FCC

SRF & RF power sources summary

Frank Gerigk
on behalf of the speakers and conveners:

Olivier Brunner, Frank Peauger, Ivan Karpov, Shahnam Gorgi Zadeh, Marco Garlasche, Marc Timmins, Mathieu Therasse, Guillaume Rosaz, Sosoho-Abasi Udongwo, Anne-Marie Valente Feliciano, Linhao Zhang, Claire Antoine, Gloria Bellini, Antonio Bianchi, Carlota Pereira Carlos, Lorena Vega Cid, Thomas Proslier, Steward Leith, Zaib Un Nisa, Graeme Burt, Torsten Koettig

FCC Week 2022
03-06-22

Outline

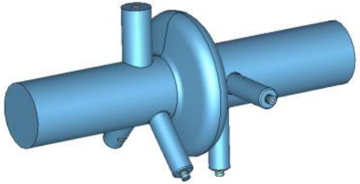
- Revised SRF cavity baseline
- R&D for baseline
- High-effiency klystron developments
- R&D towards improved performance
- Alternative concept

Revised baseline: for collider + booster, F. Peauger (CERN)

less 400 MHz modules, 2-cell 400 MHz instead of 4-cell, ~1300 cavities in total, 20 CM less

Z: Modules with 4x400 MHz 1-cell cavities

Booster: ~~400~~ → 800 MHz



(5.1 → 5.7 MV/m)

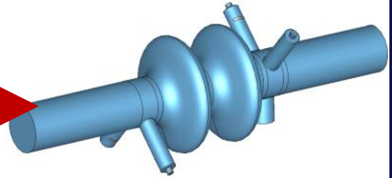
W, H: Modules with 4x400 MHz 4-cell cavities

B: ~~400 MHz~~

(10 MV/m) →

W, H: Modules with 4x400 MHz 2-cell cavities

B: 800 MHz



(12 MV/m)

ttb: Modules with 4x800 MHz 4-cell cavities

B: ~~400~~ → 800 MHz

(20 → 25 MV/m)

	Z	W, H (4-cell)	W, H (2-cell)	ttb
CDR	26 modules	102 modules		213 modules
New	28 modules		70 modules	224 modules

reduced RF power per 2-cell cav., improved HOM damping, less surface to coat (better chances of having «perfect» surfaces), significant reduction of 4-cell specific SRF infrastructure needs, better fit for W

RF parameters

- with new beam parameters -

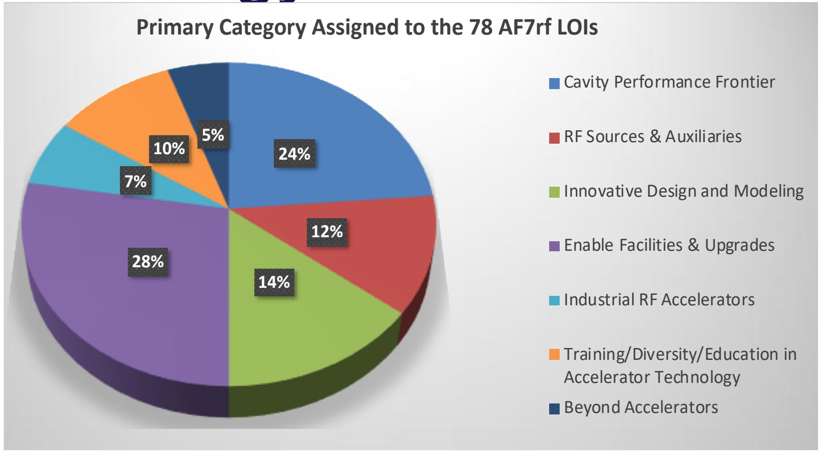
24th May 2022	Z		W		H		ttb2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1000	1000	2480	2480	2480	9190	11670
Eacc [MV/m]	5.72	6.23	11.91	24.26	11.82	25.45	11.82	24.52	25.11
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	8.93	22.73	8.86	23.85	8.86	22.98	23.53
#cells	56	120	224	220	560	520	560	2000	2480
# cavities	56	24	112	44	280	104	280	400	496
# CM	14	6	28	11	70	26	70	100	124
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	19	0.5	174	7	171	8	171	51	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	3.2E+05	1.2E+06	8.9E+06	1.5E+06	1.2E+07	8.3E+06	4.9E+06	5.3E+07
Detuning [kHz]	8.939	4.393	0.430	0.115	0.123	0.031	0.025	0.040	0.005
Pcav [kW]	880	205	440	112	352	95	62	207	20
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.36	0.36	0.74	0.74	0.70	0.90	0.85
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.005	0.010	0.010	0.001

one RF system per beam

Previously one RF system per beam, now common RF system for both beams

- Booster (10% beam current and 15% duty cycle) at 800 MHz for W, H, ttb – to be confirmed for Z by Ivan
- RF voltage at 400 MHz for H and ttb to be updated (2.08 GV instead of 2.48 GV)
- quasi on-crest acceleration (cos phi = 0.9) at ttbar energy with 800 MHz cavities (RF power limited to ~ 200 kW max)

SRF program in Snowmass strategy, A.-M. Valente-Feliciano (JLAB)



- High-Q, high-gradient (bulk Nb, incl. basic material R&D)
- SRF theory
- Field emission mitigation
- Thin films, Nb/Cu,
- New materials, A15 or other higher-temperature superconductors, e.g. Nb_3Sn has already reached 22 MV/m
- Multilayers for ultimate gradients and as yet to be explored characteristics

- For the first time thin films feature at Snowmass.
- Films, HTS and multi-layers are needed to break new ground in SRF!

