Design of high gradient LINAC with the new “Gasket-Clamping” technique and compact low pulsed heating couplers

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Outline

• Gasket-Clamping fabrication technique
• **BOLT Project:** Design and realization of a LINAC prototype implementing the gasket clamping fabrication technique
  1. Electromagnetic design
  2. Mechanical design and assembly procedure
  3. Vacuum test on single cell
• **New compact low pulsed heating coupler studied @INFN-LNF**
  1. Ultra-Fast C-band RF Gun
  2. Coupler proposal and preliminary results
• Summary and future work
The accelerating structures generally are realized by a **brazing process**, but this:

- Requires large vacuum furnaces
- Is very expensive
- Poses a not negligible risk of failure
- At the end of the process the copper is “soft”

Avoiding it should be possible to decrease the BDR and reduce the conditioning time.

**New technology** developed at INFN-LNF called «**Gasket-Clamping**» fabrication technique [1] that does not involve any brazing step.

**Use of special RF/vacuum Gaskets:**

- Machined components joined by screws
- Copper gasket compressed of 0.2 mm after clamping
- Simultaneously guarantees the **vacuum seal and the RF contact** avoiding sharp edges and gaps

This technique has been successfully used for the realization of:

- An **RF Gun prototype** currently in operation at **UCLA** since three years at low rep. Rate (90 MV/m, 5 Hz) [2]
- The **ELI-NP RF electron gun** that has been tested at full power (120 MV/m, 14 MW input power, 1.5 us @100 Hz) at Bonn University [3]

**Extension of this technique for the realization of an entire Linac structure (S/C/X band)**

In [4] has been proposed and discussed the realization of a 10 cell TW accelerating structure to study the feasibility of this application. In 2017 starts the **project BOLT (Backthrough On Linac Technology)** that has been **funded by the INFN CNTT**.

In the framework of the upgrade of the FERMI Linac at the ELETTRA Laboratories (Trieste) an high gradient S-band prototype has been realized [5]. In order to make a comparison between a brazed and an hard-copper clamped structure, we decided to realize a similar to the «FERMI» layout. The prototypes have a symmetrized model layout:

To implement the gasket clamping fabrication technique and also lower the realization costs we need to consider some design choice that influence directly the electromagnetic design:

- **Use of magnetic coupling (MC) coupler with a racetrack slot**
  - The implementation of a waveguide coupler (EC) with gaskets at the coupling cell is under study.

- **Internal edge roundings of the cells** have been used to tune the cells at the right frequency
  - The cell radius is kept constant along the structure and this allows to use the same type of gasket to join all the cells -> lower realization cost for the gaskets.

Linac with gaskets: cell analysis and tolerances

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cell Phase advance [degree/um]</th>
<th>Frequency Shift [kHz/um]</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.14</td>
<td>-79</td>
</tr>
<tr>
<td>a</td>
<td>-0.04</td>
<td>20</td>
</tr>
<tr>
<td>t</td>
<td>-0.014</td>
<td>7.6</td>
</tr>
<tr>
<td>d</td>
<td>0.015</td>
<td>-8.6</td>
</tr>
<tr>
<td>or</td>
<td>-0.05</td>
<td>28</td>
</tr>
</tbody>
</table>

\[ \Delta \text{freq} = -3 \text{ kHz/um} \]
\[ \Delta \phi = 0.005 \text{ degree/um} \]
Linac with gaskets: coupler design

- **Slot coupler** with MC that → ease the GC technique implementation
- **Double feed** → no dipole magnetic field component
- **Racetrack shape** → compensation of the quadrupolar component
- **Coupling holes with strongly rounded profiles** → surface fields and pulsed heating reduction

Coupler tuned with the *short circuit method* [6], in order to minimize the S11, have flat E field and constant phase advance per cell.

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Linac with gaskets: coupler design (II)

- **Quadrupole field components**

  The azimuthal magnetic quadrupolar field component along an arc of \( r=5\text{mm} \) at the center of the coupler have been considered in figure. A fine compensation of the quadrupolar component has been performed, acting on \( \Delta Y \).

