SRF Cavity Review: Focus on some low beta cavities developments in Europe and WW

Sébastien Bousson

CNRS/IN2P3/ IPN– Paris-Sud University

Outlook

- A (very) brief history of SRF
- Main SRF developments in Europe for protons /ions accelerators
    - Spiral-2
    - IFMIF
    - ESS
- Worldwide SRF “at a glance”: C-ADS, FRIB
- Conclusion

** HiE-ISOLDE is the other important SRF project in EU but not depicted in this overview since there is dedicated talks in this same meeting*

What is not covered…

Not an exhaustive review, but one could refer to the following on-going activities to be complete:

- In Europe:
  - for MYRRHA (spoke, elliptical)
  - several R&D programs in INFN Legnaro, U. Frankfurt, IPN Orsay, CEA Saclay, STFC, INFN Milano…
  - for SPL (elliptical): CERN, CEA, IPN Orsay
- Worldwide:
  - for ADS programs (India, Japan)
  - R&D programs in Fermilab, Jlab & ODU, Univ. Beijing, Triumf…
  - for machine upgrades: @ANL, @SNS, @TRIUMF
  - for project/construction: RAON (Korea), SARAF (Israel)
  - for deflecting cavities (crab): BNL, SLAC, ODU, Daresbury

A bit of history…

SRF Technology for accelerators:

- **Has started in 1961** when W. Fairbank (Standford University) proposed for the first time a superconducting accelerator
- **In 1964** W. Fairbank, A. Schwettman, P. Wilson (Standford University) have first accelerated electrons with a SC lead cavity
- **In 1970,** J. Turneaure (Standford University) reached Epk=70 MV/m and Qo ~10^{10} in a 8.5 GHz cavity !
- **Between 1968 and 1981**, Mc Ashan, J. Turneaure, A. Schwettman, T. Smith, P. Wilson (Standford University) developped and constructed the SCA (e^-)

SRF Technology then gained maturation:

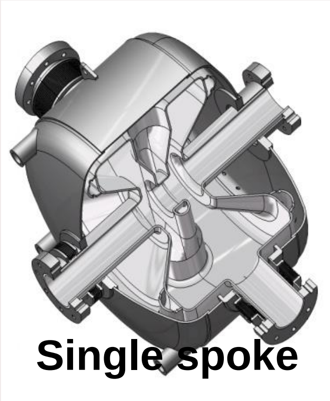
- **With facilities : CEBAF (@ Jlab) and LEP-II (CERN)**
- **With the TESLA collaboration (mid 90s) :** important effort to develop the SRF technology (TTF, FLASH) up to a real industrial scale with XFEL

A bit of history…

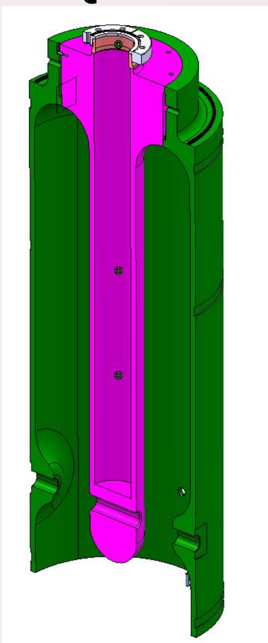
2 SRF categories: electron cavities (β=1, elliptical in 99% of the cases)

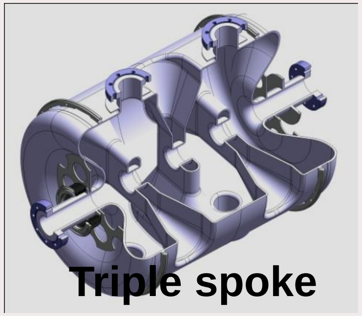
proton/ion cavities (β<1, multiple shapes)

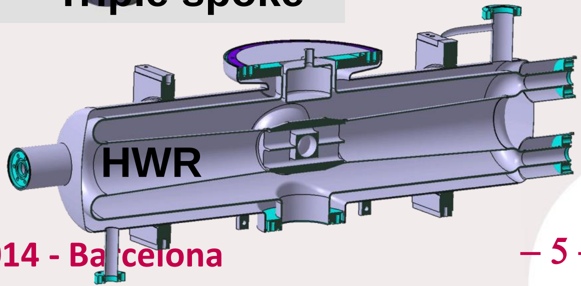
Same core technology, but design and optimization issues very different



