ELIMAIA: a laser-plasma ion acceleration platform for fundamental and applied user science

D. Margarone, F. Schillaci, L. Giuffrida, G.A.P. Cirrone

Director of Research and Operations, ELI Beamlines

The Extreme Light Infrastructure ERIC

LIGHT Collaboration Meeting, GSI, Oct 30, 2024

Outline

- The ELI Beamlines Facility of ELI ERIC

- The ELIMAIA beamline
  - ✓ Motivation and mission
  - ✓ The Ion Acceleration platform
  - ✓ ELIMED: beam transport and dosimetry

ELI ERIC (established in 2021)

European Research Infrastructure Consortium

Czechia,
Host of Seat

Hungary,
Host

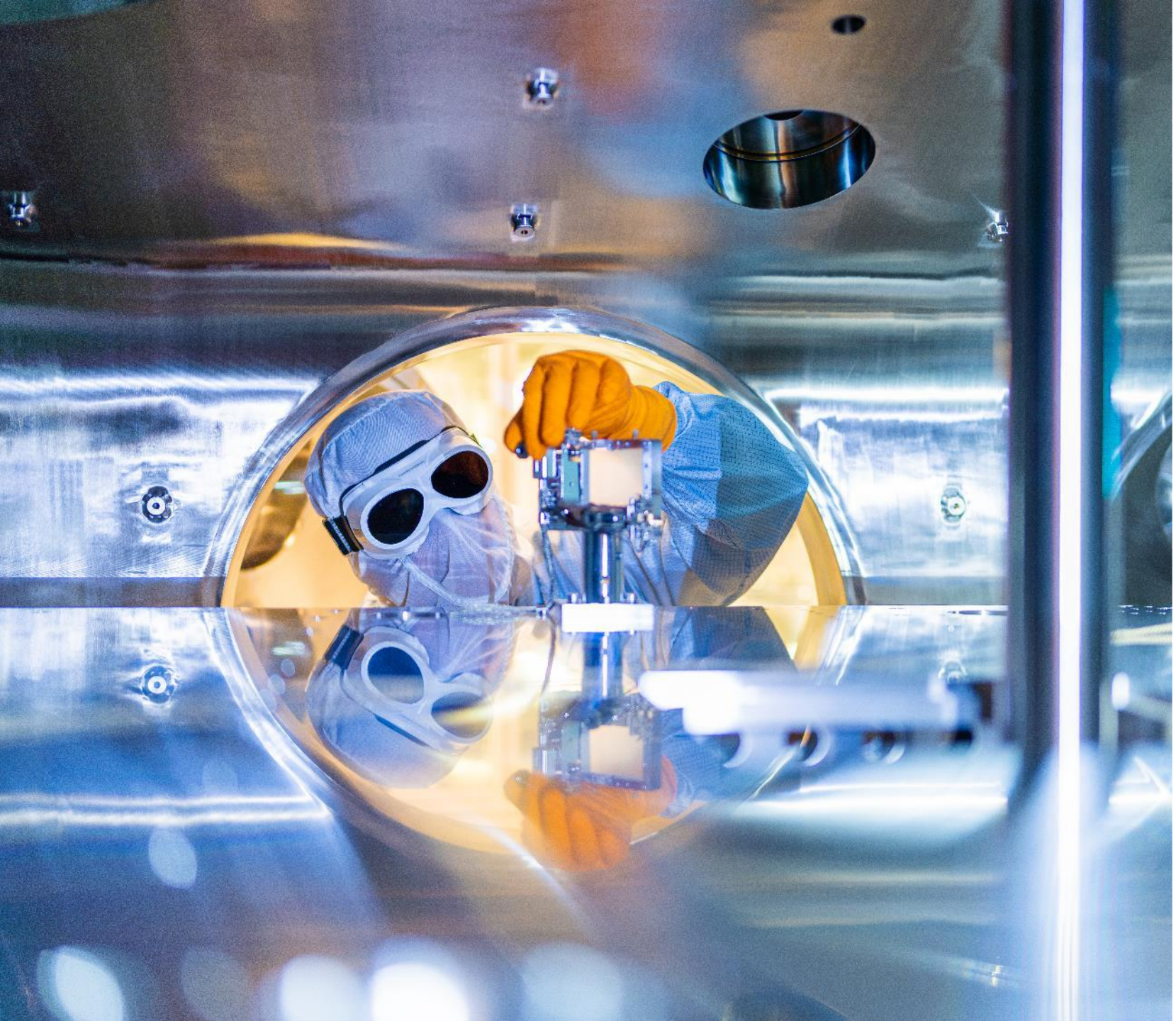
Italy
Member

Lithuania
Member

Germany
Observer

Bulgaria
Observer

Romania
Observer

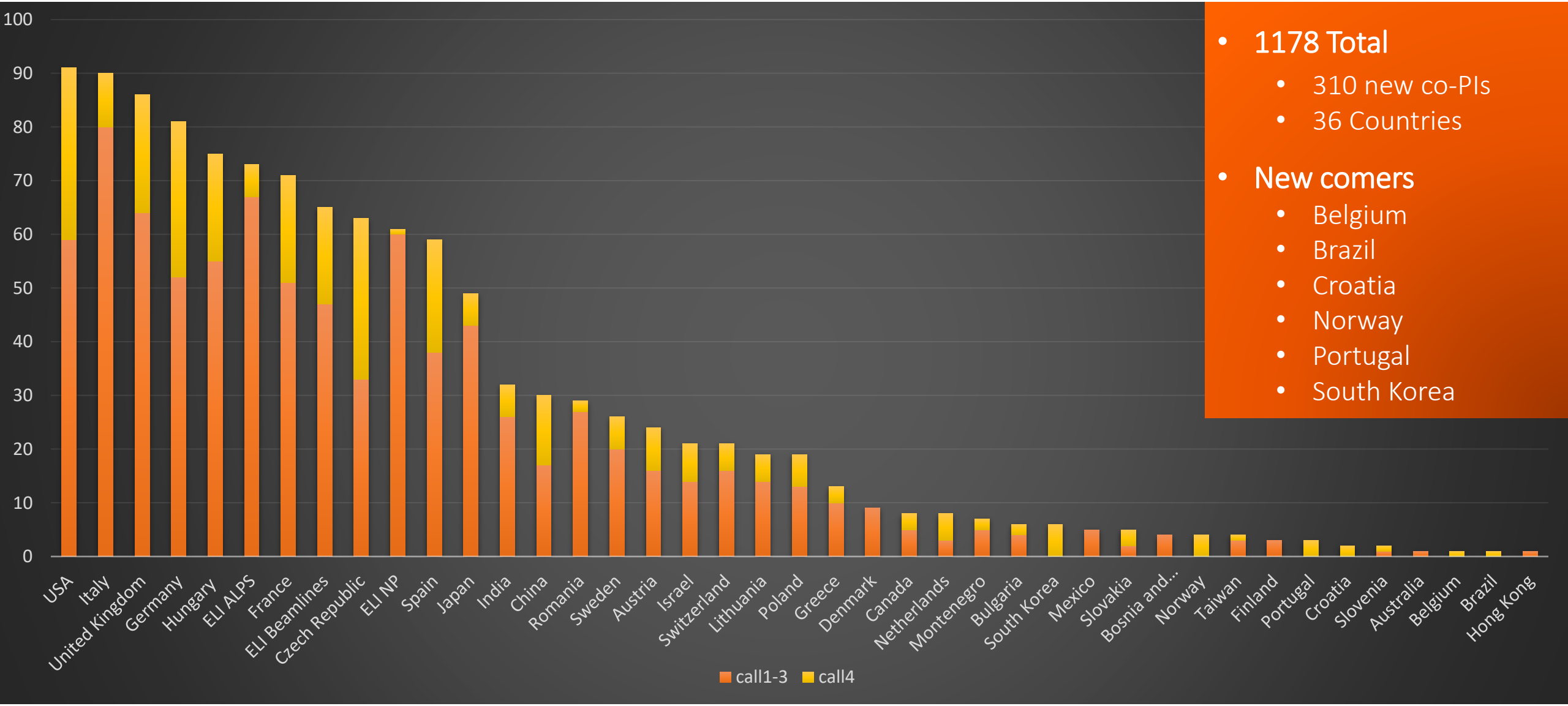


The ELI User Programme

- **ELI is open to international users and provides free access based on external peer-reviewed selection**
- **ELI Open-access Calls**
  - ✓ **4** Calls since 2022
  - ✓ **341** Proposal Submitted
  - ✓ **154** Proposals Granted
  - ✓ **1178** Unique Applicants
  - ✓ **605** Unique Users
  - ✓ **36** Countries
- **Call 5 (open):** September 25th, 2024
  https://up.eli-laser.eu
  Deadline: ***October 31st !!!***

Unique Applicants 2022-2024

co-PIs (Call 1 to Call 4)



