High Power Accelerator Modules: latest developments worldwide and perspectives for ion accelerators for stable beams

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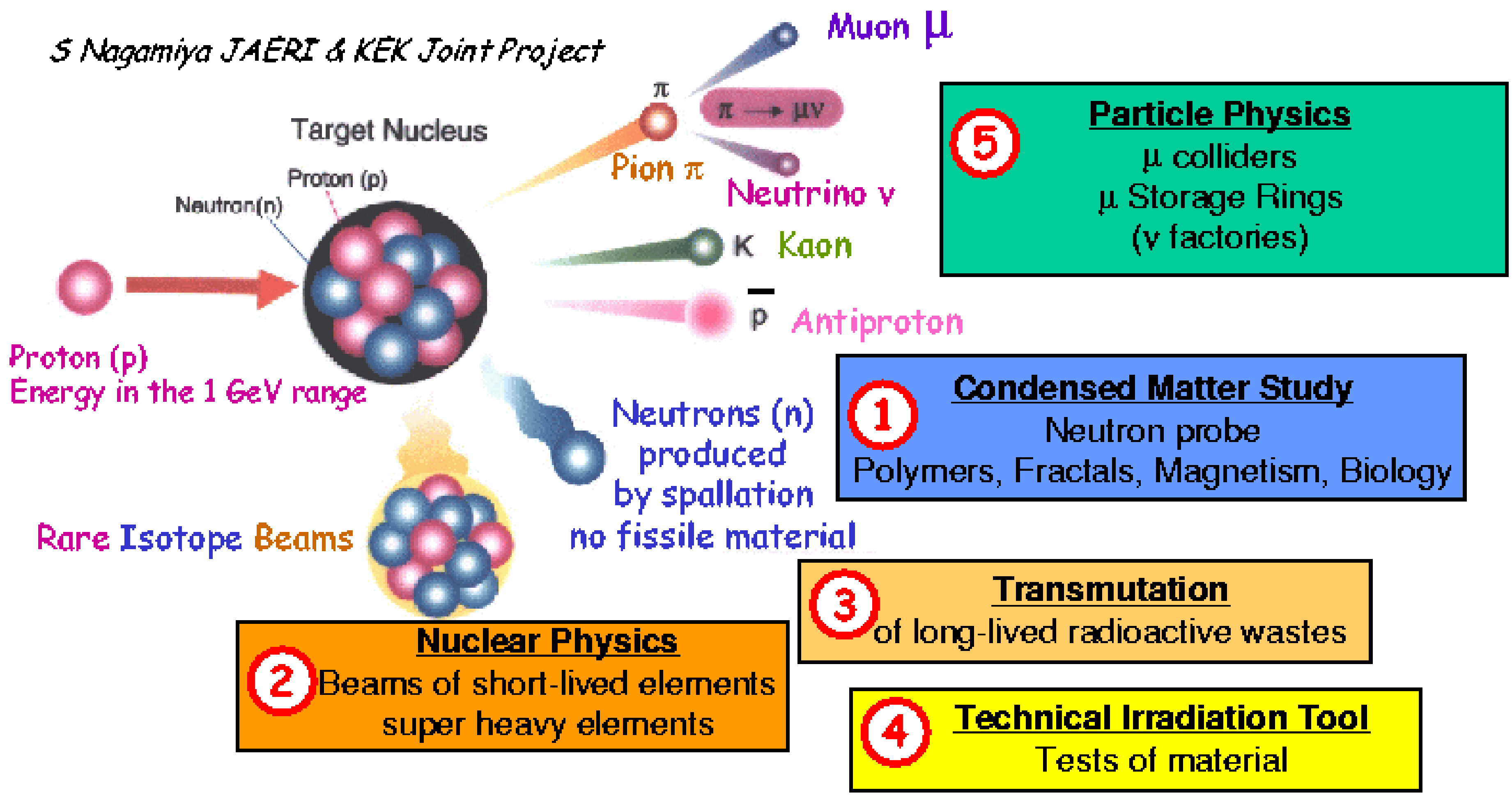
CNRS/IN2P3/ IPN– Paris-Sud University

ECOS Workshop – 18-21 June 2012 – Villa Vigoni

Why High Power Accelerators ?

Secondary beams produced by a high energy proton beam in a target : 5 applications in fundamental and applied research



INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

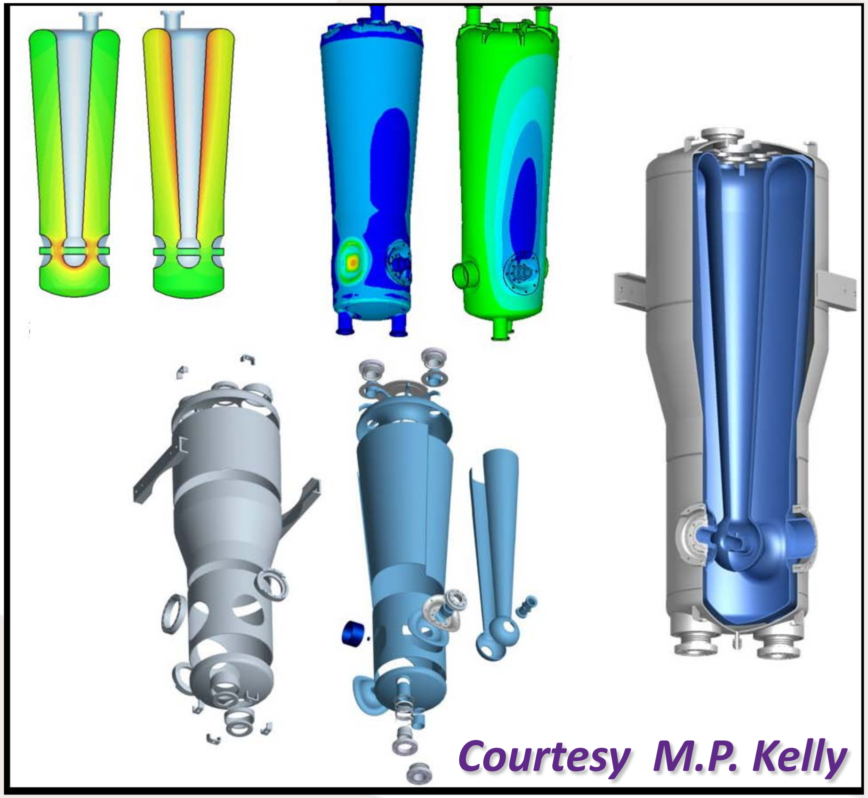
ATLAS
(ANL, USA)

ANL : ATLAS UPGRADE (1)

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 = $\beta\lambda$)**



Courtesy M.P. Kelly

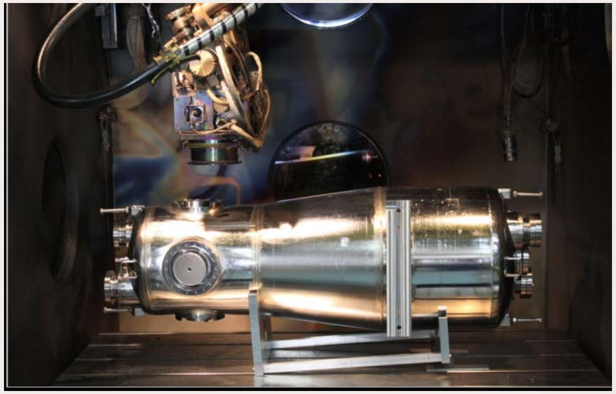
Parameter	Value	Units
Frequency	72.750	MHz
Peak Beta	0.077	
QRs	26.4	Ohm
R/Q	576	Ohm
$\beta\lambda$	31.75	cm
Design Voltage	2.5	MV
$\Delta f / \Delta E^2_{acc}$	-1.9	$Hz/(MV/m)^2$
$\Delta f / \Delta P$	-2.6	Hz/Torr
Tuning Sensitivity	~8	kHz/mm
At Eacc= 1 MV/m		
Stored Energy	0.375	Joule
E_{peak}	5.16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

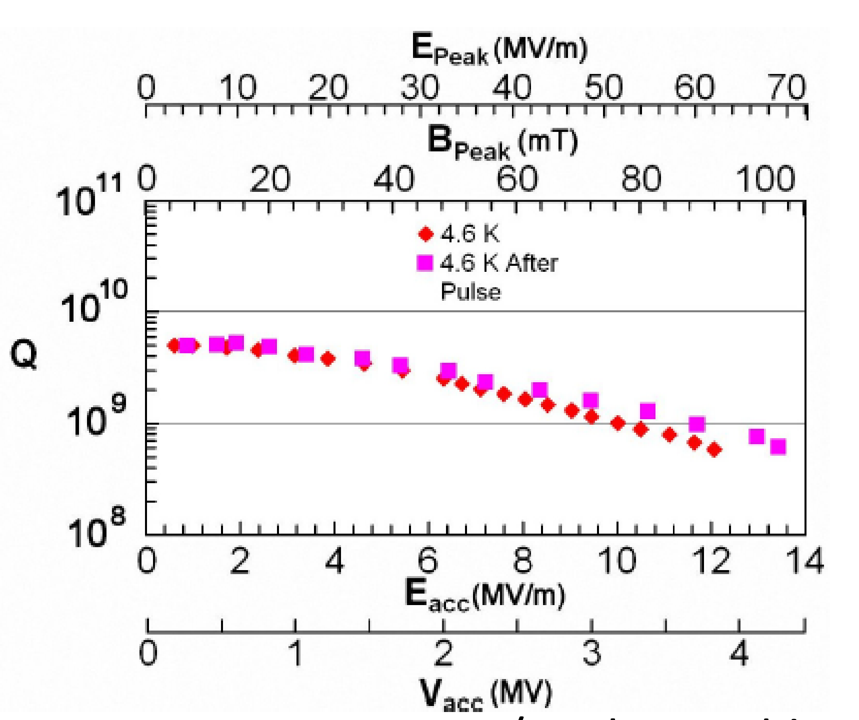
Cavity preparation:

- 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



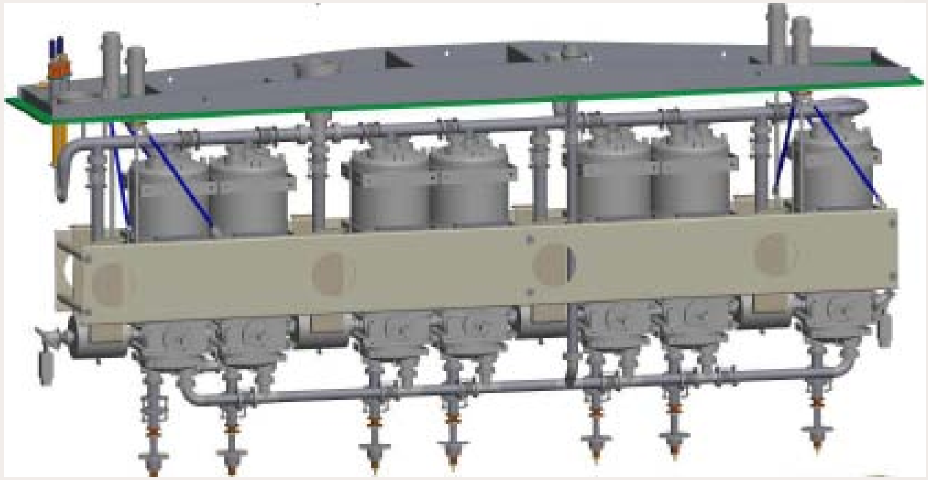
Final EB @ Sciaky

RF test of the first prototype:



A max Eacc = 13.4 MV/m obtained !

