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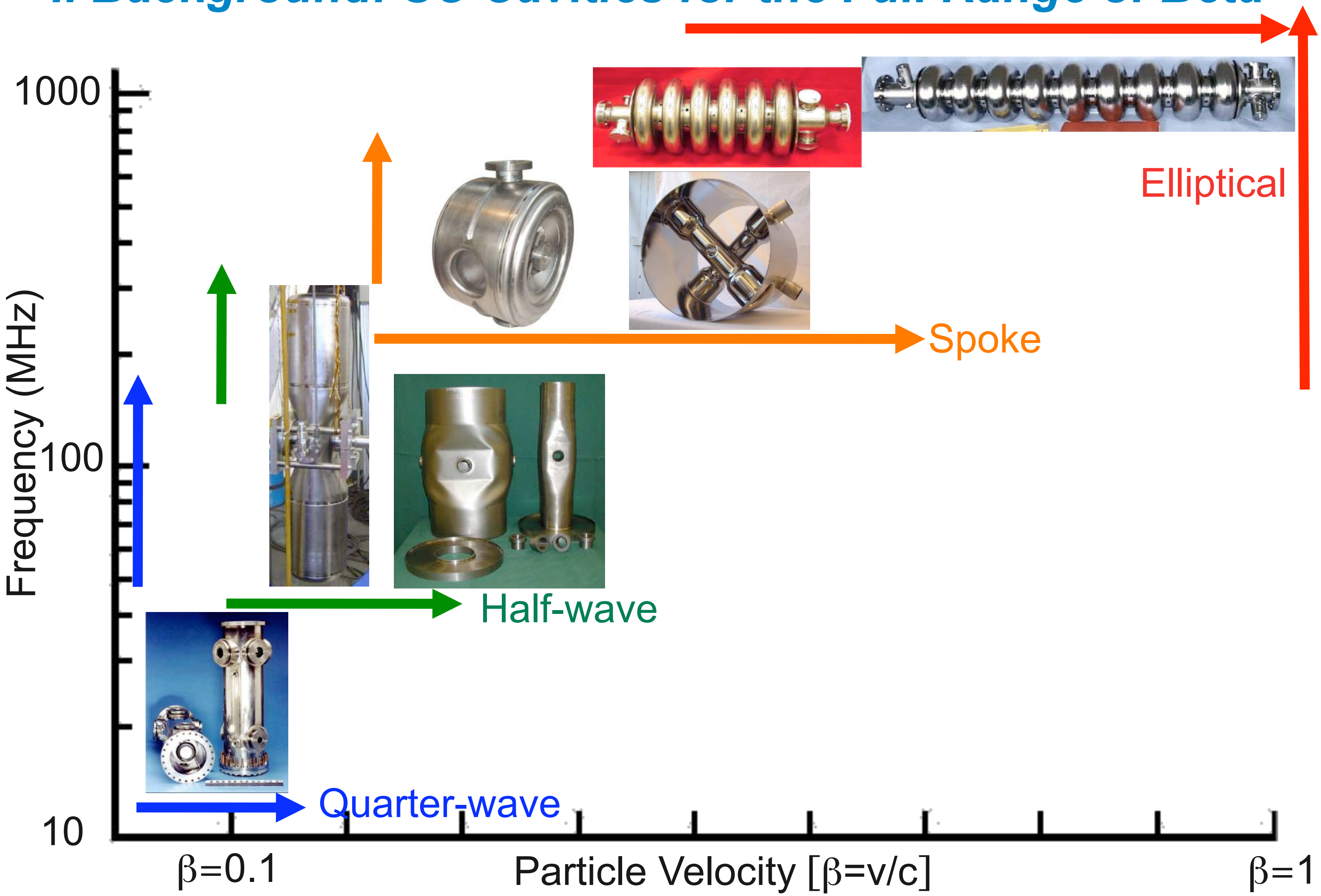
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Recent Developments in Low and Medium Beta SRF Cavities (TU3RAI02)

PAC 2009
May 4-8, 2009
Vancouver, British Columbia
Canada

Speaker: Mike Kelly

I. Background: SC Cavities for the Full Range of Beta



Outline

I. **Background**
II. **Applications**
III. **Recent Developments**
IV. **Coupler, Tuners**

THANK YOU

Bob Wagner (FNAL)
Yvgeny Zaplatine (Julich)
Walter Hartung (MSU)
Bob Laxdal (Triumf)

II. Applications: SC Quarter-wave Cavity Linacs

Location	Cavity Type	Frequency (MHz)	Beta (v/c)	# Cavities
Spiral-2/Ganil	QWR	88	0.07,0.12	26
MSU FRIB / MSU Re-Acc	QWR	80.5	0.04, 0.085	112
CERN	QWR	101	0.76, 0.12	30
Triumf	QWR	80	0.06-0.07	20
New Delhi	QWR	97	0.08	14
Canberra	Split-ring, QWR	150.4	0.09-0.11	14
INFN Legnaro	QWR	80, 160	0.05-0.13	74
Kansas State	Split-ring	96, 97	0.06-0.1	14
JAERI	QWR	130, 260	0.1	46
U. Washington	QWR	150	0.1-0.2	36
Florida State	Split-ring	97	0.07-0.1	15
Stony Brook	Split-ring, QWR	150.4	0.07-0.1	40
Argonne	Split-ring, QWR	48, 72, 97	0.01-0.10	64

Operations & Upgrades	Under construction	Planned	No longer operating

II. Applications: SC HWR and Spoke Cavity Linacs

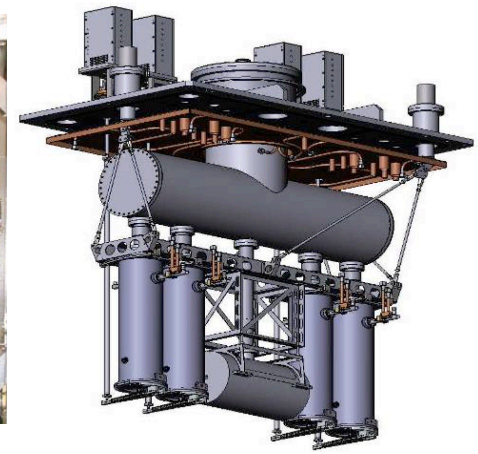
Applications	Frequency (MHz)	Beta (v/c)	Particle type	# of Spoke or HWR Cavities (total cavities)	Duty Factor
SARAF	176 (HWR)	0.09, 0.15	Proton, Deuteron	42	CW
MSU FRIB	322 (HWR)	0.285, 0.52	Proton to Heavy-Ion	224 (336)	CW
Project X	325 (Spoke)	0.2-0.6	Proton	93 (445)	Pulsed
Eurisol	176, 352	0.09-0.3	Proton, Light ion	108	CW
ESS	352 (Spoke)	0.35, 0.59	Proton	Up to 126	Pulsed
IFMIF	175 (HWR)	0.094, 0.17	Deuteron	42	CW

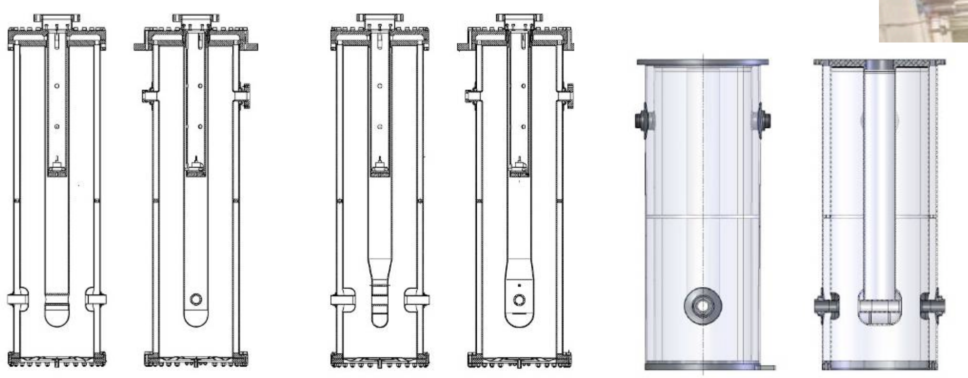
Under construction	Planned	Under consideration

TU4PBC04, WE5PFP052

II. Applications: Triumf

- Today's state-of-the-art for operational low beta linacs
- Geometry based on that from INFN Legnaro
- 5 cryostats of 20 cavities at β=0.057, 0.071 providing 20 MV accelerating potential
- Fabricating an additional 20 cavities at β=0.11 to provide another 20 MV
- Triumf working with new cavity vendor PAVAC for fabrication of β=0.11 cavities (6 delivered, 6 to ship soon, 8 in fabrication)