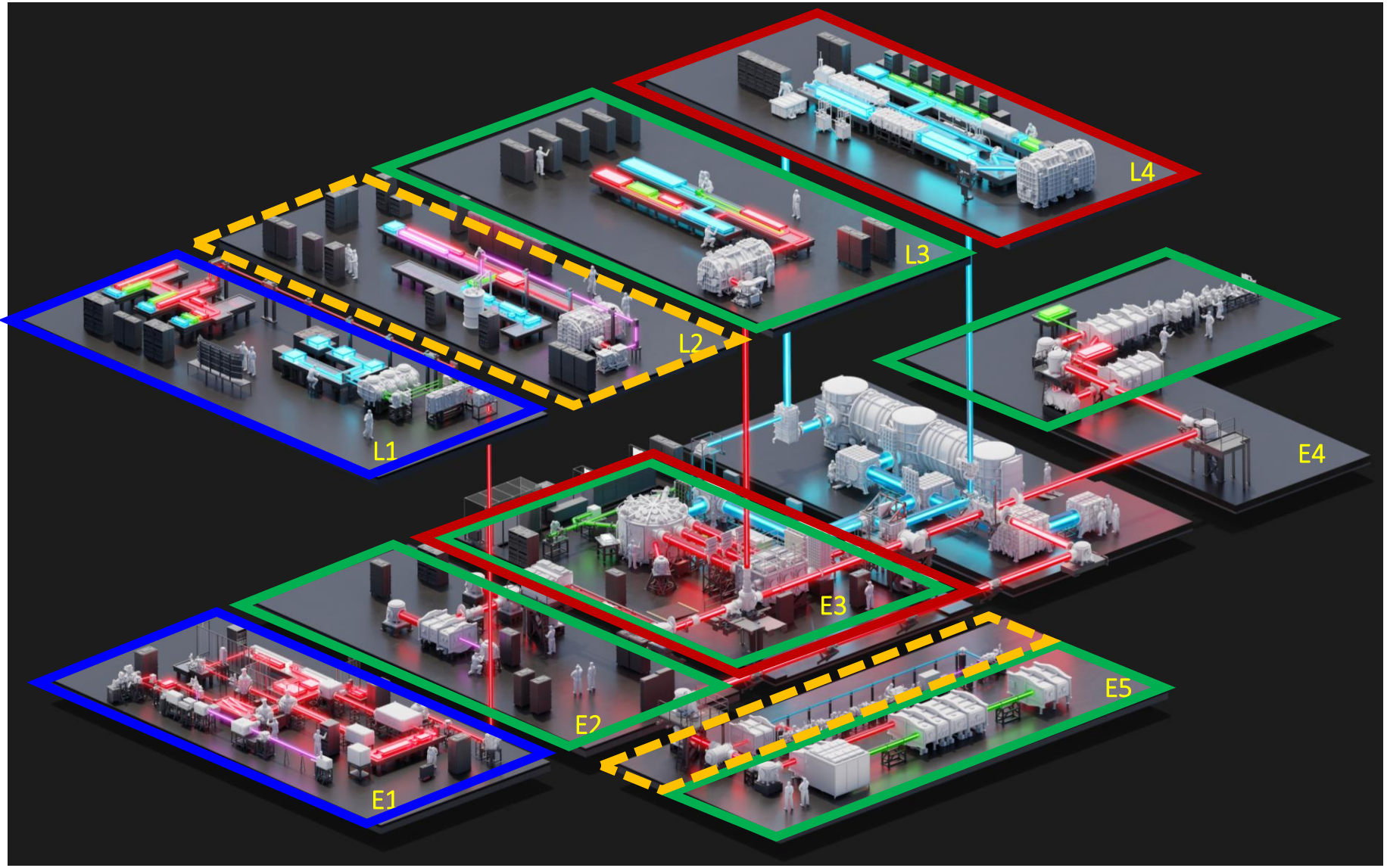
- 1178 Total
  - 310 new co-PIs
  - 36 Countries
- New comers
  - Belgium
  - Brazil
  - Croatia
  - Norway
  - Portugal
  - South Korea


eli
ELI Beamlines
Dolní Břežany, Czechia

ELI BL Facility Status (2024)

user operations, commissioning, development

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



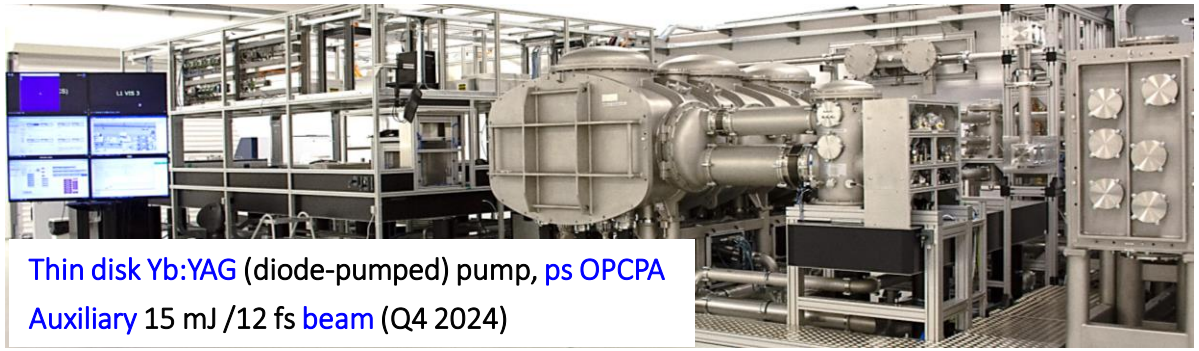
ELI BL Primary Sources (Lasers)

high-energy, high-rep-rate laser systems (0.01-1 kHz)

B. Rus et al.

L1-ALLEGRA 100mJ/12fs/1kHz (>5TW) laser system

(in operation – 50mJ/15fs/1kHz)



Thin disk Yb:YAG (diode-pumped) pump, ps OPCPA

Auxiliary 15 mJ /12 fs beam (Q4 2024)

L2-DUHA: 3J/20fs/50-100Hz (>100TW) laser system

(under development)

Cryogenic He-cooled (diode-pumped) Yb:YAG, ns OPCPA

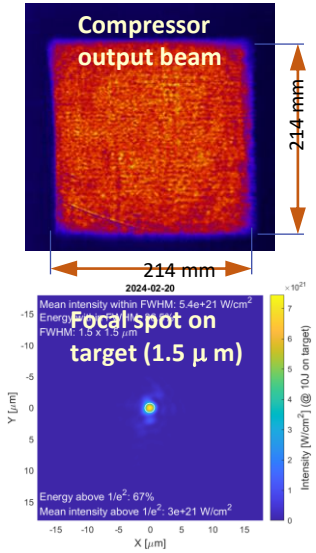
Expected availability for experiments: Q2 2025

L3-HAPLS: 30J/30fs/10Hz (1PW) laser system

(in operation – 13J/27fs/3.3Hz)

He-cooled (diode-pumped) Nd:glass pump, Ti:Sa

Ramping to 1PW level (Q1 2025)



L4-ATON: 1.5kJ/150fs/1shot/min (10PW) laser system

(long pulse in operation – 1.2kJ (0.6kJ @2w)/2-10ns/1shot/2min)

Mixed Nd:glass (>15nm spectral bandwidth)

ns-kJ pulses with programmable temporal shaping (~100ps steps)

10PW commissioning on target: Q1 2025

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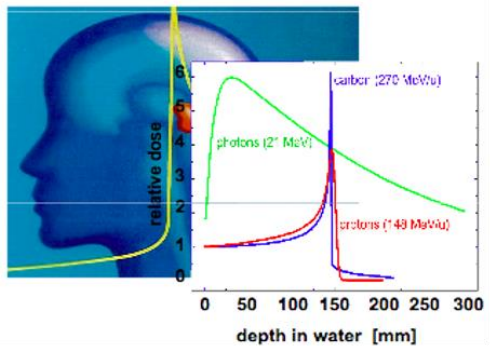
- **The ELIMAIA beamline**
  - ✓ **Motivation and mission**
  - ✓ The Ion Acceleration platform
  - ✓ ELIMED: beam transport and dosimetry

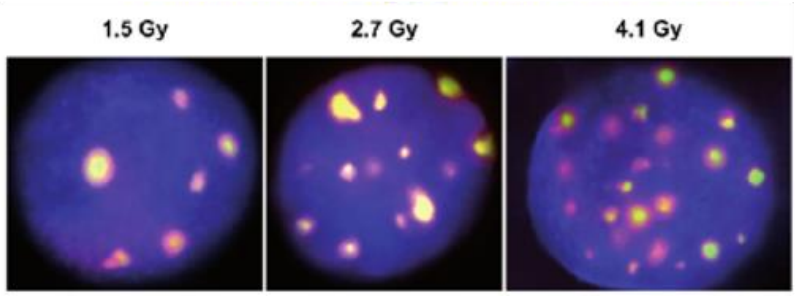
ELIMAIA-ELIMED beamline potential societal applications

cost effectiveness vs unique beam characteristics

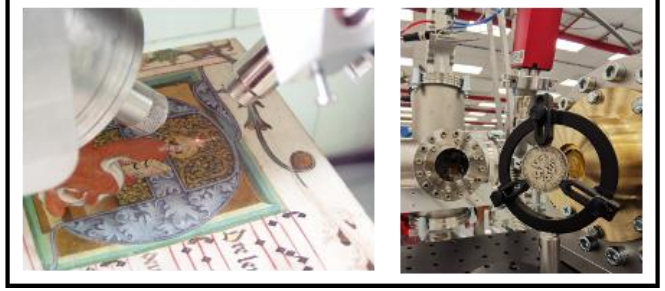
Particle Therapy of Cancer
hadrontherapy and radiotherapy



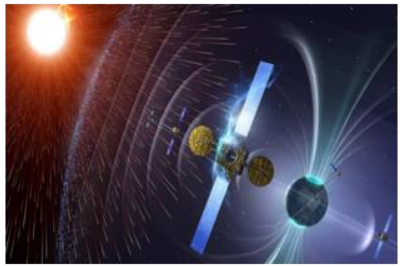
Ultrafast Radiobiology
FLASH and ultrahigh dose-rate



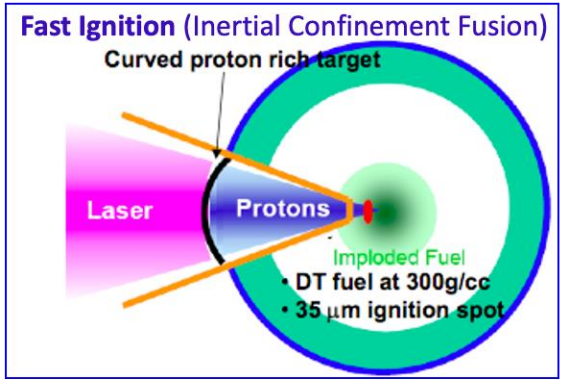
Non-Destructive Analysis
cultural-heritage/archaeology



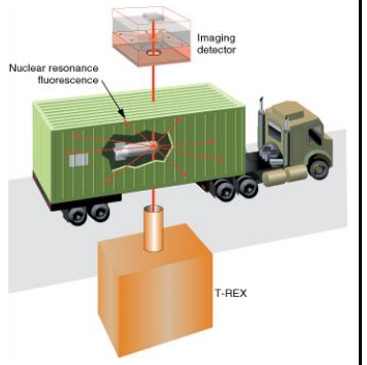
Space Radiation Testing
space industry



Fast Ignition (Inertial Confinement Fusion)



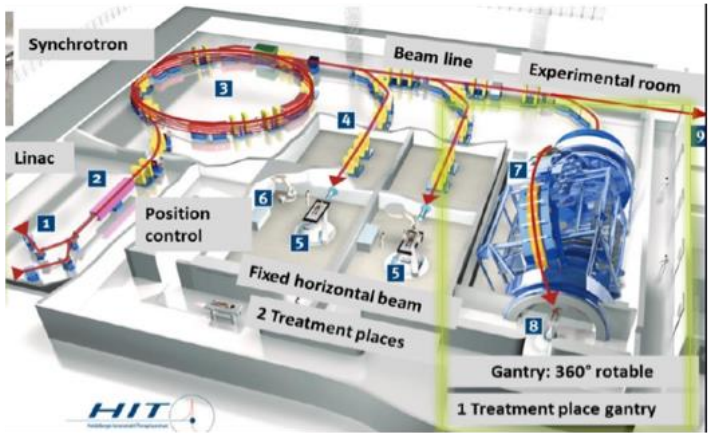
Material Inspection
neutron/γ-ray radiography

