# SWELL and other SRF split cavity development

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LINAC2022
LIVERPOOL

# Contents

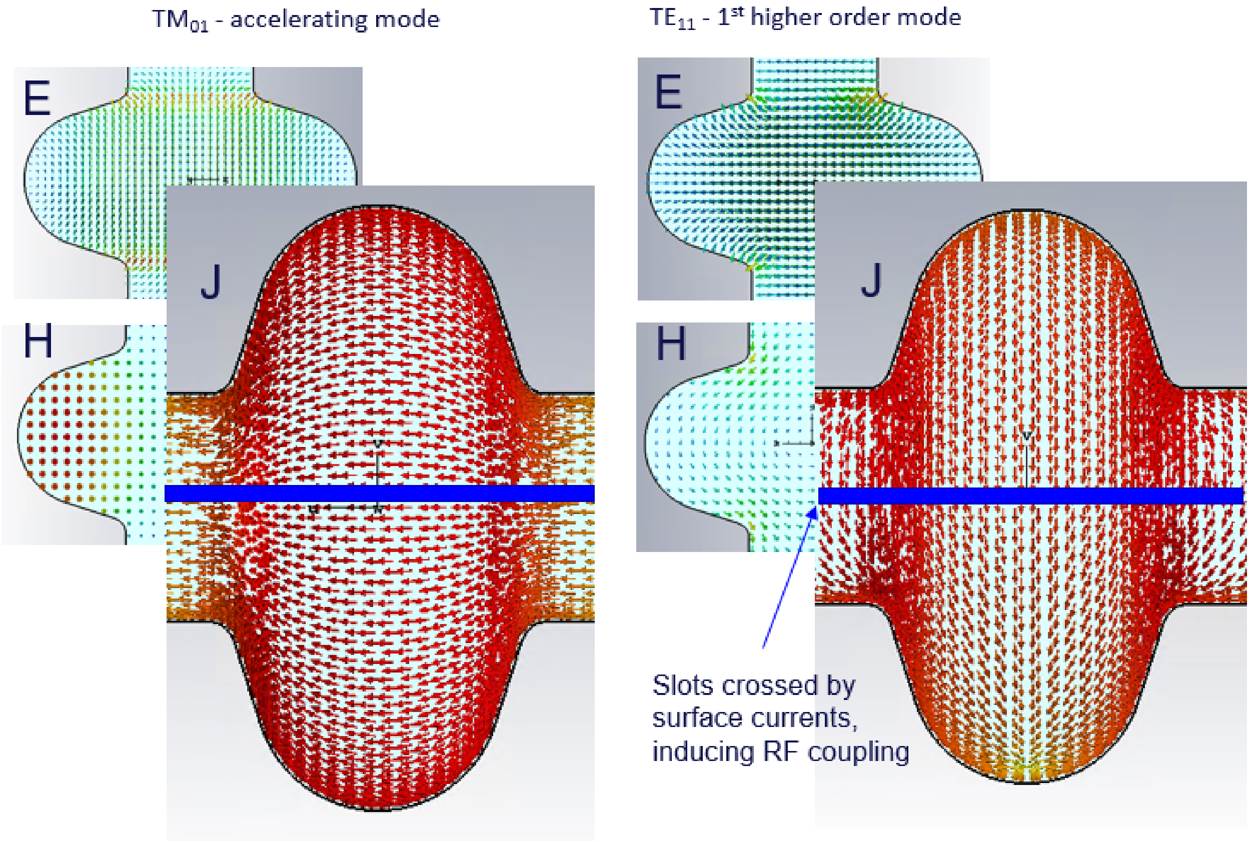
# Split cavity concept and advantages

**In elliptical cavities RF current lines are running longitudinally along the surface (parallel to the beam trajectory)**

**It is possible to divide the RF volume into sectors or to add longitudinal slots without perturbing the field pattern of the accelerating mode**

**→ "open" RF structure: surface preparation and control are easier**

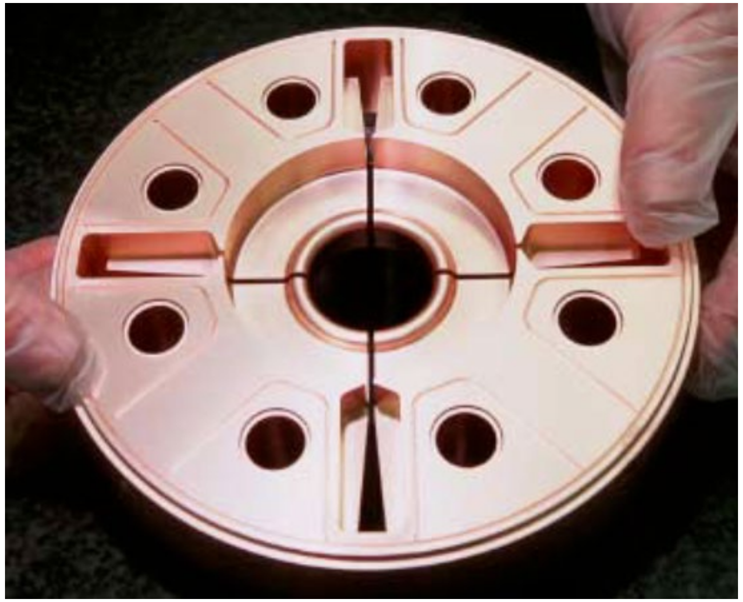
**→ can propagates and damp higher order modes**



# Past experience

## CLIC RF structures

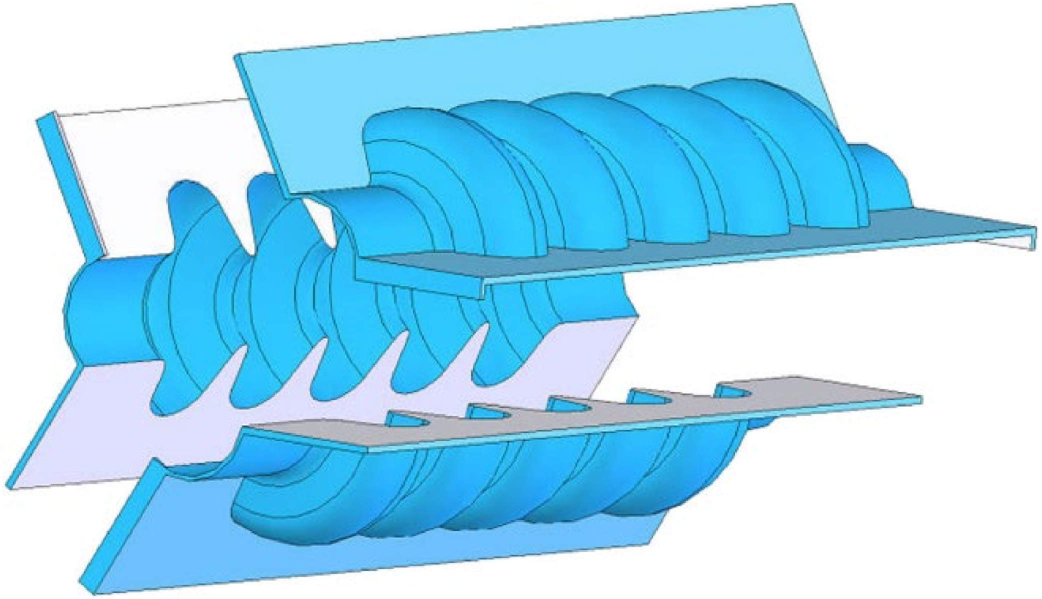
**Slotted Irises Constant Aperture (SICA) 3 GHz accelerating structure used in CTF3 for a beam current of 3.5 A**



