Low and Medium-β Superconducting Cavities

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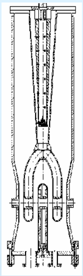
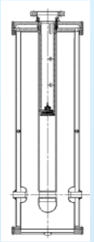
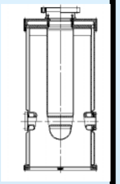
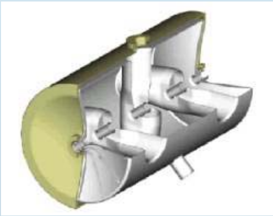
INFN-LNL

Definition

low-, medium- and high-β: **Just cavities with β<1…**

The definition, however, changes according to the community

(Approximate) definition	low β	medium β	high β
Heavy ion boosters	<0.06 	0.06 ÷0.12 	>0.12 
Proton linacs Heavy ion drivers	<0.2 	0.2÷0.8 	>0.8 

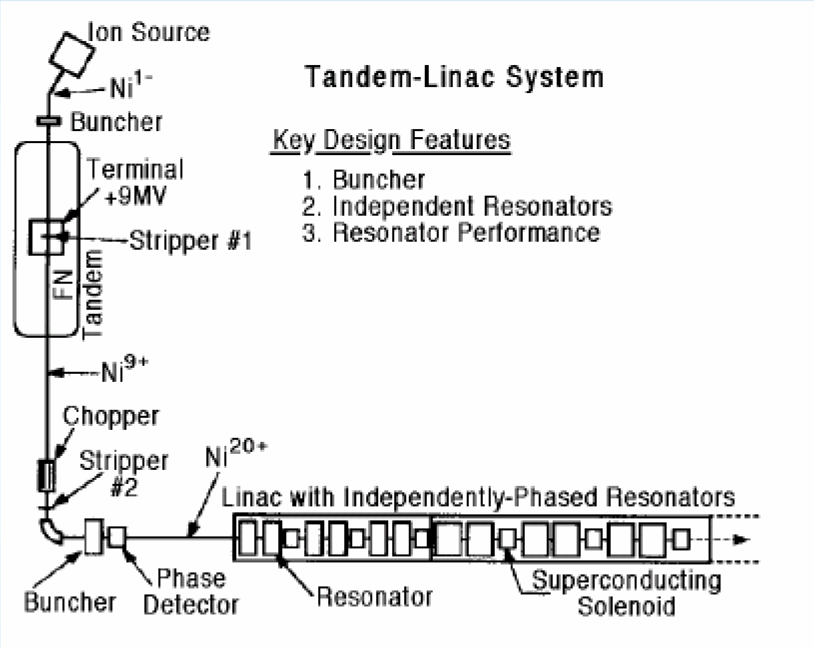
Low-β SC cavities peculiarities

- Low frequency
  - Large size
  - complicated geometries
  - High peak fields E_p, B_p
- Many different shapes
  - many different EM modes
- Short cavities
  - Many independent cavities in a linac (ISCL)
- Only a few accelerating gaps
  - Large velocity acceptance
- Mostly working at 4.2 K

The first low-β SC cavities application: HI boosters for electrostatic accelerators

First and ideal application of SC technology:

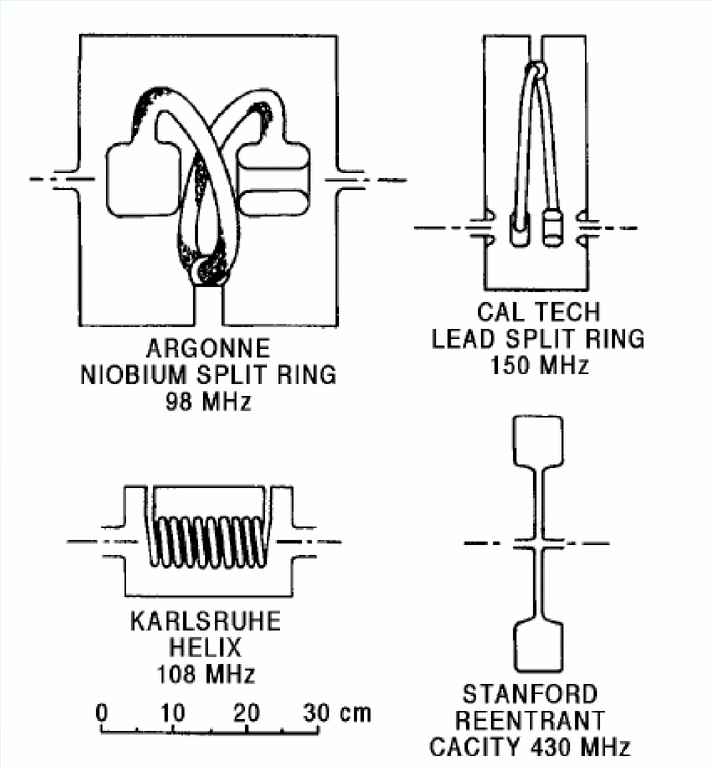
- Low beam current: all rf power in the cavity walls
- 2÷3 gap: wide β acceptance
- High gradient, cw operation
- Hardly achievable with Normal Conducting (NC) cavities



Tandem-booster system

New problems: very narrow rf bandwidth, mechanical instabilities

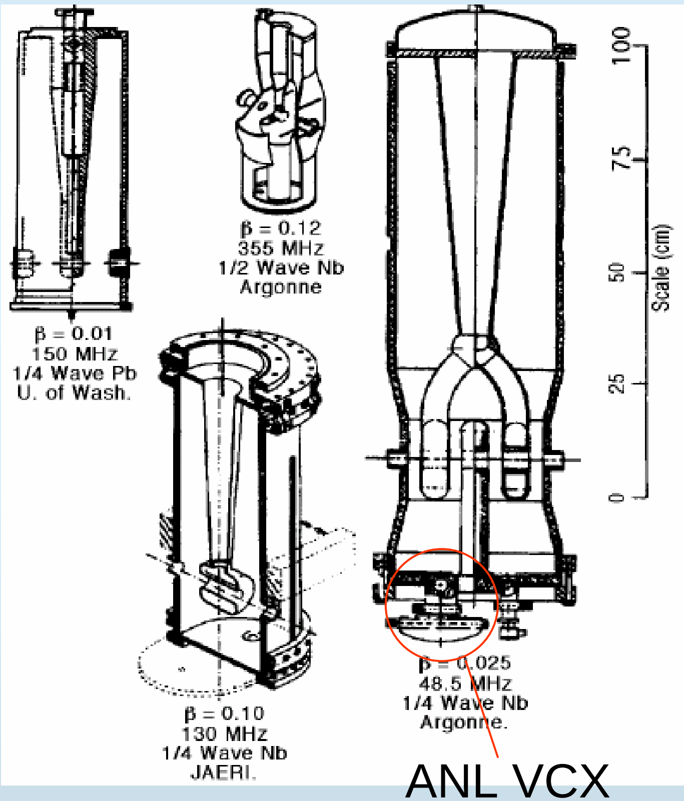
Early resonators: 70's



Low-β cavities in operation from the 70's

- Tandem boosters for light ions **β~0.1**
- Materials:
  - **Bulk Nb**
  - **Pb plated Cu**
- E_a typically **2 MV/m**
- Mechanical stability problems solved by the **first electronic fast tuners** for Helix resonators

SC low-β resonators : 80's

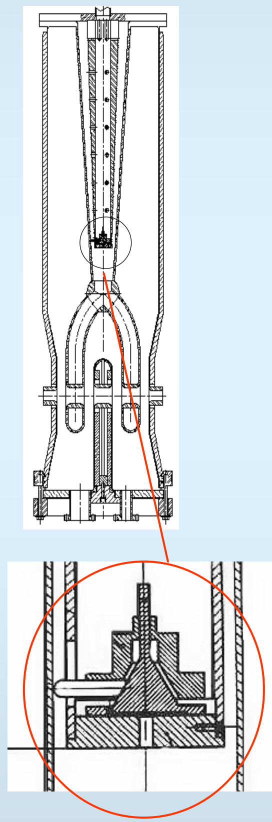


Low-β cavities in operation from the 80's

- At ANL Tandem replaced by the first low-β SC Positive Ion Injector, **β~0.001 ÷0.2**
- Heavy ions up to U
- New materials:
    - **Explosive bonded Nb on Cu**
- Mechanical stability problems solved by electronic fast tuners VCX at ANL
- E_a typically 3 MV/m; first operation above **4 MV/m**

HI SC low-β resonators: 90's

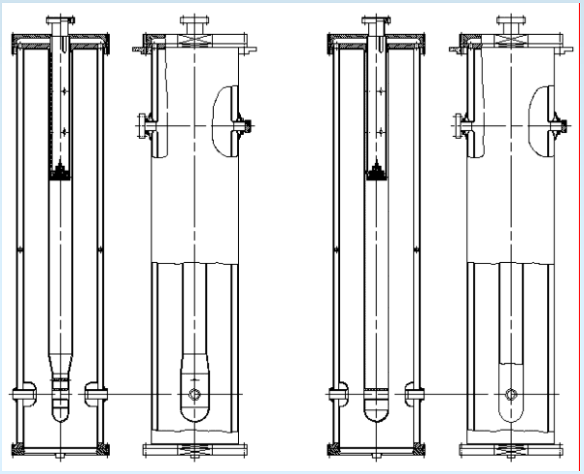
Low-β cavities
from the 90's



LNL damper

- **β~0.001 ÷0.2**
- New materials:
  - **Sputtered Nb on Cu**
- Linac project with SC RFQs starts at LNL
- Mechanical stability problems solved also by mechanical damping
- E_a typically 3 ÷4 MV/m; first operation at **6 MV/m**

Present QWR performance example: LNL bulk Nb, 80 MHz double wall



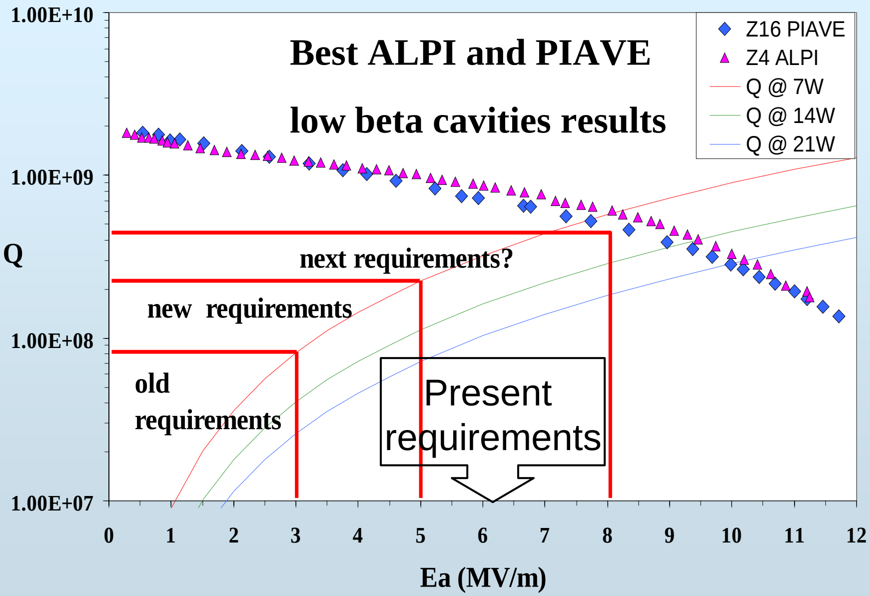
PIAVEβ=0.047 and ALPI β=0.055

Maximum fields:

- E_a=11.7 MV/m
- E_p= 57 MV/m
- B_p=120 mT

LNL 80 MHz, β=0.055 cryostat

LNL PIAVE 80 MHz, β =0.047 QWR



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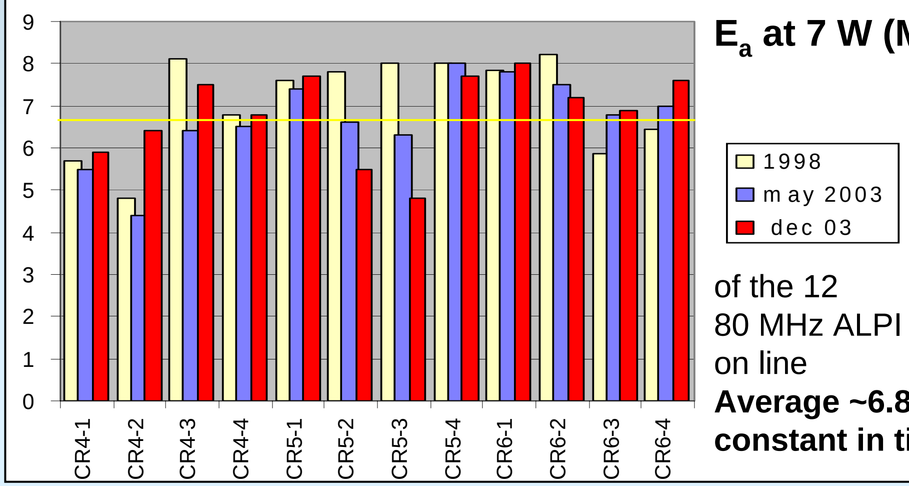
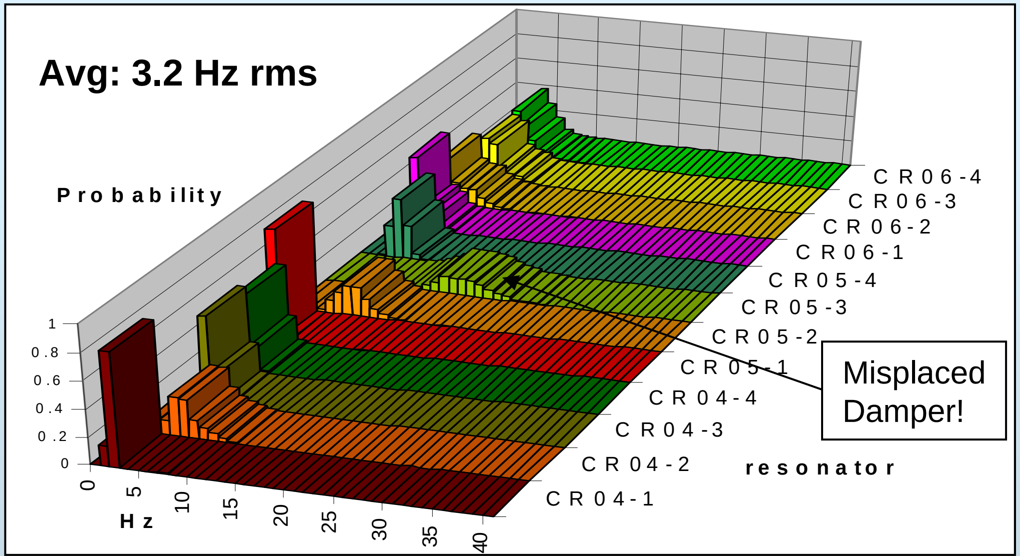
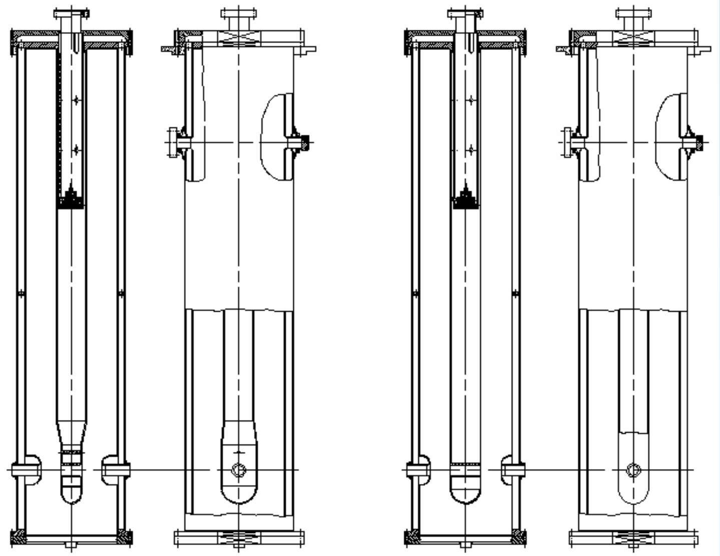
On-line resonators test



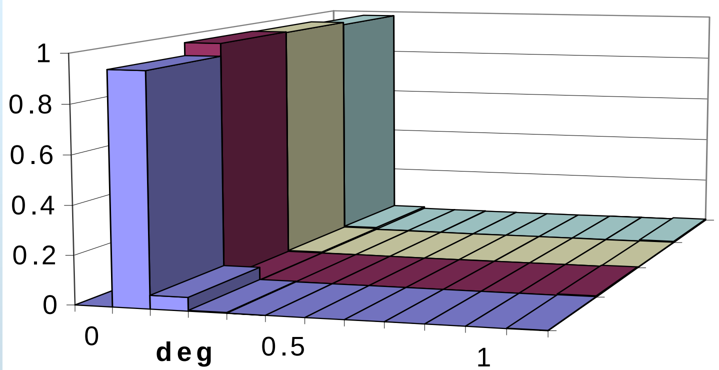
of the 12
80 MHz ALPI QWRs
on line
Average ~6.8 MV/m
constant in time



Distributions of the frequency oscillation amplitudes in a 24 hour record for all low beta cavities in ALPI.



