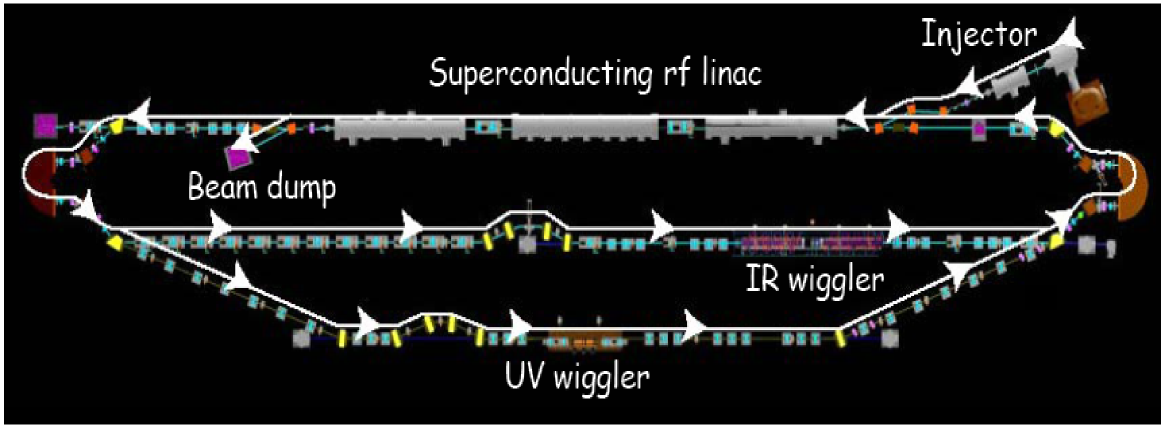


The JLab 2.13 kW IRFEL and Energy Recovery Demonstration



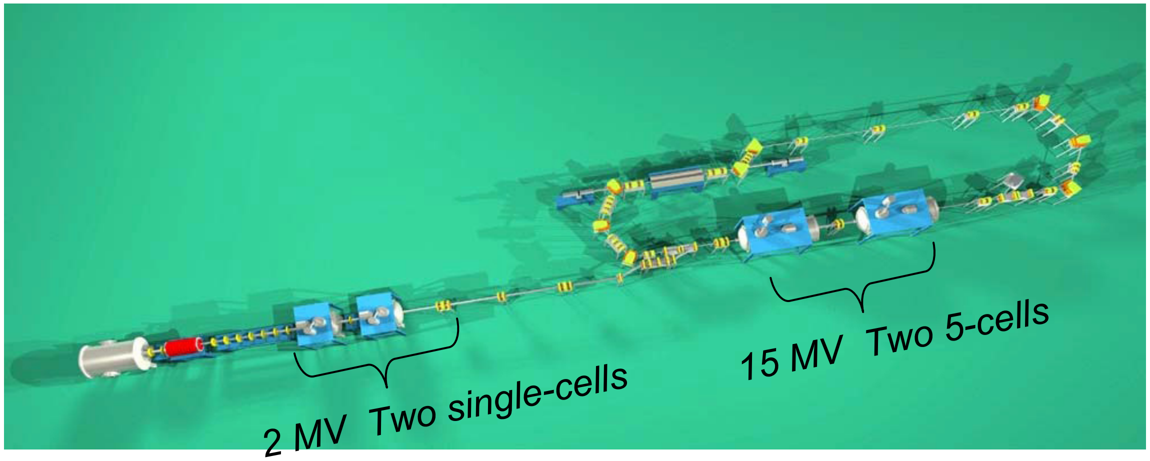
G. R. Neil, et al., "Sustained Kilowatt Lasing in a Free Electron Laser with Same-Cell Energy Recovery," PRL, Vol 84, Number 4 (2000)

Free Electron Lasers



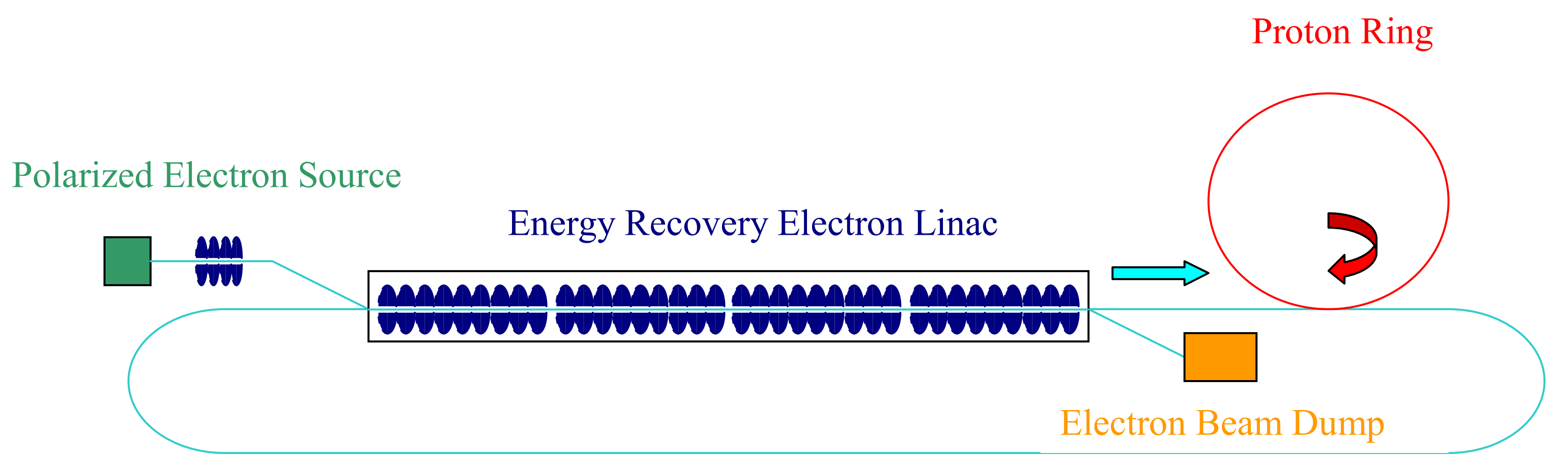
Parameter	Design Value	Test 1	Test 2
Energy [MeV]	160	145	88
Current [mA]	10	5	9

JAERI FEL with photons power of : 10 kW, IR 22µm.

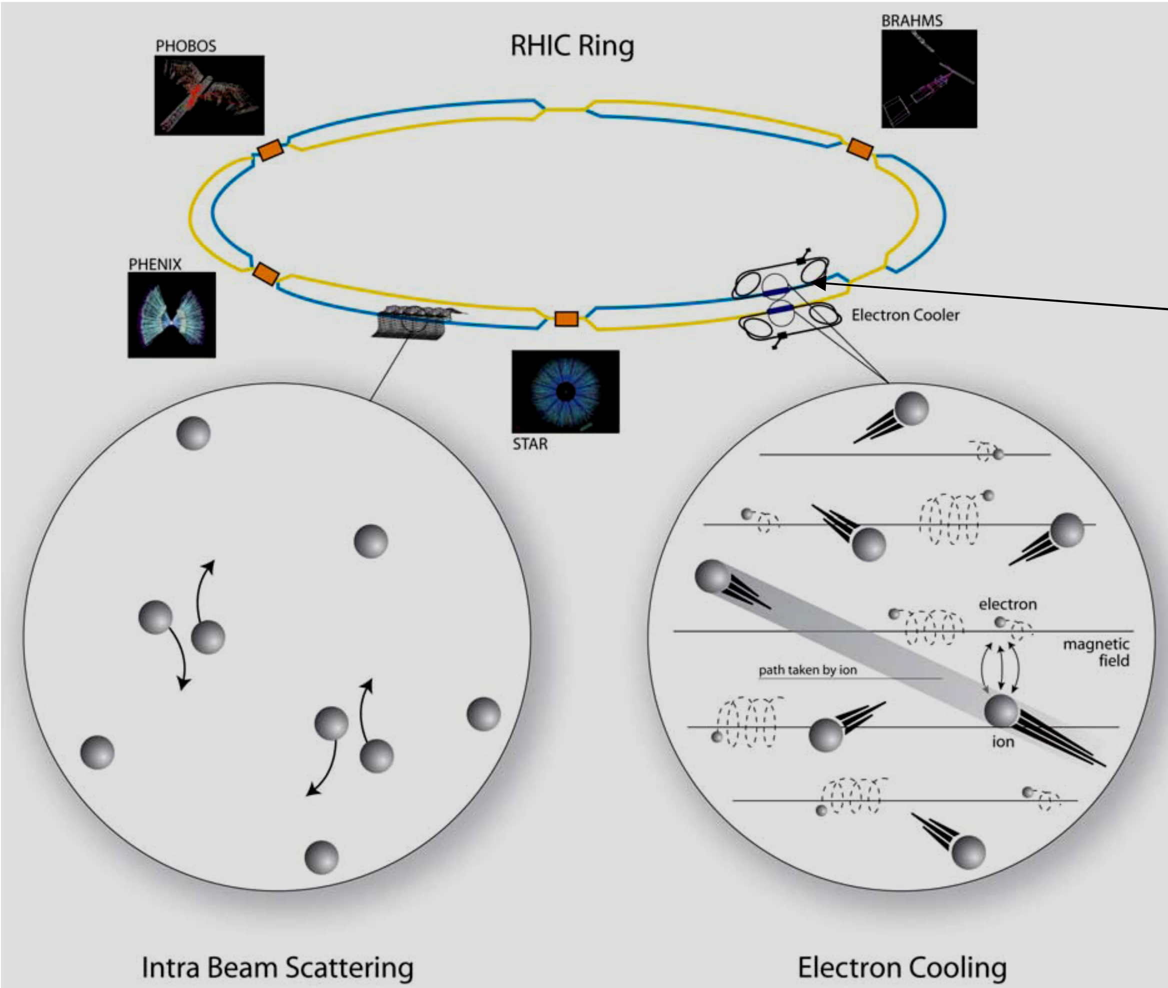


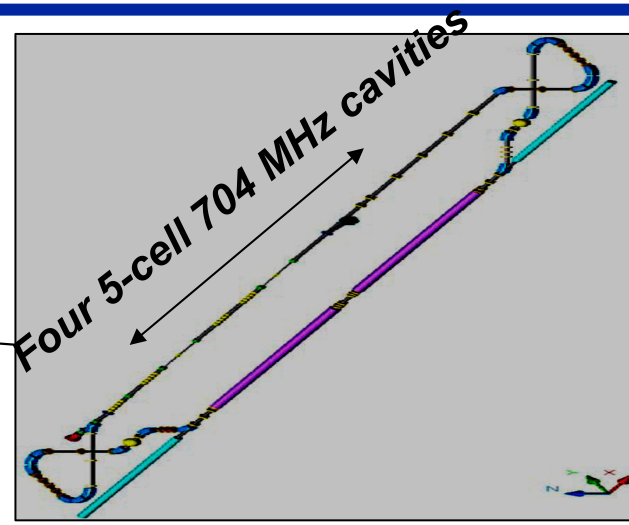
Parameter	Design Value
Energy [MeV]	17
Current [mA]	40
f [MHz]	500
q [pC]	500