*E. Jensen, 'CTF3 drive beam accelerating structures', Proceedings of LINAC2002, Gyeongju, Korea.*

## SRF bulk niobium split cavities

**Designed for high current Energy Recovery Linac (ERL) applications**



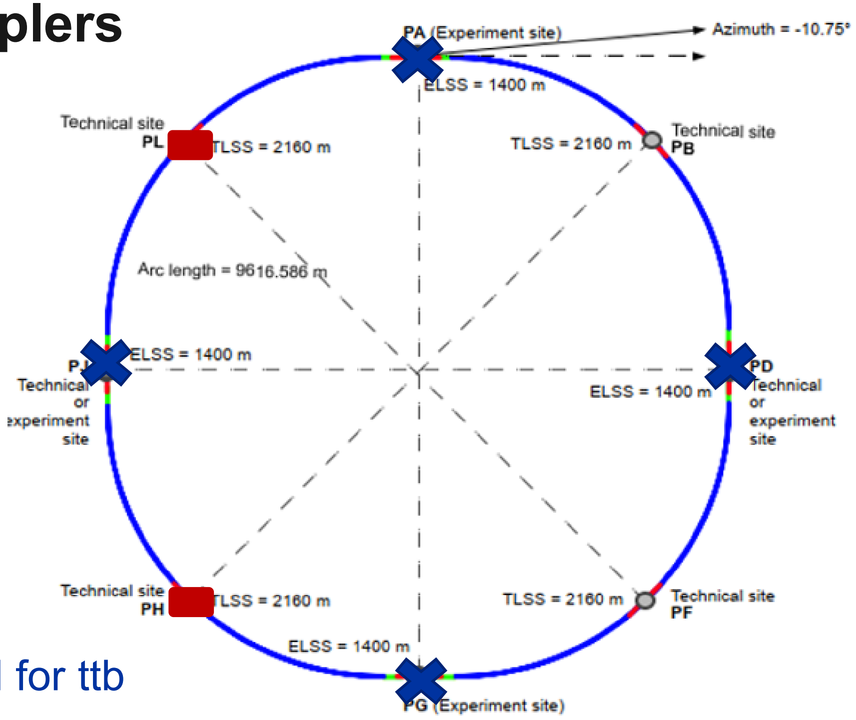
*Z. Liu et al., Novel superconducting rf structure for ampere-class beam current for multi-GeV energy recovery linacs, PRSTAB 13, 012001 (2010)*

# RF system for FCCee – baseline scenario

**Designed to provide 100 MW of RF power in CW to compensate losses by synchrotron radiation**

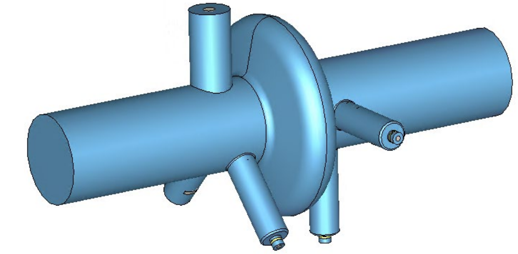
**Three SRF cavity types under study equipped mainly with standard coaxial hook-type HOM couplers**

| | Energy (GeV) | 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 |

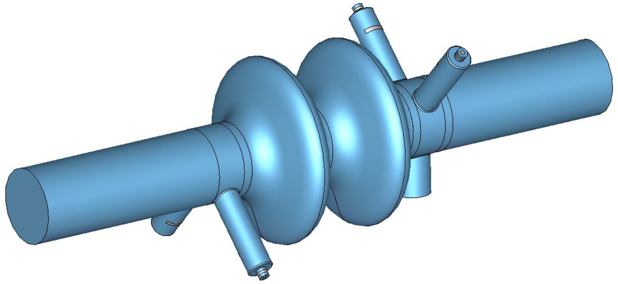



4 interaction points

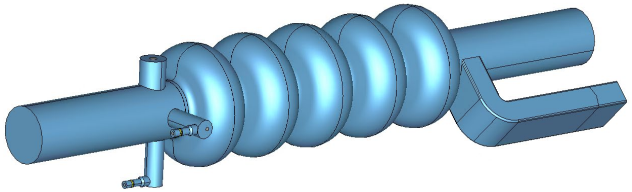
RF systems located in PL for Z, W, H and PH for ttb



400 MHz 1-cell Nb/Cu for Z



400 MHz 2-cell Nb/Cu for W&H

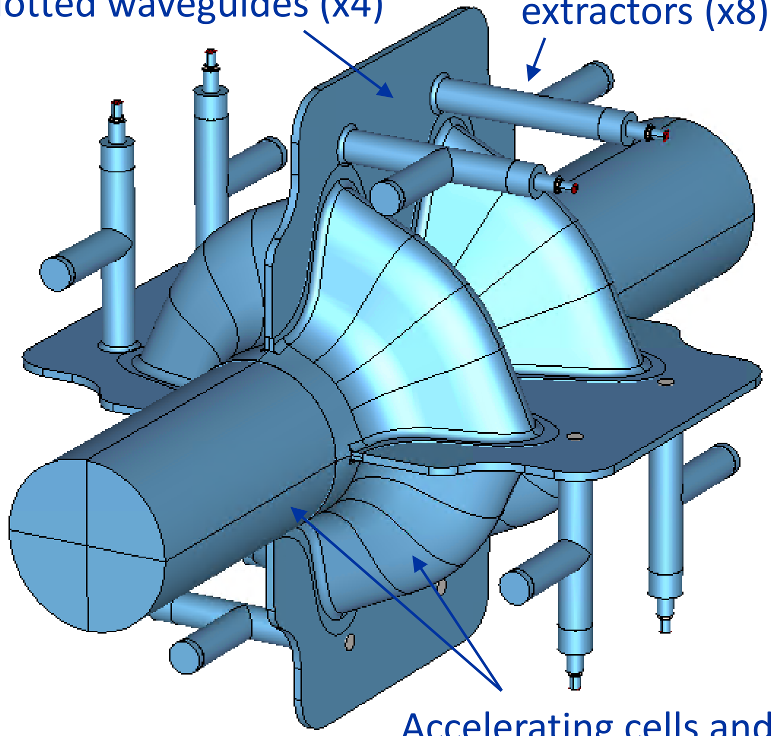


800 MHz 5-cell bulk Nb for ttb

# The SWELL superconducting cavity concept

## A good alternative candidate to have a single cavity type for (almost) all the FCCee beam energies

- Proposed in Dec. 2020 * to improve the cavity performances, to optimize the installation scenario of the RF system and to reduce its overall cost
- Can run at high gradient and high current at the same time
- Equipped with four slotted waveguides, coupled to two coaxial RF lines to extract transverse higher order modes
- Operates at 600 MHz as an intermediate frequency (compromise between cavity size and impedance)