PIAVE β=0.047 and ALPI β=0.055 80 MHz bulk niobium QWRs



Phase error distribution recorded for 24 hours in the 4 QWRs of the PIAVE cryostat n. 1, at 5 MV/m with $f_{1/2}$~3.5Hz

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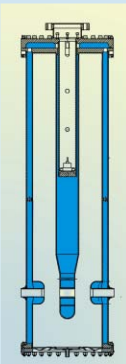
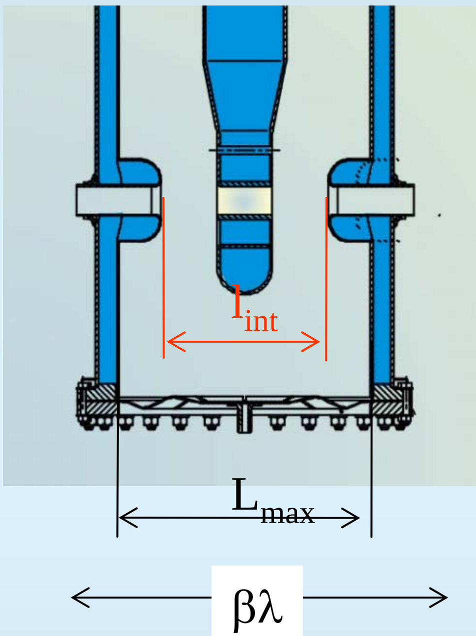
What do we learn from HI boosters?

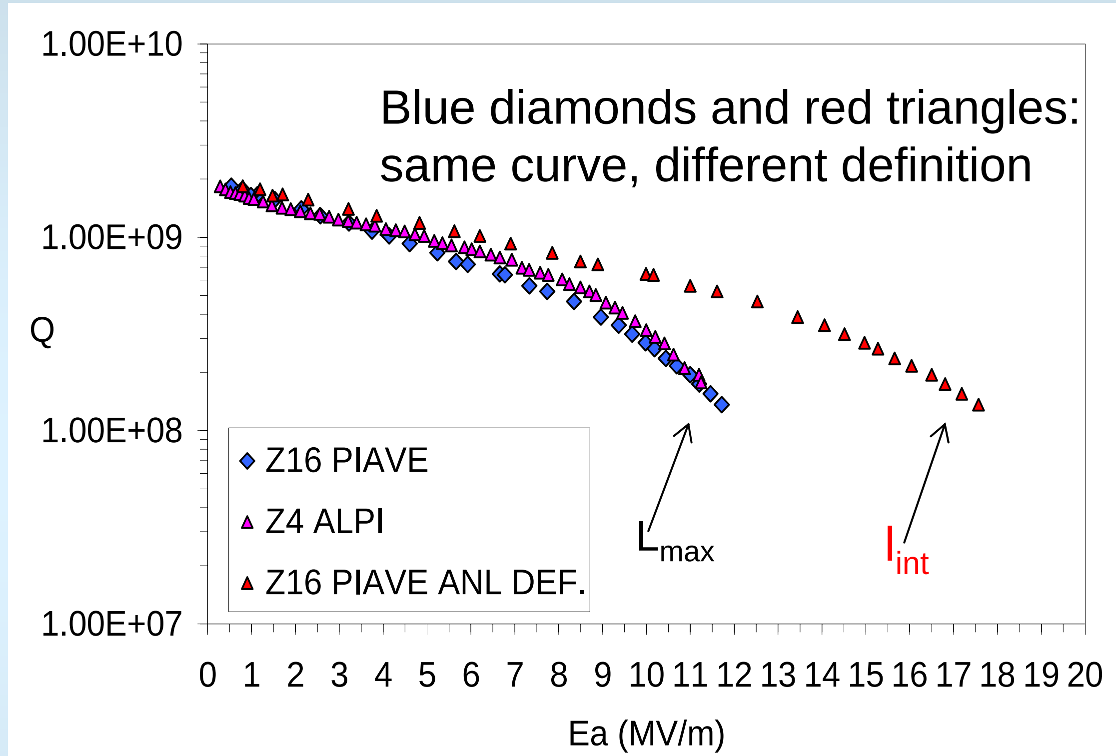
All SC low-β cavities presently in operation still belong to the low current, HI linacs category!

- QWRs are a good choice when possible
- **E_a > 6 MV/m** achievable in operation
- Max **E_p ~ 60 MV/m**
- Max **H_p ~ 120 mT**
- Very reliable machines are possible (ANL linac ~6000 h/y beam on target)
- Mechanical vibrations can be handled

Remark: different definitions of gradient in different labs







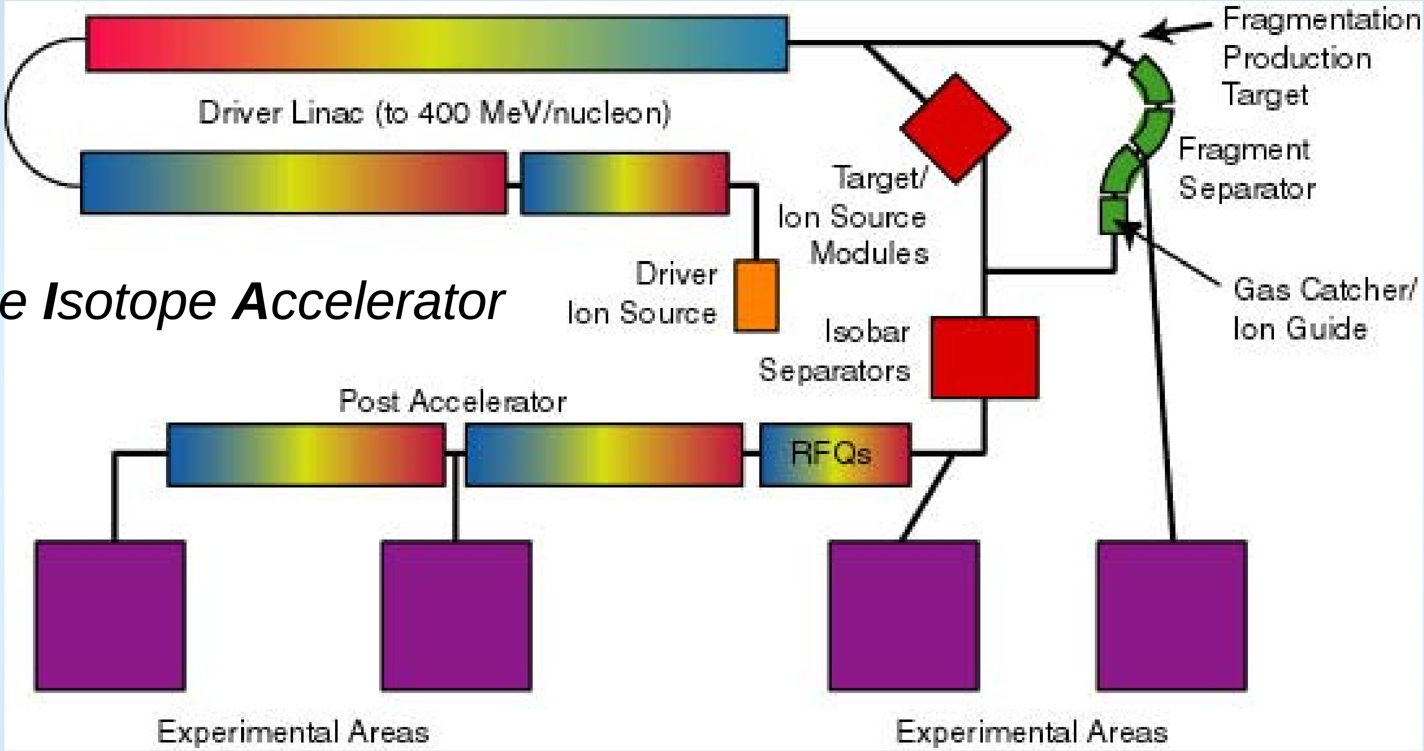
- E_a: Energy gain per unit charge at optimum β_0, divided by the effective length L
- L can be: l_{int} , L_{max} or even βλ (see figure)
- E_a defined with l_{int} give larger values than E_a defined with L_{max}
- This discrepancies do not affect the energy gain definition, which is the same

SC linacs : new trends

Low-β cavities: new applications

Type	β_{max}	A/q	current
Post-accelerators for RIB facilities	~ 0.2 (0.5)	7÷ 66	< 1 nA
HI drivers for RIB facilities	~ 0.3÷0.9	~ 1 ÷ 10	~0.1÷10 mA
***p*,*d* linacs**	~ 0.3	1 ÷ 2	~1÷10 mA
High Power Proton Accelerators	~ 0.9	1	~10÷100 mA
High Power Deuteron Accelerators for material irradiation	~ 0.3	2	~100 mA

Radioactive Ion Beam Facilities

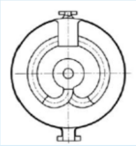


***R**are **I**sotope **A**ccelerator*

•Driver: from p tu U, I~500 μA
•Post-accelerator: variable A/q, I<< 1 nA
•Evolution of HI boosters

Moving to higher β and I

HI cavities
- $\beta \leq 0.3$
- Low current (~μA)
- Short cavities

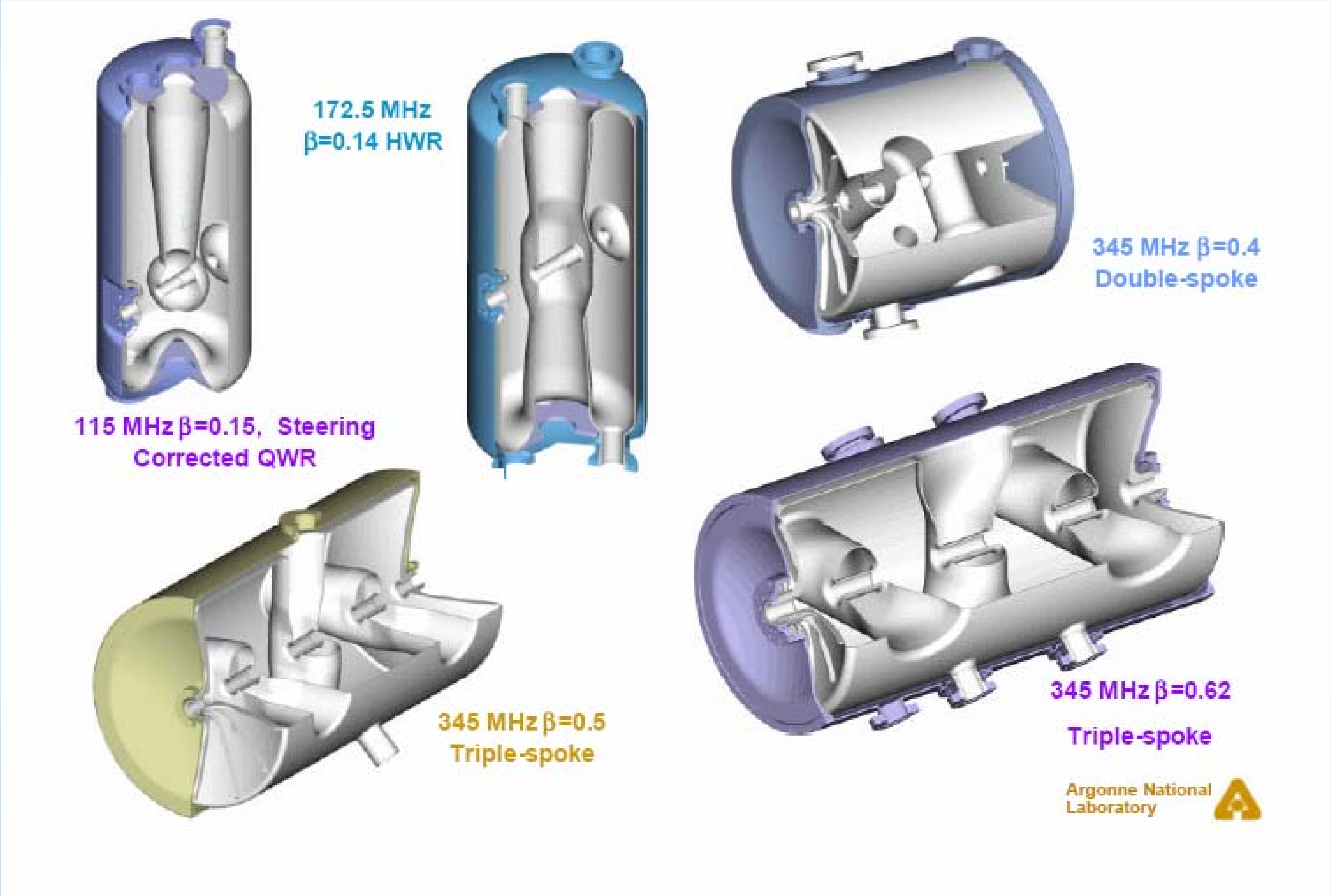


Low-intermediate β
- β=0.1÷0.5
- ⇧ High current, mA
- Short cavities

Electron cavities
- β=1
- High current (~mA)
- Long cavities

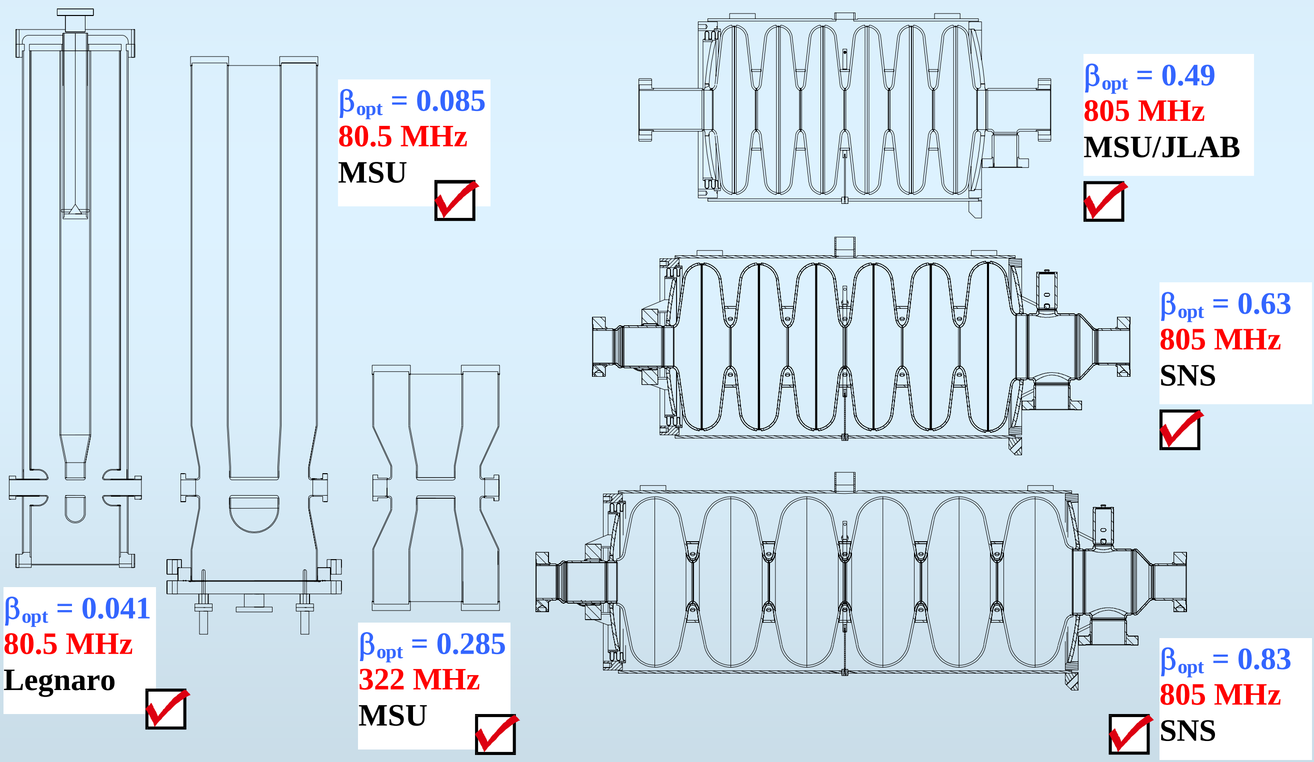
High-β
- ⇩ β=0.5÷0.9
- High current, mA
- Long cavities

