RF priorities for FCC

Frank Gerigk, CERN

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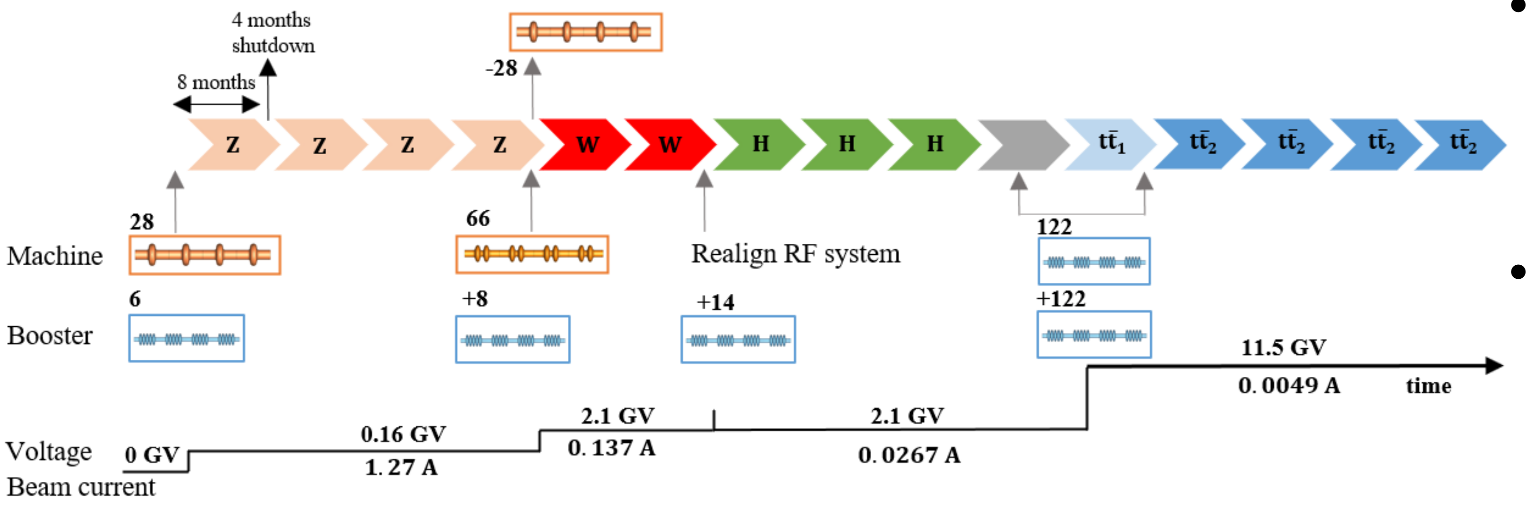
European Lab Directors Group Meeting and Accelerator R&D Workshop, 6 - 7 June 2024

Content

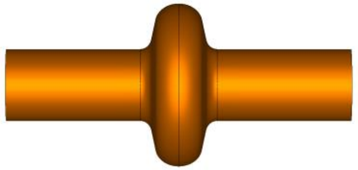
- RF baseline
- SRF R&D
- Efficient RF power sources
- RF R&D roadmap

FCC-ee SRF system baseline



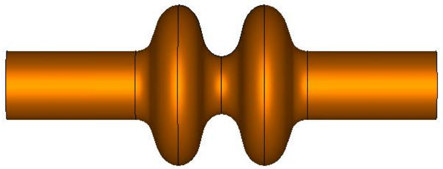
- **Baseline**: Starting with 1-cell for Z to reduce HOM power load: but 1-cell modules need to be removed for W and replaced by 2-cell modules.
- **Under study**: starting with 2-cell using increased HOM damping & transverse feedback.