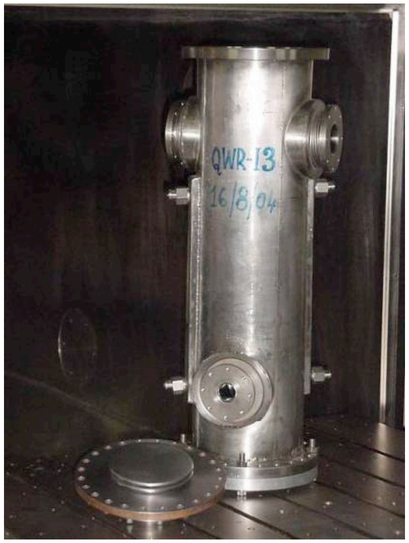


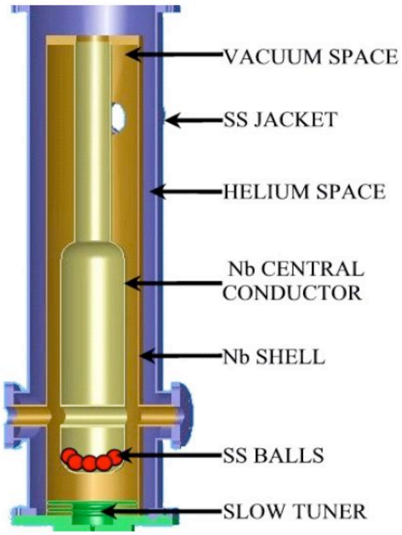


β=0.057 β=0.071 β=0.11

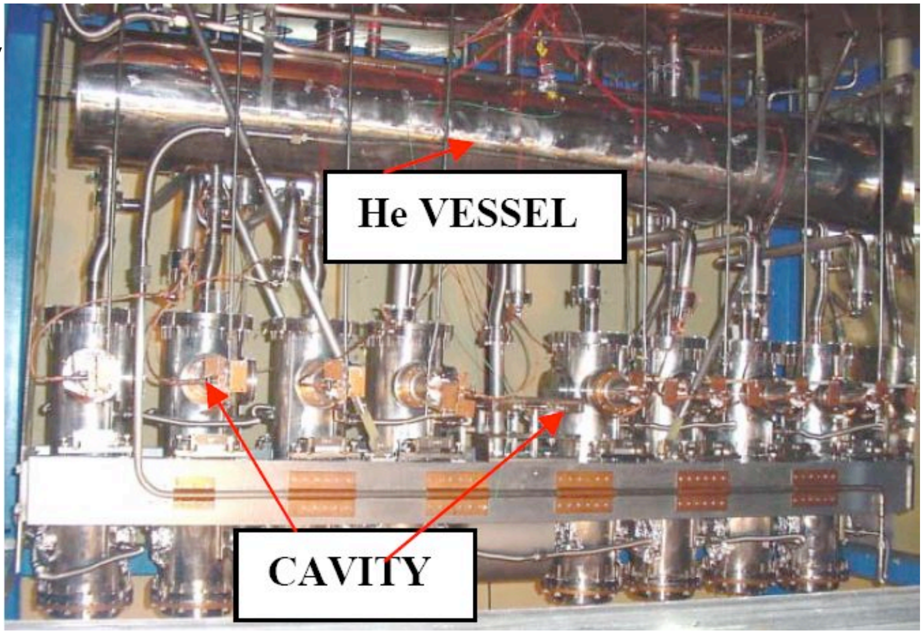
II. Applications: IUAC New Delhi

- In operations one cryostat with eight 97 MHz cavities for β=0.08
- In fabrication an additional 2 cryostats with 16 new cavities
- IUAC has full local cavity fabrication capability (niobium forming, welding, chemistry)
- Performing SRF work for others (FNAL single spoke)



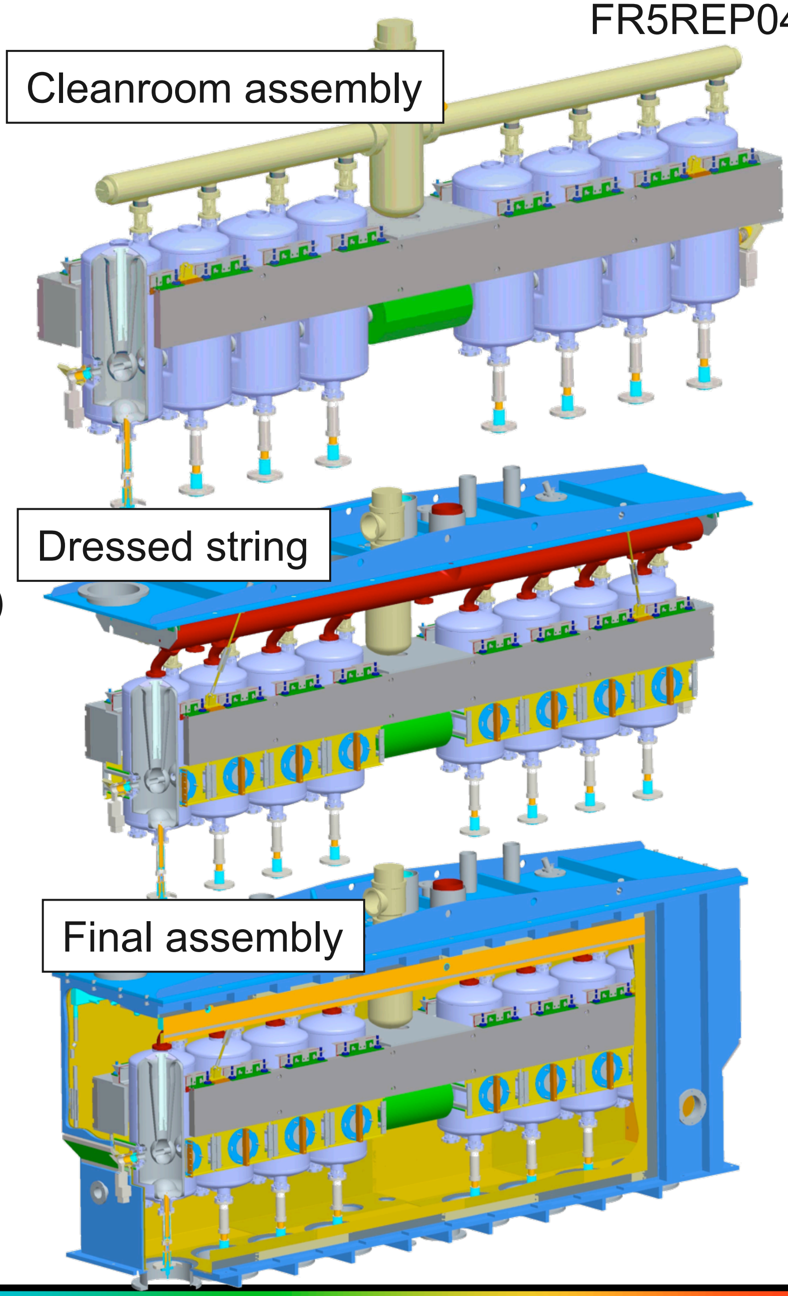


97 MHz β=0.08



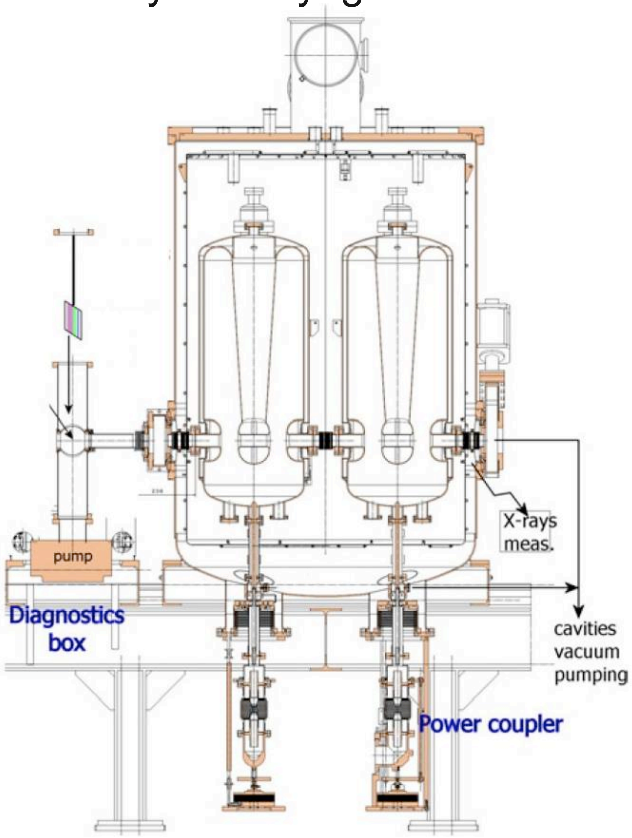
II. Applications: Argonne

- New cryomodule with seven β=0.15 109 MHz quarter-wave cavities (ANL, Sciaky and AES)
- Offline testing of cavities, subsystems April-May '09; operations in June '09
- Based on a cavity string and couplers assembled and sealed in the clean room
- Goal is (at least) 2+ MV/cavity (15 MV total with the seven installed cavities in a 4.65 meter module)



