# Laser-driven Ion Acceleration and Applications

**Daniele Margarone**

Director of Research and Operations

ELI Beamlines, Czech Republic

*HPLA, 11-12 January 2024, LNS-INFN, Catania*

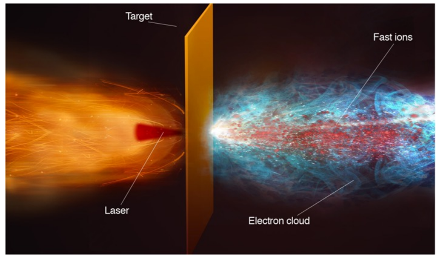
eli

INFN LNS

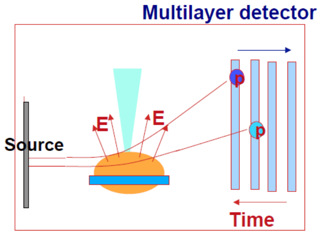
QUEEN'S UNIVERSITY BELFAST

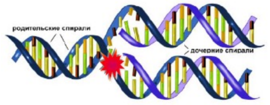
# Outline

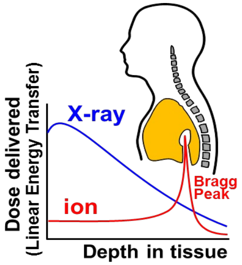
- Ion Acceleration by Laser-Plasma



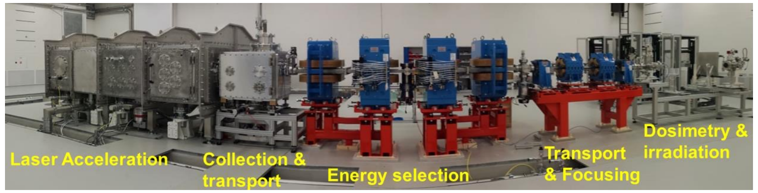

- Multidisciplinary Applications of laser-based Ion Source






- The ELIMAIA-ELIMED user beamline @ ELI Beamlines

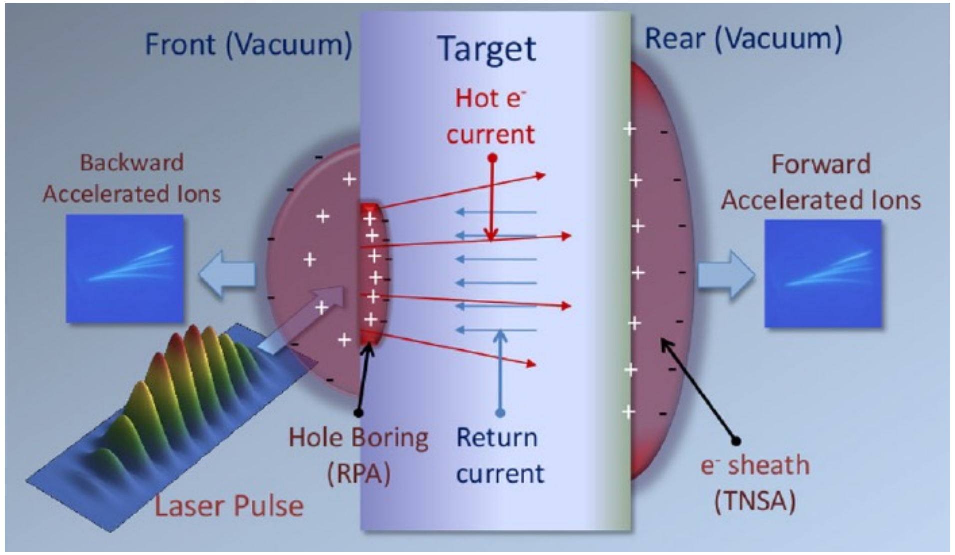


# Laser-Plasma Ion Acceleration

*physical picture*

## Target Normal Sheath Acceleration

**0.1-10 μm long**




*REVIEW PAPERS:*

- *Macchi, Borghesi, Passoni, Rev. Mod. Phys. 85 (2013) 751*
- *Borghesi et al, Springer Proc. Phys. 231 (2019) 143*

Energy Gain: **100 MeV/μm** (in a plasma medium)!!!

$I_L$ (laser intensity) = $E/\tau/S$ = $\mathbf{10^{21}\ W/cm^2}$

### Direct Laser interaction:

- $E \sim I_L^{1/2}\lambda = 10^{14}$ V/m
- $B = E/c = 3\times10^{5}$ T
- $P_{rad} = I_L/c = 3\times10^{10}$ J/cm$^3$ = 300 Gbar

### Laser-Plasma interaction:

- Debye Length

$$\lambda_D = 2.4\,\mu m \cdot \sqrt{\frac{T_{hot}}{1MeV}} \cdot \sqrt{\frac{10^{19}\,cm^{-3}}{N_{hot}}} \Longrightarrow \sim \mu m!$$

- Acceleration time

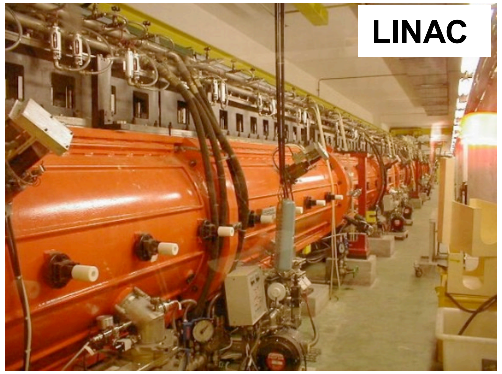
$$\tau = \sqrt{\frac{\lambda_D^2 m_{ion}}{T_{hot}}} = 0.24\,ps\sqrt{\frac{\lambda_D^2 n_{hot}}{10^{19}}} \Longrightarrow \sim ps!$$

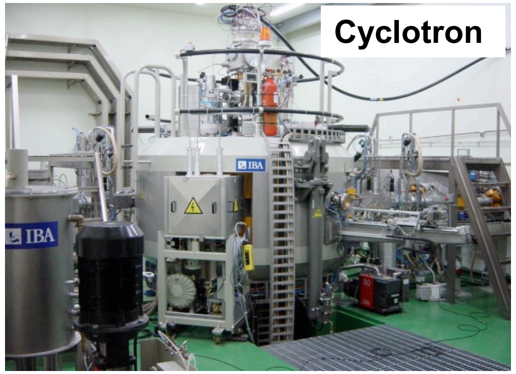
- Electric Field

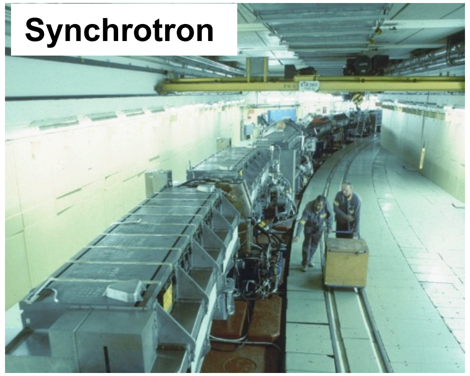
$$E = \frac{T_{hot}}{e\lambda_D} \approx \frac{MV}{\mu m} \Longrightarrow \sim TV/m!$$

# Laser-Plasma Ion Acceleration

*principal motivation*

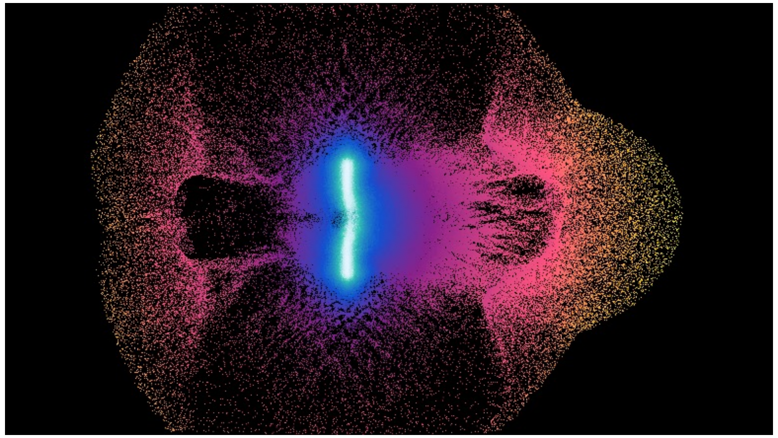



$E_{max}$ ~ 50 MV/m

$L_{acc}$ ~ 1-10 m



$E_{max}$ ~ 1 TV/m

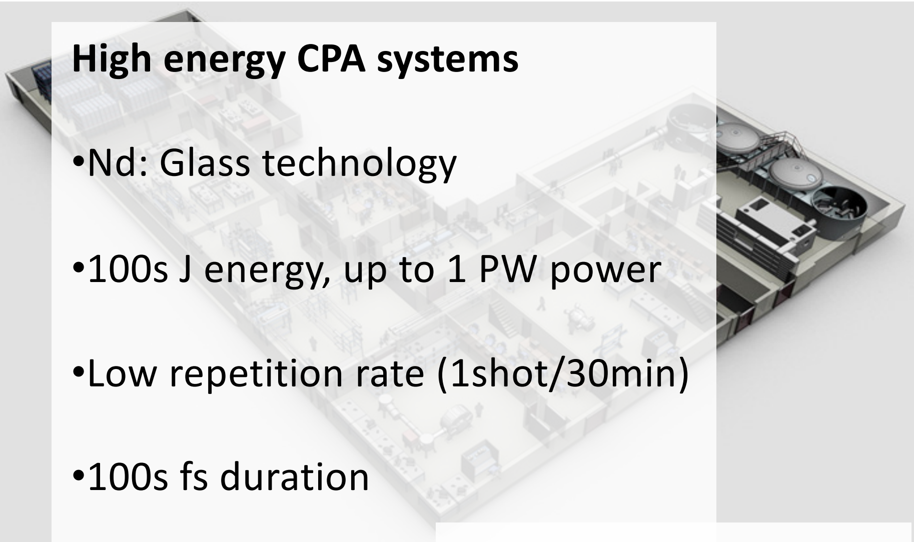
$L_{acc}$ ~ 1 $\mu$m

→ 10,000 smaller!!!

