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REVIEW

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Progress and R/D challenges for FCC-ee SRF

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Abstract

The FCC-ee machines present a huge challenge for the RF systems, which need to be adapted to very diverse beam conditions going from moderate energy and high current for the Z machine to high energy and low beam current for the ttbar. This inverse scaling results naturally from a fixed budget for the synchrotron radiation, which the SRF cavities need to compensate. A global solution was elaborated for the FCC Conceptual Design Report (Abada in Eur Phys J Spec Top 228):261–623, 2019), and is referred here as the baseline. Recently, further studies have led to a new optimized baseline, still based on traditional elliptical cavities. In parallel, a novel concept, named the Slotted Waveguide ELLiptical (SWELL), was proposed with the potential of greatly simplified logistics and reduced costs. Under several aspects, all these changes call for enhanced performance of the RF systems. A vigorous R&D program has therefore continued since the publication of the CDR, with the aim of pushing the performance and demonstrating the feasibility of a more advanced baseline and, more recently, of the SWELL option. The progress and challenges of this ambitious program were presented in the dedicated SRF sessions at FCC week 2022 (FCC week 2022 website, 2022, https://indico.cern.ch/event/1064327/timetable/) and are summarized in this paper.

Keywords: Future Circular Collider; RF superconductivity; Accelerating cavity

1 Machine parameters relevant to RF and revised SRF cavity baseline

As detailed in the FCC Conceptual Design Report (CDR) [1], the RF system of the FCC lepton machines is designed to provide a constant RF power of 50 MW per beam at four different energies going from 45.6 GeV to 182.5 GeV (see Table 1).

The design choices of the accelerating cavities allow to cope with beam currents and RF voltages varying by two orders of magnitude. Accelerating cells operating on the TM010 mode with elliptical shapes have been adopted for their ability to operate at high accelerating gradient (for the H and ttbar energies), hence limiting the overall length of the RF sections.

For the operation at high beam currents (Z and W modes), the power handling capacity of the fundamental power couplers, which equip each cavity, will be the limiting factor. High beam current operation will also induce higher order modes in the cavity. It is thus

Table 1 RF-relevant machine parameters

	Energy (GeV)	Peak current (mA)	RF voltage (GV)
Z	45.6	1280	0.120
W	80	135	1
H	120	26.7	2.08
ttb	182.5	5	11.67

mandatory to damp and extract them to avoid beam instabilities and overheating of the cavity surroundings.

In the CDR, the LHC frequency of 400 MHz and its first harmonic (800 MHz) were chosen for the design of the accelerating cavities. Single cell 400 MHz cavities hosted in four-cavity cryomodules and each equipped with four coaxial higher mode couplers have been considered for the Z machine. Each cavity operates at 1 MW RF power in CW mode by means of a single LHC type coaxial fundamental power coupler. For the W and H energies, the strategy described in the CDR consists in replacing the single cell cavities by 4-cell 400 MHz cavities and install progressively additional cryomodules during shutdowns to reach the desired energy. This approach is inspired by the construction and operation of the LEP RF system. The CDR targets for the FCC-ee are: 10 MV/m accelerating gradient and 1 MW RF power maximum for each 4-cell 400 MHz cavity. To reach the energy of the ttbar, 5-cell 800 MHz cavities are added to the 400 MHz RF system, all operated on-crest at 20 MV/m.

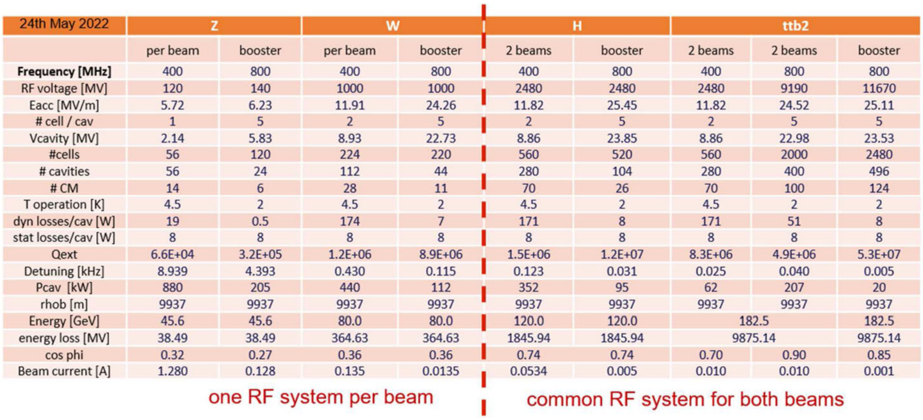
It is important to mention that the high energy booster allowing the top-up injection of the beam into the collider is a third ring in the tunnel which needs a dedicated RF system working in pulsed mode and reduced beam current. In the CDR, 4-cell 400 MHz cavities operating at the same RF voltage as for the collider were considered for this additional ring.

