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CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

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Challenges for Low beta SCRF

R. Laxdal, TRIUMF

TTC Meeting

New Delhi, Oct. 20, 2008

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

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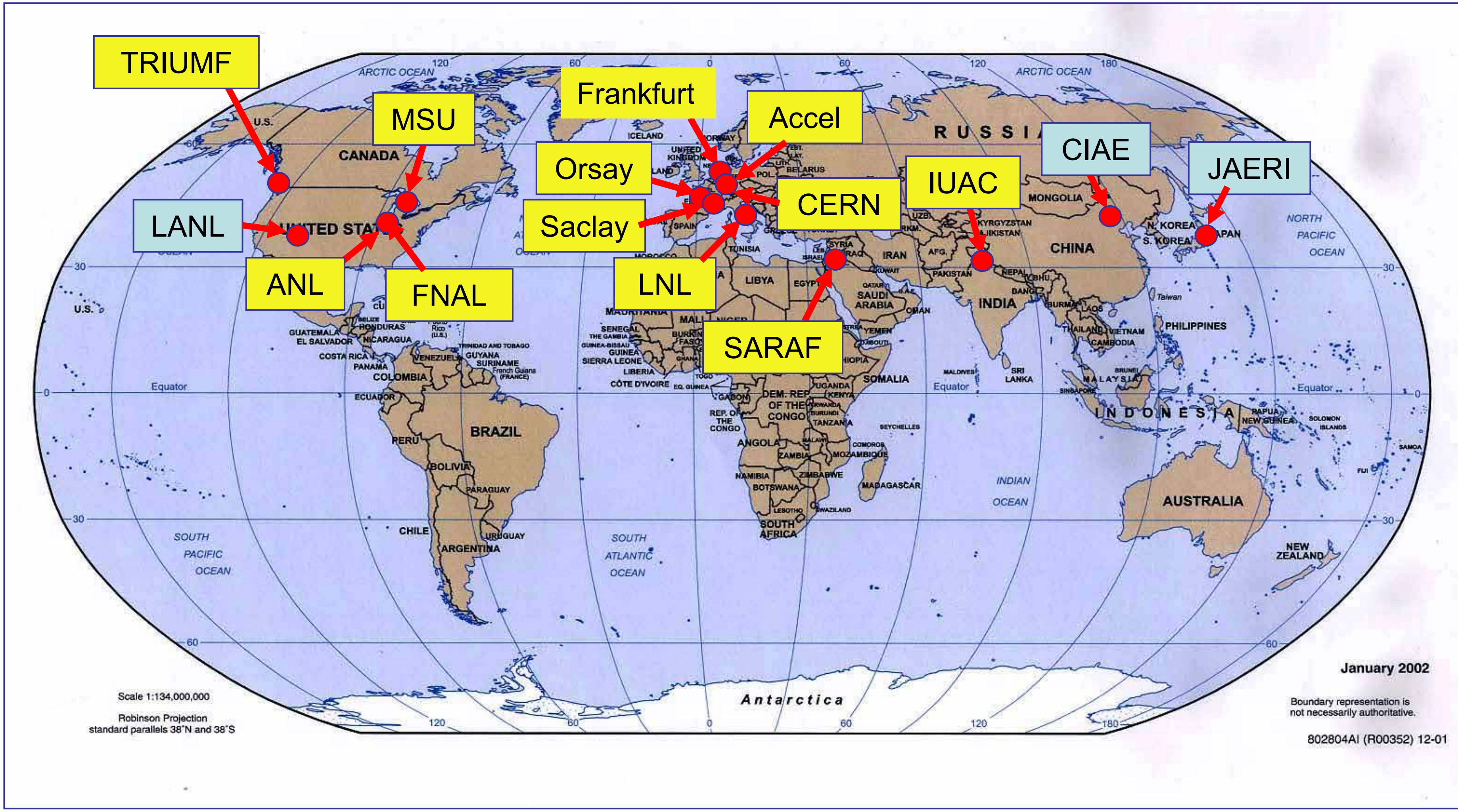
Outline

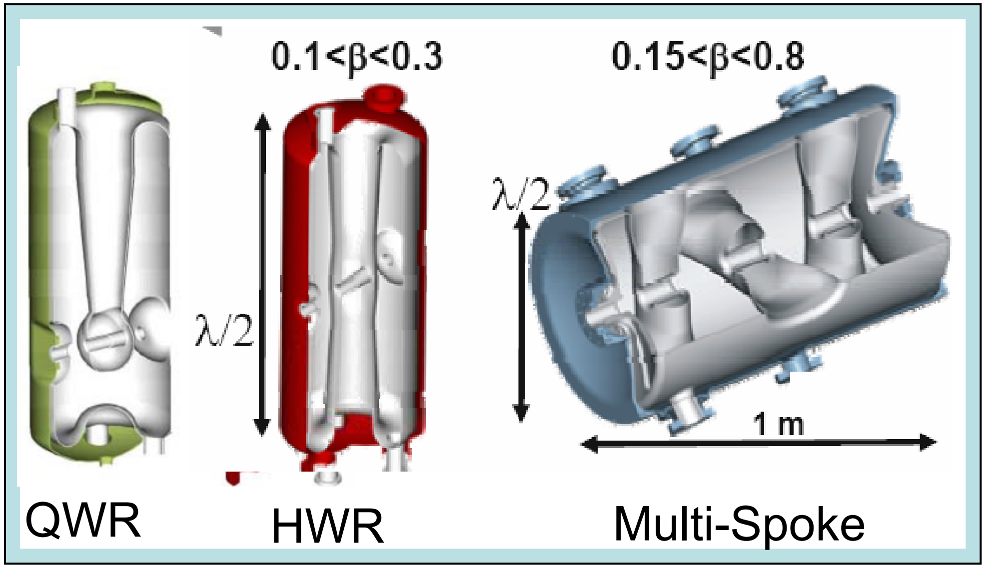
- Overview of community and goals
  - Characteristics of applications, Where are we?
    - Existing facilities
    - Projects underway
    - Proposals – in development
    - General remarks
- Technical issues
    - Performance
    - Cavity fabrication and design
    - Cavity processing
    - Bulk niobium vs sputtered
    - Couplers/Tuners
    - Q-slope
    - Cryomodules (single vacuum vs split vacuum)
- Conclusions

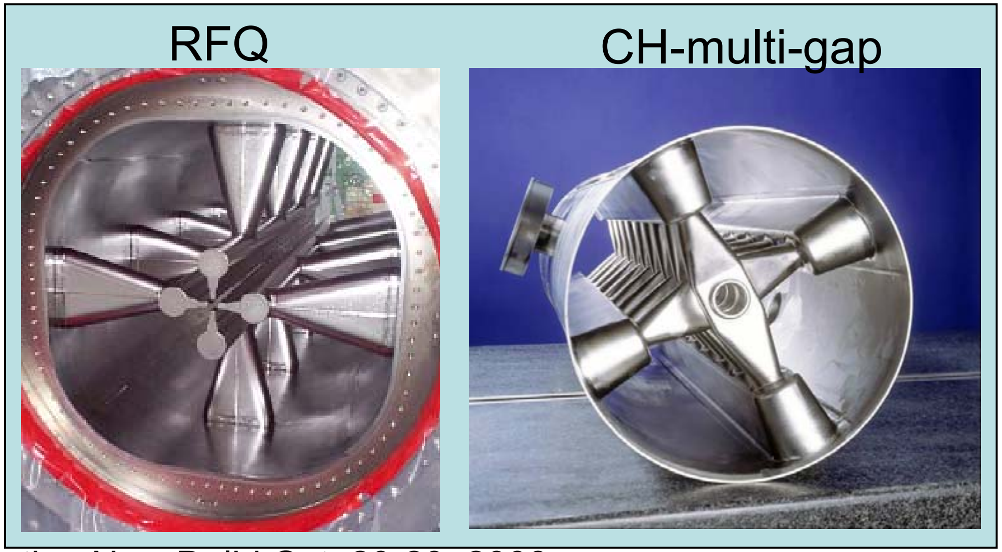
Low-Beta SC (Niobium) Community



Examples

- Quarter wave
  - ISAC-II, SPIRAL2
- Half wave
  - SARAF, IFMIF
- Spoke – single, double, triple
  - FRIB, Project X
- CH structure
  - Frankfurt
- RFQ
  - INFN-LNL



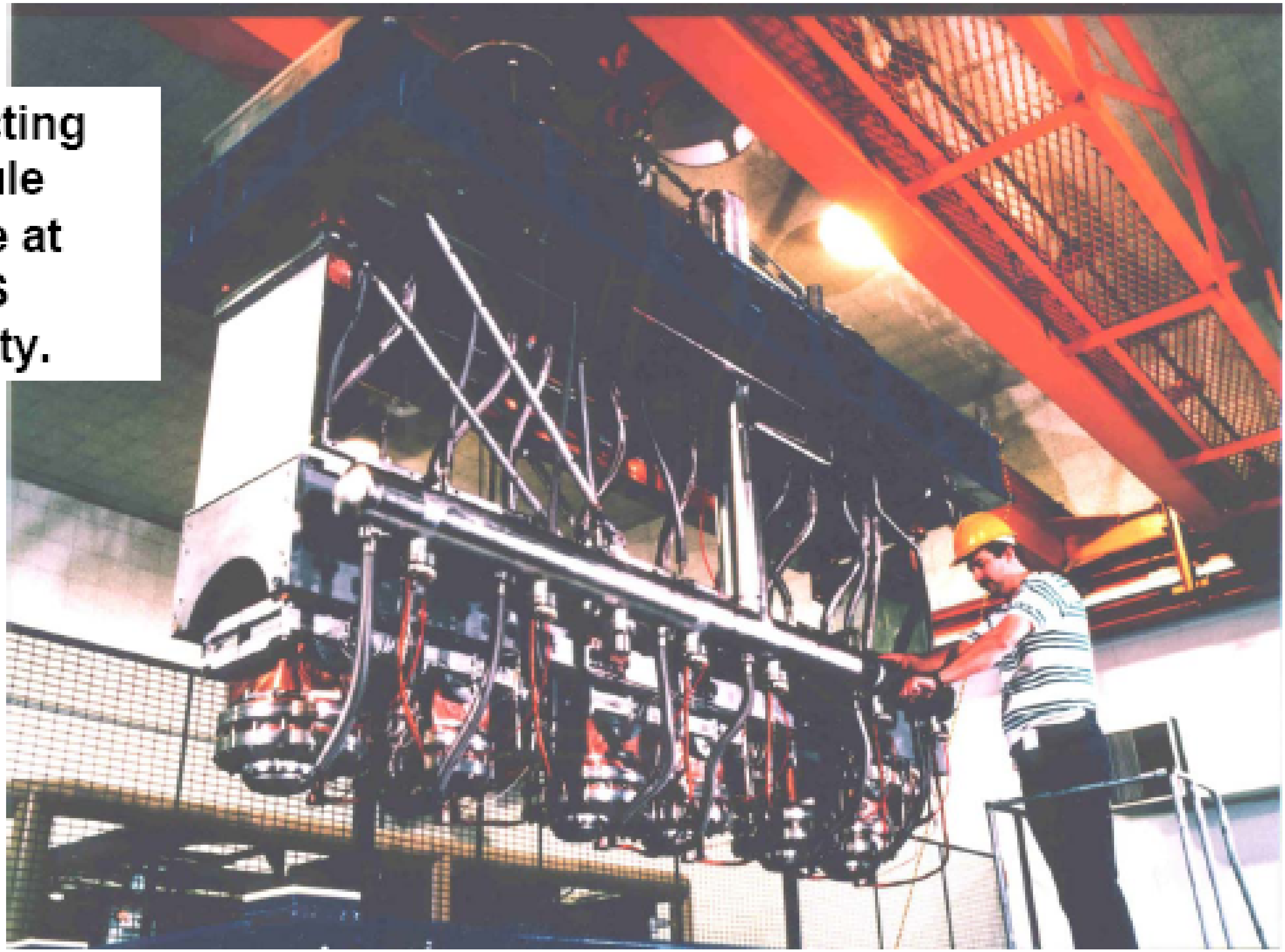


Where are we?