BUT…

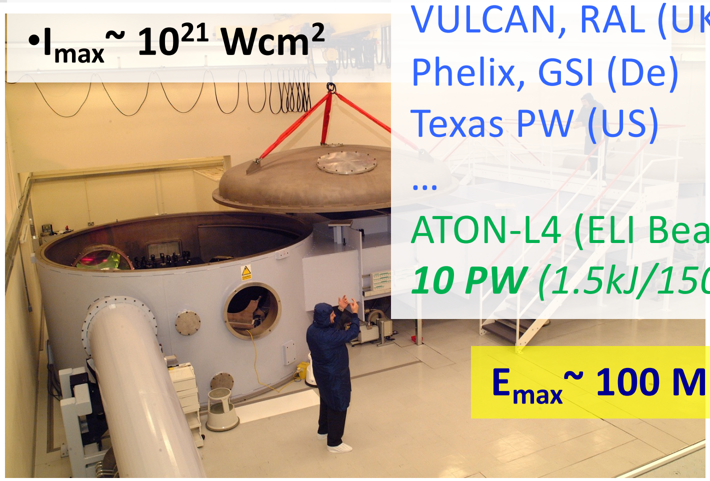
# High (Peak) Power Lasers Ion Acceleration

*current facilities*



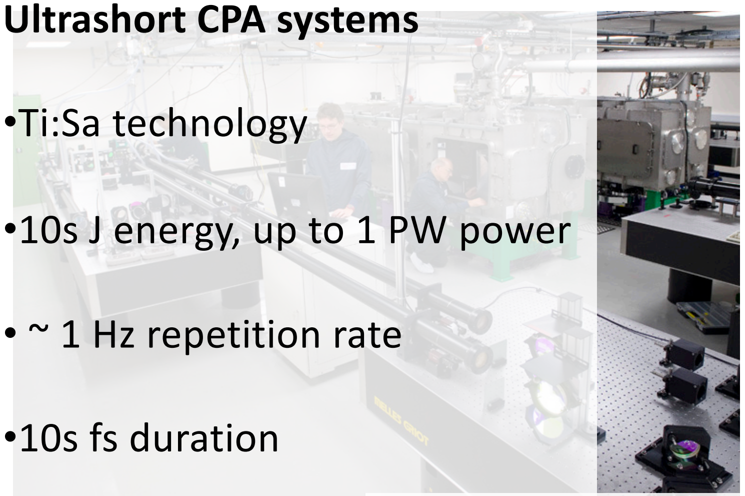
**High energy CPA systems**

- Nd: Glass technology
- 100s J energy, up to 1 PW power
- Low repetition rate (1shot/30min)
- 100s fs duration
- **$I_{max}$~ $10^{21}$ $Wcm^2$**



VULCAN, RAL (UK)
Phelix, GSI (De)
Texas PW (US)
…
ATON-L4 (ELI Beamlines)
***10 PW*** *(1.5kJ/150fs)*

**$E_{max}$~ 100 MeV**



**Ultrashort CPA systems**

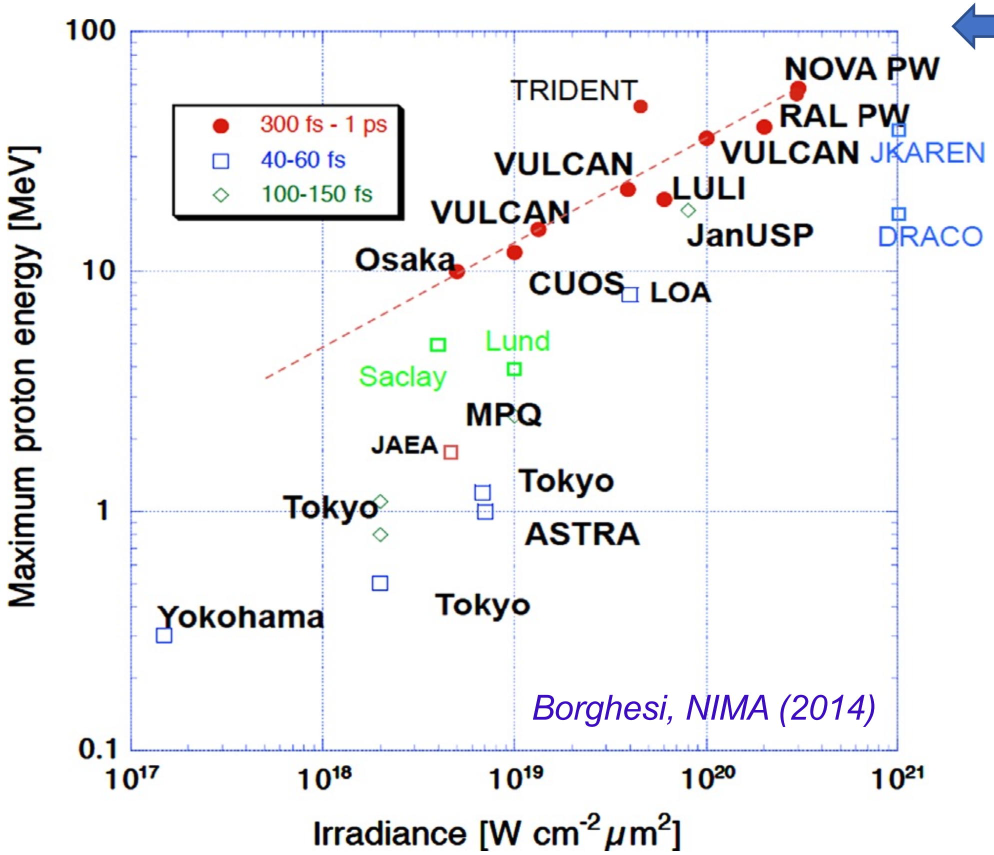
- Ti:Sa technology
- 10s J energy, up to 1 PW power
- ~ 1 Hz repetition rate
- 10s fs duration
- **$I_{max}$~ $10^{21}$ $Wcm^2$**

GEMINI, RAL (UK)
Draco, HZDR (De)
Pulser I, APRI (Kr)
J-Karen, JAEA (J)
….
HAPLS-L3, (ELI Beamlines)
***1 PW*** *(30J/30fs/**10Hz**)*