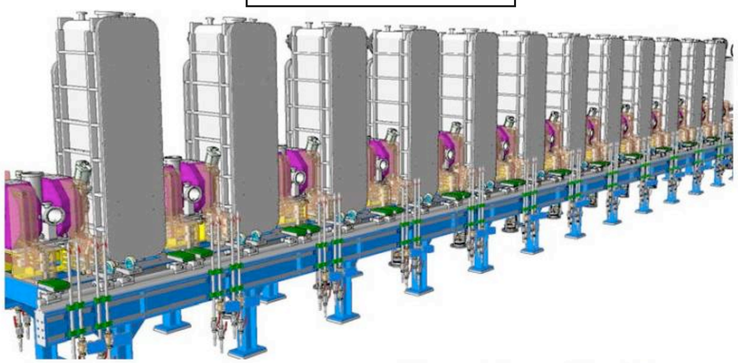
II. Applications: Spiral-2

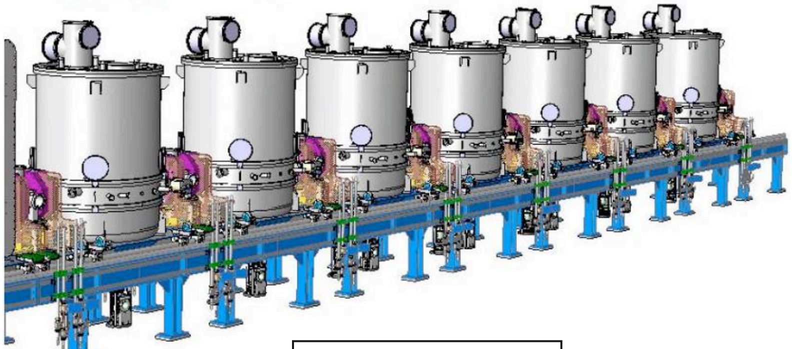
- Short cryostats with one or two cavities per module
- Total of 26 cavities to provide 40 MV accelerating potential
- Separate cavity and cryogenic vacuum systems



β=0.12 quarter-wave cryomodule

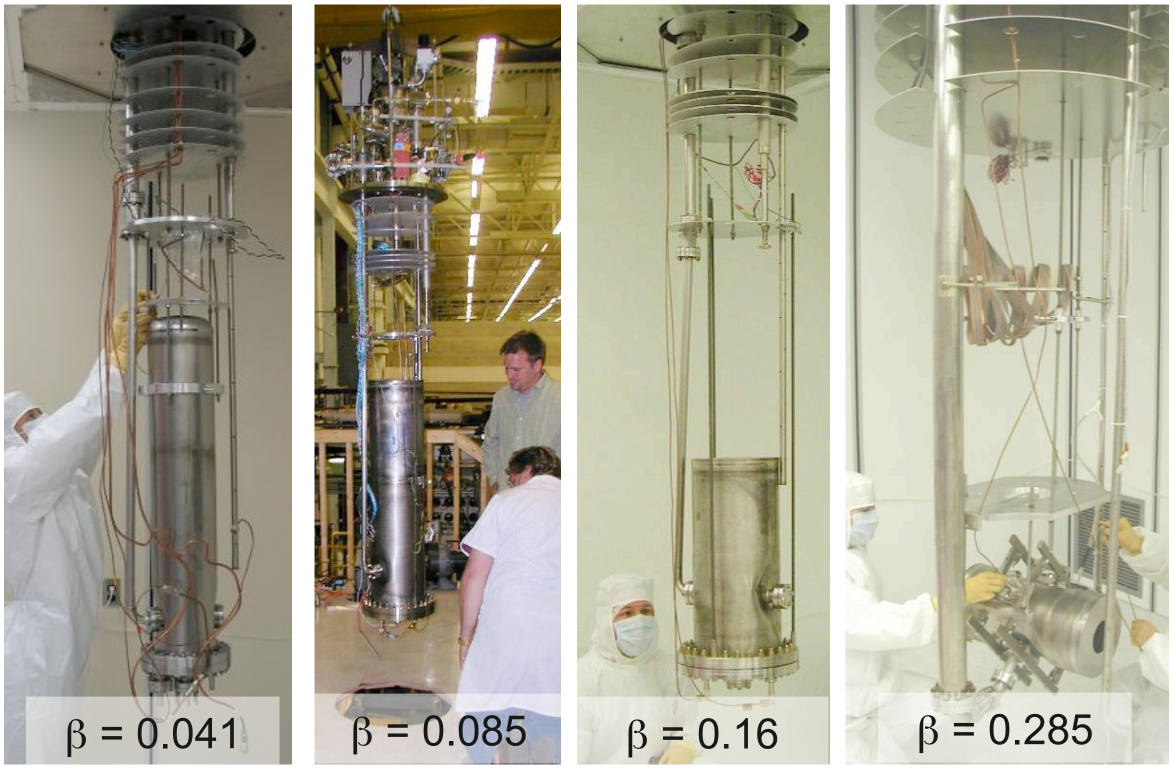
β=0.07 linac



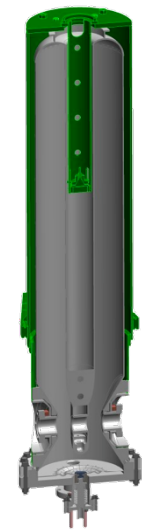


β=0.12 linac

II. Applications: MSU FRIB & Re-accelerator



Production design β = 0.041

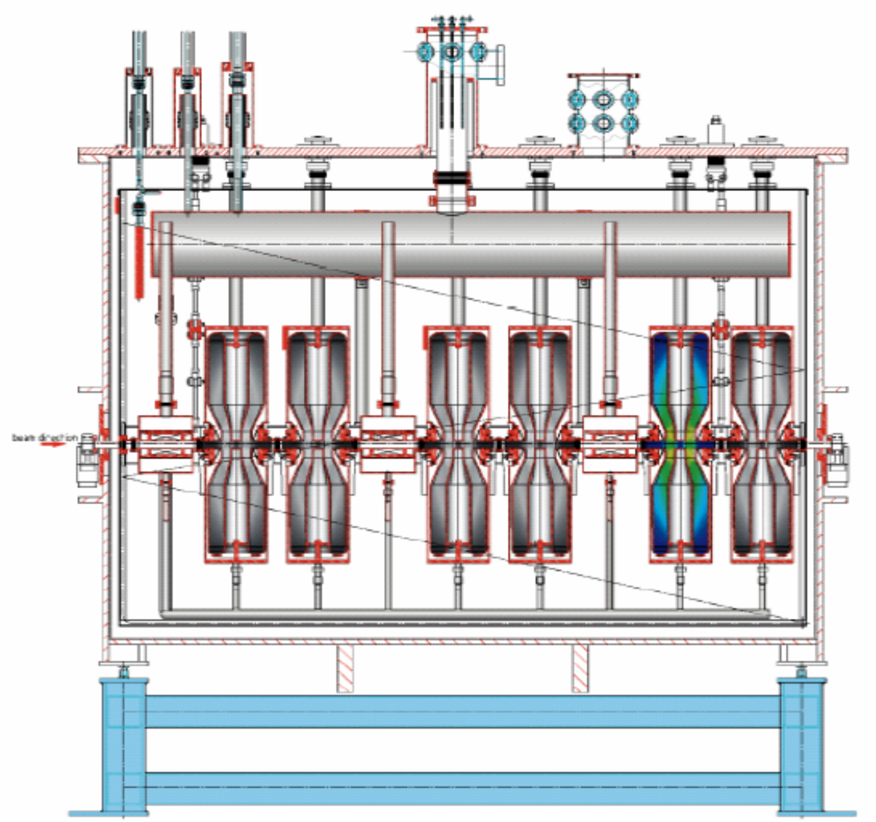


Cavity with Stiffener and He vessel

β = 0.53

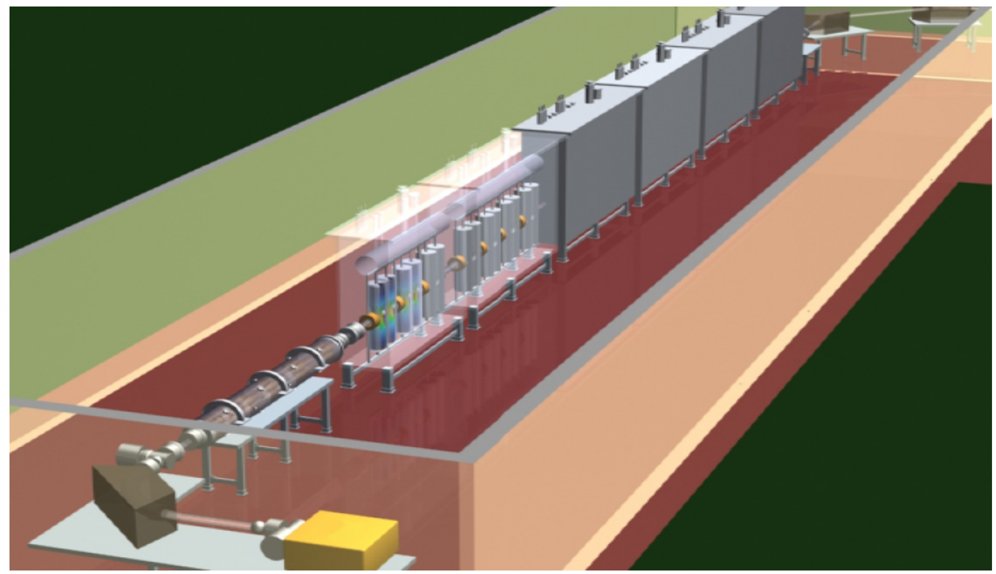
- 80 MHz quarter-wave resonators β= 0.041 and β= 0.085 for re-accelerator & FRIB
- 322 MHz half-wave resonators β= 0.285 and β= 0.53 for FRIB