RIA cavities development at ANL



RIA cavities development at MSU

- Alternative design of the RIA driver based on 80.5 MHz
- Most of the cavities are ready



Courtesy of T. Grimm, MSU

Heavy Ion and Proton linacs

• Low- and intermediate-β SC cavities for Proton linacs are very similar to the ones for Heavy Ions

• The main differences are at β <0.3:

- Higher frequency at low beta (from 350 MHz RFQs)
- larger rf power couplers, rf ports and beam aperture (from higher beam current)

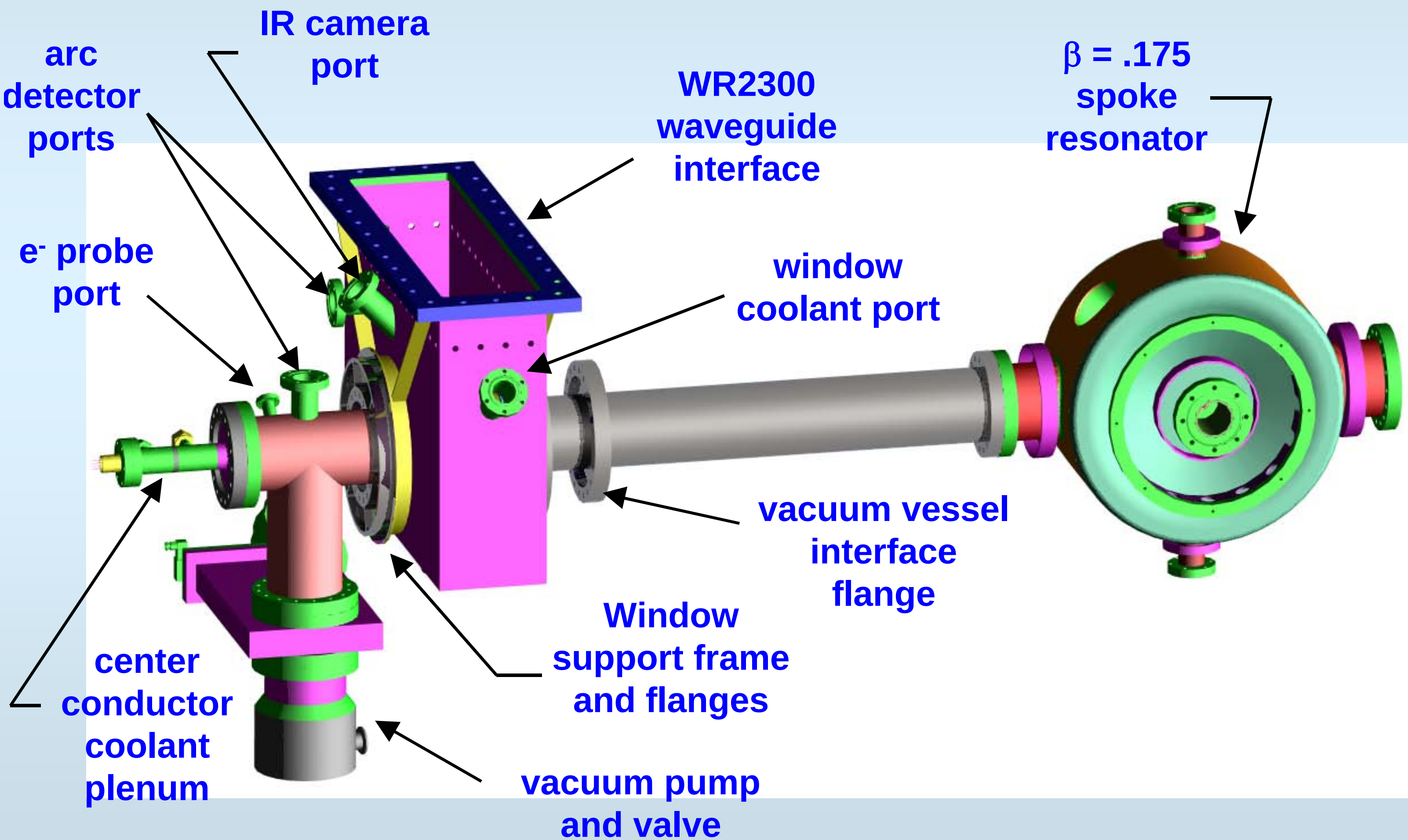
Example: β=0.1

10 mA protons $\Rightarrow$ 350 MHz cavity (reentrant, spoke, HW…)

10 μA heavy ions $\Rightarrow$ 100 MHz QWR

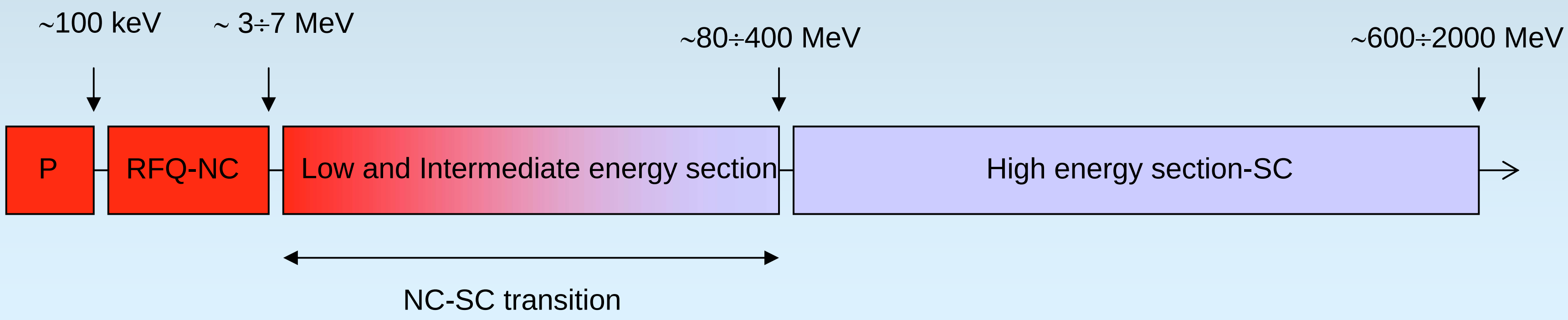
LANL

LANL β=0.175 SC spoke resonator for high power proton beams



103-mm (OD) power coupler designed for up to 100 mA beam (212 kW)

High Intensity Superconducting Proton Linacs



- Many applications
  - RIB drivers, ADS systems, spallation neutron sources, …
- Consolidated scheme
  - a proton (H^+,H^-) injector and a ~350 MHz, NC RFQ
  - a SC high energy linac with multicell, elliptical cavities
  - A low and intermediate energy linac, either NC (DTL, CCL), SC (low-β elliptical, spoke, half wave coaxial, reentrant…) or both
- Problem: where do we change from NC to SC?

Where do we change from NC to SC?

No unique answer, many points to consider:

Beam A/q

NC: fixed velocity profile

SC: ISCL (Independently-phased SC Cavity Linac) with large velocity acceptance

Pulsed vs. CW

NC E_a limited by water cooling: better pulsed

SC are very sensitive to Lorentz force detuning: better cw

Beam current

High current → high beam loading → NC high rf losses negligible

Low current → low beam loading → SC efficiency is important

Reliability issues

NC large cavities → no fault tolerance

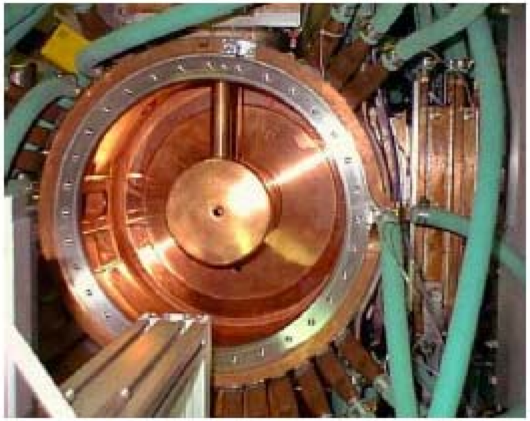
SC short cavities → some fault tolerance is possible

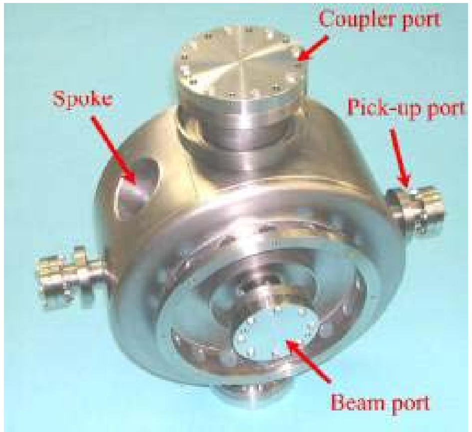
Construction and operation cost

From EURISOL studies, 5 mA 5-100 MeV NC and SC proton linacs have comparable construction cost, while SC is cheaper in operation

Where do we change from NC to SC?

- In **low power heavy ion accelerators**: **as soon as possible**
- In **high power proton accelerators** the real estate gradient at $\beta<0.3$ can hardly exceed 1 MV/m for beam dynamics constraints: NC solutions can be competitive even in cw mode



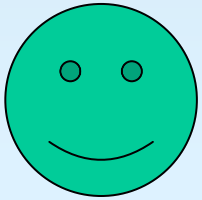


- IPHI: NC
  - 5-11 MeV, 100 mA *p* DTL
  - 352 MHz cw
  - E_a~ 0.8 MV/m r.e.
- SC ADS Driver (LANL):
  - 6.7- 43 MeV, 20 mA *p* linac
  - 352 MHz cw
  - E_a ~ 0.4 MV/m r.e.

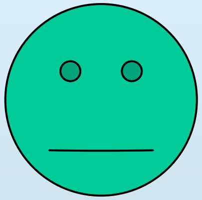
Low- and intermediate-β Resonator geometries and characteristics

Superconducting RFQ's

80 MHz, $0.001 \leq \beta_0 \leq 0.035$



- Compact
- CW operation
- High efficiency
- Down to very low beta



- Mechanical stability (fast tuners required)
- Low beam current only
- Difficult to build
- Expensive

LNL SRFQ2, A/q=8.5

SRFQs in the PIAVE Injector at INFN-LNL

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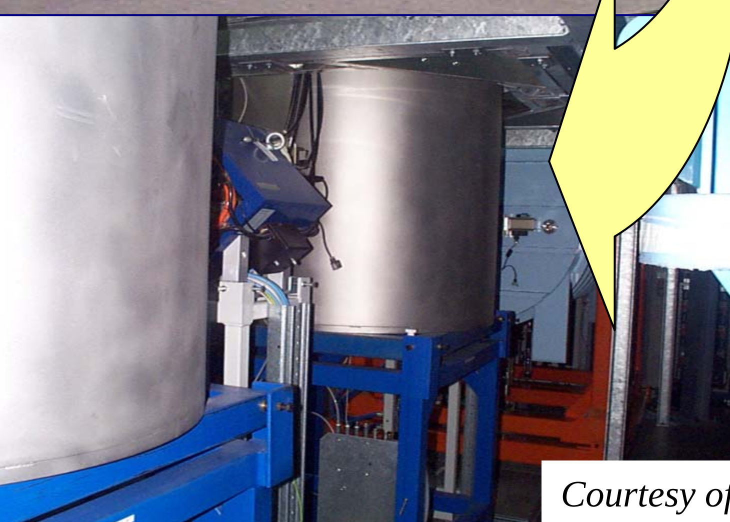
Two superconducting RFQs in one cryostat

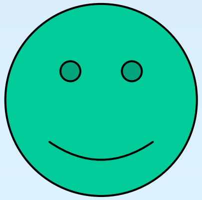


- Installation is complete
- Beam transport to the RFQs OK
- Alignment checked to be within ± 0.2 mm on the beam axis
- Q values and $E_{s,p}$ exceeding specs ($>3x10^8$ and > 25 MV/m)
- Stiff vs. mechanical noise: locking with VCX was proven to work, providing a bandwidth of 80 & 200 Hz on SRFQ1 and SRFQ2
- Slow P changes of the refrigerator (TCF50) can be controlled, to a level where the slow f-tuners can follow (~ 20 mbar/min)
- Beam acceleration through SRFQs: planned for October 2004

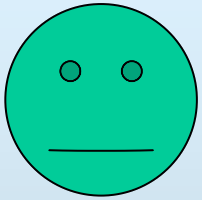
Courtesy of G. Bisoffi, INFN-LNL

Quarter-Wave resonators

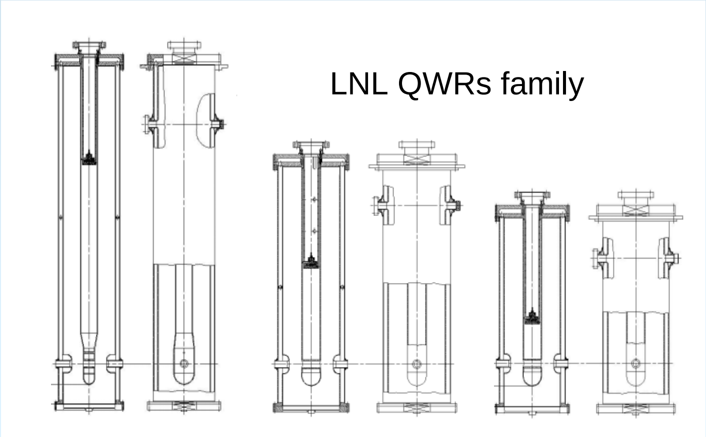
$48 \leq f \leq 160$ MHz, $0.001 \leq \beta_0 \leq 0.2$

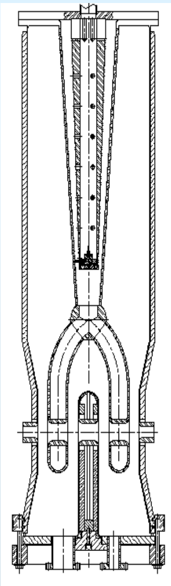


- Compact
- Modular
- High performance
- Low cost
- Easy access
- Down to very low beta

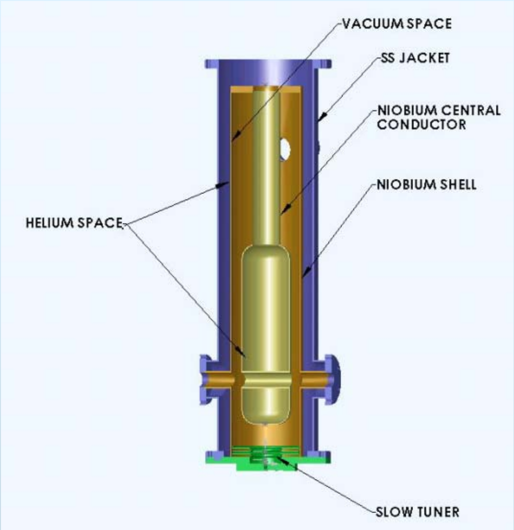


- Dipole steering above ~100 MHz
- Mechanical stability below ~100 MHz
- (Quadrupole steering: could give problems with solenoids)