SRF program in Snowmass strategy, A.-M. Valente-Feliciano (JLAB)

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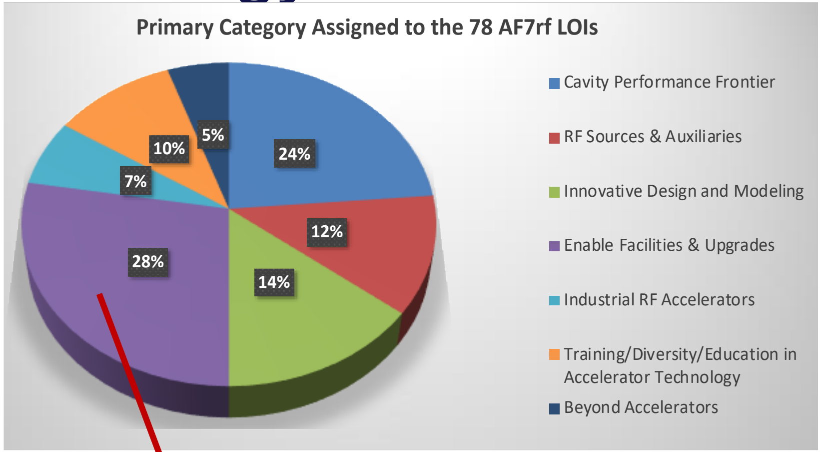


- 28% of the LOIs are related to facilities and infrastructure upgrades.

Thin Film activities in IFAST, C. Antoine (CEA)

Bulk Cu
= pure metal
Metallurgy
~- 6000 years

→

Bulk Nb
= pure metal
Metallurgy = ~ 6000 years
λ= 40 nm =>
+ Surface science: ~-100 years old

→

Higher Tc material
= Alloys, Compounds
+ Chemistry = ~ 250 years old
+ Surface science: ~-100 years old

→

Thin films
Nb or Compounds
CVD/PVD = ~ 50 years

→

Meta-material
multilayers
Advanced deposition techniques = ~ some years

9 countries, 15 institutes, 50 participants

- Innovative SC cavities
- Seamless elliptical Cu cavities
- Cavity coating and evaluation
- Surface engineering via Atomic Layer Deposition
- Improvement of SRF & mech properties by laser irradiation
- Optimisation of flat film production procedures

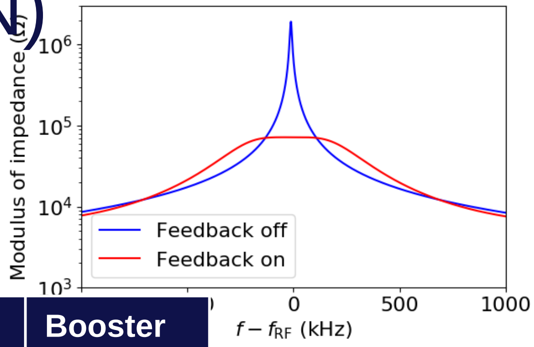
"If the accelerator community wants SRF technology to evolve*, strong investments are needed in the near future."

R&D challenges for revised baseline

400 MHz Nb/Cu (1 + 2 cell), 800 MHz bulk Nb

Longitudinal dynamics, I. Karpov (CERN)

Cavity impedance at fundamental, $Z(\omega)$

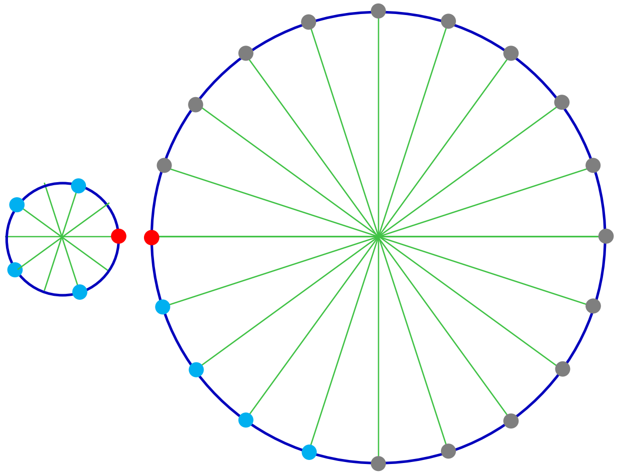


Z pole is the most challenging (high beam current, a large number of bunches, etc).

	Z	W, H, ttbar at Z calibration energy	Booster
Longitudinal CBI due to fundamental mode	Needs RF feedback	To do	To do
Longitudinal CBI due to HOMs	Suppressed by synchrotron radiation	To do	To do
Transverse CBI due to HOMs	Bunch by bunch FB system with damping time of ~100 turns	To do	To do
Collision point shift due to tr. Beam loading (abort gaps)	negligible	To do	
HOM power losses	~as in previsous baseline		To do

FCC circumference, RF frequency & injector synchronisation, L. Zhang (CERN)

Scheme	Baseline	Alternative
RF frequency [MHz]	400.79	497.34
C_{FCC} [m]	91106.187	91140.710
h_{FCC}	121800	151200
RF system	based on LHC	new
Bunch spacing [ns]	2.5, 5.0, 7.5, 10, 12.5, 15, 17.5, 25 (proposed in FCC-hh CDR)	2.01, 4.02, 6.03, 8.04, 10.05, 12.06, 14.07, 16.09, 18.1, 20.11, 24.13 (More flexible)
LHC-to-FCC transfer	297 revolutions in FCC	117 revolutions in FCC
SPS-to-FCC transfer	11 revolutions in FCC	91 revolutions in FCC
FCC-hh pre-injector	allows PS (1959!)	new
Largest prime factor	29	13