II. Applications: SARAF



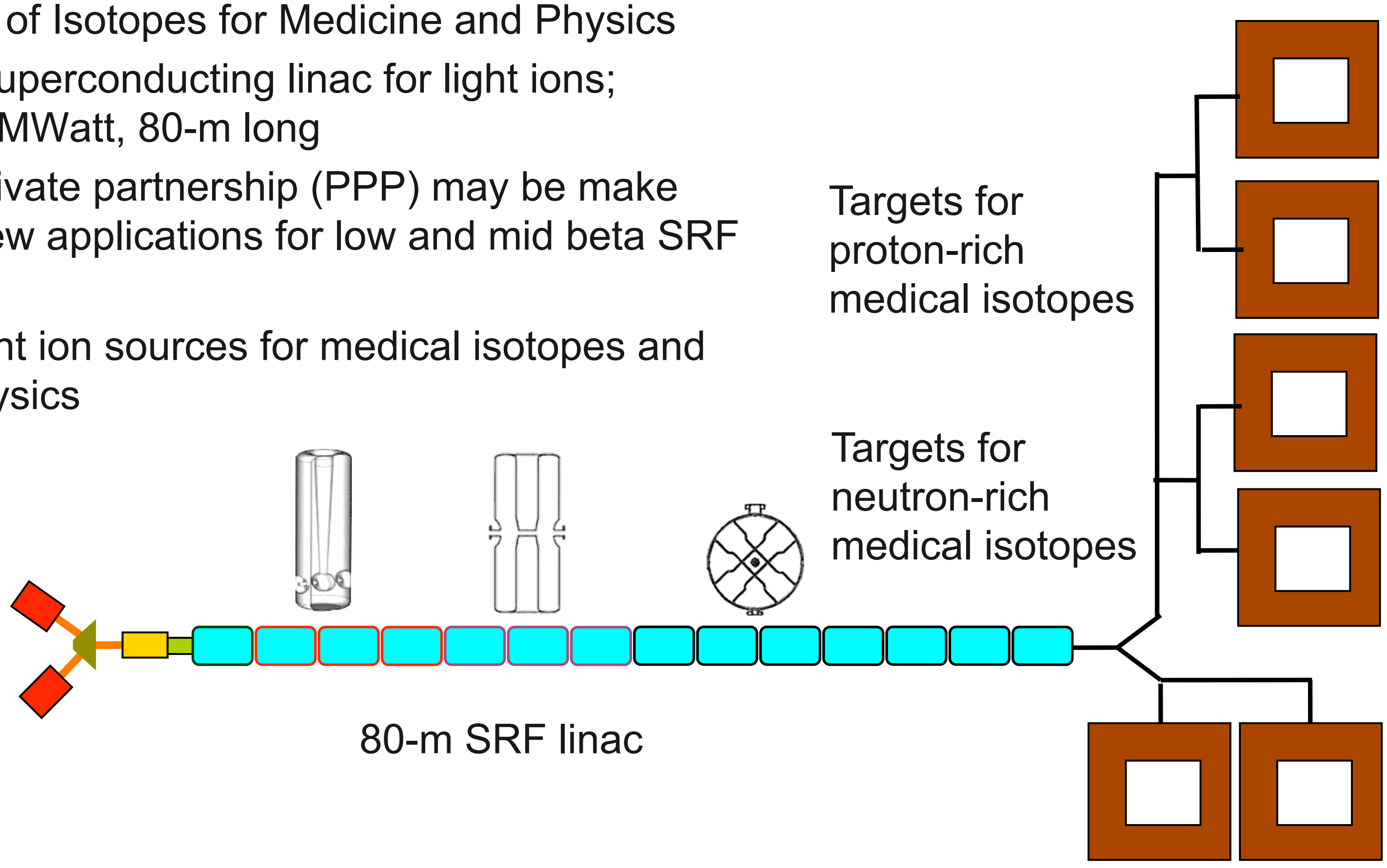
Prototype superconducting module with separate cavity and cryogenic vacuum. Fabrication by ACCEL

- Prototype superconducting module containing 6 HWR β=0.09
- World's 1st halfwave (λ/2) SC cavity linac
- Cavity choice driven at the time by good beam dynamics properties (small beam steering)
- Goal 0.86 MV/cavity (Epeak=25 MV/m) @ 10 W into 4 Kelvin
- Additional 5 cryostats with 40 resonators planned

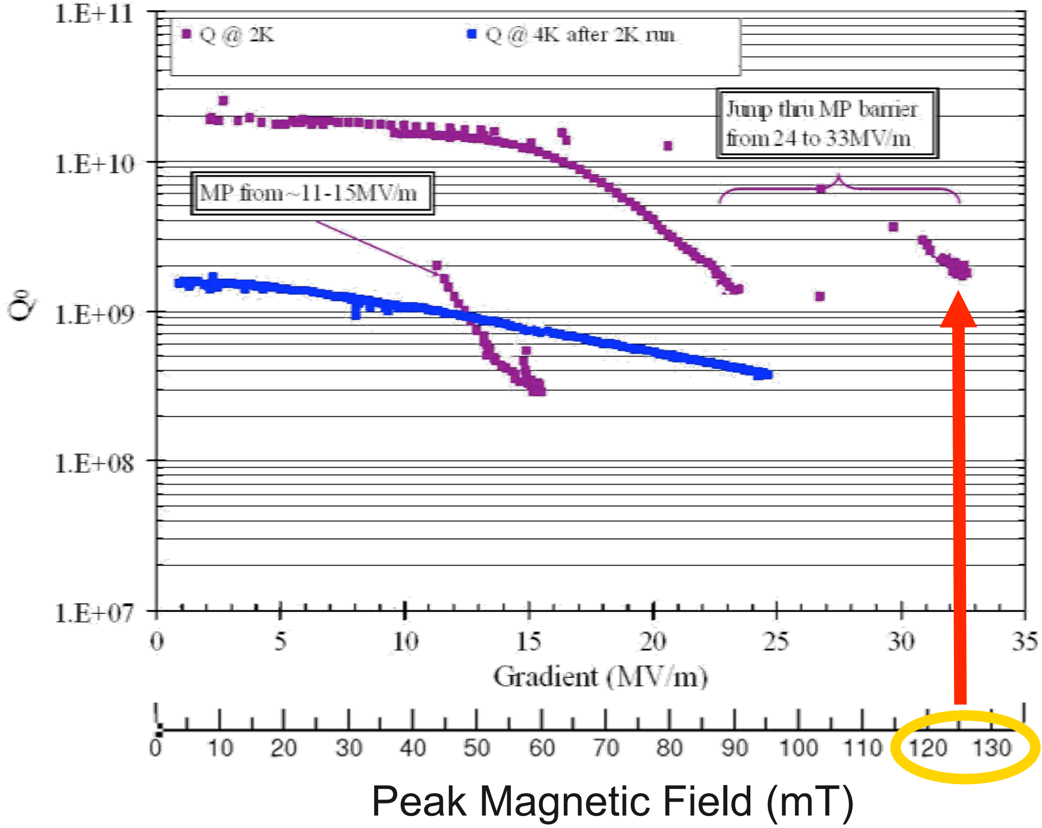


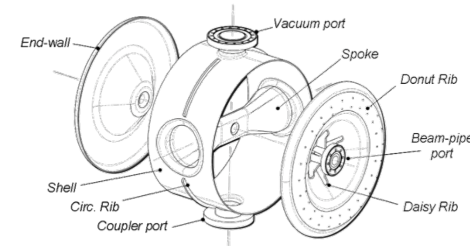
II. Applications: ANL Proposal for Future Application

- Production of Isotopes for Medicine and Physics
- Compact superconducting linac for light ions; 200 MV, 2 MWatt, 80-m long
- A public-private partnership (PPP) may be make possible new applications for low and mid beta SRF linacs
- Independent ion sources for medical isotopes and nuclear physics



