Plans and challenges for SEEIIST

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TERA Foundation and CERN

Kick-off Meeting for I.FAST-REX: REsonant eXtraction improvement
February 8-9, 2021

South East European International Institute for Sustainable Technologies

CERN

TERA Fondazione per Adroterapia Oncologica

Outline

- Presentation of SEEIIST and NIMMS projects.
- Medical requirements - beam intensity.
- Slow extraction:
  - RF-KO Extraction and spot scanning
  - Multiple-Energy Extraction
  - Oblique raster scanning
  - Alternative synchrotrons
  - Superconducting synchrotron
  - Low emittance beams
- Beam extraction for FLASH therapy
- Conclusions

What is SEEIIST?

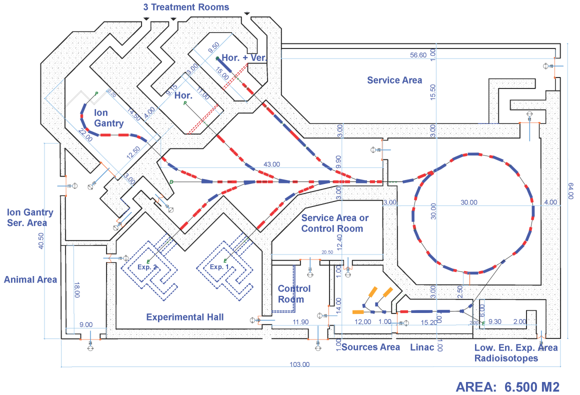
South East European International Institute for Sustainable Technologies

https://seeiist.eu

- Association with a goal to construct hadron therapy and research facility in one of East European countries
- Medical CERN with focus on cancer radiotherapy
- Research program as important as treatment
- Facility construction will end around 2030 - need to future-proof systems

SEEIIST research

Experiments at low and high energy

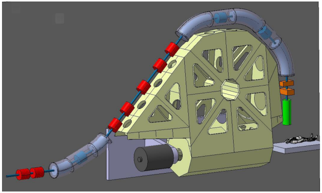


- Experimental requirements are difficult to foresee - flexible design

What is NIMMS?

Next Ion Medical Machine Study

- R&D programme for the development of critical accelerator technologies related to ion therapy
- Started in 2019
- Follows tradition of CERN involvement in medical machines (see Proton-Ion Medical Machine Study, PIMMS)
- Workpackages:
  - superconducting magnets for synchrotron and gantry
  - synchrotron
  - gantries
  - high-frequency linac
- SEEIIST is to profit from NIMMS developments



superconducting ion gantry, weight= 30 t for the rotating part (CERN & TERA)

Medical requirements - intensity

Design specifications addresses the main issues of existing machines

Requirement: treat 1 liter tumor with 2 Gy in one synchrotron fill.

Injection/Acceleration	**Unit**					
Particle after stripping		**p**	**$^{4}He^{2+}$**	**$^{12}C^{6+}$**	**$^{16}O^{8+}$**	**$^{36}Ar^{16+}$ (*)**
Energy	MeV/u	7				
Magnetic rigidity at injection	Tm	0.38	0.76	0.76	0.76	0.86
Extraction energy range (**)	MeV/u	60 – 250 (1000)	60 – 250 (430)	100 - 430	100 - 430	200 – 350
Magnetic rigidity at highest energy (for therapy)	Tm	2.42	4.85	6.62	6.62	6.62
Maximum nominal field	T	1.5				
Maximum number of particles per cycle		$2.6 \cdot 10^{11}$	$8.2 \cdot 10^{10}$	$2 \cdot 10^{10}$	$1.4 \cdot 10^{10}$	$5 \cdot 10^{9}$

source: SEEIIST ESFRI (European Strategy for Research Infrastructure) proposal

Current machines store 10^9 carbon ions per fill.

