SRF technology for proton and ion accelerators

G. Devanz CEA-Saclay

IPAC 2011 – San Sebastian

Quarter and half wave resonators

Found on ion linacs with continuous beams. Started with ATLAS, ALPI, PIAVE

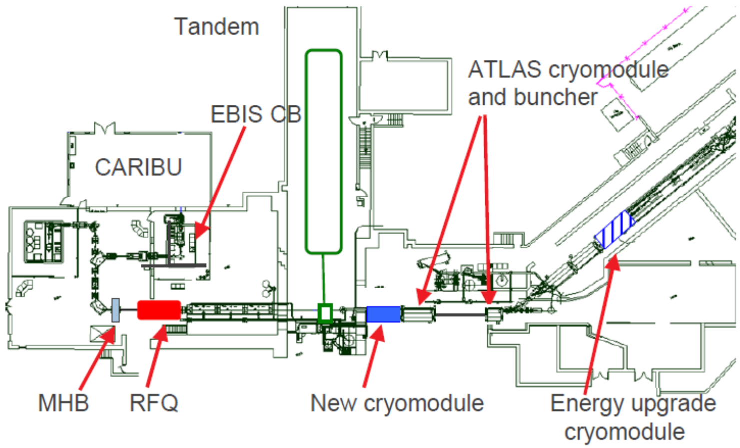
Historically, low beam intensity and narrow resonator bandwidth : technology development was focussed more on microphonics control (mechanical vibration dampers, feedback, fast tuning)

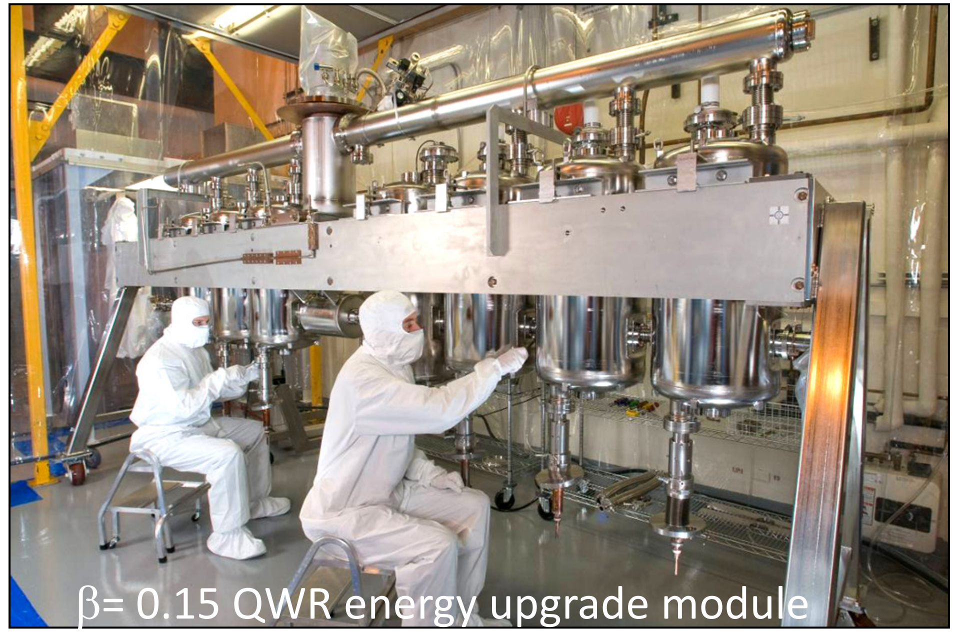
The trend is to use them for higher beam currents (from several mA to 125 mA) and at higher gradients : more emphasis is put on RF optimization for lower peak surface fields preparation and power couplers. Bulk niobium is also widely used.

When aiming at higher voltage per cavity, elliptical cavity preparation procedure are being adopted. Cryomodule vacuum and cavity vacuum separation is needed in order to be consistent with the cleanliness which is sought after.

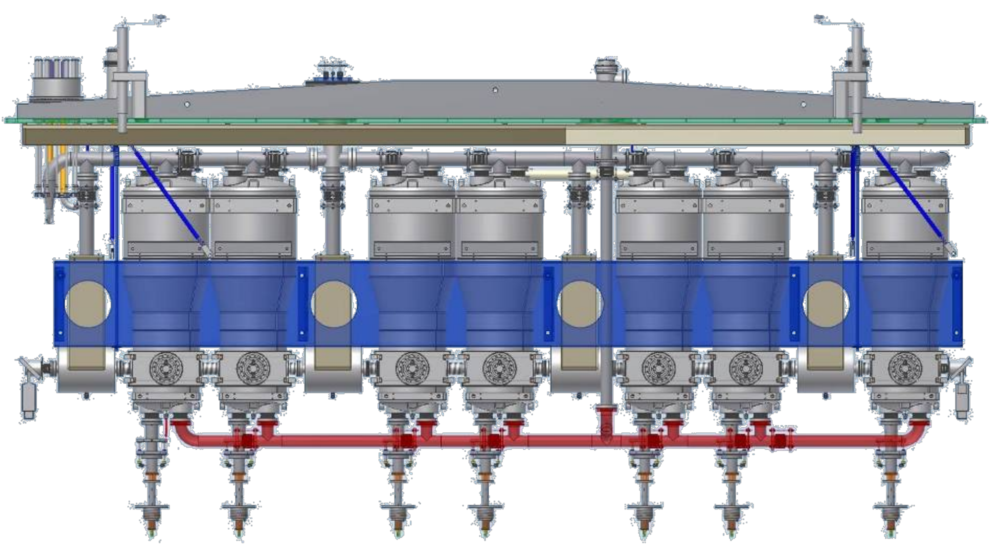
For QWRs two types of designs exist: some are fully welded, some use a removable end plate in the low magnetic field region to give access to the inside for surface treatments and inspection. In many cases this end plate region is where RF couplers or tuners are installed, is not directly cooled by He : at lot of technology is concentrated here.

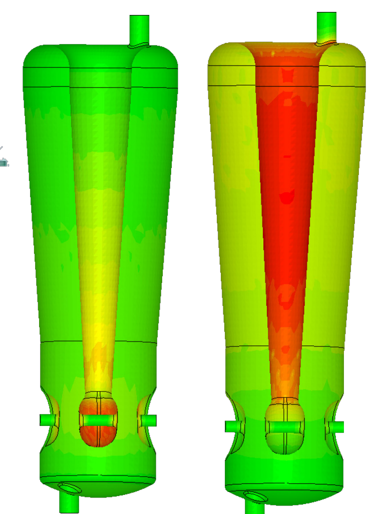
ANL-ATLAS upgrade




β= 0.15 QWR energy upgrade module

One 72 MHz β =0.077 QWR (x7) module will replace three split ring modules as part of the intensity (x10) upgrade : **17.5 MV in 5.2 m**




Electric Magnetic

- Optimized surface fields
- Minimized pressure sensitivity
- Separate vacuum
- Welded cavity
- Tuning by cavity deformation in the beam tube region

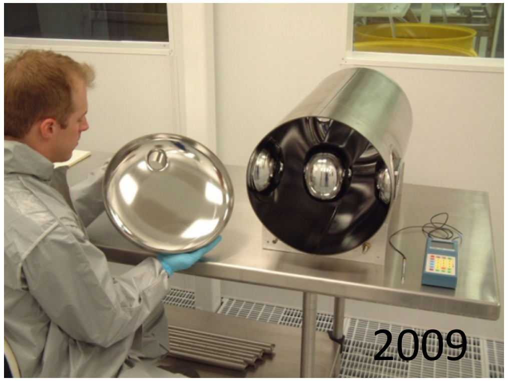
Courtesy M. Kelly

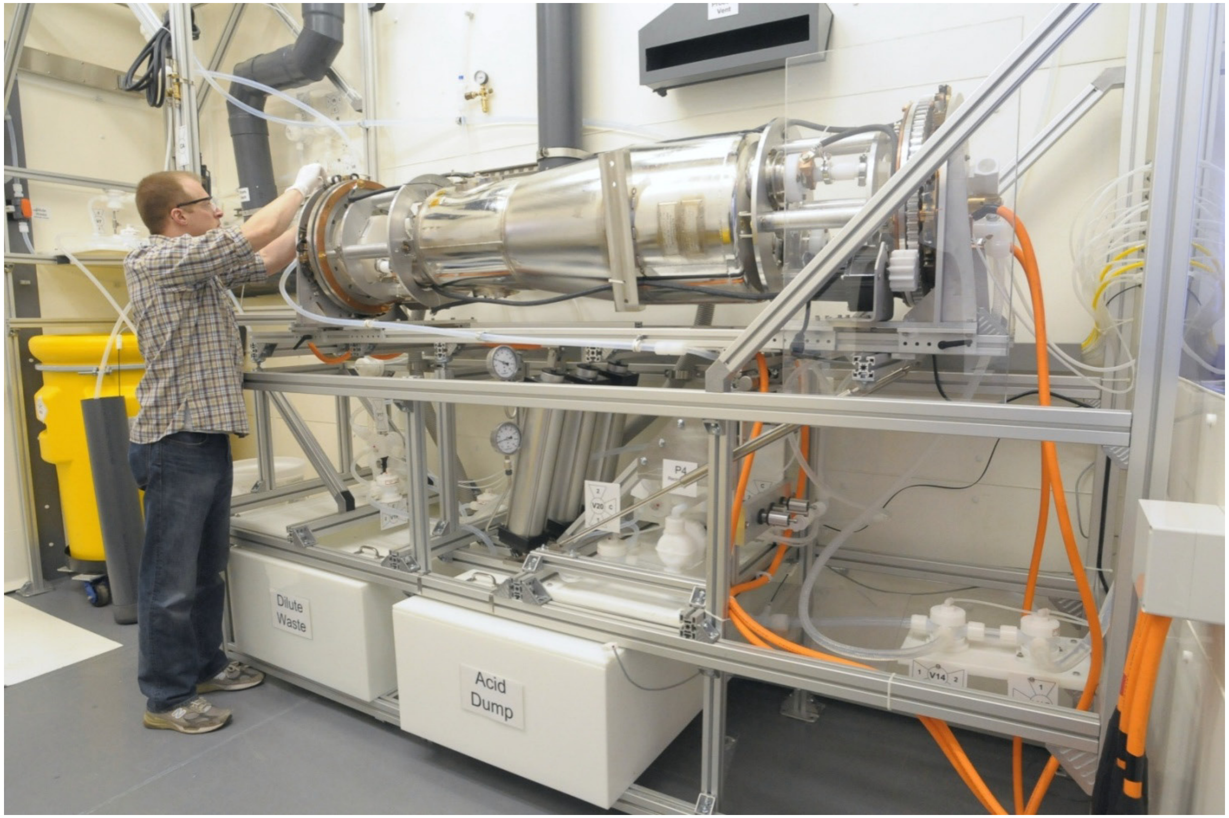
ANL-ATLAS upgrade

Long tradition of EP at Argonne on individual parts of QWR which were then welded together.