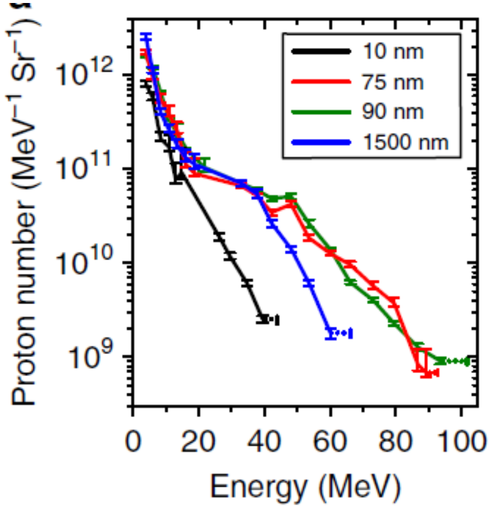
**$E_{max}$~ 70-80 MeV**

# Maximum Proton Energy

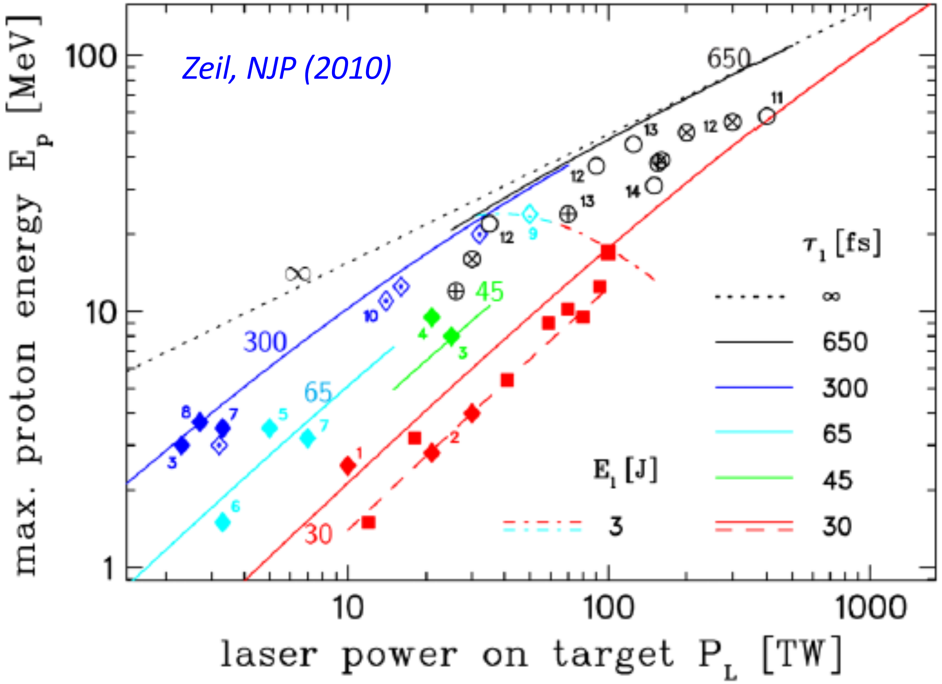
*experimental scaling laws (TNSA)*




$E \sim I_L^{1/2}$



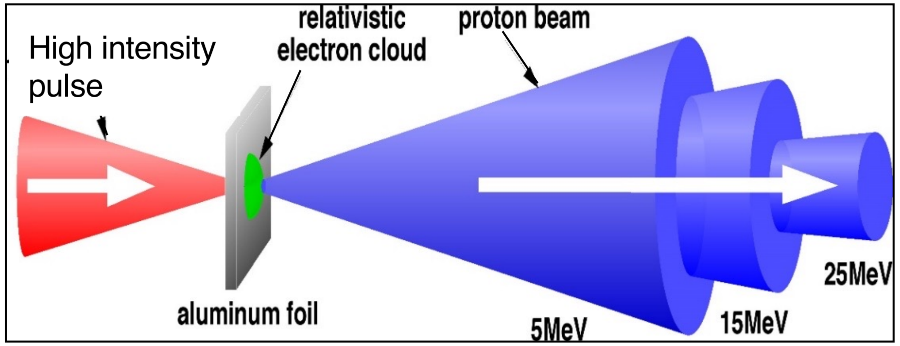

*Higginson, Nat. Comm. (2018)*

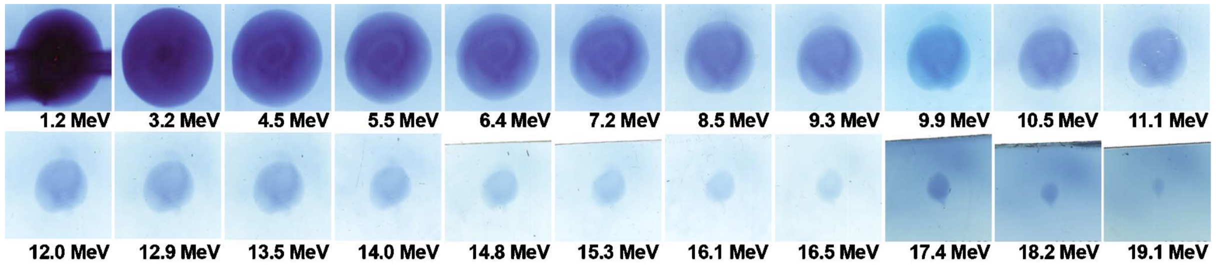


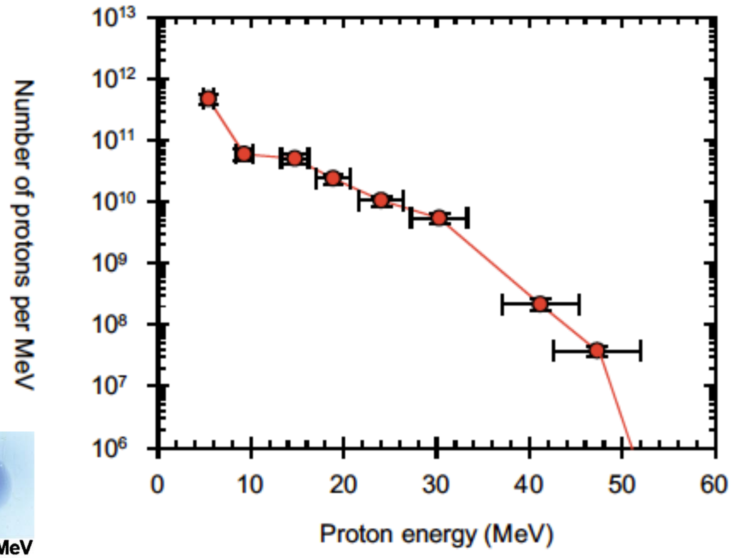
# Ion Beam Properties

*TNSA regime*

- ✓ **Short duration @ source**: bursts with duration **~ ps** *(acceleration time ~ laser pulse width)*
- ✓ **Highly laminar source**: **$\varepsilon_N$ < 0.1 $\pi$ mm.mrad** *(virtual point source: ~ μm << real source)*
- ✓ **Broad spectrum**: continuum up to cutoff energy *(lower divergence for higher energies)*