Since the publication of the CDR, investigations have continued to address some criticalities of the baseline solution. From the longitudinal beam dynamics point of view, operation at the Z pole is the most challenging, due to high beam current and large number of bunches. With the present single cell cavity design, coupled bunch instabilities are supressed by several well-known RF feedback techniques or by synchrotron radiation. Transient beam loading effects, for instance due to abort gaps in the beam structure, are well mitigated and HOM power losses are kept manageable.

In LEP, the 4-cell 350 MHz cavities were found limited to about 7 MV/m accelerating gradient in average over large statistics. The huge superconducting surface ($\sim$5 m^2) implies a higher probability to have defects during fabrication, which would induce field emission, Q_0 degradations or quenches. Improvement of such large cavities is not obvious and requires significant SRF infrastructure upgrades at CERN. It is not evident that the surface treatments recipes required to reach high gradients can be adapted to this cavity type.

In the new proposed baseline, 4-cell cavities are replaced by new 2-cell cavities at the same 400 MHz frequency. This new option facilitates the manufacturing and surface processing. The amount of RF power per cavity can be divided by two, relaxing the specification of the FPC. Each cell is now well coupled with HOM couplers placed on the adjacent

Table 2 Revised parameter table



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

common RF system for both beams

beam pipe, damping the high frequency modes in a more effective way. This configuration is better for the W operation where the beam current of 135 mA can also be considered as high. To limit to total length of the RF system, the accelerating gradient specified for the 2-cell cavities has been increased to 12 MV/m. Achieving this level of performance constitutes the main objective of the R&D program for the next years. The use of the 5-cell 800 MHz elliptical cavities and their performance specifications are also being revisited. These cavities will equip the RF system of the booster except for the Z machine. An increase of the nominal accelerating gradient from 20 to 25 MV/m was introduced to allow a drastic reduction of the total number of cryomodules. Thanks to the 2-cell 400 MHz cavity and its ability to operate at high current, the alignment of the cryomodule to use a common RF system for both beams can be performed at the level of the H energy. Table 2 summarizes the revised RF parameters, taking into account the up-to-date beam characteristics.

2 Cavity optimization for the revised baseline

For the Z and W machines, the specificity in the cavities RF design is the cancellation of longitudinal higher order modes (HOMs). Thanks to an advanced multi-parameter optimization process, the shape of the ellipses is chosen to lower the peak electromagnetic surface fields while eliminating any high frequency resonant longitudinal modes below the cut-off frequency of the beam pipe. This prevents resonant excitation of HOMs by the beam which would generate kilowatts of parasitic RF power in the cryomodules.

In the revised baseline, most of the efforts have been focused on the 2-cell 400 MHz cavity design. At the nominal accelerating gradient of 12 MV/m, the peak electric and magnetic surface fields are respectively E_p = 24.4 MV/m and Bp = 76.1 mT. With a geometric factor G of 196.3 Ω, achieving a minimum Q_0 of $3e^9$ at nominal field requires a maximum surface resistance R_s of 65 nΩ. With four hook-type couplers integrated on the beam pipes (two on each side), the transverse HOMs are sufficiently damped at about 60 kΩ/m, which is far below the beam instability threshold of 700 kΩ/m at the W working point.

Cavity studies will be pursued in the next years to continue optimizing the shape of the three cavity types. The damping schemes with coaxial couplers will be deeply analysed to ensure that mechanical errors do not jeopardize their functionality. Complementary evaluations like multipacting analyses and frequency sensitivity to Lorentz forces and microphonics will be also addressed.

3 R&D challenges for the revised baseline

As mentioned, the new baseline calls for higher nominal gradients and unloaded quality factors in the SRF cavities. The 400 MHz system shall rely on the Nb/Cu technology while for the 800 MHz, we envisage a more traditional solution based on bulk Nb. The strategy adopted is to develop the Nb coatings on 1.3 GHz mono-cells, which are cheaper to manufacture and offer higher turnaround for quick feedback on new coating and preparation methods. At the same time, practising at 1.3 GHz will keep open the possibility to adopt Nb/Cu also for the 800 MHz system, if the performance targets at high field can be met reproducibly. Nb thin films on copper have already shown [3] to sustain high accelerating fields at Q_0 in the 10^{10} range at 1.3 GHz. However, in these coatings, realised with the DC magnetron sputtering method, the surface resistance rapidly increases with the RF field, which so far limited the application of Nb/Cu to low-to-medium gradient accelerators. This phenomenon, known as the Q-slope problem [4], is still an open subject of research: several theories and models have been proposed, none of which is fully satisfactory over all the parameter space accessible to the experiments. In recent years, progress was made in the mitigation of the Q-slope, by using energetic condensation techniques such as High Power Impulse Magnetron Sputtering (HIPIMS) [5]. Along with the unwanted Q-slope, Nb films display several attractive features, like an optimized BCS surface resistance, typically a factor 2 lower than bulk Nb, which makes 4.5 K operation (where the BCS component is dominant) possible at higher frequencies than for bulk Nb.

