Research opportunities in ion acceleration and applications on the ELIMAIA beamline

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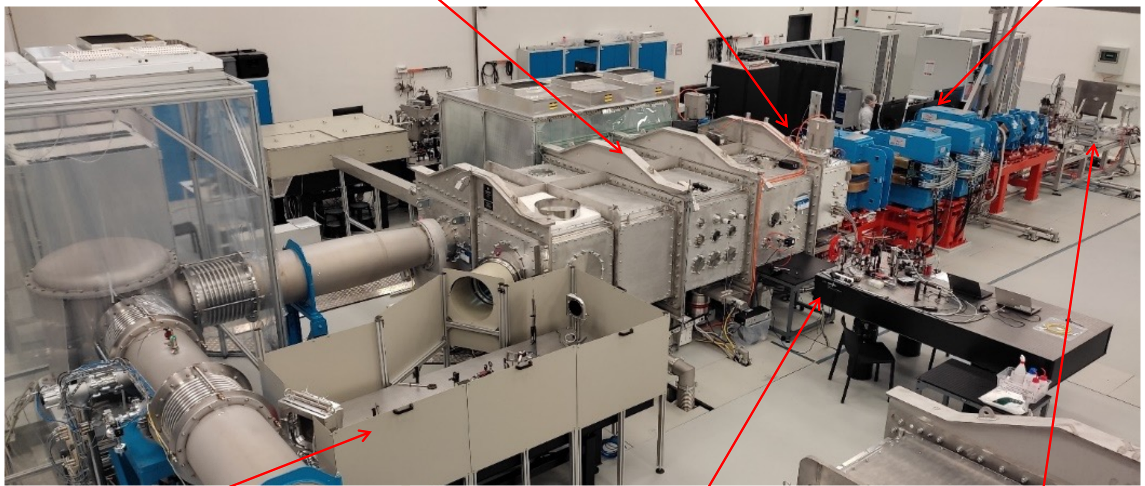
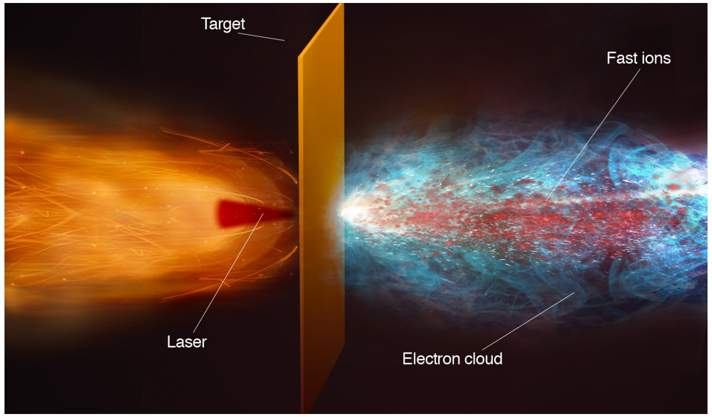
ELI Beamlines facility
Dolni Brezany, Cz



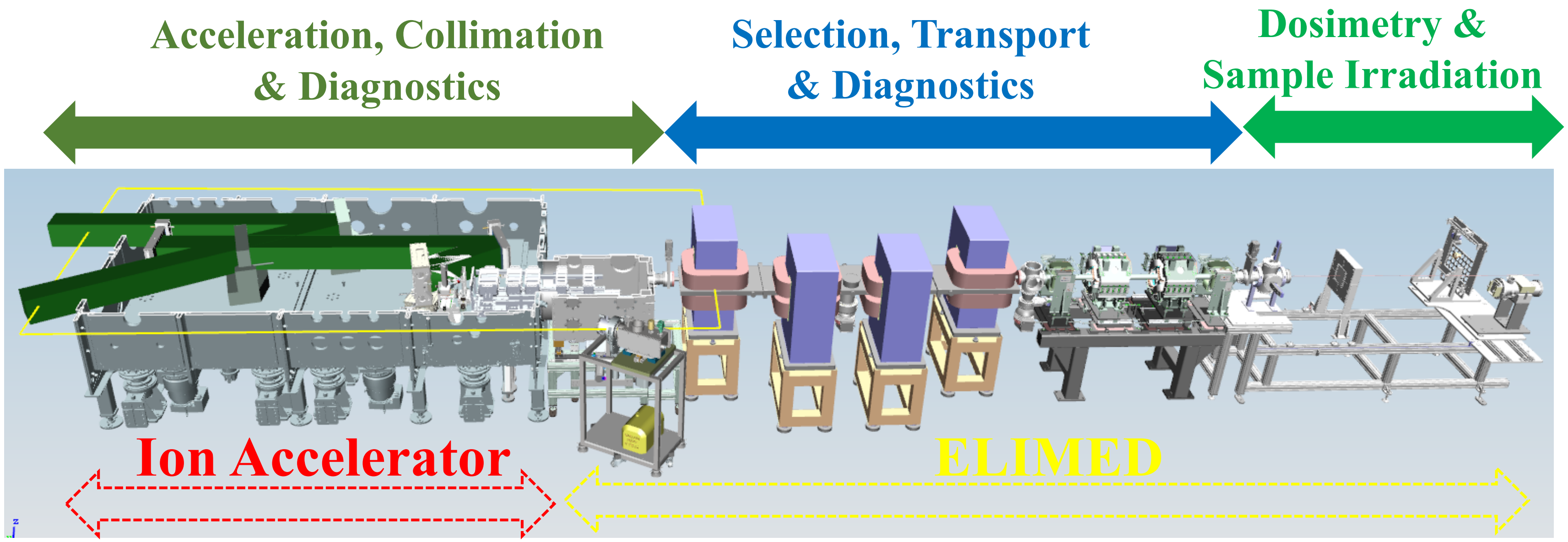
Outline

- ELIMAIA
- Proton source: current status and expectations
- Advanced acceleration mechanisms
- Target-based scheme for enhanced transport
- Application: ultra-high dose rate radiobiology



ELIMAIA user beamline

ELI Multidisciplinary Applications of laser-Ion Acceleration



ELIMAIA mission: provision of proton beams with controlled properties for multidisciplinary user-driven applications

Research opportunities will arise at every step of the process above:

Scaling of proton beam properties
Advanced mechanisms

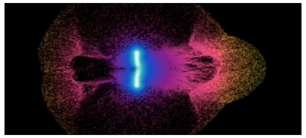
Techniques for beam collimation
Efficiency enhancement

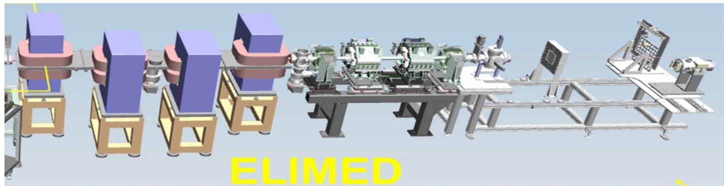
Applications
Novel dosimetry

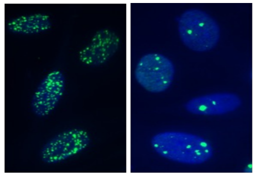
FLAIM flagship experiment (2023)

IMPULSE

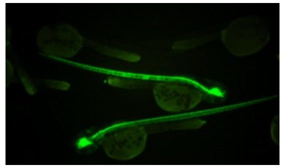
FLAIM : Flash and ultrahigh dose-rate radiobiology with Laser Accelerated Ions for Medical research

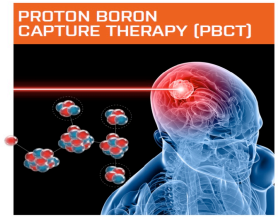






carbon proton





High quality ion source
(high energy protons)

Efficient transport

Innovative Radiobiology
(3D model, in-vivo)

