New ion therapy machine design study

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Slow Extraction and Activation Working Group
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(and other institutions)

Overview

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

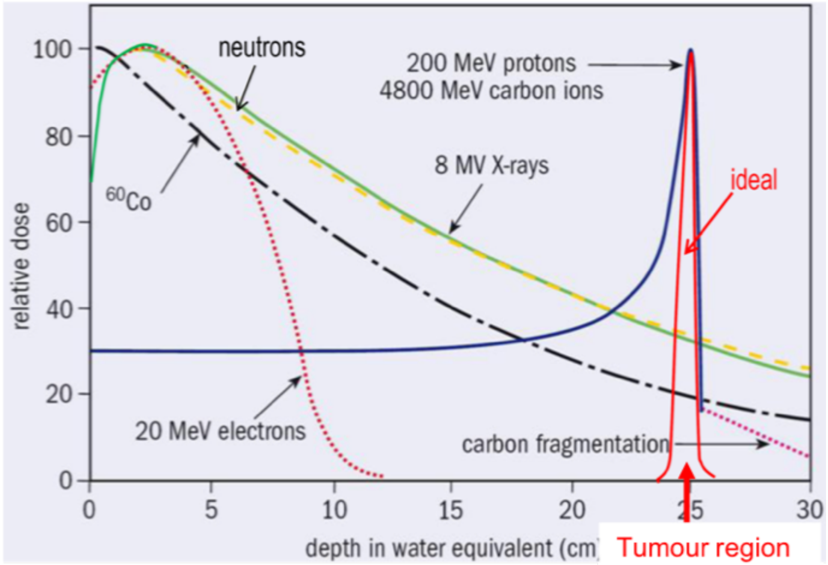
Hadron therapy (I)

- 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)

