R & D in RF Superconductivity at Michigan State University

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Michigan State University
East Lansing, Michigan

FNAL Accelerator Physics & Technology Seminar
14 September 2006

Outline

Introduction

Introduction

- Michigan State University (MSU): ~ 400 km from Fermilab.
- National Superconducting Cyclotron Laboratory (NSCL): basic research in nuclear physics and nuclear astrophysics.
- NSCL Coupled Cyclotron Facility: user facility for experiments with heavy ions.
- Nuclear physics community agrees: a new facility is needed for the next generation of experiments with heavy ion beams.
- The new facility should be a heavy ion linac. Design work ongoing for several years (Argonne, Berkeley, CEBAF, Oak Ridge, NSCL, *et al.*).

SRF for Heavy Ion Linacs

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- The heavy ion linac should operate in CW and make use of superconducting radio-frequency (SRF) cavities.
- There are several existing SRF linacs for heavy ions, *e.g.* at Argonne, INFN-Legnaro, JAERI, *etc.*
- Existing heavy ion SRF linacs generally use quarter-wave resonators (QWRs) and variants thereof.
- A next-generation linac would use QWRs, half-wave resonators (HWRs), and elliptical cavities.
- NSCL began R & D work in SRF in the year 2000, with help from CEBAF, INFN-Legnaro, and other collaborators.
- SRF facilities at MSU: fabrication, chemistry, clean room, RF testing.

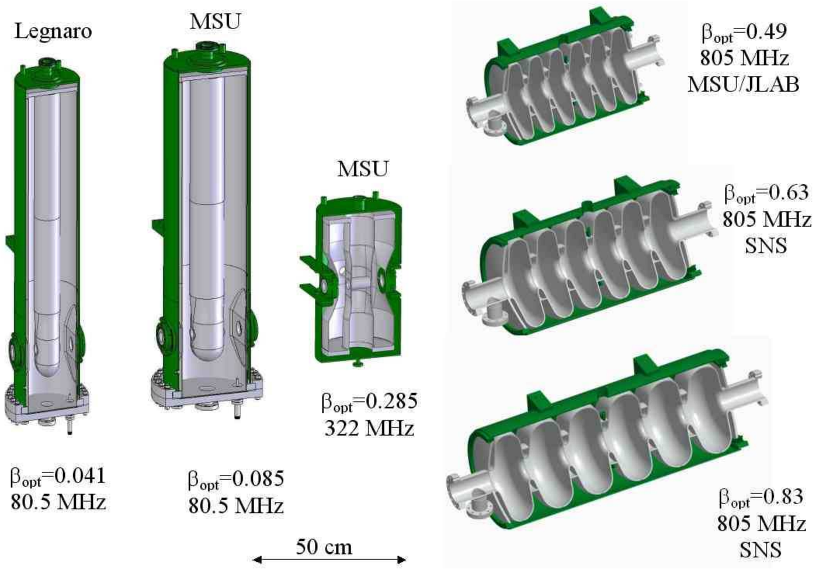
Cavity Design and Prototyping

Cavity Design and Prototyping

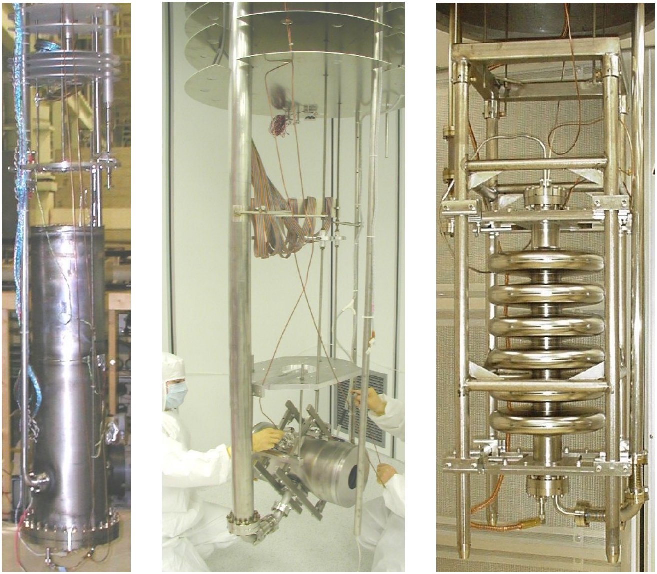
- QWRs, HWRs, and elliptical cavities were prototyped by NSCL in collaboration with CEBAF and Legnaro.
- Design work was done by INFN-Milano, INFN-Legnaro, CEBAF, and NSCL.

Cavity parameters for a heavy ion linac example: 400 MeV/nucleon, 400 kW beam power

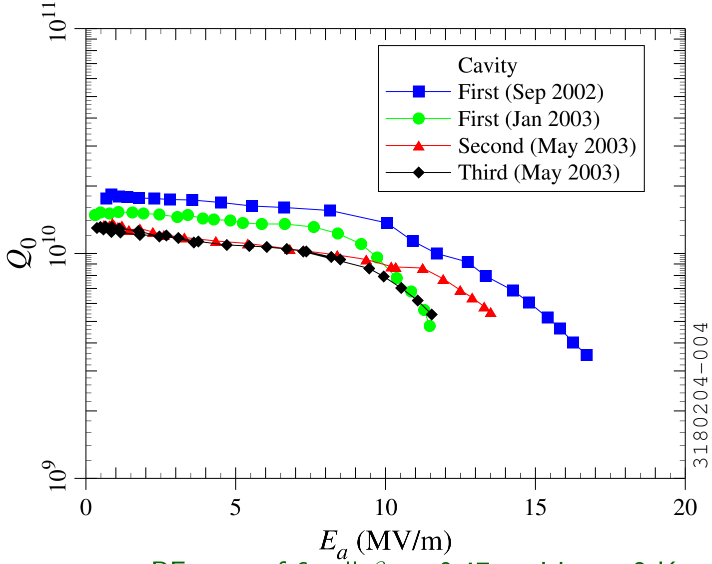
Type	$\lambda/4$		$\lambda/2$	6-cell elliptical		
β_{opt}	0.041	0.085	0.285	0.49	0.63	0.83
f (MHz)	80.5		322	805		
V_a (MV)	0.46	1.18	1.58	5.12	8.17	13.46
T (K)	4.5		2	2		
Q_0	$5 \cdot 10^8$		$5 \cdot 10^9$	$7 \cdot 10^9$	$1 \cdot 10^{10}$	$1.4 \cdot 10^{10}$
P_0 (W)	1.0	6.7	2.5	21.6	23.9	26.8
R/Q (Ω)	424	416	199	173	279	483
G (Ω)	15.7	19.0	61.0	136	180	260
Rs (nΩ)	31.4	38.0	12.2	19.4	18.0	18.6
E_p (MV/m)	16.5	20	25	32.5		
B_p (mT)	28.2	46.5	68.6	64.2	68.6	70.2
Aperture (mm)	30			77	86	98
Magnets	NbTi solenoids			Cu quads		
# cavities	18	104	208	68	64	32
# cryo-modules	2	13	26	17	16	8



