Helium-ion therapy system

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TERA Foundation and CERN

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TERA Fondazione per Adroterapia Oncologica

Outline

- Why Helium?
- History and current status of helium radiotherapy.
- Medical requirements and basic beam specifications.
- Therapy machines:
  - cyclotrons
  - high-frequency linacs
  - synchrotrons.
- Ion source and multiturn injection.
- 750 MHz RFQ.
- Helium vs. carbon.
- Conclusions.

Why helium?

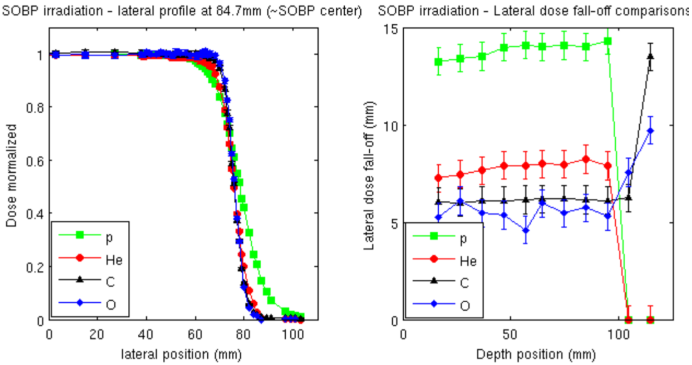
,,Helium are the better protons"

source: A. Peters, HIT

Most research done for $^{4}\mathrm{He}$, but maybe $^{3}\mathrm{He}$ is an interesting option from medical point of view?

Why helium?

Much sharper lateral penumbra compared to protons

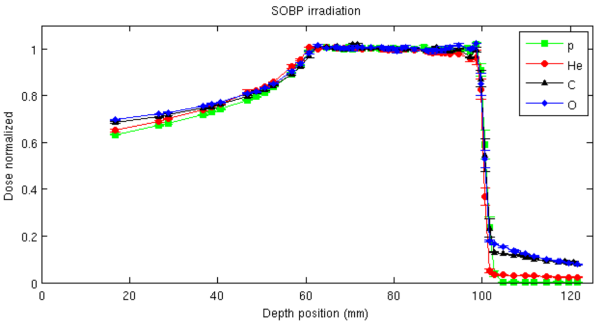


source: T. Tessonnier, PhD, Munich 2017

also: much smaller scattering in the air gap between nozzle and patient

Why helium?

Largely decreased toxic (high-LET!) fragmentation tail, compared to carbon ions.



source: T. Tessonnier, PhD, Munich 2017

Why helium?

Improved differential RBE: RBE increases in target volume but is close to 1.1 in healthy tissues (high LET at trackends)

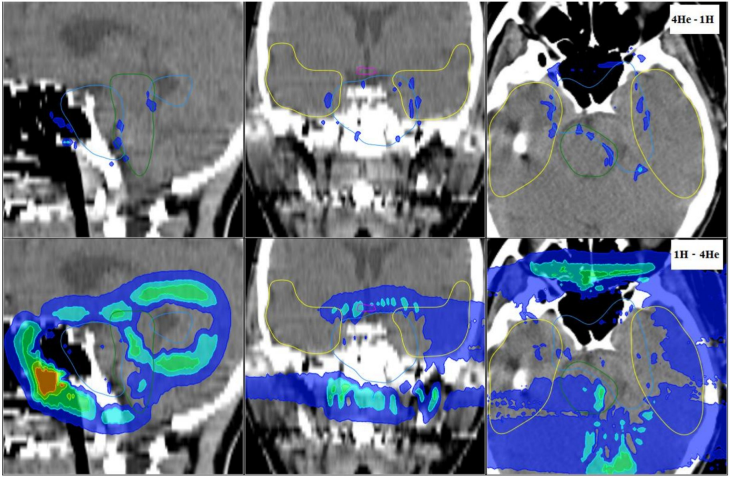


Figure 7.6: Dose difference between the helium ions and proton dose predictions for patient A: the top panel displays the overdosages due to helium ions (^{4}He-^{1}H), the bottom panels

History and current status

- First experiments in Berkeley:

  C.A. Tobias, H.O. Anger and J.H. Lawrence, "Radiological use of high energy deuterons and alpha particles," Am. J. Roentgenol. Radiat. Ther. Nucl. Med. 67: 1-27 (1952).

- Experiments in HIMAC.
- Experiments in HIT:

  Mein, S., Dokic, I., Klein, C. et al. Biophysical modeling and experimental validation of relative biological effectiveness (RBE) for 4He ion beam therapy. Radiat Oncol 14, 123 (2019).