III. Recent Developments: FNAL Single Spoke Cavity for HINS

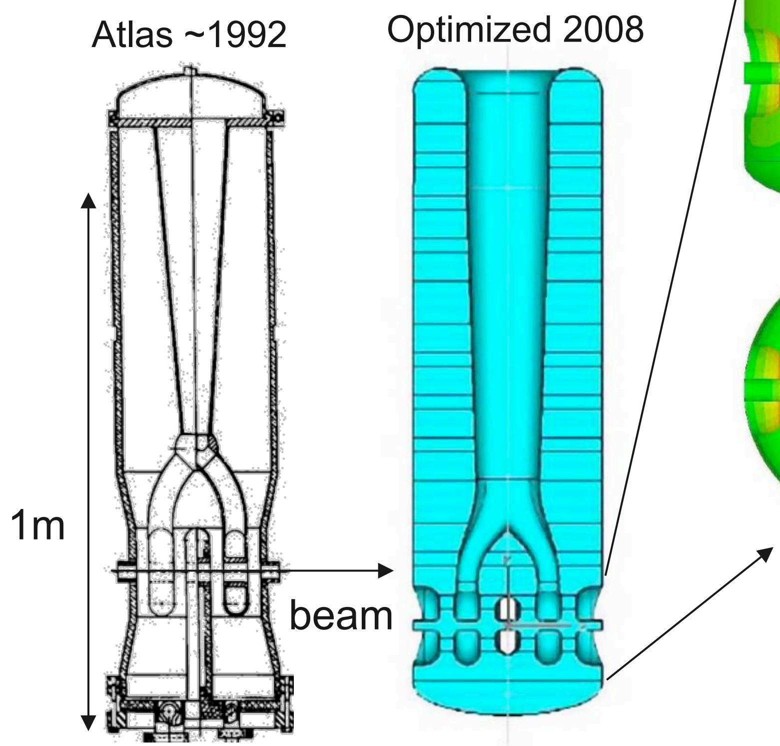


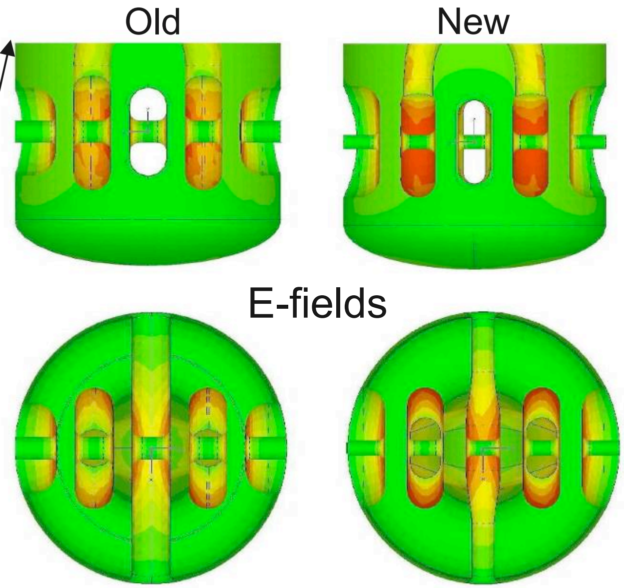


E_{peak}/E_{acc} *	2.56
B_{peak}/E_{acc} *	3.87 mT/ (MV/m)

- Most important experimental result (this speaker's words) for low-β since HPR and clean techniques first used with these cavities about 10 years ago
- Highly optimized shape + no large defects gives ~double performance relative to other cavities at this beta (fabrication at Roark)
- Comparable voltage/length as for high beta; 4.5 MV acc. voltage in 1/3 meter long cavity!

III. Recent Developments: Optimization of 48 MHz β=0.025 QWR





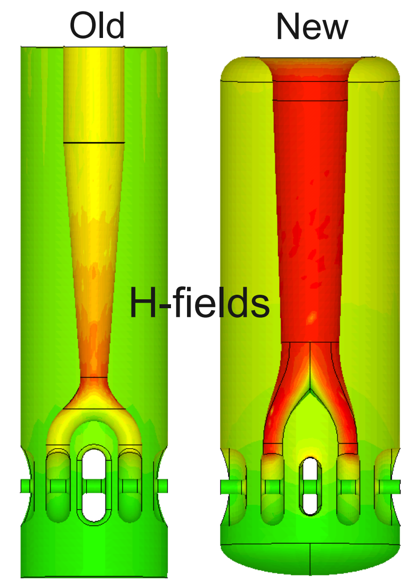


Table: At Eacc=1 MV/m

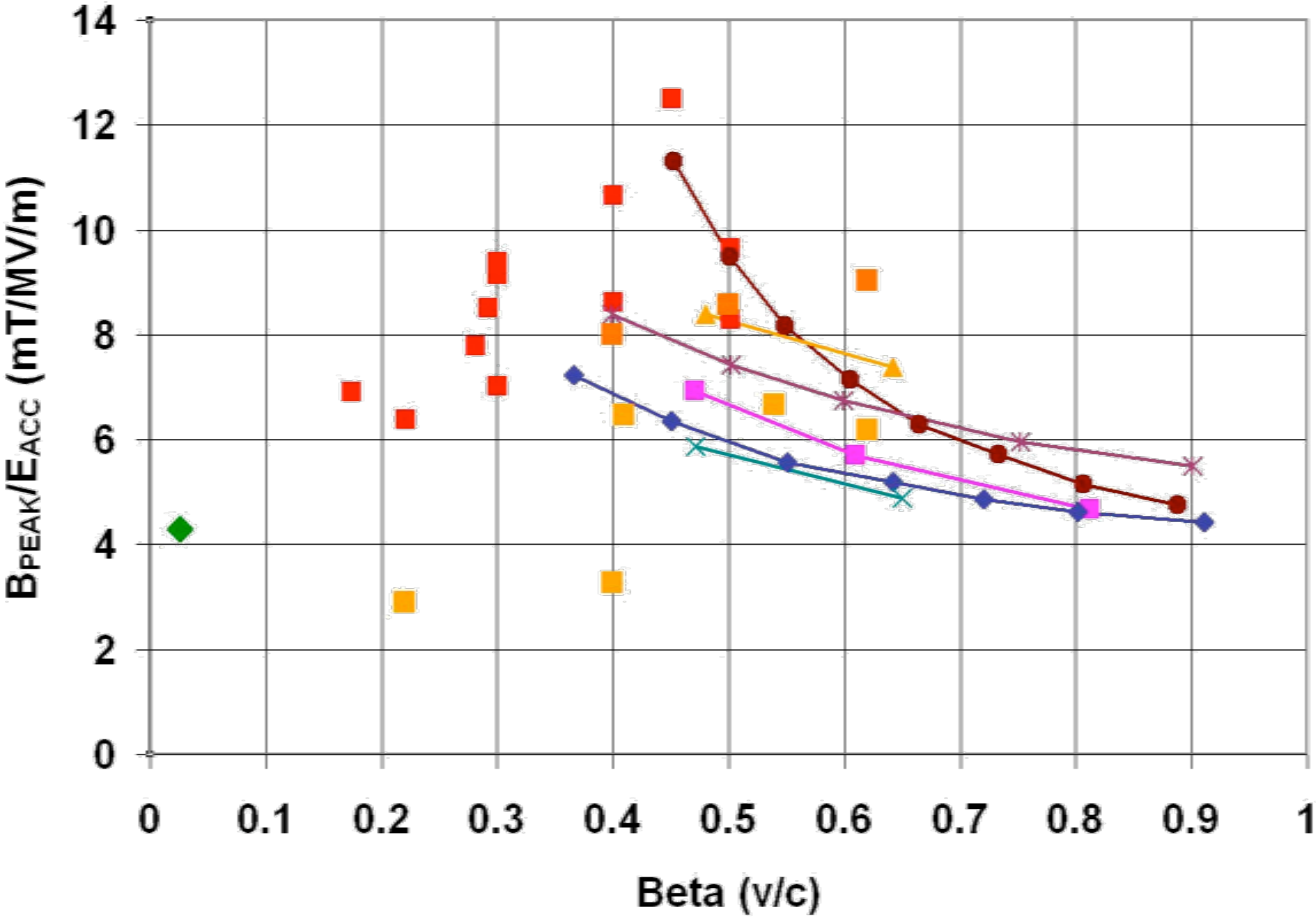
Parameter	Units	ATLAS	Optimized
E_{PEAK}	MV/m	5.04	3.41
B_{PEAK}	Gauss	117	43
Length, L_c	cm	24.638	26
U	mJ	221	150
G	Ω	13.8	18.1
R/Q_0	Ω	900	1486
β_G		0.025	0.026

- Fields distribution more uniformly in order to low peak fields
- Optimized shapes with good EM properties are possible for “complicated” lower beta cavities
- With 3D design tools and today’s fabrication techniques no need to continue design/build cavities with high surface fields

Phys. Rev. ST Accel. Beams 11, 032001 (2008)