- Traditionally low beta SC resonators were quarter waves (or split rings) used as post-accelerators for heavy ion tandems serving the nuclear physics community (Atlas, INFN-LNL, JAERI)

Argonne-ATLAS

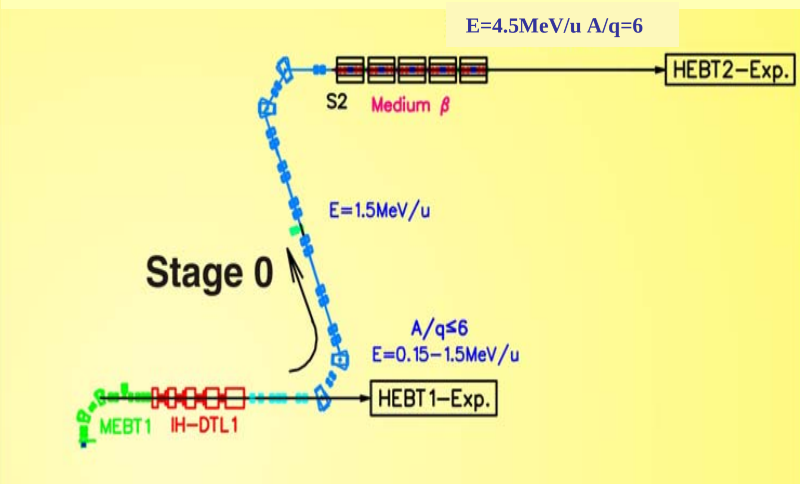
A superconducting linac cryomodule currently in use at the ANL/ATLAS heavy-ion facility.



Where are we?

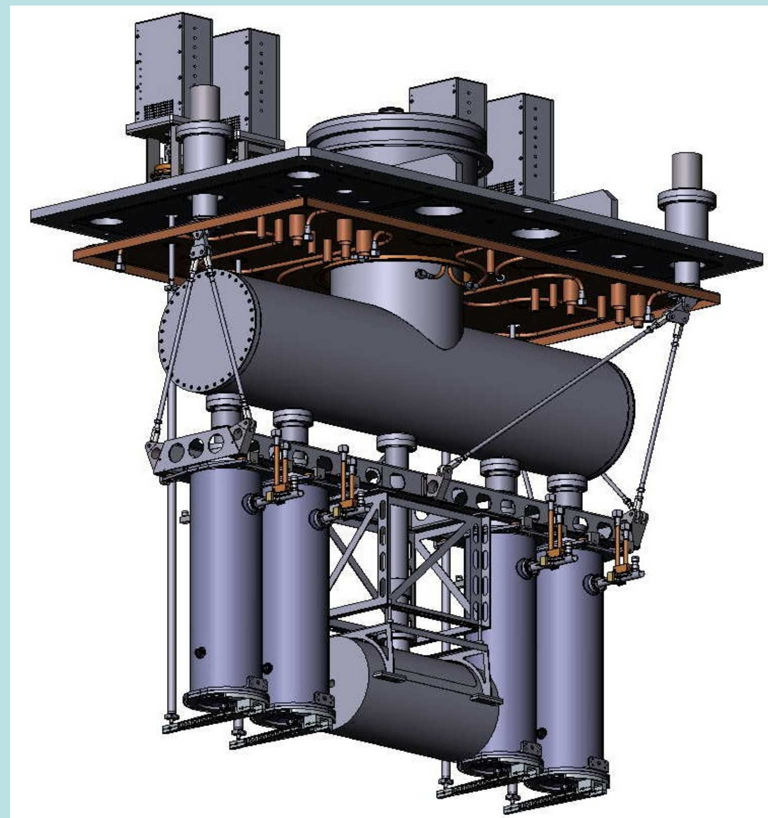
- Traditionally low beta SC resonators were quarter waves (or split rings) used as post-accelerators for heavy ion tandems serving the nuclear physics community (Atlas, INFN-LNL, JAERI)
- Increased interest in Radioactive Ion Beams (RIBs) has created a renaissance in low and medium beta SC cavity development in the last seven years for both post-accelerators and drivers (ISAC-II, SPIRAL2)

ISAC-II (Phase I - Medium Beta Section)

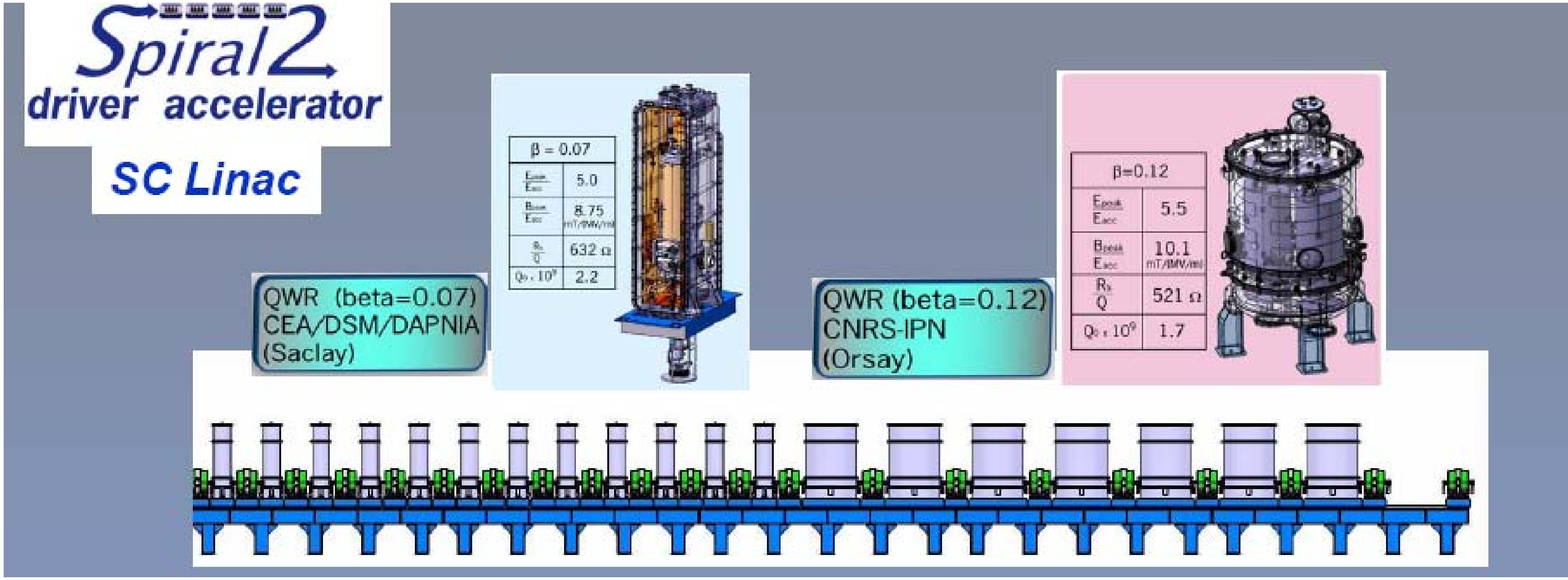


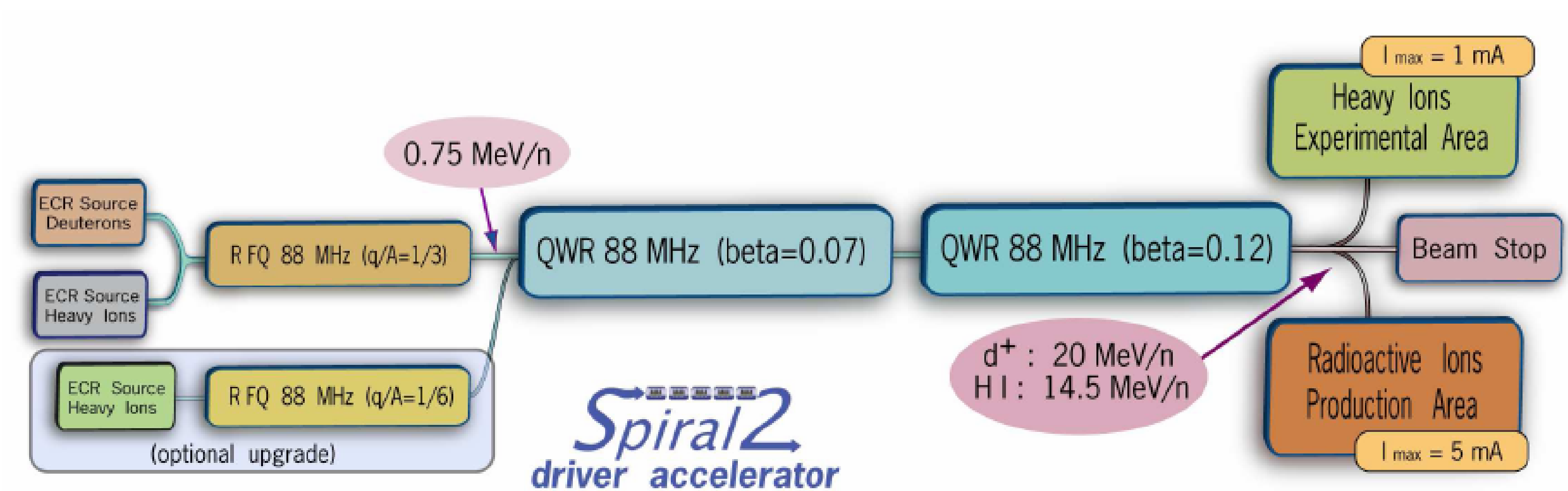
ISAC-II TRIUMF 106MHz Superconducting Linac

- Twenty bulk niobium quarter wave cavities housed in five cryomodules
- Boosts ion energy by 20MV to provide stable and RIB's above the Coulomb Barrier



SPIRAL-II GANIL (20MeV/u d+, 5mA)