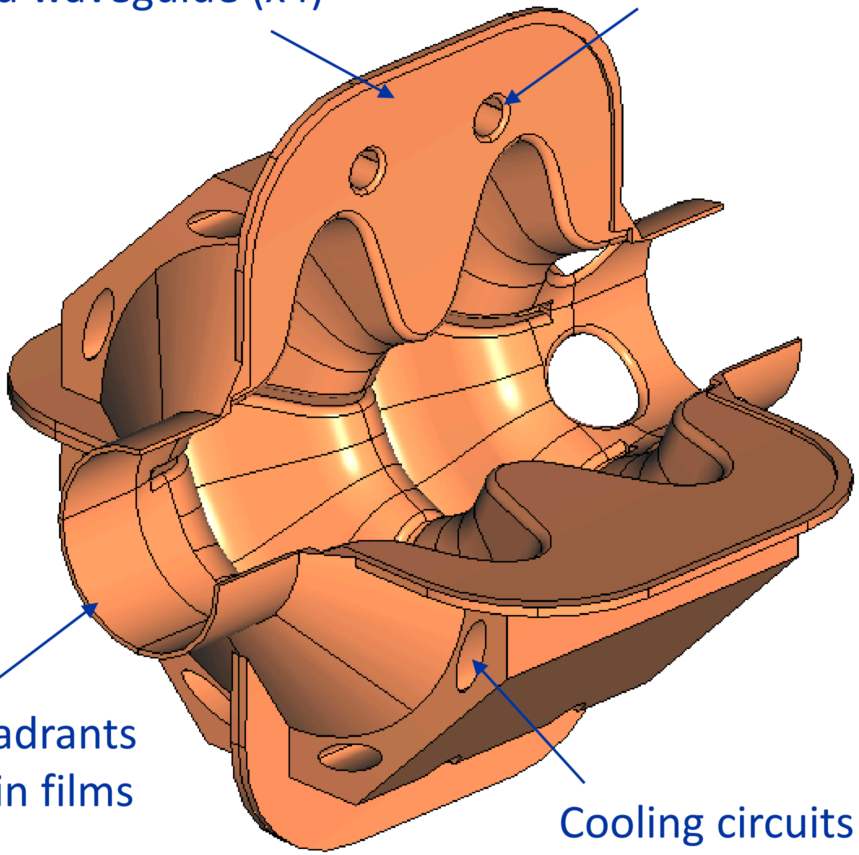

**SWELL: Slotted Waveguide ELLiptical cavity**

** I. Syratchev, F. Peauger, I. Karpov, O. Brunner, "A Super-conducting Slotted Waveguide Elliptical Cavity for FCC-ee", Zenodo. https://doi.org/10.5281/zenodo.5031953*

# The SWELL cavity manufacturing technology

## The beauty of the SWELL concept !

- Made of four independent quadrants in copper, precisely machined and clamped together
- Open structures, very favourable for surface preparation Niobium coating
- "seamless" by its nature: no assembly joints on high electromagnetic field regions
- Very stiff RF structure, robust against RF detunings due to Lorentz forces and microphonics
- Cryogenic cooling by drilled channels, which limits the volume of liquid helium
- Vacuum vessel surrounding the full structure to separate the beam vacuum from the cryomodule insulation vacuum



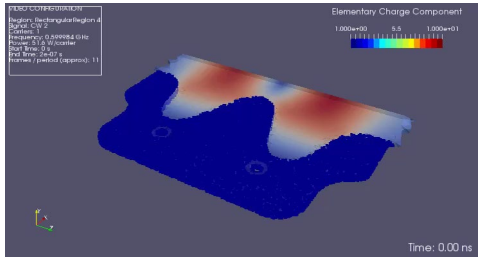
# RF surface fields minimization

**RF shape optimization strategy presented at IPAC22 in June:**

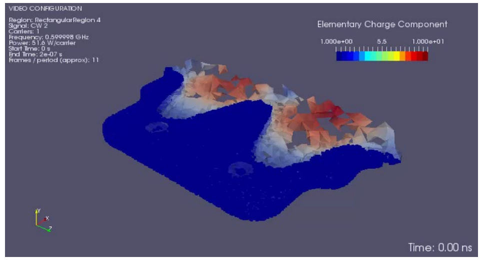
*S. Gorgi Zadeh et al., "Optimization of a 600 MHz two-cell slotted waveguide elliptical cavity for FCC-ee", Proceedings of the 2022 IPAC Conference, Bangkok, Thailand.*

**Slot gap has been increased from 10 to 20 mm to push multipacting barriers above Eacc = 20 MV/m**

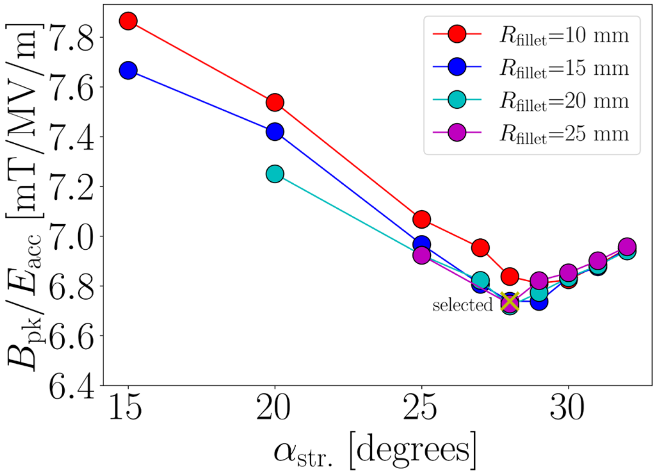
**Re-optimized shape is for $\alpha_{str}$=28° and $R_{fillet}$ = 15 mm**

