Acceleration, Transport and Diagnostic of Protons from Laser-Matter Interaction

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Outline

Istituto Nazionale di Fisica Nucleare

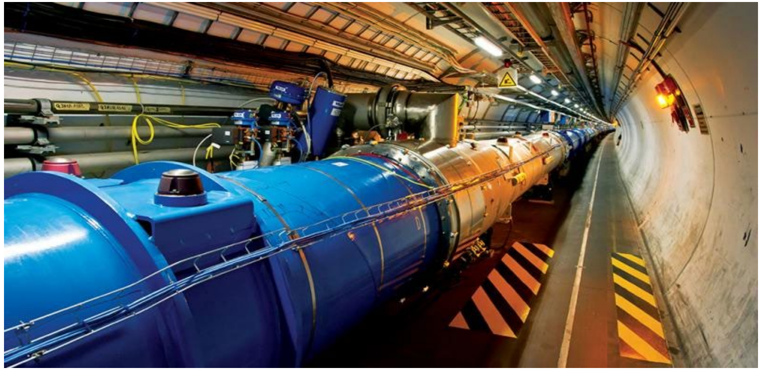
1. A laser as accelerator machine
2. Diagnostics and dosimetry of laser-driven beams
3. ELIMED @ELI-Beamlines
4. Future perspectiveness @LNS-INFN

A laser as accelerator machine

Laser-plasma ion acceleration: a super compact solution

Conventional ion acceleration

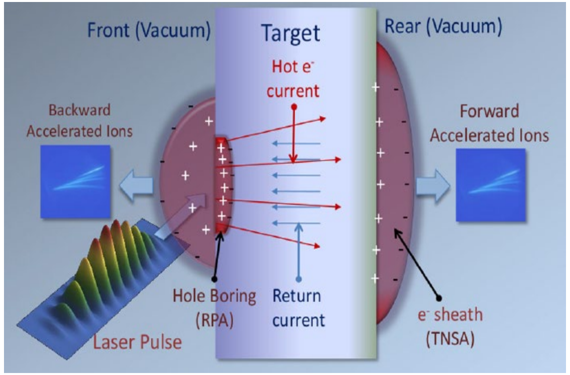
LHC @ CERN
- circular tunnel (27 km long!!!)
- superconductive electromagnets
- proton energy (per beam): 6.5 TeV



$E\text{-field}_{max} \approx$ few 10 MV/meter (Breakdown)

Laser-driven ion acceleration

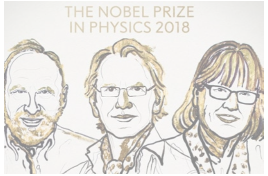
0.1-10 μm



The **energy gain** for ions in a laser-plasma accelerator is of **several tens of MeV/μm** (just few tens of MeV/m in conventional accelerators due to breakdown effects)

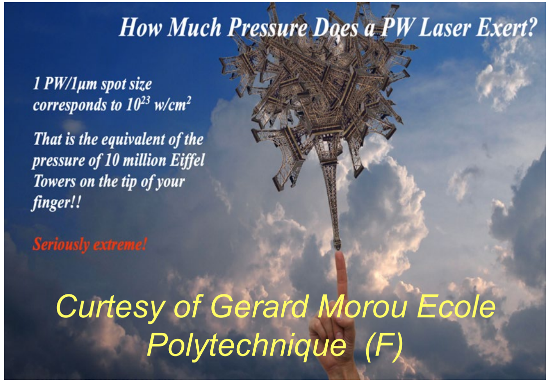
The main ingredients

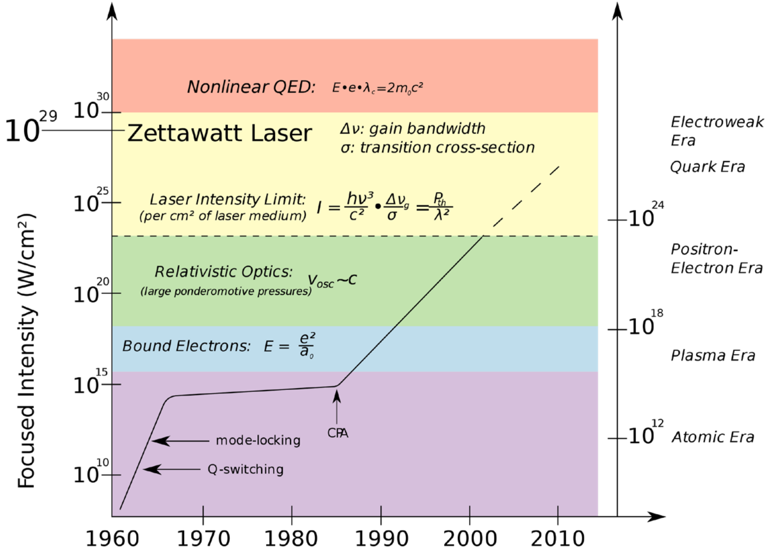
An high power (TW) short-pulse laser (20 500 fs)

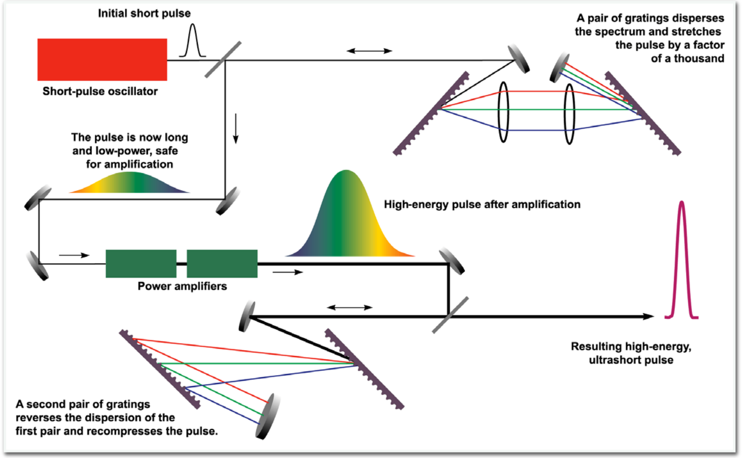


Solid state laser, typically Ti:Sapphire

700-1000 nm
20 — 100 fs
20 mJ — 5 J







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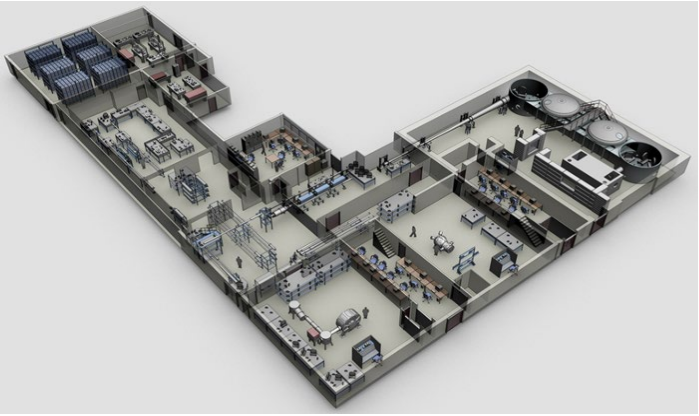
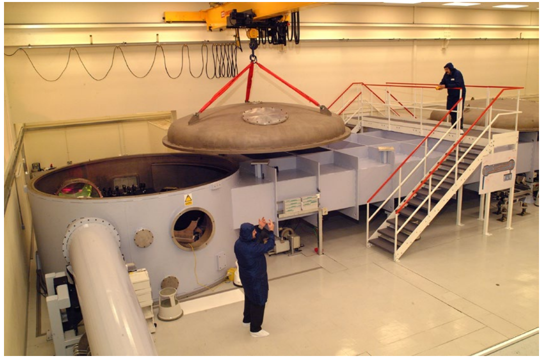
Two classes of lasers are mainly used for ion acceleration





Two classes of lasers are mainly used for ion acceleration

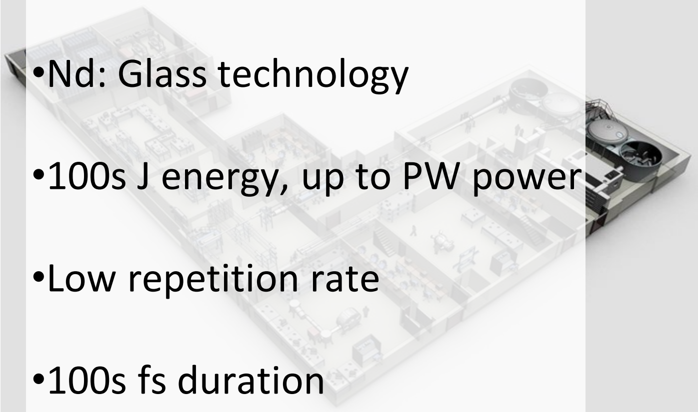
High energy CPA systems

- Nd: Glass technology
- 100s J energy, up to PW power
- Low repetition rate
- 100s fs duration
- $I_{max} \sim 10^{21}$ Wcm^2

VULCAN, RAL (UK)
Phelix, GSI (De)
Trident, LANL (US)
Texas PW, Austin (US) ..