Linac–Ring Collider: Schematic Layout



Electron Cooling





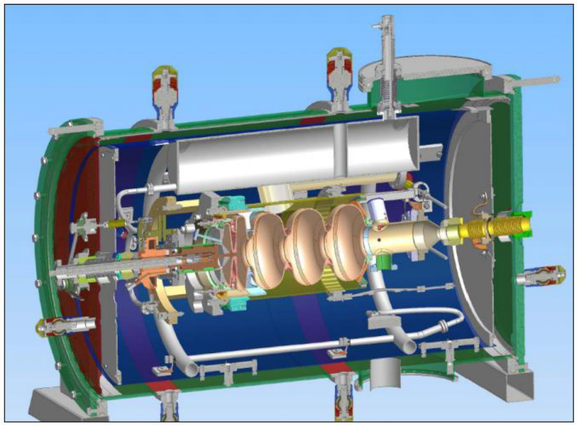
Luminosity for
$^{197}Au^{79+}$ - $^{197}Au^{79+}$*, collision increases by order of magnitude*

$7 \cdot 10^{26} \rightarrow 7 \cdot 10^{27} cm^{-2}s^{-1}$

Energy/beam : 100 GeV/u

SRF Electron Sources

FZR (since 1998)

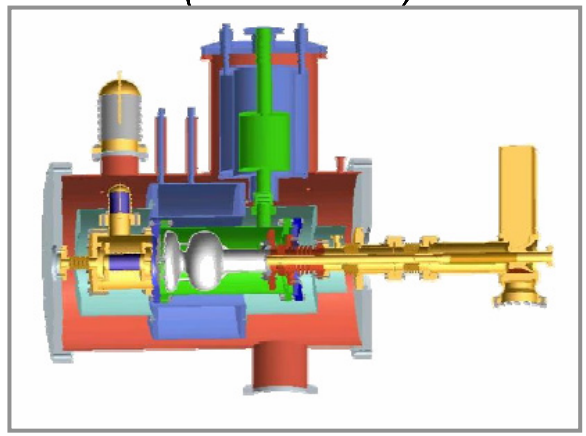


***f* =1.3 GHz**

Cs_2Te ◄ E_{RF}

Courtesy of Dietmar Janssen

IHIP PU (since 2001)

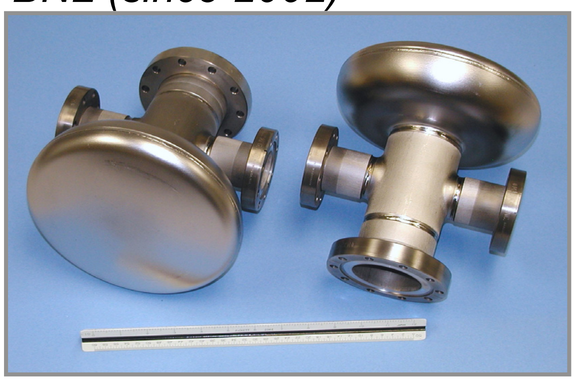


***f* =1.3 GHz**

Cs_2Te ◄ E_{DC}

Courtesy of Hao Jiankui

BNL (since 2002)

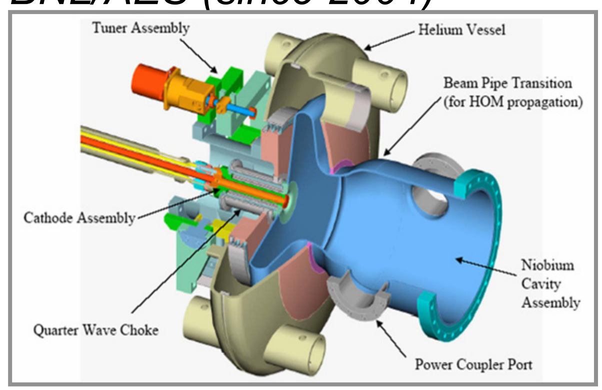


***f* =1.3 GHz**

Nb ◄ E_{RF}

Courtesy of Triveni Rao

BNL/AES (since 2004)