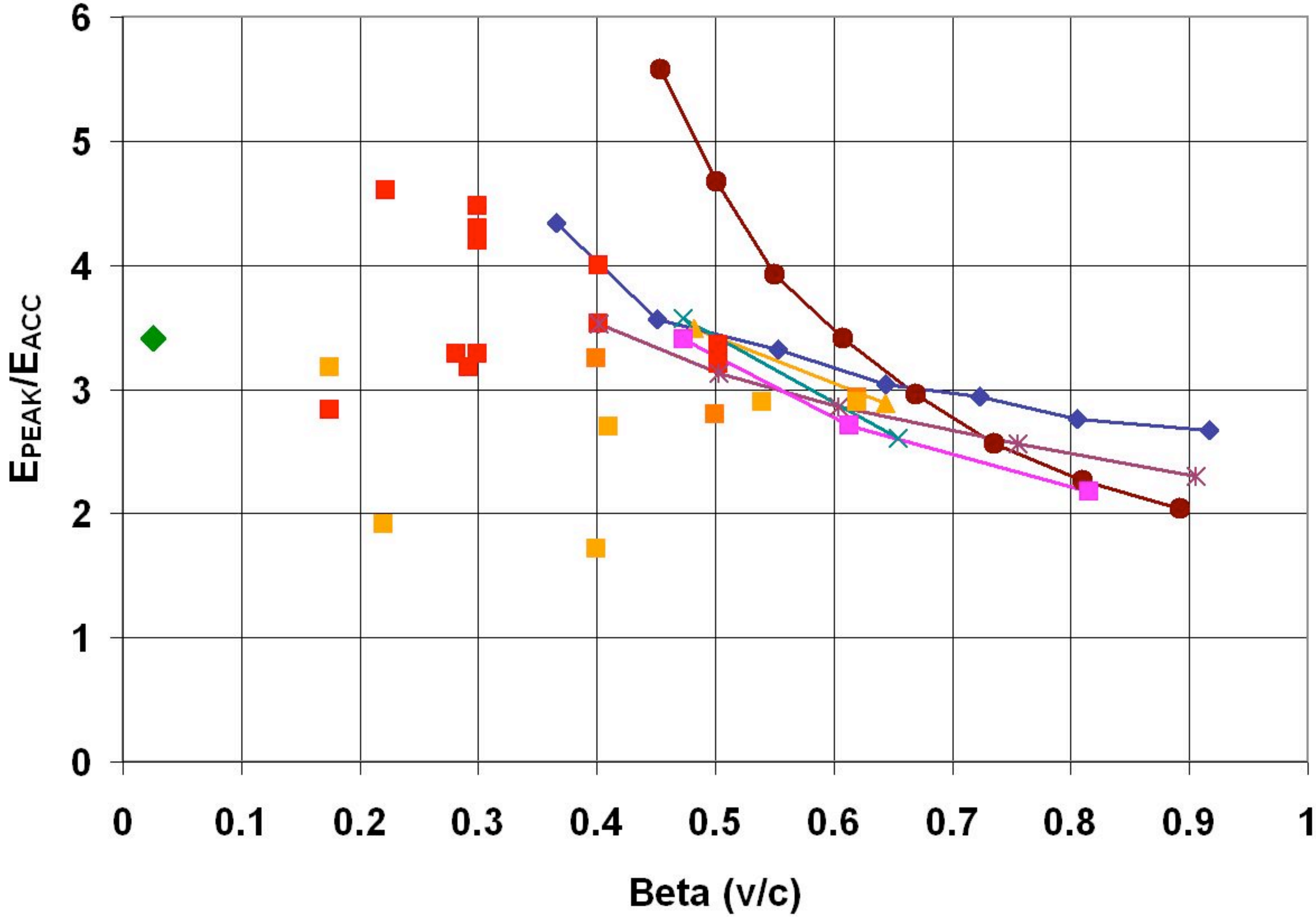
III. Recent Developments: Optimizing B_{PEAK}

Quarter-Wave → diamond   Spoke-cavities → points   E-cell cavities → solid lines



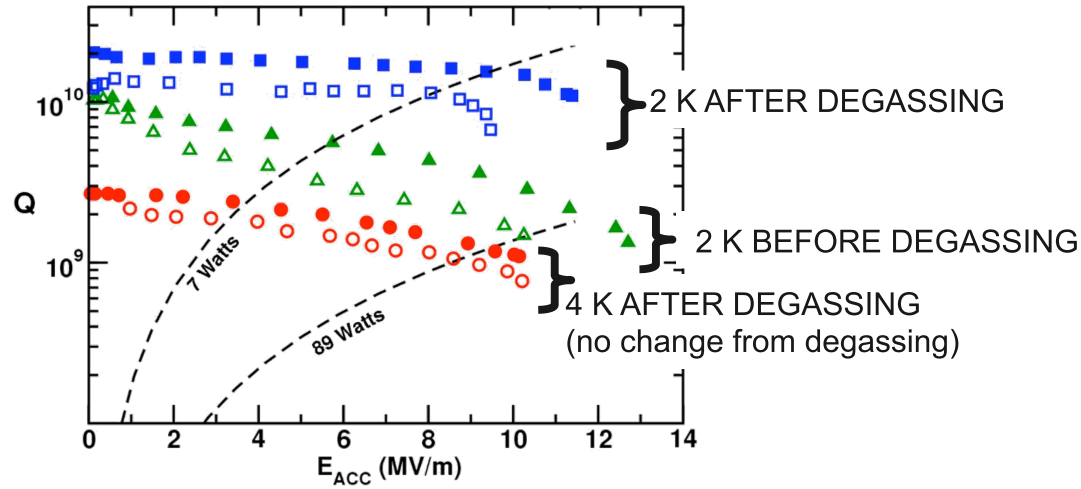
III. Recent Developments: Optimizing E_{PEAK}

Quarter-Wave → diamond   Spoke-cavities → points   E-cell cavities → solid lines



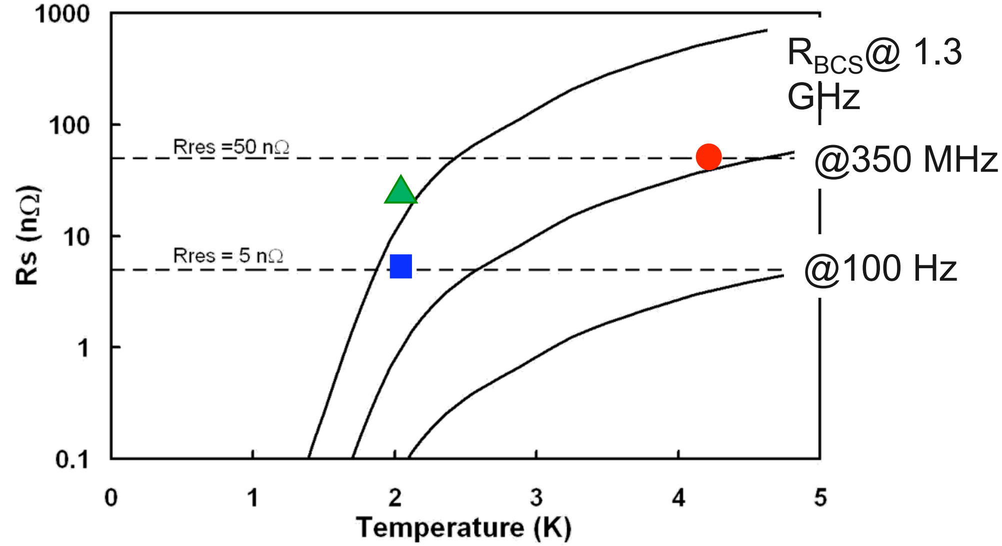
III. Recent Developments: 2 Kelvin Operation for Low and Mid Beta Cavities

350 MHz Triple-spoke cavity Q vs. E_{ACC}
After electropolishing and hydrogen degassing



Surface Resistance vs. Temperature

Points=spoke cavity residual resistance
at E_{ACC}=10 MV/m
Lines = R_{BCS} for 100, 350, 1300 MHz



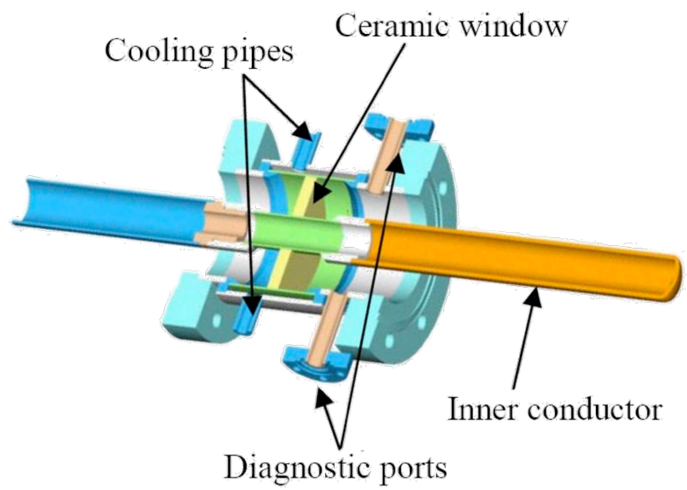
- CW applications using low- and mid-β cavities should strongly consider 2 Kelvin operation
- Savings in refrigerator capital and operating costs greater 2-3X possible for f~350 MHz