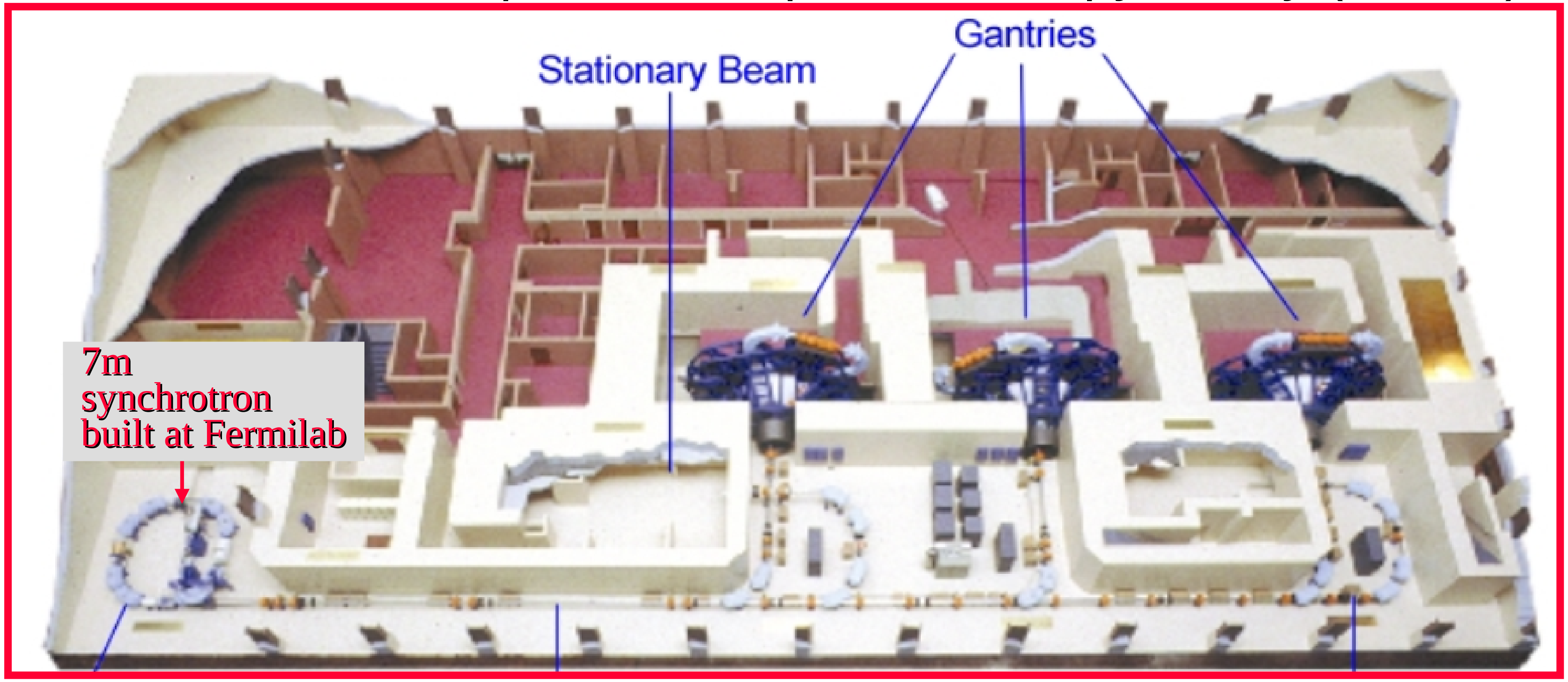


  - In Berkeley the first treatments with protons - 1954, Helium - 1957, Neon – 1975, Oxygen; Carbon was found optimal;

  - Bevalac closed in 1993

Hadron therapy (II)

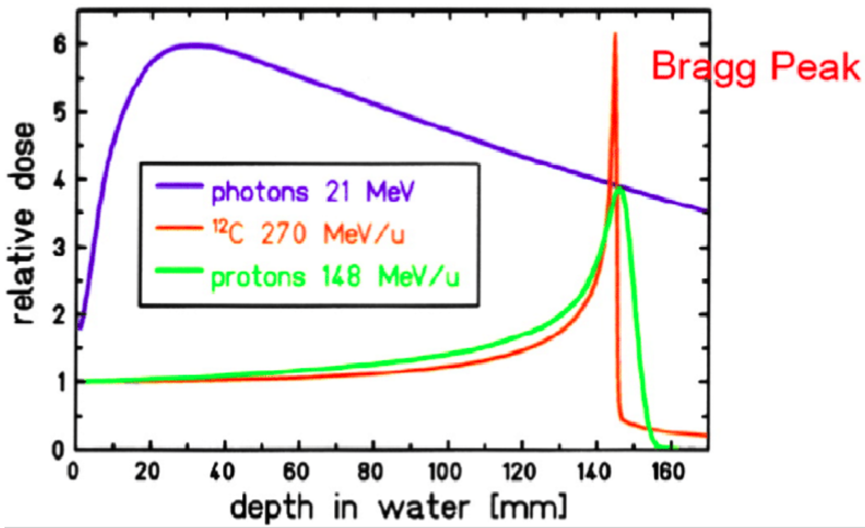
- Loma Linda – first hospital-based proton-therapy facility (1990's)