QWR



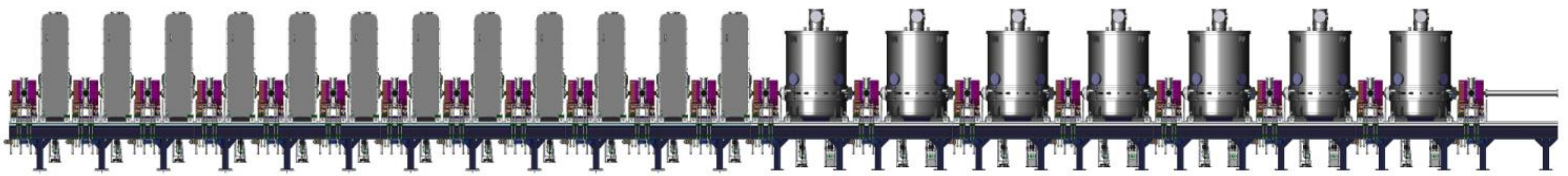


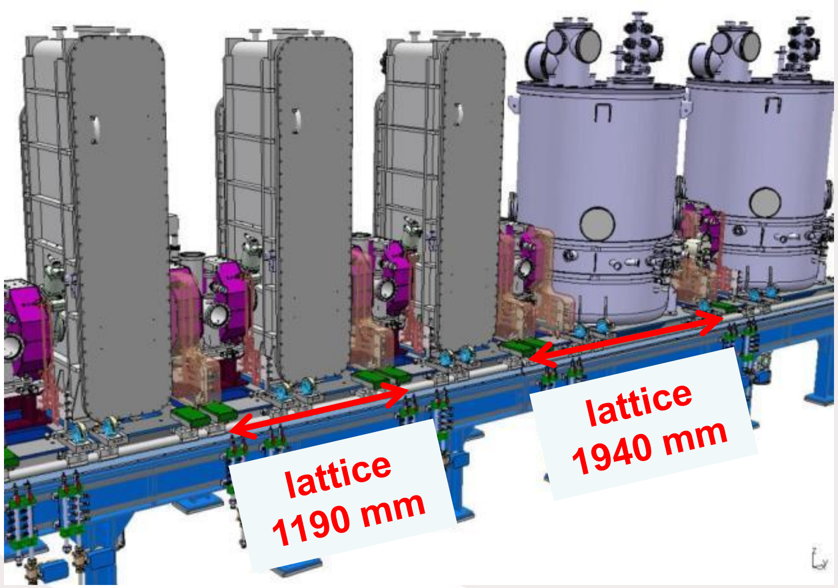


SRF Developments in Europe for protons and ions Accelerators

SPIRAL-2 *(GANIL, CEA, CNRS)*

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



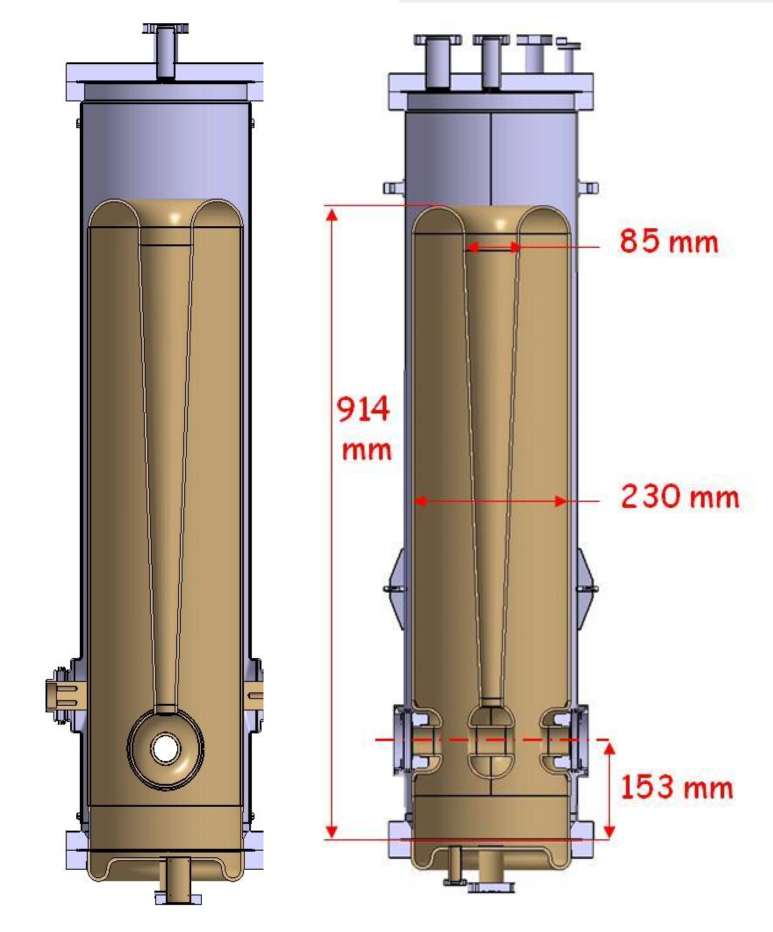


Cryomodule A	Cryomodule B	Power coupler
CEA Saclay	IPN Orsay	LPSC Grenoble

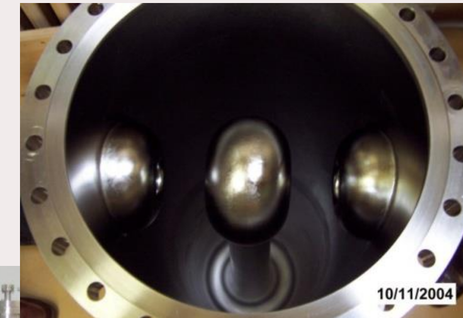
Cryomodule	A	B
Valve-to-valve length [mm]	610	1360
# cavities	12	14
f [MHz]	88.05	88.05
β_{opt}	0.07	0.12
Epk/Eacc	5.36	4.76
Bpk/Eacc [mT/MV/m]	8.70	9.35
r/Q [Ω]	599	515
Vacc @ 6.5 MV/m & β_{opt}	1.55	2.66
Lacc [m]	0.24	0.41
Beam tube ∅ [mm]	38	44

SPIRAL-2 *(GANIL, CEA, CNRS)*

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



Courtesy P. Bosland

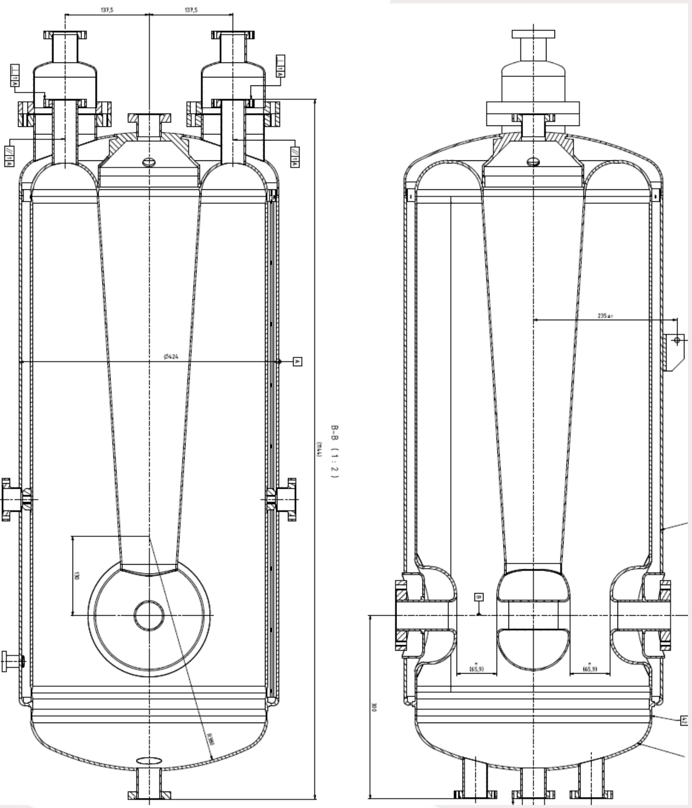


Zanon and SDMS cavities

13 cavities fabricated in total

SPIRAL-2 *(GANIL, CEA, CNRS)*

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

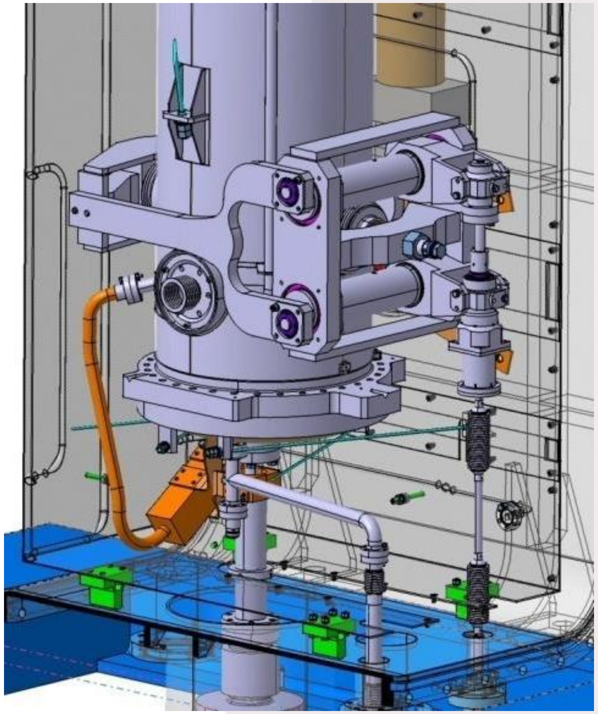


Total produced: R&D phase: 1 prototype +2 pre-series
Series production: 16 (made by Research Instruments)

SPIRAL-2 *(GANIL, CEA, CNRS)*

Low β Cold tuning system

Mechanical tuner, push system

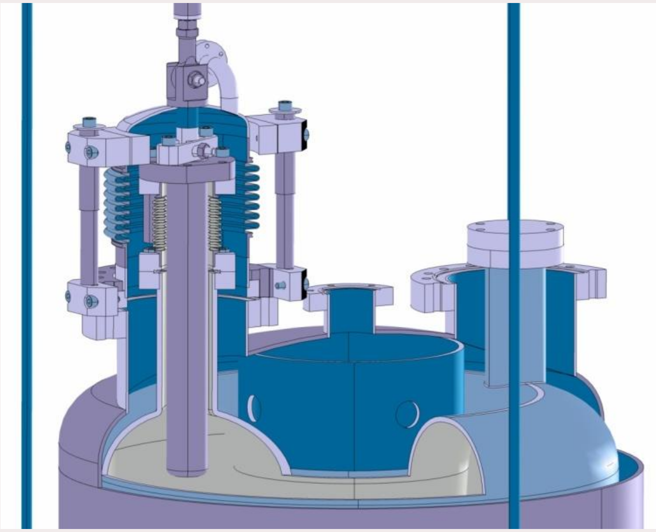


Good linearity: 0.15 Hz/motor step
Sensitivity: ~28 kHz/mm
Full range: +25 kHz

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)