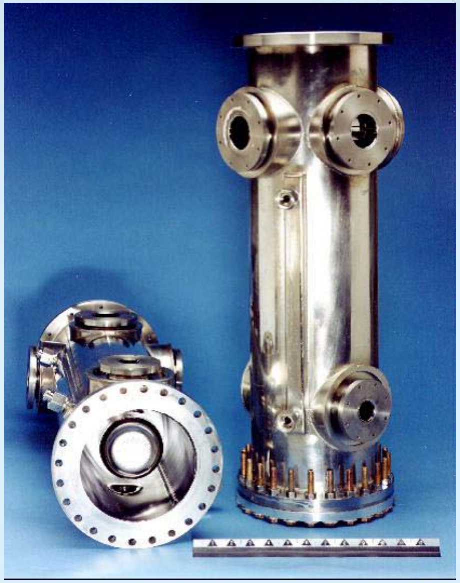


ANL 48.5 MHz, β =0.0016 QWR

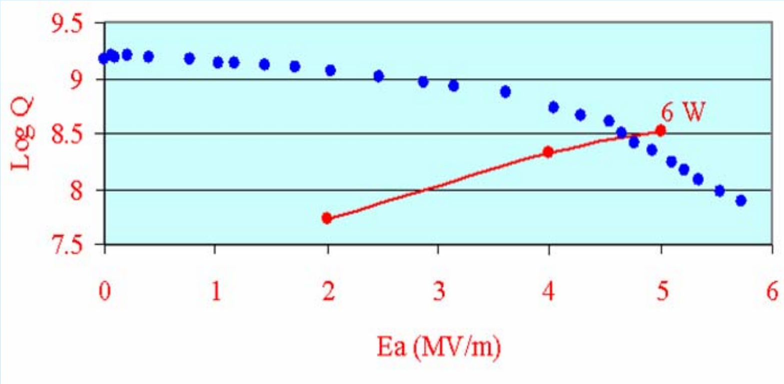


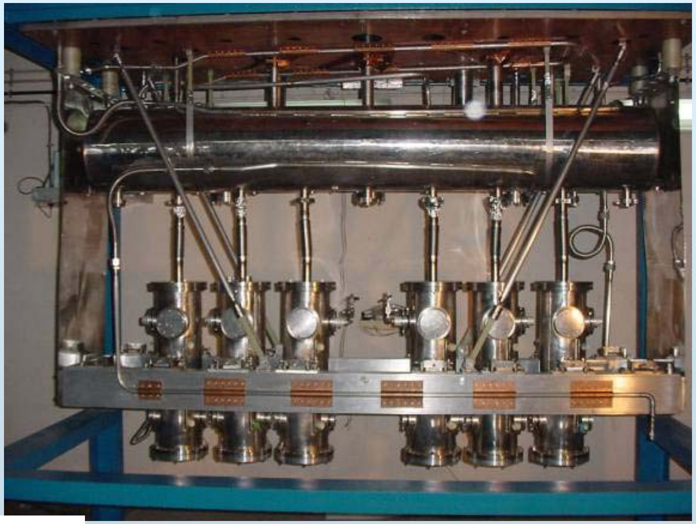
NSCL 97 MHz, β =0.08 QWR

Superconducting QWRs development at Nuclear Science Centre



- Required 26, β=0.08, 97 MHz QWRs
- 8 built in collaboration with ANL
- The rest is being built in house. A facility for Nb resonators production has been set up, with:
    - Eb welding
    - EP
    - HPR
    - High vacuum baking at 1200 °C



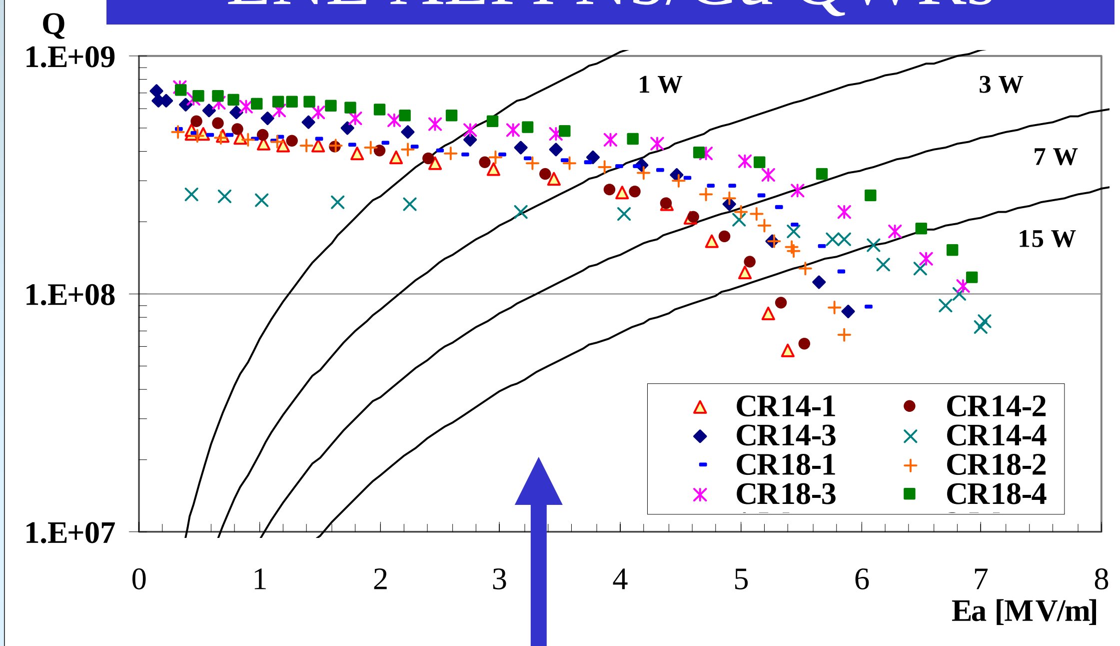


Courtesy of S. Ghosh, NSCL

INFN Legnaro

Poster TUPKF024

LNL ALPI Nb/Cu QWRs



Q-curves of QWRs installed in 2003

- 46, β= 0.11 and 8, β= 0.13, 160 MHz QWRs routinely used for beam acceleration
- Average operational Ea > 4.4 MV/m @ 7W, in spite of being produced using the recovered substrates of the previously installed Pb/Cu resonators
- Some of them are reliably locked up to 6.5-7.3 MV/m without necessity of fast or "soft" tuners and/or strong overcoupling. Frequency not affected by changes in the He bath pressure (Δf <O.01 Hz/mbar!)

Courtesy of A. Porcellato, INFN-LNL

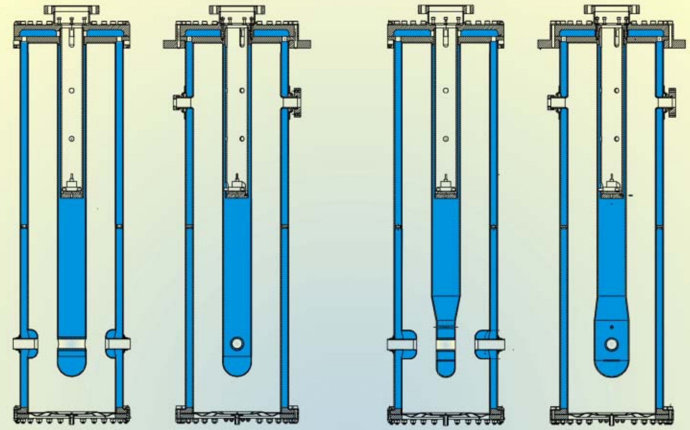
TRIUMF Vancouver

ISAC-II SC QWRs

Section	β_0 (%)	f_{RF} (MHz)	No.	E_a (MV/m)
Low β	4.2	70.7	8	5
Med β	**5.7**	**106**	**8**	**6**
	7.1	**106**	**12**	**6**
High β	10.4	141	20	6

Prototype Cavity

Medium Beta Cavities



(a) Nominal (β=7.1%) (b) Flat (β=5.7%)

freq=106.08MHz

$E_p/E_a \simeq 5$

$H_p/E_a \simeq 100\ G/(MV/m)$

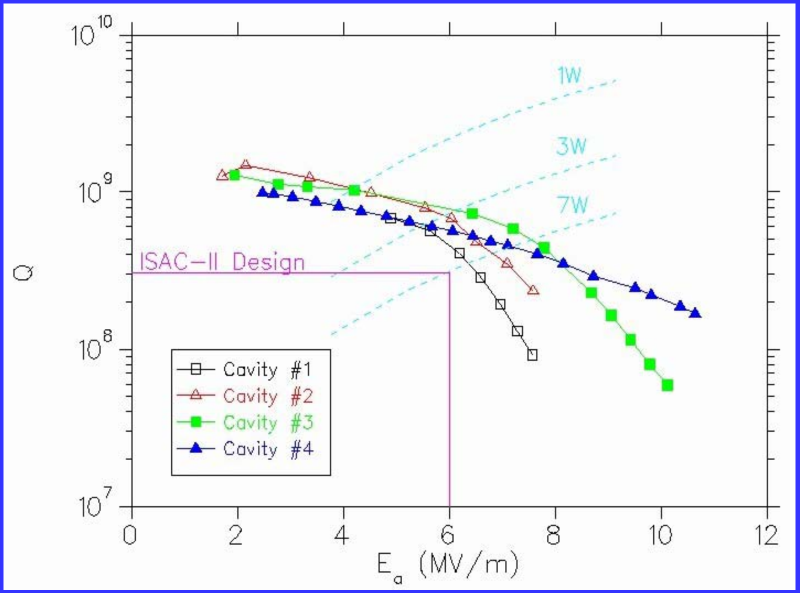
$U/E_a \simeq 0.09 J/(MV/m)^2$

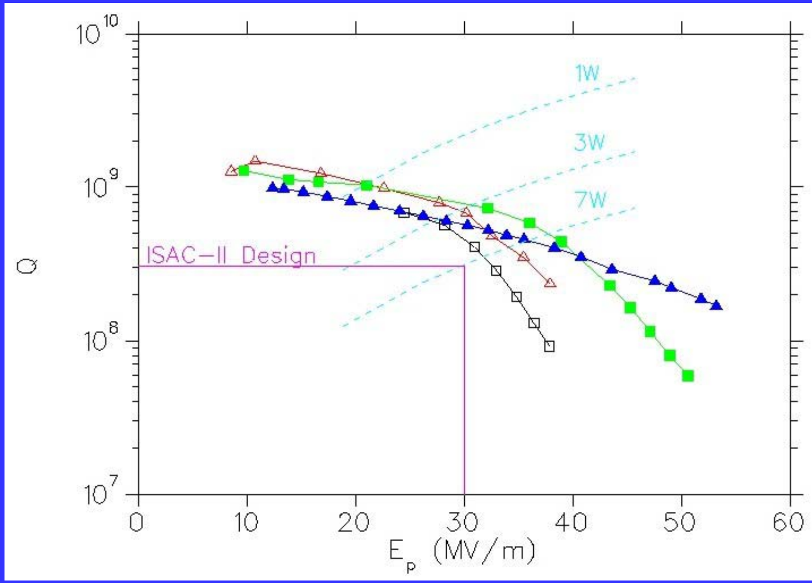
$\Gamma \simeq 19\Omega$

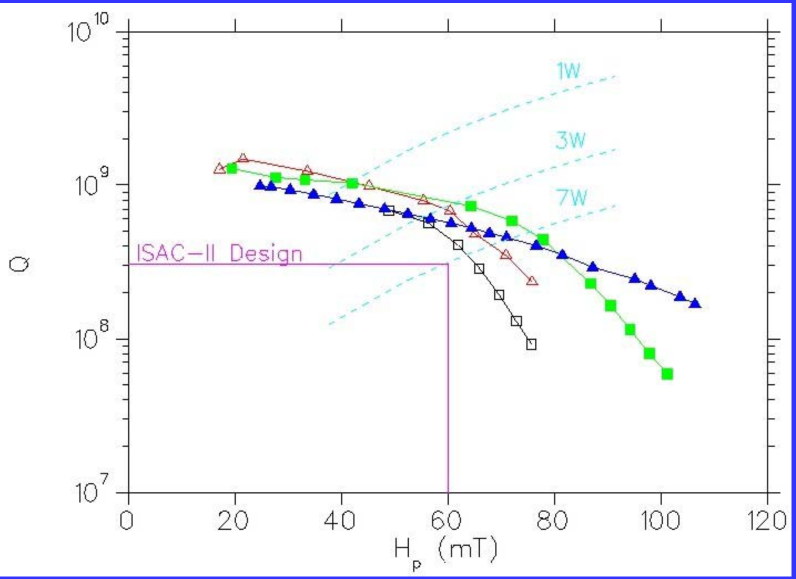
Courtesy of R. Laxdal, TRIUMF

ISAC-II QWRs Performance

- •20+1 resonators produced
- •All cavities tested up to now meet the specifications of **6MV/m @7W**
- •CP at CERN (5 QWRs) and Jlab
- •HPR at TRIUMF

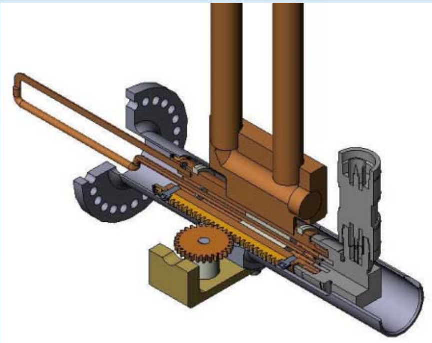






ISAC-II Medium Beta Cryomodule

First Medium beta cryomodule in assembly



LN cooled rf coupler

Mechanical tuner

Provide suitable bandwidth by overcoupling

P_f =200 W at cavity: $f_{1/2}$=20Hz at E_a=6MV/m with β_c=200

Courtesy of Bob Laxdal, TRIUMF

SPIRAL 2 low-β QWRs

SPIRAL2 HI driver

•40 MeV, 5 mA SC linac for A/q=2 and 3

•To be built at GANIL as a RIB driver

•CEA Saclay and IPN Orsay are developing the resonators

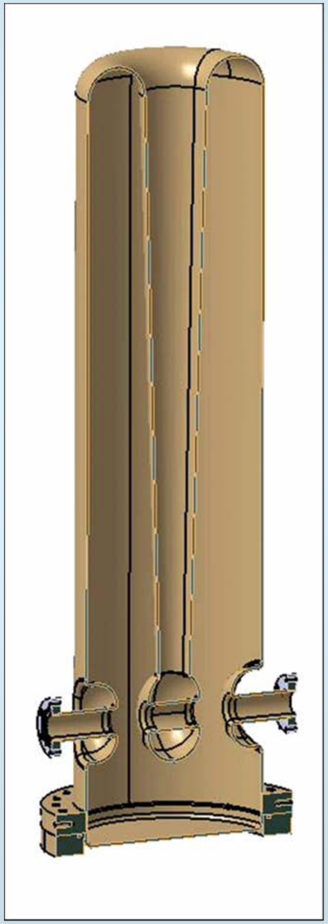
CEA prototype

•Nb QWR - 88 MHz - β=0.07

•Design goals for operation:

- •Eacc = 6.5 MV/m
- •Epeak = 32 MV/m

•Prototype under construction

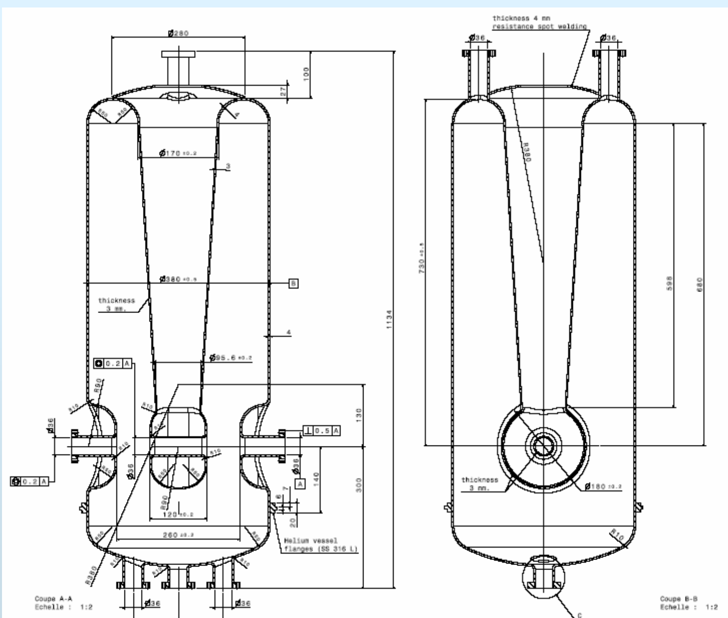


Courtesy of B. Visentin, CEA

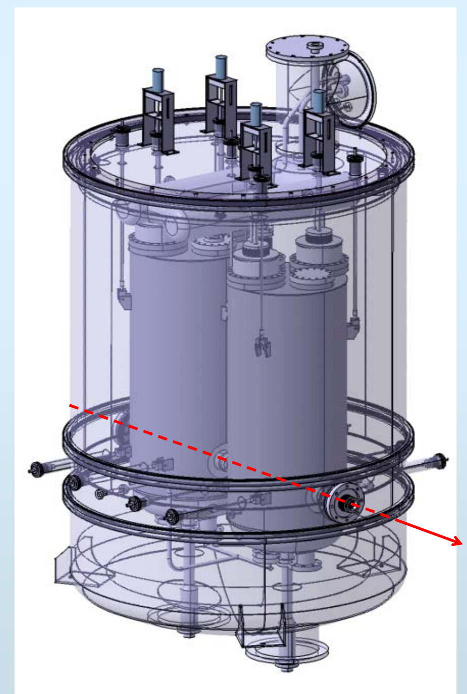
SPIRAL 2 medium-β QWRs

IPN Orsay prototype

- Nb QWR - 88 MHz - β=0.12
- Beam tube aperture: Ø36 mm
- RF coupling by Ø36 mm port
- 6 ports for HPR
- under construction, delivery in October 2004