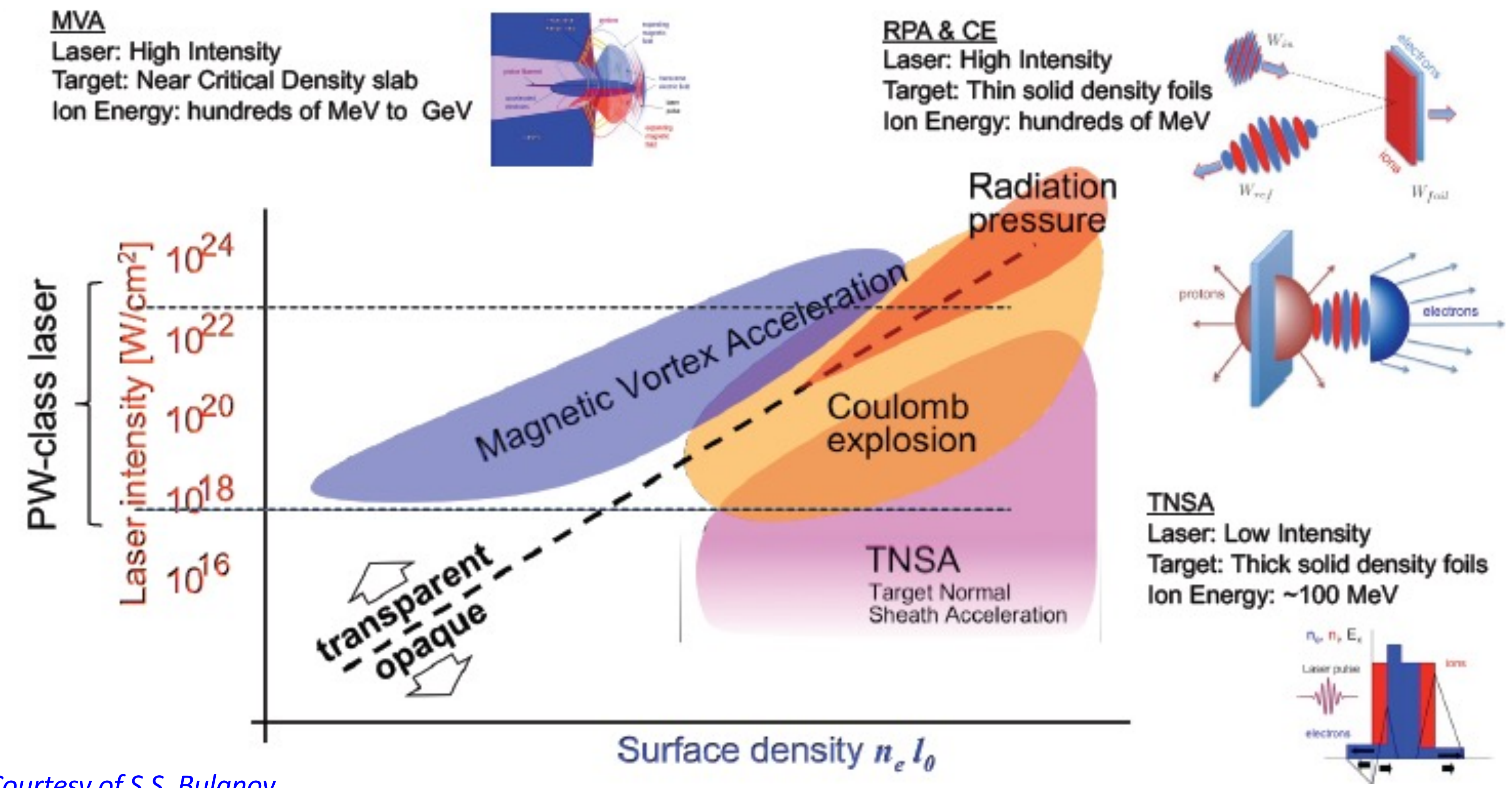




*F. Nurnberg et al, RSI, 80, 033301 (2019)*

# Laser-driven Ion Acceleration Mechanisms

*laser intensity vs. target density*

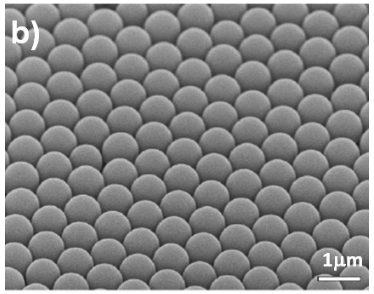


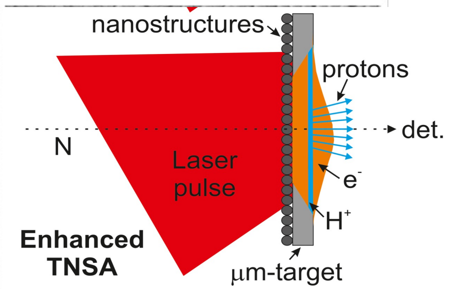

*Courtesy of S.S. Bulanov*

# Target Engineering

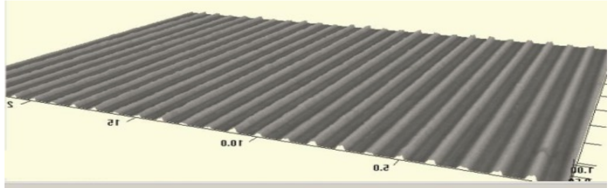
*enhanced TNSA beam properties*

## Nano- and micro-structures for enhanced TNSA

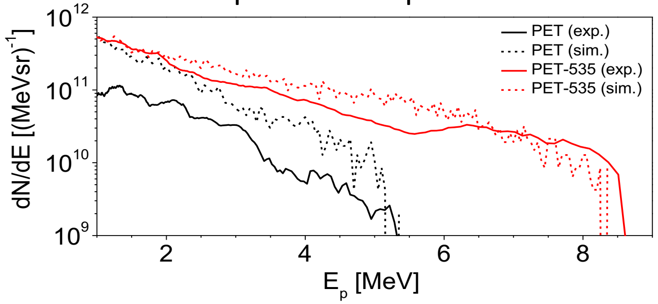


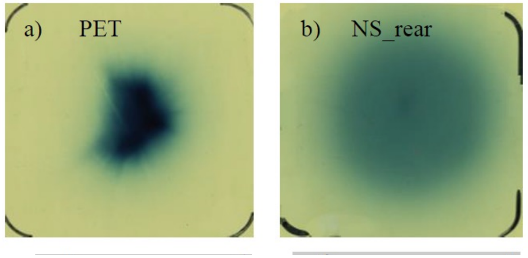

Stealth target for ion acceleration!



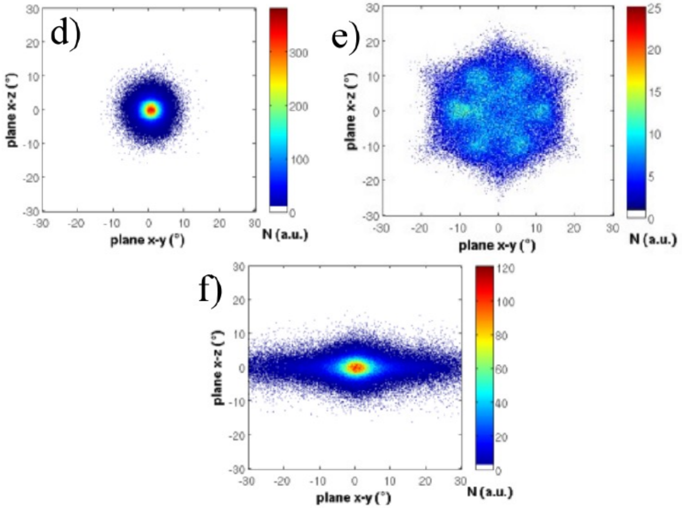
experimental spectra

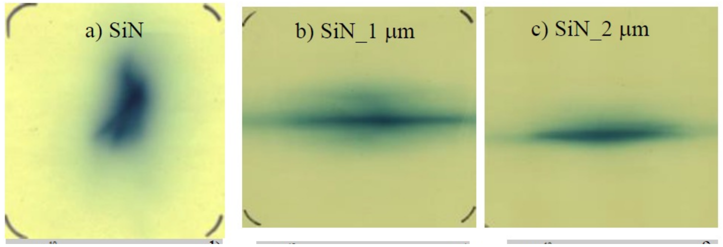



- ✓ proton cutoff energy
- ✓ proton flux
- ✓ beam homogeneity




PIC simulations

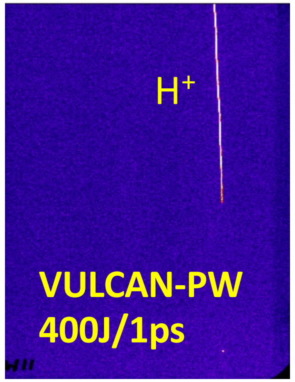


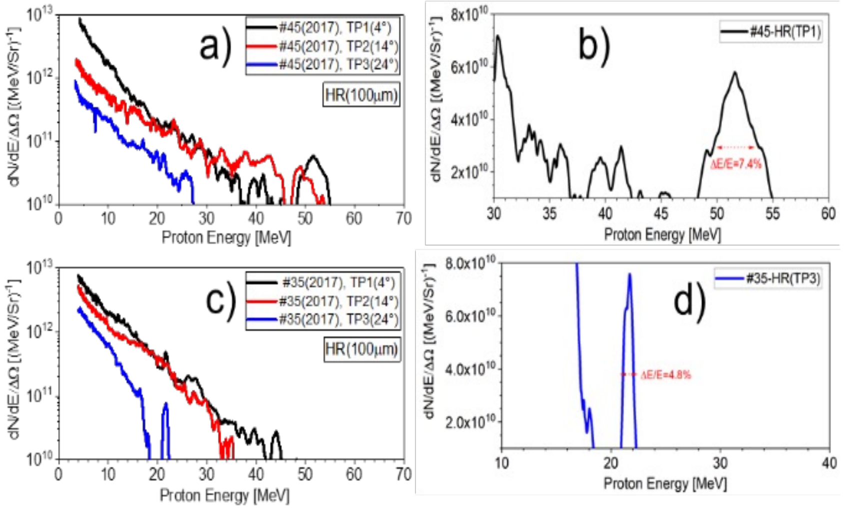

*Margarone et al, PRL109 (2012) 234801*
*Margarone et al, PRAB 18 (2015) 071304*
*Giuffrida et al, PRAB 20 (2017) 081301*