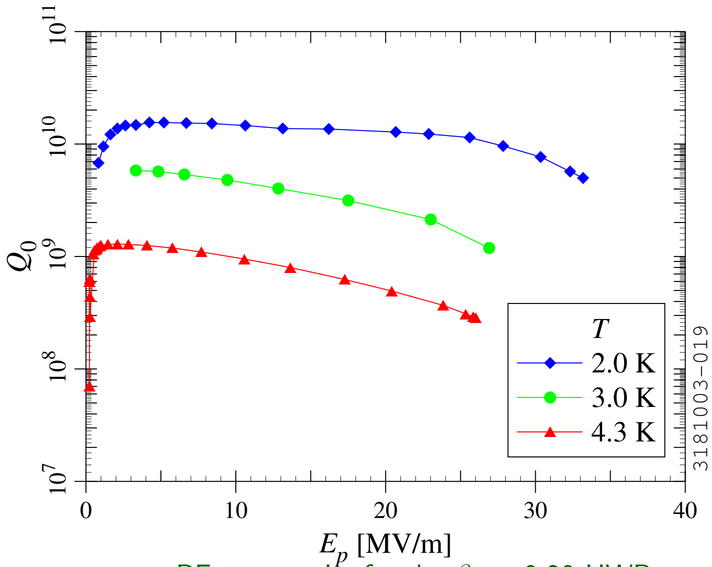
Cavities for heavy ion acceleration



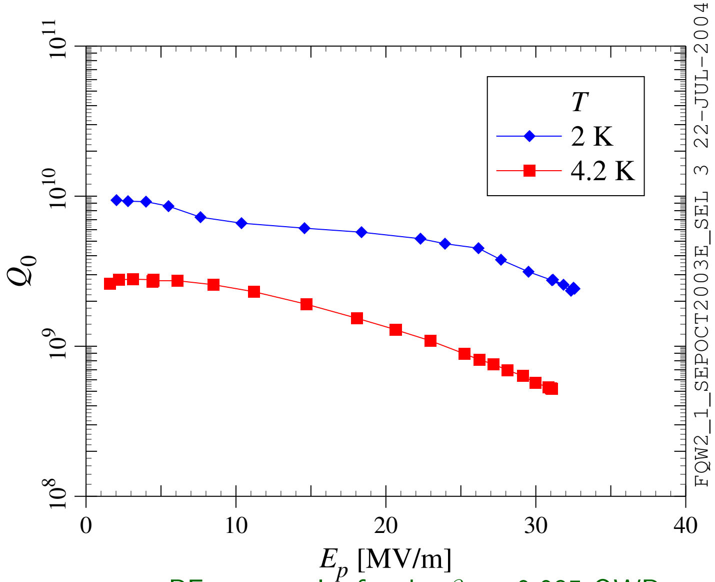
Cavities for heavy ion acceleration



RF tests of 6-cell $\beta_g = 0.47$ cavities at 2 K



RF test results for the $\beta_g = 0.29$ HWR

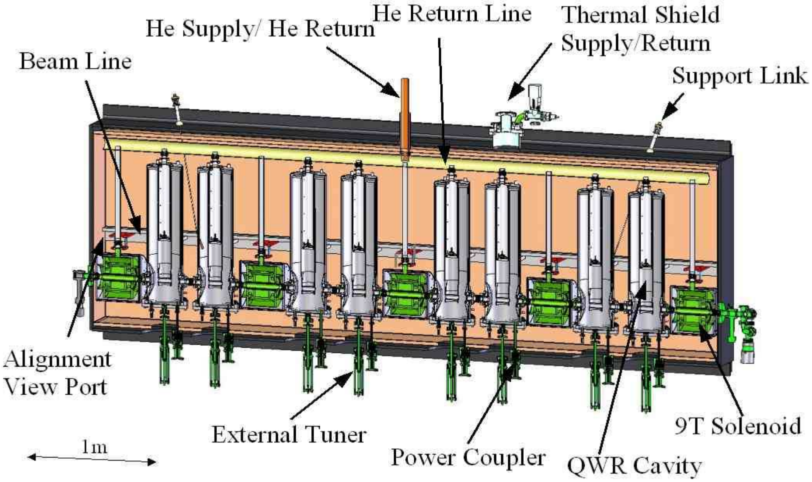


RF test results for the $\beta_g = 0.085$ QWR

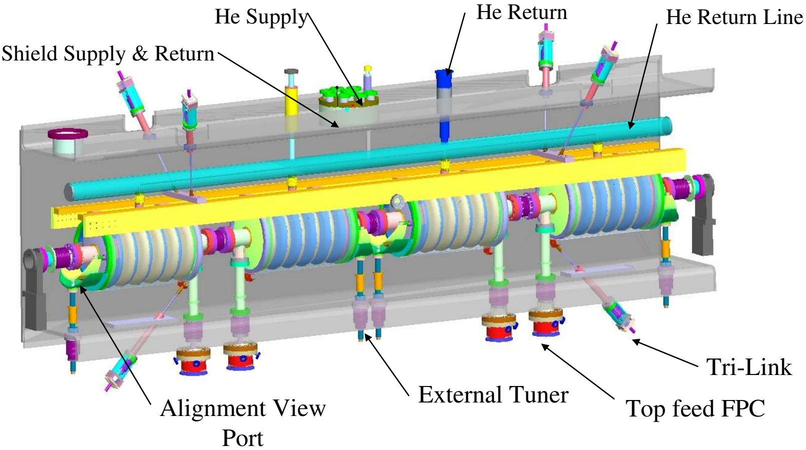
Cryomodule Design and Prototyping

Cryomodule Design and Prototyping

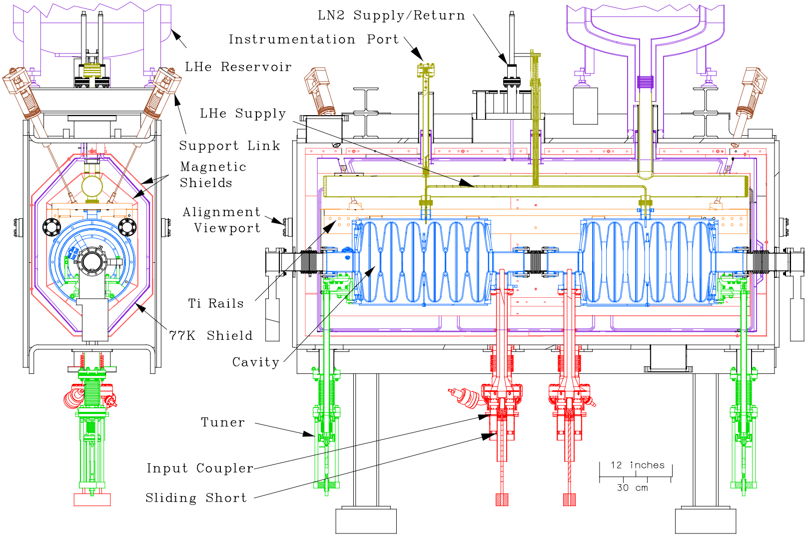
- Rectangular box cryomodule design for all cavity types.
- Prototype medium-β cryomodule: 2 elliptical cavities
- Prototype low-β cryomodule: 1 QWR, 1 HWR, 2 focussing magnets



Cryomodule design for 80.5 MHz QWRs



Cryomodule design for 805 MHz elliptical cavities



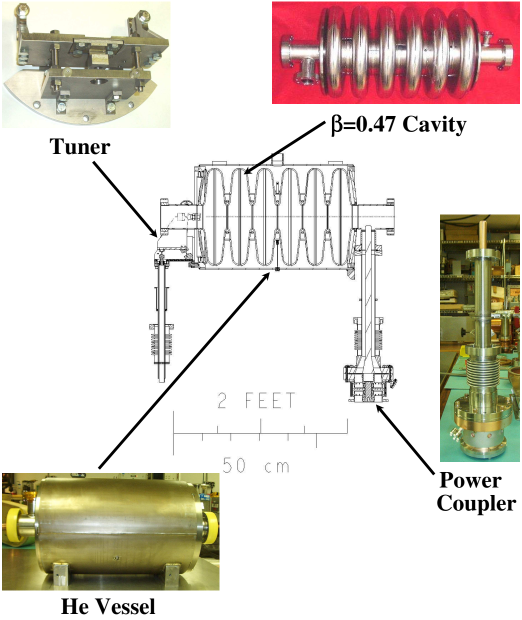
Prototype Medium-β Cryomodule

Medium-β cryomodule design parameters

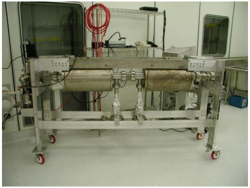
Item	Prototype	Production
Cavities	2	4
Length	2.1 m	4.0 m
2 K cold mass	210 kg	460 kg
Total mass	2200 kg	3600 kg
Bayonets	2	4
Support links	4	4
77 K heat load	< 50 W	< 100 W
2 K Heat Load		
Input coupler	1.6 W (each)	
Tuner	0.8 W (each)	
Total (RF off)	9 W	15 W
Total (RF on)	53 W	103 W

RF input coupler for medium-β cryomodule

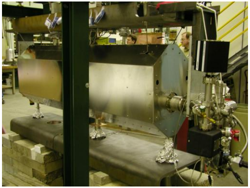
Impedance	50 Ω
Type	Planar Coax (KEK/SNS)
Cooling	conduction
Q_{ext}	$2 \cdot 10^7$
Bandwidth	40 Hz
Design power	5 kW
Max power	100 kW



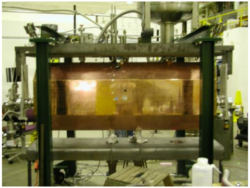
Medium-β prototype cryomodule components



(a) cold mass



(c) inner μ-metal



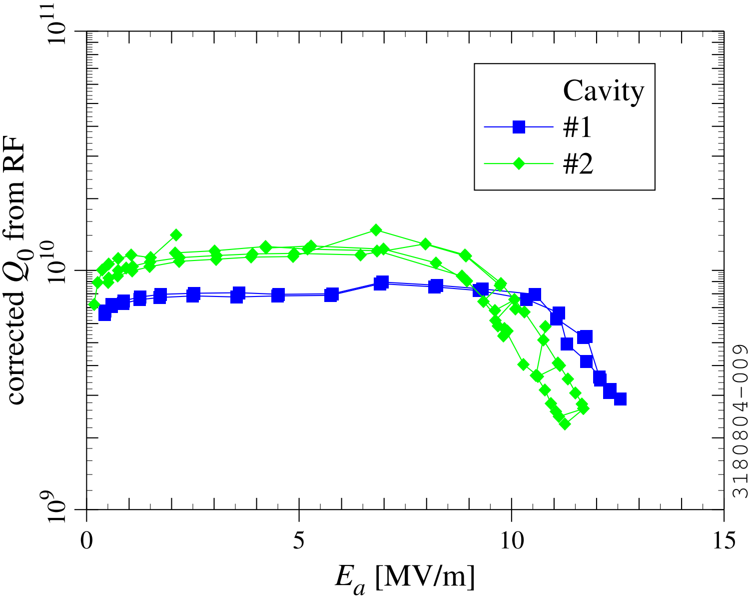
(e) 77 K shield

(b) top plate

(d) multi-layer insulation

(f) completed module

Construction of medium-β cryomodule
(completed February 2004)