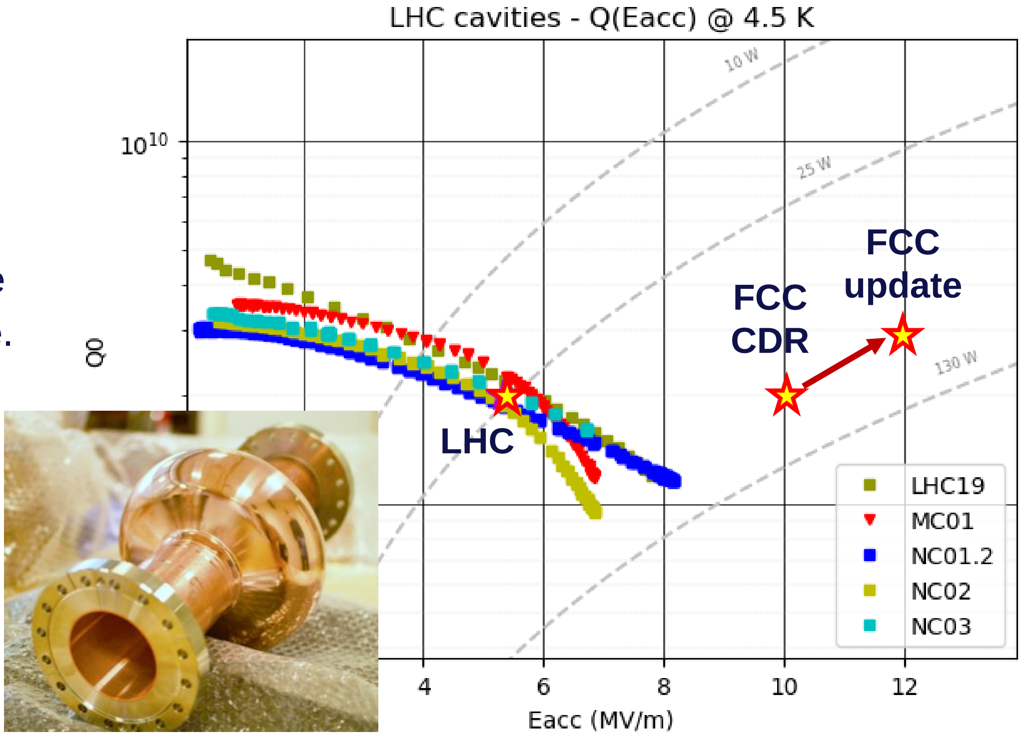
- Baseline scheme of FCC-hh circumference and RF frequency basically meets all requirements proposed in CDR
- Attractive alternative option could offer more flexibility

Elliptical cavity R&D, G. Rosaz (CERN)

Cure the Q-slope & extend the field reach!

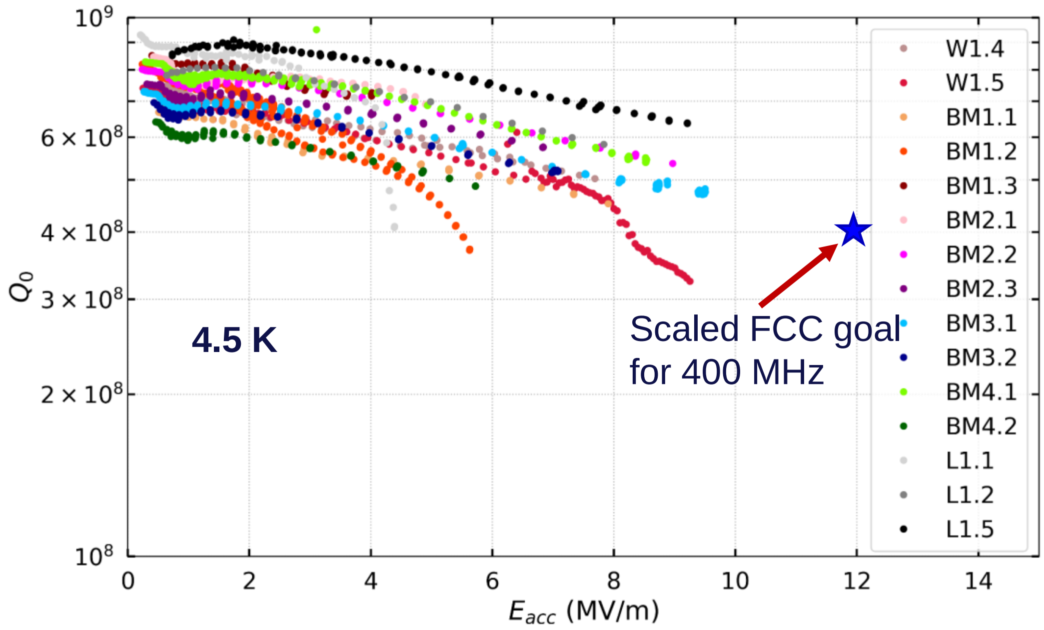
2.5 years ago the teams involved with SRF at CERN decided that this is best done by:

- Using **1.3 GHz cavities** because of: size; ease of manufacture, coating, testing; while still giving access to the residual resistance.
- Making **seamless cavities** to remove the uncertainty of the weld influence.
- Today we are using **bulk-machined** seamless cavities to explore/evaluate our SRF procedures (chemistry, coating, surface treatments, ..)



RF tests on 1.3 GHz Nb/Cu, L. Vega Cid (CERN)

Tests of welded (W), electroformed seamless (L), and bulk machined seamless (BM) cavities



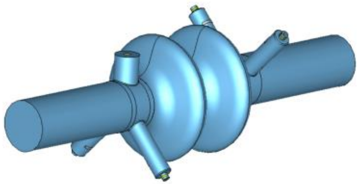
- **Bulk-like performance with minimum Q-slope.**
- Gradient only limited by missing radiation protection in cryolab.
- Promising candidates will be re-tested in SM18.
- 18 tests in the last 15 months thanks to excellent collaboration between the groups (VSC, SRF, CRG, MME)

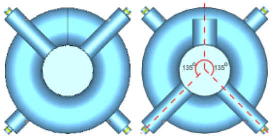
18 tests performed in the last 15 months thanks to the fruitful collaboration!