2008 : switch to open cavity and removable plate separate Eps

2011 : New horizontal low β EP tool able to polish a fully dressed cavity with a complex shape in a single operation



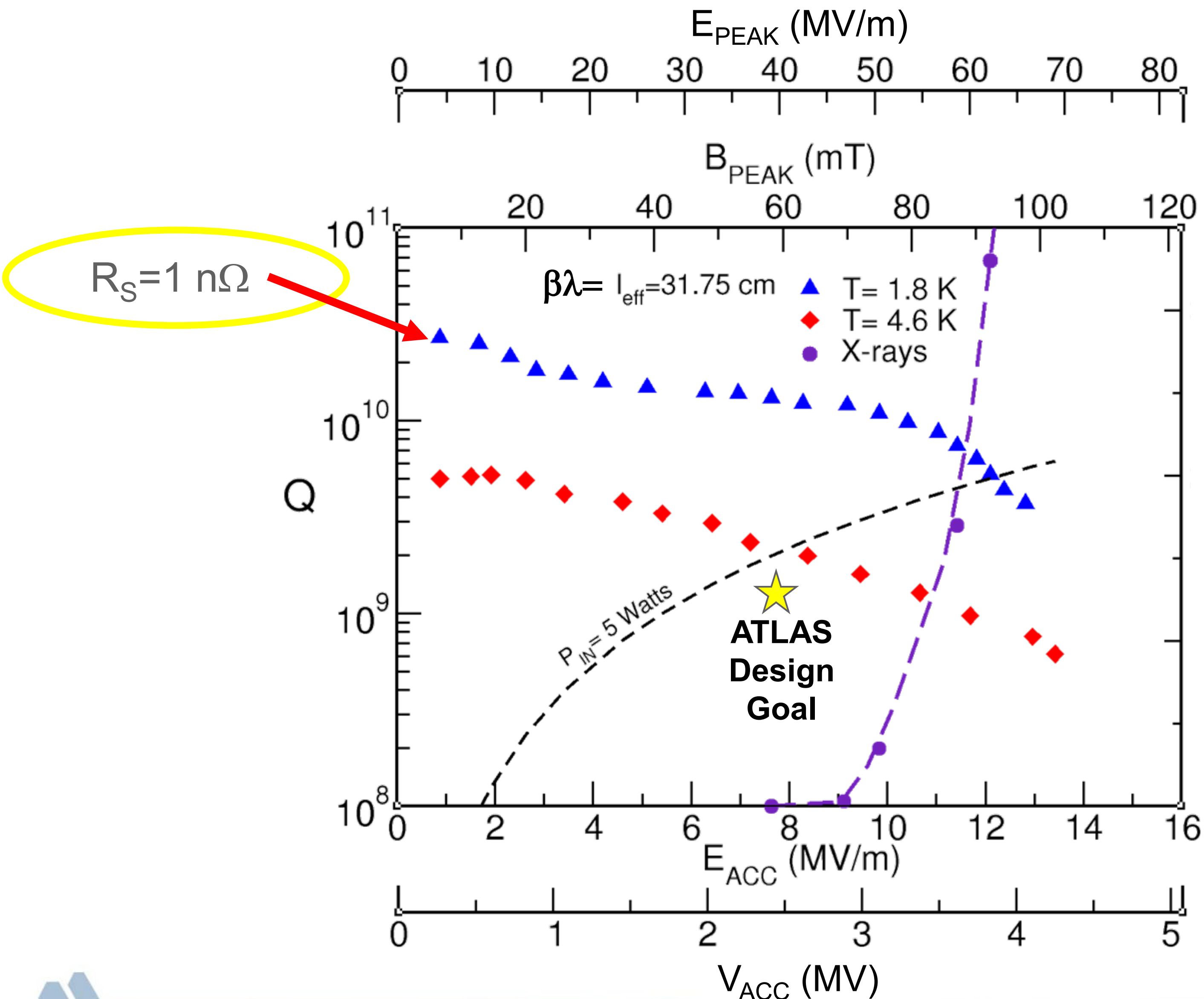


- Cooled by chilled water in the He vessel
- 4 cathodes
- rotating system

Courtesy M. Kelly, S. Gerbick

ANL-ATLAS upgrade

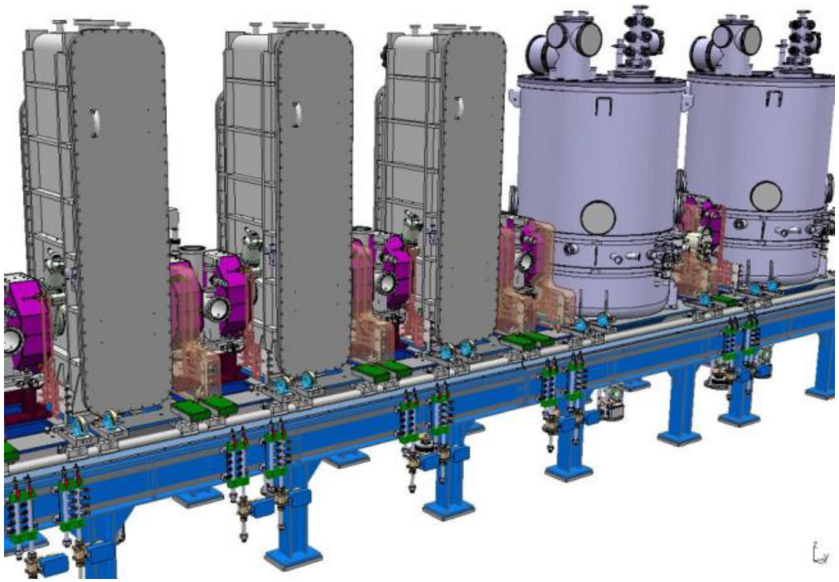
Test Results for Prototype 72 MHz QWR



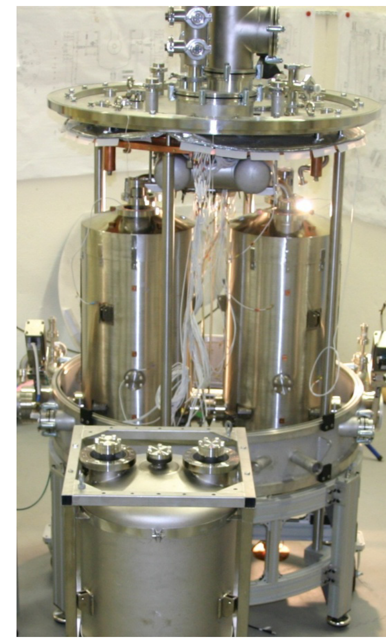
150 μm removal (12hrs EP)

Courtesy M. Kelly

GANIL – SPIRAL 2



5 mA Deuteron beam
20 Mev/u for RIB production
88 MHz SC linac
Room temperature focusing elements



β=0.07 at CEA-Saclay (12 single cavity modules)
β=0.12 at IPN Orsay (7 dual cavity modules)

Common technologies:

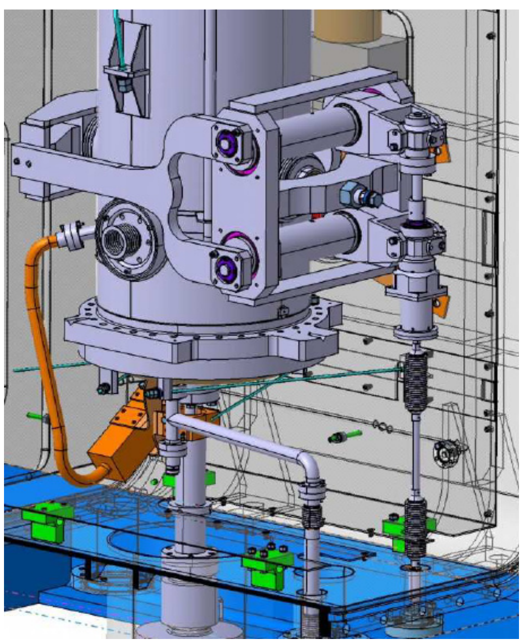
- bulk Nb
- BCP
- separate vacuum
- 20 kW CW power couplers (LPSC – Grenoble)

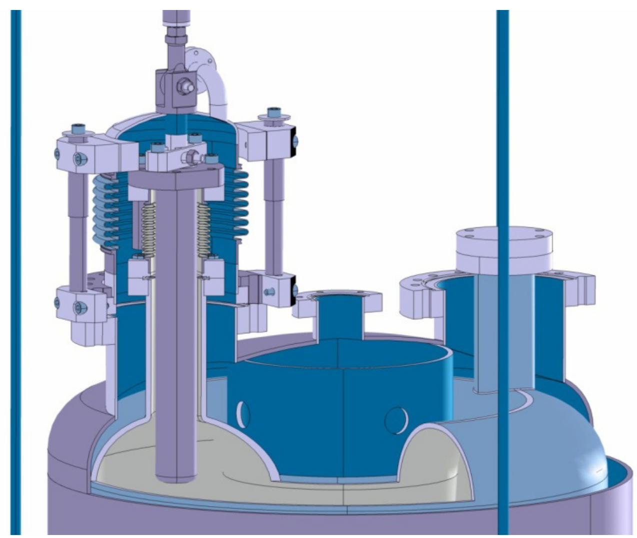
Status : cryomodule construction phase: 2 low beta CMs and 4 high beta CMs tested

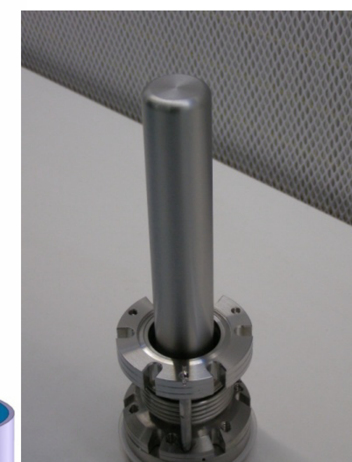
GANIL – SPIRAL 2

beta	0.07	0.12
Cavity	Copper removable end plate	Fully welded
He vessel	Stainless steel	titanium
Cold tuning system	Mechanical squeezing beam region	SC plunger
Magnetic shield	Room temperature	Actively pre-cooled cryo- specific alloy

