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SWELL AND OTHER SRF SPLIT CAVITY DEVELOPMENT

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Abstract

An innovative superconducting cavity topology has been recently proposed at CERN. It integrates longitudinal waveguide slots crossing perpendicularly the RF surface to damp transverse higher order modes. The RF current lines of the fundamental mode run along the slots, inducing no perturbation of the accelerating mode. Thanks to this approach, the cavity can be built by sectors, which is well appropriate to precise manufacturing techniques. This configuration allows direct access to the RF surface, thus facilitating the surface preparation and thin film deposition process in the case of cavities based on Nb/Cu technology. This paper covers the latest development of a 600 MHz slotted elliptical cavity called SWELL, which has been proposed as an alternative option for the FCC-ee RF system as well as the prototyping of a simplified SWELL version of a single cell 1.3 GHz elliptical cavity. The development of a new type of 6 GHz split resonator is also on-going at Lancaster University. This cavity is made of two halves and is dedicated to superconducting thin film characterization. An overview of this new development will be given.

INTRODUCTION

Elliptical radio frequency (RF) cavities operating on the TM_{010} accelerating mode have RF current lines running longitudinally along the cavity surface. It is possible to divide the cavity geometry into sectors with an arbitrary angle without perturbing the field pattern of the accelerating mode. Each cavity sector becomes an open structure, which opens new opportunities to fabricate highly performant superconducting RF (SRF) cavities. In such an approach, longitudinal slots can even be added provided that the slot width is small compared to the cavity outer diameter. The slots can act as high frequency waveguides to extract and propagate transverse Higher Order Modes (HOM) outside the resonator in order to efficiently damp them.

In the CLIC Test Facility CTF3 at CERN, the 3.5 A drive beam electron accelerator was equipped with 3 GHz Slotted Irises Constant Aperture (SICA) copper structures which adopted this strategy [1]. The CLIC 12 GHz Power Extraction and Transfert Structure (PETS) was designed to decelerate a more intense electron beam of 100 A and was built of 8 copper sectors (octants) to allow extremely strong HOM damping [2].

The slotted cavity concept was also explored in the superconducting domain for high current Energy Recovery Linac (ERL) applications [3]. A 3-cell 1.3 GHz cavity was built in bulk niobium and was preliminary tested in a vertical cryostat [4].

In this paper, we present a novel scheme of a slotted SRF cavity where the sectors are made of copper and are precisely machined, as experienced in the CLIC RF structures, and are coated with a niobium (Nb) thin film to provide an inner superconducting surface. We describe the RF design and development plan of a new Slotted Waveguide ELLiptical (SWELL) cavity proposed as an alternative solution for the FCC-ee RF system [5]. We finally give an overview of the development of 6 GHz split cavities dedicated to the exploration and RF characterization of new superconducting thin films.

SWELL SUPERCONDUCTING CAVITY DEVELOPMENT FOR FCC

The original idea of the SWELL cavity concept applied to the FCC-ee machine came up in December 2020 [6]. The wish was to improve the cavity performances, to optimize the installation scenario of the RF system and to reduce its overall cost. Since the SWELL cavity is made to operate at high beam current and high accelerating gradient at the same time, it is a good candidate to have a single cavity type for the Z, W and H working energies of FCC-ee which are listed in Table 1.

Table 1: FCC-ee Operating Modes.

Mode	RF Voltage (GV)	Beam Current (mA)
Z	0.120	1280
W	1	135
H	2.08	26.7
ttbar	11.3	5

600 MHz SWELL RF Design

The operating RF frequency of 600 MHz has been chosen as an intermediate frequency between the two FCC-ee baseline frequencies (400 MHz and 800 MHz). It is a good compromise between different factors. For example, low cavity impedance is crucial especially for the Z operating point, which runs at a beam current of 1.28 A with long trains of bunches. It prevents risks of beam instabilities and of high power RF losses due to HOMs. This is favored at low RF frequencies as the longitudinal and transverse loss factors scale with the RF frequency to the power of two and three, respectively. On the other hand, the size of the cavity and its superconducting RF surface is smaller at high RF frequency, thus reducing the risk of having surface defects, which may induce parasitic losses or may trigger quenches.

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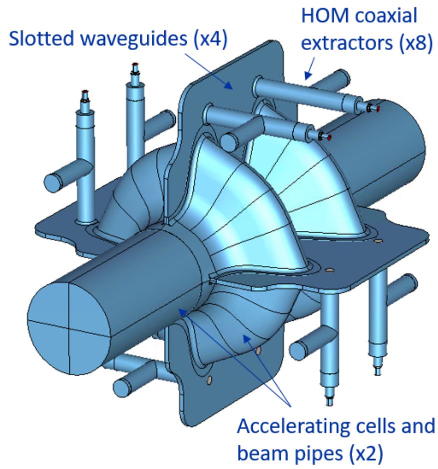

Figure 1: SWELL 2-cell 600 MHz cavity RF volume.

