FCC SRF Roadmap

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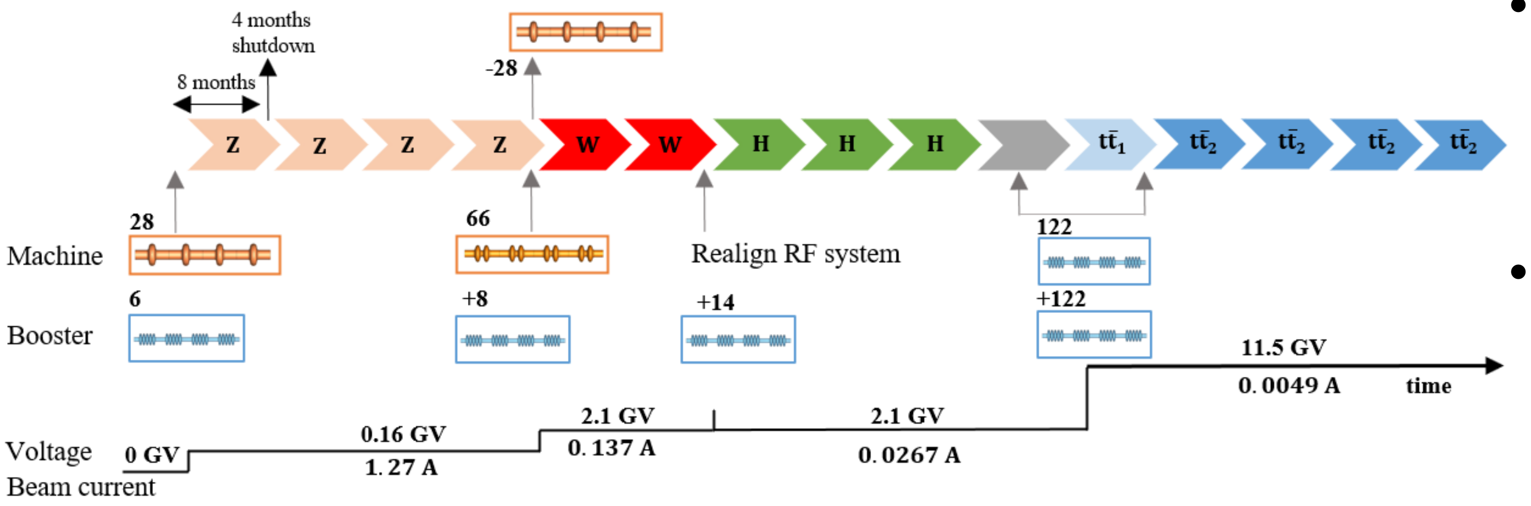
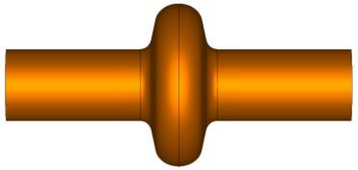
FCC-ee SRF system baseline (see F. Peauger)



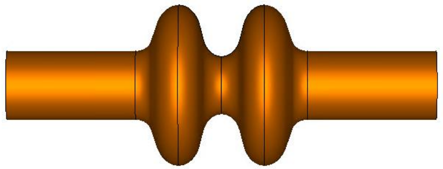
- **Baseline**: Starting with 1-cell for Z to reduce HOM power load: but 1-cell modules need to be removed for W and replaced by 2-cell modules.
- **Under study**: i) starting with 2-cell 400 MHz using increased HOM damping & transverse feedback, ii) using 6-cell 800 MHz instead of 5-cell

Z: 112 cavities
+ 24x800 MHz



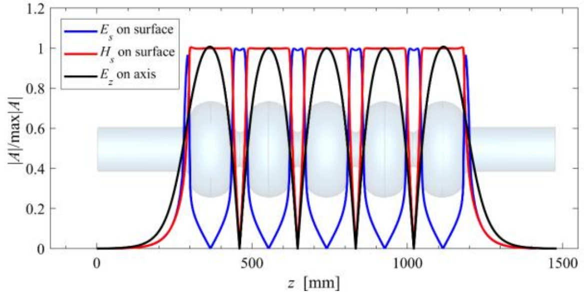
400 MHz 1-cell
Nb/Cu, 4.5 K

W, H: 264 cavities
+ 88x800 MHz



400 MHz 2-cell
Nb/Cu, 4.5 K

$t\bar{t}$ and booster: 1088 cavities



800 MHz 5-cell
Bulk Nb, 2 K

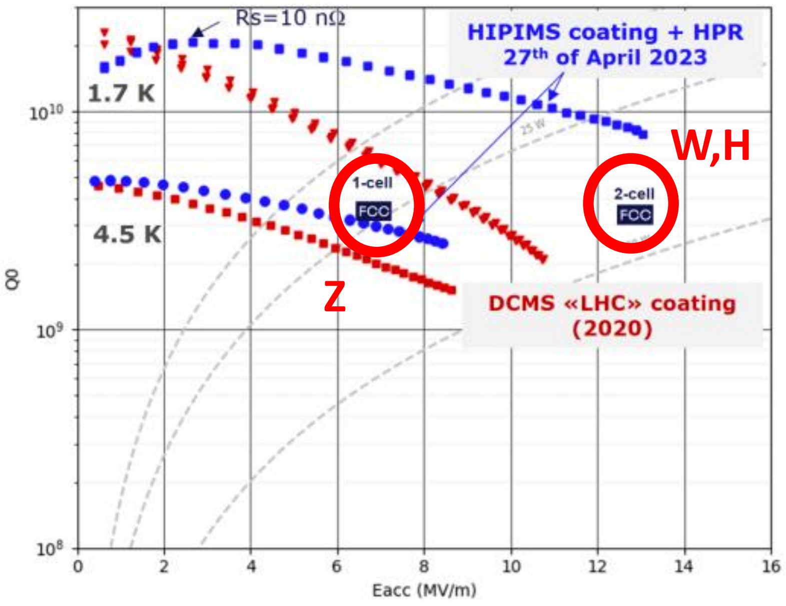
	Z	W	H	$t\bar{t}$
Energy [GeV]	45.6	80	120	182.5
Collider beam current [mA]	1270	137	26.7	4.9
RF Voltage collider [GV]	0.08	1.0	2.1	2.1/9.4
Booster beam current [mA]	0.13	0.014	0.003	0.0005
RF Voltage booster [GV]	0.06	0.4	2	11