Two classes of lasers are mainly used for ion acceleration

High energy CPA systems



- Nd: Glass technology
- 100s J energy, up to PW power
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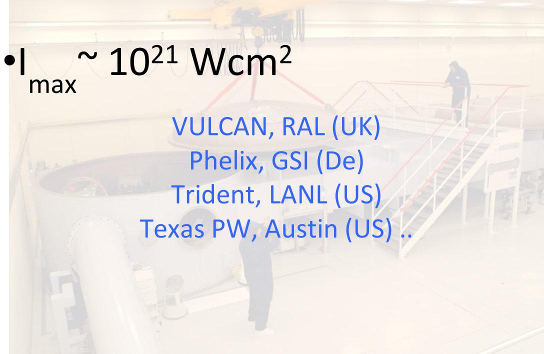
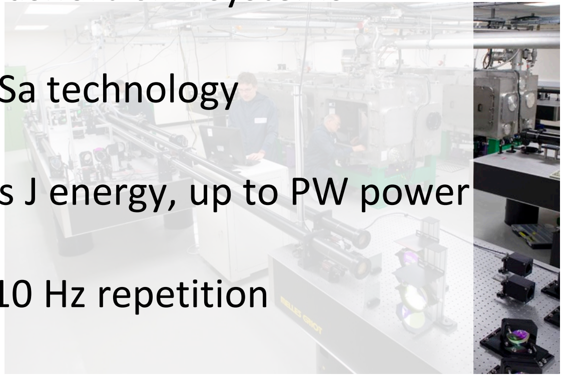


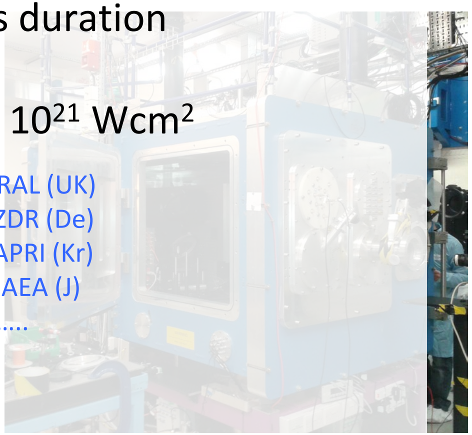
- I_{max} ~ 10^{21} Wcm^2

VULCAN, RAL (UK)
Phelix, GSI (De)
Trident, LANL (US)
Texas PW, Austin (US) ..

Ultrashort CPA systems



- Ti:Sa technology
- 10s J energy, up to PW power
- 1-10 Hz repetition
- 10s fs duration



- I_{max} ~ 10^{21} Wcm^2

GEMINI, RAL (UK)
Draco, HZDR (De)
Pulser I, APRI (Kr)
J-Karen, JAEA (J)
.....

Proton energy scaling with short and long pulse drivers

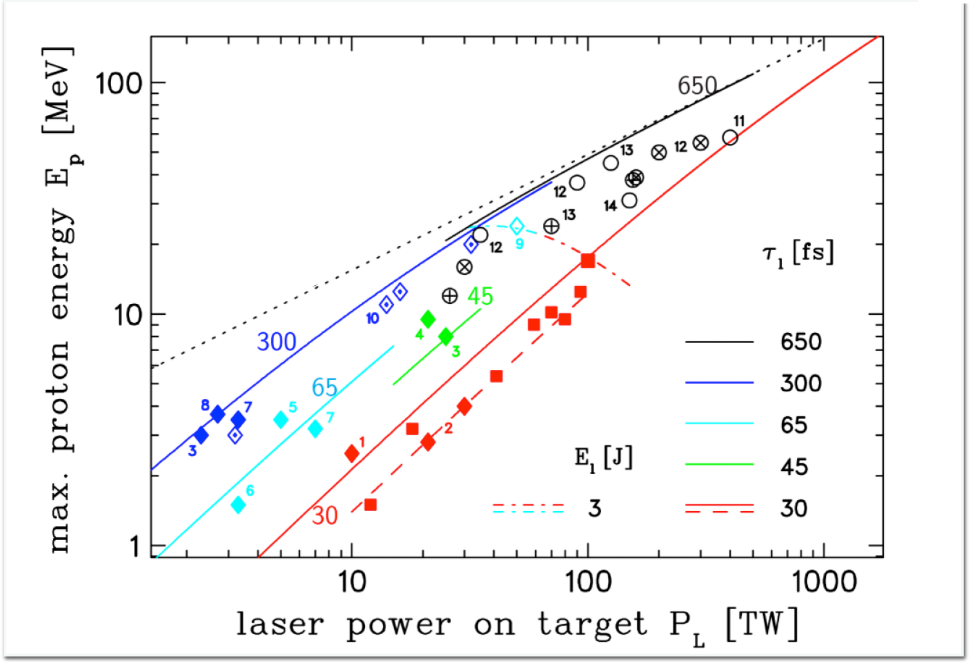
$$I \propto \frac{E_p}{\tau A}$$

proton energy ↓ E_p

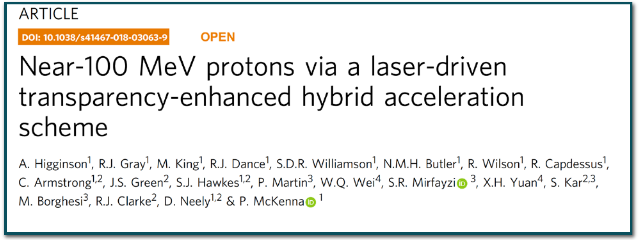
pulse lenght ↑ τ

spot surface on target ↖ A

Intensity W/cm^2 ↗ I



K Zeil et al 2010 New J. Phys. 12 045015


ARTICLE

DOI: 10.1038/s41467-018-03063-9 OPEN

Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme

A. Higginson[1], R.J. Gray[1], M. King[1], R.J. Dance[1], S.D.R. Williamson[1], N.M.H. Butler[1], R. Wilson[1], R. Capdessus[1], C. Armstrong[1,2], J.S. Green[2], S.J. Hawkes[1,2], P. Martin[3], W.Q. Wei[4], S.R. Mirfayzi[3], X.H. Yuan[4], S. Kar[2,3], M. Borghesi[3], R.J. Clarke[2], D. Neely[1,2] & P. McKenna[1]

Record on the max protons energy

TNSA Ion beams properties

Short duration source: ~ 1 ps

High brightness:
10^{11} –10^{13} protons/ions in a single shot

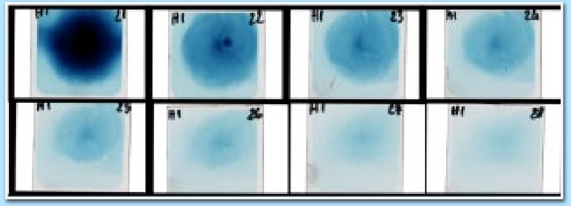
High current (if stripped of electrons): kA range

Compactness: E~1-10 TV/m with acceleration lengths ~ μm

Divergency: ~ 10s degrees

Broad energy spectrum

Curtesy of Marco Borghesi, QUB



Ion beam from TARANIS facility, QUB

E ~10 J on target in 10 μm spot
Intensity: ~10^{19} W/cm^2
duration: 500 fs
Target: Al foil 10um thickness

Can be a high power laser competitive for ion acceleration?

