A 3 GHz SRF reduced-β Cavity for the S-DALINAC

D. Bazyl*, W.F.O. Müller, H. De Gersem

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Introduction
Layout of the S-DALINAC

- $E_{in} = 250$ keV (thermionic gun)
- $E_{in} = 100$ keV (planned to be upgraded to 200 keV) (spin polarized gun)
- $f = 3$ GHz; CW
- $I < 20$ µA
- 11 SRF cavities; bulk Nb; $T = 2$ K
**Introduction**

**Current setup**

- 5 cell cavity in the tuner frame:
- Electric field distribution of TM$_{010}$ mode (transverse cut-plane 2D view):

**The main parameters:**

- SRF $\beta = 1$ cavity
- $f = 3$ GHz
- $E_{\text{acc}} = 3$ MV/m
- TM$_{010}$
- $\pi$ – mode
- $T = 2$ K
Introduction
Motivation for the upgrade

• 5 cell cavity is affected by plastic deformation
• Energy spread of accelerated beams does not reach a required value and the current capture section is one of the reasons
• Injecting a 200 keV beam directly into a $\beta=1$ RF structure results in inefficient acceleration because of the mismatch in phase
• Q-value drops over time
**Upgrade**

**SRF cavity types**

- SRF cavities spanning the full range of beta:

  - Operating frequency of the S-DALINAC is
  
    \[ \lambda \approx 10 \text{ cm} \]
Upgrade
Criteria for a new accelerating structure

- Operating frequency 3 GHz (TM_{010}; \pi – mode)
- Output energy from the capture section at the S-DALINAC of 1 MeV
- Flat top peak electric field on the central axis of the cavity E_0 < 10 MV/m
- No significant increase of the energy spread of the beam
- Fitting inside the present cryostat
- Compatible with the present input coupler
- Minimal investment cost
- Reliable in operation (mechanical model)
Upgrade
Proposed designs

- 5 cell $\beta$-graded cavity (for 100 keV):
  - $0.55$ $0.78$ $0.86$ $0.90$ $0.90$

- 5 cell reduced-$\beta$ cavity (100/250 keV):
  - $0.75$

- 5 cell $\beta$-graded cavity (for 250 keV):
  - $0.75$ $0.80$ $0.86$ $0.90$ $0.90$

- Independently driven cavities (100/250 keV):
  - $0.75$ $0.75$
Upgrade
Proposed designs

![Graph showing output energy vs peak electric field]

- Results for the $\beta$-graded cavity were better than expected
- This led to the idea of use of a reduced $\beta$ cavity
- Reduced $\beta$ cavity is less flexible but more reliable in operation

- It is not possible to accelerate the 100 keV beam using the current setup
- Implementing a $\beta$-graded elliptical cavity is in our case not recommended because of failing stability during operation and increased cavity prod. costs
- The reduced-$\beta$ cavity is capable of providing 1 MeV to the 100 keV beam after an additional optimization of the structure
- The main advantage of the reduced-$\beta$ cavity over the $\beta$-graded cavity is the much less complicated geometry
Reduced-\(\beta\) cavity
Cell shape

- Geometry of a single cell of a multi-cell elliptic cavity is formed by two ellipsoids
- Single cell 1.3 GHz TESLA \(\beta = 1\) cavity was chosen as an anchor shape
- Geometric parameters were scaled in a way such resonant frequency of the fundamental \(TM_{010}\) mode is equal to 3 GHz
- Scaled shape requires an additional optimization since \(\beta_g < 1\)
Reduced-β cavity

- A progression of compressed elliptical cavity shapes at the same rf frequency but for decreasing β values

Reduced-β cavity:
- The same length of each cell
- β < 1

Parameters to estimate:
- Number of cells
- Optimal value of geometric β
- Energy acceptance

\[ L = \frac{\beta c}{2f} = \frac{\beta \lambda}{2} \]

SNS
β=0.61

SNS
β=0.81

\( E_0 < 10 \text{ MV/m, } U > 1 \text{ MeV, low energy spread} \)
Reduced-β cavity
Number of cells and geometric β

- \( E_{\text{in}} = 200 \text{ keV} \)
- An N+1 cell cavity can be operated with a lower value of \( E_0 \) compared to an N cell cavity to achieve the same energy gain