## Cryogenic solid-H for enhanced Hole-Boring Radiation-Pressure-Acceleration


*Chagovets et al, Appl. Sci. 2021 (submitted)*

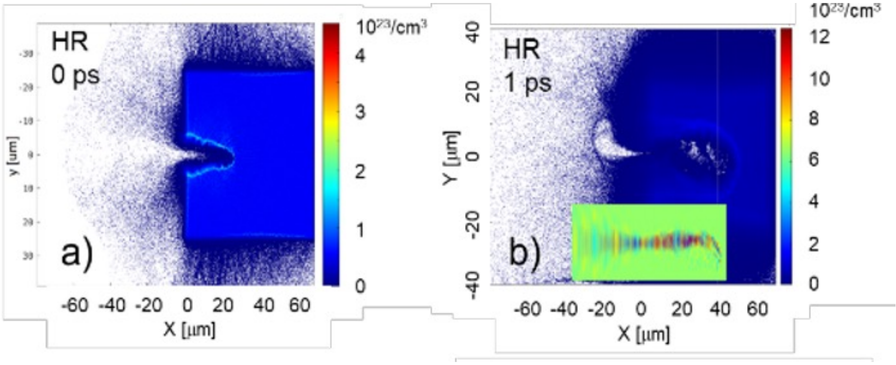




experimental spectra




*Margarone et al, PRL (submitted)*

PIC simulations

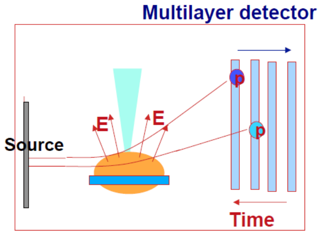


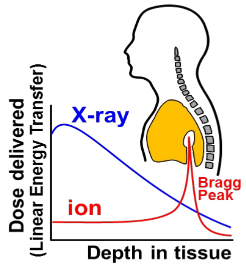

- ✓ repetition rate
- ✓ energy bandwidth

# Outline

- Ion Acceleration by Laser-Plasma

- Multidisciplinary Applications of laser-based Ion Source



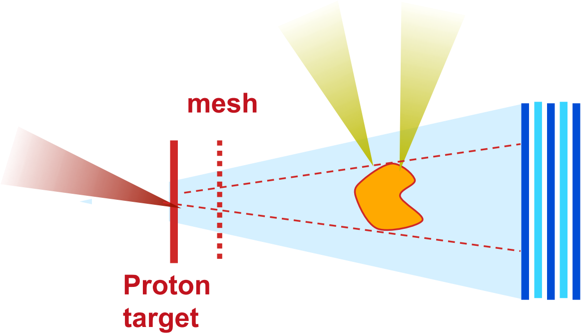




- The ELIMAIA-ELIMED user beamline @ ELI Beamlines

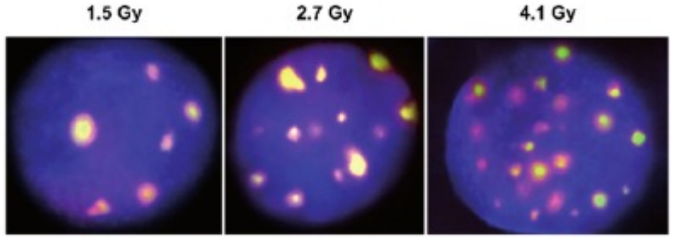
# Current Applications

*unique ion beam features*

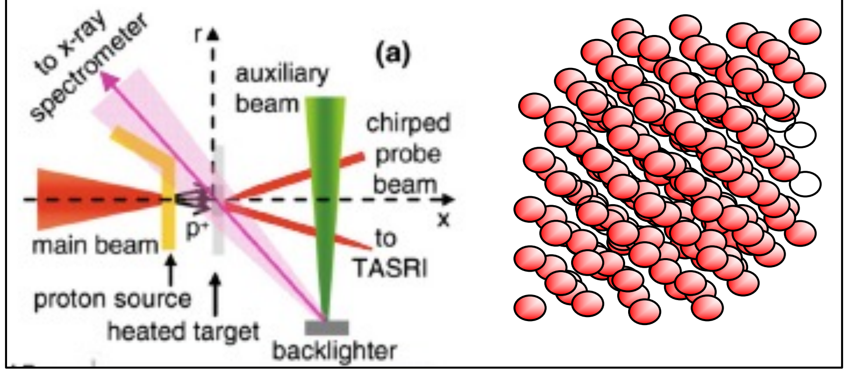
## Ultrafast proton radiography



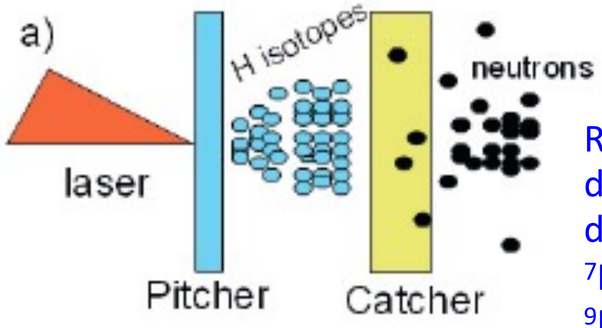

## Ultrafast radiobiology




## Warm dense matter (isochoric heating)




## Neutron generation

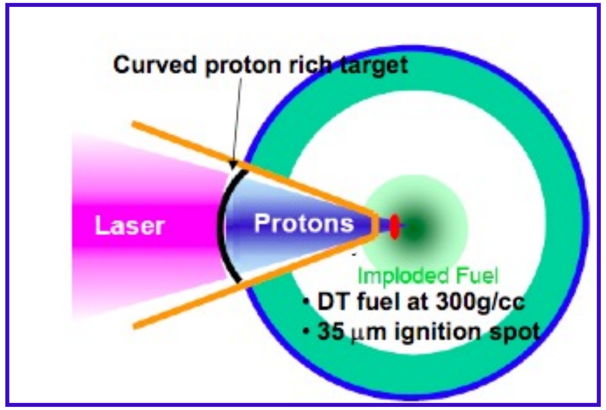



Reactions:
$d(d,n)^3He$
$d(p, n+p)^1H$
$^7Li(p,n)^7Be$
$^9Be(p,n)^9B$
.....

# Prospective Applications

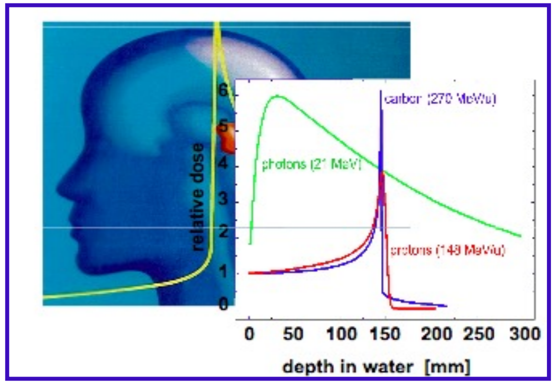
*unique ion beam features*

**Fast Ignition**
(Inertial Confinement Fusion)




7-19 MeV $10^{16}$ protons
2-4 GeV $10^{14}$ carbon ions

**Particle therapy of cancer** (hadrontherapy)




60-250 MeV protons

2-4 GeV carbon ions

Typical dose fraction: 2-5 Gy

1 Gy ~ $10^{10}$ p+, ~$10^9$ C

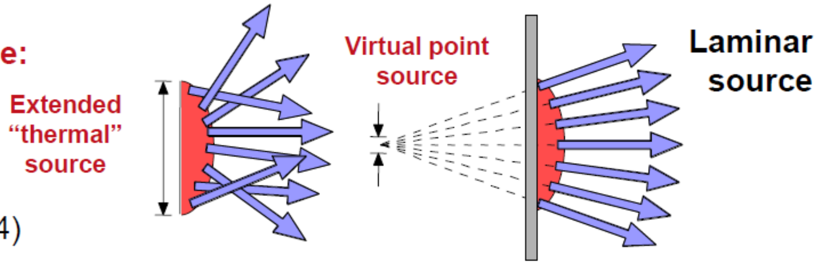
# Proton Radiography/Deflectometry

*a powerful plasma probing tool*

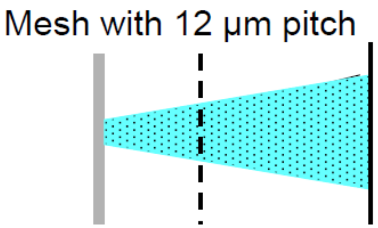
**Ultralow emittance/ virtual source:**

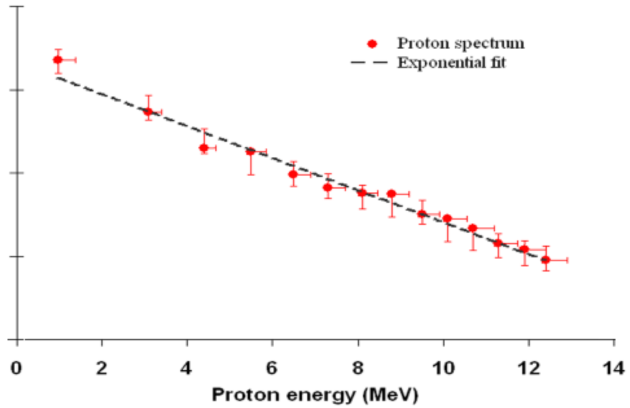
$\varepsilon_N < 0.1\ \pi$ mm.mrad @ 15 MeV

( < 0:004 mm-mrad;
T.Cowan et al, PRL, **92**, 204801, 2004)



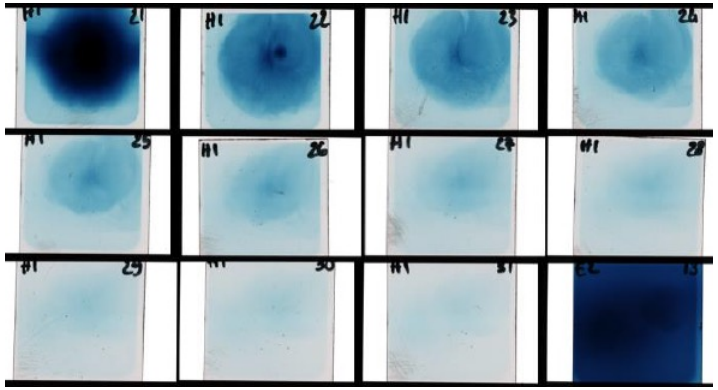




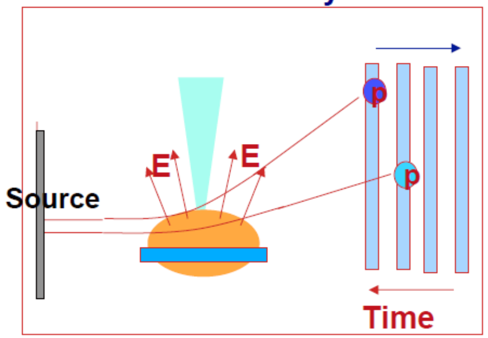




*M.Borghesi et al, Phys Rev Lett.,* ***92****, 055003 (2004))*

**RCF stack**



**Multilayer detector**




*Courtesy of M. Borghesi*

**Bragg peak deposition**
**Broad proton spectrum**
**Short burst at source**
**Time of flight dispersion**

# Laser-based Hadrontherapy

*potential advantages*

**Reduced cost/shielding**

- Laser transport rather than ion transport *(vast reduction in radiation shielding)*
- Reduced size of gantry *(?)*