Scientific Impact

- ✓ innovative regimes for ion acceleration (**protons and C-ions**) with a PW-class laser at ELIMAIA at high rep. rate
- ✓ high beam quality through dedicated **ion beam transport** at ELIMAIA/ELIMED for irradiation of biological samples
- ✓ novel **clinical dosimetry** through dedicated on-line, cutting-edge diagnostics available at ELIMAIA/ELIMED
- ✓ **in-vitro** cell (cancer and healthy tissues) and **in-vivo** (zebra fish) **irradiation** with **proton/carbon** beams using **ultrahigh dose-rate and flash** radiotherapy approaches (10^9 Gy/s)

Dedicated workshop tomorrow afternoon

L3 HAPLS laser status

High repetition rate Advanced Petawatt Laser System

J. Cupal, B. Rus (Dep.91)

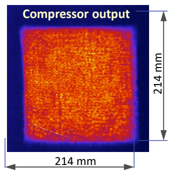
- 1 PW 10 Hz repetition rate beamline
- Nd:glass helium-cooled DPSLL pump laser
- Ti:sapphire short-pulse chain, helium-cooled power amplifier
- World’s highest peak power laser diode arrays
- High level of automation

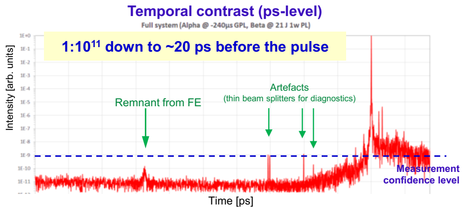
Design performance: 1 PW / 10 Hz
30 J / <30 fs

Current performance: 0.5 PW / 0.5 Hz, 3⅓ Hz
13.3 J / 27.3 fs

Ramping to PW / 10 Hz in progress:

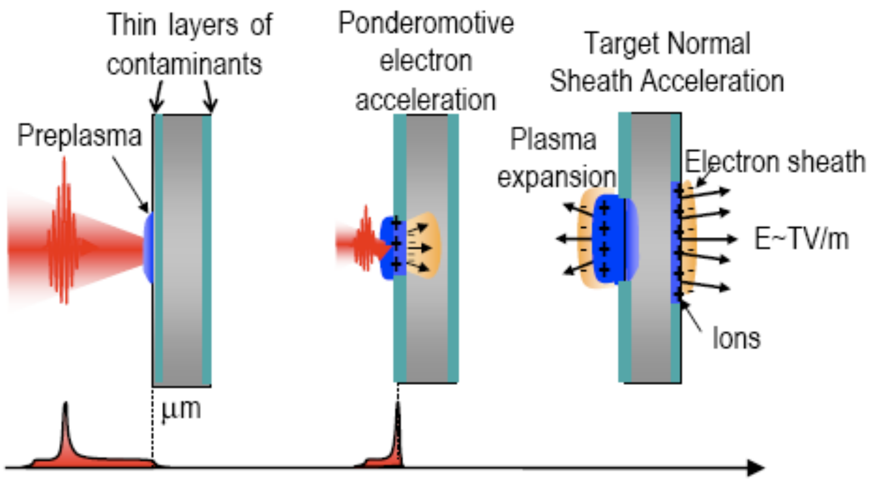
- 1 PW / shot-on-demand spring - summer 2023
- 1 PW / 3⅓ Hz spring - summer 2024
- 1 PW / 10 Hz spring - summer 2025



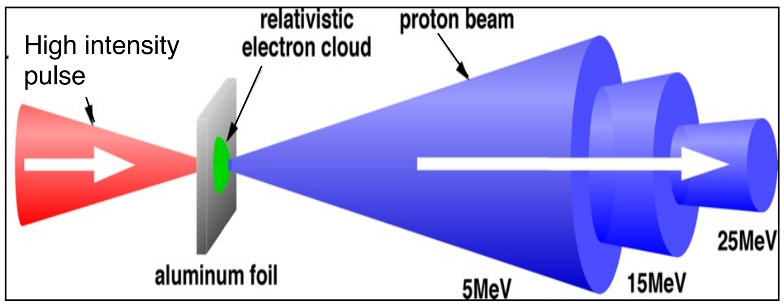


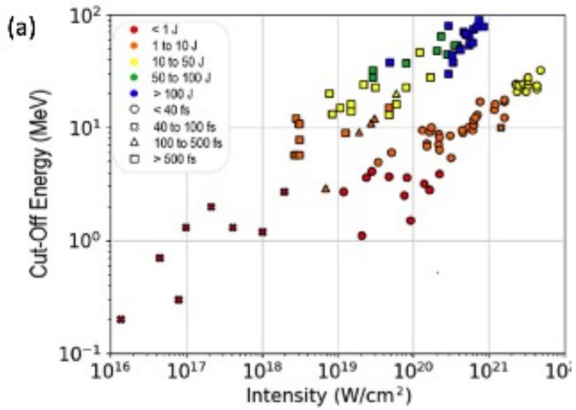
eli beamlines

Proton source:
Target Normal Sheath Acceleration (TNSA)



- Widely studied since 2000 and well established
- Broad spectrum/diverging beams
- Burst duration : ~ ps at source
- Highly laminar beams (ultralow emittance)
- High brightness beams – 10^{11}-10^{12} protons /shot
- Surface acceleration process – mostly active on proton contaminants



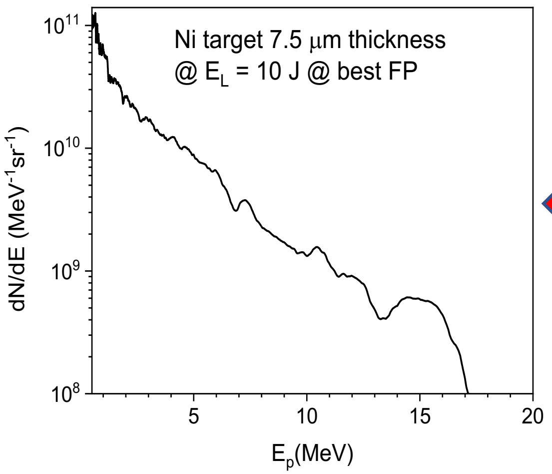


Proton cut-off energies scale with laser intensity/energy
E_{max} ~ 90 MeV for ps PW (PHELIX)
60 MeV for fs PW (DRACO)

*Zimmer, PRE **104** (2021) 045210*

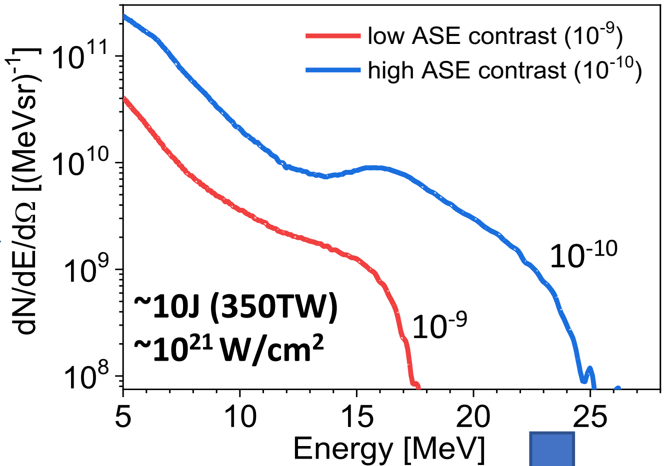
TNSA performance on ELIMAIA

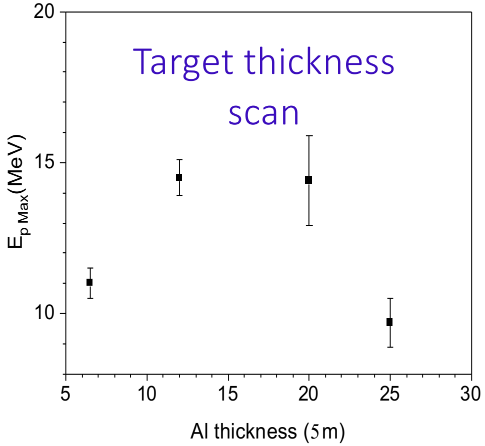
Basic commissioning (2021):