SRF R&D

Challenging SRF baseline parameters

(see C. Pereira Carlos, K. McGee)

- Current bare cavity goal:
  - $Q_0 = 3.3 \times 10^9$ at $E_{acc} = 13.2$ MV/m for 2-cell 400 MHz Nb/Cu
  - $Q_0 = 3.8 \times 10^{10}$ at $E_{acc} = 24.5$ MV/m for 5-cell 800 MHz Nb
- Surface preparation:
  - **400 MHz Nb/Cu**: HiPIMS has shown promising results on several 1.3 GHz single-cell cavities[1]. First attempt on 400 MHz LHC type cavity has been performed
  - **800 MHz bulk Nb**: 30 MV/m with Q_0 in the range of $2-3 \times 10^{10}$ at 2.0 K in Jlab[2]. R&D and collaboration with FNAL/Cornell to achieve $Q_0 = 3.8 \times 10^{10}$ or higher.
- Cavity manufacturing: enhance copper substrates by e.g. creating seamless cavities using innovative methods such as bulk machining, electroforming, or hydroforming technologies



Performance Targets

20-Apr-23	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	6.6	3.15E+09	6.3	3.0E+09	5.7	2.7E+09
2-cell 400 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 800 MHz	24.5	3.8E+10	23.3	3.64E+10	22.2	3.5E+10	20.0	3.0E+10

1. L. Vega Cid, R&D on superconducting thin films for SRF cavities, RF seminar, 2024, CERN
2. S. Posen, "R&D towards an 800 MHz cryomodule", FCC Week 2023, London, UK

Going beyond the baseline: (see M. Liepe)

Nb_3Sn for 400 & 800 MHz, rationale and first steps

- **Nb3Sn on bulk Nb (thermal diffusion of tin in Nb cavity, mostly at US-labs) state of the art:**
  - 1.3 GHz cavities reaching high Q at 4.5 K (comparable with Nb at 2 K)
  - Accelerating field limited so far <25 MV/m (potential of 100 MV/m): may come from insufficient thermal stabilization of weaker superconducting spots
- **Using copper substrates promises to overcome the field limit**, but comes with several challenges:
  - Process temperatures limited by substrate
  - Differential thermal expansion, stress , disorder
  - Copper interdiffusion, need of buffer layers
- **Active collaborations:** Univ. of Geneva, Univ. of Wien, CEA, FNAL, JLAB, Cornell, INFN, Univ. of Hamburg
- 1^{st} phase of CERN study , based on DC magneton sputtering on small samples is documented in (1)
- 2^{nd} phase with High Power Impulse Magnetron Sputtering (HIPIMS) is starting.

(1) Development of sputtered Nb_3Sn films on copper substrates for superconducting radiofrequency applications (E A Ilyina et al, Superconductor Science and Technology, Volume 32, Number 3

From samples to cavities

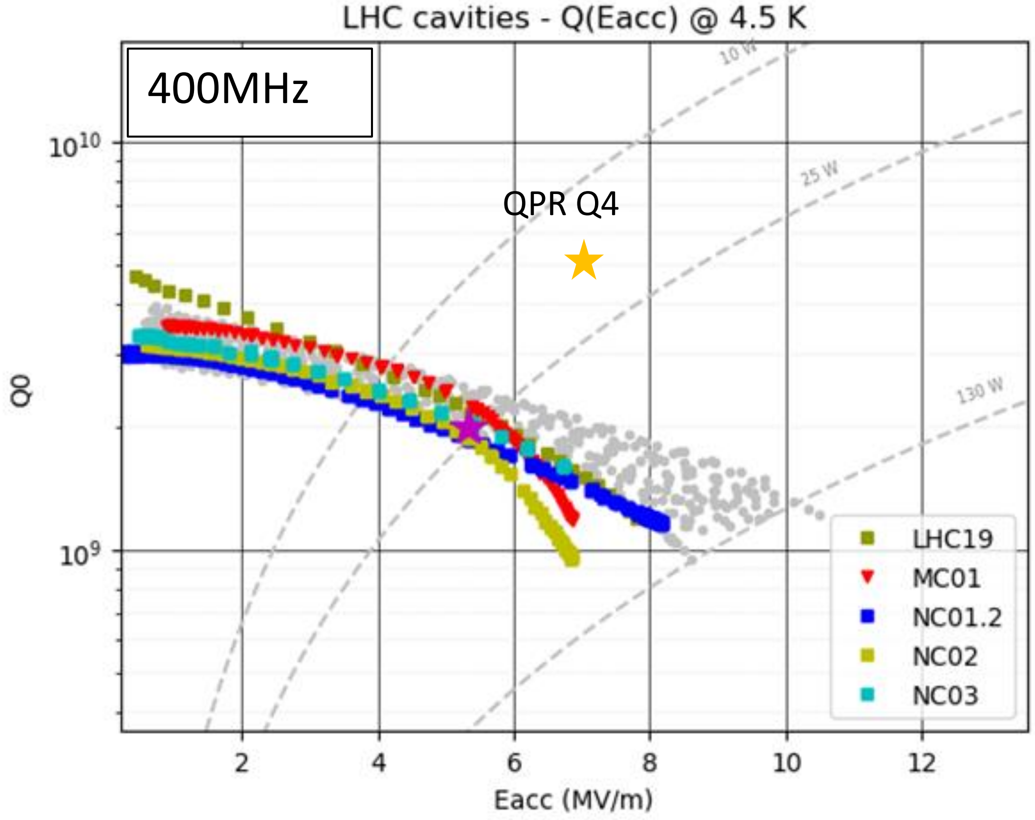
In 2023, a Nb_3Sn QPR sample reached surface resistance at 400, 800 and 1200 MHz at 4.2 K better than Nb/Cu.