4 Beyond Nb

As indicated above, reducing the BCS surface resistance is necessary if operation at superfluid helium temperatures is to be avoided, with the consequent savings in terms of capital and running costs for a large installation. Therefore, new SRF materials with higher T_c are actively investigated. Among these, Nb_3Sn is the prime candidate, and the SRF community has been developing it for a long time with very encouraging results, albeit not yet mature for operation in a real accelerator. Thus far, the main development of Nb_3Sn for SRF applications uses bulk Nb as a substrate on which the Nb_3Sn A15 phase is grown by thermally diffusing Sn from vapours at high temperature. Nb_3Sn cavities produced by thermal diffusion have reached fields in excess of 20 MV/m at 1.3 GHz and 4.5 K [6]. One of the issues for improving their performance is to guarantee enough thermal stability to avoid premature quenches. It is therefore interesting to explore the possibility to form the A15 phase on a high thermal conductivity substrate like copper. Work in this direction is ongoing in several laboratories, including CERN.

4.1 The 1.3 GHz program

In the past few years, Nb films on copper deposited with HIPIMS were optimized first on small samples measured with the QPR, and then on TESLA shape 1.3 GHz single cell cavities. Initially, progress was slow due to the lack of suitable substrates. Actually, porosities at weld location and other defects jeopardized results. To tackle this issue, CERN launched the manufacturing of high quality substrates along three different lines: from the experience with HIE ISOLDE [7] it was known that electron beam welding (EBW) of copper can

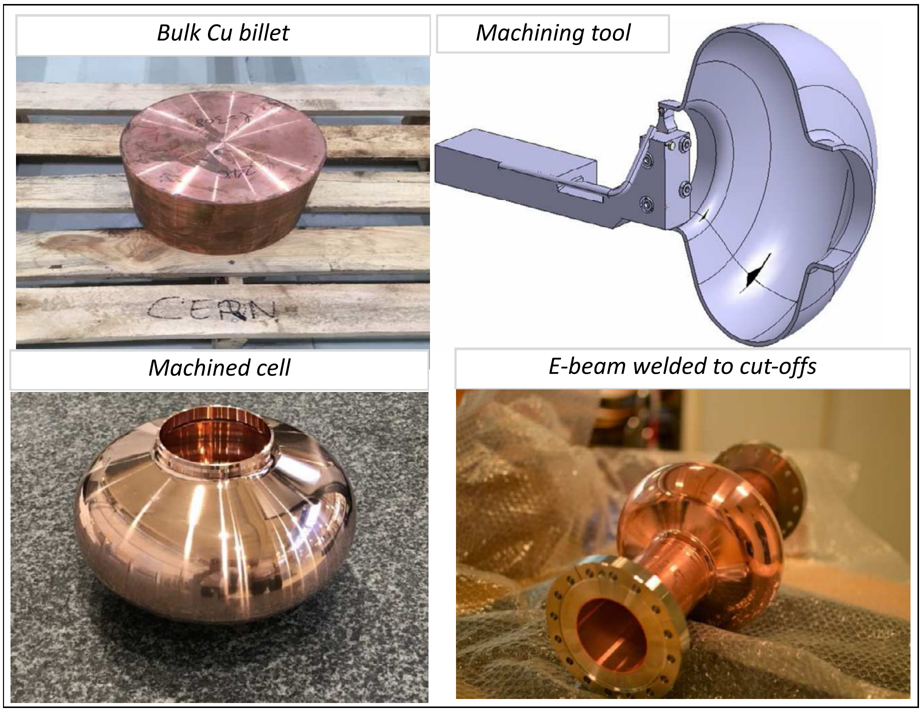


Figure 1 Some steps of bulk machining of a 1.3 GHz cavity

induce defects which spoil the final RF performance, therefore seamless techniques were pursued. In parallel, electro-polishing of elliptical copper substrates was implemented and the sputtering systems and RF test stands were optimized. Once new substrates became available, the program changed pace. In the next paragraphs the main achievements will be briefly described.