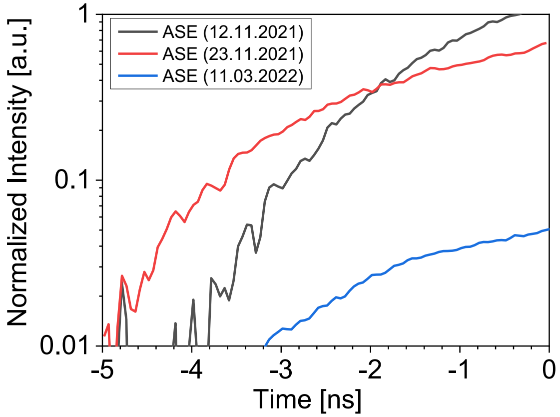


L3 HAPLS : 40 fs, 10 J, 1 Hz
350 TW, 10^{21} W/cm^2

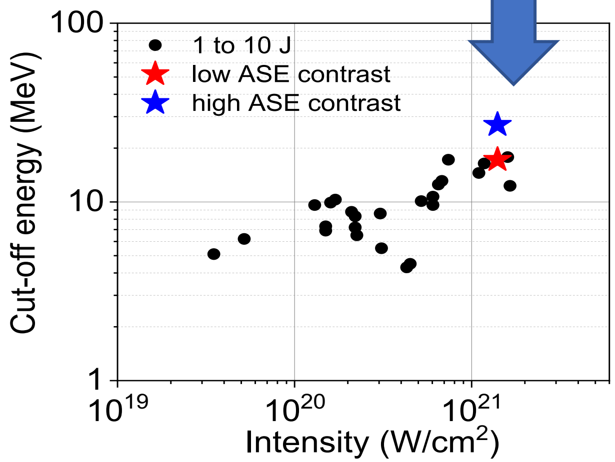
Advanced commissioning (2022):





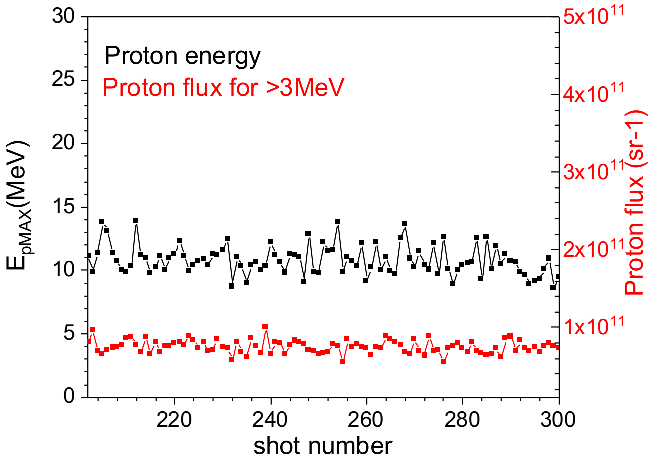


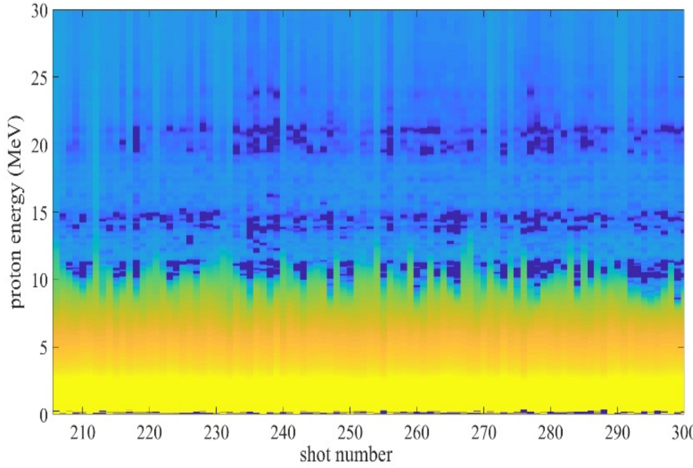
Key improvement : ASE reduction



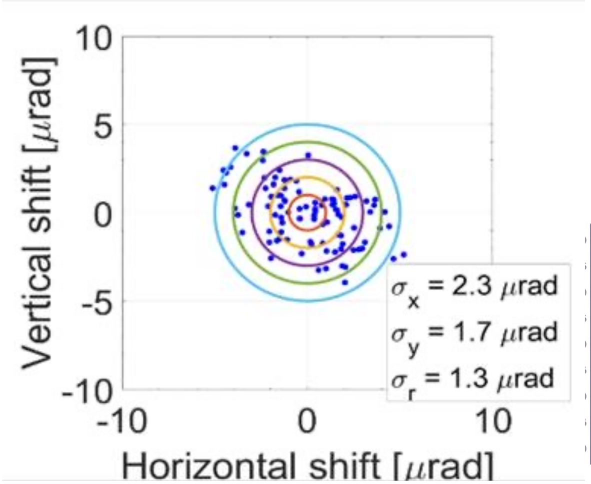
Stability tests: rep. rate series @10^{21} W/cm^2

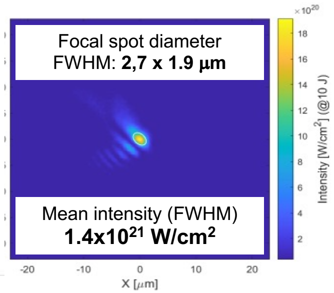
500 consecutive shots
(5x 100 shots @**0.5 Hz**)
Data acquisition and analysis also @0.5 Hz





Excellent pointing stability at high power
(<3 µmrad, 1µm on target)





Stable and reproduceable proton source

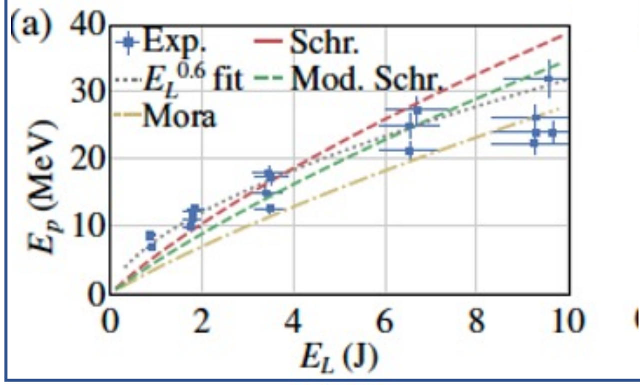
Fluctuations		100 consecutive shots @ 0.5 Hz
Laser energy	0.2%	9.58±0.02 J
Laser intensity @FWHM	2.7%	(1.33±0.04)*10^{21} W/cm^2
T_{hot}	1.1%	3.502±0.037 MeV
Photon flux	1%	
E_{pMAX}	1.1%	10.79±0.12 MeV
Proton flux >3 MeV	1.2%	7.5*10^{10}±8.5*10^{10} sr-1

Ramping up laser power and proton energies

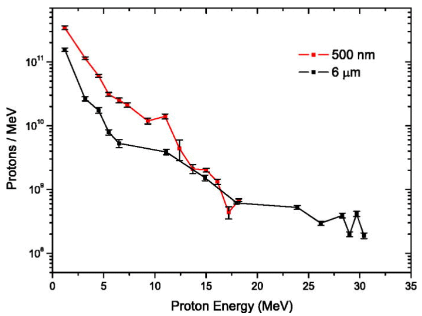
	2022		2023
Laser energy:	10 J	➡	30 J
Proton energy:	25 MeV	➡	?