Next step: scaling to cavity size

Challenges:

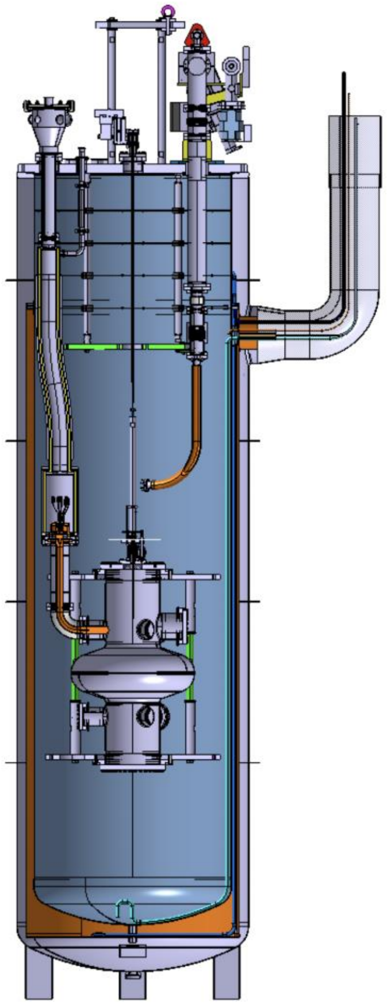
- Cavity mechanical design (support of annealed copper, tunability)
- Coating system design (cavity support and turning system, heating, multiple cathodes, target cooling, etc.)

A working group has been set up to create a long-term (10 – 20 year) roadmap to develop Nb3Sn for SRF cavities.

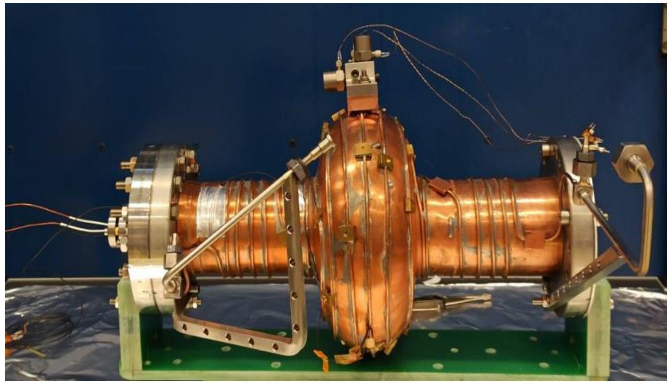


Further SRF R&D topics

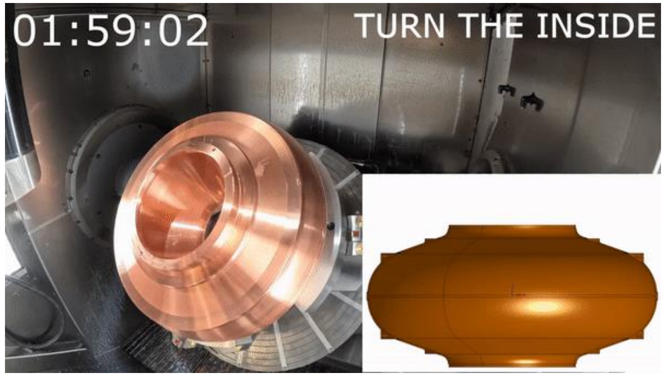
- SRF **cavity manufacturing** (seamless cavities), thin film **coating techniques**, **novel cooling methods** (to reduce He-inventory).
- **Sample tests** and magnetic **flux trapping studie**s on coatings, multi-layers.
- Routine **optical inspection** of all cavities.
- Non-mechanical tuning with **ferroelectric fast reactive tuner** (Fe-FRT) with Euclid Techlabs, HZB & JLAB.