  - system is commissioned for helium beams,
  - simulations, experiments and pre-clinical trials done,
  - TPS by RaySearch with helium option being tested,
  - expected legal permission in 2021.

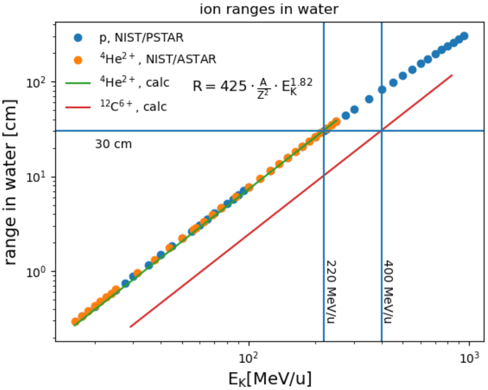
Several publications realted to HIT preparation, eg:

Knäusl B, Fuchs H, Dieckmann K, Georg D. Can particle beam therapy be improved using helium ions? - a planning study focusing on pediatric patients. Acta Oncol. 2016 Jun;55(6):751-9.

Helium is not yet used in clinical practice. No dedicated machines exists.

Medical requirements - beam energy

- particle range in the body: 30 cm
- maximum kinetic energy: as for protons (scaled per unit mass), i.e. 220 MeV/u.
- magnetic rigidity: 4.52 Tm
  - protons: 2.28 Tm,
  - $^{12}\mathrm{C}^{6+}$: 6.35 Tm,
  - $^{3}\mathrm{He}^{2+}$: 3.41 Tm
- scaling factors:
  70% wrt. Carbon machine
  200% wrt. proton machine
  (150% for ^{3}He)



Medical requirements - intensity

Baseline: treat 1 liter tumor with 2 Gy in one spill.

Ion	No of particles required
$^{1}H^{1+}$	$2.63 \cdot 10^{11}$
$^{3}He^{2+}$	$8.23 \cdot 10^{10}$
$^{4}He^{2+}$	$8.23 \cdot 10^{10}$
$^{12}C^{6+}$	$2.0 \cdot 10^{10}$

source: ESRI SEEIIST proposal

estimation based on dE/dx, RBE

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}]$$

Which machine?

Table: Particle therapy accelerators.

	cyclotrons	synchrotrons	linacs
beam energy	fixed	variable	variable
beam structure	continuous	spills (0.1-10 s)	$10\ \mu s$ pulses at 200 Hz
size (p,He,C)[m] (diameter/length)	2.5, 5.3, 6.9	5.5, 14, 20	24, 40, 54
technology state	established	established	emerging

Other options: FFAG, RCS, plasma accelerators, dielectric accelerators - not discussed here, but should not be excluded.

Which machine? - Cyclotrons

- Commercial cyclotrons with helium beams - low energies (eg. IBA Cyclone 70 - 17.5 MeV/u, radioisotope production).
- Research cyclotrons do not reach these energies (eg. RIKEN Ring Cyclotron: 135 MeV/u, total weight 2100t).
- IBA designed 300 MeV/u therapy machine (Y. Jongen, CYC2004) - 700t.
- 400 MeV/u system is being constructed in Caen (France).

Cyclotrone issues:

- charge-exchange extraction for $^4He^{2+}$ not possible(?).
- ESS system: nuclear cross section twice higher than protons - activation.
- $\mathrm{dE/dx}$: 4x higher than protons - active cooling of degraders.

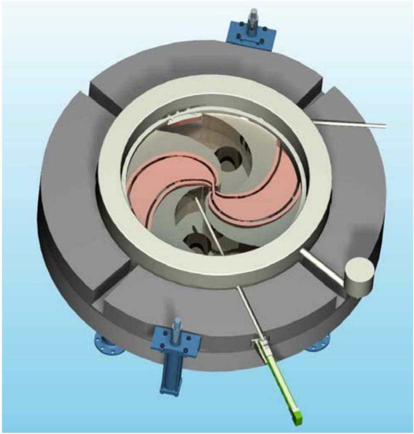


Figure 7. Artist view of the median plane in Carbon-proton, 300 MeV/u, super-conducting cyclotron.

Which machine? - High Frequency Linac

- LIGHT system for protons - by AVO-ADAM - is commissioned.
- A design for carbon is ongoing
(Caboto by TERA, now R&D at CERN - A. Lombardi)
- A version for Helium was proposed.

