LASER-HYBRID ACCELERATOR FOR RADIOBIOLOGICAL APPLICATIONS (LHARA)

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INTRODUCTION

LhARA is conceived as a novel, flexible facility dedicated to radiobiological studies. Technologies demonstrated in LhARA can be developed to allow particle-beam therapy to be delivered in a new regimen by combining a variety of ion species at ultra-high dose rates with a variety of time structures, spectral distributions, and spatial configurations.

A high-power pulsed laser will drive the creation of a large flux of protons and light ions which are captured and focused by strong-focusing electron-plasma lenses (Gabor lenses). A fixed-field alternating-gradient accelerator (FFA) enables further acceleration preserving the flexibility in time, energy, and spatial structure of the beam.

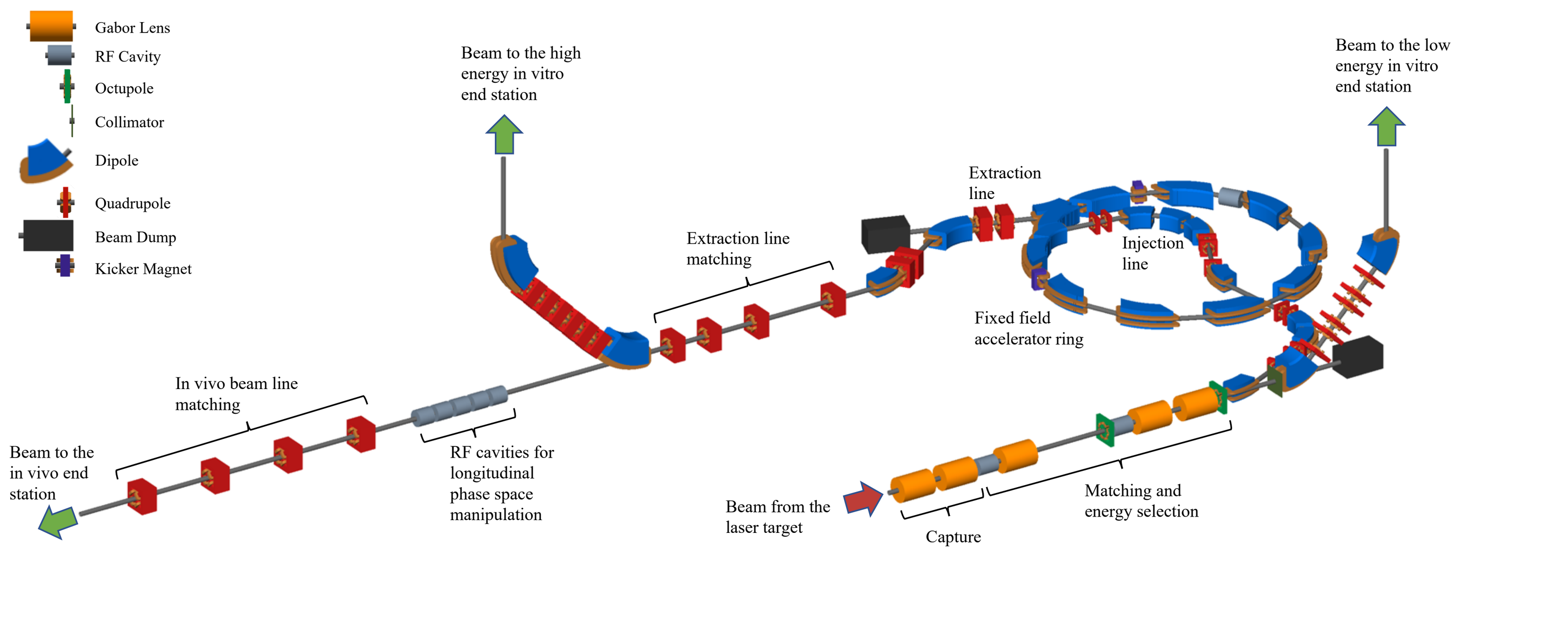

FIGURE 1: Schematic diagram of the LhARA beam lines. Particle flux from laser-driven source is given by the red arrow. The beam is transported either into a 90° bend to the low-energy *in vitro* end station, FFA injection line, or the low-energy beam dump. The FFA performs the post-acceleration where the beam is directed to either the high-energy *in vitro* end station, *in vivo* end station, or high-energy beam dump.