- The optimal value of the geometric β will depend on the operating value of \( E_0 \)
- The 6 cell cavity is favoured, however, the mechanical model must be evaluated carefully
**Reduced-\(\beta\) cavity**

**Energy acceptance**

- 5 cell cav. \(\beta = 0.85\)
- 6 cell cav. \(\beta = 0.86\)
- Both cavities are capable to accelerate the 200 keV beam to the necessary energy

- The six cell cavity is also capable to accelerate the 100 keV beam, which is an advantage over the 5-cell cavity
RF design
Problem decoupling

- Mid-cell designed independently
- End-cells consists of a half mid-cell and independently designed half-cell (half end-cell)
**RF design**

**Dispersion diagram**

- Dispersion diagram of the TM$_{010}$ mode (6-cell cavity):

\[
k_c = 5.8\% \\
\text{(typical target value 2%)}
\]

- Mid-cell with indicated boundary conditions:

\[
k_c = 2 \cdot \frac{f_\pi - f_0}{f_\pi + f_0} \cdot 100\%
\]
RF design
Field flatness

- Beam pipes introduce an additional capacitance to the cavity
- Field flatness is tuned by optimizing geometry of end-cells
- For the 6-cell cavity end-cells are identical
- Precise field flatness tuning is simulations is not required due to manufacturing error on practise
RF design
Peak fields

- Field amplitudes on surface were computed for the TM$_{010}$ mode
- Figures on the left indicate field amplitudes evaluated on curve

**Reliable amplitude range**: 

<table>
<thead>
<tr>
<th>Peak magnetic field</th>
<th>Peak electric field</th>
</tr>
</thead>
<tbody>
<tr>
<td>48-56 kA/m</td>
<td>30-35 MV/m</td>
</tr>
</tbody>
</table>

**A. Facco, TUTORIAL ON LOW BETA CAVITY DESIGN**
**RF design**
**Longitudinal stiffness**

- Current model
  - Longitudinal stiffness +1kN/mm
  - R/Q value is lower however mechanical stability have a higher priority

- Previous layout
  - R/Q is higher -> higher efficiency
  - Complicated connection to beam pipes
RF design
RF parameters

- Side view of the 6 cell reduced $\beta=0.86$ cavity:

![Side view of the 6 cell reduced $\beta=0.86$ cavity](image)

- RF parameters:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$F$, GHz</th>
<th>$\beta$</th>
<th>$K_c$, %</th>
<th>$E_0$, MV/m</th>
<th>$E_{acc}$, MV/m</th>
<th>$R/Q$, $\Omega$</th>
<th>$G$, $\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM010; pi</td>
<td>2.997</td>
<td>0.86</td>
<td>5.8</td>
<td>10</td>
<td>5</td>
<td>347</td>
<td>253</td>
</tr>
</tbody>
</table>
RF design
Comparison with the current setup

### Energy gain

- **5 cell** $\beta = 1$ cavity
- **6 cell** $\beta = 0.86$

- $1.50 \text{ MeV}$
- $0.56 \text{ MeV}$

### Energy spread

**Input beam:**

- Peak $E$-field on axis, MV/m: 10 MV/m
- Output energy of the beam, MeV: 0.56
- Energy spread growth, keV: $>30$

**Output beam:**

- $\Delta E_{\text{out}} = 6 \text{ keV}$
- $\Delta E_{\text{in}} = 3 \text{ keV}$

<table>
<thead>
<tr>
<th></th>
<th>Current setup (5 cell cavity $\beta = 1$)</th>
<th>Proposed design (6 cell cavity $\beta = 0.86$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak E-field on axis, MV/m</td>
<td></td>
<td>10 MV/m</td>
</tr>
<tr>
<td>Output energy of the beam, MeV</td>
<td>0.56</td>
<td>1.50</td>
</tr>
<tr>
<td>Energy spread growth, keV</td>
<td>$&gt;30$</td>
<td>3</td>
</tr>
</tbody>
</table>
**RF design**

**Power coupling**

- RF amplifiers provide max. 500 W
- Estimated power $P_f < 100$ W necessary to maintain 10 MV/m on axis
- Detuning is unknown
- Optimal $Q_L = 10^7 ... 10^8$

