Low-β high gradient S-band accelerating structure for hadron therapy linacs*

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  - Evgeny Savin (also in NRNU MEPhI)
  - Alexander Smirnov
Content

- Proton and carbon therapy
- Advanced Compact Carbon Ion Linac
- High gradient limits
- Accelerating structure for $\beta=0.5$-$0.7$
- Accelerating structure for $\beta=0.43$
- Accelerating structure for $\beta=0.3$
- Conclusions
X-ray and ion therapy

• Conventional compact photon therapy linacs deliver a significant amount of dose outside the tumor region

• High-energy protons and heavy ions physical depth-dose distribution in tissue is characterized by a small entrance dose and a distinct maximum (Bragg peak)

• For particles the dose before the tumor is ~50% less that at the tumor region

• Carbon ions have much narrower Bragg peak comparing to protons ~ 3 times higher efficiency

• Carbon ions ~35% better treat “radioresistant” hypoxic cells than protons, have higher Radio-Biological Efficiency

• Lower scattering before the tumor for carbons
# Accelerators for hadron therapy

<table>
<thead>
<tr>
<th></th>
<th>Cyclotron</th>
<th>Synchrotron</th>
<th>Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particles</strong></td>
<td>p or C</td>
<td>p, C</td>
<td>p, C</td>
</tr>
<tr>
<td><strong>Variable energy</strong></td>
<td>With degrader</td>
<td>From pulse to pulse without losses</td>
<td>From pulse to pulse without losses</td>
</tr>
<tr>
<td><strong>Beam quality</strong></td>
<td>Bad quality due to beam energy degrader</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>CW</td>
<td>&lt; 1 Hz</td>
<td>&lt; 300 Hz</td>
</tr>
<tr>
<td><strong>Compactness</strong></td>
<td>Best</td>
<td>Good</td>
<td>Depends on gradient</td>
</tr>
</tbody>
</table>
Advanced Carbon Ion Linac (ACCIL)

- 200-250 MeV for protons and 400-450 MeV/u for $^{12}$C$^{5+}$ in order to penetrate up to 30 cm inside the human tissue
- Total linac length 45 m with 50 MV/m accelerating gradient at S-band
- 500 ns pulse at 120 Hz rep. rate
- $10^{10}$ protons/second (27μA current) and $10^9$ ions/second (13.4μA particle current) intensity
- Beam average particle current
  - 1.62 nA - protons
  - 0.8 nA - $^{12}$C$^{5+}$
High gradient limits

Maximum surface electric field

A reliable surface field in structures with nose cones is <160 MV/m (experienced in RF guns and Side Coupled linacs)

Pulsed heating

\[ \Delta T = \frac{H_{\text{max}}^2 \sqrt{t_{\text{pulse}}}}{\sigma \delta \sqrt{\pi \rho' c_\varepsilon k}} \]

for annealed copper

\[ \Delta T_{\text{max}} = 50 \text{ K} \]

where \( \Delta T \) – is the pulsed heating value [K], \( H_{\text{max}} \) – maximum surface magnetic field [MA/m] and \( t_{\text{pulse}} \) – is the total pulse length including transient processes [\( \mu \text{s} \)]. \( \sigma \) – electrical conductivity, \( \delta \) - skin depth, \( \rho' \) - density, \( c_\varepsilon \) - specific heat, \( k \) – thermal conductivity of the metal.

Modified Poynting vector

\[ S_c = \text{Re}\{S\} + \frac{\text{Im}\{S\}}{6} \]

For 1.5 \( \mu \text{s} \) pulse length and S band the limit is \( \sim 2.8 \text{ MW/mm}^2 \) \( (10^{-6} \text{ bpp/m breakdown rate}) \).* This parameter hasn’t been confirmed for S-band linacs yet, but we will keep all 3 breakdown parameters below limits.

