STATUS UPDATE OF THE LASER-HYBRID ACCELERATOR FOR RADIOBIOLOGICAL APPLICATIONS (LHARA)

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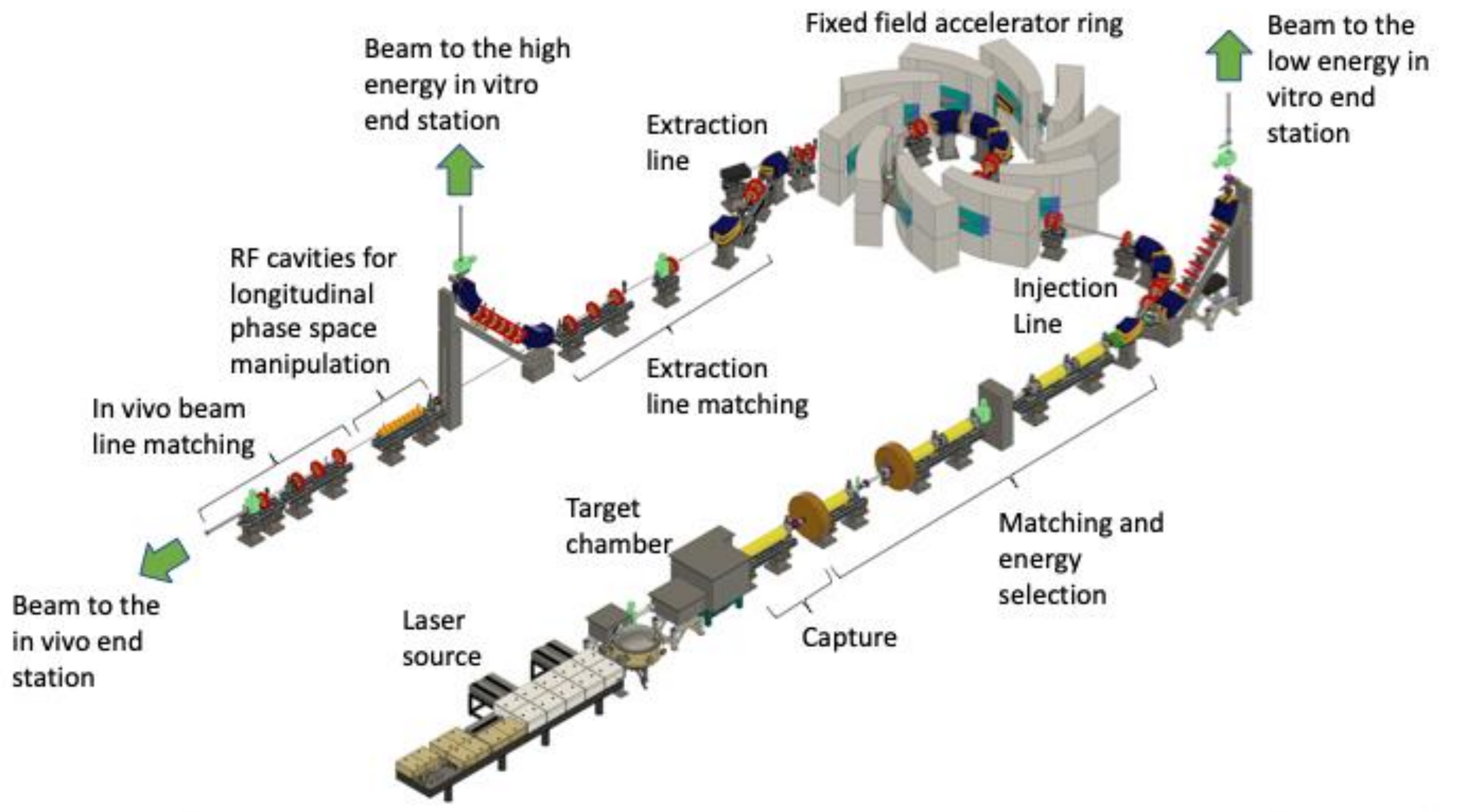
LhARA

- LhARA is a proposed multi-stage accelerator that will serve a radiobiological research program aspiring to underpin the future of radiotherapy [1,2].
- Stage 1 will generate proton and ion bunches via the transverse normal sheath acceleration (TNSA) mechanism in a laser-target scheme:
  - Design proton energies of 15 MeV ±2%
  - 10 Hz repetition rate (laser limit)
  - 10^9 protons per bunch
  - Plasma lens capture
  - Controllable bunch radii between 1-3 cm in diameter.
  - A downstream section will enable more beam delivery schemes.
- Stage 2 will employ a 10-cell single spiral scaling fixed field alternating gradient accelerator (FFA) to accelerate protons up to 127 MeV, and will be capable of fast and variable energy extraction.