Z: 112 cavities
+ 24x800 MHz



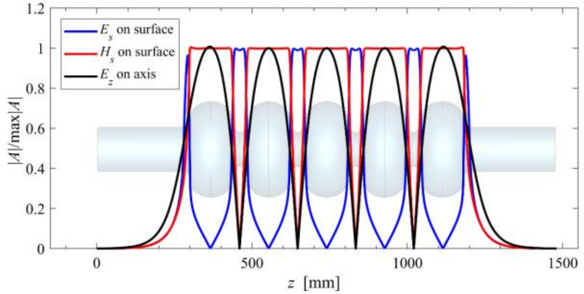
400 MHz 1-cell
Nb/Cu, 4.5 K

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

RF parameter table

	Z	Z	W	W	H	H	$t\bar{t}$	$t\bar{t}$	$t\bar{t}$
	Collider (per beam)	booster	Collider (per beam)	booster	Collider (2 beams)	booster	Collider (2 beams)	Collider (2 beams)	booster
# cell / cav	1	5	2	5	2	5	2	5	**5**
RF Frequency [MHz]	400.79	801.58	400.79	801.58	400.79	801.58	400.79	801.58	801.58
RF voltage [MV]	80	140	1050	1050	2100	2100	2100	9400	11500
Eacc [MV/m]	3.82	6.24	10.63	20.05	10.63	20.05	10.63	20.60	**20.50**
Vcavity [MV]	1.43	5.83	7.95	18.75	7.95	18.75	7.95	19.26	19.17
#cells	56	120	264	280	528	560	528	2440	3000
# cavities	56	24	132	56	264	112	264	488	**600**
# CM	14	6	33	14	66	28	66	122	150
Total length [m]	105	40	296	94	592	188	592	821	1010
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	9	0.3	129	3.4	129	3.4	129.4	23.7	3.5
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	2.6E+04	3.1E+05	9.0E+05	7.4E+06	9.1E+05	1.5E+07	4.7E+06	4.4E+06	8.3E+07
Detuning [kHz]	-13.6	-4.36	-0.6	-0.14	-0.11	-0.01	-0.01	-0.05	-0.002
Pcav [kW]	894	208	388	91	382	45	75	163	**9**
rhob [m]	9936	9936	9936	9936	9936	9936	9936	9936	9936
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5	182.5	182.5
energy loss [MV]	39	39	374	374	1890	1890	10420	10420	10420
Cos(phi)	0.49	0.28	0.36	0.36	0.90	0.90	0.96	0.86	0.91
Beam current [A]	1.270	0.127	0.137	0.014	0.053	0.003	0.010	0.010	0.0005
Lacc [m]	0.374	0.935	0.748	0.935	0.748	0.935	0.748	0.935	0.935
#cav/CM	4	4	4	4	4	4	4	4	4
R/Q [ohm]	87.6	521	181.1	521	181.1	521	181.1	521	521
G [ohm]	238.6	272.9	234.7	272.9	234.7	272.9	234.7	272.9	272.9
Q0	2.70E+09	3.00E+10	2.70E+09	3.00E+10	2.70E+09	3.00E+10	2.70E+09	3.00E+10	3.00E+10
Epk/Eacc	2.21	2.05	2	2.05	2	2.05	2	2.05	2.05
Bpk/Eacc [mT/MV/m]	5.36	4.33	5.33	4.33	5.33	4.33	5.33	4.33	4.33
Ep [MV/m]	8	13	21	41	21	41	21	42	42
Bp [mT]	20	27	57	87	57	87	57	89	89
Cavity design	**Quasi-LHC**	**UROS5**	**2-Cell-V2**	**UROS5**	**2-Cell-V2**	**UROS5**	**2-Cell-V2**	**UROS5**	**UROS5**

→ 6 (RF Frequency, booster $t\bar{t}$)

→ 30 (Vcavity, booster $t\bar{t}$)

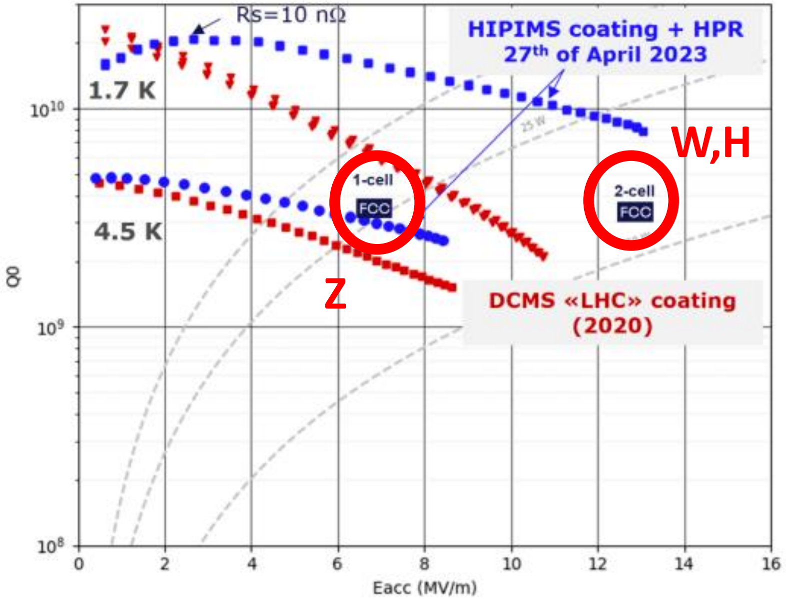
6-cell cavities instead of 5-cell:
significant potential for cost savings at 800 MHz, especially in booster cavities

Duty cycles:
- collider: CW
- Booster: ~15%

SRF R&D

R&D on SRF cavity performance

- 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 is foreseen 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

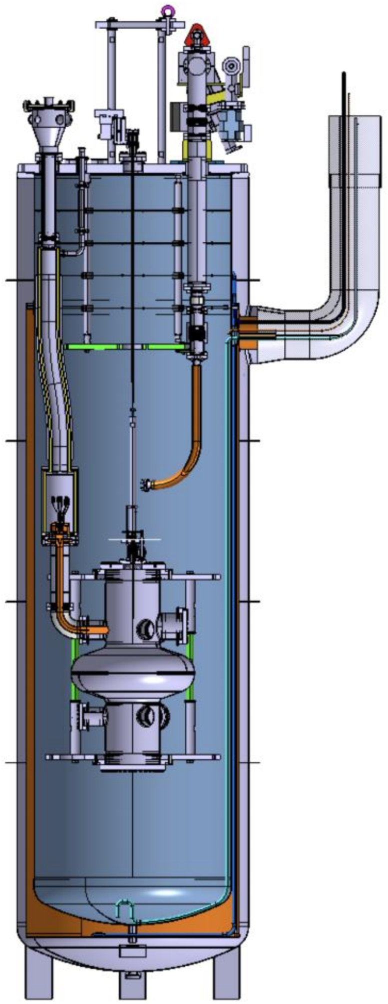


1. L. Vega Cid, R&D on superconducting thin films for SRF cavities, RF seminar, 2024, CERN
2. S. Posen, "R&D towards an 800 MHz cryomodule", FCC Week 2023, London, UK

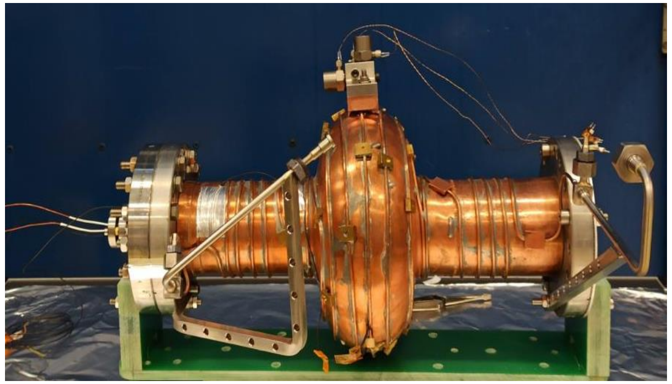
20-Apr-23	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	6.6	3.15E+09	6.3	3.0E+09	5.7	2.7E+09
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