4.1.1 Innovative substrate manufacturing

To set a standard, machining out of a bulk copper block was used to produce a few seamless mono cells. In Fig. 1, we show the tooling for internal machining, the machined cell, and the finished cavity after welding of the cut off tubes. The process was implemented in CAM and diamond finishing was applied to obtain a final roughness $R_a < 15\mu$m. Shape accuracy within 20 μm was achieved.

Other seamless manufacturing techniques for elliptical cavities include hydroforming, and Cu electrodeposition on an aluminium mandrel, which is subsequently removed chemically.

In parallel, in order to improve the quality of EB welding of copper, specifically for the equatorial weld of the cell, tooling and initial tests have been developed, so to realise a full penetration weld from the inner cavity side.

The above-mentioned activities are performed while taking into consideration process up-scalability to larger cavity sizes, such as 400 MHz. In particular, hydroforming is investigated as a potential candidate for series production in industry.

Manufacturing studies go hand in hand with related R&D. In such framework, finite element analyses are performed in order to benchmark and optimise processes such as hydroforming, spinning and machining. To this aim, specific material and failure models are being created. Furthermore, experimental studies are performed in order to understand the impact of different processes (both shaping and material removal) on the quality of coating and RF performance.

4.1.2 Electro-polishing of copper cavities

The copper substrate surface is critical for the quality of the deposited Nb film, and it needs to be processed after the manufacturing steps to remove the mechanically damaged layer. Chemical polishing was applied in the past (LEP, LHC, HIE ISOLDE), as it is simpler to implement for complex shapes. It is known, however, that electro-polishing can produce smoother surfaces as it naturally tends to preferentially etch the peaks of the surface roughness. Modelling and optimization of electro-polishing for copper cavities was the subject of recent work presented at FCC week 2022. Strong focus is put on the combined effects of electrochemistry and fluid dynamics. This study has shown that the electro-polishing plateau can be significantly shifted due to the chemicals flow. This being taken into account, a model is proposed to obtain a universal description of the process in order to ease its scale-up and enable the surface treatment of 400 MHz elliptical cavities meant to be used in the FCC-ee machine. The electro-polishing of 1.3 GHz cavities has already proven to lead to very high quality Nb thin films and the next step consists of transferring this know-how to actual 400 MHz cavities in view of reaching the FCC-ee performance target.

4.1.3 HiPIMS coatings, Nb film optimization

It is only after the copper substrate is under control that work can start to tweak the coating parameters in order to find optima in the superconducting characteristics. In fact, since PVD coatings are deposited in out-of-equilibrium conditions, and since the SRF performance is determined by the properties of a thin layer of the order of a few tens of nm, there is a virtually infinite panoply of outcomes depending on coating parameters like the substrate temperature, the sputtering gas, the working pressure, the bias voltage, etc. The main problem is to identify estimators of the final RF performance, which could be readily measured on small samples. Recent results have shown that the critical current density of Nb thin films can be used as a proper indicator of film quality. This is backed by in-depth material analyses highlighting the impact of dislocations onto the film's capacity to trap magnetic vortices. The latter being partly responsible of the quality factor degradation, it is of great importance to control defect density via tuning of the coating parameters. It has been shown that the energy of impinging Nb ions during the coating process is of prime importance and an optimum value has been identified and leads, in combination with a proper surface treatment, to high performance Nb films in 1.3 GHz resonators achieving bulk-like behaviour up to accelerating fields of the order of 10 MV/m. In view of relaxing the requirements on the surface treatment process it has also been demonstrated that the coating can be performed in two steps. The first step uses high ion bombardment energy, which results in a planarization of the layer whose surface roughness becomes independent of the substrate. Monte-Carlo simulations proved to be an efficient tool to predict such planarization effect. Soon the impact of such two-step process will be evaluated on actual RF resonators.

4.1.4 Cavity testing results

1.3 GHz single cell cavities are tested at CERN in a vertical cryostat, using standard RF equipment. The cavity is driven on resonance by means of a Phase Lock Loop (PLL). A variable coupler is used to minimize measurement uncertainty by maintaining critical coupling conditions throughout the measurement. The standard measurement program includes scans of Q vs E, at 4.2 K and at 1.8 K, as well as Q vs temperature at fixed field, to extrapolate the residual surface resistance, and of resonance frequency vs temperature to extract the penetration depth. In Fig. 2, we show the Q vs E curves at 4.2 K of 15 cavities tested between January 2021 and April 2022 and the 400 MHz target values scaled to 1.3 GHz. W stands for welded, BM for machined from bulk and L for electrodeposited. In general, the surface resistance at low field matches the theoretical minimum as function of mean free path, which is foreseen by the Matthis–Bardeen expressions, and the Qslope is small. The field limitation below 10 MV/m comes from administrative limits with near to zero threshold for the radiation interlock in the CERN cryolab.

