Slotted Waveguide ELLiptical (SWELL) cavity development.
I. Syratchev, F. Peauger, I. Karpov, O. Brunner.
CERN
Accelerating structures with slotted irises at CERN (CLIC).

Slotted Irises Constant Aperture (SICA)
3GHz accelerating structure used in CTF3


CLIC 12 GHz Power Extraction and Transport Structure (PETS). Built of 8 octants.

CST/3D (MWS) uses perturbation method to calculate $Q_{\text{external}}$. This method is based on assumption that the mode under investigation is a standalone mode. Thus, designer could draw wrong conclusion when using CST/3D for simulations of the slotted coupled cavities in the presence of external load.
SWELL damping slot geometry configuration

- Slot length of **430 mm** was chosen. Increasing the length does not improve HOM damping, whilst with this choice cut-off frequency of TE\(_{20}\) waveguide mode is 700 MHz – well above the operating frequency.
- **10 mm** slot width was considered as a compromise between SCRF and HOM performances.
Fundamental modes external Q factors (HFSS)

- Depending on the phase advance of the cavity modes, each of them has a preferential waveguide mode (TE_{N,0}) to couple with.
- In a system with modes frequencies located closely, modes will be coupled through the slot as well. Thus, coupling to the waveguides modes mixture will happen.
- Heavily damped slot modes are the legit eigen oscillations in the system with external RF power absorption (HFSS free radiation boundary).
- Slot modes can modulate accelerating modes coupling to the waveguide modes (Q external) and distort the longitudinal filed symmetry of the modes inside the cavity.
Fundamental modes external Q factors (HFSS)

- With infinite length of the damping waveguide, the slot modes spectra will be dense enough, so that integrated effect of slot modes on the accelerating modes external coupling shall disappear.
- With a waveguide of the finite length, there shall be a specific length, where two nearby slot modes could compensate each other.
- At this point, the field symmetry in the cavity shall be restored (red color lines on the left plots) and external Q factors of the modes are expected to be similar:
Planar HOM power coupler (HPC) with coaxial feedthrough’s. Conceptual design.

**HPC design objectives**

- HPC has to evacuate efficiently the RF power of HOM generated in the cavity and be able to deal with both waveguide modes.
- Sparse slot modes spectra (transverse and longitudinal) and provide their heavy damping.
- The HOM power will be collected at the HPC outputs and evacuated with coaxial cables outside the cold volume.
SWELL cavity with coaxial HPC

\[ Q_{\text{ext}} = 3.45 \times 10^8 \]

- Accelerating modes behavior is similar to the situation with infinitely long matched waveguide, due to the short extraction circuit length with strong detuning of the slot mode(s).
- Measured external Q factor can be accepted for the FCC_ee Z option where loaded Q factor is \( 2 \times 10^4 \), but can be barely accepted for the low current cases like H option where loaded Q factor is \( 6.5 \times 10^5 \) (0.2% of RF power [600 W] will be lost in HOM loads).

\[ Q_{\text{ext}} = 3.41 \times 10^8 \]
Assembly/fabrication tolerance issues

- The sheer longitudinal shift between two pairs of adjusted quadrants appeared to have the most dramatic effect on the operating mode Q factor degradation.
- With such an asymmetry, the operating mode couples strongly to TE\textsubscript{20} mode in the slots oriented along the shift plane.
- With compact HPC arrangement, decay properties of TE\textsubscript{20} mode vanished away and Q\textsubscript{ext} degrades very rapidly. Whilst longitudinal field symmetry of the modes is not perturbed.

0.1 mm shift: Q\textsubscript{ext} = 2.4 \times 10^6
1 mm shift: Q\textsubscript{ext} = 2.0 \times 10^6
External lambda/half coaxial rejecters can trap efficiently both waveguide modes at a designated frequency.

These separate RF devices can be tuned individually and connected to SWELL after the cavity is fully assembled.
Simultaneous longitudinal and transverse 1 mm sheer shift of 2 blocks pairs:

- With new HPC configuration, external Q factor is remarkably stable and stays well above $10^{10}$ in the shifts range (both planes together) up to 1 mm. Thus, SWELL + HPC_R shall be compatible with all types of FCC_ee machines.
- In application to the beam acceleration, the actual required tolerances on the shift values will be defined later in the beam dynamic simulation.
SWELL with FPC and 1.1 GHz WG dampers

- FPC is represented by the **30 Ohms** coaxial feedthrough with an outer diameter of 100mm. Total linear stroke of the inner conductor tip position of 45mm allows to cover the range of the loaded Q factors from $2 \times 10^4$ up to $6.5 \times 10^5$ and provides necessary frequency detuning.

- As a last modification of the damping circuit we introduced two orthogonal waveguides with cut-off frequency of 0.95 GHz. The objective of these waveguides is to damp the longitudinal trapped modes at the beam pipe cut-off frequency around 1.1 GHz.
The tuning post is located on the opposite side of the FPC. Changing the length of the post, frequency tuning range can be achieved within +/- 50KHz (25 mm total stroke).

To avoid the needs for the mechanical movement during operation, the pool of such tuners with different length can be stocked and the necessary one to be installed and fixed during the final cavity assembly in warm environment.
SWELL extrapolated SCRF performance

Data for extrapolation is based on measured performance of the 100 MHz seamless Nb/Cu QWR.