Further SRF R&D topics

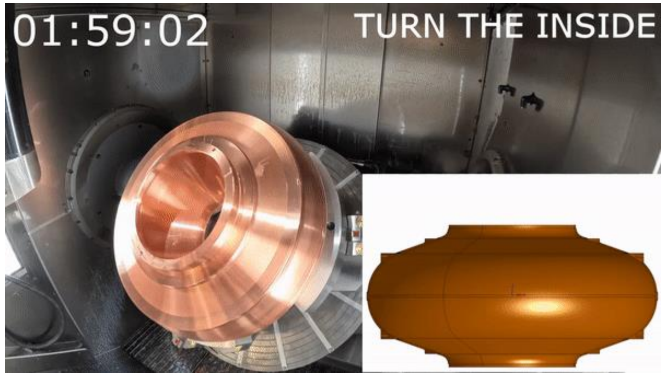
- SRF cavity manufacturing (seamless cavities), thin film coating techniques, novel cooling methods (to reduce He-inventory).
- Sample tests and magnetic flux trapping studies on coatings, multi-layers.
- Routine optical inspection of all cavities.
- Non-mechanical tuning with ferroelectric fast reactive tuner (Fe-FRT) with Euclid Techlabs, HZB & JLAB.
- To be established: **dedicated Nb_3Sn roadmap until 2040 (see Annex)**.



Validate transient detuning compensation for LHC with Fast Reactive Tuner



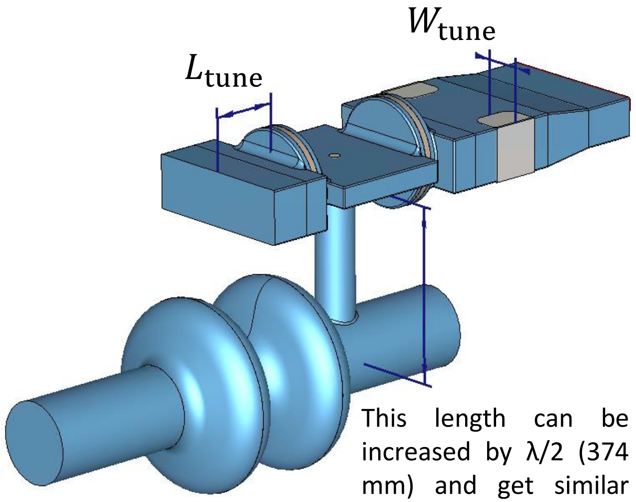
Quasi-dry cooling

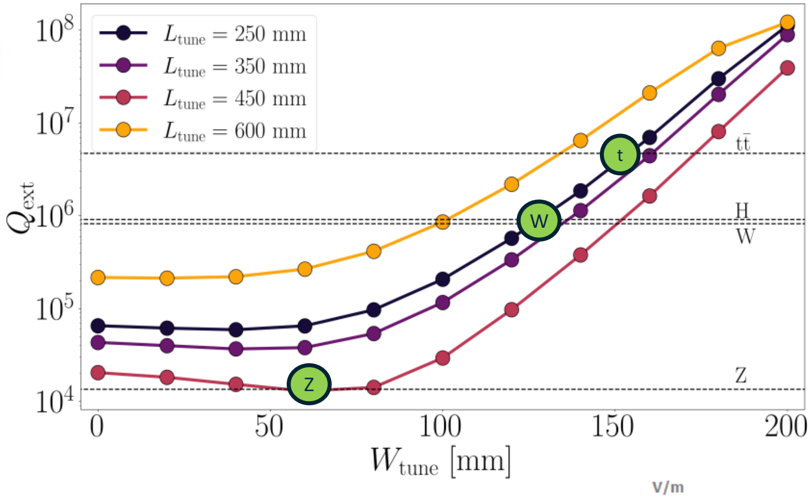


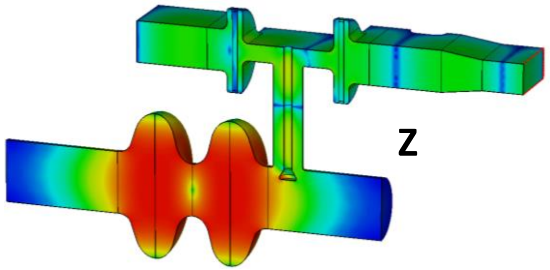
Seamless cavities via bulk machining as reference cavities

New adjustable power coupler concept

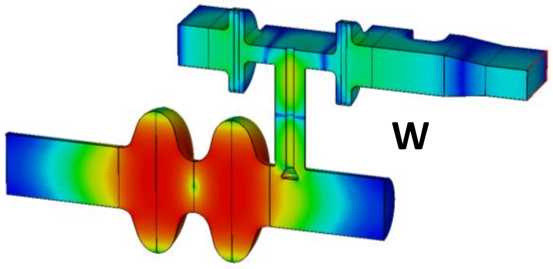
- Two windows (LINAC4-like) are placed outside the cryomodule → challenging to integrate after cryostating (similar to LHC cavity)
- A more robust and easier-to-cool down window design → easier to cover all four working points
- Providing ~1 MW in CW operation with variable coupling for Z, W, H, ttbar.
- Prototyping starting.



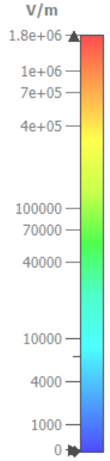




$L_{\text{tune}} = 450$ mm,
$W_{\text{tune}} = 55$ mm,
$Q_{\text{ext}} = 1.33e4$,
$E_{\text{pk-window}} = 0.18$ MV/m,
$E_{\text{pk-air}} = 0.22$ MV/m



$L_{\text{tune}} = 250$ 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

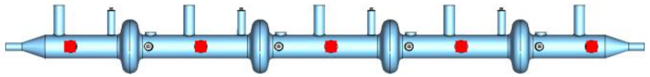


E normalized to 1J stored energy

HOM power in 400 MHz cavities at Z working point

- **~12 kW increase in HOM power with 2-cell cavity** and potentially additional ~10 kW in case of resonant excitation.