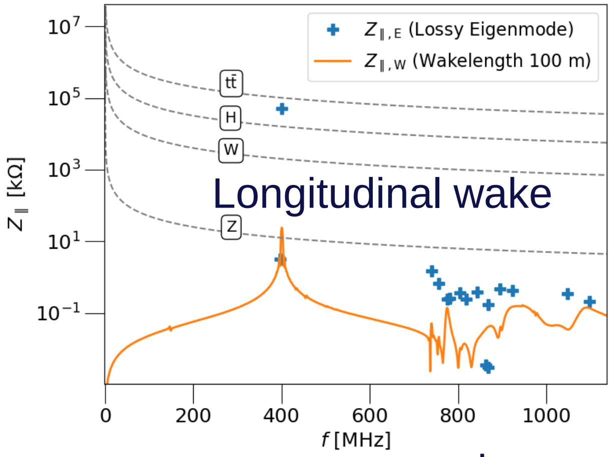
New baseline cavity designs, S. Udongwo (Rostock Uni.)

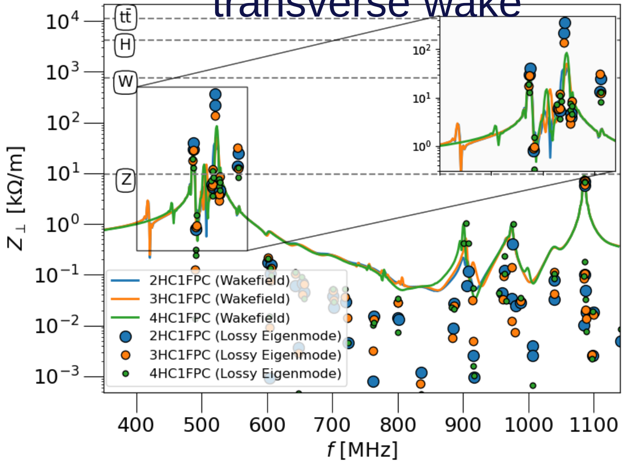
400 MHz single-cell (Z) and double-cell (W)

- Optimised cavity shapes
- HOM coupler configurations
- HOM coupler design
- Impedance stablity limits are respected.







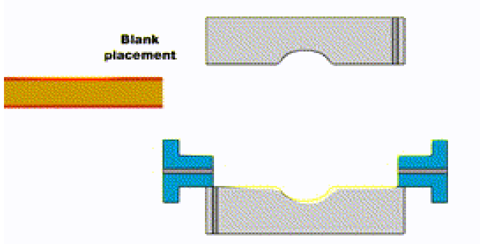


Elliptical cavity fabrication, M. Garlasche (CERN)

Making the perfect substrate

- Bulk machining of 1.3 GHz reference cavity.
- Exploration of **hydroforming** for series production of seamless 400 MHz cavities. 1.3 GHz experiments started.
- Internal weldings.
- R&D on:
  - influence of manufacturing techniques on Hydrogen content.
  - Surface layer optinisation.
  - Reducing roughness.

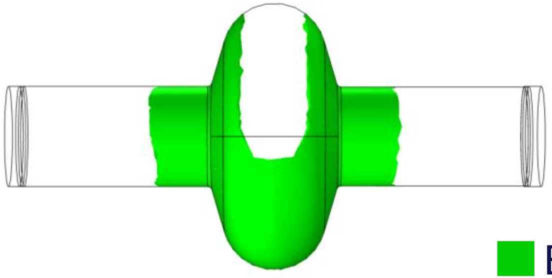
Bulk-machined cell

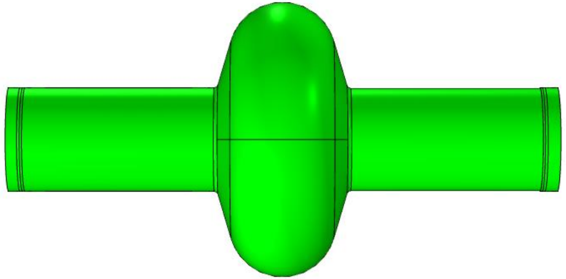


Electropolishing of Cu cavities, G. Bellini (CERN)

Original 1.3GHz cavity

1.3GHz cavity with optimized EP parameters





Electropolished area

Mass flow rate: 30 L/min
Temperature: 15 °C
0.5 rotations per minute
Overall applied tension: 7.4 V

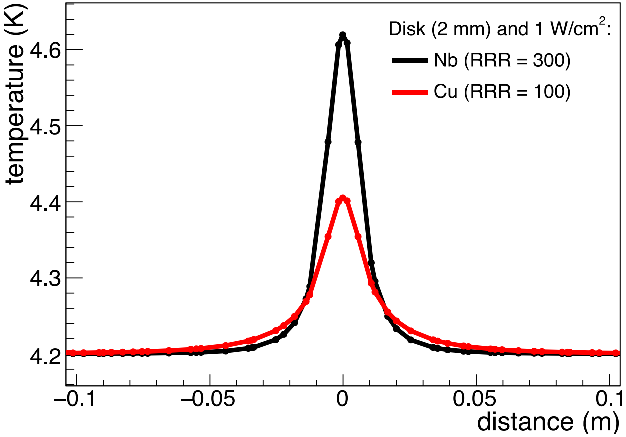
Mass flow rate: 10 L/min
Temperature: 15 °C
0.5 rotations per minute
Overall applied tension: 10.6 V