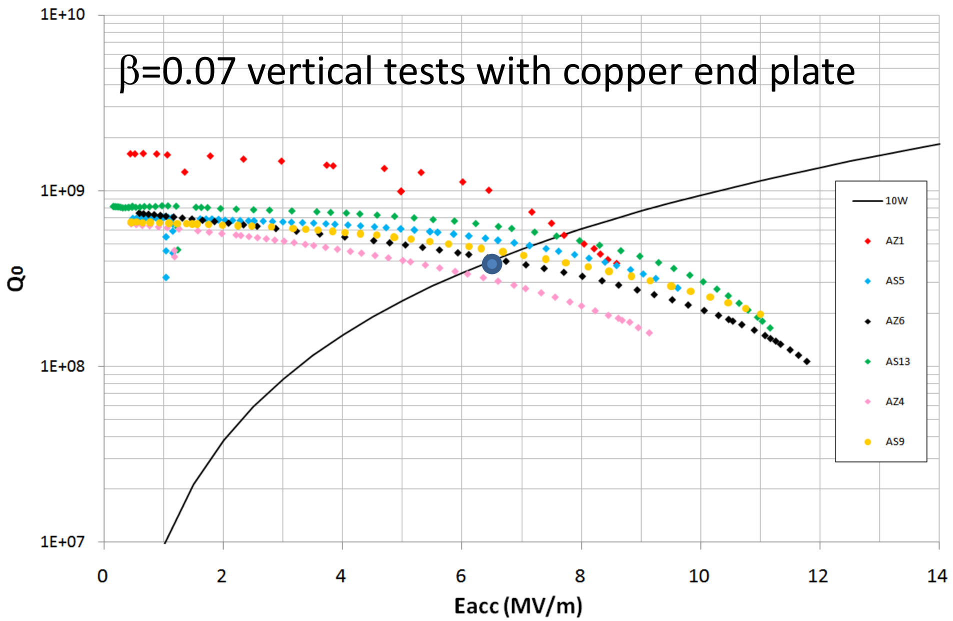
Tuner options

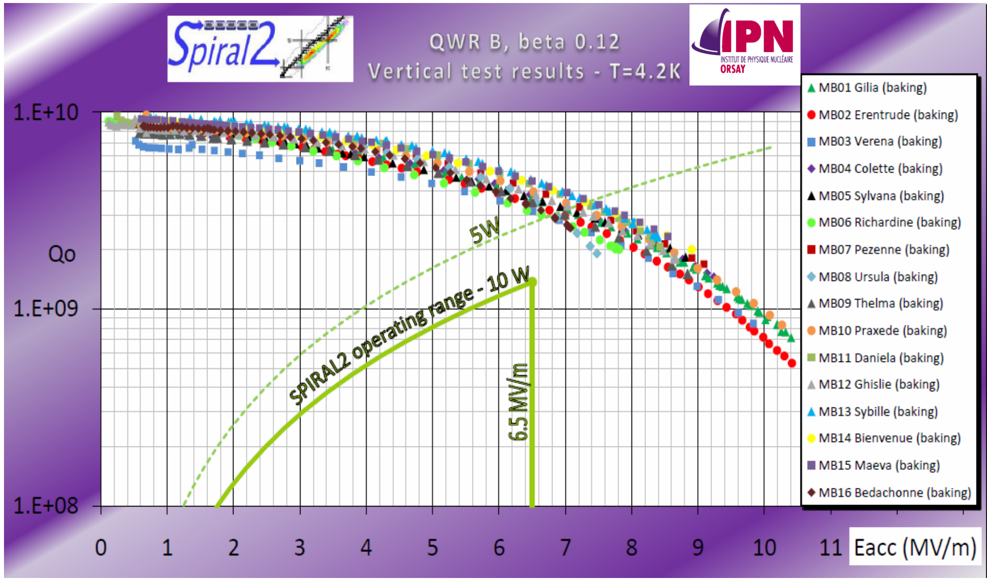






GANIL – SPIRAL 2

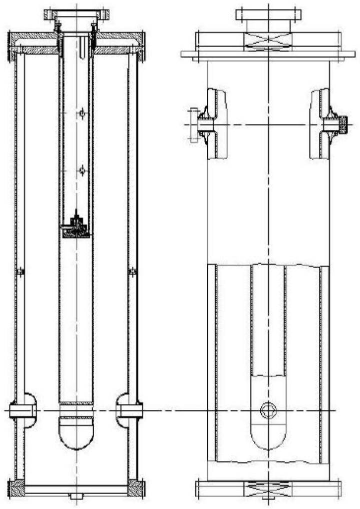




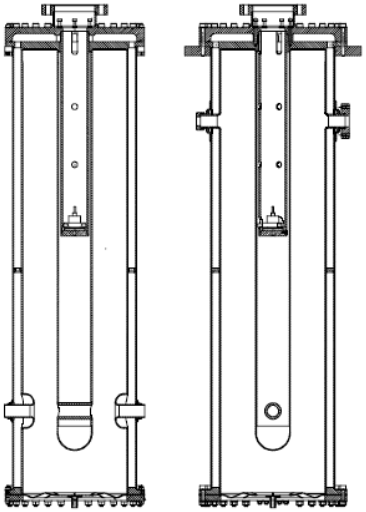
TRIUMF – ISAC II

- simple cylindrical resonator design adopted from ALPI-PIAVE from INFN-Legnaro
- cavity and cryomodule share the same vacuum
- tuning is achieved by flexible Nb end plate at cavity bottom
- narrow bandwidth : microphonics must be minimized
    - reduce the pressure sentitivity Df/DP
    - run the cavities overcoupled with respect to matched coupling
    - damp mechanical vibrations (Legnaro friction damper installed in the stem)

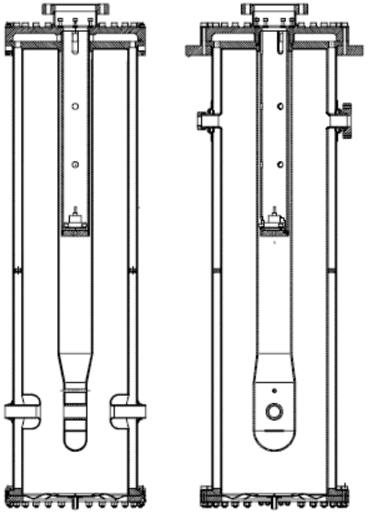
106 MHz



2001 :β=0.072
prototype

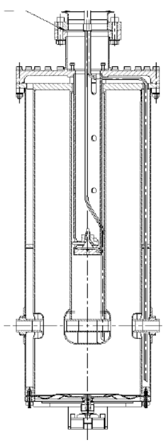


β=0.072



β=0.057

ISAC II phase 2 : 141 MHz
3 added CMs
Specs 7W 6 MV/m



β=0.11

TRIUMF – ISAC II

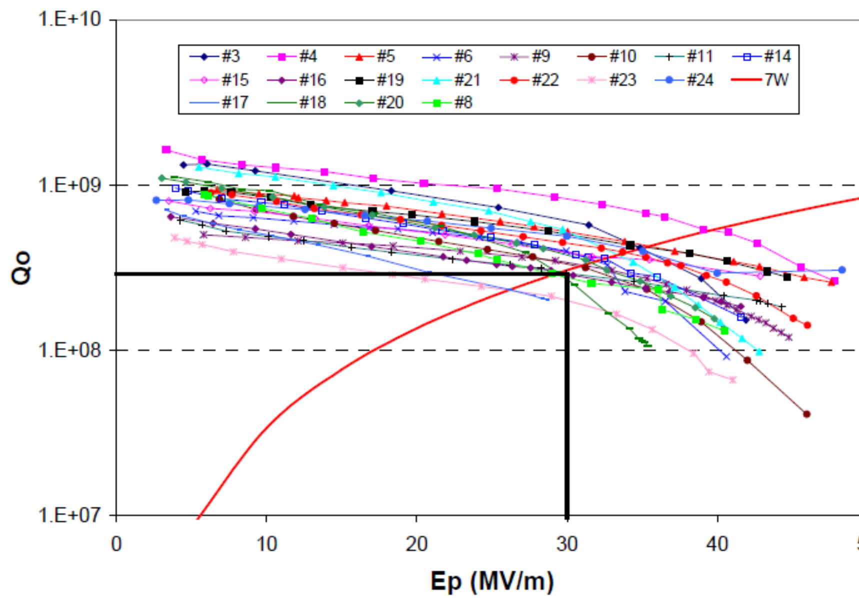
β=0.11 top assembly insertion in CM tank

Phase I : 8 x β=0.057 + 12 x β=0.072
Phase II : 20 x β=0.11 added

Operating experience:
Problems mainly due to interruptions in He delivery to the CMs. Observed consequences are

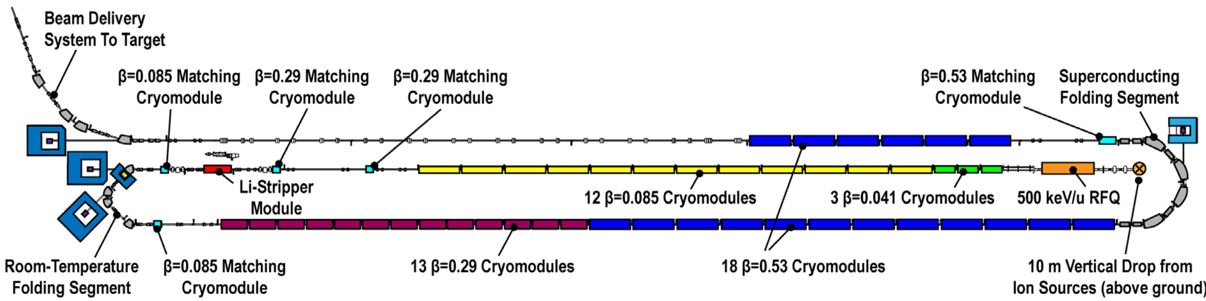
- trapped flux
- the necessary warm up is followed by multipacting activity which has to be processed before beam operation

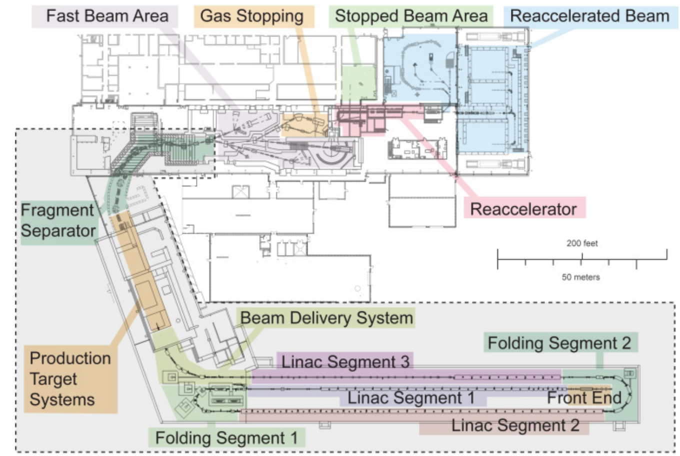
Phase II cavity performance



Courtesy D. Longuevergne

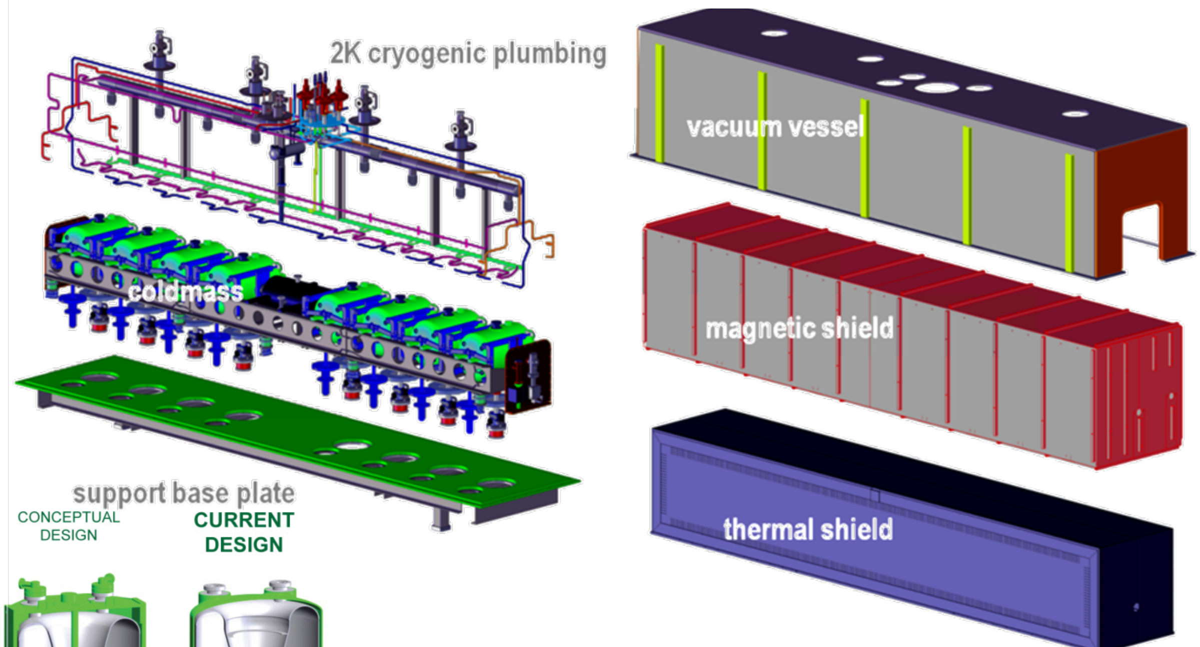
MSU - FRIB

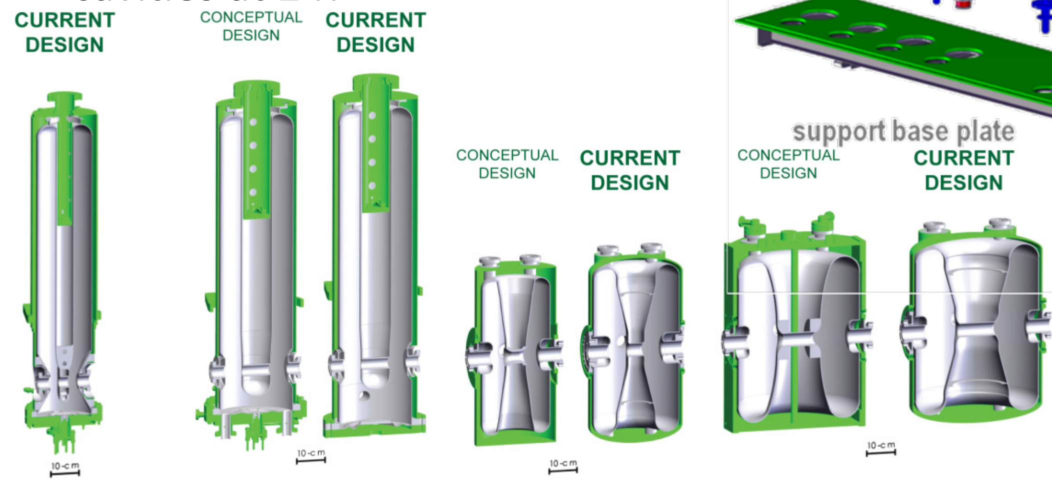




Rare isotope beam formed from stable ions (He to U) with a minimum energy of 200 MeV/u
400 kW maximum beam power