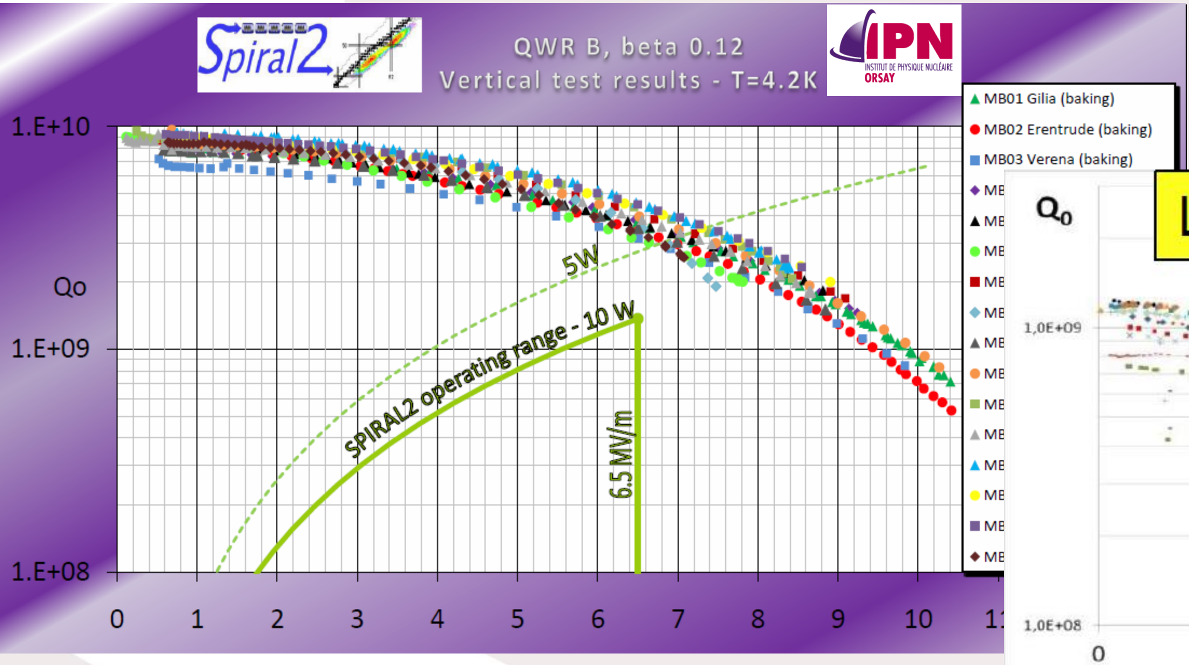
First "coarse" tuning: + 50 kHz

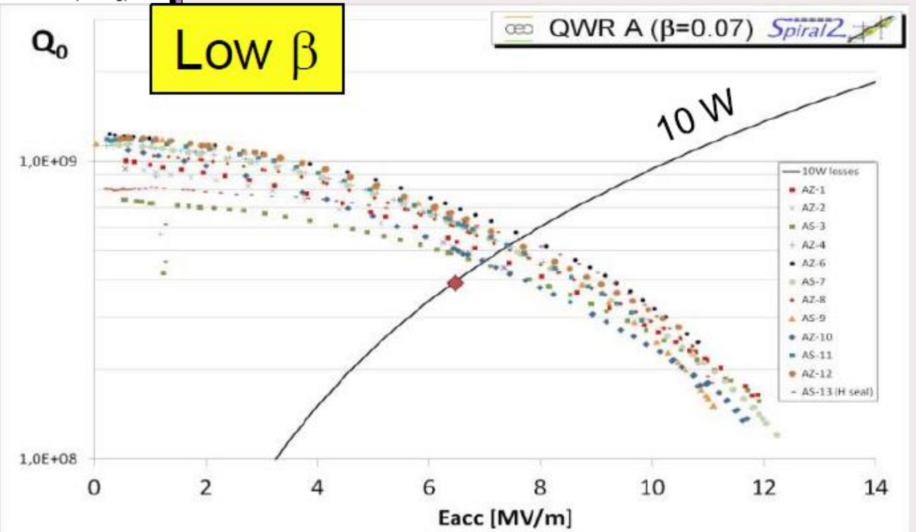
then fine tuning: +/- 4 kHz

SPIRAL-2 *(GANIL, CEA, CNRS)*

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: all cavities tested are in the spec. Some have Eacc > 10 MV/m !
- High β cavities: all series cavity tested and in the spec with important margins !



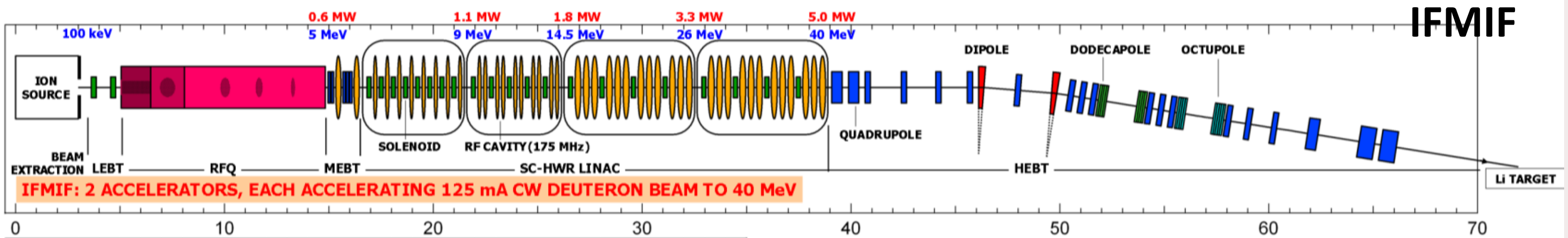


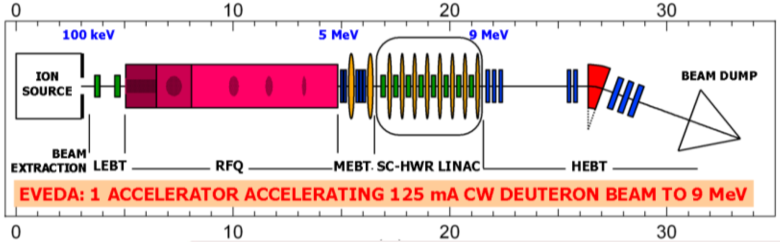
Cryomodule production:

8/12 low β CMs and 5/7 high β assembled, tested and delivered to Ganil

IFMIF-LIPAC *(CEA, CIEMAT)*

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.

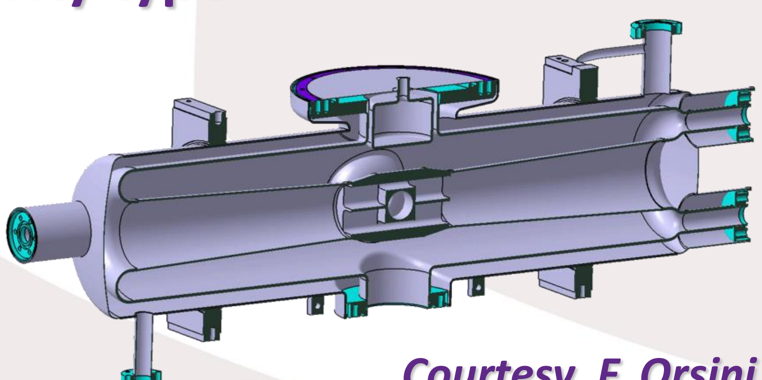




EVEDA (demonstrator)