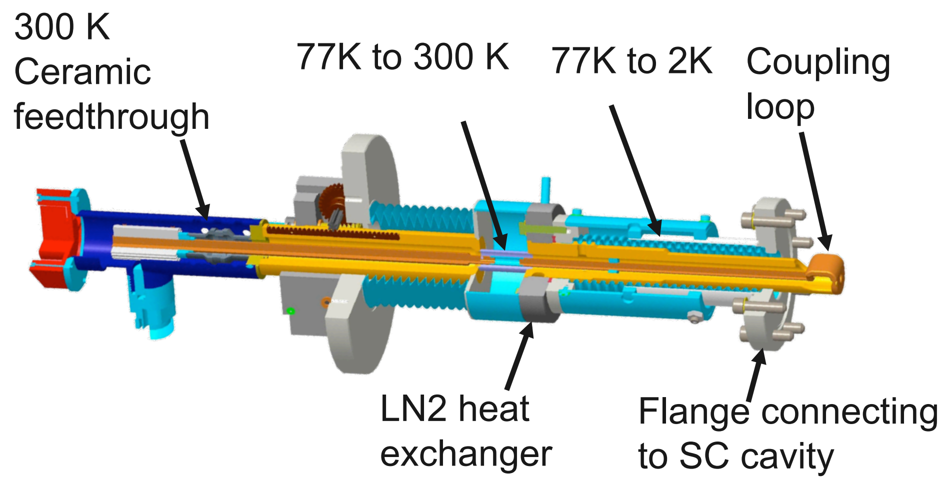
IV. Couplers, Tuners

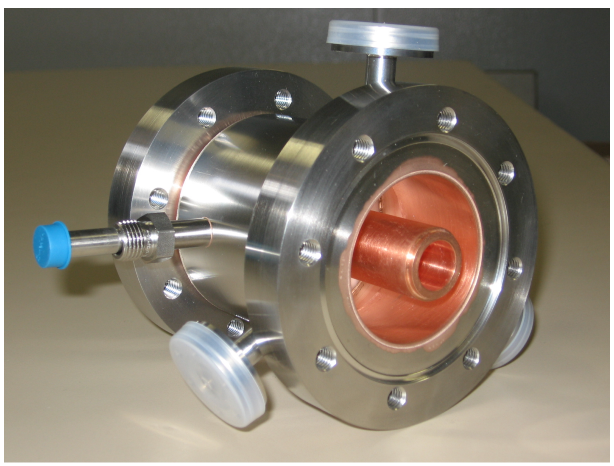
- Couplers and tuners are opportunity for creativity; also source of headaches
- (1) Provide ample, not just adequate capability; (2) Don't sacrifice cavity performance

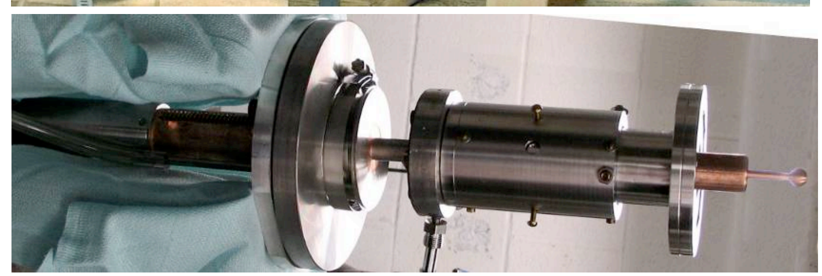
	Type	Comments
Couplers	Capacitive	simplicity ↑, better suited for $\lambda/4$?
	Inductive	cooled center conductor; better for $\lambda/2$?
	Fixed	simplicity ↑, cost ↓
	Variable	rf power needs ↓, easier conditioning
Slow Tuner	Pneumatic bellows	moving parts ↓
	Lever/motor + tuning plate	size ↑, serviceability ↑
	Cold motor driven lever	size ↓
	Niobium plunger	Penetration into rf space
Fast Tuner	None/overcoupling	parts count ↓, rf power needs ↑
	Mechanical	development required
	Variable reactance	cost ↓, limited applicability

IV. Couplers, Tuners







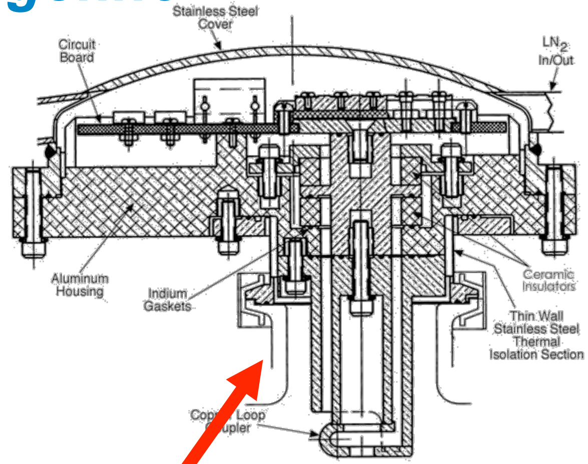


- IPN fixed cw capacitive power coupler designed for 5 kW; extended to 20 kW for 352 MHz spoke cavity

- ANL inductive and capacitive power couplers
- Fully variable over 50 dB (tested CW up to ~800 W)

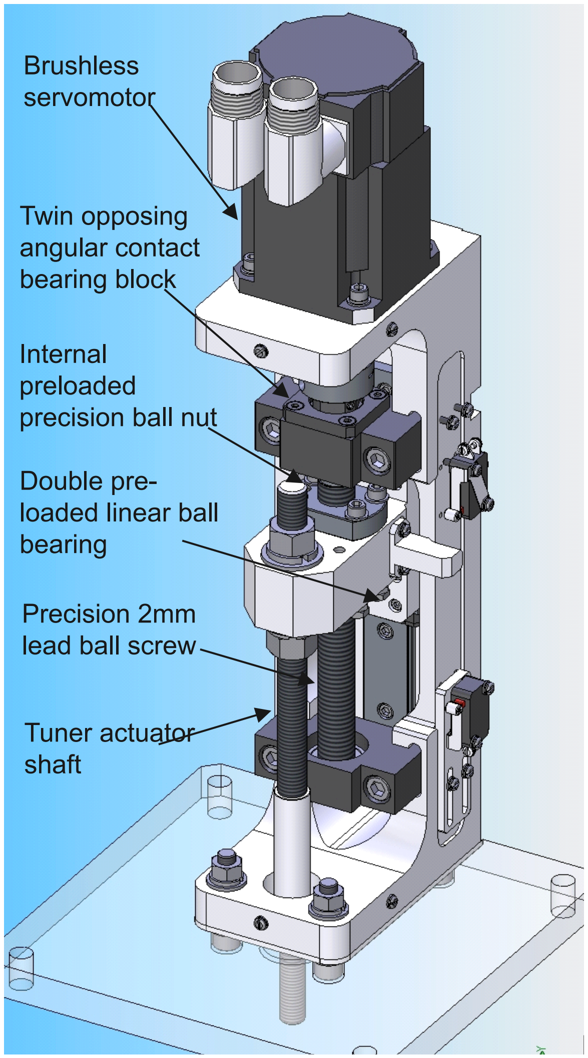
IV. Couplers, Tuners: VCX Fast Tuner at Argonne

- Based on a set of 10 parallel 77 K PIN diodes
- Coupled directly to the cavity fields through an inductive loop mounted on a cavity coupling port
- Diodes are switched on and off; switching the cavity between two frequency states in order to adjust cavity phase
- Reliable, inexpensive
- Only developed for f<150 MHz; limited switching power; a fast mechanical tuner is desired for future ATLAS upgrades

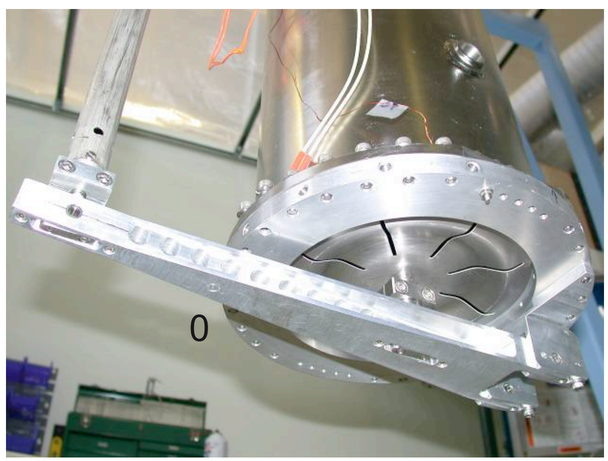


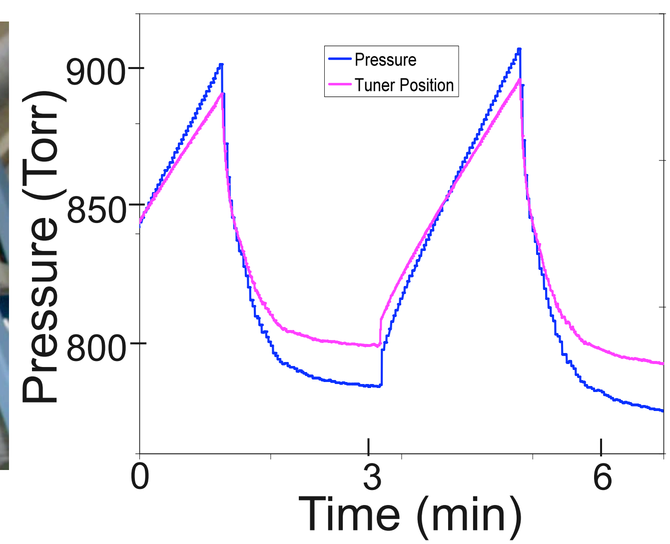
IV. Couplers, Tuners: "Slow" Tuner at Triumf