Courtesy M.P. Kelly

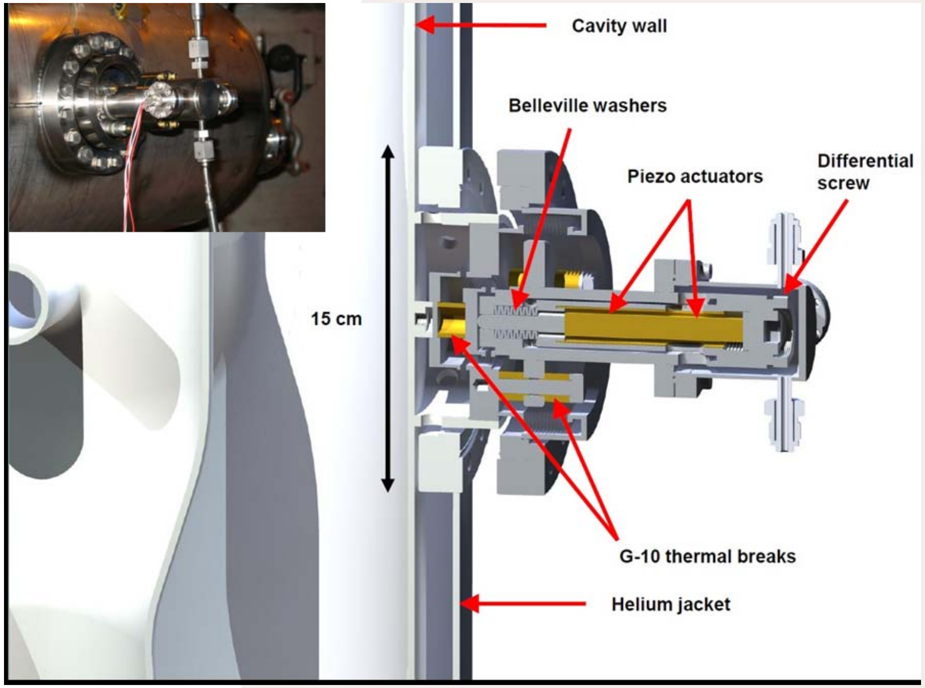


Cryomodule design: 17.5 MV in 5.2 m
Clean cavity string (separate vacuum)

ANL : ATLAS UPGRADE (3)

Cold Tuning System

Cavity wall deformation by piezo



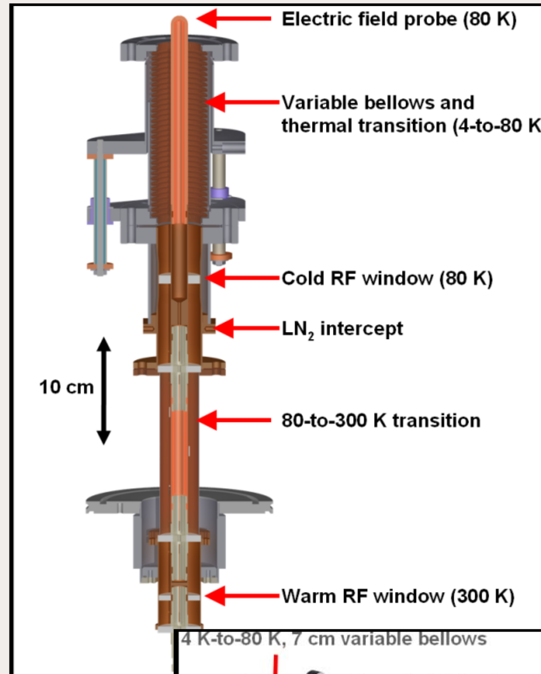
2 Noliac piezo stacks : 10x10x40 mm

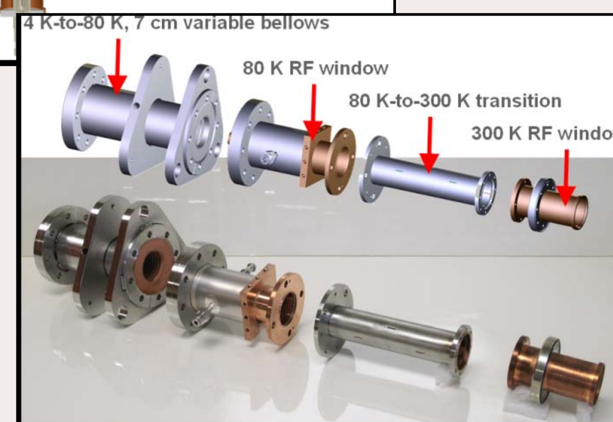
Preload: by compressing 14 Belleville washers

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

HIE ISOLDE
(CERN)

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).

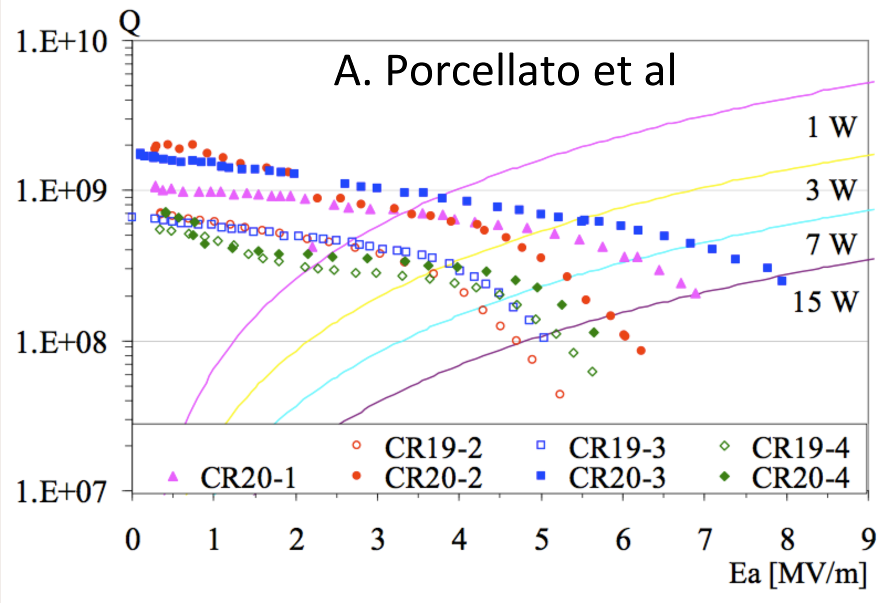
Cavity type: Quarter-wave resonators, Nb/Cu, f=101.28 MHz

- 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

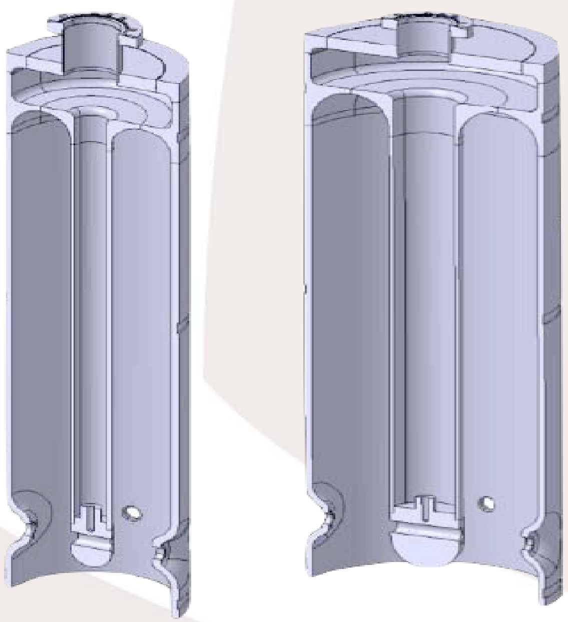


CERN : HIE ISOLDE (2)

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.

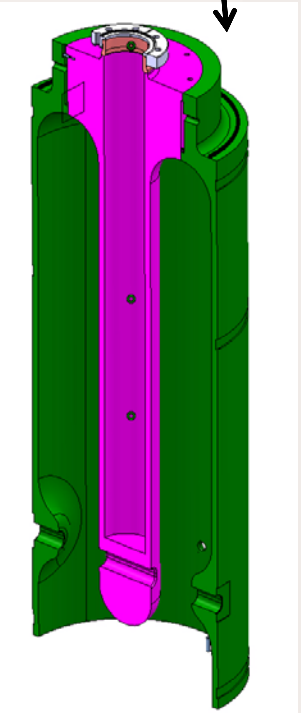
Low β   High β



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

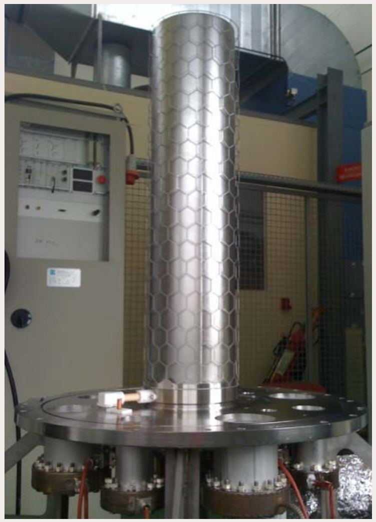


New mechanical design, for a 3D fabrication from a billet

CERN : HIE ISOLDE (3)

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

Bias Diode Sputtering



Magnetron Sputtering

First prototype

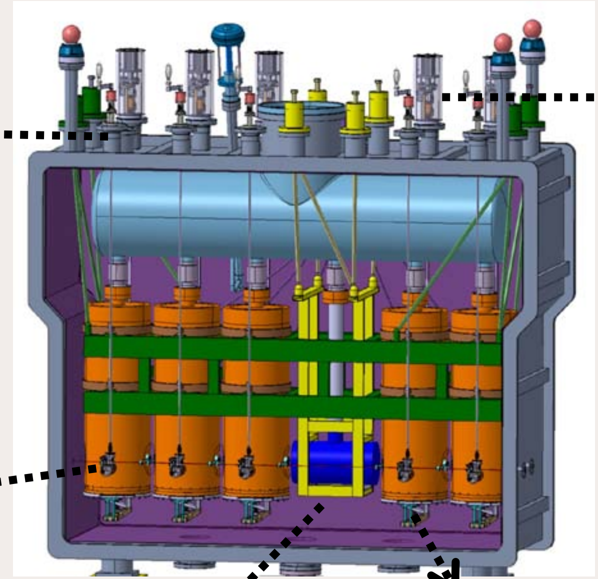
Courtesy M. Pasini

- **Ongoing RF test on cavity prototype**: an accelerating field of 3 MV/m reached, with an important slope on the Q_0. Most recent results showed improvement on Eacc & Qo.
- Optimization of deposition parameters are undergoing (first main goal: increase the RRR of the Nb film)

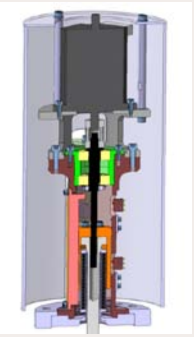
CERN : HIE ISOLDE (4)

Cryomodule: common cavity/cryomodule vacuum, superconducting solenoid

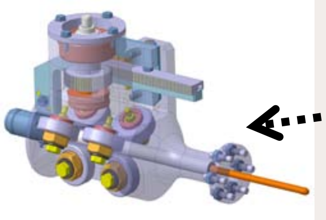
COUPLER POSITIONNER



TUNER MOTORISATION

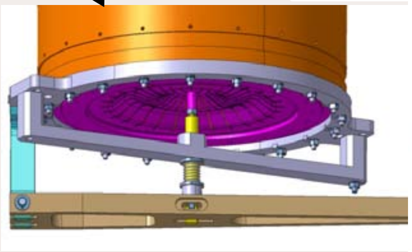


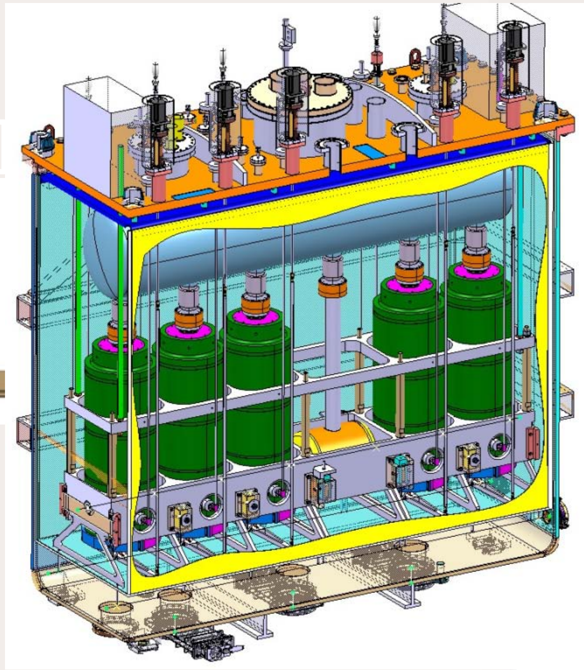
MOBILE COUPLER



PROTOTYPE SOLENOID
***Nb3Sn** (TE/MSC)*

TUNER





Courtesy
O. Capatina

ISAAC-II
(Triumf, Canada)

ISAC - II : TRIUMF

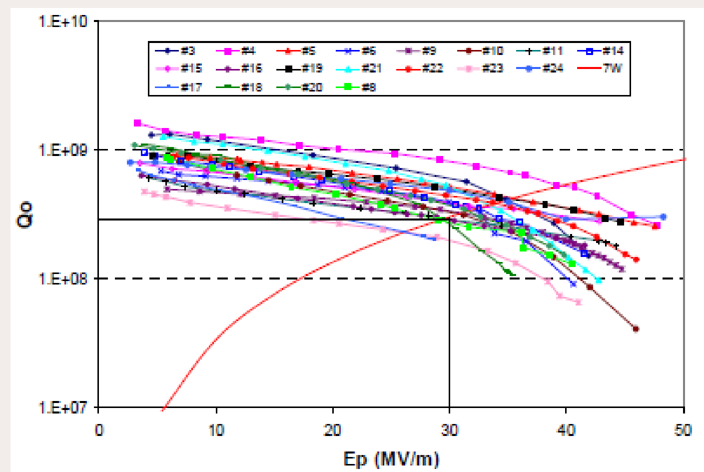
Project objectives: Upgrade of ISAC II (Phase 2)