Experimental results: medium-β cryomodule

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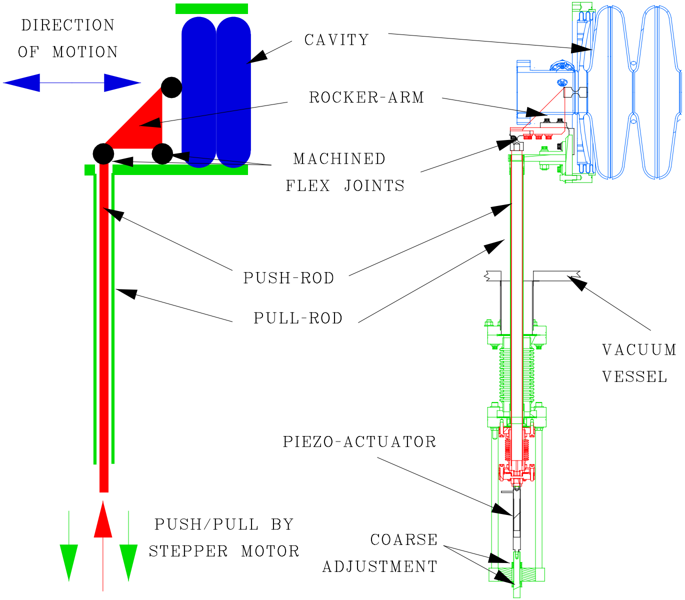
Item	Measured		Design
	Cavity #1	Cavity #2	
Fixed Q_{ext}	$1.4 \cdot 10^7$	$1.3 \cdot 10^7$	$2.0 \cdot 10^7$
Variable Q_{ext}	$6 \cdot 10^4$ to $6 \cdot 10^9$		
$\frac{df}{dP}$ (kHz/torr)	0.36	0.46	
$\frac{df}{dE_a^2}$ [Hz/(MV/m)^2]	-16		-14
Static load at 4.3 K	9 W		
Static load at 2 K	10–11 W		9 W

Variable Q_{ext} = standing wave in input coupler

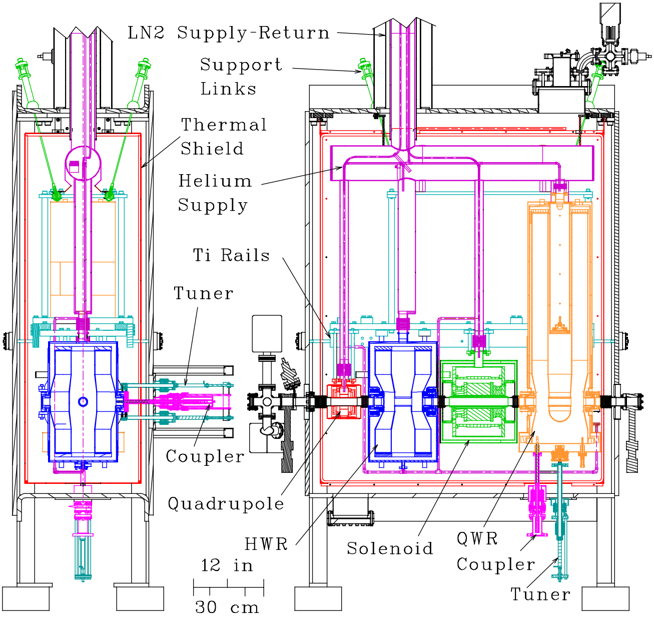
Measured static load includes the liquid He reservoir



Tuner with actuator at room temperature

Tuner with actuator at room temperature

Item	Design	Measured
Range	$\pm$250 kHz	$\pm$500 kHz
Tuning coefficient	$>$ 200 kHz/mm	208 kHz/mm
Cavity spring constant	$<$ 1750 N/mm	1910 N/mm
Resolution	1 Hz	
Compliance	0.7 (rigid)	0.5



Prototype Low-β Cryomodule

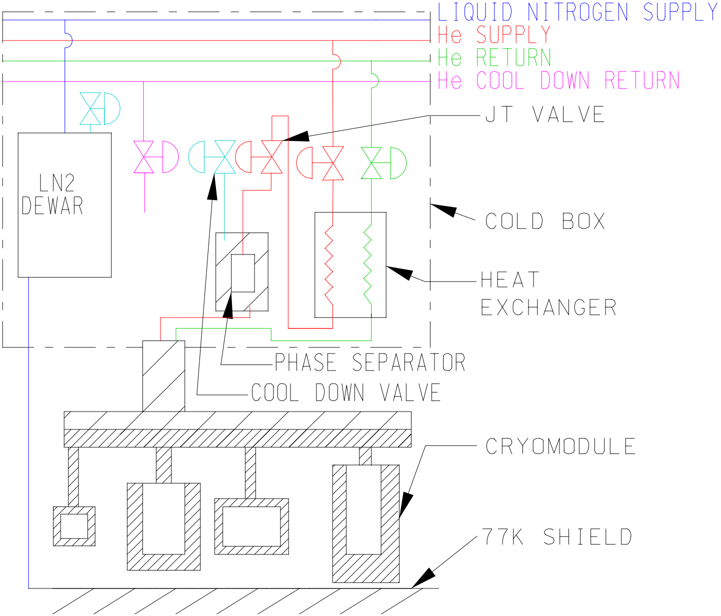
Prototype low-β cryomodule design parameters

Magnets		
Item	Quadrupole	Solenoid (Dipole)
Effective length	50 mm	100 mm
Aperture	40 mm	40 mm
Strength	31 T/m	9 T (0.01 T·m)
Turns	78	16 813 (40)
Current	63 A	68 A (50 A)

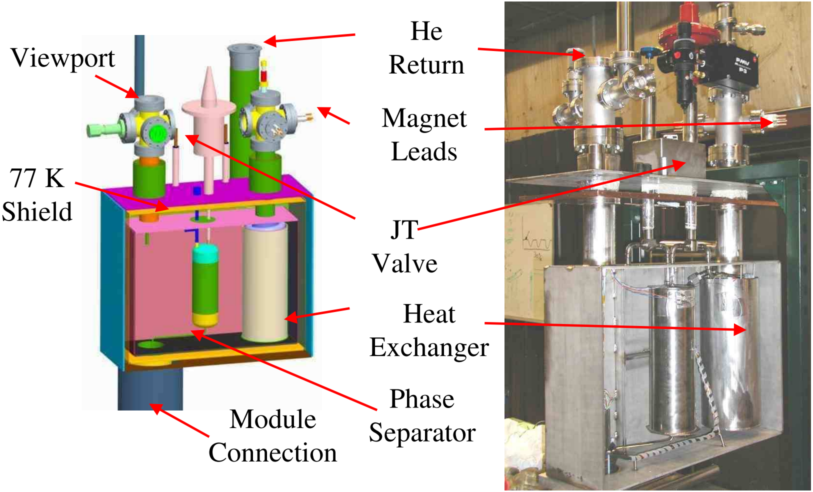
Heat Load to Liquid He		
Item	QWR	HWR
Input coupler	0.40 W	0.60 W
Tuner	0.63 W	0.38 W
Total/RF off	6 W	
Total/RF on	15.2 W	

Prototype low-β cryomodule design parameters

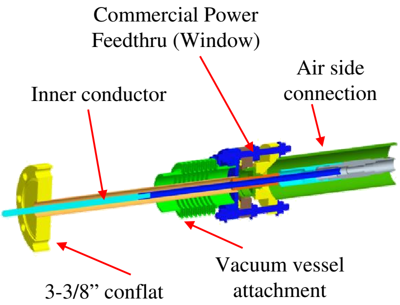
Cryomodule	
77 K shield load	< 100 W
Length	1.54 m
Cold mass	310 kg
Total mass	2000 kg

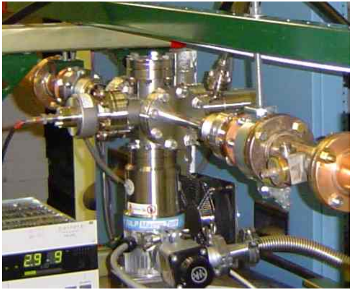


Cryogenics for the low-β cryomodule

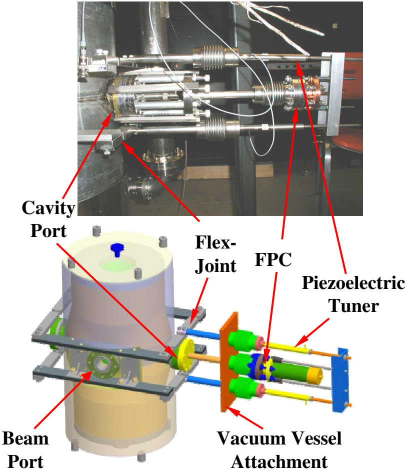


Cold box for the low-β cryomodule

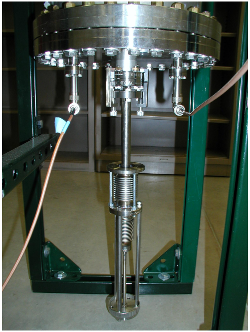




RF Couplers for the low-β cryomodule
conditioned to 1.1 kW (QWR) and 2 kW (HWR)



