Possible configurations for multicell RF structures for muon cooling

Alexej Grudiev (CERN)

18/01/2024
Outline

• Introduction

• Different type of RF coupling
  • Distributed RF coupling
  • Magnetic (inductive) cell-to-cell RF coupling
  • Electric (capacitive) cell-to-cell RF coupling

• Standing and Travelling wave RF structures

• Conclusions
### RF system for muon cooling (MAP design)

<table>
<thead>
<tr>
<th>Region</th>
<th>Length [m]</th>
<th>N of cavities</th>
<th>Frequencies [MHz]</th>
<th>Gradient [MV/m]</th>
<th>Magnetic field [T]</th>
<th>Peak RF power [MW/cav.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buncher</td>
<td>21</td>
<td>54</td>
<td>490 - 366</td>
<td>0 - 15</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Rotator</td>
<td>24</td>
<td>64</td>
<td>366 – 326</td>
<td>20</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>Initial Cooler</td>
<td>126</td>
<td>360</td>
<td>325</td>
<td>25</td>
<td>2</td>
<td>3.7</td>
</tr>
<tr>
<td>Cooler 1</td>
<td>400</td>
<td>1605 x2</td>
<td>325, 650</td>
<td>22, 30</td>
<td>2-3, 4-6</td>
<td>4, 2</td>
</tr>
<tr>
<td>Bunch merge</td>
<td>130</td>
<td>26 x2</td>
<td>108 - 1950</td>
<td>~ 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooler 2</td>
<td>420</td>
<td>1746 x2</td>
<td>325, 650</td>
<td>22, 30</td>
<td>2-5, 8-13</td>
<td>4, 2</td>
</tr>
<tr>
<td>Final Cooling</td>
<td>140</td>
<td>96 x2</td>
<td>325 - 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~1300</td>
<td><strong>7424</strong></td>
<td></td>
<td></td>
<td></td>
<td>=&gt; ~20GW</td>
</tr>
</tbody>
</table>

*It is a very large and complex RF system*

---

**Ionisation Cooling**

---

**Summarized from: David Neuffer Chris Rogers**
Muon cooling demonstrator layout (2023)

Even this, small part of the cooling complex, is a large test facility.
Muon cooling demonstrator layout (2021)

High peak power klystron: 24 MW

RF for cooling: Max. gradient **30 MV/m**

Building -> Gallery: (underground might be possible)
30m x 12m
Height: 8-10 m

WG distribution with phase adjustment to feed 2 x 4 cavities

- **RF for 120 cavities at ~30 MV/m**
- 30m x 15m
- **15 RF stations**
Muon cooling demonstrator layout (2023)

High peak power klystron: 24 MW

- Waveguide distribution with phase adjustment to feed 4 cavities with independent RF phase control is bulky
- It also requires RF coupler and cryomodule feed-through for each cavity

Building -> Gallery:
(underground might be possible)
30m x 30m
Height: 8-10 m

RF for 120 cavities at
44 MV/m
30m x 30m
30 RF stations
1.4 times higher gradient
=> 2 times more RF power
Distributed RF coupling

**Advantages:**
- Minimum RF power per cell, highest gradient
- Arbitrary cell-to-cell RF phase advance, high transit time factor
- No RF phase shifters, less active components
- Compatible with beam window, high R/Q

**Example:** S. Tantawi, SLAC, LCWS2019

**Disadvantages:**
- It is still a bulky waveguide distribution system
- It still requires RF coupler and cryo-module feed-through per cell
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited
Magnetic (inductive) cell-to-cell RF coupling

Advantages:
- Single RF coupler and cryo-module feed-through
- Compact RF waveguide network
- Single RF cavity unit: RF structure
- Compatible with beam window, high R/Q

Disadvantages:
- Highest power in the RF coupler
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited
- Cell-to-cell RF phase advance is \( \pi \), lower transit time factor

Example: LEP RF cavity
Electrical (Capacitive) cell-to-cell RF coupling

Advantages:
- Single RF coupler and cryo-module feed-through
- Compact RF waveguide network
- Single RF cavity unit: RF structure

Disadvantages:
- Highest power in the RF coupler
- Cell-to-cell RF phase advance is fixed, beam energy variation is limited
- Cell-to-cell RF phase advance is 180 degree: Pi-mode, lower transit time factor
- NON-Compatible with beam window, lower R/Q
- **High electric field on the iris**, RF breakdown

Example: LEP2 RF cavity
Travelling wave structure with recirculation

Advantages:
• Arbitrary cell-to-cell RF phase advance, high transit time factor
• Single RF cavity unit: RF structure
• Compatible with both Electric and Magnetic cell-to-cell coupling

Disadvantages:
• Less compact RF waveguide network
• Two RF couplers and cryo-module feed-throughs
• Highest power in the RF couplers
• Cell-to-cell RF phase advance is fixed, beam energy variation is limited

Example: BTW structure for proton therapy, PRAB20, (2017)

RF recirculation, see I. Syratchev LINAC12
Conclusions I

• Combining a set of independent RF cavities into a multicell RF structure requires giving up independent RF phase control of each cavity.

• The RF phase difference between cavities become fixed to cell-to-cell RF phase advance

• This is true for all concepts presented above

• Some flexibility in operation is lost. The RF structure only works effectively in a certain limited range of beam energies, since relativistic beta < 1

• On the positive side, the complexity of the system is greatly reduced

• In fact, this is how all the low energy ion linacs are designed and operated. Each RF structure works in a certain limited energy (beta) range

Example: CERN Linac4
PIMS structure PAC2009
Design beta = 0.43
Energy range: 102-160 MeV/p
Conclusion II (Baseline proposal)

- In case, beam window can be used. **Magnetic coupled standing wave structure** provide solution with the most compact waveguide network
- Only **one RF coupler** and cryo-module feed-through is necessary to feed all the RF cells
- Number of **beam windows** is reduced from 2\*Ncells to Ncells+1
- There are two disadvantages:
  - Higher ( x Ncells) RF power per coupler
  - Lower transit time factor: from 0.83 (Chris’s design) to 0.7 (pi-mode)
- …
Conclusion III (Interesting alternatives)

- Magnetic coupled traveling wave structure with recirculation provide solution with higher transit time factor.
  - But the price to pay is:
    - Two RF power couplers: input and output
    - Special waveguide component for recirculation: directional coupler
    - More (shorter) cells for the same total RF structure length

- Electric coupled structure provide solution in case beam window cannot be used
  - There are some disadvantages compared to magnetic coupling:
    - High electric field on the iris, RF breakdown
    - Lower R/Q, in particular for large aperture