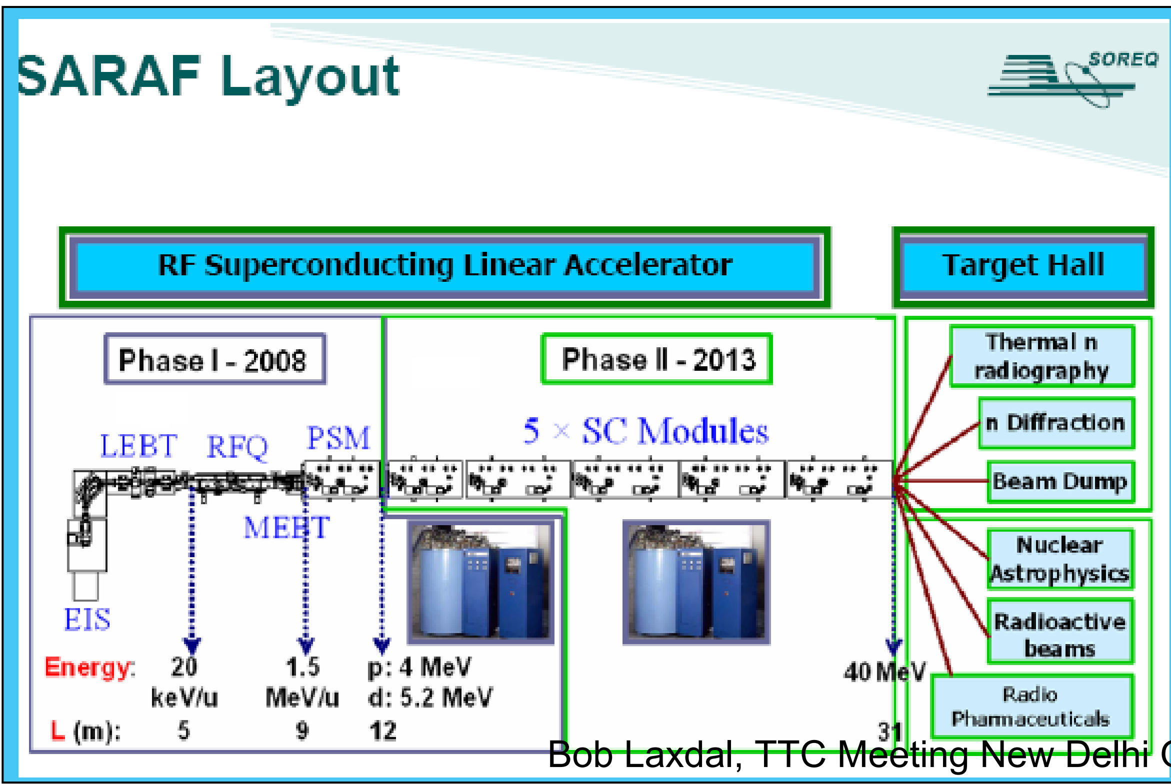


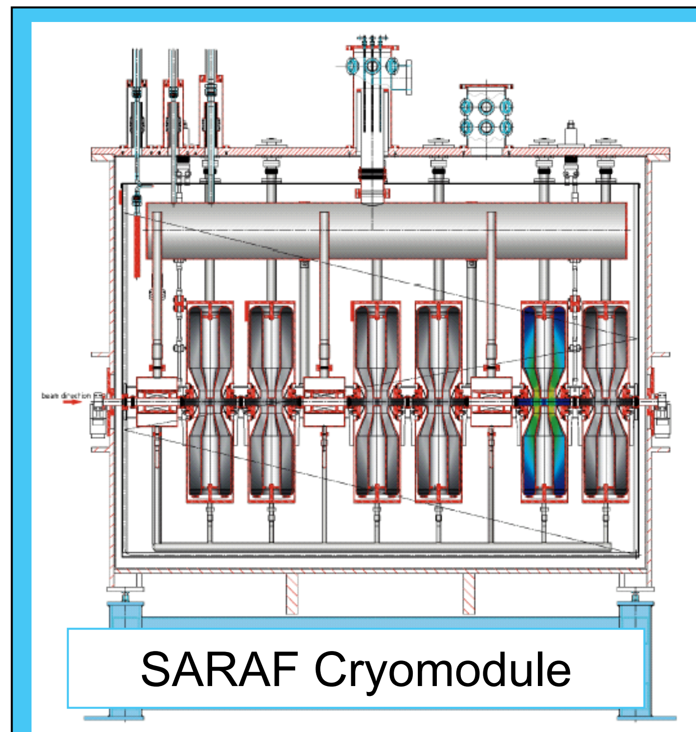
Where are we?

- Traditionally low beta SC resonators were quarter waves (or split rings) used as post-accelerators for heavy ion tandems serving the nuclear physics community (Atlas, INFN-LNL, JAERI)
- Increased interest in Radioactive Ion Beams (RIBs) has created a renaissance in low and medium beta SC cavity development in the last seven years for both post-accelerators and drivers (ISAC-II, SPIRAL2)
- High duty cycle driver linacs of protons and ions are now proposed with SC sections beginning at lower beta values (SARAF, FRIB)
  - Rise in performance (and relevance) of multi-gap spoke cavities and half-wave resonators (HWR) in the mid-beta regime

SARAF – High Intensity p-d Driver (20MeV/u - 2mA d+)

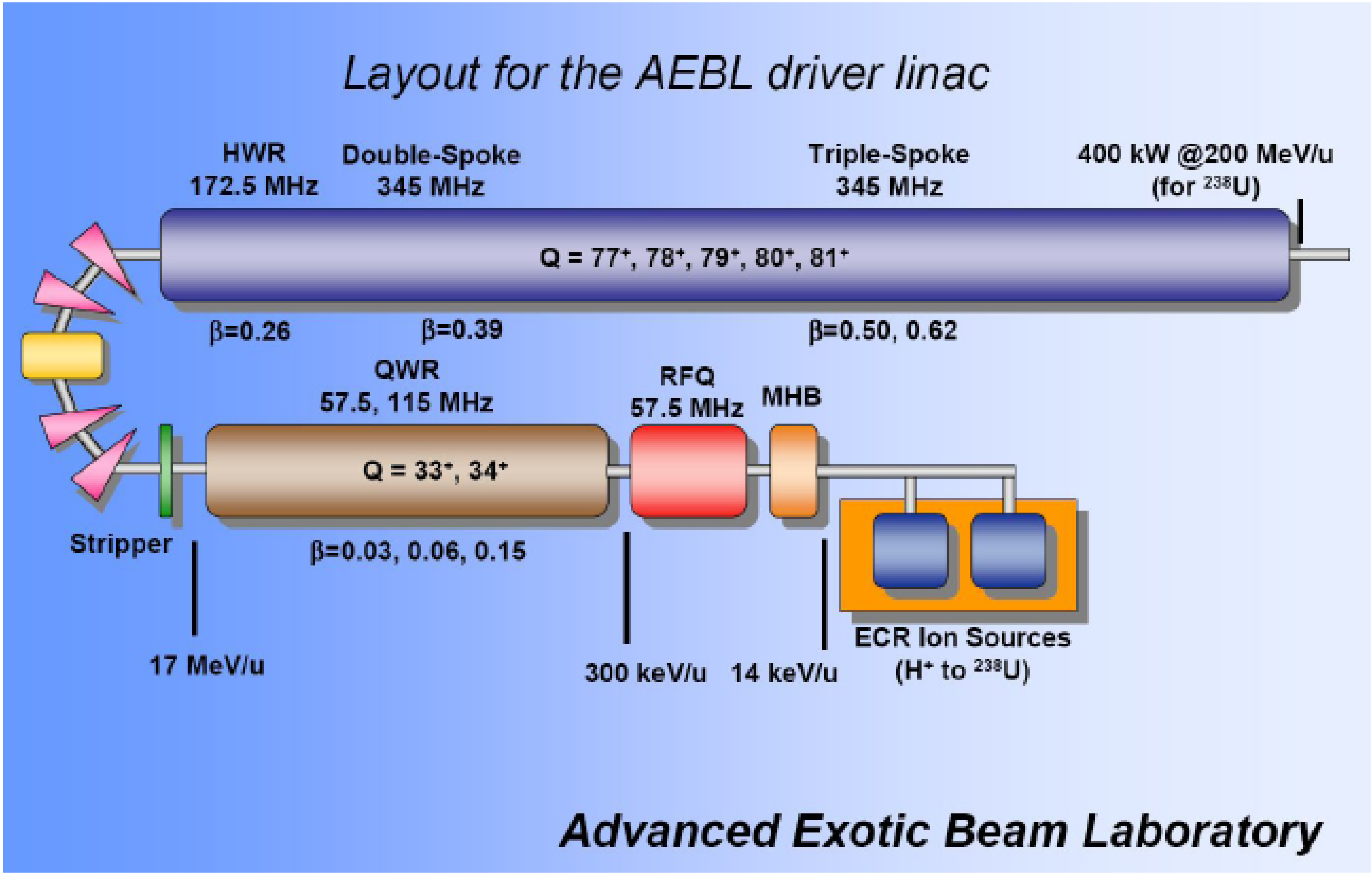
- First high intensity proton/deuteron machine using low beta superconducting structures
- Phase I commissioning test in progress





AEBL Driver – FRIB Proposal

II. Applications: Spoke –cavity based AEBL



Low to Medium Beta Cavities

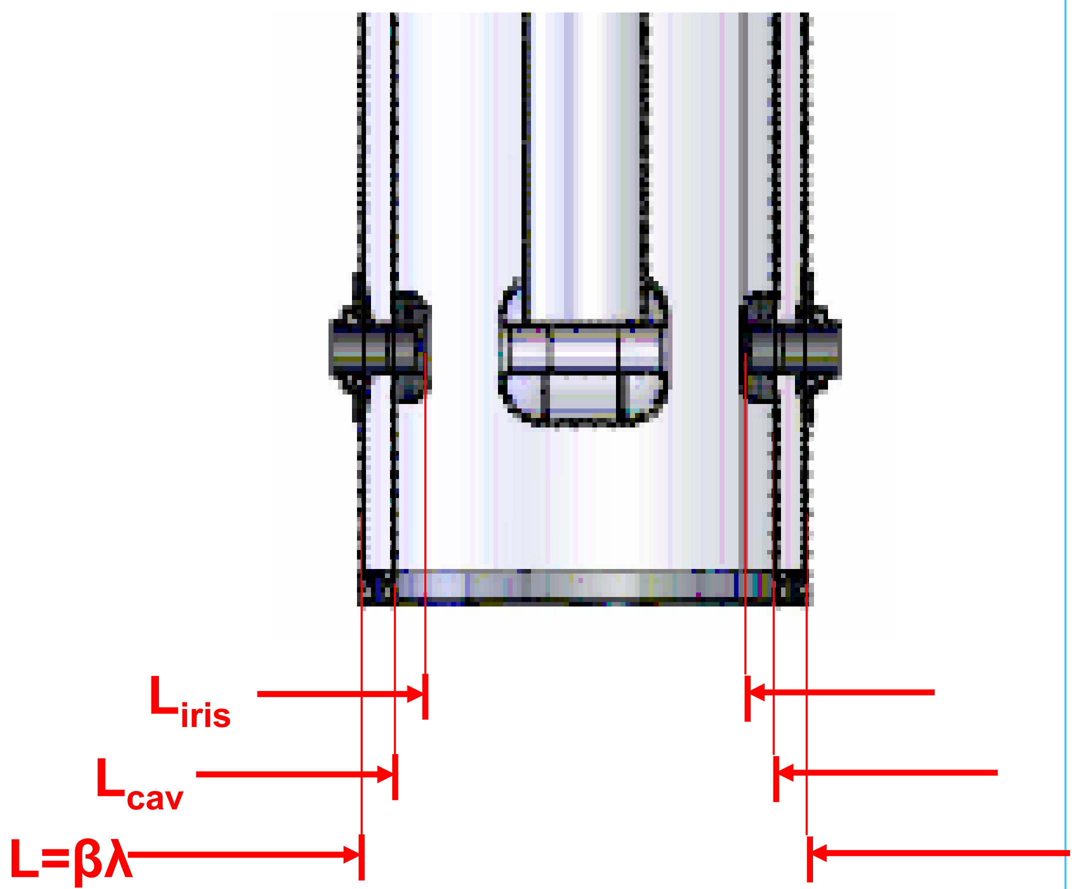
- Superconducting allows
  - cw and high duty cycle operation
  - Larger apertures, lower frequencies for increased acceptance
- Drivers – conservative gradient required
  - longer machines typically – large velocity swing – several cavity regimes
  - Treat as almost fixed gradient machine
  - Beam loss (halo) an issue; careful beam dynamics required
  - Beam loading dominates rf power
- Post-accelerators
  - Shorter machines typically – broad velocity acceptance
  - Utilize maximum gradient to improve performance and/or reduce cost – operate each cavity at fixed power
  - short independently phased cavities give flexibility to beam delivery
  - Beam loading not an issue

