Innovative handling and transport solutions for laser-driven ion beams

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on behalf of the ELIMED Collaboration

Targetry for Laser-driven Proton (Ion) Accelerator Sources: First Workshop Institute for Advanced Study (IAS), Garching, Germany, 9–11 Oct 2013
ELI-Beams, ELIMAIA beam-line and the ELIMED idea

ELIMAIA beamline in Prague
ELI Multidisciplinary Applications of laser-Ion Acceleration

Why ELIMAIA?

Realization of a facility at ELI-Beamlines

as first User’s beam line to study the laser-driven proton (ion) application:

- Irradiation of biological and other samples
- Radiation damage on different components
- Detectors characterization
- Pump probe investigations
- Demonstration of new irradiation modalities for radiotherapy
Investigating the possibility to use the laser-driven ion beams generated at ELIMAIA for Hadrontherapy application:

⇒ a good candidate for a demonstration-case

A medical application is the most demanding in terms of beam characteristics and performances. It will require:

- Target investigation
- Beam delivering system
- Diagnostic tools suitable for non-conventional beams
- Innovative technique for absolute and relative dosimetry, radiobiology
Hadrontherapy, a potential user case

...and a possible future for laser-driven based hadrontherapy facilities?

Spread is limited as respect conventional facility:

- High complexity for the beam production, acceleration and transport
- High cost: 150-200 M€, ~70 M€ for the eye therapy

Why laser-driven proton beams?

- **Compactness**
- **Cost-reduction**
- **Innovative treatment modalities:**
  - Variable energies in the accelerator (no degraders needed)
  - Short beam pulses (very useful for fast scanning and to reduce organ motion issues)
Typical laser-driven ion beam characteristics

**Benefits**

- Large accelerating field (> GV/m)
- High flux and high dose-rate per bunch: ~ $10^9$ Gy/sec
  (≈ 10 Gy/sec maximum for conventional accelerators)

**Challenges**

- Very short bunch duration: < 100 psec
  (> 5 nsec for conventional accelerators)
- Tunable energy spectrum
- Significant angular divergence (±25°)

**Solutions to study and control the beam parameters**

- Target with special shape and composition
- Systems for the beam handling and energy selection
ELIMAIA first goal: 60 MeV @ 1 PW, 30 fs

Tumor distribution vs depth in water

- Protons, 250 MeV
- Protons, 60 MeV, eye-melanoma treatment, a demonstration case
- Protons, 150 MeV

Future ELIMED applications

HIMAC Facility (Japan), overall diseases distribution (2000)

Demonstration of eye proton-therapy, ELIMAIA first phase, 2016-2017
Target and ELIMAIA areas
The future ELIMAIA beamline

Target and laser interaction

Beam handling and diagnostic

Dosimetry and radiobiology
Beam Handling and Diagnostic

Goal: study of new particle transport solutions to obtain a beam suitable for multidisciplinary applications
Beam transport ideas

• **Tunably**
  deliver beam of different energies, energy spread and species

• **Large acceptance**
  Control the large chromatic emittance due to the high energy spread of the transported beam

• **Modularity**
  Flexibility to meet different experimental set-up and new ideas for Users experiments

• **Cost effective**
  Use of only conventional device
**Beam transport ideas**

*Possible layout of collecting and transport sections*

**A**

- solenoid
- 1st TQP
- 2nd TQP

Maximize the transmission efficiency (>50%), but low optimization in energy spread (>50%)

**B**

- 1st solenoid
- 2nd solenoid
- collimator
- 1st TQP
- 2nd TQP

Maximize the energy spread of the pre-selection beams (<40%) but low transmission efficiency (<30%)
Beam transport ideas: The Energy Selection System (ESS)

- Final and finest step in the energy selection

ESS Prototype already developed @ LNS-INFN:

- Wide energy range (1–60 MeV)
- Controlled energy spread (1-30 %)
- Compact design
- Passive magnetic elements
ESs prototype: working principles

- Transversal moving of the slit permits the energy selection
- Transversal moving of dipoles #2 and #3 to decrease the selectable low energy limit
- Longitudinal moving of dipole #4 to compensate the magnetic field asymmetries of the whole structure

E. Fourkal, J. S. Li, M. Ding, T. Tajima, and C.-M. Ma
Med. Phys. 30, 1660 (2003);
ESS prototype realization @ LNS (CT)

Design, Construction and Assembly of the ESS

Technical design

The First dipole prototype

The ESS

The ESS inside the vacuum chamber
Status of the ESS prototype @ LNS (CT)

Magnetic field profiles measured on the 3 axes along the radial plane

April 2013: First experimental test in air on the ESS prototype @ CATANA using a 62 MeV proton beam delivered by the Superconductive Cyclotron
ESS Geant4 simulation

Monte Carlo Simulation of the ESS

ESS simulation: Magnetic field treated with the hard-edge approximation

Monte Carlo Simulation for the Transport Beamline
AIP Conf. Proc. 1546, pp. 63-69

- Entrance energy: 0-80 MeV
- Beam shape: Uniform
- First collimator hole size (diameter): 3 mm
- Slit hole size: 1 mm
- Slit Material: W, 6 mm thick
- Final collimator hole size (diameter): 1 mm
- Window material: Kapton

Graph: Slit position vs. Energy [MeV]

Legend:
- Analytical
- GEANT4
Calibration performed using the proton beam delivered by the TANDEM at LNS

Proton energies: 4.5 - 12 MeV

Experimental run aims:

- Calibration of the slit position as function of the beam energy
- 4° dipole position calibration
- Beam profile
- Transmission efficiency
- Validate ESS simulation
Monte Carlo activity with Geant4

- Design and optimization of the ELIMED beamline
  - Energy selection system
  - Transport beam line optimization
  - Irradiation approach
  - Radioprotection and dosimetry

- Simulation of the available test-site facility
  TARANIS (UK), LULI (F), JAEA (Japan) for an accurate delivered dose evaluation
**The TARANIS experiment**

**Laser beam** (Ti:sapphire-Nd:glass)
Intensity -> $10^{19}$ W/cm$^2$
Pulse duration -> 700 fs
laser wavelength -> 1053 nm

Proton beam detectors:
- **CR-39**
- **RCF, GafChromic**
- **Si** detector (Surface barrier or Strips)
- **SiC**
- **Diamond** detector

November-December 2013
Dosimetry and radiobiology

Study and design of a dosimetric system for dose measurements and irradiation of bio-samples
Dosimetric system

Solutions adopted for relative dosimetry:
- GafChromic films (passive)
- High-rates Transmission chamber (on-line)

Solutions adopted for the absolute dosimetry:
- Faraday cups coupled with:
  - GafChromic/CR39 stacks for energy spectrum and beam spot measurements at the entrance (passive)
  - Scintillating fibers for energy spectrum measurements (on-line)

On-line relative dosimetry:
- Transmission IC
- ELIMON detector

Absolute dosimetry:
- Faraday cup

Energy spectrum measurements:
- Radiochromic films (stack)
- CR39 detectors
- Scintillating fibers (real-time)

Preliminary design of a dedicated dosimetric system
Thank you