112 QWRs and 229 HWR cavities at 2 K





β = 0.041 cavity (12 cavities in FRIB linac)
β = 0.085 cavity (12 cavities in FRIB linac)
β = 0.29 cavity (12 cavities in FRIB linac)
β = 0.53 cavity (12 cavities in FRIB linac)

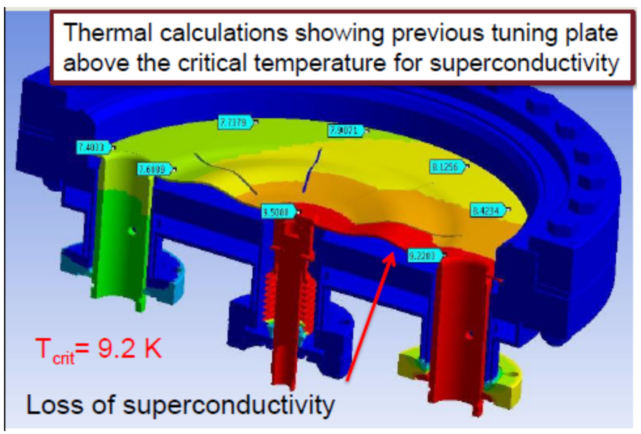
Courtesy M. Leitner

ReA - FRIB

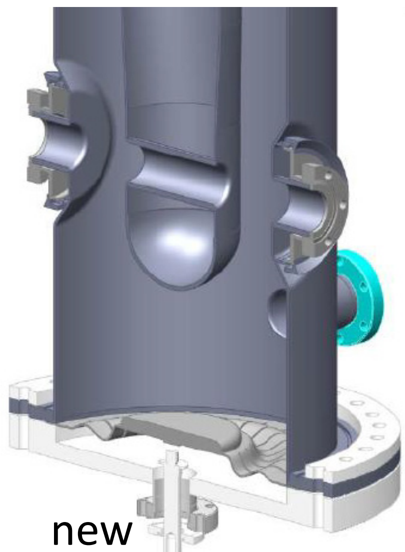
ReA is re accelerator for rare isotope beams produced by MSU Coupled Cyclotron Facility
ReA3 is the first stage of ReA
ReA also serves as a prototype for FRIB linac

First module 0.041 1 rebuncher cavity + 2 solenoids
Module 2 : 6 QWR β = 0.041+ 3 solenoids -> commissioned with beam
Module 3 : 8 QWR β = 0.085 + 3 solenoids - > testing cavities

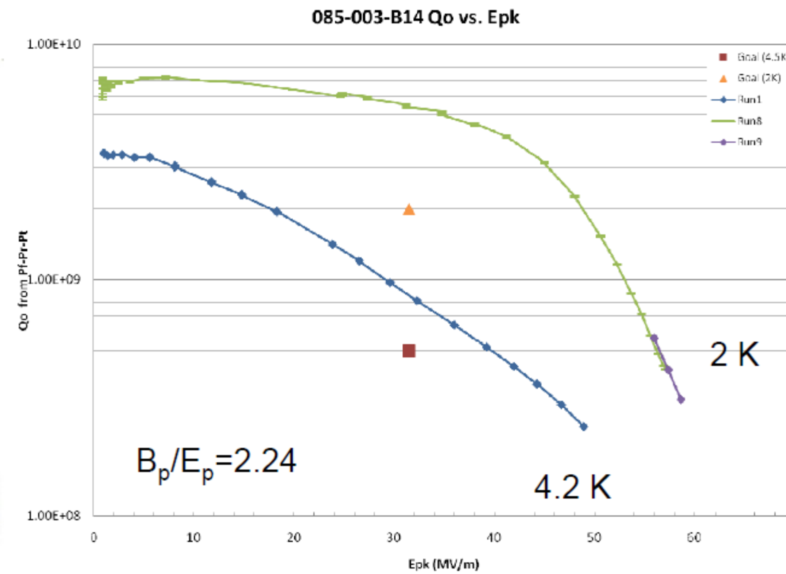
Critical part for removable endplate QWR (thermal stability problems and gasket heating or leaks occurred on many projects):



old



new

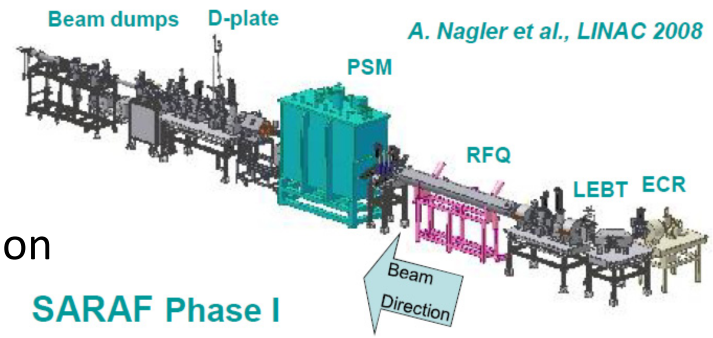


• slotted flexible plate (initiated by ISAC - II design) combined with separate vacuum design
• RF ports moved to the cavity side (reduction of thermal flux on the plate)

β=0.085 Cavity test:
Ep=58 MV/m Bp = 130 mT

Courtesy A. Facco

SOREQ - SARAF



2 mA, 40 MeV Deuteron

First HWR cryomodule in operation with beam (β = 0.09)

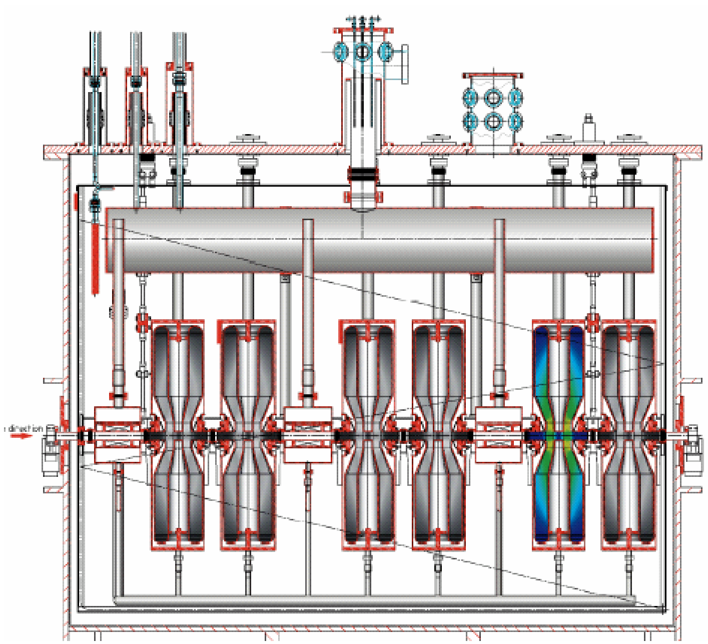
Early problems of field emission in the cryomodule situation

Helium processing used for reduction of F.E.

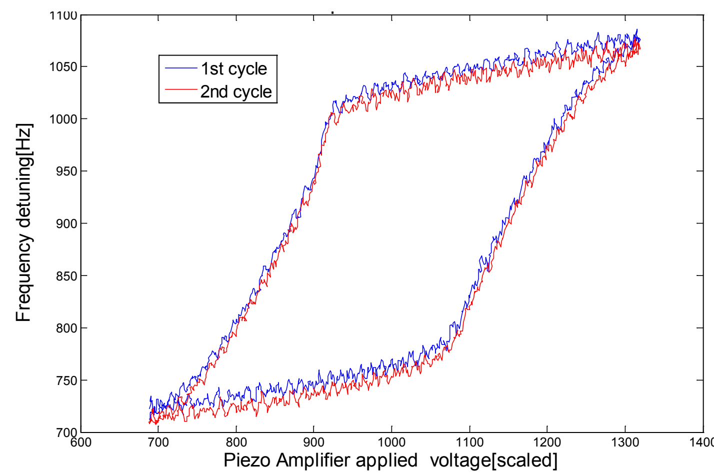
Cavities operate at Vacc = 0.84 MV (Epk=25 MV/m) (total cryo losses 62 W)

Instabilities : high PHe sensitivity (60 Hz/mbar) and Lorentz force detuning 11 Hz/(MV/m)^2

The hysteresis of the tuner RF prevents the regulation of the cavity voltage : more RF power will be installed (2 -> 4 kW)

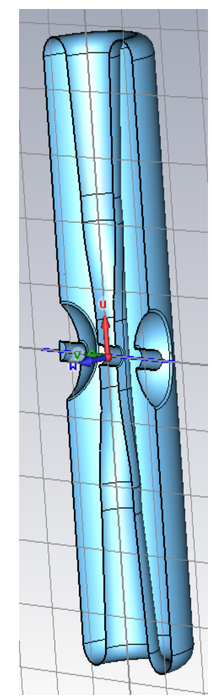


176 MHz β = 0.09 cryomodule



Phase 2 designs:

Beta 0.13 cavity

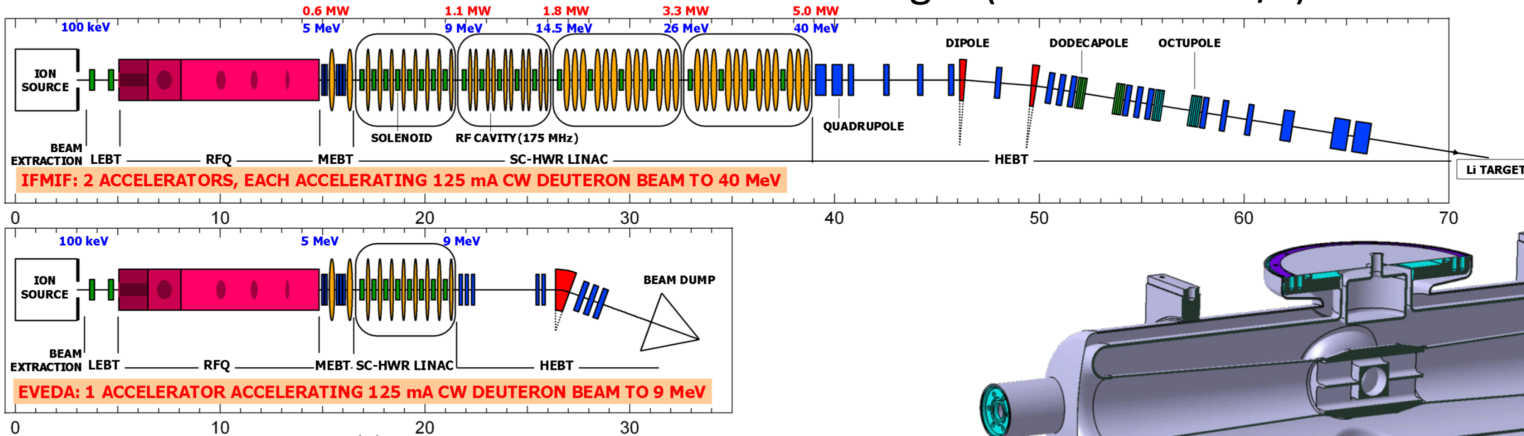


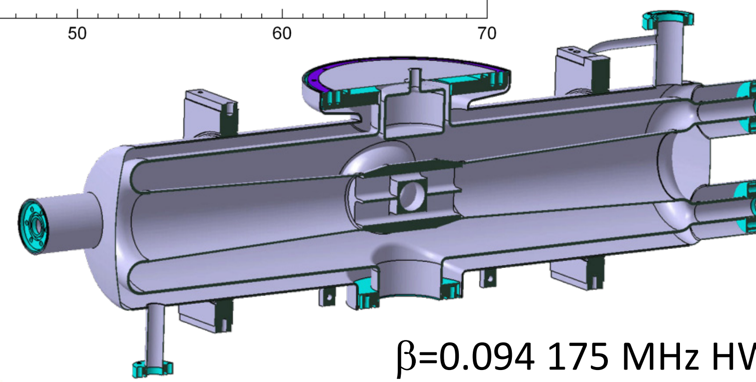
Courtesy A. Perry

CEA – IFMIF EVEDA SRF Linac

For fusion material irradiation

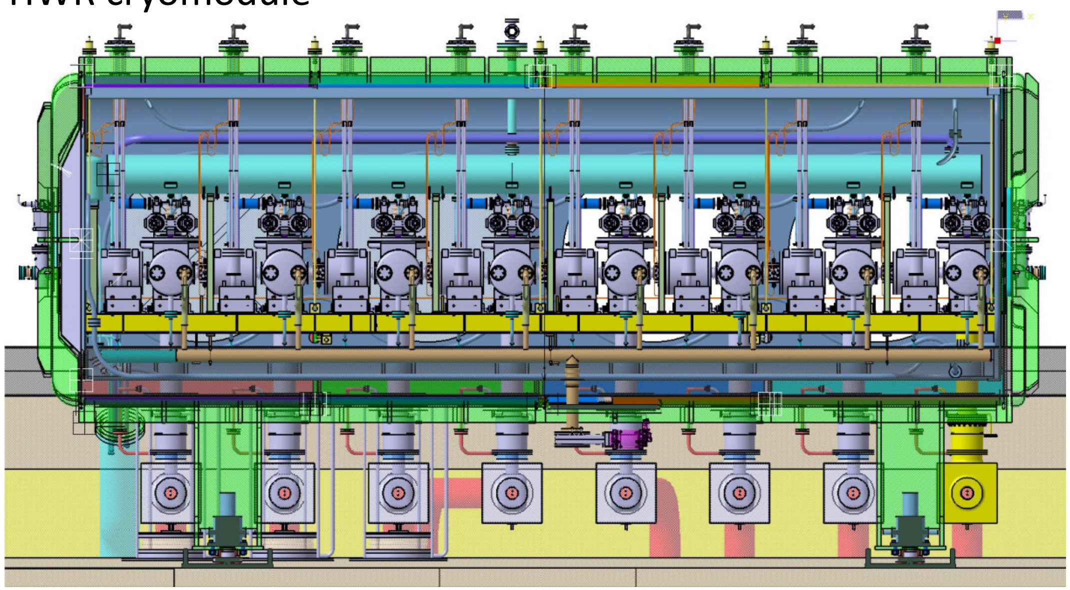
Two 125 mA 40 MeV Deuteron beams on Li Target (10^{17} neutron/s)

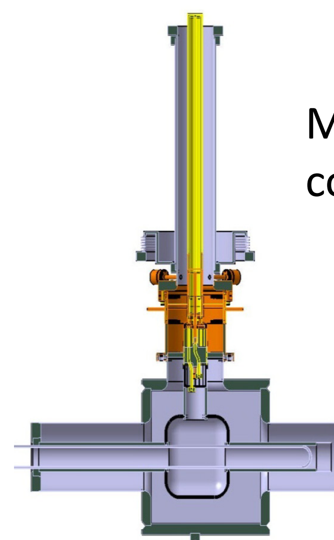




β=0.094 175 MHz HWR

HWR cryomodule





Max. 200 kW power coupler

F. Orsini

IFMIF

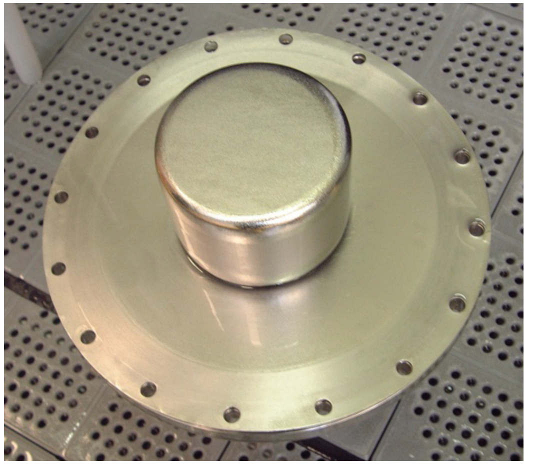
First tests on prototype HWRs:

• strong MP at in the tuner port before installation of the plunger prevented the HWR qualification

• Tests done with NbTi membrane supporting the plunger with quench at low field.

• A modified version of the tuner is being designed

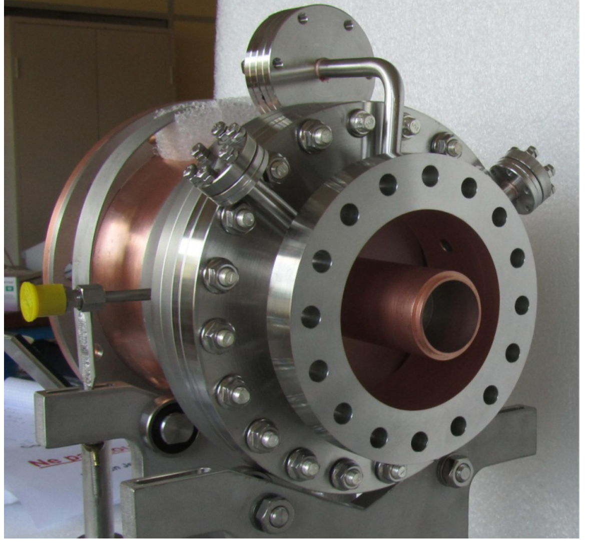
Plunger tuner



Vertical test setup at IPN Orsay

HWR equipped with Ti He vessel and SC plunger

RF window prototype



High power H+/H- SRF accelerators

- Machines and projects:
  - Operating and pioneer: SNS
  - LHC
  - Projects with on going R&D and prototypes :ESS, SPL,MYRRHA
  - Planned SRF linacs CSNS, CIADS,
  - R&D demonstrators: MSU, J-PARC,EUROTRANS
- Recurring questions:
  - HOM couplers or not?
  - Cryomodule architecture (cryo-losses vs maintenance and availability)
  - Should the transition between RT and SC sections be lowered using low beta structures, e.g. spokes?

Spoke resonators performance

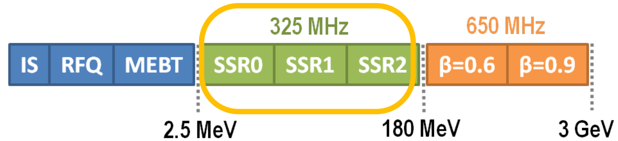
Lab	Type	Frequency	Opt beta	Eacc,max	Vmax	Epk/Eacc	Bpk/Eacc
IPN Orsay	Single	352	0.20	4.8	0.8	6.7	14.5
	Single	352	0.36	8.1	2.5	4.7	12.8
	Triple	352	0.30			4.1	9.1
ANL	Single	855	0.28	4.4	0.3	5.5	12.7
	Single	345	0.29	8.7	2.2	4.6	12.1
	Single	345	0.40	7.0	2.4	6.3	16.7
	Double	345	0.40	8.6	4.5	4.7	9.2
	Triple	345	0.50	7.6	6.6	3.7	11.5
	Triple	345	0.62	7.9	8.7	3.9	12.0
FZ-Juelich	Triple	760	0.2	8.6	1.4	5.1	13.3
LANL	Single	350	0.21	7.5	1.3	5.1	13.3
	Single	350	0.21	7.2	1.3	5.0	10.1
FNAL	Single	325	0.21	**21**	4.3	3.6	5.8

Data normalized with Lacc = $\beta\lambda/2$ per gap

Many spoke resonators reach Eacc ≈ 8 MV/m

Courtesy G. Olry

FNAL - Project X



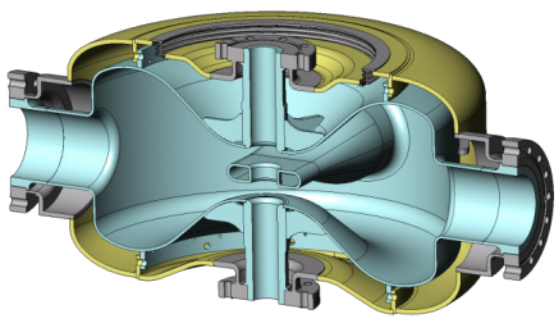
3 GeV, 1 mA CW proton linac followed by a 3-8 GeV pulsed linac

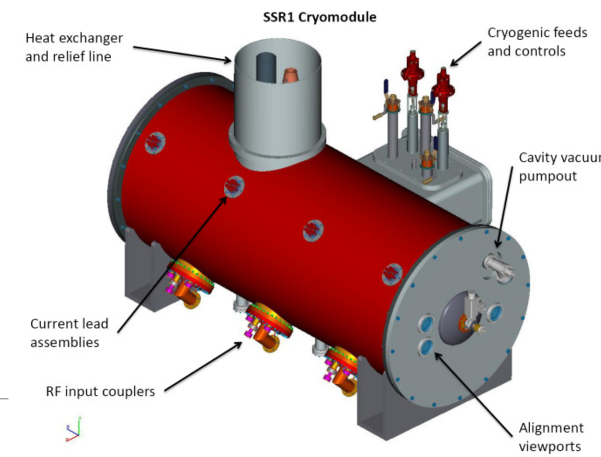
	SSR0	SSR1	SSR2 A	SSR2 B
β optimal	0.115	0.215	0.414	0.480
CMs x Cavities	2 x 9	2 x 10	4 x 10	4 x 8
Design Eacc [MV/m]	9	11	10	10
Max surf Field [mT]	61	64	56	59
Q_0	> 6.5E6	> 6.5E6	> 6.5E6	> 6.5E6
Bpeak/Eacc [mT/$^{MV}/_{m}$]	6.83	5.81	5.64	5.9
Epeak/Eacc	5.66	3.84	3.78	3.5
Leff (2*βλ/2) [mm]	106	198	382	443
G [Ω]	51	84	109	119
R/Q_0 [Ω]	109.2	242	247	304
TOT FE length [m]	59/54.3	59/54.3	59	54.3

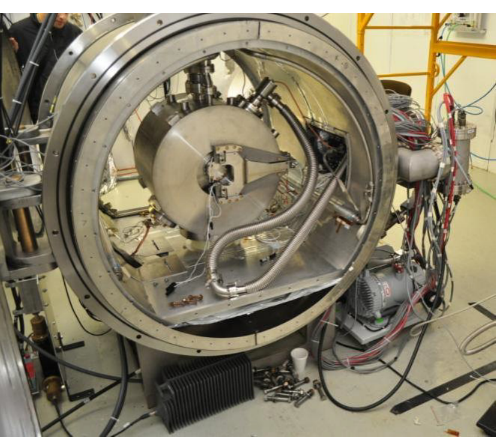
SSR0 with improved He vessel

- Lowering the Df/dP + ASME pressure vessel code compliant
- Tuning on one side only
- Temperature 2K