* A. Grudiev et al. RF design of a novel S-band backward traveling wave linac for proton therapy, Proceedings LINAC’14
$\beta=0.3-0.7$ accelerating structures. Main goals

- 19 accelerating tanks with fixed phase velocities
- Accelerating gradient 50 MV/m
- S-band
- Pulse flat-top 500 ns
- Rep. frequency 120 Hz
- Consider standing and traveling wave structures
$\beta=0.5$-$0.7$ Traveling wave structures

- Disk-loaded waveguide based structure with magnetic coupling is used
- Constant gradient is chosen
- One can control group velocity along the linac keeping aperture radius constant
- There is pulsed heating at magnetic coupling spots

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shunt impedance, MOhm/m</strong></td>
<td>56</td>
<td>58</td>
<td>67</td>
</tr>
<tr>
<td><strong>Filling time, ns</strong></td>
<td>1000</td>
<td>1000</td>
<td>1500</td>
</tr>
<tr>
<td>$P_{\text{in peak}}, \text{ MW}$</td>
<td>40</td>
<td>54</td>
<td>54</td>
</tr>
</tbody>
</table>

![Graph showing gradient vs. $z$ (m)](image)

- Shunt impedance, MOhm/m
- Filling time, ns
- $P_{\text{in peak}}, \text{ MW}$
$\beta = 0.43$ Traveling wave structure

- Although noses increase shunt impedance, surface E field is at the breakdown limit level

$\Delta f = 0.316$ MHz
Iris thickness 2 $\rightarrow$ 4 mm
Stress 81 $\rightarrow$ 54 MPa

<table>
<thead>
<tr>
<th></th>
<th>Noses</th>
<th>No noses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>$5\pi/6$</td>
<td>$5\pi/6$</td>
</tr>
<tr>
<td>$E_{acc}$, MV/m</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$E_{max}$, MV/m</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>Shunt impedance, MOhm/m</td>
<td>51</td>
<td>36</td>
</tr>
<tr>
<td>Group velocity, %</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Pulsed Heating, K (limit 50)</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>$&lt;\text{Sc}&gt;$, MW/mm² (limit ~2.8)</td>
<td>0.7</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Stress, MPa

Δ$F = -0.316$ MHz
Iris thickness 2 $\rightarrow$ 4 mm
Stress 81 $\rightarrow$ 54 MPa
β=0.43 Standing wave geometries

- Biperiodic (BPS), Side coupled (SCL) and Disks and Washers (DAW) compensated structures were compared to BTW
- BTW shows higher shunt impedance at lower peak fields
- BTW filling time is lower

<table>
<thead>
<tr>
<th>Structure type</th>
<th>BPS</th>
<th>BTW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling, %</td>
<td>4.6</td>
<td>36</td>
</tr>
<tr>
<td>Shunt impedance, MOhm/m</td>
<td>32</td>
<td>36</td>
</tr>
<tr>
<td>Eacc, MV/m</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Emax, MV/m</td>
<td>112</td>
<td>90</td>
</tr>
<tr>
<td>Pulsed Heating, K (limit 50)</td>
<td>15.7</td>
<td>18</td>
</tr>
<tr>
<td>&lt;Sc&gt;, MW/mm^2 (limit ~2.8)</td>
<td>1.35</td>
<td>1.3</td>
</tr>
<tr>
<td>100% filling time, ns</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Power (20 cells, 50 MV/m), MW</td>
<td>35.5</td>
<td>30</td>
</tr>
</tbody>
</table>

- Side Coupled
- Disks and Washers
- Biperiodic
\( \beta = 0.3 \) BTW

- Accelerating cell length is too small to consider BPS => BTW is chosen
- Highest shunt impedance is at \( 2\pi/3 \) mode
- Cell length is too small -> needs to be increased

\[ \theta = 2\pi/3, \ 50 \text{ MV/m} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D hole, mm</td>
<td>8</td>
</tr>
<tr>
<td>( a ), mm</td>
<td>3</td>
</tr>
<tr>
<td>( t ), mm</td>
<td>1.5</td>
</tr>
<tr>
<td>( L ), mm</td>
<td>10.5</td>
</tr>
<tr>
<td>Shunt impedance, MOhm/m</td>
<td>23.5</td>
</tr>
<tr>
<td>( E_{\text{max}} ), MV/m</td>
<td>112.5</td>
</tr>
<tr>
<td>Pulsed Heating, K</td>
<td>33</td>
</tr>
<tr>
<td>( &lt;\text{Sc}&gt; ), MW/mm^2</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Spatial harmonics

• There is an infinite number of spatial harmonics for periodic structures

\[ L = \frac{\beta \lambda (\theta \pm m \pi)}{2\pi} \]

• Accelerating cell length \( L \) is calculated with this formula.