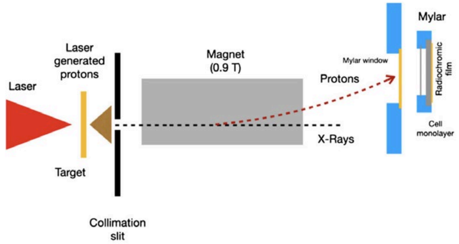
1. Enhancing the maximum proton energy and flux

2. Reducing the beam angular divergence or improving the beam homogeneity

3. Reducing the ion contamination of the beam

4. Developing new technologies and strategies to shoot at high repetition rate (1–10 Hz)

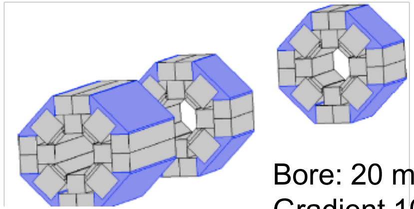
Main adopted solutions to select and transport proton beam



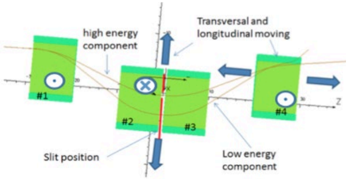
Dipole field: 0.9 T
Length: 100 mm
Energy selection:
up to 30 MeV proton

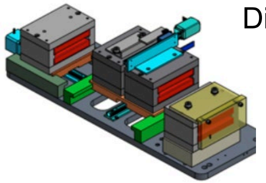
Single dipole for energy selection

F Hanton, et al.
Scientific Reports 9, 4471 (2019)



Bore: 20 mm;
Gradient 100 T/m

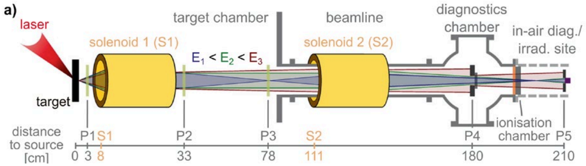




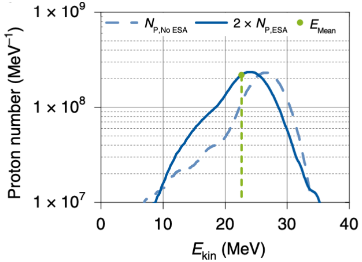
Dipole field: 0.8 T

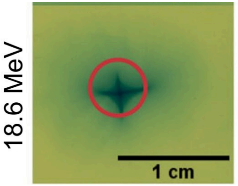
Quadrupoles + energy selector
Transport up to 30 MeV with an energy revolution of 5 %

F Schillaci, et al.
NIMA, 837, 80-87 (2016



On-axis magnetic field up to 19.5 T
Rep rate: up to 3 pulse per minute





Pulsed solenoids

F Kroll et al. Nature Physics 18, 316–322 (2022)

Diagnostic and dosimetry of laser-driven beams

Which diagnostic for laser-driven beams?

Diagnostic and dosimetry of laser-drive ion beams is still a challenge

up to 10E11 ppb in 10 ns → up to 10E9 Gy/s

"Passive" detectors

- Reliable
- Not affected by the electromagnetic noise
- Not affected by the beam dose rate
- Easy to handle
- Not good for high repetition rate lasers

[Radiochromic films, CR39 track detectors, image plates ….]

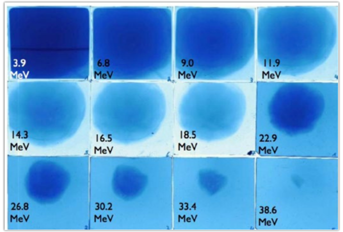
"Active" detectors

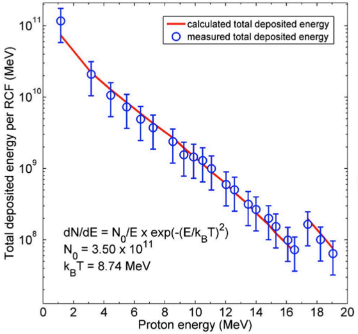
- Reliable
- Could affected by the electromagnetic noise
- Could affected by the beam dose rate
- Real-time acquisition and analysis
- Necessary for high repetition rate laser systems

[Thomson-like spectrometers, Time-of-Flight detectors, Integrated Current Transformer …]

Example of passive detectors

Radiochromic films
beam profile and energy spectra reconstruction



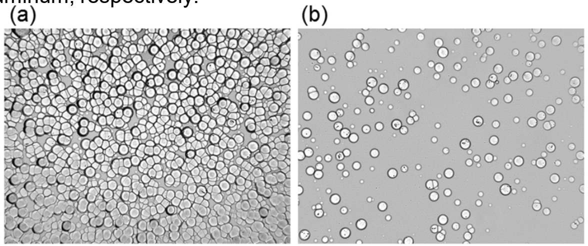


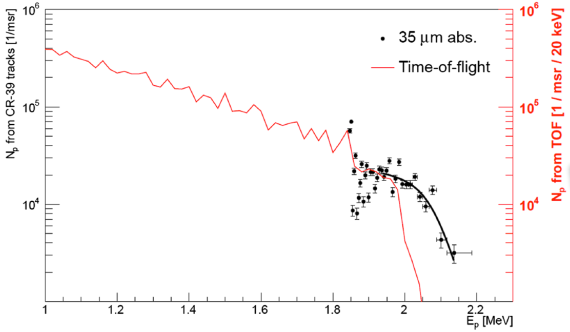
TRIDENT laser-driven protons
RAL (UK)

F Nürnberg, et al.
Review of Scientific Instruments 80, 033301 (2009);

CR39
Flux measure
Energy spectra

Microscopic images of CR-39 samples exposed to a single laser shot (example 3), covered with (a) 25 µm and (b) 35 µm of aluminum, respectively.

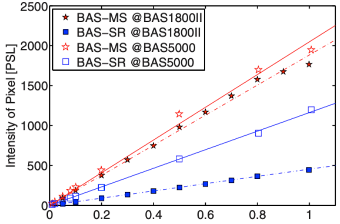


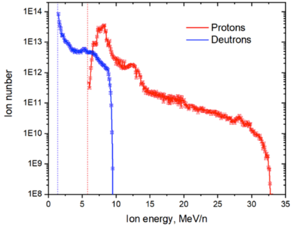


M Seimetz, et al.
Review of Scientific Instruments 89, 023302 (2018);

Image plate are photostimulable phosphor screen [BaFBr:Eu2+]
Flux measure
Energy spectra
Beam distribution

PSL: photo stimulated luminescence





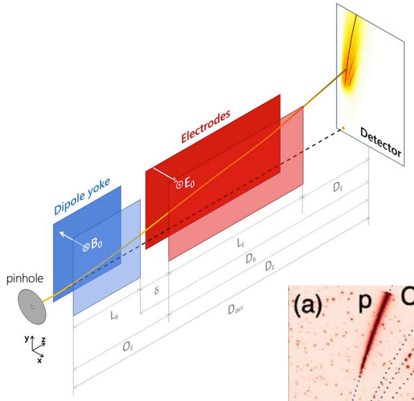
Laser -driven spectra of protons and deuterons

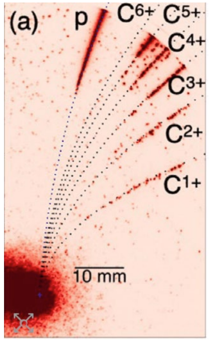
D O Gloving et al.
JINST 16 T02005 (2021);

Example of active detectors

Thomson-like spectrometer

Particle max energy
Plasma species detection
Energy spectra if properly calibrated



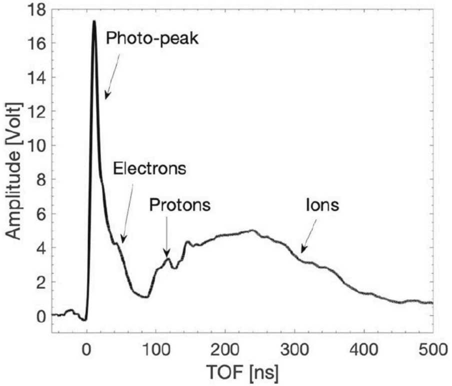


Principle:
Orthogonal Electric and magnetic fields
==>
charge separation and energy evaluation

A Alejo et al.
JNIST **11** C10005 (2016)

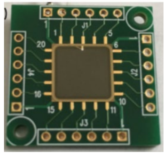
TOF - approach detectors

Particle max energy
Energy spectra

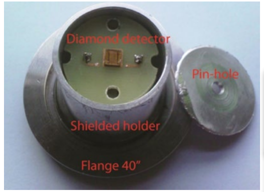


Typical Time of Flight spectra

Energy spectra can be derived



New generation of Silicon Carbide (left), Diamonds, Faraday Cups properly shielded for the EMP, are often used in this configuration



A diamond detector typically used in laser-driven experiments

M Marinelli et al.
JNIST **11** C10005 (2016)

G Milluzzo et al.
Review of Scientific Instruments **90**, 083303 (2019);SI **11** C10005 (2016)