Validate transient detuning compensation for LHC with Fast Reactive Tuner



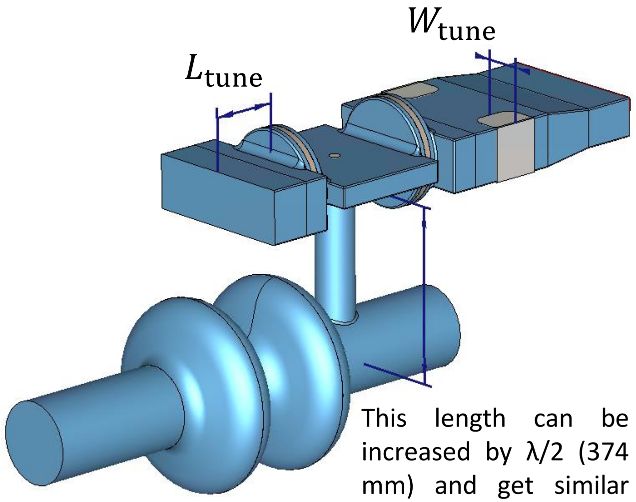
Quasi-dry cooling



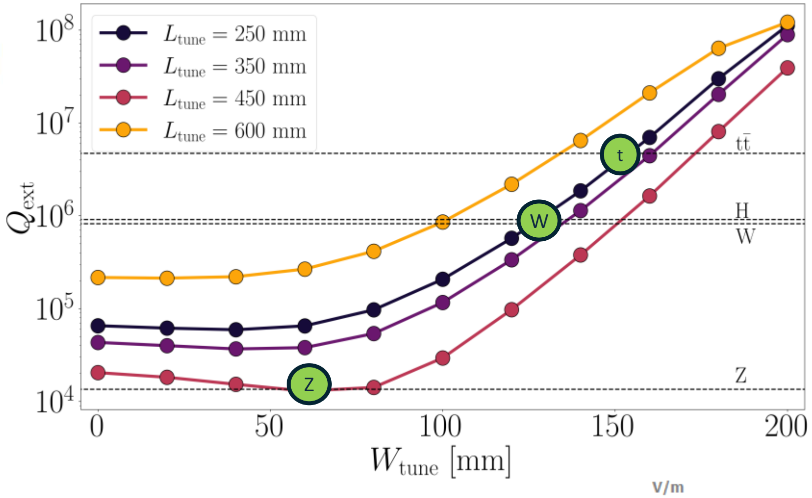
Seamless cavities via bulk machining as reference cavities

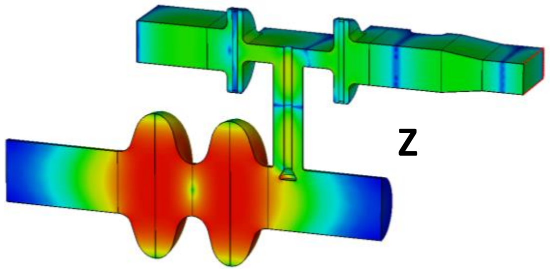
New adjustable power coupler concept

- Two windows (LINAC4-like) are placed outside the cryomodule → integration challenge after cryostating
- A more robust and easier-to-cool down window design → easier to cover all four working points
- Providing ~1 MW in CW operation with variable coupling for Z, W, H, ttbar.
- HOM power see: F. Peauger & I. Karpov
- Prototyping starting.

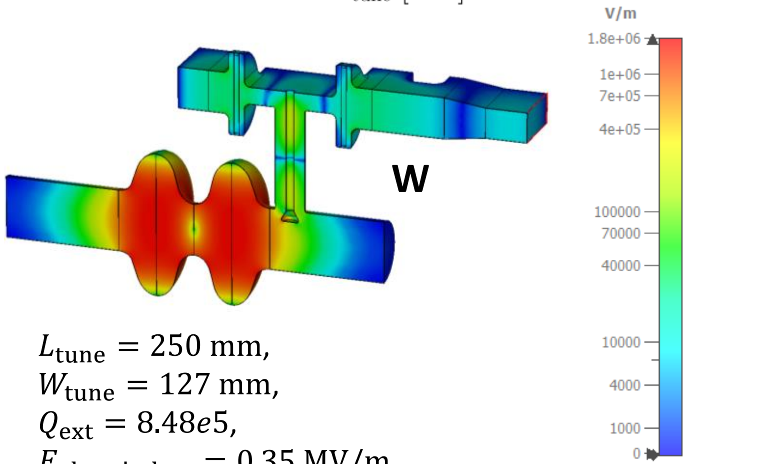


This length can be increased by λ/2 (374 mm) and get similar results





$L_{\text{tune}} = 450$ mm,
$W_{\text{tune}} = 55$ mm,
$Q_{\text{ext}} = 1.33e4$,
$E_{\text{pk-window}} = 0.18$ MV/m,
$E_{\text{pk-air}} = 0.22$ MV/m

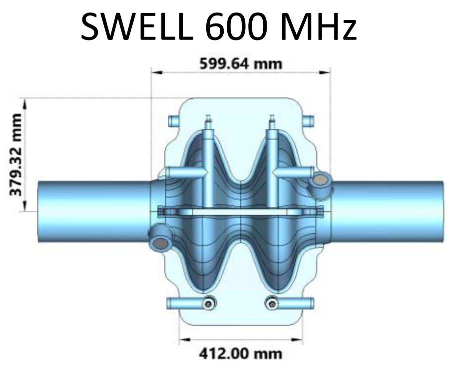


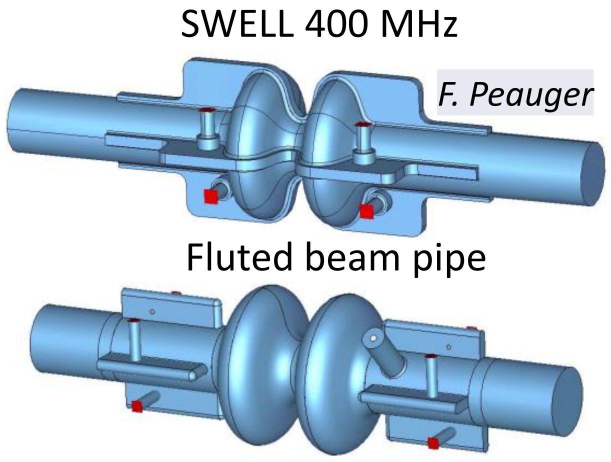
$L_{\text{tune}} = 250$ mm,
$W_{\text{tune}} = 127$ mm,
$Q_{\text{ext}} = 8.48e5$,
$E_{\text{pk-window}} = 0.35$ MV/m,
$E_{\text{pk-air}} = 0.61$ MV/m