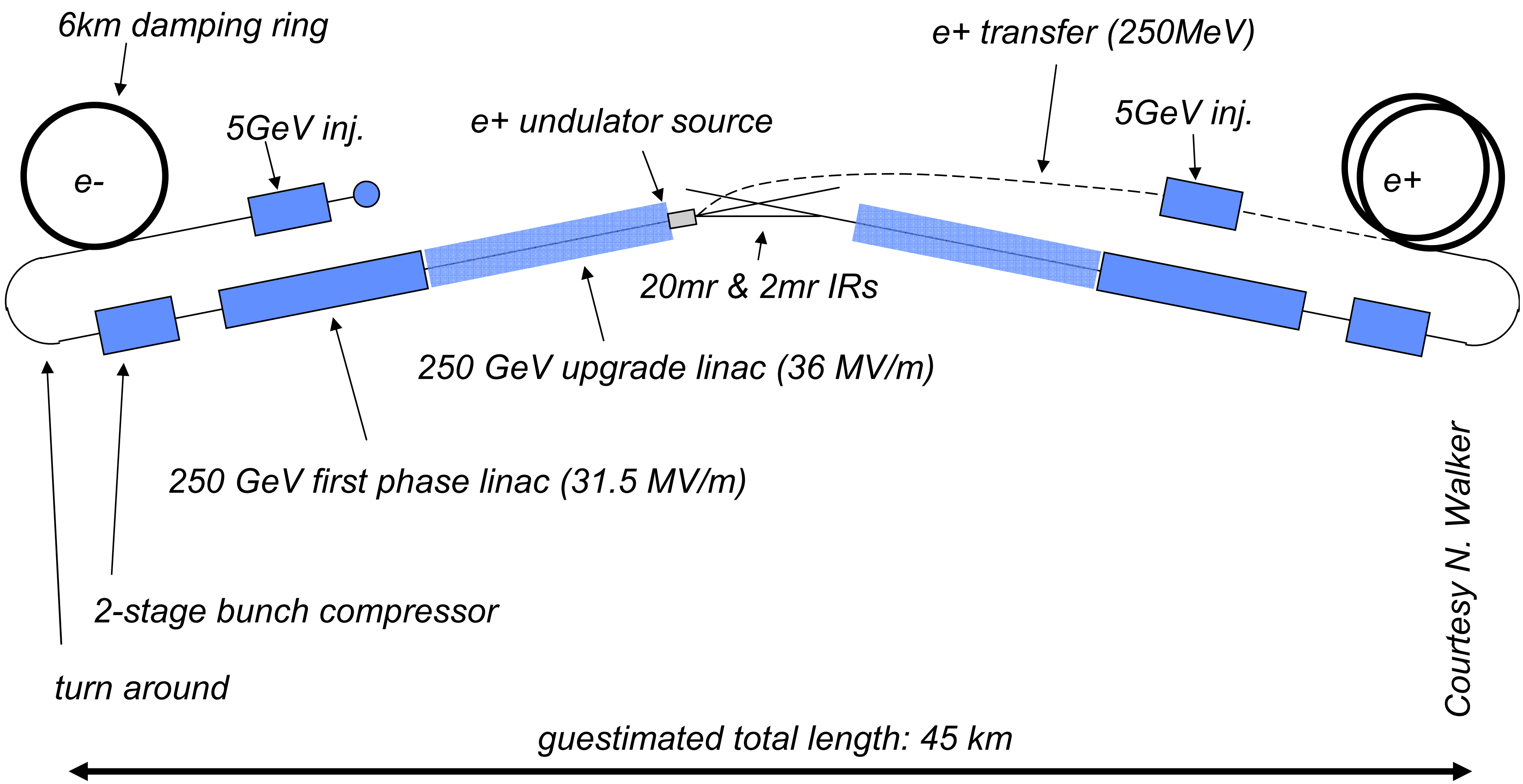


***f* =703.75 MHz**

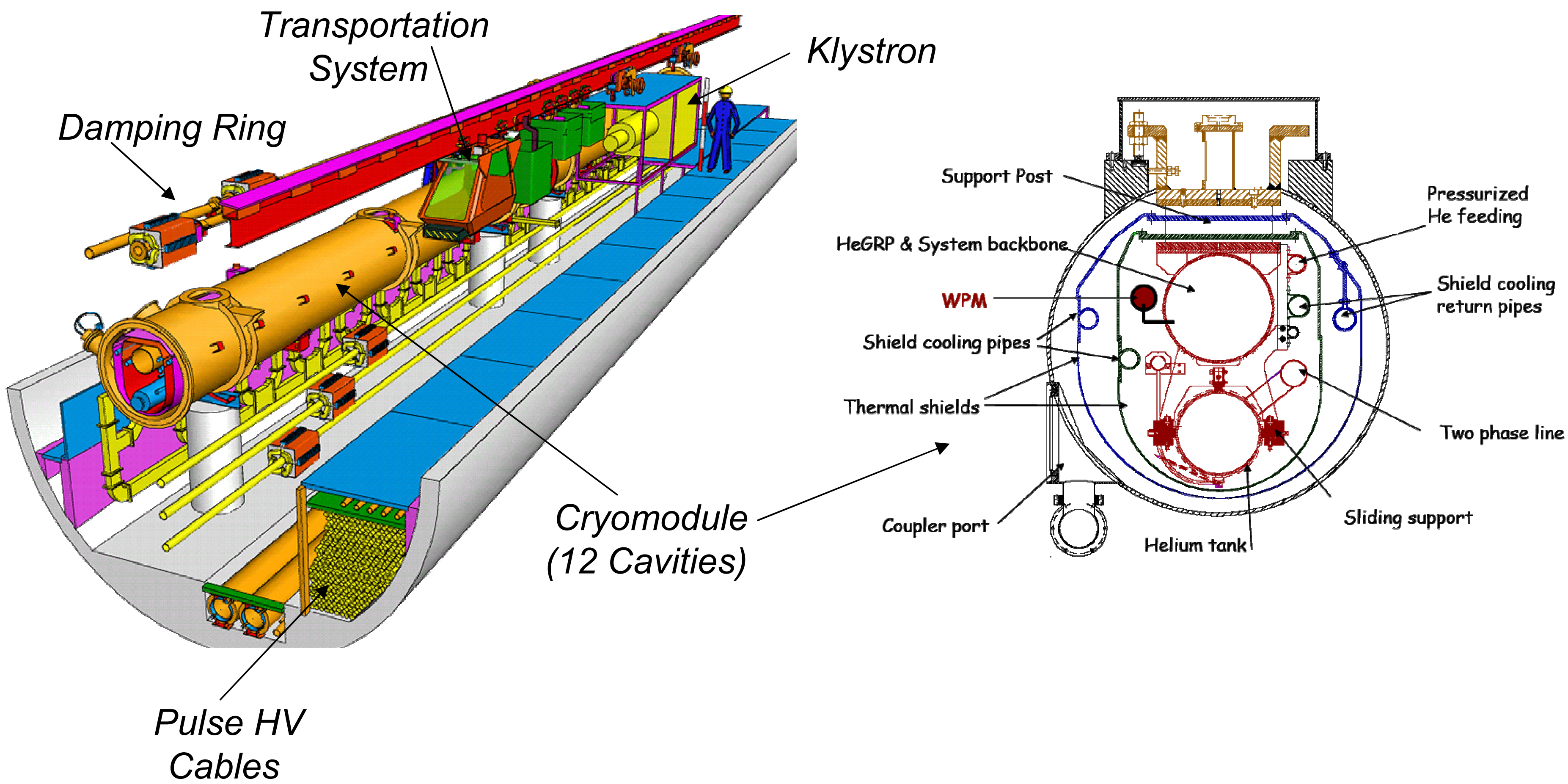
Alkali+◆ ◄ E_{RF}

Courtesy of Alan Todd

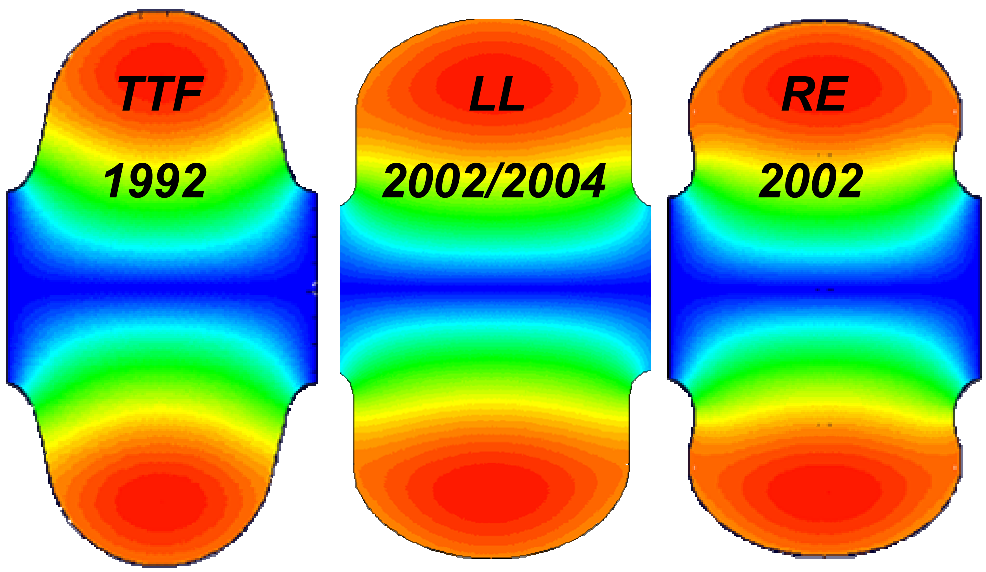
Linear Collider



Linear Collider

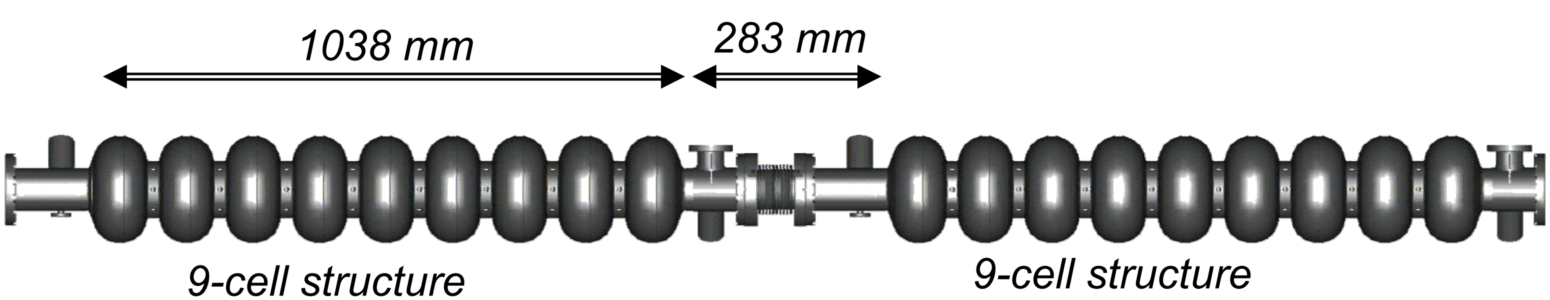


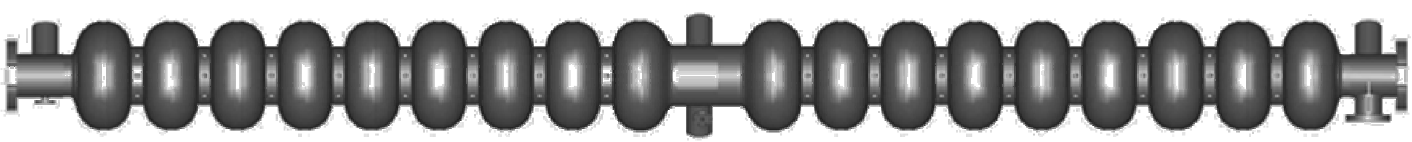
Cavity shapes for the International Linear Collider



r_{iris}	[mm]	35	30	33
k_{cc}	[%]	1.9	1.52	1.8
E_{peak}/E_{acc}	-	1.98	2.36	2.21
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76
R/Q	[Ω]	113.8	133.7	126.8
G	[Ω]	271	284	277
R/Q*G	[Ω*Ω]	30840	37970	35123

Cavities for the ILC

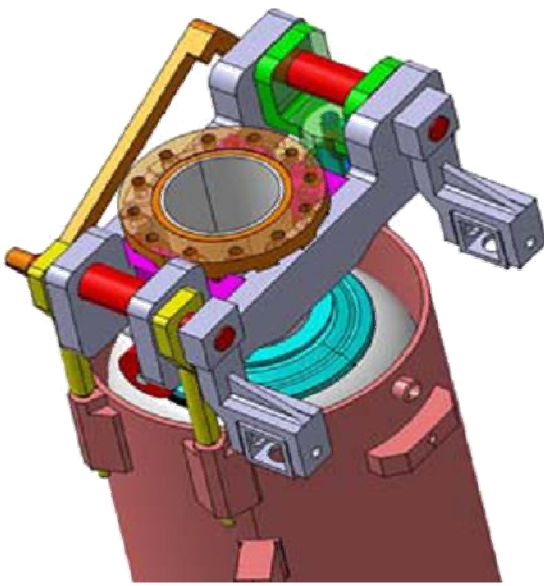


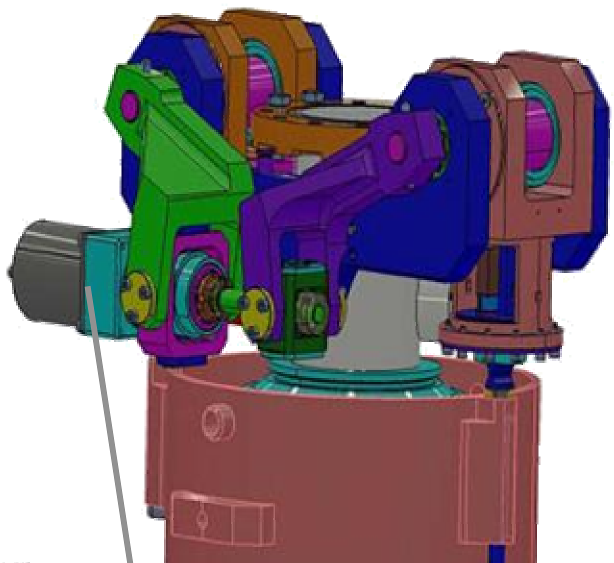


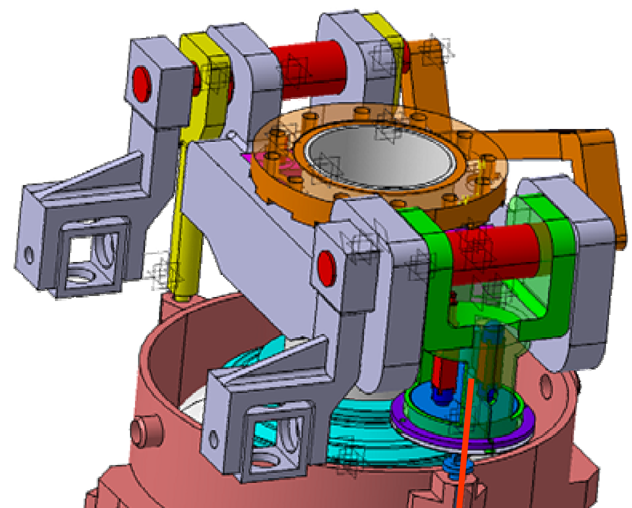
Frequency Tuners

Saclay Lever Tuner spec.