Scintillators both in single and stack configuration

Beam profile and energy spectra reconstruction

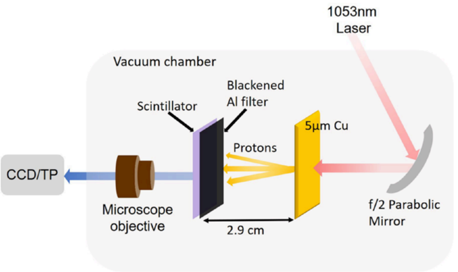
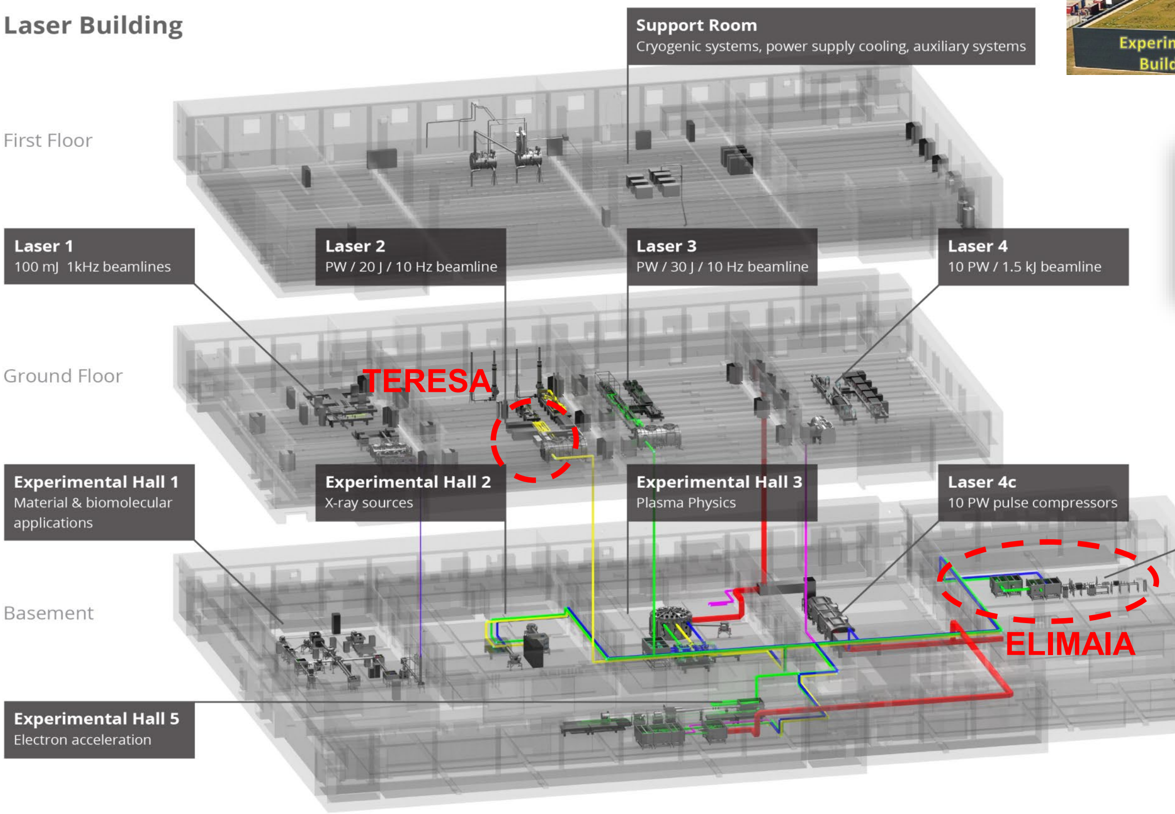


FIG. 1. A schematic of the experimental setup. A 1053 nm high intensity laser pulse is focused by a f/2 parabolic mirror onto a 5 μm Cu target to generate TNSA proton beams. The proton beam is measured either by the TP spectrometer to measure the energy spectrum or by the scintillator imaged onto a CCD with/without a microscope objective system to diagnose the spatial resolution.

H Tang et al.
Rev. Sci. Instrum. 91, 123304 (2020);

ELIMED solution @ELI-Beamline

E4: ion acceleation and target area @ELI



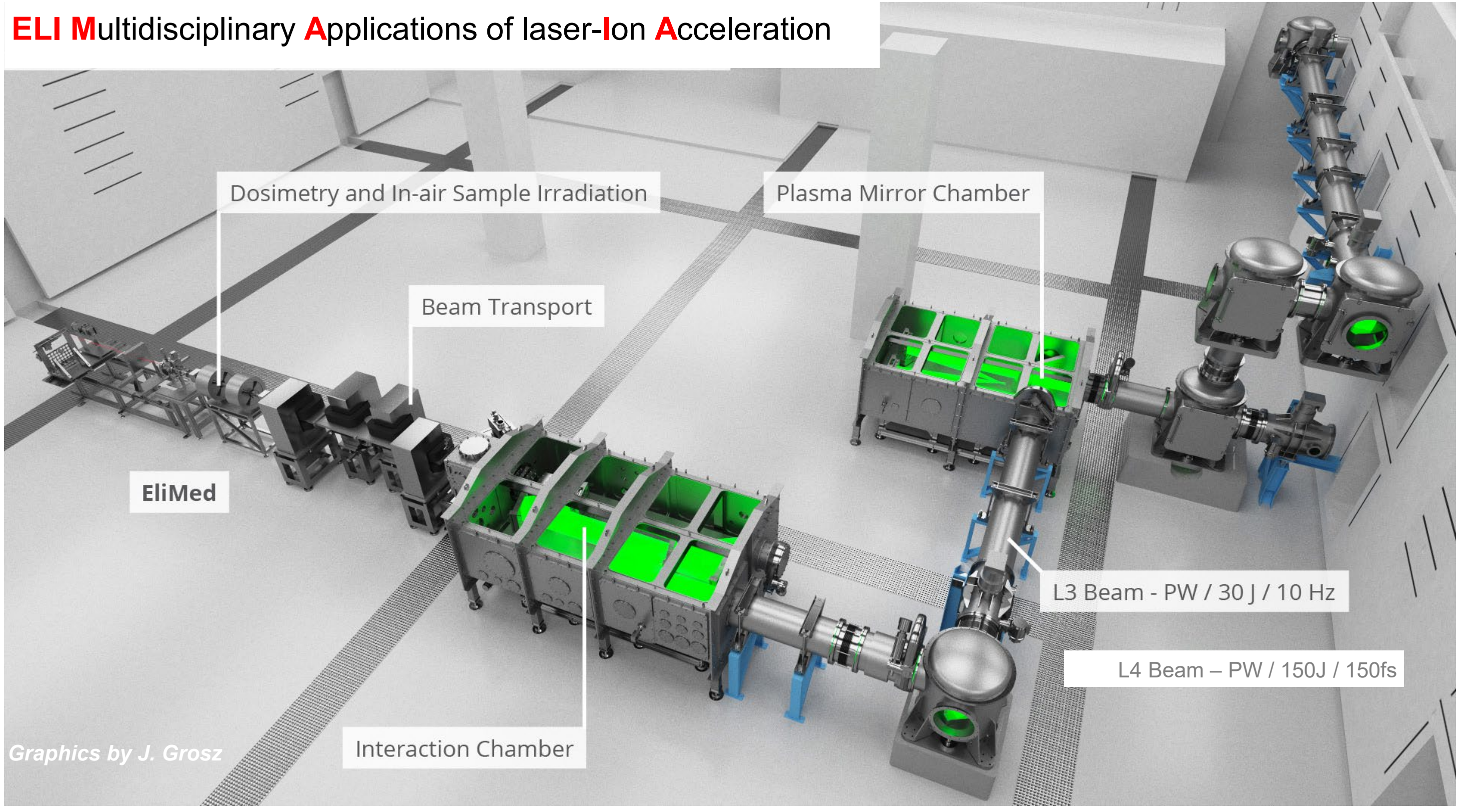
www.eli-beams.eu

Laser aviability in E4

Beamline	L1 ALLEGRA	L2 DUHA	L3 HAPLS	L4 ATON
Peak power	7 TW	100 TW	≥1 PW	10 PW
Energy in pulse	100 mJ	1.5	≥30 J	≥1.5 kJ
Pulse duration	<15 fs	<15 fs	≤30 fs	≤150 fs
Rep rate	kHz	20 Hz	10 Hz	1 per min
Supplier	Pump lasers from industry (Trumpf)	Subsystems from STFC	LLNL	National Energetics
ELI-Beamlines	**OPCPA pulse chain, pulse compressors, controls & timing systems**	**Pump laser subsystems, ps OPCPA, controls & timing systems**	**Compressor, short pulse diagnostics, controls & timing systems**	**Compressor design, OPCPA design, short pulse diagnostics, timing system**