Parametrized Source Description

- Our source description uses a parametrized model from which energies for Monte Carlo particle tracking can be via inverse transform sampling. The kinetic energy spectrum is given by [3] :

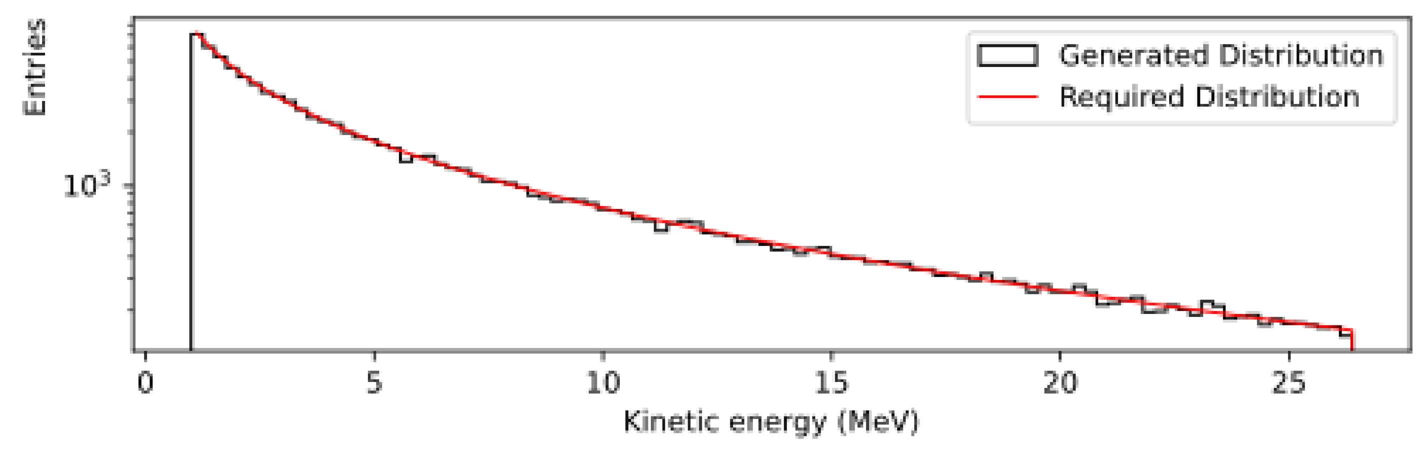
$$\frac{dN}{dK} = \frac{n_{e0} c_s t_{laser} S_{sheath}}{\sqrt{2KT_e}} \exp\left(-\sqrt{\frac{2K}{T_e}}\right)$$

- The high energy cut-off, which has been experimentally demonstrated, is given by [4]:

$$K_{max} = X^2 2 Z m_e c^2 \sqrt{\frac{f P_{laser}}{P_R}} \qquad \frac{t_{laser}}{t_0} = X\left(1 + \frac{1}{2}\frac{1}{1-X^2}\right) + \frac{1}{4}\ln\left(\frac{1+X}{1-X}\right)$$

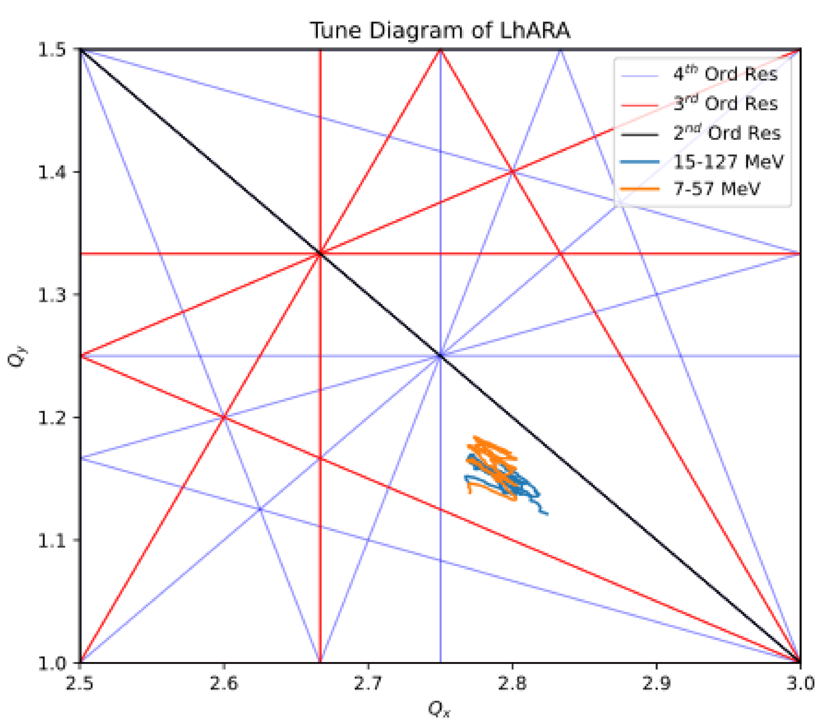
N : number of protons/ions
K : kinetic energy
n_{e0} : hot electron density
T_e : hot electron temperature
c_s : ion acoustic velocity,
t_{laser} : laser pulse duration
S_{sheath} : area over which the TNSA mechanism occurs
Z : ion charge
m_e : electron mass
c : speed of light
f : energy conversion efficiency
P_{laser} : laser power,
P_R : relativistic power unit
t_0 : acceleration time considered as ballistic.