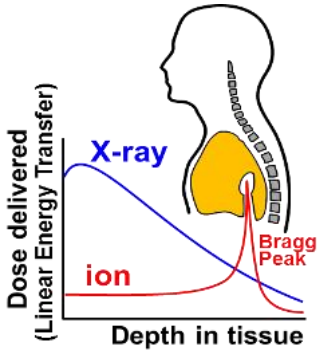


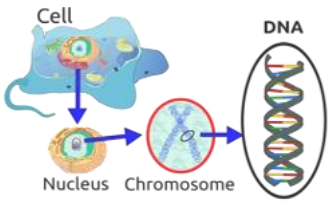
ELIMAIA-ELIMED ultra-fast radiobiology and clinical research

ultra-high dose-rate, ultra-short proton/ion bunches

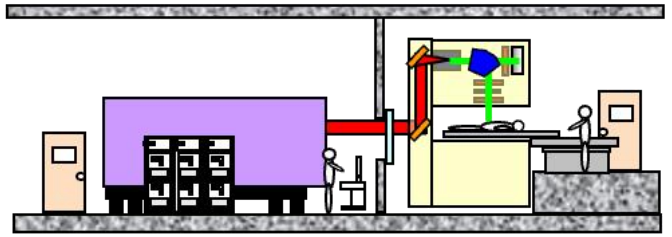
Conventional hadrontherapy (C-ions)



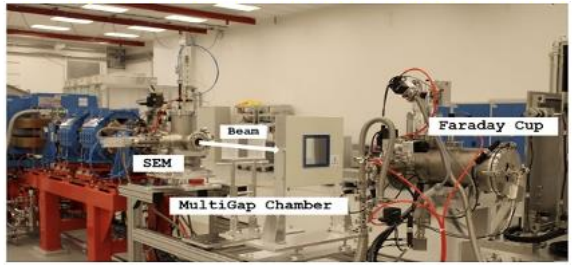




Laser based hadrontherapy *(concept)*



The ELIMED endstation at ELI BL

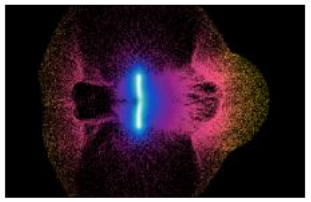


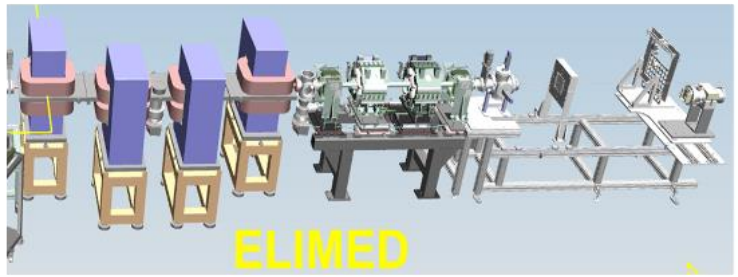
IMPULSE

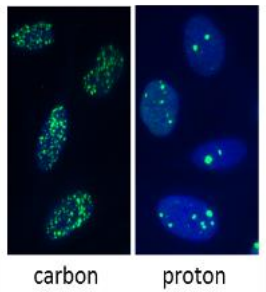
INFN LNS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud

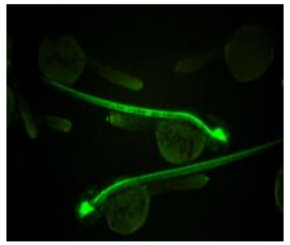
QUEEN'S UNIVERSITY BELFAST

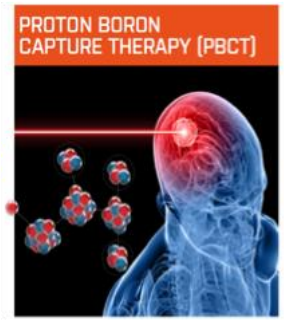
FLAIM flagship experiment: Flash and ultrahigh dose-rate radiobiology with Laser Accelerated Ions for Medical research





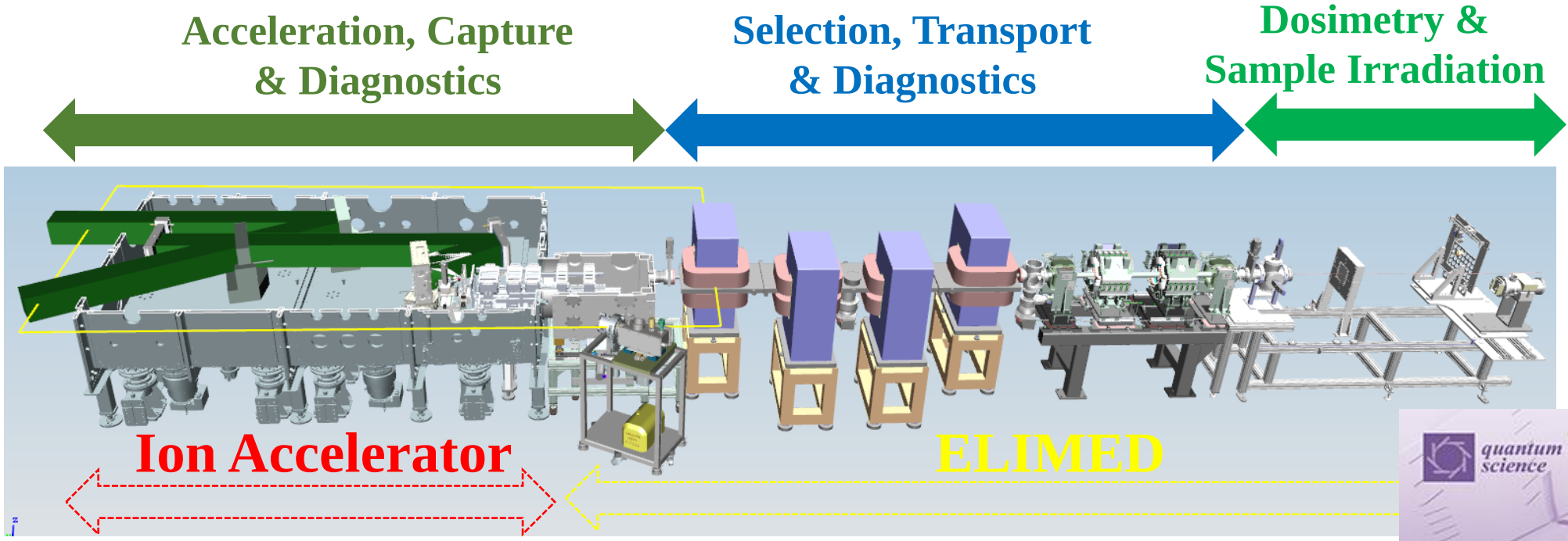






The ELIMAIA-ELIMED User Beamline

ELI Multidisciplinary Applications of laser-Ion Acceleration



*D. Margarone et al., "**ELIMAIA: A Laser-Driven Ion Accelerator for Multidisciplinary Applications**", Quantum Beam Science 2 (2018) 8*

*G.A.P. Cirrone et al., "**ELIMED-ELIMAIA: The First Open User Irradiation Beamline for Laser-Plasma-Accelerated Ion Beams**", Frontiers in Physics 8 (2020) 564907*

*F. Schillaci et al., "**The ELIMAIA Laser-Plasma Ion Accelerator: Technology Commissioning and Perspectives**", submitted to QuBS, Laser-Driven Irradiation Facility special issue*

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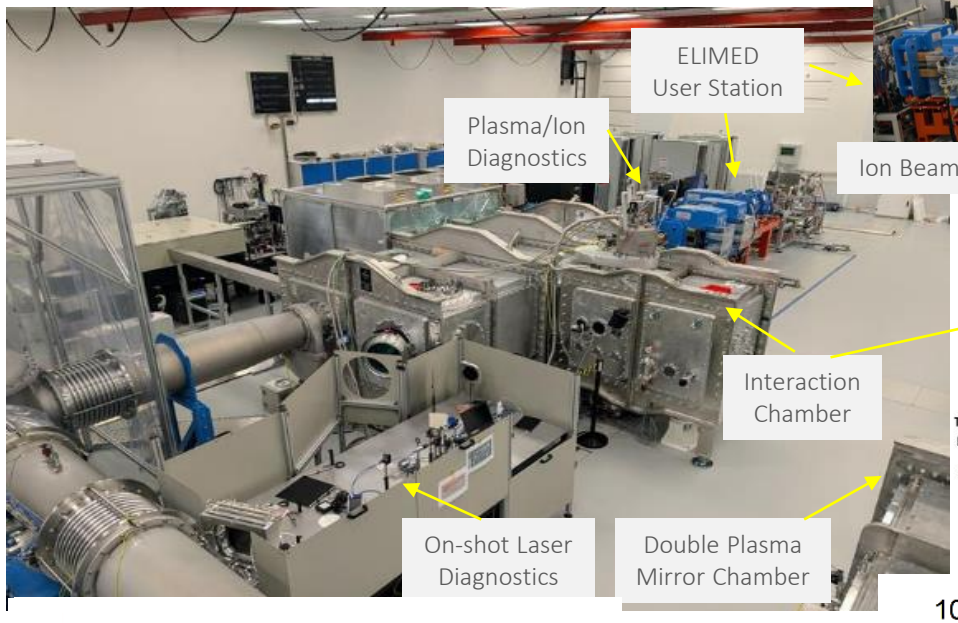
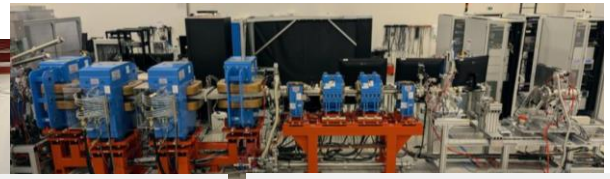
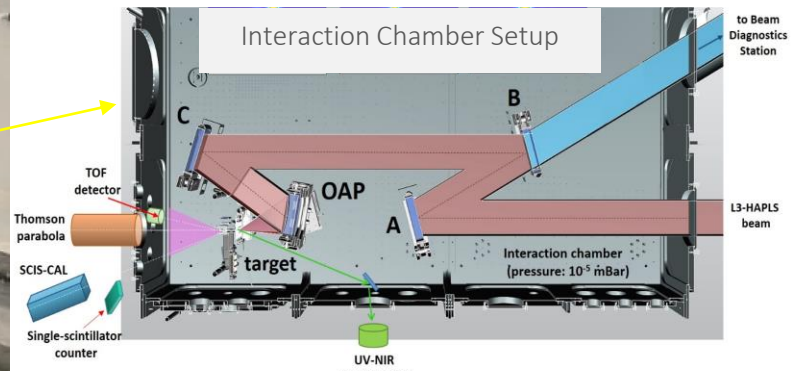
ELIMAIA-ELIMED Laser-Plasma Ion Accelerator (E4)