LhARA will be developed in two stages.

- Stage 1 – *In vitro* studies with proton beams of up to 15 MeV.
- Stage 2 – FFA to provide proton beam energies up to 127 MeV and carbon 6+ ions up to 33.4 MeV/u for both *in vitro* and *in vivo* studies.

LASER SOURCE

Operate in a laser-driven sheath-acceleration regime for ion generation.

- An intense, short laser pulse is focused on a target.
- A strong space-charge electric field, 'sheath', is created as accelerated electrons exit the rear surface of the target.
- This field accelerates surface-contaminant ions, which has been shown to produce ion energies greater than 40 MeV/u at highest laser intensities.
- A commercial laser system capable of delivering a significant proton flux at 15 MeV will be used.

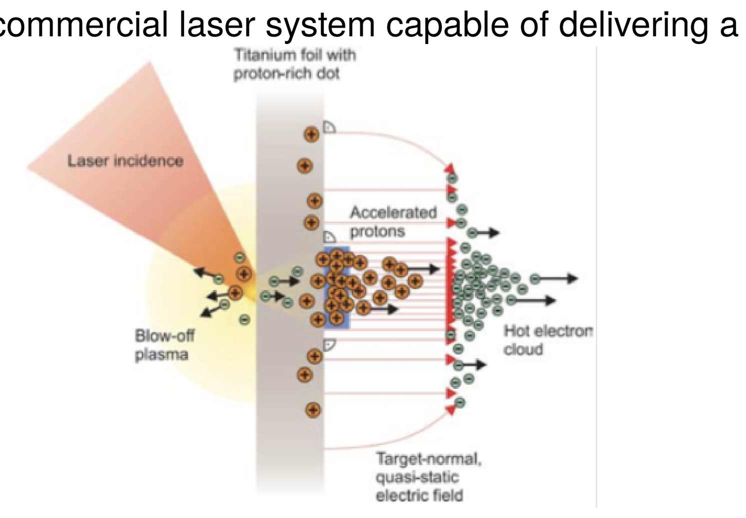

FIGURE 2: Schwoerer, H. et al., 2006; Nature, 439(7075).

Parameter	Value	Unit
Laser power	100	TW
Laser energy	2.5	J
Laser pulse length	25	fs
Laser rep. rate	10	Hz
Required max. proton energy	15	MeV

TABLE 1: Table of parameters for the laser-driven proton and ion source.

GABOR LENS

An electron cloud can be used as a focusing element for charged-particle beams.

- An electron cloud can be confined within a lens using a long cylindrical anode placed within a uniform solenoid field.
- For a given focal length, the magnetic field required in the Gabor lens is reduced compared to a solenoid which allows for lower costs.
- A theoretical investigation of lens stability is underway with VSim [2], a particle-in-cell code, followed by construction of a test Gabor lens.

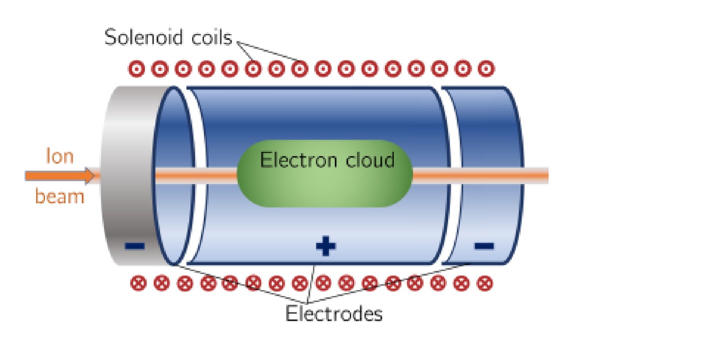

FIGURE 3: Schematic diagram of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA. The confining electrostatic potential is provided using a central cylindrical anode and two cylindrical negative end electrodes.

FIXED-FIELD ALTERNATING-GRADIENT ACCELERATOR (FFA)

A FFA will be used to accelerate the beam in LhARA Stage 2. Typically the beam momentum will increase by a factor of three which translates to energies:

- Up to 127 MeV protons
- Up to 33.4 MeV/u carbon ions

Some advantages of an FFA for both medical and radiobiological applications include:

- The capability to deliver high and variable dose.
- Rapid cycling with repetition rates ranging from 10 Hz to 100 Hz or above.
- The ability to deliver various beam energies without the use of energy degraders.
- A combination of both compactness in size with multiple ion species acceleration.