Slow extraction requirements

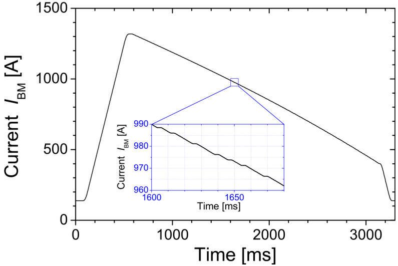
Baseline: RF-KO extraction, active scanning

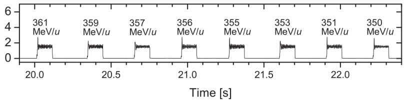
- Beam rigidity between 2.3 and 6.7 Tm (the same as in other medical facilities)
- RF-KO extraction - baseline for Multiple-Energy operation
- spill duration in range 0.5-30 s (or shorter, see FLASH discussion)
- spill quality: for raster scanning each voxel dose withing 3-5% with respect to treatment plan (including range uncertainty, patient positioning, energy error)
- spot irradiation time $t_s = 13 - 15\ ms$, margin needed: R&D on faster scanning magnets
- maximum spot dose usually 2 Gy, but can be 60 Gy (hypofractionation)
- rescanning possible

Multiple sources of information, eg: **M. Palm, CERN-THESIS-2013-421**

Multiple-Energy Extraction

MEE greatly shortens the irradiation time!





sources:
K. Mizushima et al., NIM B 331 (2014) 243–247
K. Mizushima et al., NIM B 406 (2017) 347–351

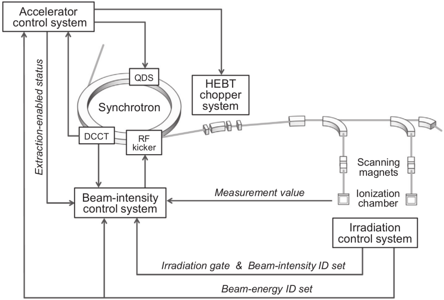
- extraction of ion beams with various energies in a single synchrotron cycle
- spill duriation: 100 ms, between spills: 220 ms
- HIMAC: up to 200 energy levels, $\Delta\mathrm{E} = 1 - 7\ \mathrm{MeV}$
  (typical treatment: 40-80 layers)
- MEE is commercially available in Hitachi proton synchrotron:
  - only up to 4 layers per fill
  - irradiation time reduced by 35%

J.E. Younkin et al., Advances in Radiation Oncology (2018) 3, 412–420

Multiple-Energy Extraction

Issues and potential improvements:

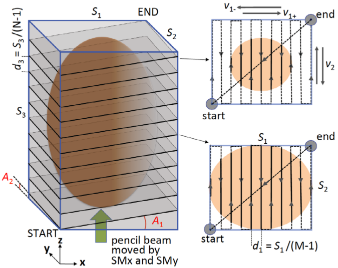
- HIMAC: tune fluctuations due to energy ramping suppressed by fast quadrupoles
- still intensity spike after each energy change - removed by HEBT chopper
  - chopping spikes contributes to 220 ms between energy layers, can it be reduced by KO-exciter or better power converters?
- Intensity feedback from dose delivery detectors
  - as fast as possible (RF exciter controller)
  - with new detector technologies (eg. scintillating fibers),
  standarized interface needed?



Oblique raster scanning

Continuous Multiple-Energy extraction

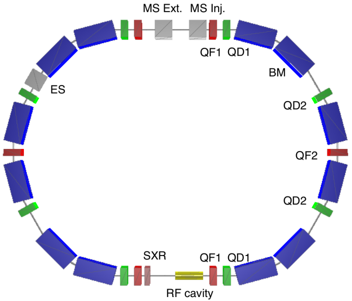
- why not to go a step further and ramp the energy continuously during the scan?
- this saves irradiation time and helps to avoid problems of optics jumps
- relaxes ramp-rates of superconducting magnets
- U. Amaldi, Phys. Med. Biol. 64 (2019) 115003
- for scanning velocity of 20 m/s it can save even 50% of irradiation time



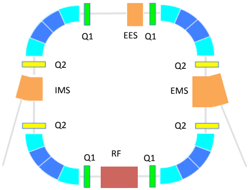
- the treatment plans must be validated for this method
- the new KO-exciter should allow for continuous modulation of excitation pattern and amplitude
- i.e. it should follow the continuous ramp of the revolution frequency

RF-KO in superconducting synchrotron

- SEEIIST baseline design is based on PIMMS: large machine (75 m), quite complex but flexible (needed for experimental programme)
- Other desings are considered eg. based on Double-Bend Achromat (55 m)
- Ongoing work on superconducting ring (30 m)
- The exciter should fit to smaller machine and
  DCCT should measure ripple with SC magnet in the circuit



machine protection issues (quenching)
superconducting septum
vertical extraction?