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)

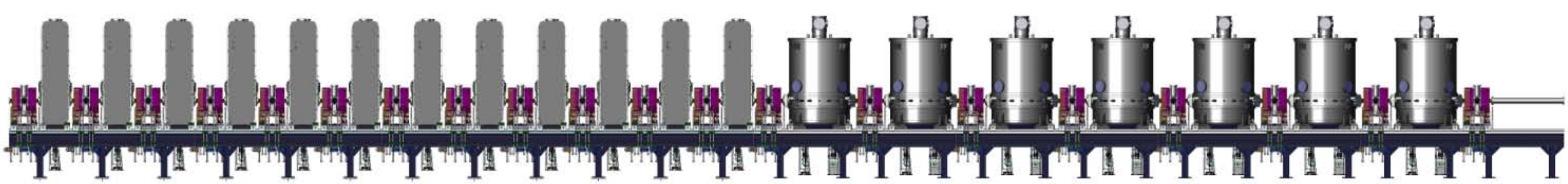


- All cryomodules are installed since March 2010 and have accelerated beam with Epk=26 MV/m in average. Some studies are ongoing to increase cavity performances.*
- Common vacuum between cryomodule vacuum (thermal insulation) and beam vacuum => simplfied cryomodule design but issues with cleanliness… (conditionning)

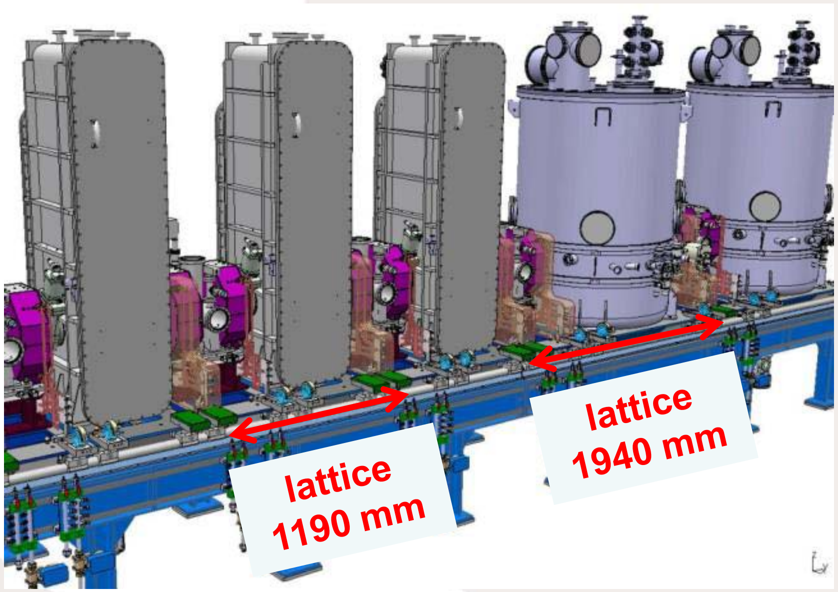
SPIRAL-2
(GANIL,France)

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**

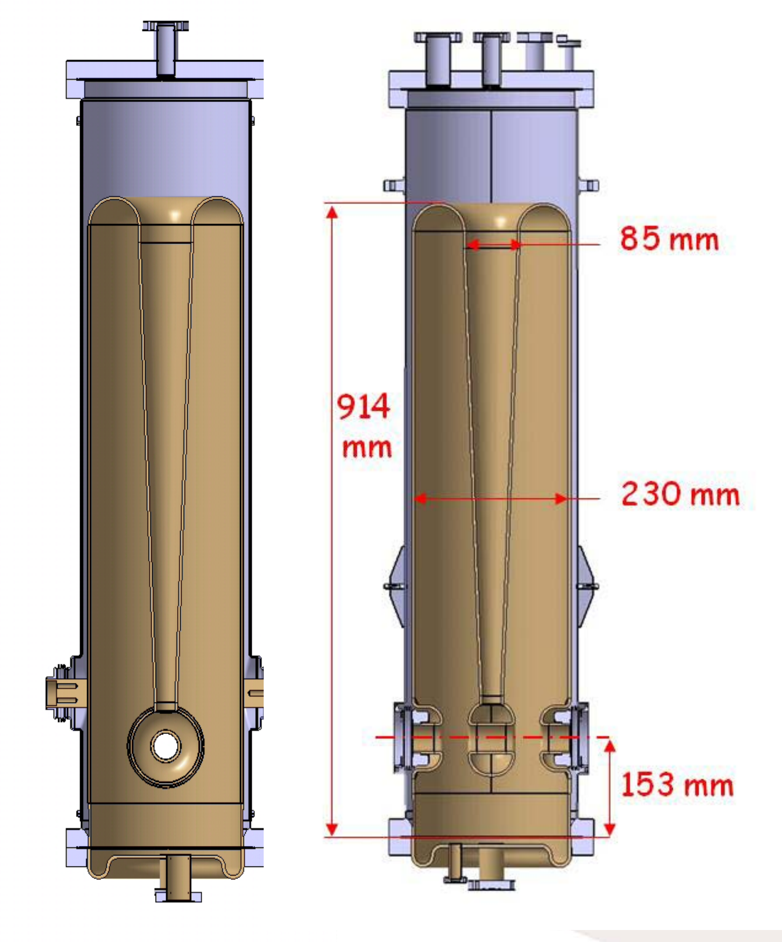


Cryomodule A	**Cryomodule B**	**Power coupler**
CEA Saclay	IPN Orsay	LPSC Grenoble

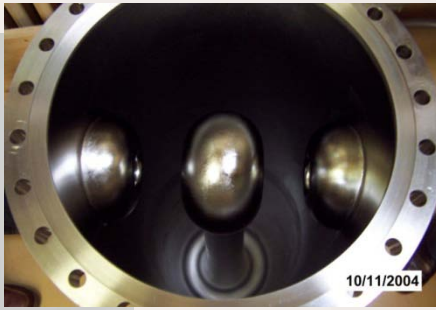
Cryomodule	A	B
Valve-to-valve length [mm]	610	1360
# cavities	12	14
f [MHz]	88.05	88.05
β_{opt}	0.07	0.12
Epk/Eacc	5.36	4.76
Bpk/Eacc [mT/MV/m]	8.70	9.35
r/Q [Ω]	599	515
Vacc @ 6.5 MV/m & β_{opt}	1.55	2.66
Lacc [m]	0.24	0.41
Beam tube ∅ [mm]	38	44

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

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



Courtesy P. Bosland

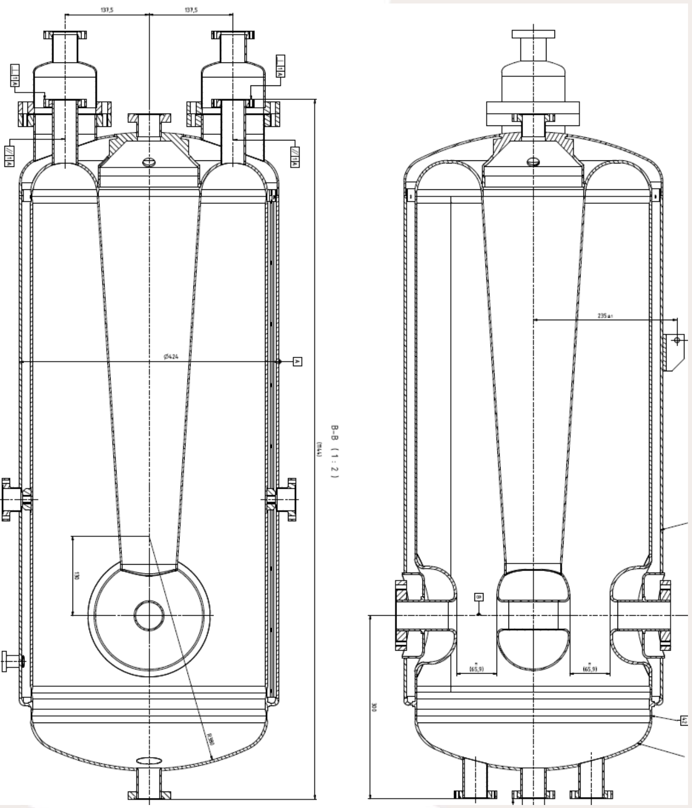


Zanon and SDMS cavities

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.

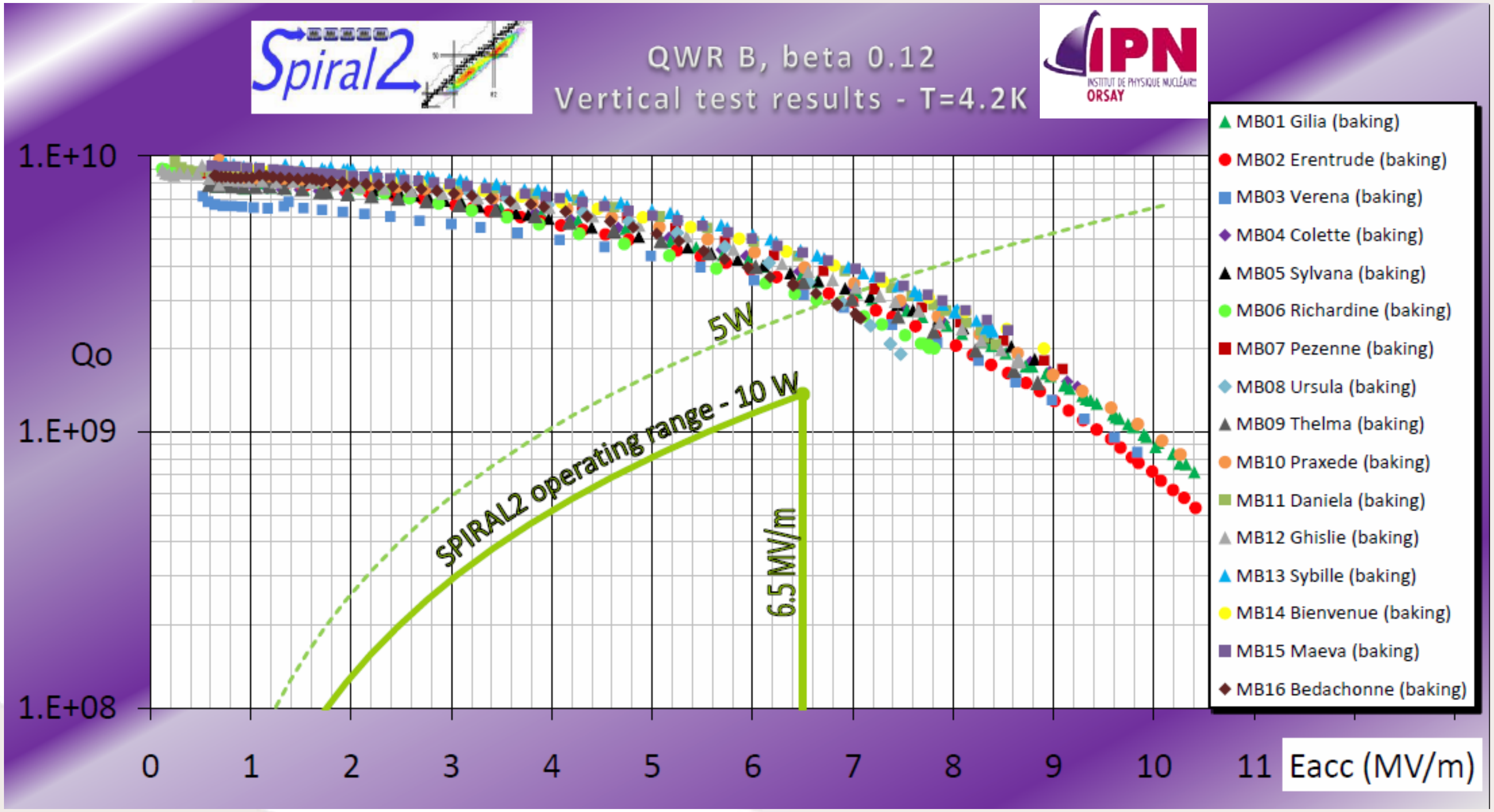


Total produced: R&D phase: 1 prototype +2 pre-series
Series production: 16 (made by Research Instruments)

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: The 10 cavities tested so far are in the spec.
- High β cavities: all series cavity tested and in the spec with important margins !