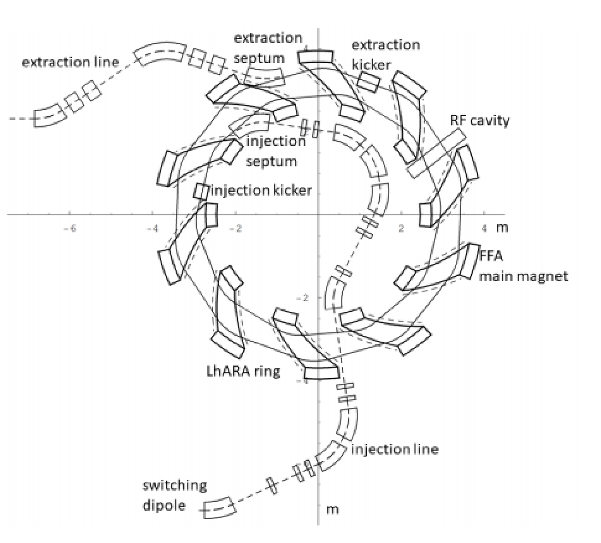

FIGURE 4: Layout of the injection line from the switching dipole to the injection septum together with the FFA ring, and the first part of the extraction line.

LHARA STAGE 1

Stage 1 of LhARA consists of the elements of the laser source to the first *in vitro* arc.

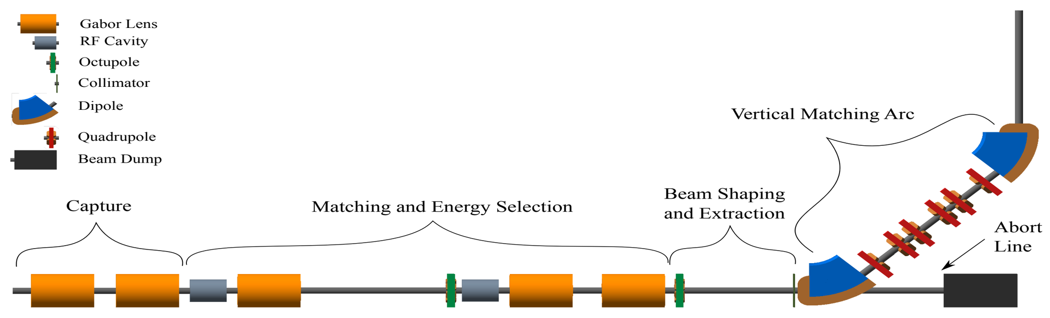

FIGURE 5: The five sections composing Stage 1 of LhARA visualised in BDSIM. The total length of this beam line is 17.3 m.

An idealised Gaussian beam was generated with a spot size of 4 μm FWHM, angular divergence of 50 mrad, 35 fs FWHM bunch length, and an energy spread of 1×10^{-6} MeV and tracked in BDSIM [3], this was repeated in GPT [4] to include the effects of space charge.

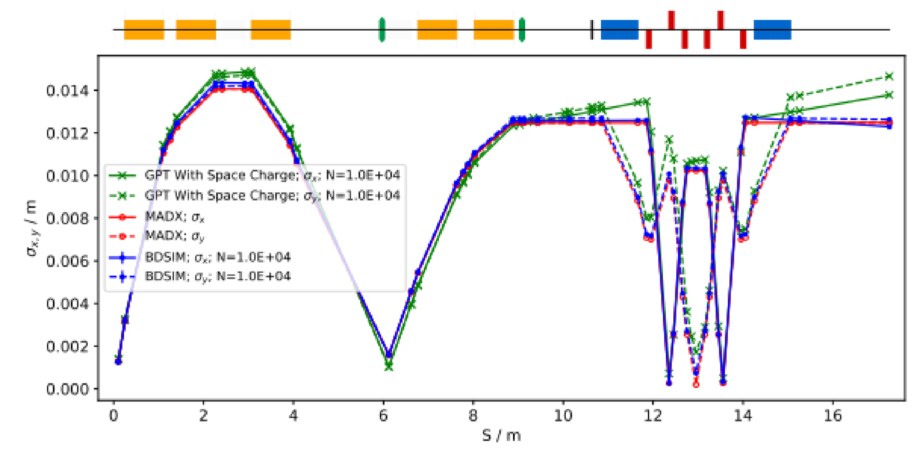

FIGURE 6: Simulation of horizontal and vertical transverse beam sizes between BDSIM, MAD-X, and GPT for 10^4 macroparticles representing a full bunch charge of 10^9 protons.

