Advances in SRF for Low β Ion Linacs

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CNRS/IN2P3/ IPN Orsay – Paris-Sud University

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Disclaimer

This review is covering a wide range of low beta ion cavities developments for several applications, excepted high energy physics and neutron sources:

Refer to these 2 others talks to have a complete picture:

- ✓ ***SRF Development for High Energy Physics,*** **Mark Champion**
- ✓ ***Advances in SRF for Neutron Sources ,*** **Sang-Ho Kim**

Outlook

- Facility upgrades
  - ATLAS (ANL)
  - HIE-ISOLDE (CERN)
  - Re A3 (MSU)
  - ISAC-II (TRIUMF)
- New projects
  - SPIRAL-2 (GANIL, CEA Saclay, IPN Orsay)
  - SARAF (SOREQ)
  - FRIB (MSU)
  - IFMIF (CEA Saclay)
- Other low beta SC cavities R&D

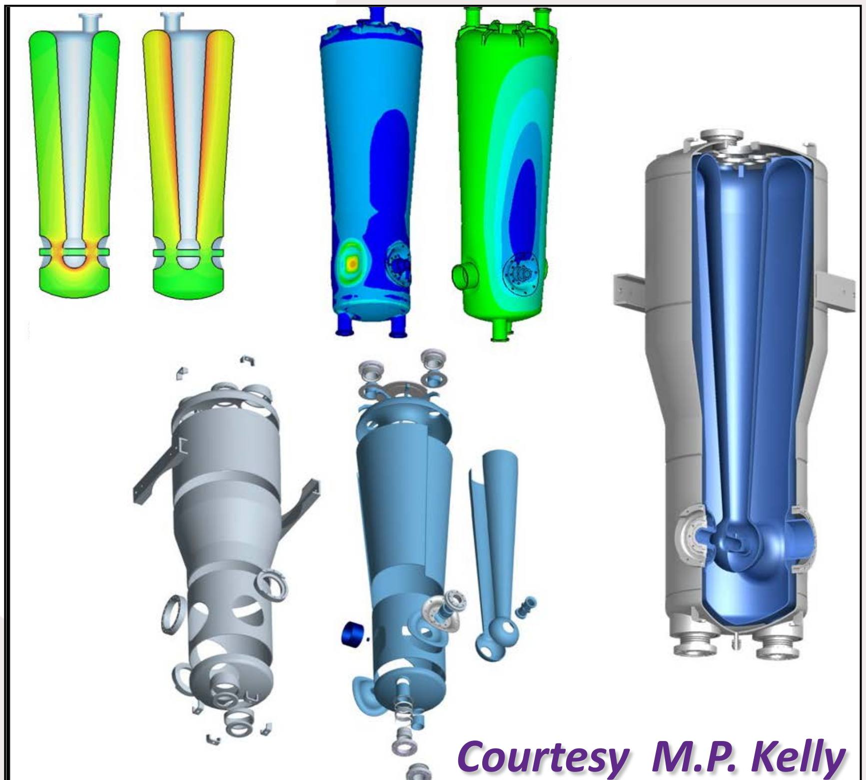
ANL : ATLAS UPGRADE (1)

Argonne NATIONAL LABORATORY

Project objectives: Replace the 3 existing 97 MHz split-rings by a new cryomodule to increase beam transport efficiency (↗ acceptance & ↘ emittance growth)

Cavity type: Quarter-wave resonators, f=72 MHz, β=0.077

Goal: Voltage = 2.5 MV (Eacc ~ 7.5 MV/m with Leff = βλ)



Courtesy M.P. Kelly

Parameter	Value	Units
Frequency	72.750	MHz
Peak Beta	0.077	
QRs	26.4	Ohm
R/Q	576	Ohm
$\beta\lambda$	31.75	cm
Design Voltage	2.5	MV
$\Delta f / \Delta E^2_{acc}$	-1.9	$Hz/(MV/m)^2$
$\Delta f / \Delta P$	-2.6	Hz/Torr
Tuning Sensitivity	~8	kHz/mm
At Eacc= 1 MV/m		
Stored Energy	0.375	Joule
E_{peak}	5.16	MV/m
B_{peak}	76.2	Oe

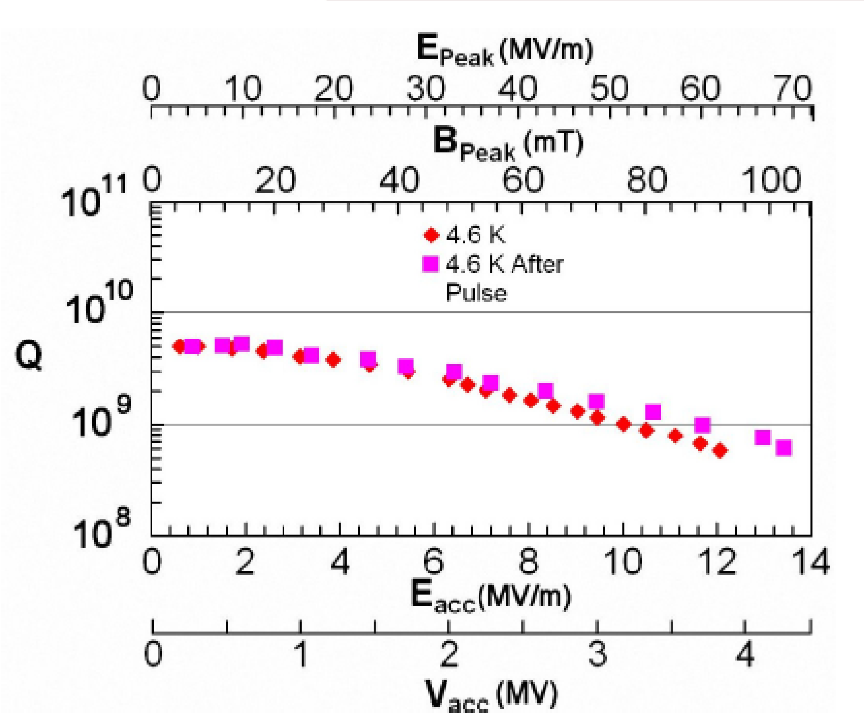
EM design: a conical-shape outer housing reducing by 20 % the ratio Bpk/Eacc

ANL : ATLAS UPGRADE (2)

Cavity preparation:

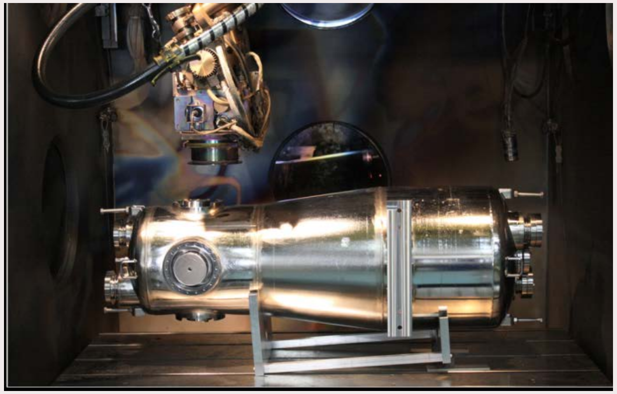
- **150 µm removed by EP (12 hours total EP time) on the new ANL EP system**
- **HPR and assembly in a class 100 clean room**

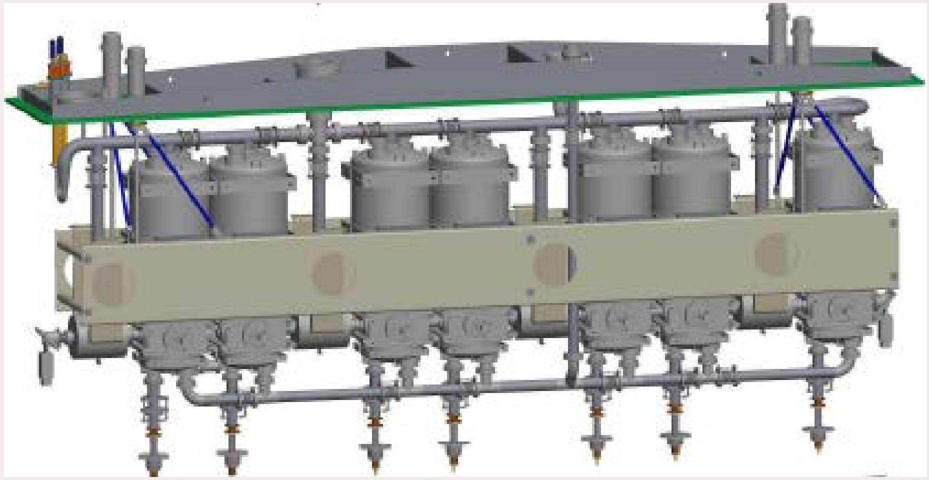
RF test of the first prototype:



A max Eacc = 13.4 MV/m obtained !