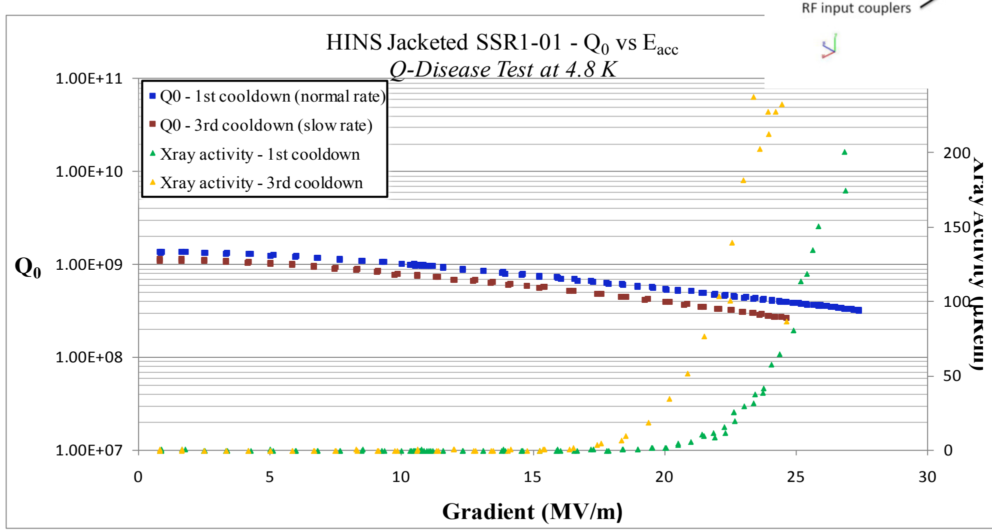
Updated designs for CW mode



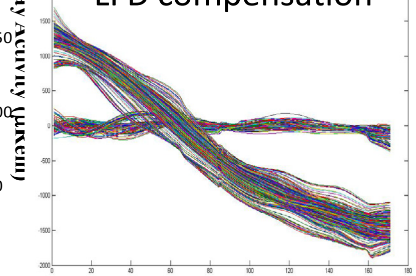




SSR1 horizontal test

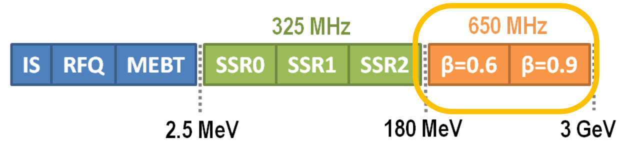


LFD compensation



Courtesy L. Ristori

FNAL - Project X

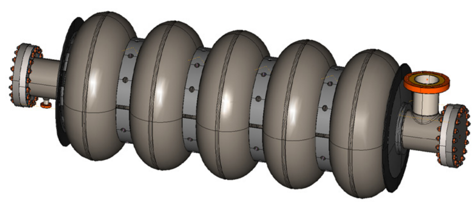


Elliptical cavities

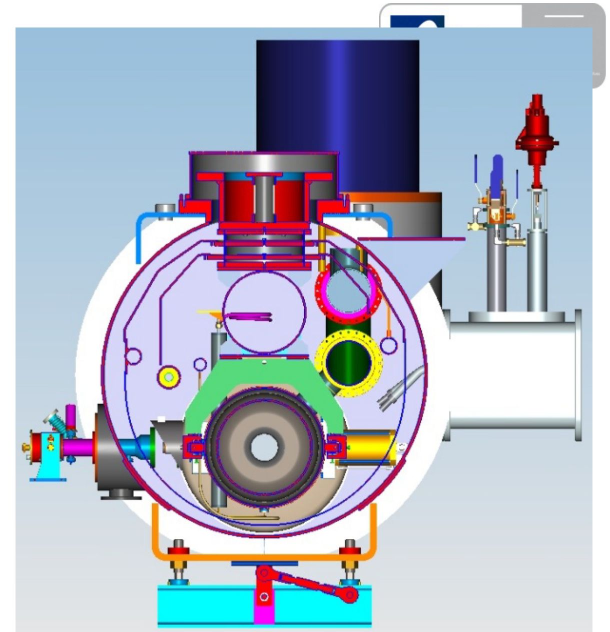
650 MHz 5 cell cavities

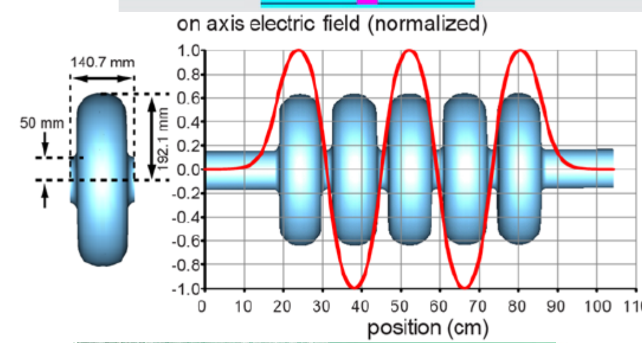
Maximum load at 2K is 250 W per module

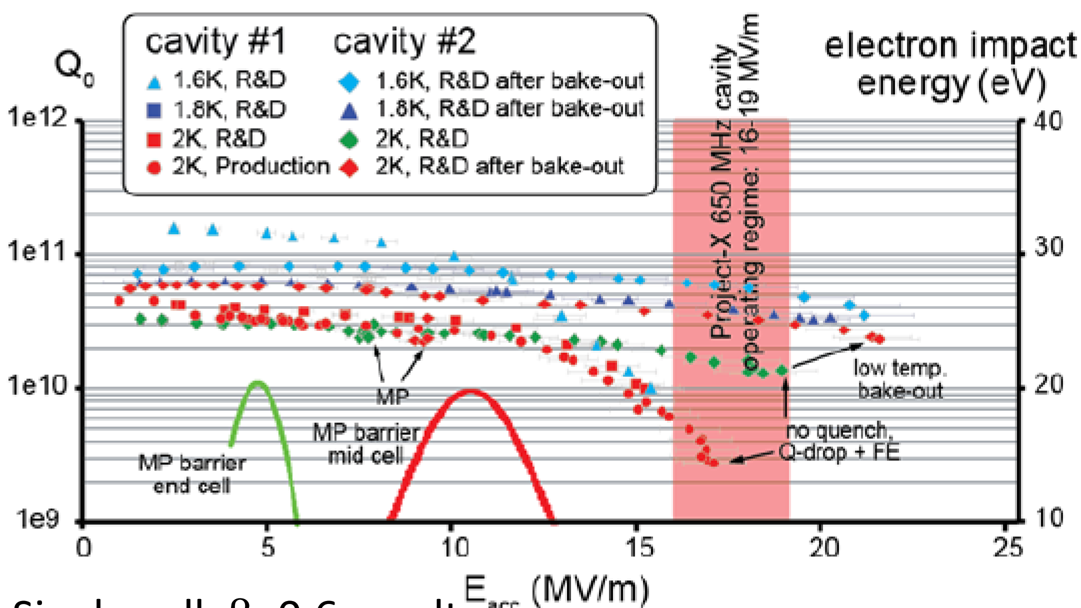
Parameter	Unit	JLab	FNAL
β		0.61	0.61
number of cells		5	5
frequency	MHz	650	650
equator diameter E	mm	380.4	389.9
iris aperture A	mm	100	83
E/A		3.83	4.70
active length	mm	694	705
cell-to-cell coupling	%	1.4	0.75
E_{peak}/E_{acc}		2.71	2.26
B_{peak}/E_{acc}	mT/(MV/m)	4.78	4.21
R/Q	Ω	297	378
G	Ω	190	191
R/Q·G	Ω^2	56430	72198



β=0.9 5-cell





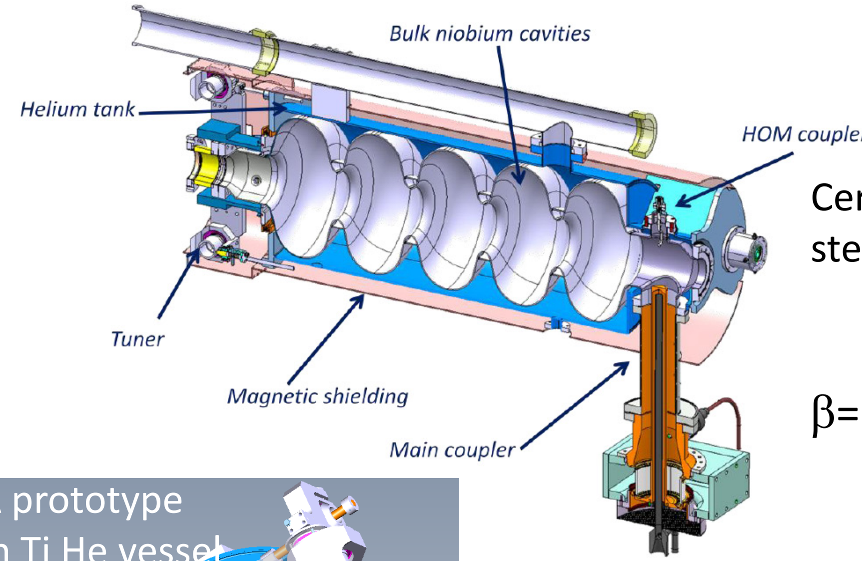


Single cell β=0.6 results

Courtesy C. Ginsburg, F. Marhauser

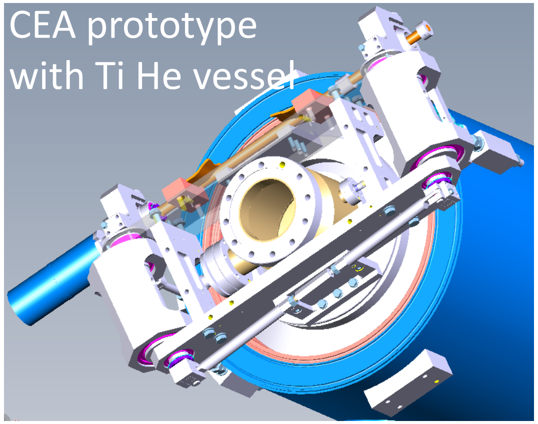
CERN - SPL

beta	0.65	1
f (MHz)	704.4	704.4
Epk/Eacc	2.63	2
Bpk/Eacc (mT/MV/m)	5.12	4.2
K (%)	1.45	1.9
r/Q (Ohm)	275	566
G (Ohm)	197	270

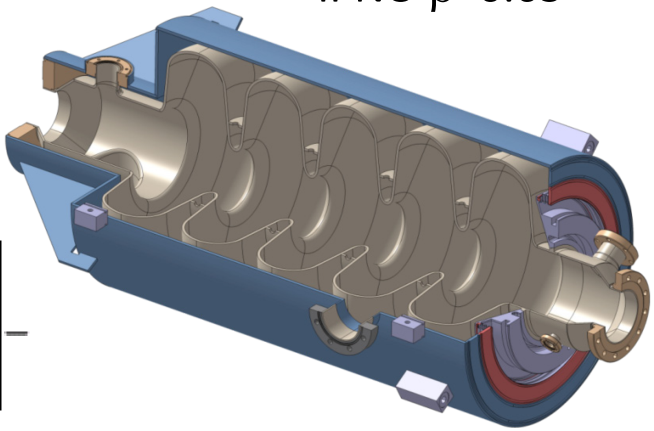


Cern stainless steel He vessel

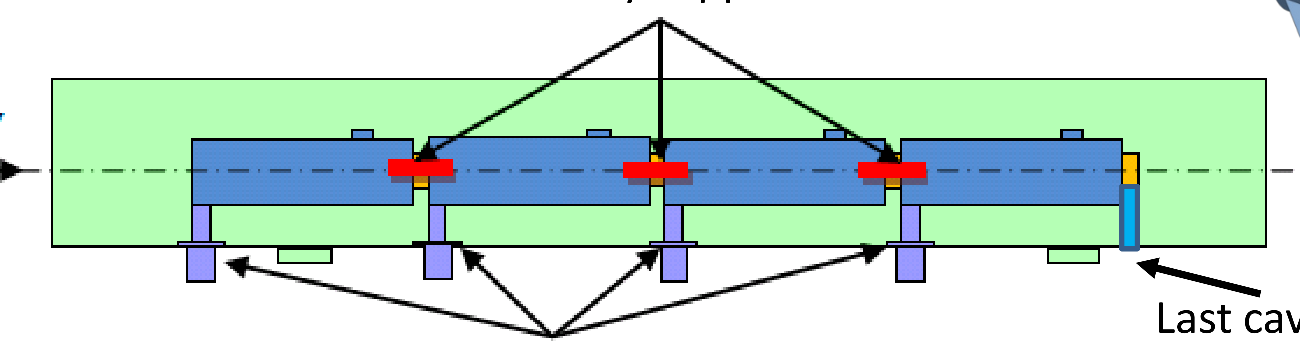
β=1 5-cell cavity



IPNO β=0.65



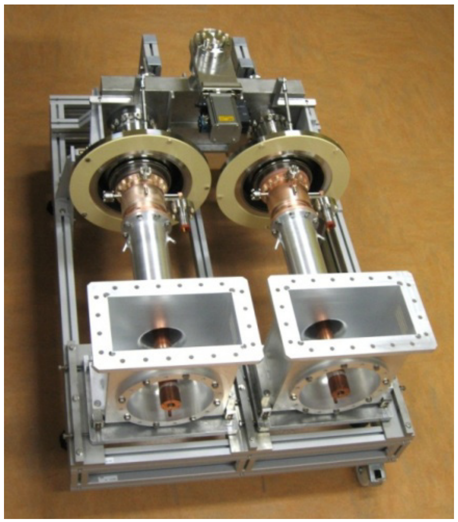
Short cryomodule prototype concept



RF coupler double-walled tube flange fixed to vacuum vessel

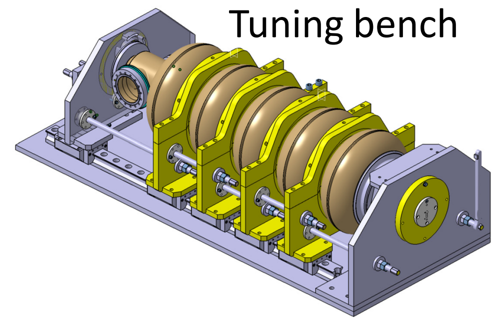
CERN – SPL R&D

CEA-Saclay coupler tested up to 1.2 MW 50Hz 2ms
Design derived from KEK-SNS style coupler