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	

Cavity type: Half-wave resonators



Courtesy F. Orsini

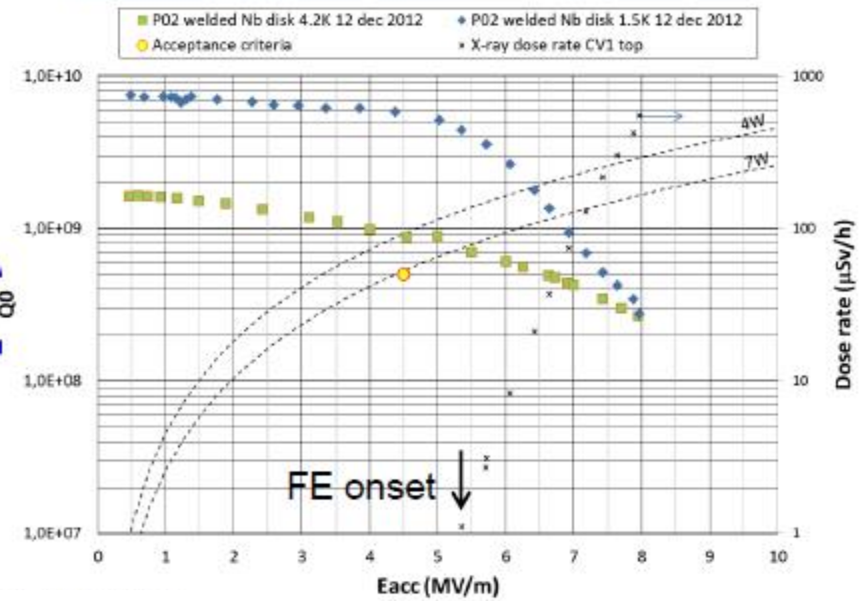
IFMIF-LIPAC *(CEA, CIEMAT)*

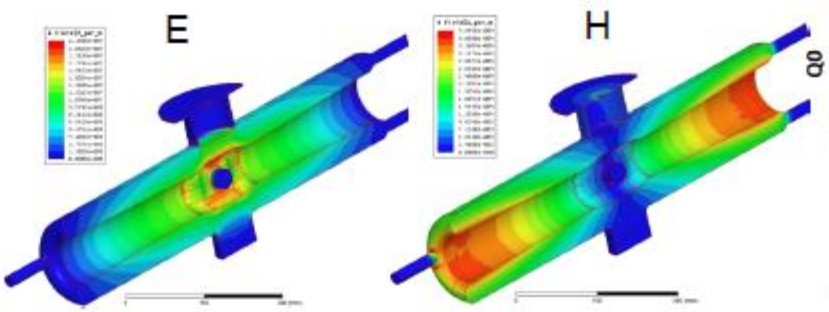
Parameter	Value	Unit
Frequency	175	MHz
Maximum r/Q	150	Ohm
Optimum beta	0.11	
Design beta	0.094	
r/Q @ design beta	140	Ohm
Epk/Eacc	4.8	
Bpk/Eacc	11	mT/(MV/m)
Nominal Eacc	4.5	MV/m
Nominal Qo	$5\ 10^8$	

After plunger tuner removal prototype P02 performance exceed specifications

G. Devanz

Linac 2014

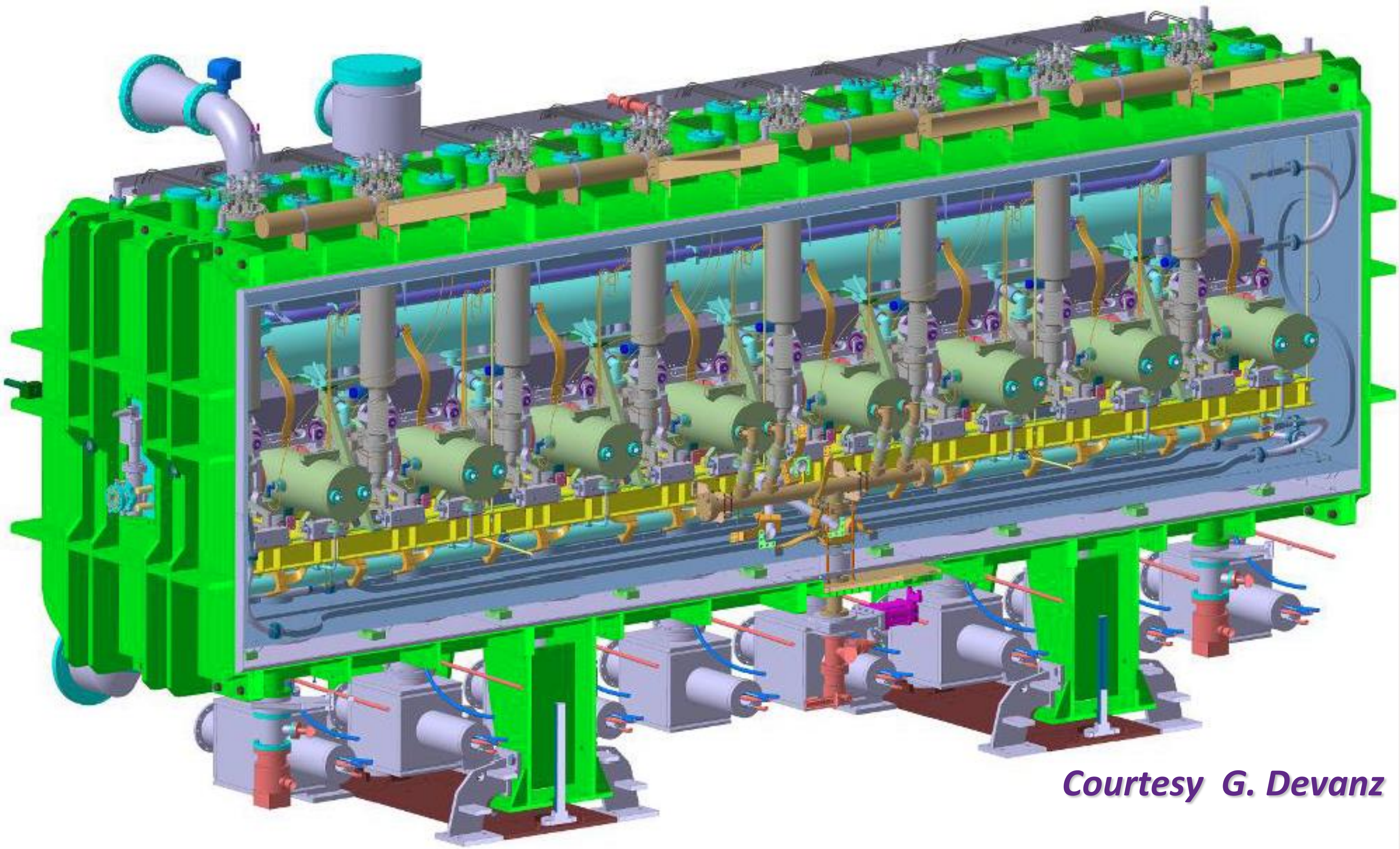




The original cavity design includes a superconducting plunger tuner

New cold tuning system: compression tuner (cavity body deformation)

IFMIF-LIPAC *(CEA, CIEMAT)*

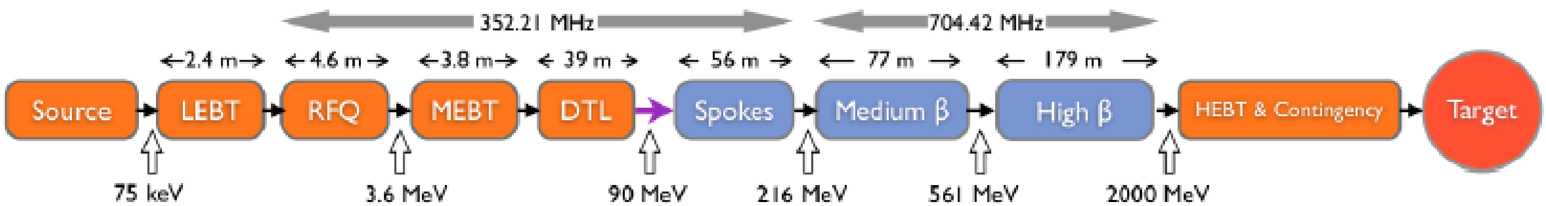


Courtesy G. Devanz

Cryomodule: 8 HWR + 8 solenoïd package (solenoïd, steerer, BPM)

ESS (17 Eu countries)