- *$\pm$ 460 kHz tuning range*
- *4 nm resolution = 1.2 Hz (sufficient if <5Hz)*
- *~ 1kHz fast compensation by piezo*



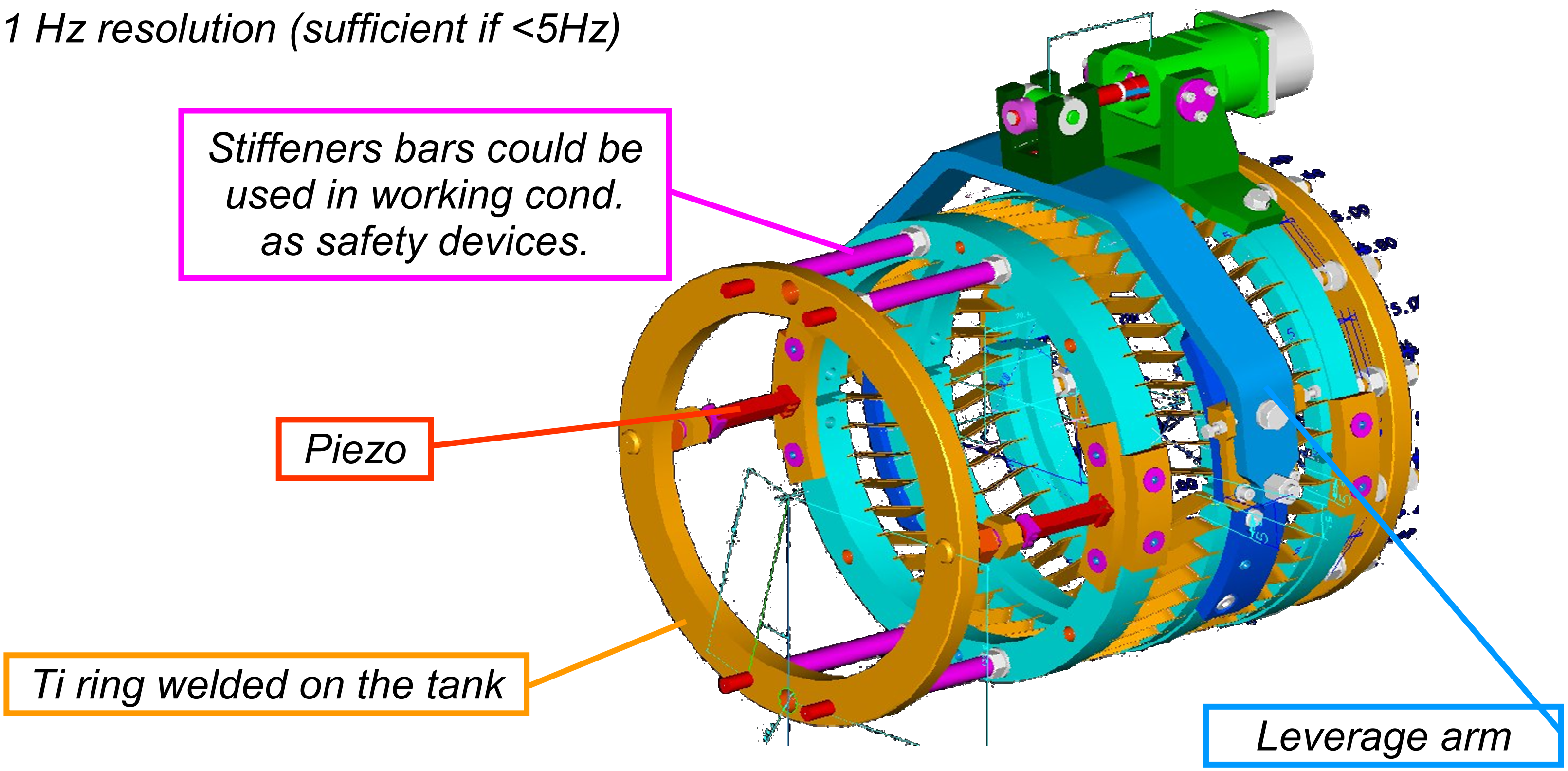




Frequency Tuners

Blade Tuner spec.

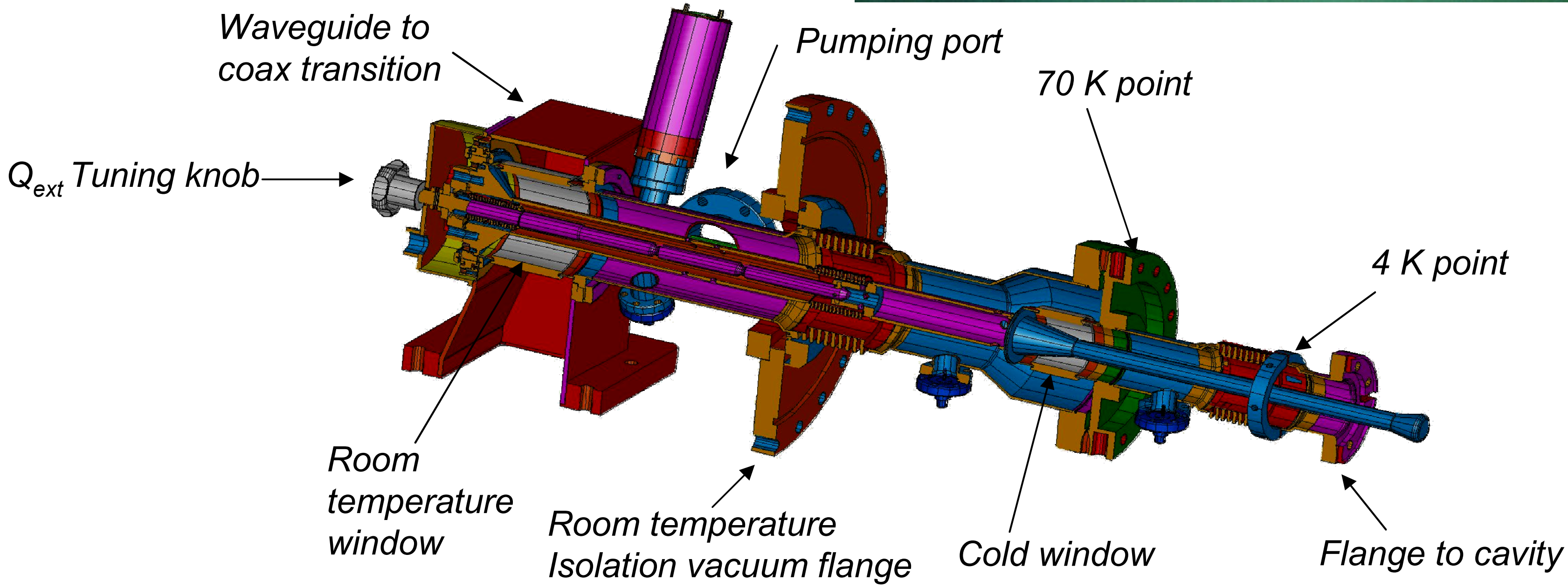
- *± 1 mm fine tuning (on cavity) → ΔF on all piezo (sum) ≈ 3.5 kN*
- *1 kHz fast tuning → ≈ 3 μm cavity displacement → ≈ 4 μm piezo displacement*
- *4 μm piezo displacement → ≈ Δ F on all piezo ≈ 11.0 N*
- *~1 Hz resolution (sufficient if <5Hz)*



Fundamental Power Coupler

Test showed that FPC (TTFIII)

- *Power capability is 1 MW in the TW mode.*
- *SW capability is at least 1 MW*
- *Processing time is of concern*



Applications of low and medium-β superconducting structures

	High Current	Medium/Low Current
CW	Accelerator driven systems waste transmutation energy production	Nuclear structure studies Production of radioactive ions
Pulsed	Pulsed spallation sources	

High-current ion cw accelerators

- **Beam: p, H^-, d**
- **Technical issues and challenges**
  - **Beam losses (~ 1 W/m)**
  - **Activation**
  - **High cw rf power**
  - **Higher order modes**
  - **Cryogenics losses**
- **Implications for SRF technology**
  - **Cavities with high acceptance**
  - **Development of high cw power couplers**
  - **Extraction of HOM power**
  - **Cavities with high shunt impedance**

High-current ion pulsed accelerators

- **Beam: p, H^-**
- **Technical issues and challenges**
  - **Beam losses (~ 1 W/m)**
  - **Activation**
  - **Higher order modes**
  - **High peak rf power**
  - **Dynamic Lorentz detuning**
- **Implications for SRF technology**
  - **Cavities with high acceptance**
  - **Development of high peak power couplers**
  - **Extraction of HOM power**
  - **Development of active compensation of dynamic Lorentz detuning**

Medium to low current ion cw accelerators

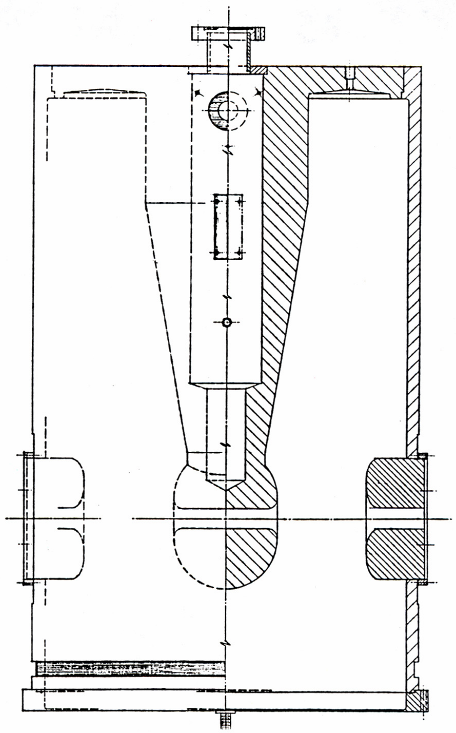
- **Beam; p to U**
- **Technical issues and challenges**
  - —Microphonics, frequency control
  - —Cryogenic losses
  - —Wide charge to mass ratio
  - —Multicharged state acceleration
  - —Activation
- **Implications for SRF technology**
  - —Cavities with low sensitivity to vibration
  - —Development of microphonics compensation
  - —Cavities with high shunt impedance
  - —Cavities with large velocity acceptance (few cells)
  - —Cavities with large beam acceptance (low frequency, small frequency transitions)