Projects and Proposals at Low Velocity

Project	Lab	Driver	Post-accelerator	Particle	Structure
ISAC-II	TRIUMF		√	HI	QWR
SPIRAL-II	GANIL	√		P, d, HI	QWR
SARAF	SOREQ	√		P, d	HWR
IUAC			√	HI	QWR
Upgrade	ANL		√	HI	QWR
Re-accel	MSU		√	HI	QWR
FRIB	ANL,MSU	√	√	HI/HI	QWR, HWR, Spoke
EURISOL	-	√	√	P, d / HI	QWR, HWR, Spoke
Project-X	FNAL	√		P	QWR, HWR, spoke
IFMIF		√		d	HWR
HIE-REX	CERN		√	HI	QWR (sputter)

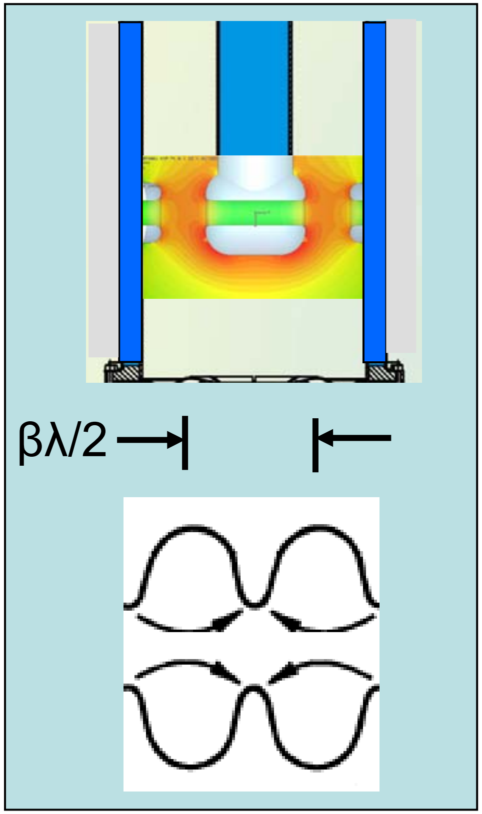
Low beta gradient: Definition

- No well accepted definition of cavity length
  - Ea's dependent on definition of cavity length
  - Ea=Veff/L
  - ISAC-II beta=0.07 cavity
    - Ea=9, 7 or 6.4MV/m depending on L_{iris}, L_{cav} or $L=\beta\lambda$ definition but Veff=1.3MV for all
- Ep and Hp give a meaningful physical measure of cavity performance
  - ISAC-II operation; Ep=35MV/m and Hp=70mT



Low beta (0.1) vs High beta (1) performance

- E_{peak} at design P_{cav} gives a physical parameter that can be useful in comparing cavity performance
  - Typically E_{peak}/E_a=4-5 for low beta QWR's while E_{peak}/E_a~2 for elliptical cavities.)
- For CW machines performance limited by LHe consumption - P_{cav} (Q at operating point) and not maximum achievable gradient (Cornell ERL Ea~15-20MV/m for elliptical cavities or Ep~30-40MV/m)
- TRIUMF's ISAC-II linac QWR's now operate cw with Ep~35MV/m (Ea~7MV/m)



Performance of Existing Facilities

CW heavy ion SC-linacs with Nb technology

- ATLAS at Argonne
  - Bulk niobium – Ep~15-20MV/m
- INFN-Legnaro
  - Sputtered Nb on Cu (former Pb) - Ep~22MV/m
  - Bulk niobium cavities – higher gradients demonstrated but little on-line experience
- JAERI
  - Explosively bonded Nb on Cu – Ep~25MV/m
- ISAC-II
  - Bulk niobium cavities – Ep=35MV/m

TRIUMF Toward Higher Gradient

General Considerations

- **Higher stored energy, U_o**
  - Overcoupling used to broaden natural bandwidth
  - Requires $P_{forward}=\pi U_o \Delta f_{1/2}$
    - Increase amplifier, cables and coupling loop rating
  - Eigenfrequency excursions, Δf, from microphonics (fast) and helium pressure fluctuations (slow)
    - Adopt accurate constant-tracking tuner
- **Higher peak surface field**
  - Clean surfaces to reduce field emission, raise Q
  - Clean assembly techniques
- **Higher rf defocussing fields (at φ_s=-25deg)**
  - Adopt strong focussing lattice

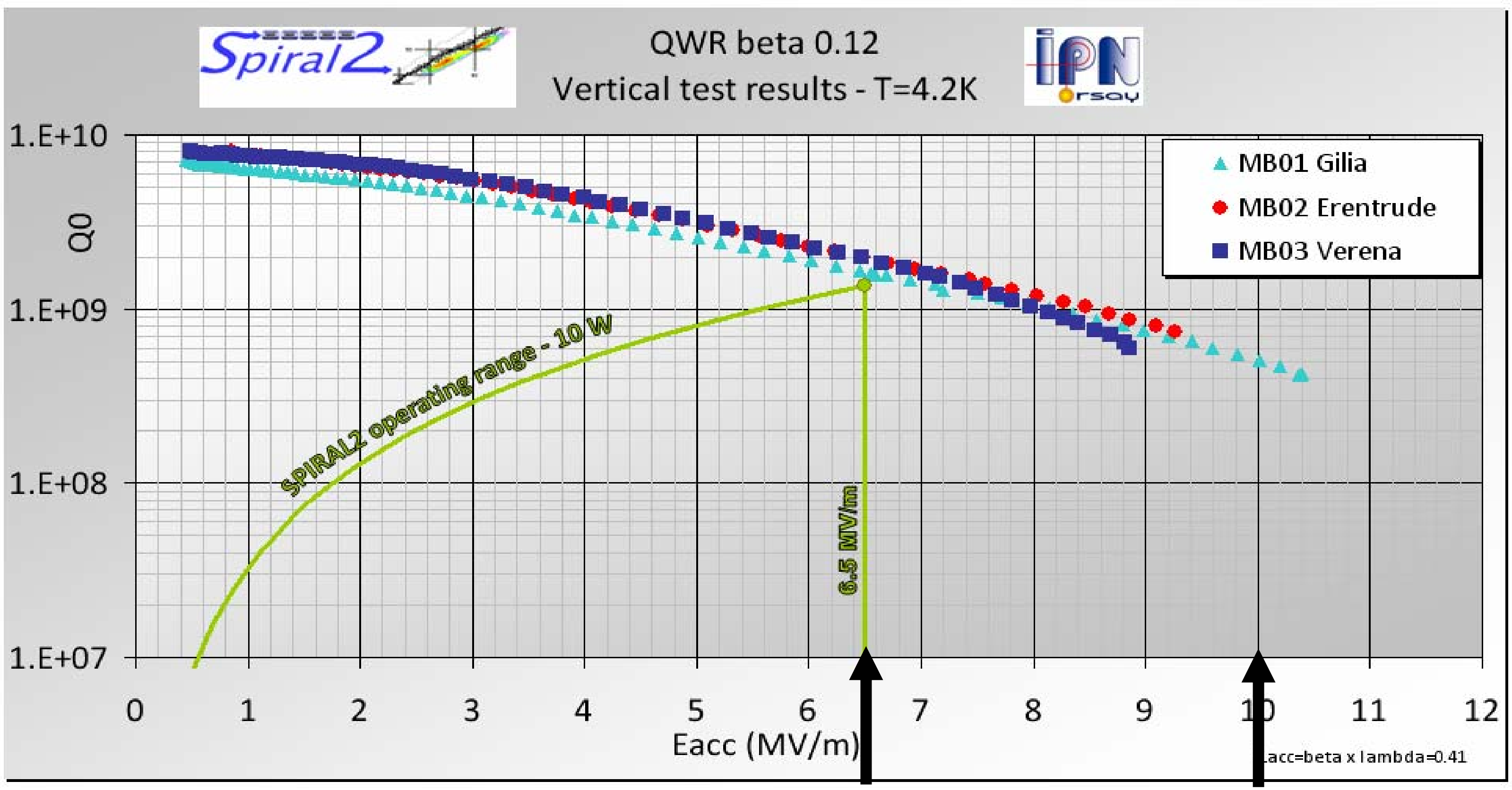
ISAC-II

- **Choose Ep=30MV/m**
  - dV=1.1MV/cavity, Ea=6MV/m
  - Uo=3.2 Joules
  - $P_{forward}$=200W gives $\Delta f=\pm 20$Hz
    - ☑ Amplifier and cables compatible with 800W
    - ☑ Loop compatible with $P_{forward}$=250W
  - ☑ New fast tuner developed
- ☑ **Clean room assembly**
  - Single vacuum space for insulating vacuum and beam
- ☑ **9T solenoid in each cryomodule**
  - Solenoid complete with `bucking' coil to reduce fringe field in cavity region.

Challenges

Challenges1 – High Qo

- High duty cycle application is typical
  - High Qo rather than high Epeak is important
  - BCP usually sufficient since operating point is defined by P_{cav} well away from maximum peak field



Ep=35MV/m

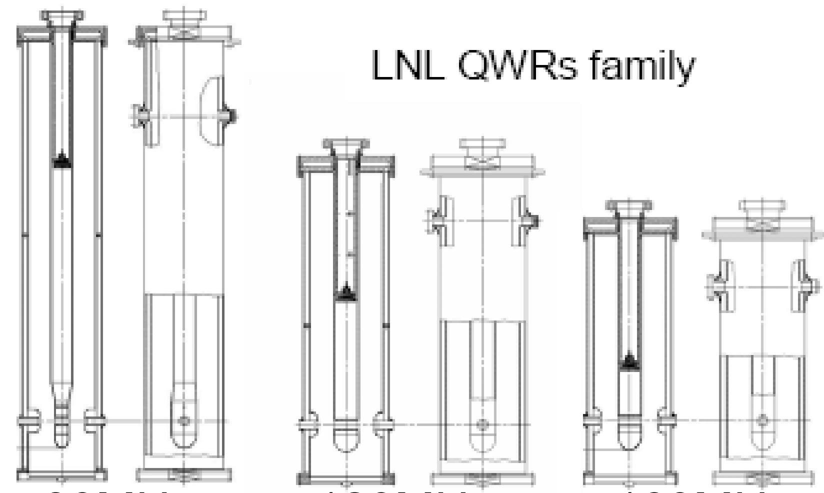
Ep=55MV/m

Challenges 2 - Variety

- Many different structures spanning wide frequency and beta range
  - Lack of standard designs
  - Each project has a favourite frequency and beta family
- Structures require a variety of tooling, fabrication and processing specifications
    - Parts preparation
      - either machined or formed or combination
      - welded into sub-assemblies or formed from larger pieces

Example - Quarter waves

- Many quarter wave prototypes have been built and tested world-wide over the last 15 years