- Design goals for operation:
  - Eacc = 6.5 MV/m
  - Epeak = 36 MV/m
  - Bpeak = 66 mT
- Design of the cryomodule

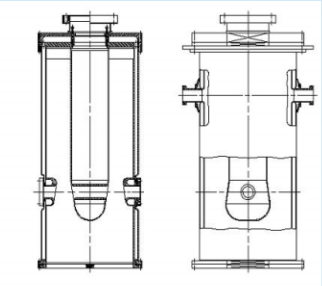


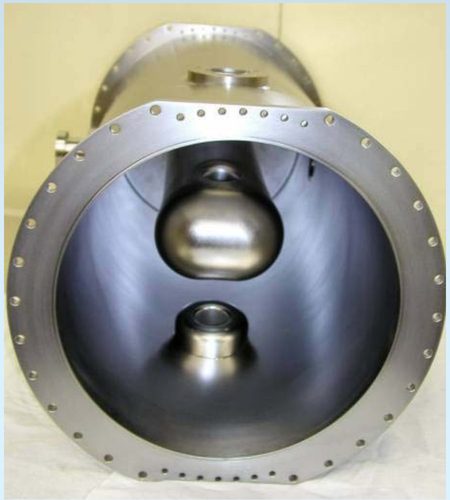
Preliminary design of the β 0.12 cryomodule

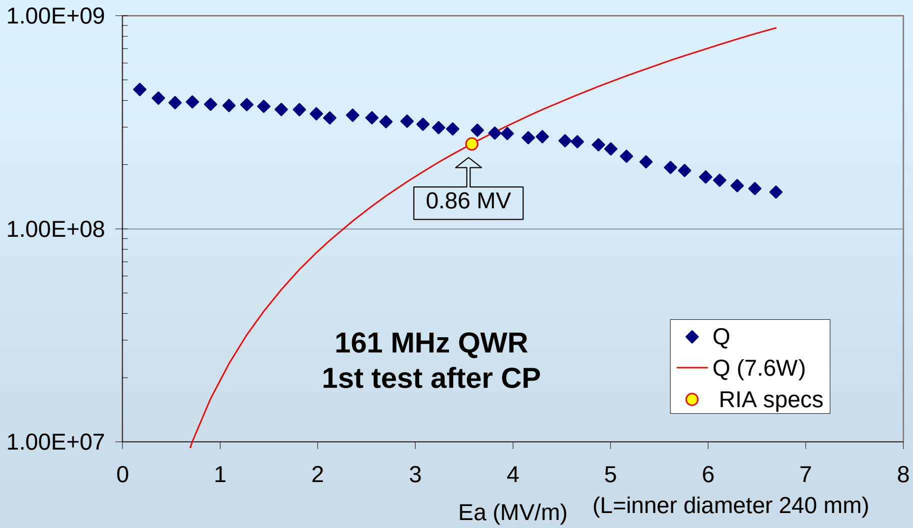
Courtesy of G. Orly, IPNO

MSU- LNL: QWR with steering correction

- 161 MHz, β=0.16
- separate vacuum is possible
- Extendable to different *f* and *β*
- first preliminary test before HPR
- RIA specifications already fulfilled





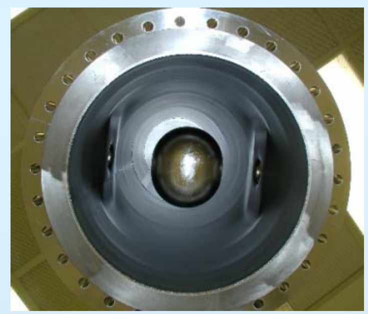


QWRs and HWRs for RIA

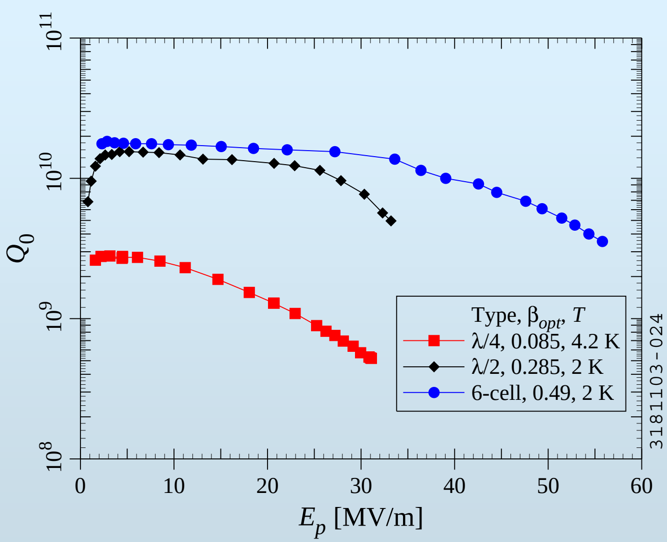
- Prototypes built and tested
- RIA specifications met
- Cryomodule under construction

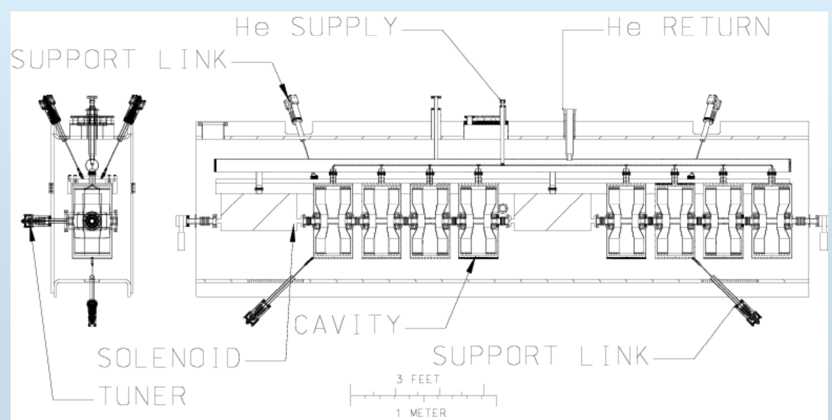
322 MHz
β=0.28

80.5 MHz,β=0.08



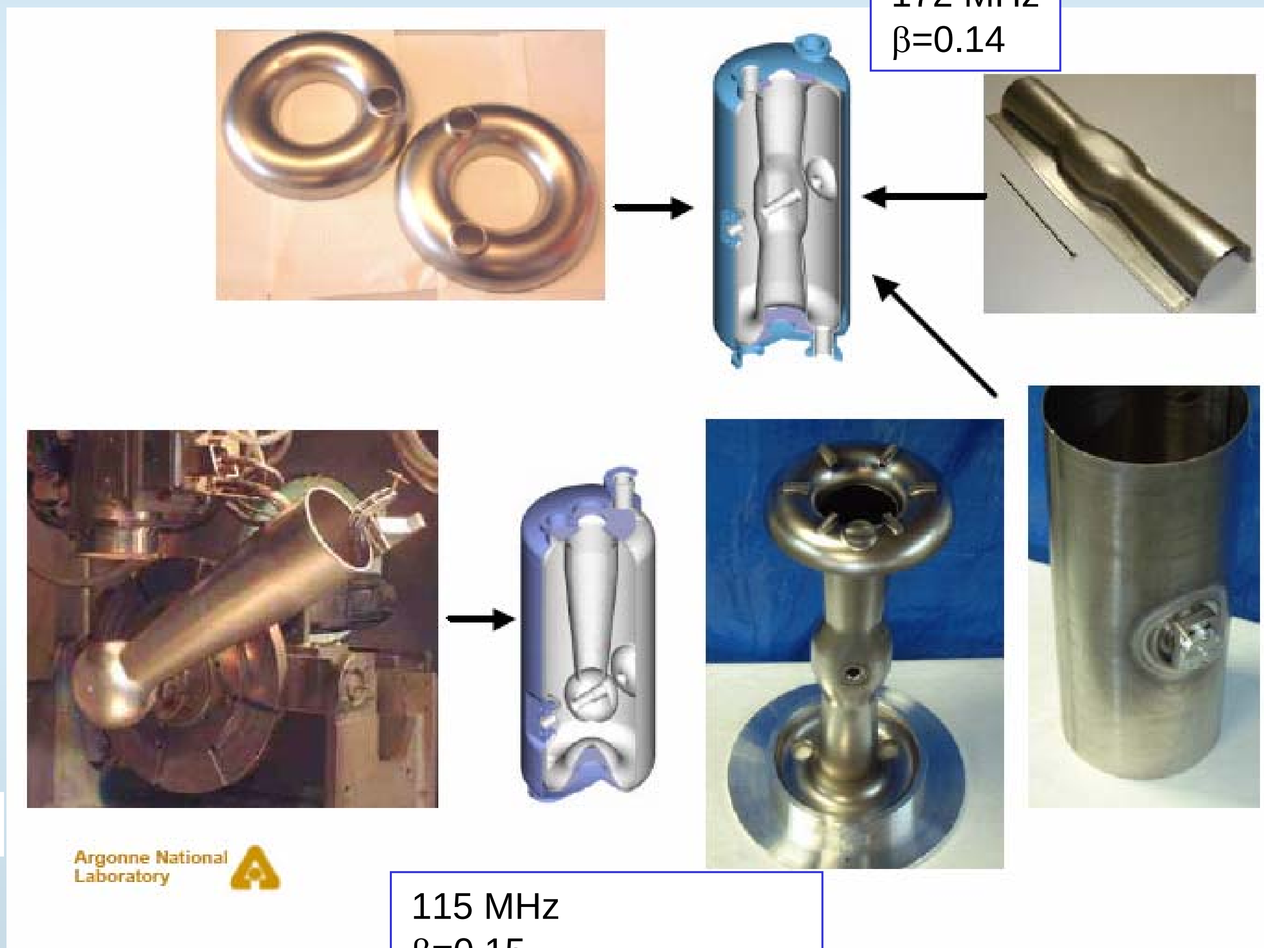
161 MHz
β=0.16
(MSU-LNL)





ANL QWR and HWR prototypes for RIA

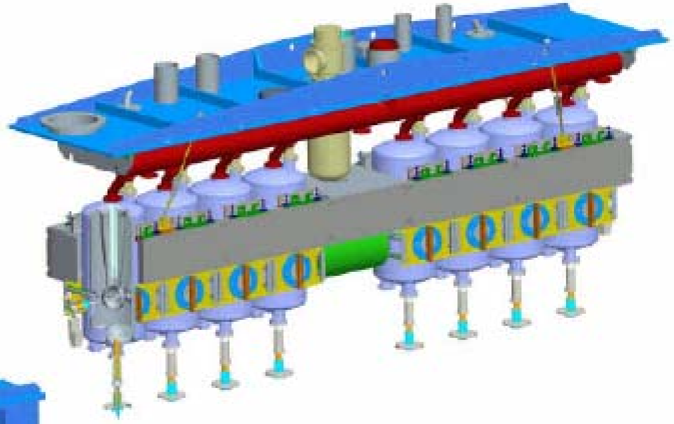
- Prototypes constructed and under testing
- The preliminary results are very encouraging and final results will be persented at the LINAC conference

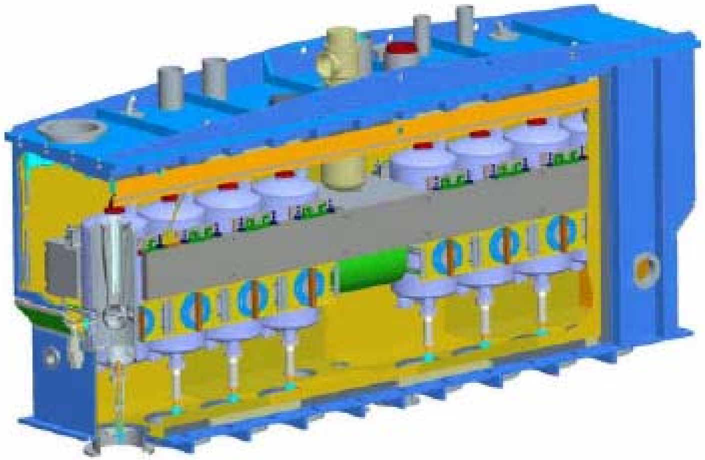


Courtesy of K. Shepard, ANL

ANL QWR prototype cryomodule

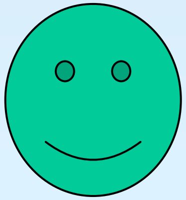
Prototype cryomodule will be completed in summer of 2004



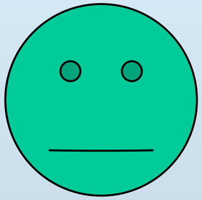


Half-Wave resonators

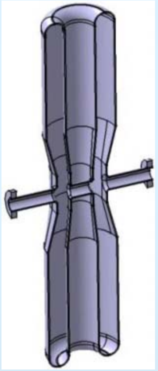
160≤f≤352 MHz, 0.09 ≤ β_0≤ 0.3



- **No dipole steering**
- High performance
- Lower E_p than QWRs
- Wide beta range
- Very compact



- Not easy access
- Difficult to tune
- Less efficient than QWRs
- (Quadrupole steering)



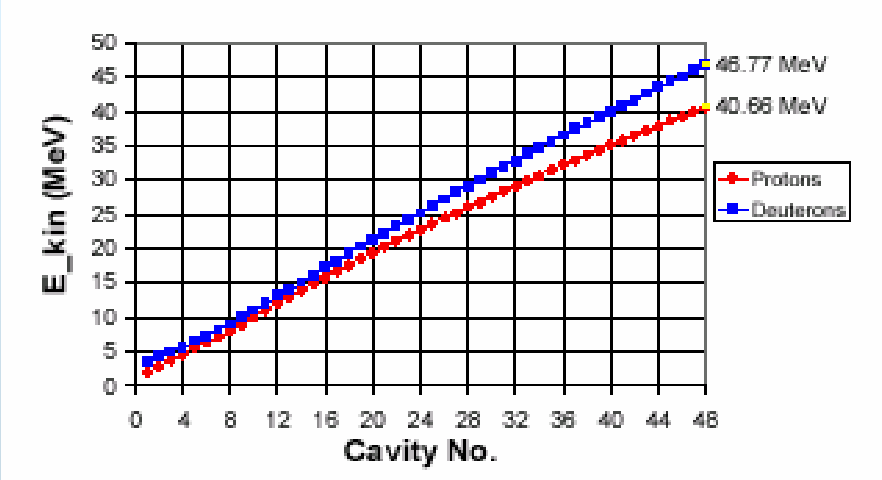
MSU 322 MHz β=0.28

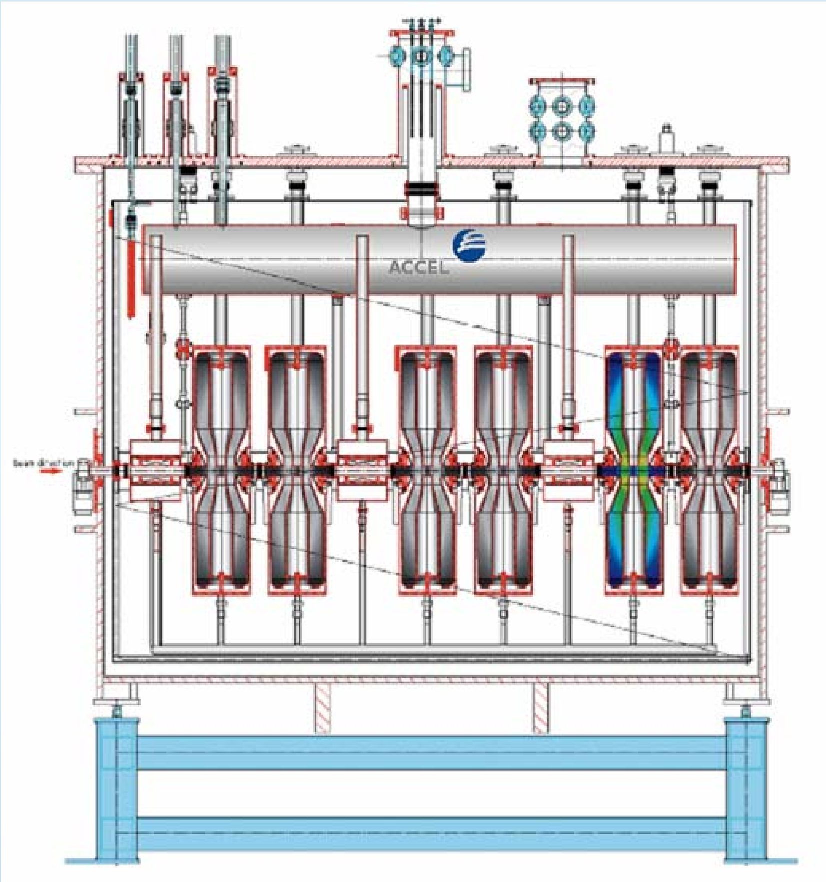
The first 355 MHz SC HWR ANL - β=0.12

ACCEL 176 MHz SC HWR β=0.09

ACCEL cavities for SARAF

- ACCEL is currently building a 40 MeV linear accelerator for 2 mA cw protons and deuteron for the SARAF (SOREQ APPLIED RESEARCH ACCELERATOR FACILITY) at SOREQ NRC, Israel;
- 176 MHz superconducting half-wave-resonators
- 2 HWR families: β=0.09 and β= 0.15