HWR tuner



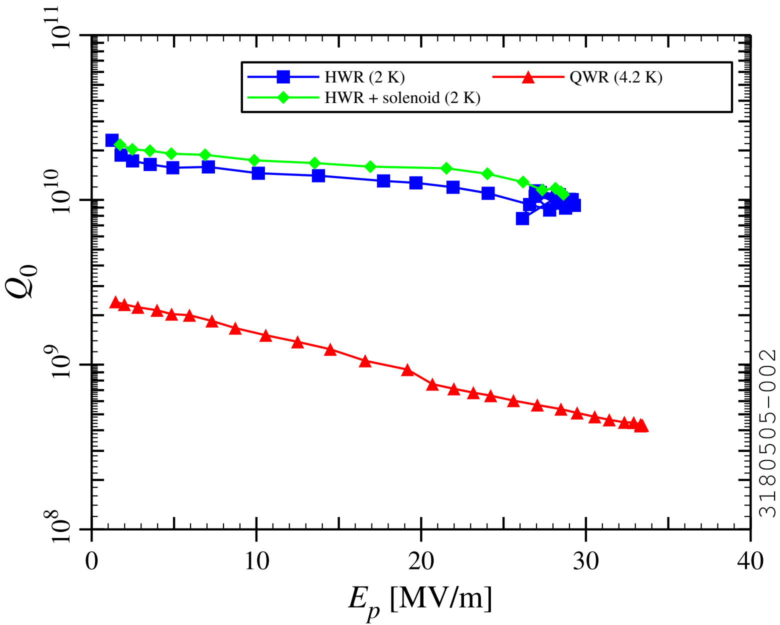
QWR tuner

Tuners for low-β cryomodule with actuators at room temperature

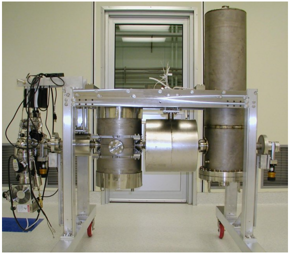
HWR + Solenoid

HWR + Quadrupole

Vertical tests: low-β cavities and magnets



Vertical tests: low-β cavities and magnets



(a) cold mass

(c) inner MLI

(e) outer MLI

(b) top plate

(d) 77 K shield

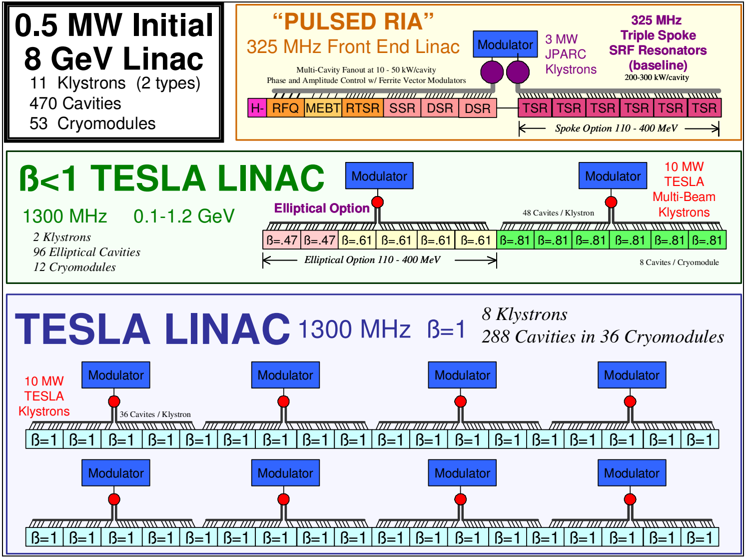
(f) vacuum vessel

Construction of low-β cryomodule

Proton Driver Cavity Development Effort

Proton Driver Cavity Development Effort

- Collaboration with Fermilab and CEBAF on development of cavities for the Proton Driver Linac began in 2005.
- Elliptical cavity for $\beta_g = 0.81$ is being designed and prototyped.
- Four single-cell cavities (1.3 GHz) have been fabricated: 2 fine grain, 2 large grain. RF testing in progress.
- Two 7-cell cavities are being fabricated.



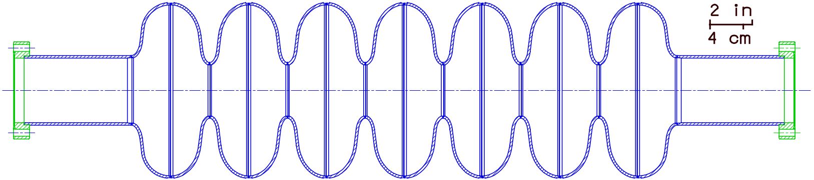
Layout for the Proton Driver baseline Linac

Cavity Design

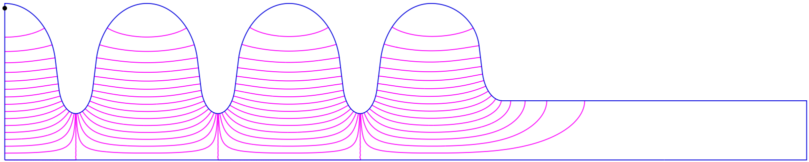
Selected cavity parameters and comparison with SNS and TTF cavities

Cavity	TTF 9-cell	SNS 6-cell	Proton Driver 7-cell	Proton Driver 1-cell
β_g	1	0.81	0.81	0.81
wall inclination	13.3°	7°	7°	7°
E_p/E_a	2.0	2.19	2.19	2.18
cB_p/E_a	1.28	1.44	1.41	1.58
cell-to-cell coupling	1.8%	1.5%	1.6%	-
R/Q per cell	115 Ω	80.8 Ω	79.1 Ω	62.3 Ω
Geometry factor	270 Ω	233 Ω	227 Ω	229 Ω

Values for Proton Driver cavity were calculated with SUPERFISH



7-Cell $\beta_g = 0.81$ Cavity



Electric field lines from SUPERFISH

Cavity Fabrication and Preparation

- Sheet Nb of thickness 2.8 mm was used.
- Forming done at MSU and in local area; electron beam welding by industry.
- Nb-Ti flanges with knife edges were electron-beam welded to the beam tubes.

Fine Grain Cavities

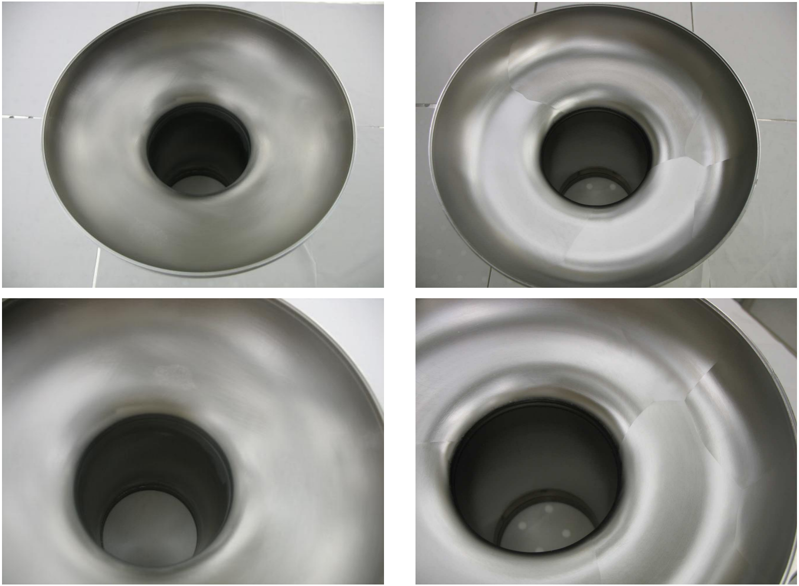
- Nb sheet of RRR $\geq$ 260 was rolled.
- Cu gasket knife edge seal.
- Not fired in vacuum furnace.
- c. 180 μm etch (BCP); 30 to 50 μm for repeat etching.
- High-pressure rinse with ultra-pure water for 45 to 120 minutes.
- Second cavity was baked out under vacuum for 12 hrs 20 min at 120°C after the first RF test.

Large Grain Cavities

- Nb sheet was cut via wire EDM from an ingot with RRR $\sim$ 280 and Ta content $\sim$ 800 ppm.
- After iris weld, half-cells were mechanically polished to smooth off grain boundaries.
- Knife edges were machined off and In seals were used.
- Fired in vacuum at 600°C for 10 hours for H degassing.
- 50 μm etch (BCP) before firing, another 50 μm after firing.
- High-pressure rinse with ultra-pure water for 60 minutes (HPWR).