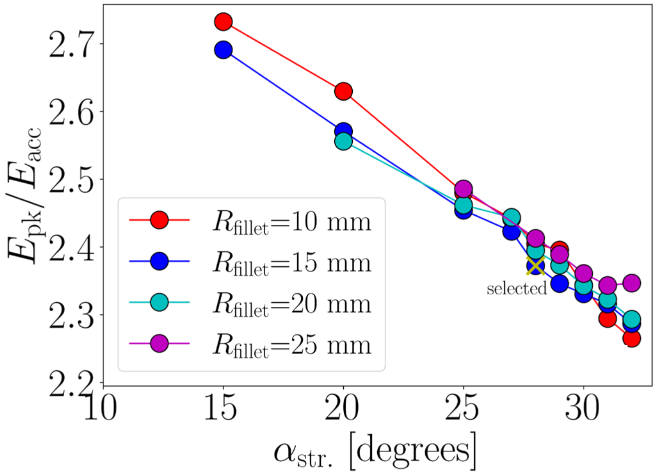


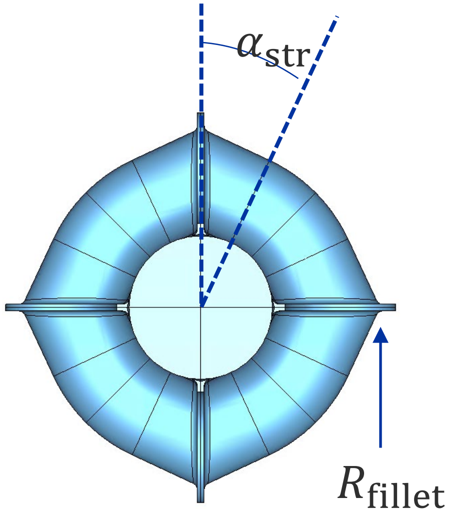

Slot gap = 10 mm, $E_{acc}$=16 MV/m




Slot gap = 20 mm, $E_{acc}$=16 MV/m



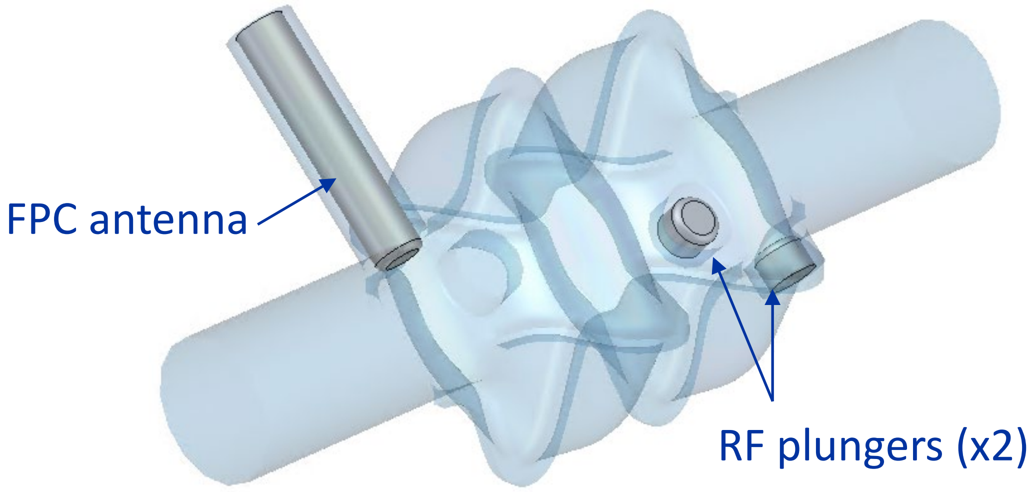

S. Gorgi Zadeh

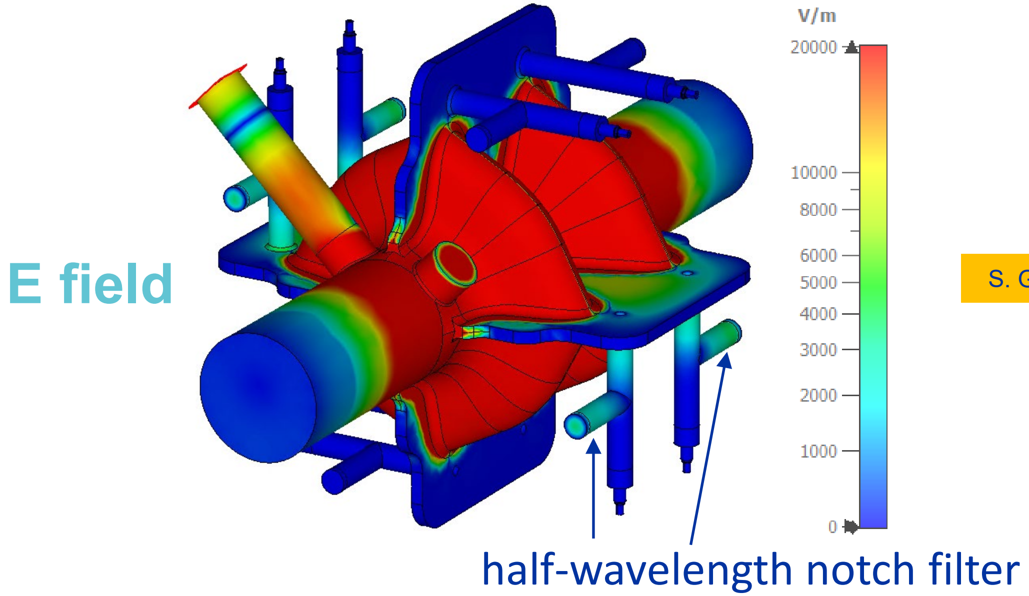
# RF coupling and tuning of fundamental mode

**One FPC with variable antenna to minimize the required RF power at each operating energy of FCC-ee – $Q_L$ ~2.10$^4$ to 2.10$^6$ with 45 mm antenna tip displacement**

**Two RF plungers to allow RF tuning during operation (compensation detuning due to beam loading) – tuning range of 170 kHz**

**Field asymmetry and leakage in slots due to FPC and plungers taken into account in the design process**




S. Gorgi Zadeh

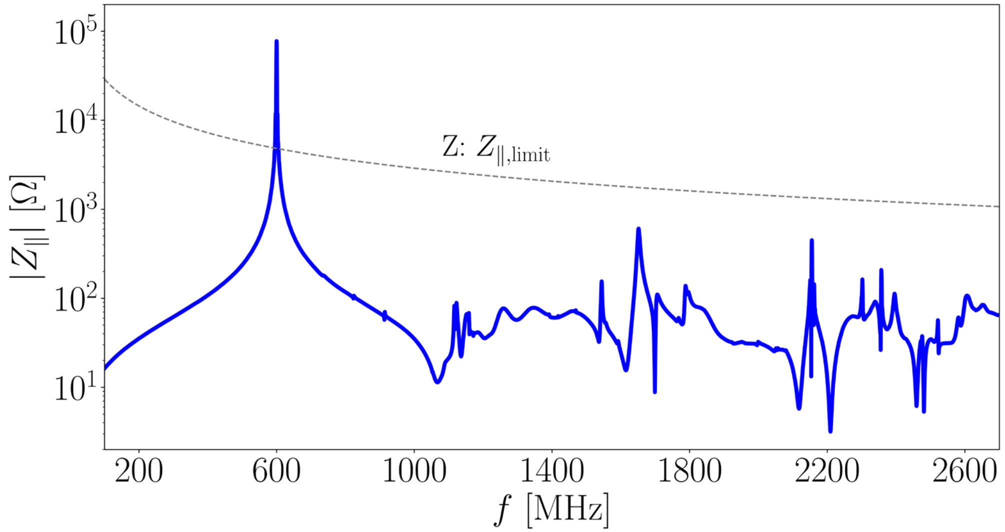
# Impedance and HOM damping

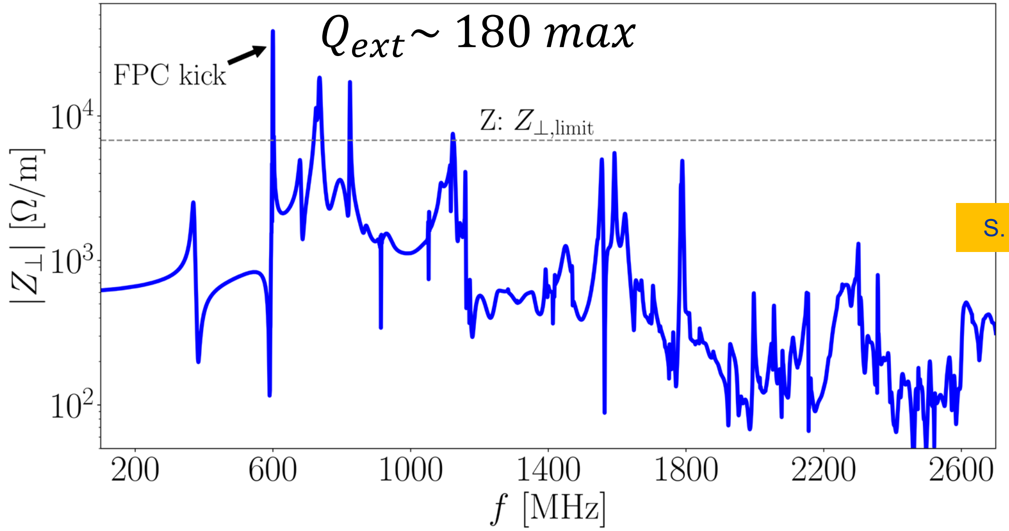
**Longitudinal coupled bunch instabilities due to the FM will be mitigated by direct RF feedback, as performed in the LHC**