For the FCC program as presently defined, CERN envisages to use Nb coated cavities at 4.2 K, therefore the achieved results are already satisfactory, if transposed at the lower frequencies of interest. However, our efforts aim to understand and study the contributions to the residual resistance, which dominates at lower temperatures. Bringing these under control would enable application of the Nb/Cu technology to all FCC machines, besides offering a valid alternative for high-energy colliders at large.

Figure 3 shows the Q vs E curves at 1.85 K. At these low temperatures, the BCS component is suppressed, and the non-linear behaviour of the residual surface resistance is highlighted. A larger scatter in the results is apparent from the comparison of Figs. 2 and 3: at low temperature, in some cases, the Q slope is low and even comparable with bulk Nb, while in other cases it remains larger. Table 3 summarizes the superconducting parameters of the HiPIMS Nb/Cu cavities measured so far. Again, we note the high reproducibility of fundamental quantities such as the critical temperature and the penetration depth, indicating good control of the Nb film growth, while the residual resistance shows more spread results. Since sensitivity to temperature gradients upon crossing T_c is systematically observed, all reported scans were taken after thermal cycles above T_c, which optimise the homogeneity of the superconducting transition.

On some of the tested cavities, the measurement was carried out severel times interleaved with thermal cycles up to room temperature. The results were fully reproducible, showing that the coating withstands well the stresses induced by the different coefficient of thermal expansions between copper and niobium.

4.1.5 Thermal mapping

Even when the superconducting properties of the coating have been optimised, local imperfections may still limit the cavity performance. Defects such as bad adhesion or local contamination of the Nb film show up as hot spots when the cavity is powered. Thermal mapping is a powerful tool to locate such defects and gain insight on how to prevent their occurrence. While this is a standard tool for studies on bulk Nb cavities, special care must be taken in the case of copper cavities, due to the much larger thermal diffusivity, resulting in smaller signals for the same amount of dissipated power.

A new thermal mapping system for 1.3 GHz cavities was developed at CERN. It comprises 192 Allen Bradley thermometers in contact with the cavity surface and mounted