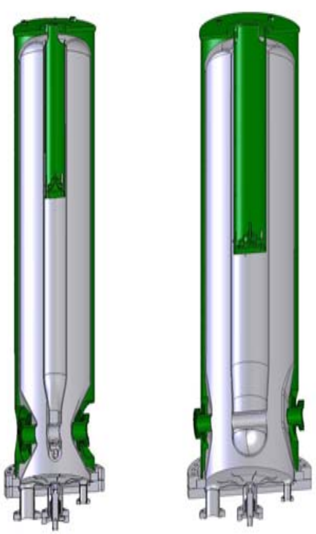


80MHz
4.7%

120MHz
8%

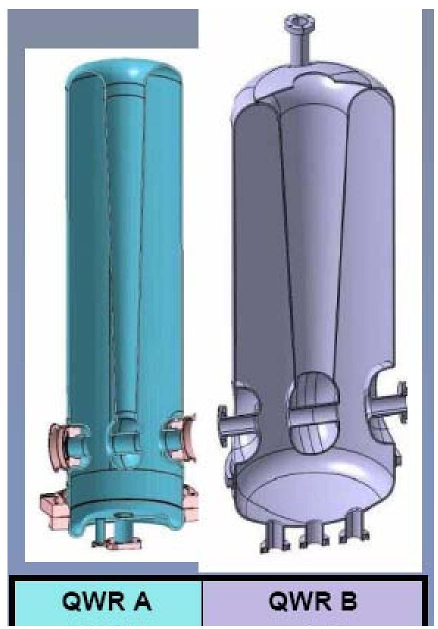
160MHz
11%

MSU



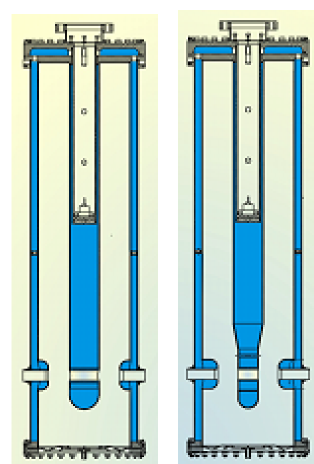
80.5MHz
4.1%, 8.5%

SPIRAL-2



88MHz
7%, 12%

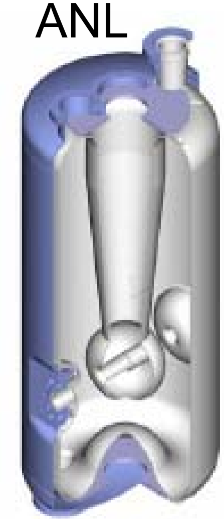
ISAC-II



106MHz
7%, 5.7%

141MHz
12%

ANL



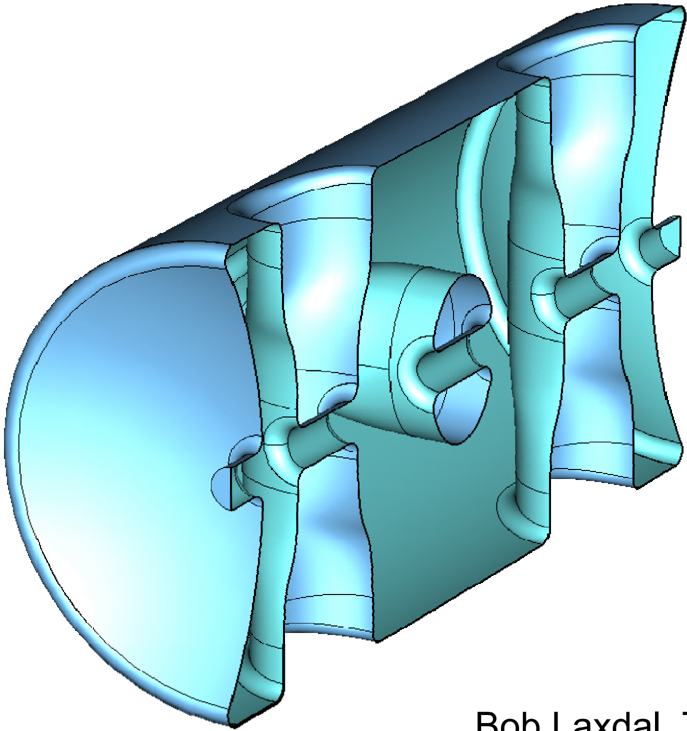
109MHz
14.4%

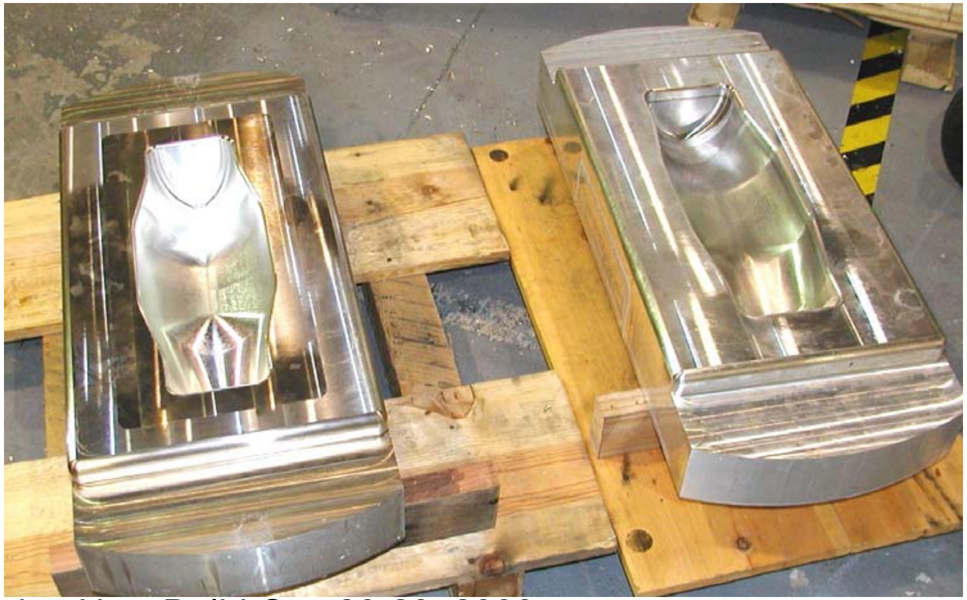
Cavities in mid-beta range

Applications	Frequency (MHz)	Beta (v/c)	Particle type	# of Spoke or HWR Cavities (total cavities)	Duty Factor
AEBL	345	0.4,0.5, 0.62	Proton to Heavy-Ion	134 (207)	CW
ISF	322 (HWR)	0.285, 0.425	Proton to Heavy-Ion	297 (481)	
EURISOL	352	0.3, 0.385	Proton Light-Ion	100-200	
XADS, APT	350	0.17,0.35	Proton	100 (190)	
Project X	325	0.2-0.6		90 (420)	Pulsed
SARAF	176 (HWR)	0.09, 0.15	Proton, Deuteron	42	CW

The ANL 345 MHz Triple-spoke cavities

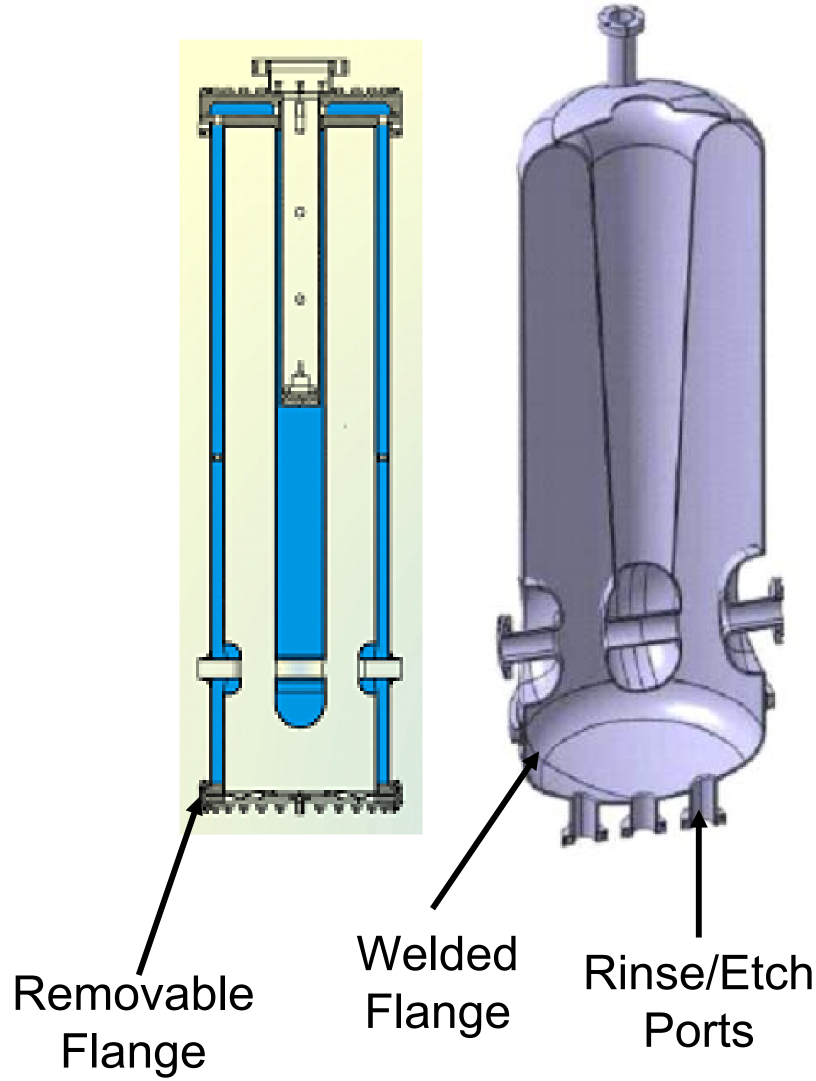
- AES forms major components prior to welding at Sciaky





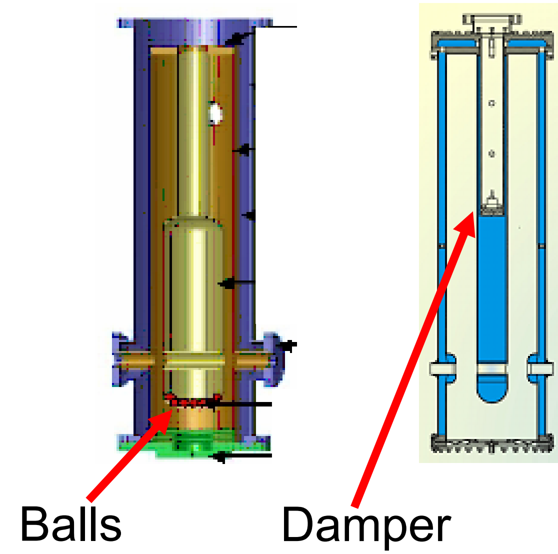
Challenges 3 – Cavity Shape

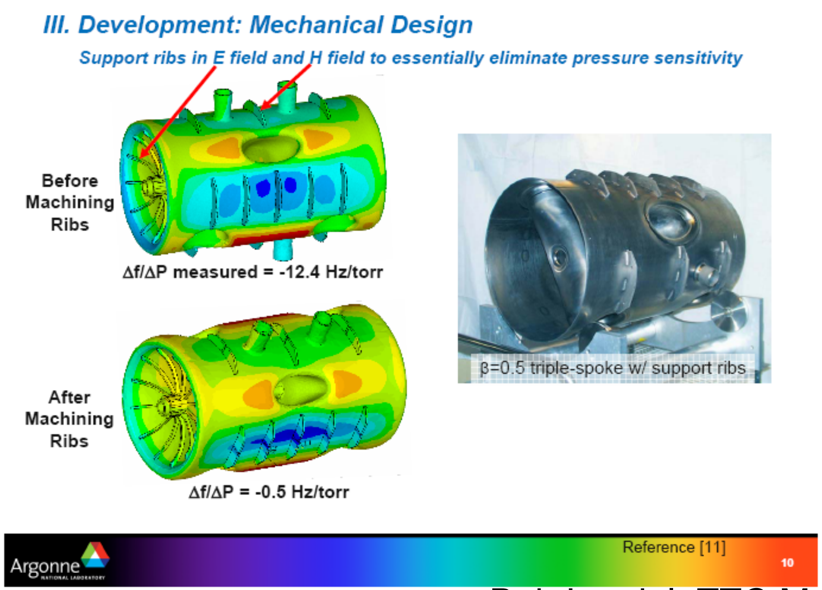
- Optimizing cavity shape – a trade-off
  - Minimize Ep and Hp
    - Leads to formed shapes
  - Minimize material and fabrication costs
  - Allow for rinsing and post-weld etching
    - removable end plates vs welding shut geometry with access ports
  - Allow for cavity tuning
  - Maintain good mechanical stability
    - Minimize sensitivity to helium pressure fluctuations and Lorentz force detuning
      - Reinforcing struts
    - Passively or actively damp microphonics
      - Mechanical dampers
      - Piezo tuners

