HEATHER: HElium ion Accelerator for radioTHERapy

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EPSRC Engineering and Physical Sciences Research Council

Roadmap

- Current efforts in particle therapy
- Should we bother with helium?
- What are we doing about it
- Conclusions and future work

Particle therapy

- Ion and proton therapy hold advantages over conventional radiotherapy

- Physical benefits
  - Dose distribution
  - the way the particles interact with matter
  - Linear energy transfer (LET)

- Biological benefits
  - Radiobiological effectiveness (RBE)

Ion therapy

- At the moment ion therapy just means carbon ions

- Advantages of Carbon ions over protons
  - Improved Dose distribution
  - Higher LET correlating to higher RBE

- Disadvantages
  - Variable high energy RBE –difficult to model
  - Dose tail
  - Size of the required facility

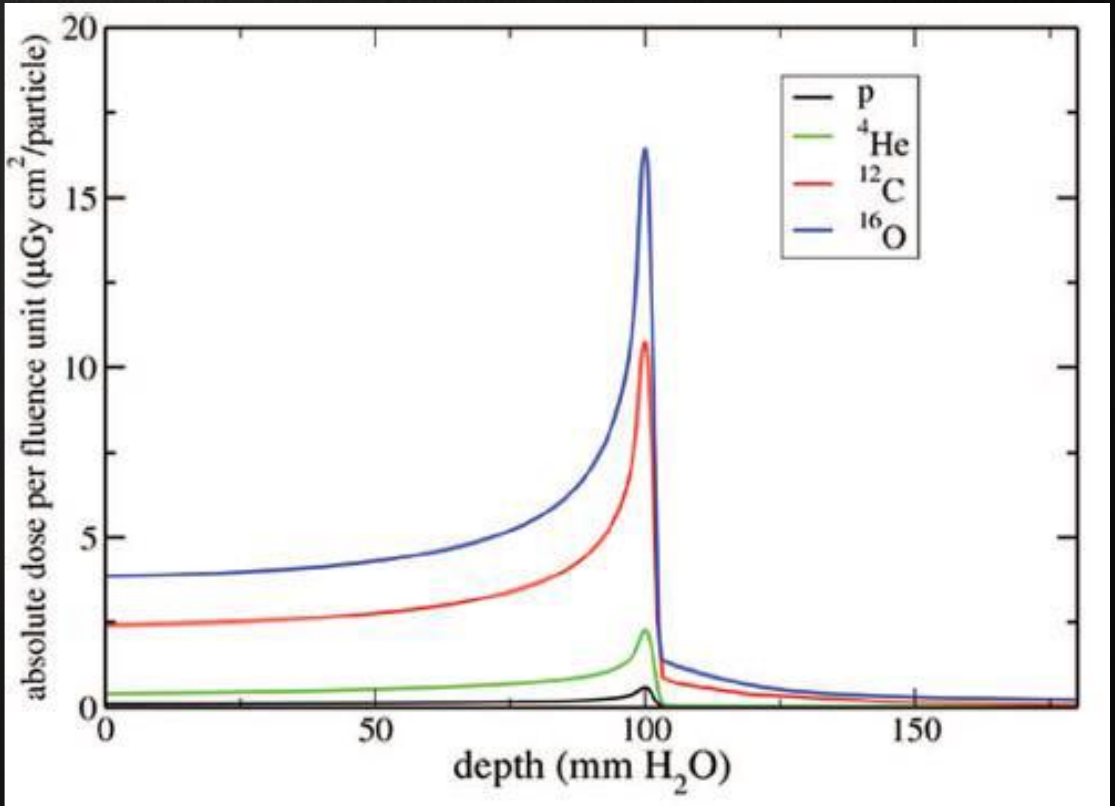


Figure 1[1]. A comparison Absolute dose per unit fluence for protons and a range of ions.

Biologically carbon has issues

- Fragmentation is more prevalent in carbon ion therapy
  - Secondary particles from inelastic nuclear interactions between the ion and the tissue -which adds to the total damage [1-7]
- The created low-z fragments have a longer range, creating a dose tail beyond the Bragg peak
  - problematic for organs at risk
- The use of lighter ions like helium have a reduced fragmentation tail [1,4-6]

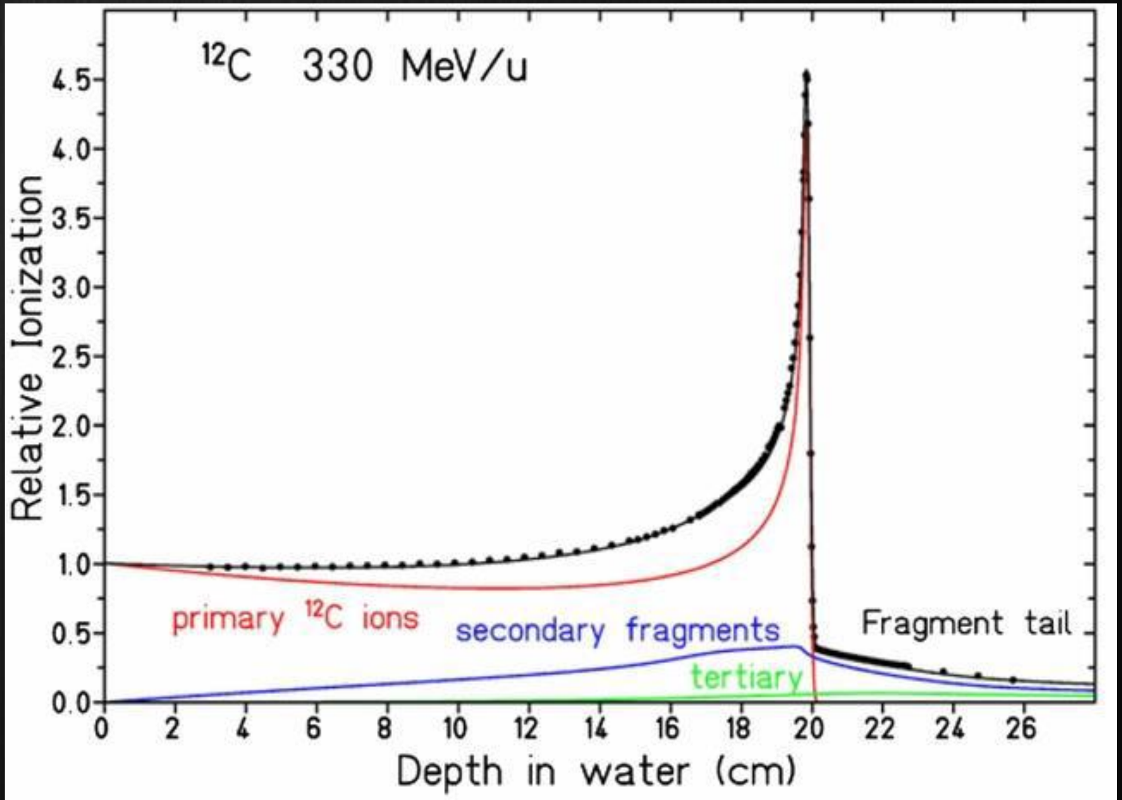


Figure 2[2]. A description of the relative ionisation against depth for 330MeV/u carbon ions, highlighting the fragmentation tail

