



**60<sup>th</sup> International Winter Meeting  
on Nuclear Physics**

**22 - 26 January 2024  
Bormio, Italy**



High power lasers for basic  
science and applications:  
the perspectives of the I-LUCE  
Italian facility

*Pablo Cirrone - INFN*

*Bormio (I), January 22-26, 2024*

# Outline

2

High power lasers and particle acceleration

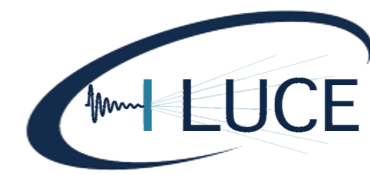
I will better **focus on proton** beams

The upcoming INFN I-LUCE **high-power laser facility** with some example of future perspectives



Lasers and particle  
acceleration?

# The main ingredients for radiation productions



4

## A laser

High power (TW - PW)

Short pulse duration (ps - fs)

Intensity  $> 10^{16}$  W/cm<sup>2</sup>

## A Target:

Thin/thick solid/liquid/gaseous

...

## Other useful things

High contrast laser

High quality target fabrication

High quality wave front-end

.....

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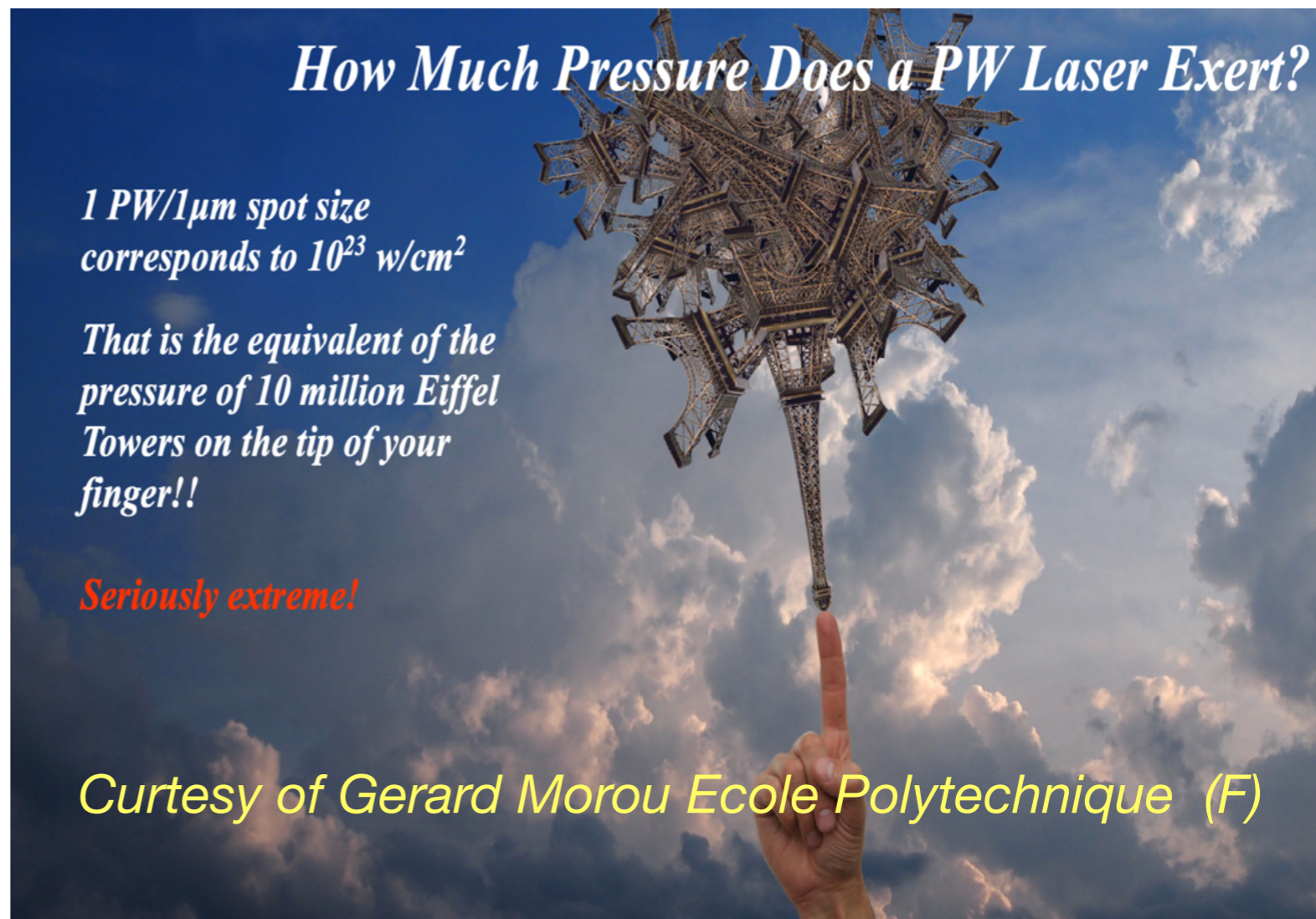
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.....



*How Much Pressure Does a PW Laser Exert?*

*1 PW/1 $\mu$ m spot size corresponds to  $10^{23}$  w/cm<sup>2</sup>*

*That is the equivalent of the pressure of 10 million Eiffel Towers on the tip of your finger!!*

*Seriously extreme!*

*Curtesy of Gerard Morou Ecole Polytechnique (F)*

# The main ingredients for radiation productions

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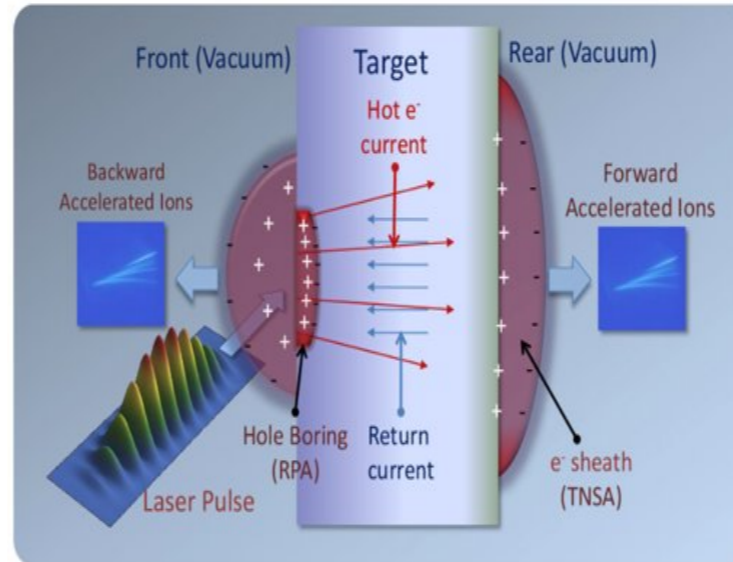
## A Target:

thin/thick solid/liquid/gassous ...

## Other useful things

- High contrast laser
- High quality target fabrication
- High quality wave front-end
- .... [ many other laser and target parameters]

## Laser-solid target interaction for protons, ions acceleration



- Multi species production: g, e<sup>-</sup>, p, ions

- E<sub>max</sub> ~ 10 TV/m
- Short distance (~μm)

### Proton characteristics

- High energy: up to ~ 100 MeV
- Pulse duration ≈ 10s fs - 100s ps
- ppb ≈ 10<sup>8</sup>-10<sup>11</sup>
- Broad energy spectra (100%)
- Wide angular divergence (≈ 10°-20°)

## Laser-driven ion acceleration from plastic target

2D particle-in-cell simulation of the interaction of high-intensity laser pulse (parameters are relevant to L3 laser and thus ELIMIAA beamline) with a micrometer-thick flat plastic target. Acceleration of both protons (pink color) and carbon ions (green color), to maximum energy 150 MeV/nucleon and 40 MeV/nucleon, respectively, can be clearly distinguished in the visualization as well as different ion acceleration mechanisms (from the target front side and from its rear side). Such high-energy protons and ions have a great importance for various foreseen applications in Physics, Biology, Medicine, Chemistry, Materials Science, Engineering, and Archaeology.