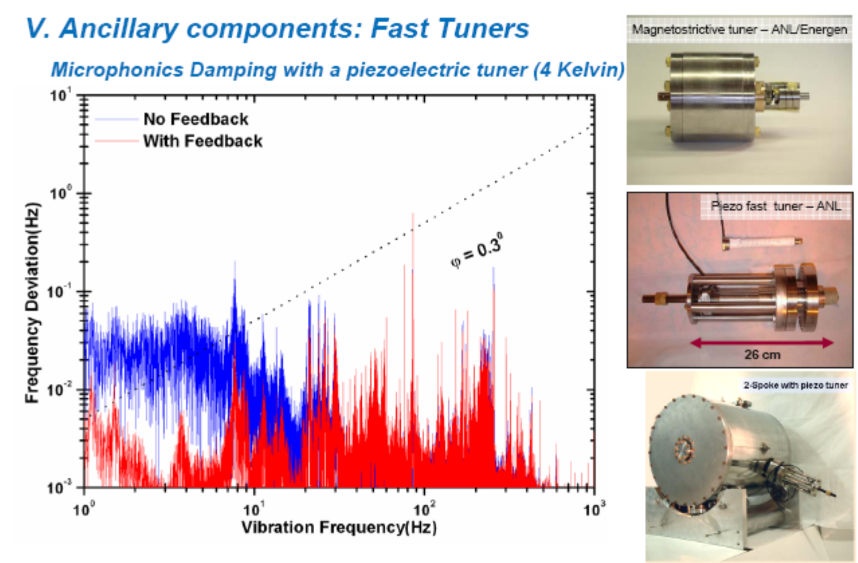


Mechanical stability

- Cavity shape can affect sensitivity to helium pressure fluctuations and affect microphonics
- Various techniques used to counter microphonics
  - Mechanical damping
  - Piezo tuner compensation
- Stability determines required rf bandwidth to maintain lock



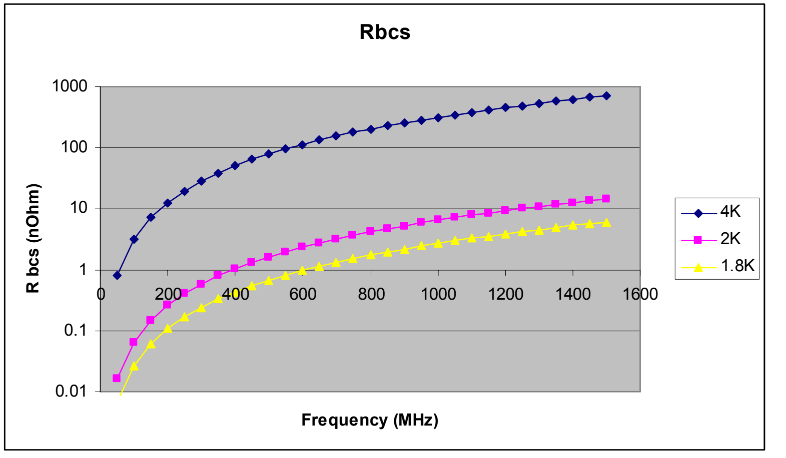


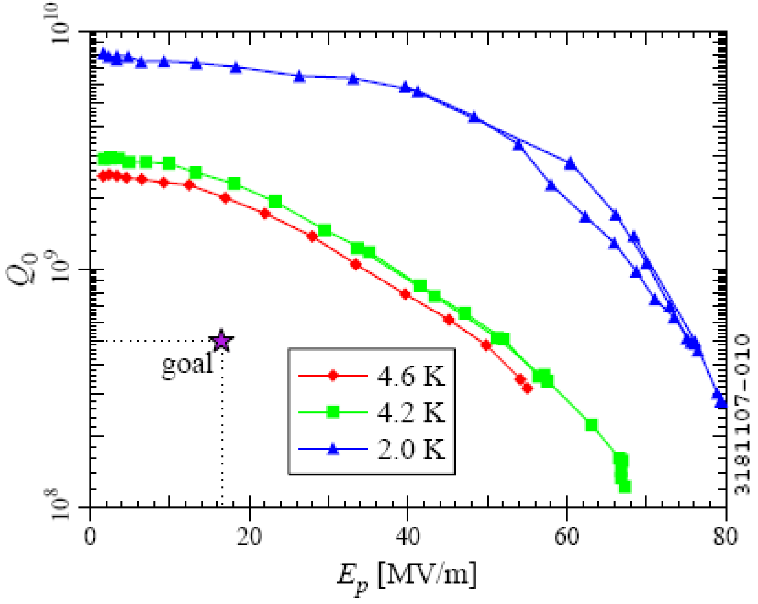


- Electro-mechancial properties of SC Spoke Cavities – Ph.D. Thesis, Zack Conway

Q-slope

- Many low-beta cavities have an enhanced Q-slope that reduces substantially at 2K
  - Is it a sign of global heating due to helium boiling
  - Can the effects be minimized by cavity design





MSU QWR β=0.041, 80.5MHz, Rs=2nΩ; Toroidal shorting plate a la Spiral and ANL - TRIUMF slotted tuning plate

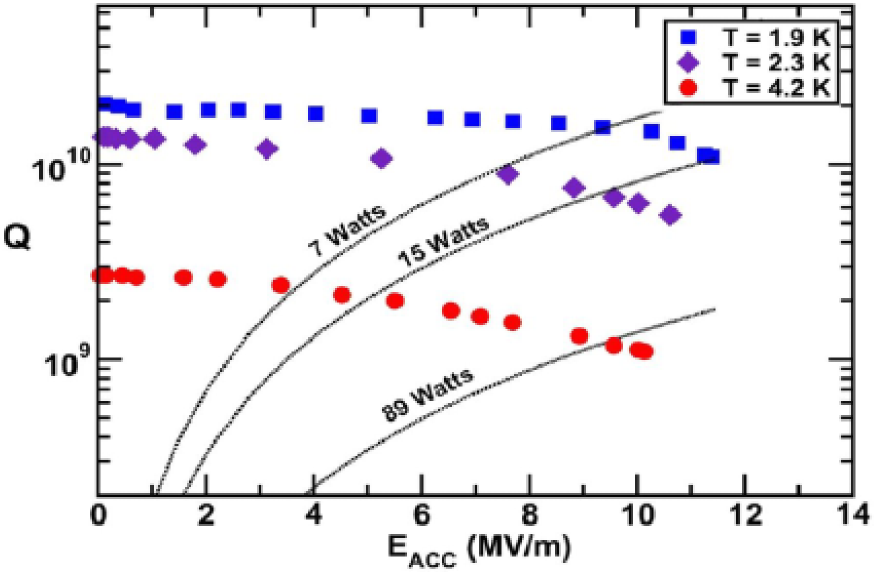


Figure 9: Q-curves and lines of constant rf power for an ANL 345 MHz β=0.63 triple-spoke cavity. At T=2 K, only 7 Watts rf power produces a gain of 7 MV/cavity.

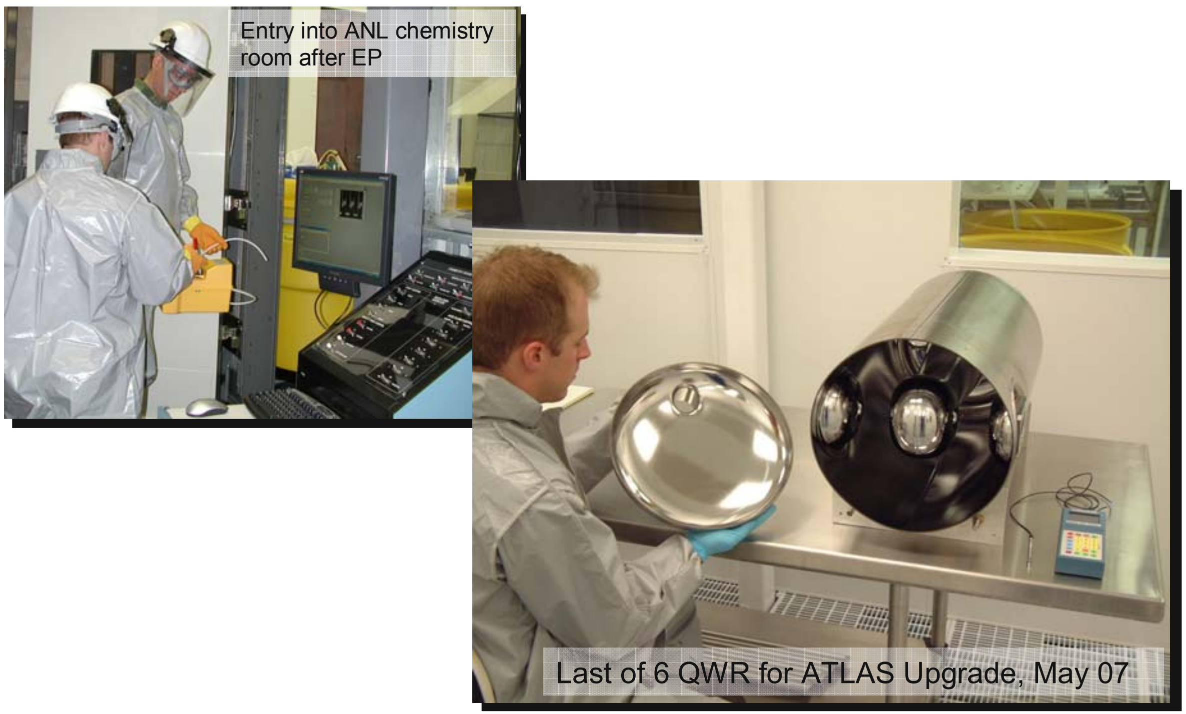
Challenges 4 - Etching

- Typical etching treatment is BCP
  - High duty cycle operation precludes operating at surface fields where EP has an advantage
  - Geometries are not conducive to EP
- Argonne and IUAC Electropolish parts before final weld with a light 5-10mic BCP to treat the weld
- TRIUMF/ANL collaboration on EP process

EP at ANL/IUAC

Argonne and IUAC Electropolish parts before final weld with a light 5-10mic BCP to treat the weld