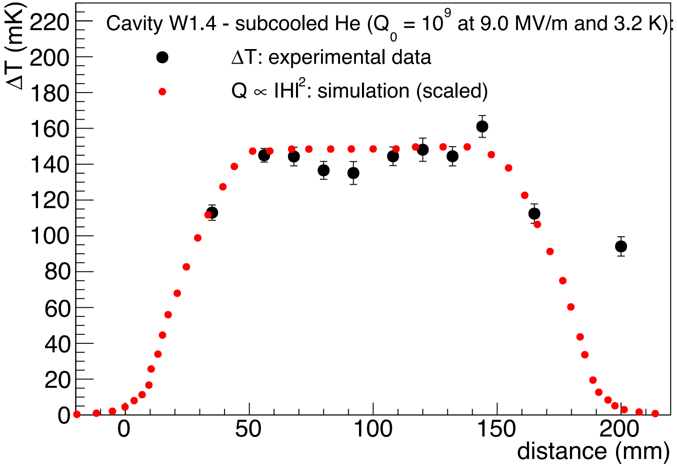
Benchmarking with real cavities needed for better predictions: more tests!

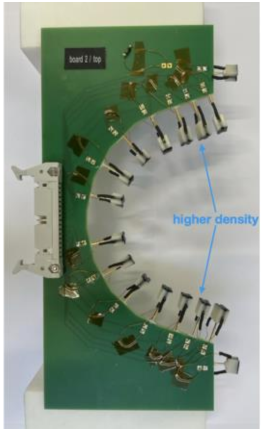
Thermal mapping, A. Bianchi (CERN)

Challenge:
Resolution of much smaller **ΔT** than on Nb cavities

First measurements:
Show good agreement with simulations







Final system (1.3 GHz) consists of:

- 192 thermometers in 12 boards
- 4 calibrated thermometers
- 480 feedthroughs in 3 PCBs
- 6 multiplexers + 12 ADC channels

Nb/Cu HIPIMS coatings, C. Pereira Carlos (FTC)

1st BIPOLAR HiPIMS cavity coating (400 MHz) on 05/2022

RF performance to be measured June/July 2022

BIPOLAR HiPIMS

- RF performance 1ST HiPIMS + PP to be measured
- Optimize coating setup and parameters

HiPIMS + DC bias

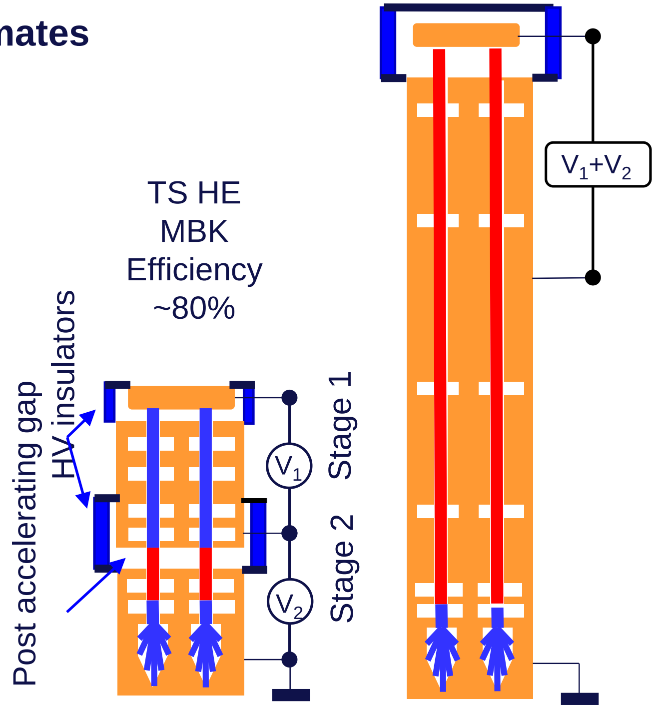
- Proven on 1.3GHz
  - Lot of RF data
- More complex coating setup
  - Upgraded cathode under study
  - Grid like anode needed + cavity insulation
- 3 RF tests / year foreseen

2-stage 400 MHz, 1.2 MW High-Efficiency Multi-Beam Klystron for FCC-ee, Z. Un Nisa (CERN)

Performance already assumed in present electrical power estimates

- Length: 2.8 m instead of 5.5 m
- Efficiency: 80% instead of 65%
- Cathode voltage: 58 kV instead of 100 kV (no oil tanks, simplified modulators)
- Reduced waste heat (less CV)
- Simplified installation

- Development financed by HE klystron project & FCC
- Prototyping with industry foreseen within the next years.



R&D challenges beyond revised baseline

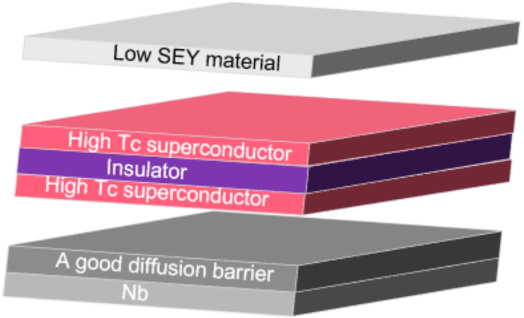
Applicable to 400 MHz Nb/Cu (1 + 2 cell), 800 MHz bulk Nb
And other cavity geometries

Atomic layer deposition, T. Proslier (CEA)

Deposition of homogenous single atomic layers to:

- Precise engineering of surfaces
- Reduce SEY
- Controlled thickness
- Engineering of multi-layers
- Doping of SRF surfaces
- Insulating barriers for HIPIMS Nb/Cu
- Avoid post-treatment chemistry