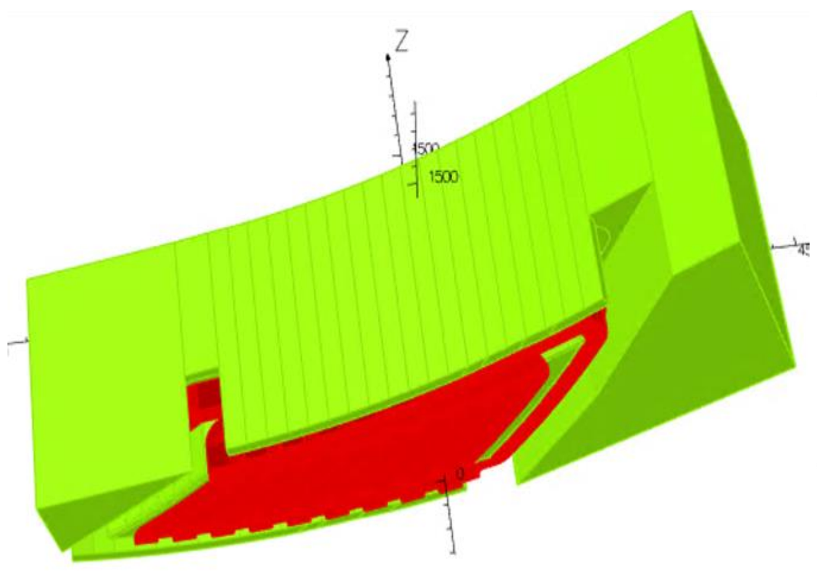
- Combined with a user-defined low-energy cut-off, the generated and theoretical spectra agree well.



FFA Magnet Design and Performance

- The FFA magnet is achromatic to avoid resonance crossing in tune space resulting in beam loss.
  - The magnetic field is arranged on the midplane with the scaling law.
  - It is generated by a distribution of trim coils that cross the pole face and return on the pole side.
  - Our baseline spiral angle is now 53.9 degrees to improve the vertical focusing.