Commissioning the SCSPF: Electropolishing



Argonne NATIONAL LABORATORY 11

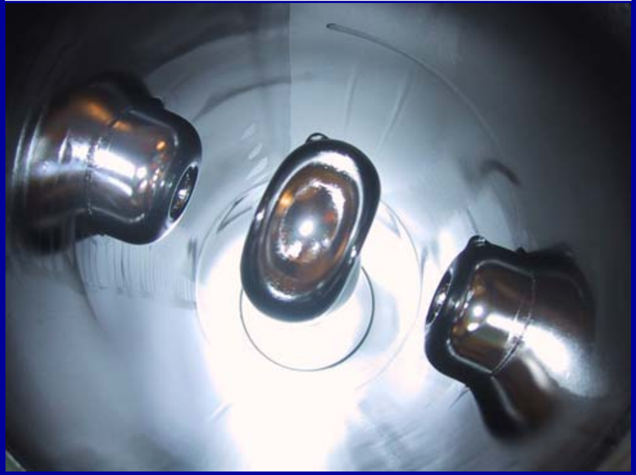
Central Conductor parts

IUAC

TRIUMF/Argonne* Collaboration – Cold Test Results

Before EP

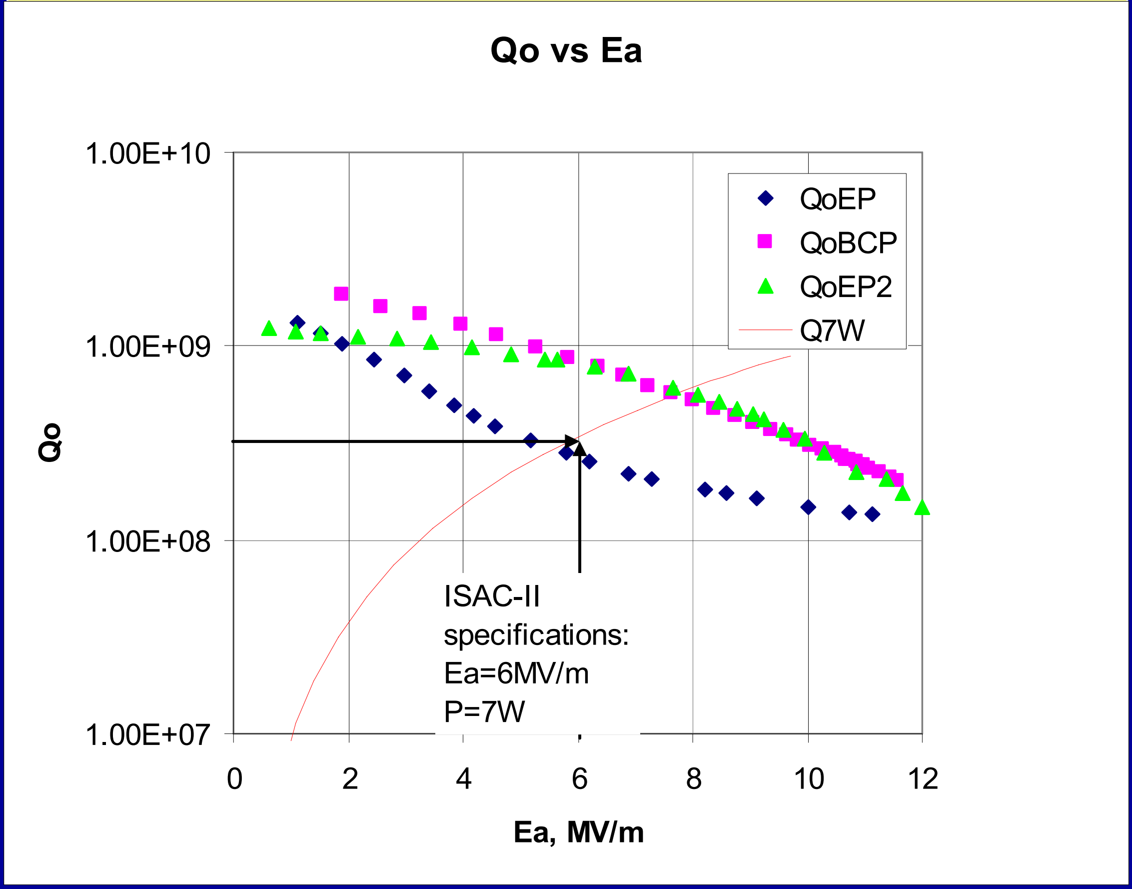
After EP



Cavity 11- BCP 130μm, EP ~65-150μm

-Yields lower Qo but less Q-slope and slightly higher Q at high gradient

- Early measurement shows effects of Q-disease



* K. Shepard, M. Kelly, M. Kedzie

Challenge5 - Technology

•Most projects choose bulk niobium as the technology for cavity fabrication

- •Fabrication of complicated shapes relatively straightforward
- •Technical performance superior – better Q

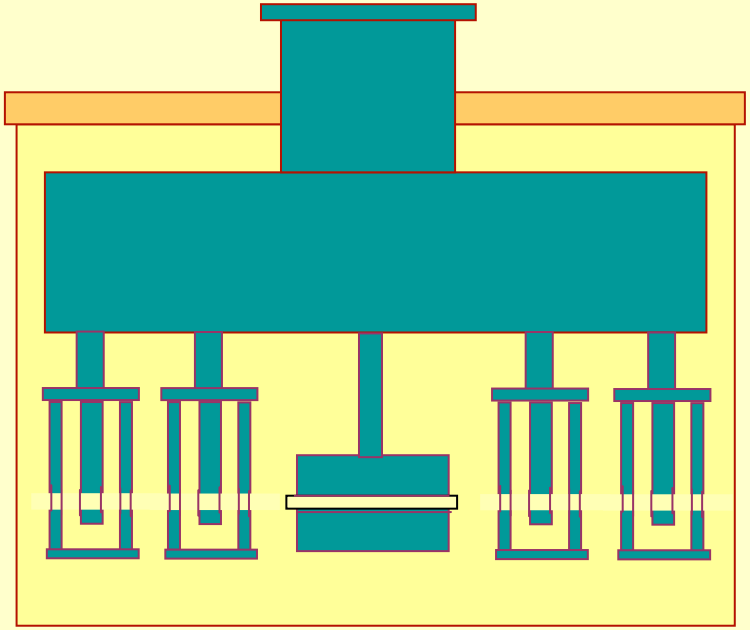
•Some projects have opted for sputtered niobium on copper

- •INFN-LNL replated ALPI cavities originally lead plated and achieved significant performance gains
- •CERN – REX ISOLDE is choosing to resurrect sputtering expertise to sputter quarter waves for ion acceleration
    - •copper substrate less sensitive to helium pressure fluctuations makes tuning less demanding
- •CIAE Beijing – booster linac with QWR

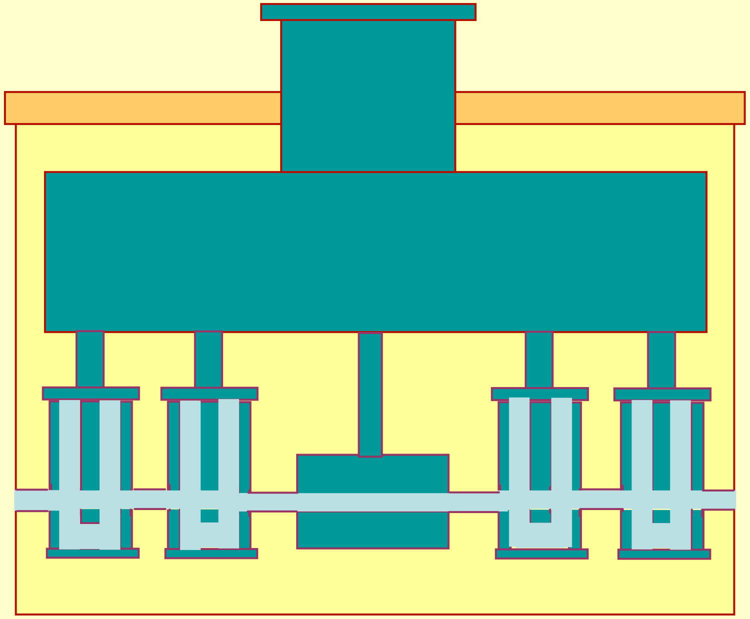
Sputtering chamber

Single Vacuum vs Double Vacuum

- Cavity vacuum and thermal isolation vacuum share the same space
- Engineering easier but thermal vacuum must be done carefully (particulate control)
- ISAC-II, ATLAS, Legnaro, JAERI

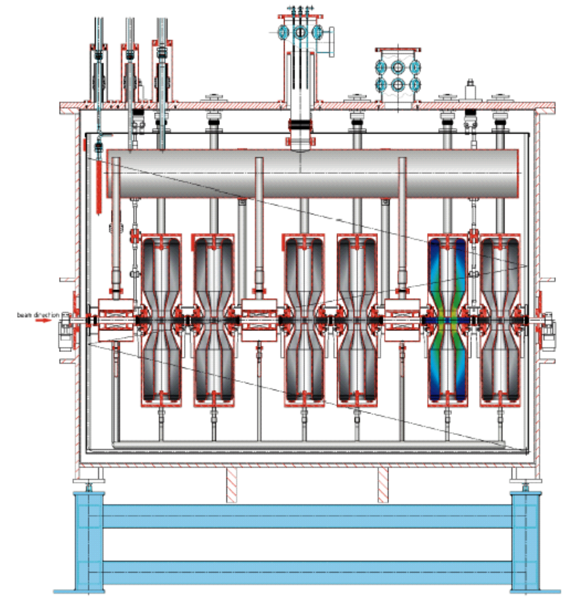


- Cavity vacuum connected through beam pipe and isolated from thermal vacuum
- Engineering more complex but eases cleanliness requirements in thermal vacuum space
- RIA, SPIRAL-II, SOREQ



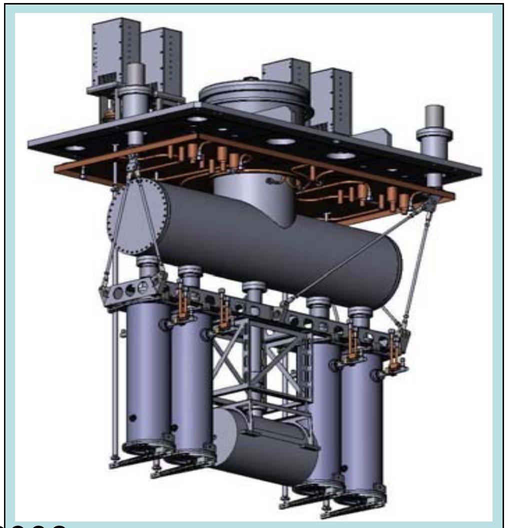
PS1 tests separate vacuum - Saraf

	Vertical Test		Horizontal test	
Cavity	Pcav@25MV/m	Q	Pcav@25MV/m	Q
HWR1	7.3	6e8	6.3	7e8
HWR2	7.3	6e8	31.4	1.4e8
HWR3	6.3	7e8	22	2e8
HWR4	6.3	7e8	22	2e8
HWR5	5.5	8e8	11	4e8
HWR6	7.3	6e8	14.7	3e8



ISAC-II tests – common vacuum- TRIUMF

- Average peak surface field in vertical tests was 38MV/m at 7W
- Average peak surface field in on-line tests (with beam) was 35MV/m at 7W
- Little reduction in performance over the first two years of operation

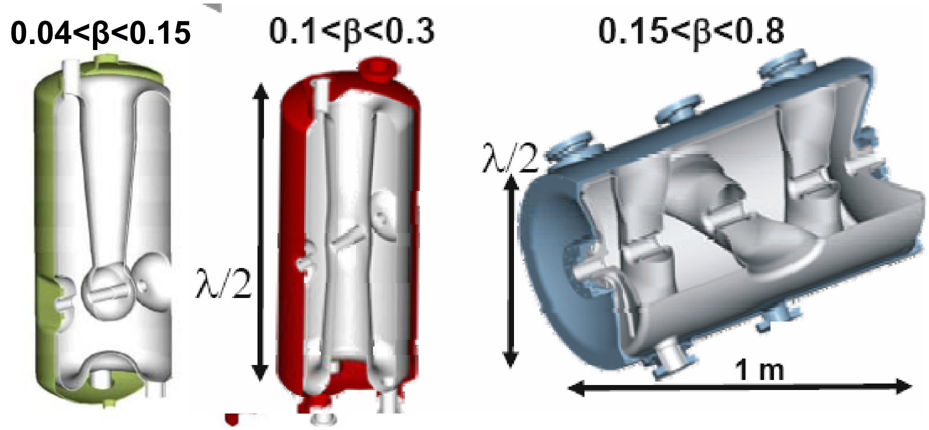


Challenge 6: RF Ancillaries

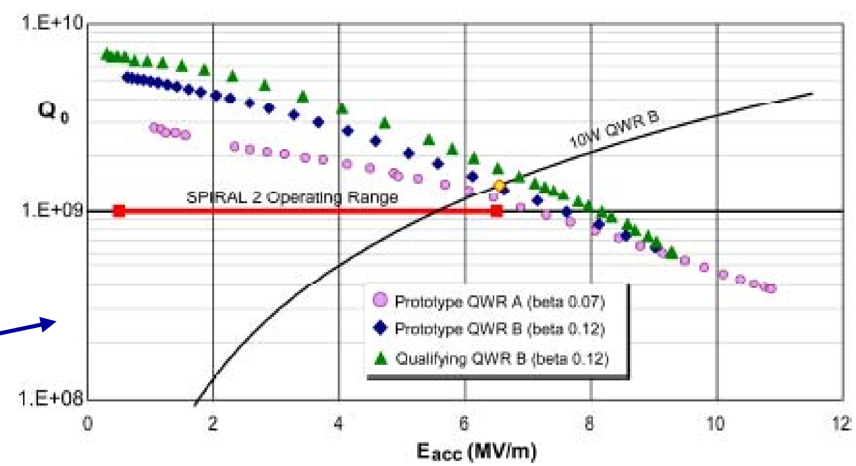
- Want to supply sufficient rf bandwidth to maintain lock
  - Reduce required bandwidth by
    - controlling microphonics passively
    - Specifying a tuner sufficient to compensate for environmental de-tuning effects like helium pressure and vibrations
- Coupling loop must be sized to accommodate expected rf beam loading and forward power with acceptable heat load to helium
- Tuners
  - many designs, very little commonality, from actuating a tuning plate, to squeezing at the beam ports to introducing a plunger into the high magnetic field
- Loops
  - Variable vs fixed, LN2 cooled or helium, many designs
- More from Amit Roy this afternoon

