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Memo

DATE: *April 1, 2005*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the April 1, 2005 Meeting**

Present: Ilan Ben-Zvi, Andrew Burrill, Rama Calaga, Alexei Fedotov, Wolfram Fischer, Ady Hershcovitch, Dmitry Kayran, Vladimir Litvinenko, Derek Lowenstein, William Mackay, Nikolay Malitsky, Thomas Roser, Dejan Trbojevic, Gang Wang (SUNY Stony Brook), Jie Wei.

Topics discussed: JLAB Workshop, Power Couplers.

JLAB Workshop: most of the meeting consisted of a presentation by Rama on the third Working Group (WG3) at the JLAB ERL Workshop that took place during March 18^{th} - 23^{rd}, 2005. About 158 people attended the workshop. The areas of interest of WG3 consisted of the following topics:

1. Cryomodules
2. Cavity Shape & HOMs
3. Surface Treatment
4. Tuners
5. Power Couplers
6. Cryogenics
7. ERL Injectors

Some of the WG3 presentation highlights are: JLAB future FEL upgrade involves 100-mA electron beam; Peter Kneisel gave a very thorough presentation on surface treatment; and the RIA SRF cavity has external room temperature tuner. Regarding the latter, Thomas expressed concern about use of stepper motors at cryogenic temperatures. Ilan replied that these motors are greaseless for vacuum compatibility, and have had 10's of years of reliable operation. Rama's complete presentation is attached below.

Power Couplers: in answer to Thomas's question Andrew gave a short report on a trip he took together with Alex Zaltsman and Dan Weiss to ORNL regarding conditioning, installation and operation of power couplers. BNL is expecting two 50 kW power couplers from AES (that are to be fabricated using parts from Toshiba and Meyer Tools). ORNL has a 750 kW system. Based on what was learned at ORNL, no problems or difficulties are expected with the BNL system.

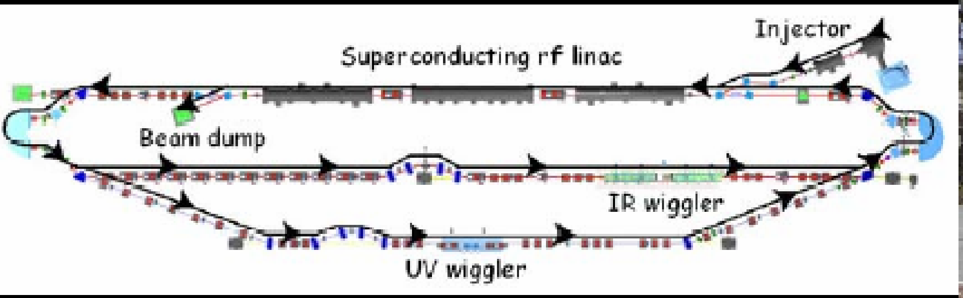
JLAB ERL Workshop WG3

March 18th - 23rd, 2005

Cryomodules

Now – FEL 10 kW Upgrade

- 2nd identical CEBAF module added; 3rd module built: 7-cell cavities and $\langle E_{acc} \rangle$ increased to 14.5 MV/m → 80 MV; FEL energy up to 160 MeV
- Measured BBU threshold (HOMs in new module) ~2.7 mA
- 10.6 kW @ 6μ with 5.5 mA and 145 MeV; circulating power up to 1.1 MW
- Four techniques (2-active; 2-passive) to increase BBU threshold were tested – ALL were effective!

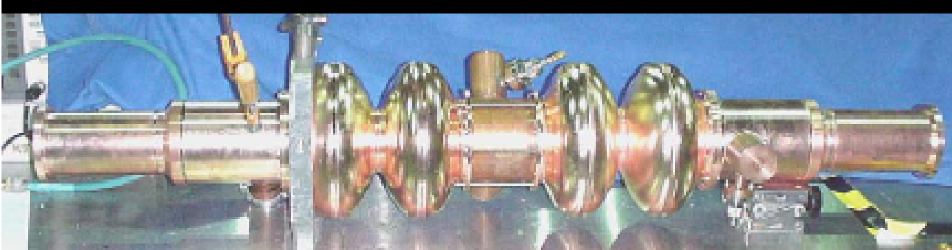


The Future – 100 mA Injector

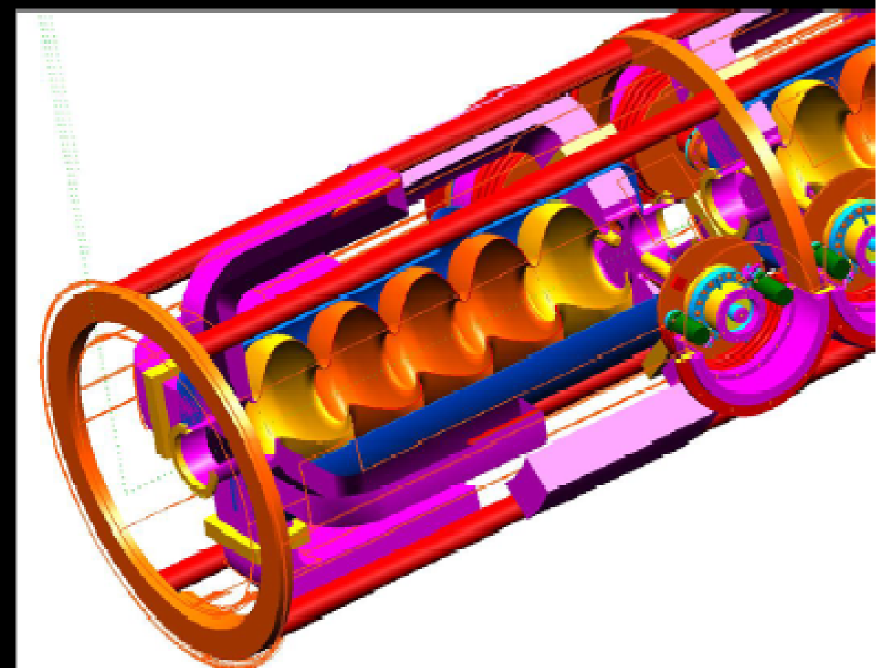
- Collaboration with Advanced Energy Systems
- DC RF gun: 750 MHz; 135 pC
- E_{out} = 7.5 MeV
- Three single-cell cavities, plus third harmonic cavity for linearization of longitudinal phase space
- Construction complete 2006; testing dependent on availability of RF sources

The Future: 1 A Cryomodules

- CW; 750 MHz
- 2005: conceptual design & copper models
- 2006: working Nb version
- Two concepts being evaluated:

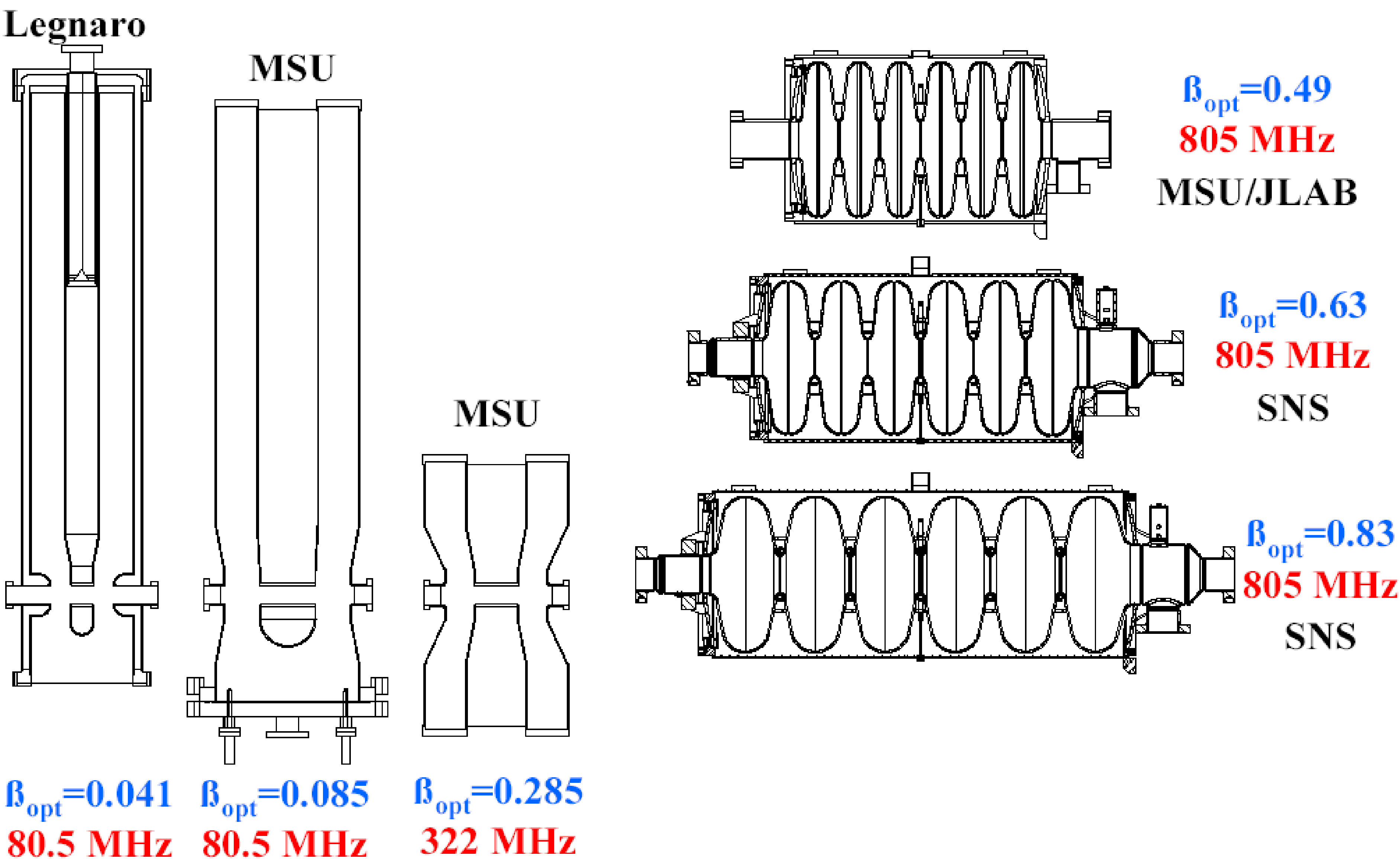


1.5 GHz model of 'superstructure' cavity with coaxial HOM couplers



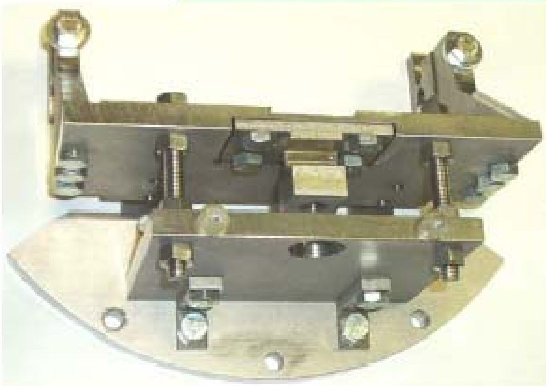
5-cell cavity with enhanced waveguide coupling of HOMs

RIA SRF Cavities

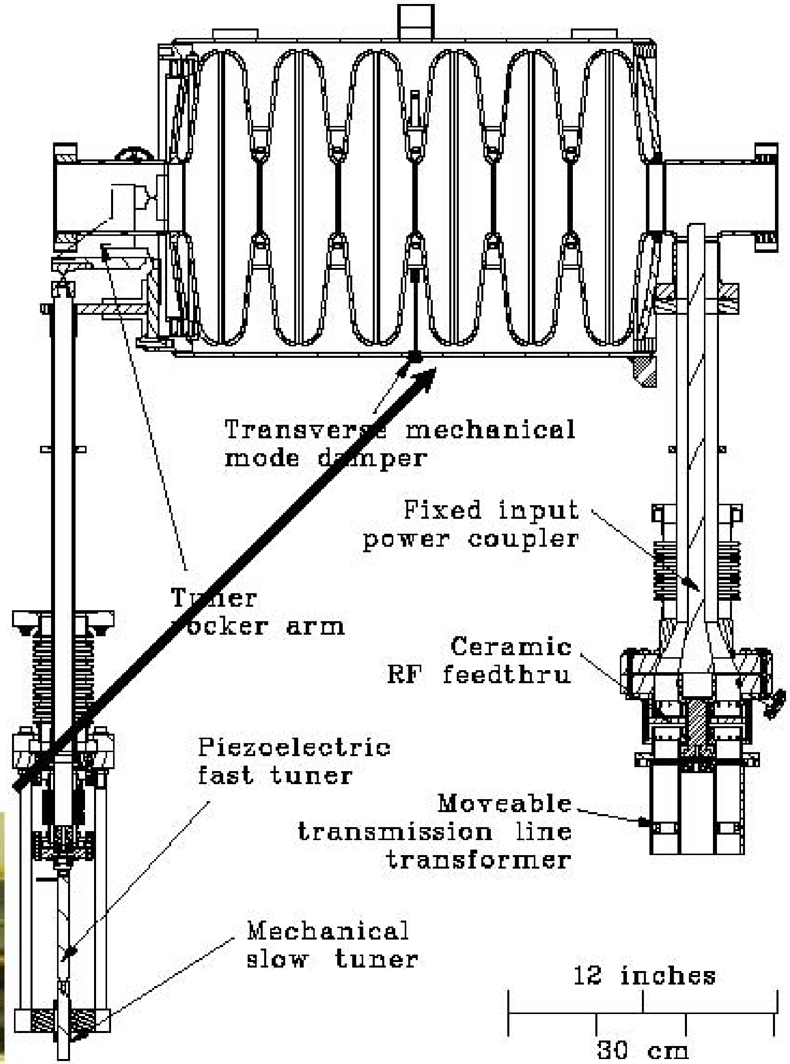


NSCL

β=0.47 Tuner-Cavity-Power Coupler



Tuner



He Vessel

Power Coupler

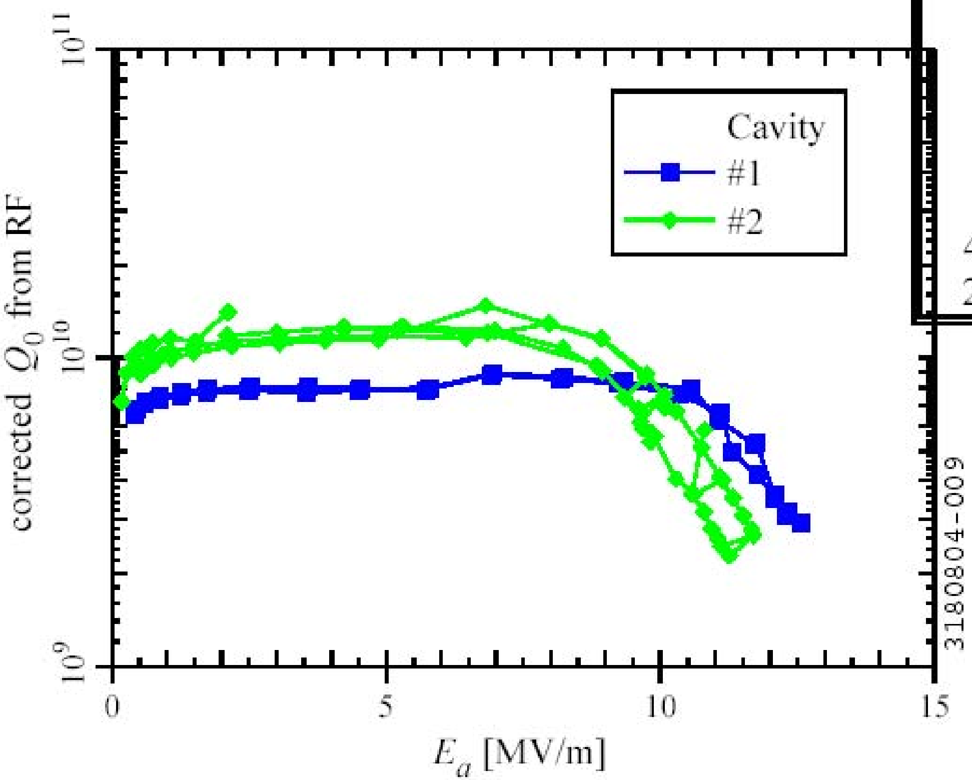
Experimental Results

	Cavity #1	Cavity #2	Design
Q_{ext}, fixed	$1.4x10^7$	$1.3x10^7$	$2x10^7$
Q_{ext}, transformer	$6x10^4$ - $6x10^9$		
df/dp (kHz/torr)	0.36	0.46	
Lorentz (2 K, $Hz/(MV/m)^2$)	-16		-14

Static Heat Leak
10-11 W @ 2 K
9 W @ 4.3 K
(includes L_{He} reservoir)

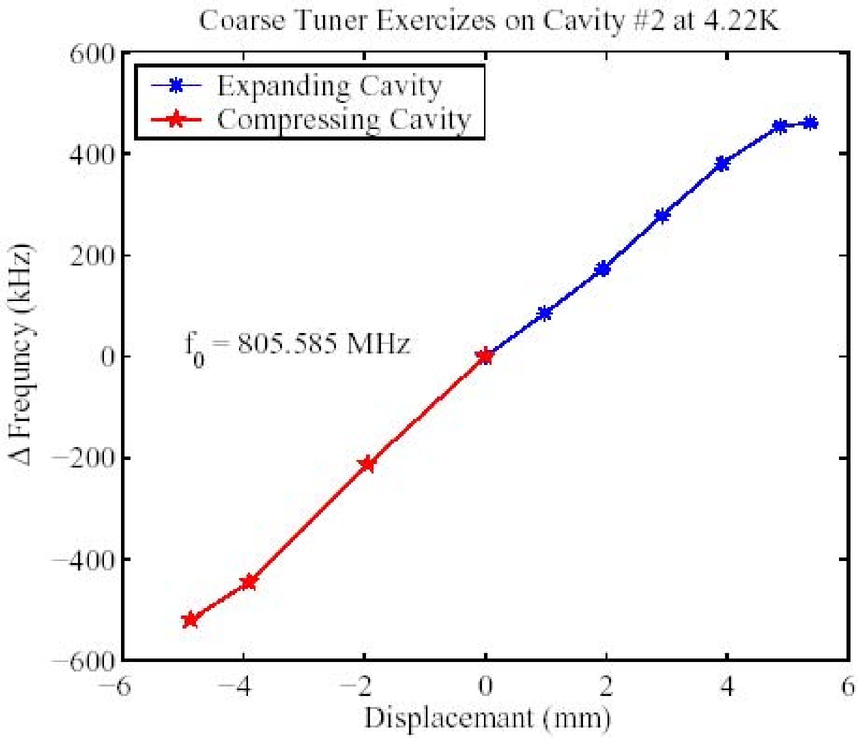
Design
4-Cavity cryomodule 15 W
2-Cavity prototype 9 W

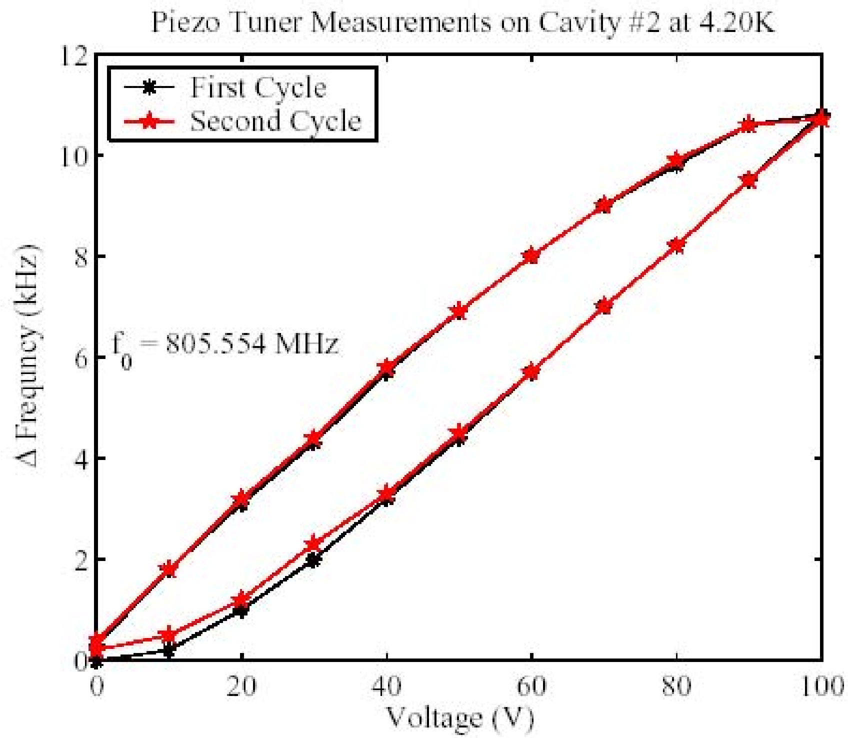
RIA Design Gradients
E_a = 10 MV/m
E_p = 32.5 MV/m
B_p = 64.2 mT
Q_o = $7x10^9$
P_o = 21.6 W



RF Measurements on the β=0.47 Cavities at 2 K after RF processing.

