New trends in proton and carbon ion therapy

LINAC’18 CONFERENCE
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Presented by M. Vretenar, CERN
Hadron therapy rationale

Beam direction

The dose (energy deposited per unit mass) is more focused for protons and light ions – Bragg peak.

Carbon ions have a sharper peak, and an higher radiobiological effectiveness.

Image from GSI, Darmstadt

Courtesy of PSI
Worldwide facilities

- Solid growth trend
- About 30% are ‘single-room’ facilities
- About 15% are carbon ion facilities

Data from www.ptcog.ch
Design choices in medical linacs

- Historically, an RF frequency of 3 GHz was chosen
- Beam dynamics design and average accelerating gradient choice remarkably affect the efficiency (ZTT)
- Carbon therapy linacs have a factor four difference in the overall voltage gain per nucleon – fundamental difference wrt proton therapy linacs

\[ \Delta W \propto \sqrt{ZTT \cdot P_d \cdot L} \]

ZTT is also related to the choice of linac gradient and length: operating frequency, cavity design (BD and heat dissipation), beam dynamics choices (beam aperture)
Low energy beam acceleration
Design choices for low energy beam acceleration

Commercial injector

Cyclinac

RFQ

SCDTL

H-type DTL

Qualitative assessment between RFQ, DTL and H-type cavities for low energy acceleration. RFQ in blue, DTL in orange, H-type cavities in green.

U. Amaldi, Cyclinac: Novel fast-cycling accelerators for hadrontherapy, 2007
The 750 MHz IH

ZTT $\propto \sqrt{\text{RF Frequency}}$
if bore radius scales as well

Here constant 2.5mm bore radius

Similar graphs widely studied, here for the first time a ‘medical application’ comparison is proposed – RF frequencies and beam aperture

S. Benedetti, A. Grudiev and A. Latina, Design of a 750 MHz IH structure for medical applications, Linac16
Matching section: issues of a frequency jump

Challenge if **IH after RFQ**: from FODO lattice to triplet focusing

Challenge if **DTL after RFQ**: frequency jump from 750 MHz to 3 GHz

- Factor 4 in **phase acceptance** for shorter wavelength $\lambda$ and in the **RF defocusing** $\Delta p_r$.

$$\Delta p_r = -\frac{\pi e E_0 T L r \sin \phi}{c \beta^2 \gamma^2 \lambda}$$

- Factor 2 in **energy acceptance** $w_{max}$.

$$w_{max} = \sqrt{\frac{2qE_0 T \beta^3 \gamma^3 \lambda}{\pi mc^2} (\varphi_s \cos \varphi_s - \sin \varphi_s)}$$

The longitudinal matching and the transverse control of the beam is more challenging with a frequency jump at low energy.
750 MHz IH vs 3 GHz DTL comparison

Linac comparison from 5 MeV to 20 MeV

Equal length and 100% transmission as design goals

An IH from 5 to 10 MeV followed by a DTL is advantageous for:

- Lower emittance growth
- Larger space for diagnostic
- Lower number of quadrupoles
- Machining simplicity

S. Benedetti, A. Grudiev and A. Latina, High gradient linac for proton therapy, PRAB2017
Facility size
DESIGN GOAL AND CONSTRAINTS

\[ E_a \equiv E_0 T \geq 50 \text{ MV/m} \]

\[ S_c/E_a^2 < 7 \times 10^{-4} \text{ A/V} \]

scaled values from CLIC and TERA data:

\[ S_c^8 \cdot \frac{t_{pulse}^3}{BDR} = \text{const} \]

with:

- \( S_c < 4 \text{ MW/mm}^2 \)
- \( t_{TERA} = 2500 \text{ ns} \)
- \( t_{CLIC} = 200 \text{ ns} \)
- \( \text{BDR}_{TERA} = \text{BDR}_{CLIC} = 10^{-6} \text{ bpp/m} \)

\[ 2 \times 10^{-7} \text{ bpp} \]
Cavity tuning

The cavity would be actually ready to accelerate particles

S. Benedetti et al, Fabrication and testing of a novel S-Band backward travelling wave accelerating structure for proton therapy linacs, Linac16
The cavity is performing beyond the design goals, proving that stable operation at accelerating gradient higher than 50 MV/m can be reached in a 3 GHz medical linac.

A. Vnuchenko et al, High Gradient Performance of an S-Band Backward Traveling Wave Accelerating Structure for Medical Hadron Therapy Accelerators IPAC18
Carbon ion linacs
CABOTO (CArbon BOoster for Therapy in Oncology)

Total length: 53 m
Total power: 260 MW
Average ZTT: 108 MΩ/m

IH 2.5 to 10 MeV/u – 4 cavities
- 2.5 m long
- 6.5 MV/m
- 402 MΩ/m

DTL 10 to 100 MeV/u – 50 cavities
- 11.7 m long
- 16.2 MV/m
- 117 MΩ/m

CCL 100 to 430 MeV/u – 32 cavities
- 23.1 m long
- 29.7 MV/m
- 107 MΩ/m

S. Benedetti, High-gradient and high-efficiency linear accelerators for hadron therapy, EPFL PhD Thesis
Peculiarities of the design