Time: 2 [fs]

carbon energy [MeV/nucleon] 0.01 0.1 1 10 proton energy [MeV/nucleon] 0.1 1 10 100 ax [] 0.5 1 2 5 ay [] -100 0 100

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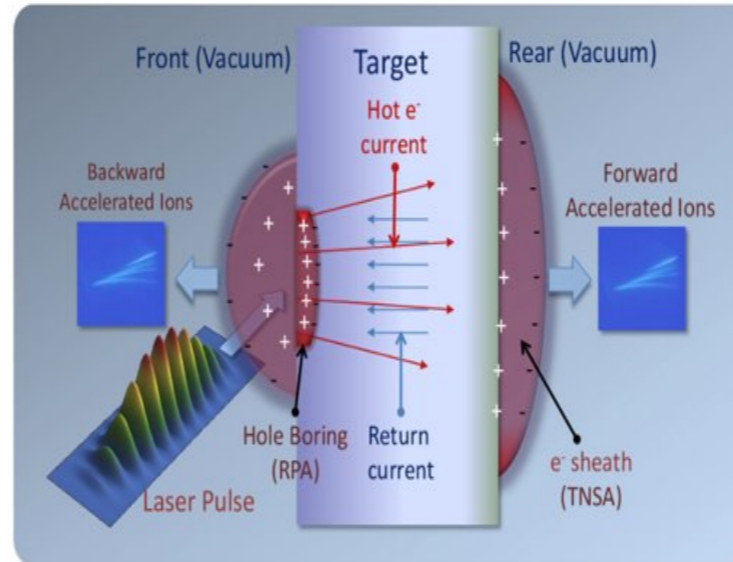
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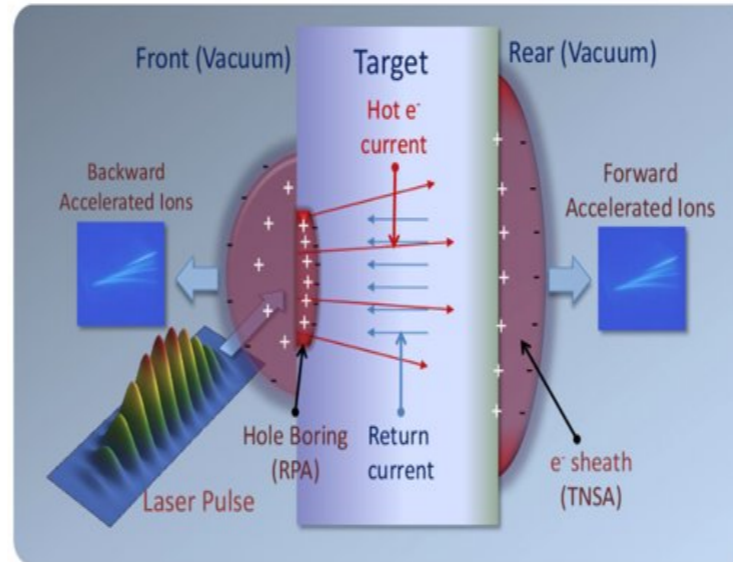
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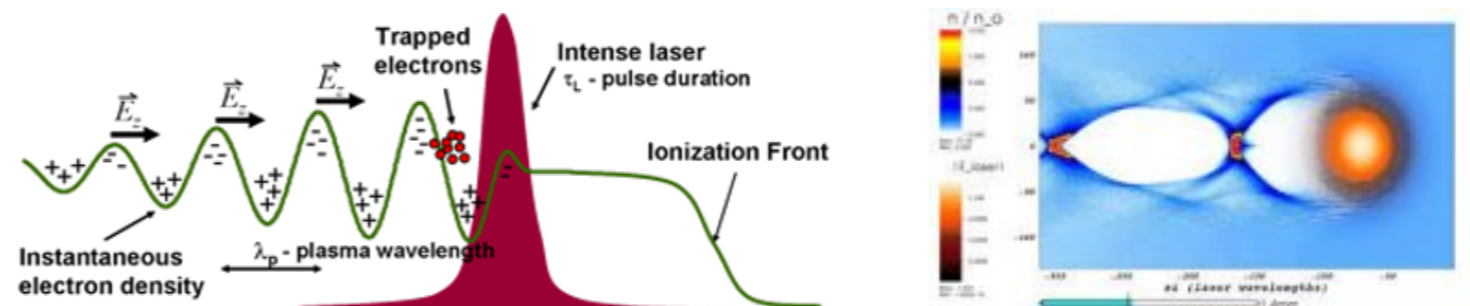


- Multi species production:  $\gamma$ ,  $e^-$ ,  $p$ , ions
- $E_{max} \sim 10 \text{ TV/m}$
- Short distance ( $\sim \mu\text{m}$ )

### Proton characteristics

- High energy: up to  $\sim 100 \text{ MeV}$
- Pulse duration  $\approx 10\text{s fs} - 100\text{s ps}$
- ppb  $\approx 10^8 - 10^{11}$
- Broad energy spectra (100%)
- Wide angular divergence ( $\approx 10^\circ - 20^\circ$ )

## Laser Wake Field Acceleration (LWFA) for electrons



7.8 GeV have been reached at the BELLA (Berkeley Lab) in 2019 using two lasers



# Laser plasma ion-acceleration

current facilities

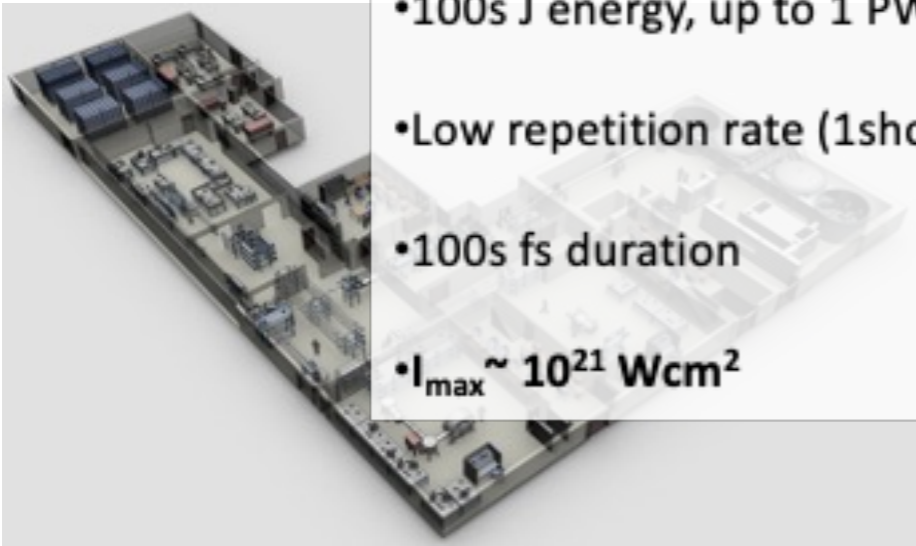


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6

## High energy CPA systems

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



$I_{\max} \sim 10^{21} \text{ W/cm}^2$



VULCAN, RAL (UK)  
Phelix, GSI (De)  
Texas PW (US)