External/room temperature tuner

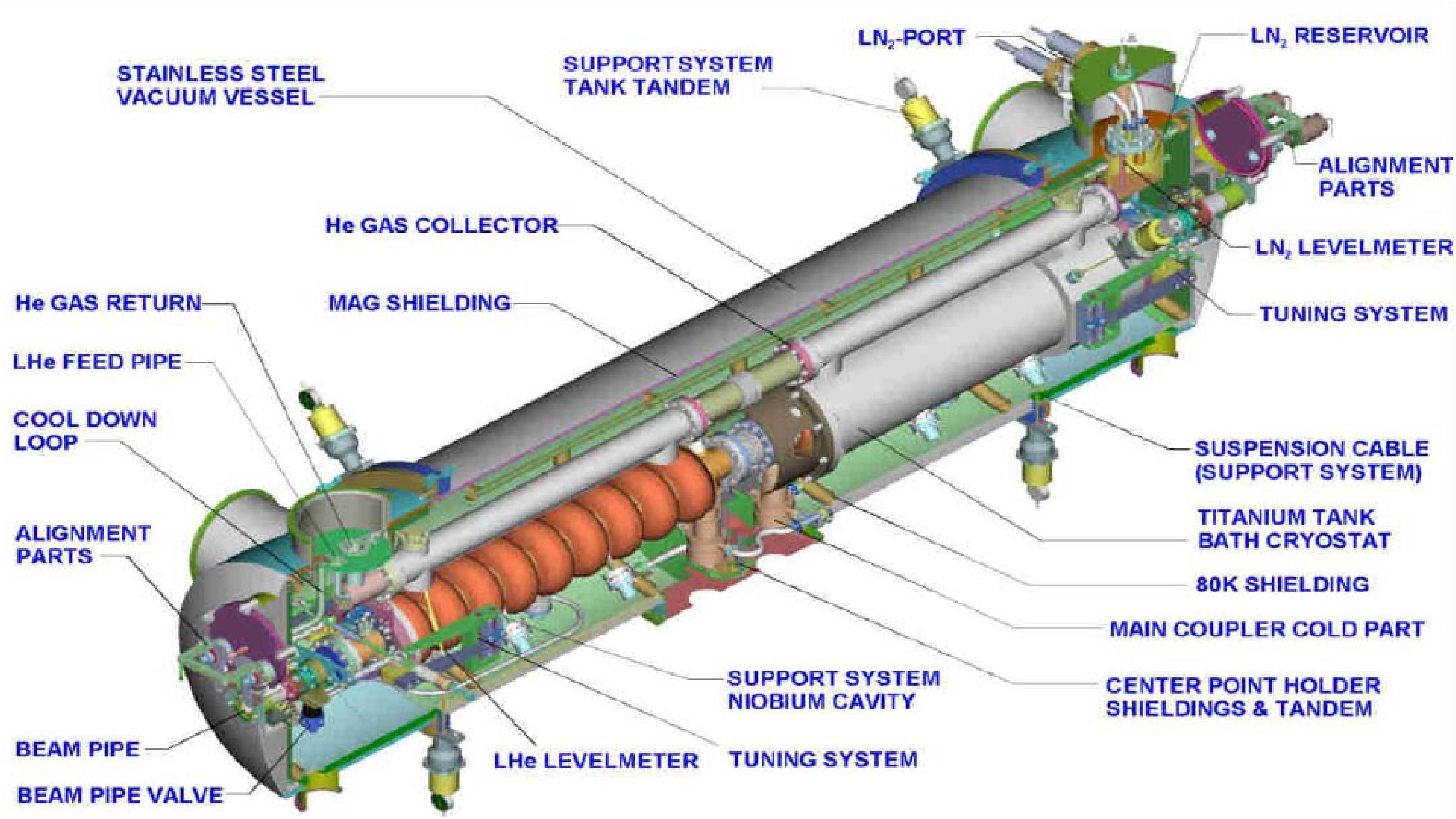




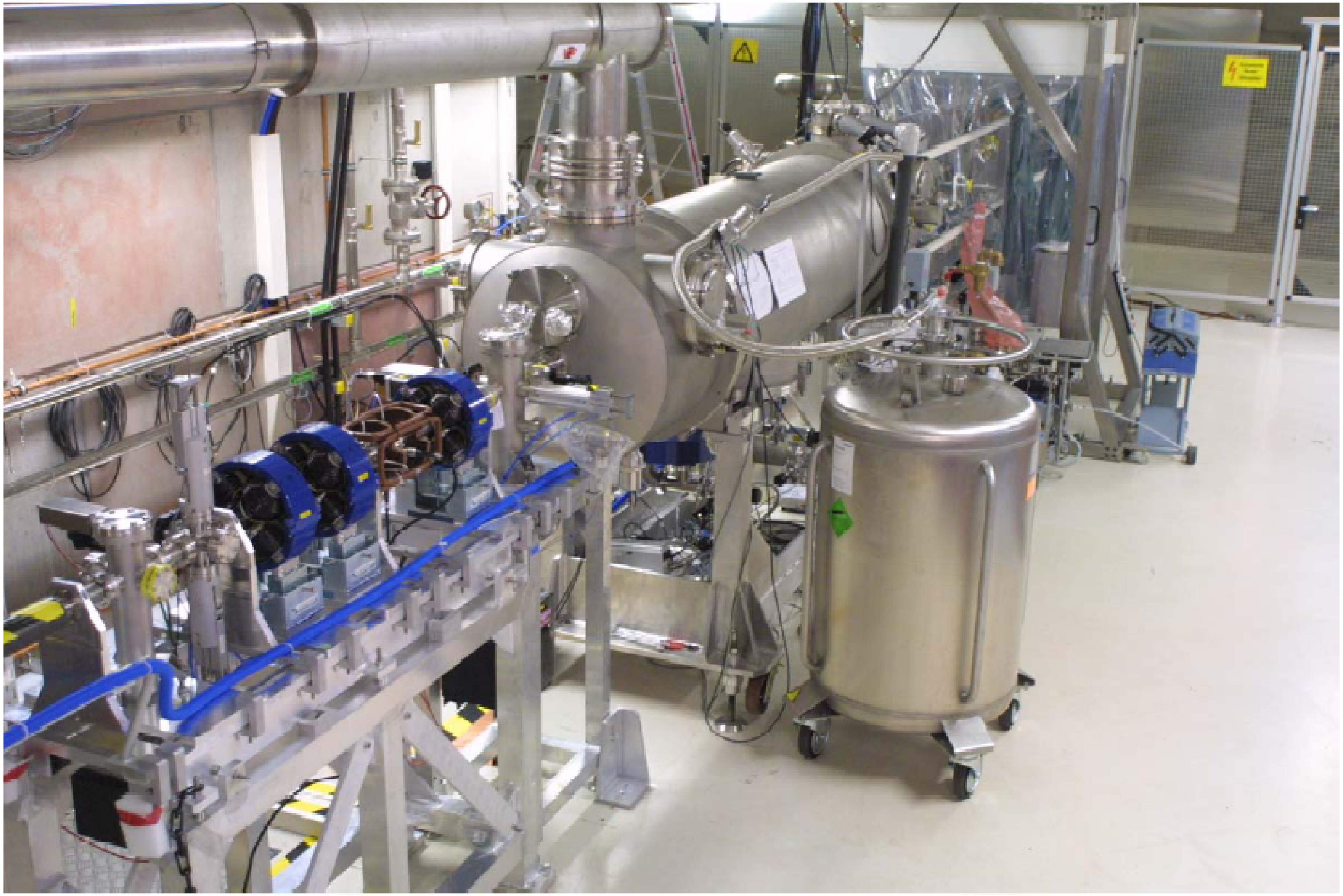
Coarse tuner ~ 1 MHz

Fine tuner ~ 10 kHz
90 μm piezoelectric (PI)

ELBE cryomodule design

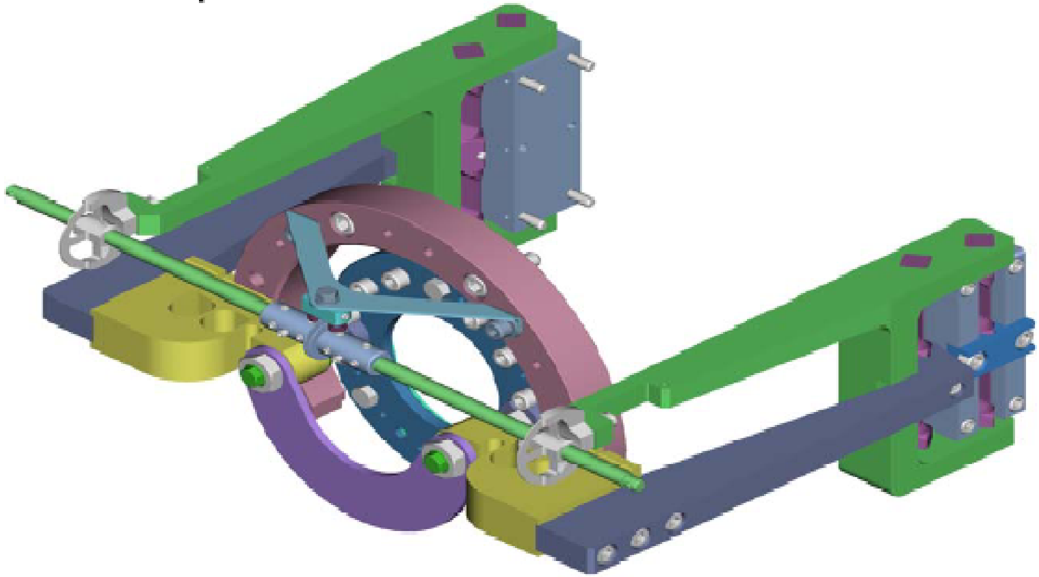


ELBE cryomodule



ELBE tuning system

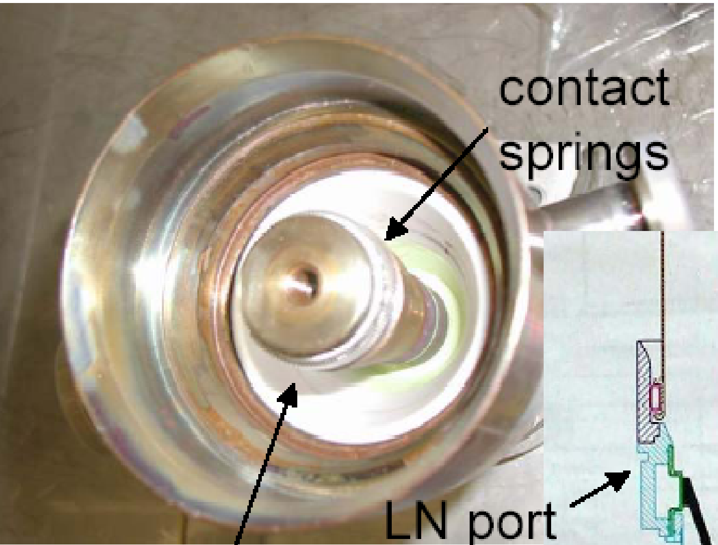
"slow" spindle/lever system
due to cw fast Lorentz-force
compensation not needed

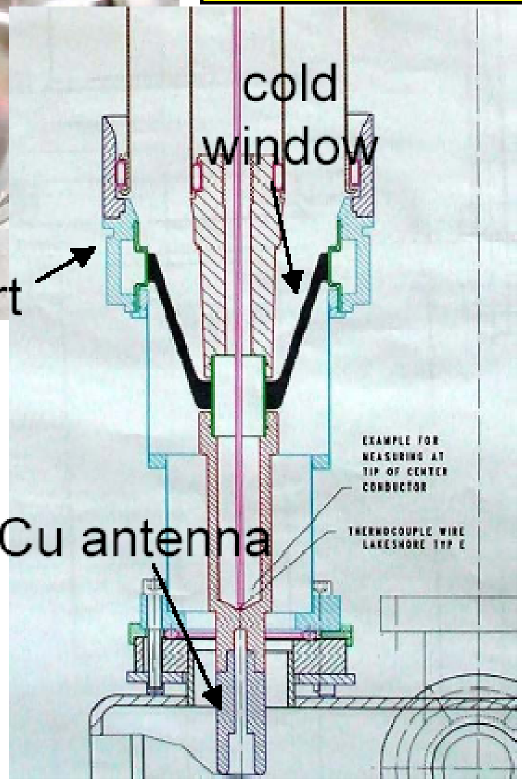


Tuning range	
mechanical:	±0.37 mm
frequency:	± 116 kHz
Tuning resolution	
mechanical:	3 nm
frequency:	1 Hz
Transfer	
156 nm/motor turn	
2.3 steps/nm	
Maximum load: 3000 N	

Lorentz-force detuning: 50 Hz @ 7 MV/m
compensation "by hand" during gradient ramp up

ELBE rf power coupler





overheated in coupler tests with 8 kW full reflection

Coupler design for 10 kW cw using the TTF conical insulator, T.Kimura/HEPL-Stanford & J.Stephan

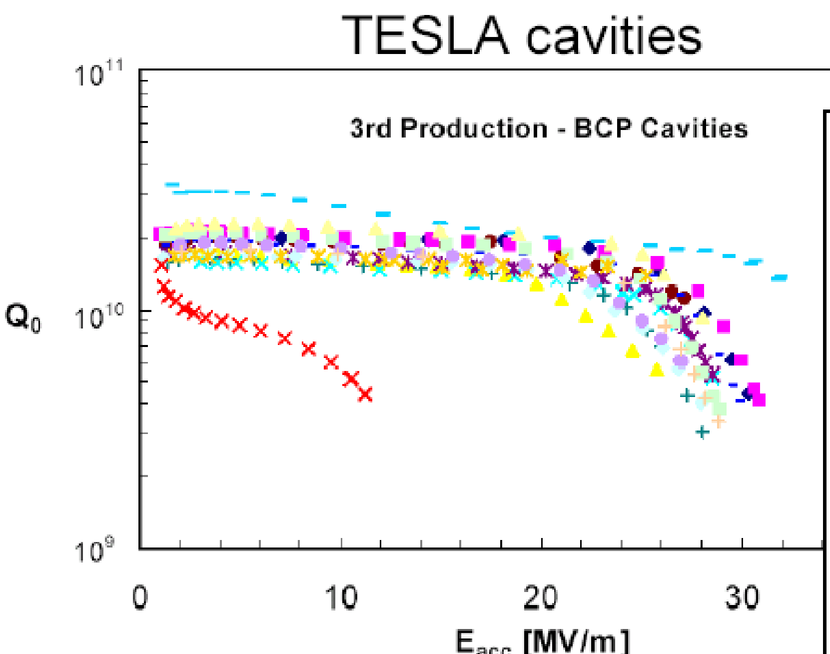
- three-stub waveguide tuner for BW adjustment
- RT planar window in waveguide REXOLITHE position at E-field waist
- conical cold window at 70 K ceramics
- Coupling is matched for 1 mA beam current at 10 MV/m

$BW = 114$ Hz

$Q_L = 1.2 \times 10^7$

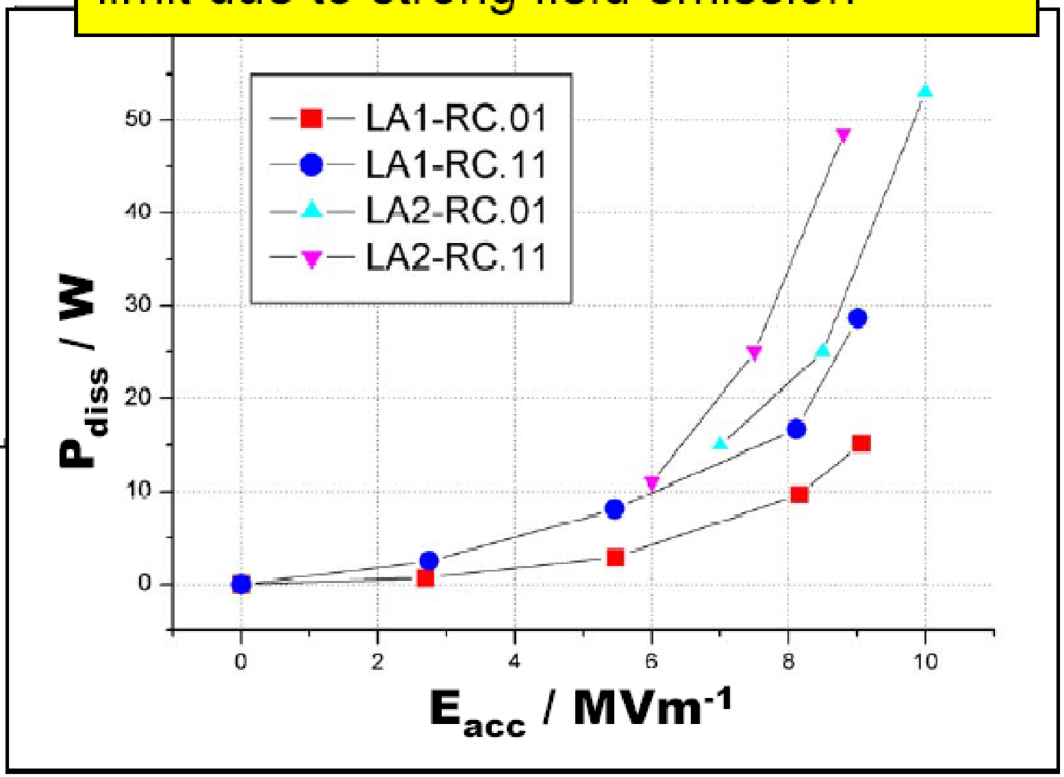
ELBE module - cavity properties

cavity operation at ELBE: Gradient limit due to strong field emission



ELBE cavities vertical test at DESY before tank welding etc.:

$Q_0 = 2 \times 10^{10}$, E_{acc} = 15... 25 MV/m



Reason: welding, assembling, storage, couplers?