ESS Linac: SRF Technology from 90 MeV to 2 GeV



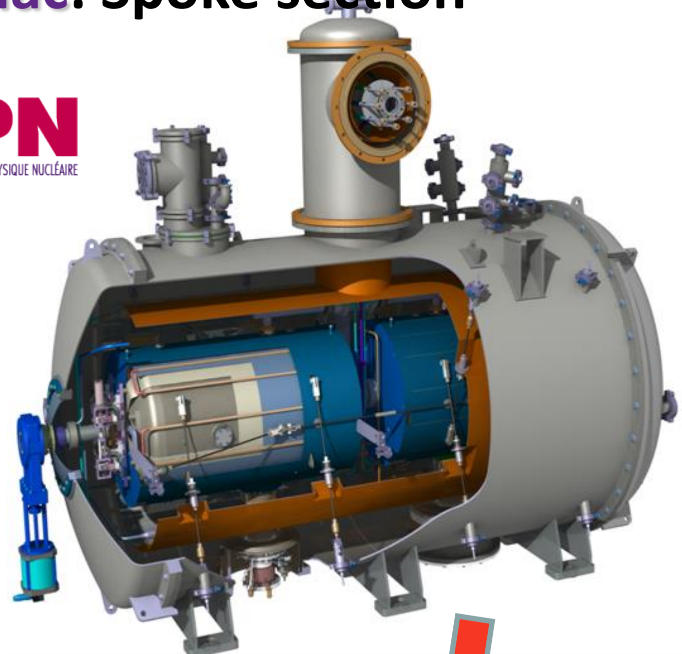
Requirements	Spoke	Medium	High
Frequency (MHz)	352.21	704.42	704.42
Geometric beta	0.50	0.67	0.86
Nominal Accelerating gradient (MV/m)	9.0	16.7	19.9
Epk (MV/m)	39	45	45
Bpk/Eacc (mT/MV/m)	<8.75	4.79	4.3
Epk/Eacc	<4.38	2.36	2.2
Iris diameter (mm)	50	94	120
RF peak power (kW)	335	1100	1100
G (Ω)	130	196.63	241
Max R/Q (Ω)	427	394	477
Qext	$2.85\ 10^{5}$	$7.5\ 10^{5}$	$7.6\ 10^{5}$
Q0 at nominal gradient	$1.5\ 10^{9}$	$> 5\ 10^{9}$	$> 5\ 10^{9}$

Beam power (MW)	5
beam current (mA)	62.5
Linac energy (GeV)	2
Beam pulse length (ms)	2.86
Repetition rate (Hz)	14

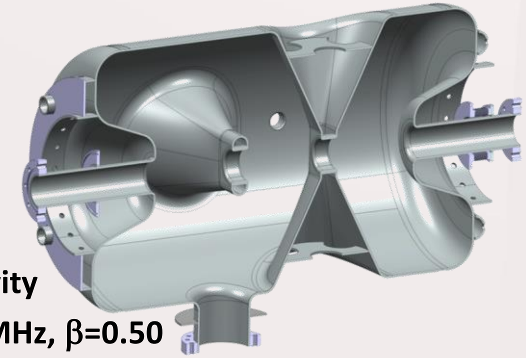
	Num. of CMs	Num. of cavities
Spoke	13	26
6-cell medium β	9	36
5-cell high β	21	84

ESS (17 Eu countries)

ESS Linac: Spoke section

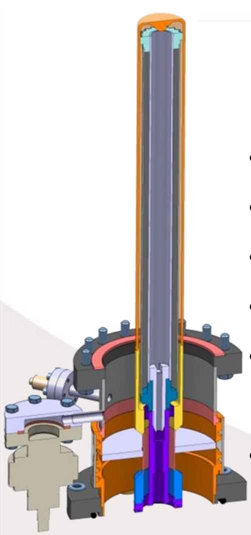


Double Spoke SRF Cavities



- Double spoke cavity (3-gaps), 352.2 MHz, β=0.50
- Goal: Eacc = 9 MV/m *[Bp= 72 mT ; Ep = 39 MV/m]*
- 4 mm (nominal) Niobium thickness
- Titanium Helium tank, Ti stiffeners
- Lorentz detuning coeff. : -4.4 Hz/(MV/m)^2
- Tuning sentivity $\Delta f/\Delta z$ = 128 kHz/mm
- 3 prototypes under fabrication (delivery sept & oct 2014)

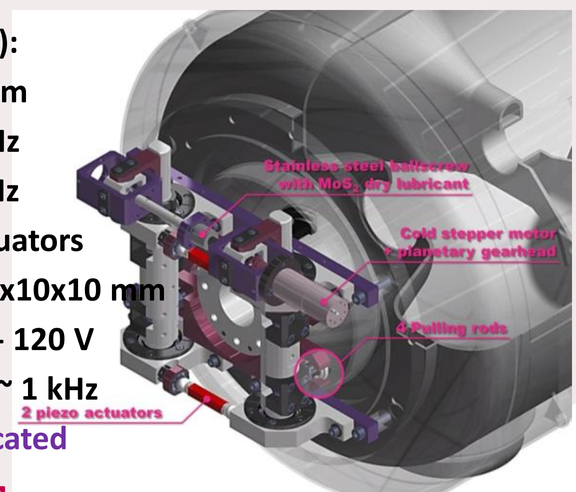
Power Coupler



- Ceramic disk, 100 mm diameter
- 400 kW peak power
- Antenna & window water cooling
- Outer conductor cooled with Lhe
- Doorknob transition from coaxial to ½ height WR2300 waveguide
- 4 prototypes under fabrication (delivery in early October 2014)

Cold tuning system

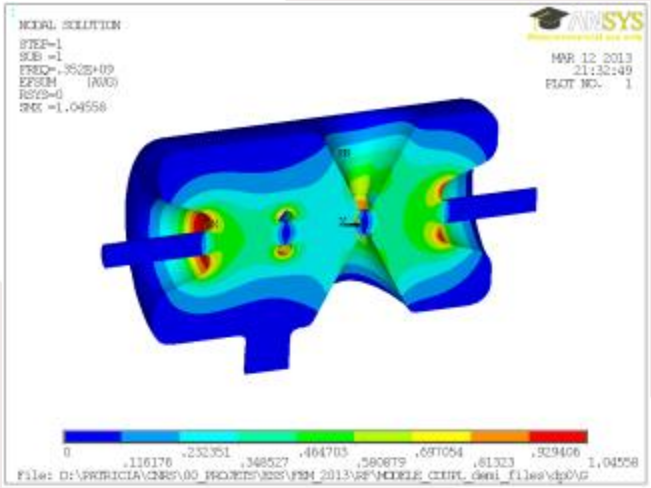
- Slow tuner (stepper motor):
  Max tuner stroke: 1.28 mm
  Max tuning range: 170 kHz
  Tuning resolution: 1.14 Hz
- Fast tuning by 2 piezos actuators
  Noliac 50x10x10 or PI 36x10x10 mm
  Applied voltage up to +/- 120 V
  Estimated tuning range: ~ 1 kHz
- 2 prototypes already fabricated

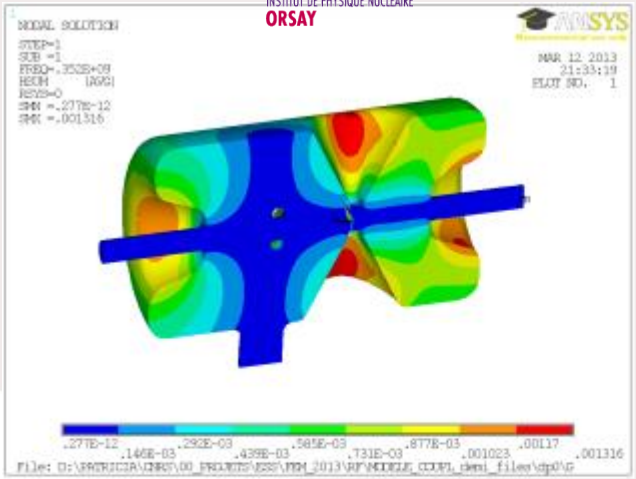


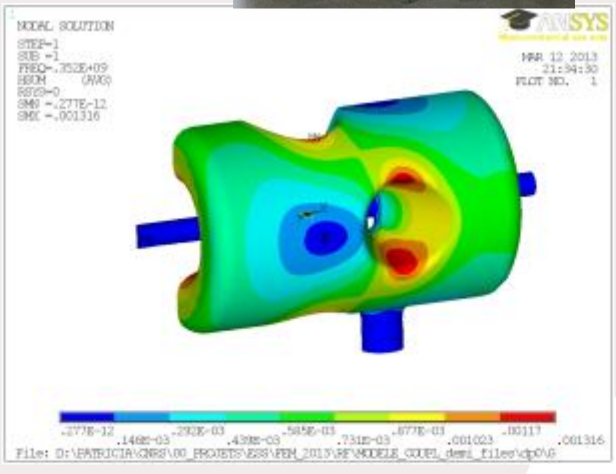
ESS (17 Eu countries)