Conclusions: New Trends and Developments

- Optimized shapes – formed parts
    - SPIRAL-II, ANL, MSU
- Closed geometries with rinsing ports
- Separated vacuum systems
    - Requires new engineering
- Improved surface preparation
    - Clean room assembly and HPWR are now standard
    - Most BCP; some EP with light BCP on cavity completion
- Improved tuners – bandwidth control
- Issues
    - Q-slope at 4K
    - for cw applications want higher Q at operating point



QWR HWR Multi-Spoke



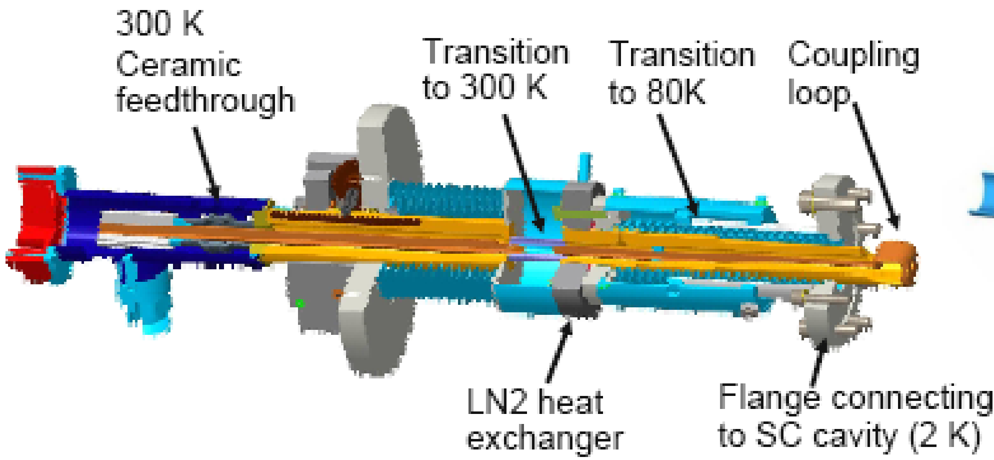
Conclusion

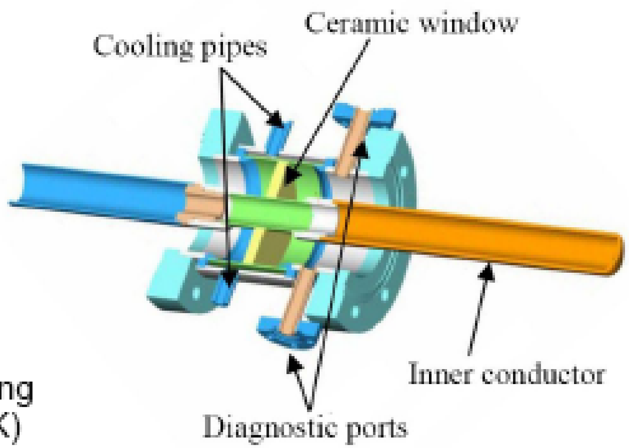
- Low to medium beta cavity field is very active with several new projects in building stage
- A renaissance in R+D over the last several years, prompted by work at high beta, has seen performance improve
  - new cavity types now regarded as `standard' building blocks for the projects of the future
- Community must work together to achieve controlled progress where improved performance is understood and repeatable

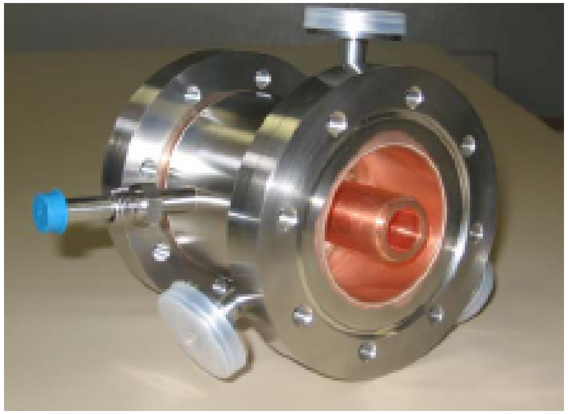
Thanks!

Couplers

V. Ancillary components: Couplers





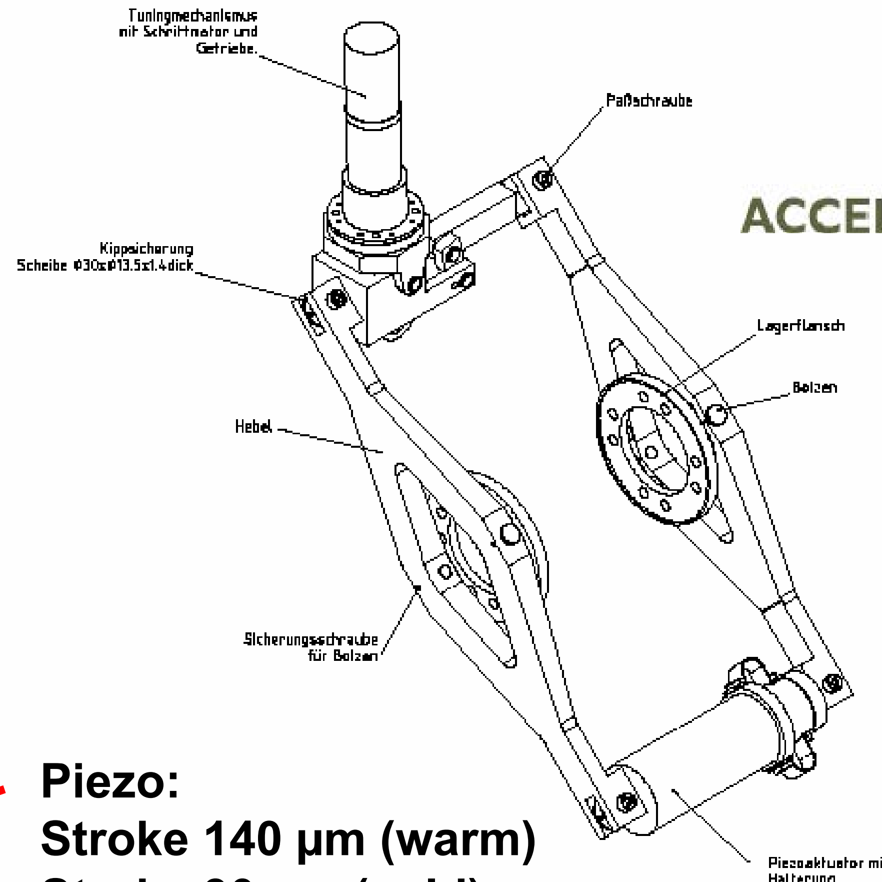


- cw inductive power coupler – ANL
- Fully variable over 50 dB

- cw capacitive power coupler (window) – IPN Orsay

Tuners

Mechanical: Warm & Cold
Sensitivity: 0.2 Hz/step



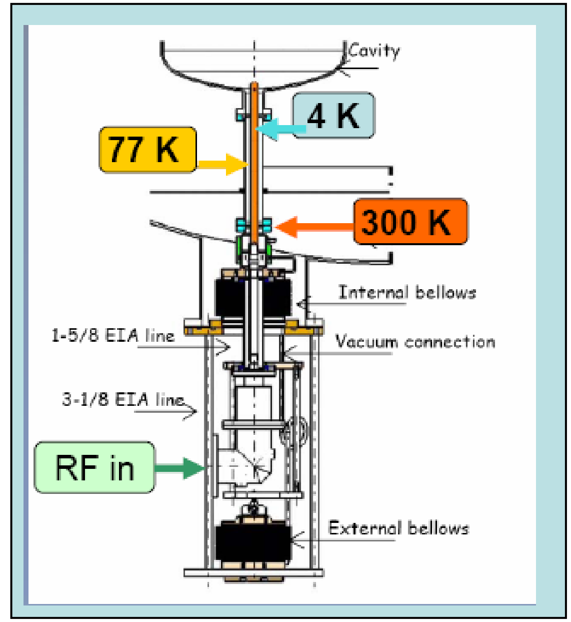
Piezo:
Stroke 140 μm (warm)
Stroke 30 μm (cold)
Usable stroke (+/-3 μm)
-> +/- 450 Hz tuning range

SARAF - Israel

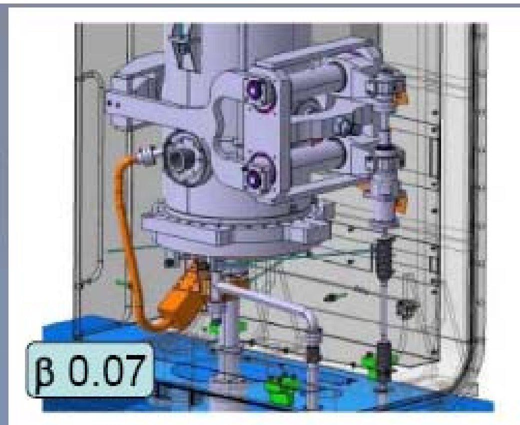
M. Pekeler
SRF 2003

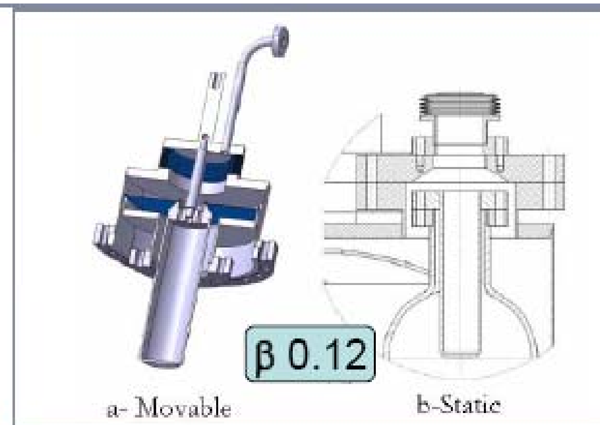
Spiral-II Ancillaries

- Both cryomodules use separate vacuum system
- Tuning by squeezing at the beam ports in cavity A and unique cold plunger in high B-field region in cavity B
- 10kW cw Power coupler with thermal staging; inserted from bottom of cryomodule



QWR Tuning





- **β 0.07 : mechanical tuner, QWR body deformation**
- **β 0.12 : plungers on QWR top volume (fixed and movable)**