...  
ATON-L4 (ELI Beamlines)  
**10 PW (1.5kJ/150fs)**

$E_{\max} \sim 100 \text{ MeV}$

# Laser plasma ion-acceleration

current facilities

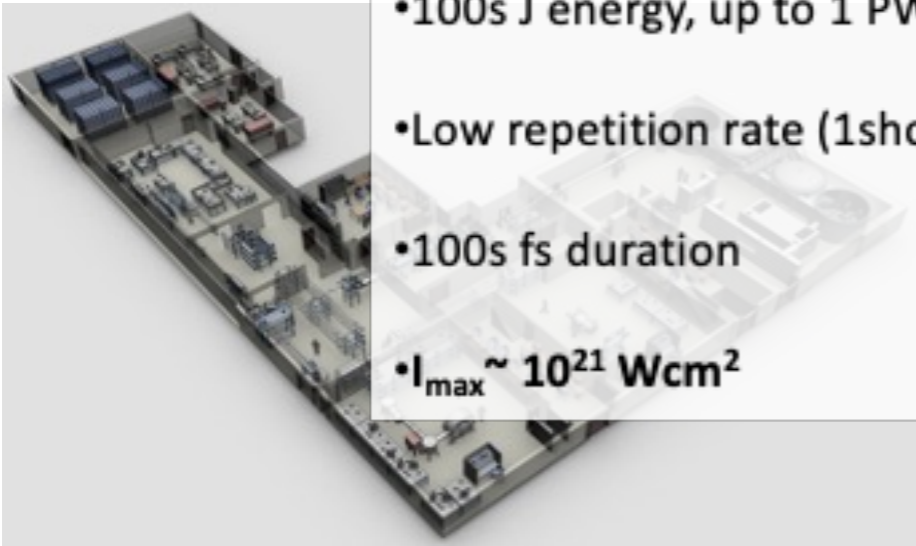


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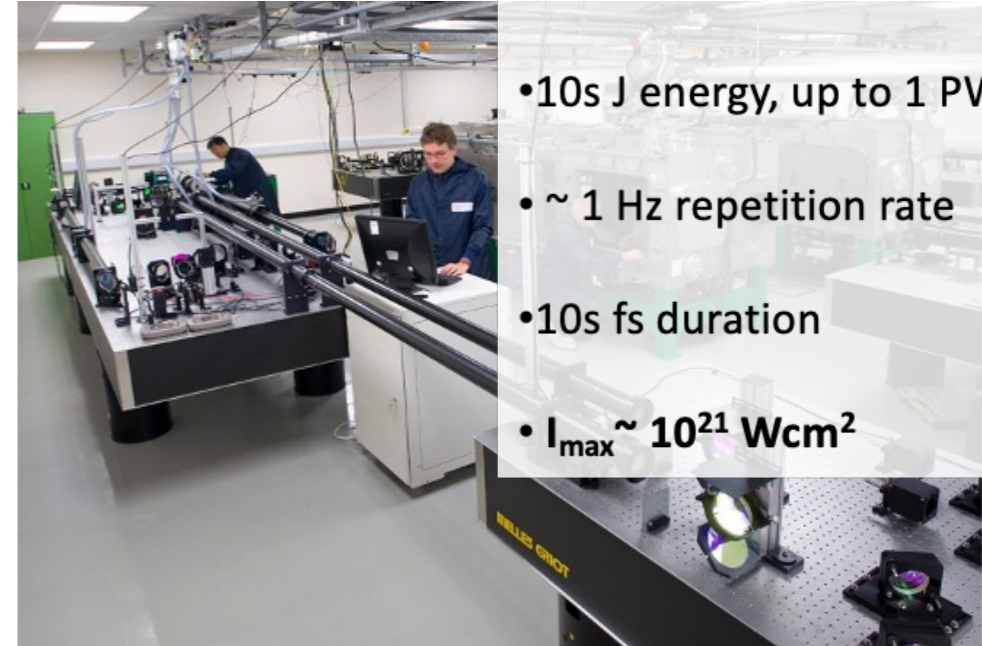
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## Ultrashort CPA systems

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



$I_{\max} \sim 10^{21} \text{ W/cm}^2$

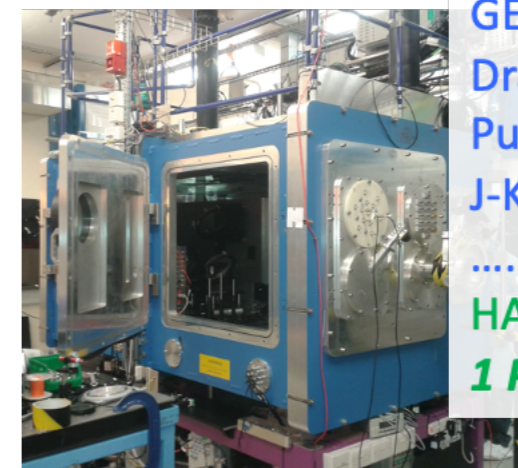


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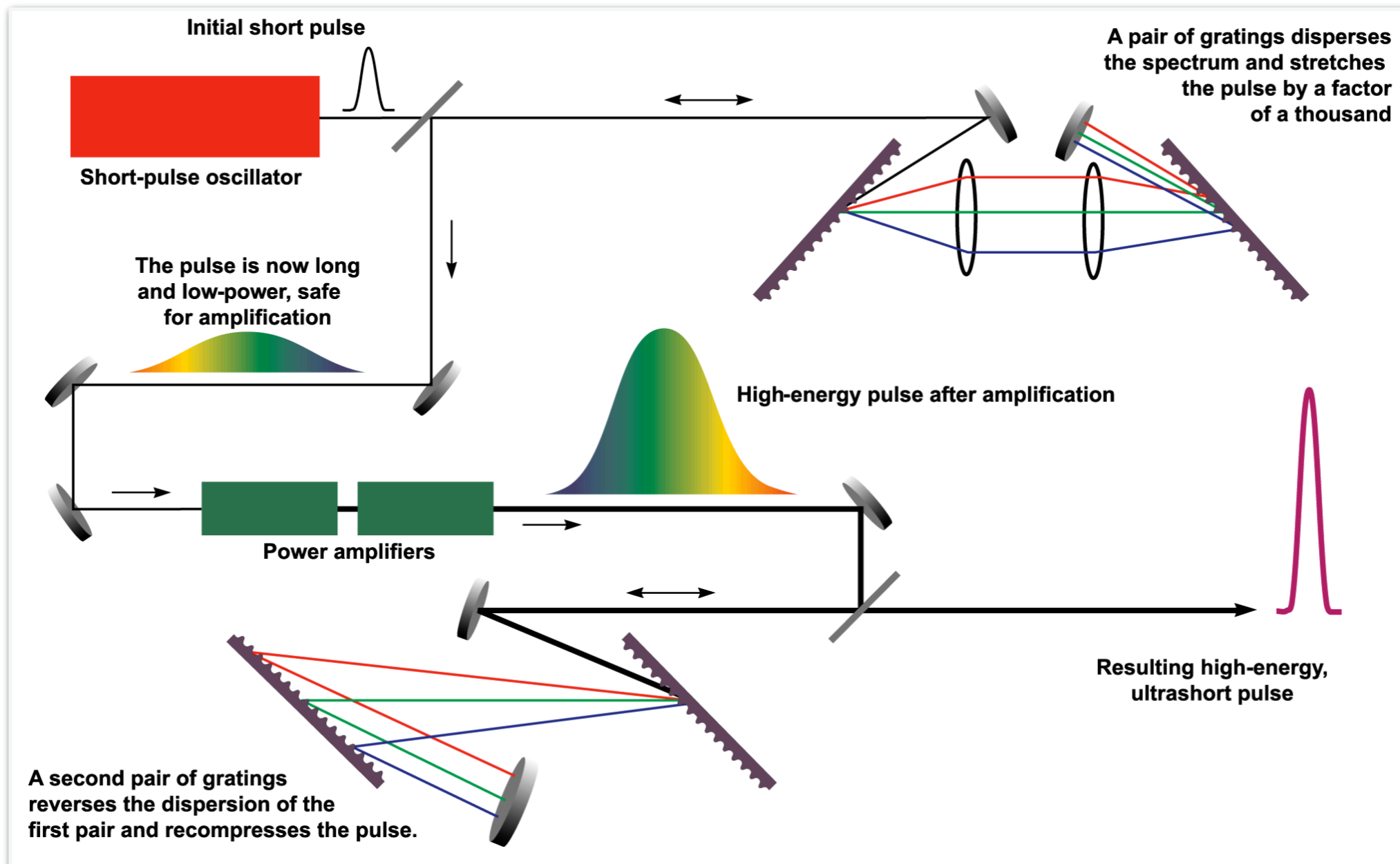
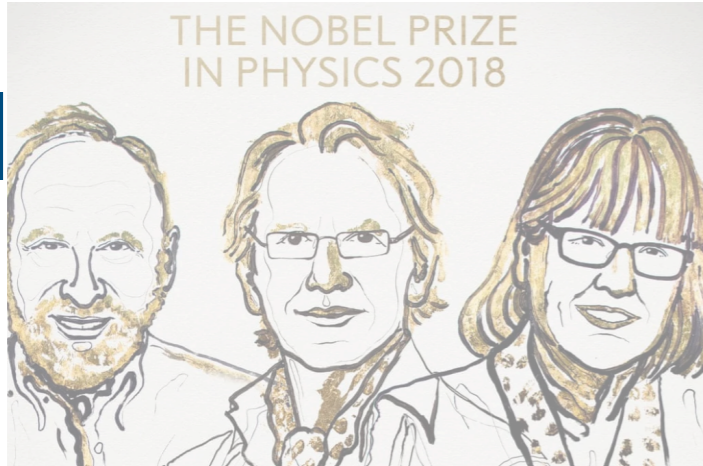
GEMINI, RAL (UK)  
Draco, HZDR (De)  
Pulser I, APRI (Kr)  
J-Karen, JAEA (J)