X. Zhang, arXiv:2007.11787

E. Benedetto, CERN-ACC-NOTE-2020-0068

High brightness beam

Electron Beam Ion Sources (EBIS)

- Currently ECR ion sources are used to provide enough intensity for injection
- Multiturn injection has to be used (20-30 turns)
- For SEEIIST advanced 18 GHz source is needed (AISHA/Catania or PK-ISIS/Pantechnik)
- or a source with smaller emittance to improve multiturn injection efficiency
- Reports on EBIS and ESIS are optimistic:

  Boytsov, Review of Scientific Instruments 86, 083308 (2015)
- EBIS/ESIS: 10 $\times$ smaller emittance
- In case of EBIS the beam brightness will be much larger, what will escalate problems with separatrix fluctuations and spill quality

FLASH therapy

What does it means FLASH with C-ions?

- FLASH effect appears at dose rates above 40 Gy/s
- Experiments show that healthy tissue is much better spared than at standard dose rates
- To reach FLASH dose rate the spill has to be less than 50 ms (exact values debatable, better assure 5-10 ms)
- The simplest method: use double scattering to get uniform dose distribution and cut it with collimators
- Probable mode of FLASH operation using synchrotron:
  - fill the machine with all intensity needed for irradiation
  - extract small portion of the beam for QA (and feed forward)
  - extract the beam either by fast extraction or driving the beam right to the resonance (maybe half-integer?)
  - RF-KO probably not helpful here (to slow)
  - use more instrumentation to control the dose delivery

FLASH therapy - scanning

Is scanning still possible?

Jolly, Owen, Schippers, Welsch, Physica Medica 78 (2020) 71–82

- FLASH with standard scanning method: need 100 times faster scanning
- Hybrid delivery: broad beam, 3 ms spills, energy change in between

> in order to switch the beam off between spots.
>
> To provide the temporal beam characteristics needed for FLASH spot scanning (see Section 4.1), the extraction time for a single energy layer will need to be reduced from several seconds to <3 ms, a reduction by 3 orders of magnitude. This clearly requires a novel approach not yet described. The large variations in current during extraction also need to be significantly reduced — ideally below 10% — in order to prevent under- or overdosing of individual spots. Ideally this new extraction method would have rise and fall times ≪ 600 ns to allow the beam to be switched off between spots when using the step-and-shoot method. This

  maybe some hybrid of burst-model slow extraction while energy ramping would do the job? M. pari et al., 0 doi:10.18429/JACoW-IPAC2019-WEPMP03

- Hybrid delivery: spot scanning using the SOBP (3D-printed range modulators), delivery time for each spot: $20\ \mu s$
- energy scanning and SOBP-spot scanning require further investigations to clarifyu= requirements for RF-KO system

Conclusions

- SEEIIST is future ion therapy and research center.
- Baseline is RF-KO extraction because of flexibility, intensity control and fast switching.
- Multiple Energy Extraction is a must from the beginning.
- 10x higher beam intensity - quality of slow extraction more critical.
- The I.FAST-REX exciter should allow for implementation of Oblique Raster Scanning:
  - continuos change of extraction parameters with beam energy.
- Dose rates, even without FLASH, will be larger, so fast feedback ability is crucial.
- Delivering FLASH doses using RF-KO extraction requires additional study and may impose very challenging requirements for the system.
- NIMMS has PhD student on slow extraction (from Imperial and John Adams), starting March 1st.

Thank you for your attention!