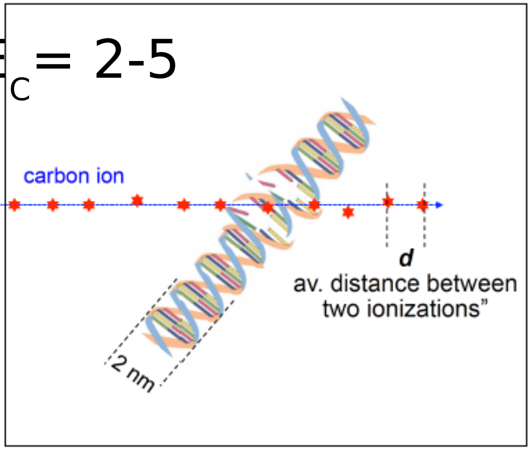


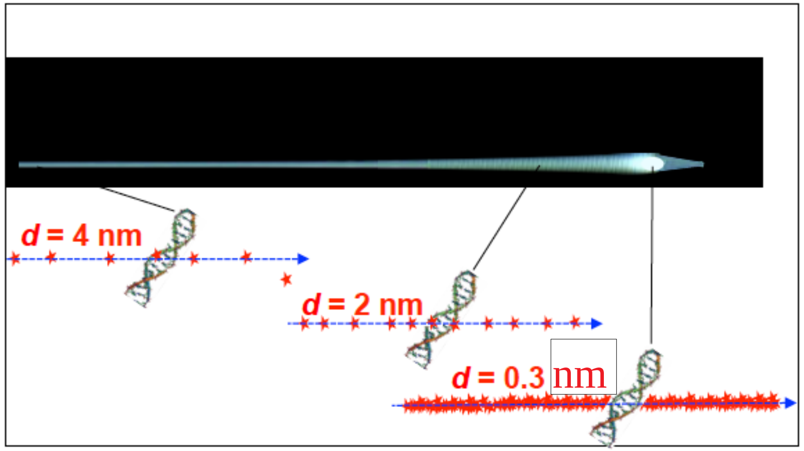
- Currently there are about 50 hospital-based proton therapy facilities, several companies sell them; About 150,000 patients were treated.
- Nowadays proton therapy is mostly based on cyclotrons!

Light-Ion therapy

- Carbon ion Bragg peak is narrower, entrance dose smaller, but fragmentation leads to a tail in does distribution
- Lateral dose distribution is better for Carbon (less scattering)
- Relative Biological Effectiveness $RBE = D_{photon}/D_{ion}$ for the same biological effect
- $RBE_{proton} \approx 1.1$, $RBE_C = 2\text{-}5$
- Distance between ionizations for C 20x shorter then for protons





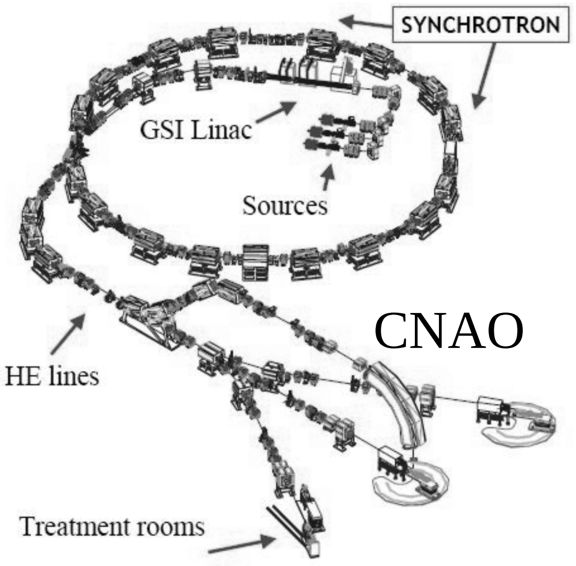


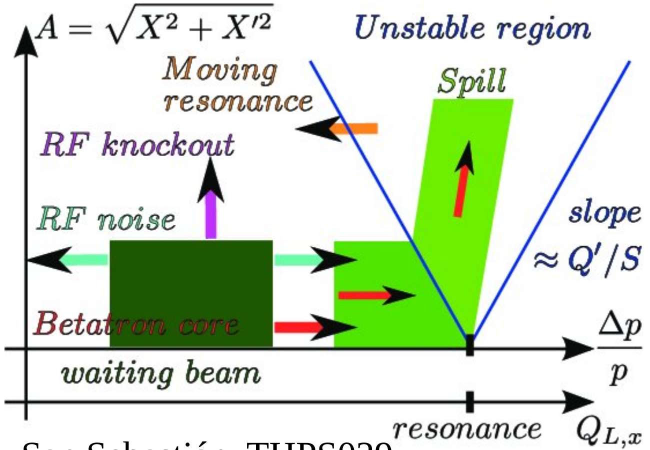
Light-ion therapy today

- 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

PIMMS

- Proton-Ion Medical Machine Study done at CERN
  n 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)