Accelerating carbon is not easy either

- The difficulty in accelerating carbon can be expressed via beam rigidity, as depicted by Figure 2
- Currently 10 facilities that can provide carbon ions for therapy[8]
    - China (2) Japan (5) Europe(3)
    - All synchrotrons
- The reduced beam rigidity of lighter ions allow for a smaller accelerator, and hence a reduced cost

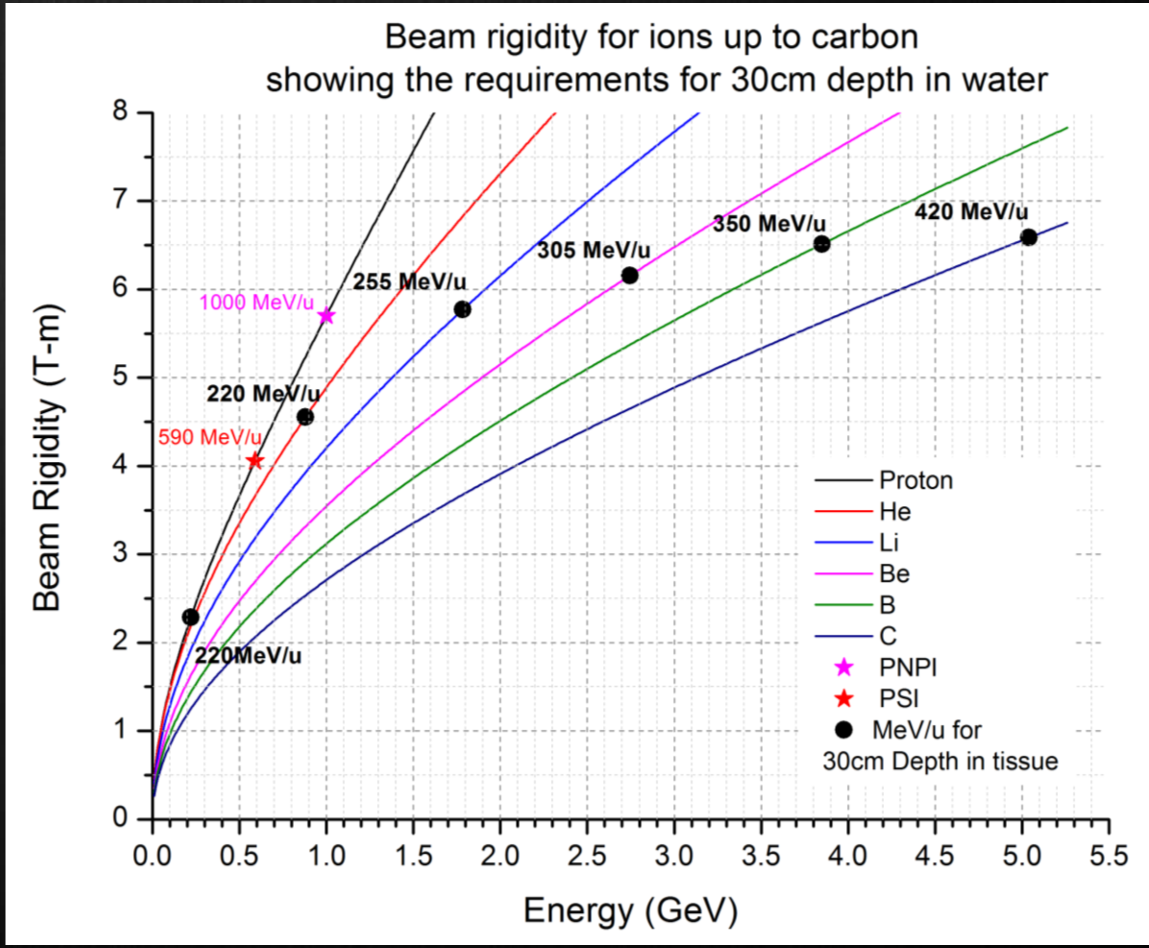


Figure 3. The bending radius necessary to bend the beam against kinetic energy for fully stripped ions up to carbon.

Why Helium?

- Used before at Berkeley (57-92) [8-9]
    - 2000 patients
- Physically
    - Easiest to accelerate after protons –same MeV/u
    - Less projectile fragmentation than carbon ions
    - Half the scattering and sharper penumbra compared to protons
- Biologically
    - Treatment plan comparison found helium RBE and conformity effects carbon and protons[3]
    - TRiP98 and LEM IV model
    - Mass is closer to protons it is easier to model with less RBE uncertainties
    - RBE values found correlate with data from Berkeley experiments
- Revival is not unrealistic
    - Research has started in Heidelberg[10](Apr 16)
    - Interaction with matter study required as for carbon ions
    - Can only be studied at current carbon facilities

What are we doing about it

- HEATHER - HElium ion Accelerator for radioTHERapy
  - Helium therapy feasibility study using an FFAG
  - 2 stage nsFFAG accelerator
- Can we isochronously accelerate He^{2+} to 900MeV (225 MeV/u)
  - deliberately designed with $\frac{q}{m} = \frac{1}{2}$
  - Can also accelerate C^{6+} (225/u approximately ~10cm depth
- If we can accelerate to 330 MeV/u we can image with H_2^+
  - Possibility to treat and image with the same machine
  - Carbon range increases to ~20cm