Final EB @ Sciaky





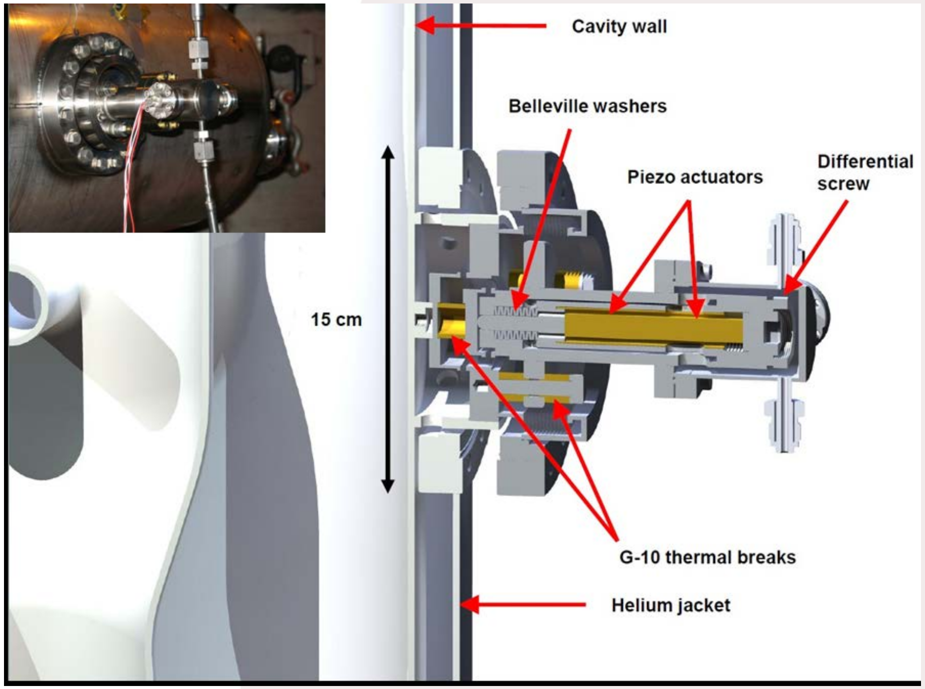
Cryomodule design: 17.5 MV in 5.2 m
Clean cavity string (separate vacuum)

Courtesy M.P. Kelly

ANL : ATLAS UPGRADE (3)

Cold Tuning System

Cavity wall deformation by piezo



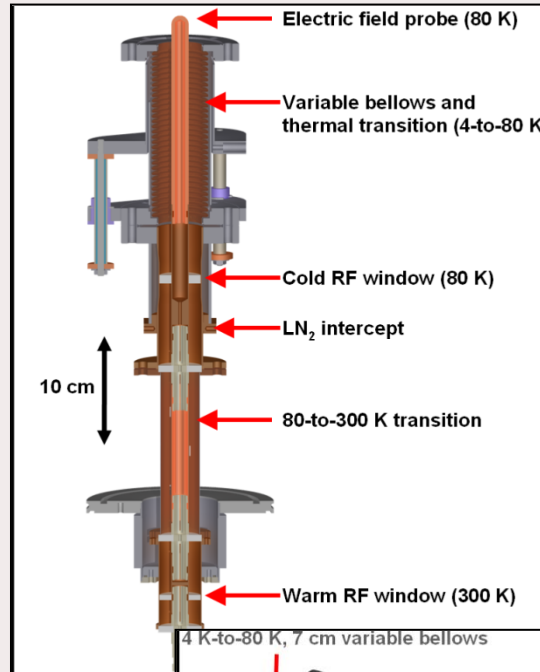
2 Noliac piezo stacks : 10x10x40 mm

Preload: by compressing 14 Belleville washers

To know more: THIOB04 by M.P. Kelly

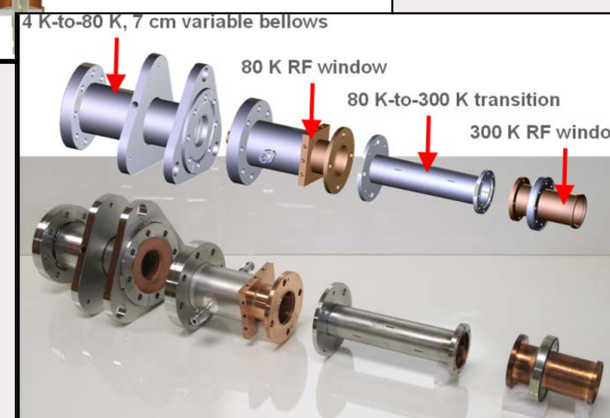
Power coupler

Design for 4 kW CW - Variable



2 RF disc windows (96 % Alumina)

Bellow: copper plated with 20 µm



CERN : HIE ISOLDE (1)

Project objectives: post-accelerate the RIB beam coming from REX-ISOLDE up to 10 MeV/u (intermediate phase at 5.5 MeV/u).

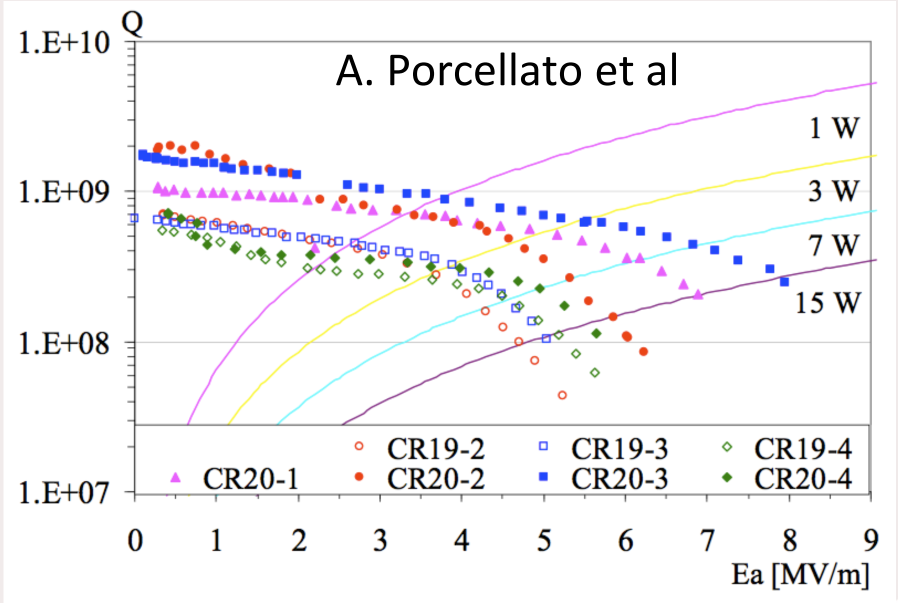
Cavity type: Quarter-wave resonators, Nb/Cu, f=101.28 MHz

- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 cavities @ β=0.1 and 12 cavities @β=0.06)

Performances goal: Eacc = 6 MV/m

and 7 W max of dissipated power

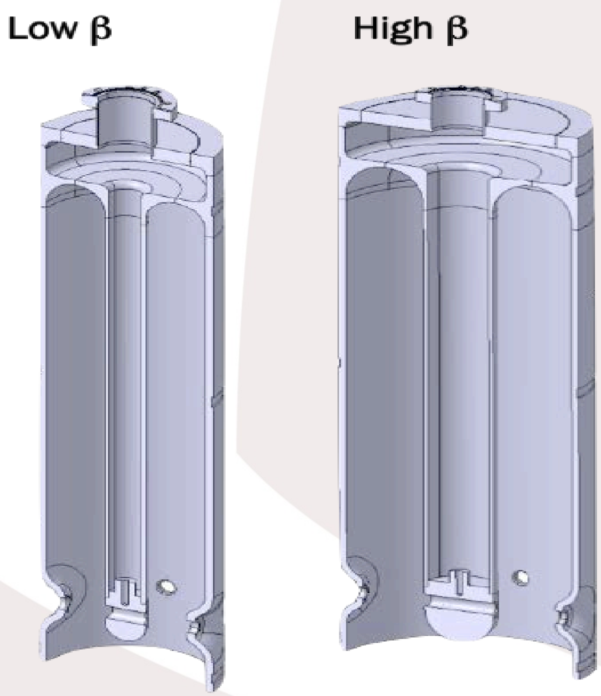
Objectives based on past experience at INFN-Legnaro on sputtered cavities developed for ALPI



CERN : HIE ISOLDE (2)

Cavity features:

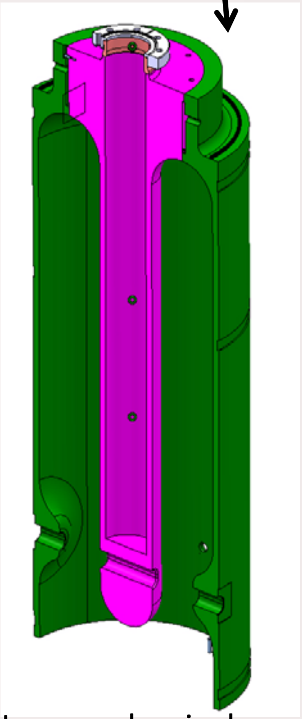
- Cavity substrate: OFE copper, 10 mm thick, cold worked; deep drawing and EB welding at CERN. A new design and fabrication process is under study.
- Specially studied beam aperture shapes (racetrack) to minimize the beam steering effect of QWR.
- Op. T° 4.2 K, LHe only on the cavity top and in the stem.



Courtesy M. Pasini

Table 1: Cavity design parameters

Cavity	Low β	highβ
No. of Cells	2	2
f (MHz)	101.28	101.28
β_0 (%)	6.3	10.3
Design gradient E_{acc}(MV/m)	6	6
Active length (mm)	195	300
Inner conductor diameter (mm)	50	90
Mechanical length (mm)	215	320
Gap length (mm)	50	85
Beam aperture diameter (mm)	20	20
$U/E_{acc}{}^2$ (mJ/(MV/m)^2)	73	207
E_{pk}/E_{acc}	5.4	5.6
H_{pk}/E_{acc} (Oe/MV/m)	80	100.7
R_{sh}/Q (Ω)	564	548
$\Gamma = R_s \cdot Q_0$ (Ω)	23	30.6
Q_0 for 6MV/m at 7W	$3.2 \cdot 10^8$	$5 \cdot 10^8$
TTF max	0.85	0.9
No. of cavities	12	20

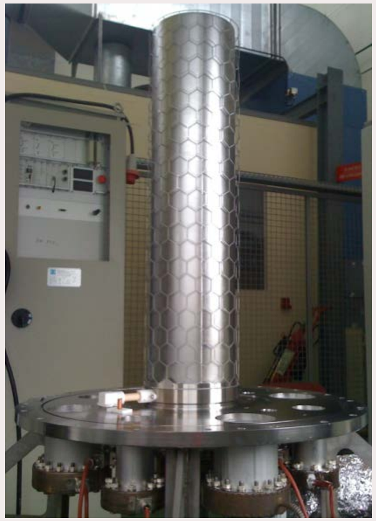


New mechanical design, for a 3D fabrication from a billet

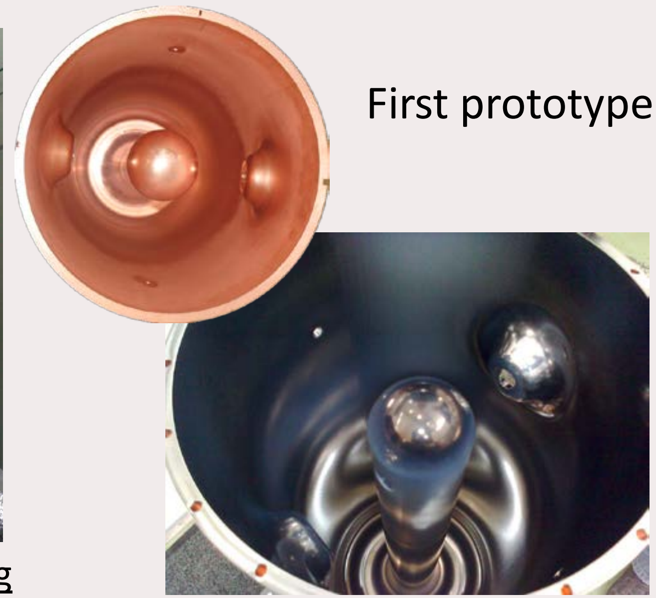
CERN : HIE ISOLDE (3)