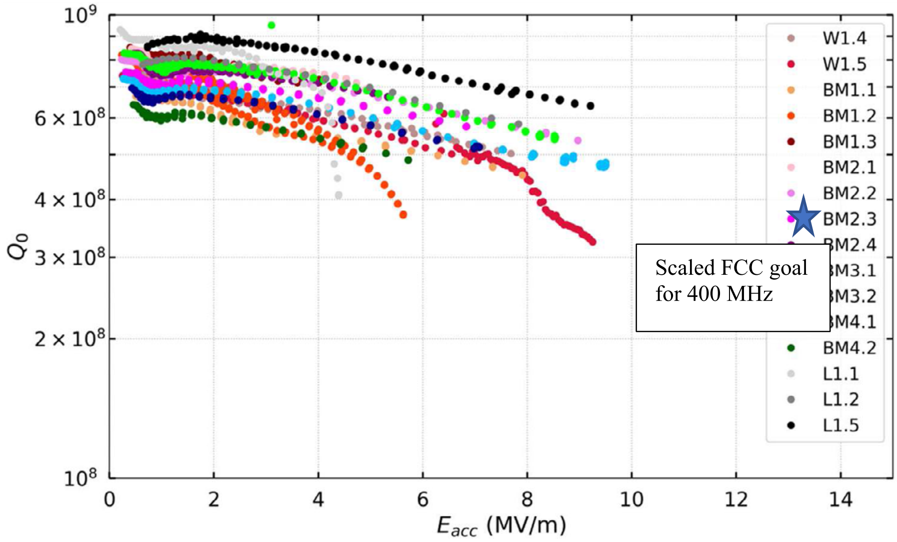


Figure 2 1.3 GHZ HiPIMS Nb/Cu cavities performance at 4.2 K

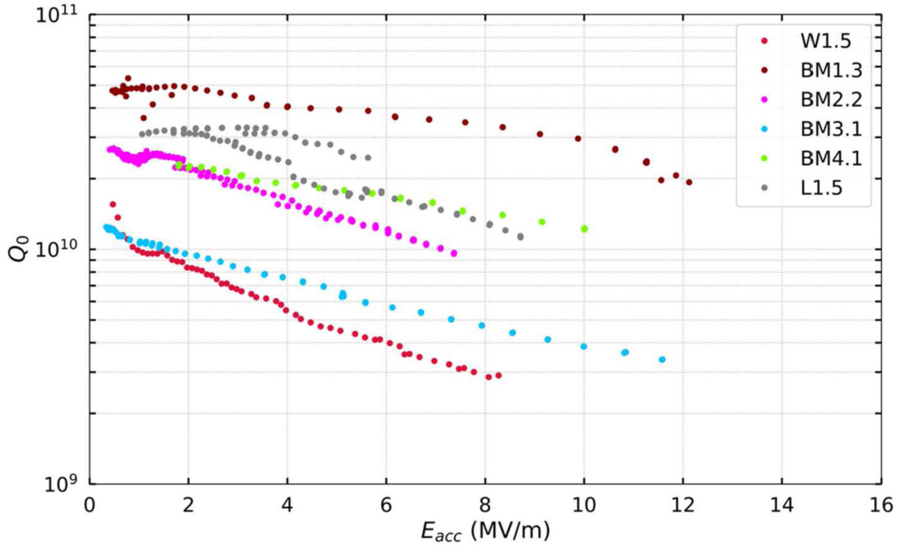


Figure 3 1.3 GHZ HiPIMS Nb/Cu cavities performance at 1.85 K

on 12 boards, signal processing is through 12 ADC channels and 6 multiplexers. Figure 4 shows a prototype board, together with the simulated and first measured temperature profiles. First results with the thermal mapping system indicate that dissipation is localised at pseudo random locations along the cell, which is an important clue for further optimisation of the coatings. More details on the thermal mapping systems are in [8].

5 Progress with Nb_3Sn on Cu

Nb_3Sn on Cu was studied at CERN since the start of the FCC study. The approach followed begins by optimizing the A15 phase formation and some key DC superconducting parameters on small samples. Good quality Nb_3Sn layers, with T_c up to 16 K, have been

Table 3 Superconducting parameters of 1.3 GHZ HiPIMS Nb/Cu cavities

	BM1.1	BM1.2	BM1.3	BM2.1	BM2.2	BM2.3	BM3.1	BM3.2	BM4.1	BM4.2	W1.4	W1.5	N4.1	L1.1	L1.2	L1.5
R_{res} [nΩ]		19.99	4.48	14.4	7.34	15.09	26.4	22.45	7.82		19.53	16.4	10.4	33.27	23.9	8.7
Δ/k_B [K]		20.11	20.33	19.96	20.1	20.3	19.8	19.8	20.6		20.38	21.23	19.1	19.75	19.8	20.27
A_{BCS} [nΩ·K·10^5]		1.56	1.46	1.34	1.55	1.69	1.52	1.59	1.71		1.75	1.98	1.11	1.40	1.68	1.74
T_c [K]	9.31	9.31	9.31	9.36	9.36	9.4	9.38	9.41	9.37	9.41	9.38	9.3579	9.35	9.3602	9.34	9.35
λ_L [nm]	55.58	51.73	51.08	49.31	48.04	47.75	48.98	46.99	55.44	50.86	49.56	49.33	48.57	51.54	56.8	48.01

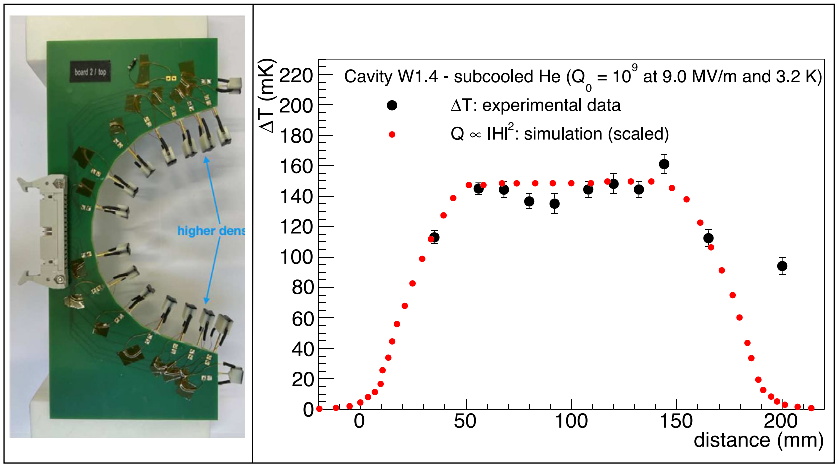


Figure 4 Prototype thermal mapping with a first validation test

deposited on copper substrates by DC magnetron sputtering from a stoichiometric target. Copper diffusion into the growing film was tackled by suitable diffusion barriers, film cracking was mitigated by using Kr as sputtering gas. In this phase, in situ annealing was recognized to be crucial in achieving the expected T_c [9]. After the coating recipe was optimized on small samples, the RF surface impedance was assessed by means of Quadrupole Resonator measurements. The results indicated a high residual resistance, which significantly increased with the applied RF field strength. Following these first indications, the deposition method was changed to bipolar HIPIMS, with a Ta interlayer. This choice was based on the recent results obtained on 1.3 GHz Nb/Cu resonators. This technique has shown to provide thin films with a Nb:Sn stoichiometry that lies perfectly in the desired range of the A15 crystalline phase. The effect of coating parameters such as pressure, temperature and bipolar HiPIMS bias voltage onto the critical temperature have been studied in depth and thin films with T_c of about 15.5 K have been obtained. The film surface contamination with copper has been highlighted as a critical point and solutions such as thermal treatment have been proposed. In the following year, the Nb_3Sn/Cu surface resistance will be evaluated and a special effort will be put on pushing the films' Tc to the bulk value of 18.3 K.

