New ion therapy machine design study

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(and other institutions)
Overview

- Hadron therapy
- Global situation
- PIMMS project
- New machine
- Extraction specification
- First ideas
- Conclusions
Hadron therapy (I)

- Ionizing radiation is used in medicine since long time (X-rays for diagnostic: 1895, first application to treat skin cancer: 1896)

- Fast neutrons were used for cancer therapy in 1938-1948, poor effects

- Particle therapy with protons was proposed by Robert Wilson in 1946 (Wilson, R.R. (1946), “Radiological use of fast protons”, Radiology 47, 487.)

  (also first director of Fermilab)

- In Berkeley the first treatments with protons - 1954, Helium - 1957, Neon – 1975, Oxygen; Carbon was found optimal;

- Bevalac closed in 1993
**Hadron therapy (II)**

- Loma Linda – first hospital-based proton-therapy facility (1990’s)

- Currently there are about 50 hospital-based proton therapy facilities, several companies sell them; About 150,000 patients were treated.

- Nowadays proton therapy is mostly based on cyclotrons!
**Light-Ion therapy**

- Carbon ion Bragg peak is narrower, entrance dose smaller, but fragmentation leads to a tail in dose distribution.
- Lateral dose distribution is better for Carbon (less scattering).
- Relative Biological Effectiveness:
  \[ RBE = \frac{D_{\text{photon}}}{D_{\text{ion}}} \] for the same biological effect.
- \( RBE_{\text{proton}} \approx 1.1, RBE_{\text{C}} = 2-5 \)
- Distance between ionizations for Carbon 20x shorter than for protons.
**Light-ion therapy today**

- Japan: 5 centres, including the oldest HIMAC (1994)
- Europe: 4 centres, Heidelberg (HIT, 2006), Marburg (MIT), CNAO and MedAustron
  - First treatments in GSI – HIT build on this fundaments
- China: 2 centres + 1 in construction
- South Korea: 2 centres in construction
- CNAO and MedAustron follow PIMMS design
- European centers (HIT, MIT, MedAustron) were build with big participation of industry
  - Siemens retracted from this business.
- Hitachi and Toschiba offer carbon-therapy solutions
- All ion therapy centres are based on synchrotrons
Proton-Ion Medical Machine Study done at CERN in 1996-2000

Documented in CERN/PS 99-010 (DI) and CERN/PS 2000-007 (DR)

Synchrotron circumference: 80 m (for protons < 25 m)

Extensive study of resonant slow extraction physics and methods:
- Betatron core acceleration
- Now most medical synchrotrons use RF-KO extraction, because it is rather easy to control (spill stop ~200 μs)

Next PIMMS

- Next Ion Medical Machine Study (NIMMS, proposed name)
- The goal is to revisit approach to medical carbon machine (PIMMS) after 20 years of technology developments
- Design machine for treatment and research (data for space)
- An association of Balkan countries (SEEIIST) as one of major driving forces – idea of mixed therapy and research centre in SE Europe
- Collaboration formed, kick-off meeting April 29th, 2019, about 30 participants
- Parallel development in Japan (quantum scalp, vision presented by K. Noda at IPAC19, talk: “Review of Ion Therapy Machine and Future Perspective”)
Main requirements:

- Smaller footprint
- Faster dose delivery
- Cheaper
- Small emittance (active scanning)
- Multiple beams - radiography (eg. $^4\text{He}^{2+}$ and $^{12}\text{C}^{6+}$ beams together)

Technical choices:

- All linac solution (keyword: CABOTO)
  – like AVO-ADAM but for Carbon – lot of R&D still required
- **Superconducting synchrotron – our baseline**
- Cyclotron, FFAG, Rapid-Cycling Synchrotron - studied for comparison
New superconducting magnets

- To decrease synchrotron size need to use superconducting magnets
- Canted Cosine Theta technology
- Design choices:
  - 90 deg bends with nested quads
  - Powered in series
  - Bmax=3.5 T
  - rho = 1.9 m
- See Elena’s talk at Archamps workshop
Superconducting synchrotron

Main specifications:

- $E_{\text{inj}} = 10 \text{ MeV/u}$, $E_{\text{ext}} = 100-430 \text{ MeV/u}$
- protons, He… C, O… heavier?
- Beam intensity: $10^{10} \text{C}^{6+}$ (treatment in one fill)
- Norm. emitt = 1 mm mrad
- Extraction duration: 0.5-60 s
- Typically 30 (50) fractions, 0.1 s each, up to several Gy/s (for voxel scanning)
- Energy change (1-7 MeV/u) between fractions
- Fast beam abort or pause (synch. with breath)
- ‘flash’ extraction ~100 Gy/s (1-2 ms) – SPS burst mode
- Flexible, easy to operate (control system!) and reliable
Superconducting synchrotron

Our baseline layout:

- Total length: ~27 meters
- Injection of $10^{10}$ Carbon ions is a challenge (ongoing work on multi-turn injection, high-current source, 10 MeV/u injector linac)
- Aperture 60 mm
- $t_{rev} = 0.12$ μs
- Magnets ramp rate: 120 AMeV/s
Some aspects of extraction

- Sextupoles:
  - Chromaticity control
  - Resonance control - dispersion-free section (Elena new lattice design: double-bend achromat)
  - Current optics: max $k_2 l = 0.4 \text{ m}^{-2}$
- Bumpers:
  - Closing bumper location?
- E-Septum:
  - $L=0.8 \text{ m}, \ E=5 \text{ MV/m}$
- M-Septum:
  - Superconducting?
Extraction study just started

- Tracking with MADX-PTC
- Some python scripts inherited from A.Garonna (BioLEIR project)
  - Especially for RF-KO
- Following PIMMS report
- Hardt condition difficult with current layout
- Iterative procedure

Single particle $^{12}$C$^{6+}$ at 430 MeV/u
$dp/p=-0.005$
Sextupole ramp: from 0 to 0.339 m$^{-2}$

$Q_H = 1.67$ example
Where we could use some help?

- Feedback and tips on hardware choices for RF-KO and fast extraction
  - eg. superconducting magnetic septum?
- Could burst mode be used to provide flash therapy beam?
  - If yes – what is needed (fast quadrupoles, control system capabilities)
  - If not, what else? Use half-integer resonance?
- Possibility to discuss advancements of slow extraction design at this meeting.
Conclusions

- New generation carbon therapy and biophysics research machine is being designed
- It must be small, fast, stable, flexible
- Extraction from a small synchrotron is an interesting problem, especially that 3 types are needed:
  - RF-KO, fast and ‘fast-slow’ (burst mode)
- Flash therapy requires very short spills/fractions and getting them in a stable way is not trivial
- Suggestions and discussions are welcome