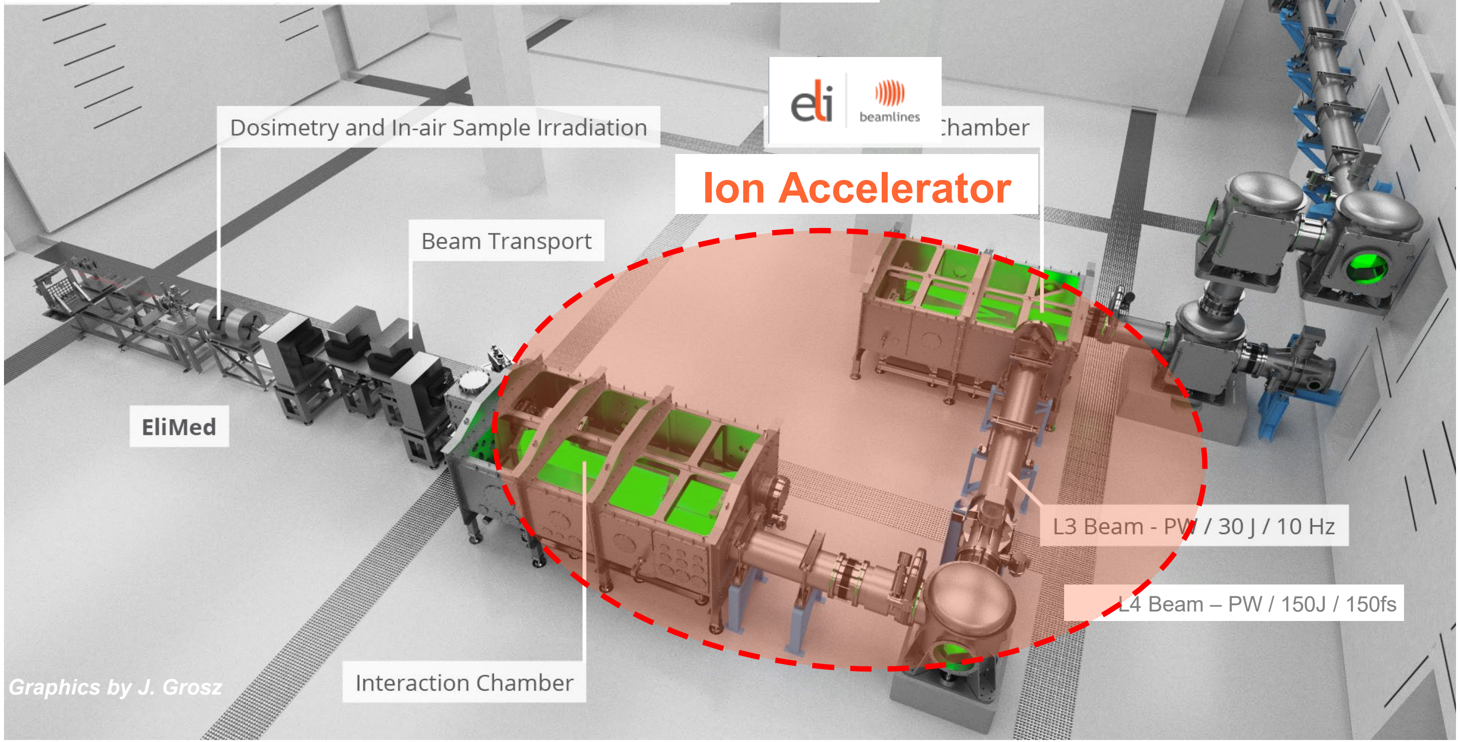
ELIMAIA: a User beamline

ELI Multidisciplinary Applications of laser-Ion Acceleration

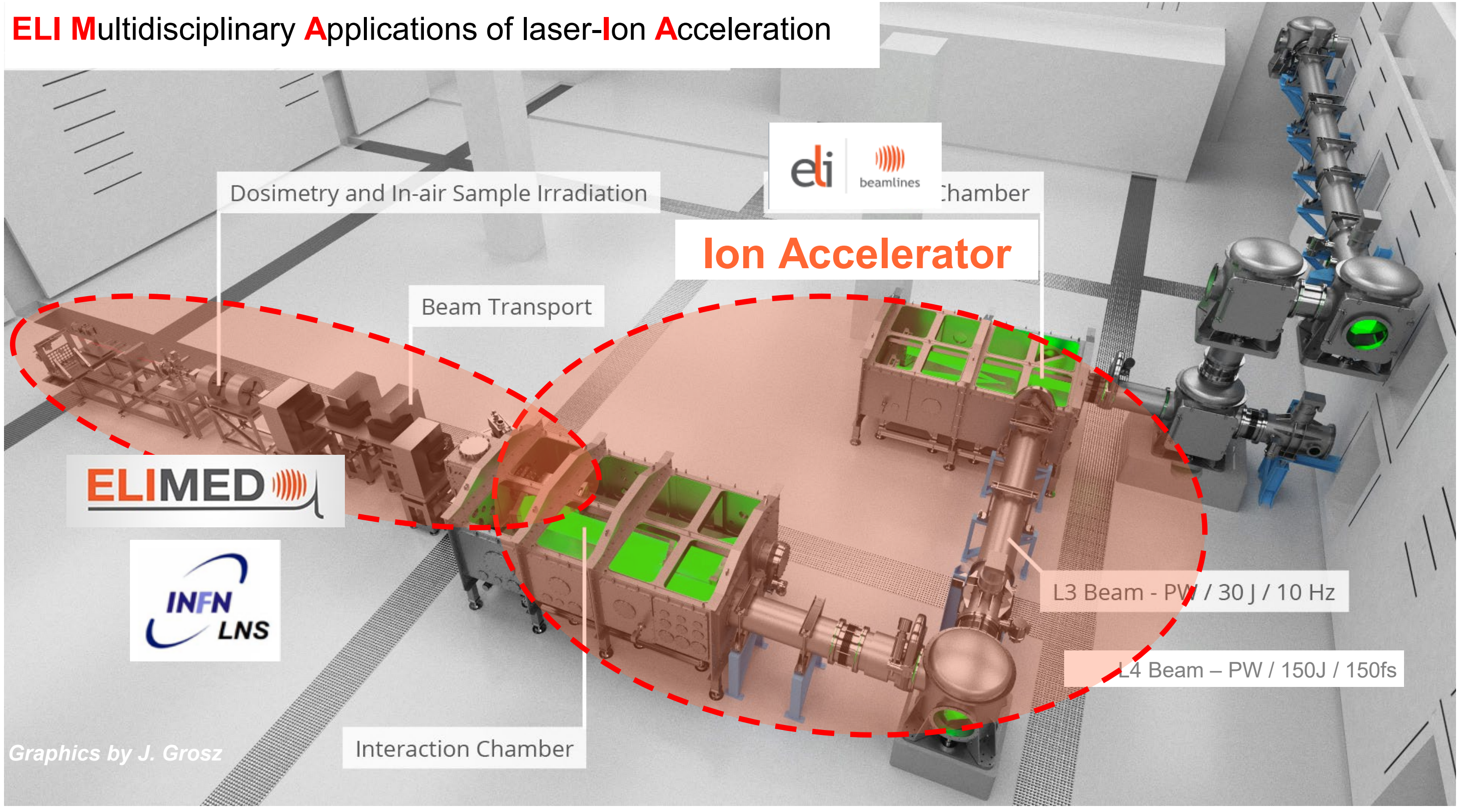


ELIMAIA: a User beamline

ELI **M**ultidisciplinary **A**pplications of laser-**I**on **A**cceleration



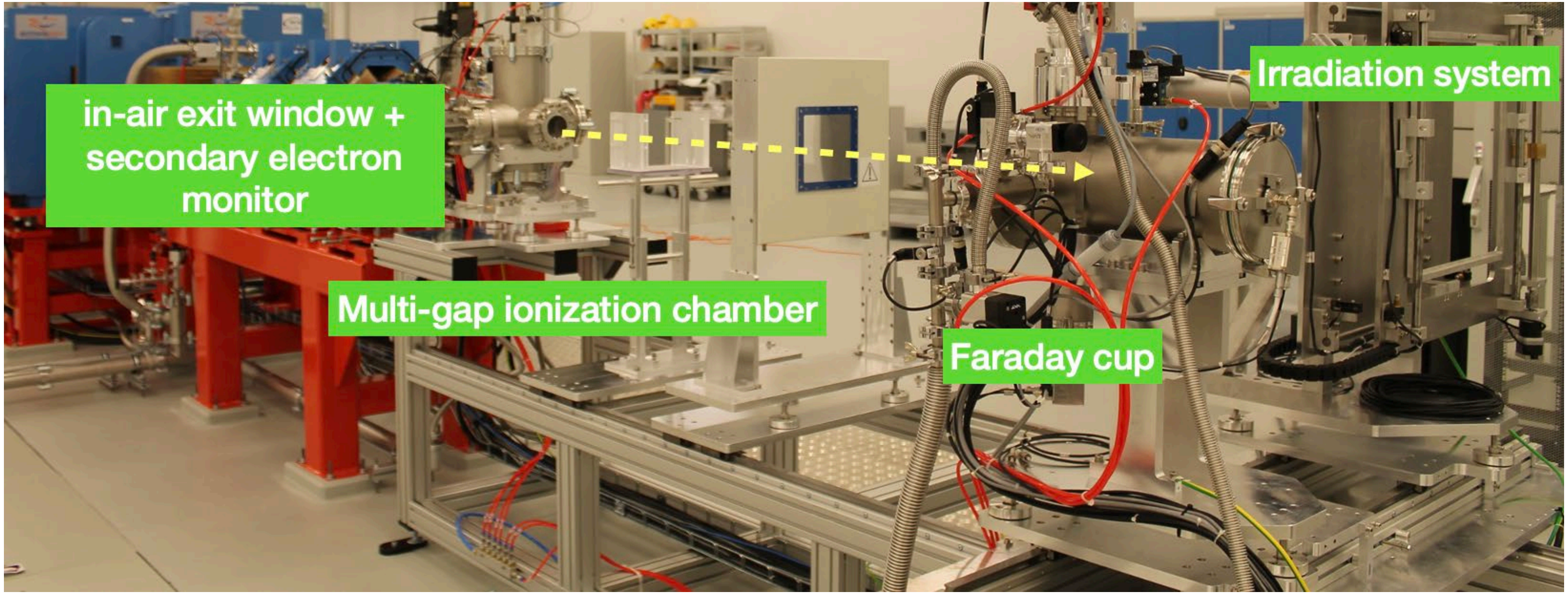
ELIMAIA: a User beamline



ELIMAIA installation in E4

ELI Multidisciplinary Applications of laser-Ion Acceleration

Dosimetric approaches in E4

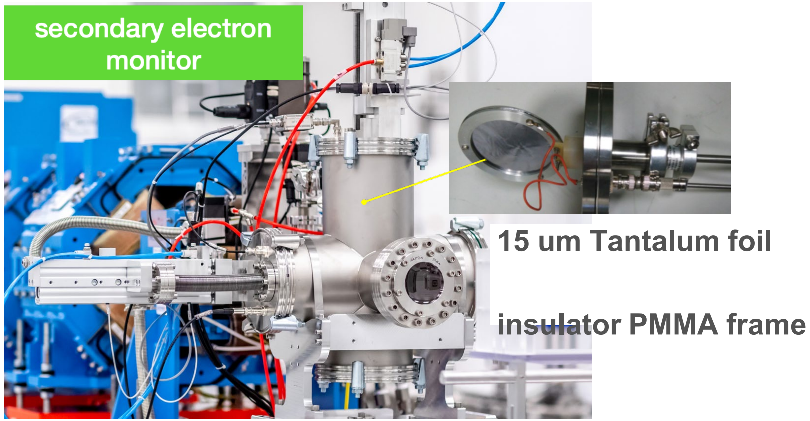


Faraday cup in a special design for absolute dosimetry

Dual gap ionisation chamber for ion recombination correction

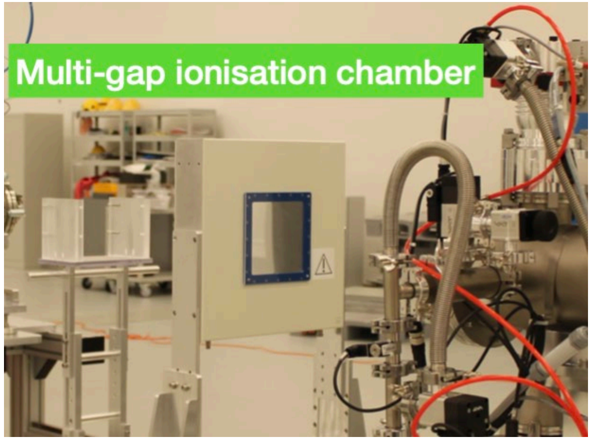
Radiochromic films and plastic detector for spectroscopy(first phase, low-energy)

Relative dosimetry



- Time Of Fligth configuration
- Charge integration for normalisation purposes
- Scattering foil for beam diffusion

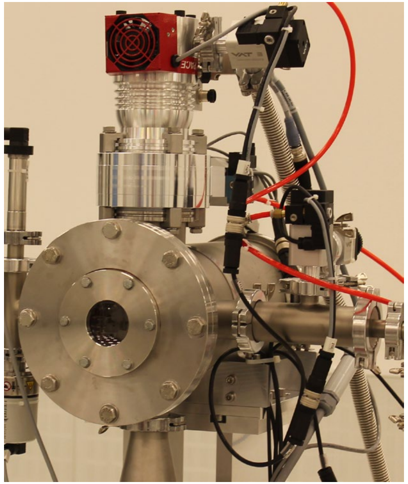
Supplied by DE.TEC.TOR. Devices & Technologies Torino Srl, Italy

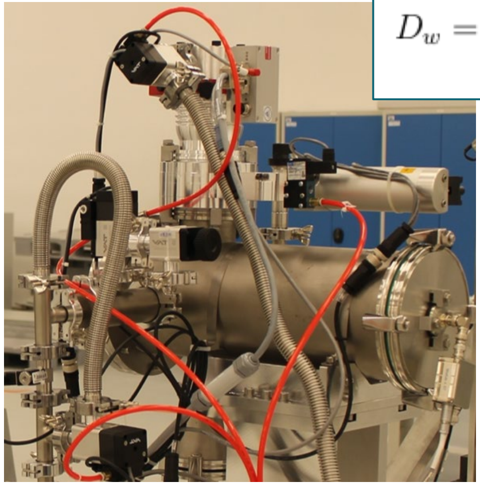


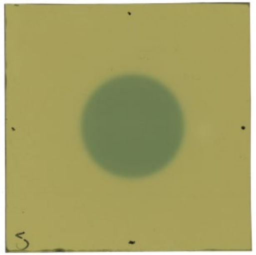
- Two adjacent IC, gaps of 5 mm and 10 mm, independently biased (maximum applied voltage ± 1000 V and ± 2000 V, respectively)