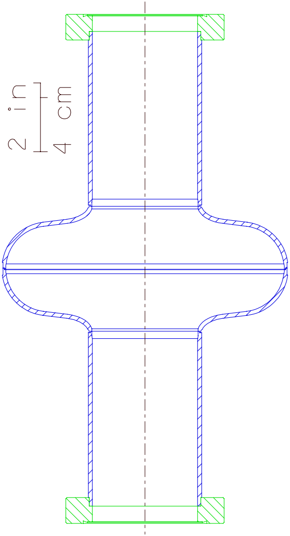
RF Test	Preparation
# 1	see above, no additional heat treatment
# 2	vacuum bake-out for 12 hours at 120°C
# 3	2 hour Ti treatment at 1250°C, 50 μm etch, HPWR
# 4	vacuum bake-out for 12 hours at 120°C

Dies for deep drawing of half-cells



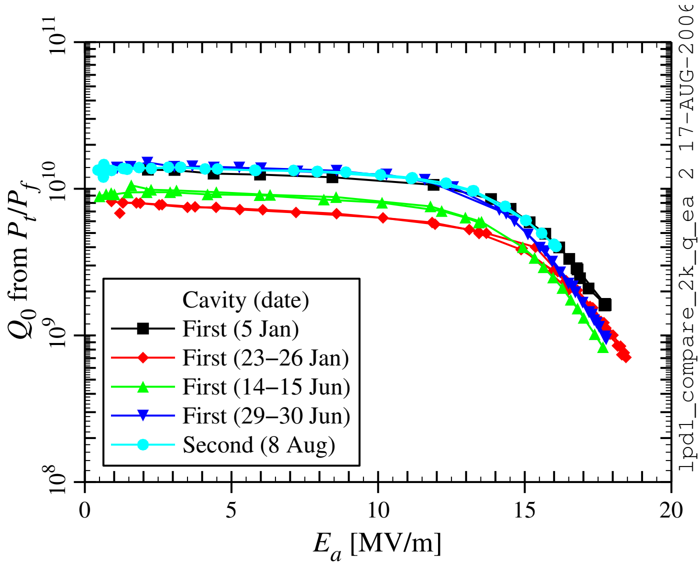
Fine grain (left) and large grain (right) half-cells

Etching and rinsing of fine grain cavity

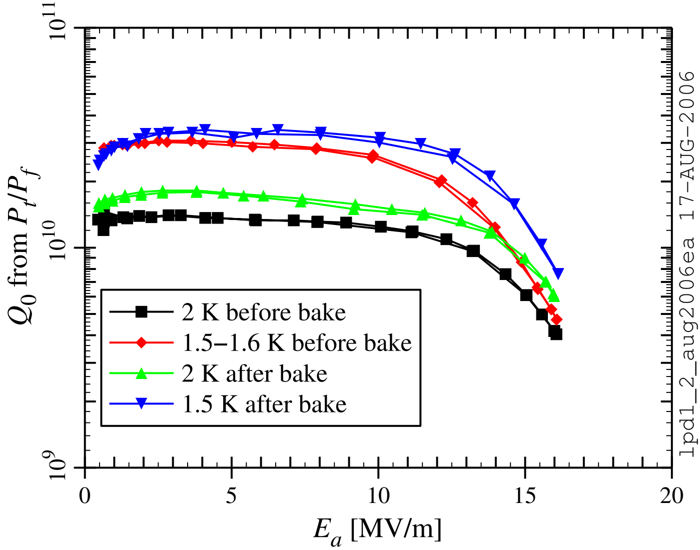


Single-cell $\beta_g = 0.81$ cavity

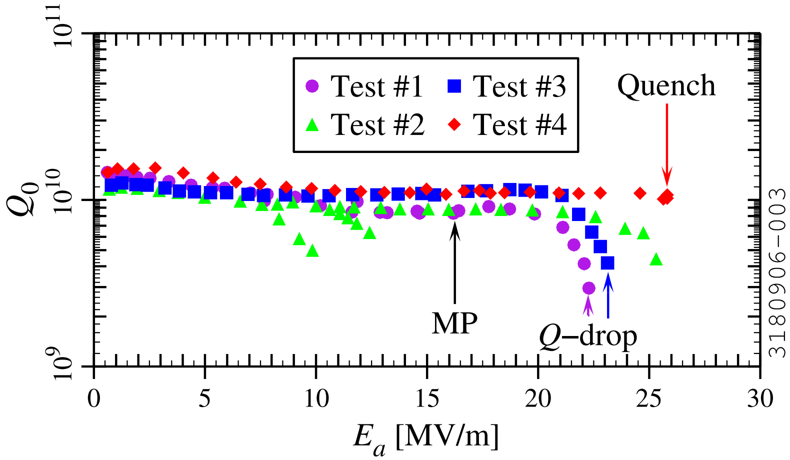
Fine grain cavity on insert



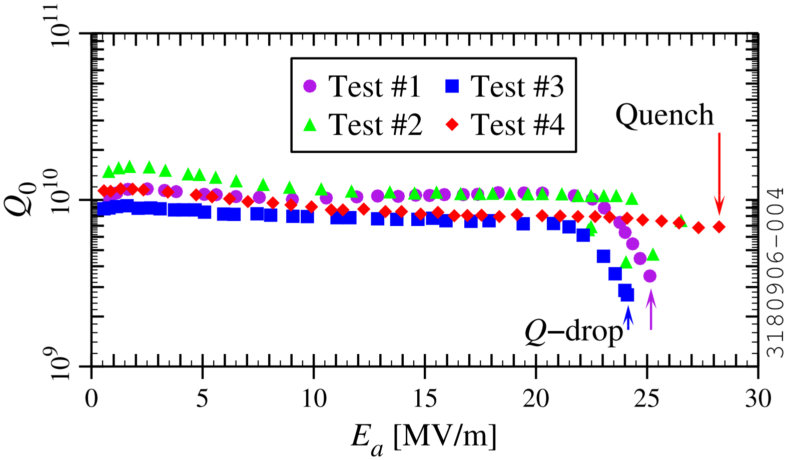
Fine grain cavity RF testing at 2 K (no thermal treatment)



Second fine grain cavity RF testing: 120°C bake-out



First large grain cavity RF testing at 2 K



Second large grain cavity RF testing at 2 K

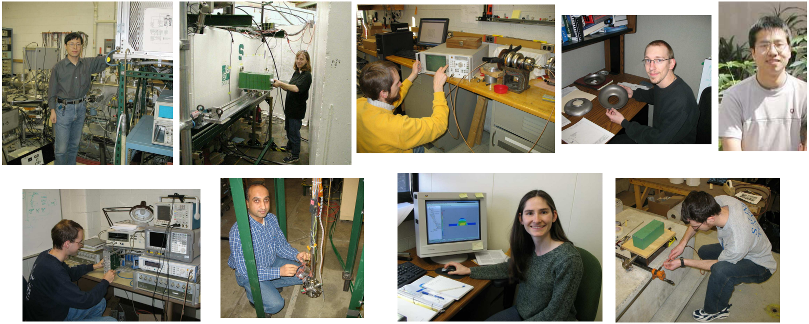
Parts for $\beta_g = 0.81$ large-grain 7-cell cavity

SRF Research

SRF Research

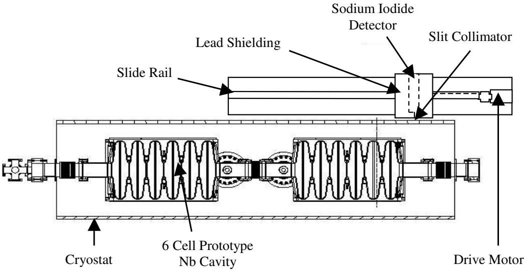
- x-ray imaging of SRF cavities
- Heat transfer studies for SRF cavities
- Material properties characterisation, surface texture studies
- Alternative cavity designs
- Alternative cavity fabrication techniques
- SRF electron sources
- Liquid-filled cavities

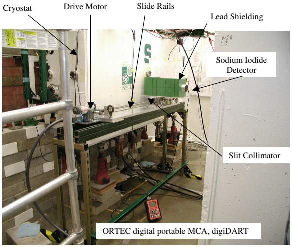
Graduate students in accelerator physics at MSU

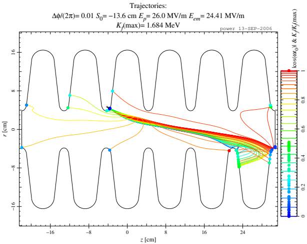


From left to right, top: Yingjie Li (Physics), Susan Musser (Physics), Dave Meidlinger (Physics), Derek Baars (MSE), Hairong Jiang (MSE) bottom: Nathan Usher (EE), Ahmad Aizaz (ME), Mandi Meidlinger (Physics), Jonathan Delauter (Physics)

PhD research: S. Musser





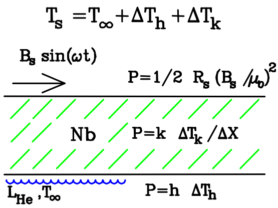


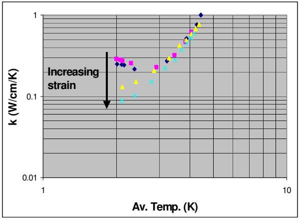
In-situ x-ray imaging of superconducting cavities

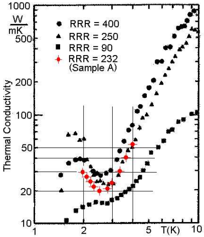
PhD research: A. Aizaz

Nb heat transfer studies

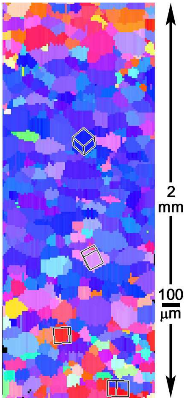
Thermal conductivity of Nb at 2 K depends on internal stress, as well as purity; heat treatment of Nb affects both.