DOUBLE-SPOKE CAVITIES	
Frequency [MHz]	352.2
Beta_optimal	0.50
Operating gradient [MV/m]	9
Temperature (K)	2
Bpk [mT]	61
Epk [MV/m]	38
G [Ohm]	133
r/Q [Ohm]	427
Lacc (=beta optimal x nb of gaps x λ /2) [m]	0.639
Bpk/Eacc [mT/MV/m]	6.8
Epk/Eacc	4.3
P max [kW]	300

Spoke cavities for ESS







ESS (17 Eu countries)

EUROPEAN SPALLATION SOURCE

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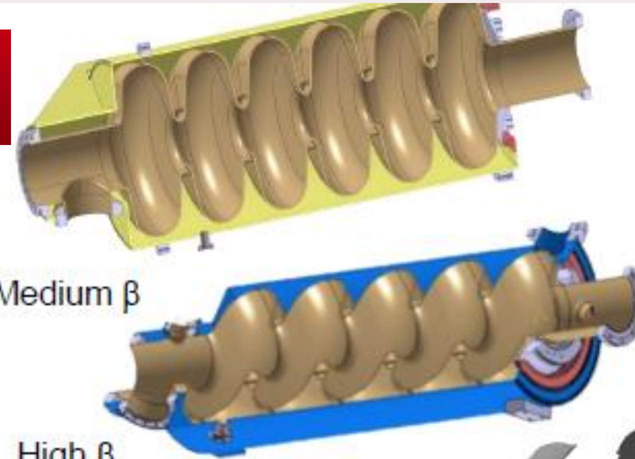
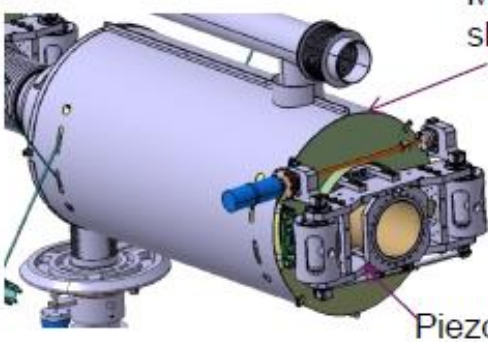
ESS high energy sections: 704 MHz elliptical cavities

	Medium	High
Geometrical beta	0.67	0.86
Number of cells	6	5
Length (mm)	1259	1316
Nominal Accelerating gradient (MV/m)	16.7	19.9
Nominal Accelerating Voltage (MV)	14.3	18.2
Q_0 at nominal gradient	> 5e9	
Cavity dynamic heat load (W)	4.9	6.5
Q_{ext}	$7.5\ 10^5$	$7.6\ 10^5$
Iris diameter (mm)	94	120
Cell to cell coupling k (%)	1.2	1.8
π and $5\pi/6$ (or $4\pi/5$) mode separation (MHz)	0.53	1.2
E_{pk}/E_{acc}	2.35	2.2
B_{pk}/E_{acc} (mT/(MV/m))	4.78	4.3
Maximum. r/Q (Ω)	397	477
Optimum β	0.705	0.92
G (Ω)	197	241
Static KL (Hz/(MV/m)²) with tuner	-2	-1



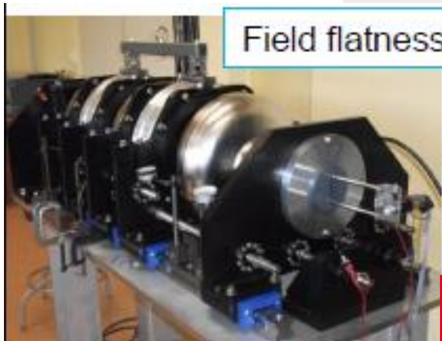


Courtesy G. Devanz

- No HOM couplers
- Cold magnetic shield over the He jacket (target 1.4 μT)
- Use as far as possible tesla technology material (Ti tank, Al gaskets)

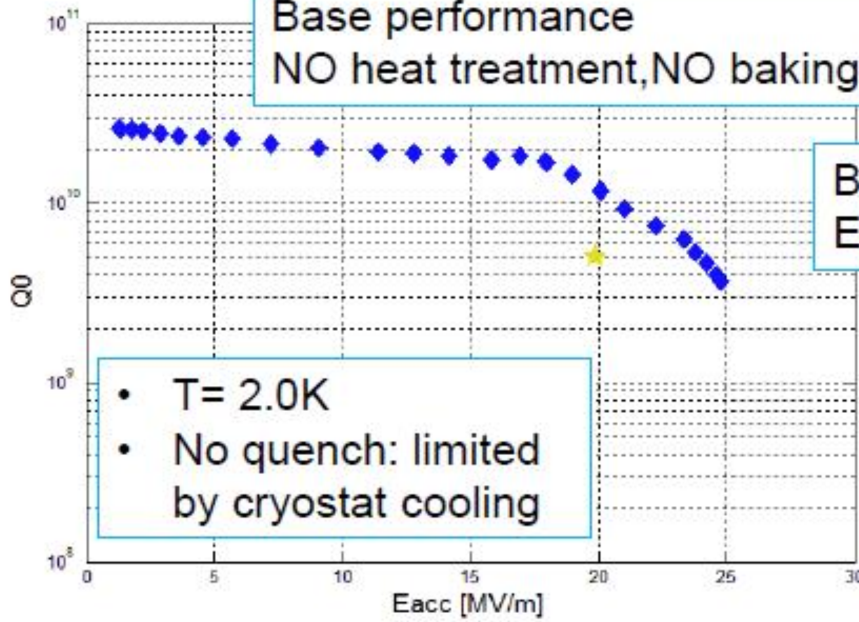
ESS (17 Eu countries)

ESS high energy sections: 704 MHz elliptical cavities



Field flatness:92%

FNP 1-1-2.4 etching performed on BCP/EP cabinet



Base performance
NO heat treatment,NO baking yet

- T= 2.0K
- No quench: limited by cryostat cooling

Bpk =105 mT
Epk = 54 MV/m

Prototype #2
Is ready for
vertical test

Courtesy G. Devanz

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Main SRF Developments worldwide for protons and ions accelerators

FRIB *(MSU)*

FRIB: Produce RIB using a 400 kW CW HI driver linac (p to U) up to 200 MeV/u.