**Three transverse modes remain above the stability threshold:**

- Spike 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 748 and 830 MHz a bunch-by-bunch feedback system with a damping time of about 100 turns

*I. Karpov, "Beam-cavity interaction studies for the FCC-ee – RF frequency considerations", presented at the FCC Week 2022, Paris, France, May 2022*



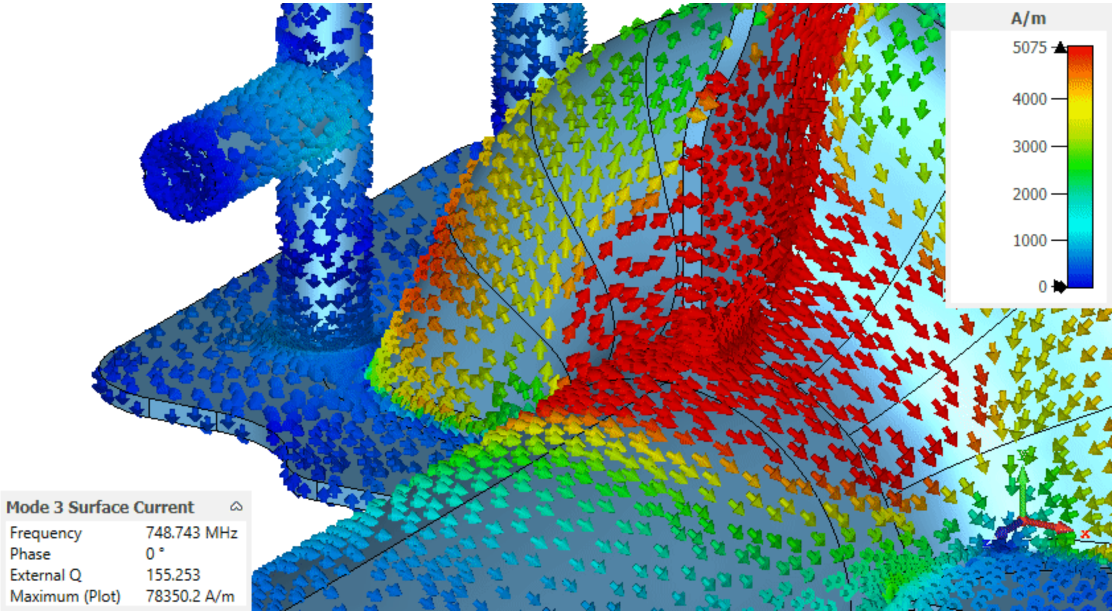

S. Gorgi Zadeh

# Example of HOM damping mechanism

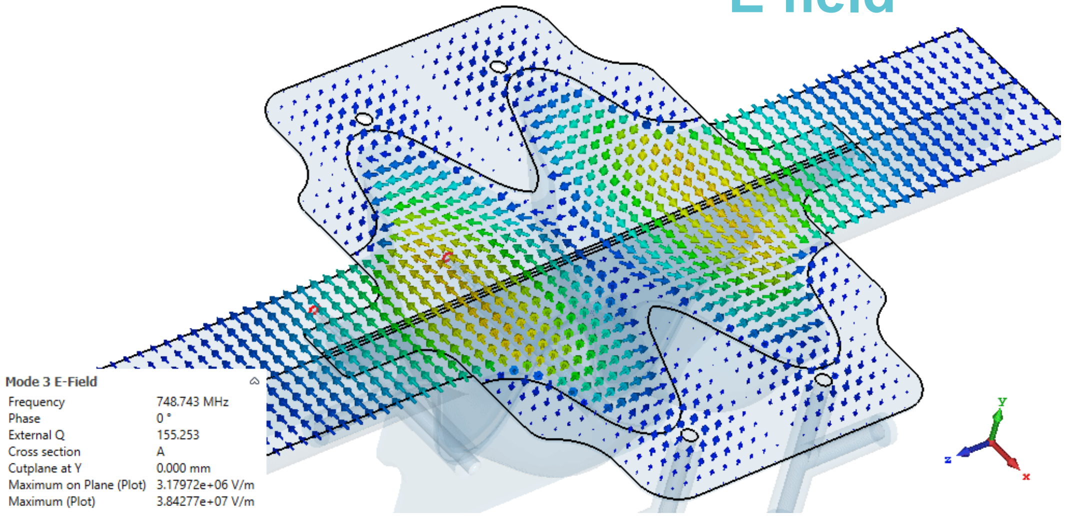
**TE mode - F = 748 MHz**

**Qext factor is reduced to 155**

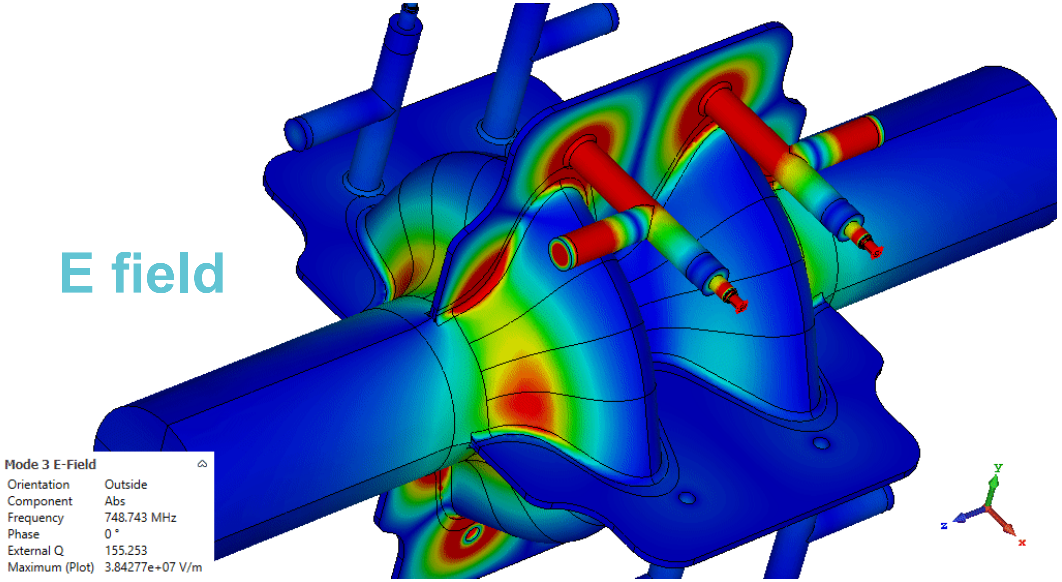
Surface current




E field




E field



# FCCee with SWELL cavities up to the Higgs energy

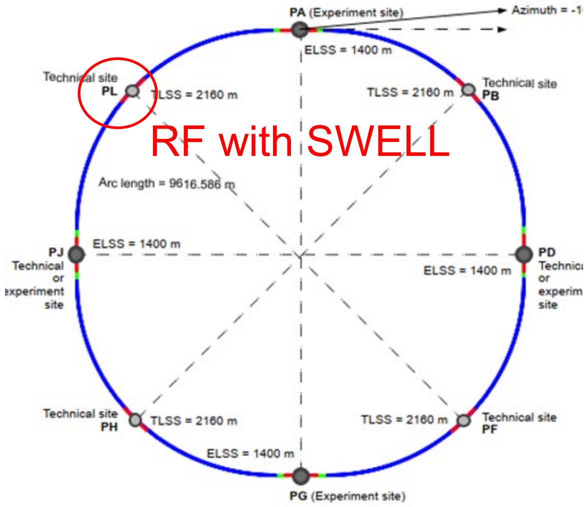
**344 cavities in total for the Z, W and H operating points**