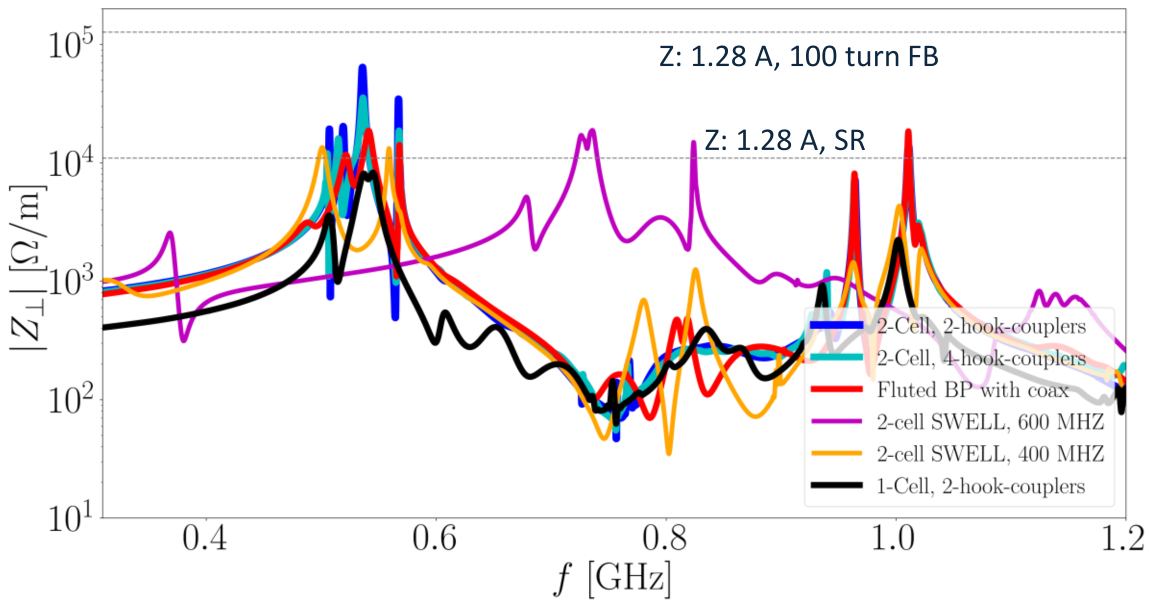
E normalized to 1J stored energy

Alternative cavity designs

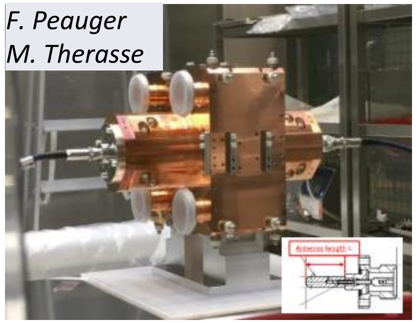
Alternative 2-cell cavity design aimed at reducing transverse impedance peak

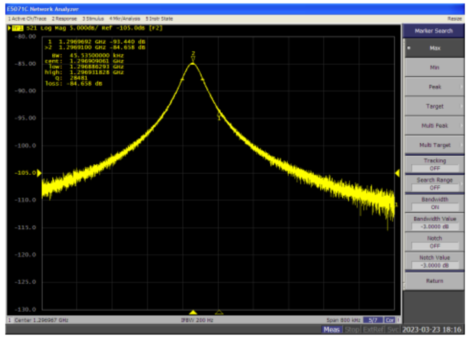


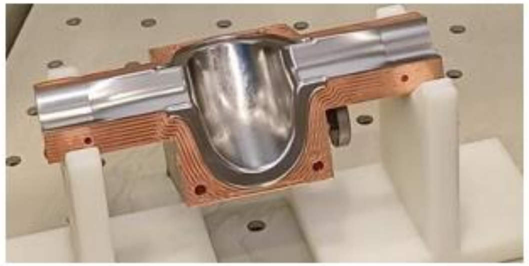




SWELL 1.3 GHz cavity prototype







(Guillaume et al.)

Warm RF measurements of SWELL cavity 1.3 GHz before Nb coating. 0.006% error in f (-78kHz) and 0.1% error in Q_0

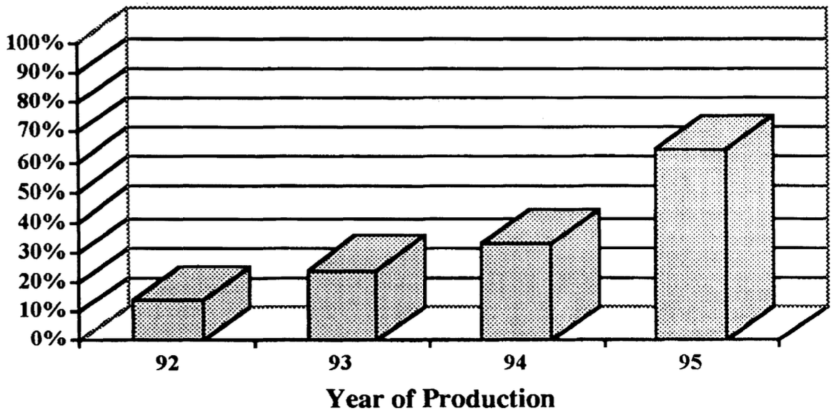
Niobium thin film coating of the four quadrants and surface treatment in progress