Sputtering: 2 techniques are studied: bias diode and magnetron sputtering

Bias Diode Sputtering



Magnetron Sputtering



First prototype

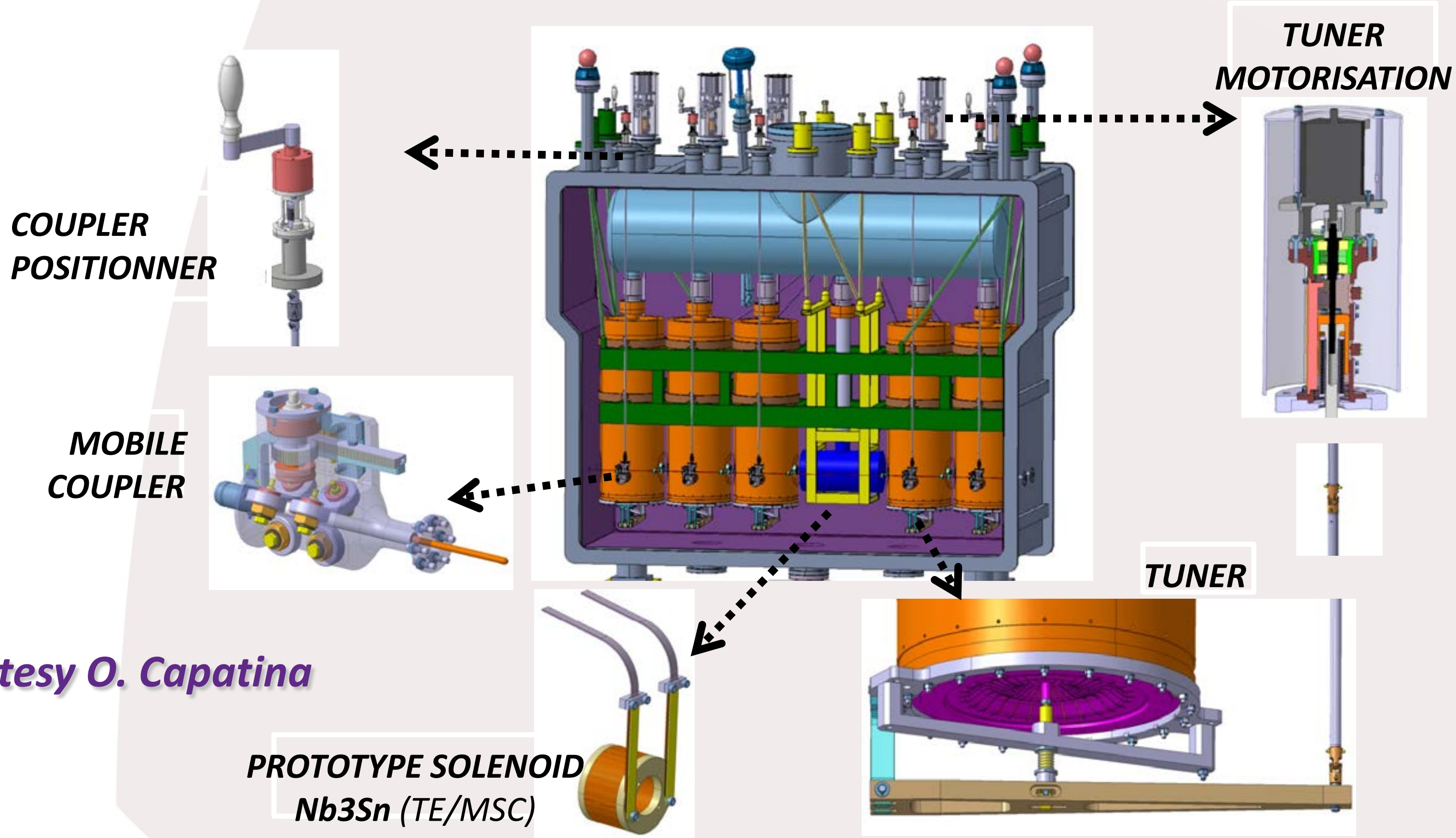
Courtesy M. Pasini

First RF test on the prototype: an accelerating field of 3 MV/m reached, with an important slope on the Q_0.

Optimization of deposition parameters are undergoing (first main goal: increase the RRR of the Nb film)

CERN : HIE ISOLDE (4)

Cryomodule: common cavity/cryomodule vacuum, superconducting solenoid



Courtesy O. Capatina

To know more:

THOB07: M. Pasini: HIE Isolde QWR

TUP 0067: G. Lanza, S. Calatroni et al. : QWR sputtering

ISAC - II : TRIUMF

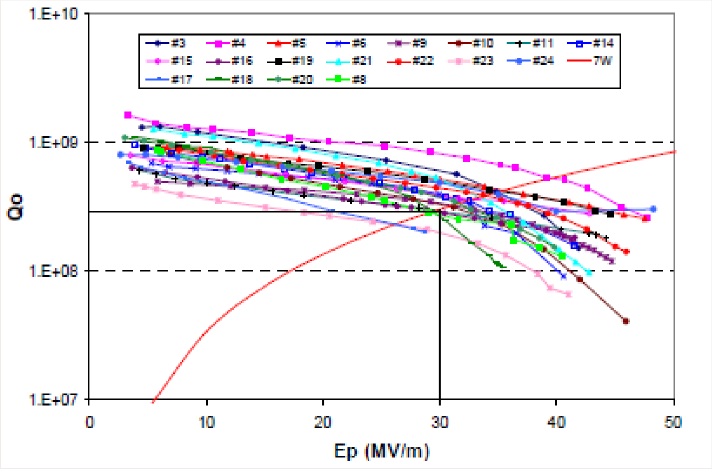
Project objectives: Upgrade of ISAC II (Phase 2)

Cavity type: 20 more quarter-wave resonators, beta 0.11 @ 141 MHz.

Specifications: P<7 W/cavity and voltage = 1.08 MV. All cavities fabricated by local company PAVAC.

Performances:

- Individual cavity testing: Almost all cavities above specs. (average Epk=32 MV/m)



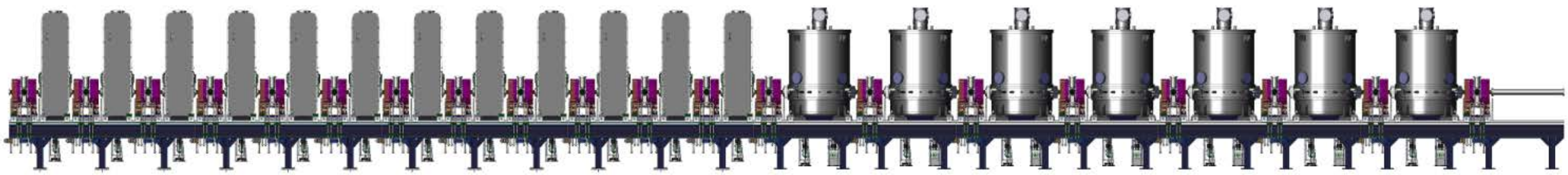
- All cryomodules are installed since March 2010 and have accelerated beam with Epk=26 MV/m in average. Some studies are ongoing to increase cavity performances.

More information : Talk by R. Laxdal on Thursday THIOB06

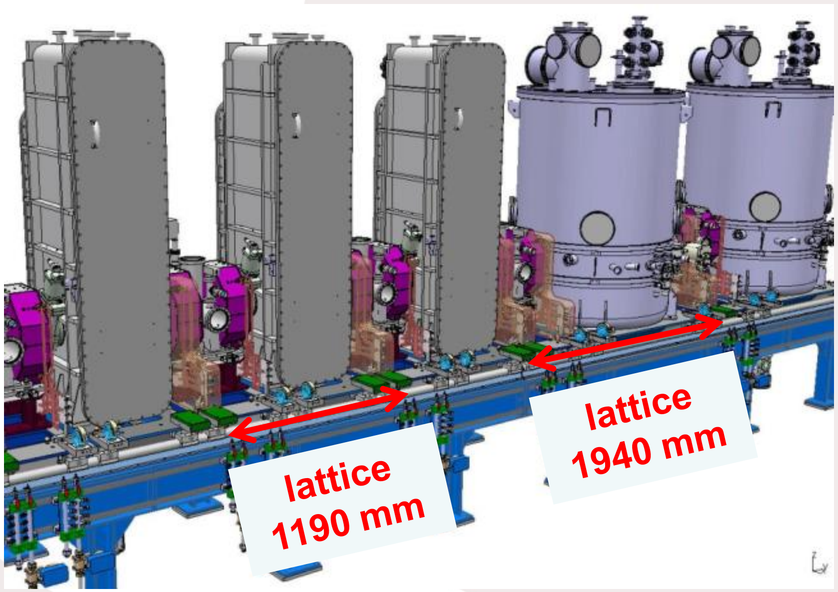
Poster by D. Longuevergne MOPO017

GANIL, CEA, IPNO : SPIRAL-2 (1)

Project objectives: construction of a 40 MeV deuterons accelerator (which can also accelerate q/A = 1/3 and 1/6) as a driver for RIB production