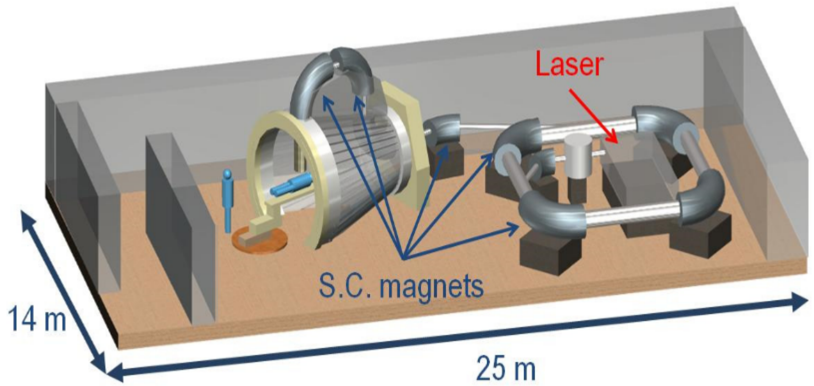




G. Feldbauer, et al.
Proceedings of IPAC2011, San Sebastián, THPS029

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 scalpel, vision presented by K.Noda at IPAC19, talk: “Review of Ion Therapy Machine and Future Perspective”)

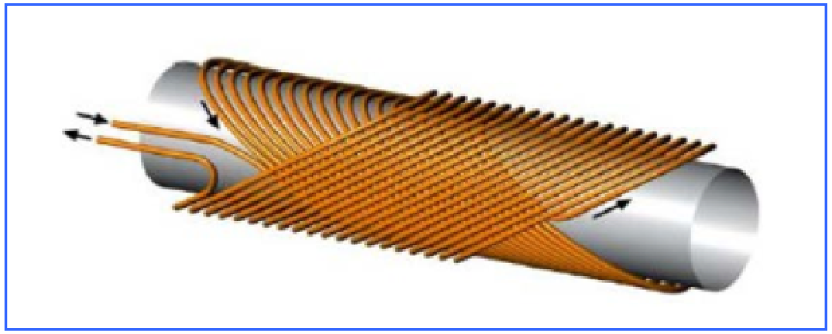


NIMMS

- Main requirements:
  - Smaller footprint
  - Faster dose delivery
  - Cheaper
  - Small emittance (active scanning)
  - Multiple beams - radiography (eg. $^{4}He^{2+}$ and $^{12}C^{6+}$ 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 June 2018: https://indico.cern.ch/event/682210/contributions/3040451/attachments/1671076/2723570/IONS2018_EBenedetto.pdf

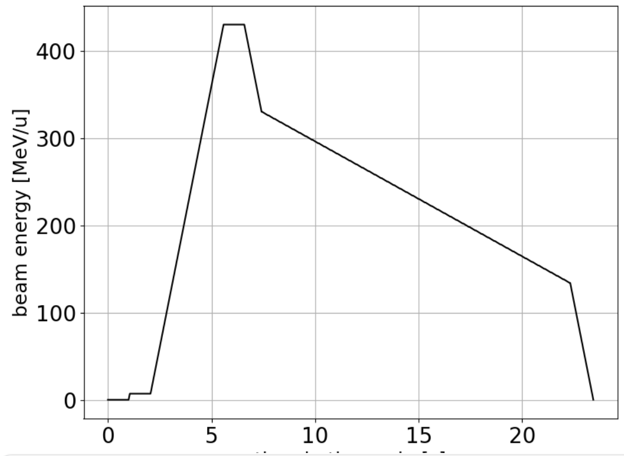


Berkeley

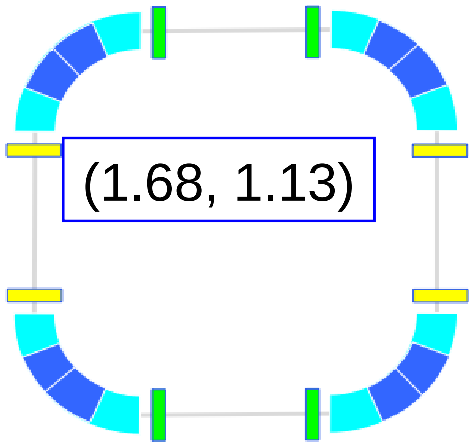
Superconducting synchrotron

<u>Main specifications:</u>

- E_{inj}= 10 MeV/u, E_{ext} = 100-430 MeV/u
- protons, He… C, O… heavier?
- Beam intensity: 10^{10} 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