- **Surface fields and pulsed heating evaluation** @ \( P_{\text{in}} \approx 65\text{MW}, 30\text{MV/m} \)

  \( E_{\text{surf}} = 80 \text{ MV/m max on the first iris} \)

  \( H_{\text{surf}} = 180 \text{ kA/m max on the coupler} \)

  \( Sc = 0.8 \text{ W/}\mu\text{m}^2 \) max on the first iris

  \( \rightarrow BDR = 10^{-12} \text{bpp/m } (t_p=1\mu\text{s}) \)

  \( \Delta T = 7^\circ\text{C with }1\mu\text{s pulse length} \)

  \( 10^\circ\text{C with }2\mu\text{s pulse length} \)
**Linac with gaskets: Electromagnetic results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>fres</td>
<td>2998.01 MHz</td>
</tr>
<tr>
<td>mode</td>
<td>$2\pi/3$</td>
</tr>
<tr>
<td>Cell length</td>
<td>33.332 mm</td>
</tr>
<tr>
<td>Total prototype length</td>
<td>415 mm</td>
</tr>
<tr>
<td>N° cells</td>
<td>7+2 (coupler cell)</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$\approx 15900$</td>
</tr>
<tr>
<td>$v_g/c$</td>
<td>2.2 %</td>
</tr>
<tr>
<td>r shunt</td>
<td>72 MΩ/m</td>
</tr>
<tr>
<td>Working Temp.</td>
<td>35 °C</td>
</tr>
<tr>
<td>$E_{acc}/\sqrt{P_{in}}$</td>
<td>3.6 MV/m/√MW</td>
</tr>
<tr>
<td>Pulsed heating</td>
<td>$\approx 10^\circ C$ @ 2μs pulse length, 65MW Pin</td>
</tr>
</tbody>
</table>

**Amplitude and Phase of the Electric field along the axis of the structure**

$\Delta \phi = 120^\circ \pm 0.5^\circ$
In the overall design a continuous **feedback between the electromagnetic design and the mechanical model** has been necessary to match electromagnetic and mechanical constraints.

The structure is composed by the input and output couplers, six cell structures and two half cells. Each cell has eight screw holes disposed at 45° to one another to **provide homogeneous force on the gasket** when the cells are clamped together.

Each part will be **fabricated from cylinders of Oxygen Free High Conductivity (OFHC) copper** using high precision lathe and milling diamond machines. Nowadays mechanical design has been finalized and the realization has been assigned to an italian company.
The assembly procedure is divided into 3 different phases.

The structure will be assembled starting from the first half cell **stacking up one cell after the other**, inserting the gaskets between them and **fixing each part with the previous one by screws**, up to the second half cell.

At each step of assembling a vacuum leak test of the joint will be done to test the correct and uniform compression of the gasket.

An **alignment prism** will be used in this phase to guarantee the cell alignment.
Each coupler is completed by two LIL flange junction, made of steel, that are connected by rectangular copper gaskets. The fine alignment of the two couplers is guaranteed by two Dowel pin.

The proposed setup for assembling give the possibility of coupler replacement re-opening the structure and changing the gasket.
Linac assembly procedure: Final configuration

The presence of the screws around the cells limit the available space so for convenience an external cooling system has been designed for the prototype.

For high power test the structure will be fed through a 3 dB power splitter.
Vacuum test on a single cell clamped

**Vacuum leak test:**
A leak test has been performed after the connection of the two half cells, with a He sensitivity lower than $1.6 \times 10^{-9}\, \text{mbar} \cdot \text{l/s}$ and no leaks have been detected. The test has been repeated after gasket replacement and different baking cycle have been performed with the two gaskets:

**First gasket:**
- 2x baking thermal cycle @120°C for 10 hours  
**Second gasket:**
- 4x baking thermal cycle @120°C for 10 hours  
- 2x baking thermal cycle @150°C for 10 hours  
- 2x baking thermal cycle @200°C for 10 hours

Leak tests have been repeated during the baking and once after the cell cooling @24°C.

A final leak test after the baking was achieved with a He sensitivity $1.2 \times 10^{-10}\, \text{mbar} \cdot \text{l/s}$ and no leaks have been detected.