**Flexibility/modularity**

- Controlling output energy and spectrum
- Possibility of varying accelerated species
- Spectral shaping for direct "painting" of tumor region *(no degrader needed)*

**Novel therapeutic/diagnostic options**

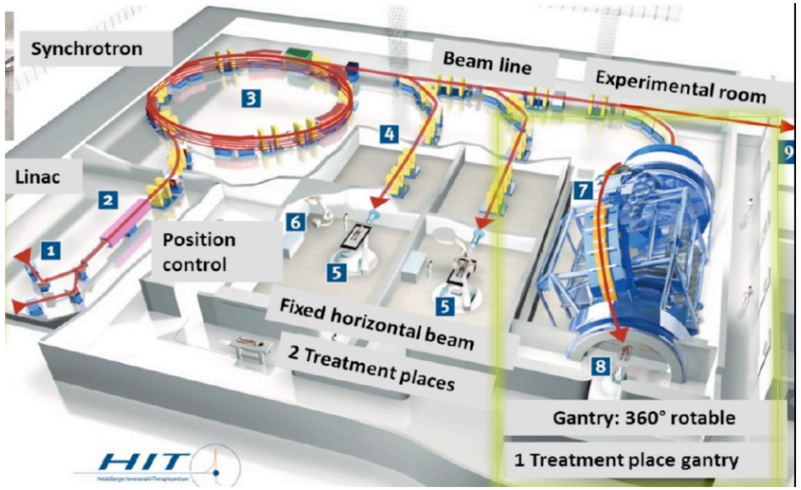
- Mixed fields: ions, X-rays, electrons, neutrons
- In-situ diagnosis *(PET, X-rays)*

**Radiobiological advantages**

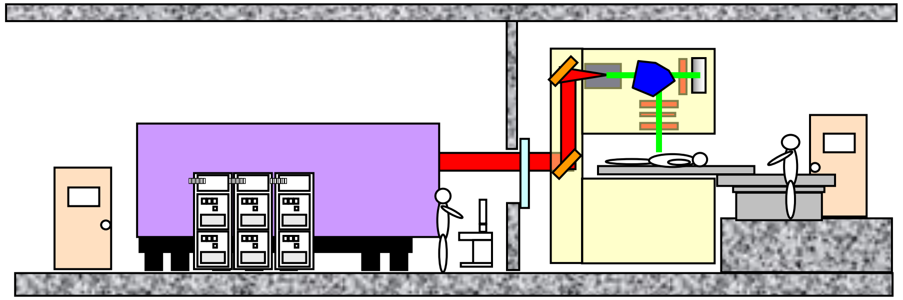
- Short pulse radiation might reduce damage to healthy tissues *("flash" effect)*
- Increase in RBE (relative biological effectiveness) of tumor cells *(?)*

**Conventional hadrontherapy (C-ions)**

*https://www.ptcog.ch/images/ptcog58/Scientific/0930_Debus.pdf*

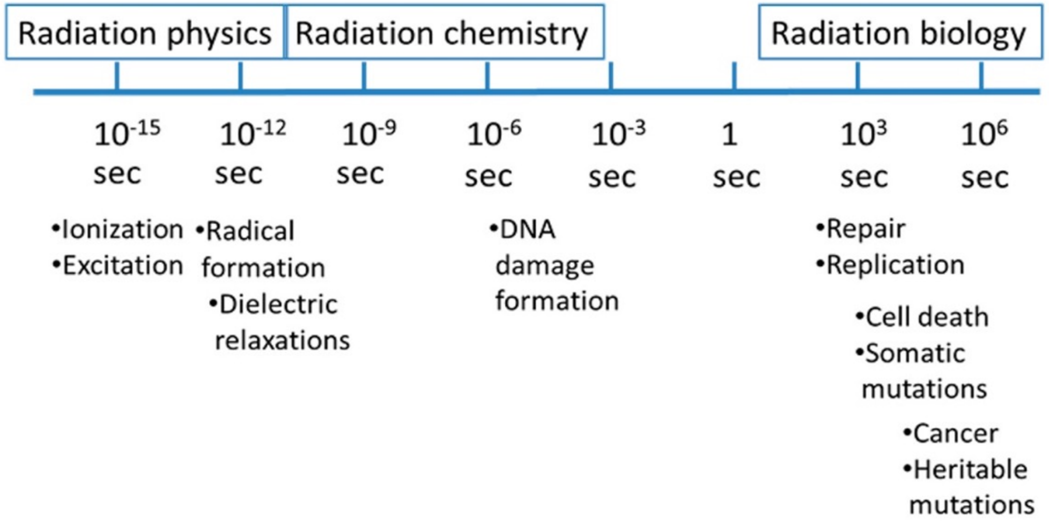


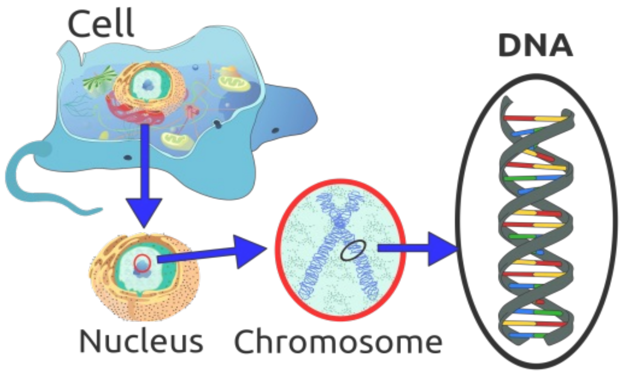

**Laser based hadrontherapy *(concept)***



# Radiobiology

*ultra-fast regime*




**Remarks**

- ✓ Laser-driven ions are emitted at the source within a time ΔT~ ps resulting in dose deposition at the sample in **100s ps - ns pulses**
- ✓ Peak **dose rates > $10^9$ Gy/s** can be achieved *(compared with Gy/min average dose rates used in radiotherapy)*

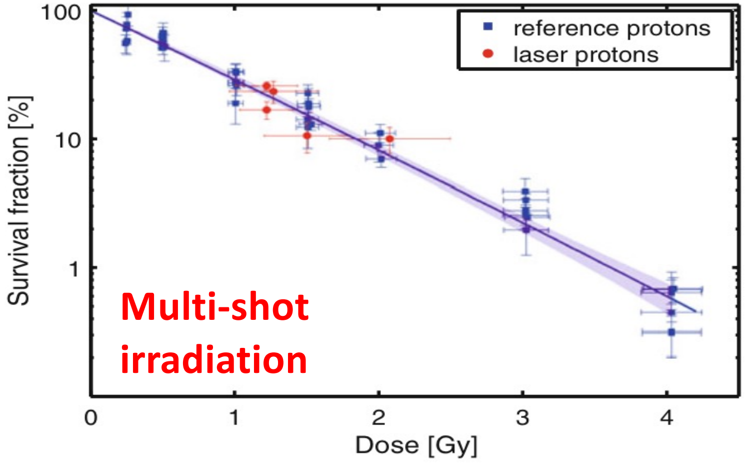
**Possible effects proposed in the literature**

- **Spatio-temporal overlap of independent tracks** causing collective effects and enhancing LET (hence RBE) in cancer cells
- **Local depletion of oxygen** causing a reduction in cell radiosensitivity of healthy tissues (***FLASH*** *radiotherapy*)