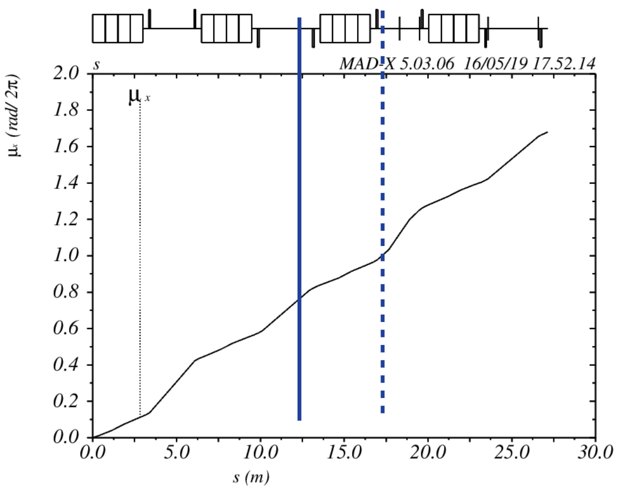


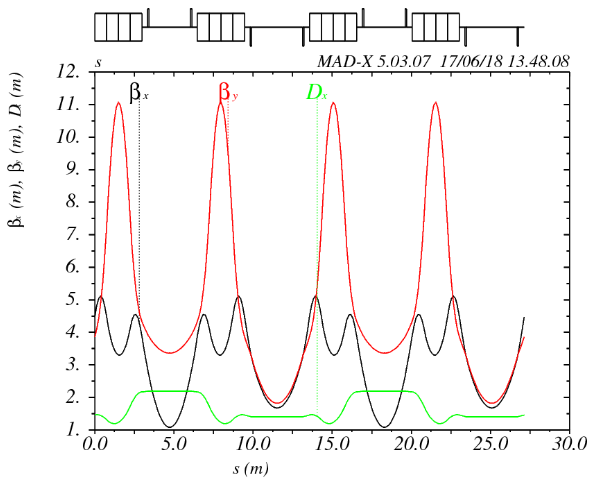
Superconducting synchrotron



<u>Our baseline layout:</u>

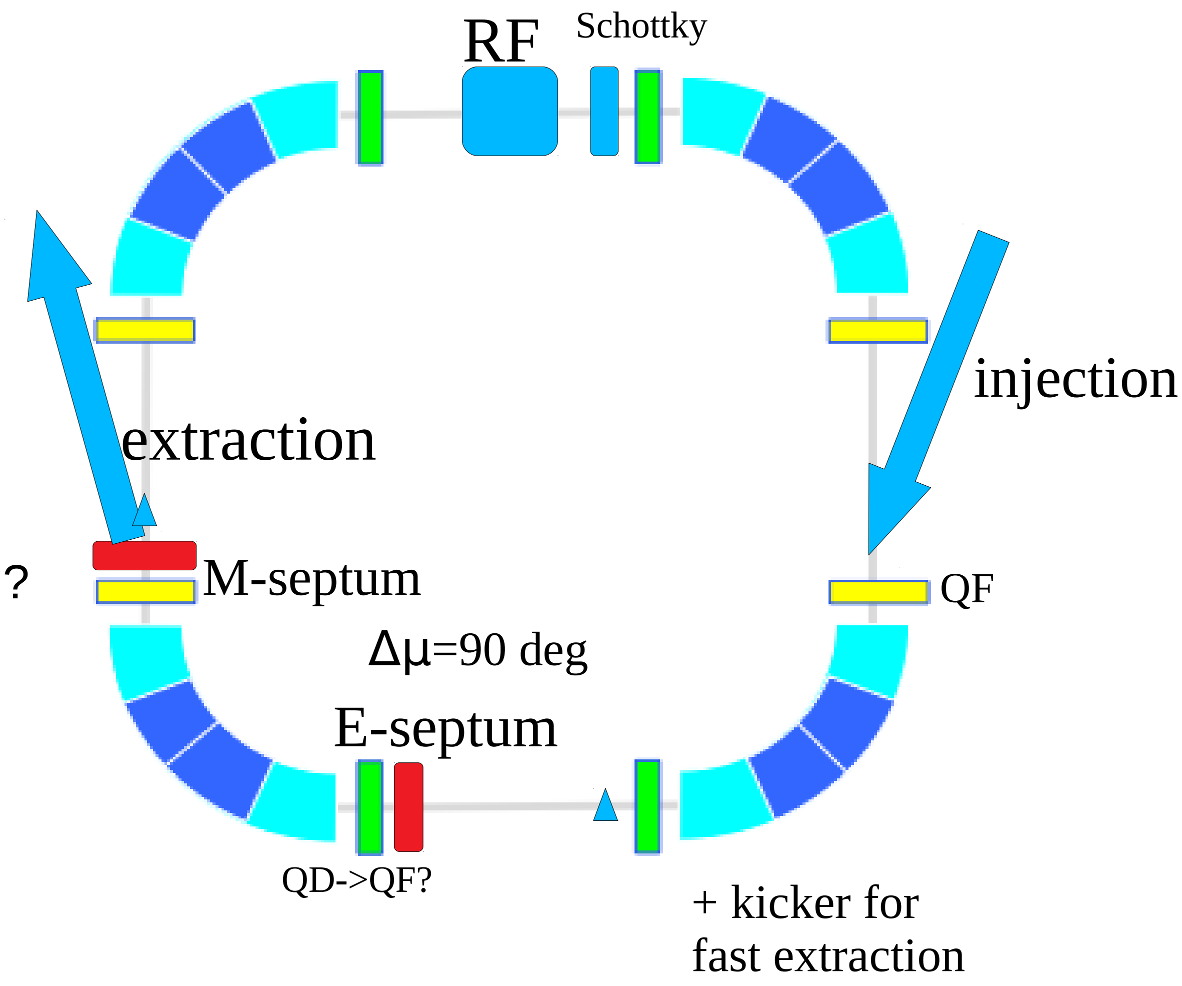
- Total length: ~27 meters
- Injection of 10^{10} Carbon ions is a challenge
  (ongoing work on multi-turn injection,
  high-current source, 10 MeV/u injector linac)
- Aperture 60 mm
- t_{rev}=0.12 µs
- Magnets ramp rate:
  120 AMeV/s