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
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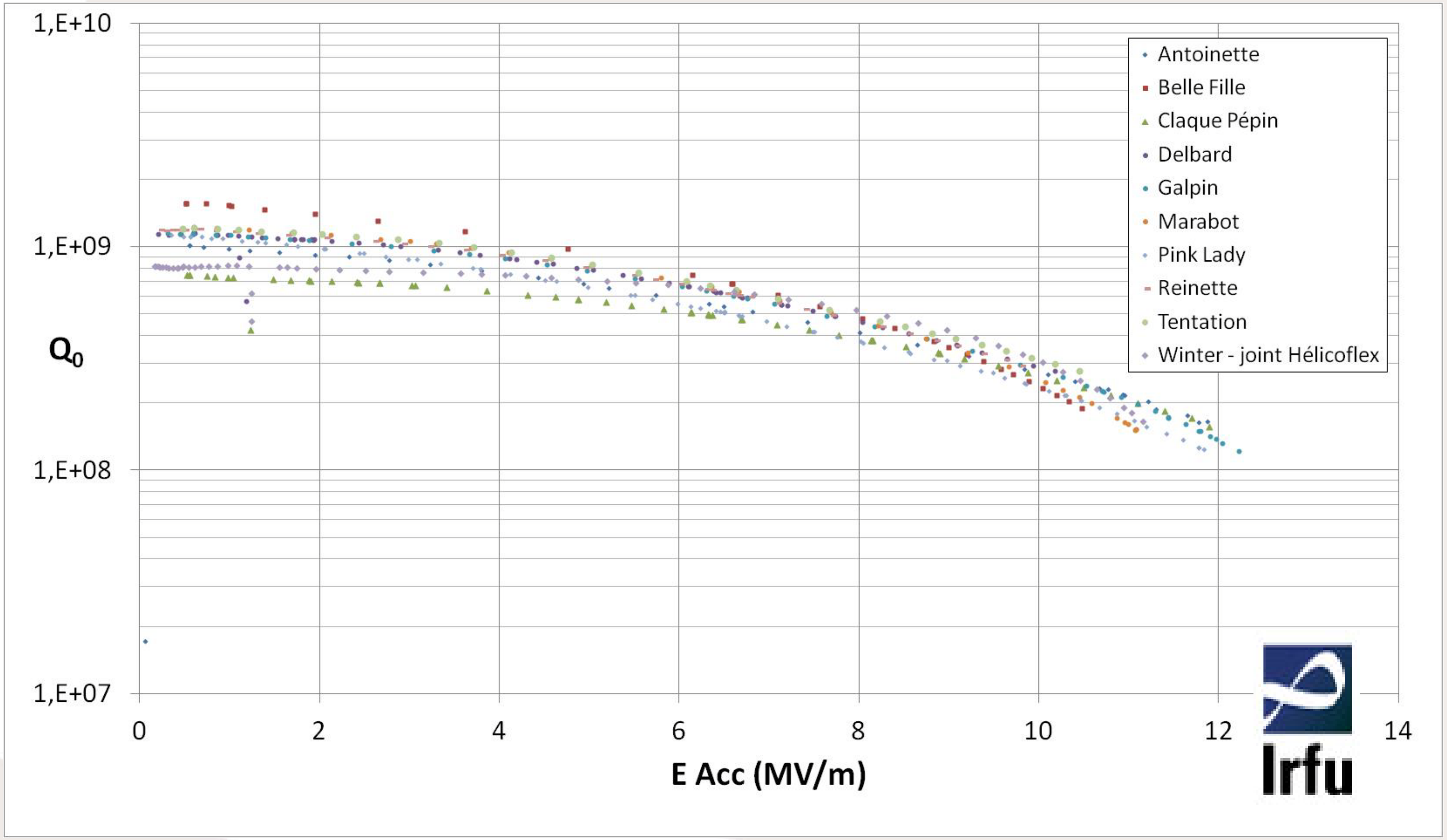


GANIL, CEA, IPNO : SPIRAL-2 (4)

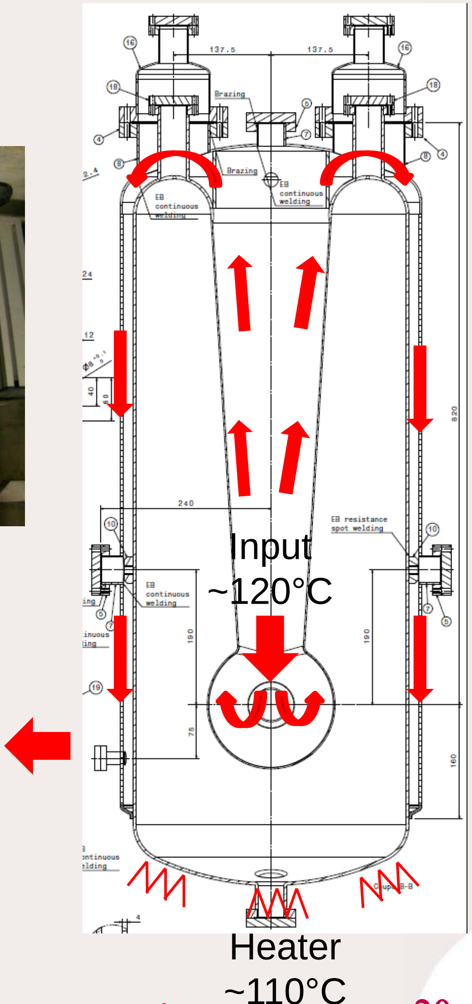
High beta cavities : baking effect

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

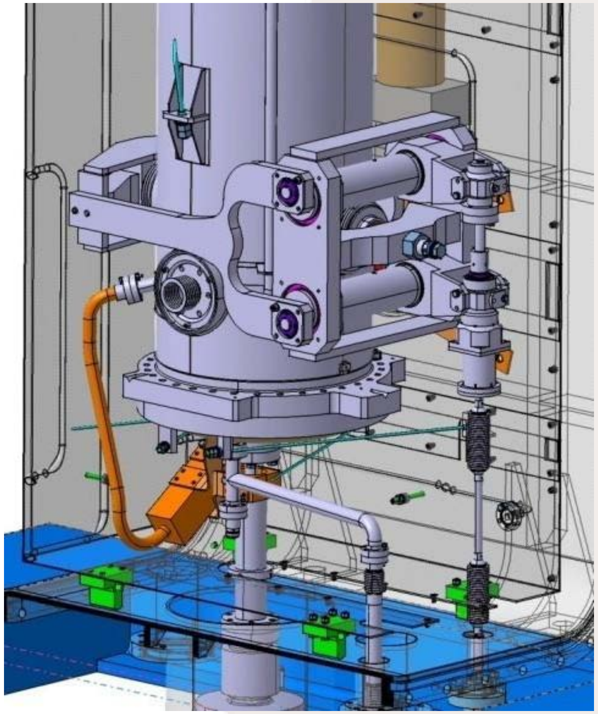


Losses divided by ~2 @ Eacc=6.5 MV/m

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

Low β Cold tuning system

Mechanical tuner, push system

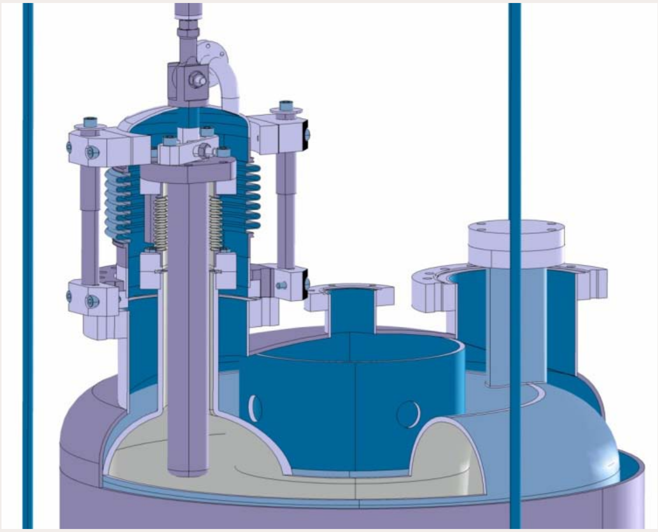


Good linearity: 0.15 Hz/motor step
Sensitivity: ~28 kHz/mm
Full range: +25 kHz

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

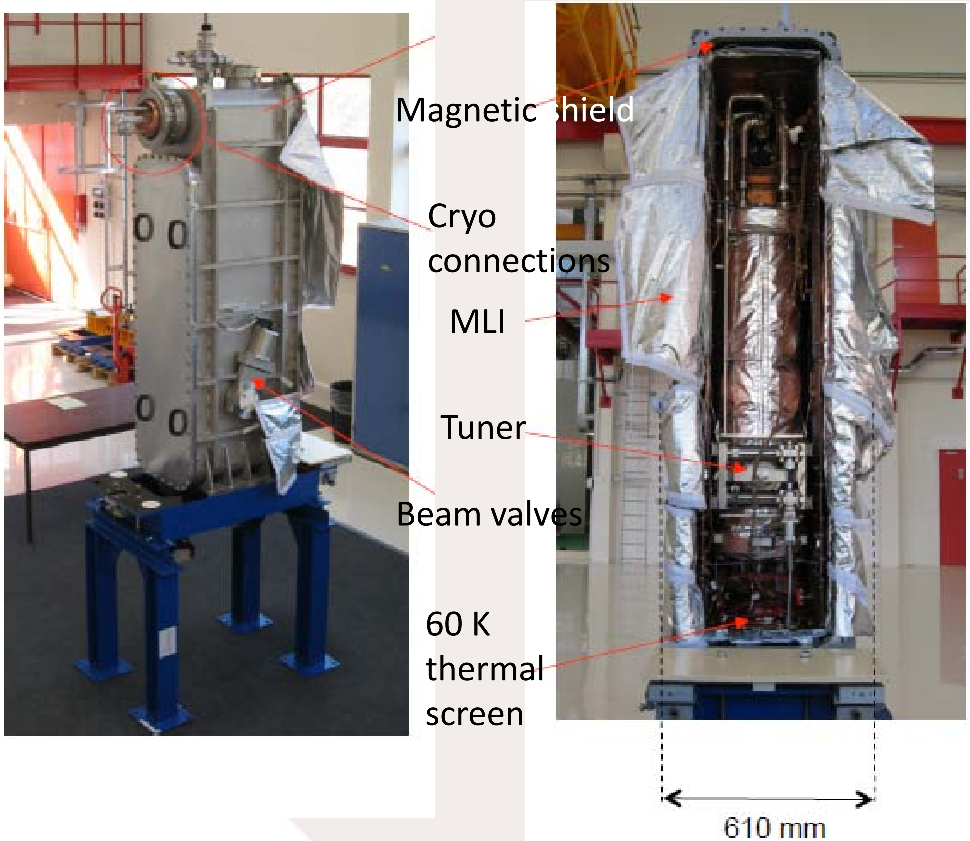
Introducing one plunger by 50 mm(Ø 30 mm)

First “coarse” tuning: + 50 kHz

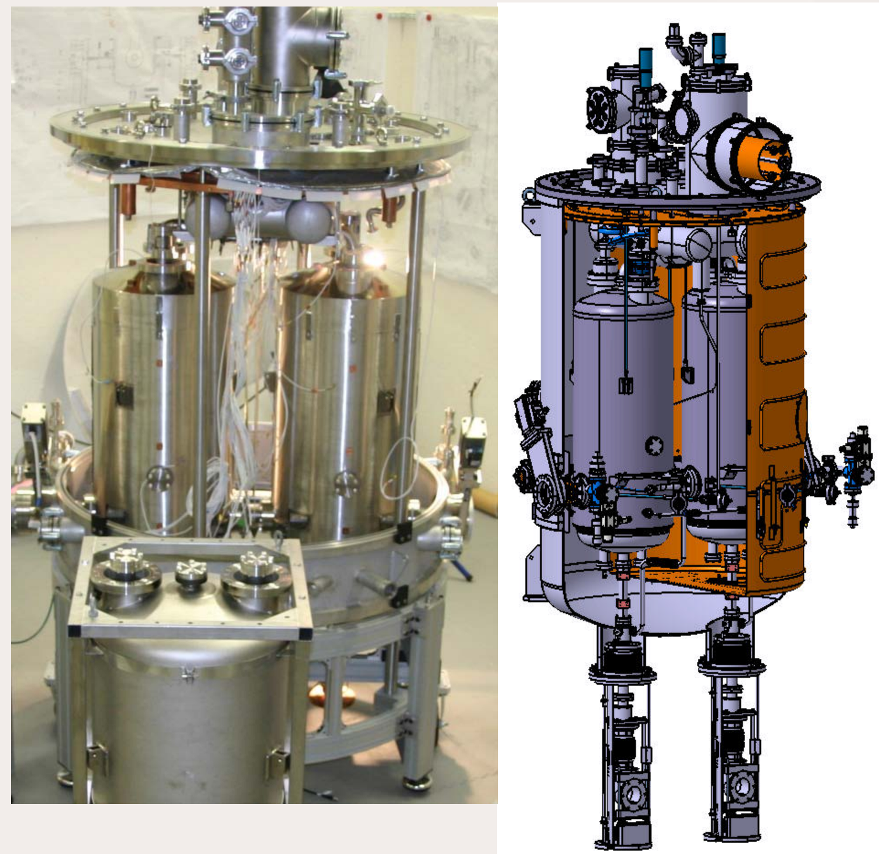
then fine tuning: +/- 4 kHz

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, prepared and conditionned by LPSC Grenoble