HEATHER Stage 1

- Superconducting ring
- 1 MeV > 400 MeV
- 2.5m radius

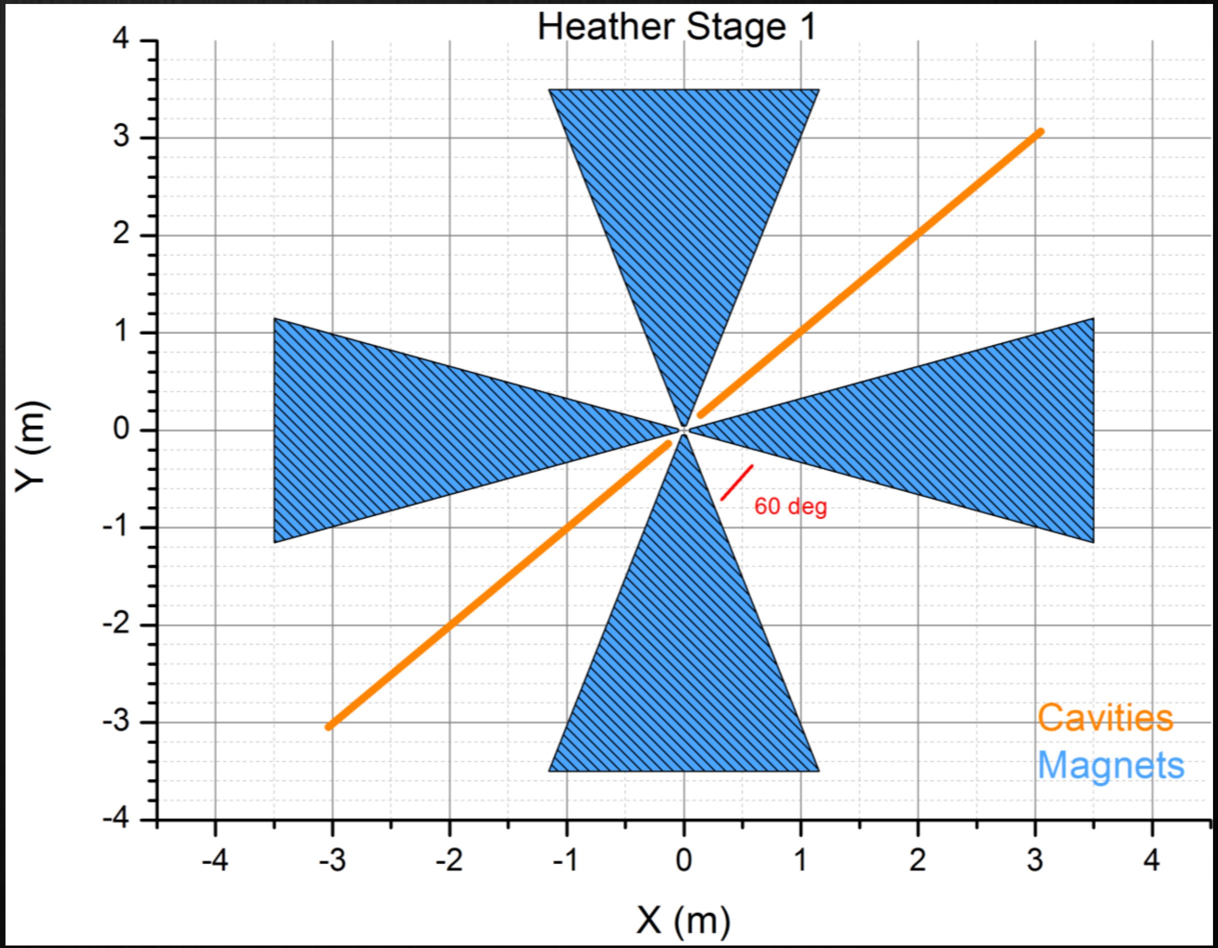


Figure 4. HEATHER stage 1 magnet layout showing stable orbits from 0.5 MeV through to 400 MeV

HEATHER Stage 2

- Superconducting racetrack
- 400 MeV > 900 MeV
- 4 x 4.5m radius

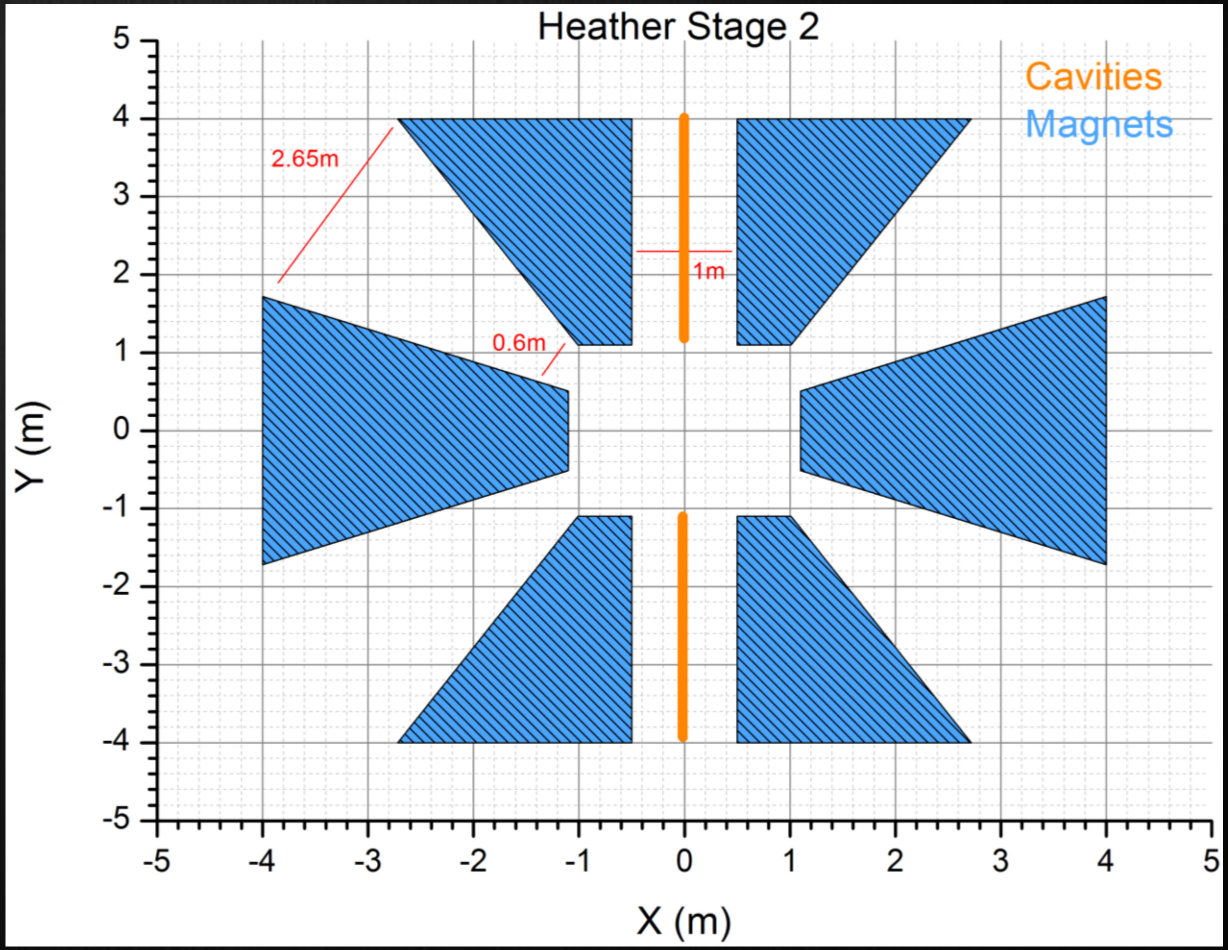


Figure 5. HEATHER stage 2 magnet layout showing stable orbits from 400 MeV through to 900 MeV

Isochronicity

- Percentage difference compared to the mean ToF over all energies in COSY and OPAL
  - Good agreement between the two codes
- Initial Overlapping fringe fields supresses vertical tune and increases ToF
- Isochronous enough to accelerate at fixed frequency RF