ELBE cryomodule - summary

- ELBE cryomodules are suitable for cw-operation @ 10 MV/m & 1 mA

  most of module parameters better/equal to design specifications
  common He pressure control with cold compressors,
  separate He level control (heater) in each module,
  analog phase and amplitude rf control for each cavity,
  sophisticated coupler/window diagnostics,
- Higher gradients:

  1. limit due to field emission in cavities, difficult to reach 20 MeV,
     extended quality management for next module
  2. At ELBE: capacity limit of the cryogenic plant,
- Higher current (rf power):

  1 mA (10 kW) seems near to the limit of the rf power couplers,
- Energy drift:

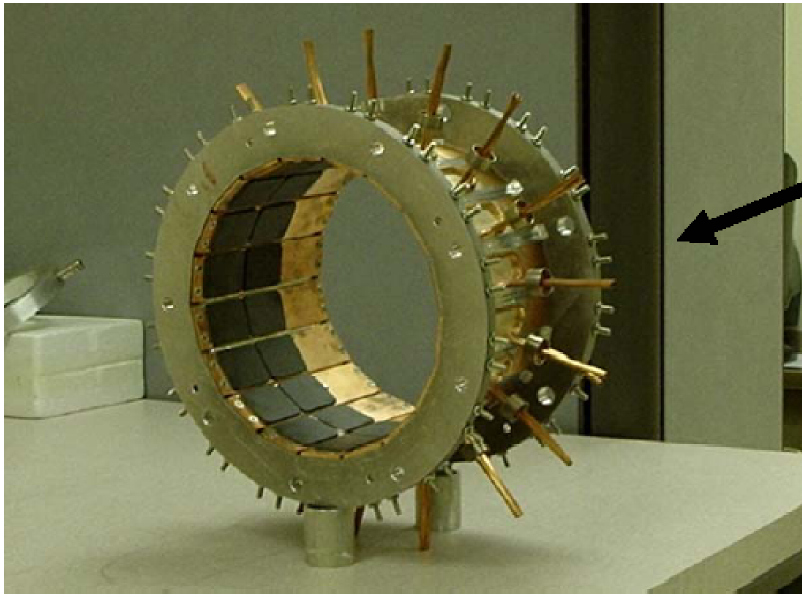
  cw-operation causes 1 MeV energy drift within first hours,
  source is in module (temperature effect) , no rf control

Nb Cavity Manufacturing (A. Burger, D. Holmes et.al.)

Middle Cell (Dumbbells)

End Groups

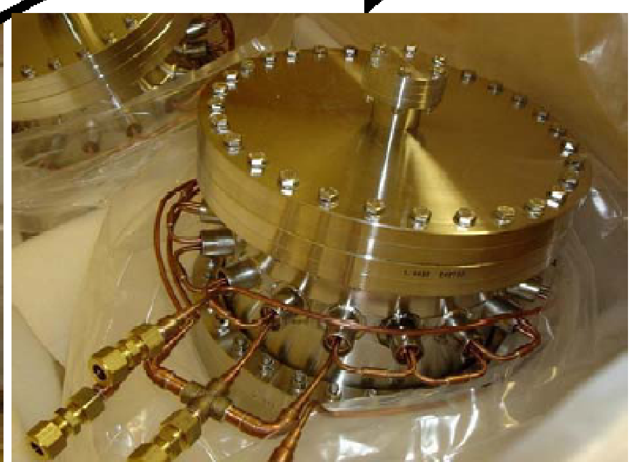
Ferrite Dampers



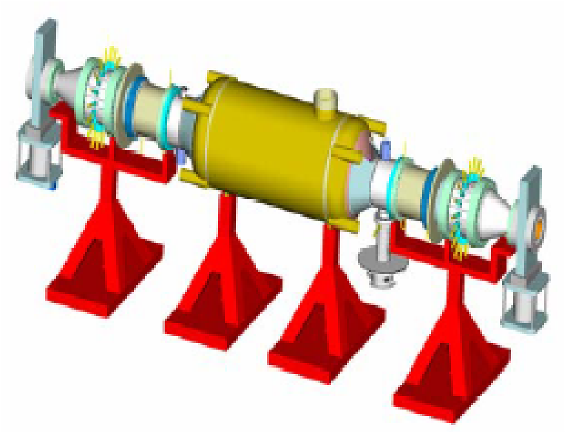
Ferrite prototype for testing

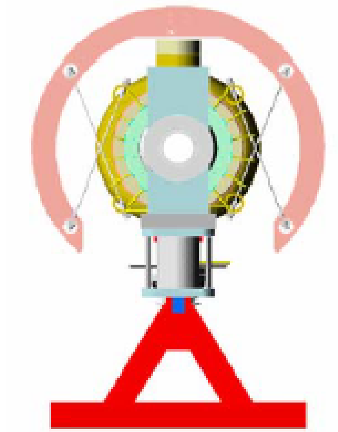
HOM Power Capacity: 5-10 kW/ferrite

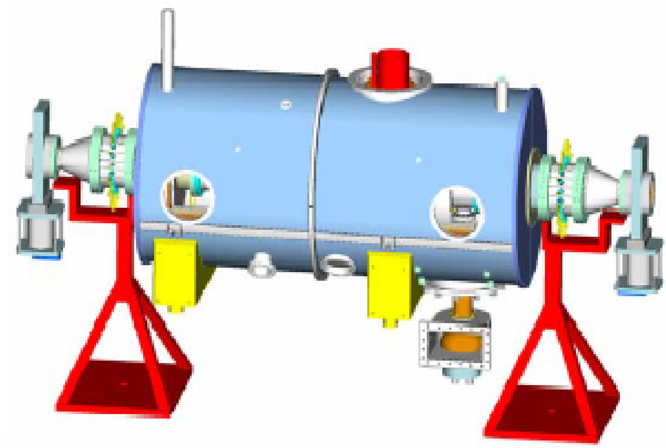
Real Ferrite Absorbers
(Vendor: ACCEL)

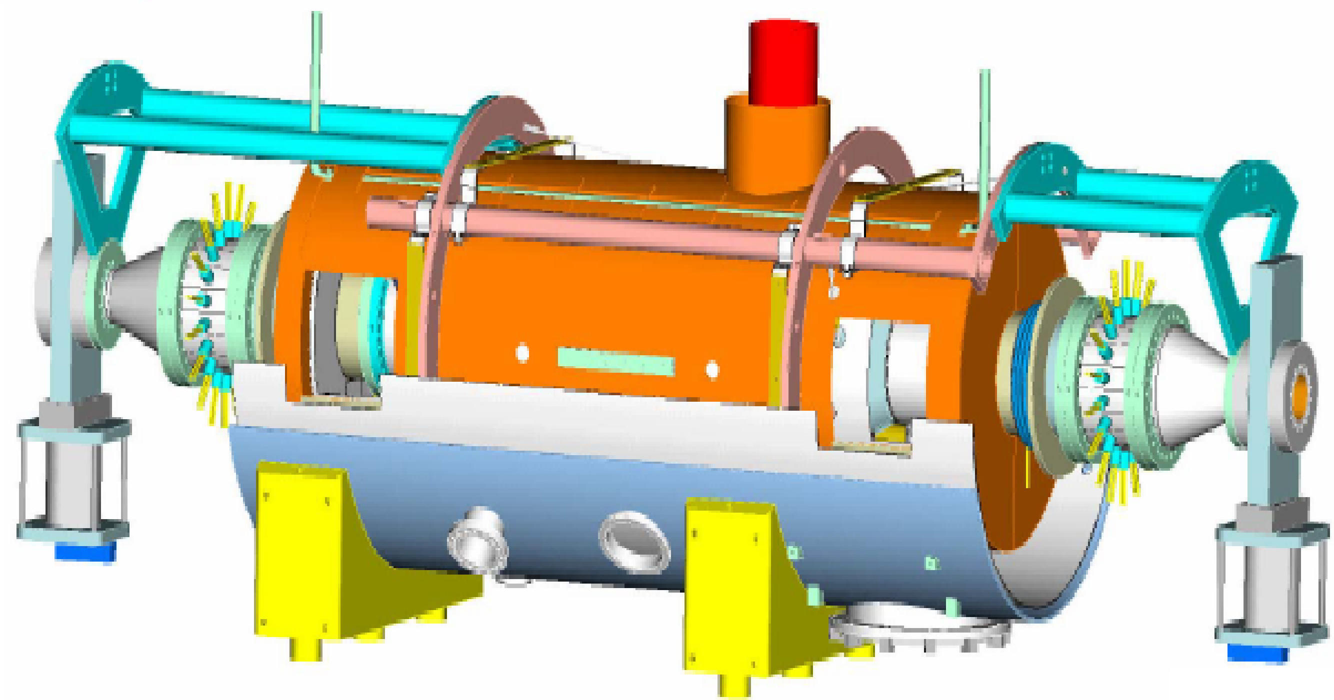


Cryomodule Assembly (BNL, AES, JLAB)







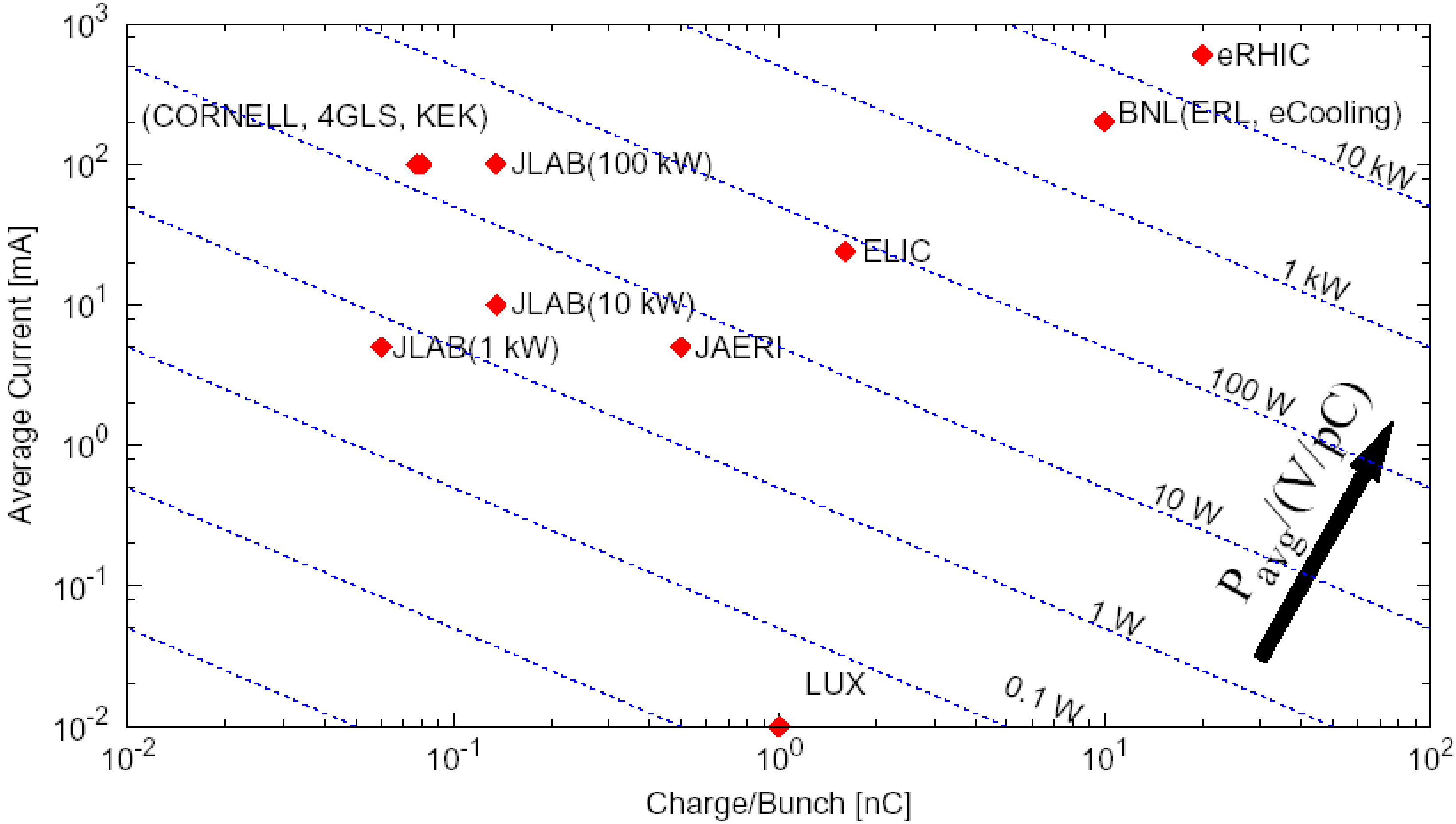


Advanced Energy Systems, Inc.

BROOKHAVEN NATIONAL LABORATORY

Cavity Shape & HOMs

Existing & Future ERLs

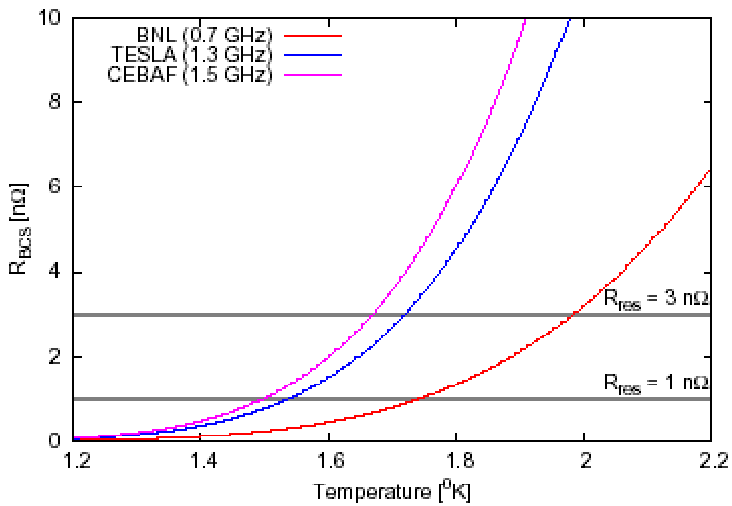


*** Avg. Power Normalized to 1 V/pC

Design Criteria: Approx. Scaling Factors

Fund. Mode:

- $P_{cav} \propto \frac{Rs}{(R/Q)G}$
- $R_s \propto \omega^2 \ (R_s = R_{BCS} + R_{res})$
- $\frac{R}{Q}G \propto const. \ (E_{acc} \propto \omega)$
- $a \propto \frac{N^2}{k_{cc}}$ (field sensitivity)



Loss Factor:

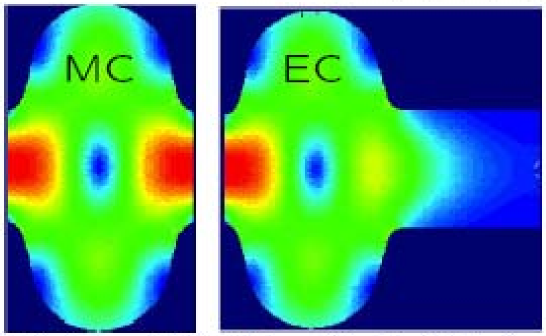
- $k_{||} \propto \frac{1}{\mathrm{R_{iris}}}\sqrt{\frac{d}{\sigma_z}}\sqrt{N_c}$
- $k_{||} \propto \omega^2 \ (Q_b \propto \omega^{-1})$
- $k_{\perp} \propto \frac{1}{R^3_{iris}}\sqrt{d\sigma_z N_c}$
- $\delta E \propto k_{||}Q, \quad \gamma\delta\epsilon \propto k_{\perp}Q$

Threshold Current:

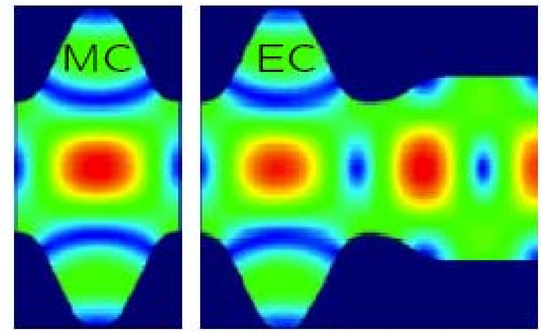
- $I_{thr} \propto \frac{1}{\omega e^{-\frac{\omega}{2Q}t_r}}$
- $I_{thr} \propto \frac{1}{\left(\frac{R}{Q}\right)\mathrm{Q_{ext}}}$
- $k_{cc}(\downarrow) \ \Rightarrow$ trapped modes

Design Criteria: Trapped Modes

Frequency Difference

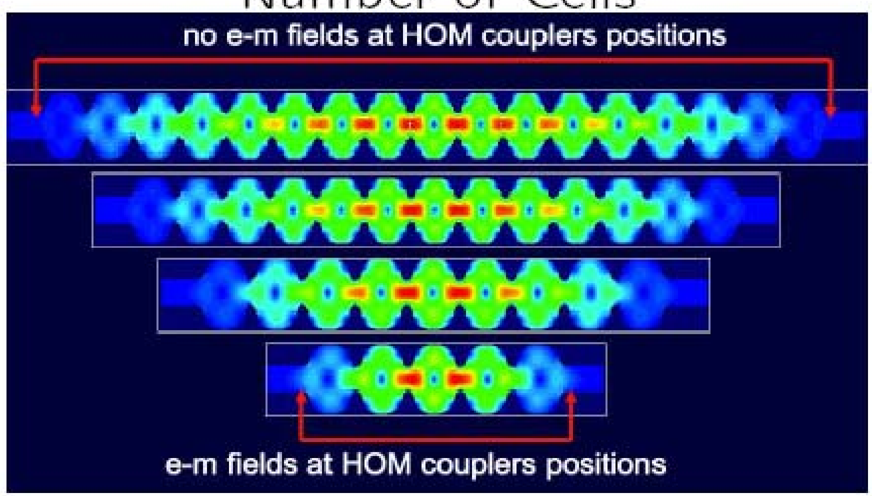


$\Delta f = 30MHz$ (2.4 GHz)