Current performance in line with expectations

N.P.Dover et al, PRL, **124**, 084802 (2020)



JKaren, QST (Japan)
f/1.4 , 40 fs,
f.s~ 1.5 µm FWHM ,
I_{max}~ 5 10^{21} W/cm^2



GEMINI, 10 J, 45 fs
f/2, f.s.~2.5µm FWHM
I ~ 10^{21} W/cm^2

J.S. Green *et al*, APL, **104**, 214101 (2014)

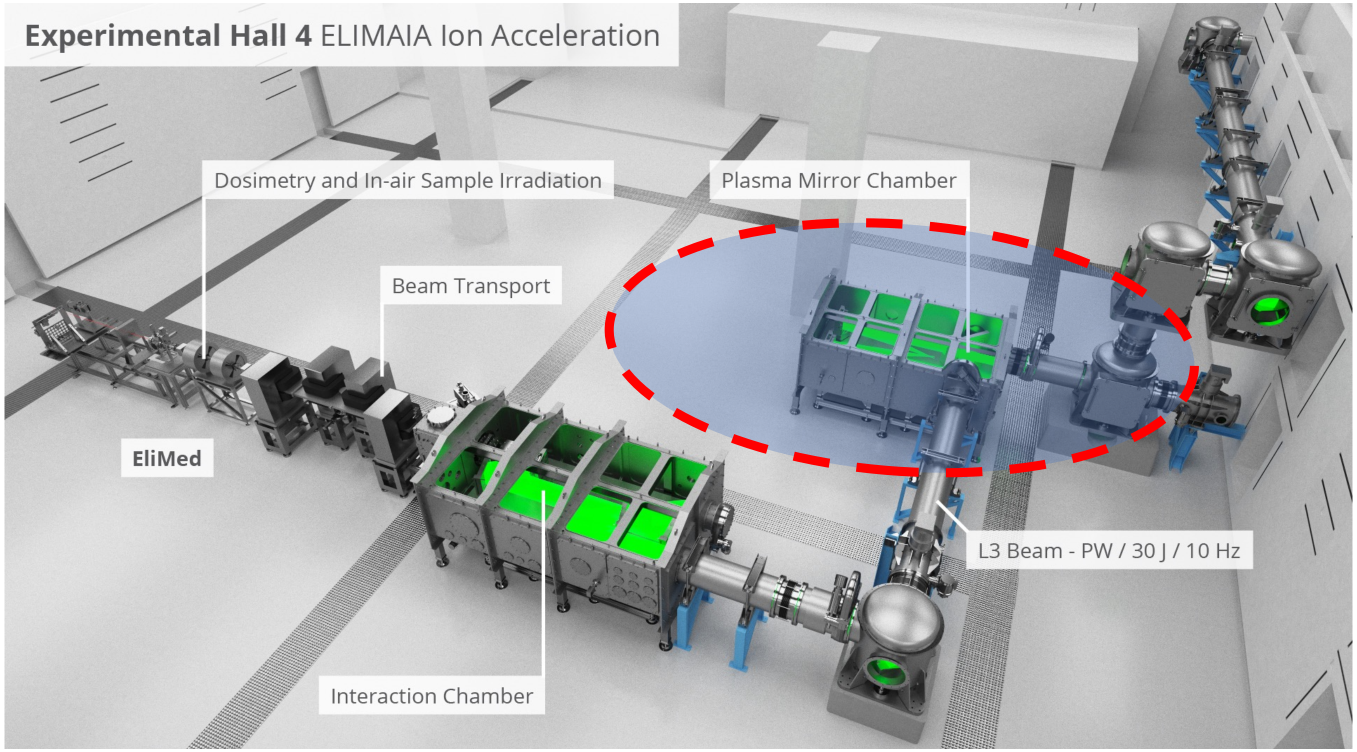
Experimental proton energy scaling: $E_p \sim E_L^{0.6}$

suggests **50 -60 MeV** cut-off for 30 J, 1 PW pulses

Further optimization is possible through secondary factors (laser profile, phase, etc):
40-60 MeV obtained on DRACO laser(HZDR) with ~ 20 J laser energy

T. Ziegler *et al*, Sci Rep., **11**, 7338 (2021)

Beyond TNSA: advanced mechanisms for enhanced beam provision

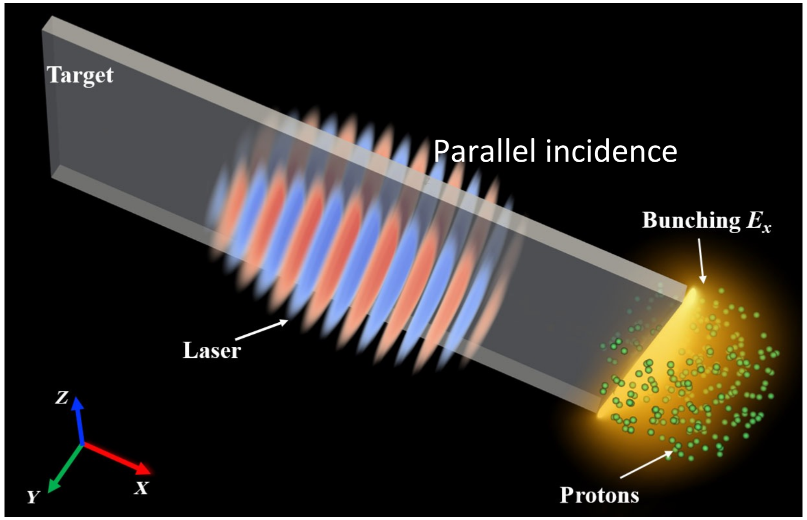


- **Proton acceleration at grazing/parallel incidence**
- **Radiation Pressure Acceleration from ultrathin foils**
- Relativistic transparency regimes
- Hole Boring processes in low density media
- *Synchronized/slow light* acceleration

…….

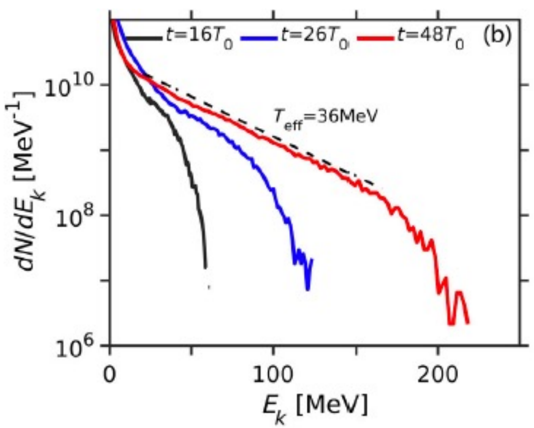
Commissioning of plasma mirror chamber will open to investigation new acceleration mechanisms

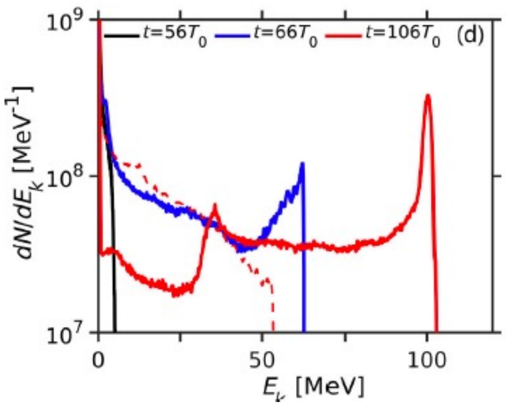
New acceleration processes through high-field plasmonics