Beta 0.07 energy section L~35 m **Beta 0.12 energy section**

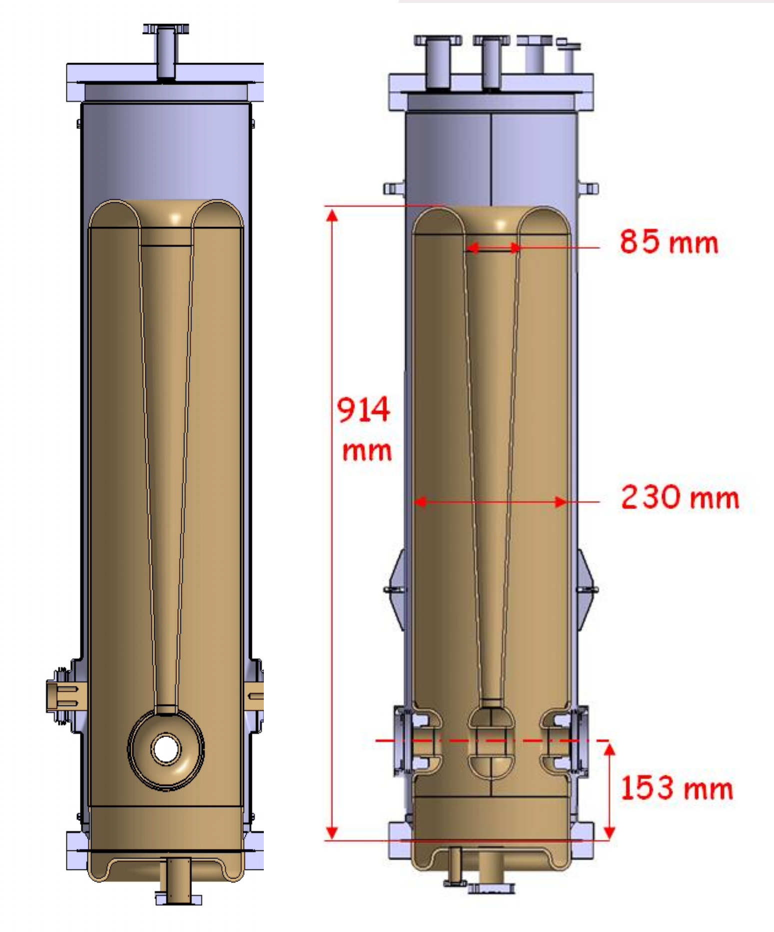


Cryomodule A	Cryomodule B	Power coupler
CEA Saclay	IPN Orsay	LPSC Grenoble

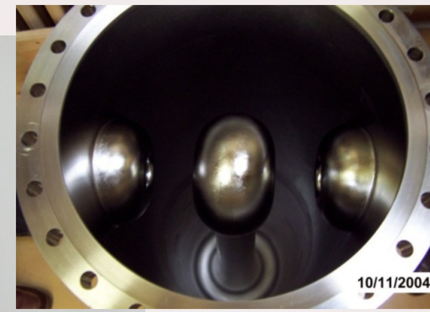
Cryomodule	A	B
Valve-to-valve length [mm]	610	1360
# cavities	12	14
f [MHz]	88.05	88.05
β_{opt}	0.07	0.12
Epk/Eacc	5.36	4.76
Bpk/Eacc [mT/MV/m]	8.70	9.35
r/Q [Ω]	599	515
Vacc @ 6.5 MV/m & β_{opt}	1.55	2.66
Lacc [m]	0.24	0.41
Beam tube ∅ [mm]	38	44

GANIL, CEA, IPNO : SPIRAL-2 (2)

Low beta cavities ("A" type): developped by CEA Saclay: QWR with dismountable copper bottom flange



Courtesy P. Bosland

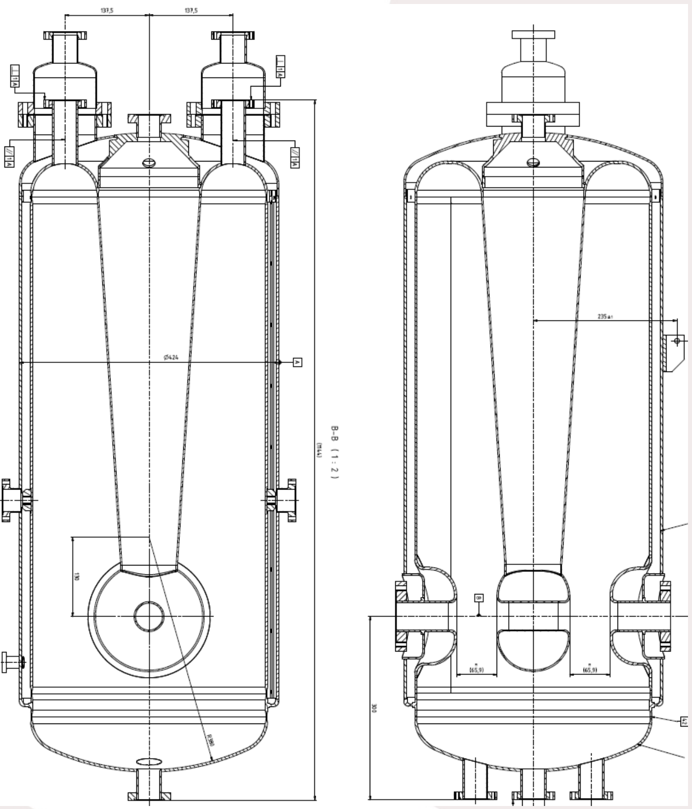


Zanon and SDMS cavities

12 over 13 cavities received – 1 under repair

GANIL, CEA, IPNO : SPIRAL-2 (3)

High beta cavities ("B" type): developed by IPN Orsay: QWR with welded Nb bottom flange, Titanium He tank (4 mm), SS cavity flanges.

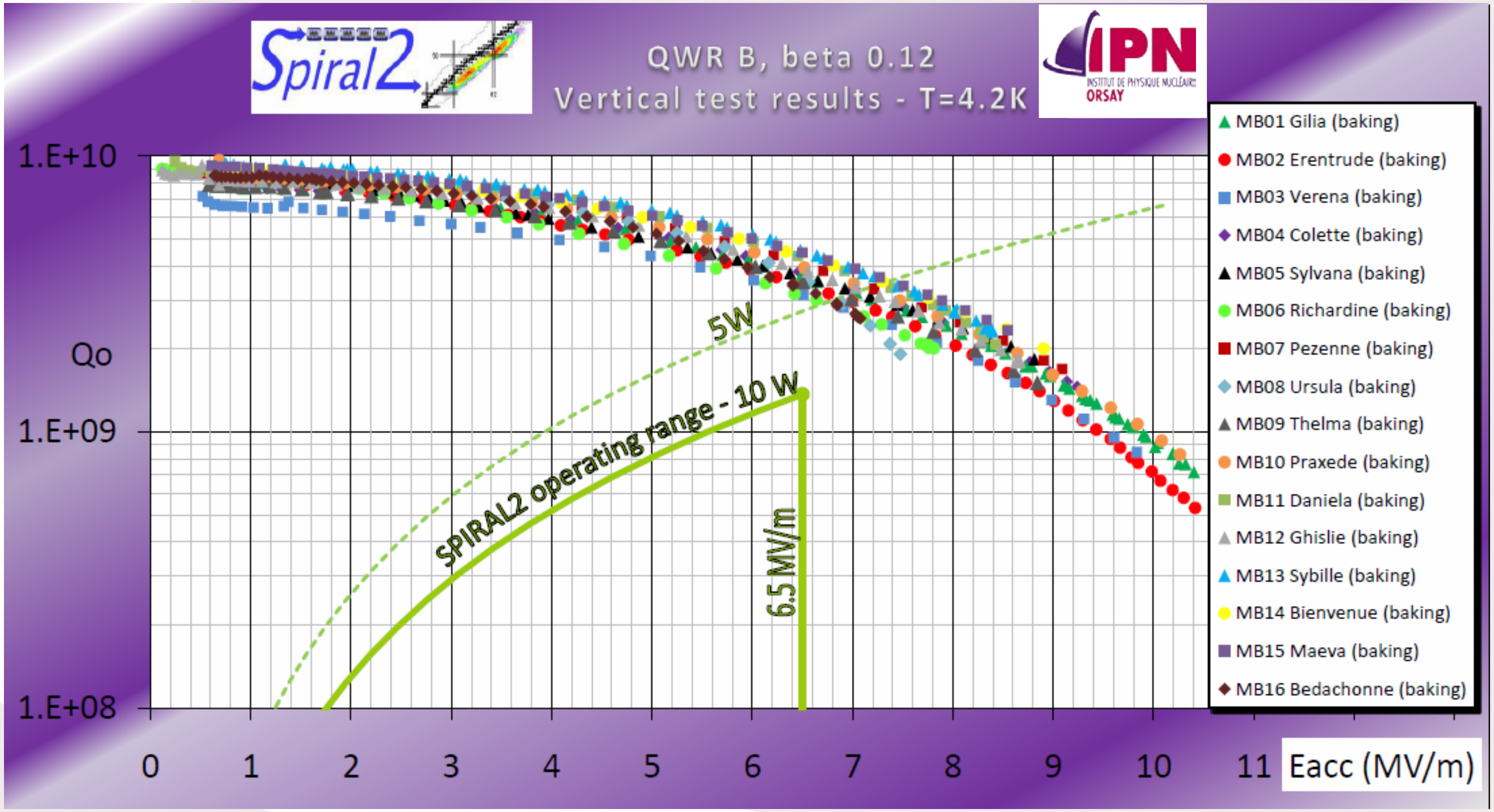


Total produced: R&D phase: 1 prototype +2 pre-series
Series production: 16 (made by Research Instruments)

GANIL, CEA, IPNO : SPIRAL-2 (4)

Performance Goal : 6.5 MV/m and 10 W max.

- Preparation: standard BCP, HPR @ 100 bar, class 10 clean room assembly
- All cavities exhibits multipacting. MP Barriers above 1 MV/m are easily processed. FE level and onset is variable, but when present, it is always processed in VT.
- Low β cavities: cavities tested so far are in the spec. Some have Eacc > 10 MV/m !
- High β cavities: all series cavity tested and in the spec with important margins !



IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

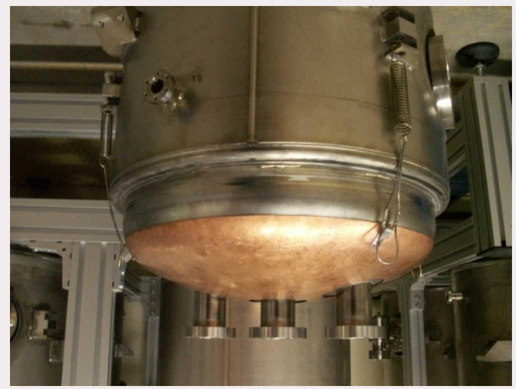
GANIL, CEA, IPNO : SPIRAL-2 (4)

High beta cavities : baking effect

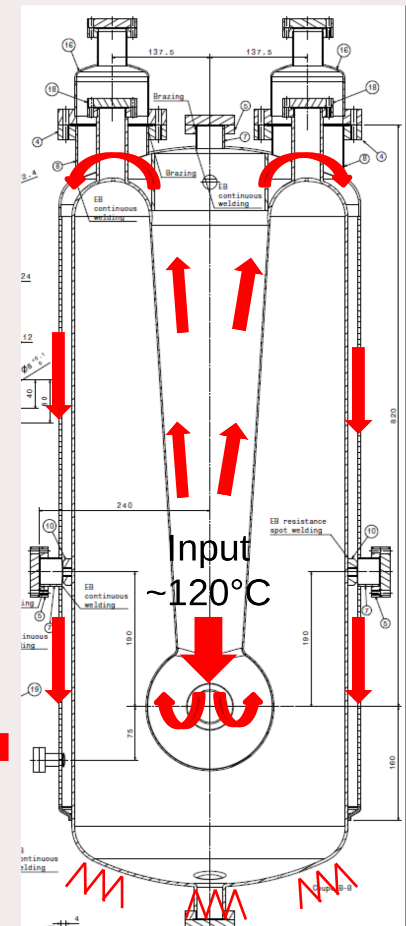
Courtesy G. Olry

- After 72h drying -> 48 h baking @ 120°C
- “Forced” air flow inside the helium vessel + heater on the cavity bottom
- Cavity wrapped in a foil blanket

Cavity	Losses @ 6.5 MV/m [W]	
	No baking	With baking
MB01	8.5	3.7 (-56%)
MB02	6.9	4.1 (-41%)
MB03	7.0	4.4 (-47%)
MB04	8.4	3.6 (-58%)
MB05	7.2	3.5 (-51%)
MB06	7.5	4.8 (-36%)
MB07	6.9	3.4 (-51%)
MB08	X	4.0
MB09	8.9	3.9 (-56%)
MB10	7.1	3.5 (-51%)
MB11	X	3.1
MB12	X	3.8
MB13	X	3.0
MB14	X	4.0
MB15	X	3.1
MB16	X	3.9
Mean value	**7.6**	**3.7**



Heater (not shown) glued onto the copper cap



Output ~110°C

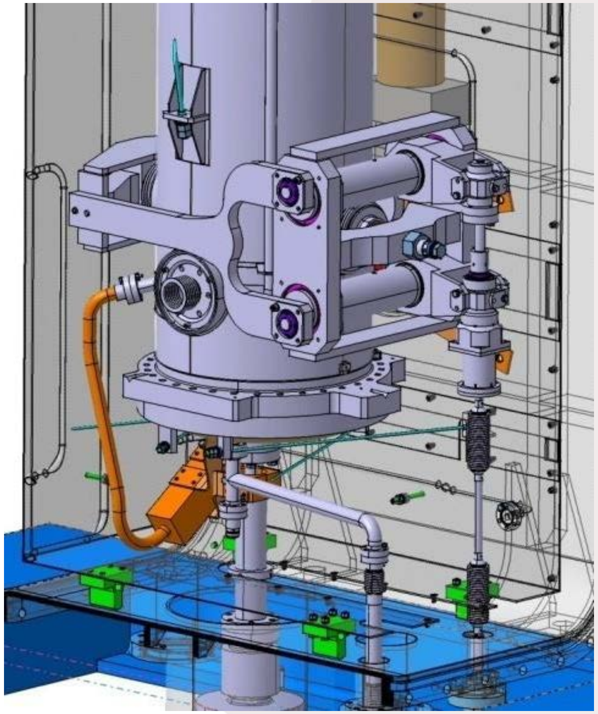
Heater ~110°C

Losses divided by ~2 @ Eacc=6.5 MV/m

GANIL, CEA, IPNO : SPIRAL-2 (5)

Low β Cold tuning system

Mechanical tuner, push system

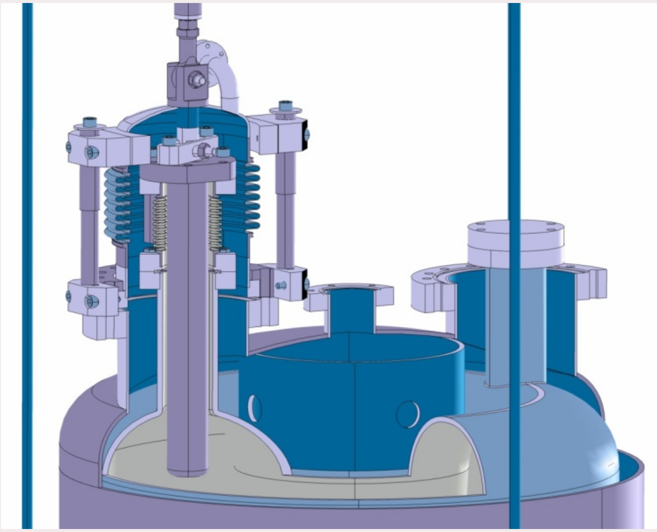


Good linearity: 0.15 Hz/motor step
Sensitivity: ~28 kHz/mm
Full range: +25 kHz

High β Cold tuning system

Tuning by insertion of an Nb rod

2 ports on the top of the cavity:
a) One static plunger
b) One moving plunger



Sensitivity ~1 kHz/mm with Ø 30 mm plunger

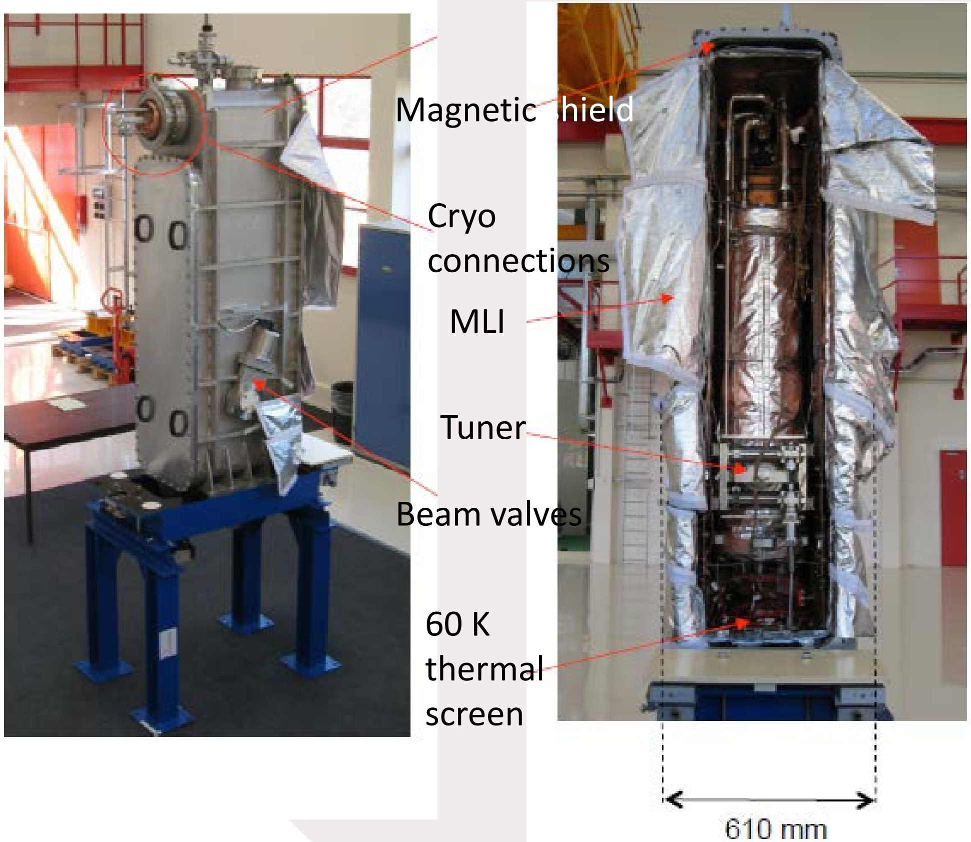
Introducing one plunger by 50 mm(Ø 30 mm)