LHARA STAGE 2

Stage 2 of LhARA consists of the FFA and all downstream elements. An idealised Gaussian beam was simulated for the high-energy *in vitro* beam line and the *in vivo* beam line.

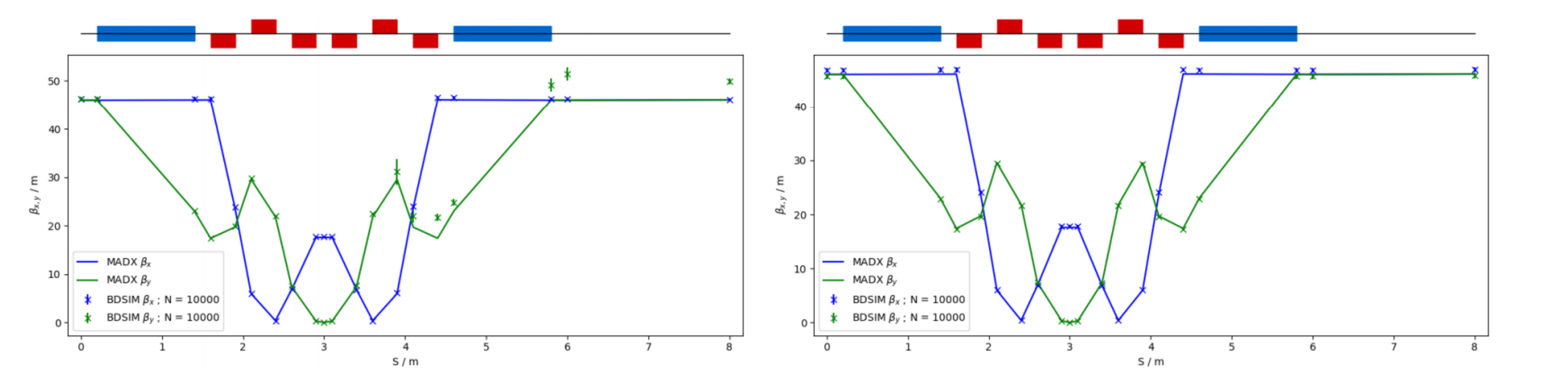

FIGURE 7: Comparison of particle tracking in MAD-X and BDSIM of a 40 MeV (left) and 127 MeV (right) proton beam passing through the high-energy *in vitro* arc for 10^4 macroparticles representing a full bunch charge of 10^9 protons.