....  
HAPLS-L3, (ELI Beamlines)  
**1 PW (30J/30fs/10Hz)**

$E_{\max} \sim 70-110 \text{ MeV}$

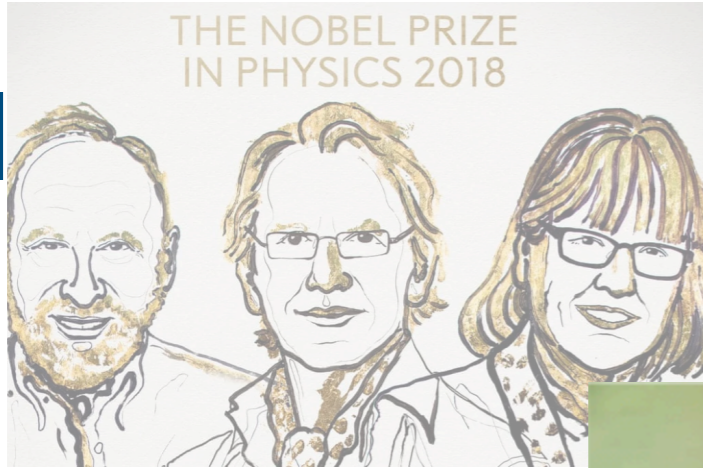
# The basic ingredients: an high-power, short-pulse laser

7



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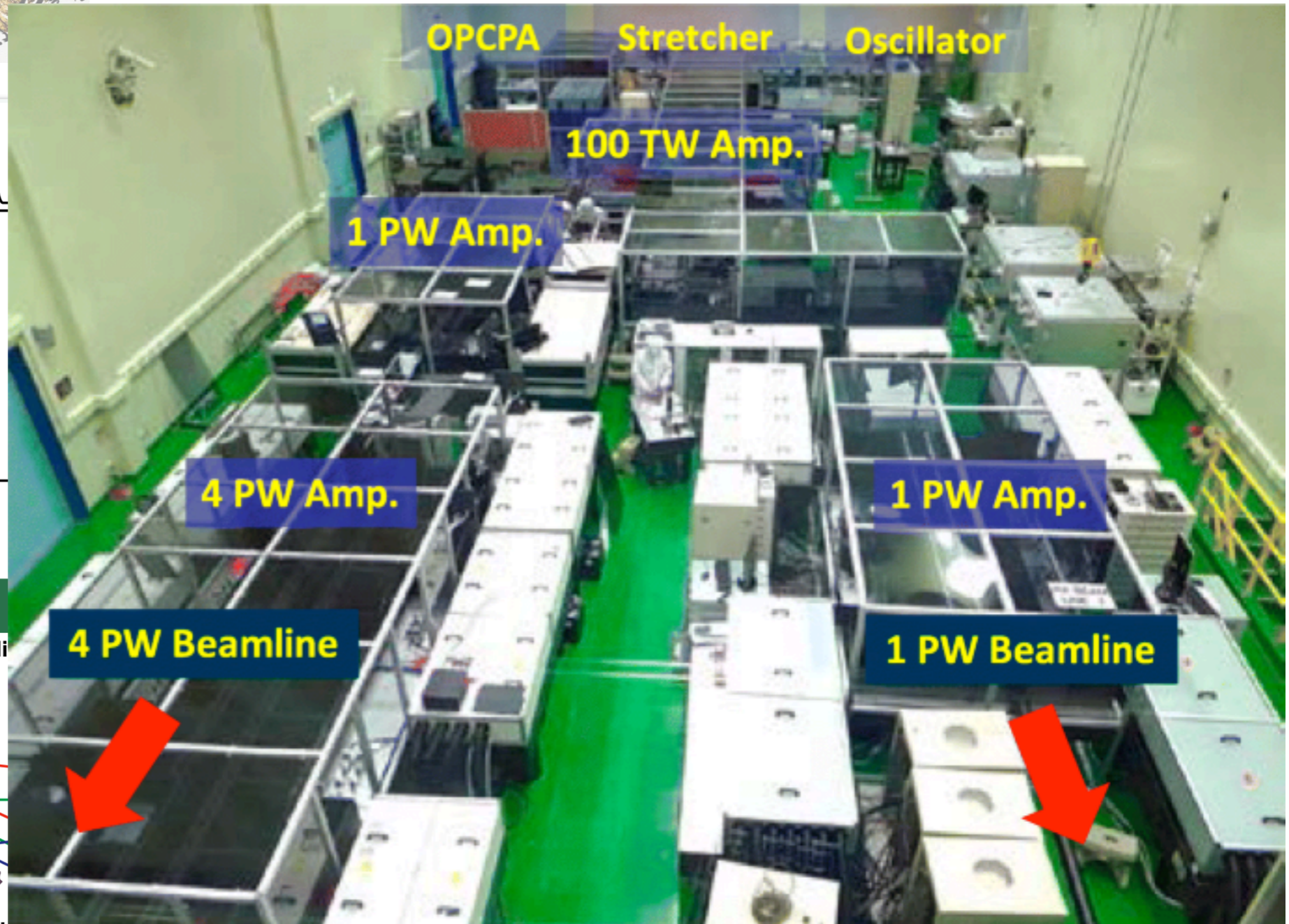
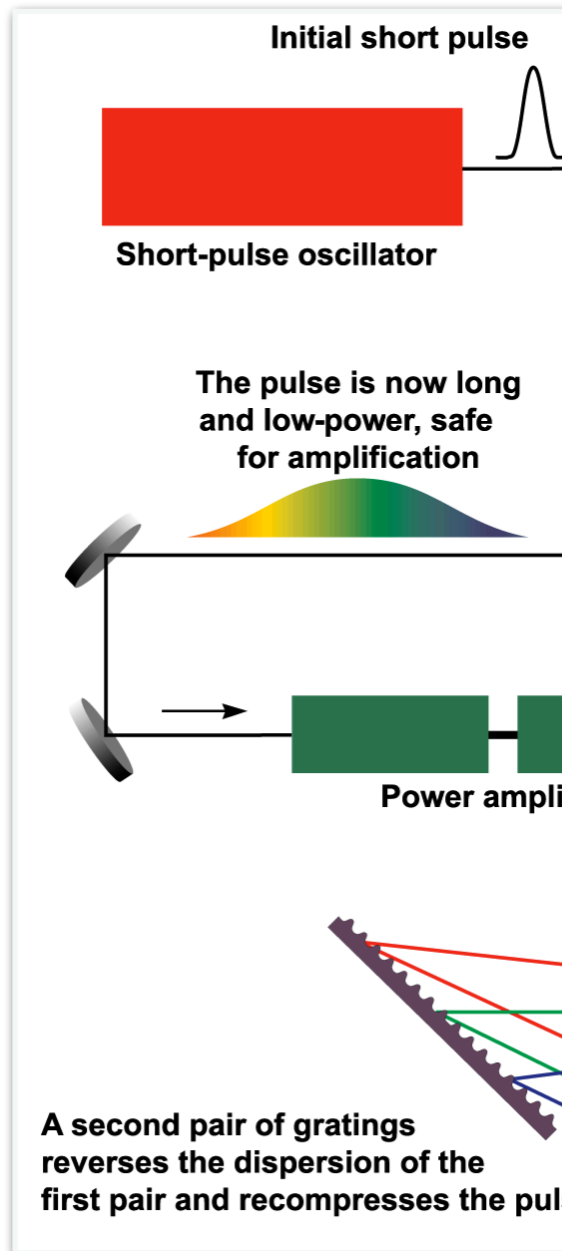
7