The SWELL cavity is a 2-cell elliptical cavity equipped with four slotted waveguides, as shown in Fig. 1. Each slot is coupled to two coaxial RF lines to extract transverse higher order modes. For the SWELL fabrication technology, the strategy is to build four independent quadrants precisely milled and clamped together, without any brazing or welding operation. The stiffness of the RF structure is very high, making it robust against RF detunings due to Lorentz forces and microphonics. Each quadrant is an open structure, thus very favourable for Nb coating and visual inspection. It is also seamless by its nature, meaning that there is no assembly joints in high electromagnetic field regions. The cryogenic cooling can be performed by forced convection using horizontally drilled channels in the four quadrants, limiting drastically the amount of liquid helium involved. A vacuum vessel surrounding the full structure is envisaged to separate the beam vacuum from the cryomodule insulation vacuum.

Since the last RF design presented in [7], the cavity shape has been re-optimized to take into account the risks of multipacting in the slotted waveguides. The slots width has been increased from 10 to 20 mm, pushing the first dangerous multipacting barrier in the slots above E_{acc} = 20 MV/m. The new geometric parameters of the cavity to slot connection profile leads now to maximum surface electric and magnetic field ratios of $(E_{\mathrm{pk}}/E_{\mathrm{acc}}) = 2.37$ and $(B_{\mathrm{pk}}/E_{\mathrm{acc}}) =$ 6.74 mT/(MV/m).

Each HOM coaxial extrator is equipped with a half-wavelength notch filter tuned at the frequency of 600 MHz. This is highly important to avoid RF leakage of the Fundamental Mode (FM) in the HOM feedthroughs. This occurs mainly when the symmetry of the cavity is broken by the fundamental power coupler (FPC) and tuning plungers or in case of misalignment of the quadrants.

A variable antenna is envisaged for the FPC to be able to minimize the required RF power at each operating energy of FCC-ee. The shape of the FPC port and antenna tip are designed to achieve both the optimal coupling factor and RF detuning compensation due to beam loading at the same time. With a FPC port diameter of 80 mm, the maximum displacement of the antenna tip is 45 mm between the Z and H operating points. In addition, to allow RF tuning of the cavity during operation, two RF plungers are incorporated into the beam tube on the opposite side of the FPC. A tuning range of 170 kHz has been achieved with a plunger geometry similar to the FPC extremity. As shown in Fig. 2, the integration of the FPC and the two plungers breaks the symmetry of the FM field pattern. Taking into account this asymmetry, and with a longitudinal misalignment of 50 µm, the external quality factor of the FM seen by the eight coaxial HOM ports stays very high and is $Q_{\mathrm{ext}} = 10^{14}$, thanks to the good rejection properties of the notch filters. A fourth 80 mm diameter port is added on the beam pipe on the FPC side at 45° as a spare port (for RF field measurement for example).

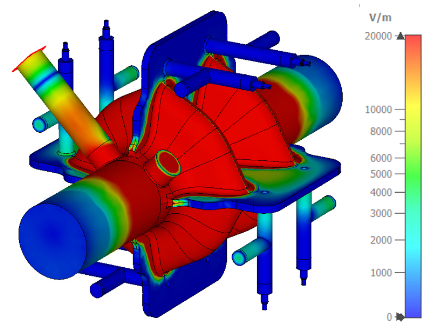

Figure 2: Electrical field at the H working point of the FM on the SWELL cavity surface equipped with one FPC and two RF plungers (not visible on the picture). The field scale is cut to 20 kV/m for easier understanding of the field distortion in the slots.

The longitudinal and transverse impedances are presented in Fig. 3 and compared to the beam stability threshold for the operation at the Z energy, which is the most demanding operating mode.

The longitudinal coupled bunch instabilities due to the FM will be mitigated by direct RF feedback, as performed in the LHC. The waveguide slot shape and the coaxial HOM couplers have been re-optimized to maximise the RF damping of the first dipole passband. Only three transverse modes remain above the stability threshold and have an impedance of 20 to 30 kΩ/m. The spike occurring at the FM frequency is due to coupler and plunger asymmetry and can be compensated by alternating their orientation along the accelerator. For the two other modes at 740 and 830 MHz a bunch-by-bunch feedback system with a damping time of about 100 turns of revolution of the beam can be implemented to suppress the risks of beam instabilities [8].