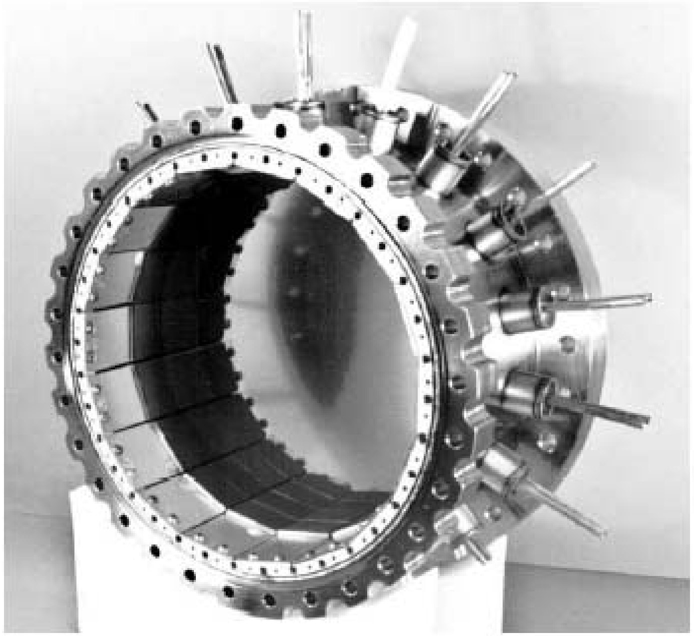
$\Delta f = 13MHz$ (1.4 GHz)

Number of Cells



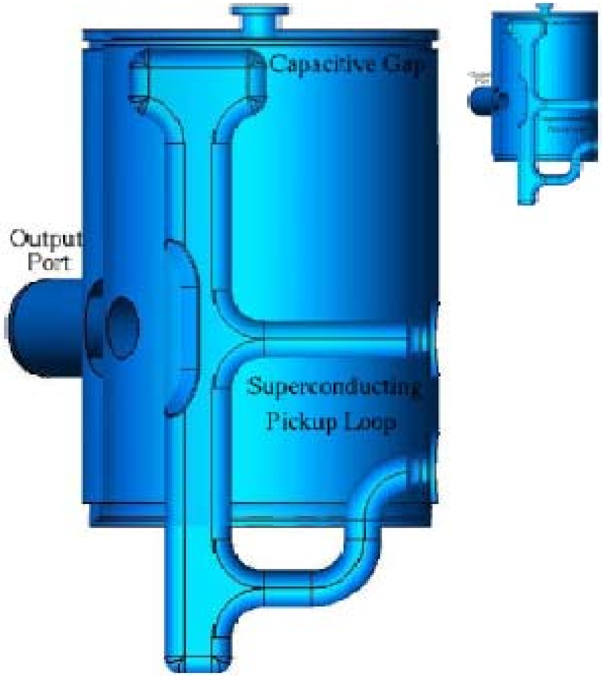
HOM Extraction & Damping

Ferrite Absorbers
Broadband (300 K)



(CORNELL)

Loop Couplers
Resonant Ciruit (4 K)

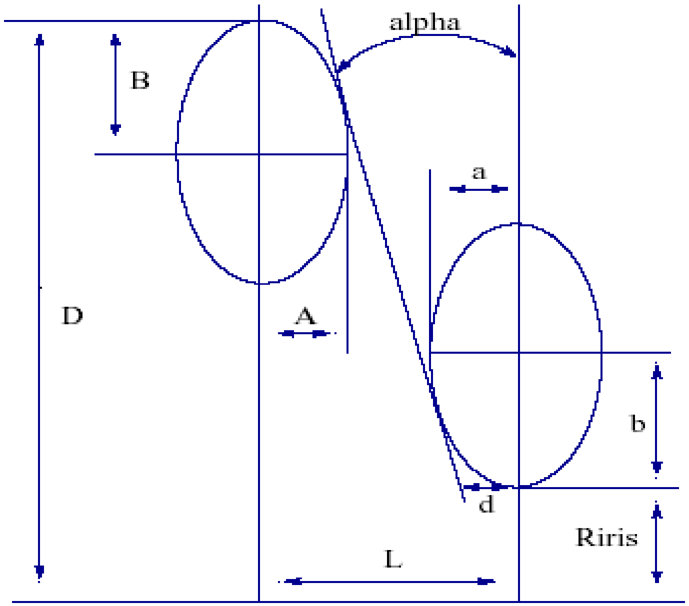


(TESLA)

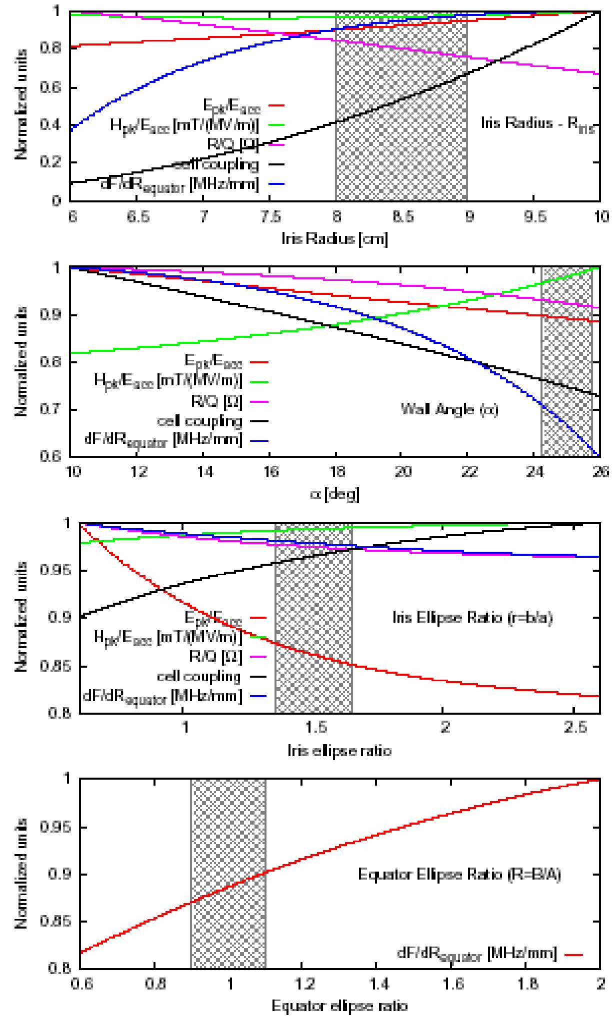
Comparison of RF Parameters

Parameter	BNL(HC)	CEBAF(HG)	TESLA(HG)
Frequency [MHz]	703.75	1497	1300
Number of cells	5	7	9
$(R/Q) * G$ [Ω^2]	9×10^4	2.1×10^5	2.8×10^5
$k_{\|\|}$ $(\sigma_z - 1mm)$ [V/pC]	4.25	10.71	13.14
$k_\perp$ $(\sigma_z - 1mm)$ [V/pC/m]	0.1	2.24	2.07
Q_{ext} (Dipole)	$10^2 - 10^4$	$10^3 - 10^6$	$10^3 - 10^7$
E_p/E_a	1.97	1.96	1.98
H_p/E_a $[mT/MV/m]$	5.78	4.15	4.15
cell to cell coupling (k_{cc})	3%	1.89%	1.87%
Sensitivity Factor $(\frac{N^2}{\beta k_{cc}})$	8.3×10^2	2.6×10^3	4.1×10^3
Lorz. Det. Coeff $[Hz/(MV/m)^2]$	1.2 (UnStiff)	2	1

Cavity Design (Build Cavity)



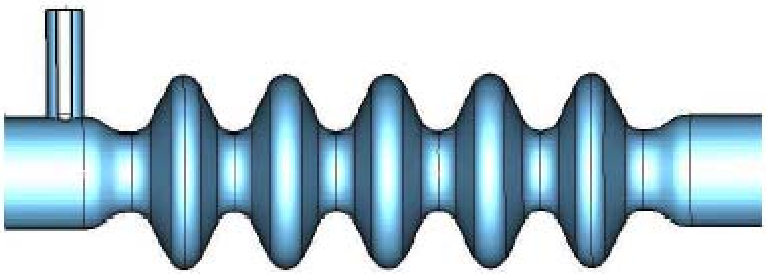
Iris Radius, R_{iris}	8.5 [cm]
Wall Angle, α	25 [deg]
Equatorial Ellipse, $R = \frac{B}{A}$	1.0
Iris Ellipse, $r = \frac{b}{a}$	1.1
Cav. wall to iris plane, d	2.5 [cm]
Half Cell Length, $L = \frac{\lambda\beta}{4}$	10.65 [cm]
$H = D - (R_{iris} + b + B)$	4.195 [cm]
Cavity Beta, $\beta = \frac{v}{c}$	1.0



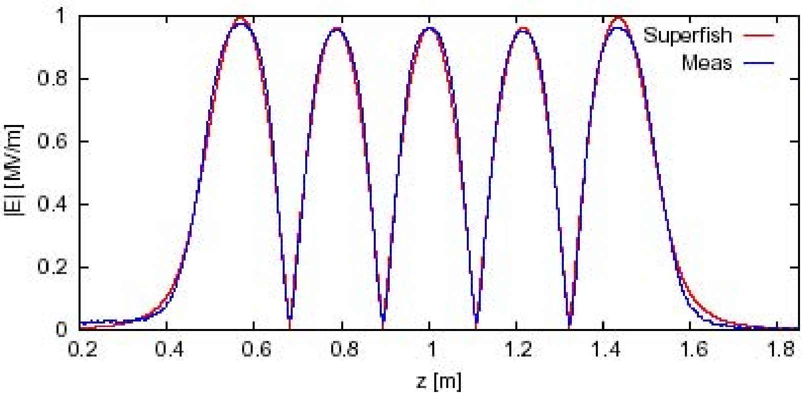
BNL High Current Cavity

Main Parameters:

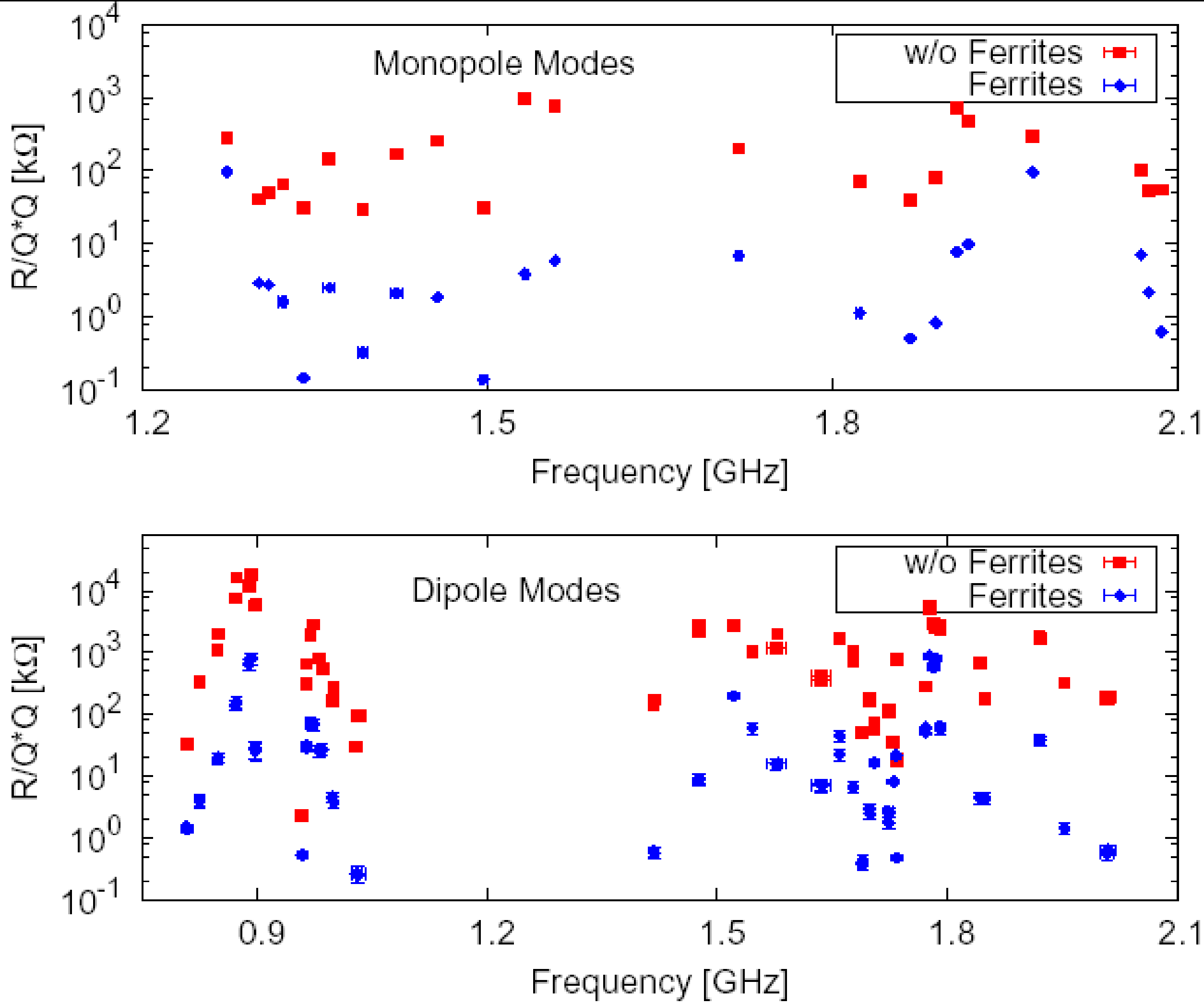
Frequency	703.75 [MHz]
RHIC Harmonic	25
Number of cells	5
Active cavity length	1.52 [m]
Iris Diameter	17 [cm]
Beam Pipe Diameter	24 [cm]
G (Ω)	225
R/Q	403.5 [Ω]
Q BCS @ 2K	4.5×10^{10}
Q_{ext}	3×10^{6}
E_p/E_a	1.97
H_p/E_a	5.78 [$mT/MV/m$]
cell to cell coupling	3%
Sensitivity Factor ($\frac{N^2}{\beta}$)	833
Field Flatness	96.5 %
Lorentz Detuning Coeff	1.2 [Hz/MV/m]
Lowest Mech. Resonance	96 [MHz]
$k_{\|\|}$ ($\sigma_z - 1cm$)	1.1 [V/pC]
$k_{\perp}$ ($\sigma_z - 1cm$)	3.1 [V/pC/m]
HOM Power (10-20 nC)	0.5-2.3 [kW]