We want to operate at spatial harm. -1

• After the change of the spatial harmonic, group velocity remains the same

• Length (m=-1)=21 mm for \( \theta = \frac{5\pi}{6} \)

• With 21 mm cell length there is a room for noses
β=0.3 BTW at -1 spatial harmonic

- $5\pi/6$ mode allows to achieve the highest shunt impedance at -1 spatial harmonic
- In the longer structure noses can be introduced to increase shunt impedance
- Elliptical noses profile allows to decrease the maximum surface fields

<table>
<thead>
<tr>
<th></th>
<th>m=0, $2\pi/3$</th>
<th>m=-1, $5\pi/6$, no noses</th>
<th>m=-1, $5\pi/6$, noses</th>
</tr>
</thead>
<tbody>
<tr>
<td>t, mm</td>
<td>2</td>
<td>3</td>
<td>2.5</td>
</tr>
<tr>
<td>$&lt;\text{Sc}&gt;$, MW/mm^2</td>
<td>1.4</td>
<td>2.03</td>
<td>1.3</td>
</tr>
<tr>
<td>Pulsed heating, K</td>
<td>24</td>
<td>33.46</td>
<td>28.2</td>
</tr>
<tr>
<td>Emax, MV/m</td>
<td>92.5</td>
<td>130</td>
<td>156.5</td>
</tr>
<tr>
<td>Shunt impedance, MOhm/m</td>
<td>22</td>
<td>18.58</td>
<td>31.7</td>
</tr>
<tr>
<td>$\Delta T$, C (22C ambient)</td>
<td>39.2</td>
<td>21.2</td>
<td>15.6</td>
</tr>
<tr>
<td>Von Mises stress, MPa</td>
<td>57</td>
<td>75</td>
<td>59.6</td>
</tr>
<tr>
<td>Length, mm</td>
<td>10.5</td>
<td>21</td>
<td>21</td>
</tr>
</tbody>
</table>

E. Savin et al. Low-beta high gradient S-band accelerating structure for hadron therapy linacs RuPAC 2016

Stress, MPa

- 59.6
- 43.6
- 16.4
- 0.22

E, MV/m

- 156.5
- 0

$\beta=0.3$ BTW at -1 spatial harmonic
Conclusions

• Carbon ion therapy is more efficient than X-ray and have higher Radio Biological Efficiency

• Treatment with linacs is more efficient than with cyclotrons and synchrotrons due to the better beam quality and faster energy variation

• Argonne National Laboratory and RadiaBeam Systems developed an Advanced Compact Carbon Ion Linac, which accelerates carbon ions up to 450 MeV/u at 45 m length

• S-band accelerating structures were developed for both protons and carbon ions acceleration in the velocity range $\beta=0.3..0.7$

• BTW and BPS for $\beta=0.43$ were designed to satisfy requirements of a compact carbon ion linac

• For $\beta=0.3$ a BTW accelerating structure was designed to operate at -1 spatial harmonic

• An advantage of using a -1 spatial harmonic for very low betas over the fundamental spatial harmonic is shown
References

• P.N. Ostroumov et al., Compact Carbon Ion Linac, Proceedings of Na-PAC 2016, Chicago, IL, USA
• A. Plastun et al., Beam Dynamics Studies for a Compact Carbon Ion Linac for Therapy, Proceedings of LINAC 2016, East-Lansing, MI, USA
• S.V. Kutsaev et al., High Gradient Accelerating Structures for Carbon Therapy Linac, Proceedings of LINAC 2016, East-Lansing, MI, USA
Accelerating efficiency. Transit time factor

- S-band was chosen for high gradient section, because it was proven to sustain 50 MV/m*
- Pillbox cavity – typical S-band structure

- S-band in pillbox has the highest efficiency at β=0.3-0.7

* S.V. Kutsaev et al., High Gradient Accelerating Structures for Carbon Therapy Linac, Proceedings of LINAC 2016, East-Lansing, MI, USA