The different configurations of the FCC-ee RF system at the Z, W and H energies considering the 600 MHz SWELL cavities are detailed in Table 2.

For the H machine, the cryomodules are re-aligned to allow the passage of the two beams in the same cavities. The beam current is then doubled and is 53.4 mA. In total, up to 344 cavities are needed to cover to three operating

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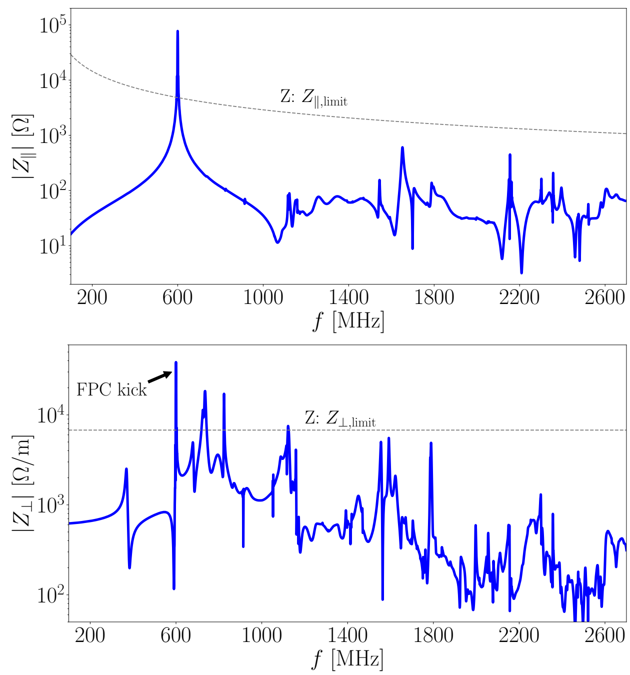

Figure 3: Longitudinal and transverse impedance of the 600 MHz SWELL cavity.

modes. The RF power per cavity is about 600 kW for the Z pole and goes down to 300 kW for the W and H machine. The maximum surface fields are reached for the H scenario. At E_{acc} = 12.1 MV/m, the peak surface fields are E_{pk} = 28.7 MV/m and B_{pk} = 81.5 mT. The operating temperature of the SWELL cryomodules is set to 4.5 K as a challenging target. For the ttbar energy and the booster ring, it is envisaged to complete the RF system with 600 MHz 5-cell elliptical cavities running at 2 K, which can be manufactured using Nb or Nb on Cu film technology. The target accelerating gradient is 25 MV/m at 2 K. With this new scheme at the unique frequency of 600 MHz, and considering four cavities per cryomodule, the total number of cryomodules needed for FCC-ee machine goes down from 322 to 254 compared to the RF baseline with standard 1-cell, 2-cell and 5-cell elliptical cavities at 400 and 800 MHz. It is a reduction of about 20 % on the quantity of cryomodules to be built, which saves significantly on the RF system investment cost.

Table 2: RF Configurations of FCC-ee with the 600 MHz SWELL Cavities (Machine Bending Radius of 9935 m).

Operating modes	Z	W	H
Beam energy (GeV)	45.6	80	120
Energy loss per turn (MeV)	38.5	364.6	1845.9
RF voltage (MV)	120	1000	2080
cos (Φ) factor	0.32	0.36	0.89
Beam current (mA)	1280	135	2 x 26.7
RF power per cavity (kW)	550	290	290
Number of cavities	90x2	172x2	344
Accelerating gradient (MV/m)	2.67	11.6	12.1
Accelerating voltage (MV)	1.33	5.8	6.05
Peak surface electric field (MV/m)	6.3	27.6	28.7
Peak surface magnetic field (mT)	18	78.4	81.5

1.3 GHz SWELL Cavity Demonstrator

A SWELL version of the "standard" 1.3 GHz single cell SRF cavity has been specially designed, derived from the well known TESLA single cell cavity shape. The target is to demonstrate the feasibility of the SWELL concept. The cavity geometry is simplified with closed slots. There is no HOM coupler included in the structure. The main purpose is to build a prototype and measure its performances at low temperature to evaluate the maximum accelerating gradient achievable with this technology.

Using the same shape optimization process as for the 2-cell SWELL cavity, the maximum surface field ratios obtained are (E_{pk}/E_{acc}) = 2.01 and (B_{pk}/E_{acc}) = 4.61 mT/(MV/m). The magnetic field map is shown in Fig. 4. The maximum magnetic field occurs at two places on the equator. Field enhancement also arises on the straight part of the cavity wall at the slot entrances but stays below the maximum values spotted on the equator.