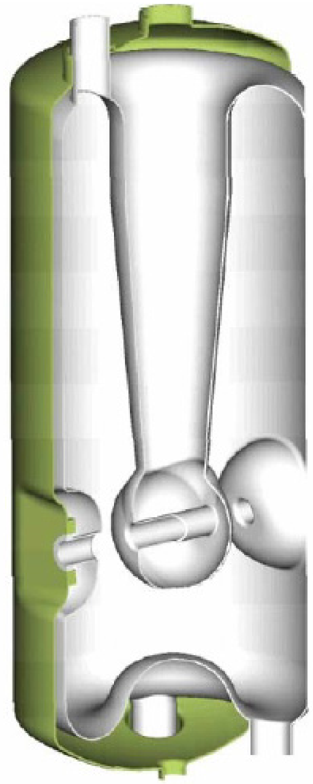
Basic Structure Geometries

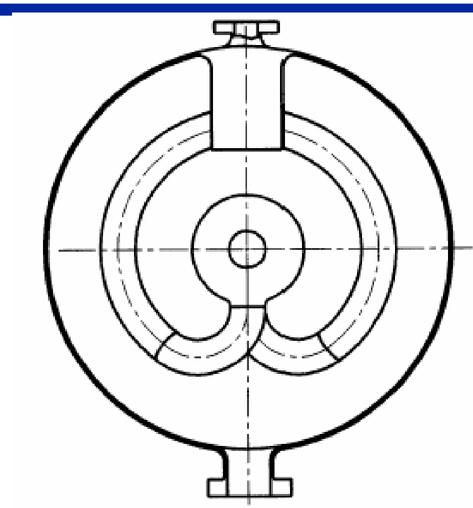
Resonant Transmission Lines

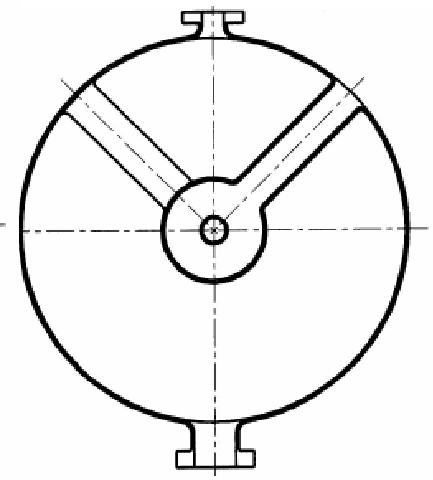
- $\lambda/4$
  - **Quarter-wave**
  - **Split-ring**
  - **Twin quarter-wave**
- $\lambda/2$
  - **Coaxial half-wave**
  - **Spoke**
  - **H-types**
- TM
  - **Elliptical**
  - **Reentrant**
- Other
  - **Alvarez**
  - **Slotted-iris**