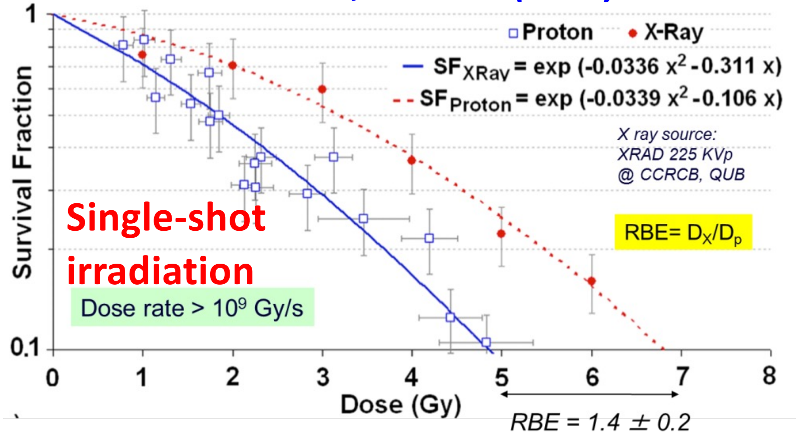
# Radiobiology

*pre-clinical studies on cancer cells*

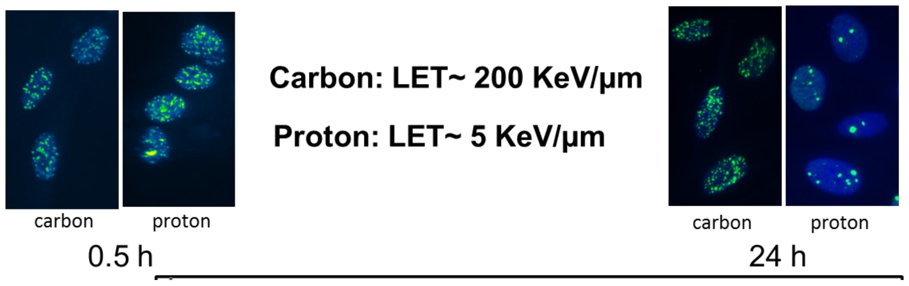
*Zeil et al, Appl. Phys. B (2013)*




*Doria et al, AIP Adv. (2012)*




**Recent results with C-ions *(courtesy of M. Borghesi)***




*flash dose rates > $10^3$ Gy/s*

COMMENTARY

**Faster and safer? FLASH ultra-high dose rate in radiotherapy**


[1]MARCO DURANTE, PhD, [2]ELKE BRÄUER-KRISCH, PhD and [3]MARK HILL, PhD

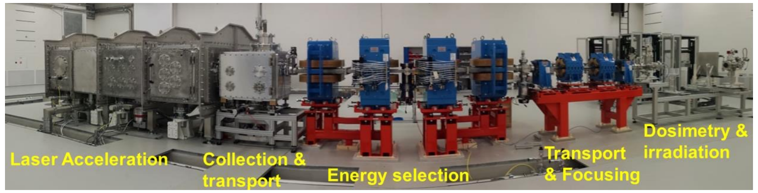
[1]National laboratories, Trento Institute for Fundamental Physics and Applications (TIFPA), National Institute of Nuclear Physics (INFN), University of Trento, Trento, Italy
[2]National laboratories, ESRF-The European Synchrotron, Grenoble, France
[3]Department of Oncology, CRUK/MRC Oxford Institute for Radiation Oncology, Gray Laboratories, University of Oxford, Oxford, UK

# Outline

- Ion Acceleration by Laser-Plasma

- Multidisciplinary Applications of laser-based Ion Sources

- The ELIMAIA-ELIMED user beamline @ ELI Beamlines



# ELI Beamlines

*Dolní Břežany, Czechia*

# ELI Beamlines

*the High-Energy Beam Pillar of the Extreme Light Infrastructure*

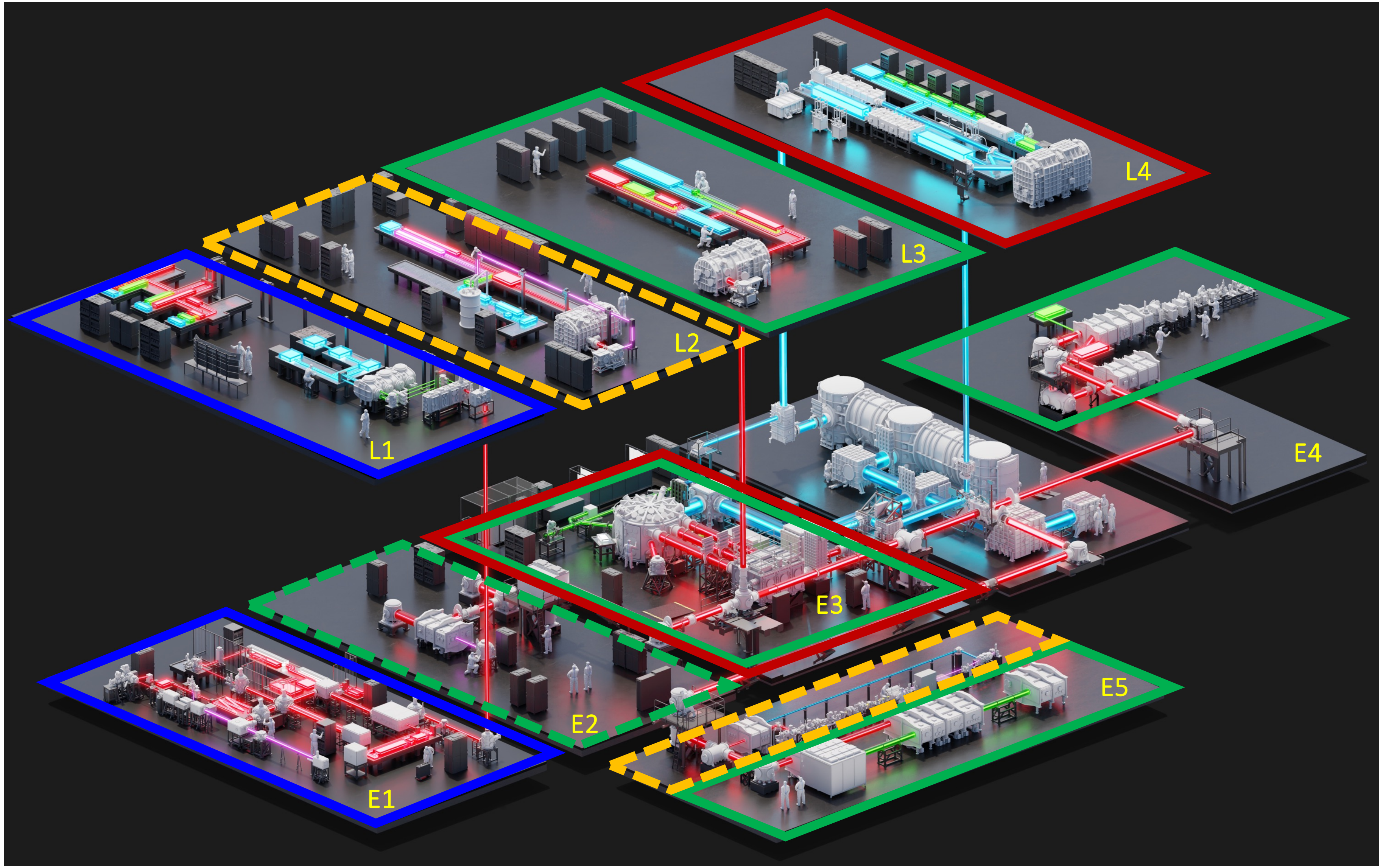
## ELI Beamlines mission profile

- Operate cutting edge, high-peak power femtosecond laser systems with high energy, high repetition-rate capability
- Explore interaction of light with matter (plasma) at ultrahigh laser intensities
- Offer secondary sources (X-rays and accelerated particles) with unique capabilities to users
- Enable pioneering research not only in plasma physics, high-field physics, nuclear fusion and laboratory astrophysics, but also in material science, biology, chemistry, medicine and other disciplines with strong multidisciplinary application potential

# ELI BL Facility Status (Dec 2023)

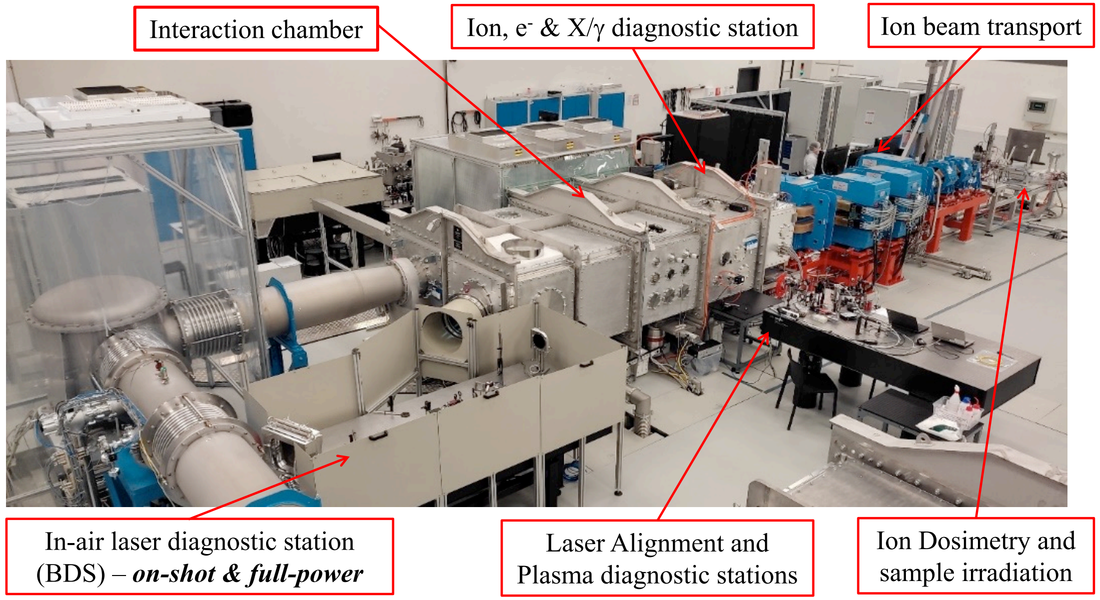
*user operations, commissioning, development*