New SRF infrastructure at CERN: SA18

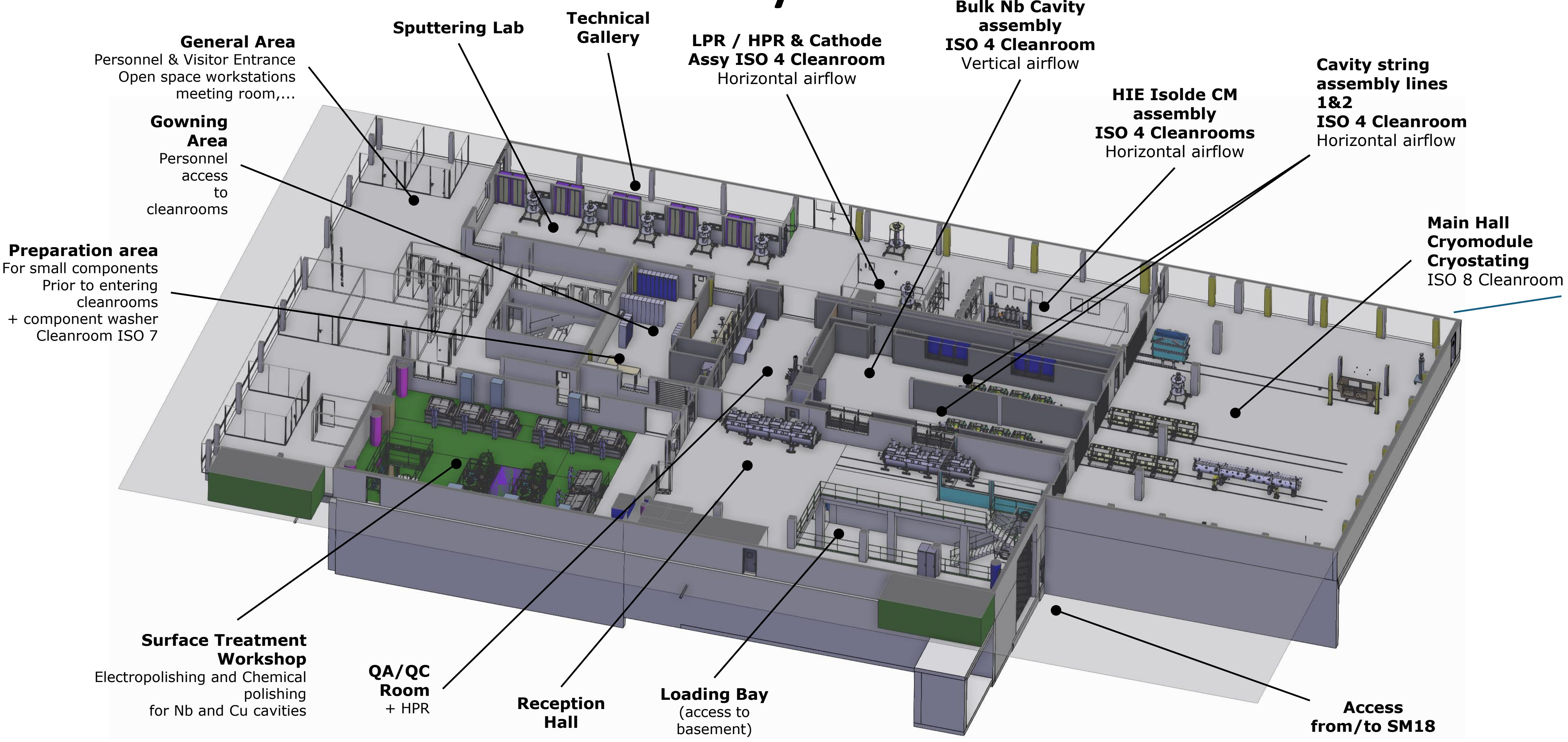
Unique facility for thin film (and bulk) SRF R&D

- Chemistry, high-pressure water rinsing, cavity coating, clean room assembly, cryo-module assembly in one building.
- Better environmental and process control.
- Maximum throughput for rapid improvement (possible throughput at max staffing: ~ 1 cavity/w , 6-9 CM/y).
- Delivery foreseen for end of end of 2028 to start installing SRF process infrastructure (1 – 1.5 years).
- Increasing coating success rate. Today with LHC spares: 25%.

LEP first coating success rate



Ground Floor Process Layout



Efficient RF power sources

Energy savings: RF power generation

Radiofrequency systems are the biggest loads

- Power demand for RF Storage ring Z, W, H
- P_{RF} = 100MW
- P_{EL} = 100 / ηklystron / ηmodulator / ηdistribution
- P_{EL}= 100 / 0.8 / 0.9 / 0.95 = 146MW
- Booster: P_{ELav} = P_{EL} * booster duty cycle = 1.7MW

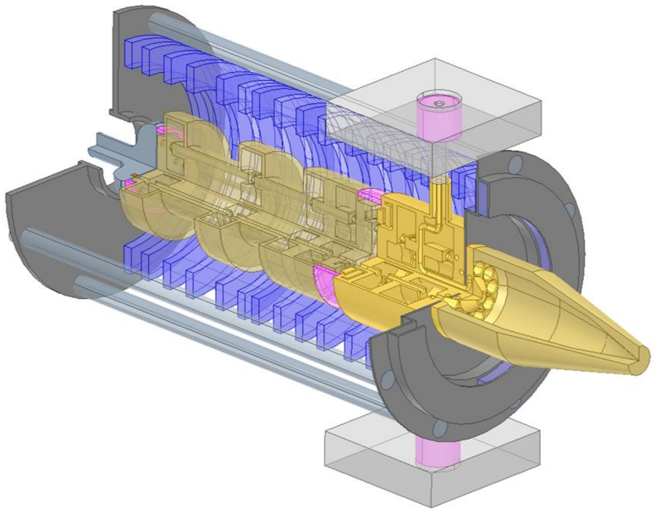
- With 55% efficiency, the RF power demand would be 212MW,
- 66MW reduction expected: 300GWh/y of energy saving

Assumption of 80% efficiency, not existing today!