Field Flatness

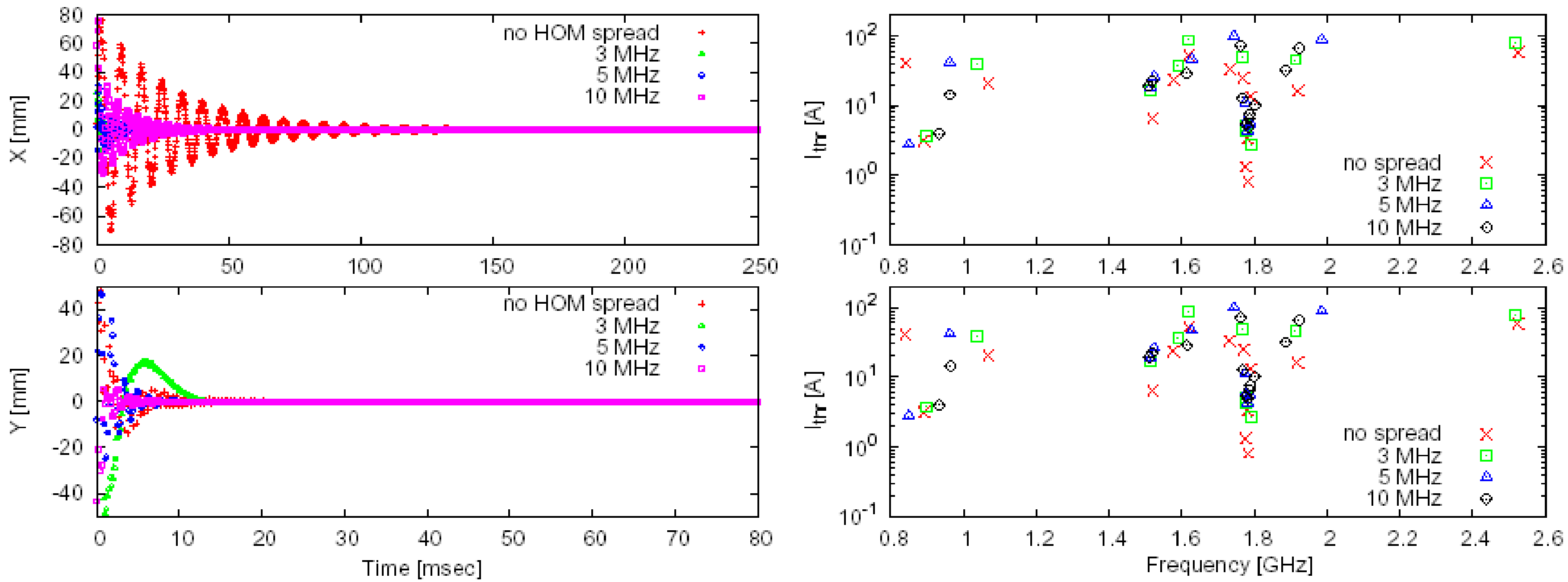


HOMs: Measurements from Cu Prototype



Multibunch BBU

TDBBU   MATBBU

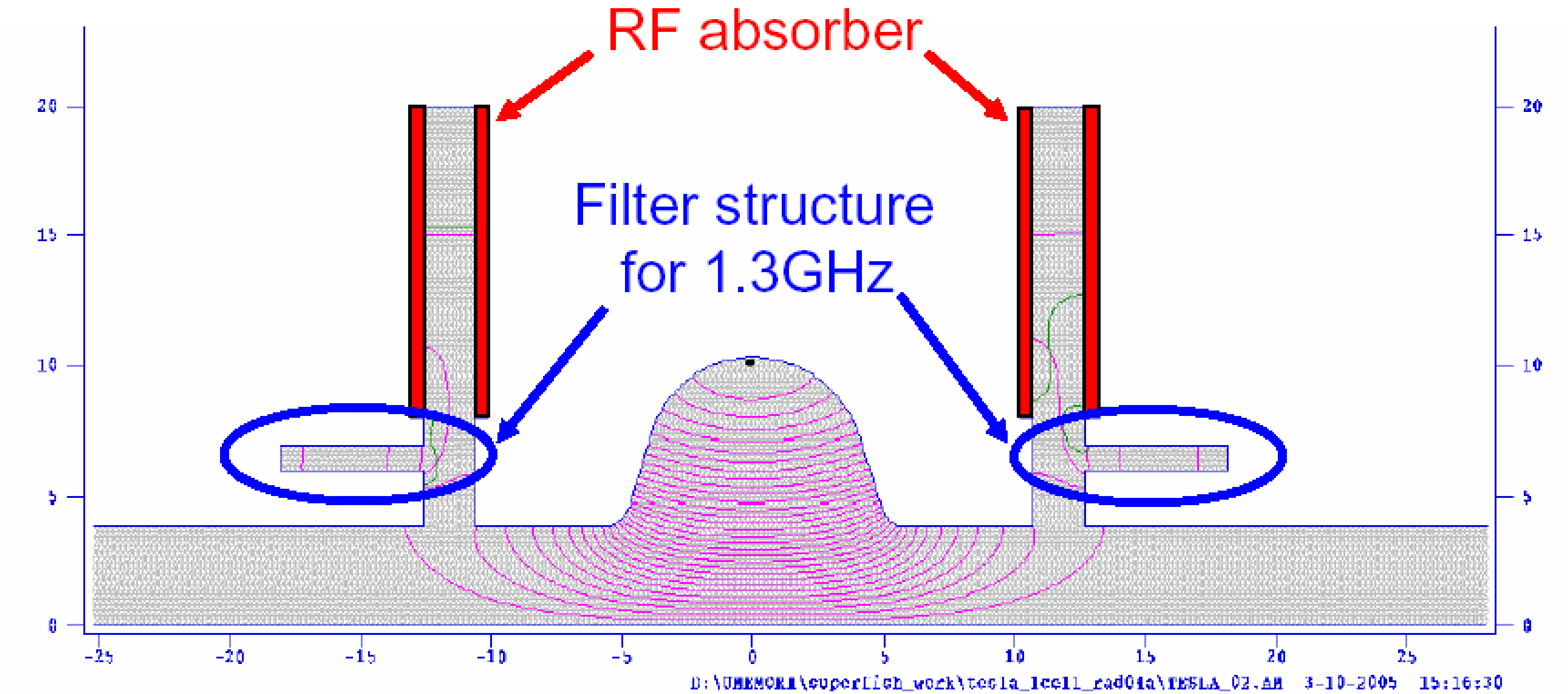


Threshold Current > 2 Amps

BNL eCooling Configuration - 4 Cavities - 54 MeV

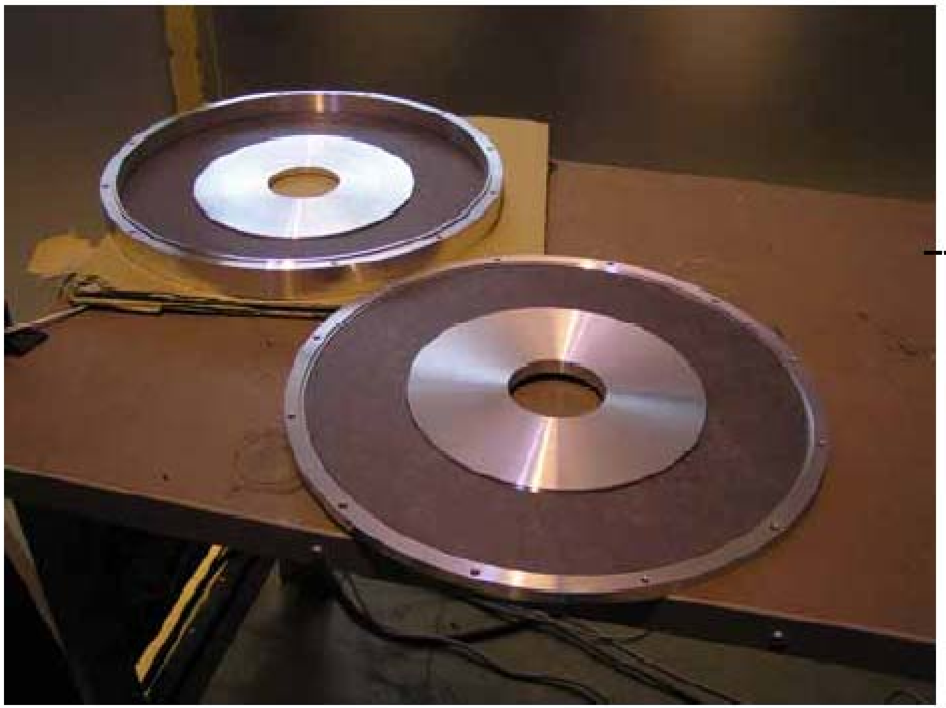
(Numerical Codes from JLAB)

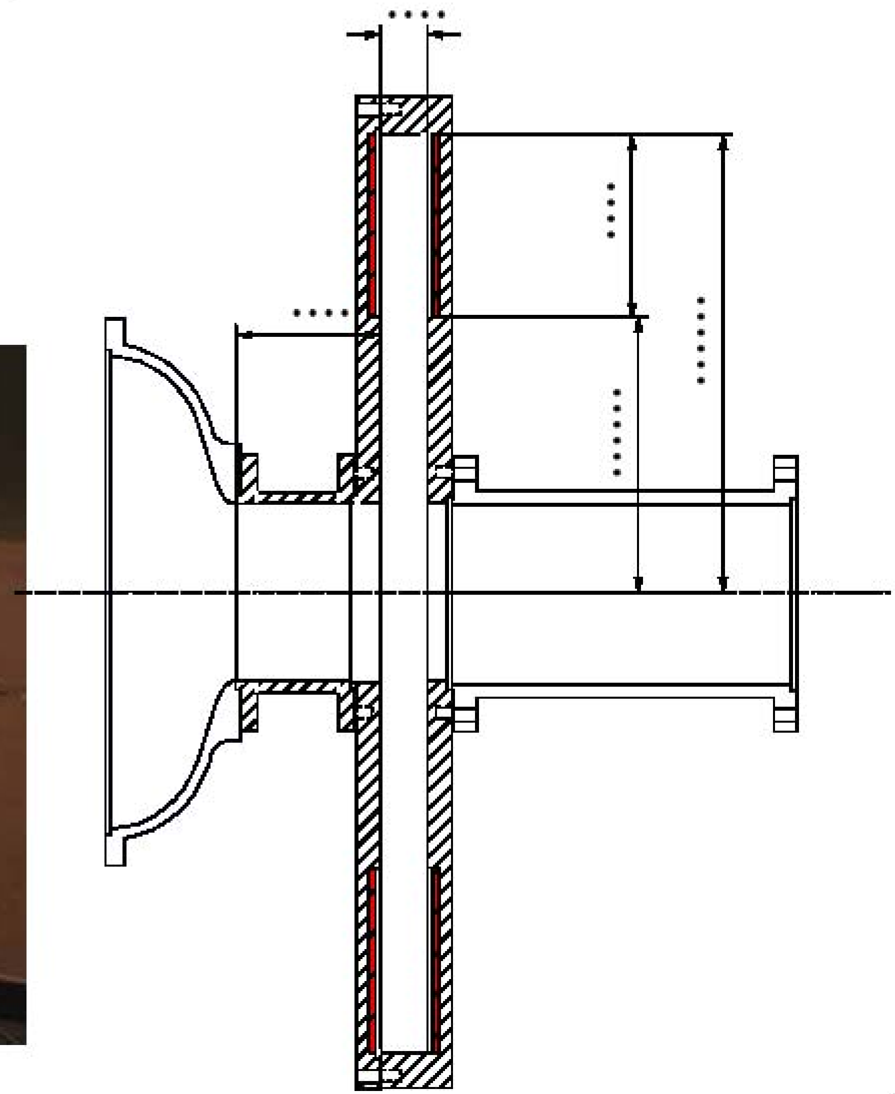
Concept of HOM damper using a radial transmission line with filter structure



Original idea was proposed by T. Shintake for normal conducting cavity.

RF absorber
(TDK IRL02, 2mm thick)

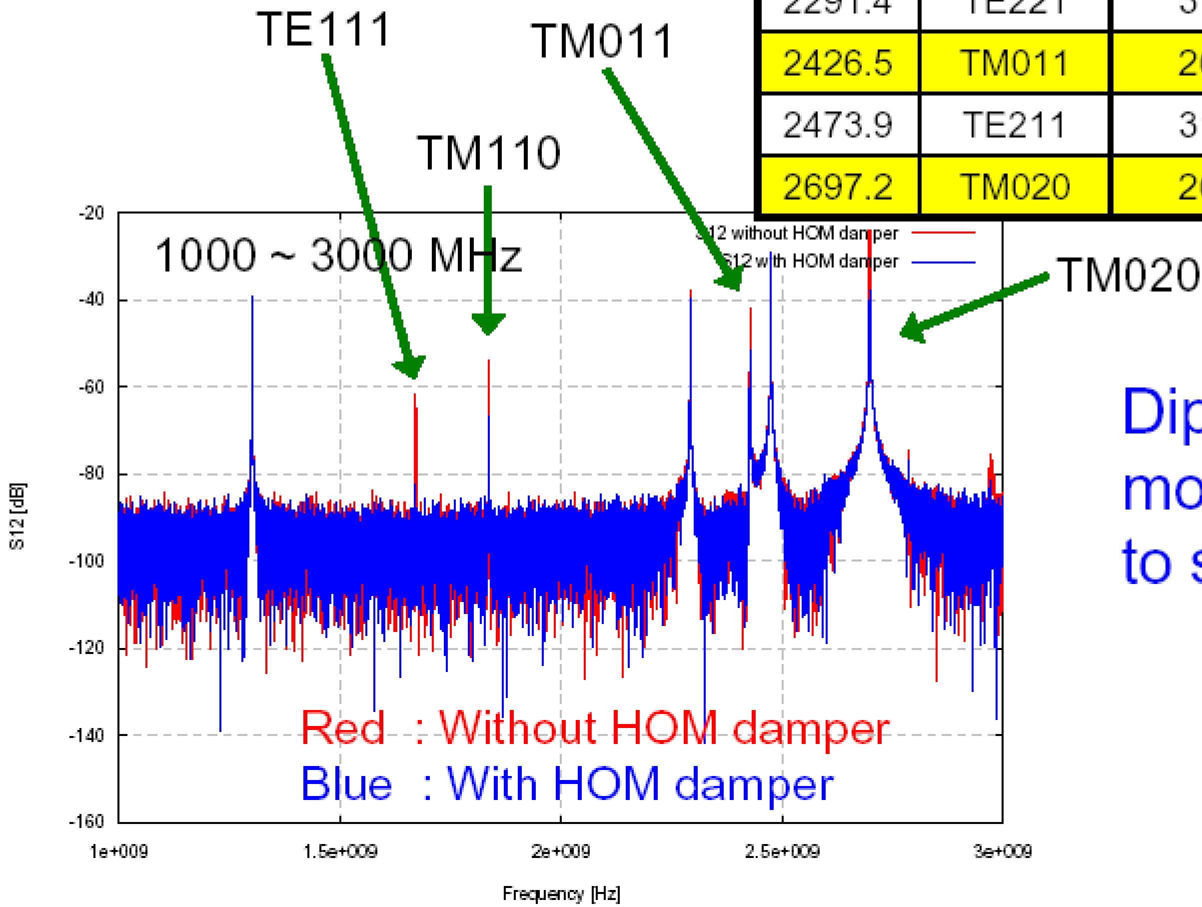




$\varepsilon' = 207.0 \quad \varepsilon'' = 8.5 \quad \mu' = 5.1 \quad \mu'' = 6.3 \quad @2GHz$

Results (1cell)

Freq.	Mode	Q value w/o damper	Q value w/ damper	External Q of damper
1301.6	TM010	27073	25803	550234
1670.0	TE111-1	25447	2758	3093
1671.0	TE111-2	25675	2609	2904
1834.4	TM110-1	27249	5637	7170
1835.5	TM110-2	24927	5464	6998
2291.4	TE221	31936	30726	811134
2426.5	TM011	26964	7649	10670
2473.9	TE211	31414	30688	1326699
2697.2	TM020	26198	3660	4255

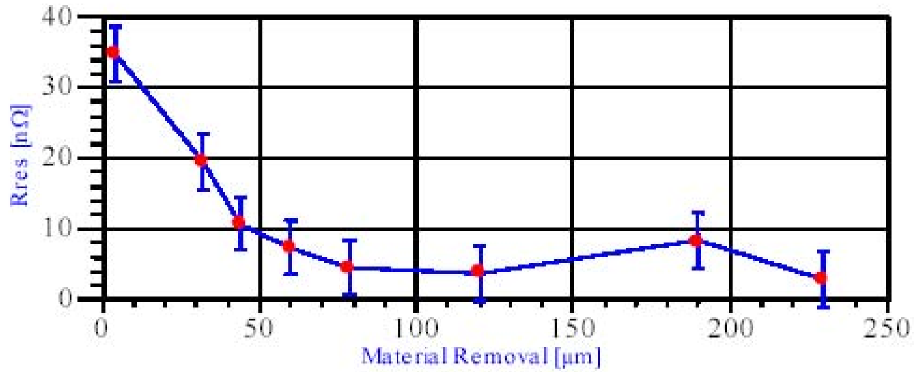


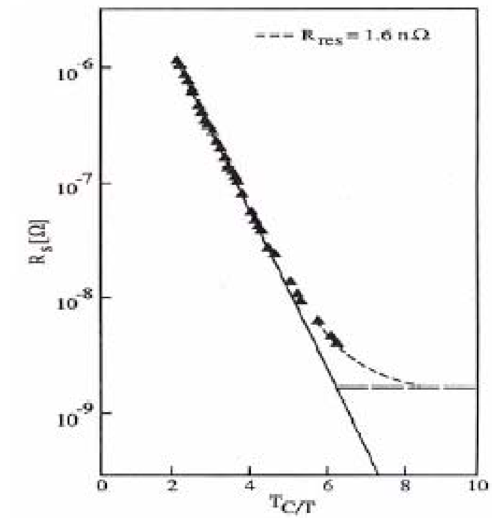
Dipole and monopole modes are damped to several thousands.

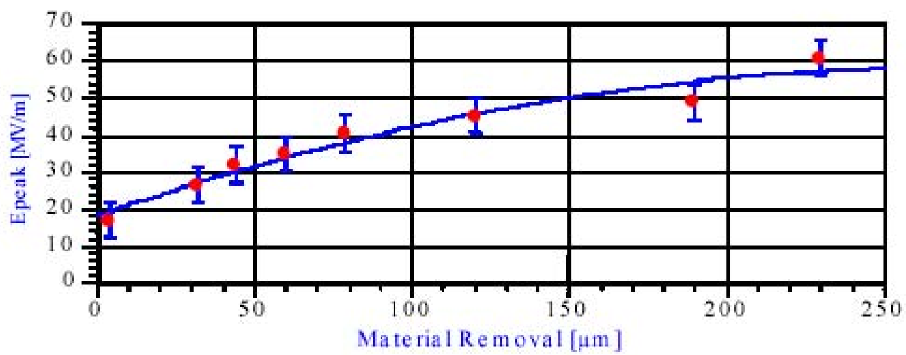
Surface Treatment

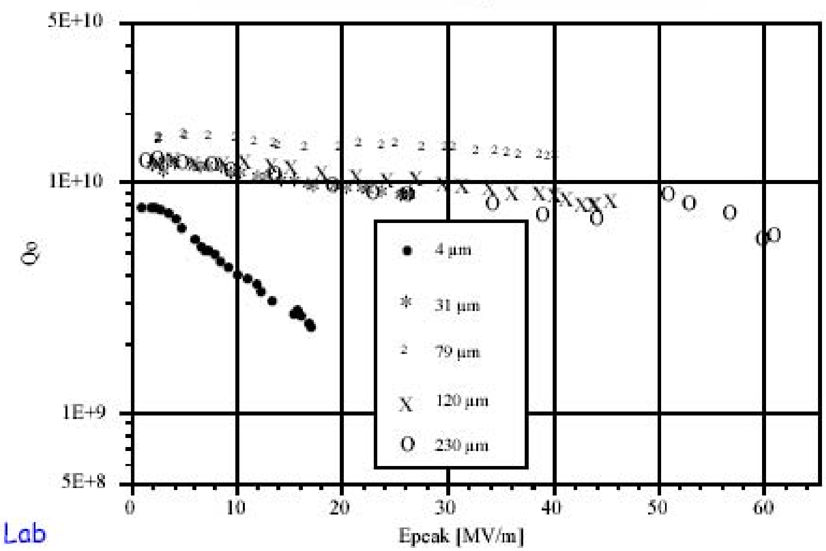
Why Surface Treatment?

Damage layer influences cavity Performance









Q vs E_{acc} , "Q-drop"

- For high RRR niobium often a degradation of the Q value is observed at gradients (magnetic surface fields) above ~ 20 MV/m (>90 mT)
- "In situ" baking of the cavities at 120C for long periods of time (~48 hrs) improves the Q-values

  at lower power and in the Q-drop regime
- The improvement is often more pronounced for EP cavities, but is also observed for BCP'd cavities
- The physics of the Q-drop is still not understood

  explanations range from field enhancements at grain boundaries to effects in the metal-oxide interface or weak links at grain boundaries
- It is clear that oxygen diffusion from the surface into the material plays a role; the depth of the affected zone is several hundred nm

Q vs E_{acc} , "Q-drop"

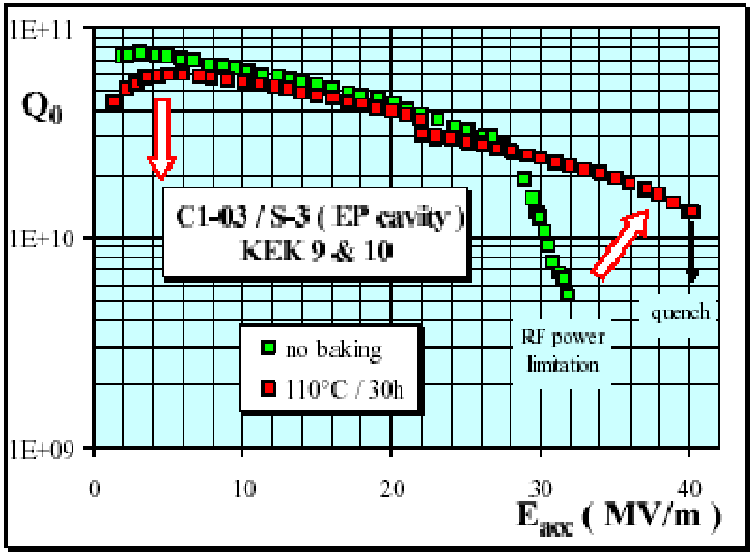
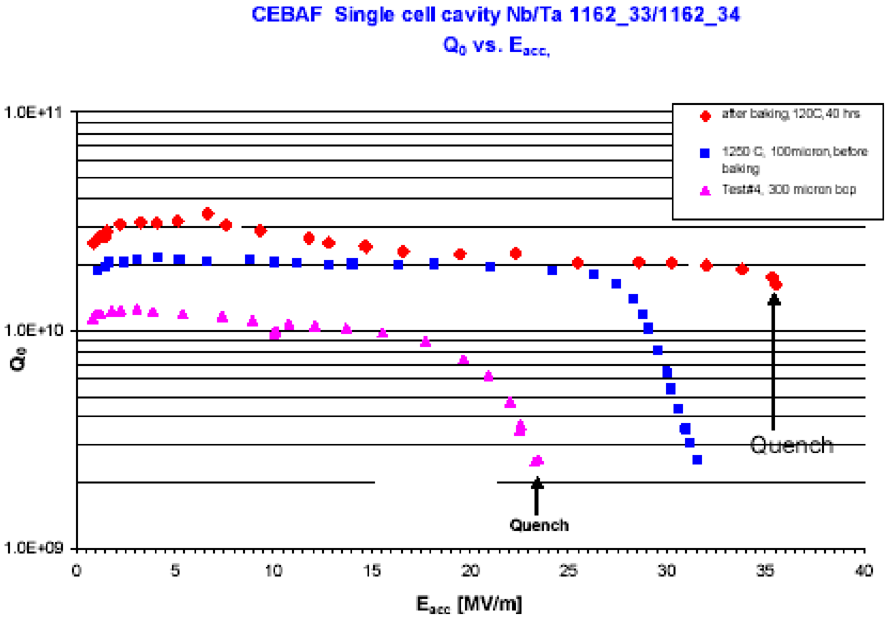


Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].