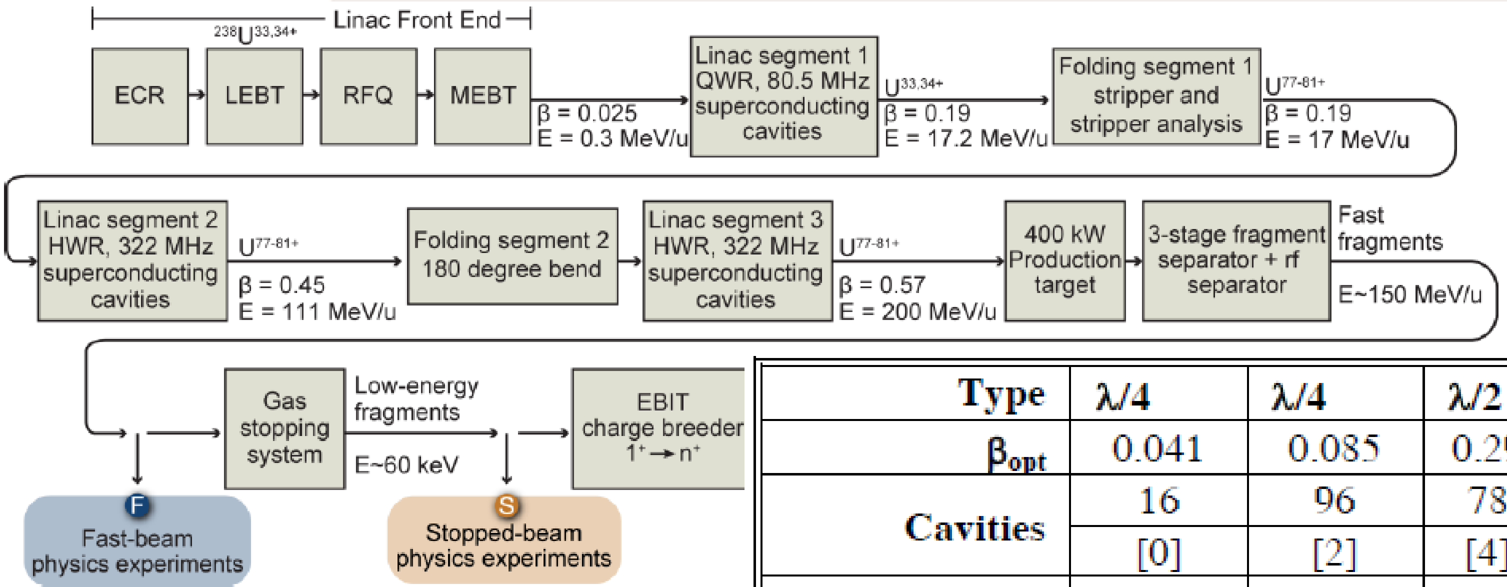
FRIB
(MSU, USA)

MSU : FRIB (1)

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

MICHIGAN STATE UNIVERSITY

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

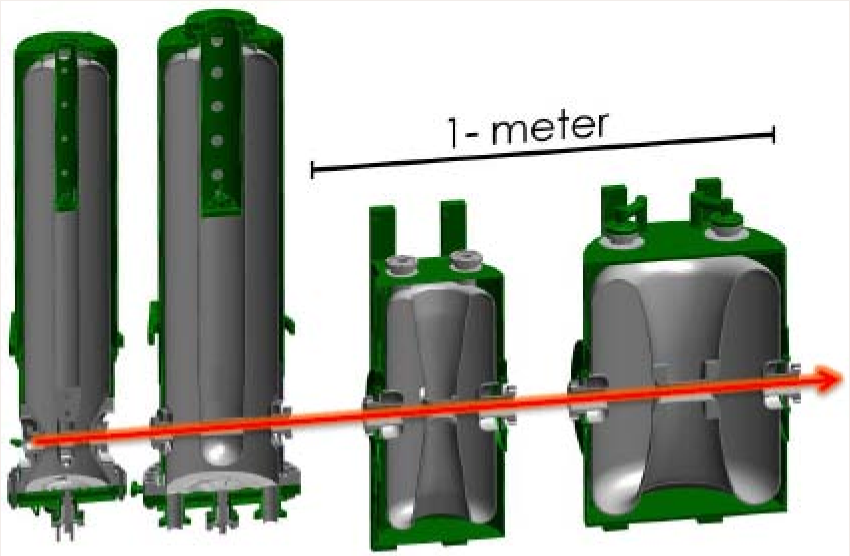
Courtesy Q. Zhao, R. York

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

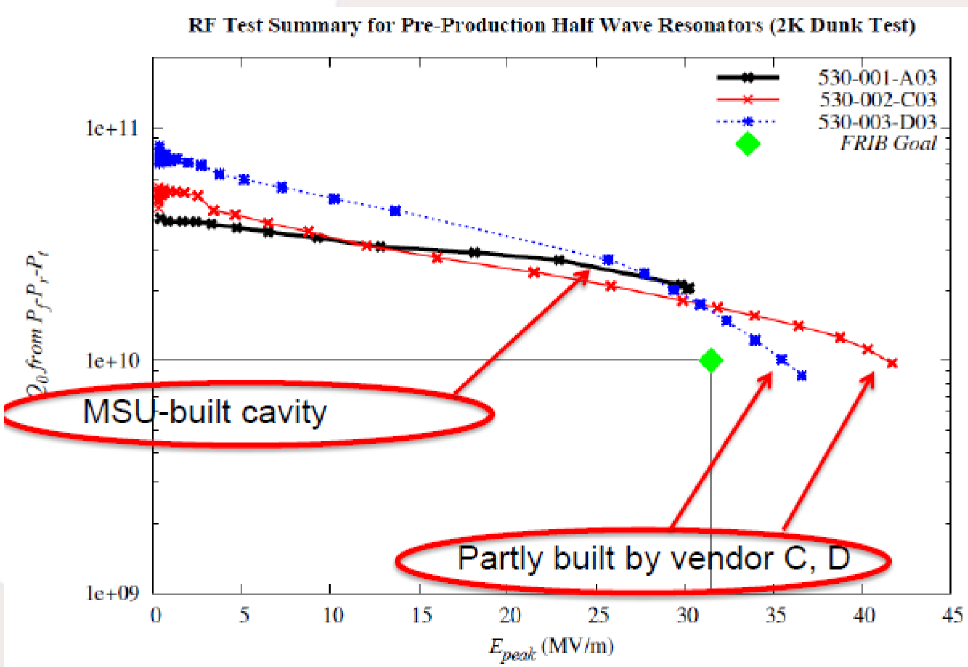
4 cavity types and 2 frequencies



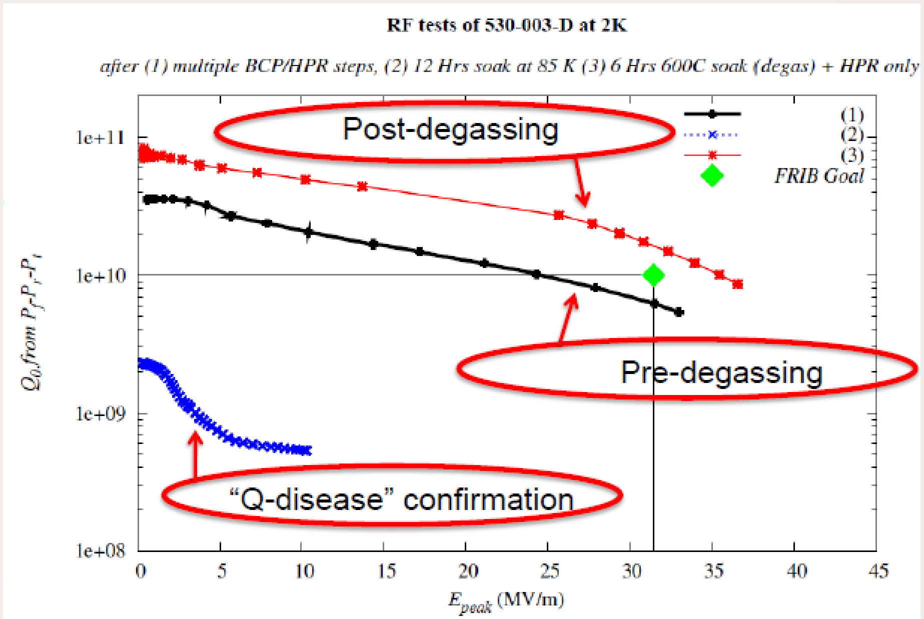
MSU : FRIB… and ReA3 (3)

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

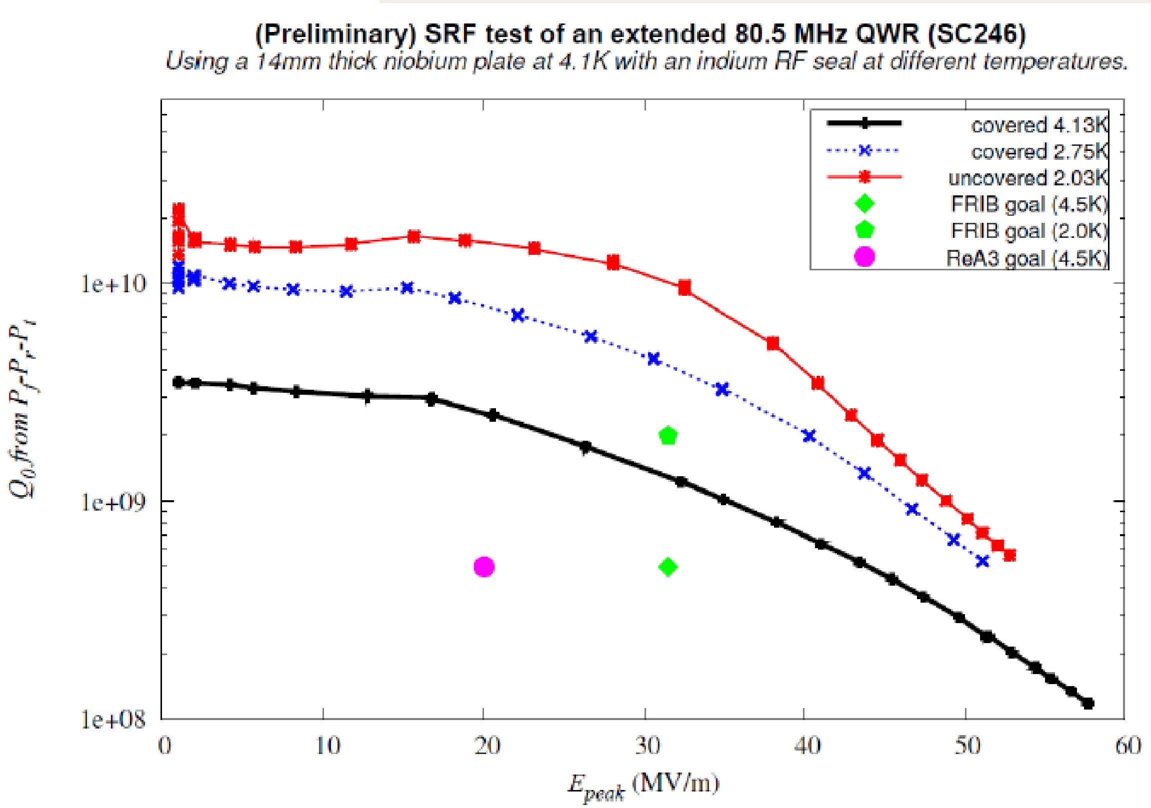


Study of Q-disease

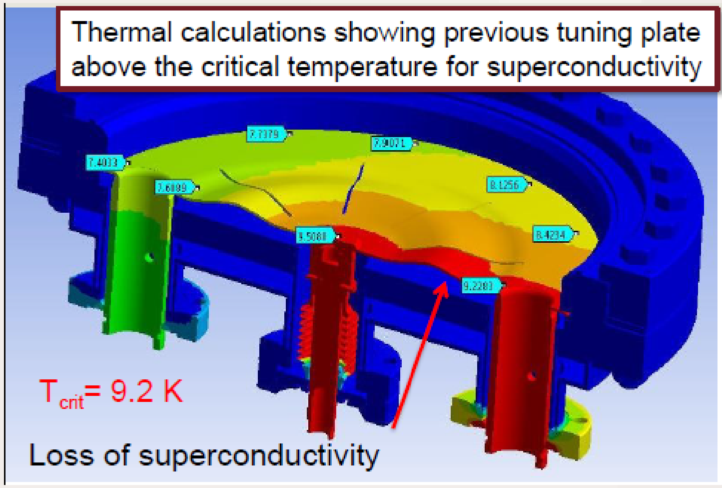
MSU : FRIB… and ReA3 (4)