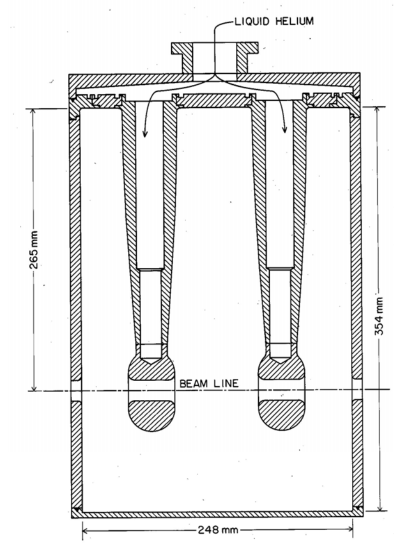
λ/4 Resonant Lines

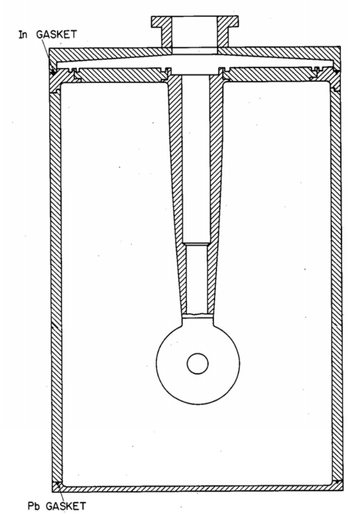




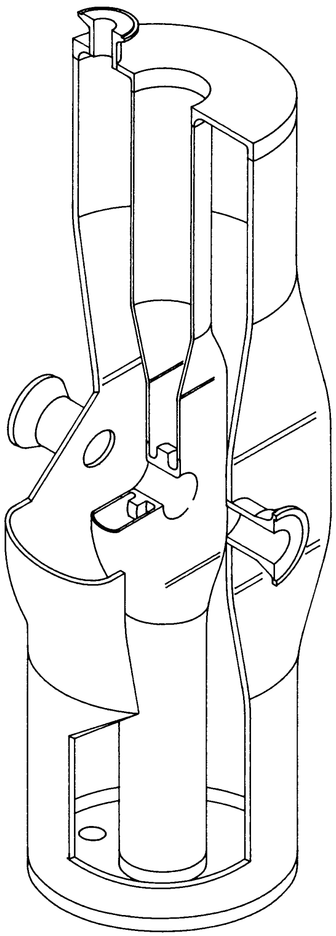


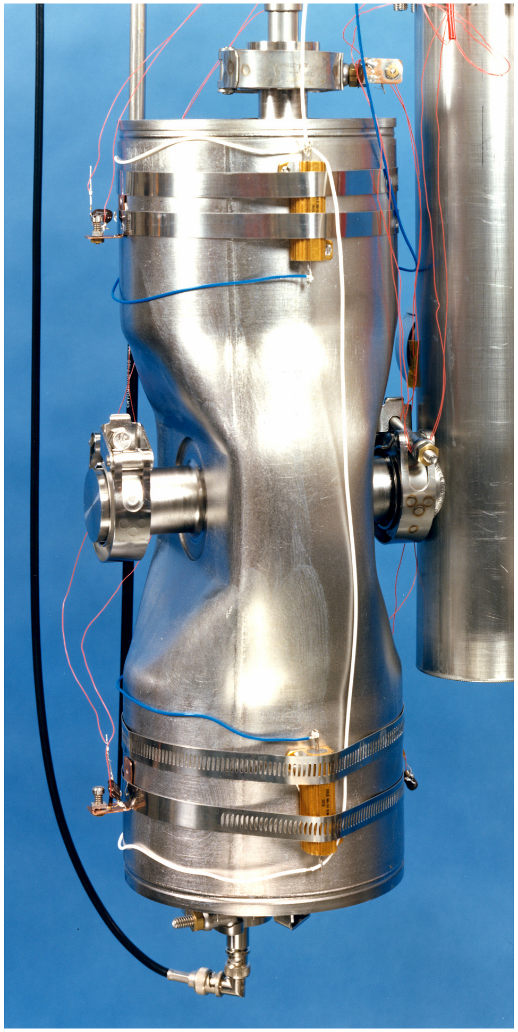


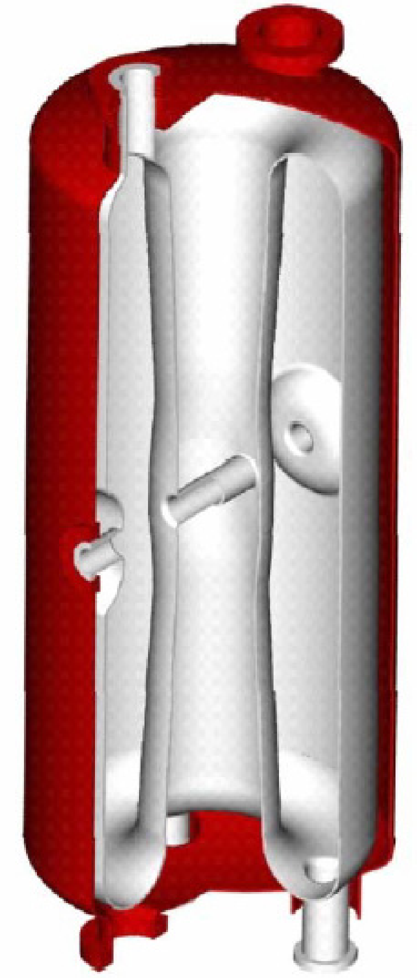




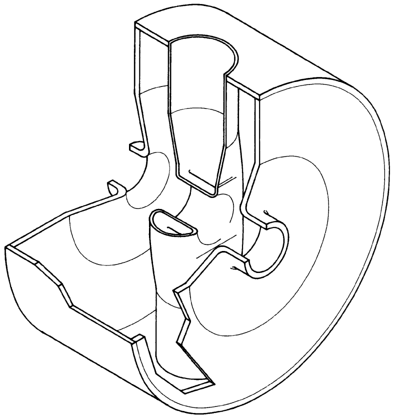
λ/2 Resonant Lines

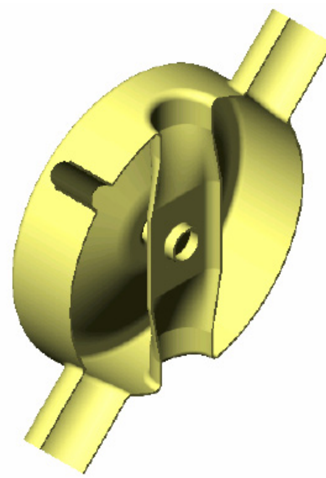


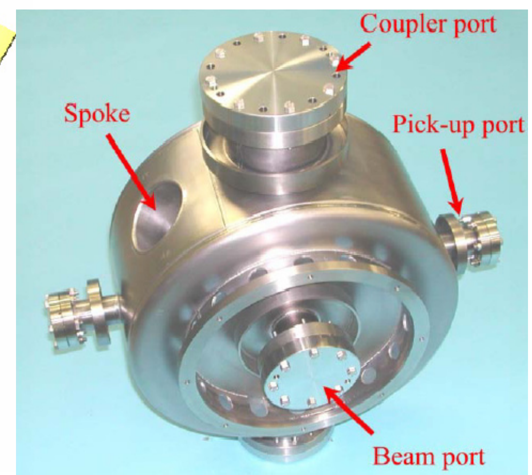




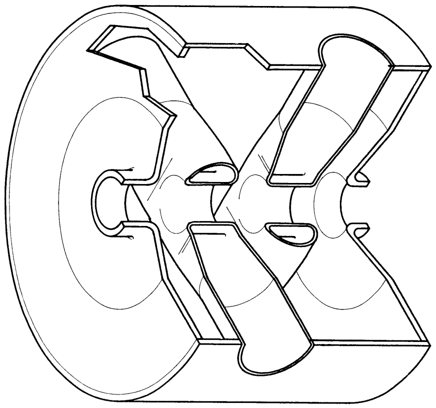
λ/2 Resonant Lines – Single-Spoke

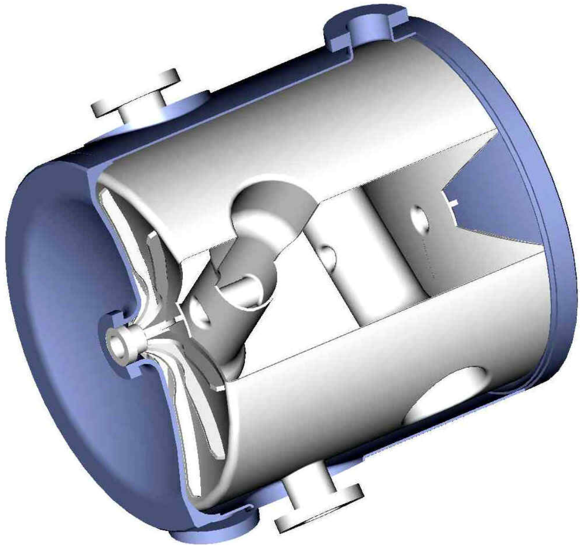


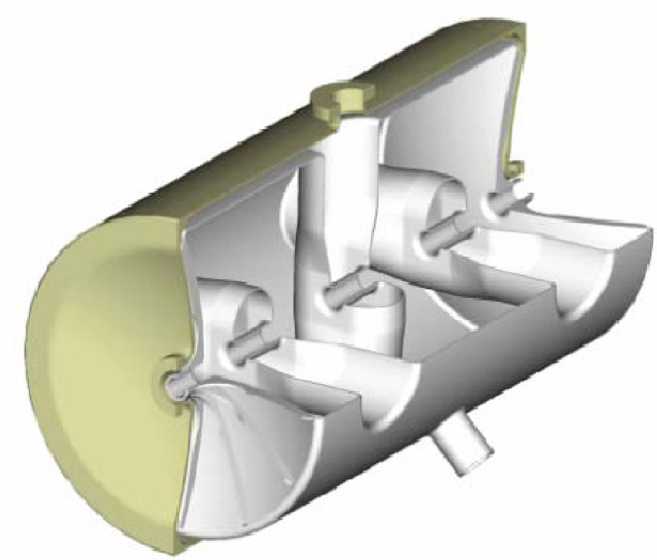




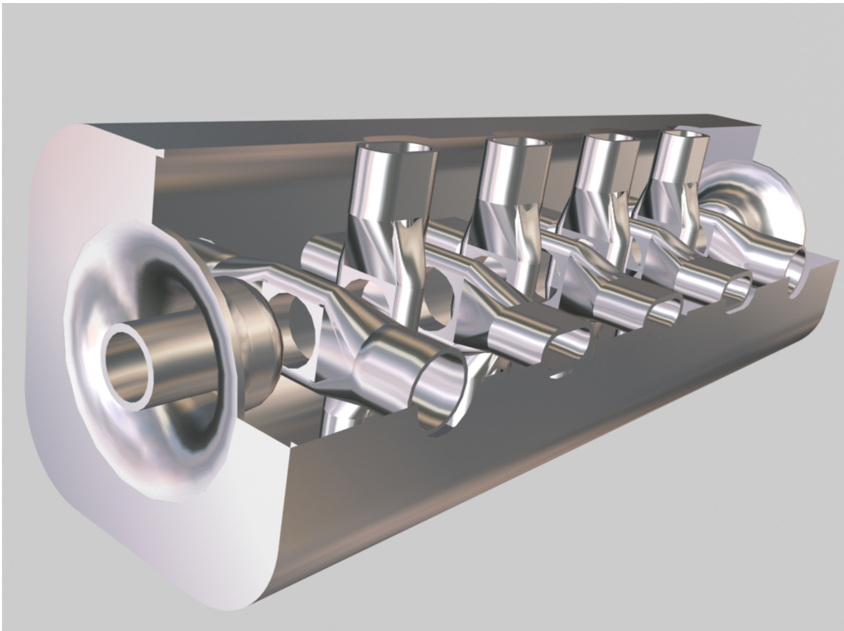
λ/2 Resonant Lines – Double and Triple-Spoke