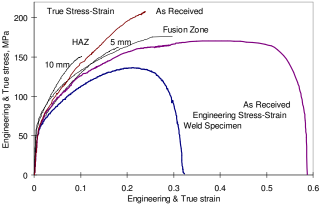




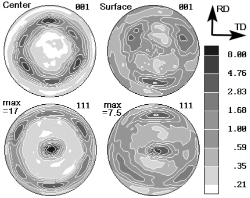
PhD research: H. Jiang, D. Baars



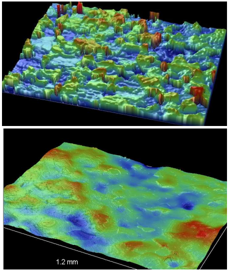
Scan of material cross section



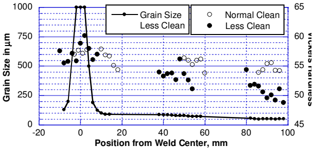
Stress-Strain Plot



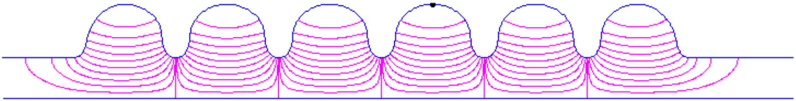
X-ray derived distribution of lattice structure

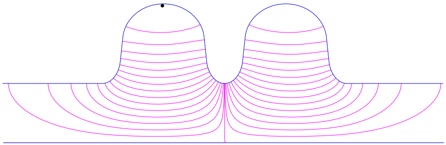


Surface Roughness Measurements

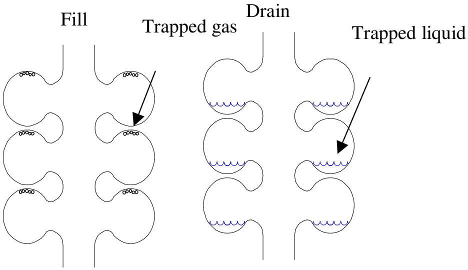


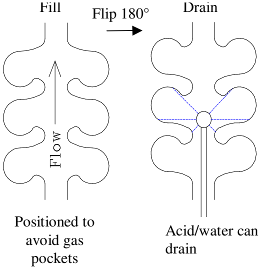
Studies of material and surface properties

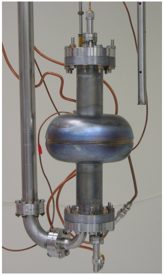




High-current cavity (PhD research: D. Meidlinger)





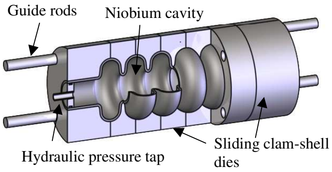


High gradient cavity (PhD research: M. Meidlinger)

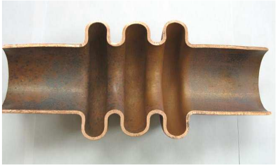
Alternative forming methods for superconducting cavities

TIG welding: alternative to electron beam welding?

Hydroforming: alternative to deep drawing for seamless cavity?