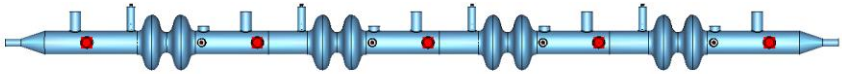
- kWs of HOM power extracted by two rigid **coaxial** lines → **need experimental demonstration.**



HOM power from loss factor (BS bunch length):

$P_{\mathrm{HOM}}\ [\mathrm{kW}] \approx 8.9 + 5 \times 1.5 + 4 \times 3.7 = \mathbf{31.2}$

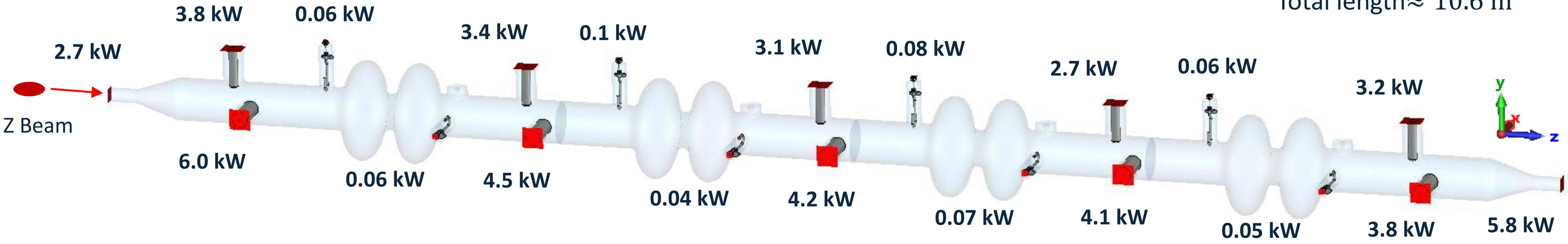
Tapers   2-coax couplers   Cavities



HOM power from loss factor (BS bunch length):

$P_{\mathrm{HOM}}\ [\mathrm{kW}] \approx 8.9 + 5 \times 1.5 + 4 \times 6.7 = \mathbf{43.2}$

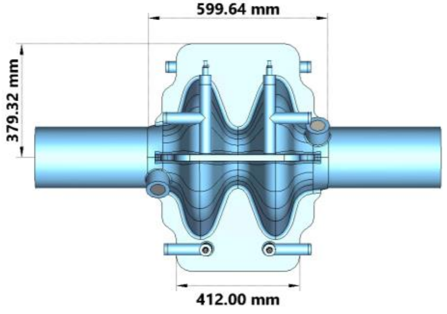
Z: $P_{\mathrm{HOM}} \approx 47.9\ \mathrm{kW}$