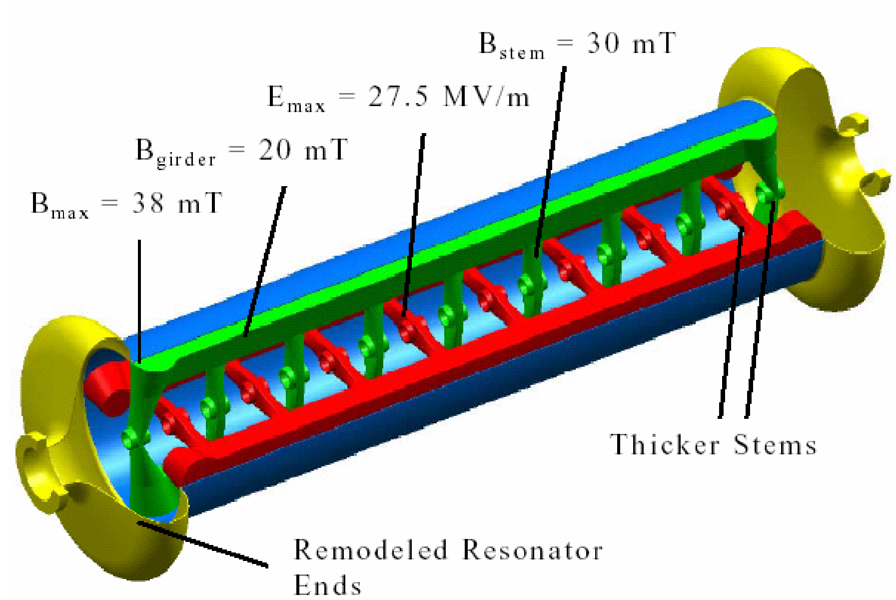




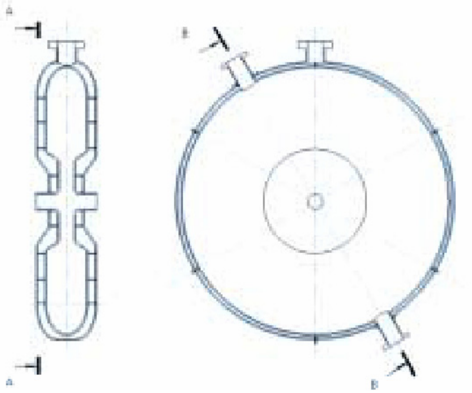


λ/2 Resonant Lines – Multi-Spoke

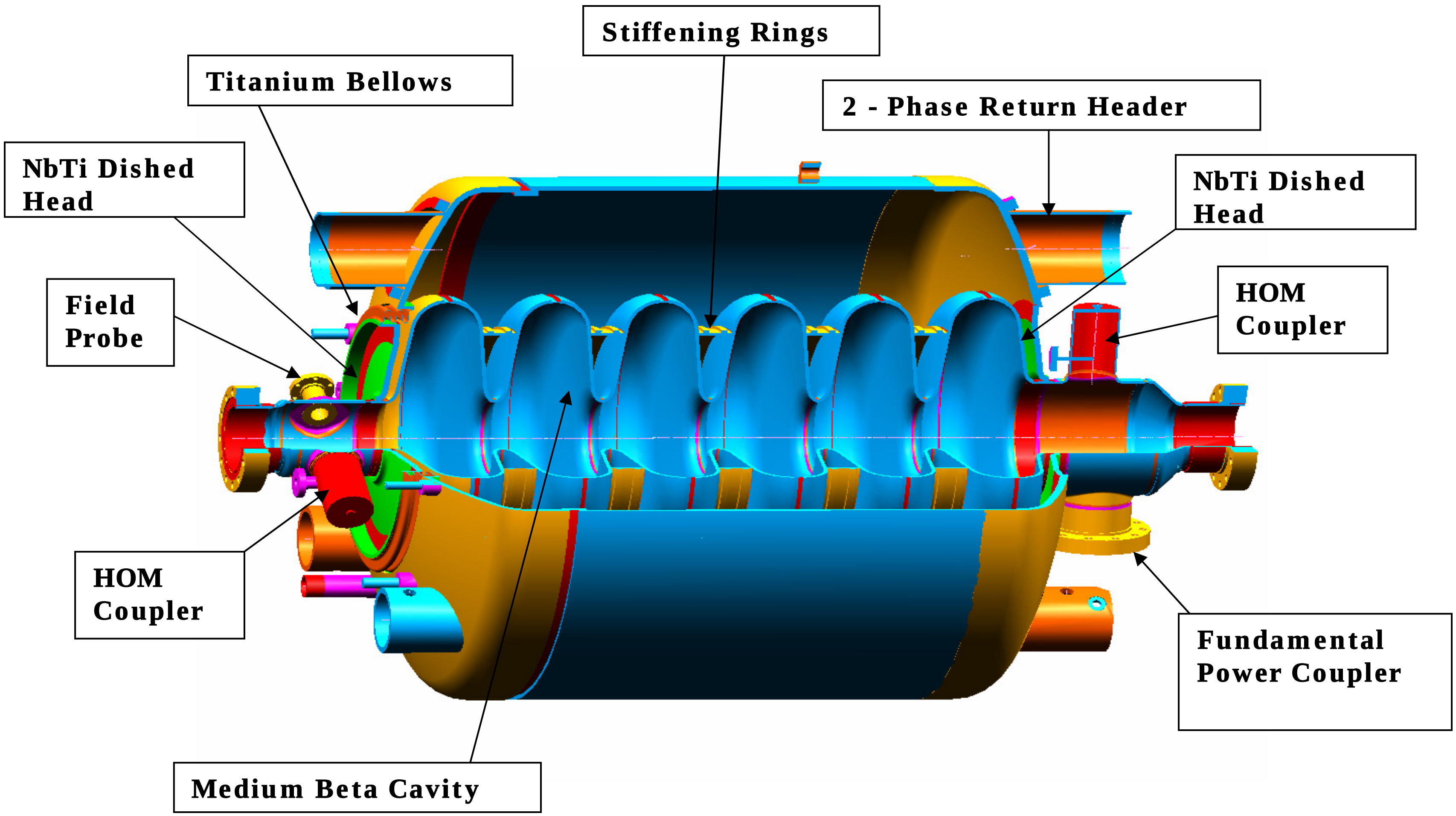




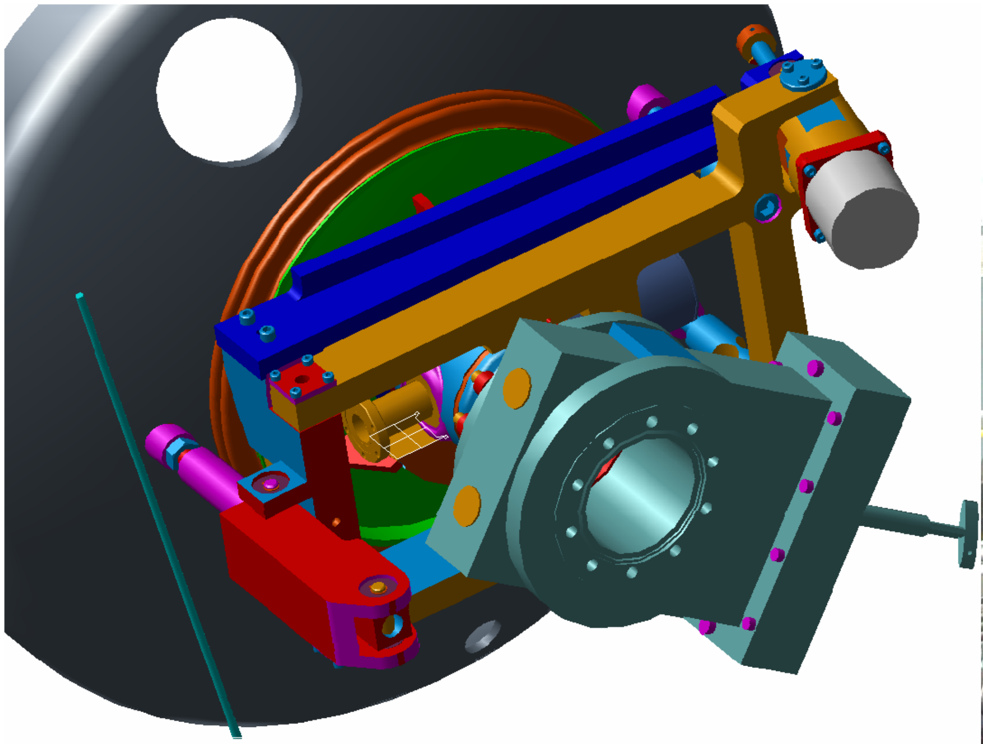
TM Modes

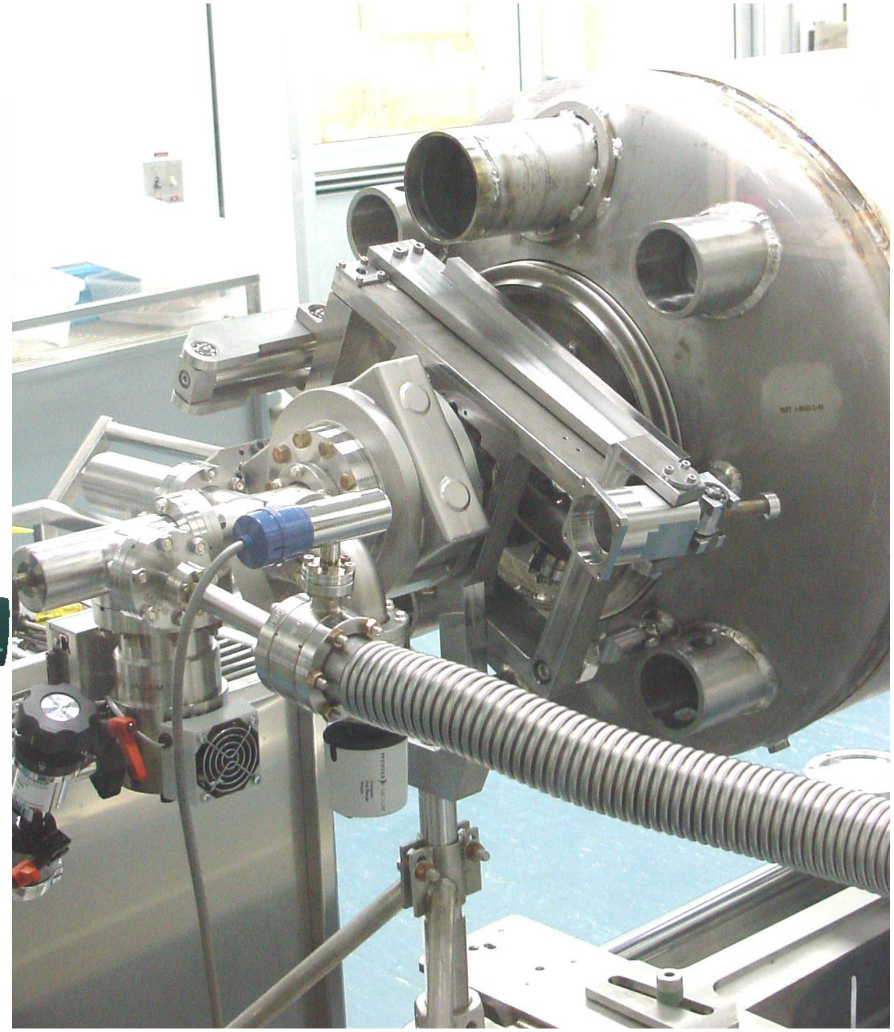


Cavity in Titanium Helium Vessel



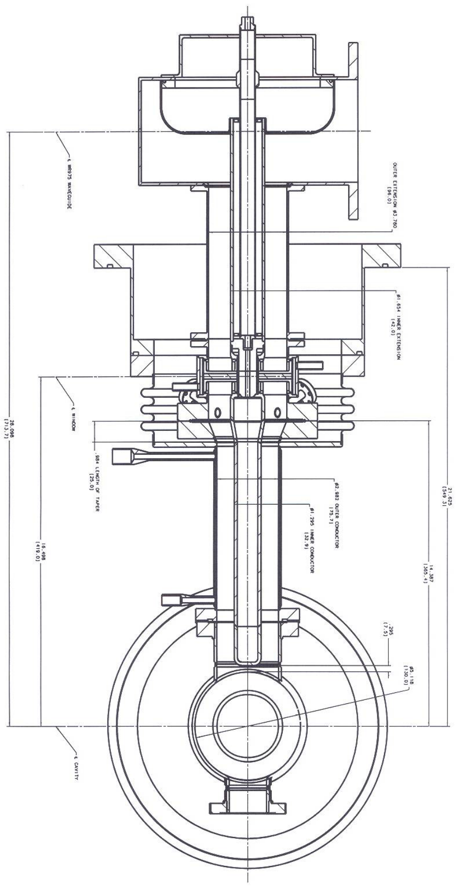
Tuner with Piezo Actuator Installed on Helium Vessel & Cavity