First "coarse" tuning: + 50 kHz

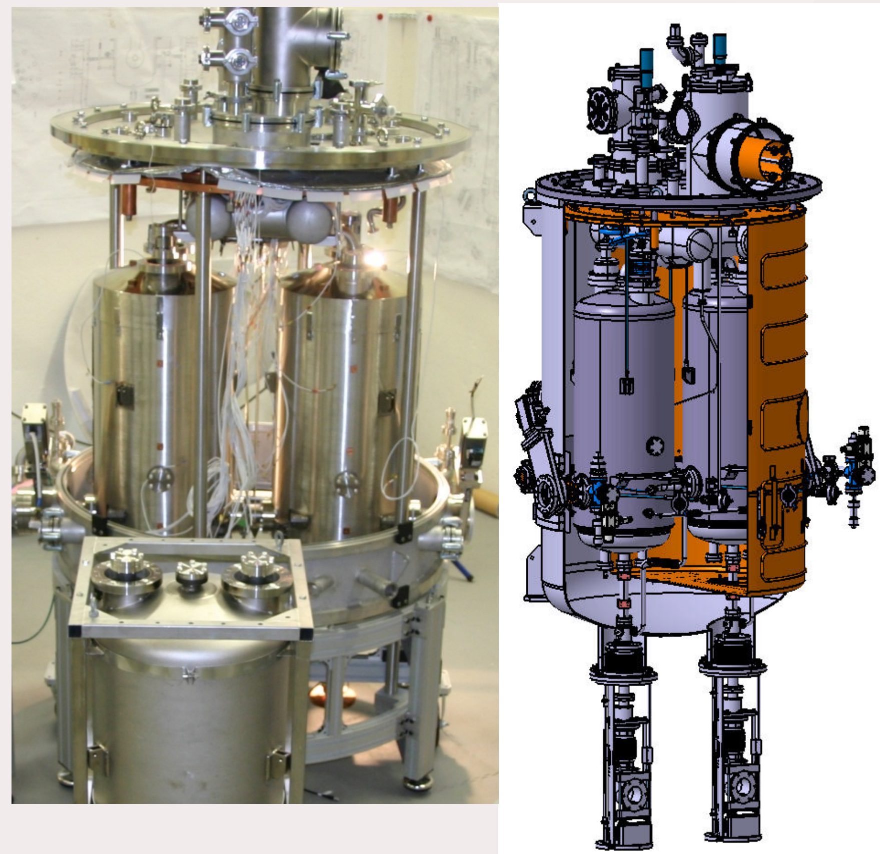
then fine tuning: +/- 4 kHz

GANIL, CEA, IPNO : SPIRAL-2 (6)

Low β Cryomodule



High β Cryomodule



Two different layout, but both have separated vacuum (clean string assembly)

Power couplers: developed by LPSC Grenoble: see FRIOA04 by Y. G. Martinez

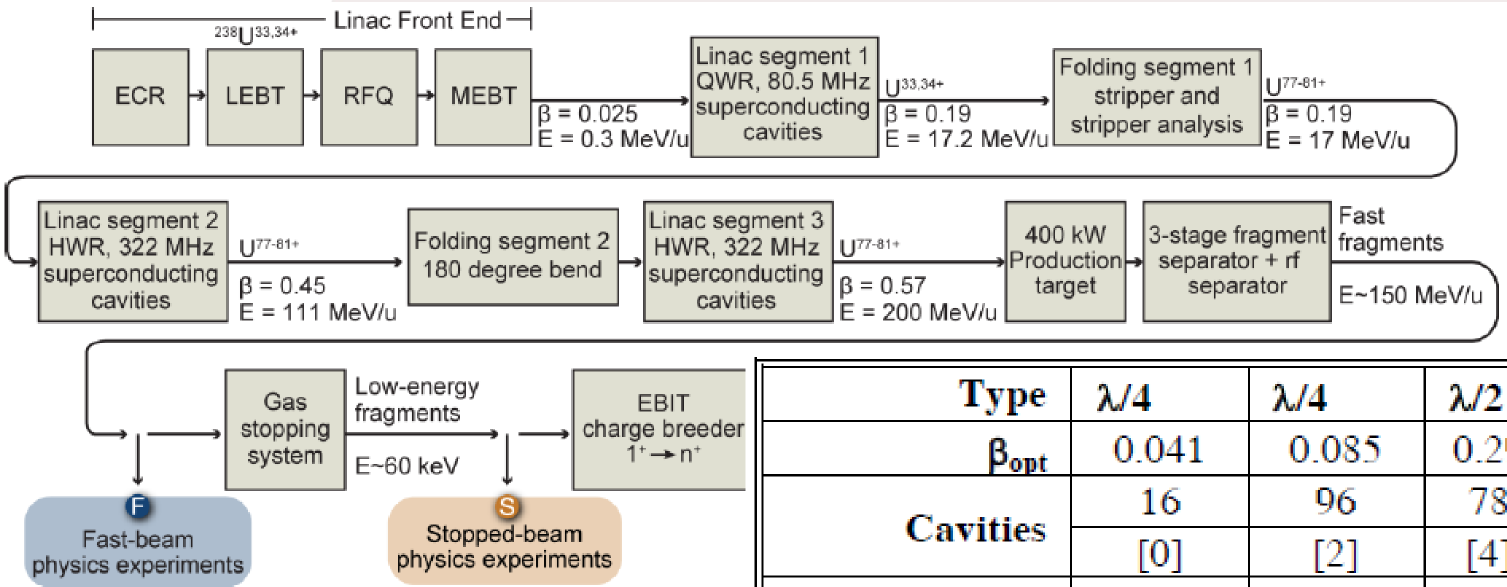
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

MSU : FRIB (1)

MICHIGAN STATE UNIVERSITY

Project objectives: Produce RIB using a 400 kW CW heavy ion driver linac (p to U) up to 200 MeV/u.

Cavity type: Quarter-wave resonators (80.5 MHz) and half-wave resonators (322 MHz), bulk niobium for a total of 344 cavities and 52 cryomodules



Type	λ/4	λ/4	λ/2	λ/2	
β_{opt}	0.041	0.085	0.29	0.53	Total
Cavities	16	96	78	144	
	[0]	[2]	[4]	[4]	344
Solenoids	16	36	13	8	
	[0]	[0]	[2]	[2]	87
Cryomodules	4	12	13	18	
	[0]	[1]	[2]	[2]	52

in []: matching cryomodule

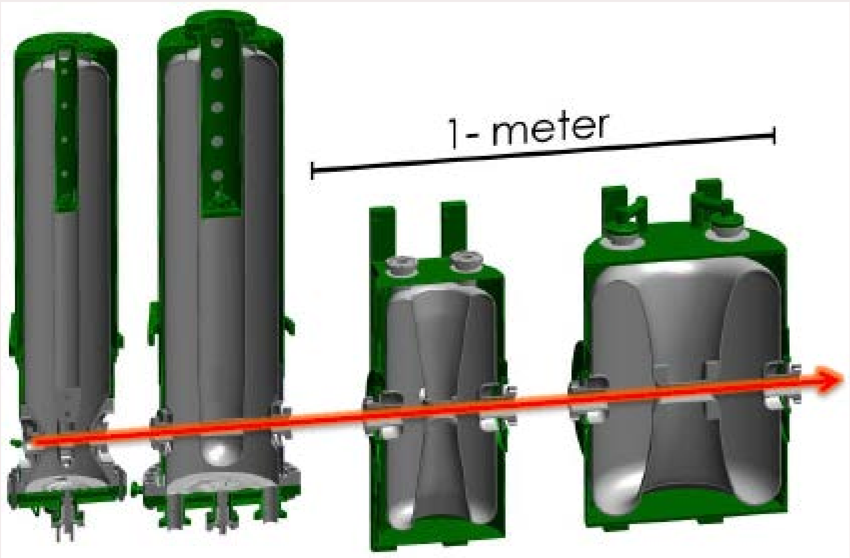
Courtesy Q. Zhao, R. York

MSU : FRIB (2)

Cavity type: Quarter-wave resonators (80.5 MHz) and half-wave resonators (322 MHz), bulk niobium for a total of 344 cavities and 52 cryomodules

Type	λ/4	λ/4	λ/2	λ/2
β_{opt}	0.041	0.085	0.29	0.530
f(MHz)	80.5	80.5	322	322
Aperture (mm)	30	30	30	40
V_a (MV)	0.81	1.62	1.90	3.70
E_p (MV/m)	30.0	31.5	31.5	31.5
B_p (mT)	53	71	75	77
T(K)	4.5	4.5	2.0	2.0

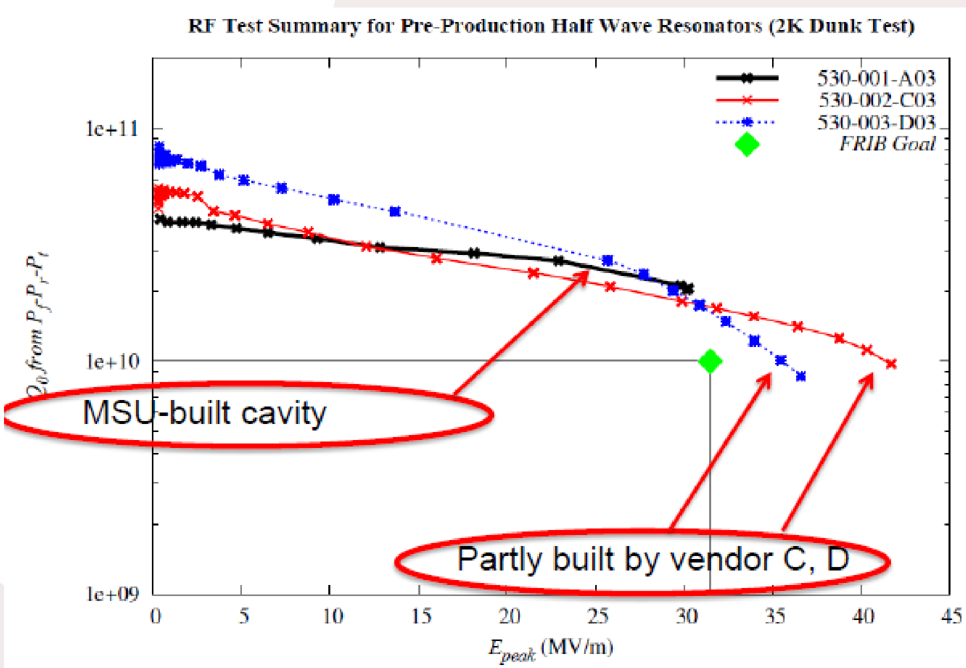
4 cavity types and 2 frequencies



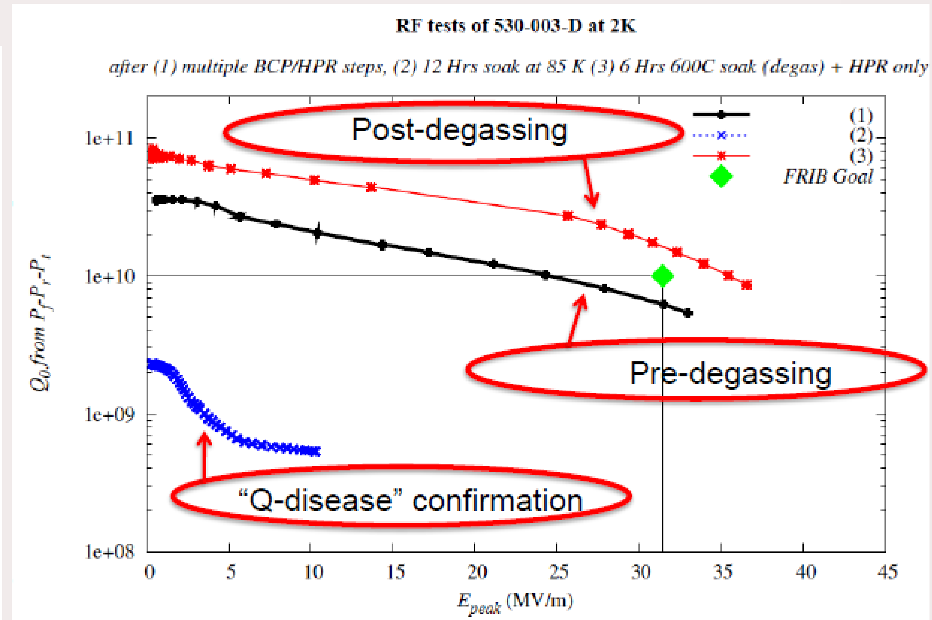
MSU : FRIB… and ReA3 (3)