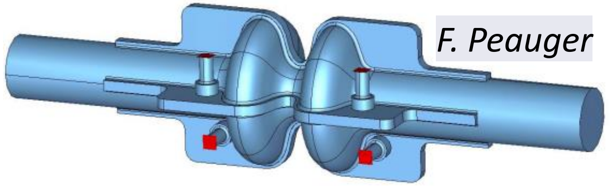
Alternative cavity designs

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

SWELL 600 MHz

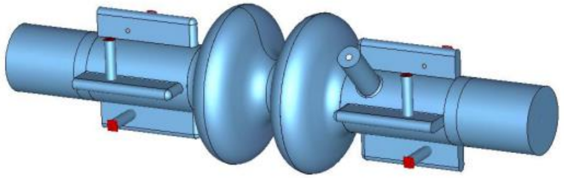


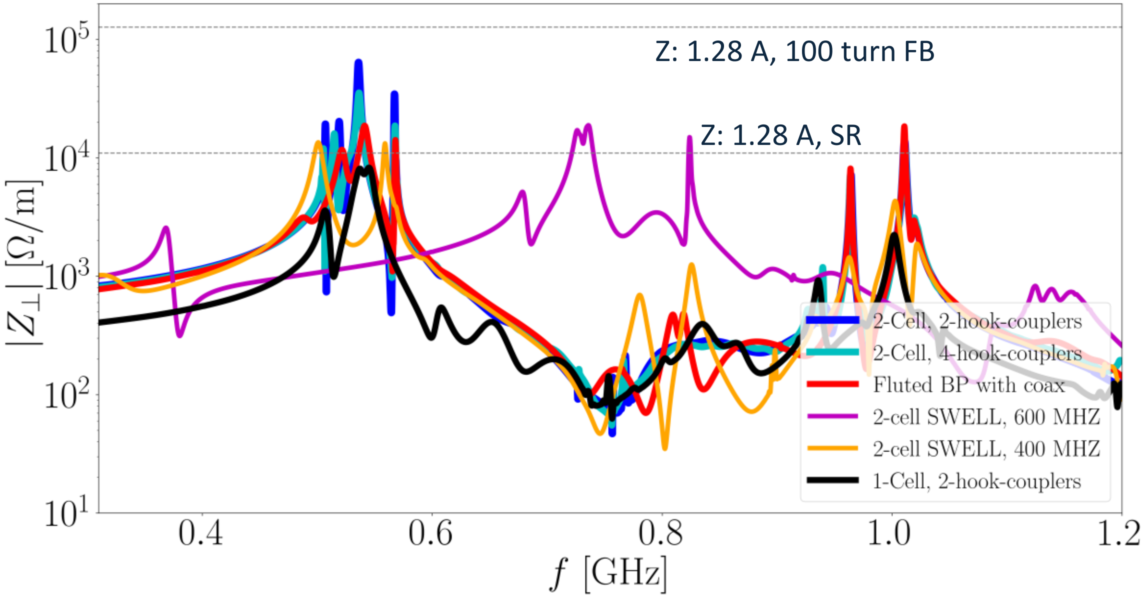
SWELL 400 MHz



F. Peauger

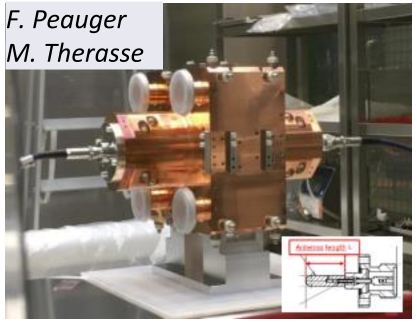
Fluted beam pipe

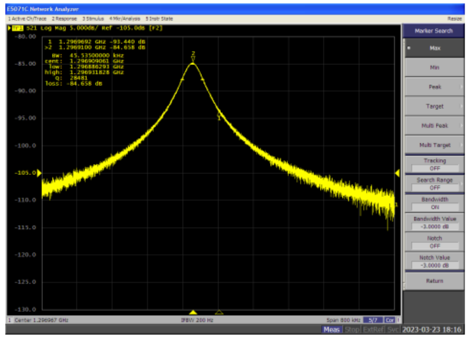




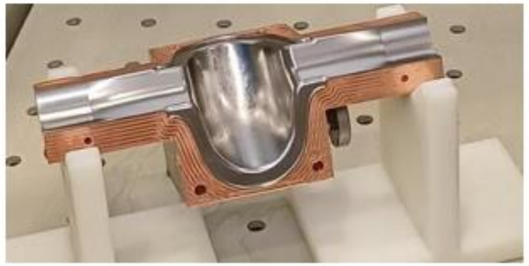
SWELL 1.3 GHz cavity prototype

F. Peauger
M. Therasse





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



(Guillaume et al.)

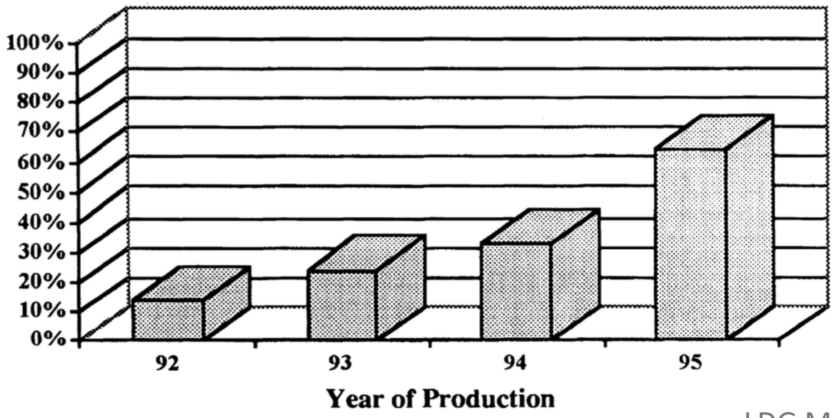
Niobium thin film coating of the four quadrants and surface treatment in progress

New SRF infrastructure at CERN: SA18

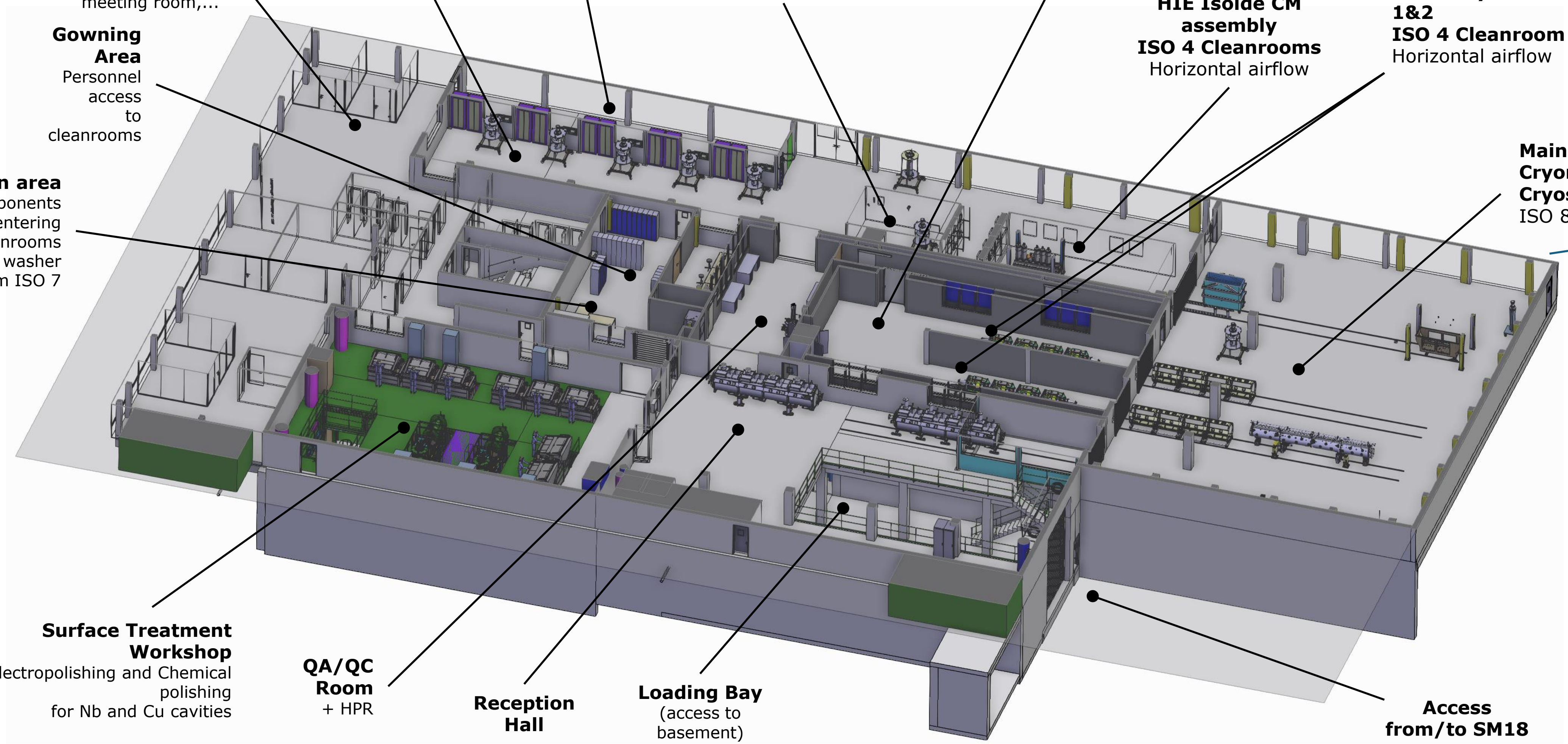
Unique facility for thin film (and bulk) SRF R&D