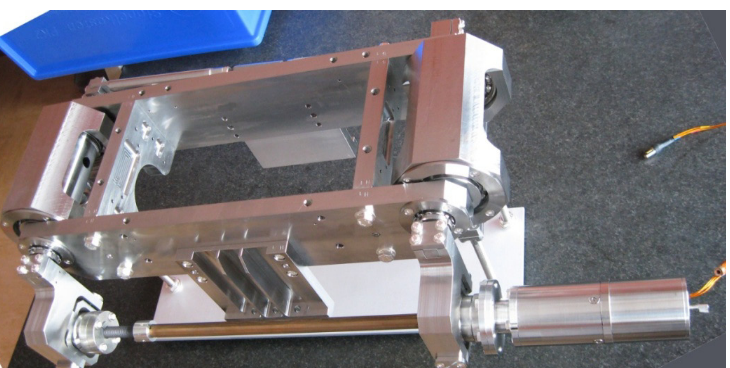


CERN prototype power coupler

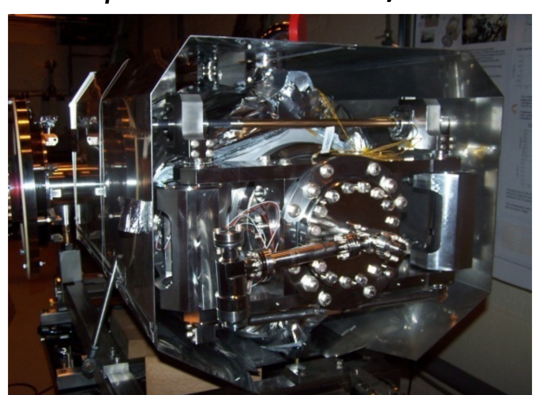
Tuning bench

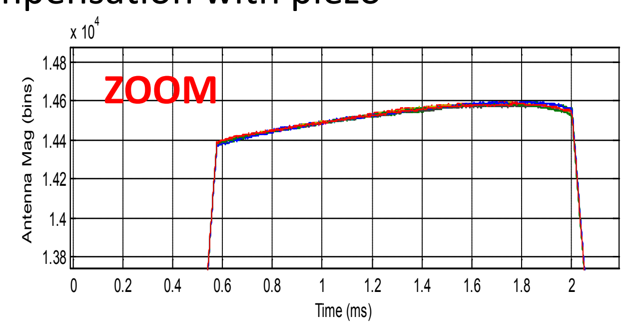


Saclay-V type piezo tuner for SPL cavities



Integrated test in Cryholab of power coupler and tuner on a β=0.5 5cell cavity. LDF compensation with piezo





Amplitude excursion reduced to 1.4% and phase shift within ± 8 deg.

ONRL - SNS

SNS has demonstrated:

- The suitability of SRF technology for a high power pulsed H- linac
- Operational flexibility of independently phased cavities

Problems :

Field emitted electrons propagating from cavity to cavity.

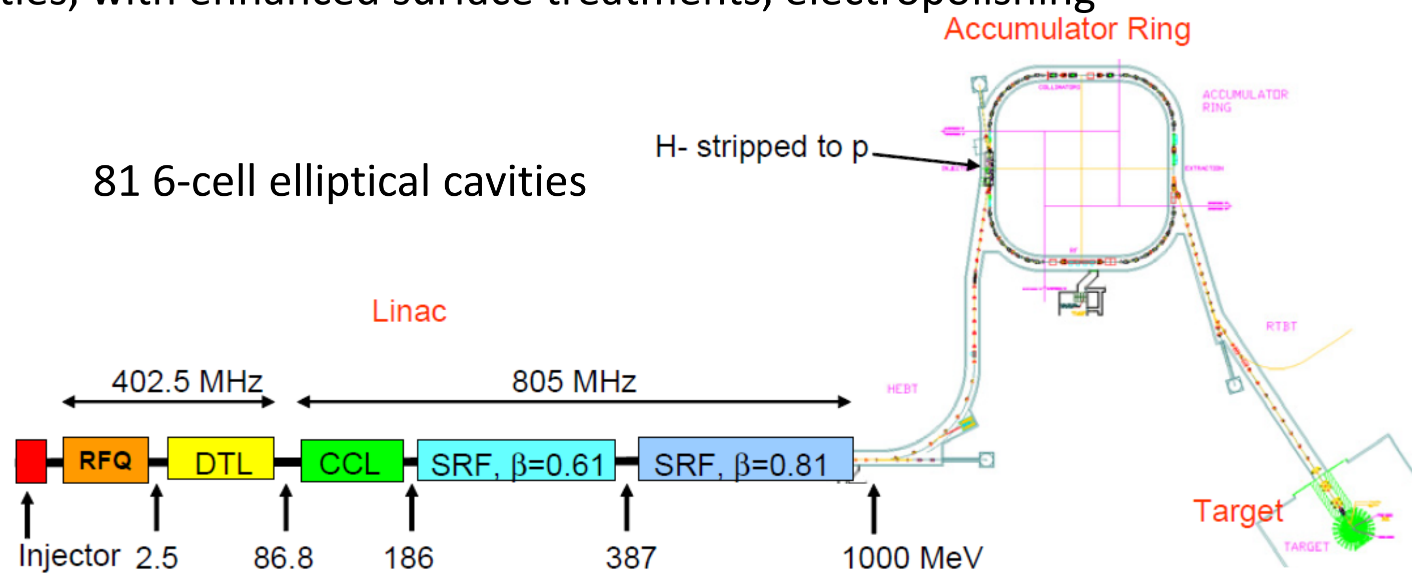
Multipactor in HOM couplers ultimately detuning the notch filter and damaging the coupler

Cures:

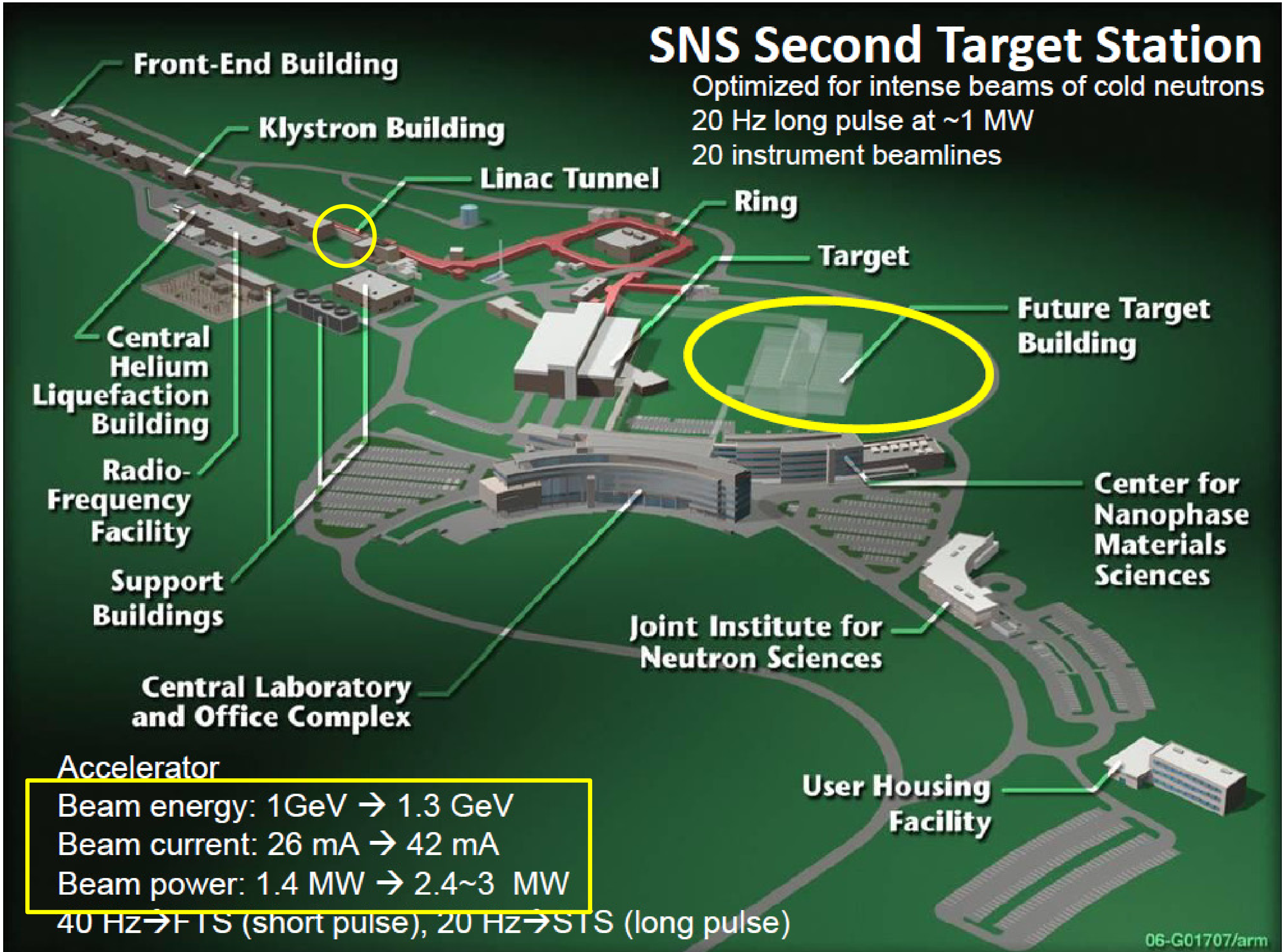
Remove HOM probes

Re-process the cavities, with enhanced surface treatments, electropolishing

81 6-cell elliptical cavities



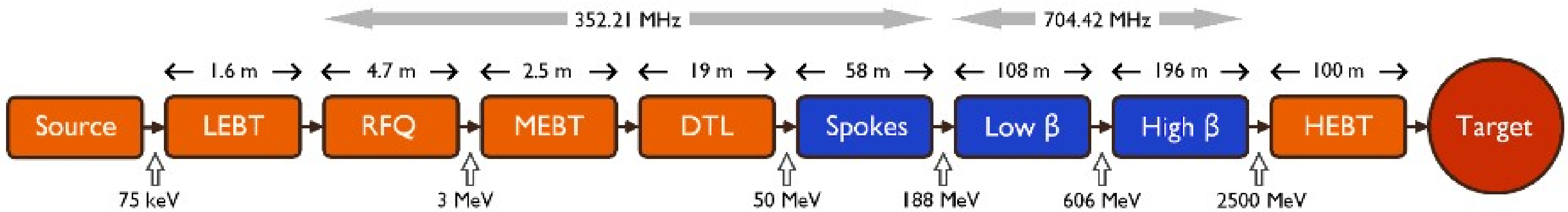
ONRL – SNS – Power upgrade



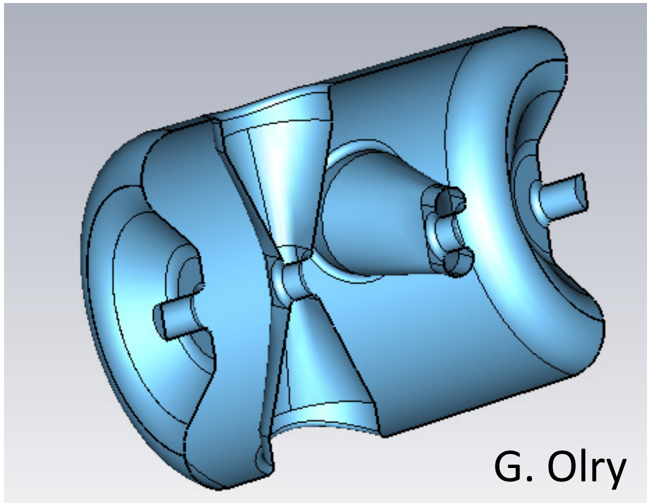
S.-H. Kim

ESS - European Spallation Source

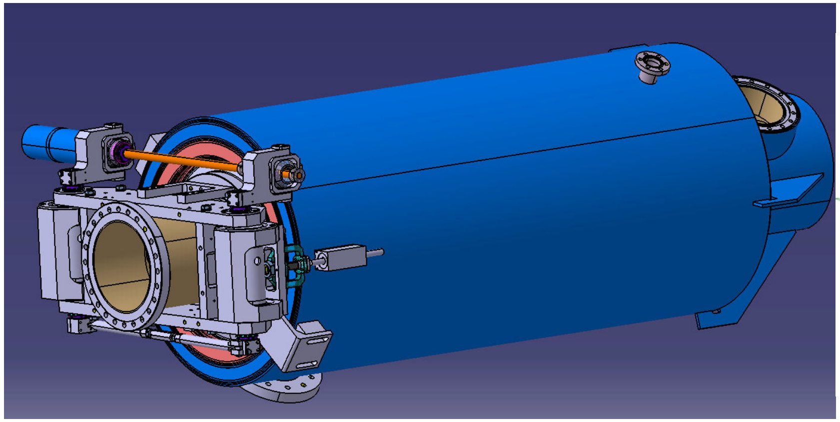
2.5 GeV 50mA pulsed proton linac

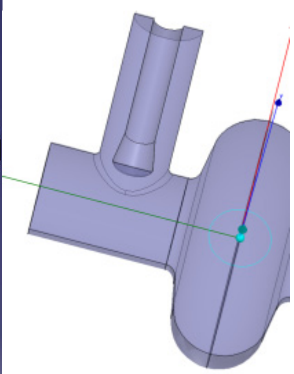


Preliminary design of β=0.57 352 MHz double spoke cavity (IPN Orsay)



β= 0.86 prototype cavity design (CEA-Saclay)





Frequency (MHz)	704.42
Number of cells	5
Operating temperature (K)	2
Maximum surface field in operation (MV/m)	40
Nominal Accelerating gradient (MV/m)	< 18
Q_0 at nominal gradient	> 6e9
Repetition rate (Hz)	14
Beam pulse length (ms)	2.86
Nominal peak power transmitted by power couplers (kW)	< 900

Geometrical beta	0.86
Iris diameter (mm)	120
Cell to cell coupling κ (%)	1.8
π and 4π/5 mode separation (MHz)	1.2
Epk/Eacc	2.2
Bpk/Eacc (mT/(MV/m))	4.3
Maximum. r/Q (Ω)	477
Optimum beta	0.92
G (Ω)	241

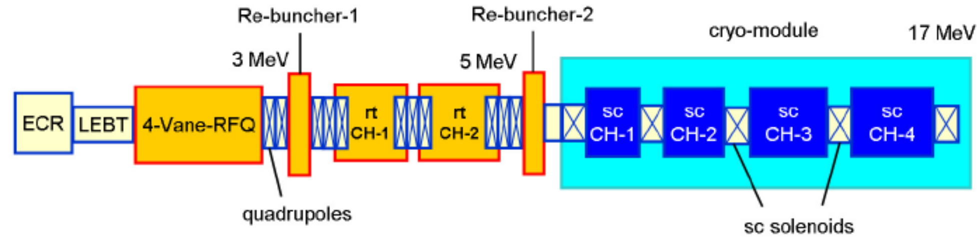
Prototypes of spokes and high beta elliptical cavities tests planned in 2012

ADS - MYRRHA

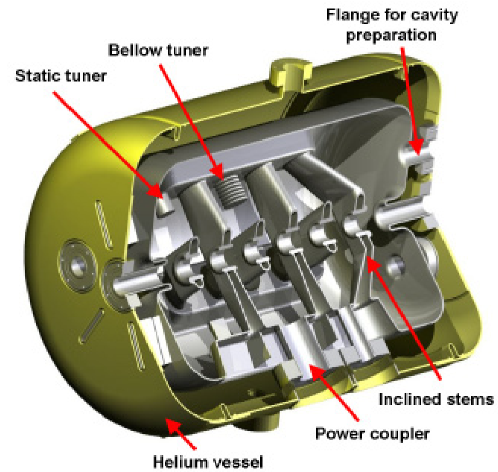
600 MeV 4 mA CW proton linac

Section #	#1	#2	#3
E_{input} (MeV)	17.0	86.4	186.2
E_{output} (MeV)	86.4	186.2	605.3
Cav. technology	Spoke	Elliptical	
Cav. freq. (MHz)	352.2	704.4	
Cavity geom. β	0.35	0.47	0.65
Nb of cells / cav.	2	5	5
Focusing type	NC quadrupole doublets		
Nb cav / cryom.	3	2	4
Total nb of cav.	63	30	64
Nominal E_{acc}* (MV/m)	5.3	8.5	10.3
Synch. phase (deg)	-40 to -18	-36 to -15	
5mA beam load / cav (kW)	1 to 8	3 to 22	17 to 38
Section length (m)	63.2	52.5	100.8

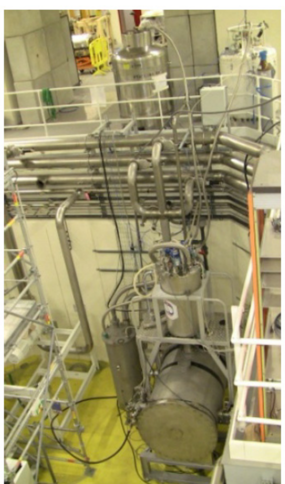
*E_{acc} is normalized to $L_{acc}=N_{cell}\beta_{opt}\lambda/2$, & given at β_{opt}

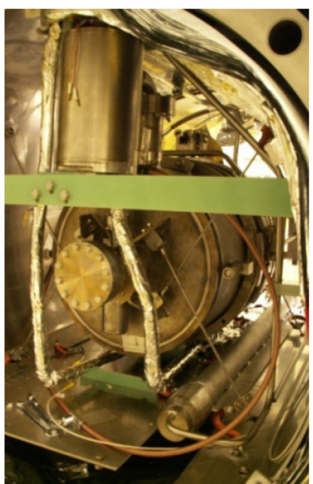


17 MeV Injector : dual injector for fault tolerance

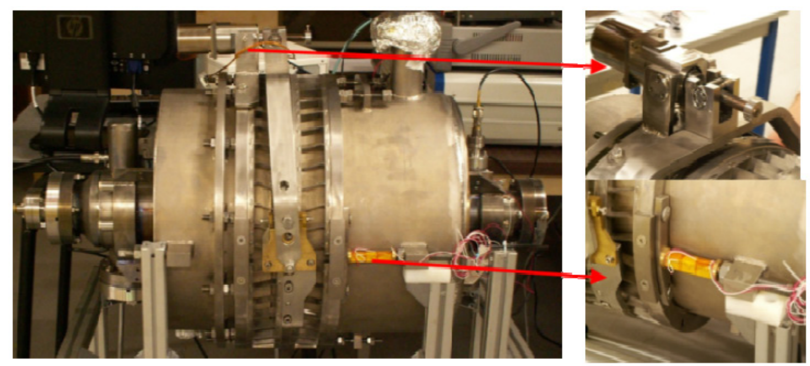


IAP- Frankfurt
CH structure





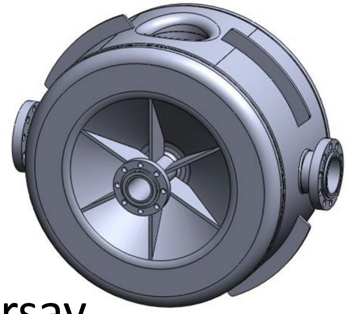
Eurotrans test cryomodule at IPN Orsay with INFN-Milano β=0.5 5-cell cavity equipped with the blade tuner



Courtesy J.-L. Biarrotte

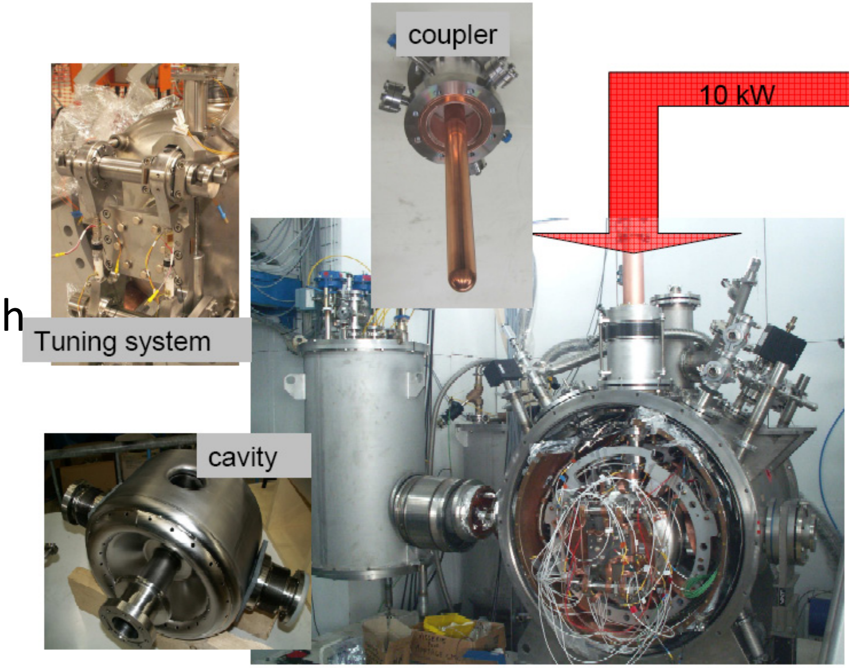
Medium beta related R&D

- BARC : 325 MHz spoke resonators and 650 MHz elliptical cavities
- RRCAT 650 MHz β=0.9 single cell prototype in 2011
- PEFP in Korea 700 MHz β=0.42
- PKU 450 MHz β= 0.2 single spoke



- Chinese ADS : CIADS spoke & HWR R&D
- Full cavity testing of 352 MHz spoke at IPN Orsay

Single spoke equipped with power coupler and tuner



S. Bousson

Conclusion

- very wide and active field due to the many cavity types available
- ion and proton cavities benefit from the preparation techniques developed on electron cavities, and their performance has been greatly improved during the last decade
- Spoke resonators are now included in several machine baseline. Beam testing of a spoke based system has not been carried out yet, but huge progress has been achieved recently in spoke technology

Thanks to

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E. Montesinos
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Thank you for your attention