## Center for Relativistic Laser Science

Explore the interaction between ultra-intense light and matter

South Korea



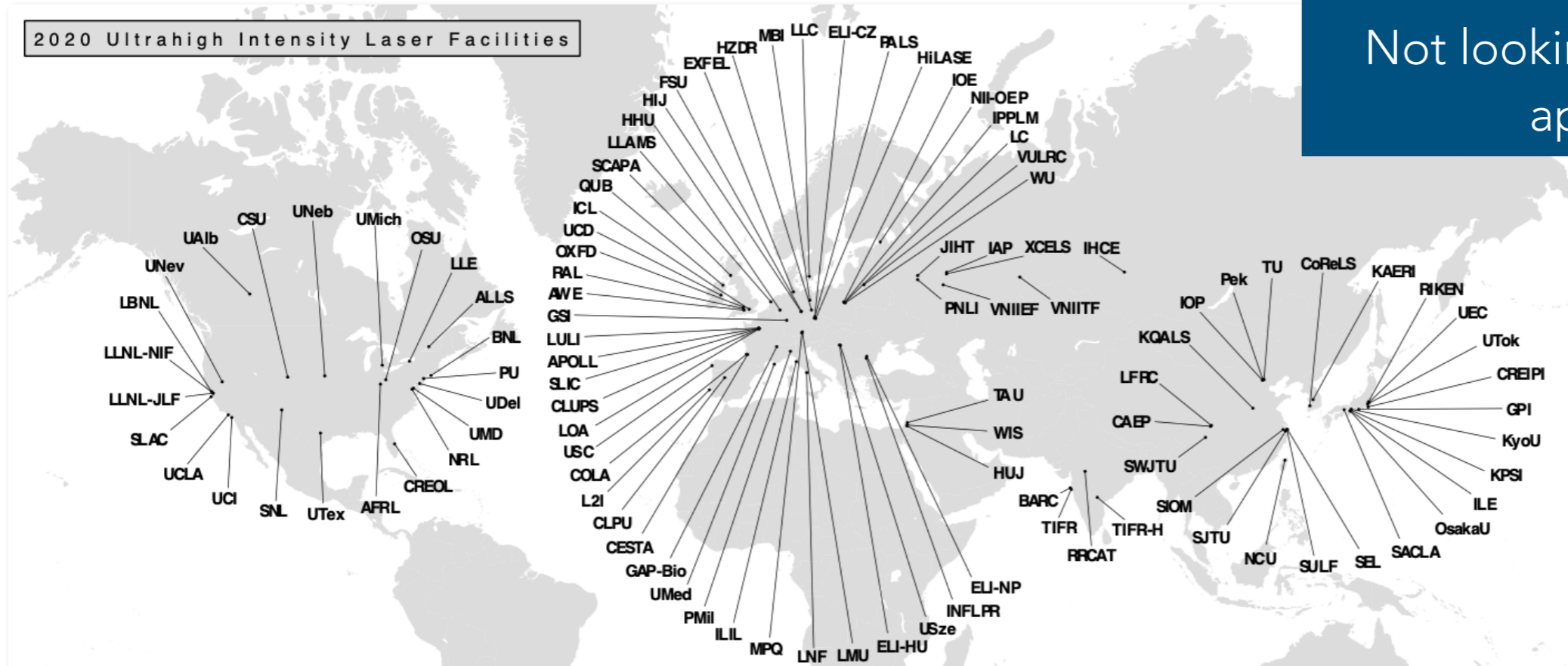
# 2020 world lasers facilities



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102 facilities (approx > 1TW)  
Not looking to the specific application