- 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

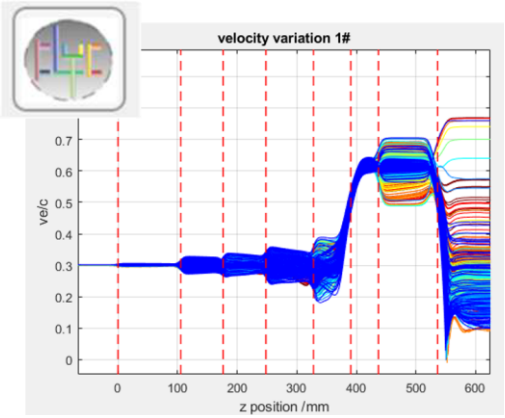
Assumption of 80% efficiency, not existing today!

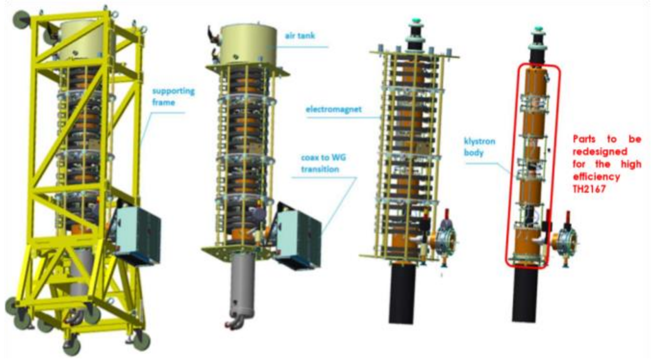
Storage ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
PRF (MW)	100	100	100	100
Klystron efficiency	0.8	0.8	0.8	0.8
PRF EL (MW)	146	146	146	146

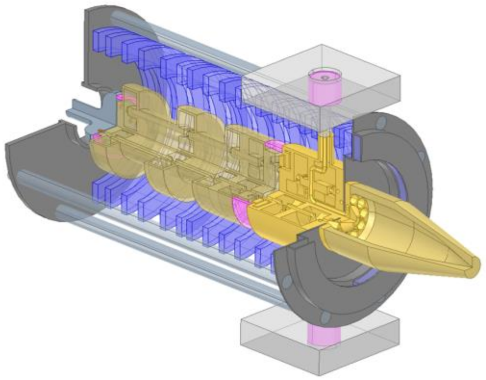
Booster	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
PRFb (MW)	7.5	7.5	7.5	7.5
Klystron efficiency	0.7	0.7	0.7	0.7
Booster duty cycle	0.15	0.15	0.15	0.15
PRFb EL (MW)	2	2	2	2

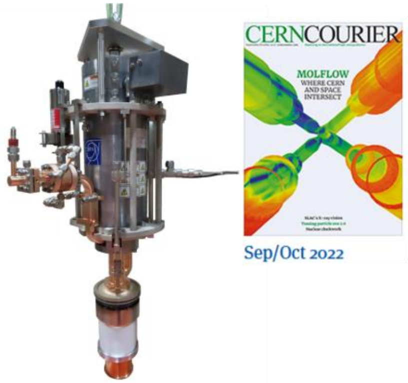
High Efficiency Klystron Project

- Collaboration with Lancaster University & Industry (Thales, Canon)
- **FCC scope: increase klystron efficiency from ~55% today to >80%. 400 MHz 2-stage: design ready, 800 MHz: probably IOT solution.**









Design & simulation

CERN made klystron code: KlyC.

HE LHC klystron

Under construction, prototype expected summer 24.

2-stage klystrons with >80% efficiency

- 400 MHz 1MW CW klystron for FCC.
- **Electrical design ready, discussion with industry starting. Prototype ~2027**