**Tuning test of Hard Copper cell:**
4 tuners with different thickness from the internal wall  
1 mm, 1.25 mm, 1.5 mm, 1.75 mm  
$\rightarrow$ 500 kHz of $\Delta f_{req}$ with 1-1.25mm
In the framework of the XLS Compact Light collaboration – WP3: Gun and Injectors activities @INFN-LNF an Ultra Fast C-band photocathode gun with high peak electric field on cathode 240 MV and short filling time is under study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\pi}$</td>
<td>5.712 GHz</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>$\approx$ 100 MHz</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>10450</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2.93</td>
</tr>
<tr>
<td>$\tau_F$</td>
<td>148 ns</td>
</tr>
<tr>
<td>$E_{\text{cath}}$</td>
<td>240 MV/m</td>
</tr>
<tr>
<td>$S_{11 \ @ \text{res}}$</td>
<td>-5.86 dB</td>
</tr>
<tr>
<td>$E_{\text{surf}}/E_{\text{cathode}}$</td>
<td>0.9</td>
</tr>
<tr>
<td>Max Sc on coupler surface</td>
<td>3 W/µm²</td>
</tr>
<tr>
<td>Field flatness</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>$H_{\text{surf \ on \ coupler}}$</td>
<td>700 kA/m</td>
</tr>
<tr>
<td>$T_{\text{pulsed \ @ \ 100 \ ns \ (square \ pulse)}}$</td>
<td>45°C</td>
</tr>
<tr>
<td>$T_{\text{pulsed \ @ \ 200 \ ns \ (square \ pulse)}}$</td>
<td>65°C</td>
</tr>
</tbody>
</table>

$E_{\text{cath}} = 240 \text{MV/m}$

$P_{\text{in}}, P_{\text{refl}}, P_{\text{diss}}$

Power Splitter

MC slot coupler

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Low pulse heating coupler

We need to have a **compact gun** to have the possibility to place the solenoid immediately after the full cell (no mode launcher type) and low surface fields and pulsed heating.

Proposed coupler: **Electric coupling (EC)** coupler based on **TM020** mode on the full cell. Different kind of geometries have been investigated:

**Type A**
- Waveguide comes aligned with the half cell
- The short circuit plane and the slots are shaped to match the field at the coupling cell
- Needs a power splitter
- Waveguide short circuited at $\sim \lambda_g/4$

**Type B**
- Waveguides run sideways the half cell
- Coupled with rounded slots
- Needs a power splitter
- Waveguide short circuited at $\lambda_g/4$
- Circular slot
- Tapered waveguide
- Symmetric ports for vacuum pumping and quadrupolar component compensation