S. Benedetti, PhD, EPFL, 2018

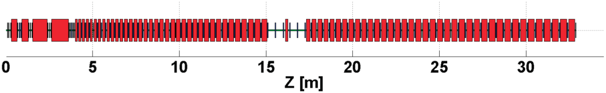
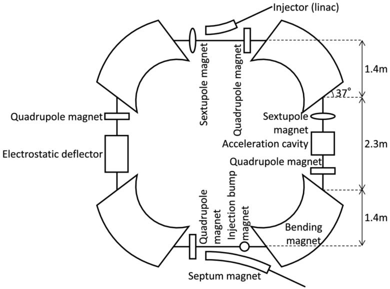


Figure 4.14 – Sketch of the He linac longitudinal dimensions.

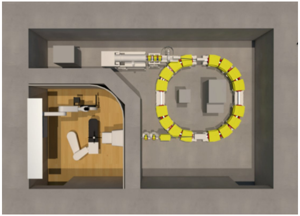
Type of structure	Output energy [MeV/u]	Active Length [m]	Peak power [MW]
750 MHz RFQ	2.5	ND	ND
750 MHz IH	10	2.5	0.3
3 GHz DTL	70	7.6	16.6
3 GHz CCL	70-230	11.2	103.1

Which machine? - proton synchrotrons

- Loma Linda - the first (1990) dedicated proton therapy facility
  - edge-focusing synchrotron.
- Commercial systems: Hitachi (old design 6 dipoles, new design 4 dipoles) and Protom (Radiance 330).
- Designs focus on small footprint and simplicity to compete with cyclotrons.



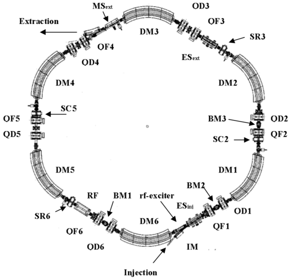
Hitachi (new)



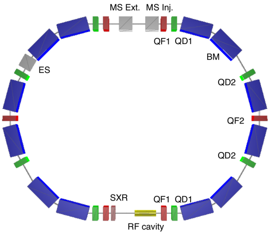
Protom

Which machine? - carbon synchrotrons

- Heidelbeg synchrotron - compact (65 m), very heavy dipoles (4.6 m, 23.5 tons) - inspired by proton machine (?).
- Siemens system: split dipoles and other modifications.
- PIMMS design: large (75 m), more complex but flexible.
- other designs eg., eg. DBA (55 m), Korean (TBA, 60 m), superconducting (E. Benedetto, 30 m).
- Carbon machines are usually more complex than scaled-up proton machines - flexibility needed for various ions and for research programs.



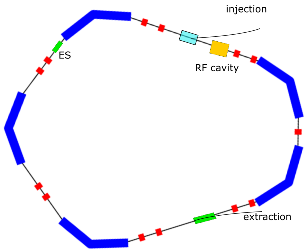
Heidelberg

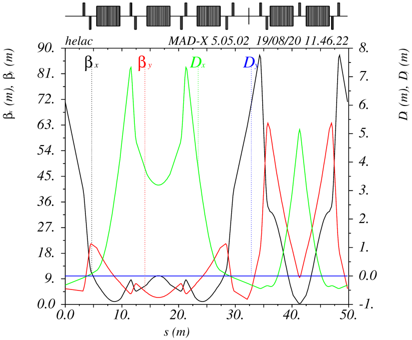


DBA (X. Zhang, arXiv:2007.11787)

Helium synchrotron

- Scale up proton synchrotron or scale down carbon machine - established designs
- Dispersion free regions desirable for injection, extraction and RF
- Look for new optimal, try exotic lattices, eg. DBA+TBA





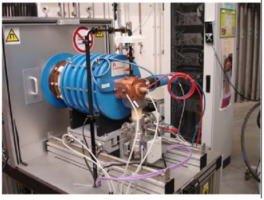
Circumference 50 m (45 m is feasible), two long dispersion-free regions, dipoles 4.1 m long.

arXiv:2008.08674 [physics.acc-ph]

Ion source and multiturn injection

- Multiturn injection at 4 MeV/u, 30 turns, 50% efficiency:
  $I_{source} = 977\mu A$ - Supernanogan(Pantechnik) provides that intensity
- Reports on EBIS and ESIS are optimistic:
  Boytsov, Review of Scientific Instruments 86, 083308 (2015)
- EBIS/ESIS: 10 $\times$ smaller emittances - easier multiturn injection, smaller aperture

ion / Q	1	2	4
H	2000		
He	2000	1000	
C			200



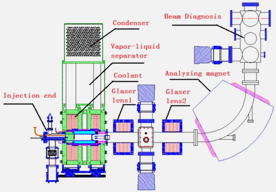


Figure 1. A schematic cross-section view of the LECR4 source body and M/Q selector system