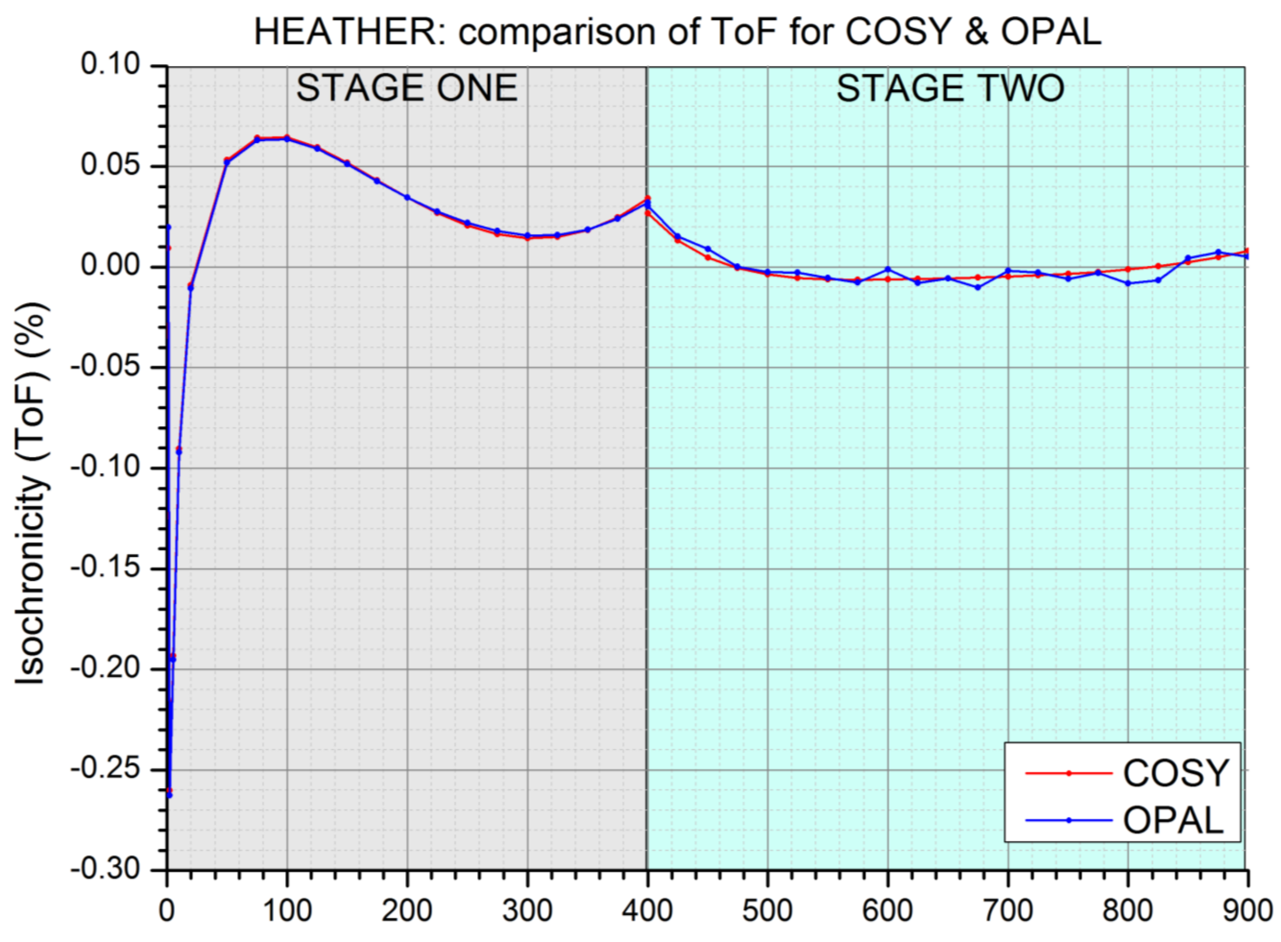
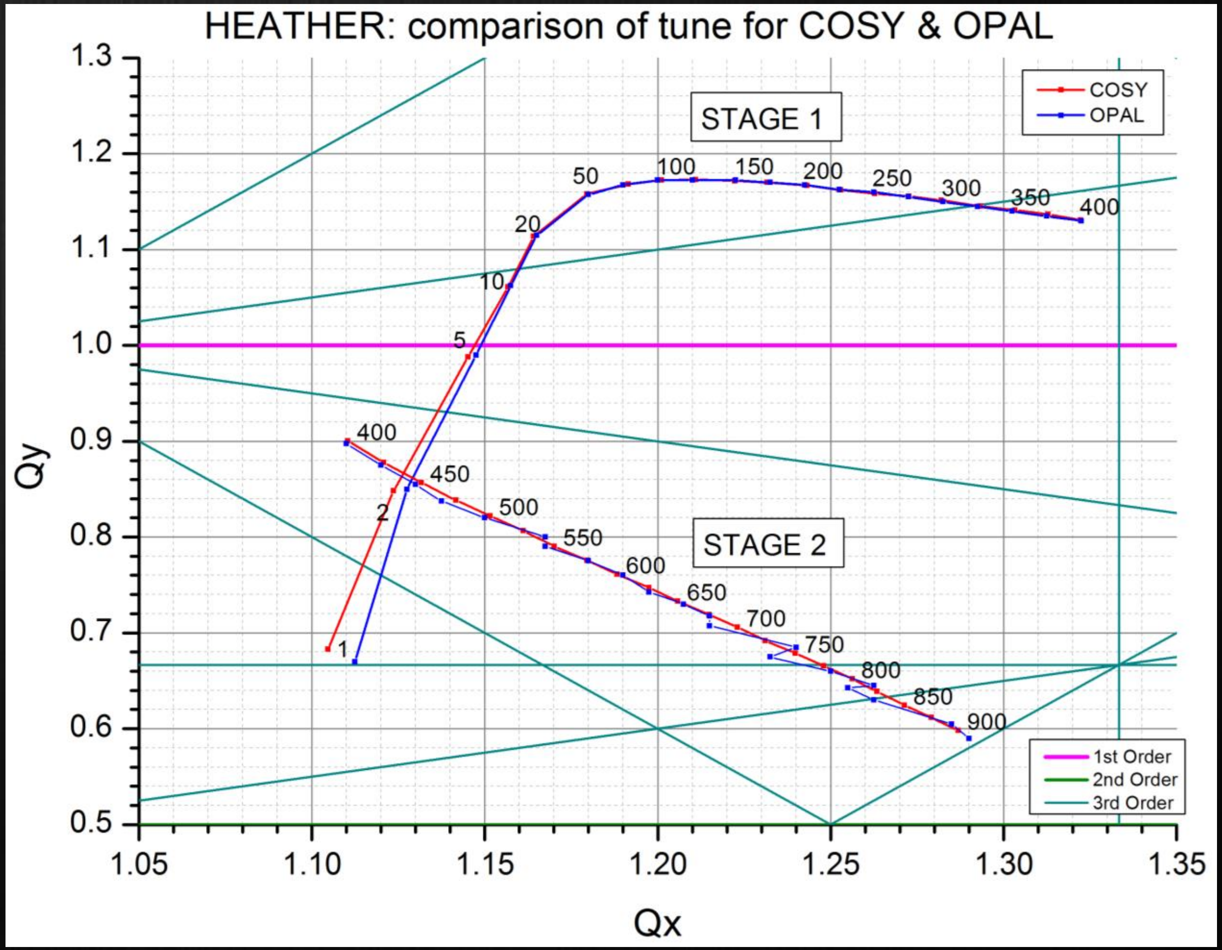