Challenge: All SRF from low β(0.041) to middle β(0.53)

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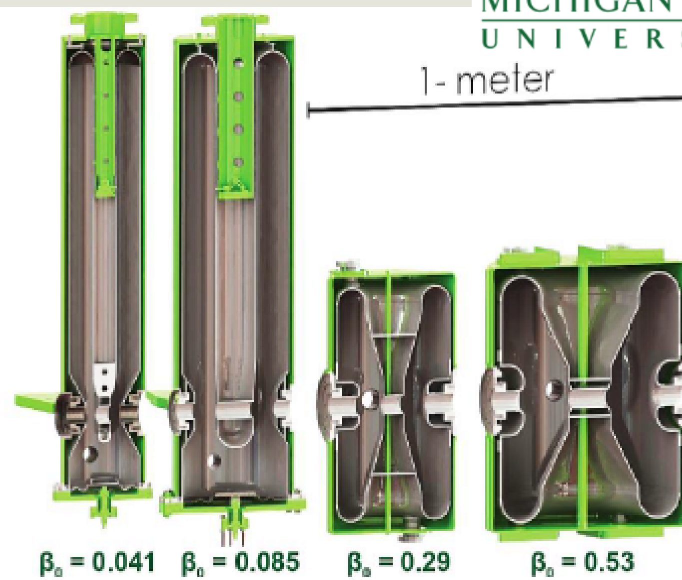
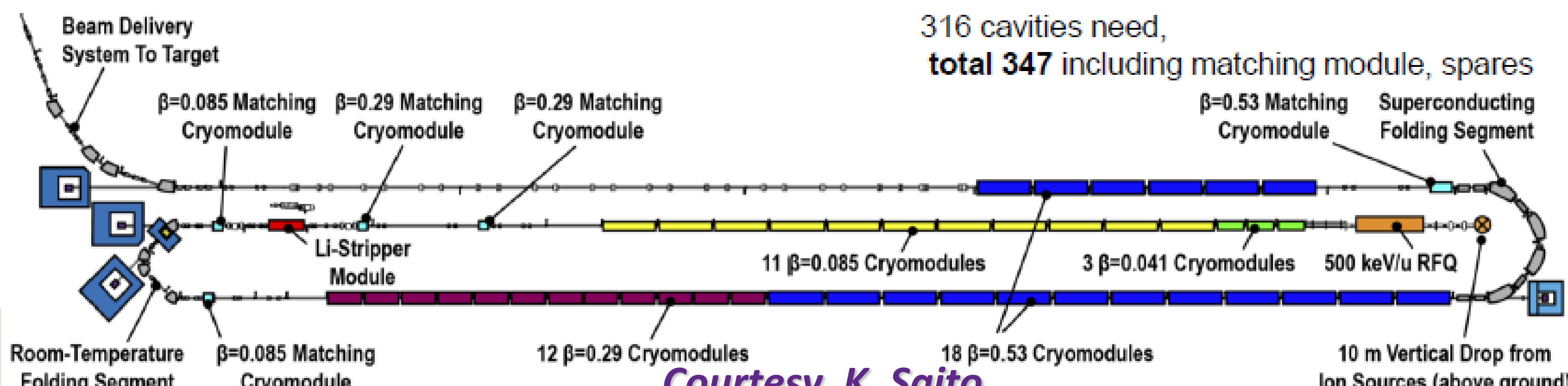
Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p/E_{acc}	5.82	5.89	4.22	3.53
B_p/E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
G [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning [Hz/(MV/m)²]	< 4	< 4	< 4	< 4
Specific Q_0@VT	1.4E+9	2.0E+9	5.5e+9	9.2E+9
Q_L	6.3E+6	1.9E+6	5.6E+6	9.7E+6



N = 12 88 72 144

316 cavities need,
total 347 including matching module, spares

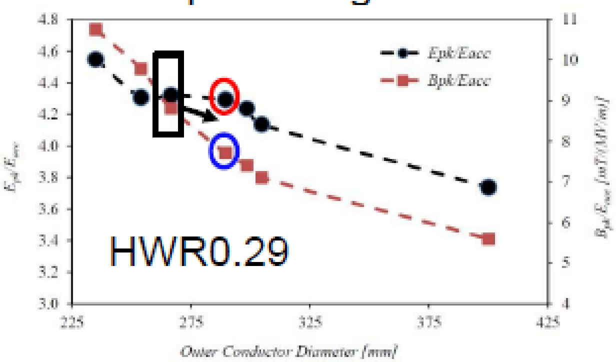


Courtesy K. Saito

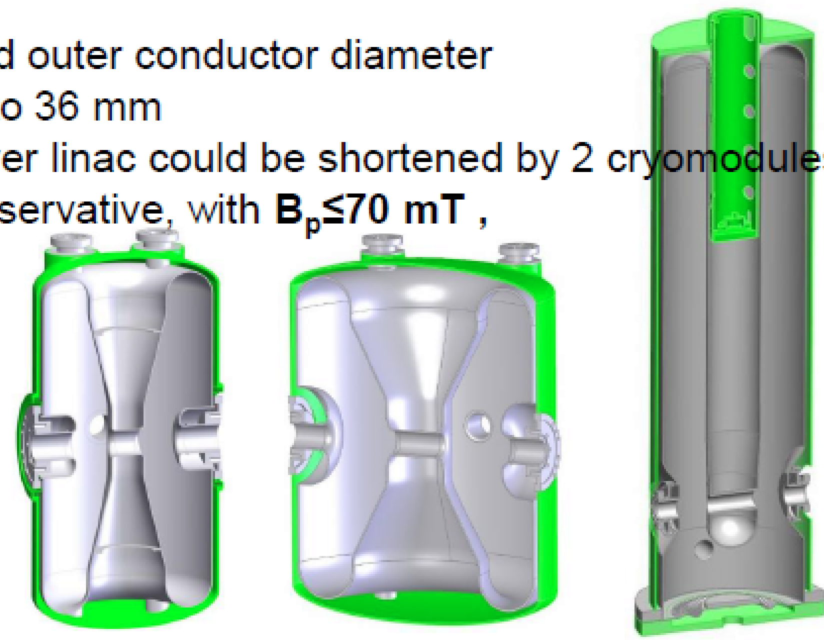
FRIB *(MSU)*

Improved cavity design with lower Hp/Eacc and Ep/Eacc

- The SRF Review Committee in 2011 recommended not to exceed **E_p=35 MV/m** and **B_p=70 mT** in operation based on experimental data of 40 QWRs in operation at TRIUMF
- FRIB has adopted this specification to guarantee reliable operation of its linac with a good safety margin
  - **lower E_p & B_p, higher R_{sh}** by increased outer conductor diameter
  - Increased aperture of QWRs from 30 to 36 mm
  - Increased operation **E_{acc}**: the FRIB driver linac could be shortened by 2 cryomodules
  - FRIB operation gradient now more conservative, with **B_p≤70 mT** ,



cavity	E_p/E_{acc}	B_p/E_{acc}	R_{sh}	E_{acc}
QWR085	-9%	-11%	+38%	+10%
HWR29	-3%	-28%	+47%	+10%
HWR53	-17%	-19%	+13%	(+6)%