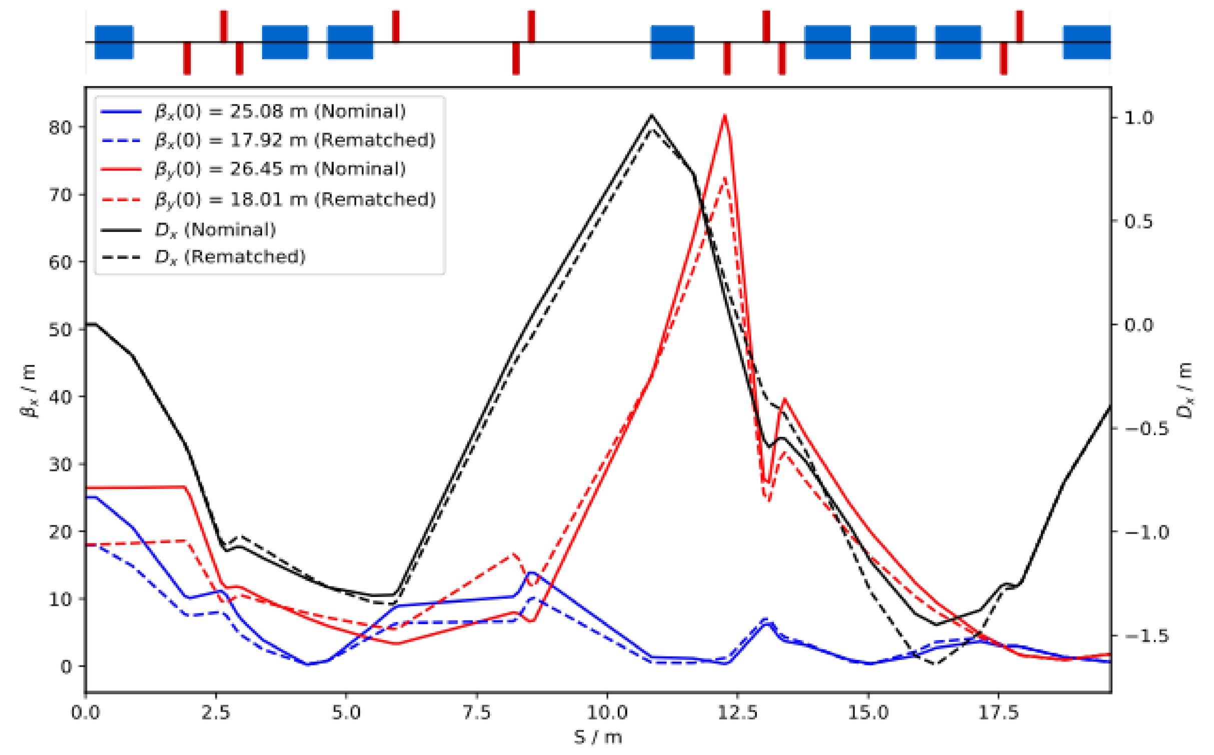




- The FFA magnet is designed in Opera 3D:
  - The main and trim coil currents are optimized for two energy ranges.
  - Beams were tracked through 3D field maps in Fixfield [5].
  - Working tune points avoid resonances up to the fourth order.
- A more detailed description of LhARA's FFA magnet design can be found in [6].

Stage 2 Injection Line Performance

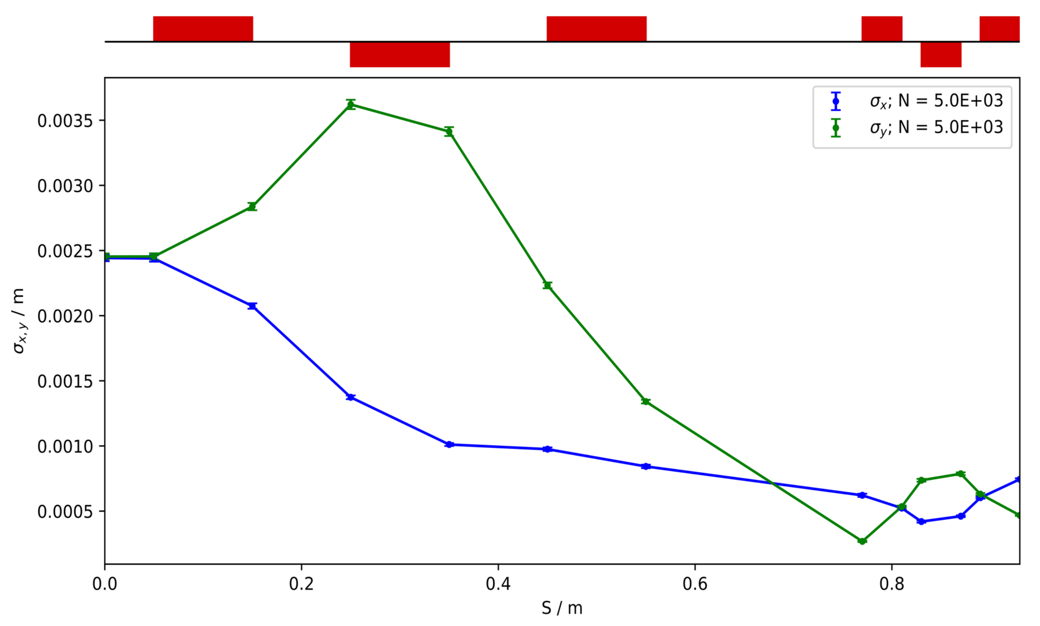
- The injection line has been redesigned to:
  - Prevent the ring crossing colliding with the FFA magnet due to the change in the spiral angle.
  - Allow sufficient space for installation and maintenance of injection magnets.