Table 2. Yield Comparison of Various Ion Sources

Ion Source	f (GHz)	Pw (kW)	He^{2+}(emA)
LECR4	18	1.7	8.74
VENUS	18+28	1.7+1.0	11

pantechnik.com

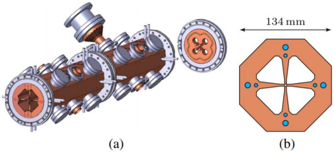
C. Qian, 2018, SESRI project

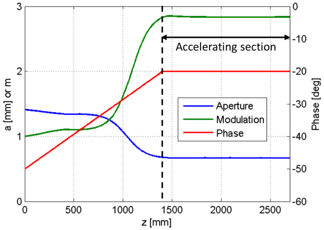
RFQ

- At 4 MeV/u the injector could be just RFQ - 750 MHz "CERN" RFQ - great simplification, discussed already in:

R. Becker et al., "An EBIS/RFQ-injector for a cancer therapy synchrotron," Rev. Sci. Instrum, 63, p. 2812 (1992).

- Space-charge tune shift at injection at 4 MeV is about -0.13 (ECRIS emittances)



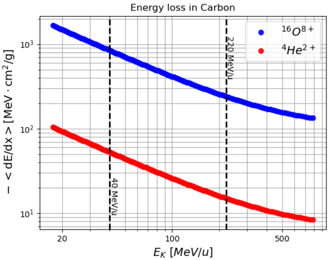


Phys. Rev. Accel. Beams 22, 052003 (2019)

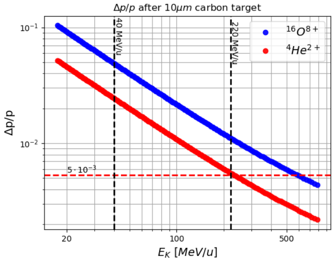
V. Bencini, 2018

Beam cleaning

- m/q of $^4He^{2+}$ the same as $^{16}O^{8+}$, $^{14}N^{7+}$, etc...
- EBIS-ESIS sources are "cleaner" than ECR (lower vacuum)
- A cleaning procedure based on difference of dE/dx could be developed
- In order to fit resulting Δp to machine acceptance - cleaning at high energy



dE/dx - factor 15



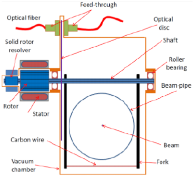
machine acceptance $5 \cdot 10^{-3}$
at max energy

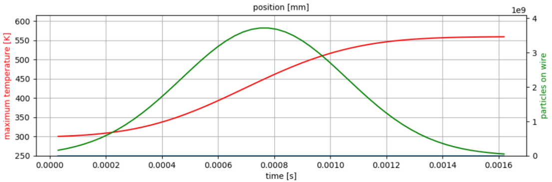
Beam cleaning

Cleaning could be done with:

- wire scanner,
- fast orbit bump to carbon foil ,
- gas jet (see presentation of H. Zhang yesterday).

Wire scanner:
Temperature evolution of $10\mu m$ carbon fiber moving through the beam with 5 m/s.





About 30-40% of the beam particles pass through fiber at single scan (depends on tune, beams size, wire speed).

He cannot replace C

- Helium-therapy (RBE $\sim$ 1.8) cannot replace carbon-therapy (RBE $\sim$ 5) (especially important for radioresistant tumors)
- Carbon synchrotrons are large enough to allow for experimentation with other beams, eg. oxygen.
- Carbon machines give possibility of simultaneous CT scan with helium beam!

NB.

helium synchrotron can accelerate protons to energies allowing pCT

(but not in the same cycle)

Conclusions

- Helium ions give better sparing of Organs At Risk (less dose to healthy tissue) than protons.
- Helium ions fragmentation tail much less than carbon ions.
- RBE of 4He is not enough to treat radioresistent tumors (Carbon still needed).
- Clinical use of helium beams expected in 2021.
- Helium synchrotron - twice as large as proton one but similar complexity.
- EBIS/ESIS sources reaching required intensities with much smaller emittances.
- 750 MHz RFQ - only injector - simplification of the system.
- dEdx beam cleaning method could be developed.
- Helium machine allows for pCT.
- 3He could be used in already existing proton machines with reduced range (?).
- Clinical case for helium radiotherapy is strong.
- Opportunity to develop new, compact, dedicated machine.

Thank you for your attention!

Acknowledgements

Andreas Peters (HIT),
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Araceli Navarro Fernandez (CERN)

Thank you for your attention!

Additional slides:

Wire Scanner: particles crossing the wire.