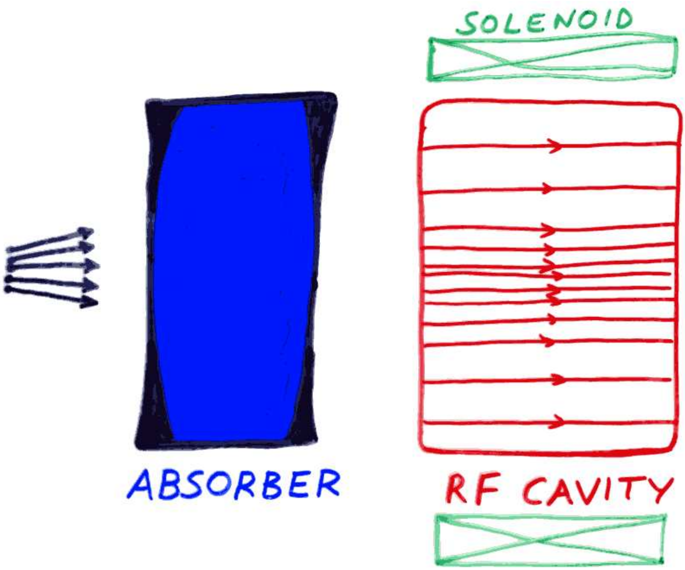


Cavity after hydro-forming

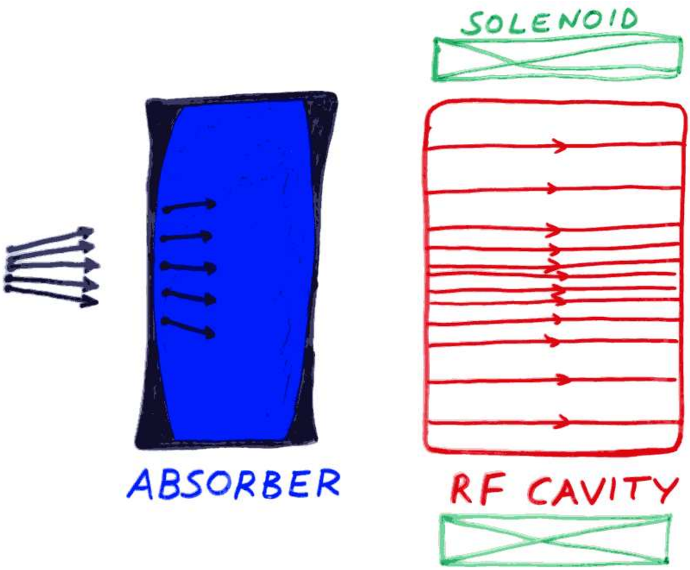


Prototype copper cavities hydro-formed in US Industry

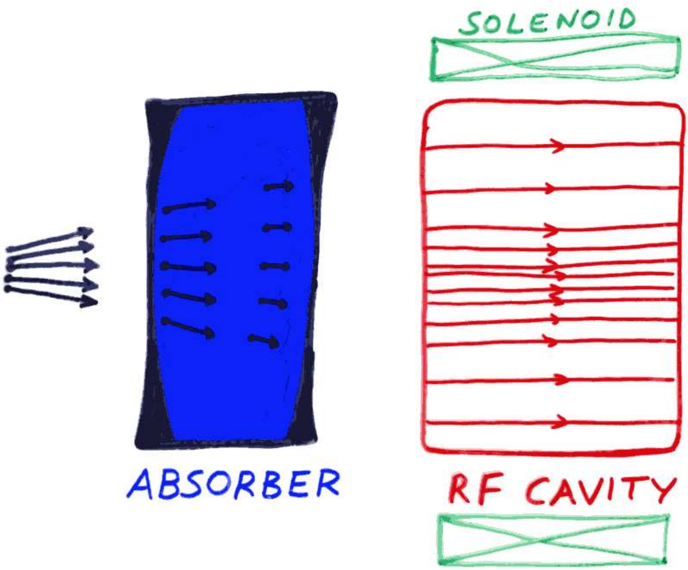
Liquid-Helium-Filled Cavities



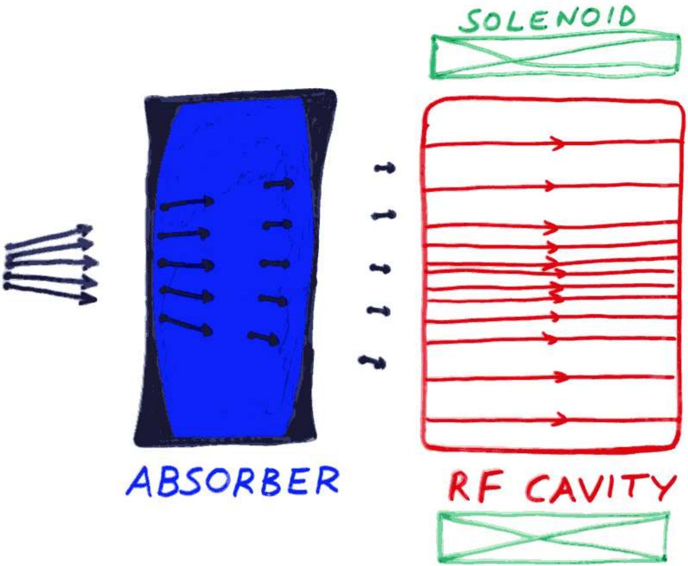
Ionisation Cooling



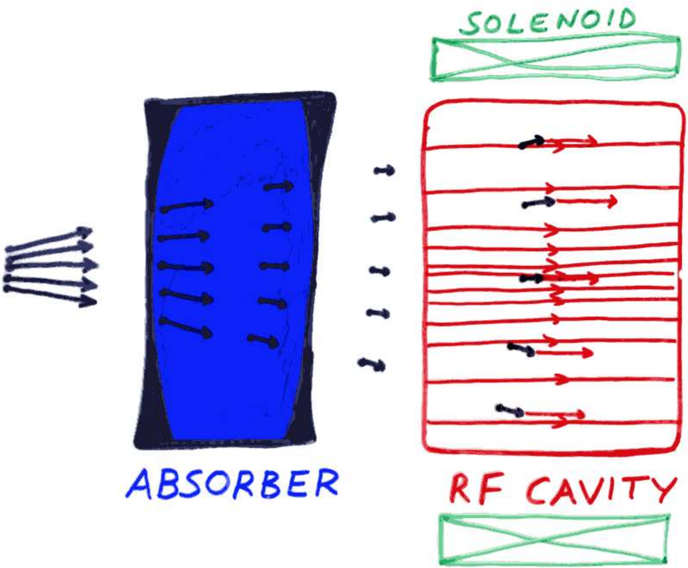
Ionisation Cooling



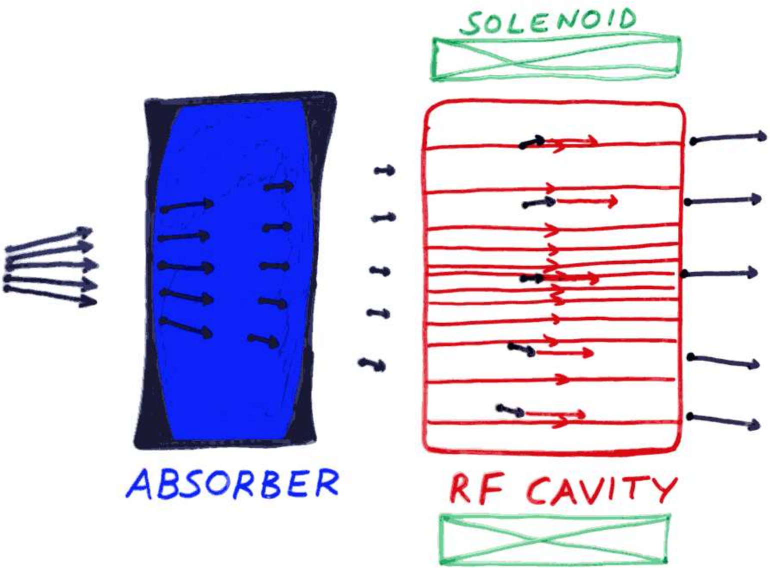
Ionisation Cooling



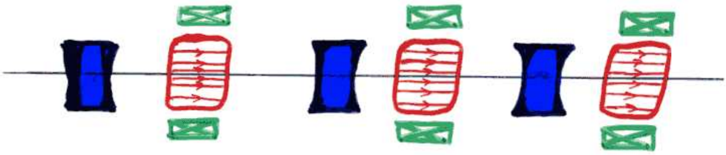
Ionisation Cooling



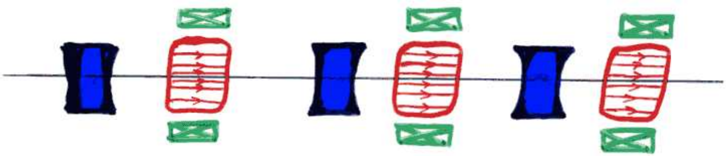
Ionisation Cooling



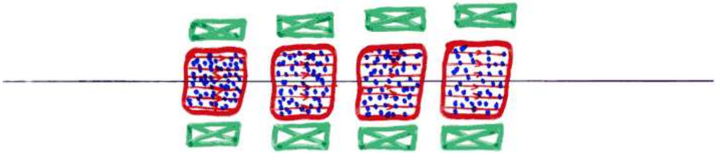
Ionisation Cooling



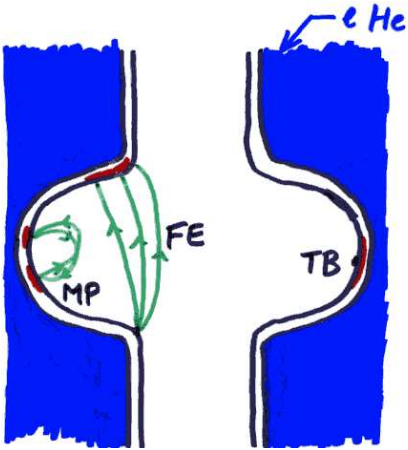
Cooling channel: Liquid hydrogen cells and RF cavities



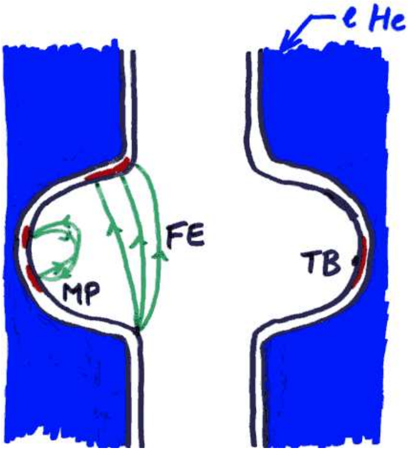
Cooling channel: Liquid hydrogen cells and RF cavities



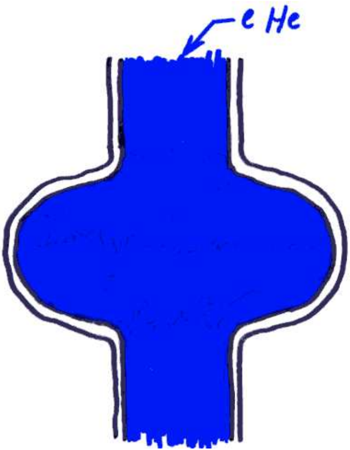
Cooling channel: RF cavities filled with hydrogen gas



Vacuum-filled SRF cavity



Vacuum-filled SRF cavity



Liquid-filled SRF cavity

Properties of Liquid He: Literature

DC: dielectric constant vs temperature: known (*e.g.* Donnelly & Barenghi 1998).

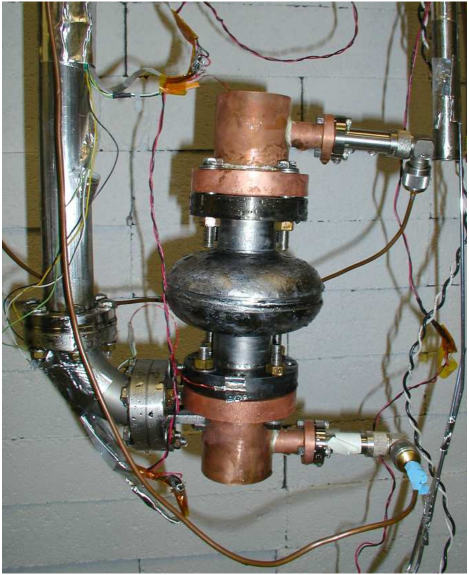
DC: dielectric strength: studied (*e.g.* Gerhold 1998):

- Dust particles can produce discharges (field emission).
- Breakdown field = 40 to 100 MV/m possible under well-controlled conditions (short times, small gaps, polished electrodes, no particulates, ...).
- Breakdown fields for pressurised liquid can be as much as twice those of saturated liquid.

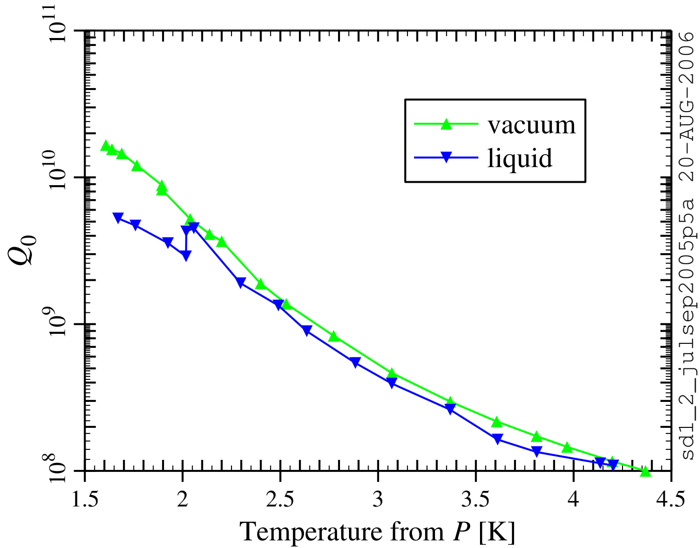
RF: Prediction: $\tan\delta \sim 10^{-25}$ at 3 GHz (Allen et al 1969).