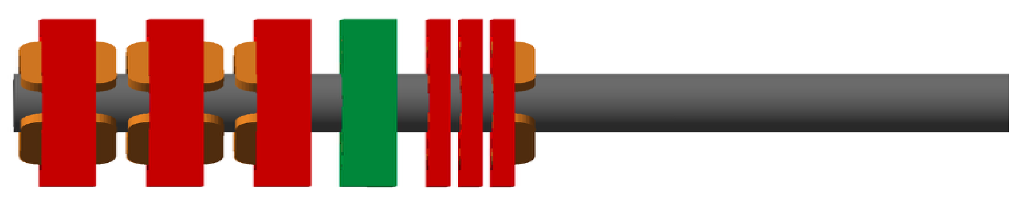


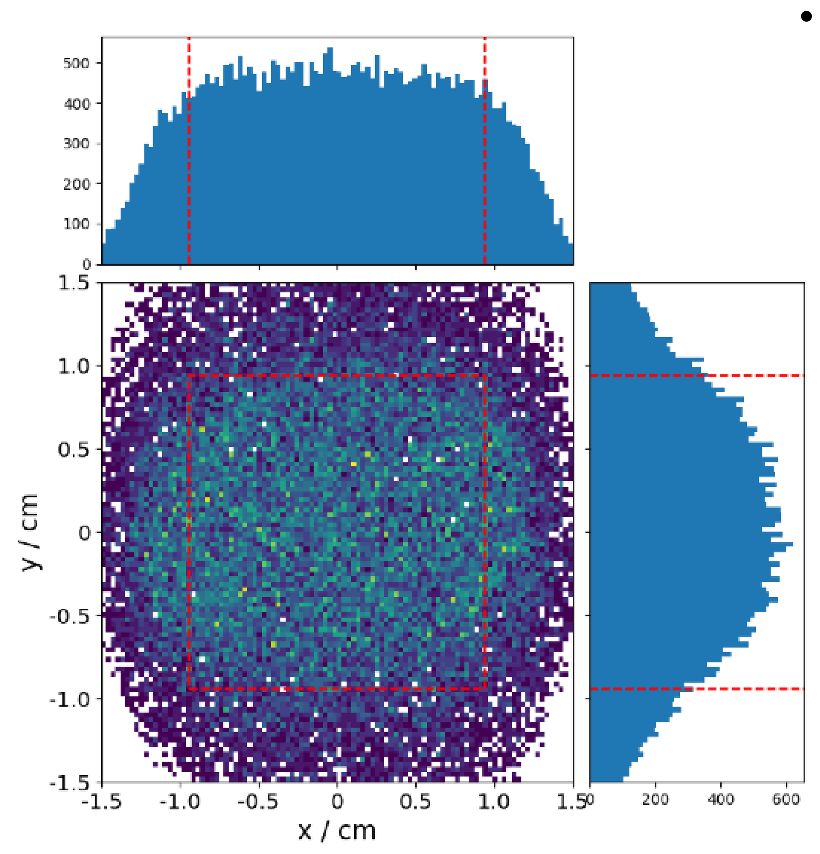
- The injection line starting conditions ($\beta_{x,y}$ = 25 m, $\alpha_{x,y}$, D_x = 0) could not be met when optimizing stage 1:
  - An emittance growth to approximately 4.3 × 10^{-6} m rad occurs during transit through the Gabor lenses.
  - Optimizing can meet a smaller $\beta_{x,y}$ of ~ 18 m.
  - The injection line quadrupoles are then re-optimised in MADX [7], showing good agreement with the nominal design
  - The injection is therefore considered strongly flexible.

Stage 1 Beam Delivery Schemes

- To improve magnetic mini-beam generation, the quadrupole doublet scheme [8] has been modified to two triplets both in a D-F-D configuration.
  - Triplet 1: magnet lengths of 0.1 m, K_1 strengths of 30.26 m^{-2} & -53.40 m^{-2}.
  - Triplet 2: magnet lengths of 0.04 m, K_1 strengths of 302.56 m^{-2} & -551.73 m^{-2}.
- Beam sizes of $\sigma_x \approx$ 0.74 mm and $\sigma_y \approx$ 0.46 mm only partially satisfies the mini-beam criterion ($\sigma \leq$ 0.5 mm).







- Octupoles are chosen to deliver transverse uniformity whilst minimising impact to the deliverable dose.
  - They are most effective under strong transverse asymmetry.
  - The uniform width is maximized when the phase advance to the target is approximately $n\frac{\pi}{2}$.
  - The mini-beam quadrupoles can be tuned to achieve the necessary asymmetry and phase advance.
  - Modelled in BDSIM [9], an octupole strength of K_3 = −3905 m^{-4} achieves the target (95 ± 0.5) % uniformity within the predicted 1.88 cm width, capturing, 55.7% of the beam.

Summary

The most recent updates to the LhARA accelerator design have been presented. The Stage 1 design remains strong with the presented efforts demonstrating LhARA's flexibility. Stage 2 remains the primary focus going forwards, with the FFA magnet design highlighting the excellent promise of the design.

References

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