Cryomodule n.1 – *p* and *d* from 1.5 MeV/u

Courtesy of ACCEL

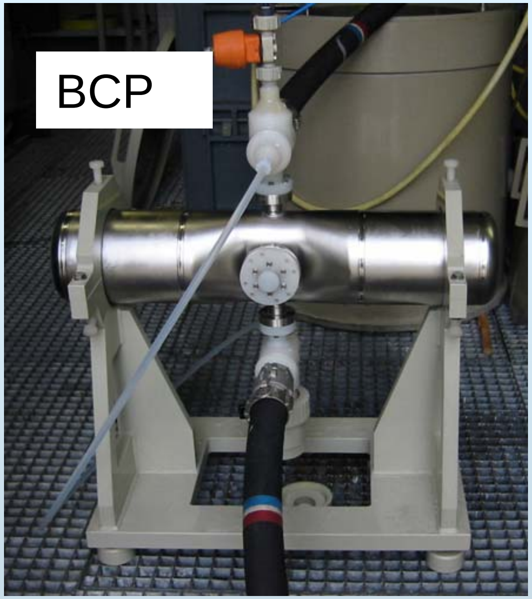
Parameters of β = 0.09 SARAF HWR

Cavities are produced out of RRR > 250 bulk niobium, design goal: E_p = 25 MV/m

Parameter	Value	Unit
Frequency	176	MHz
Cavity height h	835	mm
Diameter of inner conductor	80	mm
Diameter of outer conductor	180	mm
Wall thickness	3	mm
Cavity volume	17	l
Accelerating length[1] L_{acc}	99	mm
Optimum beta	9	%
Geom. constant $G = R_S \times Q_0$	24.5	W
Shunt Impedance R/Q	164	W
E_{peak} / E_{acc}	2.9	
B_{peak} / E_{peak}	2.1	mT/MV/m
B_{peak} / E_{acc}	6.2	mT/MV/m

[1] Measured from start of the first to the end of the second acceleration gap of the HWR, excluding leakage field in beam tubes

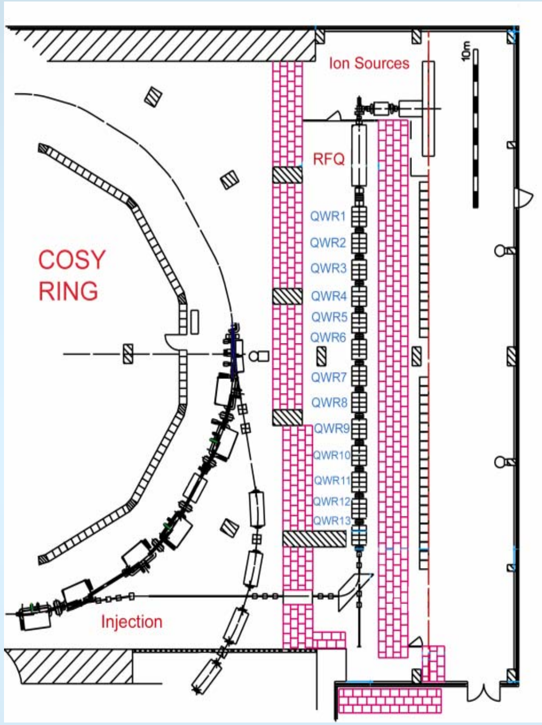
- The 1st prototype is under testing
- The 1st cryomodule is under construction
- The β = 0.15 prototype and cryomodules will follow



β = 0.09 prototype

IKF Juelich

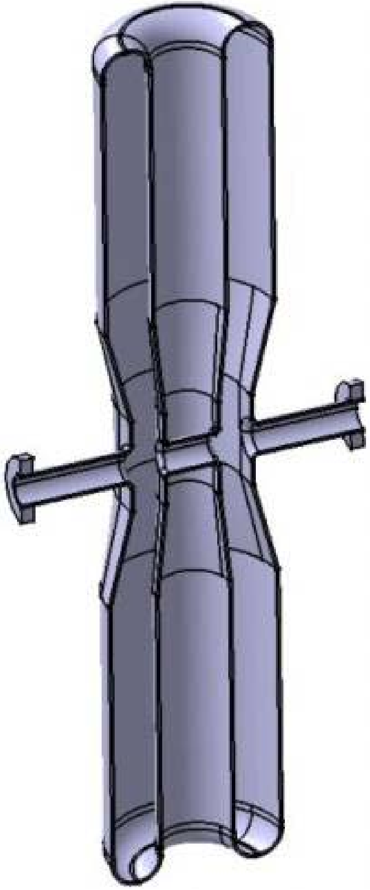
H^-,D^- injector



COSY Injector project (temporary suspended)

- 50 MeV with both H^- and D^- beams
- 2 mA (COSY space charge limit)
- 0.5 ms pulses @ 2 Hz
- 44 HWRs
- 160-320 MHz
- 8 MV/m
- β=0.11-0.2

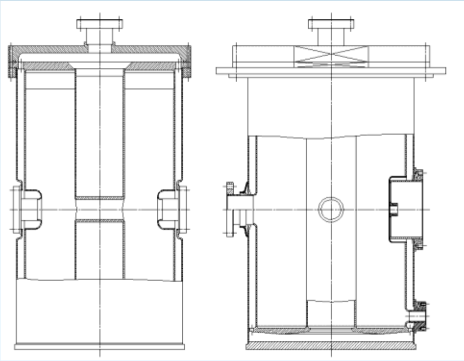
160 MHz, β=0.12 HWR
Designed for the
COSY injector

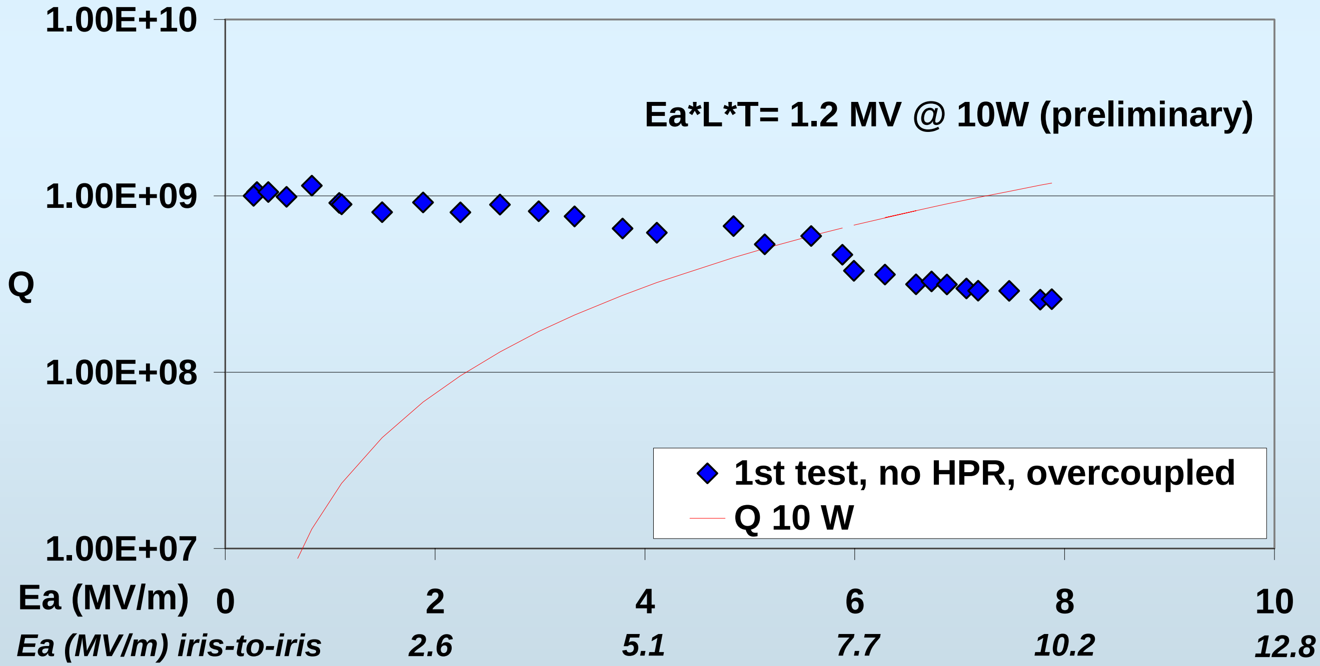


- A first 160 MHz prototype has been built and is presently under testing
- Preliminary results very encouraging

LNL: 352 MHz, β=0.3 HWR

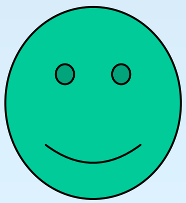
- **Modular design** for high intensity p and HI linacs (SPES, EURISOL) , extendable to different β and f
- Very compact and stiff structure including He vessel
- **Side tuner** insensitive to He pressure





SPOKE resonators

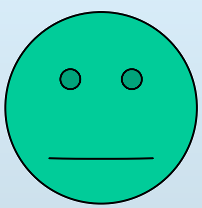
$345 \leq f \leq 805$ MHz, $0.15 \leq \beta_0 \leq 0.62$



- No dipole steering
- High performance
- **Higher R_{sh} than HWRs**
- Wide beta range
- **Multi-cell possibility**

LANL β=0.2
SPOKE

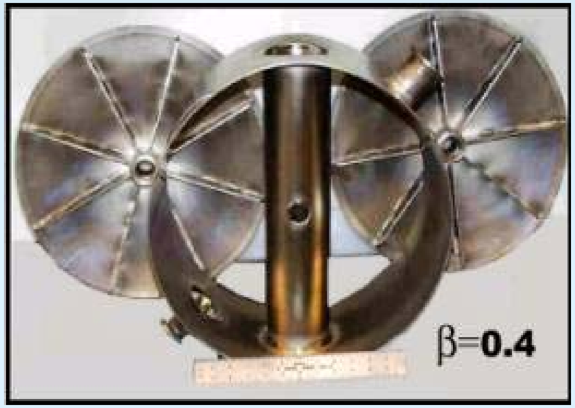
ANL β=0.4
Double SPOKE

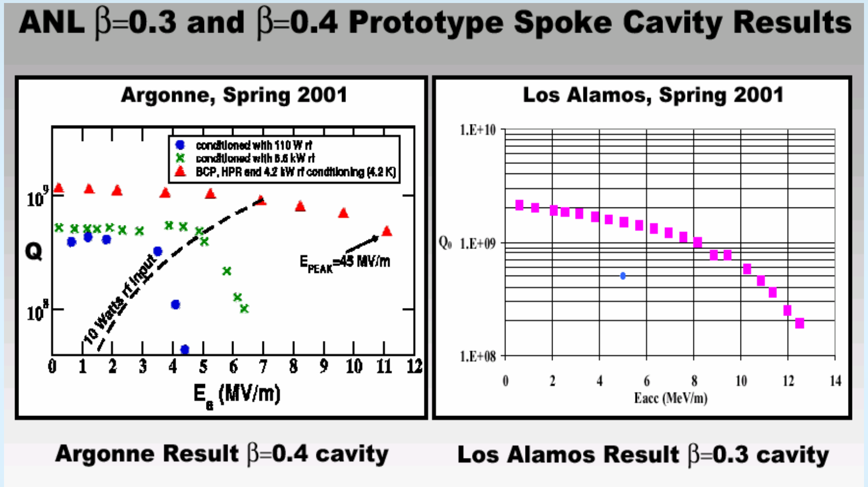


- Not easy access
- Difficult to tune
- Larger size than HWRs
- More expensive than HWRs
- (Quadrupole steering)

IPNO SPOKE, β=0.35
352 MHz

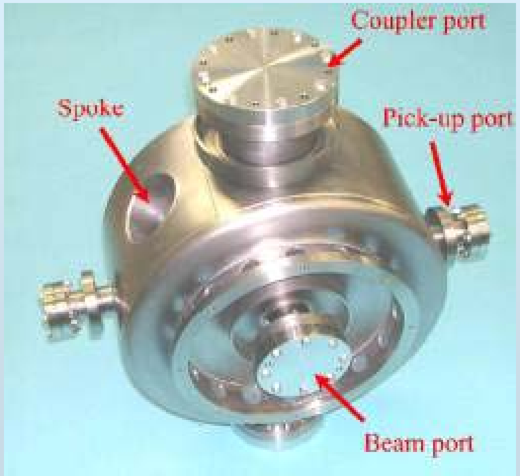
SPOKE resonators performance example: ANL and LANL 352 MHz cavities