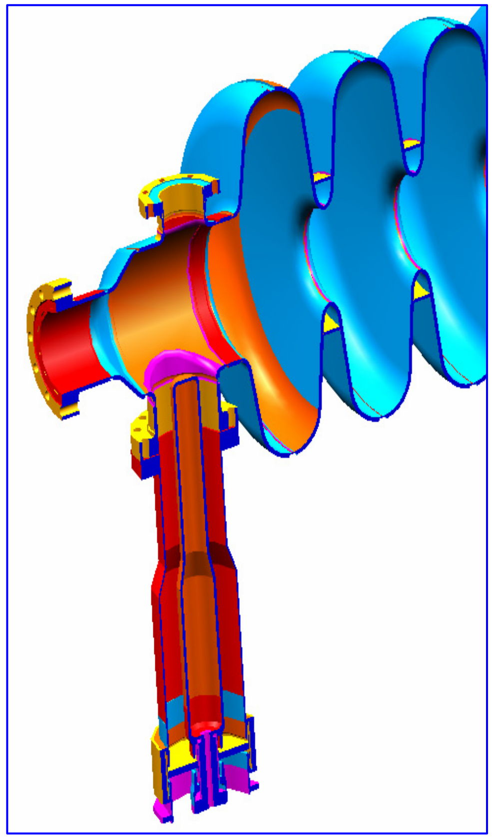


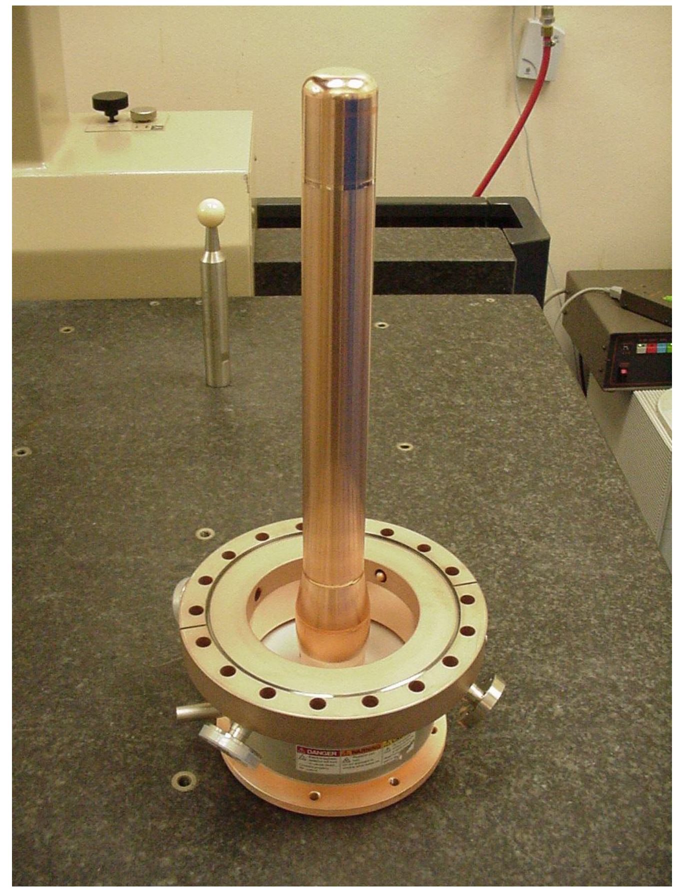


Fundamental Coupler

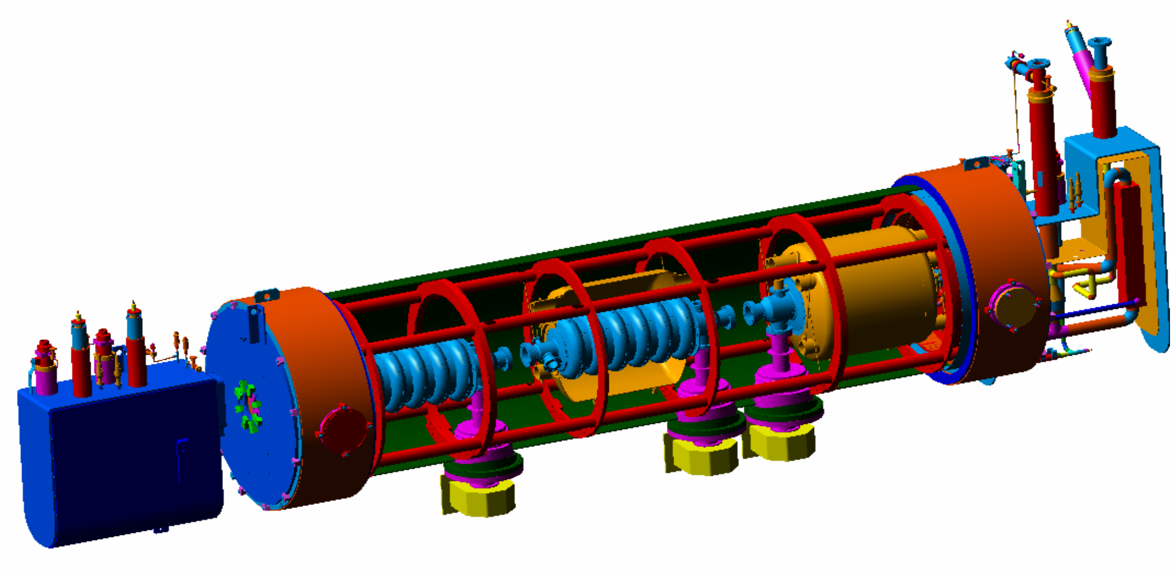
Design is scaled from KEK design

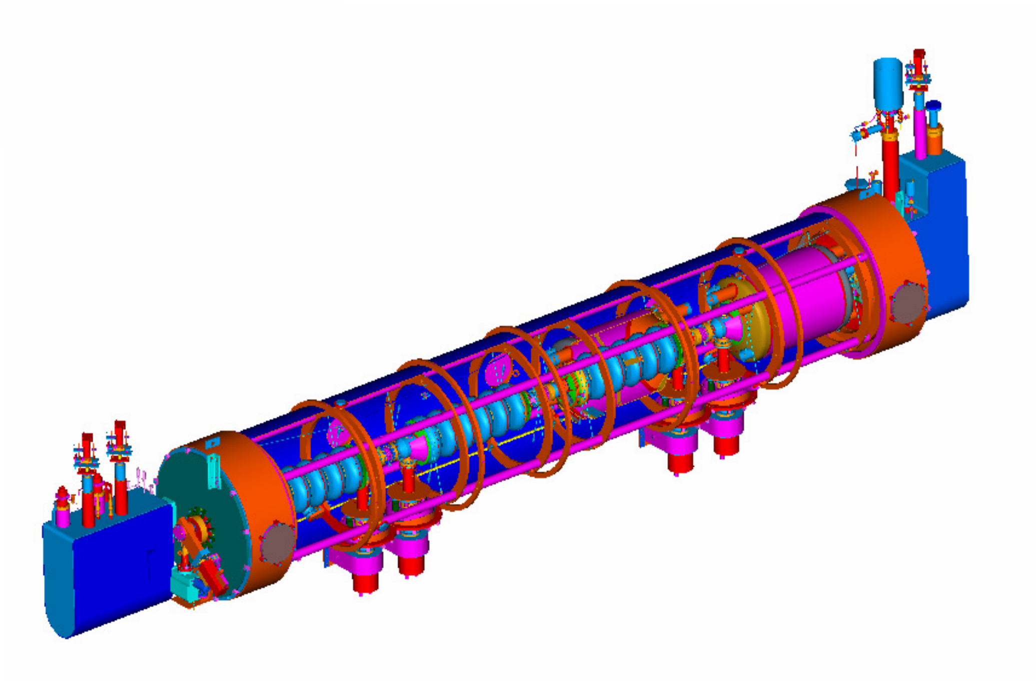




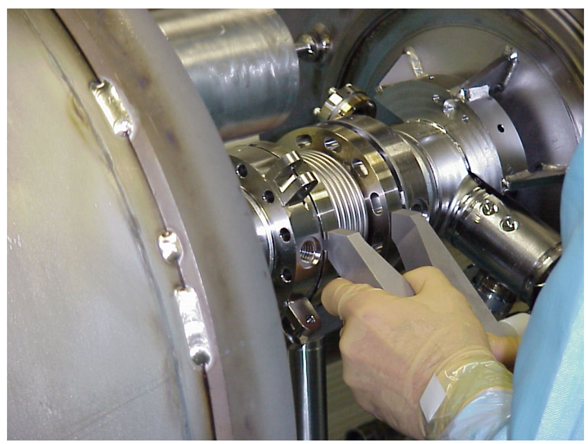


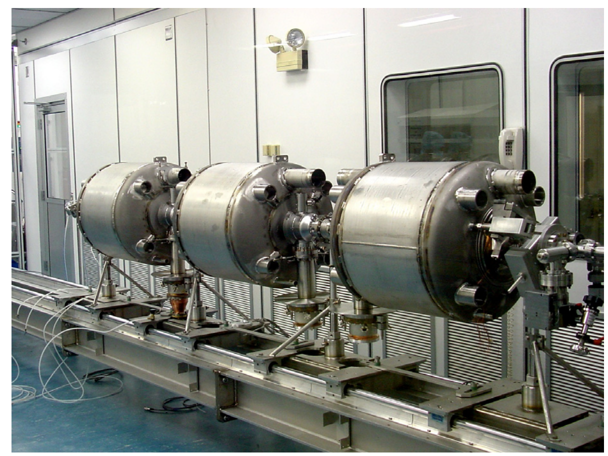
SNS Medium and High Beta Cryomodules



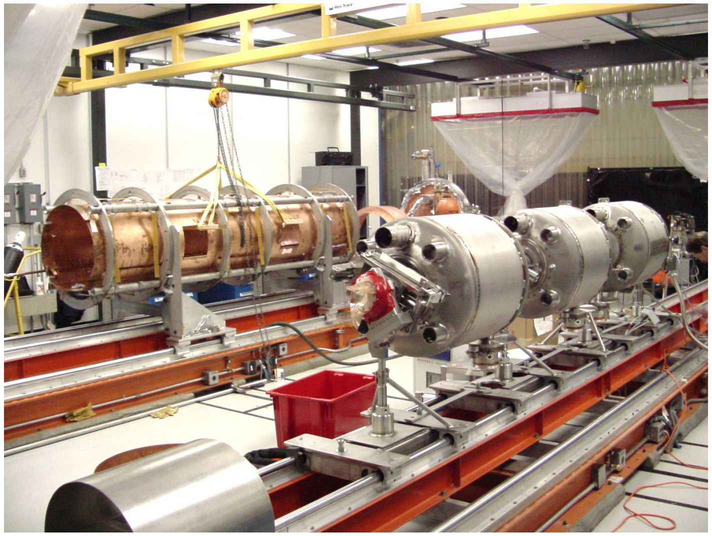


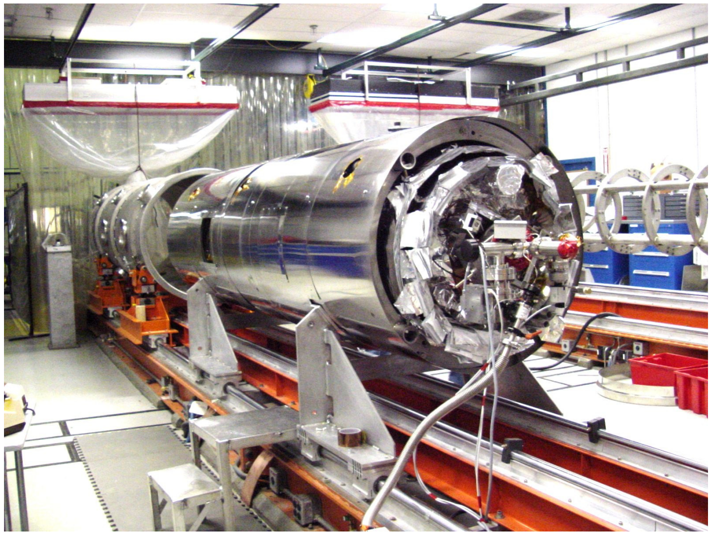
Cavity String Assembly

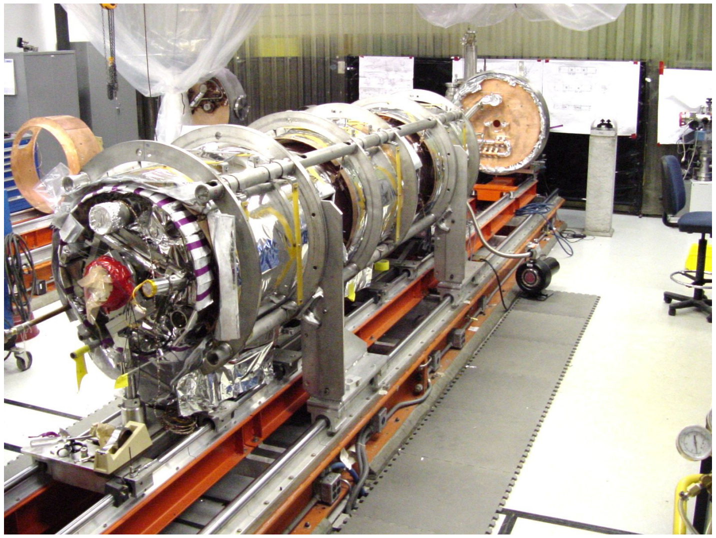


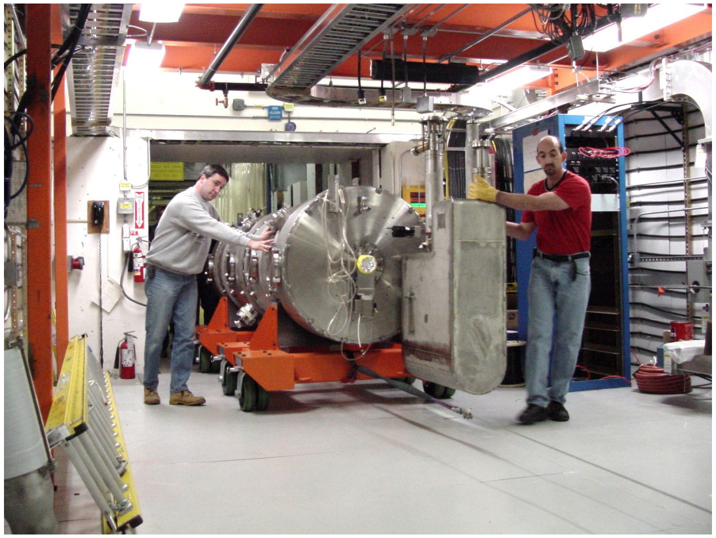


Cryomodule Assembly









Parting Words

- SRF for accelerators has been an active area of research and development for 40 years
- Much progress has been done
- Many machines have been successfully built and operated
- We have not yet achieved the full potential of the “easiest” superconductor for rf applications (Nb)

Parting Words

- SRF involves many areas of physics and engineering
  - Quantum mechanics, solid state physics
  - Electromagnetism
  - Materials science, thin films, deposition techniques
  - Surface physics
  - Chemistry and electrochemistry
  - Vacuum science
  - Contamination control
  - Feedback systems and rf control
  - Cryogenics
  - Mechanical and thermal engineering

- There is plenty left to do