**2 beams in the same cavities for the H machine (re-alignement of the cryomodules)**

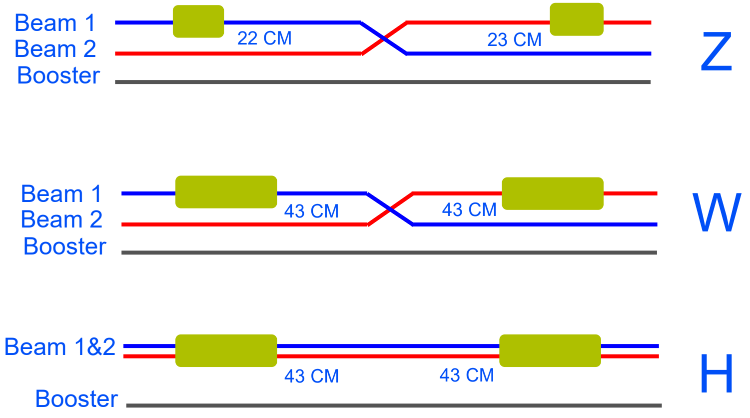
**RF power per cavity: ~ 600 kW for Z, and ~ 300 kW for W and H**

**Maximum surface fields: ~30 MV/m and 82 mT at 4.5 K**

| 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 |




TIWG 29/09/2021



# SWELL feasibility demonstration at 1.3 GHz

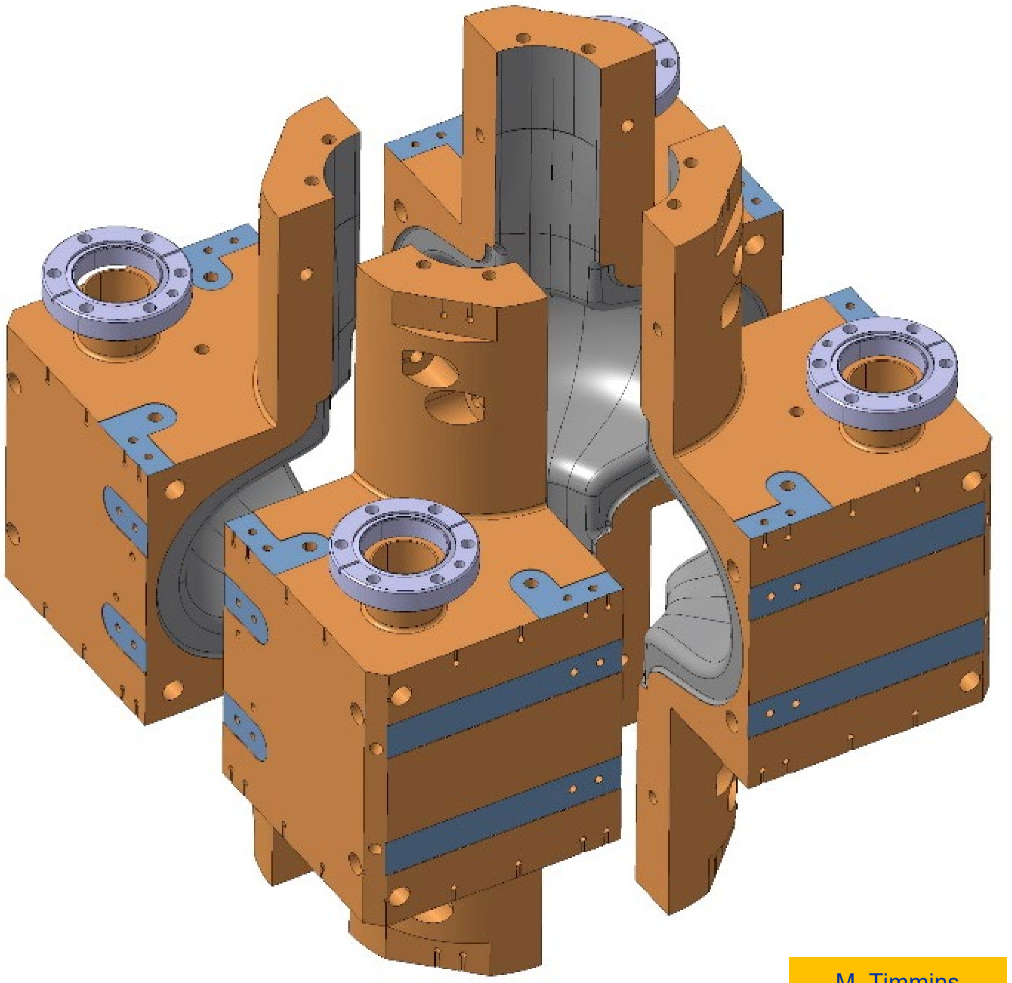
SWELL version of the TESLA 1.3 GHz single cell SRF cavity

Simplified geometry (closed slots) in order to evaluate the maximum accelerating gradient achievable with this technology

Objectives @ 4.5 K

→ $E_{acc}$ > 15 to 18 MV/m

→ $Q_o > 3.10^8$ (50 W of RF losses)