HE X-band klystrons: 10-50 MW

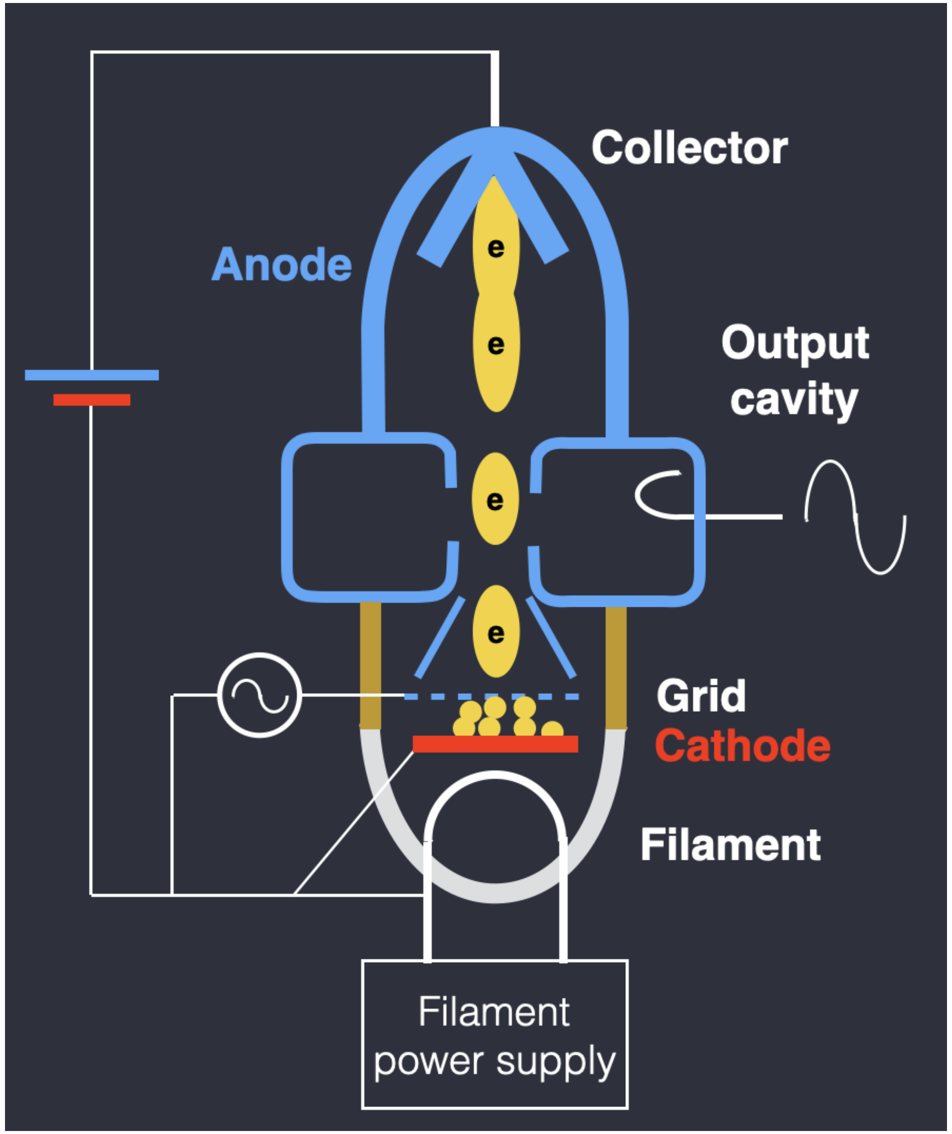
First CERN-designed & industry produced prototype successfully tested in 2022

800 MHz Inductive Output Tubes (IOT) for the booster

- **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**.

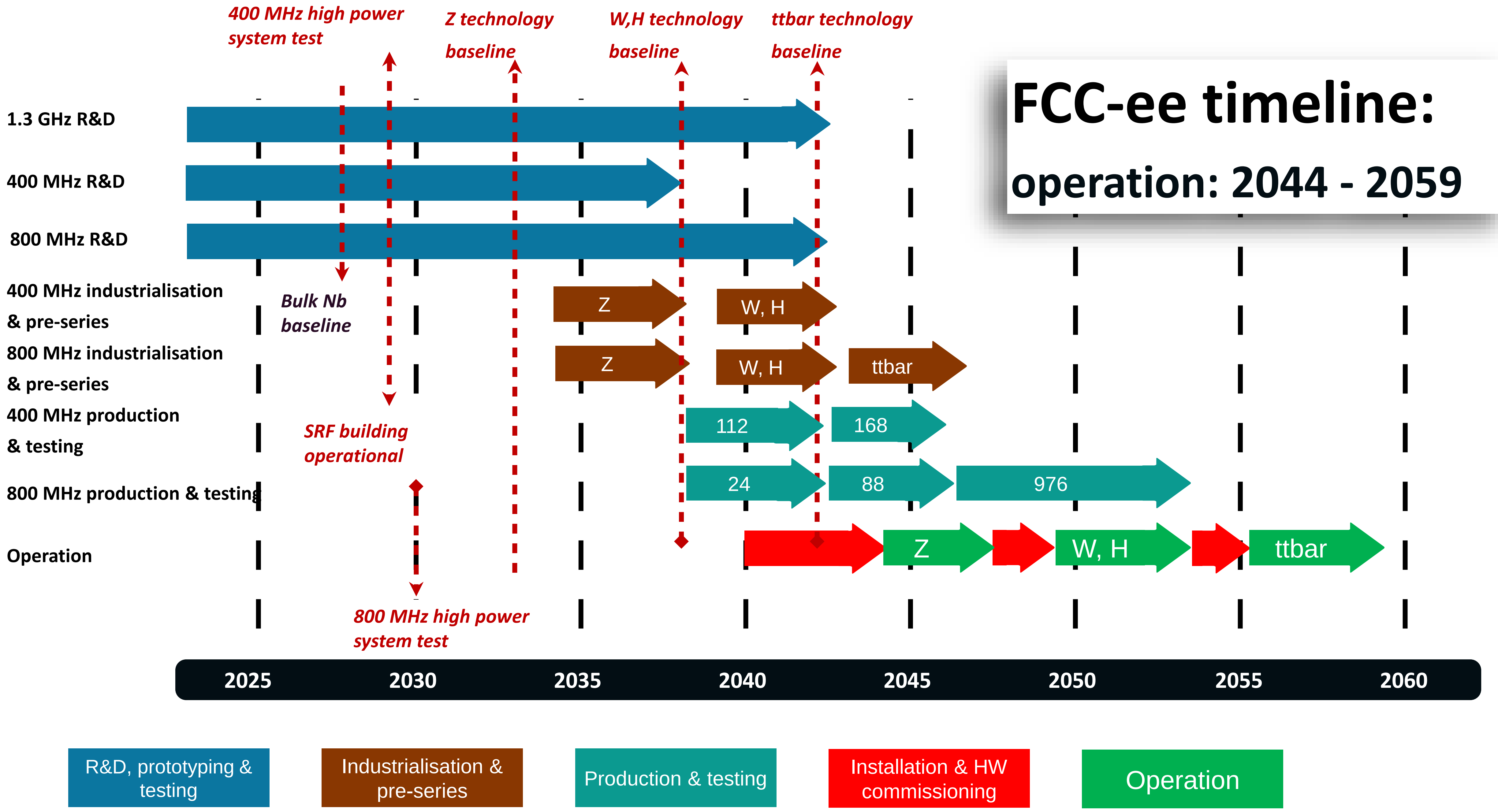
➢ Development of a cost-efficient IOT based RF system combining several tubes to cover the 800 MHz power needs (60 - 250 kW) for Z, H, W. (Thales collaboration)