Cavity study status:

- **Developments for ReA3: a FRIB technology "prototype"** : β=0.041 QWR cavities successfully accelerates beam at ReA3; tested for FRIB gradients (first accelerated beam by the cryomodule in May 2011)
- **5 β=0.53 HWR** prototypes fabricated and 3 tested



Tests in March 2011

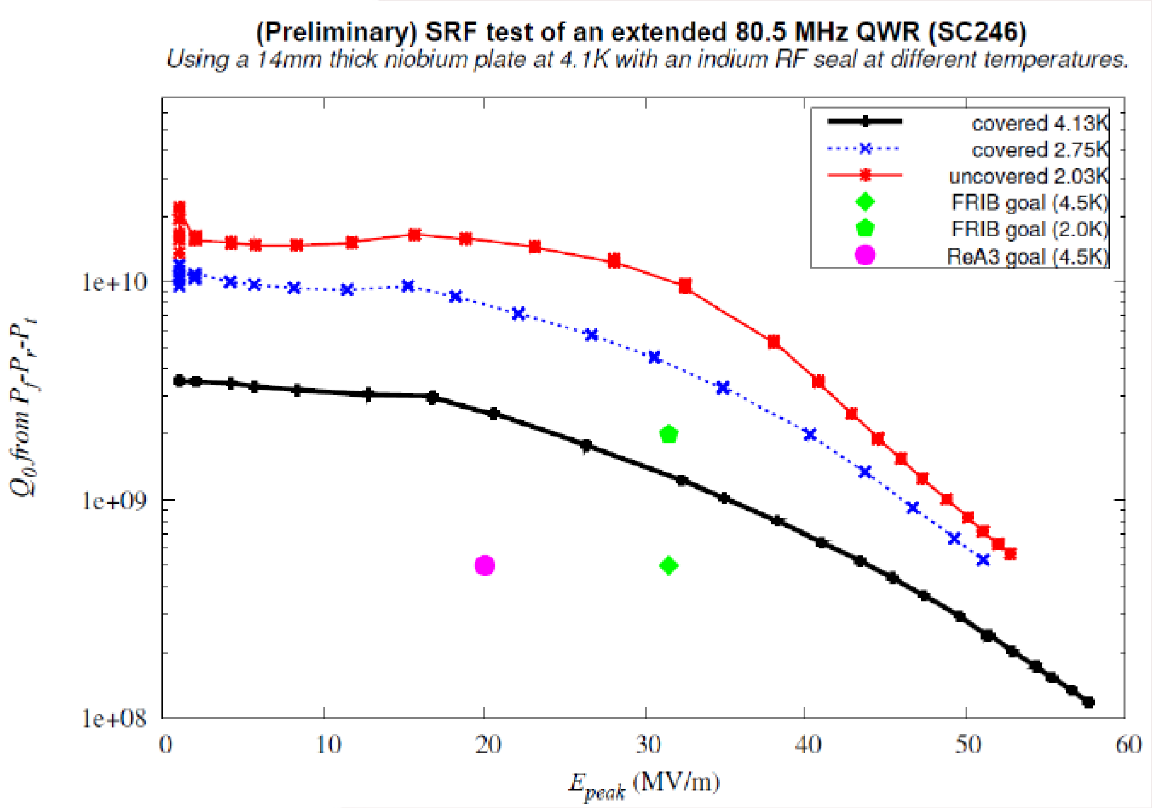


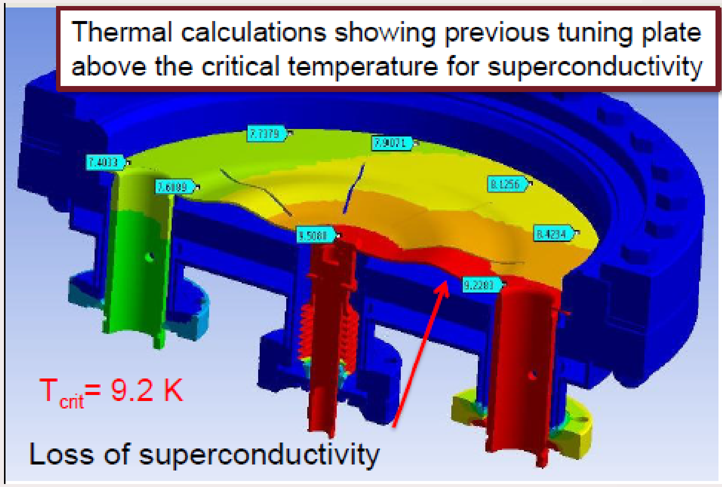
Study of Q-disease

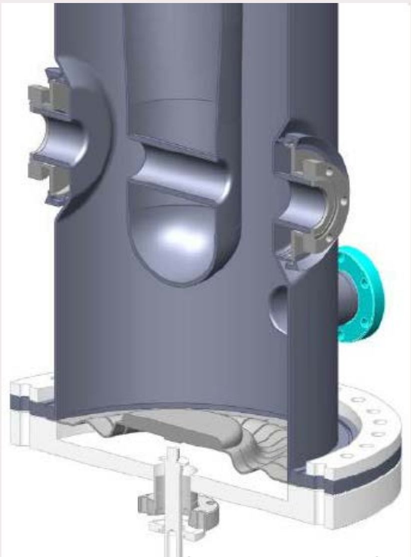
MSU : FRIB… and ReA3 (4)

Cavity study status:

- **Test of β=0.085 QWR** prototype







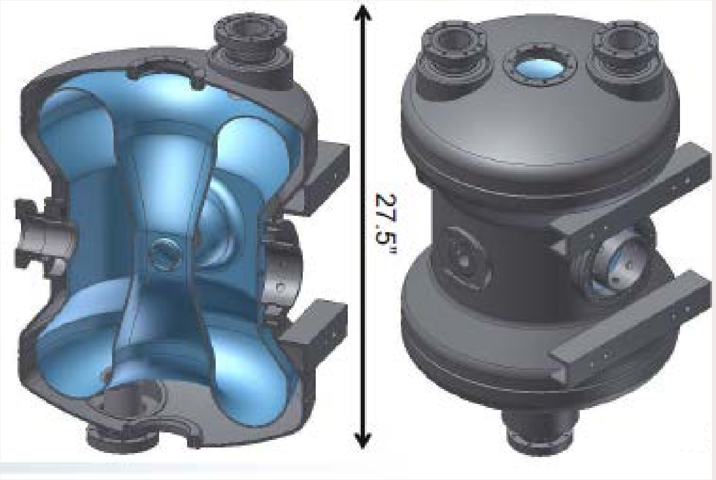
Cavity tests performed at 2K and 4.2 K

Improved tuner design under progress

MSU : FRIB… and ReA3 (5)

Study of alternatives:

- **Feb 2011:** Down selection between 161 and 322 MHz -> 322 MHz chosen
- **April 2011**: Down selection between single spoke & HWR -> HWR chosen
- **An optimized β=0.29 HWR** prototype as anpotential alternative will be studied by ANL.

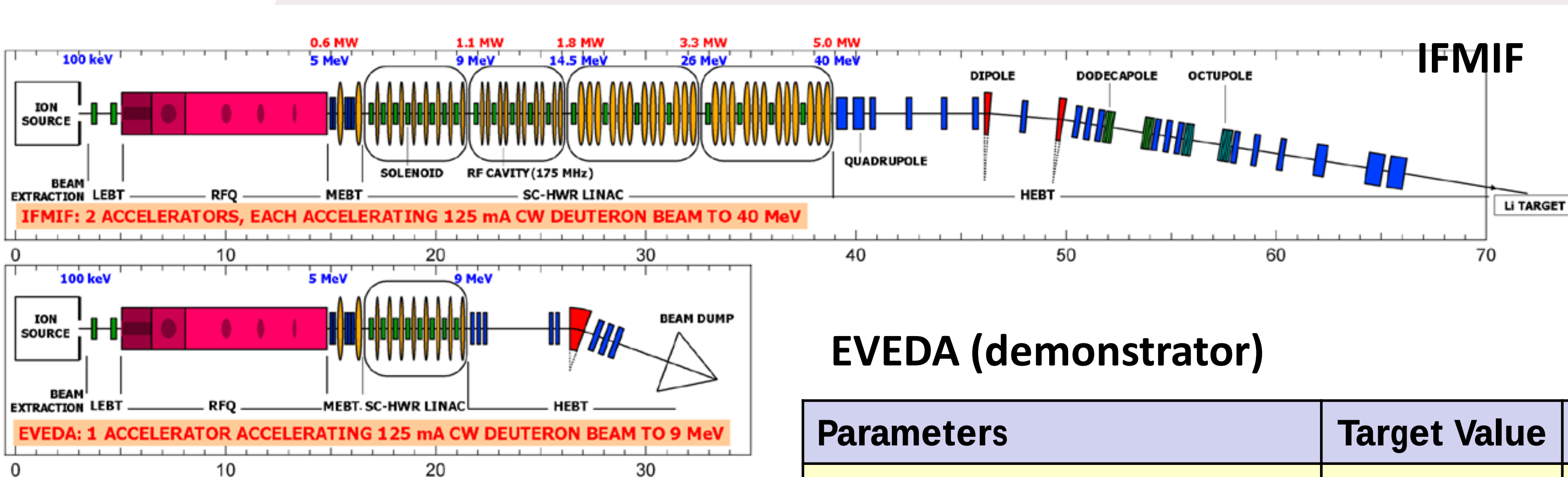


More information on FRIB : Poster MOPO009 by M. Leitner et al.