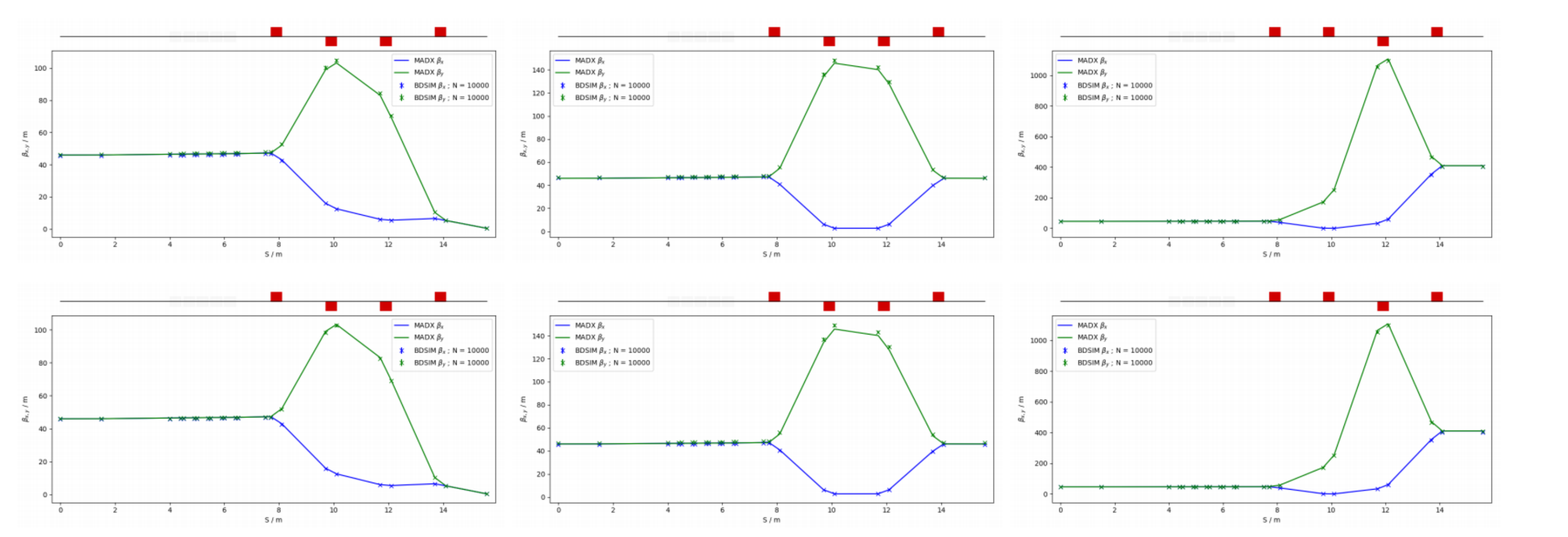

FIGURE 8: Simulation of the *in vivo* beam line for 40 MeV (top row) and 127 MeV (bottom row) comparing MAD-X and BDSIM. Columns represent different quadrupole settings showing the flexibility of the beam size that can be delivered.

BIOLOGICAL END STATION

The *in vitro* end stations are envisioned for the irradiation of 2D monolayer and 3D-cell systems in culture.

- Sealed units allow for cells to be incubated prior to and during irradiation.
- Robotics will enable numerous cell culture plates to be placed into and taken out of the beam.

The *in vivo* end stations will be used to irradiate small-animal models.

- An image guidance system will be used to enable a high level of precision and accuracy.
- The flexibility in beam sizes allows for different irradiation conditions such as through passive scattering, pencil-beam scanning, and micro-beam irradiation at both conventional and FLASH dose rates.

BDSIM was used to evaluate the maximum dose distributions that LhARA can be expected to deliver.

- The integrated energy deposition within a fixed volume of water at the Bragg peak was recorded:

	12 MeV Protons	15 MeV Protons	127 MeV Protons	33.4 MeV/u Carbon 6+
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

TABLE 2: Expected maximum dose rates LhARA can deliver for various beam energies at minimum beam size.

CONCLUSION

- The flexibility of LhARA enables the systematic study of the radiobiology of proton and ion beams.
- LhARA has the potential to demonstrate novel techniques which can drive a step-change in particle beam therapy.
- Initial concept has been developed [1] and has been accepted for publication in Frontiers Physics, section Medical Physics and Imaging.
- Prototype evaluations are in progress:
  - Simulations of the laser source for a more realistic beam distribution.
  - Investigations of Gabor lens stability.

REFERENCES

[1] G. Aymar, T. Becker, S. Boogert, M. Borghesi, R. Bingham, C. Brenner, P. N. Burrows, T. Dascalu, O. C. Ettlinger, S. Gibson, T. Greenshaw, S. Gruber, D. Gujral, C. Hardiman, J. Hughes, W. G. Jones, K. Kirkby, A. Kurup, J.-B. Lagrange, K. Long, W. Luk, J. Matheson, P. McKenna, R. Mclauchlan, Z. Najmudin, H. T. Lau, J. L. Parsons, J. Pasternak, J. Pozimski, K. Prise, M. Puchalska, P. Ratoff, G. Schettino, W. Shields, S. Smith, J. Thomason, S. Towe, P. Weightman, C. Whyte, and R. Xiao, "The laser-hybrid accelerator for radiobiological applications," 2020.

[2] Tech-X, "Vsim,"

[3] L. J. Nevay *et al.*, "Bdsim: An accelerator tracking code with particle-matter interactions," *Computer Physics Communications*, p. 107200, 2020.

[4] PulsarPhysics, "General particle tracer,"