Figure 6. HEATHER isochronicity variation comparison in percentage across both stage 1 and stage 2 using COSY and OPAL

Tunes

- Acceptable tunes
- Good agreement between COSY and OPAL
- Fast integer resonance crossing around 5MeV

Figure 7. HEATHER tune map comparing the tune for both stage 1 and 2 using COSY and OPAL



Initial 'ideal' RF studies

- 2 Single gap cavities
- 1st Harmonic, 1cm gap
  - Stage 1 2@300 KeV
  - Stage 2 @ 500 KeV

- Overlapping fringe fields supresses vertical tune - hence large phase slip in stage 1

- 10.0913 MHz

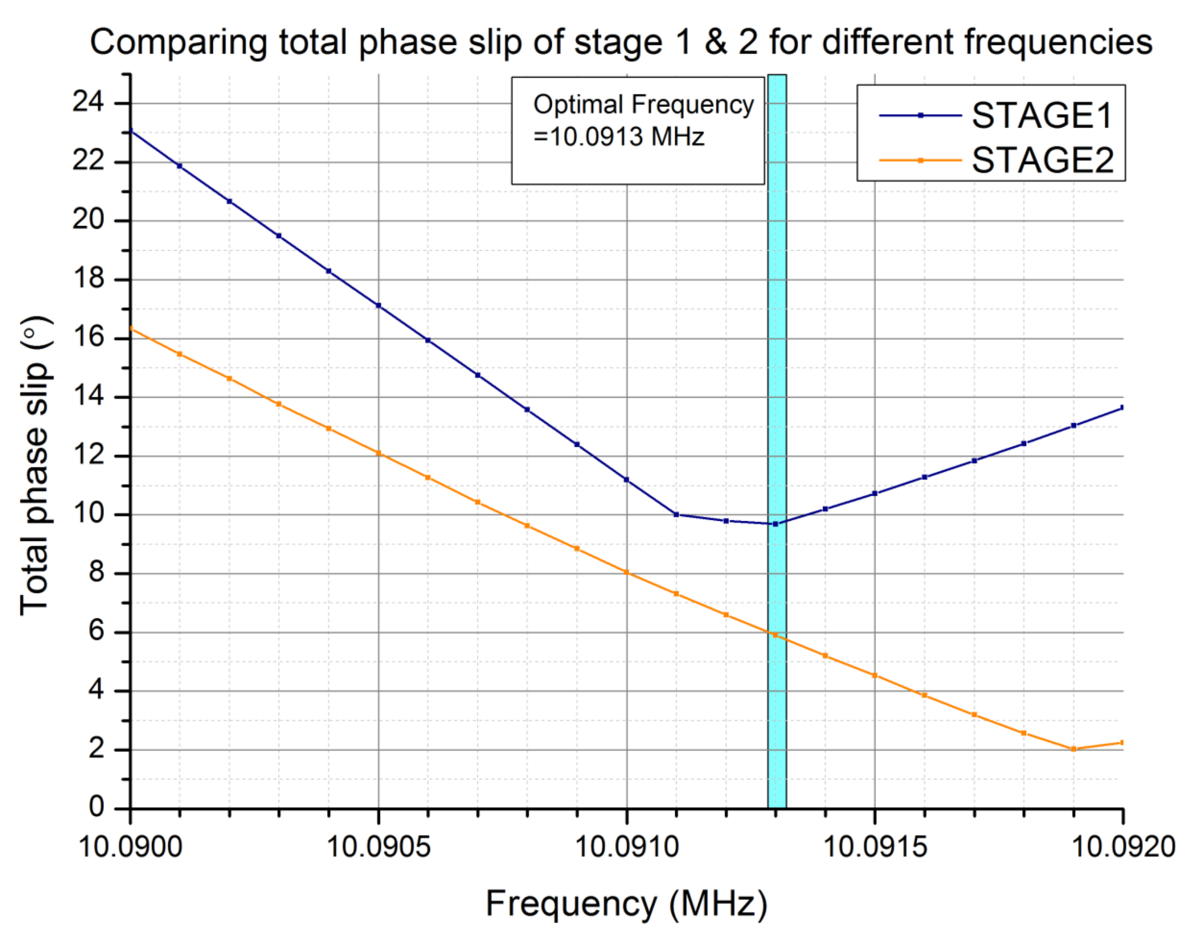


Figure 8. The total change in phase slip across acceleration for stage 1 and stage 2 of HEATHER whilst changing the operational frequency.

Realistic RF studies

- 1st harmonic 10MhZ - $\frac{\lambda}{2} \sim 15m$
  - HUGE CAVITIES!!!
- Need to be looking at least 4th
  - 4th harmonic 40MhZ - $\frac{\lambda}{2} \sim 4m$

Keeping 300KeV cavities
  - Kilpatrick limit
  - Gap size needs to be at least 4cm