2020 Ultrahigh Intensity Laser Facilities



International Committee on Ultrahigh Intensity Lasers  
www.icuil.org

AFRL	Air Force Research Laboratory	Dayton	FSU	Friedrich Schiller University of Jena	Jena	KyU	Kyoto University, Institute for Chemical Research	Kyoto	ILS	Prague Asterix Laser System Research Centre	Prague	TU	Tsinghua University	Beijing
ALLS	Advanced Laser Light Source	Varennas	GAP-Bio	Université de Genève, GAP-Biophotonics	Geneve	L2I	Laboratory for Intense Lasers (L2I)	Libon	Pek	Peking University	Peking	UKA	University of Alberta	Edmonton
APOLL	APOLLON at Université Paris Saclay	Saclay	GG	Graduate School for the Creation of New Photonics Industries	Darmstadt	BNL	Lawrence Berkeley National Laboratory	Berkeley	PMI	Politecnico Milano	Milan	UCD	University College Dublin	Dublin
AWE	Atomic Weapons Establishment	Adlestrop	HHU	Heinrich Heine Universität	Düsseldorf	LC	Centrum Laserowe, Instytut Chemii Fizycznej	Warsaw	PNL	PN Lebedev Institute of Russian Academy of Science	Moscow	UCI	University of California, Irvine	Irvine
BARC	Bhabha Atomic Research Centre	Mumbai	HIJ	Heinrich Heine Universität	Düsseldorf	LFRC	Laser Fusion Research Center at the CSEP	Manly	PU	Princeton University, Extreme Light-Matter Interactions Lab	Princeton	UCLA	University of California, Los Angeles	Los Angeles
BNL	Brookhaven National Lab, ATF	Upton	HJ	Helmholtz Institute Jena	Jena	LLAM	Laser Lab Amsterdam	Amsterdam	QUB	Queen's University Belfast, Centre for Plasma Physics	Belfast	UCD	University of Delaware	Newark
CAP	Chinese Academy of Engineering Physics	Mianyang	HLASE	Helmholtz Zentrum Dresden-Rossendorf	Dresden	LLC	Lund Laser Center	Lund	RAL	Rutherford Appleton Laboratory, Central Laser Facility	Didcot	UMD	University of Maryland	College Park
COLA	Centre Optique et Laser en Aquitaine	Bordeaux	HZDR	Heinrich Heine Universität	Dresden	LLN	Laboratory for Laser Energetics	Rochester	RNZN	Rikugun Kanjyukan	Tokyo	UMed	Université de la Méditerranée, Laboratoire LPS	Marseille
CESTA	Centre d'Etudes Scientifiques et Techniques d'Aquitaine	Le Bep	IAP	Institute of Applied Physics, Russian Academy of Sciences	Nizhny Novgorod	LLNL-NIF	Lawrence Livermore National Lab - National Ignition Facility	Livermore	RRCAT	Raja Ramanna Centre for Advanced Technology	Indore	UMich	University of Michigan, Center for Ultrafast Optical Science	Ann Arbor
CLPU	Centro de Lasers Púlsados	Salamanca	ICL	Imperial College London	London	LLNL-JLF	Lawrence Livermore National Lab - Jupiter Laser Facility	Livermore	SACLA	Spring 8 Angstrom Compact Free Electron Laser	Sayo	UNL	University of Nebraska-Lincoln, Extreme Light Laboratory	Lincoln
CLUPS	Laser Center of the University of Paris - Sud	Paris	ILIL	Institut Optique - Graduate School of Photonics	Orsay	LNF	Laboratori Nazionali di Frascati, SWNIC Lab	Frascati	SEL	Station for Extreme Light	Shanghai	USC	University of Nevada at Reno, Nevada Testwest Facility	Reno
CoReLS	Center for Relativistic Laser Science	Gwangju	IOE	Institute for Laser Engineering, Osaka University	Osaka	LOA	Laboratoire d'Optique Appliquée-ENSTA-Ecole Polytech.	Palaiseau	SJTU	Shanghai Jiao Tong University	Shanghai	USze	University of Santiago de Compostela, LZAZ	Santiago
CREOL	Central Research Institute of Electric Power Industry	Yokosuka	IPPLM	Institute of Plasma Physics and Laser Microfusion	Warsaw	LLI	Laboratoire pour l'Utilisation des Lasers Intenses	Palaiseau	SUTU	Shanghai University	Shanghai	UTok	University of Tokyo, Institute for Solid State Physics	Tokyo
CSU	Colorado State University	Fort Collins	IOE	Institute of Optoelectronic, Wroclaw Academy of Technology	Wroclaw	MPQ	Max Born Institute	Berlin	SWJTU	Southwest Jiaotong University	Shanghai	WIS	Wizman Institute of Science	Jerusalem
ELI-HU	Extreme Light Infrastructure Attosecond Light Pulse Source	Szeged	IPPLM	Institute of Plasma Physics and Laser Microfusion	Warsaw	MPQ	Max Born Institute	Berlin	TAU	Tel Aviv University, Intense Lasers and Ultrafast Science Group	Tel Aviv	WU	Warsaw University, Ultrafast Phenomena Lab	Warsaw
ELI-CZ	Extreme Light Infrastructure Beamlines	Opotik Břežany	IPPLM	Institute of Plasma Physics and Laser Microfusion	Warsaw	MPQ	Max Born Institute	Berlin	TIFR	Tata Institute of Fundamental Research	Mumbai	XCELS	Exawatt Center for Extreme Light Studies	Nizhny Novgorod
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EXFEL	European XFEL, High Energy Density Group	Schenefeld	IPPLM	Institute of Plasma Physics and Laser Microfusion	Warsaw	MPQ	Max Born Institute	Berlin						

From ICUIL (International Committee on Ultra-High Intensity Lasers)

<https://www.icuil.org/>



Let's concentrate on  
ion acceleration

# Laser plasma ion-acceleration

*principal motivation*



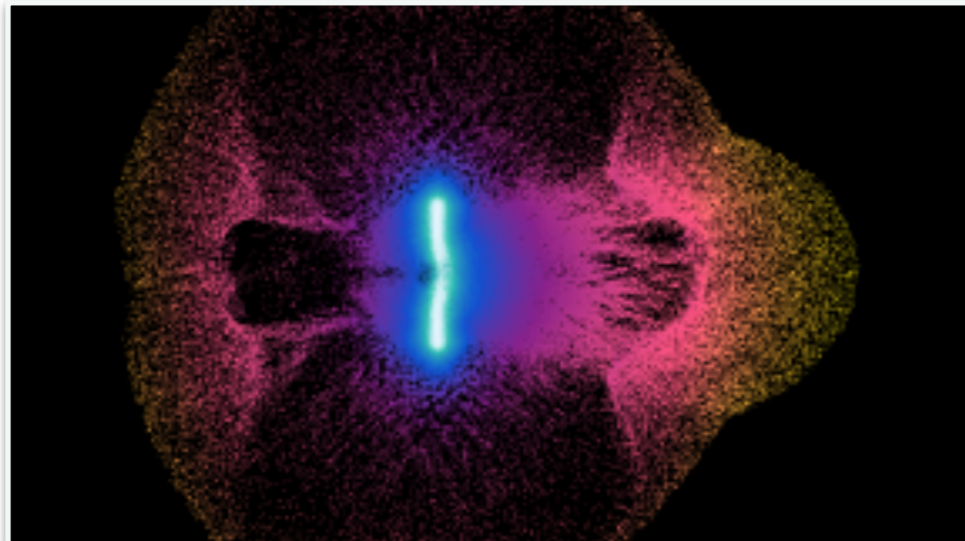
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10



$$E_{\max} \sim 50 \text{ MV/m}$$

$$L_{\text{acc}} \sim 1\text{-}10 \text{ m}$$



$$E_{\max} \sim 1 \text{ TV/m}$$

$$L_{\text{acc}} \sim 1 \mu\text{m}$$



**10,000 smaller!!!**

**BUT...**

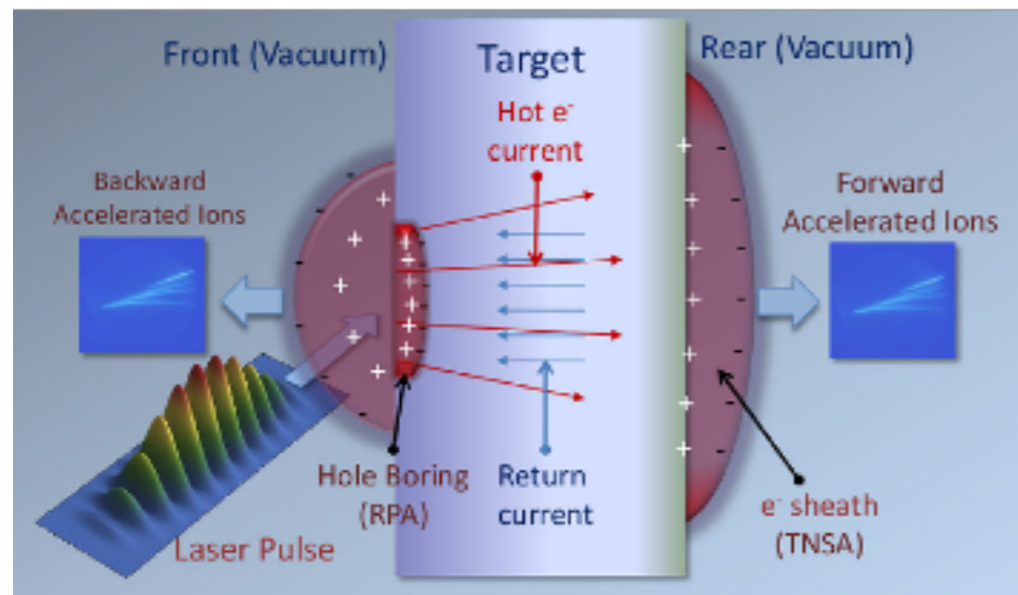
# Laser plasma ion-acceleration

physical picture

11

## Target Normal Sheath Acceleration

0.1-10 μm long



## Role of the ponderomotive force on electrons energy gain

In an oscillating, quasi-monochromatic electromagnetic field described by a vector potential  $\mathbf{a}(\mathbf{r},t)$ , the relativistic ponderomotive force is given by:

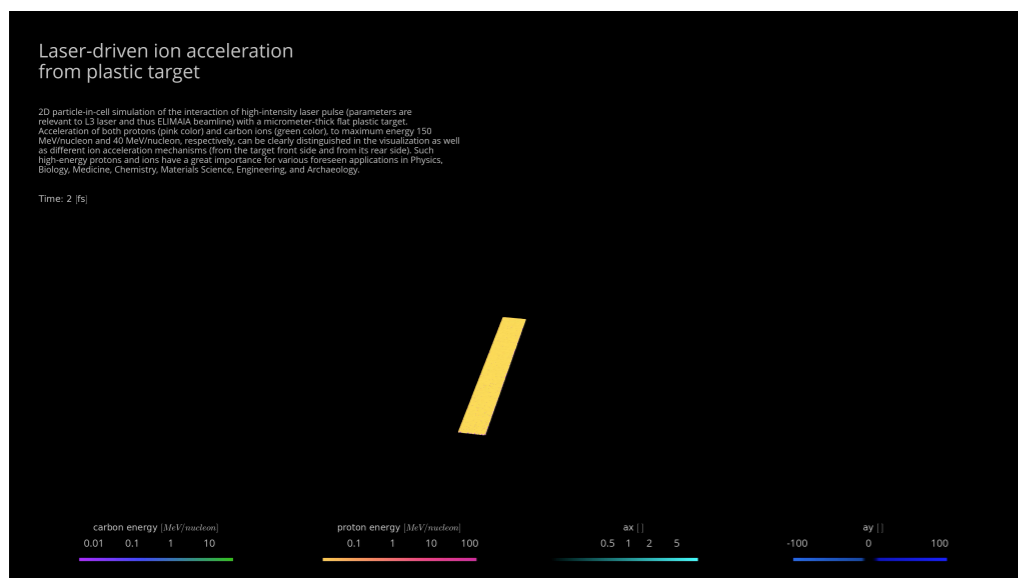
$$f_p = -m_e c^2 \nabla \sqrt{(1 + \langle a \rangle^2)}$$

$$f_p = \frac{dp^s}{dt} = -mc^2 \nabla \gamma$$

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

### REVIEW PAPERS:

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





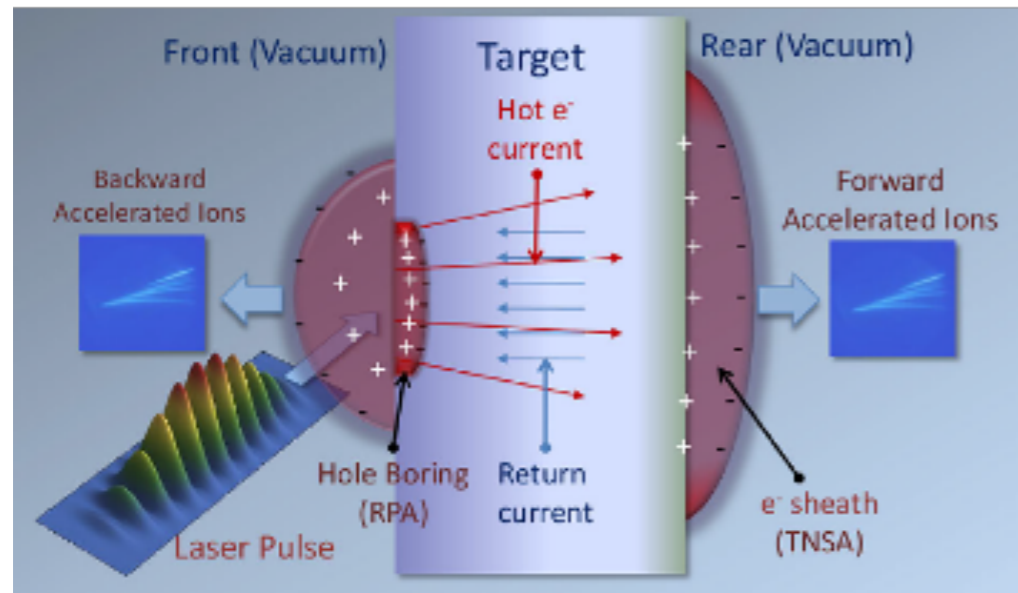
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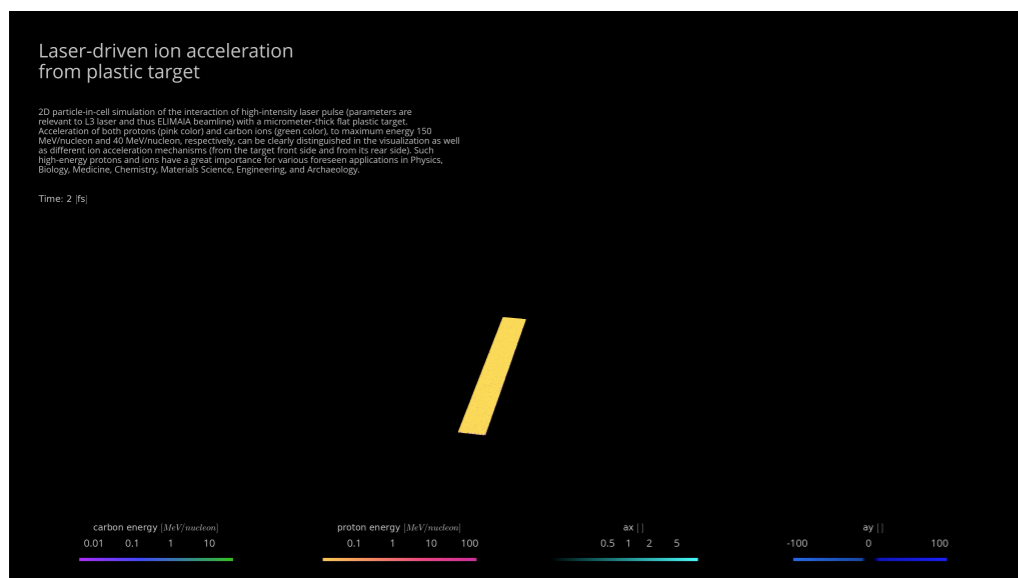
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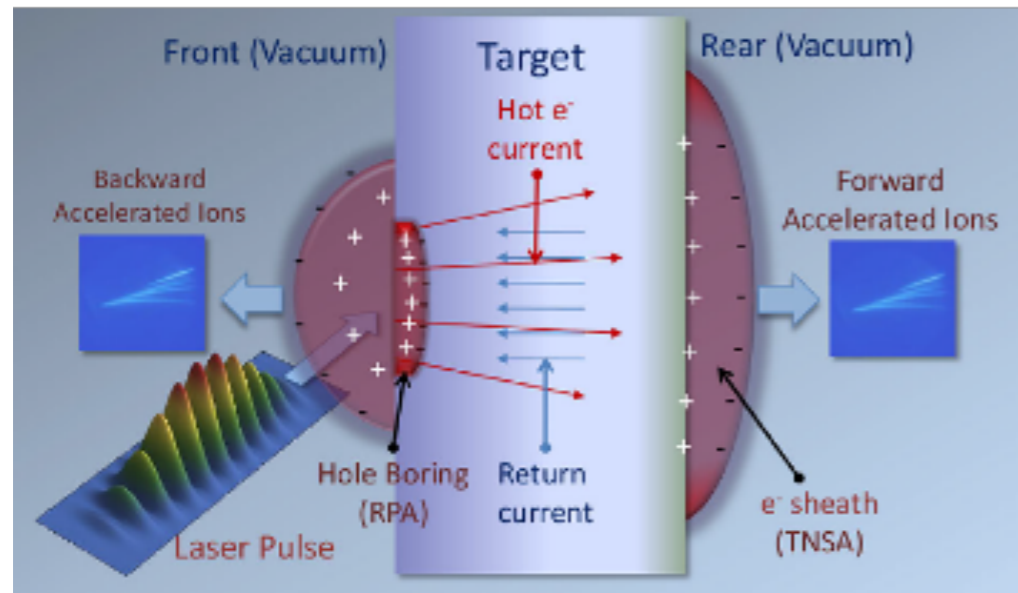
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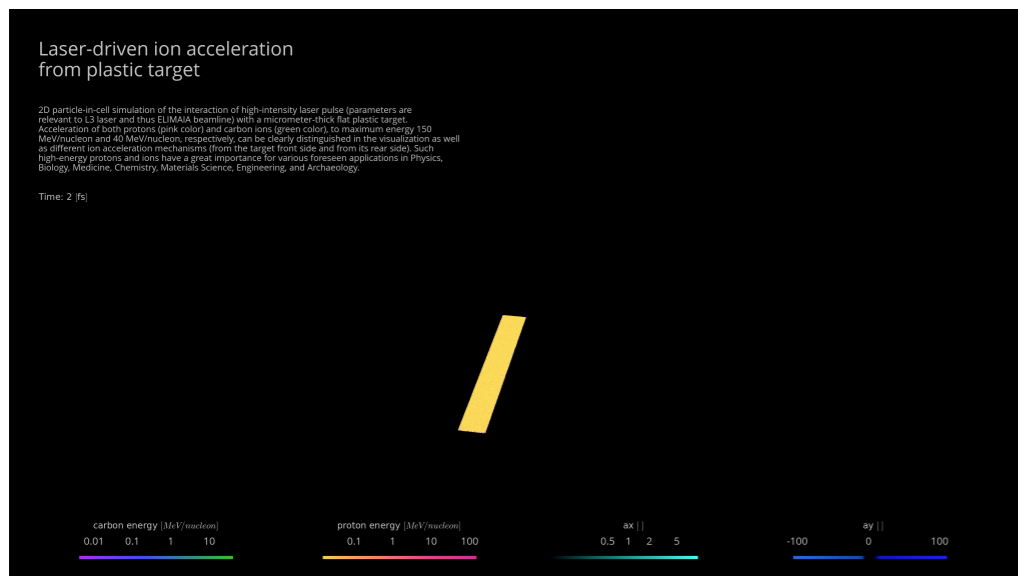
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$$I_L \text{ (laser intensity)} = E/\tau/S = 10^{21} \text{ W/cm}^2$$