A. Miyazaki and W. Venturini Delsolaro., ‘Two different origins of the $Q$-slope problem in superconducting niobium film cavities for a heavy ion accelerator at CERN’, PRAB 22, 073101 (2019)

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<th>Z</th>
<th>W</th>
<th>H</th>
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<td>Frequency [MHz]</td>
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<td></td>
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<td></td>
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<tr>
<td>$r/Q$ [W] (circuit definition)</td>
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<td>Transit Time Factor</td>
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<td>$G$ [W]</td>
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<td>$L_{acc}$ [m]</td>
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<td>Accelerating voltage [MV]</td>
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<td>Accelerating gradient $E_{acc}$ [MV/m]</td>
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<td>Stored energy [J]</td>
<td>2</td>
<td>12.3</td>
<td>87.8</td>
<td>137.2</td>
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Slot edge fillet radius is gradually increased from 12 mm at the iris tip, up to 35 mm at the cavity equator. Compared to symmetrical cavity, $E$ field enhancement factor is 1.34 and for $H$ field is 1.28.
Slot modes in SWELL

- The drawback of HPC_R is that RF length associated with slot modes is increased due to external rejecters, thus modes frequencies were moved down in frequency.
- The monopole mode responsible for the modulation of accelerating modes coupling to the slots is still far apart (+100 MHz).
- The dipole slot modes are more of a challenge, as they moved closer to the HPC_R frequency stop bands. Still their impedances are lower than the ones of the damped dipole HOM.

**Monopole slot mode (SML)**

- $F=697$ MHz; $Q_{ext}=36$; $R/Q=1.5 \times 10^{-4}$ Ohms

- The monopole mode responsible for the modulation of accelerating modes coupling to the slots is still far apart (+100 MHz).

**Dipole slot modes**

- $F=661$ MHz; $Q_{ext}=120$; $R/Q=8.6$ Ohms
- $F=941$ MHz; $Q_{ext}=450$; $R/Q=0.8$ Ohms
### HOM modes in SWELL

<table>
<thead>
<tr>
<th>Modes</th>
<th>F (MHz) SWELL</th>
<th>R/Q longitudinal (linac ohms)</th>
<th>R/Q transverse (linac ohms)</th>
<th>Q external SWELL</th>
<th>F(MHz) ELL</th>
<th>Q external ELL</th>
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<tr>
<td>TE_{11} – π mode</td>
<td>754.4</td>
<td>-</td>
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<td>61</td>
<td>724.3</td>
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<tr>
<td>TE_{11} – 0 mode</td>
<td>740.7</td>
<td>-</td>
<td>15.2</td>
<td>202</td>
<td>752.6</td>
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<tr>
<td>TM_{11} – π mode</td>
<td>811</td>
<td>-</td>
<td>38.3</td>
<td>9.5</td>
<td>817</td>
<td>8.7x10^5</td>
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<tr>
<td>TM_{11} – 0 mode</td>
<td>861.9</td>
<td>-</td>
<td>8.1</td>
<td>280</td>
<td>866</td>
<td>700</td>
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<tr>
<td>Trapped mode (1)</td>
<td>1085.4</td>
<td>4.2</td>
<td>-</td>
<td>196</td>
<td>1088</td>
<td>5.5x10^5</td>
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<td>Trapped mode (2)</td>
<td>1097.1</td>
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<td>-</td>
<td>59</td>
<td>1100</td>
<td>1.9x10^5</td>
</tr>
</tbody>
</table>

**Diagrams:**
- **TE_{11} – π mode**
- **TE_{11} – 0 mode**
- **TM_{11} – π mode**
- **TM_{11} – 0 mode**
- **Trapped mode (1)**
- **Trapped mode (2)**
Simulated wake length is 100 m. Frequency resolution on the impedances plots is ~ 3MHz.
The efficient rejection of the fundamental modes in the SWELL cavity makes it as a good candidate to be used as a high resolution beam position monitor.

Beam off-set in simulations was 5mm in X direction. The residual coupling between x-y HPC branches comes from the FPC field symmetry distortion. With filtered $TE_{11}$ ‘$\pi$’ mode at 861 MHz and fundamental mode relative rejection at a level of $>$60dB, the internal beam position resolution can go down to the sub micrometer levels.
Future Circular Collider

REPORT

A SUPERCONDUCTING SLOTTED WAVEGUIDE ELLIPTICAL CAVITY FOR FCC-ee

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<td>Igor Syratchev, Franck Peauger Ivan Karpov, Olivier Brunner</td>
<td>CERN</td>
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https://zenodo.org/record/5031953#.YNXjUG6xVp8

DOI is: https://doi.org/10.5281/zenodo.5031953
Second SWELL generation (work in progress).

- New Compact HPC
- Special cavity shape with optimized/reduced surface E/H fields

### Table: Properties

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<tbody>
<tr>
<td>Energy, J</td>
<td>2</td>
<td>12.3</td>
<td>87.8</td>
<td>137.2</td>
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<tr>
<td>$E_{\text{surf max}}$, MV/m</td>
<td>5.93</td>
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<td>$B_{\text{surf max}}$, mT</td>
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<td>31</td>
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Thanks for your attention!