RF: X-band measurements in superfluid, TE_{011} mode: $\tan\delta < 10^{-11}$ (SLAC Quarterly Report 1970).

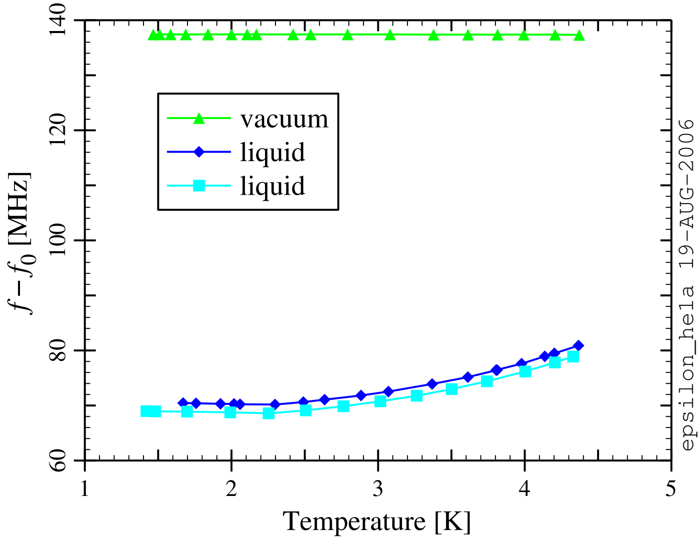
2.45 GHz single-cell Nb cavity: vacuum-filled test



2.45 GHz single-cell Nb cavity: liquid-filled test

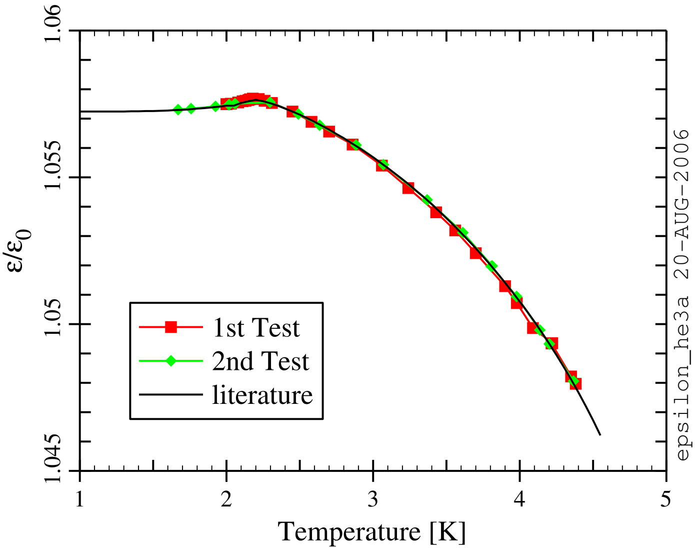


Low-field measurements: vacuum-filled vs liquid-filled

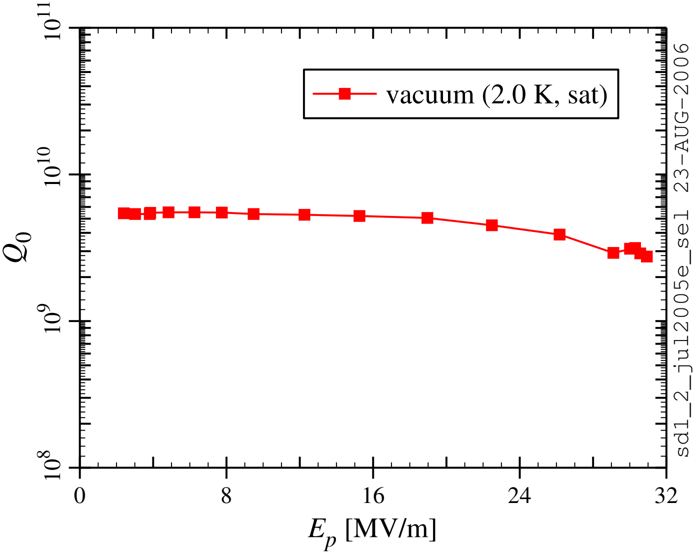


Frequency shift with temperature during pump-down

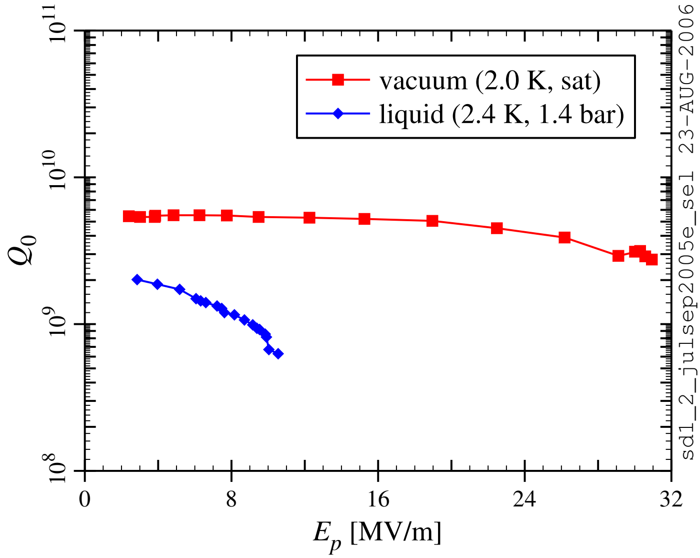
$f_0 = 2300$ MHz; vacuum: $\Delta f \approx 70$ kHz; liquid: $\Delta f \approx 10$ MHz



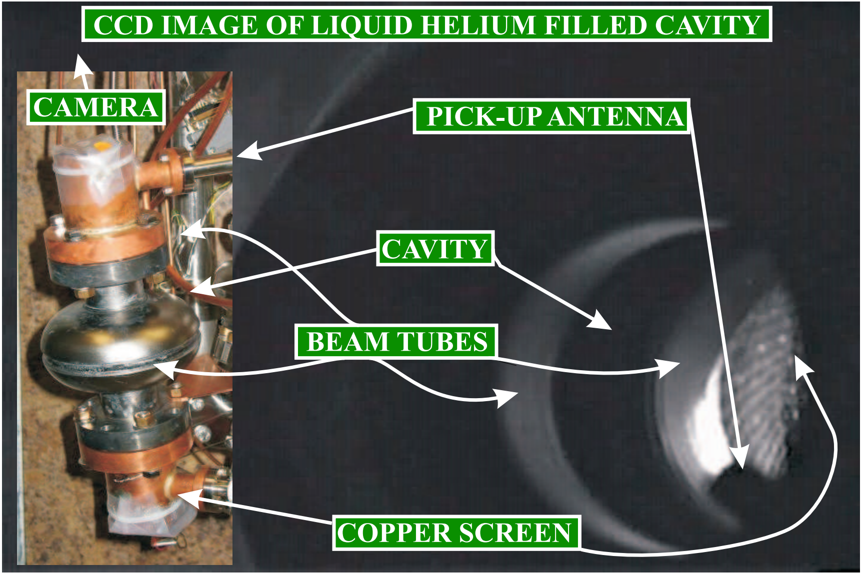
Permittivity of liquid helium inferred from the frequency



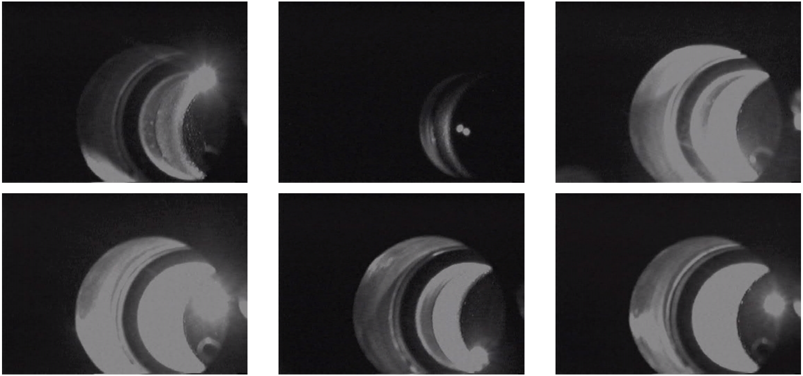
CW measurements: vacuum-filled



CW measurements: vacuum-filled vs liquid-filled



Peeking inside a liquid-filled cavity



Video images looking inside the liquid-filled cavity
Black & White video camera

Conclusion

Conclusion

- MSU has developed capabilities and facilities for design, fabrication, and testing of SRF cavities and cryomodules
- SRF research at MSU is underway
- Primary motivation is for heavy ion accelerators
- MSU is also helping with other projects (*e.g.* FNAL Proton Driver) and is open to new possibilities

People

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A. Facco *et al.* (INFN Legnaro)
V. Yarba, P. Bauer, *et al.* (Fermilab)