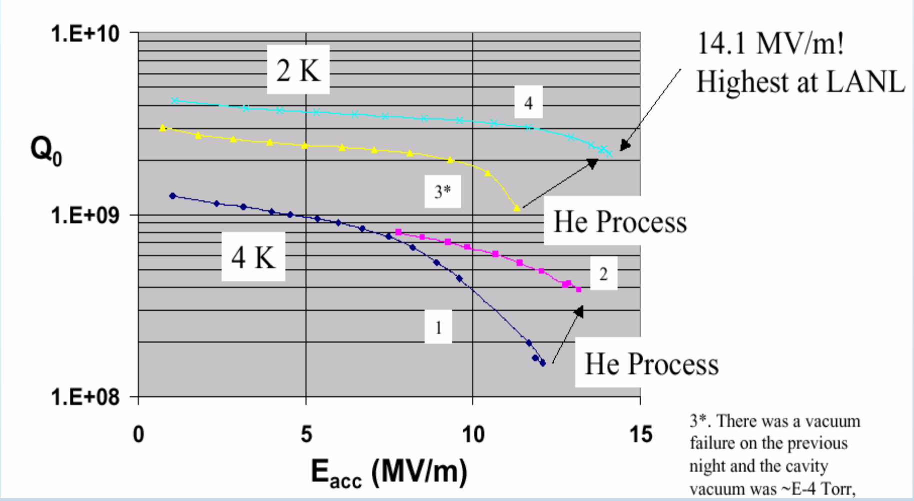




ANL β=0.3 and β= 0.4 prototypes

LANL β=0.2 prototypes



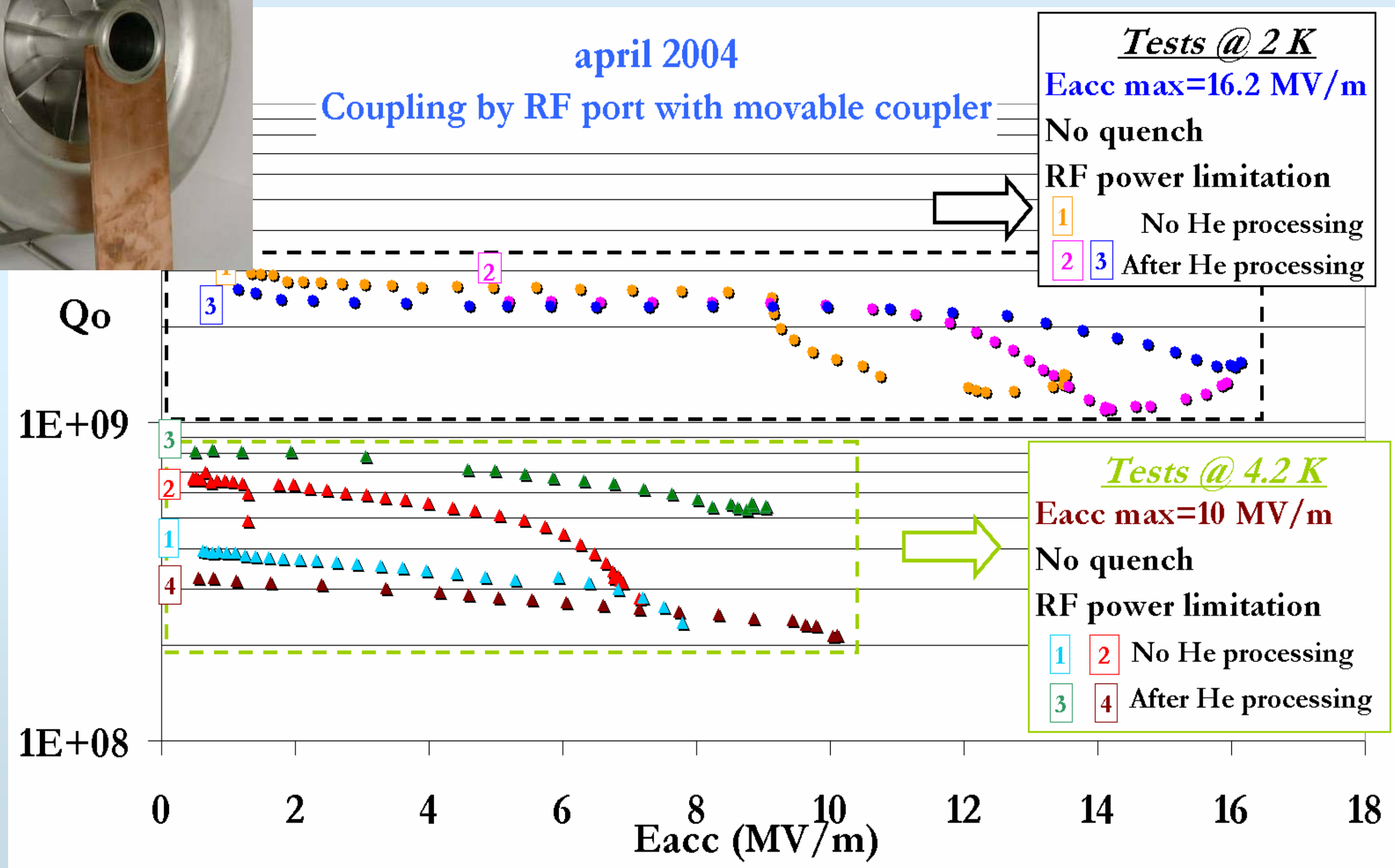


A. Facco – EPAC 2004

IPN Orsay

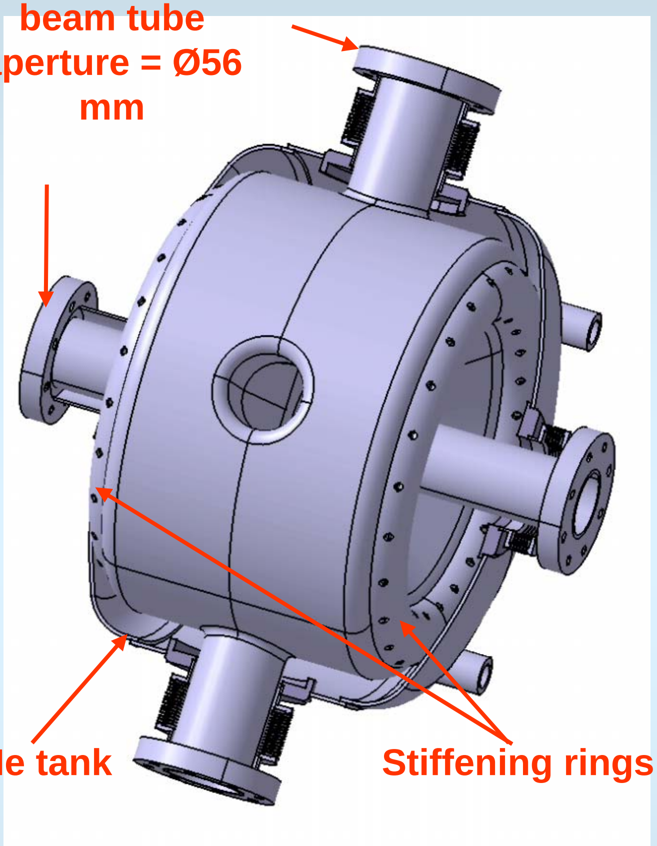
IPNO - β 0.35, 352 MHz spoke cavity

New tests in 2004 @ 4.2 K & 2 K



A. Facco – EPAC 2004

New β 0.15, 352 MHz spoke cavity design



- New stiffeners
- RF port bigger and @ 90°/spoke bar
- Nb: RRR250, 3 mm thick

Delivery in September 04

RF parameters (MAFIA calculations)

Qo[a] (@ 4.2K)	1.4 E+09
r/Q [Ω]	88
G [Ω]	67
Ep/Eacc	3.97[b]
Bp/Eacc [mT/MV/m]	7.95[b]
Voltage gain @ Ep=30 MV/m [MV]	0.63

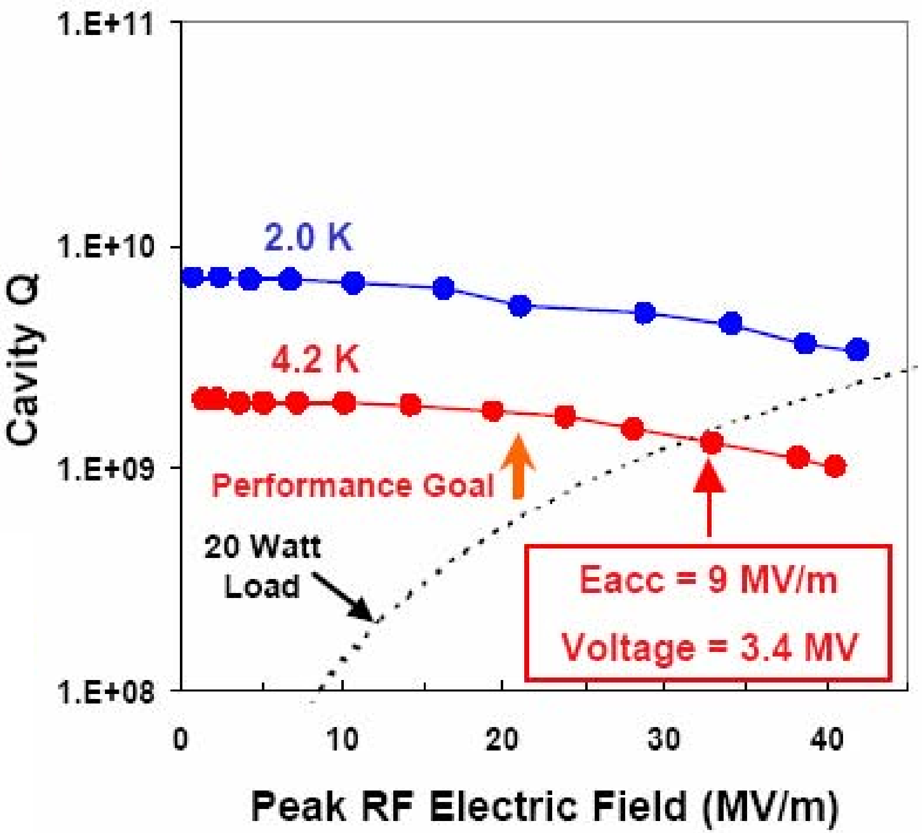
[a] assuming a 10 nOhm residual resistance
[b] Lacc=iris-to-iris length=0.2 m

Mechanical parameters (COSMOS & MICAV calculations)

Maximum stress under 1 bar [MPa]	< 39
Stiffness with stiffening rings (without stiffening rings) [N/mm]	6200 (3200)
Tuning sensitivity (using beam tubes) [kHz/mm]	~1100

ANL

Double SPOKE β=0.4



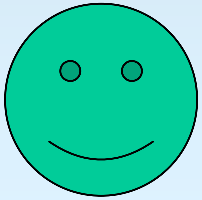
Maximum fields:

- **E_a=11.5 MV/m**
- **E_p=40 MV/m**
- **B_p=79 mT**

Argonne National Laboratory

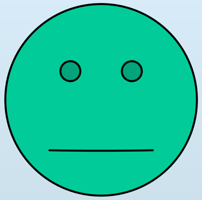
Elliptical resonators

352≤f≤805 MHz, 0.47≤ β_0≤ 1



- **Highly symmetric field**
- High performance
- Low E_p and B_p
- Multi cell possibility
- **Large aperture**

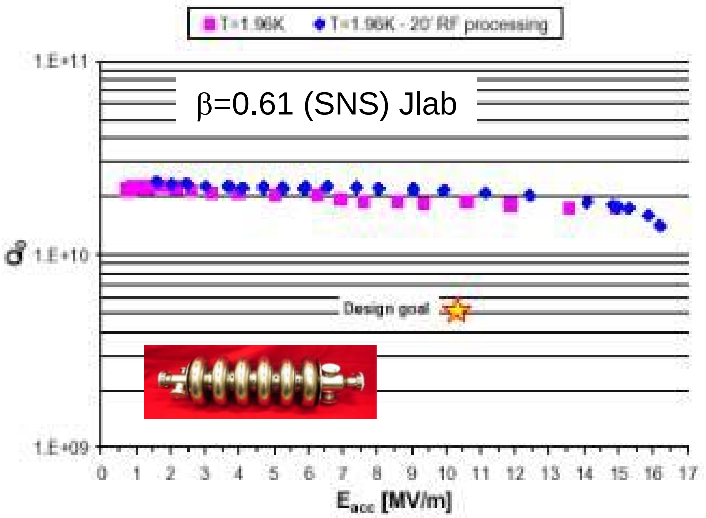
INFN Milano 700 MHz, β=0.5

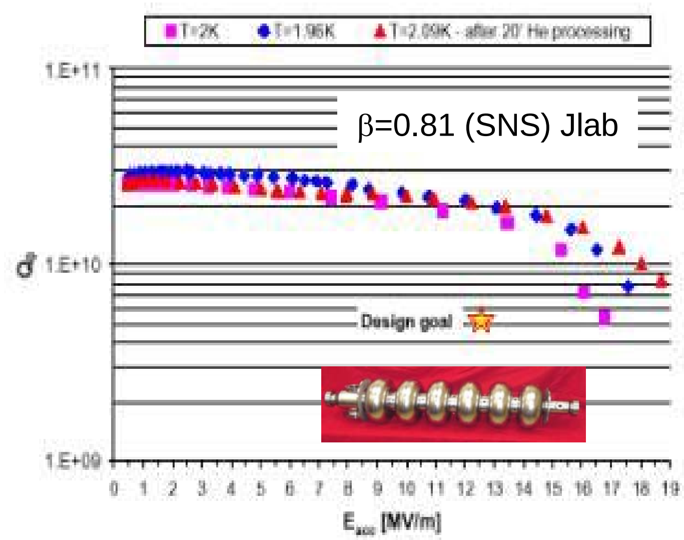


- Not suitable for β<0.4
- Operation at 2K (with one exception)

CERN 352 MHz, β=0.8
Sputtered Nb on Cu

β<1 Elliptical resonators examples





- Prototypes successfully developed at JLAB, KEK, JAERI, LANL, CEA Saclay, IPN Orsay, INFN Milano, CERN
- SNS cavities and cryomodules under production, very good performance

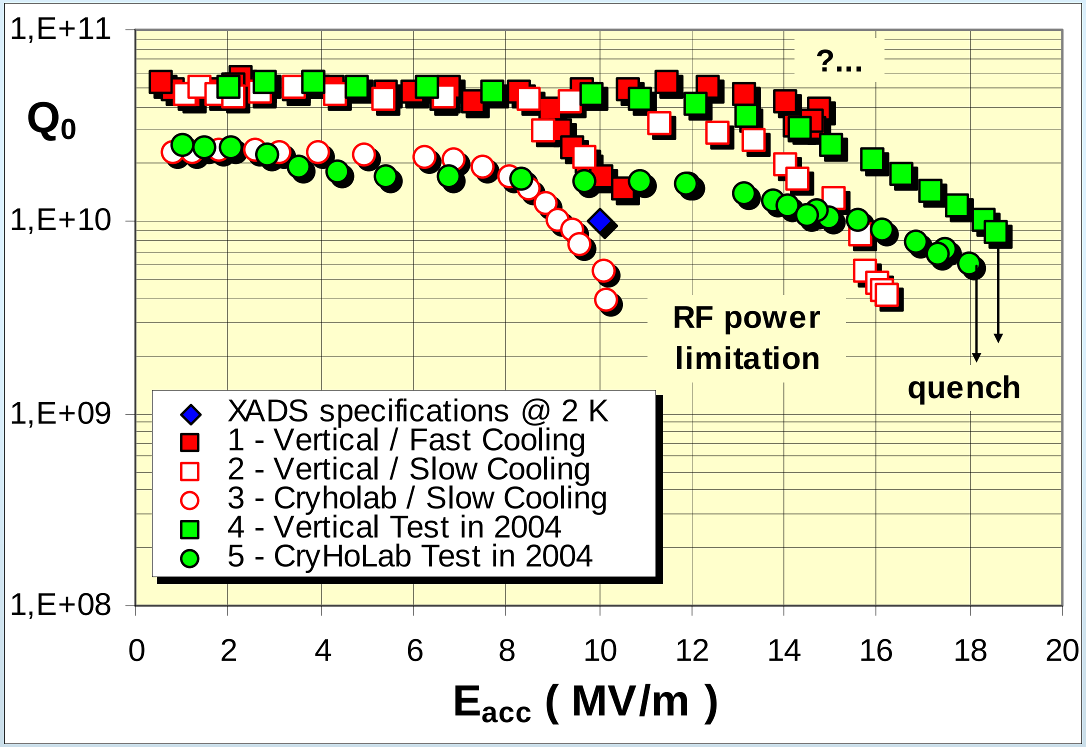
CEA Saclay

Intermediate-β cavities

Nb Cavity (5-cell 700 MHz β = 0.65)

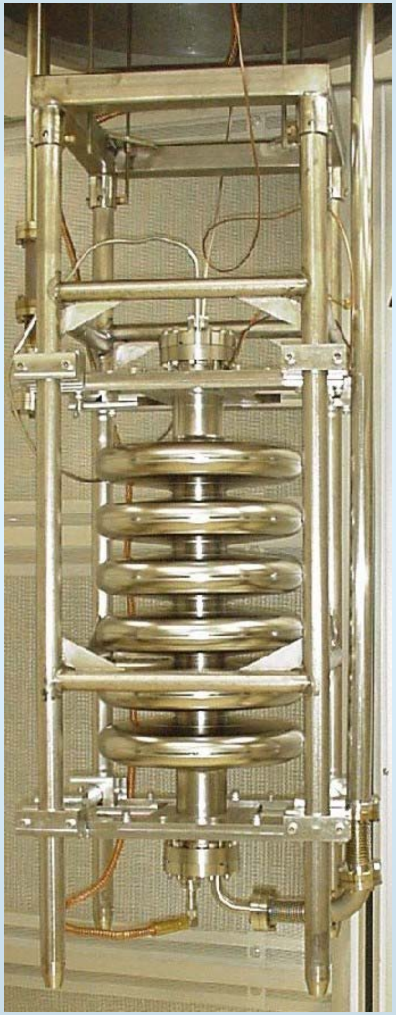
In collaboration with IPNO

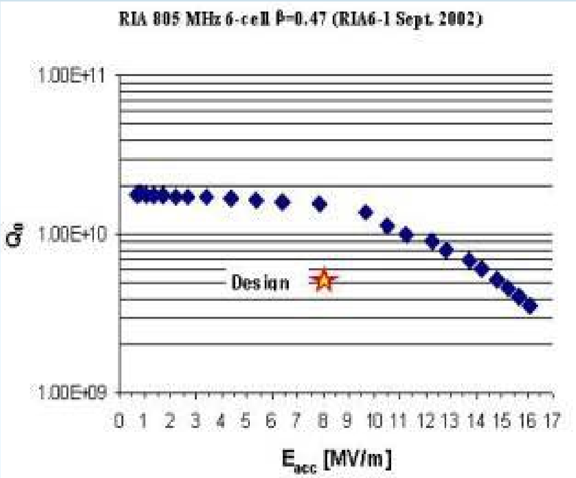
Results Improvement in Vertical Cryostat and Cry-Ho-Lab