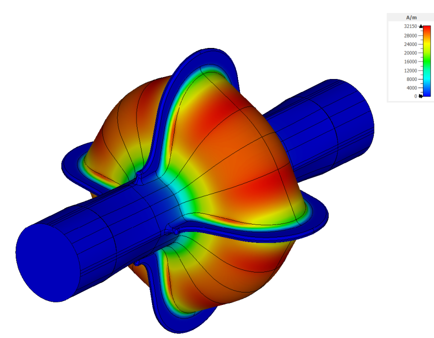

Figure 4: Magnetic field in the 1.3 GHz SWELL cavity for 1 Joule of stored energy.

The mechanical design of the SWELL 1.3 GHz cavity is shown in Fig. 5. It is made of four copper quadrants precisely machined, coated with niobium thin film and assembled together by clamping. Each quadrant is 400 mm long and approximately 25 kg mass. It is equipped with a single liquid helium cooling channel. Five axis machining is performed on the RF surface to achieve 40 µm shape accuracy. The four blocks are aligned thanks to fiducial surfaces on the outside of the cavity. A precision of 5 µm is expected for the final positioning of the four quadrants.

A first unit of the 1.3 GHz SWELL cavity has been successfully machined in the CERN mechanical workshop (see Fig. 6). The inner surface measured in metrology after final machining is within 20 µm compared to the theoretical surface shape.

To complete the fabrication, the following steps will be performed:

- Chemical electropolishing of the copper blocks by immersion with an optimized cathod shape. A total copper

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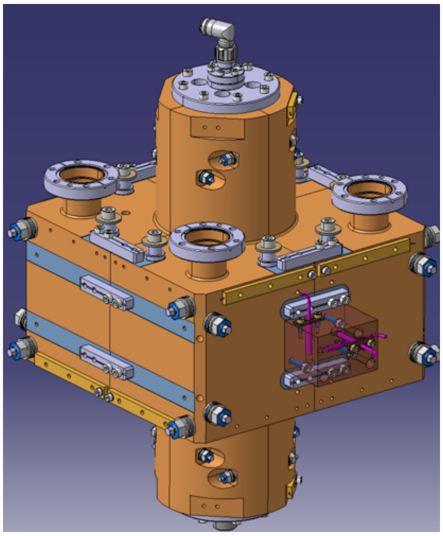

Figure 5: 3D view of the mechanical design of the 1.3 GHz SWELL cavity.

Figure 6: First 1.3 GHz SWELL cavity machined.

thickness of 50 µm can be removed on the inner RF surface. The quadrant contact surfaces will be masked by dedicated toolings.

- Niobium coating using Bi-polar High power impulse magnetron sputtering (HiPIMS) to obtain a dense and void-free film. It is planned to re-use an existing chamber at CERN. A first coating has been successfully performed on a flat Quadupole Resonator (QPR) sample in this chamber. A surface resistance of Rs = 5 nΩ was measured at the frequency of 400 MHz and the temperature of 2 K, which is one of the best results obtained on QPR measurements.
- Clean room assembly after ultra-pure water rinsing at low pressure of each quadrant. Their mechanical alignment and their assembly will be performed in an ISO 5 clean room at CERN.

The cold RF tests of the cavity in a vertical cryostat will be done at CERN in the SM18 laboratory. The 1.3 GHz SWELL cavity has the particularity to have a common vacuum system, meaning that the cavity vacuum is the same as the insulation vacuum. The V5 vertical test stand in SM18 is dedicated to the qualification of 100 MHz quarter wave resonators for the HIE-ISOLDE superconducting linac. It operates also in a common vacuum configuration and is fully operational. Thus, it was decided to modify an existing spare V5 insert and adapt it to the 1.3 GHz SWELL cavity. Experience and procedures from the HIE-ISOLDE project such as the insert installation in clean environment will be re-used for the SWELL program. The RF tests will be performed both at the temperature of 4.5 K and at around 2 K to fully characterize the superconducting properties of the cavity. The minimum achievable temperature of this cryostat in superfluid helium and sub-atmospheric pressure is 1.7 K with full pumping capacity applied on the helium bath reservoir.

The V5 cryostat is equipped with an active thermal shield, which allows the active control and regulation of the cooldown process. The common vacuum in the cryostat can reach a pressure of 10^{-9} mbar at low temperature. Magnetic flux compensation coils are available to cancel the earth magnetic field in the cavity. A full set of instrumentation is integrated to control the cavity temperature, the magnetic field near the cavity surface and the liquid helium level in each quadrant. A new cryogenic distribution system has been developed to allow an equal distribution of liquid helium in the four blocks. The 3D model of the 1.3 GHz SWELL cavity mounted on the V5 cryostat insert is shown in Fig. 7. The RF measurement at low temperature is performed thanks to two fixed antenna located on the beam pipes. First RF tests at low temperature are planned in the beginning of 2023.