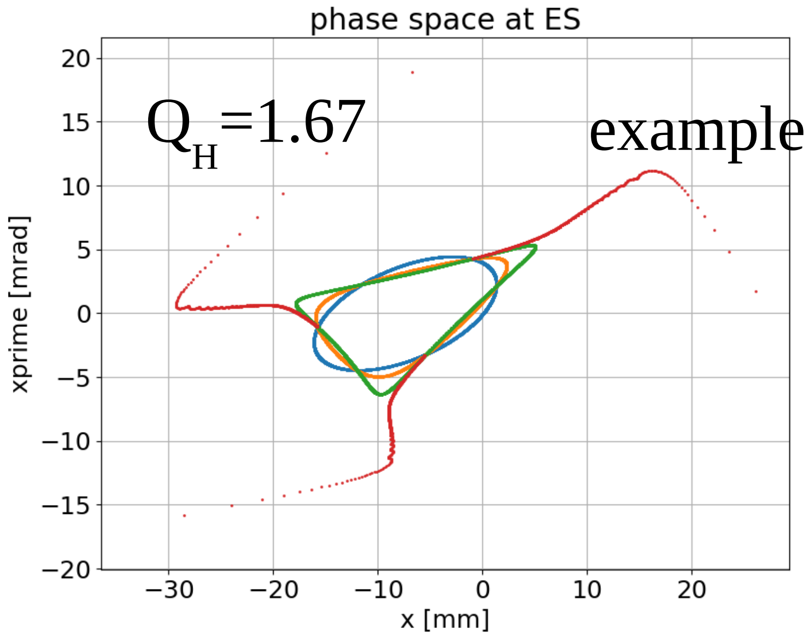
Some aspects of extraction

- Sextupoles:
  - Chromaticity control
  - Resonance control -
    dispersion-free section
    (Elena new lattice design:
    double-bend achromat)
  - Current optics: max $k_2l = 0.4\ m^{-2}$
- Bumpers: ▲
  - Closing bumper location?
- E-Septum:
  - L=0.8 m, E=5 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}

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