Peeler acceleration

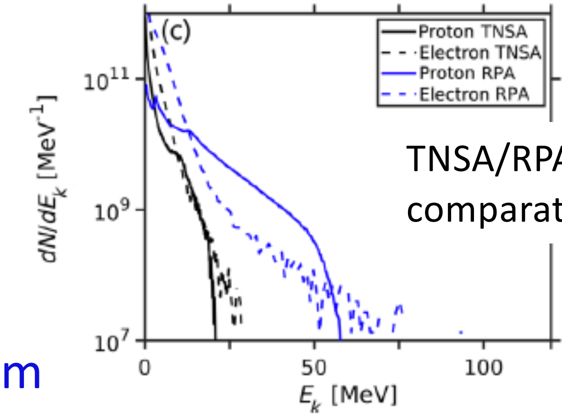
X.F. Shen, A. Pukhov, B. Qiao, Phys Rev X, 11, 041002 (2021)





- Parallel incidence – electrons *peeled* from the surface
- Electron acceleration by surface plasma waves
- Electrons propagate along surface
- Strong sheath field formed at target edge
- Many more electrons than protons available:
  proton collimation and narrow band

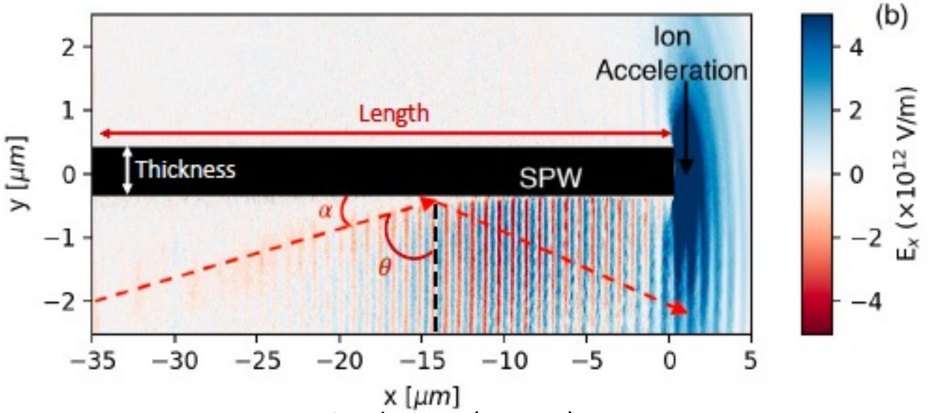
3D Pic simulations for I~ 8 10^{20} W/cm^2 τ ~ 45 fs, r ~ 7.5 μm



TNSA/RPA comparator

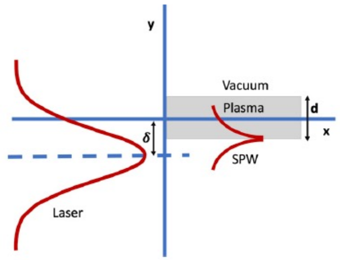
Mechanism also works at grazing incidence

J. Sarma *et al*, New J Phys, **24**, 073023 (2022)

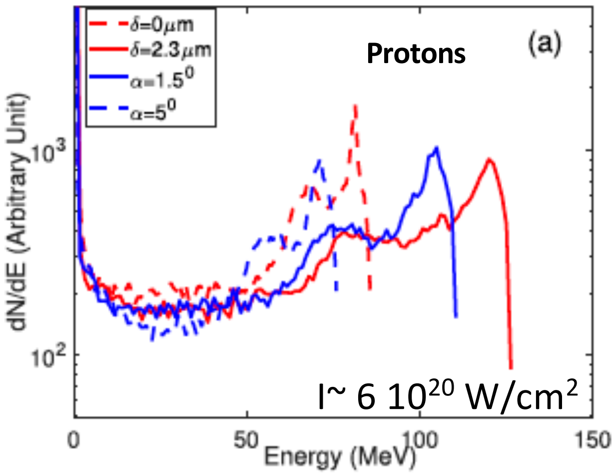


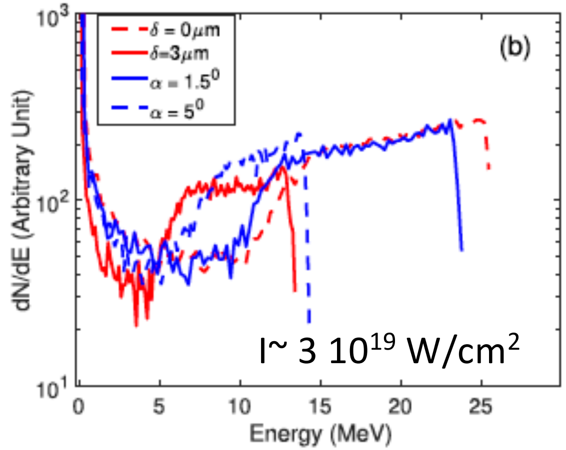
2D PIC simulations (EPOCH)

SPW excitation previously studied at larger incidence angles and using pre-imposed periodic structures



- Strong dependence on grazing angle
- For parallel case, significant dependence on lateral shift



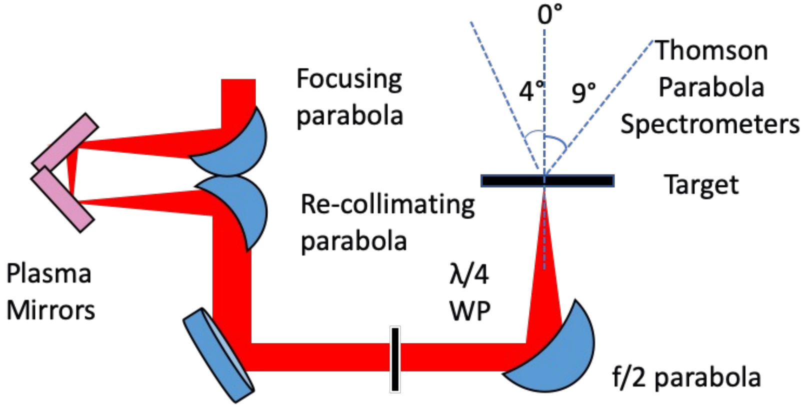


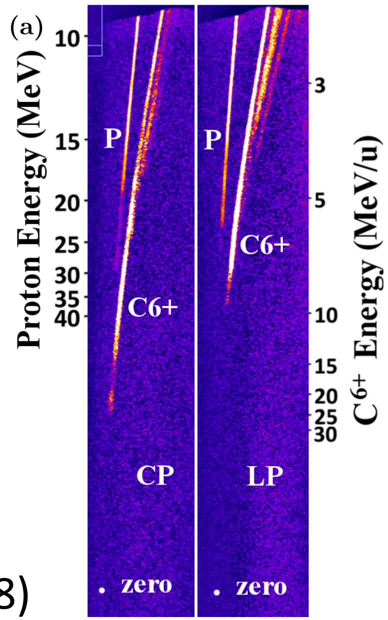
Experimental verification forthcoming (GEMINI, Jan 2022)