[B.Visentin,SRF2003]

electropilished

Buffered Chemical Polished(1:1:1)

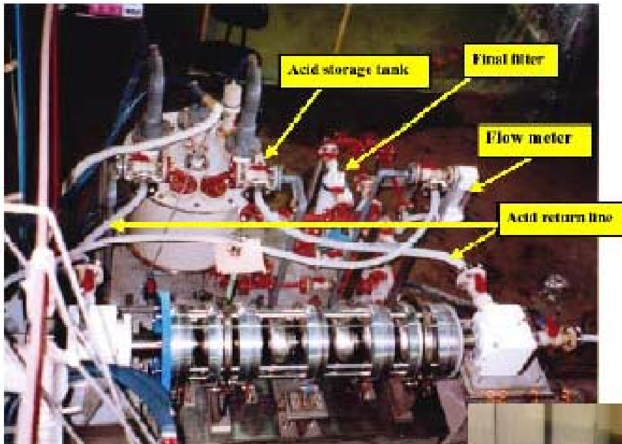


Surface Treatment Procedures

- Eddy CurrentScanning, Squid Scanning
  (successfully used at DESY on TTF cavities)
- Degreasing (ultrasound + soap+water, solvents)
- BCP (HF:HNO_3 :H_3PO_4 as 1:1:1, 1:1:2,1:1:4)
  (room temperature or below to avoid excessive hydrogen pick-up)
- Electropolishing (HF/H_2SO_4 Siemens-KEK-Recipes)
- Barrel Polishing
- High pressure Ultrapure Water Rinsing
- High Temperature Heat Treatment (600C to 1400C for Hydrogen degassing, Post Purification)
- "In-situ" baking (typically 120C for> 24 hrs)
- Alternative Cleaning:CO_2 Snow, Megasonic, UV Ozon..

EP- Systems

KEK/Nomura Plating

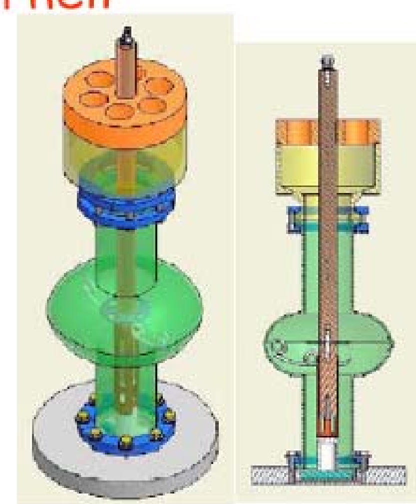


DESY

JLab

INFN

Cornell

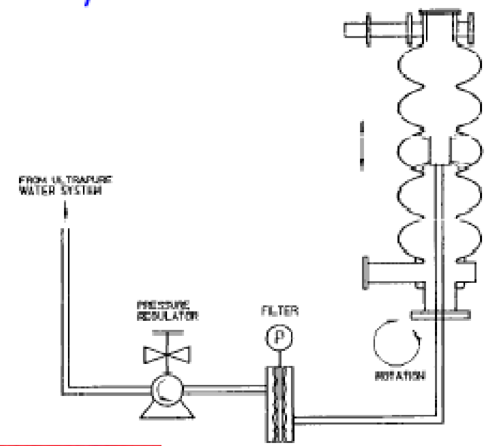


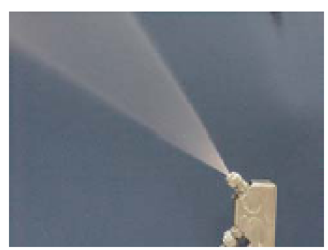
High Pressure Rinse Systems

DESY-System

Jlab HPR Cabinet

KEK-System





High Temperature Heat Treatment

UHV Heat Treatment of Niobium used since the "beginning of times"; nowadays :

- Hydrogen degassing: 600C for 10 hrs at Jlab
  750 C for 3 hrs at KEK
- Annealing: 800 C, several hrs
- Post- Purification: 1200C to 1400C in presence of a solid state getter, e.g.Ti
  Improvement of RRR
  Loss of mechanical properties
  grain growth

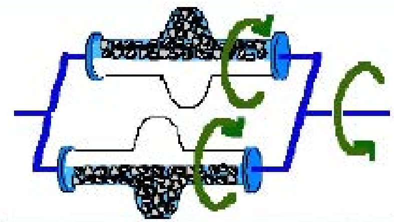
Centrifugal Barrel Polishing(2)

Purpose of mechanical grinding

Embedded | Cracks | Sputter balls

Mechanical grinding is a powerful method to remove surface defects

Centrifugal Barrel Polishing (CBP)



[T.Higuchi, K. Saito, SRF 2003]

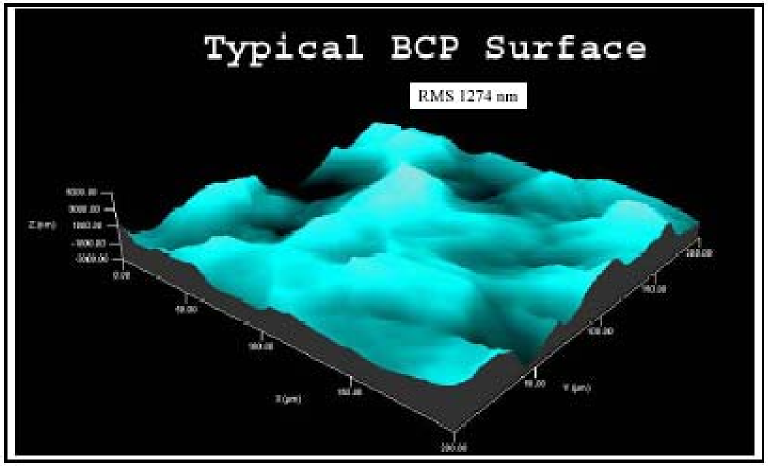
CO_2 Snow Cleaning

Developed at DESY (D.Reschke) as an alternative to HPR or "in situ" cleaning for modules

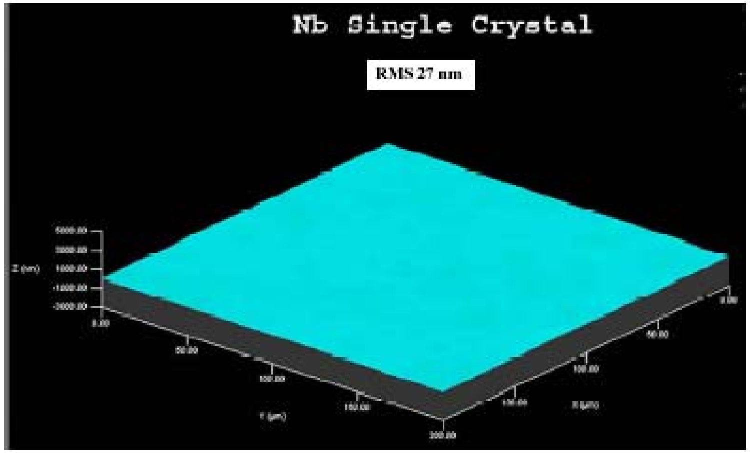
- A prototpye system has been fabricated and initial tests have been made on samples and on single cell cavities
- optimization of process necessary
  (cleaning effect; avoidance of condensation, mass flow)
- A production system is under construction and will be completed some time in the autumn of 2005

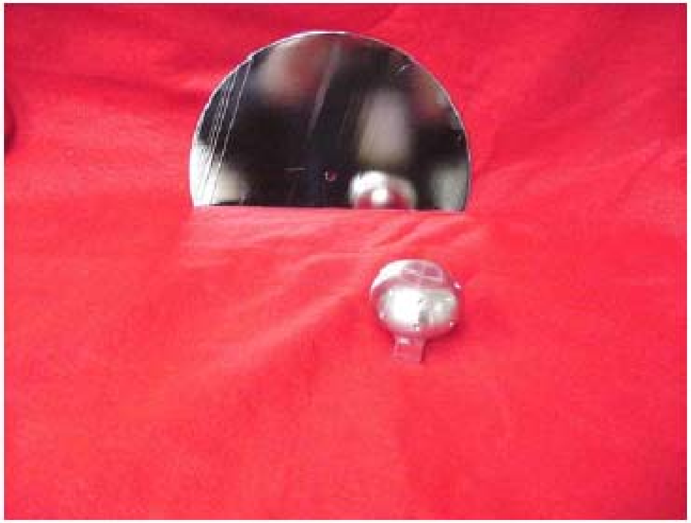
Single Crystal BCP

Provides very smooth surfaces as measured by A.Wu, Jlab



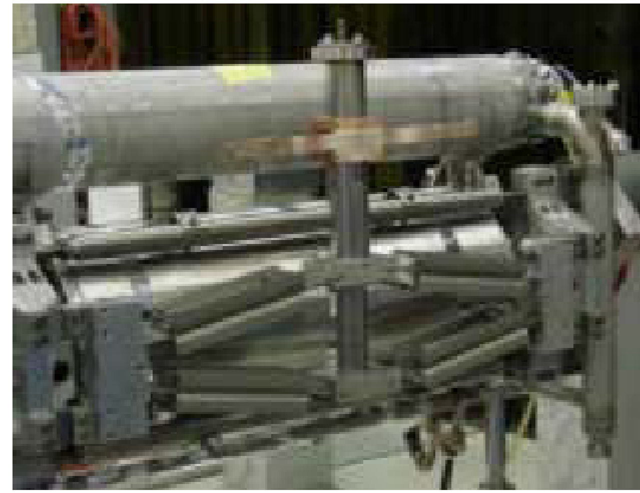
RMS: 1274 nm fine grain bcp
27 nm single crystal bcp
251 nm fine grain ep

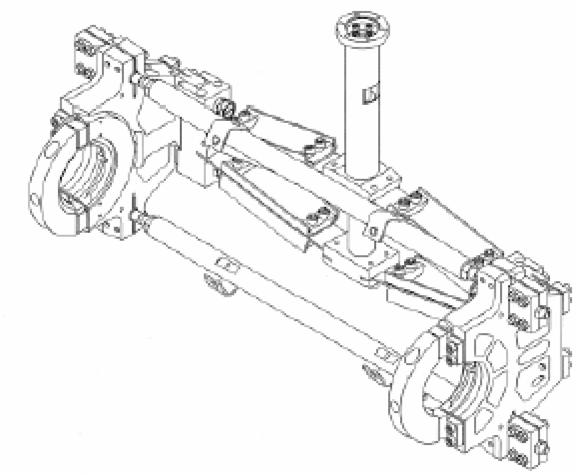




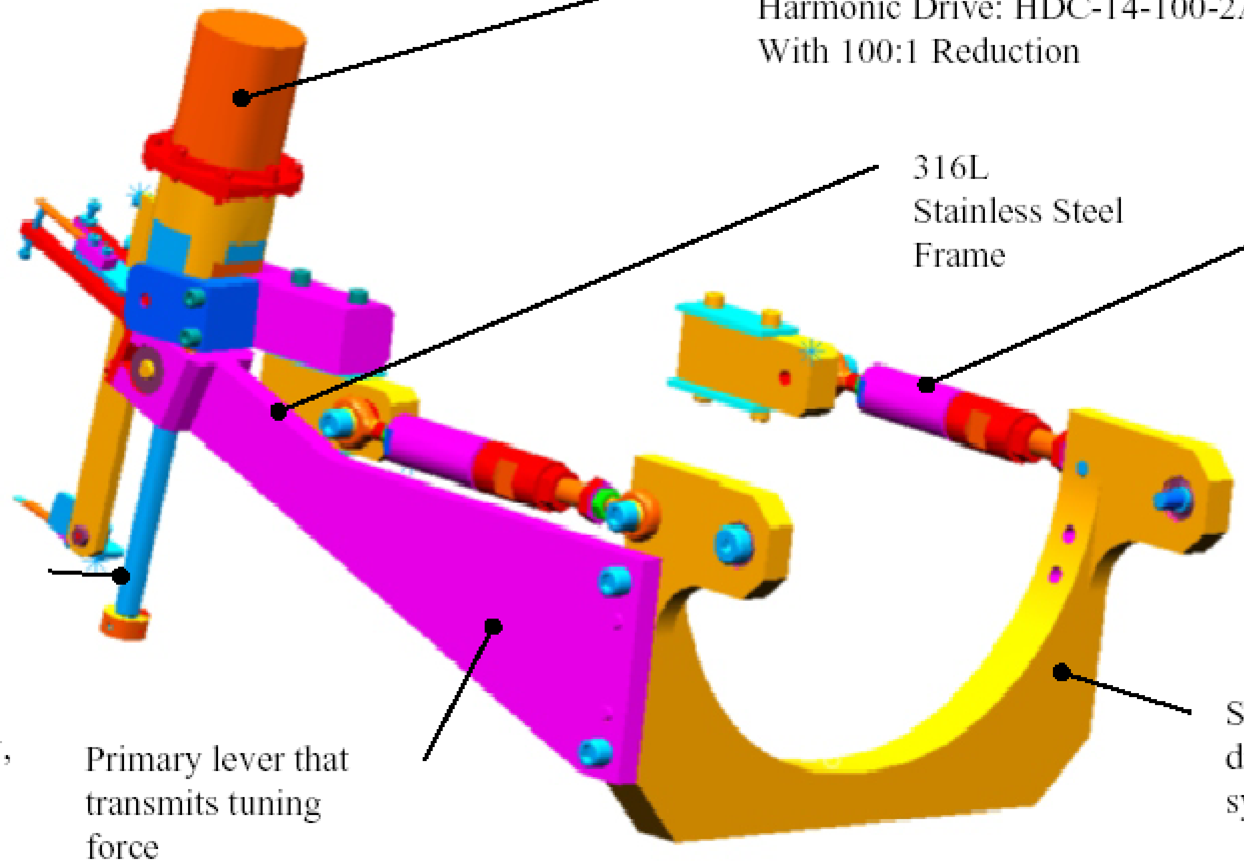
Upgrade Tuner for SL21 and FEL03 Cryomodules - Description

- Scissor jack mechanism
  - Ti-6Al-4V Cold flexures & fulcrum bars
  - Cavity tuned in tension only
  - Attaches on hubs on cavity
- Warm transmission
  - Stepper motor, harmonic drive, piezo and ball screw mounted on top of CM
  - Openings required in shielding and vacuum tank
- No bellows between cavities
  - Need to accommodate thermal contraction of cavity string
  - Pre-load and offset each tuner while warm