Storage ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
PRF (MW)	100	100	100	100
Klystron efficiency	0.8	0.8	0.8	0.8
PRF EL (MW)	146	146	146	146

Booster	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
PRFb (MW)	7.5	7.5	7.5	7.5
Klystron efficiency	0.7	0.7	0.7	0.7
Booster duty cycle	0.15	0.15	0.15	0.15
PRFb EL (MW)	2	2	2	2

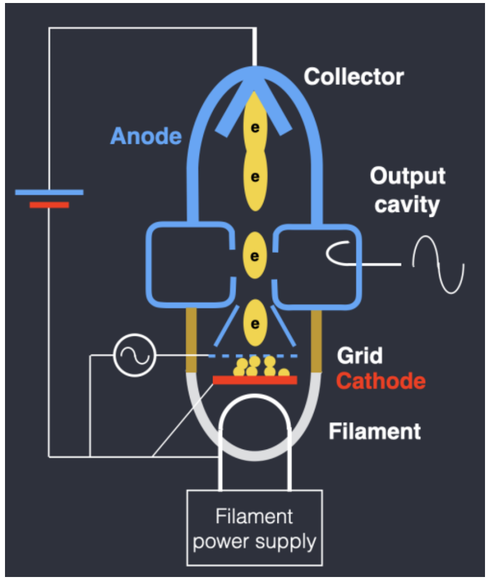
Efficient RF power (see F. Pauger)



- **400 MHz:** Development of 2-stage high-efficiency klystron with industry.
- **800 MHz, Z, W, H:** Low average power consumption in the booster (~2 MW vs. 150 MW in storage ring) and high efficiency of existing IOTs (~70%): **focus on lowering capital investment rather than increase of efficiency**.

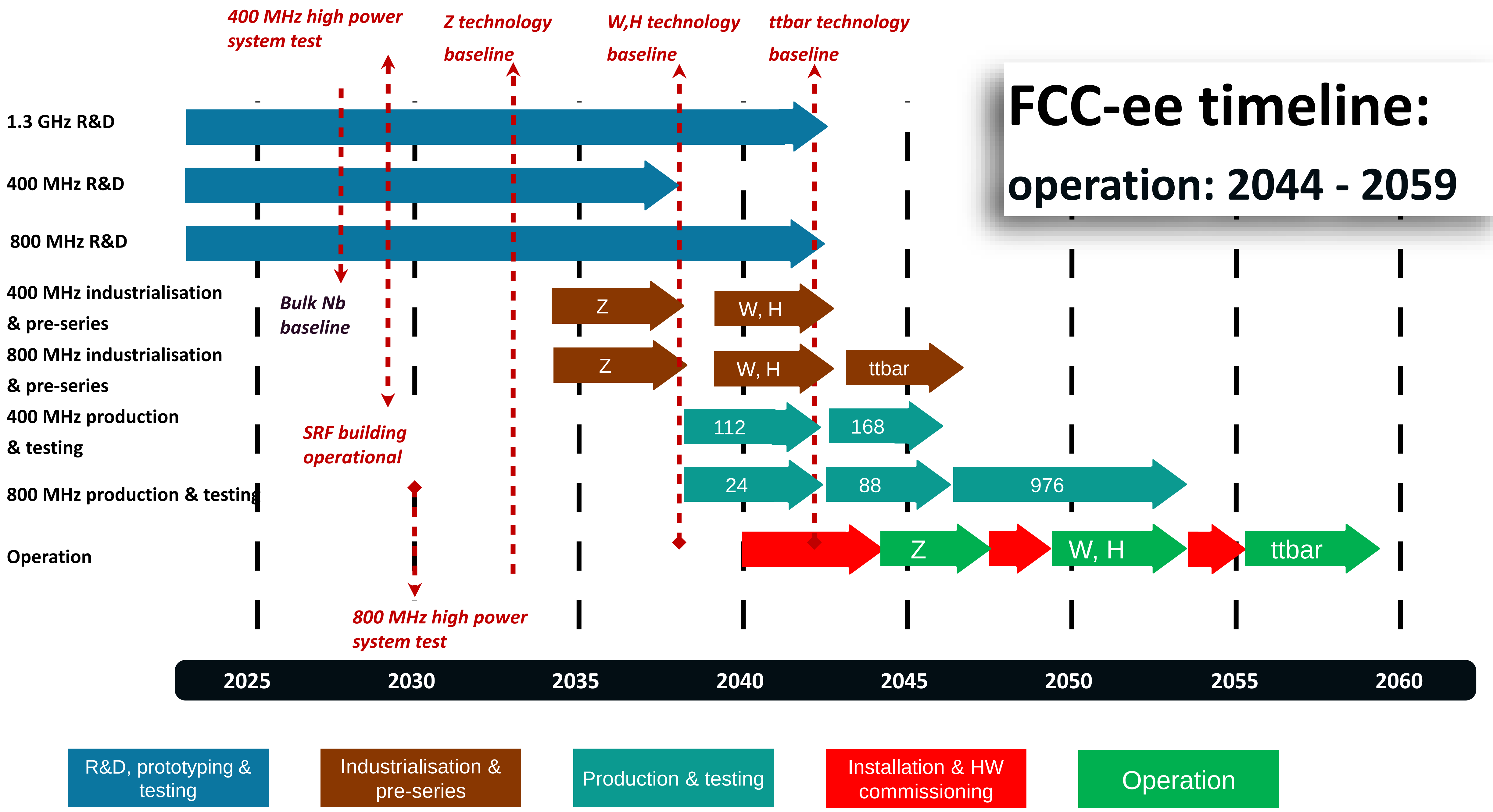
➢ Development of a cost-efficient IOT based RF system combining several tubes to cover the 800 MHz power needs (60 - 250 kW) for Z, H, W. (Thales collaboration)

➢ **ttbar** (with 800 MHz in the storage ring) merits the development of a new high-efficiency system (MB-2-stage IOT, klystron, or solid state).