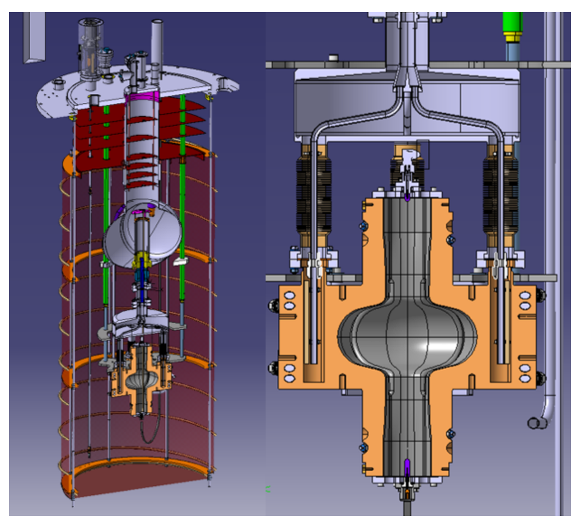

Figure 7: V5 vertical cryostat equipped with the 1.3 GHz SWELL cavity.

6 GHZ SPLIT CAVITY FOR THIN FILM QUALIFICATION

Lancaster University has been developing split cavities at 6 GHz for thin film coatings. Unlike the SWELL cavity,

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the 6 GHz cavity has two halves rather than four quadrants. The program is focused on coatings and RF measurements rather than cavity design. The advantage of a split topology is that it is suitable for Nb, Nb3Sn and multilayer coatings at the Daresbury Laboratory. It is easy to coat with either conventional planar magnetron or in tubular geometry used for RF cavities. There is no electromagnetic field on contact faces and it is a stiff RF structure, which allows to avoid cracking. Finally it is easy to inspect visually.

Three units of the 6 GHz split cavities have been fabricated and are being coated. The first cavity has been coated with Nb. It was a quick coating with non optimised parameters for deposition so that the surface measurement facility could be tested. A second cavity has been coated using an optimized process (magnetron sputtering) and is in the cryostat for RF measurements. Pictures of 6 GHz the split cavities after machining and after coating are shown in Fig. 8.

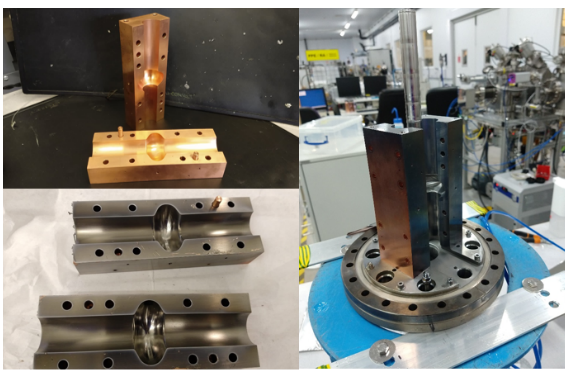

Figure 8: 6 GHz split cavities after machining and surface coating.

SUMMARY AND PERSPECTIVES

We have proposed a new SRF cavity concept called SWELL for the Ampere-class high energy FCC-ee accelerator. An update of the advanced and detailed RF design study of a 2-cell SWELL cavity with strong HOM damping features has been presented. The cavity RF design meets all the requirements to operate successfully at the Z, W and H working energies. It is important to mention that depending on the results of future beam dynamic studies, it will be possible to scale the cavity geometry to another RF frequency value, which can typically be in the range of 500 MHz to 650 MHz. A "TESLA like" SWELL cavity is being developed in parallel to experimentally demonstrate the feasibility of the concept. The cavity has been machined with great success and is ready for surface preparation and niobium coating. First RF tests at low temperature are planned in 2023. The RF design of the SWELL 2-cell cavity may evolve again on the basis of the 1.3 GHz cavity test results. After this last iteration, a detailed mechanical study could be launched including the design of a test horizontal cryostat integrating all RF couplers and RF tuning systems. Discussions have started with international partners to collaborate on the SWELL cavity development program. The IN2P3-LPSC laboratory in Grenoble (France) is interested in participating to advanced multipacting studies with experimental verifications. Jefferson Laboratory has expressed his enthusiasm to explore a deep-drawn version of the SWELL cavity. Finally, other accelerator projects like EIC in USA or CEPC in China, where high intensity beams need to be accelerated in an innovative and efficient way, could find an interest in looking into the SWELL cavity options.

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