- May need to change cavity type

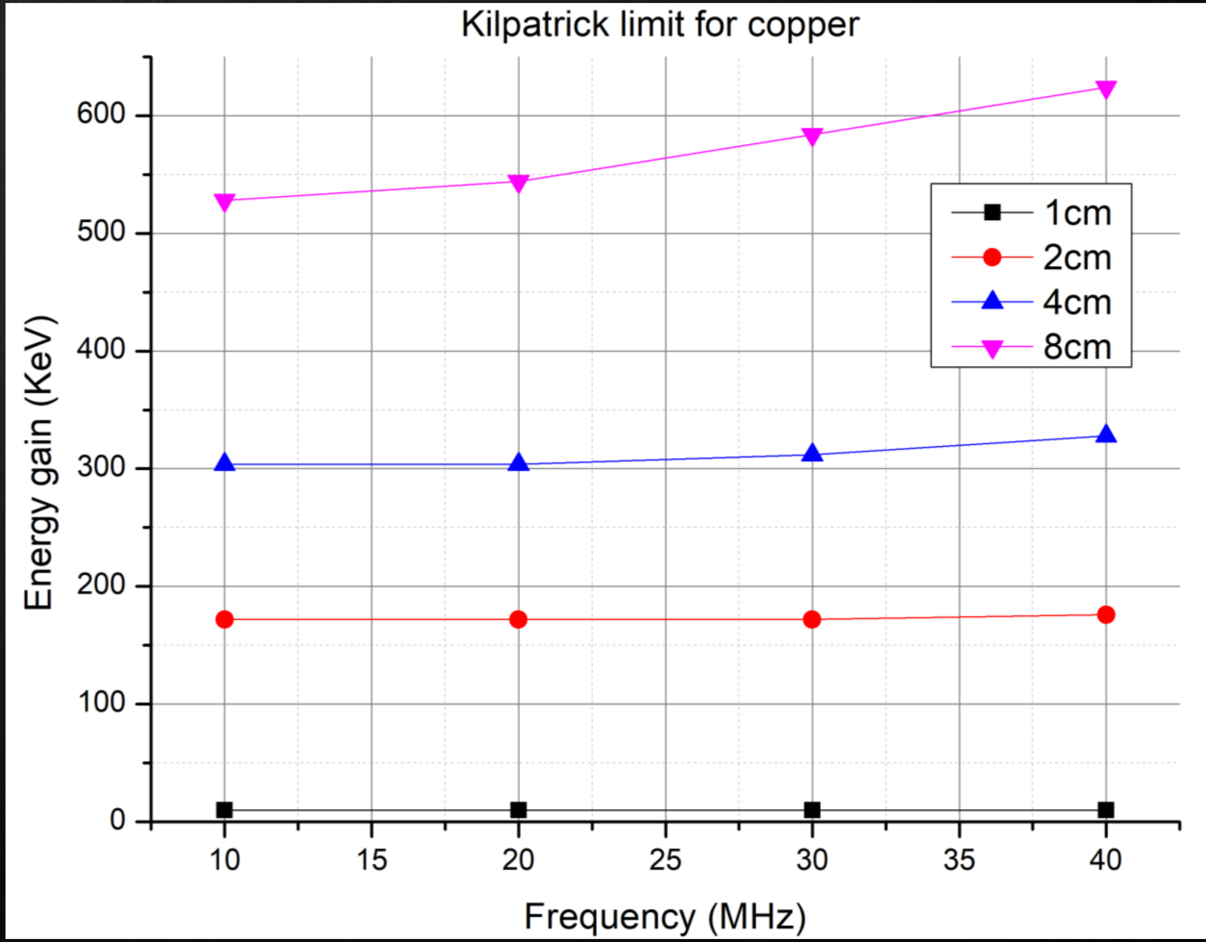


Figure 9. An interpretation of the Kilpatrick limit for copper for different cavity accelerating gap size

Stage 1 RF

- Changed to Delta-type double-gap resonators
  - 4cm gap
  - Typically used
- Simulated up to 4th harmonic successfully at 300 KeV per gap and at 200 KeV per gap per cavity

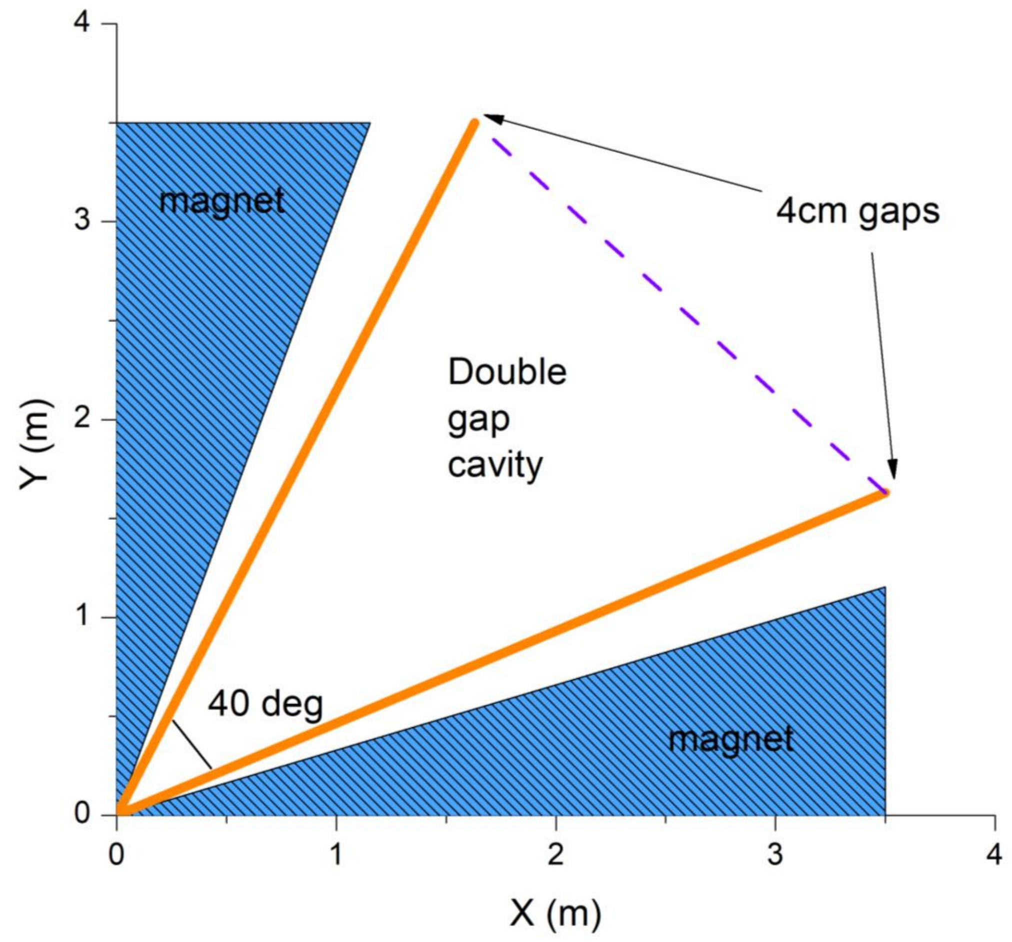
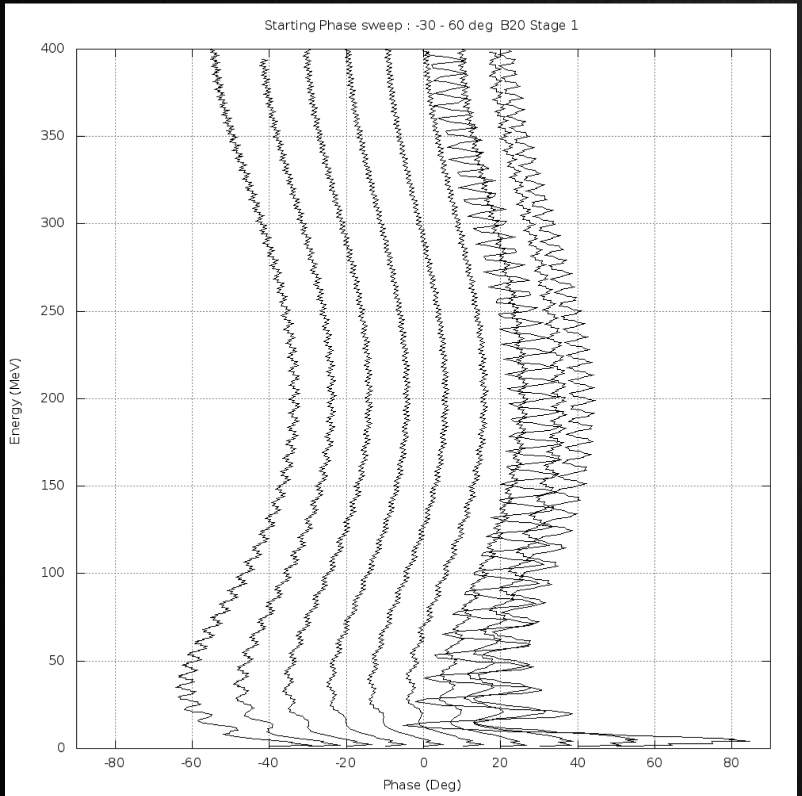