**Type C**
- Waveguide run around the half cell
- Coupled with rounded slots
- Doesn’t need a power splitter
- Waveguide short circuited at $\lambda_g/4$
- Circular slot
- Tapered waveguide
## Low pulse heating coupler results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>slot coup.</th>
<th>Type A</th>
<th>Type B</th>
<th>Type B comp.</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{res}} )</td>
<td>5.712 GHz</td>
<td>5.7124 GHz</td>
<td>5.7144 GHz</td>
<td>5.7141 GHz</td>
<td>5.714 GHz</td>
</tr>
<tr>
<td>freq. separation ( 0/\pi ) mode</td>
<td>( \approx 100 \text{ MHz} )</td>
<td>( \approx 80 \text{ MHz} )</td>
<td>( \approx 80 \text{ MHz} )</td>
<td>( \approx 80 \text{ MHz} )</td>
<td>( \approx 80 \text{ MHz} )</td>
</tr>
<tr>
<td>( Q_0 )</td>
<td>10455</td>
<td>14421</td>
<td>14347</td>
<td>14368</td>
<td>14350</td>
</tr>
<tr>
<td>( \beta )</td>
<td>2.93</td>
<td>2.95</td>
<td>2.96</td>
<td>2.94</td>
<td>3.17</td>
</tr>
<tr>
<td>( Q_L )</td>
<td>2660</td>
<td>3646</td>
<td>3623</td>
<td>3649</td>
<td>3416</td>
</tr>
<tr>
<td>( \tau_F )</td>
<td>148 ns</td>
<td>203 ns</td>
<td>201 ns</td>
<td>203 ns</td>
<td>191 ns</td>
</tr>
<tr>
<td>( E_{\text{cath}} ) [MV/m]</td>
<td></td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Esurf/Ecath (on the coupler)</td>
<td>0.34</td>
<td>0.88</td>
<td>0.91</td>
<td>0.88</td>
<td>0.86</td>
</tr>
<tr>
<td>Hsurf [kA/m] (on the coupler)</td>
<td></td>
<td>700 kA/m</td>
<td>340 kA/m</td>
<td>357 kA/m</td>
<td>379 kA/m</td>
</tr>
<tr>
<td>( T_{\text{pulsed}} ) (square pulse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 100 ns</td>
<td>46°C</td>
<td>11°C</td>
<td>12.2°C</td>
<td>13.8°C</td>
<td>10°C</td>
</tr>
<tr>
<td>@ 200 ns</td>
<td>65°C</td>
<td>15.6°C</td>
<td>17.3°C</td>
<td>19.5°C</td>
<td>14.2°C</td>
</tr>
<tr>
<td>Max Sc [W/( \mu^2 )] (on the coupler)</td>
<td>3</td>
<td>4.1</td>
<td>4</td>
<td>3.9</td>
<td>4</td>
</tr>
<tr>
<td>( \frac{E_{\text{CAT}}}{\sqrt{P_{\text{diss}}} \left[ \frac{MV}{m\sqrt{MW}} \right]} )</td>
<td>61.5</td>
<td>56</td>
<td>56.4</td>
<td>55.64</td>
<td>55.92</td>
</tr>
</tbody>
</table>

Results obtained with Ansys Electronic Desktop simulations.

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In the slot coupler and type B gun the magnetic quadrupolar field component has been compensated introducing symmetric port holes connected with circular pipes below cut-off, to be used as pumping ports.
C-band TW structure: coupler type B

- Racetrack coupling slot
- Waveguides run sideways the accelerating cells
- 5 cells + 2 coupling TM020 cells

Preliminary results:
- \( f_{\text{res}} = 5.712 \, \text{GHz} \)
- \( S_{11} = -35 \, \text{dB} \)
- \( H_{\text{surf}} = 118 \, \text{kA/m} \)
- Pulsed heating @\( P_{\text{in}}=40\,\text{MW} \) T<5°C with 1us pulse length
The «gasket-clamping» is a new technique for the realization of RF structures that avoids copper brazing (and the associated drawbacks). This technique has been successfully used for the realization of two S-band RF guns.

- The possibility to extend the use of this technique to the realization of a Linac (S/C/X band) has been investigated through the design of a prototype in the project BOLT (funded by INFN CNTT).
- The electromagnetic and mechanical design of a 7 cell TW S-band prototype have been presented together with the assembly procedure.
- Vacuum test on single cell joint has been successful. A vacuum test on the Coupler cell joint is foreseen.
- The mechanical design with all the tolerances has been completed and the realization of the different parts has been assigned to an Italian company. The components will be ready in September and we will start the assembling procedure.
- After the realization and assembly of the prototype, vacuum and low power RF test will be performed at INFN-LNF laboratories. The high power test will be carried out probably in January at ELETTRA-Sincrotrone Trieste laboratory.

In the framework of XLS Compact Light an high gradient ultra fast C-band gun is under study at INFN-LNF.

- In order to have a compact RF gun, a design based on the magnetic coupling slot type coupler has been investigated. The main limitation for this type of coupler remains the high surface magnetic field and pulsed heating on the coupling slot.
- Thus, different couplers geometries have been studied based on a TM020 mode full cell electrically coupled with the waveguide.
- The feasibility of such couplers has to be further investigated and electromagnetic design has still to be optimized. Preliminary simulations give promising results as far as the pulsed heating is concerned.
- Simulations also open the possibility of using this type of coupler to feed a TW accelerating structure.
Thank you for the attention

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