- Anode: thin layers of 5 μm of copper and 2 μm of nickel, deposited on a 25 μm layer of kapton
- Cathode:12 μm-thick layer of aluminized mylar

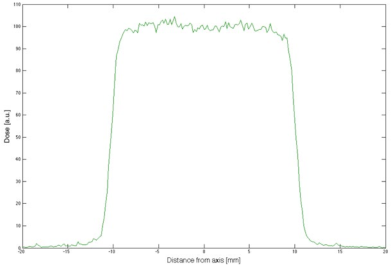
Absolute dosimetry: Faraday cup

$$D_w = \frac{1}{A} \cdot \frac{\int (S(E))_w N(E) dE}{\int N(E) dE} \cdot \frac{Q}{e} \cdot 1.602 \cdot 10^{-10} \quad (Gy)$$







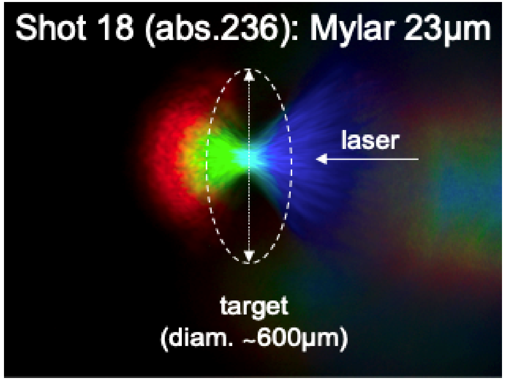


The cylindrical symmetry of the electric field provided by the external electrode is broken due to the presence of the internal one.

The resulting effect is a strongly asymmetric electric field, characterized by a significant transversal component able to maximize the deflection of the secondary electrons generated by both the entrance window and the cup.

September 2021: pre-commissioning phase @ELIMAIA!

plasma imaging

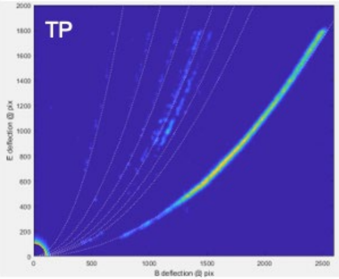


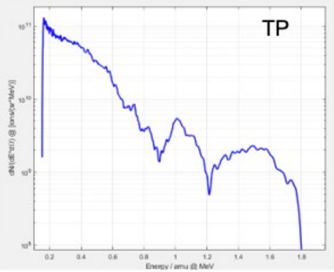
Timofej Chagovets, Pablo Cirrone,Lorenzo Giuffrida, Filip Grepl,Valeria Istokskaia,Vasiliki Kantarelou, Georg Korn, Tadzio Levato, Daniele Margarone, Giada Petringa, Francesco Schillaci, Stanislav Stancek,Marco Tosca, Maksym Tryus, Andriy Velyhan,Martina Zakova

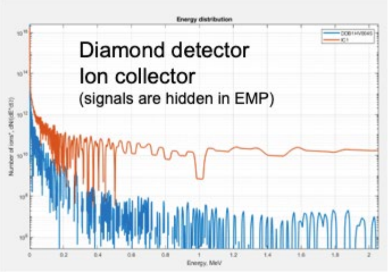
More than 20 online diagnostics working @1Hz repetition rate!