L. Giuffrida, F. Schillaci et al.

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

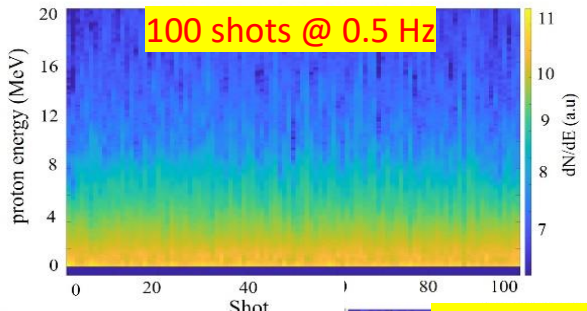


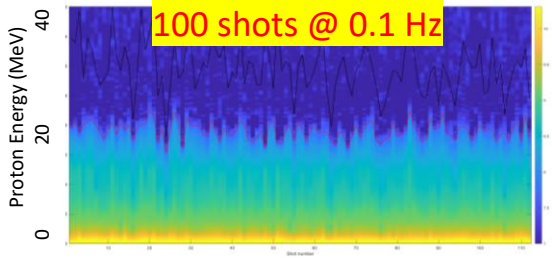


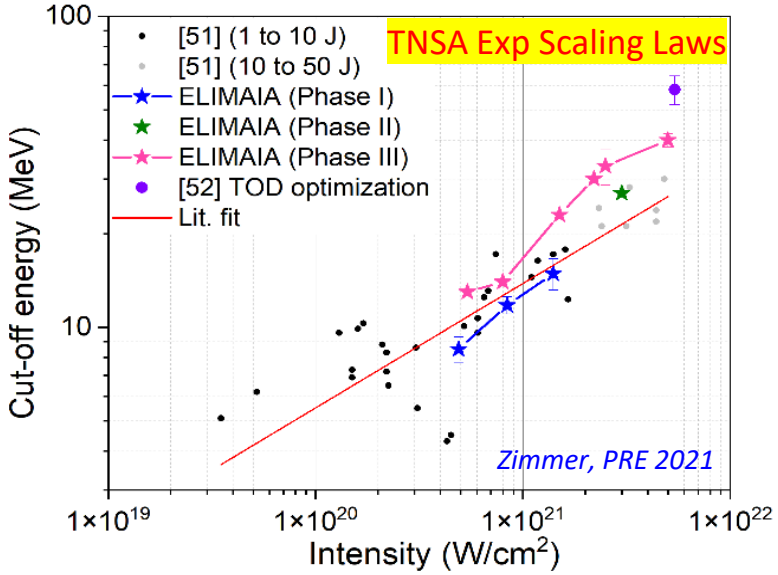


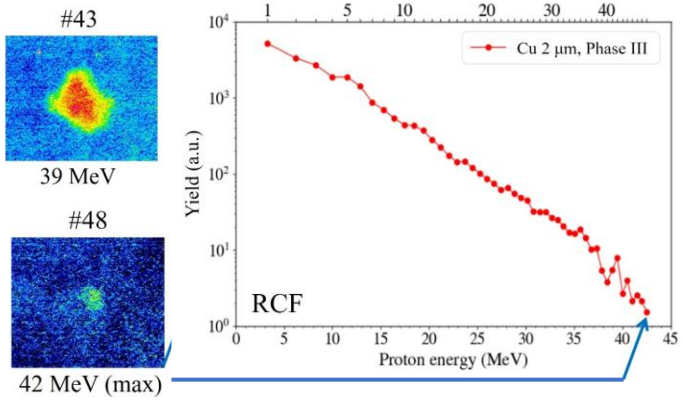
L3 - Ion Accelerator	Available	Design
Laser intensity	$5{\cdot}10^{21}$ W/cm^2	10^{22} W/cm^2
Laser energy	~10 J	30 J
Laser pulse width	<30 fs	<30 fs
Repetition rate	~1 Hz	10 Hz
Proton energy cutoff	~40 MeV	100 MeV
Proton flux (>3 MeV)	~10^{11}/sr	>10^{11}/sr

ELIMED station	Available	Design (@usample)
Ion energy	5-30 MeV/nucl	5-60 MeV/nucl
Bandwidth	~10%	<10%
Ions/shot	10^9-10^{10}/sr	10^9-10^{10}/sr
Duration	~10ns (~10^7Gy/s)	1-10ns (~10^9Gy/s)
Divergence	1deg	1deg
Spot size	0.1-10mm	0.1-10mm
Rep rate	~1Hz	10Hz





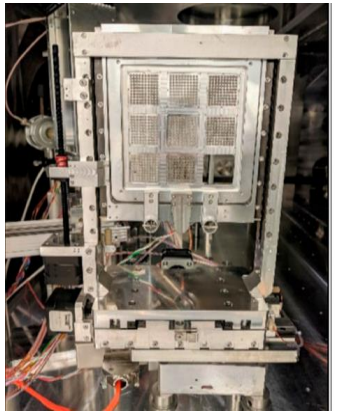


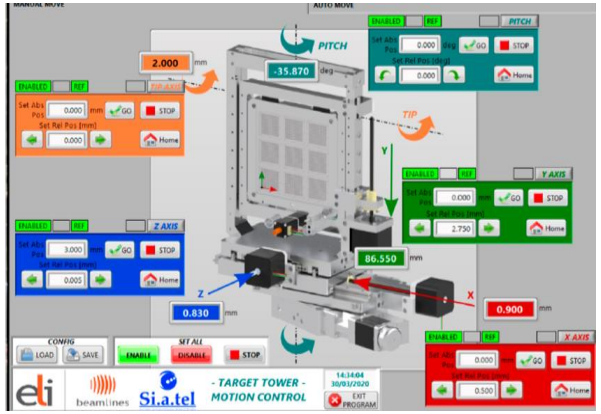


High rep rate targetry for L3 driven experiments (1-10 Hz)

tape, cryogenic, liquid target delivery systems

*Raster target for thin foils (**~1 Hz**)*



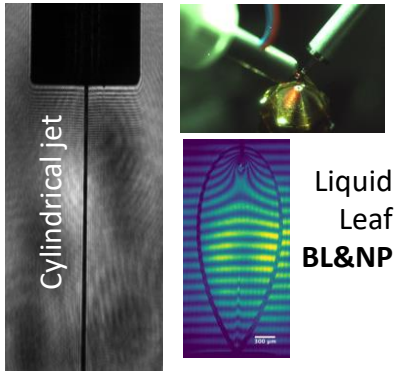


Article

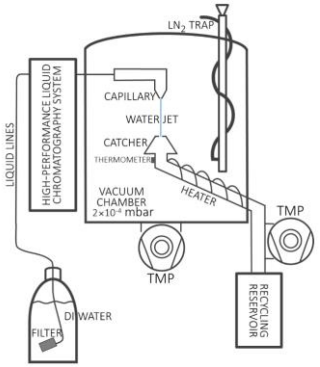
Automation of Target Delivery and Diagnostic Systems for High Repetition Rate Laser-Plasma Acceleration

Timofej Chagovets [1,*], Stanislav Stanček [1], Lorenzo Giuffrida [1], Andriy Velyhan [1], Maksym Tryus [1], Filip Grepl [1,2], Valeriia Istokskaia [1,2], Vasiliki Kantarelou [1], Tuomas Wiste [1], Juan Carlos Hernandez Martin [1], Francesco Schillaci [1] and Daniele Margarone [1,3]

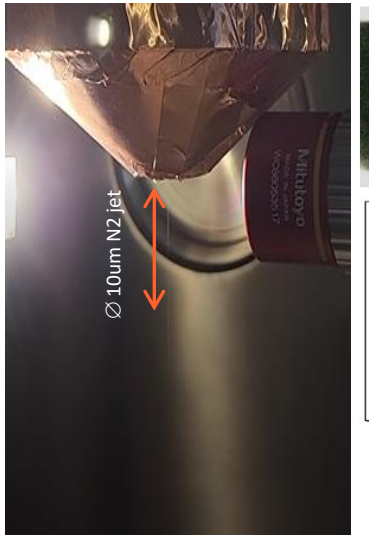
*Liquid jet targets (**10 Hz**)*

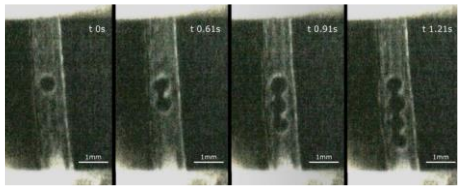


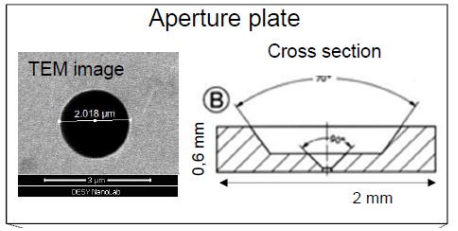
Liquid Leaf **BL&NP**

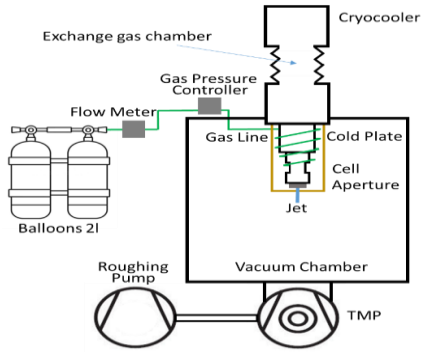


*Debris-free Cryogenic targets (**3-10 Hz**): H2, D2, He, N2, Ar, Xe, Kr*









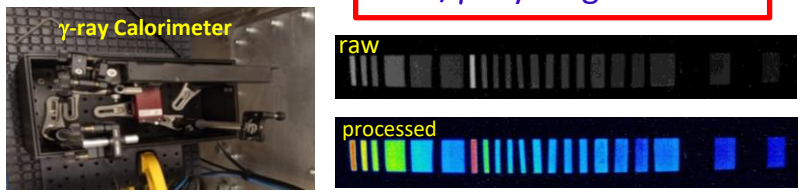
A Cryogenic Hydrogen Ribbon for Laser Driven Proton Acceleration at Hz-Level Repetition Rate