---

\[
P_f = \frac{V_{acce}^2}{4 \left( \frac{R}{Q} \right) Q_L} \left( 1 + \frac{\left( \frac{R}{Q} \right) Q_L I_b}{V_{acce} \cos \phi_b} \right)^2 + \left( \frac{\Delta f}{f_{1/2}} + \frac{\left( \frac{R}{Q} \right) Q_L I_b}{V_{acce} \sin \phi_b} \right)^2 \]  

RF design
Power coupling

- Cross section of the input power coupler of the 6-cell cavity
- Q-factor vs penetration depth of inner conductor of coaxial line
Mechanical model
Introduction

• ANSYS is used for structural analysis

• Mechanical model of the 3.9 GHz β=1 cavity (DESY XFEL/TTF) was used to gain information about mechanical behaviour of an SRF cavity in this frequency range
  o Wall thickness: 2.8 mm before polishing inner surface -> 2.5 mm after
  o No stiffening rings required – cavity is rigid enough* without them (cheaper production costs, less analysis)

*DEVELOPMENT OF THE 3.9 GHZ 3RD HARMONIC CAVITY AT FNAL, N. Solyak, H. Edwards et., al. SRF 2003
*This fact was also mentioned in a private communication of Simon Weih with RI GmbH representative
• **Microphonics** can be defined as dynamic cavity detuning caused by structural vibrations transmitted to the RF structure

• The source can be:
  • Ground motion
  • Helium pressure fluctuations
  • Lorentz forces
  • Any external source of noise
**Mechanical model**

**Microphonics**

- Resonant frequencies of the first 7 mechanical modes were obtained
- Main purpose of these computations is not to estimate detuning of the cavity due to microphonics but to know the location of the longitudinal modes in a frequency range below 1 KHz

![Graph showing resonant frequencies and mode shapes]

- Frequency $f$, Hz
- Mode number $N$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Resonant Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
</tr>
<tr>
<td>6</td>
<td>1200</td>
</tr>
<tr>
<td>7</td>
<td>1400</td>
</tr>
</tbody>
</table>

**Legend**
- **Red diamond**: Longitudinal
- **Green diamond**: Transverse

**Color Scale**
- **Max**
- **Min**
Mechanical model
Characterization related to tuning

- External mechanical loads act on cavity walls and shift the resonant frequency of the fundamental mode and also affect the field flatness
- Tuning system for the cavity during the operation is required to compensate deformations and remain the designed value of the frequency of the fundamental mode
- Three characteristics are required for the tuner: df/dp, df/dl and longitudinal stiffness of the cavity
- Boundary conditions used in simulations:

<table>
<thead>
<tr>
<th>Material properties used in simulations:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
</tr>
<tr>
<td><strong>Wall thickness, mm</strong></td>
</tr>
<tr>
<td><strong>Temperature, K</strong></td>
</tr>
<tr>
<td><strong>Young’s modulus, GPa</strong></td>
</tr>
<tr>
<td><strong>Poisson ratio</strong></td>
</tr>
</tbody>
</table>

*TD ER-10163, M. Merio, October 2011*
Mechanical model
Characterization related to tuning

- Frequency vs pressure
- Longitudinal stiffness of the cavity
- Frequency vs Displacement

Pressure sensitivity $\frac{df}{dp}$, Hz/mbar

<table>
<thead>
<tr>
<th>Pressure sensitivity $\frac{df}{dp}$, Hz/mbar</th>
<th>Longitudinal stiffness $K$, kN/mm</th>
<th>$\frac{df}{dl}$, kHz/μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>4.6</td>
<td>2.1</td>
</tr>
</tbody>
</table>

- Example: deformation caused by applied pressure (the scale of the deformation is exaggerated)
Current status

- Agreement with Research Instruments
- Manufacturing will take ~1 year from now
- Estimated price ~ 100 000 EUR (including inside surface preparation)
- Additional beam diagnostics system at the S-DALINAC is required for commissioning of the 6-cell cavity
Conclusion

• Reduced β cavity has more advantages than other proposed layouts with respect to design criteria for a new cavity
• RF design is done (without HOM dumping system)
• Necessary RF power is covered by RF amplifiers available at the S-DALINAC
• Cavity is compatible with the present input power coupler
• Cavity fits into the existing cryostat
• Production should be finished in 2020
Mechanical model
ANSYS

Deformed mesh* is sent to HFSS -> df/dp; df/dl

*the scale is exaggerated
~3 mln.