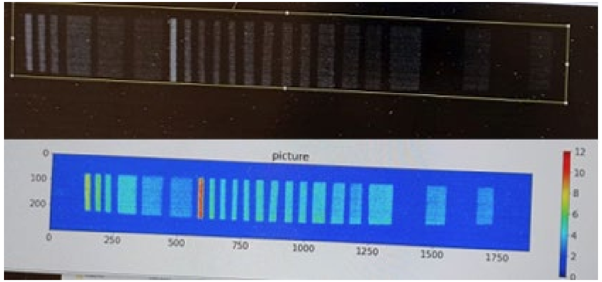
charged particles, neutrons, xrays, eletromagnetic pulse, electrons, plasma, laser on target

Thompson Parabola, Time Of Flight detectors , Ion Collectors and Calorimeter for gamma emission









Courtesy of D. Margarone, QUB (UK) and ELI-Beamline

PRAGUE project

Proton RAnGe measure Using silicon Carbide

Main aim

Realize the **first** on-line dosimeter for conventional and laser-driven ion beams based on a **new generation of Silicon Carbide**

- **dose rate independent**
- **LET independent**
- **linear responce with absorbed dose**
- **higher spatial resolution**
- **saving time**
- **application in biological irradiation**

IMPULSE

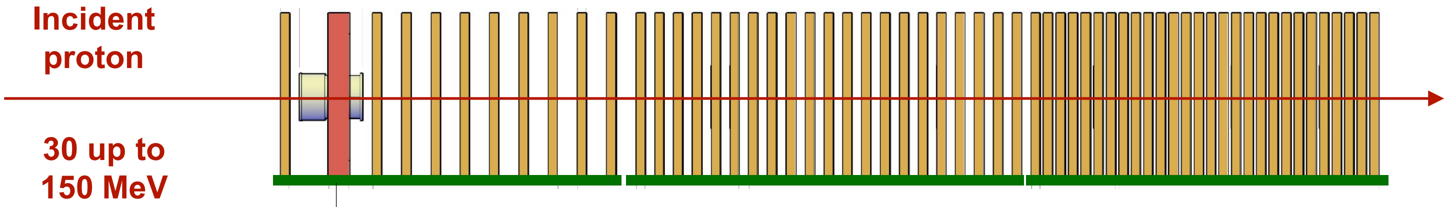
MARIE CURIE ACTIONS

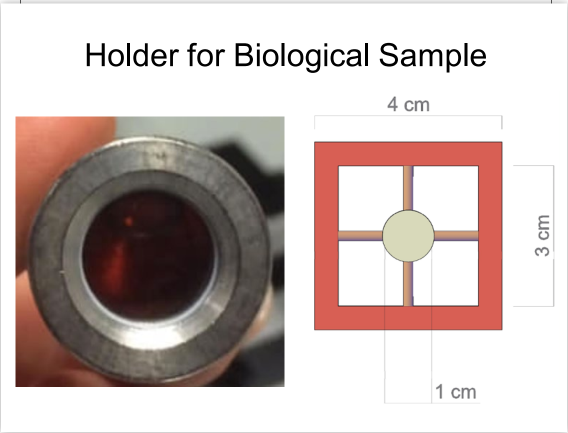
INFN Istituto Nazionale di Fisica Nucleare

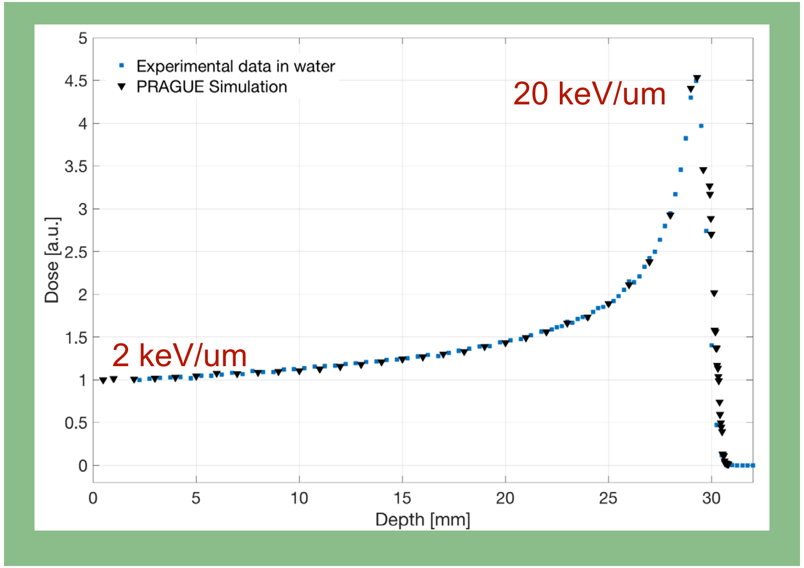
eli beamlines

The assembled detector

60 Silicon Carbide in stack configuration





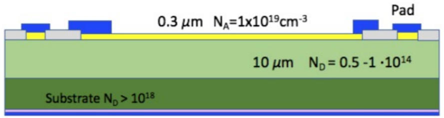


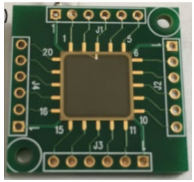
G Petringa, PhD - giada.petringa@lns.infn.it

Adopted Silicon Carbide

Properties	Diamond	Silicon	4H-Silicon Carbide
Energy Gap [eV]	5.45	1.12	3.26
Relative dielectric constant ε_r	5.7	11.9	9.7
Breakdown electric field (MV/cm)	10	0.2-0.3	2.2-4.0
Density (gr/cm^3)	3.52	2.33	3.21
Atomic Number Z	6	14	10
e-h pair energy (eV)	13	3.62	7.78
Saturated electron velocity (10^7 cms^{-1})	2.2	1.0	2
Hole mobility [cm^2/Vs]	1200-1600	450-600	100-115
Electron mobility [cm^2/Vs]	1800-2200	1400-1500	800-1000
Threshold displacement energy (eV)	40-50	13-20	22-35
Thermal conductivity (W/cm °C)	20	1.5	3-5
Max working temperature (°C)	1100	300	1240
Hole lifetime τ_p	10^{-9}	$2.5*10^{-3}$	$6*10^{-7}$

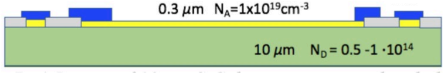
Entrance and proximal position reconstruction





15 x 15 mm^2

Distal position reconstruction

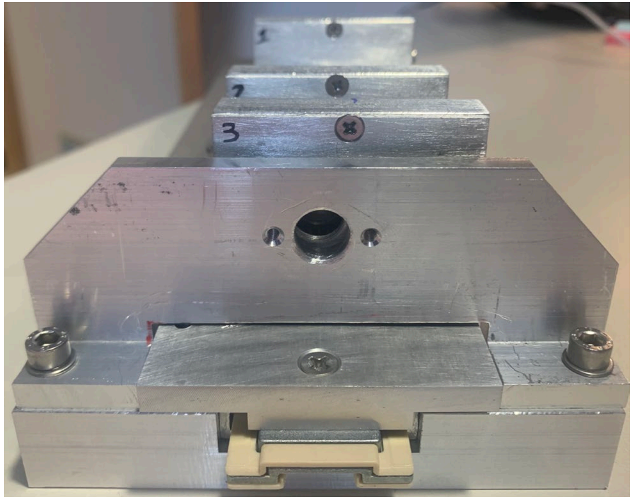


15 x 15 mm^2

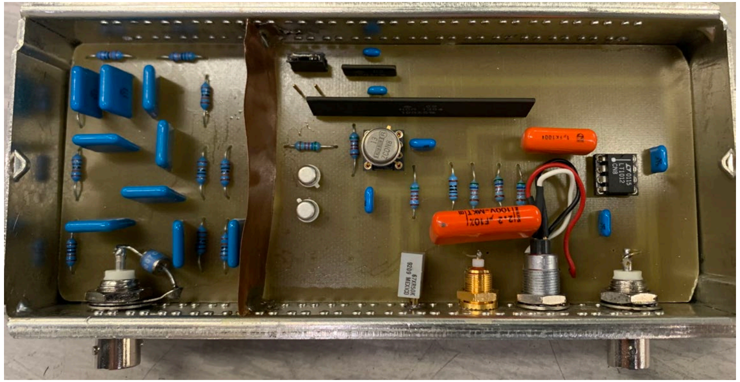
PRAGUE detector prototype

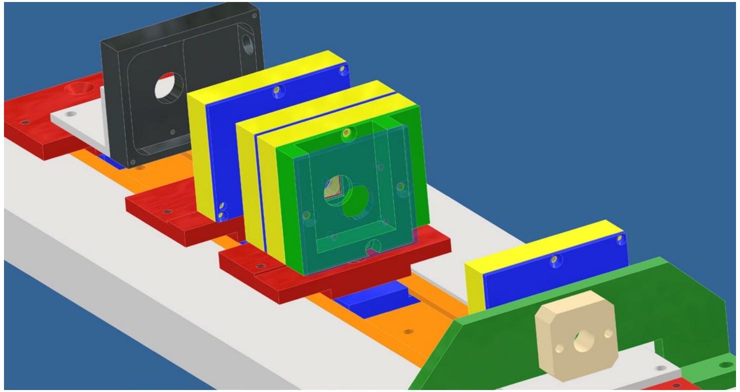
The First Prototype was realized and tested @PTC of Trento (IT) @Ústav jaderné fyziky av cr (CZ) @INO-CNR (IT)