T. Chagovets [1], J. Viswanathan [2], M. Tryus [1], F. Grepl [1,3], A. Velyhan [1], S. Stancek [1,4], L. Giuffrida [1], F. Schillaci [1], J. Cupal [1,3], L. Koubikova [1], D. Garcia [2], J. Manzagol [2], P. Bonnay [2], F. Souris [2], D. Chatain [2], A. Girard [2] and D. Margarone [1,5]*

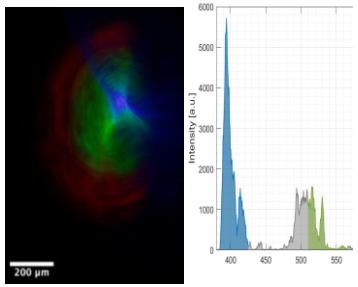
Online L3 laser/plasma/particle/X-ray diagnostics

example of online diagnostics in the E4 exp hall (1-10 Hz)

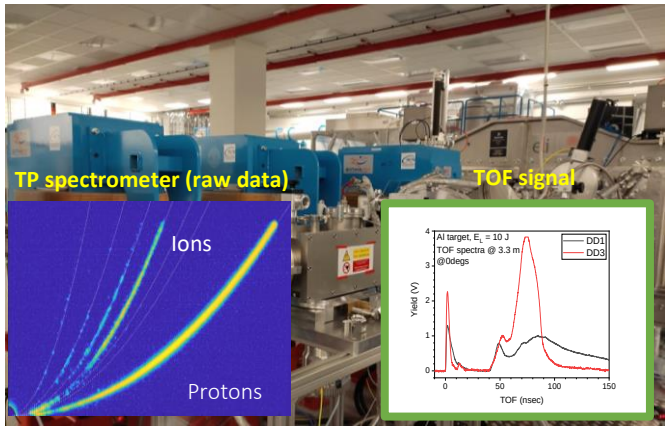
X/γ-ray diagnostics



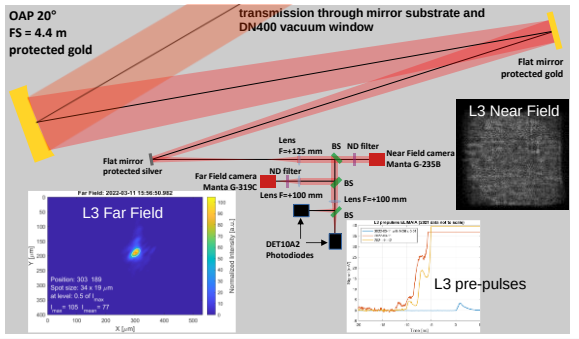
Plasma imaging/ spectroscopy



Particle diagnostics



On-shot laser diagnostics



Online data analysis (1-10 Hz)

- Further **software development** for real-time **data analysis** at high rep rate
- Implementation of **ML/AI algorithms** for secondary source optimisation/data curation

User Science Highlight I

"Optimizing high rep-rate radiography with machine learning" Call-2, L3-ELIMAIA, ELIUPM-156, PI: Hill (LLNL, USA)
"Compact, high-rep dose delivery system employing helical coil targets", S. Kar (QUB, UK)

- Demonstration of **robust diagnosis of laser-accelerated ions and electrons** from solid targets at high intensity in **rep rate**
- **Machine-learning optimization** algorithm to the laser front-end
- Repeatedly demonstration of **optimization of ion yield** above the nominal baseline performances

Harnessing Machine Learning for Breakthroughs with High-Power Lasers

A team of international scientists from Lawrence Livermore National Laboratory (LLNL), Fraunhofer Institute for Laser Technology ILT, and ELI collaborated on an experiment to optimise high-intensity high- ion yield above the nominal baseline performance. The experiment utilised the state-of-the-art High-Repetition-Rate Advanced Petawatt Laser System (L3-HAPLS) to generate protons in the ELIMAIA Laser-Plasma Ion

Lawrence Livermore National Laboratory

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

QUEEN'S UNIVERSITY BELFAST

- Hot electrons expelled from target
- Target strongly positively charged
- Return current and **giant EMP** propagating to ground
- **Helical coils** attached to target harness EMP to **focus and post-accelerate protons**
- Proton beam energy: **>46MeV** (only with 10J)
- Proton beam divergence: **<1deg**
- Proton dose **>10Gy/pulse @32MeV**
- ~0.5 rep rate tested (tape target and detached coil)

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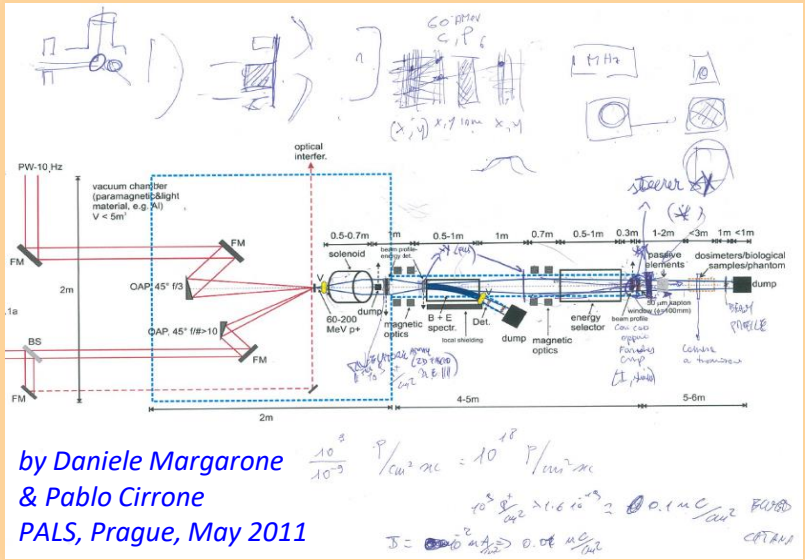
ELIMAIA-ELIMED first concept and prototype

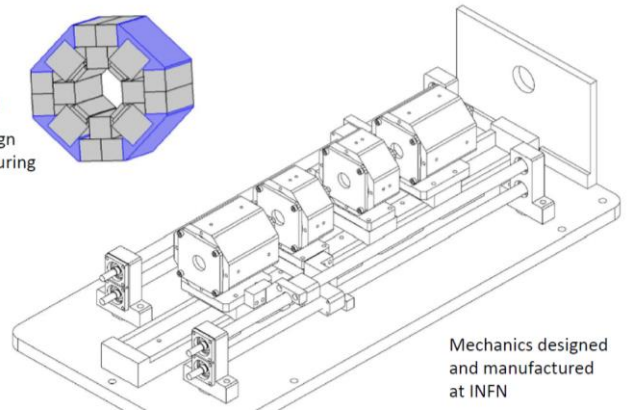
since May 2011…



by Daniele Margarone & Pablo Cirrone
PALS, Prague, May 2011

ELIMED V0
The injection system

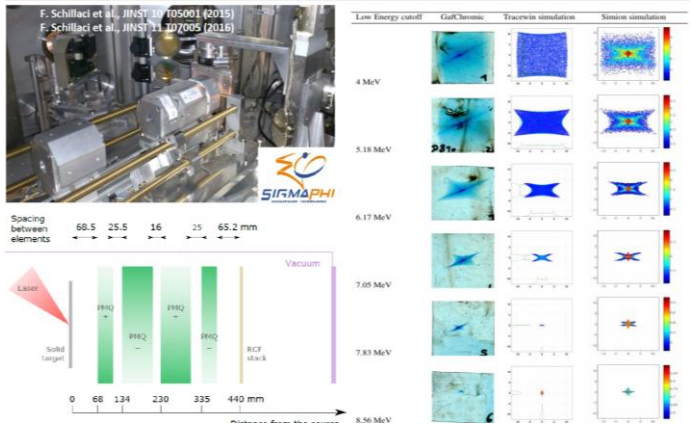
Magnetic design and manufacturing



Mechanics designed and manufactured at INFN

designed, assemblied, and tested by F. Schillaci et al.

Beam Transport Test @ LOA (Fr)

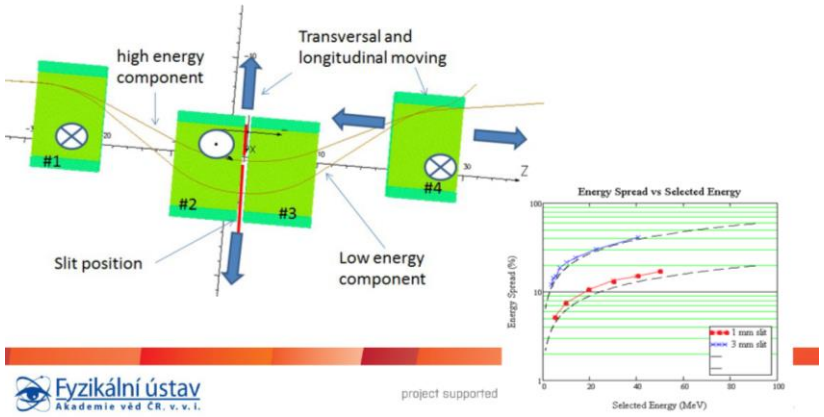


ELIMED V0
The energy selector

Beam handling and transport solutions

M. Maggiore, G. A. P. Cirrone, M. Carpinelli, G. Cuttone, F. Romano, F. Schillaci, V. Scuderi, and A. Tramontana

Citation: AIP Conference Proceedings **1546**, 34 (2013); doi: 10.1063/1.4816603

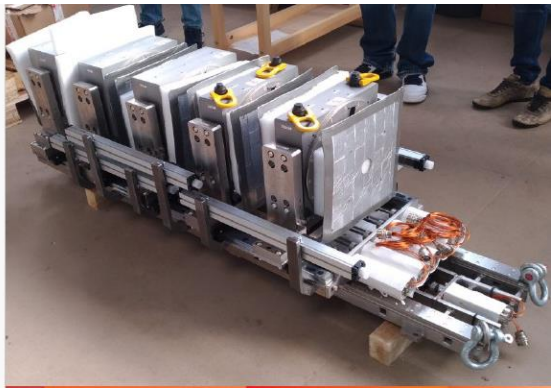


Fyzikální ústav Akademie věd ČR, v. v. i.