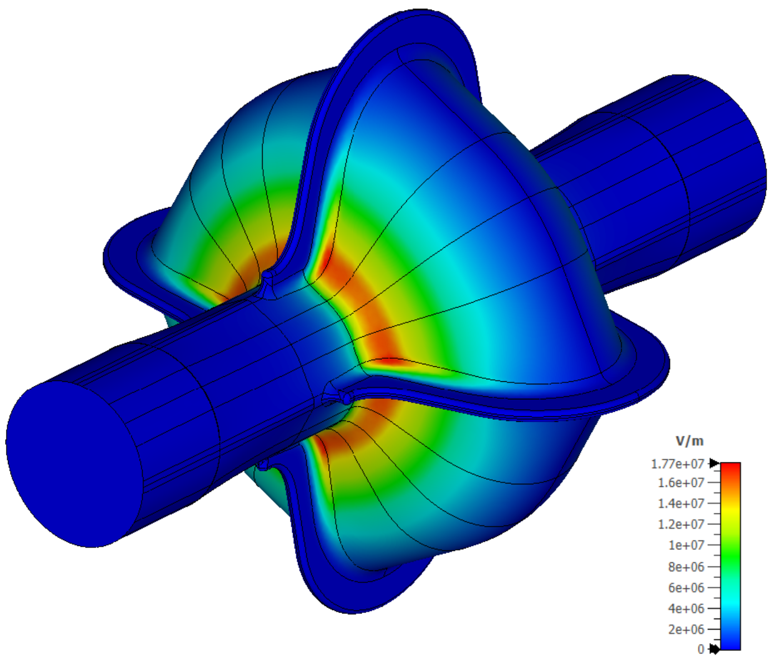


M. Timmins

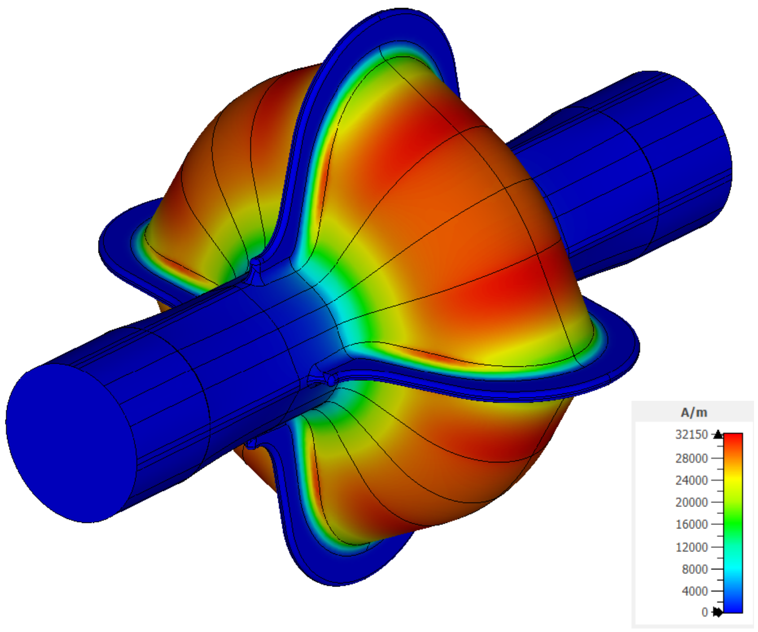
# SWELL 1.3 GHz cavity RF design

| Parameters | Values |
|---|---|
| F (GHz) | 1.3 |
| R/Q linac (Ω) | 122.9 |
| Lacc (mm) | 115.3 |
| Epk/Eacc | **2.01** |
| Bpk/Eacc (mT/(MV/m)) | **4.61** |
| G (Ω) | 265.56 |

**E field**




**H field**




for 1 Joule stored energy

# Precise machining in the CERN workshop


M. Garlasche
-
Picture courtesy Romain Ninet and Karol Scibor - CERN

# SWELL 1.3 GHz cavity surface preparation

## Electropolishing

- By immersion with an optimized cathod shape
- Masks on contact surface between quadrants

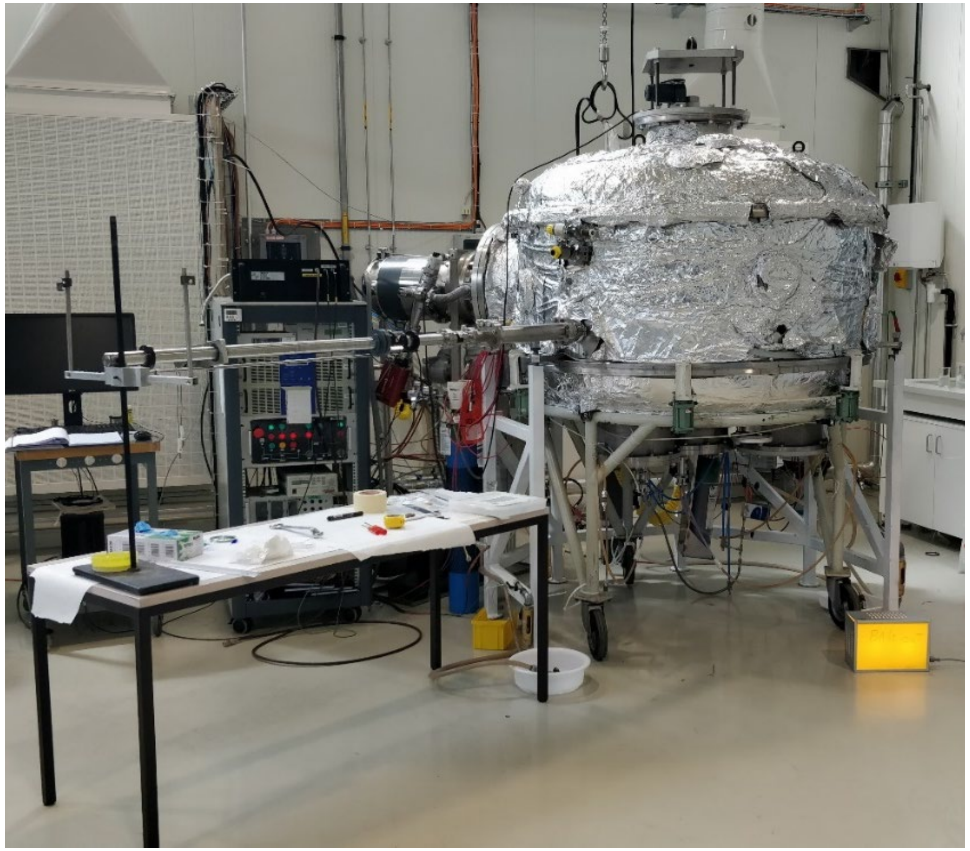
## Niobium coating

- Bi-polar HiPIMS* sputtering to obtain a dense film
- Using of an existing chamber at CERN (photo)
- First coating successfully performed on a flat sample

→ Rs = 5 nΩ @ 400 MHz, 2 K, 30 mT

## Clean room assembly

- Ultra-pure water rinsing at low pressure
- Mechanical alignement and assembly in ISO5 clean room



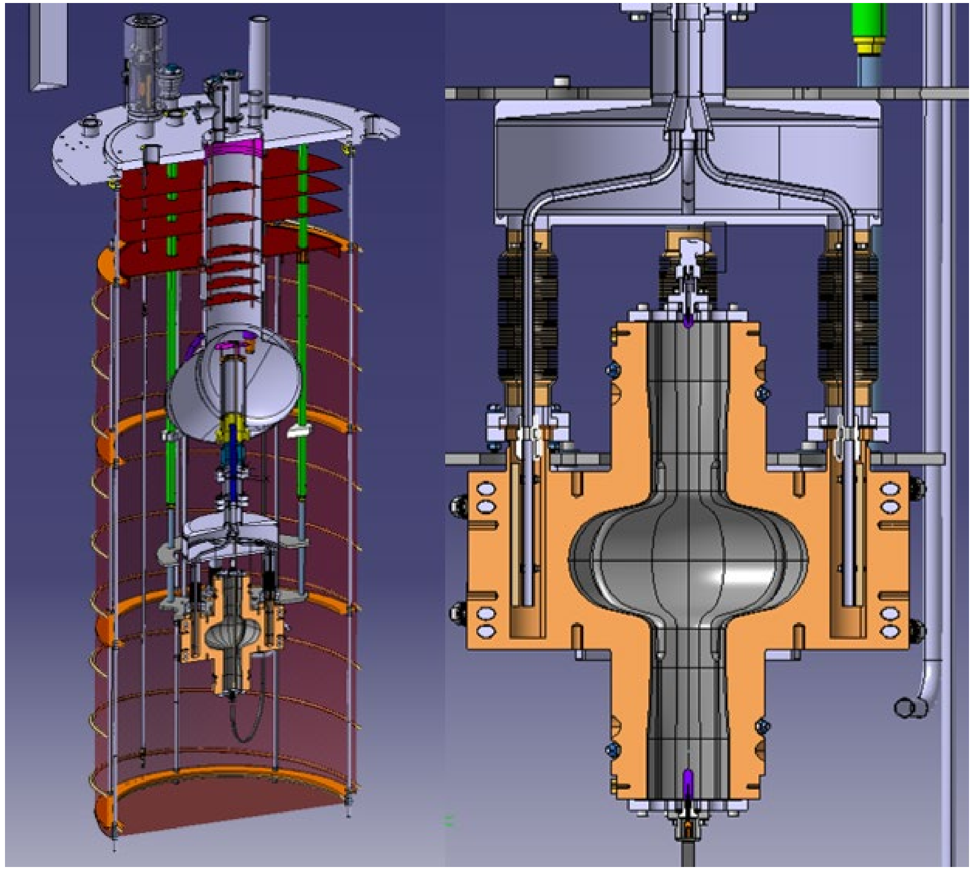
G. Rosaz,
W. Venturini Delsolaro

* High power impulse magnetron sputtering

# RF testing at low temperature

## Test at CERN in SM18 in V5 cryostat

- Common vacuum system - the cavity vacuum is the same as the insulation vacuum, $10^{-9}$ mbar achievable (legacy of HIE-ISOLDE superconducting linac project)
- Particle free environment (local clean room around the cryostat insert)
- RF measurement setup upgraded from 100 MHz to 1.3 GHz
- Earth magnetic flux compensation possible
- 4.5 K and 2 K operation with new cryogenic distribution system to cooldown the 4 quadrants in a uniform way