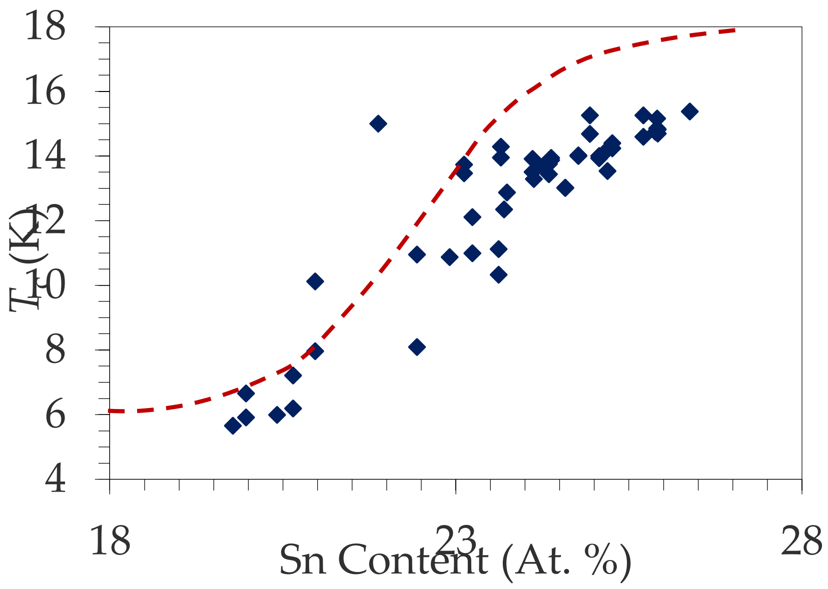
- Looking forward to the first cavities!



Bipolar HIPIMS for Nb_3Sn on Cu, S. Leith (CERN)

Tests on QPR samples:

- **Motivation:** Nb_3Sn: Q_0 at 4.2 K ~ bulk Nb at 2 K
- **Challenges:** A15 phase formation, stoichiometry control (16% - 18% of Sn), influence of the Cu substrate?
- First results for Nb3Sn and Ta

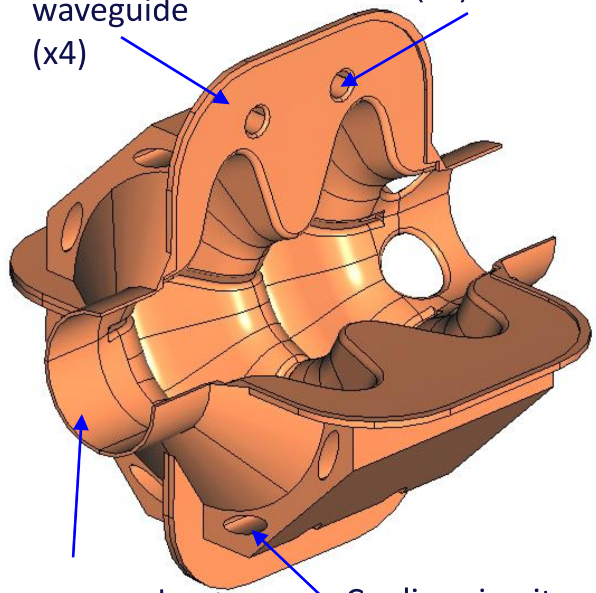


The alternative concept

The SWELL superconducting cavity concept, F. Peauger, O. Brunner, I. Syratchev, I. Karpov (CERN)

Slotted Waveguide Elliptical Cavity

- A mixture of elliptical cavities and CLIC-type mode damping with slots
- **One cavity type for Z, W, H** and the **same frequency** (600 MHz) with standard 5-cell elliptical cavities **for ttbar**. 12.5 MV/m, 600 kW.
- Strong HOM damping due to slots
- **No helium tank**: direct cooling with helium channels.
- **No welding in high-field areas**: “seamless” performance expected.
- Open access to inner surface for chemistry and coating.



Why is this exciting? F. Peauger

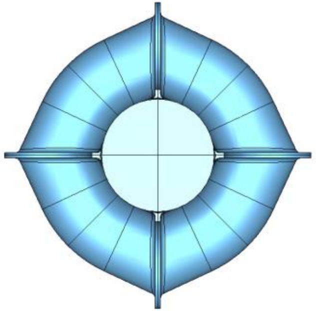
Combine the SWELL (Z, H, W) with 5-cell elliptical cavities (600 MHz)

- **No need to remove cavities** after Z-operation!
- For the Z **at 600 MHz we can use either bulk Nb** cavities (e.g. 650 is used for PIP-II), **Nb/Cu, or A15 on Cu.**
- Possibility to **run at 2 K or 4.5 K** (optimisation to be done)
- If A15 coatings on Cu succeed, these can be applied to SWELL and 600 MHz elliptical.
- **One RF frequency for the all FCC-ee scenarios.**

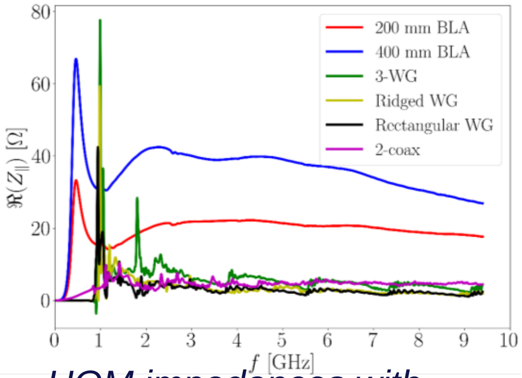
	Z		**W**		**H**		**ttb2**			
	coll	boost	coll	boost	coll	boost	coll	coll	boost	
CDR BASELINE 400/800	**26**	3	26	13	68	34	**68**	**93**	**34 +120**	-> 341 Cromodules
NEW BASELINE 400/800	**28**	6	56	11	70	26	**70**	**100**	**124**	-> 322 Cryomodules
SWELL OPTION 600	22	2	72	8	100	20	**100**	**74**	**94**	-> **268 Cryomodules**