6 Atomic layer deposition for SRF cavities

Atomic Layer Deposition (ALD) is a highly conformal thin film synthesis technique that enables an unprecedented level of film thickness and composition uniformity on arbitrary complex shapes. As such ALD is an ideal platform to bridge the gap between coupons R&D scale to full size accelerator components. At CEA an intense effort is dedicated to develop and apply ALD to SRF cavities. Few research trusts are being pursued; the deposition of multilayers superconductor/insulator structure on the inside of SRF cavities is predicted to enhance considerably their performances, potentially doubly the accelerating gradient. In this respect, high quality NbTiN/AlN structures have been successfully synthesized with Tc up to 16 K on Niobium samples with an enhanced vortex penetration field. The process is now being applied and tested on SRF cavities. Another research direction is the multipacting mitigation by functionalizing with ALD thin films, surfaces subject to intense RF fields. Work on TiN alloys, by CEA in collaboration with ONERA, shows a strong reduction of the secondary electron yield value and a "bulk" limit is obtained for film thicknesses ≥ 1 nm. This method has been successfully tested on SRF cavity. Finally, CEA teams are studying the growth of insulating thin films on Cu surfaces with CERN to optimize Nb thin films cavity performances.

7 The SWELL cavity program

The idea of the SWELL cavity concept [10] emerged with the wish to simplify the overall RF system of FCC-ee. Thanks to its ability to efficiently damp HOMs at high beam current and to operate at high accelerating gradient at the same time, the SWELL cavity can run effectively at the Z, W and H working points. It is also not necessary to remove cryomodules from the RF section after operation at the Z pole. Moreover, the SWELL cavity has the potential to further push the Nb/Cu technology performance at its limits. The cavity is made of four quadrants which are precisely machined and clamped together. The open RF structure greatly facilitates the surface preparation by electro-polishing and the niobium deposition by HIPIMS. The absence of welds on high electromagnetic field regions makes the SWELL cavity seamless by nature. The mechanical structure is very stiff, making it robust against frequency detuning due to microphonics and Lorentz forces. The use of copper blocks allows to integrate cryogenic cooling by drilled channels, hence reducing the required volume of liquid helium for operation. Figure 5 shows a 3D view of the 2-cell SWELL mechanical concept.

The RF design of the 2-cell resonator starts in 2D. We use the same approach as for the single cell and 2-cell 400 MHz cavities by minimizing the surface RF fields and cancelling all longitudinal HOMs. The waveguide slots are integrated into the 3D volume. The geometrical transitions from the cavity wall at the equator to the slots are carefully shaped to minimize the peak magnetic field enhancement. Slotted waveguides are extremely efficient to propagate all the transverse modes from the first dipole pass-band. The modes are extracted through two coaxial waveguides per slot. The position of the coaxial HOM extractors is optimized to minimize the external Q factors of each transverse mode. The dipole mode with the highest transverse impedance has a Q_{ext} of about 150.

7.1 Mechanical design and challenges

Based on previous experience in fabrication of accelerating systems such as the RFQs, CERN established an analogous manufacturing process for SWELL. A bulk copper cavity is mechanically assembled from 4 quadrants which are machined separately. The quadrants are machined on a high precision CNC milling centre; the RF surface is carefully

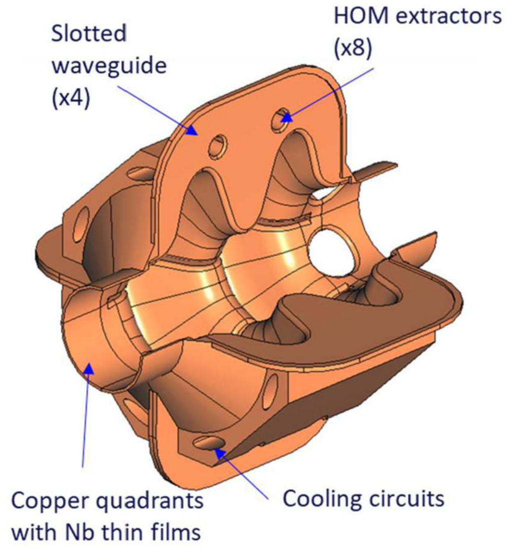


Figure 5 SWELL cavity concept

finished, while material allowance is kept on the assembly surfaces (both the ones of contact among quadrants, and the external ones used for positioning the quadrants with respect to each other).CMM metrology is performed on each quadrant, best-fitting the RF surface. Analyses are then performed to obtain the correct strategy for material removal on the contact surfaces. The quadrants are then assembled and measured. The process is implemented iteratively, until the assembled quadrants respect the overall cavity positional requirements. The external positioning surfaces are then finished, together with some reference features; this allows to maintain precision even in case of later disassembly/reassembly activities.