➢ **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

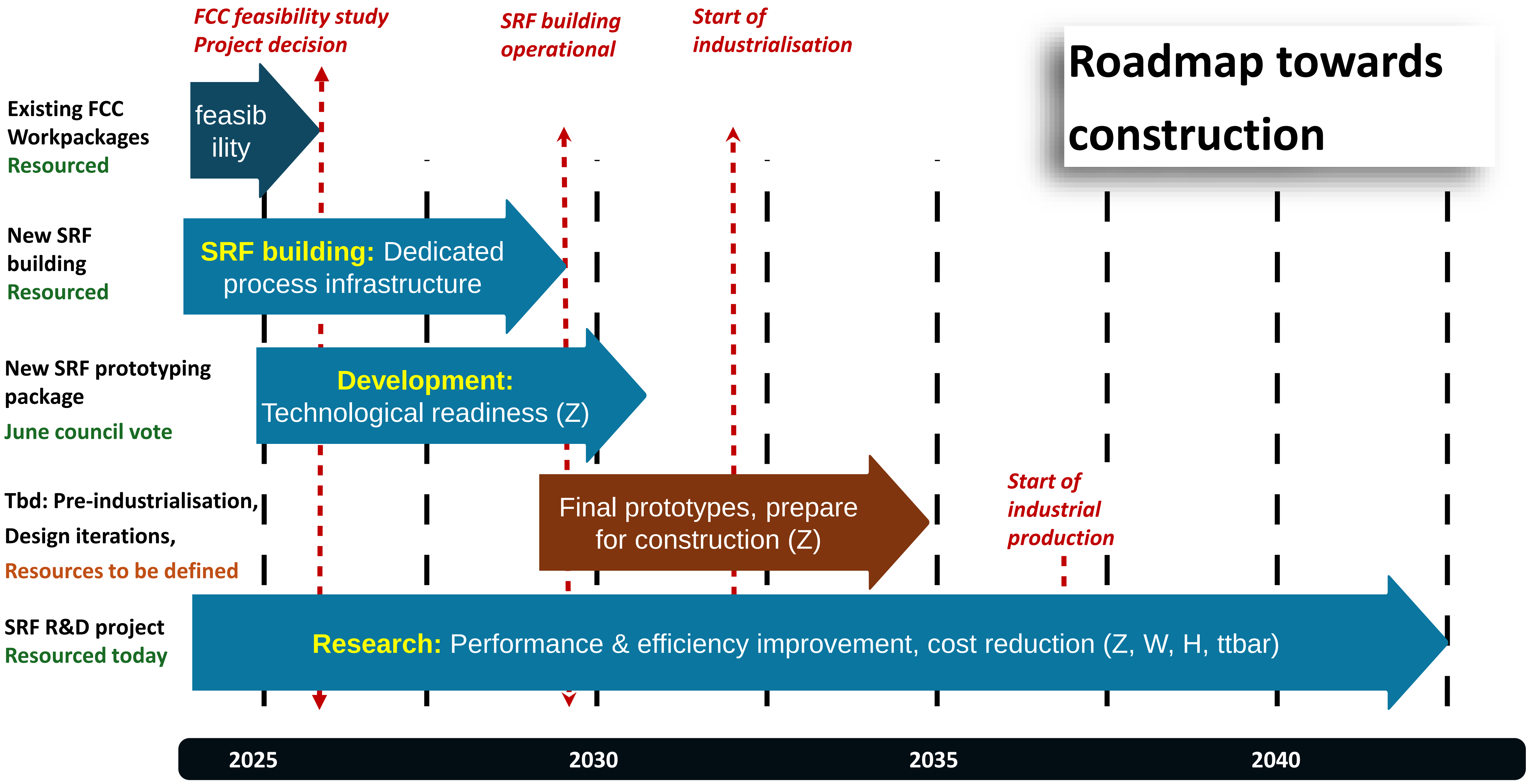
FCC-ee timeline: operation: 2044 - 2059



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 construction



Key technologies and technological readiness

- RF technology exists to build this machine today though not at the desired specifications.
- **Research** is needed to reach nominal specs, to keep capital cost under control and to potentially increase energy efficiency.
- **Development** (prototyping) of cavities, couplers, cryomodules is a time-consuming process and needs to start now.
- 400 MHz largely at CERN, 800 MHz so far planned in the US.
- CERN is making a strategic investment in a dedicated new SRF facility, is setting up a significant SRF R&D effort, and is developing 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

Nb_3Sn/Cu for SRF, 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
- 1st phase of CERN study , based on DC magneton sputtering on small samples is documented in (1)
- 2nd 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, QPR sample reached surface resistance at 400,800 and 1200 MHz and 4.2 K better than Nb/Cu but not as good as Nb_3Sn/Nb

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.

Collaborations on thin films & Nb_3Sn with: INFN, CEA, FNAL, JLAB, Cornell, University Hamburg, Wien Technical University, Geneva University, ..