SWELL cavity design, S. Gorgi Zadeh (CERN)

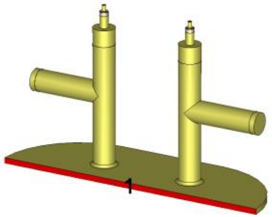
- Cavity shape **optimised for min. impedance and low peak fields**.
- Coax, waveguide, and beamline **HOM dampers were compared**.
- Bunch by bunch feedback to damp CBI (as for baseline).
- **Alignment precision of 0.1 mm needed** to avoid cavity multipacting
- Tuning via plungers or mechanical deformation under study.

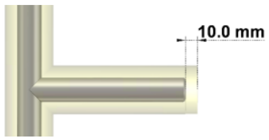


Shape for decreased peak fields at slot transition

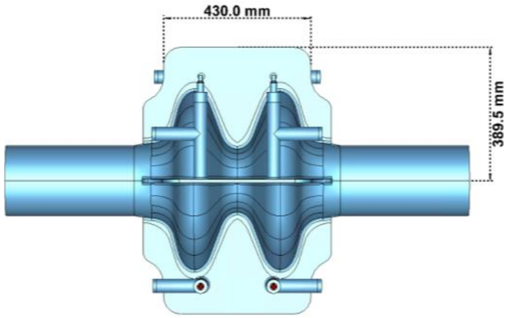


HOM impedances with different HOM couplers



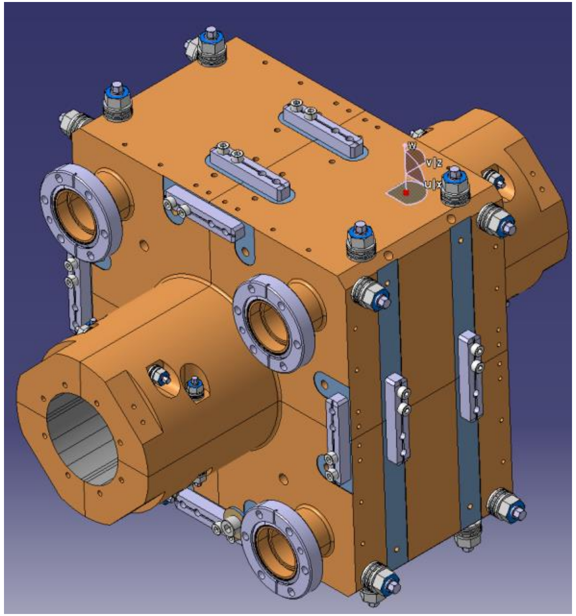


Fundamental mode rejection filters on waveguide slots



Shape for minimum beam coupling impedance

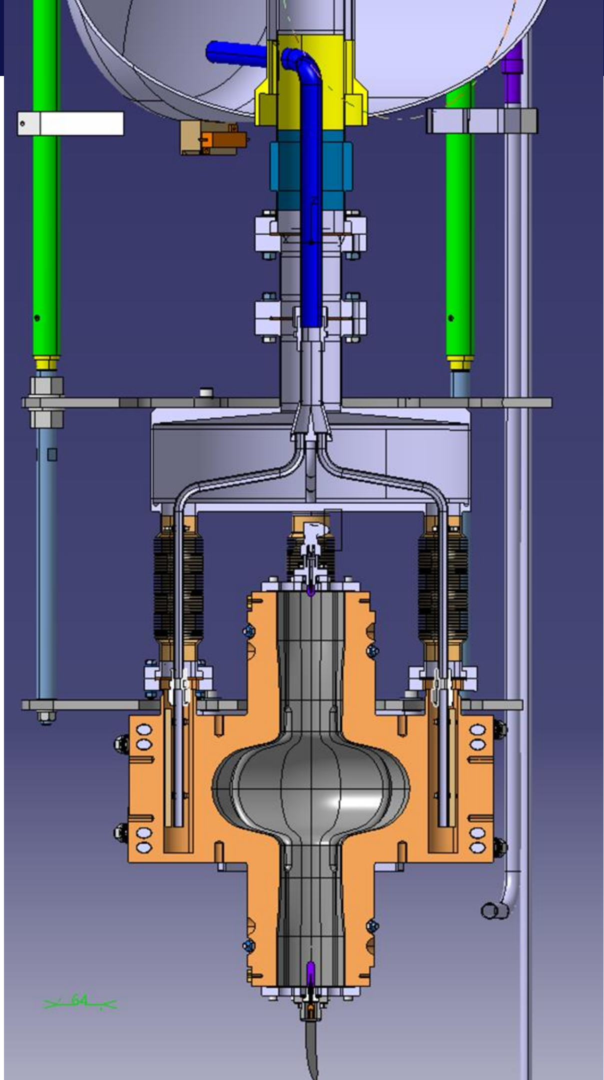
SWELL mechanical design of 1.3 GHz prototype, M. Timmins (CERN)



- Prototype designed and **manufactured at CERN.**
- Metrology of inner surface within ±10 µm.
- Flanges to be welded.
- Tooling for clean handling, chemistry, and coating under construction.