RF R&D roadmap

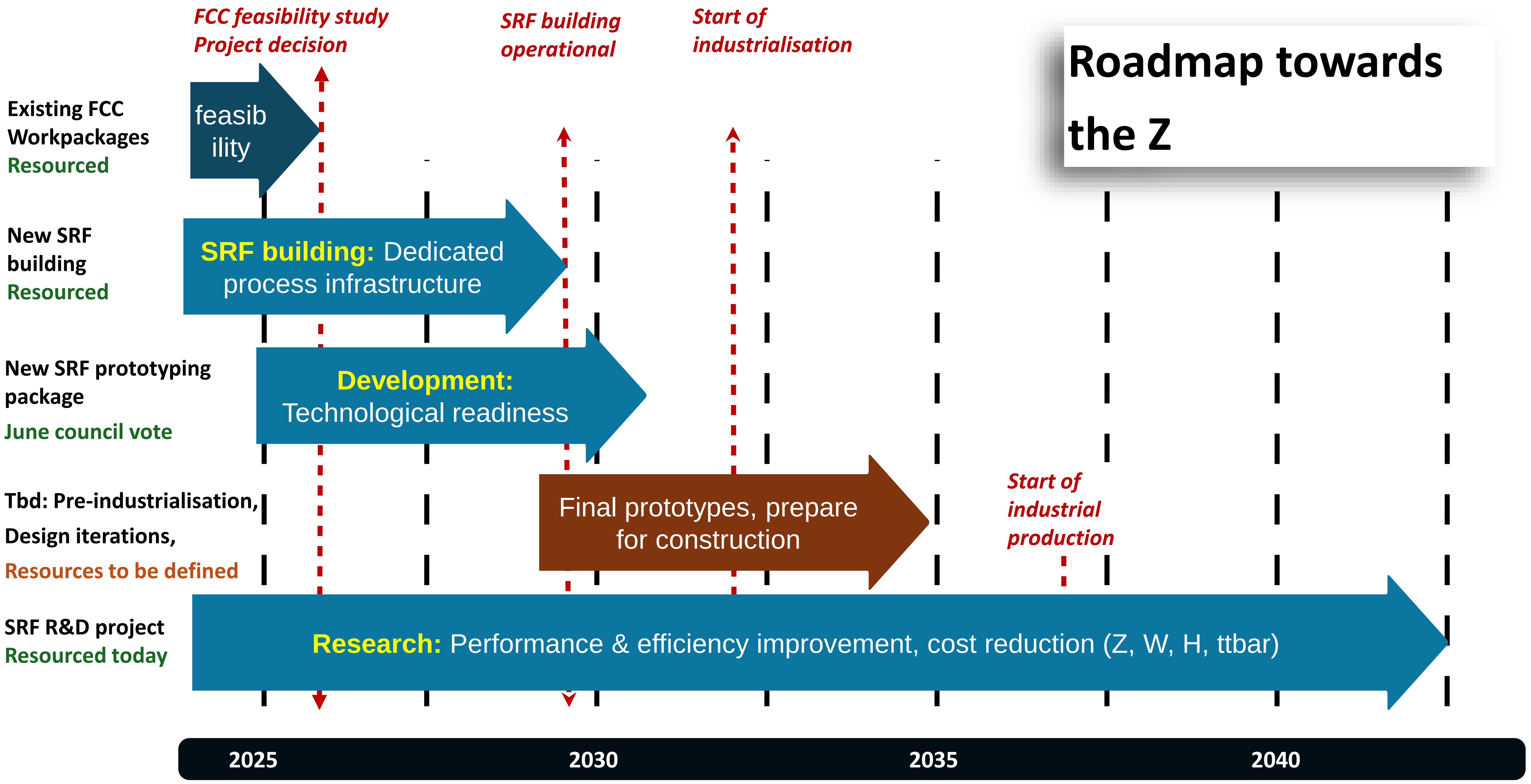
FCC-ee timeline: operation: 2044 - 2059



Planned prototyping effort to prepare for FCC (or other future accelerators), Council vote in June

#	Deliverable	2025	2026	2027	2028	2029	2030	2031
1	**2x 400 MHz 1-cell**	manufacturing coating, VT1	recoating, VT2 & 3, He tank	He tank, VT4				
2	**4x 400 MHz 2-cell**	`	fabrication	coating, VT1, re-coat, VT2	re-coat, VT3, He-tank	VT4		
3	**4x 400 MHz 2-cell**				design update	coating, VT1, re-coat, VT2	re-coat, VT3, He-tank	VT4
4	**400 MHz HE klystron/ 800 MHz IOT**	design	design/fabrication	fabrication, test stand prep.	test stand prep. & testing at CERN	test and design update		
5	**400 & 800 MHz FPC for full system test**	design	construction	construction/test	ready for full test at 400 MHz	ready for full test at 800 MHz		
6	**Horizontal test cryostat**	construction	construction & installation	**testing, 400 MHz system test (1 cell)**	**400 MHz full power system test (2 cell)**	**800 MHz full power system test (5 cell)**		
7	**400 MHz CM (4x 2-cell-cavities)**	design	design	design folder, start construction,	construction	start assembly	**CM test**	cavity exchange
8	**800 MHz CM (4x 4 cell cavities FNAL)**	design	design	design folder, start construction	construction/ assembly	assembled	**CM test**	**CM test**

Roadmap towards the Z



Key technologies and technological readiness

- RF technology exists to build this machine today, although not at the desired specifications.
- **Research** is needed to reach nominal specs, to keep capital cost under control and to increase energy efficiency beyond the baseline.
- **Development** (prototyping) of cavities, couplers, cryomodules is a time-consuming process and needs to start now.
  - 400 MHz centred at CERN,
  - 800 MHz started with strong US collaboration,
- **CERN is making a strategic investment in a dedicated new SRF facility, in fundamental SRF R&D, in prototyping and in the development of high-efficiency RF sources.**
- The ttbar starting date (2055) justifies a long-term research program for Nb3Sn cavities. Any progress until 2040 – 2045 will significantly impact cost & efficiency of the ttbar run. **This is the time for a major technological step forward.**

Thank you