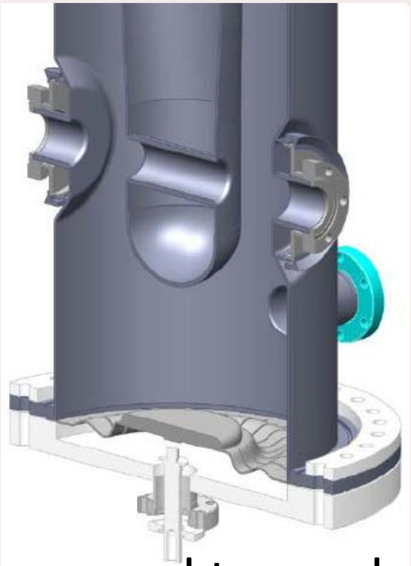
Cavity study status:

- **Test of β=0.085 QWR** prototype



Cavity tests performed at 2K and 4.2 K



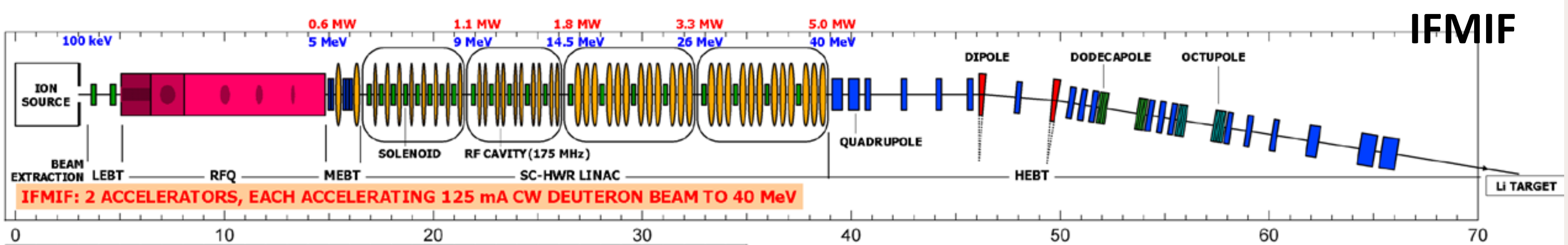


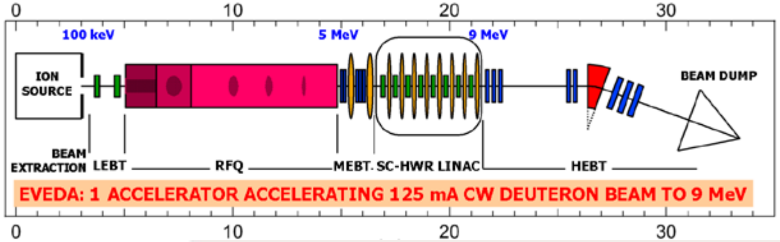
Improved tuner design under progress

IFMIF
(EU, Japan)

IFMIF - EVEDA

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. **EU + Japan Collaboration**

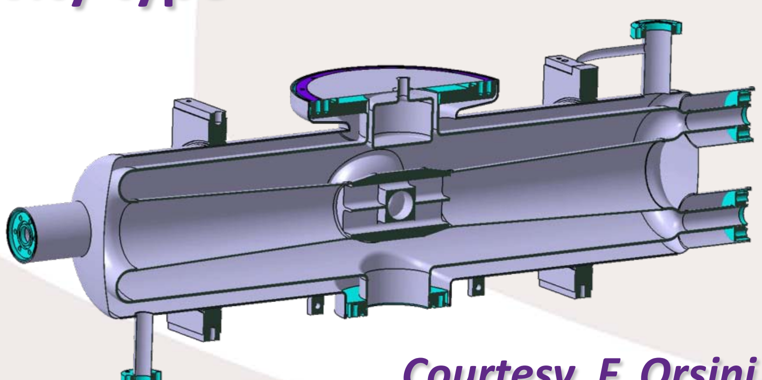




EVEDA (demonstrator)

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	50	kHz
Max. transmitted RF power by coupler (CW)	200	kW
External quality factor Q_{ex}	6.3 10^4	

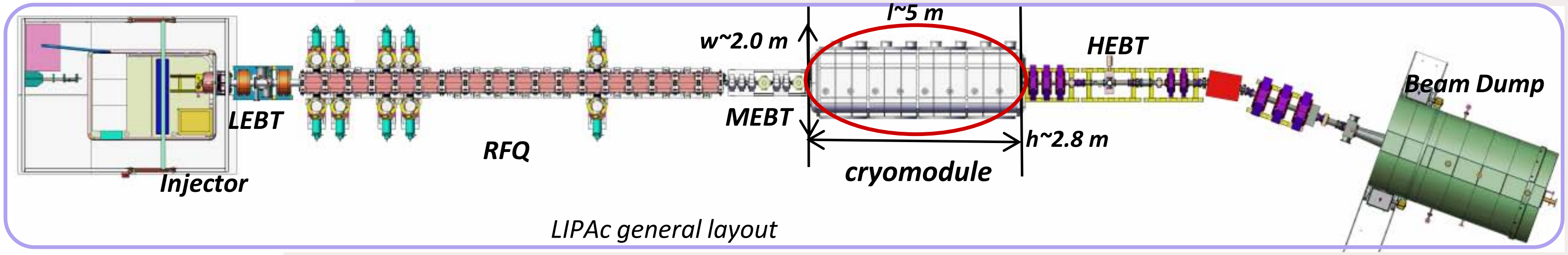
Cavity type: Half-wave resonators



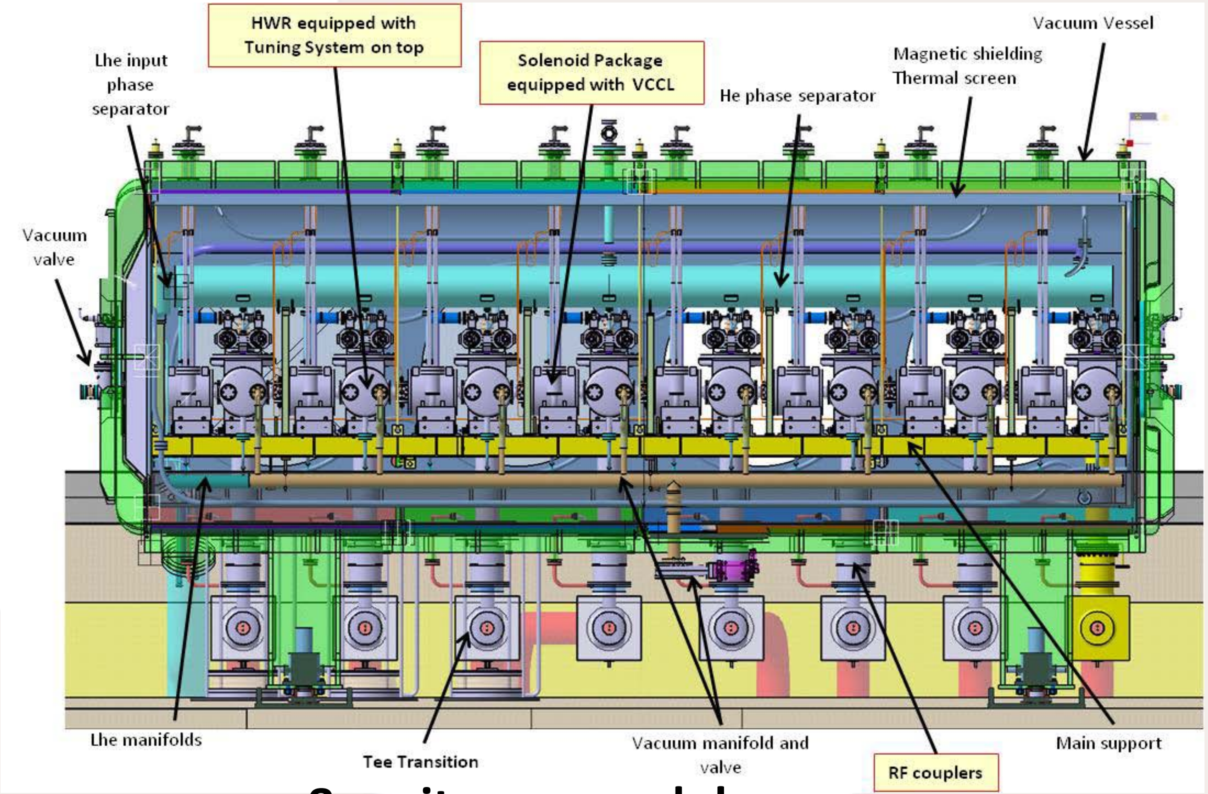
Courtesy F. Orsini

IFMIF - EVEDA

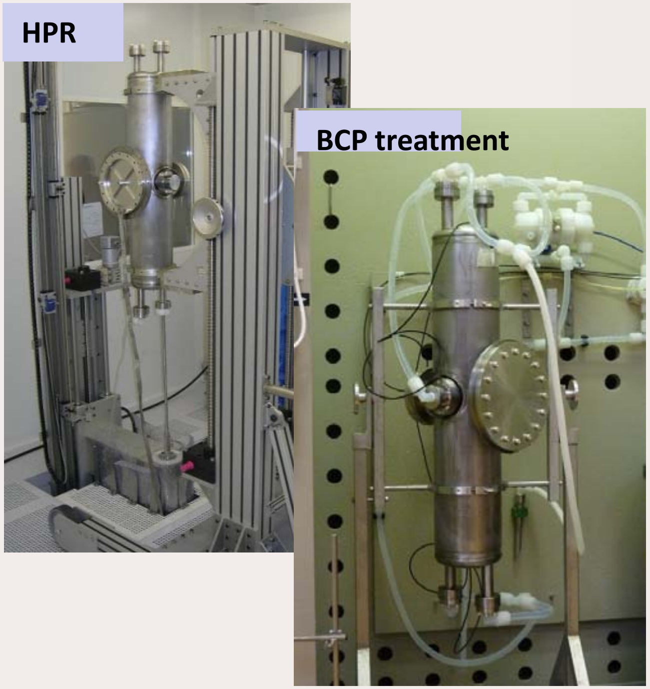
IFMIF Linac : 2 X deuteron beam 40 MeV, 125 mA CW each



LIPAc general layout



8 cavity cryomodule

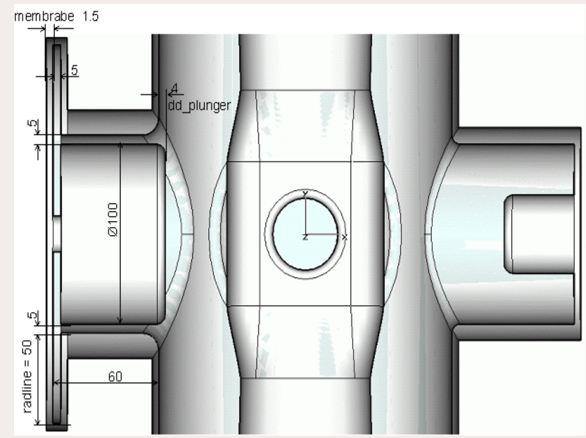


Surface treatment + clean room assembly @ IPNO

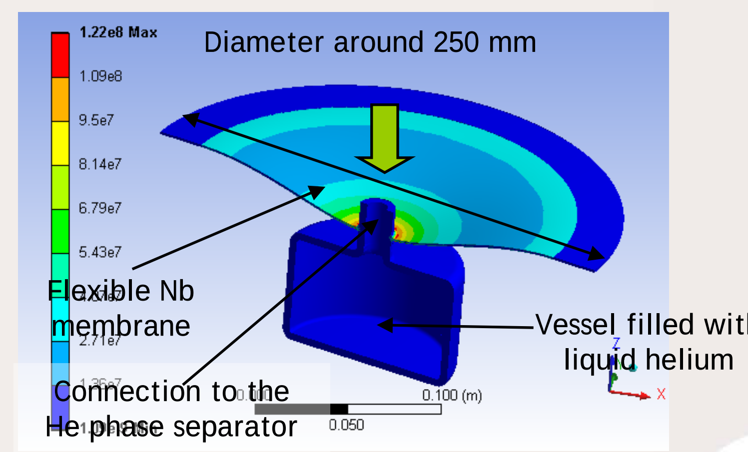
IFMIF - EVEDA

Prototyping status: 2 prototypes have been fabricated and are under testing phase. Results shows strong MP barriers, abnormal dissipation in the cold tuning system location. .