The system was entire simulated with TOPAS



The current will be converted in voltage through an I-V converter

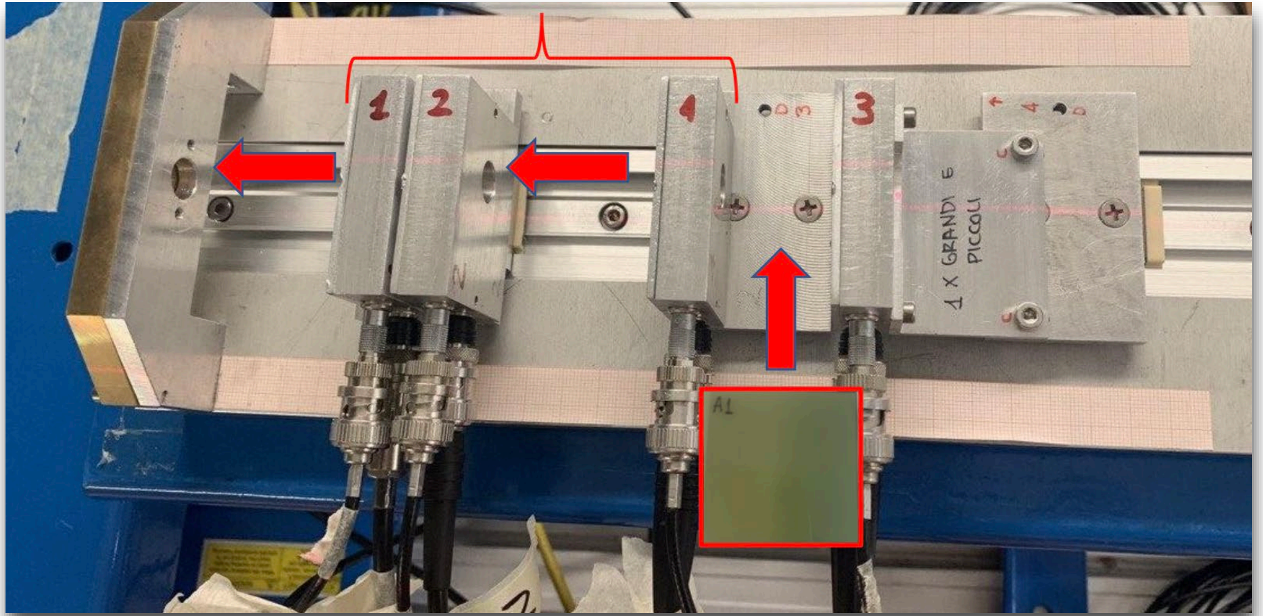




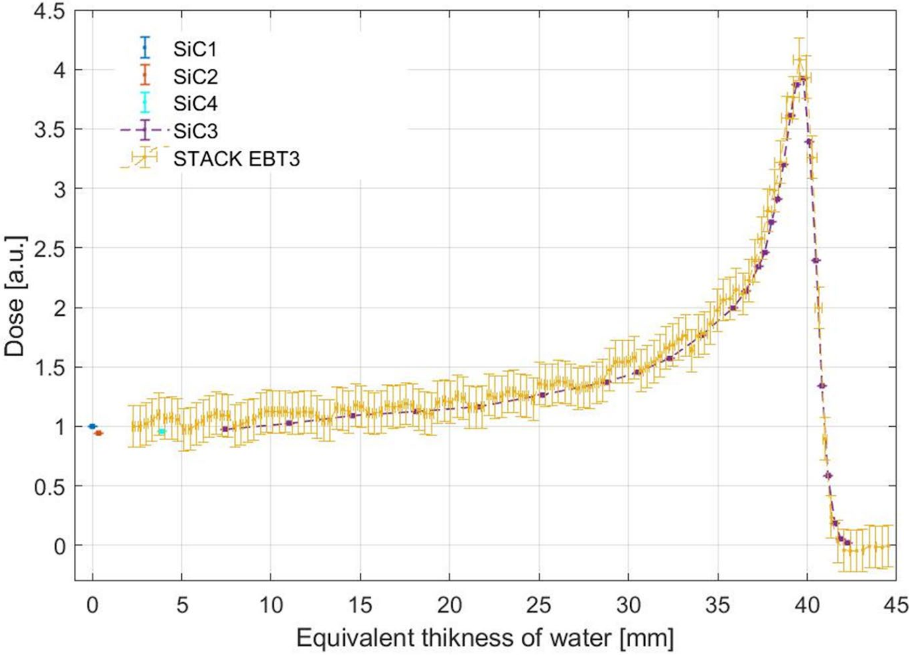
Experimental run @APSS Trento protontherapy center

 Main aim of the experimental run: depth dose deposition extimation

Proton beam energy: 70 MeV
Fluence: 10^6 s/cm^2
Irrafiation field: circular shape; 10 mm in diameter



Experimental run @APSS Trento protontherapy center



EBT3 Peak - Plateaux ratio	SiC Peak - Plateaux ratio
4.08	3.92

3.92% discrepancy

Future perspectiveness @LNS

I-LUCE: INFN Laser indUced aCcEleration facility

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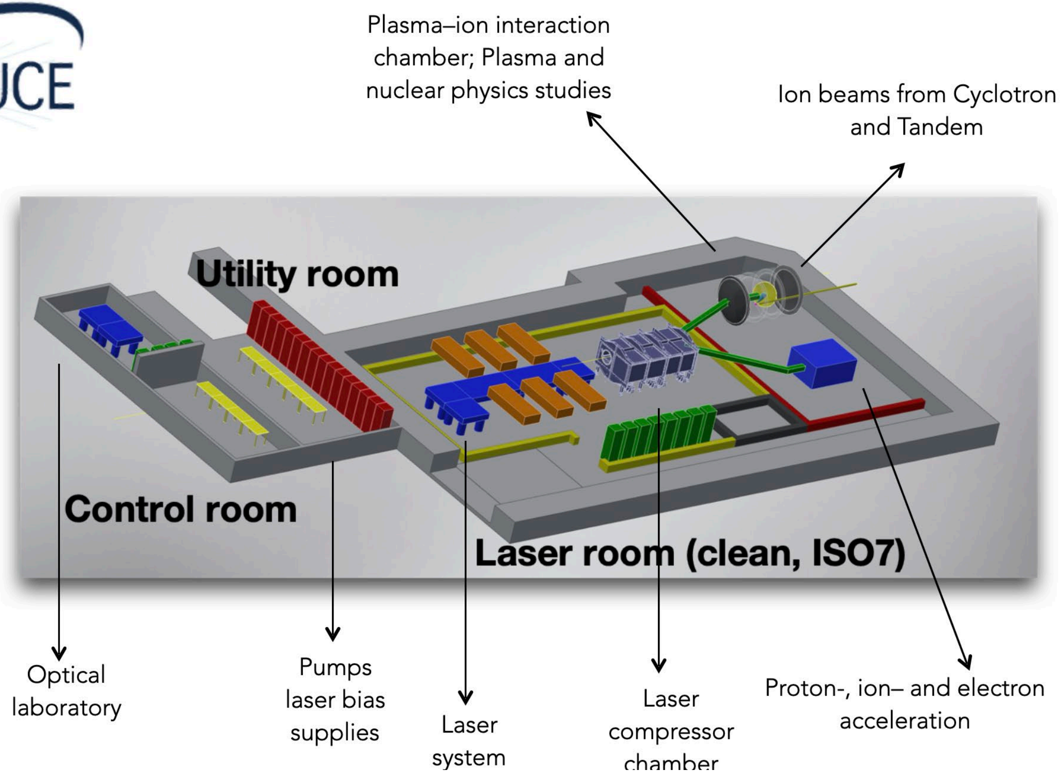
EuAPS



Energy on target:
500 TW
Pulse duration: <25fs
Repetition rate: 1 Hz
System designed to be upgradable up to 1 PW

Protons

~ 40 MeV

~ 100 MeV with future upgrades

Electrons

~ 800 MeV

Thanks for Listening

Left to right:
Roberto Catalano, Davide Passarello, Pablo Cirrone, Emilio Zappalà, Nino Amato, Luciano Pandola, Giuliana Milluzzo, Michele Costa, Mariacristina Guarrera, Serena Fattori, Antonio Russo, Beatrice Cagni, Alma Kurmanova, Carmen Altana,Andrea Matamoros, Giuliana Navarra, Salvo Tudisco, Giacomo Cuttone, Giada Petringa, Gustavo Messina
INFN-LNS Medical Physics Group - Catania, April 30, 2021