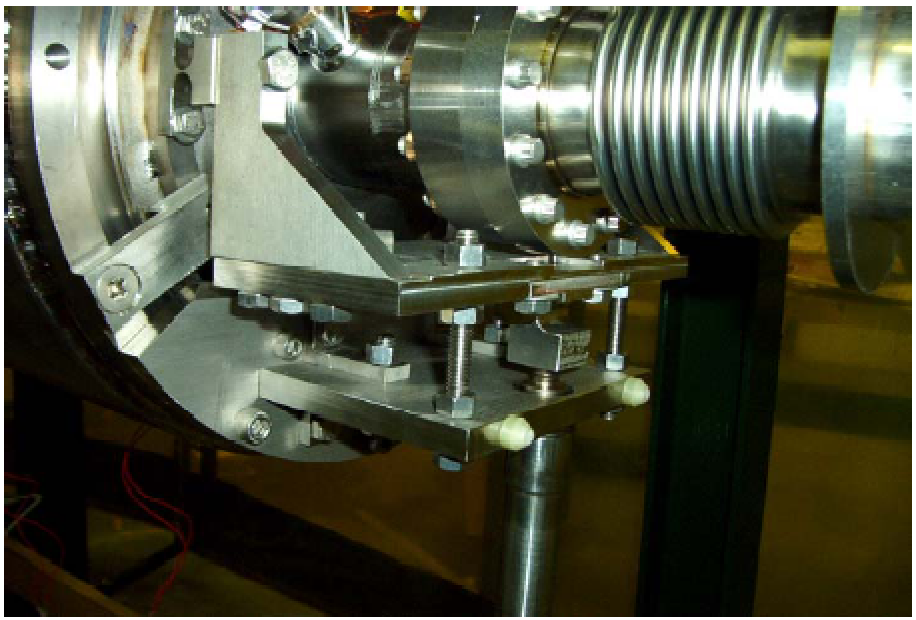


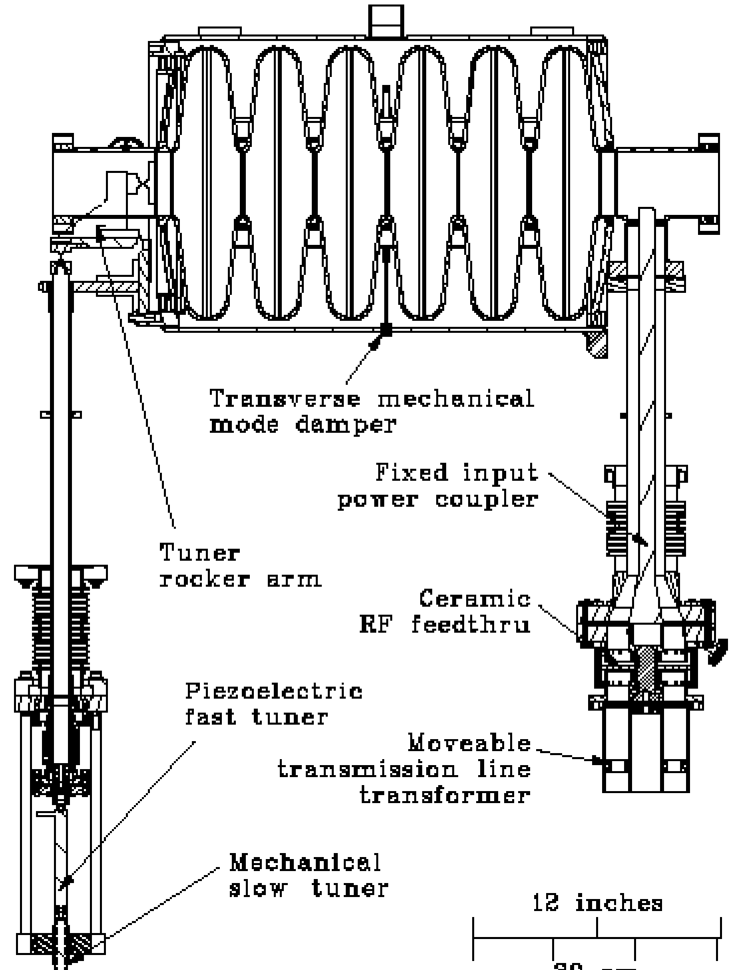


Renascence Tuner Assembly with Two Cold Piezo Actuators

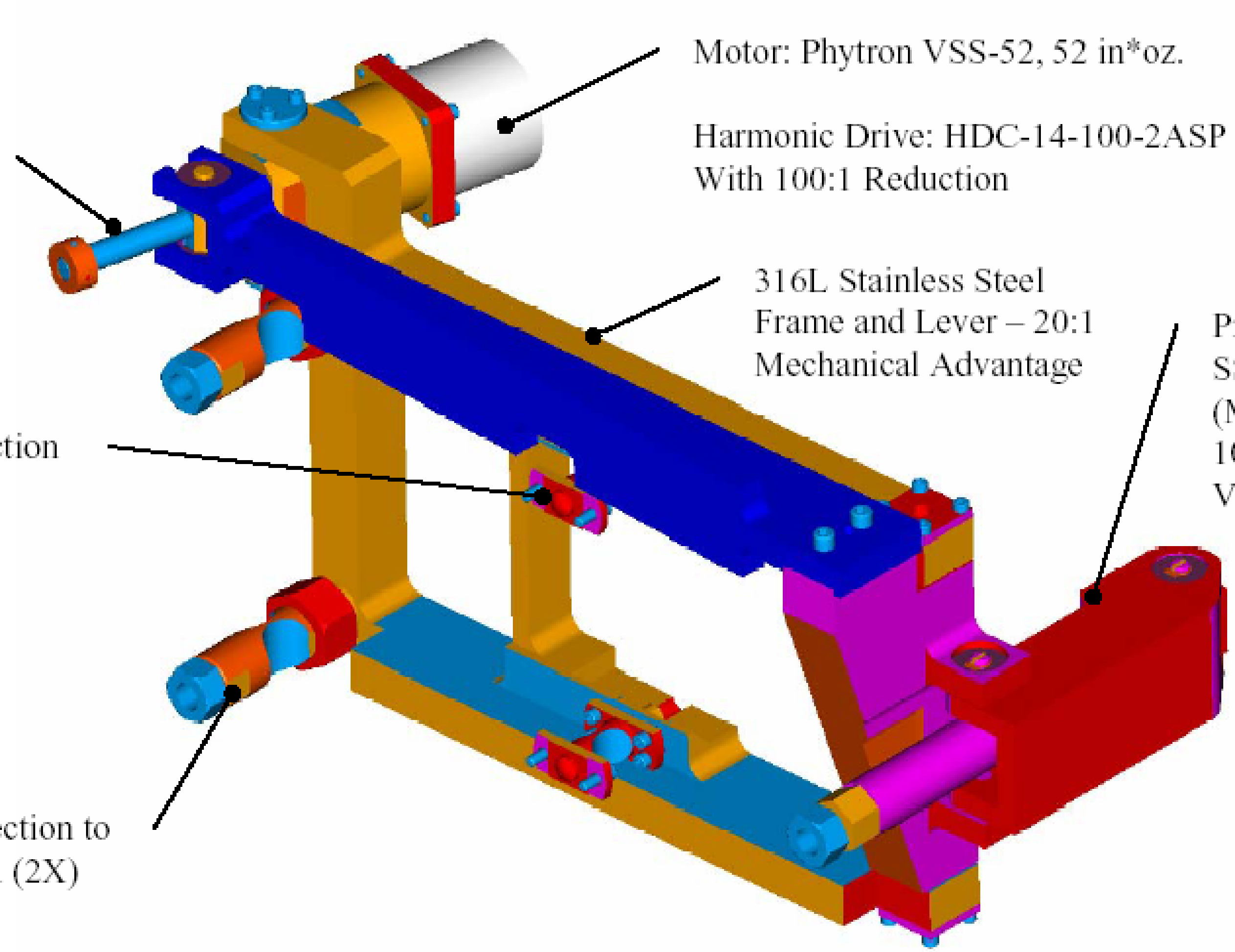


RIA Tuner – Rocker Arm / Schematic

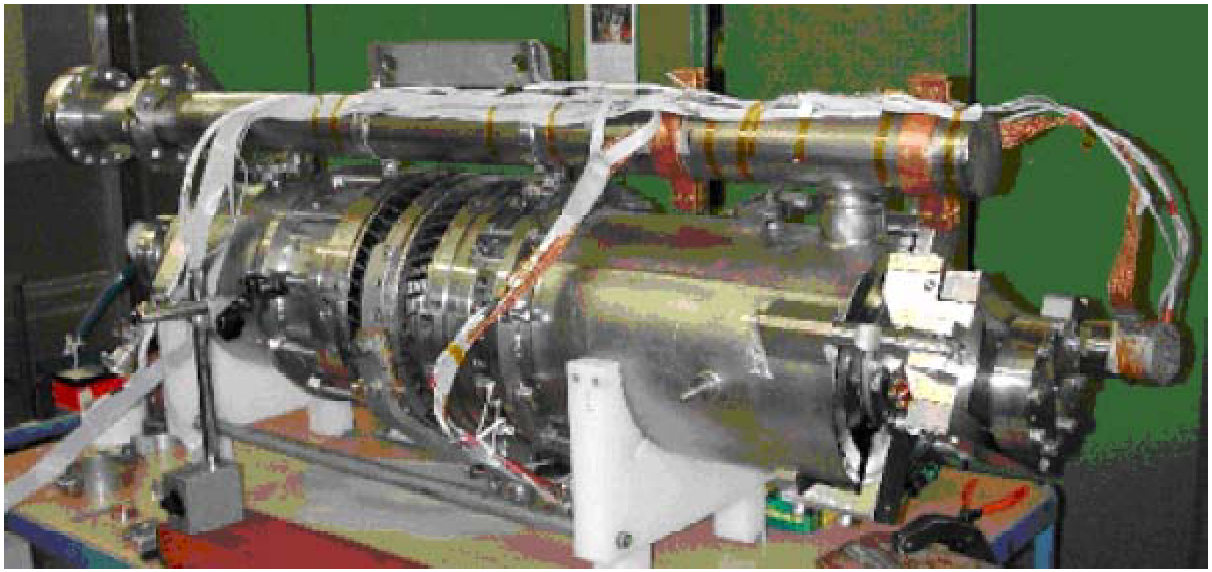


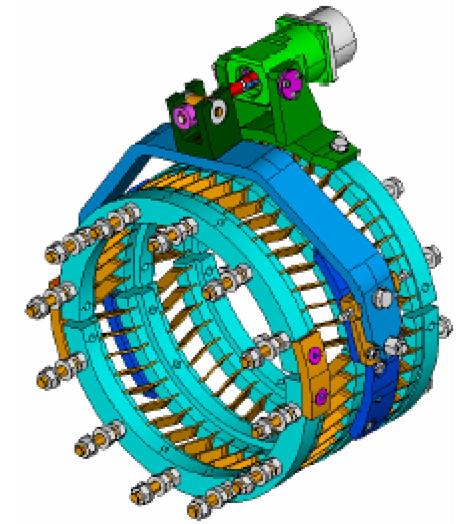


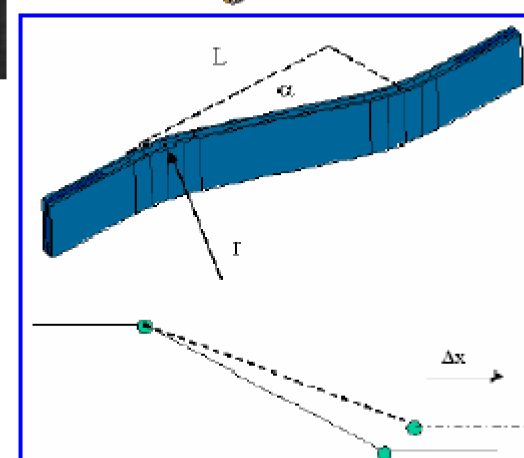
SNS Tuner Assembly w/ Piezo Actuator



TESLA - Blade Tuner







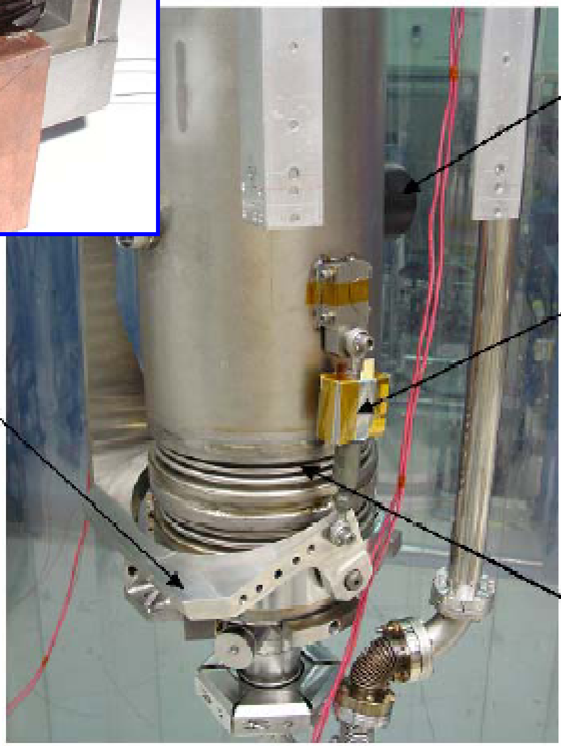
- Mechanism – All cold, in vacuum components
  - Titanium frame
  - Attaches to helium vessel shell
  - Pre-tune using bolts pushing on shell rings
  - Dicronite coating on bearings and drive screw
  - Cavity tuned in tension or compression – blades provide axial deflection

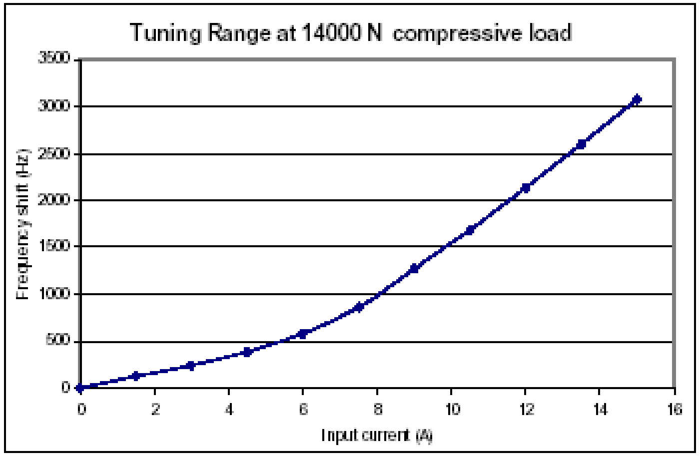
Renascence Cavity – VTA Test Results:

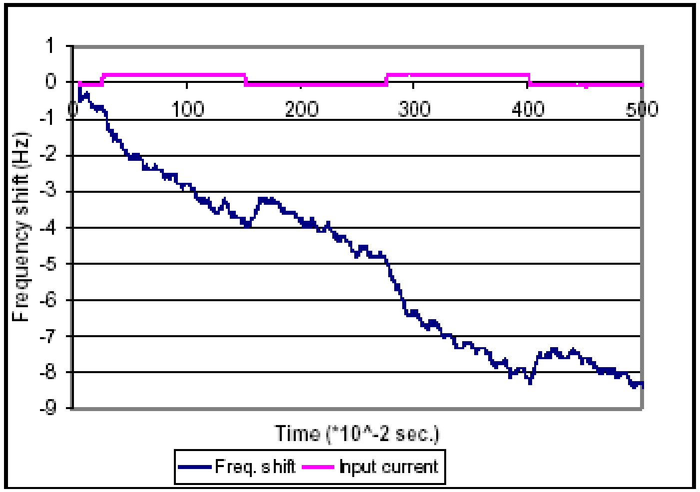
Magnetostrictive Actuator on Tuner

RANGE OF THE MAGNETOSTRICTIVE TUNER AT DIFFERENT LOADS

Compressive Load (N)	Max. Tuning Range (Hz)
No Load	2,600
7100	5,892
10,200	3,423
14,000	3,088

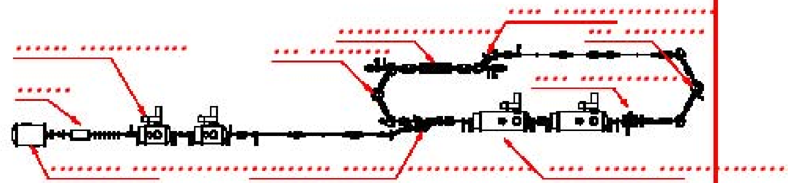






Power Couplers

Layout of the JAERI ERL-FEL

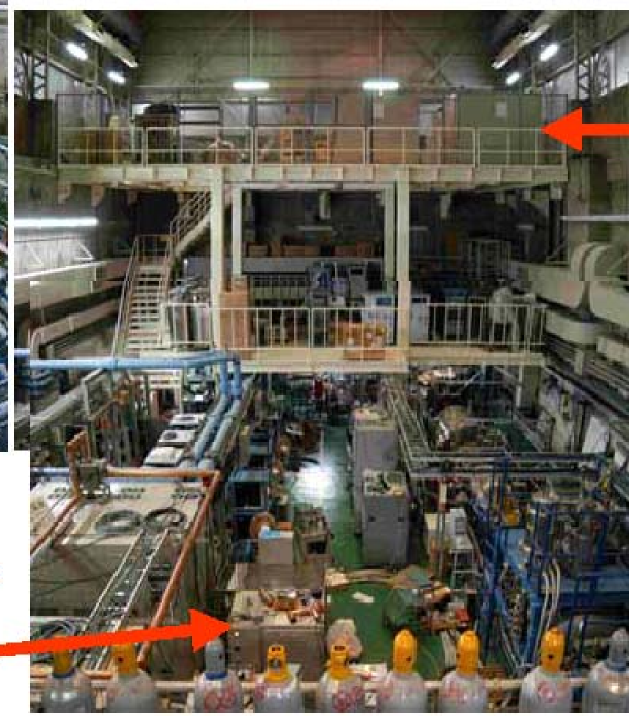


before

6kW All-Solid-State Amp

50kW All-Solid-State Amp

50kW IOT



HV for

50kW IOT

now

Cost for 500MHz RF Source

	Pulse	CW
All-Solid-State	~¥70M JPY ~$0.7M	~200M JPY ~$2M
IOT		~26M JPY ~$0.26M

100 JPY=$1

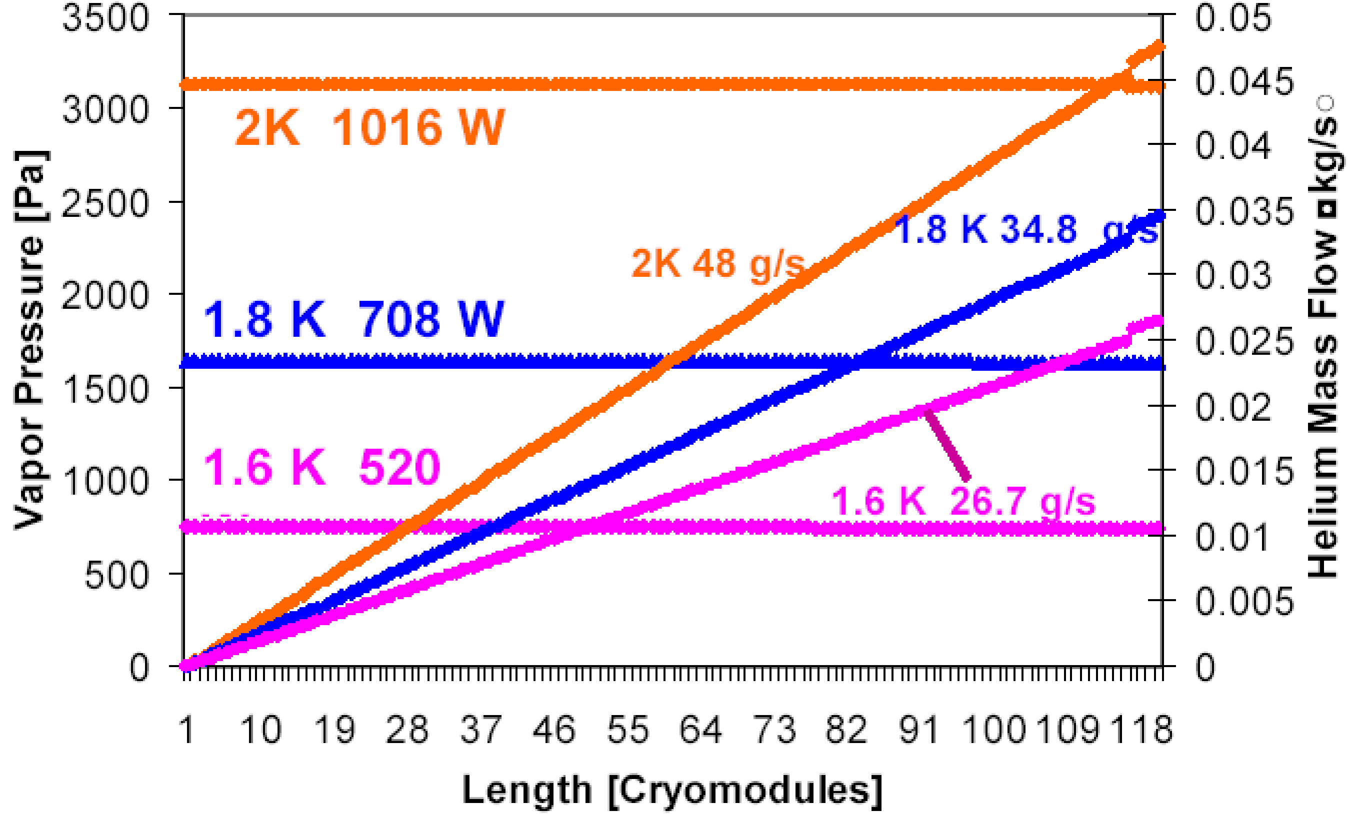
IOT Solid

Tube$0.05M*35+$0.26 ~ $2M

No of replacement

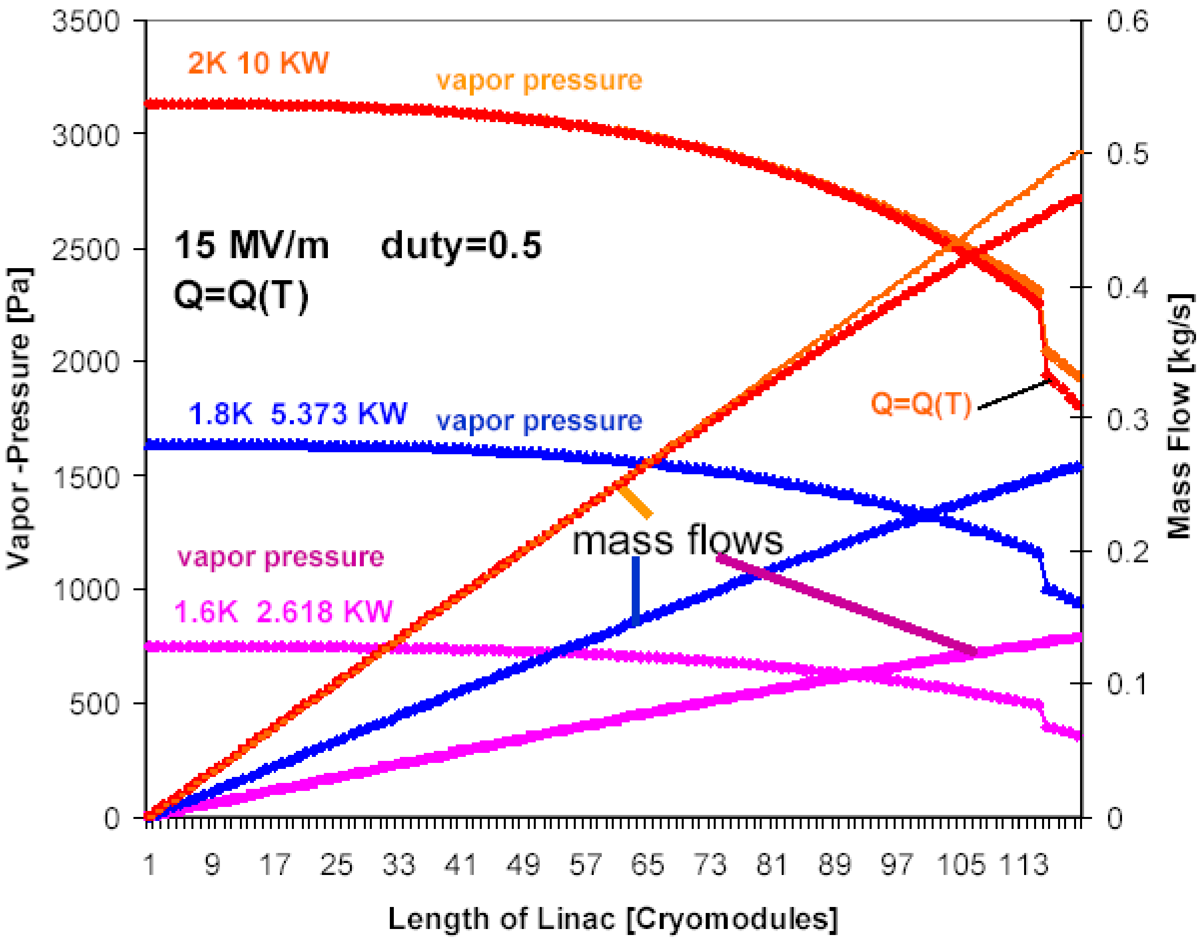
Cryogenics

20 GeV XFEL parameters 10 Hz
650 µs Pulse 23.5 MV/m



ERL2005 Bernd Petersen DESY

XFEL ERL-up-grade ?