on ReA3 : Talk THIOB03 by D. Leitner

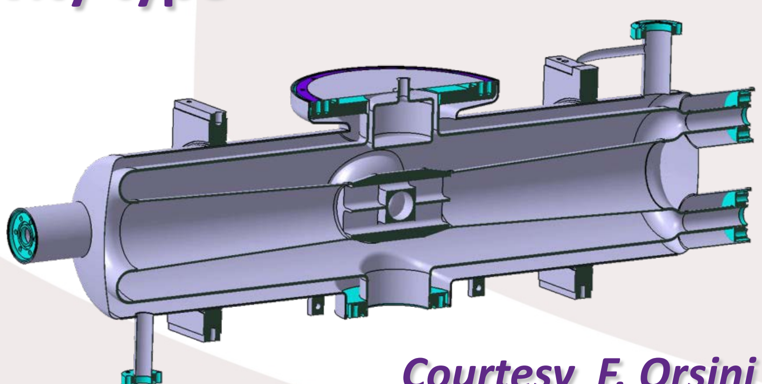
CEA Saclay : IFMIF

Project objectives: characterization of materials with intense neutrons flux (10^{17} n/s) for the future Fusion Reactor DEMO (~150 dpa). Based on two CW 40 MeV deuterons SC linac, 125 mA each.



EVEDA (demonstrator)

Cavity type: Half-wave resonators



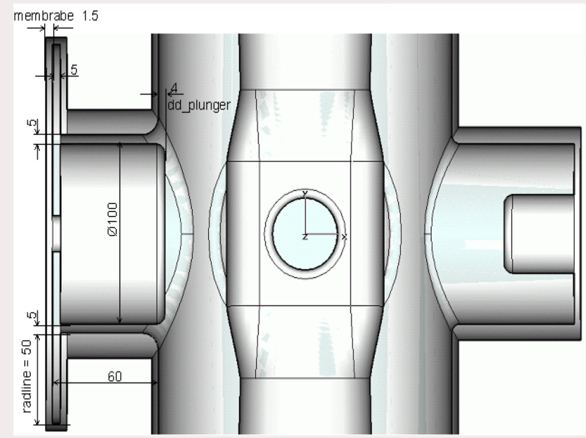
Courtesy F. Orsini

Parameters	Target Value	Units
Frequency	**175**	**MHz**
β value	0.094	
Accelerating field E_a	4.5	MV/m
Unloaded Quality factor Q_0 for R_s=20 nΩ	1.4×10^9	
Freq. range of HWR tuning syst	$\pm$ 50	kHz
Max. transmitted RF power by coupler (CW)	200	kW
External quality factor Q_{ex}	6.3×10^4	

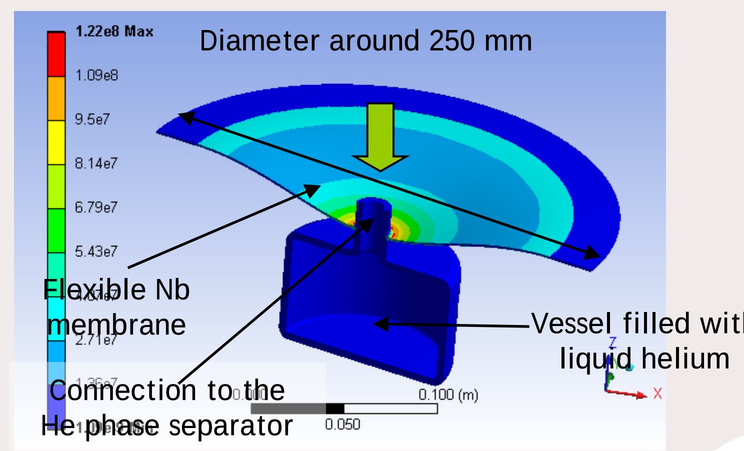
CEA Saclay : IFMIF (2)

Prototyping status: 2 prototypes have been fabricated and are under testing phase. Preliminary results shows strong MP barriers.

Cavity HPR at IPNO



Cold tuning system ("mushroom")



More information :

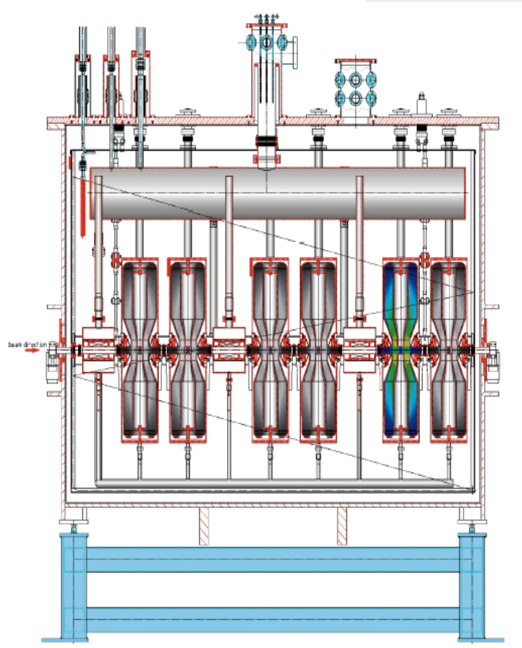
F. Orsini talk on Thursday (THIOB02)

SOREQ : SARAF

Project objectives: SARAF phase 1 : a 2 mA protons and deuterons beam up to 4 MeV (resp. 5 MeV).

Cavity type: 6 Half-wave resonators / module; beta 0.09 @ 176 MHz.

Specifications: P<10 W/cavity @ Epk=25 MV/m (Eacc=5MV/m)



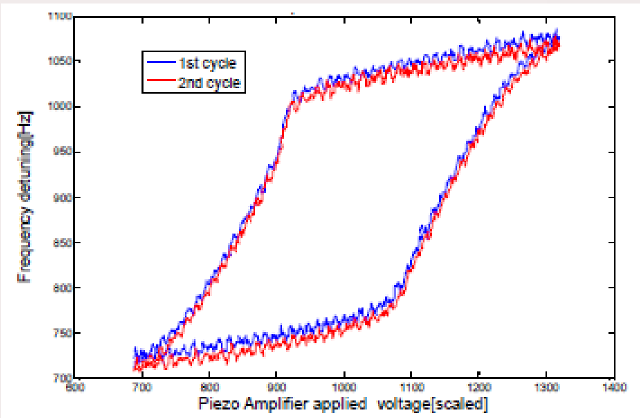
Courtesy I. Mardor

PSM Cryomodule test:

- Each of the cavities individually reached stable operation at its specified field (Epk of 25 MV/m, corresponding to a voltage of 840 kV).
- FE: Improvement after He processing (a few 10^{-5} mbar)
- Difficulties with stable simultaneous operation of all cavities at nominal field due to cavity high sensitivity to He pressure variations (60 Hz/mbar).

-> difficult to compensate with the tuner (strong hysteresis)

- Increase of available RF power from 2 to 4 kW to compensate

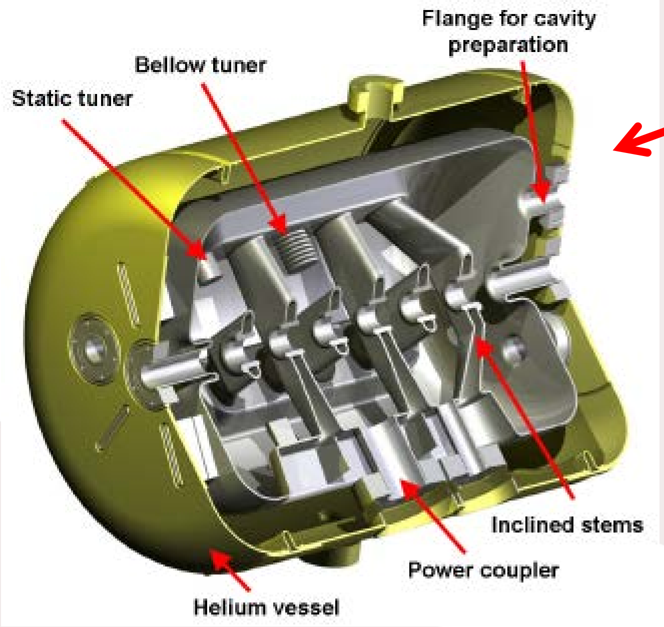


More information : Poster by A. Perry, MOPO011

Other R&D on low β SC cavities

IPN Orsay: Triple spoke development for EURISOL. Reference solution to accelerate the p beam between 60 and 140 MeV.

-> Prototype fabricated (352 MHz, β 0.35), BCP, HPR and assembly done. To be tested in vertical cryostat in september 2011.



IAP Frankfurt: SC CH structure (MYRRHA & CW ion linac). High real-estate gradients for acceleration at low velocities

-> A new prototype fabrication has started, 325 MHz, 7 gaps, beta 0.16.

More information: poster by M. Amberg MOPO035

Conclusion

- SC RF developments for low beta ion accelerators is very active worlwide; many projects are under study or construction and drive intense R&D programs on such accelerating structures.

- There are many issues faced by all projects for these structures: field emission, multipacting, tuning capabilities, and all required a dedicated study because all cavities are different (cavity type, beta, coupling or tuning solutions)…

- Progress done are tremendous, and in some cases, peak fields achieved start to be comparable with the ones obtained on electron cavities.

THANK YOU FOR YOUR ATTENTION!

Acknowledgment

Many thanks to all people who provided me material for this presentation