Cavity HPR @ l'IPNO



Cold tuning system ("mushroom")



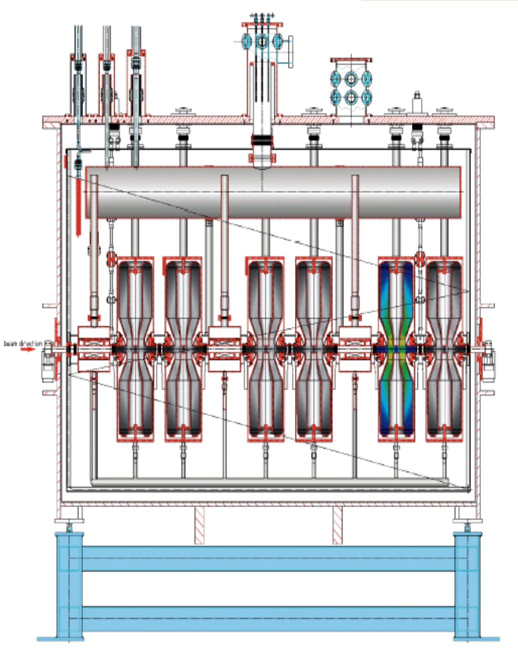
SOREQ
(Saraf, Israel)

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)



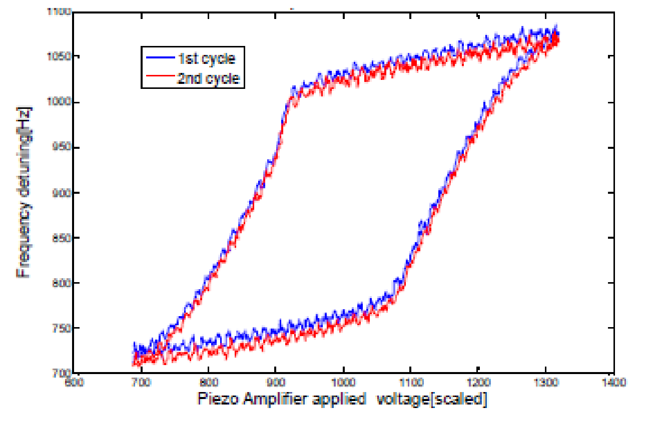
Courtesy I. Mardor

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



ESS
(Lund, Sweden)

ESS (European Spallation Source)

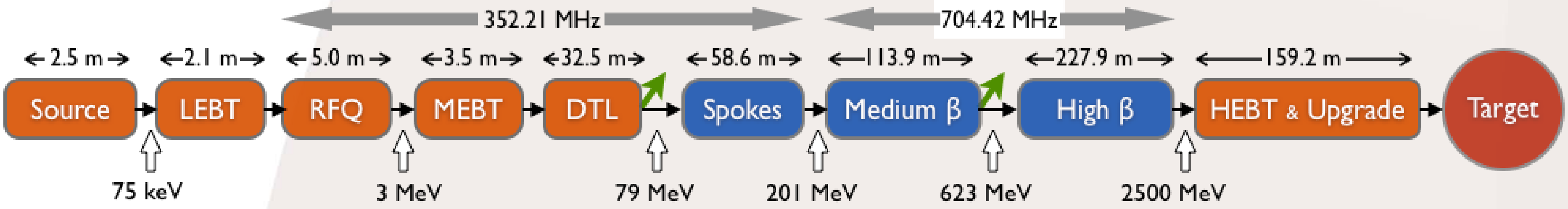
ESS Linac: High power proton accelerator, 5 MW

- Pulse 2.86 ms
- Rep. rate: 14 Hz
- Protons (H+)
- Low loss
- High reliability >95%
- Modular design for future upgrade

Investment cost: 1478 M€ over ~ 10 years
Operation cost: 106 M€ / year
Dismounting : 346 M€
(2008 costs)

ESS (European Spallation Source)

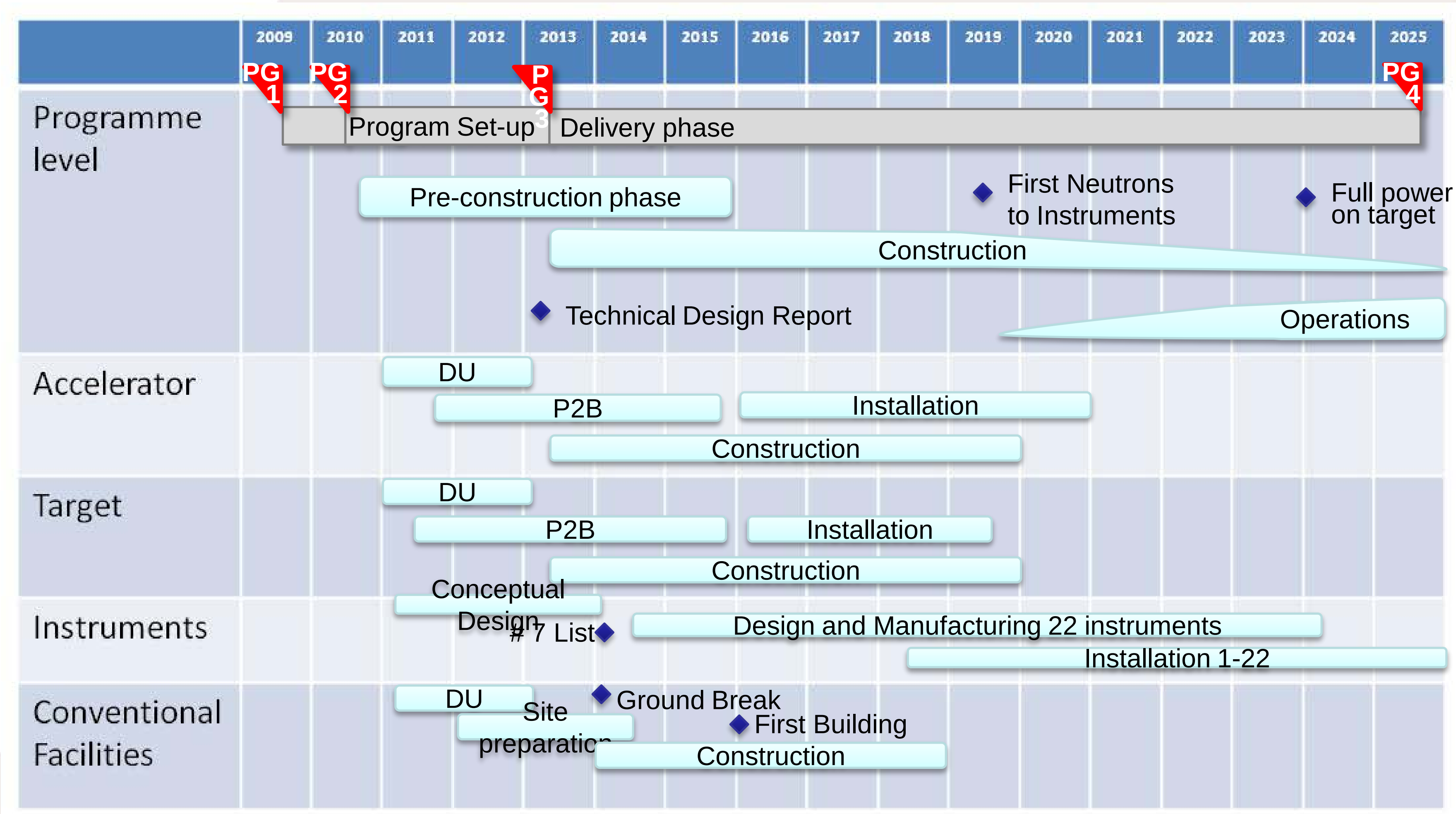
FDSL_2012_05_15



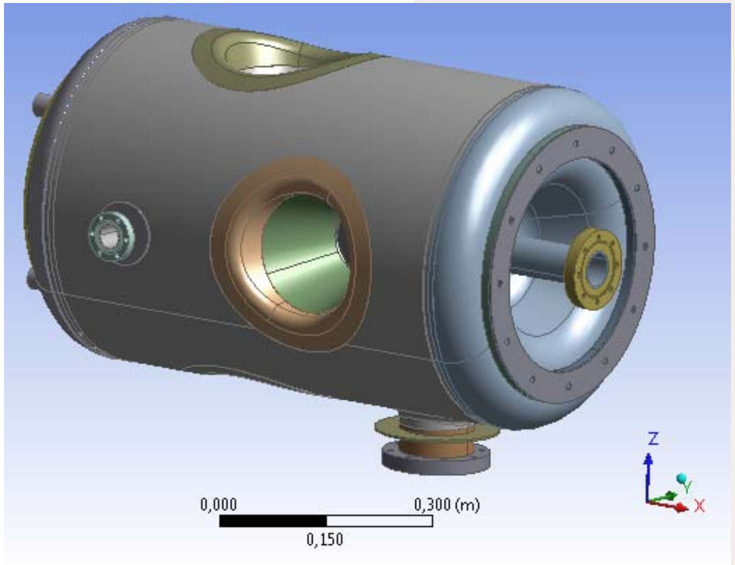
	Length (m)	Input Energy (MeV)	Frequency (MHz)	Geometric β	# of Sections	Temp (K)
LEBT	2.05	75×10^{-3}	--	--	--	≈ 300
RFQ	4.95	75×10^{-3}	352.21	--	1	≈ 300
MEBT	3.53	3	352.21	--	--	≈ 300
DTL	32.58	3	352.21	--	4	≈ 300
Spoke	58.46	79	352.21	0.50	14 (2C)	≈ 2
Medium Beta	113.84	201	704.42	0.67	15 (4C)	≈ 2
High Beta	227.86	623	704.42	0.92	15 × 2 (4C)	≈ 2
HEBT (Projection)	158.66	2500	--	--	--	--

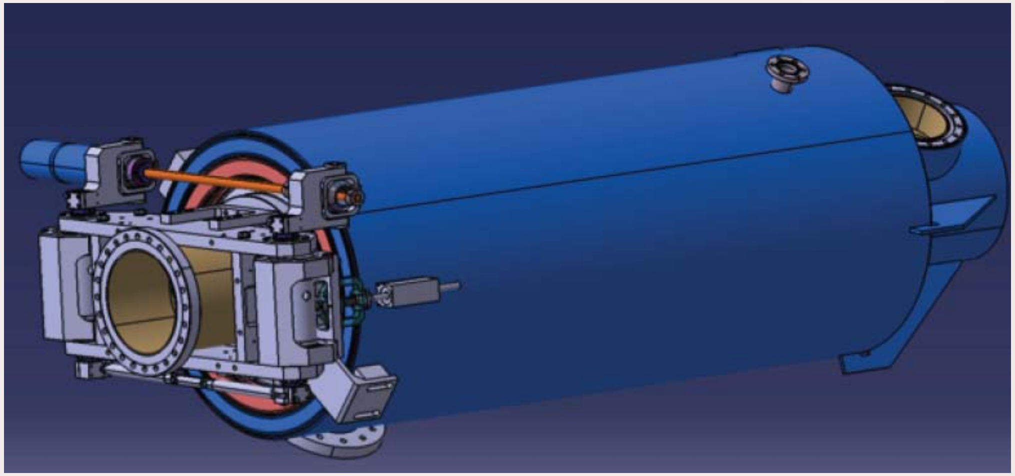
ESS (European Spallation Source)

ESS Master Programme Schedule



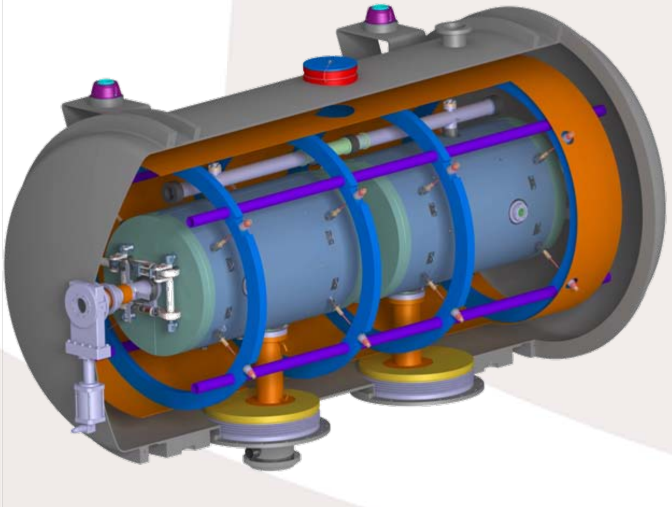
ESS (European Spallation Source)