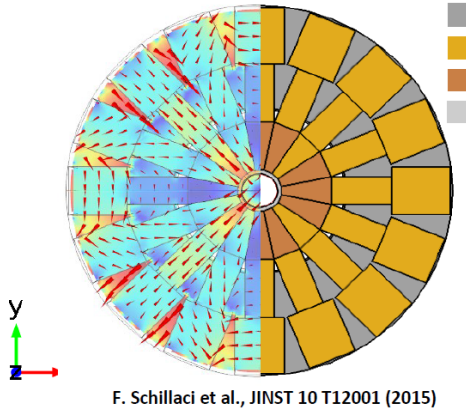
project supported

ELIMED beam transport elements I

permanent quadrupoles (PMQs) for ion beam "capture" (injection)



Permanent Magnet Quads Preliminary Design

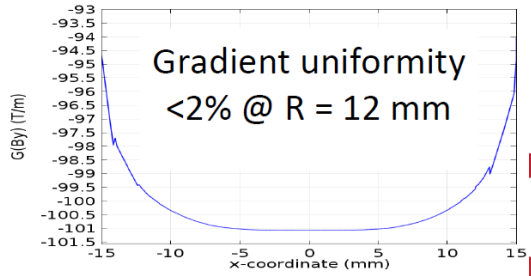


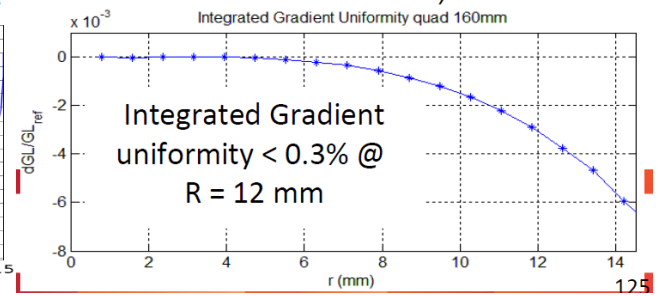
F. Schillaci et al., JINST 10 T12001 (2015)

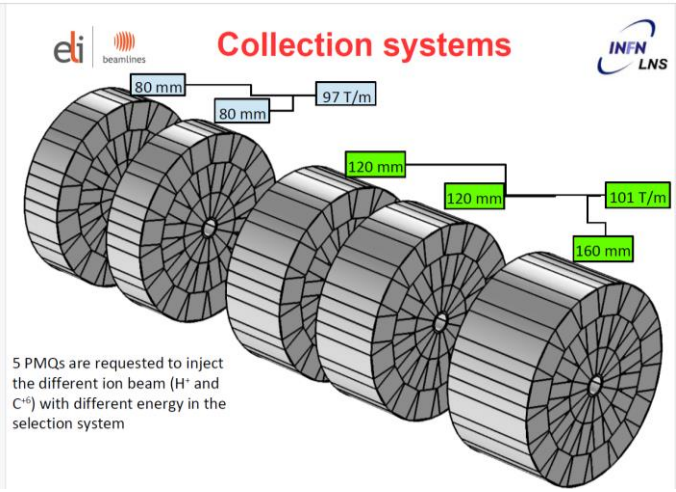
NdFeB N48H	NdFeB N38UH
(Br = 1,39 T	(Br = 1,26 T
Hc= 1273 kA/m)	Hc= 1990 kA/m)

Hybrid multiarray:

- 36 mm magnetic bore
  (3 mm shield + 30 mm for the beam)
- Inner Halbach trapezoidal
  (122 mm outer diameter, two NdFeB alloys)
- 2 external arrays with rectangular blocks
  (223 mm and 322 mm outer diameter)



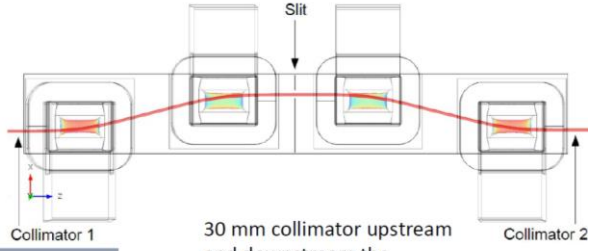


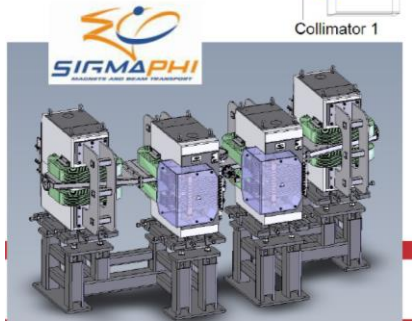


ELIMED beam transport elements II

ion beam energy selection and transport

Double Dispersive Mode Magnetic Chicane





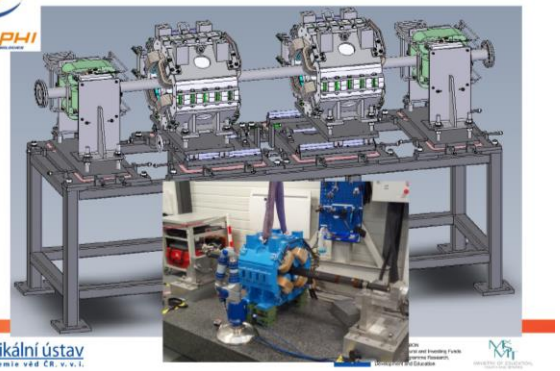
30 mm collimator upstream and downstream the chicane
(200 mm far from dipoles)

Variable slit aperture size (4 up to 20 mm)

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

project supported by:

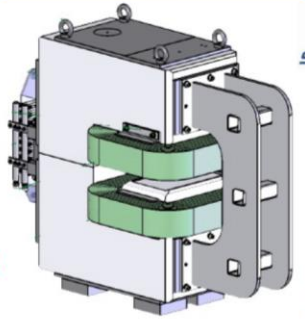
Quads and Steerers



Fyzikální ústav

Energy Selector Features

n° of Dipoles	B field	Geometric length	Effective length	Gap
4	0.06 – 1.226 T	400 mm	450.23 – 448.34 mm	55 mm (shim)
Good Field region (GFR)	**Field uniformity**	**Curvature radius**	**Bending angle**	**Drift between dipoles**
100 mm	0.4 %	2.570 m	10.10°	500 mm



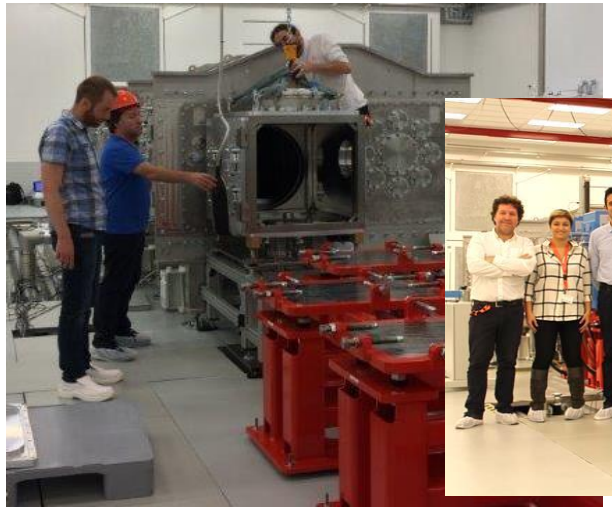
- Magnet efficiency: 97%
- Packing factor: 99% (1 mm lamination)
- 116x116 mm coil section (10x10 turns, 0.4 mm of insulator, 4 mm water channel)
- Max current: 300 A
- Total weight: 2.6 Tons
- < 28 kWatt in total