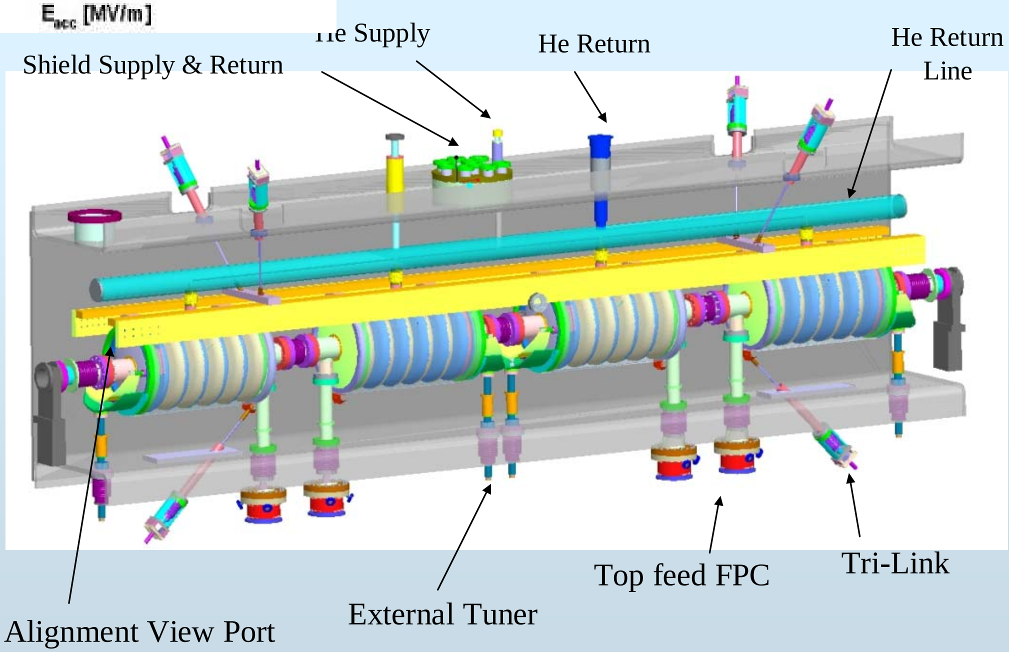
$Q_0 = 9.10^9$ at $E_{peak} = 43$ MV/m, $B_{peak} = 83$ mT

MSU-JLAB 6-cell elliptical β=0.47



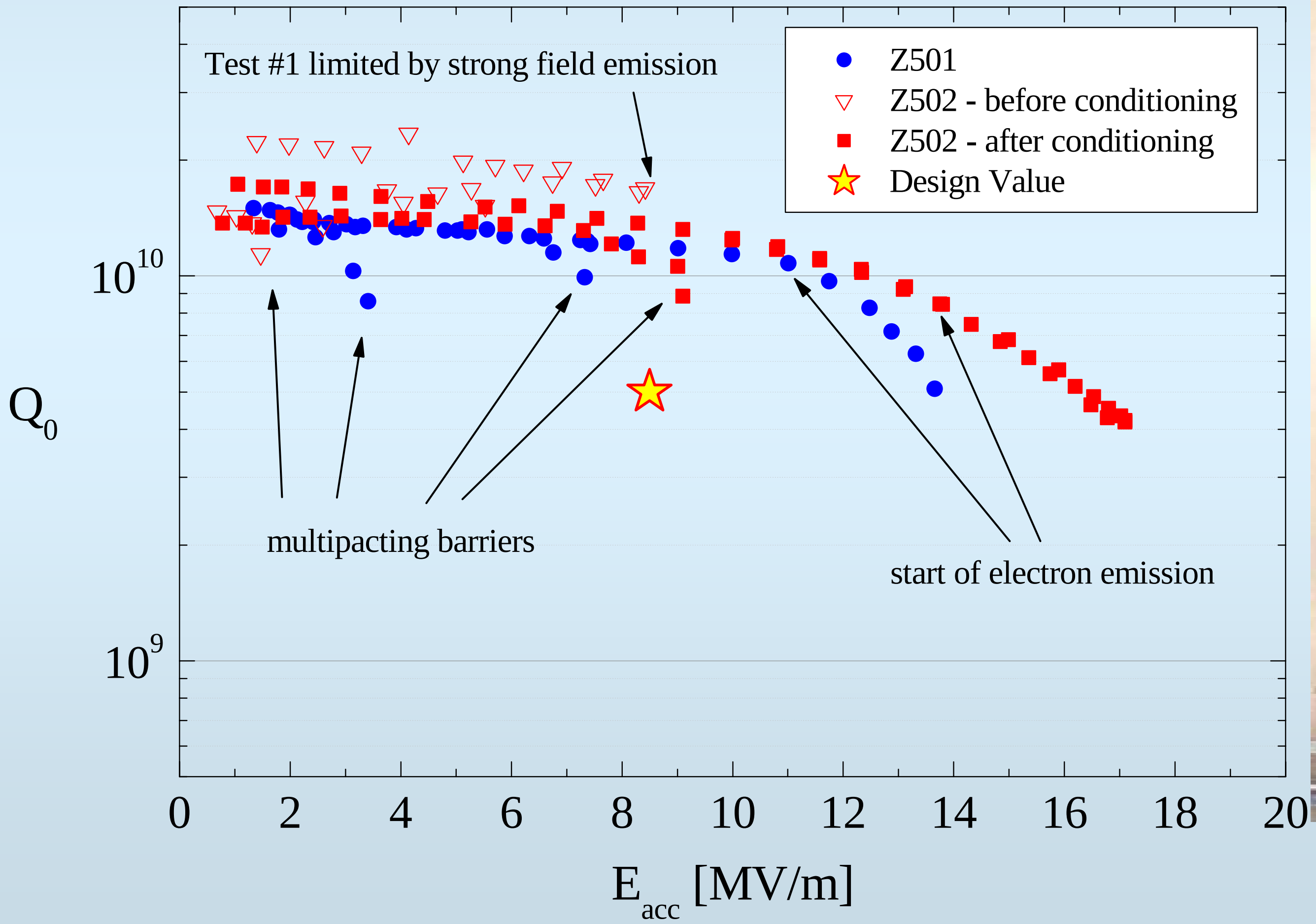


- β=0.47 Criomodule built and tested
- Actively damped the 0.47 microphonics using adaptive feedforward



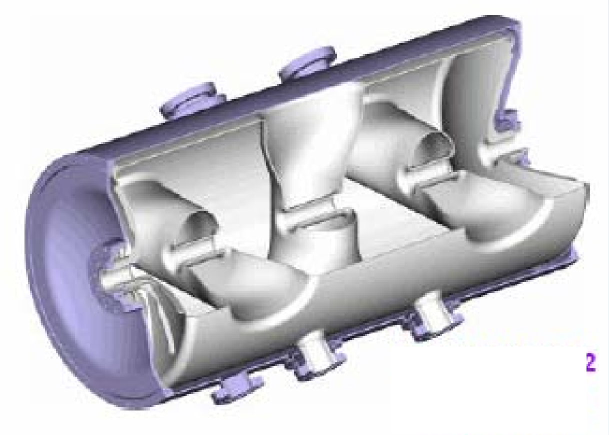
INFN Milano-LASA

TRASCO/ADS β=0.47



3-Spoke or 6-cell?

- *3-SPOKE advantages:*
  - lower n. of cavities if B_p of 82 mT in operation is used
  - Higher longitudinal and transverse acceptance
  - 4.2 K instead of 2 K

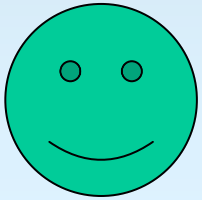


- *On the other hand:*
  - B_p=82 mT in operation is rather challenging
  - 6-cell are well developed, 3-SPOKE not yet
  - 2 K have some advantages in terms of mechanical stability
  - According to MSU calculations both SPOKE and 6 cell have adequate acceptance for RIA, and their cost, using realistic B_p, would be the same

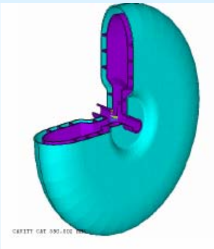
- The discussion is still open to new results.

Reentrant cavities

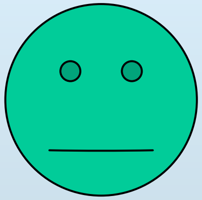
$352 \leq f \leq 402$ MHz, $0.1 \leq \beta$



- Highly symmetric field
- Very Compact
- Low E_p and B_p
- Widest velocity acceptance
- Possibility of large aperture



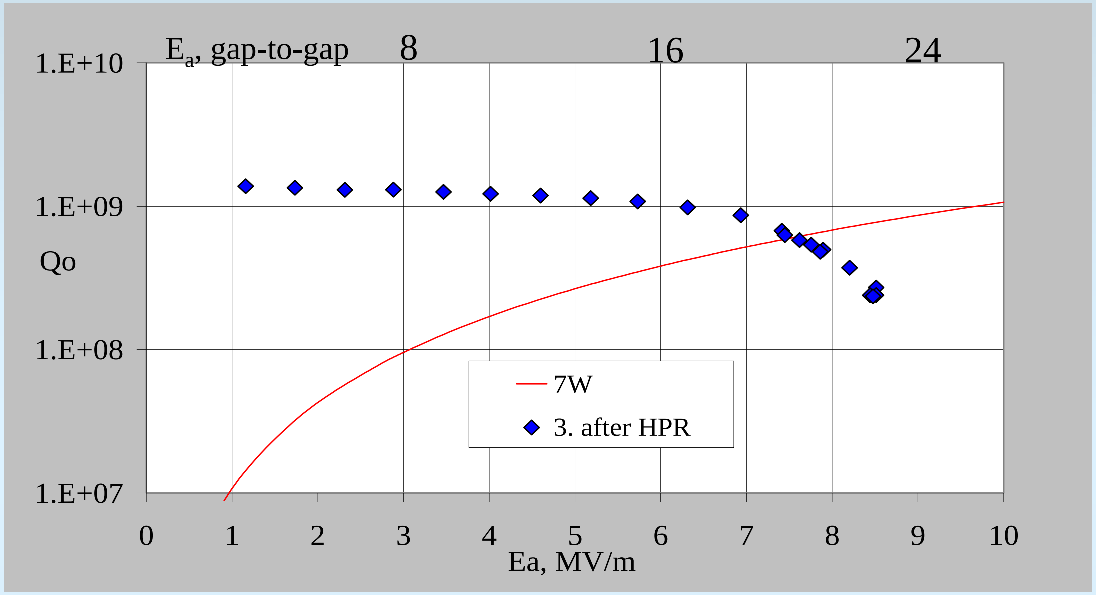
The first reentrant cavities - SLAC

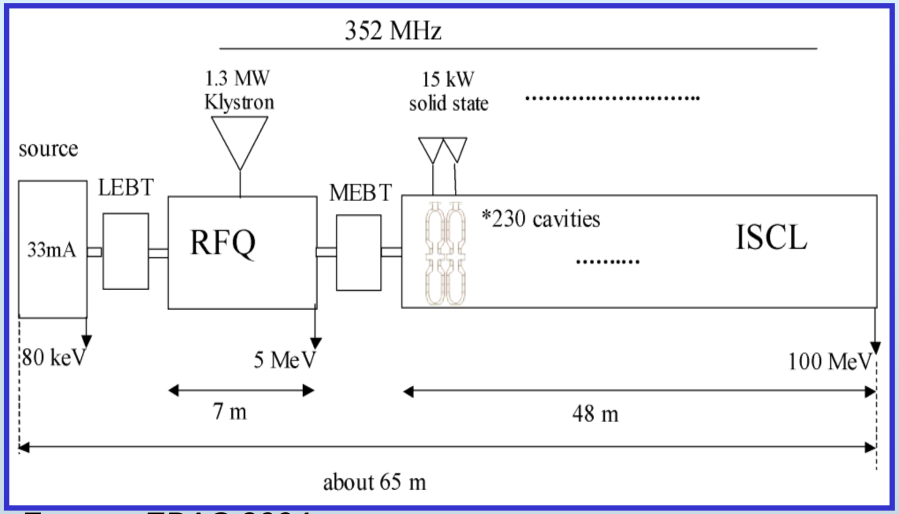


- short accelerating length, little E gain
- mechanical stability
- inductive couplers only

LNL 352 MHz
reentrant cavity

LNL β>0.1, 352 MHz Reentrant cavity





TRASCO 30 mA Fault tolerant Linac with Reentrant Cavities

- 5÷ 100 MeV
- 230 cavities
- Cavity aperture 30 mm
- Superconducting quadrupole singlets in a FODO lattice

- SC Linac length : 48 m

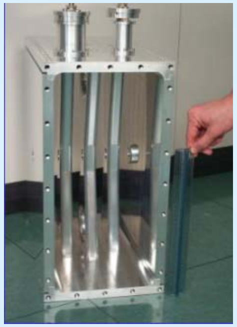
A. Facco – EPAC 2004

Other multi-gap SC cavities

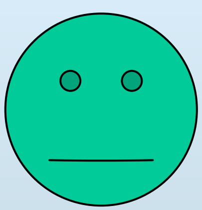
$174 \le f \le 352$ MHz, $0.1 \le \beta_0 \le 0.3$

•Very efficient
•large energy gain
•They can be made for rather low β

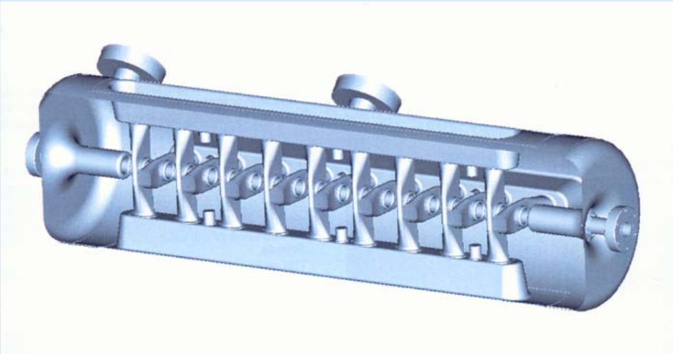
4 gap ladder l
352 MHz, β=0.12
INFN-LNL



β=0.2
784 MHz
IKF Juelich



•β acceptance
•Difficult to have large aperture
•difficult to build and expensive
•Not yet demonstrated

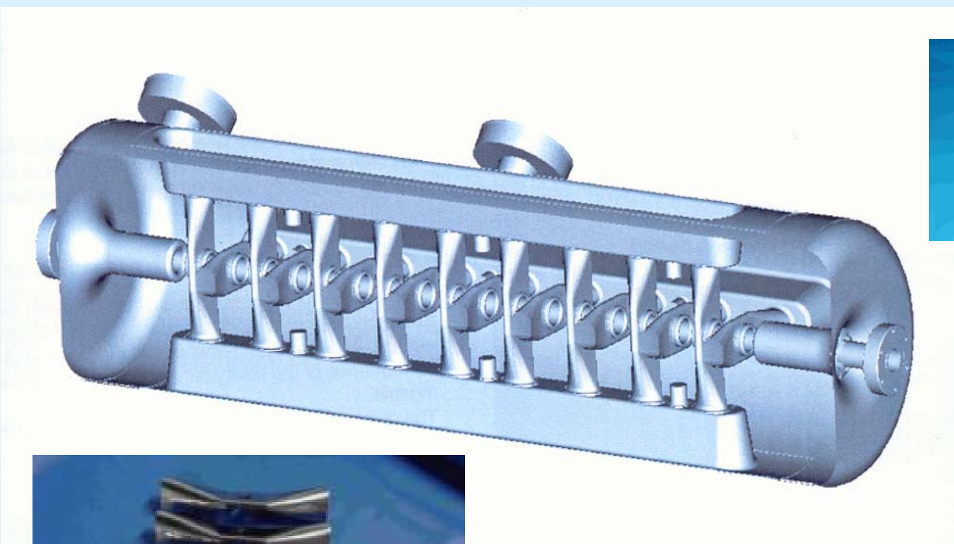


19 gap CH, β=0.1
352 MHz, IAP Frankfurt

IAP-Univ. of Frankfurt

19 gap, 352 MHz, β=0.1

Fixed velocity profile, high energy gain resonator
Under construction



Cells	19
Length (cm)	105
Frequency (MHz)	352
β	0.1
Material	Bulk Niobium
E_0 (MV/m)	4
E_a=ET (MV/m)	3.2
E_p (MV/m) @ 3.2 MV/m	21.0
B_p (mT) @ 3.2 MV/m	23.3
G=R_sQ_0 (Ω)	56
R_a/Q (Ω) (T incl.)	3220
(R_a/Q)G (Ω^2)	180000
Q_0 (BCS, 4K, 352 MHz)	1.5×10^9
Q_0 (total R_s=150 nΩ)	3.7×10^8
W (mJ/(MV/m)^2)	155
W @ 3.2 MV/m (J)	1.58
P @ 3.2 MV/m and R_s=150 nΩ =(W)	9.5

Conclusions

- After two decades of heavy ion SC boosters, new applications for low- and intermediate-β superconducting resonators
- Low- and intermediate-β cavities reach nowadays E_p~60 MV/m and B_p ~ 120 mT, and approximately half of these values are considered reliable in operation
- Strong development in SC cavities is pushed by new high power proton accelerator and heavy ion linac projects
- Large variety of shapes and characteristics for different applications
- In high current proton linacs ,however, NC DTLs choice can be still competitive for $\beta<0.3$, even in cw
- The time of commercial SC linacs for HPPA is maybe starting