- Relatively low gradient choice (30 MV/m)
- Structures can be designed shorter
- Beam envelopes are smaller
- Cavity apertures are smaller, ZTT is increased

Lower gradient allows a sharper nose design, but the greatest improvement comes from the aperture reduction.
CERN TwinEBIS and $^{12}\text{C}^{6+}$ RFQ

**TwinEBIS**: In the present set up should be able to provide $1 \times 10^9$ $^{12}\text{C}^{6+}$ ions in a 5 μs pulse ($2 \times 10^{11}$ ions/s)

**LEBT**: aimed to transport and match the beam to the RFQ

**RFQ**: Accelerate the beam up to 2.5 MeV/u (or 5 MeV/u)

V. Bencini et al, High Gradient Performance of an S-Band Backward Traveling Wave Accelerating Structure for Medical Hadron Therapy Accelerators, this conference

TwinEbis should deliver $10^8$ $^{12}\text{C}^{6+}$ at 300-400 Hz in 1.5 μs spill. This beam would be accelerated by the RFQ with 56% transmission and output emittances in the acceptance of CABOTO. Final current of $2.2 \times 10^{10}$ ions/s are 30 times higher than state-of-art carbon ion synchrotrons.
Different design choice with respect to CABOTO, privilege to compactness

Specifically, HG BTW envisaged from 45 to 450 MeV/u, 50 MV/m accelerating gradient

Commercial $^{12}\text{C}^{5+}$ ECR, 476 MHz RFQ to 3 MeV, $^{12}\text{C}^{6+}$ stripping, 476 MHz DTL till 45 MeV/u

S. Kutsaev et al., High-gradient low-$\beta$ accelerating structure using the first negative spatial harmonic of the fundamental mode, PRAB2017
# Carbon ion linacs comparison

<table>
<thead>
<tr>
<th>Source</th>
<th>CABOTO all-linac</th>
<th>ACCIL</th>
<th>CABOTO cyclinac</th>
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<tr>
<td>Source</td>
<td>TwinEBIS (CERN) $^{12}$C$^{6+}$</td>
<td>ECR (commercial) $^{12}$C$^{5+}$</td>
<td>Cyclotron ion source</td>
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<tr>
<td><strong>Low energy acceleration</strong></td>
<td>RFQ (750 MHz), H-type (750 MHz) up to 10 MeV/u, SCDTL up to 100 MeV/u</td>
<td>RFQ (476 MHz), DTL (476 MHz) up to 45 MeV/u</td>
<td>Cyclotron up to 150 MeV/u</td>
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<tr>
<td><strong>High energy acceleration</strong></td>
<td>CCL (3 GHz) up to 430 MeV/u, 30 MV/m accelerating gradient, 30 m long</td>
<td>HG BTW (3 GHz) up to 450 MeV/u, 50 MV/m, 23 m long (estimation)</td>
<td>CCL (3 GHz) up to 400 MeV/u, 30 MV/m accelerating gradient, 23 m long</td>
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<tr>
<td><strong>Pro</strong></td>
<td>Lower power consumption than ACCIL</td>
<td>More compact in length than CABOTO all-linac</td>
<td>Shortest in length, no low-energy acceleration ‘issues’</td>
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<td><strong>Con</strong></td>
<td>Longer than ACCIL</td>
<td>Higher power consumption than CABOTO all-linac</td>
<td>Losses and mismatch at the 150 MeV/u cyclotron-linac transition</td>
</tr>
<tr>
<td><strong>Main reference</strong></td>
<td>S. Benedetti, High-gradient and high-efficiency linear accelerators for hadron therapy, EPFL PhD Thesis</td>
<td>P.N. Ostroumov et al, Compact carbon ion linac, NAPAC16</td>
<td>S. Verdu Andres, CABOTO, a high-gradient linac for hadrontherapy, JRR 54</td>
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Facilities under construction
CERN spin-off company ADAM SA is building in Geneva a commercial linac for proton therapy, with reported acceleration up to 16 MeV (SCDTTL module 2)
ERHA (Enhanced Radiotherapy with HAdrons)

Commercial development of proton therapy linac by ITEL SRL in Puglia (southern Italy) is reported to progress with significant milestones reached.

Many similarities with the IMPLART research project: commercial injector, 3 GHz SCDTL, 3 GHz CCL.

The company policy is less outreach than ADAM SA, thus the current status of the project is not known.
Conclusions

Significant breakthroughs have changed the direction of hadron therapy linacs research in the past years

An efficient acceleration at low energy is now possible thanks to the 750 MHz RFQ built at CERN

An ideal continuation have been proven to be a 750 MHz IH DTL up to 10 MeV/u, for both carbon and proton therapy linacs

After many years of preliminary tests, a high-gradient 3 GHz cavity has been built, and it has proven stable operation at 60 MV/m, demonstrating the feasibility of compact linac-based facilities

The research is now mostly focused on carbon therapy linacs, which present many advantages over state-of-art synchrotron design.
Thank you for your attention
(and for your patience in listening to the replacement speaker!)