Volumetric acceleration from ultrathin foils

Radiation Pressure Acceleration

ASTRA GEMINI, 350 TW

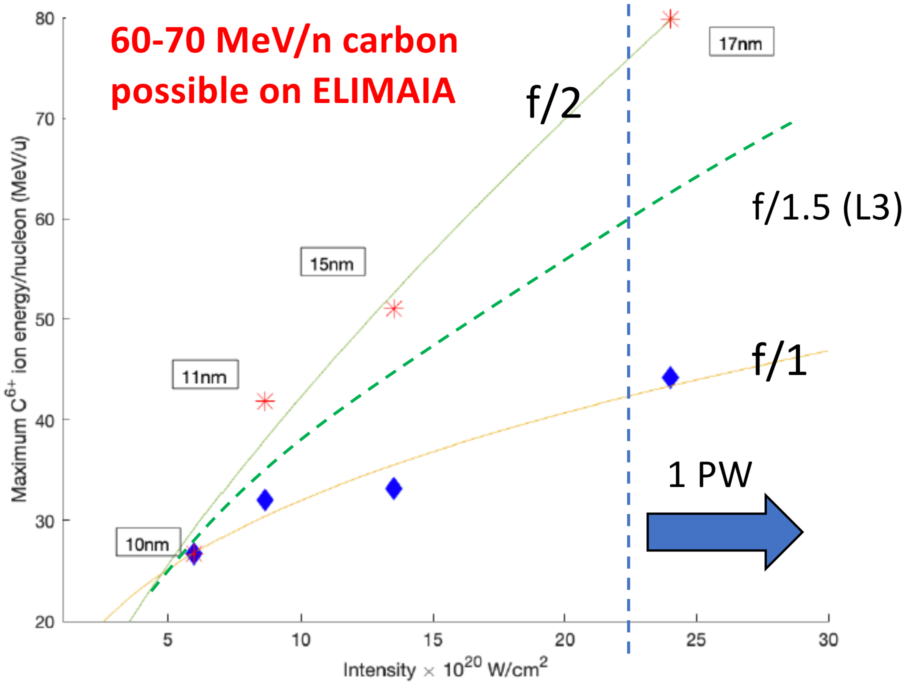




C. Scullion et al, PRL, **119**, 054801 (2018)

A.McIlvenny et al, PRL **127**, 194801 (2021)

Scaling to PW power

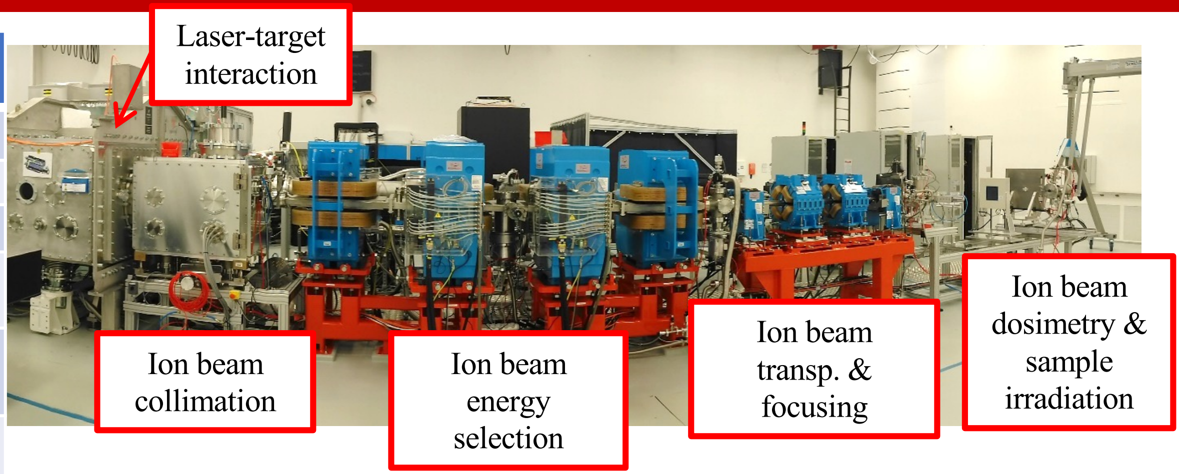


- **Strong dependence on polarization, onset of Light Sail acceleration**
- **Particularly interesting for bulk Carbon acceleration**
- **Existence of an intensity dependence, optimum target thickness**
- **Opportunities for pure carbon beam delivery**

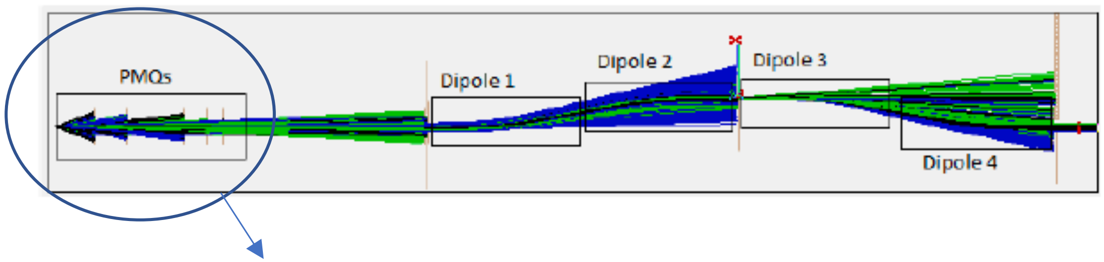
QUEEN'S UNIVERSITY BELFAST

ELIMED ion beam transport

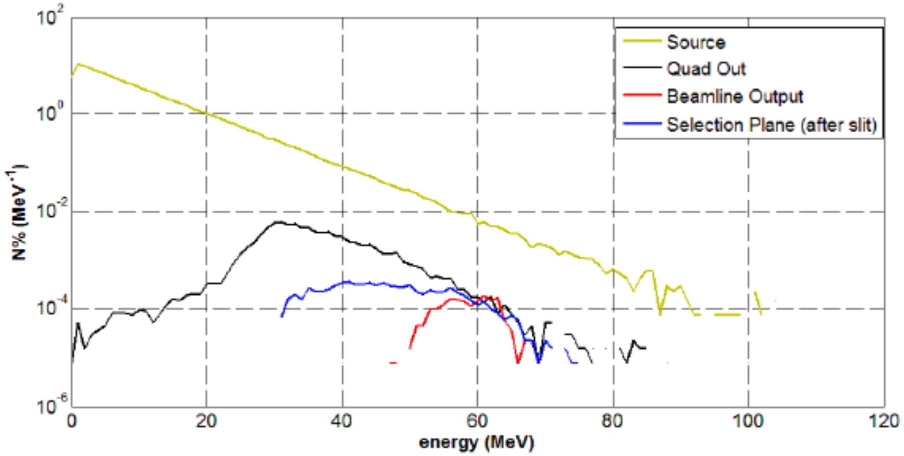
ELIMED Station	Design parameters @ user sample
Proton energy	5-60 MeV
Ions/shot	$1{\cdot}10^{8}$-$1{\cdot}10^{10}$/sr
Bunch duration	1-10 ns (>10^{9} Gy/s)
Ion beam aperture	~ 1deg (FWHM)
Ion beam spot size	0.1-10 mm (FWHM)
Repetition rate	Possible active modulation (1Hz)



Simulated transmission through ELIMAIA transport section ~ 4-12% (depending on assumptions on angular distribution within spectral band)
5° divergence FWHM assumed



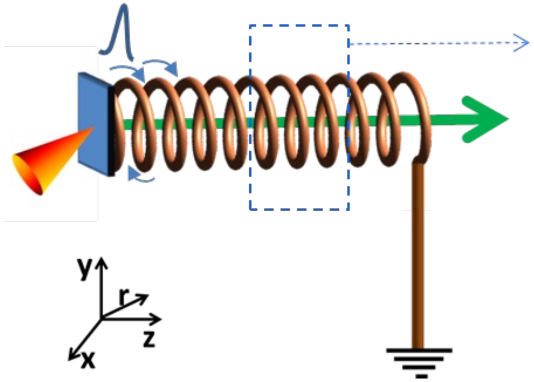
Unavoidable losses associated to beam divergence