- L1-E1 user operation (call1,2,3)
- L3-P3/ELIMAIA user operation (call2)
- L3-ELBA/ELIMED commissioning (call3)
- L4n-P3 user operations (call2,3)
- L3-Gammatron to be commissioned
- L2-LUIS R&D

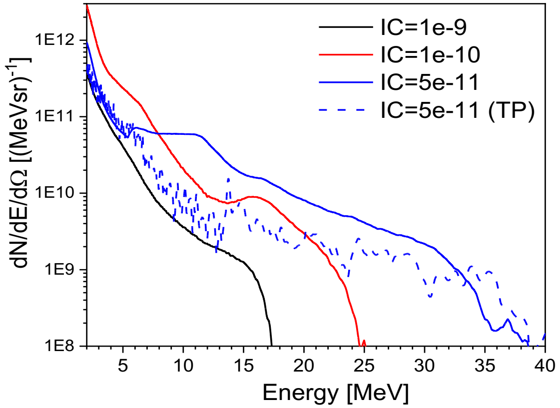


# ELIMAIA-ELIMED Laser-Plasma Ion Accelerator (E4)

## *ELI Multidisciplinary Applications of laser-Ion Acceleration (1 Hz)*

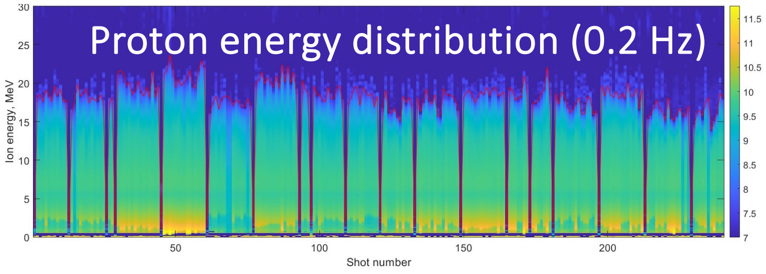



*L. Giuffrida et al.*




| L3 - Ion Accelerator (user call) | Demonstrated | Design parameters |
|---|---|---|
| Laser intensity | $4 \cdot 10^{21}$ W/cm$^2$ | $10^{22}$ W/cm$^2$ |
| Laser energy | >10 J | 30 J |
| Laser pulse width | <30 fs | <30 fs |
| Repetition rate | ~ 1 Hz | 10 Hz |
| Proton energy cutoff | ~ 40 MeV | 100 MeV |
| Proton flux (>3 MeV) | ~ $1 \cdot 10^{11}$/sr | > $1 \cdot 10^{11}$/sr |






GDD, TOD, FOD scan *(M. Hill et al.)*

Lawrence Livermore National Laboratory

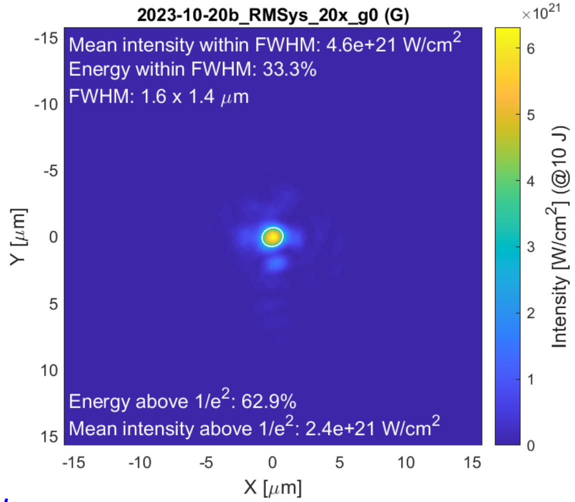
| ELIMED end station (commissioning) | Design parameters @ user sample |
|---|---|
| Ion energy | 5-60 MeV/nucleon |
| Energy spread | <10% |
| Ions/shot | $1 \cdot 10^{8}$-$1 \cdot 10^{10}$/sr |
| Bunch duration | 1-10 ns (>$10^9$ Gy/s) |
| Ion beam aperture | ~ 1deg (FWHM) |
| Ion beam spot size | 0.1-10 mm (FWHM) |
| Repetition rate | Active modulation (1Hz) |

# Call-2 experiment with L3-ELIMAIA

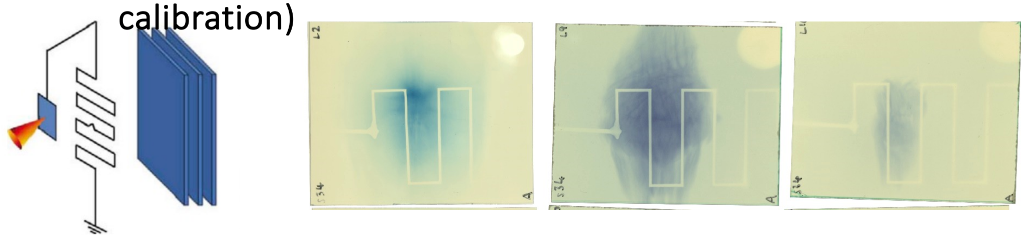
*“Compact, high-rep dose delivery system employing helical coil targets”, S. Kar (QUB, UK)*

L3 performance (Call-2):

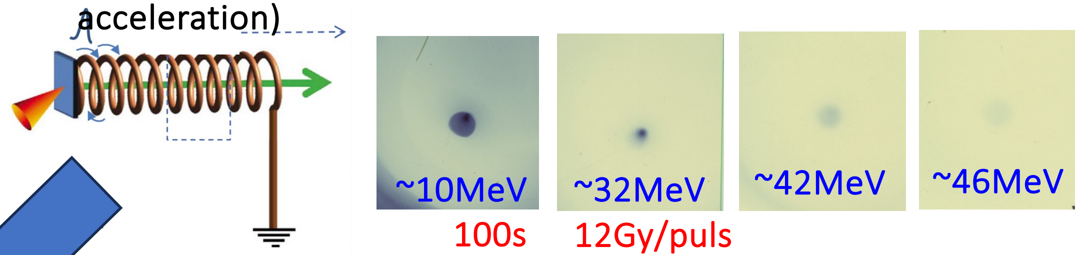
- ✓ 10 J on target
- ✓ ~$4 \times 10^{21}$ W/cm$^2$ (FWHM)
- ✓ single shot; 0.5 Hz (tape drive)




Proton radiography of “wire target” (coil calibration)



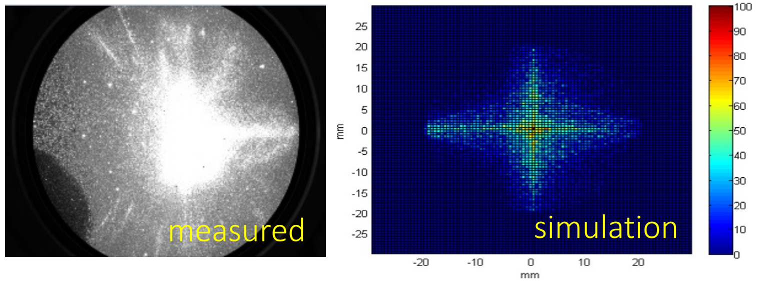
Proton beam from “coil target” (collimation and post-acceleration)




100s Gy/pulse

12Gy/pulse ~1deg div.

*ELIMED user assisted commissioning results (F. Schillaci, G.A.P. Cirrone, M. Borghesi)*




*First proton beam transported, collimated, and selected at the output of ELIMED (~10m)*

- Hot electrons expelled from target during high intensity laser interaction
- Target volume strongly positively charged
- Return current results in positively charged EM pulse propagating to ground
- Pulse profile can be probed using proton radiography
- Helical coils attached to foil harness EM pulse to focus and post-accelerate TNSA-accelerated protons
- Bunch energies >46 MeV detected at ELIMAIA (L3, 10 J) in single shot
- high repetition rate basis using a tape drive target tested (L3, 0.5 Hz)

# Conclusive Remarks

*a few hints to implement and operate a high-power laser-based facility*

- Robust expertise and experience
  - ✓ engineering support ☺
  - ✓ installation and operation of large equipment ☺
  - ✓ operation, fine tuning (daily), and trouble shooting of high-power (fs) lasers ☹
  - ✓ knowledge and know-how in Plasma, Laser-Plasma, Diagnostics, Targetry, applications ☺

- Substantial investment and human resources → ~ 50 (200/4) !!!
  - ✓ senior + junior laser scientists and laser operators ☹
  - ✓ senior + junior laser-plasma (relativistic) interaction scientists (overcritical, undercritical) ☹
  - ✓ specialists in diagnostics of secondary sources ☺

? Physics!

- Education and Training
  - ✓ PhD students
  - ✓ undergraduate students