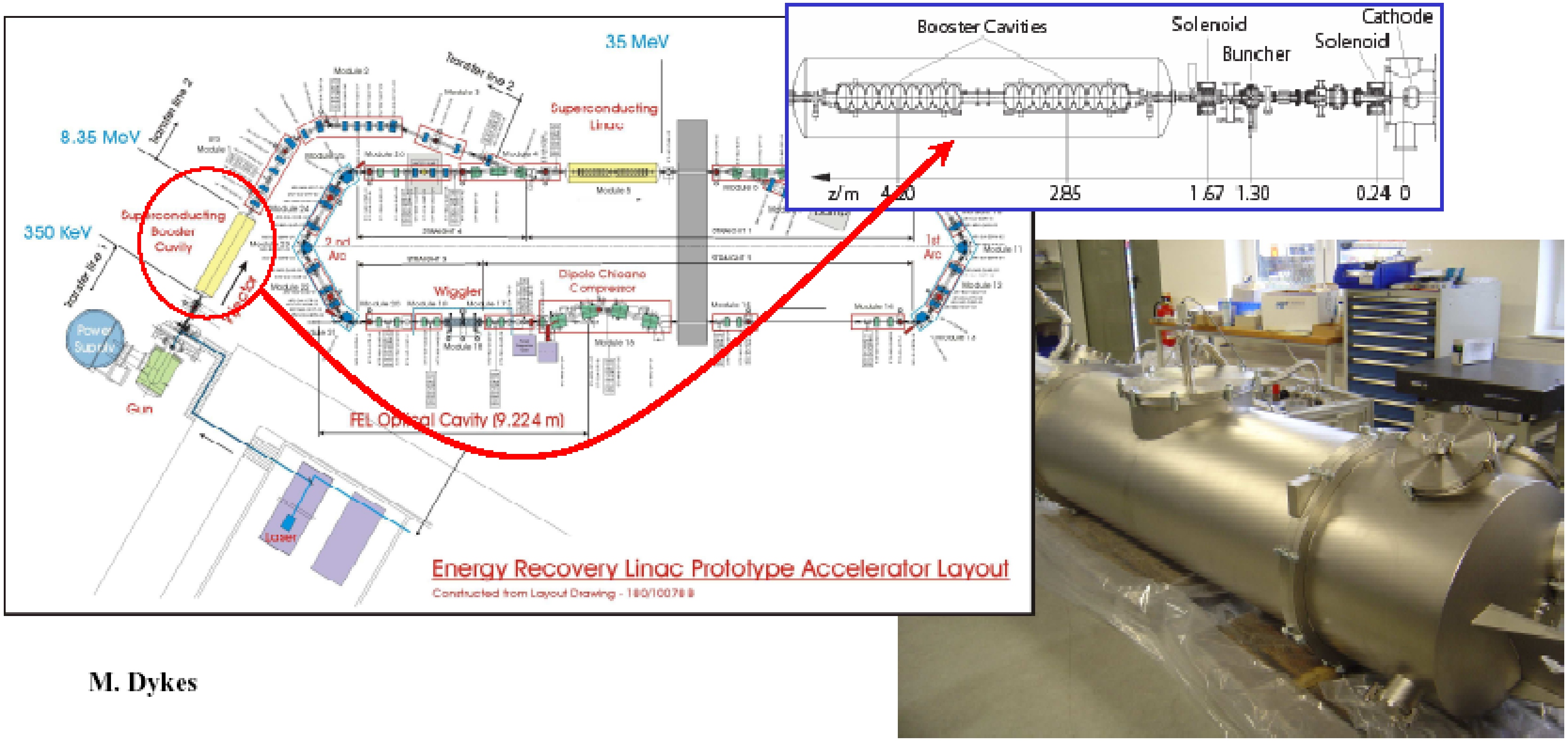
Conclusions

- Lowering the temperature seems to be effective as long as Q = Q(T) follows BCS and the temperature dependent dynamic loads dominate (reasonable lower limit 1.5 K)
- Watch the temperature independent loads: HOMs, couplers…, static
- The long term stability of the Q = Q(T) characteristic has to be proven
- HeII cooling might become unstable below 1.8 K – tests required
- Another cold compressor stage is required for each 0.2 K temperature step to lower temperatures – investment costs and system complexity increase
- In view of pressure drops, critical gas velocities, work of compression and general sizing the lower gas densities at lower temperatures seem to be balanced by the lower cooling loads and the related lower mass flows
- If the cryogenic layout is suited for 2 K operation, it should also allow operation at lower temperatures as long as Q = (T) works (beside the necessity of more CC stages) – for the time beeing this is our baseline for the XFEL

ERL Injectors

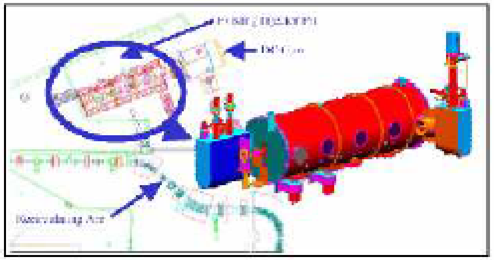
Example 2: ELBE cryomodules in 4GLS ERLP

At Daresbury ELBE cryomodules were chosen for 4GLS ERLP project and are used both in the injector and in the main linac. The booster cavities will operate at a reduced gradient of 4 MV/m.

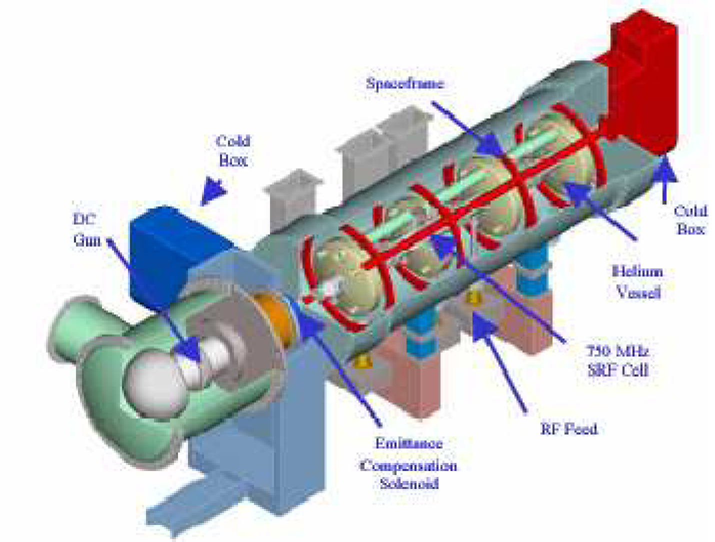


M. Dykes

Example 3: JLAB 100 kW FEL injector



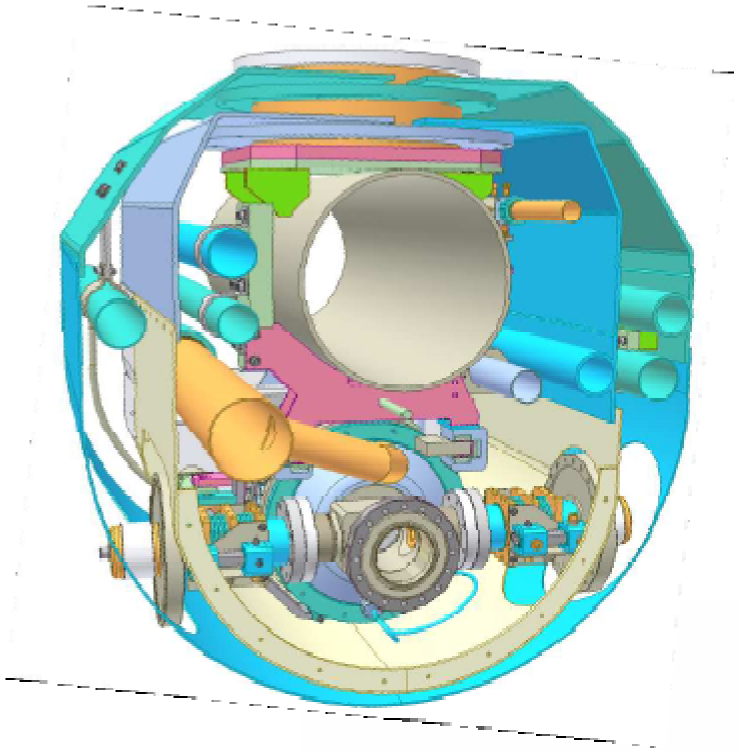
The cryomodule is designed to replace the existing ¼ cryomodule injector. This will boost injector average beam current from 10 mA to 100 mA. It is developed by AES in collaboration with JLab.



Parameter	100 kW FEL requirements	Simulations
Beam current	> 100 mA	100 mA
Beam energy	7 MeV	7 MeV
Energy spread	< 1 %	0.5 %
Transverse emittance	< 10 microns	1.2 microns
Longitudinal emittance	< 100-200 keV×psec	44 keV×psec

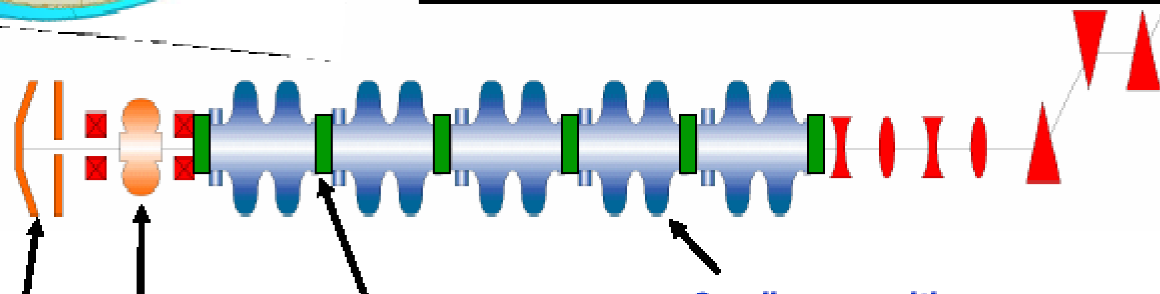
A. Todd, et al., PAC'2003
H. Bluem, et al., EPAC'2004

Exampe 4: Cornell ERL injector



Beam Parameters:

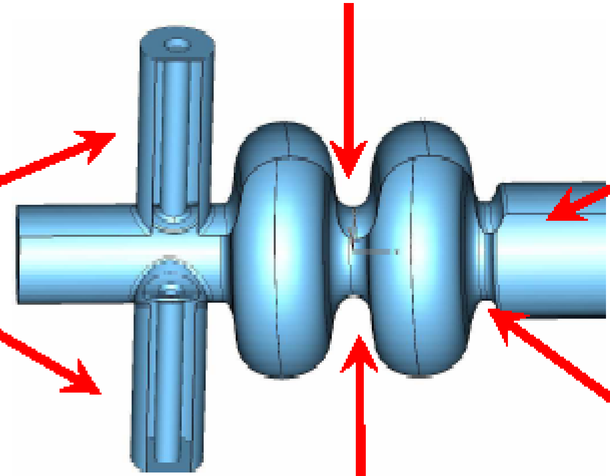
max beam current at q = 77 pC	100 mA
max beam current at q= 1 nC	1 mA
bunch repetition rate	1.3 GHz
transverse emittance	< 0.5 μm rad
max. emittance growth	< 0.1 μm rad
bunch length	0.6 mm
beam energy gain	5 MeV



Cavity design:
Two-cell kick-free, dipole-mode-free superconducting cavity

2 cells:
Upper limit set by 100 kW coupler power (max. energy gain per cavity)
Lower limit: Maximum field gradient < 20 MV/m

Symmetric twin input coupler

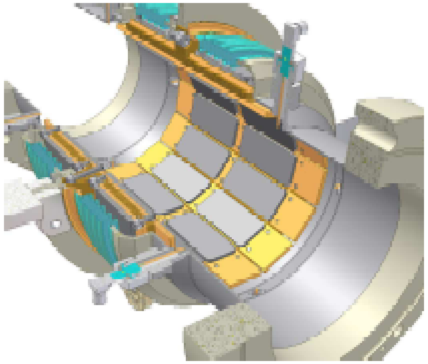


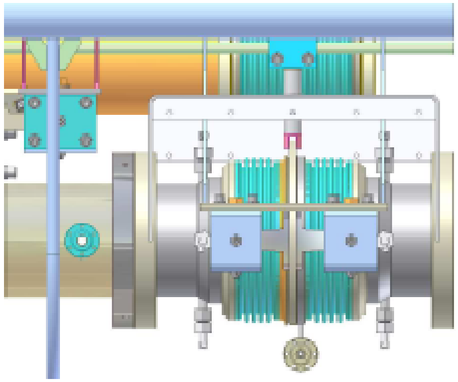
Large 106 mm diameter tube to propagate all TM monopole HOMs and all dipole modes

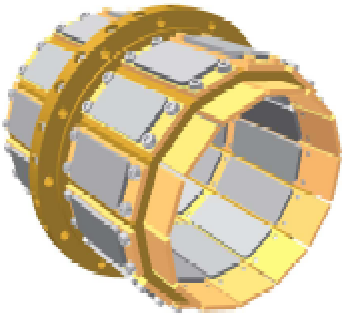
Reduced iris to maximize R/Q of accelerating mode

f_{acc} = 1.3 GHz (TESLA)
Optimum: 1 GHz – 1.5 GHz
Lower f: Larger cavity surface, higher material cost,...
Higher f: Higher BCS surface resistance, stronger wakes, ...

Ferrite HOM load parameters

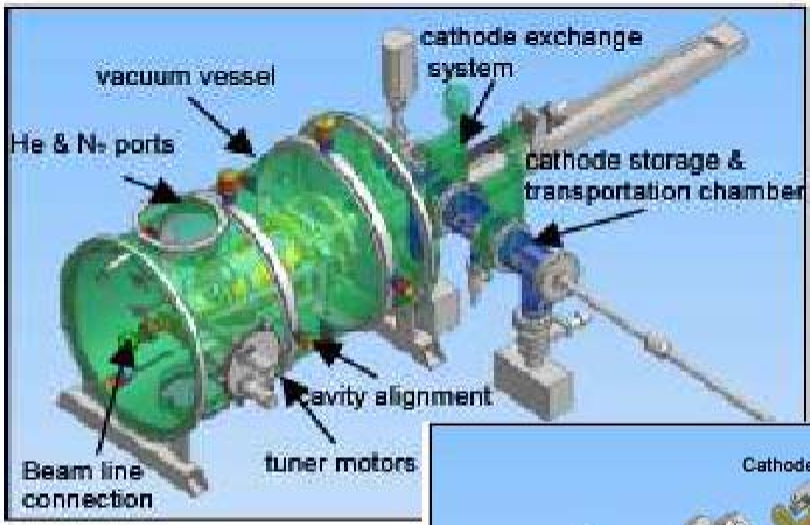


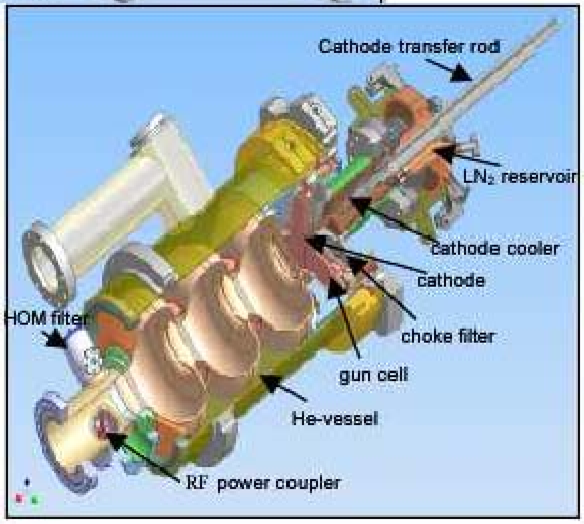




Total number of absorbers	3 + 3
Average dynamic power per absorber	26 W
Max. power/absorber	200 W
HOM frequency range	1.4 to 100 GHz
Operating temperature	80 K
Coolant	Cold He gas
Absorber types (very prelim.)	TT2, hex Z, C10

Example 5:
Rossendorf's 3½ -cell superconducting RF gun cryomodule





Energy	9.5 MeV
Beam current	1 mA
Frequency	1.3 GHz
RF power	10 kW
Ez max (½ cell)	33 MV/m
Ez max (TESLA cells)	50 MV/m
ε (q = 77 pC)	0.5 mm mrad
ε (q = 1 nC)	2.5 mm mrad

D. Janssen, et al., FEL'2004