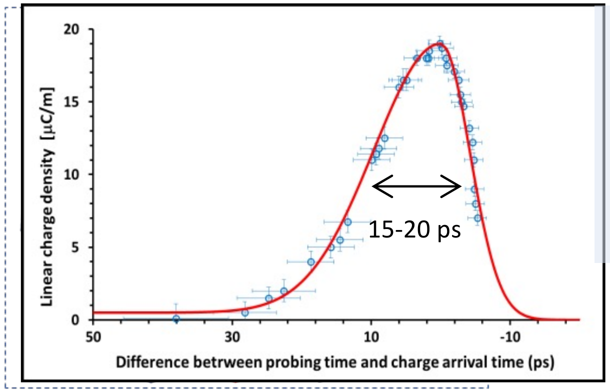


F.Schillaci *et al*, JINST, **11**, P08022 (2016)

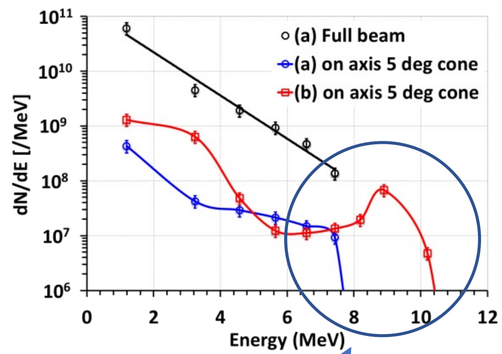
Target-based approach for pre-collimation

S. Kar *et al.*, Nature Communications, **7**, 10792 (2016)



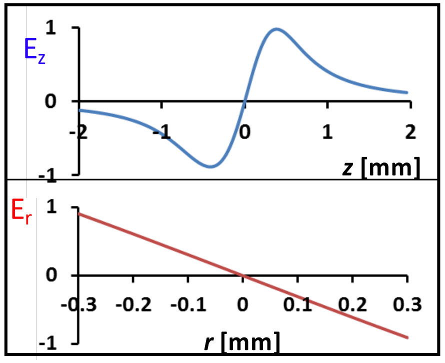


EM pulse propagating along coiled wire at v ~ c

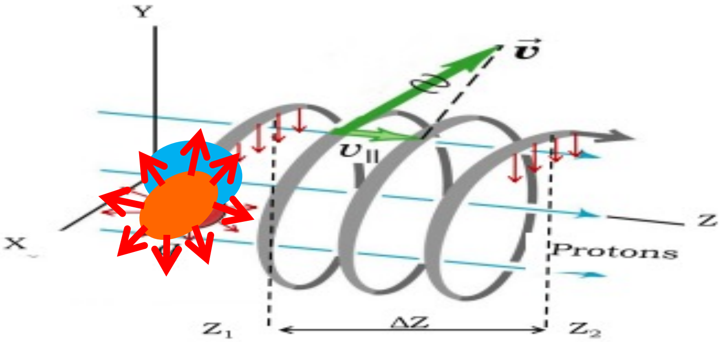


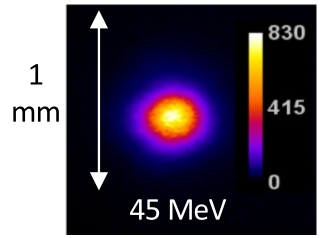
Re-accelerated bunch

The field structure is essentially equivalent to the field of a **charged ring**



Choice of geometry(coil diameter, pitch) allows "longitudinal"synchronization with a group of protons

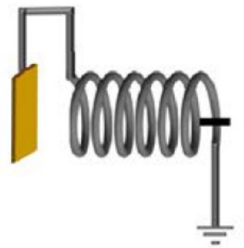


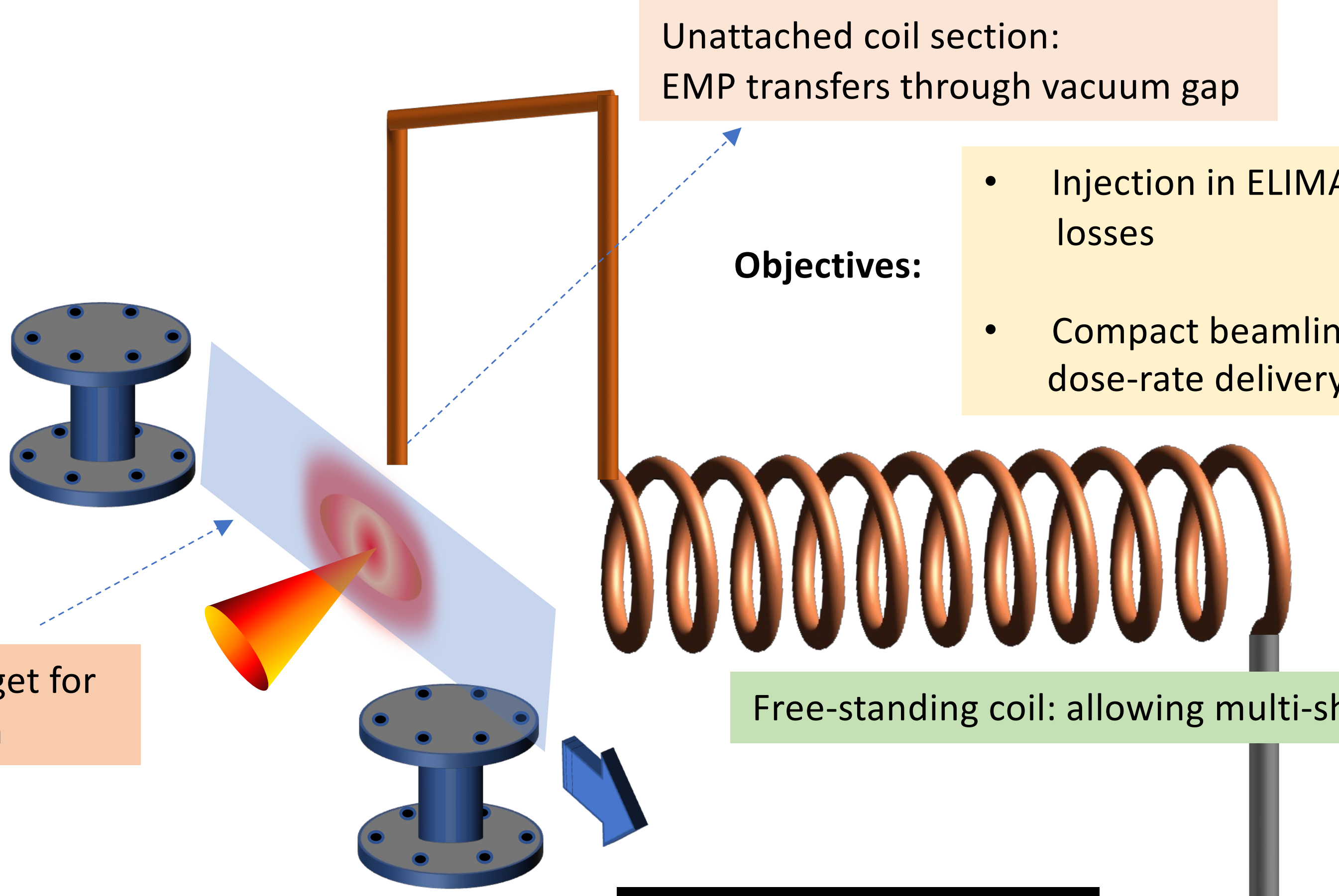


0.2° divergence

Dose profile on VULCAN PW at 5 cm from target

From single shot device to high-rep operation



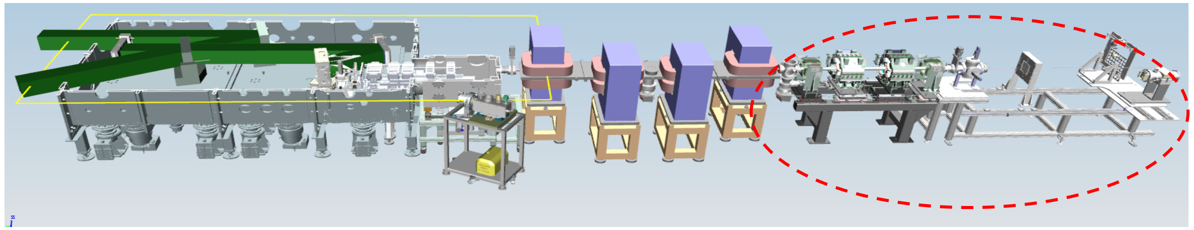


Objectives:

- Injection in ELIMAIA transport with no losses
- Compact beamline for high-dose, high dose-rate delivery

QUB contribution to IMPULSE project

Applications : radiobiology at ultra-high dose rate



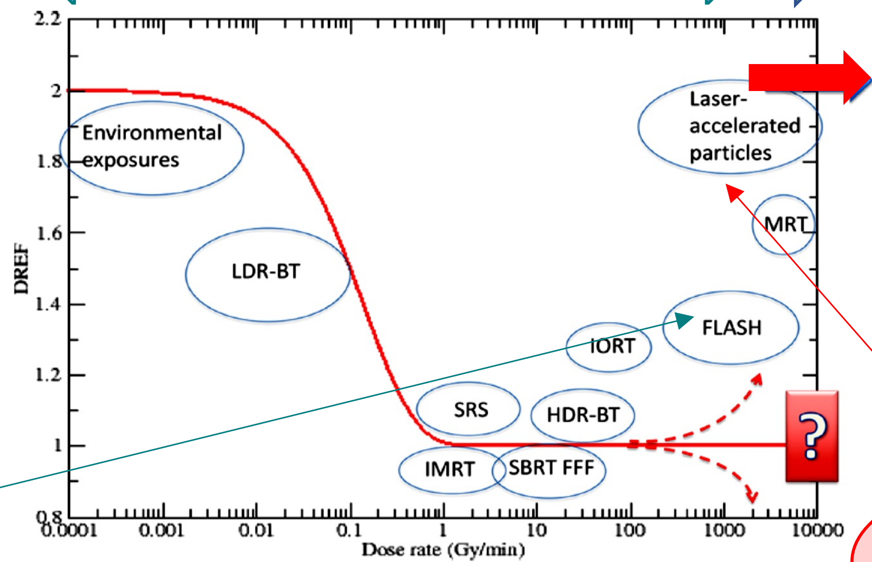
Ultrashort ion bursts :
ps at source, 1-10 ns at irradiation site
Dose: 0.1 Gy – Gy

Conventional dose-rate
0.01-0.1 Gy/s (1-10 Gy/min)

FLASH dose-rate
>40 Gy/s (>2400 Gy/min)

Laser-driven dose-rate
$>10^9$ Gy/s ($>10^{11}$ Gy/min)

Studies
- Investigations of DNA damage
  and repair dynamics
- Survival studies
- Sub-lethal damage investigations



M Durante *et al*, BJR,2014

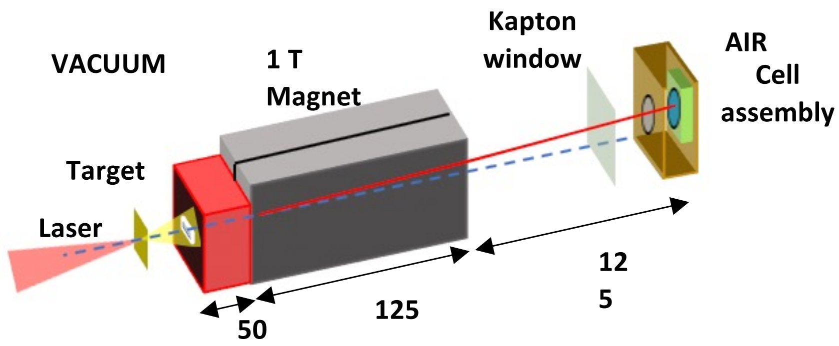
Possible effects
- Spatio-temporal overlap of independent tracks
- Local depletion of oxygen
- Potential commonalities with **FLASH effects**

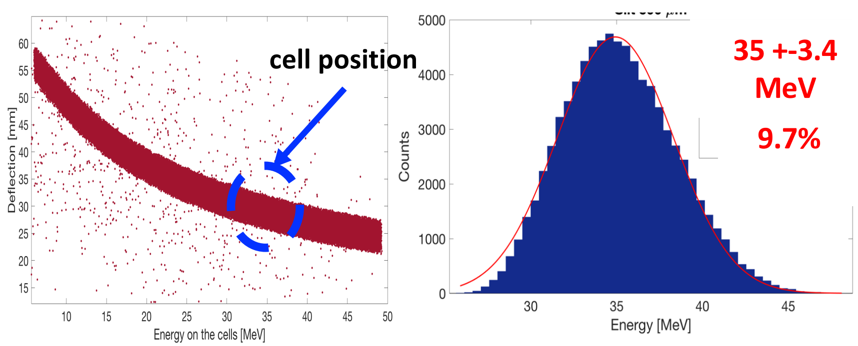
Spare normal tissues preserving the anti-tumor activity

A Novel regime of radiobiology

Experimental arrangements for high-dose rate studies

Compact set-up for single shot irradiations (VULCAN, GEMINI, CLF)

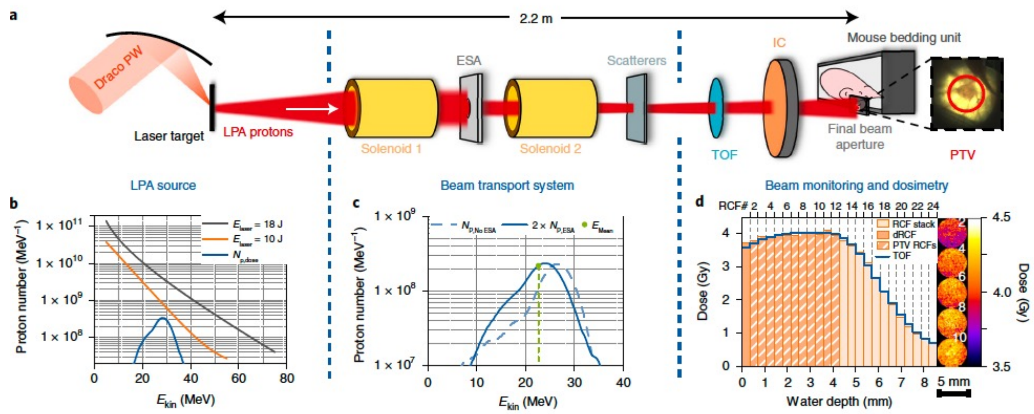




Experiments in a reconfigurable user facility

Chaudhary P, et al, (2021). *Front. Phys.* **9**:624963.

Magnetic beamline for in-vivo irradiations (HZDR, Germany)



F. Kroll et al, Nature Phys., **18**, 316 (2022)

ELIMAIA offer new opportunities for these studies :

- open user facility
- permanent irradiation set-up
- high-rep, multi-pulse, etc…
- In-vitro, in-vivo

Conclusions

ELIMAIA beamline:

- Primary mission: provision of ion beams to users for multidisciplinary applications

Advanced Commissioning (ongoing)

○ Proton source - 25 MeV, stable production

○ Source optimization (ongoing)

○ Demonstration of transport - *User assisted commissioning (2023)*

Flagship experiment

○ FLAIM (planning stage – workshop tomorrow)

User experiments:

Research opportunities in ion acceleration: scaling of acceleration, advanced mechanisms

○ Novel solutions for transport optimization

○ Broad range of opportunities in radiobiology

(+ applications in material studies, radiochemistry, cultural heritage, HEDP, ….)