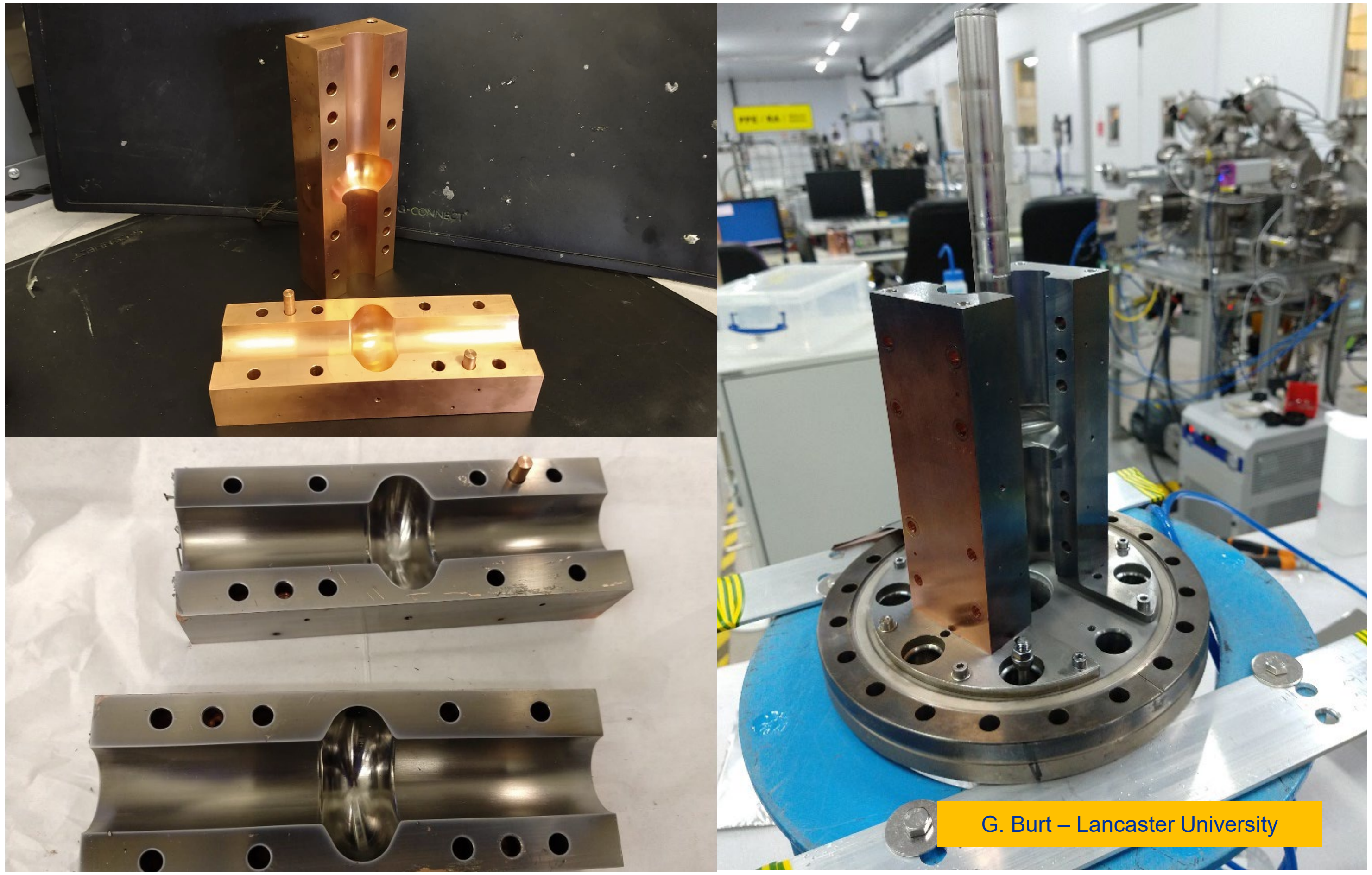
M. Therasse, T. Koettig

# Split SRF cavities 6 GHz

**Lancaster University have been developing split cavities for thin film coatings**

**Unlike SWELL we have two halves rather than four quadrants**

**The program is focused on coatings and RF measurements rather than cavity design**



# Split SRF cavities 6 GHz

## Split cavity advantages

- Cavity developed to be suitable for Nb, Nb3Sn and multilayer coatings
- Easy to coat with either conventional planar magnetron or in tubular geometry used for RF cavities, no fields on contact faces, stiff to avoid cracking, easy to inspect

## Status

- 3 x 6 GHz cavities made and are being coated
- First cavity has been coated with Nb. It was a quick coating (non optimised parameters for deposition so that the Rs measurement facility could be tested, now optimising coating at STFC)
- Second Cavity has been coated using an optimized process:
  - ✓ pulsed DC sputtering of a pure niobium target without any further polishing.
  - ✓ The sputtering was performed with a 300 W pulse with 2.10 A, 143 V. The pulse frequency was 350 kHz, the dual time was 1.1 μs for 3 hours at $3.85\times10{-2}$ mbar of krypton at room temperature.
  - ✓ The surface resistance at 4.2 K was measured to be $5.32.10^{-1}$ mΩ, the BCS resistance for niobium at 4.2 K at 6 GHz is $1.15\times10^{-2}$ mΩ

# Summary

## New innovative SRF cavity concept proposed for FCCee which would potentially reduce the quantity of cryomodules by 20 %

- Detailed RF design study of a 2-cell 600 MHz SWELL cavity with a strong HOM damping features finalized, compatible to operate at the Z, W and H working energies

- Depending beam dynamic studies, it will be possible to scale the cavity geometry to another RF frequency, typically between 500 MHz to 650 MHz

- A "TESLA like" SWELL cavity is being developed in parallel to demonstrate experimentally the feasibility of the concept. A first unit has been machined with great success and is ready for surface preparation and niobium coating. First RF tests at cryogenic temperature are foreseen in 2023.

- In parallel, SRF coating studies at 6 GHz are on-going at Lancaster University

# Perspectives

- **Mechanical study of SWELL 2-cell cavity including the design of a test horizontal cryostat integrating all RF couplers and RF tuning systems**

- **Possible collaborations on the SWELL development program:**
  - IN2P3-LPSC (France) – multipacting studies with experimental validation
  - Jefferson Laboratory
  - …

- **Other Ampere-class high energy accelerator projects like EIC (USA) or CEPC (China) could find an interest in looking into the SWELL cavity options**

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**Thank you for attention**

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