β=0.29 β=0.53 β=0.085

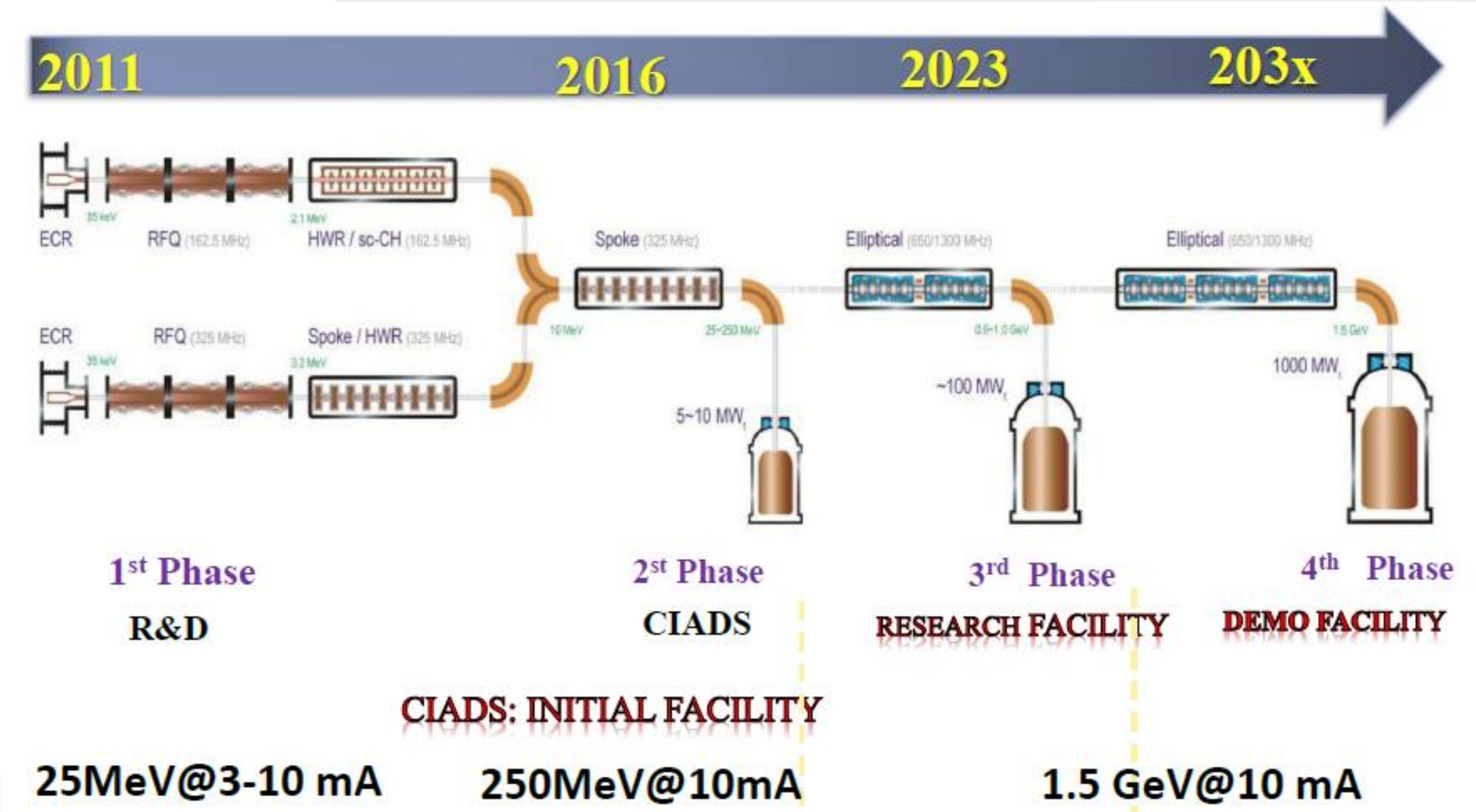
eams

MICHIGAN STATE UNIVERSITY

Courtesy K. Saito

Chinese-ADS (IMP & IHEP)

C-ADS: Roadmap of the project



Courtesy H. Zhao

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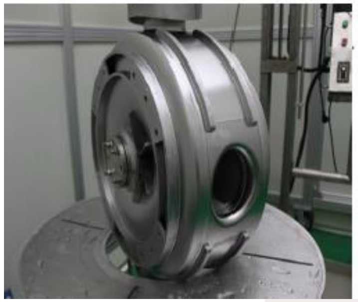
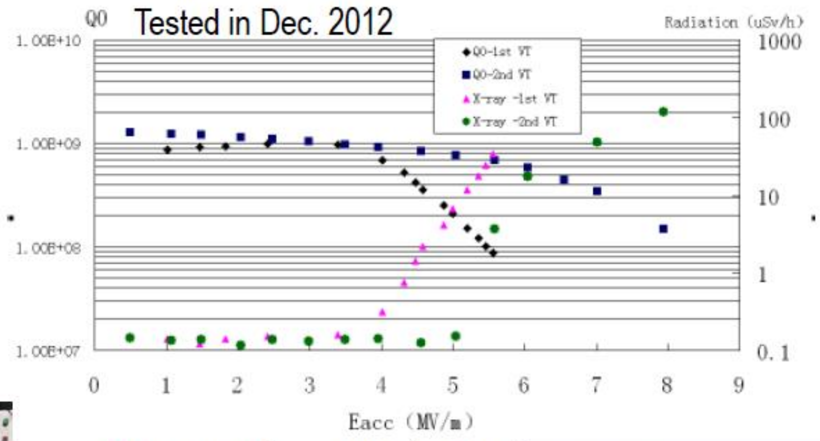
Chinese-ADS (IMP & IHEP)





Injector I: **Spoke012**

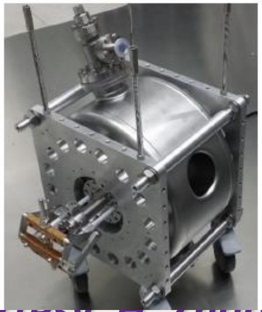
✓$Q_0 = 5.8 \times 10^8$ @6MV/m, 4K;

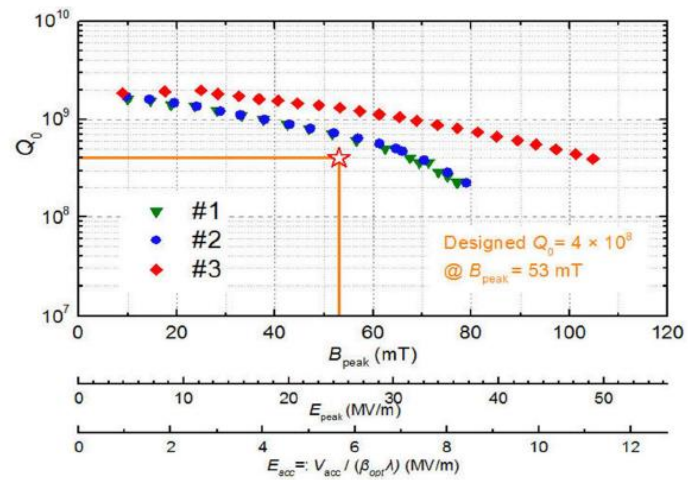
✓$Q_0 = 3.4 \times 10^8$ @7MV/m, 4K

✓Max. Eacc. >14.6MV/m

No quench but heavy MP a

Bulk BCP 150 um
Annealing 750 C, 3 hours
Light BCP 30um





✓Max. B_{peak}=107 mT @ $Q_0 = 4.0 \times 10^8$

Main Linac: **Spoke021**

Courtesy H. Zhou

Conclusions

Conclusion

SRF technology for accelerators

- Is a technology of choice for high power acceleration / high duty cycle, 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 $\beta \sim 0.05$)
- 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

β < 1 superconducting cavities

- SC RF developments is very active in Europe (and worldwide), especially (this is quite recent) for developing low beta cavities ; many projects are under study or construction and drive intense R&D programs on such accelerating structures.

-> Potential for real technological synergies between projects.

- There are many issues faced by all projects for these structures: field emission, multipacting, tuning capabilities, mechanical stiffness, 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.

Conclusion

Some Trends & Future

- Still increasing number of labs worldwide developing SRF Technology, (specially low beta) due to the variety of potential applications.
- But most of the labs involved in project development (engineering) rather than upstream R&D (fundamental research on SRF)
- SRF Technology is mature, and we are starting to touch the limits of bulk niobium technology -> need alternatives (thin films: various deposition methods, various SC material).
- Several very high power projects (IFMIF, ESS,…) for which the limiting technology is the power coupler -> topic of highest interest in the coming decade.
- Many Spoke-type cavities developments worldwide, even at β=1

Conclusion (4)

From G. Olry

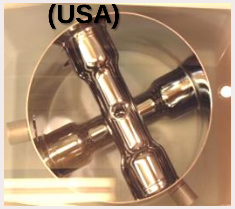
ANL (USA)

IPN (F)

LANL (USA)

ANL (USA)

ANL (USA)

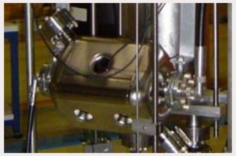


ANL (USA)

ANL (USA)

ANL (USA)

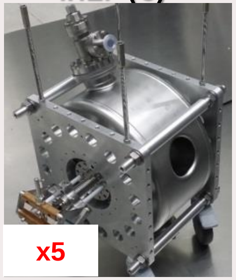
FZJ (D)



FZJ (D)

IPN (F)

IHEP (C)



IHEP (C)

PKU (C)

ODU/JLAB (USA)

ODU/JLAB (USA)

IMP (C)

Fermilab (USA)

From Big Bang to 1992

1 cavity

From 1992 to 2004

+6 cavities

From 2004 to nowadays

+ >30 cavities

INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

THANK YOU !