1.3 GHz prototype cold test preparation, M. Therasse (CERN)

- Cold test in V5 (HIE-ISOLDE cryostat).
- Cool-down of 4 parts using intermediate Helium tank with diffusor.
- Instrumentation, RF pick-ups, RF antenna, in preparation.
- Clean room assembly procedure is developed.
- Summer 2022: Insert preparation and commissioning.
- **October 2022: Cavity preparation in clean room and cold test.**

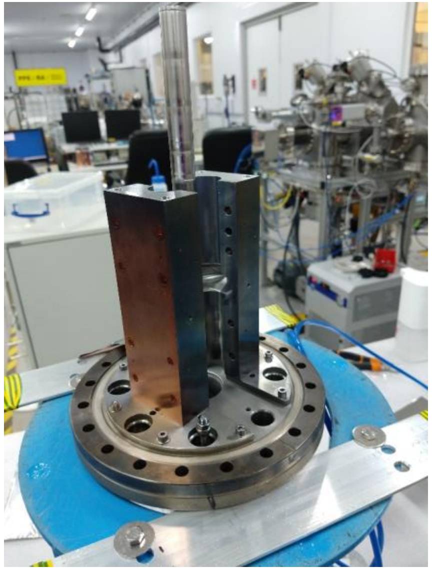


Heat transfer study for prototype, T. Koettig (CERN)

- Heat transfer has been **tested up to 17.5 W → 70 W in 4 quadrants**
- Flow by self-sustained convection loop (corresponding to V5 condition in SM18 at CERN).
- Stable end temperatures have been observed.
- **No thermal run-away** effect.
- Vertical temperature distribution depends on local boiling phenomena
- dT up to 0.75 K in respect to the He I bath supply
- Link to movies and pictures: https://edms.cern.ch/document/2732654/1

Slotted cavity tests, G. Burt (Lancaster Uni.)

- **6 GHz** slotted structures for **quick evalulation of coating recipies**.
- No RF current is crossing the contact line.
- First (quick and dirty) tests already done.
- **Optimised sample is presently under test.**



SWELL to do list

- Beam dynamics validation of all scenarios.
- Proof of principle demonstration with scaled prototype: before end of 2022.
- Separation of beam vacuum from cryostat vacuum.
- Define viable tuning concept.
- For 600 MHz machining out of pre-shaped pieces instead of bulk Cu blocks.
- Optimised coating set-up.
- Tolerance reduction for industrial production.
- Defining minimum Cu specs for production.
- Etc.

- **And convince the management that it is worth pursuing this concept..**

Summary

- Revised 400/800 MHz baseline: 2-cell 400 MHz instead of 4-cell, more aggressive performance goals. R&D needed on cavity fabrication, chemistry, coating and clean handling/testing.
- RF systems and associated cryogenics represent 50% of the FCC-ee electricity consumption.
- Future breakthroughs in SRF performance are likely to come from: HTS (A15), film technology, and possibly multilayers. **A factor 2 in Q will reduce the cryogenic consumption by 50%** (e.g. for ttbar from 47.5 MW to 23.7 MW) Needs intense R&D & adequate infrastructures.
- Two-stage high-efficiency klystrons are under development and are already assumed as baseline performance.. Finalisation of technical design and prototyping with industry needed.
- The SWELL concept is a very enticing alternative but needs further R&D to make it viable.

FCC

“If the accelerator community wants SRF technology to evolve, strong investments are needed in the near future.”

Claire Antoine, FCC week 2022

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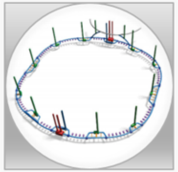
The FCC SRF programme at CERN (2020 – 2025)

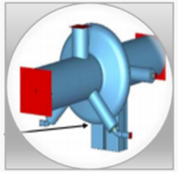


WP0

Coordination, parameters and design

- Coordination and review
- Challenge the baseline

O. Brunner



WP1

Cavity Studies & Beam Dynamics

- Determine the cavity design for each FCC machines.
- Validate the HOM damping schemes
- Carry out the beam-cavity interactions studies
- Evaluate the cavity control system (LLRF) challenges

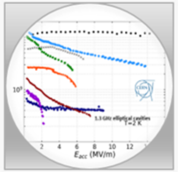
F. Peauger, I. Karpov, I. Syratchev, R. Calaga, S. Gorgi Zadeh

WP2

Cavity Engineering & Fabrication

- Push the limits of fabrication technologies: seamless, internal welding, precision machining
- Build a cavity for Z machine
- Demonstrate SWELL

S. Atieh, A. Dallochio, M. Garlasche



WP3

SRF & Substrate Preparation

- Establish the limits of surface preparation and Nb coatings
- Optimize HIPIMS coatings using 1.3 GHz seamless cavities
- Pursue exploration of A15
- Prepare and validate a cavity for Z machine

G. Rosaz, W. Venturini Delsolaro

WP4

Cryomodule Development

- Develop a test bed for new cavity, FPC and CM technologies
- re-assess generic CM challenges: thermal performances, magnetic shielding, cavity & FPC support,…
- study HOM power extraction schemes for Z machine
- define feasibility of 2K and 4.5 K operation (SWELL)

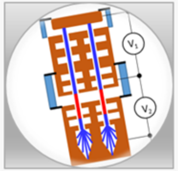
V. Parma, O. Capatina, M. Timmins, M. Therasse

WP5

FPC & HOM Couplers

- Push the limits of FPC performances
- Towards 1 MW (baseline)
- Towards large adaptability (SWELL, baseline)
- HOMC mechanical design & production

E. Montesinos, J. Mitchell



WP6

High power RF Systems

- Challenge RF power systems and power distribution schemes
- Demonstrate HE two stage technology (baseline)
- Evaluate alternative technologies (SWELL, baseline)

O. Brunner, Y. Syratchev

Promote R&D activities in collaboration with international partners