Thanks to this technique, the high precision assembly requirements are met, ensuring that the RF surfaces of each quadrant are positioned within $\pm 10\ \mu$m with respect to each other. To achieve the best cavity surface, optimal machining parameters and machining path strategies have been implemented, stemming from CERN workshop experience and ongoing R&D.

A remaining problem is achieving adequate sealing of the structure for beam vacuum along the cavity string. Finally, as mentioned, a suitable conduction-cooling scheme is being developed to manage the heat generated by RF losses. For the time being, this is still based on liquid helium, since the cooling power needed is not easily attainable with commercially available cryo coolers.

7.2 SWELL 1.3 GHz mock up

In order to test the SWELL idea, CERN built a reduced scale model resonating at 1.3 GHz. The main purpose of this mock-up cavity is to demonstrate the RF properties (preservation of Q_0 for the fundamental mode, and HOM extraction). A dedicated test cryostat insert was designed and built for this purpose. Figure 6 illustrates some of the initial steps of this endeavour.

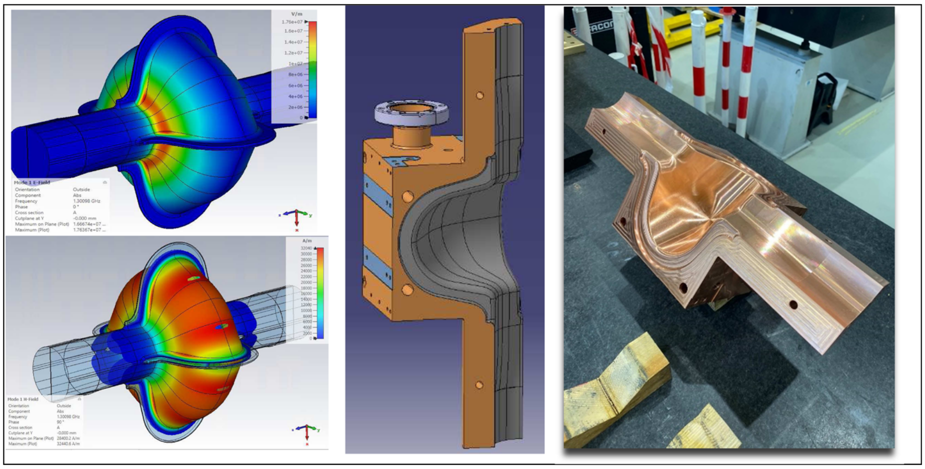


Figure 6 1.3 GHz SWELL mock-up cavity RF field patterns, mechanical design and finished quadrant

8 Conclusions and future work

The revised baseline for the RF system of the FCC-ee machines calls for extensive R&D efforts aimed at improving the performance of thin film SRF cavities. Several technical obstacles were tackled and solved using 1.3 GHz elliptical mono-cells as test cavities. Within the 1.3 GHz program, the SRF performance of Nb/Cu at 4.2 K is being optimized. The next challenge is to scale up the coating recipe to the large surface of the 400 MHz cavity, while work is continuing to understand and control the main contributors to the residual resistance.

R&D work on cavity manufacturing aims at a viable technology to circumvent the typically problematic equatorial weld in prospect of series production of copper substrates.

In a longer perspective, alternative materials, like Nb_3Sn, and novel concepts, like the SWELL, offer great advantages, justifying the research efforts invested on these promising lines of development.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author contributions
WVD: design of the paper, drafting and revising. MG: design, analysis, text contribution, revising. FP: analysis, text contribution. GR: analysis, text contribution. IK: analysis. LZ: analysis. AMV: substantial revision. SAU: analysis. AB: design,

cavity measurements, analysis. GB: design, analysis. LMAF: design, analysis. CPF: cavity and sample coating, analysis. LVC: simulations, cavity measurements, analysis. SL: cavity and sample coating, analysis. TP: analysis, text contribution. SGZ: simulations, analysis. MT: design. MT: design. TK: measurements, analysis. SA: substantial revision. OB: substantial revision. FG: substantial revision. All authors read and approved the final manuscript.

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