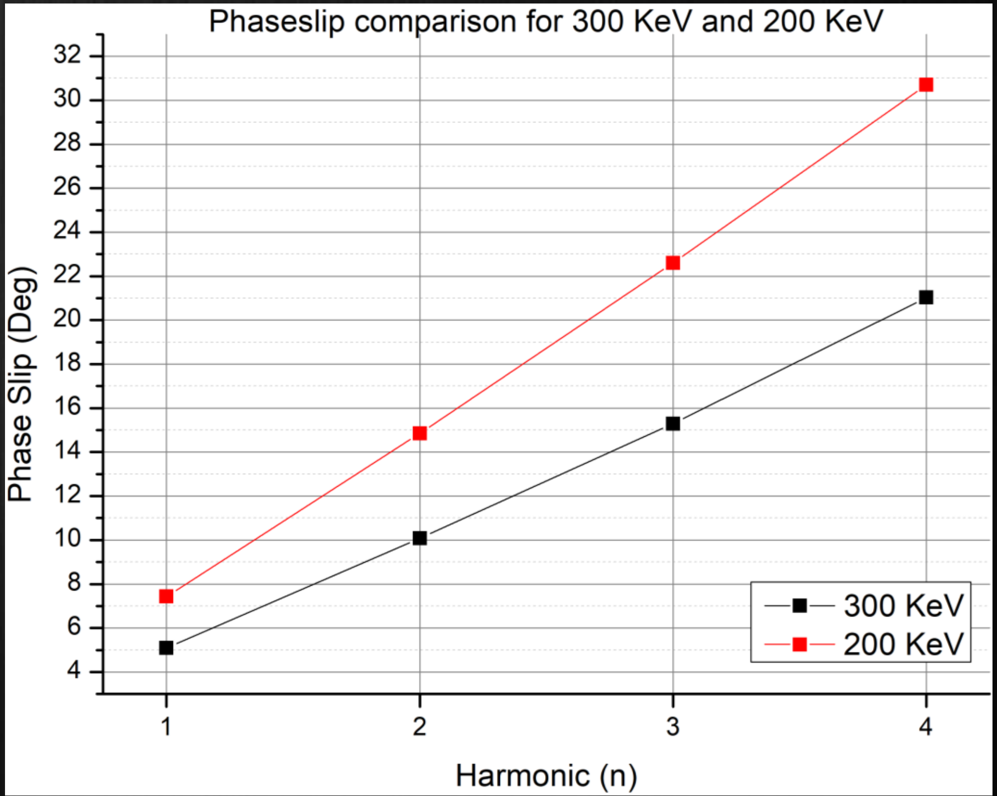
Figure 10. Visual representation of the simulated double gap delta type cavity in stage 1

Stage 1 RF



(Left) Figure 11. RF phase space of HEATHER stage 1 from 1 MeV to 400 MeV.

(Right) Figure 12. A comparison of total phase slip for 200 KeV and 300 KeV gap acceleration at different harmonics.



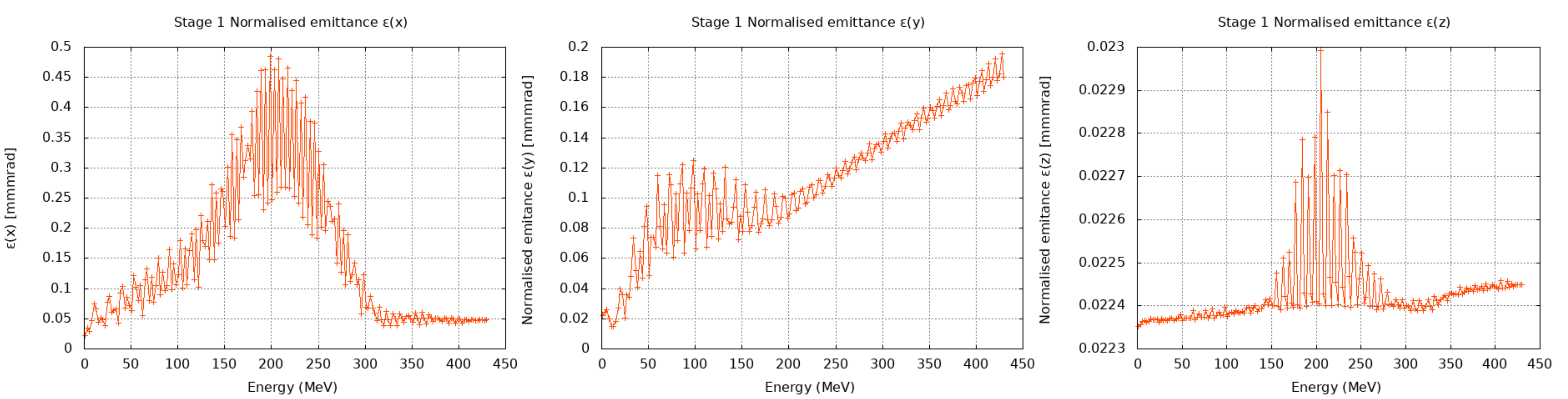
- 300 KeV - 4th Harmonic acceleration achievable with good phase acceptance (90°) with a total phase slip of 20°
- 200 KeV – 4th Harmonic acceleration achievable with phase acceptance at (80°) and a larger phase slip of 30°

Beam acceleration

- Accelerate a beam through with new RF and look at extraction for stage

- 3 beam emittances
  - $1\pi\ mm\ mrad$, $5\pi\ mm\ mrad$ and $10\pi\ mm\ mrad$
  - Look at orbit extraction and emittance growth
  - Analysis still ongoing…