External motor drive



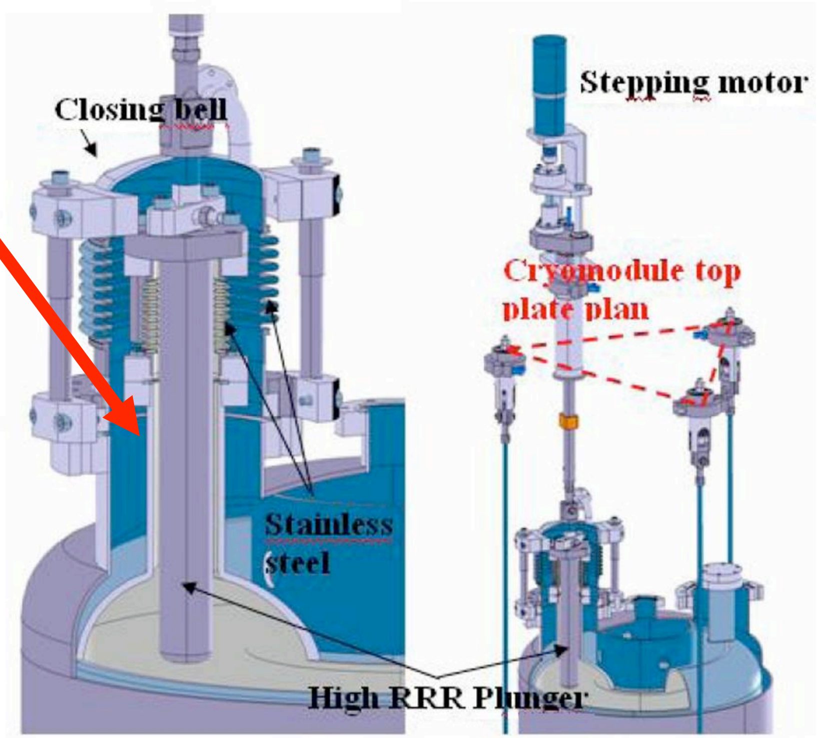
- Precision servo-motor and ball screw on top of cryomodule
- Actuator extends (through bellows) to a lever mechanism to the tuning plate
- Relatively fast response time, up to 30 Hz
- Tuner sensitivity 0.04 Hz/step; corresponds to 5nm/step
- Tuner accurately tracks induced helium pressure fluctuations (lower right)



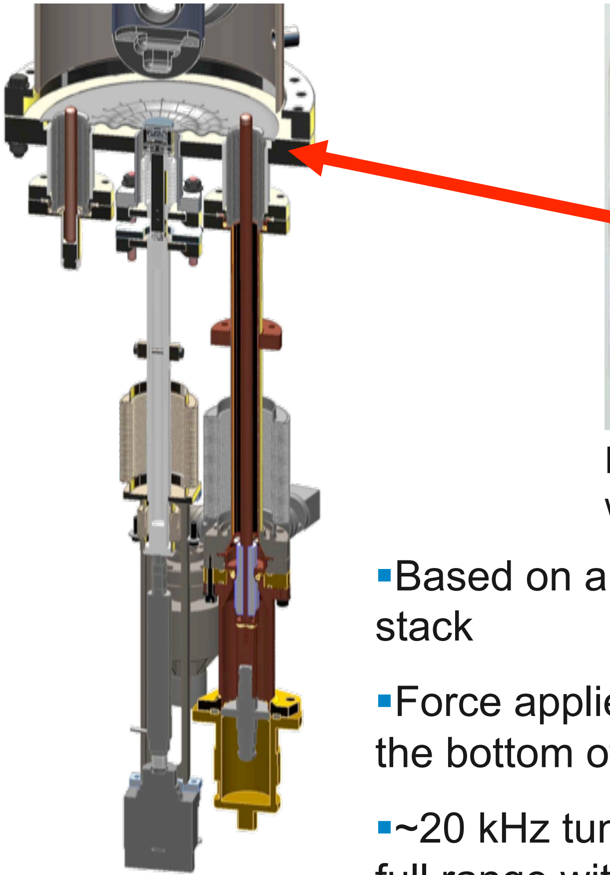


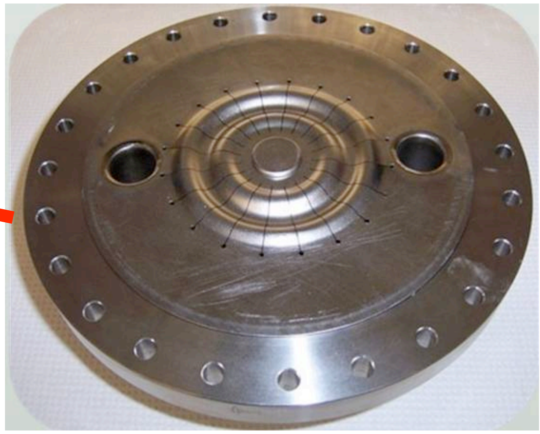
IV. Couplers, Tuners: Slow Tuners for Spiral-2

- High RRR 3 cm niobium plunger into the cavity rf space
- 1100 Hz/mm tuning sensitivity; large 90 kHz tuning window
- 11% additional rf loss at 6.5 MV/m; mostly on SS flange and bellows



IV. Couplers, Tuners: Fast and Slow Tuner Planned for MSU Re-accelerator



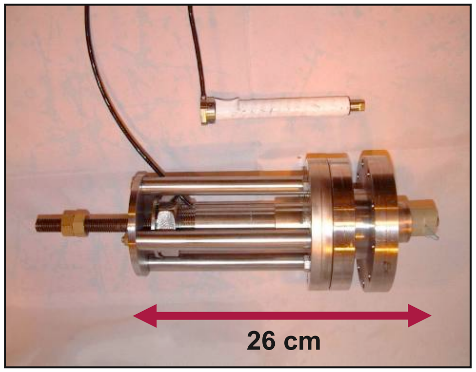


Niobium push-pull tuning plate with convolutions and cuts

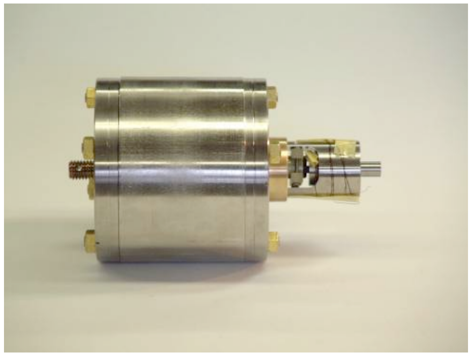
- Based on a warm linear stepper motor plus piezo electric stack
- Force applied through to a tuning rod to a tuning plate on the bottom of the cavity
- ~20 kHz tuning range (+/- 25 mm) using stepper; 300 Hz full range with piezo

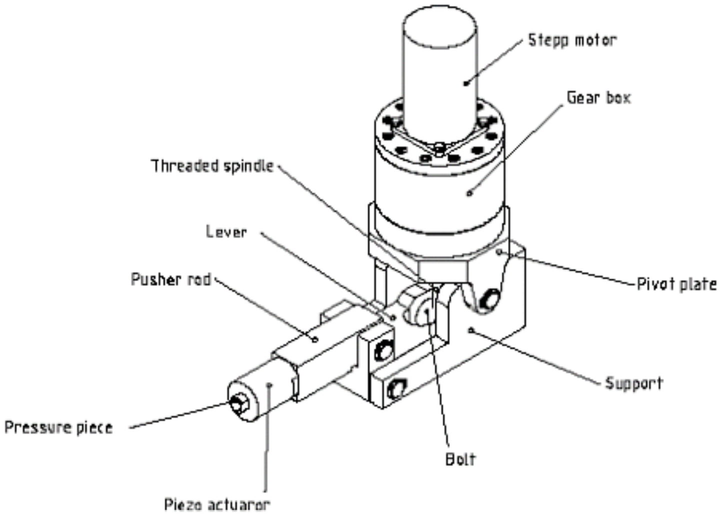
IV. Couplers, Tuners: New/prototype Fast Tuners

Piezo fast tuner – ANL

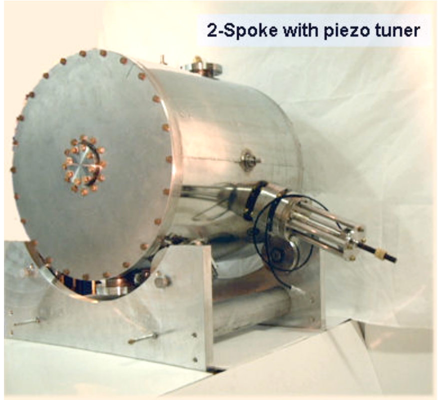


Magnetostrictive tuner – ANL/Energen





Combination fast/slow tuner – SARAF/ACCEL



- No fast mechanical tuners of these types in routine operation with low-, mid-beta SRF linacs

Outlook for Low and Mid Beta Superconducting Cavities

- There are many well developed SRF structures covering the low and medium velocity range so that together with elliptical cell cavities established solutions are available for the entire velocity range
- Several new projects underway using $0.1<\beta<0.2$ SRF cavities using many established solutions (cavity geometries, techniques, tuners)
- Low and medium beta linac projects have been slow to adopt new techniques and solutions (some of these to be had at little or no additional cost/risk)
- Many areas where majors gains still to be had with modest R&D
  - Gradient/linac size
  - Refrigeration costs
  - RF power
- Realization of these gains will drive interest in future applications of low and medium velocity SRF cavities