Reinforcemente to guarantee 42 mm inner clearence in the vacuum chamber

ELIMAIA-ELIMED installations in E4

July 2017



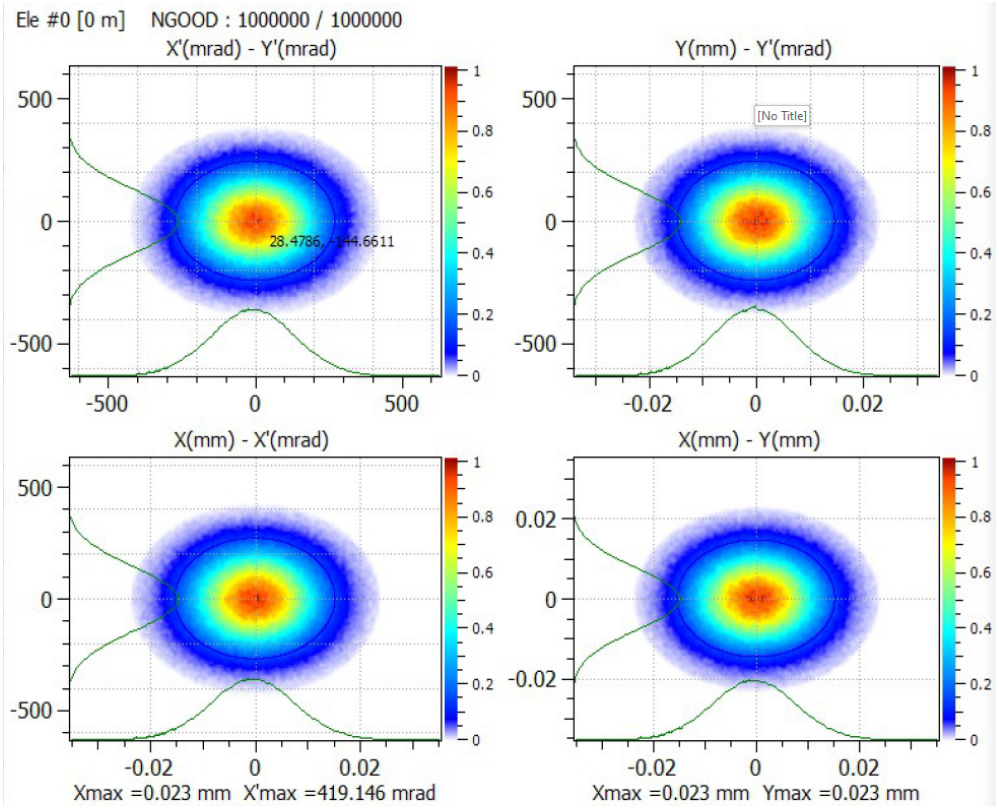



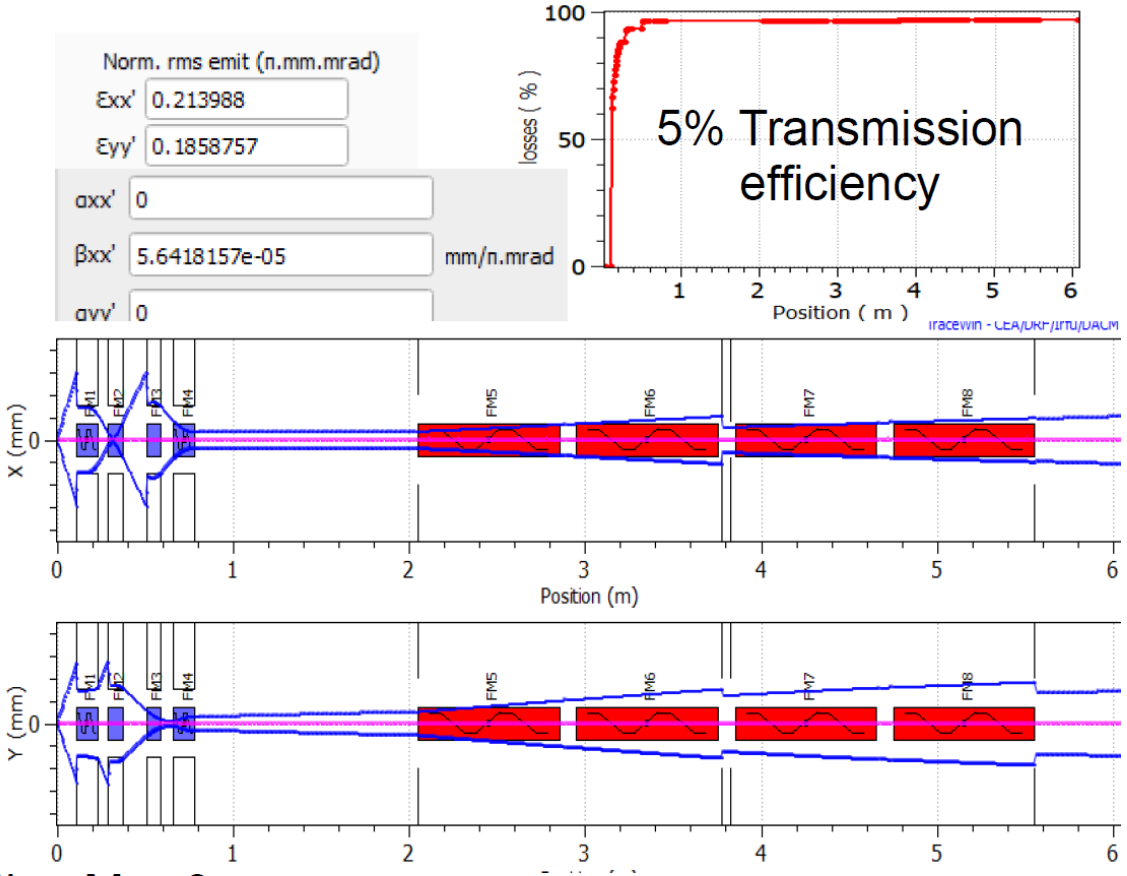




ELIMED technical commissioning I

PMQs setup preparation (20 MeV)

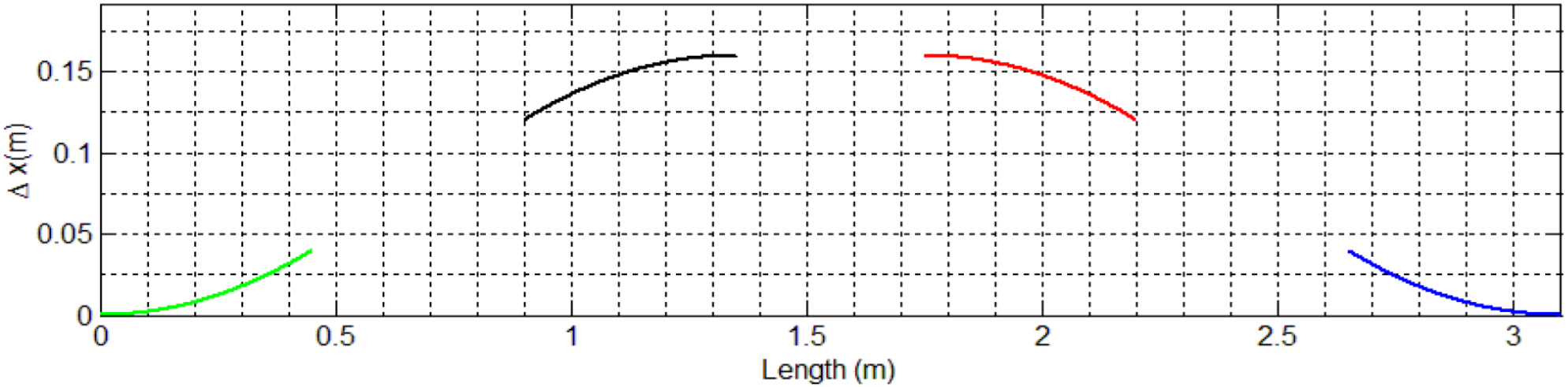


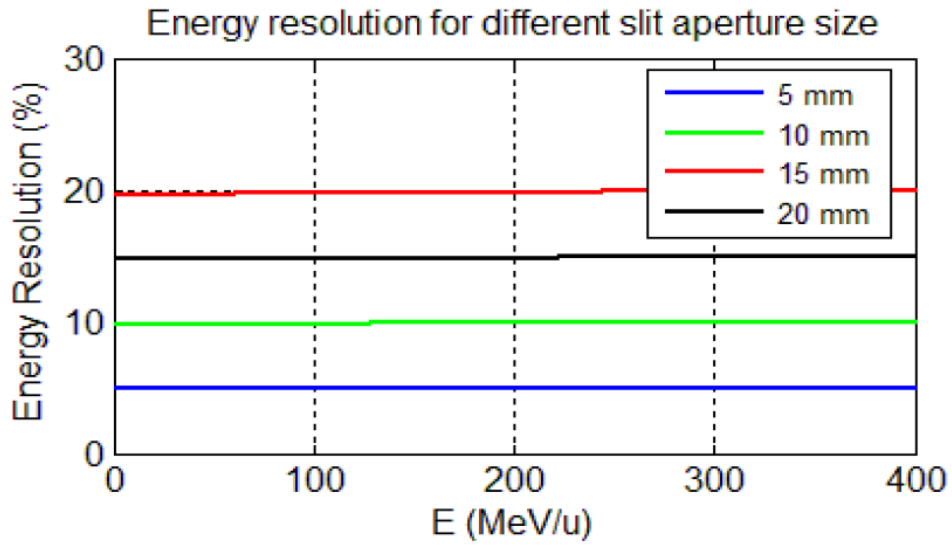


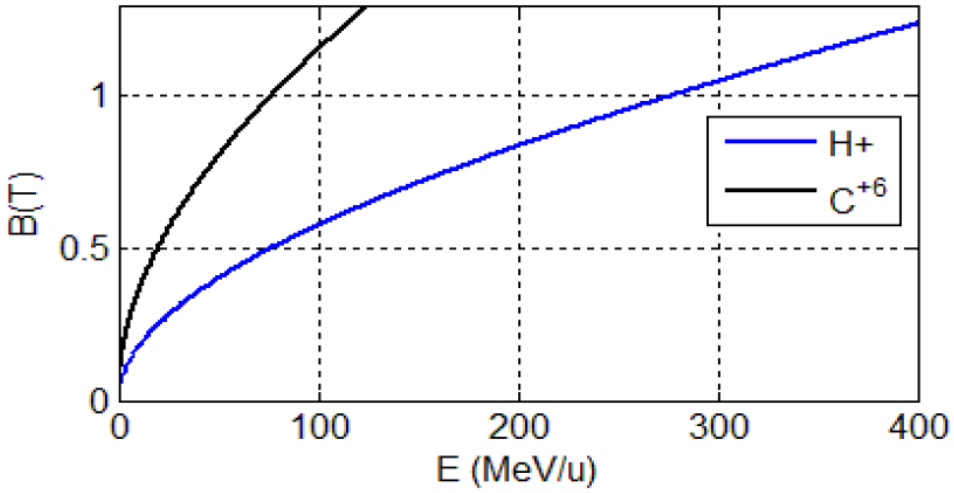
1) Waist close to the slit on the radial direction $M_{12}=0$
2) Parallel beam on the transverse plane $M_{44}=0$
3) Fixed beam dimensions at the selection plane (to fit the slit aperture size)

ELIMED technical commissioning II

ESS setup preparation

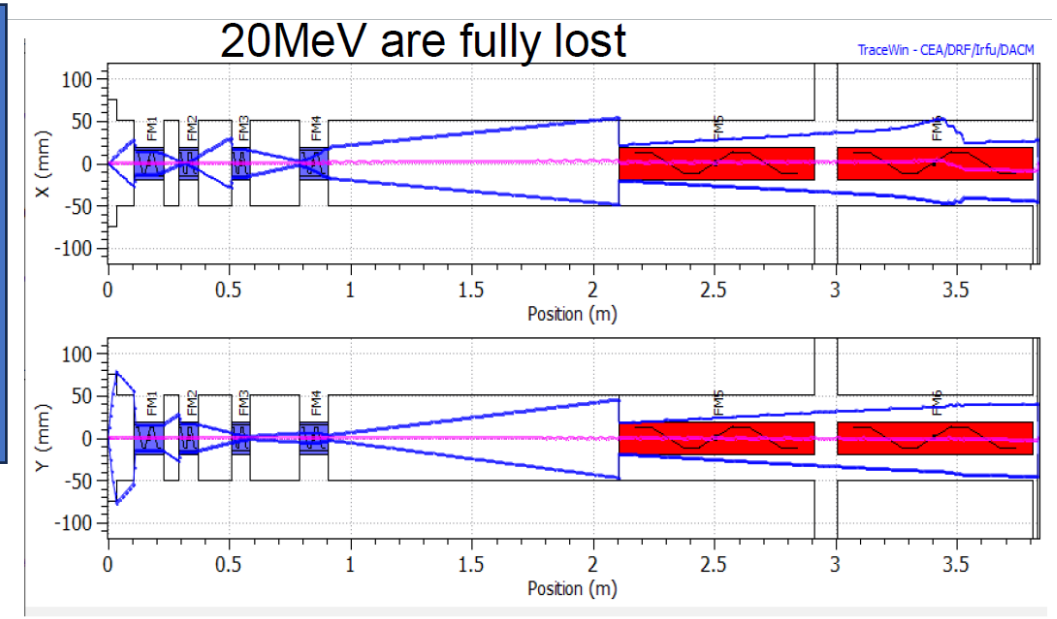


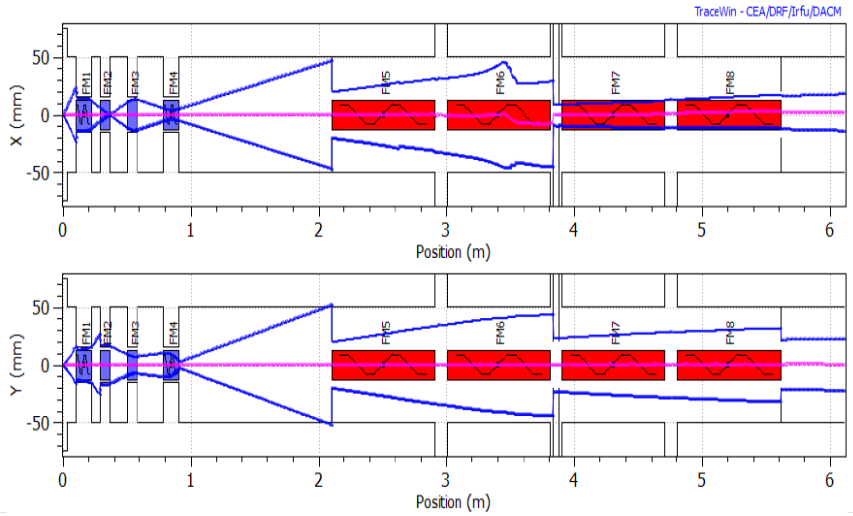




ELIMED technical commissioning III

expectations vs reality!