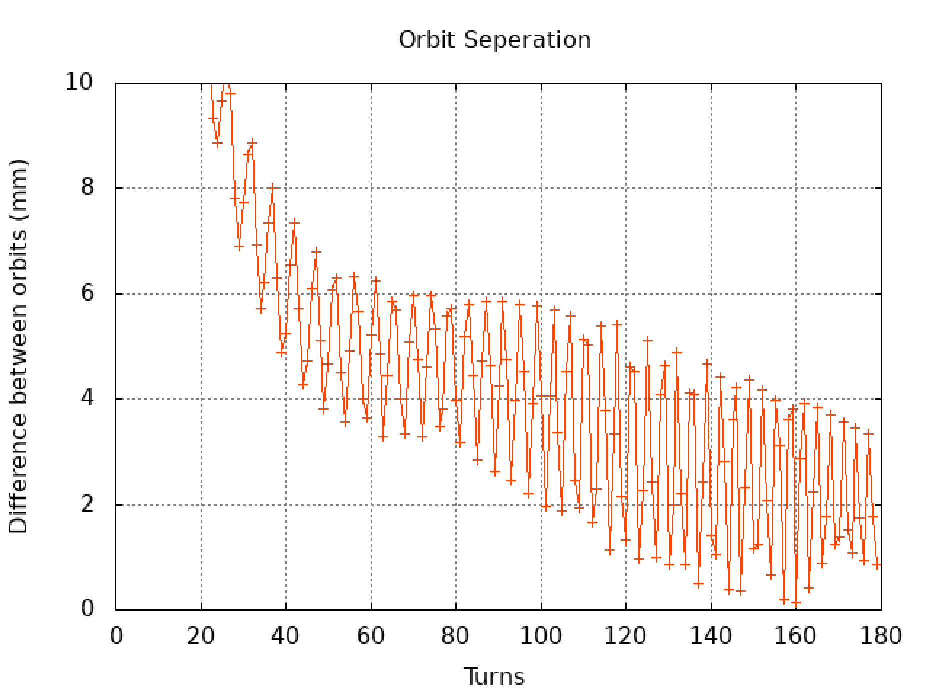
For 1 πmm mrad



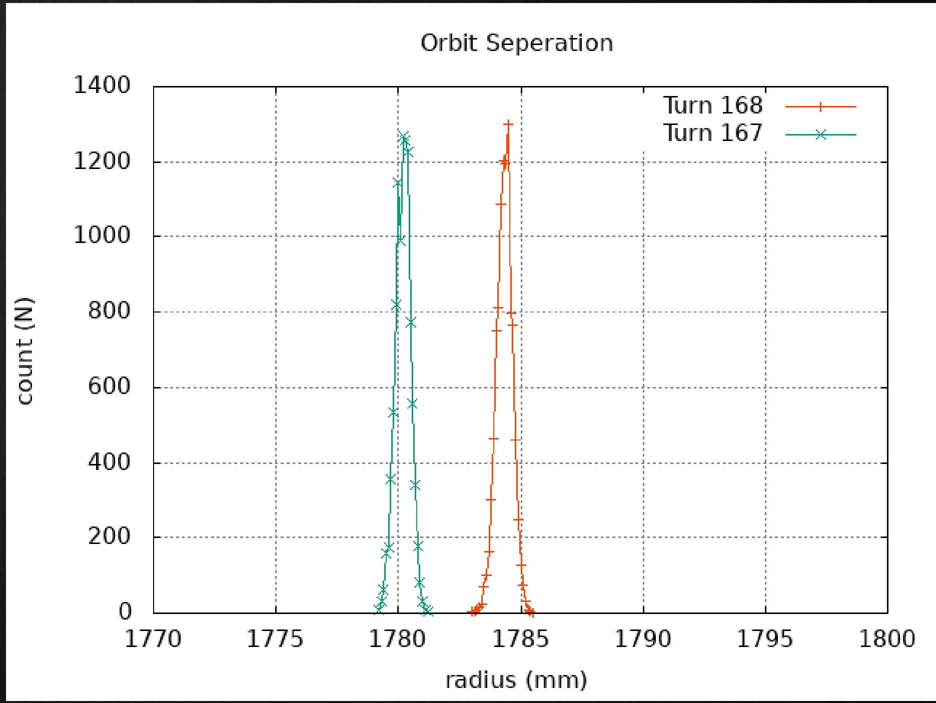
(Left) Figure 13. Normalised emittance for all 3 planes for an input geometric emittance of 1πmm mrad

- 10^4 particles simulated with no losses observed
- Emitance growth observed in the x plane
  - Cause unknown but we think it could be a higher order resonance

Orbit seperation



(Left) Figure 14. separation difference in mm between each turn for a given radius

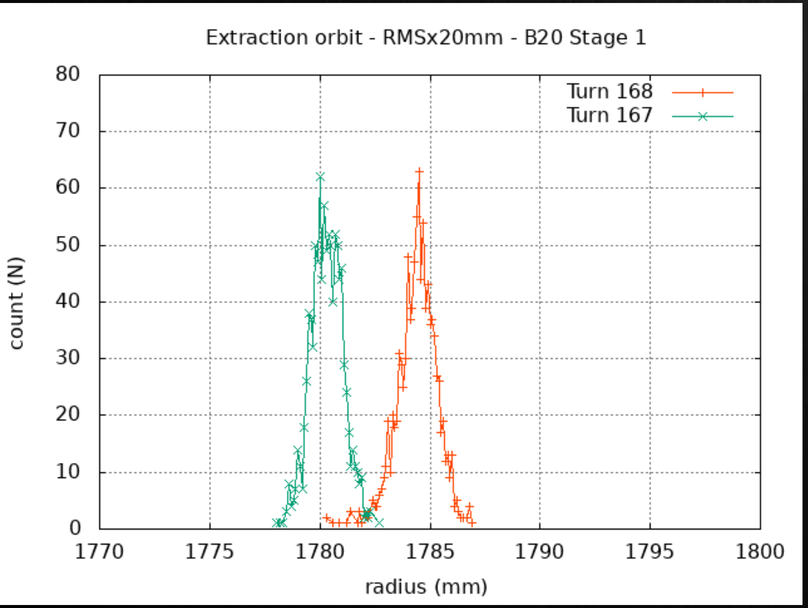


(Right) Figure 15. Extraction orbit separation

- no orbit overlapping observed
- Clean separation observed for extraction

Other emittances

- Typically expect what has been observed already
  - Optimisation is still required
  - But no losses



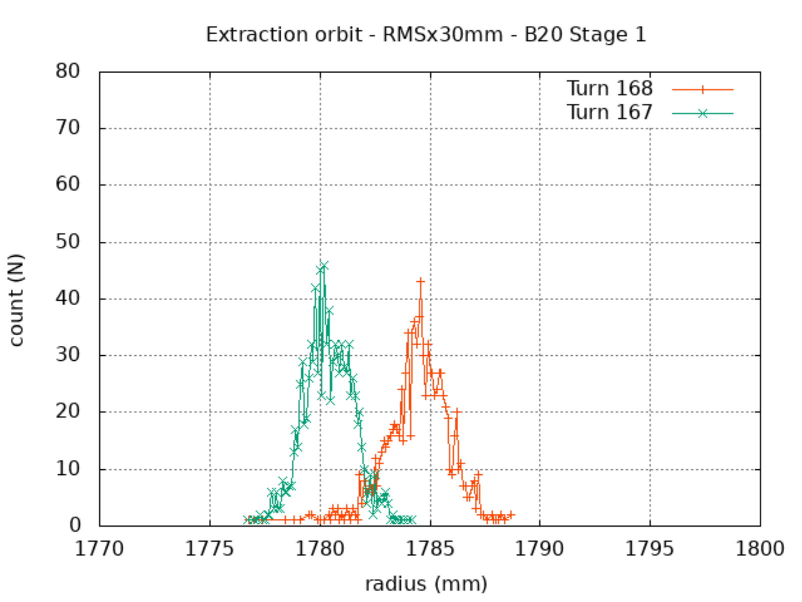


Figure 16. current extraction orbit separation for 5 π mm mrad and 10 π mm mrad respectively

Conclusions

- We need to increase the availability Ion therapy
  - Helium could be the compromise
  - There is no superior Ion -therapeutic advantage

- It is definitely feasible to isochronously accelerate He^{2+} to 900MeV

- Most of the work has been done on stage 1
  - 100 MeV/u He^{2+} is approximately 10cm tissue depth
  - Potential to be a stand alone machine!

Thankyou

If you are interested and want to get involved please get in touch

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