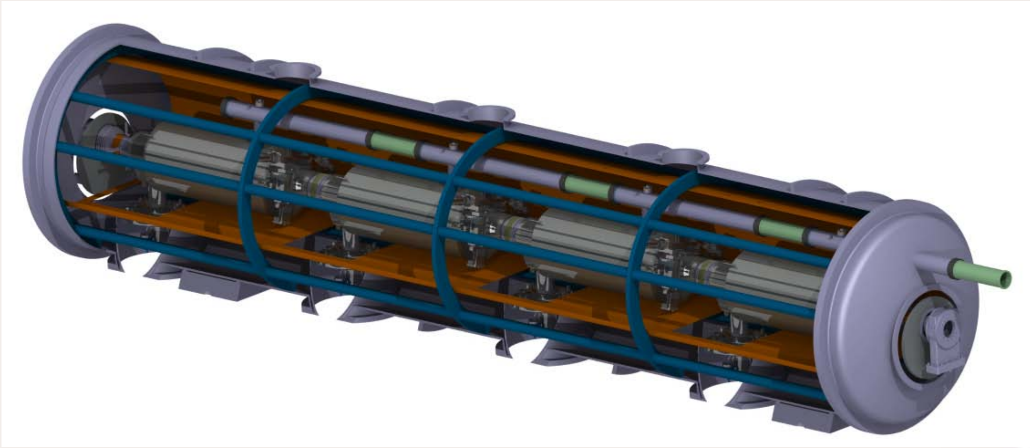




Spoke cavity & cryomodule (IPNO)

Elliptical cavity & cryomodule
(IRFU + IPNO)





MYRRHA
(Mol, Belgium)

MYRRHA

Main goal: nuclear waste transmutation with and ADS

- MYRRHA (Multi-Purpose hYbrid Research Reactor for High-tech Applications)
- Project initiated and lead by SCK-CEN (Mol, Belgium)
- Goal: operation ~2023
- ISOL @ MYRRHA possible

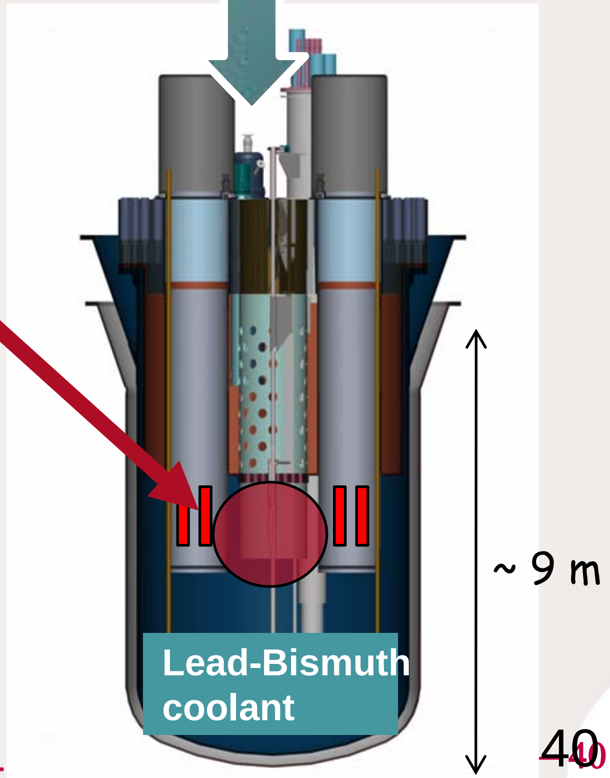
Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

Accelerator
(600 MeV – 4 mA proton)

Spallation source

Fast neutron source

Multipurpose flexible irradiation facility



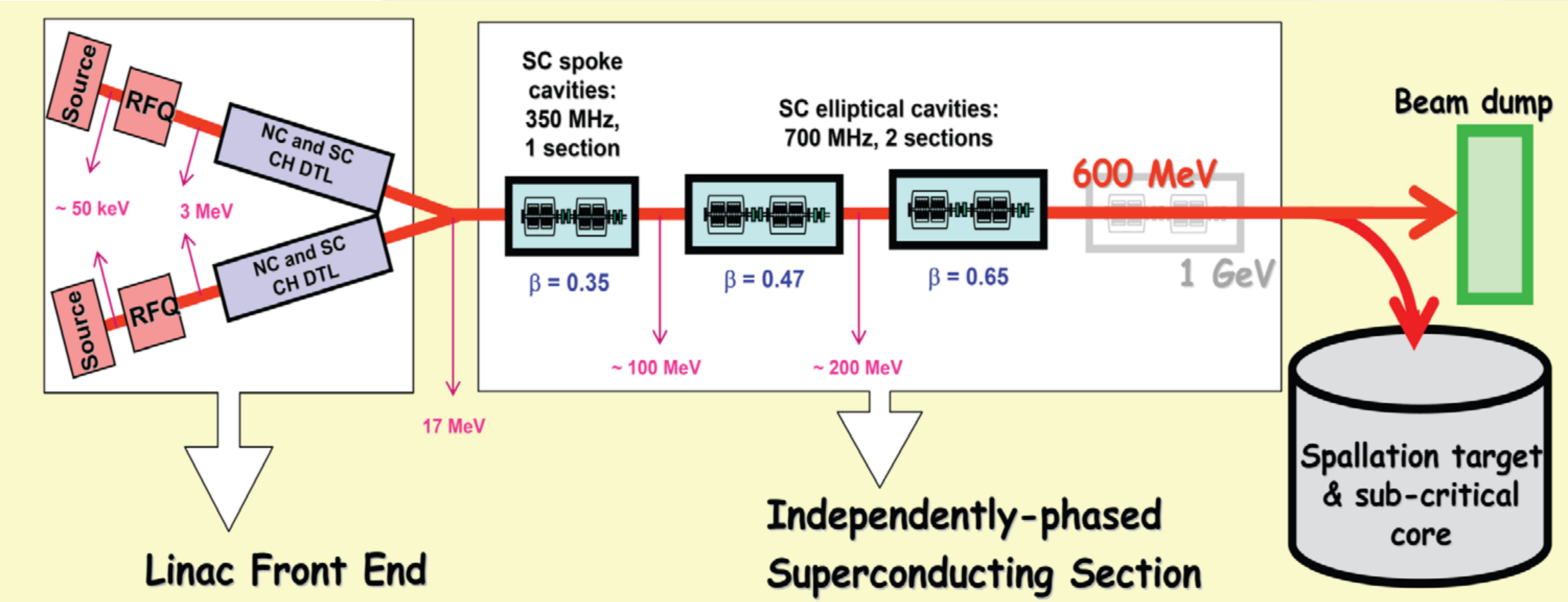
MYRRHA

	Transmuter demonstrator (XT-ADS / MYRRHA project)	Industrial transmuter (EFIT)
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	800 MeV
Allowed beam trips nb (>3s)	~ <10 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ±1% - Current: ±2% - Position & size: ±10%	
Beam time structure	CW (w/ low frequency 200μs beam "holes" for sub-criticality monitoring)	

Challenge #2: Extreme reliability required !

Challenge #1: High power CW beams

MYRRHA



<u>Reliability guidelines have been followed during the ADS accelerator design</u>

1. <u>Strong component design & derating:</u> components derated with respect to tech. limitations; prototyping & test on each key components (FP6-7 EU programs)
2. <u>Redundancies in critical areas:</u> Front-end duplication, solid-state RF amplifiers
3. <u>Capability of fault-tolerant operation</u> : Expected in the highly modular superconducting RF linac (from ~20 MeV) -> Implies reliable and sophisticated digital RF control systems (preset op. set points)

Conclusions

Conclusion (1)

<u>Intrinsic advantage of cold cavities</u>

Almost no losses on the cavity wall (thanks to superconductivity)

$\Rightarrow$ ~100% of the injected RF power goes to the beam : very high efficiency !!!

- **<u>Operating cost gain</u>** as compared to warm structures (which dissipate ~10^5 times higher)
- **Possibility to accelerate CW beams or beams with a high duty cycle (> 1 %) with high accelerating gradients** (impossible with warm structures)

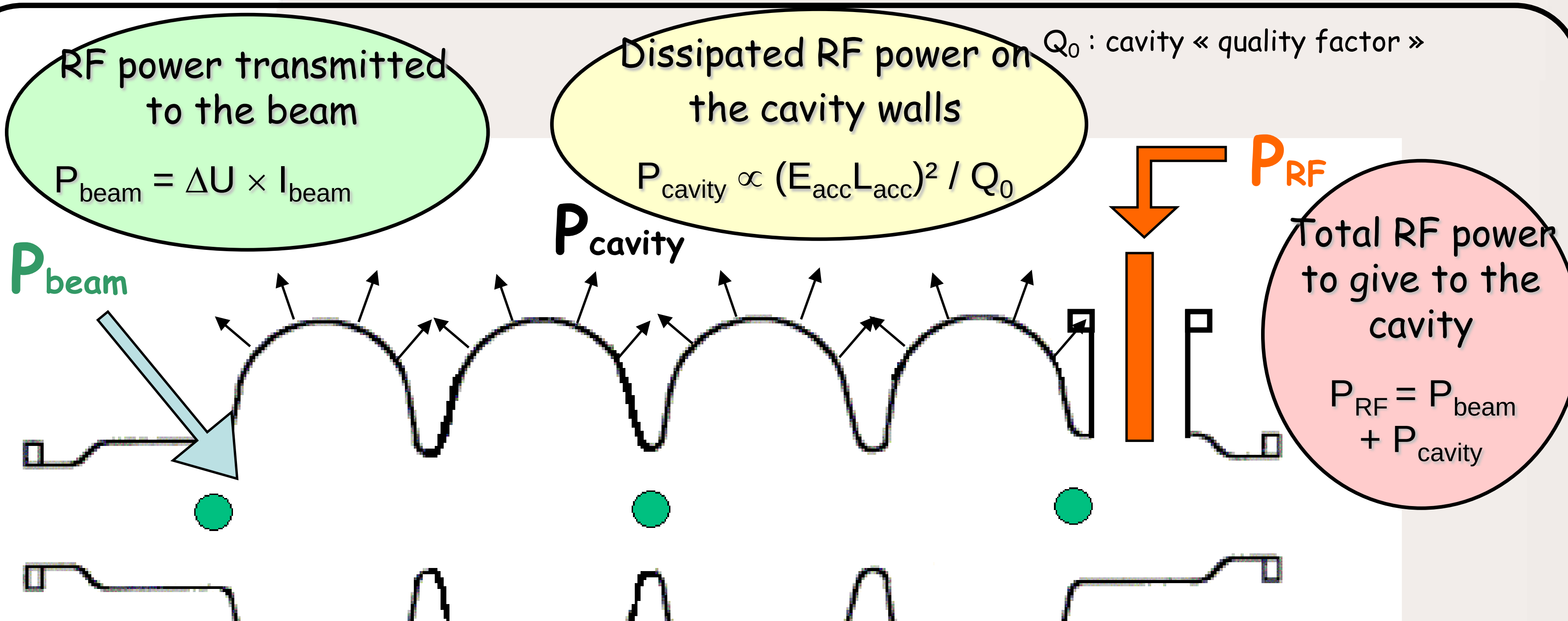
- Possibility to relax the constraints on the cavity RF design: choosing larger beam port aperture is possible $\Rightarrow$ reduction of the activation hazard = <u>security gain</u>
- High potential for **reliability and flexibility**

- **Main drawback** : need to be operated at cryogenic temperature

Conclusion (2)

Almost no losses on the cavity wall (thanks to superconductivity)

$\Rightarrow$ ~100% of the injected RF power goes to the beam : very high efficiency !!!



Order of magnitude *(700 MHz cavity - β = 0,65 - 5 cells- 10MV/m - φ=-30° - protons beam 10 mA)*

SC cavity (Q_0 ~ 10^{10}) : P_{beam} = 6 MeV × 10 mA = **60 kW**

$P_{cavity} \approx$ **16 W**

"Warm" cavity (Q_0 ~ 3.10^4) : P_{beam} = 60 kW also

$P_{cavity} \approx$ **5,5 MW !!!** ← *not possible in CW !*

Conclusion (3)

Superconducting technology:

- Is a technology of choice for high power acceleration, thanks to intrinsic efficiency and its maturity gained over the past 25 years.
- Can efficiently accelerate high (and low…) power ion beam starting from a few MeV/u (starting at β ~ 0.05)
- The type of cavity and implementation in the accelerator needs to be carefully chosen according to beam specifications and requirements: range of β, beam current, variety of beam species to accelerate, final energy, reliability, upgradability, … and cost !
- The cavity type or design IS NOT the whole story: coupling the power to the beam, tuning the cavity, prepare the cavity (dust is a tough and invisible enemy !), integration in a cryomodule are even more potential sources of problems.

Conclusion (4)

Low beta superconducting cavities

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

  -> Potential for real technical synergies between the projects

- 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, frequency, β, 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!