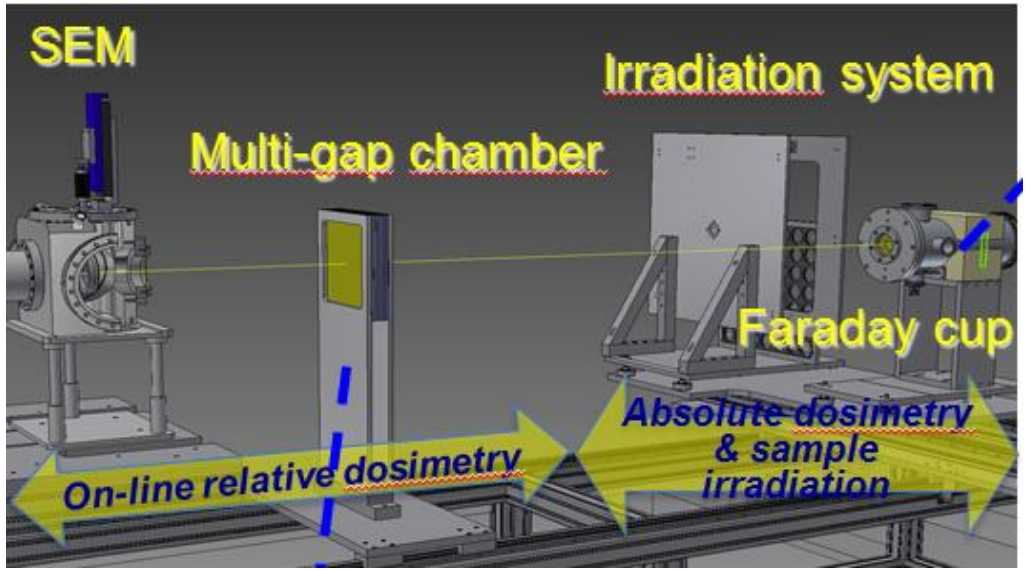
WORK IN PROGRESS!

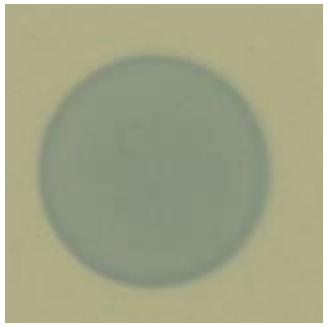
- ✓ Ion transmission: much lower than expected
- ✓ Ion beam directionality at source: different than expected
- ✓ PMQ's tolerance (magnetic axis): ?

ELIMED technical commissioning IV

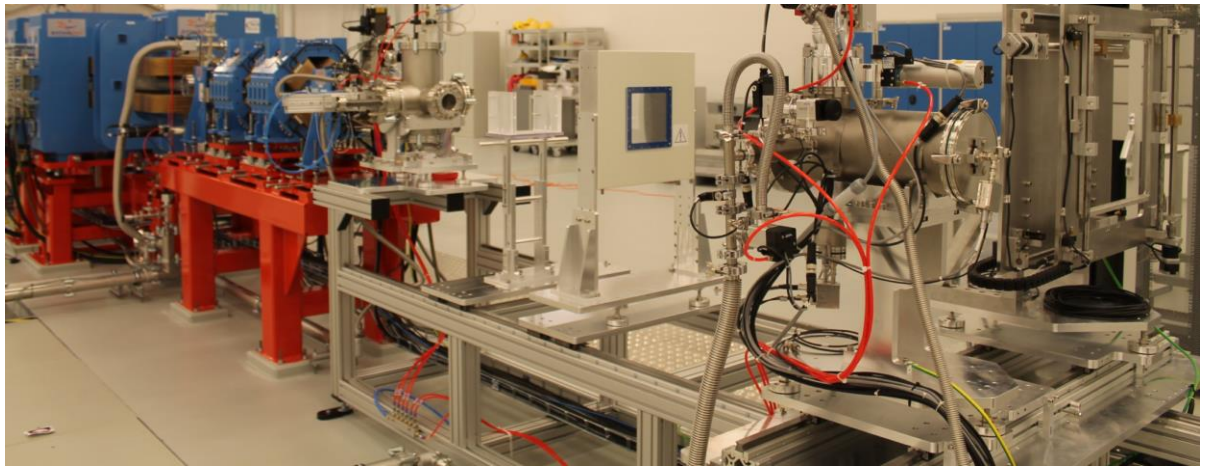
dosimetry setup commissioning

- **Complete ELIMED dosimetric chain** was tested
- Selected proton beams of **25 ± 4 MeV**
- **Absolute** and **relative dosimetry** carried out
- Proton beam spatial profile uniformity of ~5% (over 1cm)
- >10 mGy per shot (0.5 Hz)





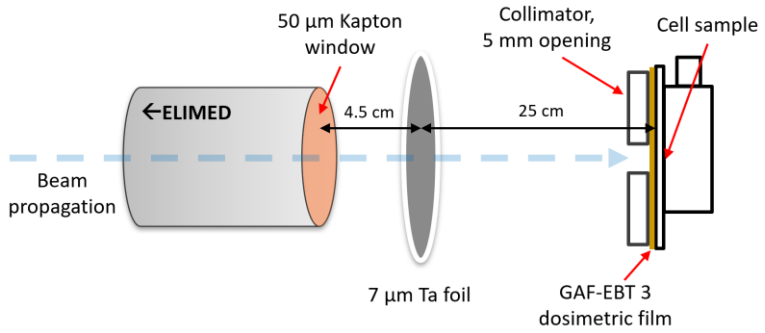
Proton beam homogeneity



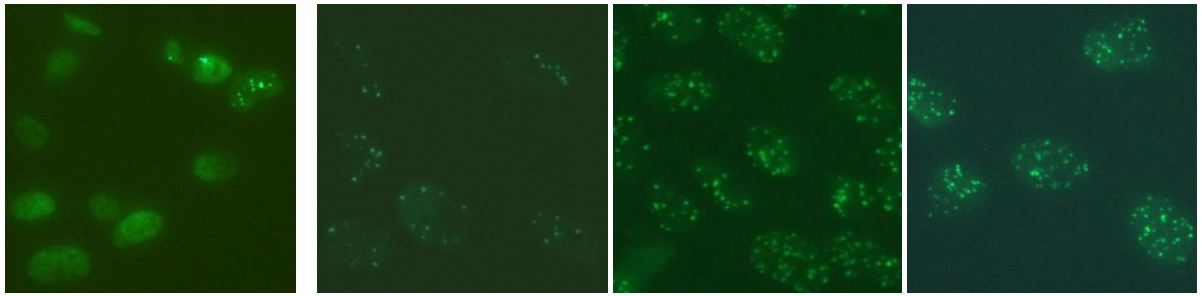
Radiobiology Pilot experiment at ELIMAIA-ELIMED I

in-vitro cell irradiation

QUEEN'S UNIVERSITY BELFAST



- **First** radiobiological campaign with laser accelerated protons (LDP) successfully conducted at ELI Beamlines
  - Multi shot LDP irradiation
  - Normal skin fibroblasts AG01522
  - DNA damage assay
    - DNA Double Strand Breaks – 53BP1 foci

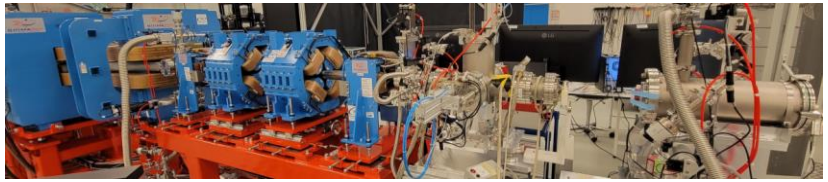


Non-irradiated sample | 0.43 Gy | 1.1 Gy | 1.48 Gy

- Results are in line with single shot LDP irradiation

Hanton F., *Scientific Reports*, 9:4471, 2019

➔ new possibilities for radiobiological research at ELI Beamlines



Radiobiology Pilot experiment at ELIMAIA-ELIMED II

European user consortium around ultra-fast radiobiology

FLAIM: "**FL**ash and ultrahigh dose-rate radiobiology with **L**aser **A**ccelerated **I**ons for **M**edical research

Innovative Radiobiology with Laser-Driven Ion Beams

- PI (external): M. Borghesi, K. Prise (**Queen's Univ. Belfast**); PI (local): L. Giuffrida (**ELI BL**)
- General Goal: showing **feasibility of radiobiology studies for pre-clinical research**
- Specific Objective: study the biological response of human cells to **ultrahigh dose rate proton bursts (fractionated dose)**
- **User Network** (collaborative effort): Queen's Univ. Belfast (UK), INFN-LNS (IT), CNR (IT), Univ. of Naples (IT), Nuclear Physics Institute CAS (CZ), Laboratory of Immunotherapy CAS (CZ), ELI ALPS, ELI-NP
- Means: **ELIMED** experimental station (part of **ELIMAIA** beamline driven by **L3**)
- **First** in-vitro **radiobiology experiment at ELI Beamlines**

5th Joint ELI Call for Users

- **ELI Facilities:**
  - **ELI ALPS,** Szeged, Hungary
  - **ELI Beamlines,** Dolní Břežany, Czech Republic
  - **ELI NP,** Magurele, Romania
- **5h Call period: 25 September - 31 October 2024 (!!!)**
- **Unique scientific opportunities provided by access to a wide range of complementary instruments**
- **Single point of access** (https://up.eli-laser.eu)
- **Access is free** based on a **peer- reviewed** evaluation of **scientific excellence**
- Contact Integrated **ELI User Office** **user-office@eli-laser.eu** or **technical contacts** listed on **User Portal**.