### Direct Laser interaction:

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

### Laser-Plasma interaction:

- Debye Length

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

- Acceleration time

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

- Electric Field

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

Energy Gain: 100 MeV/ $\mu\text{m}$  (in a plasma medium)!!!

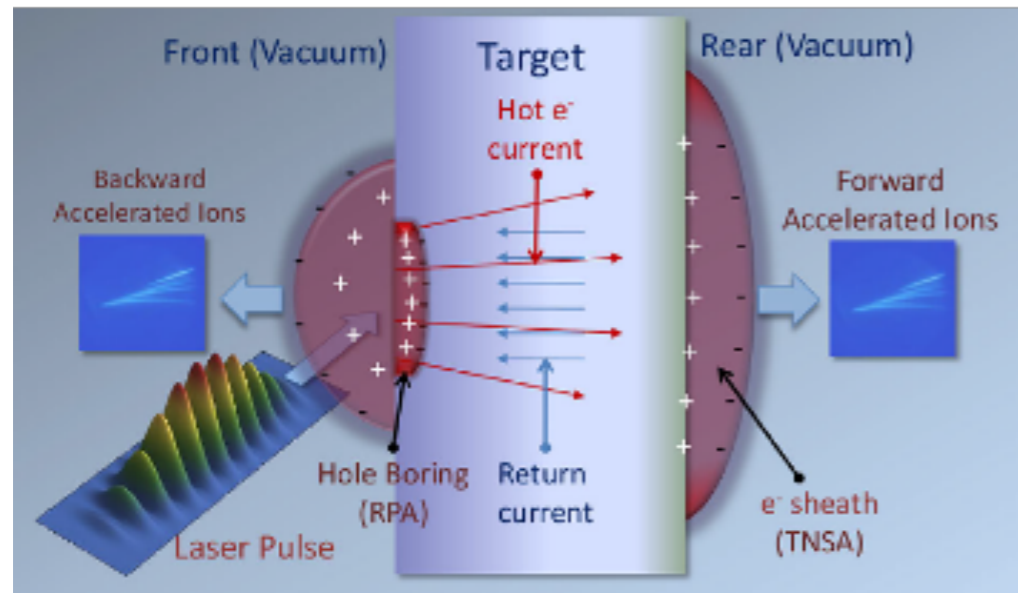
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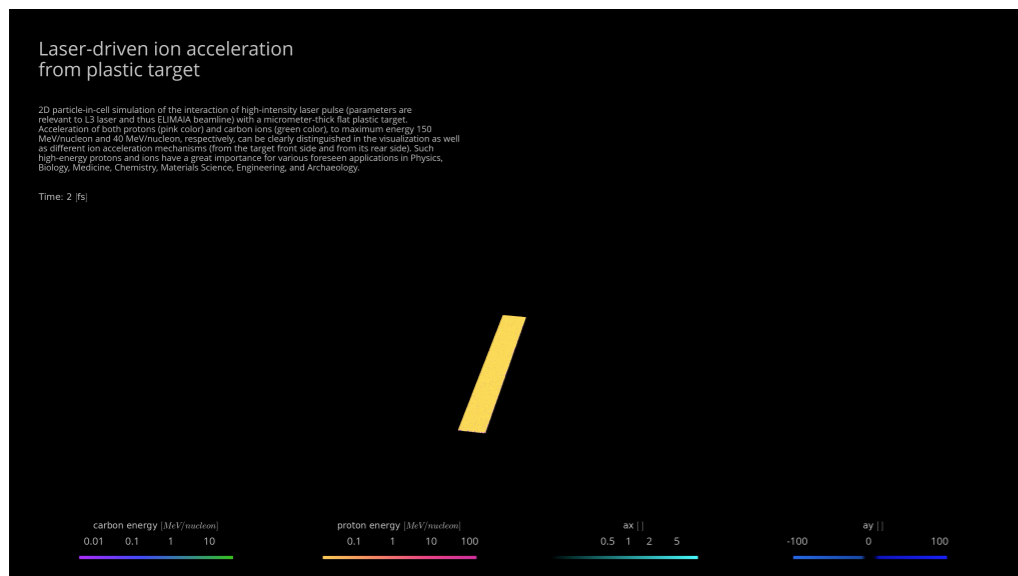
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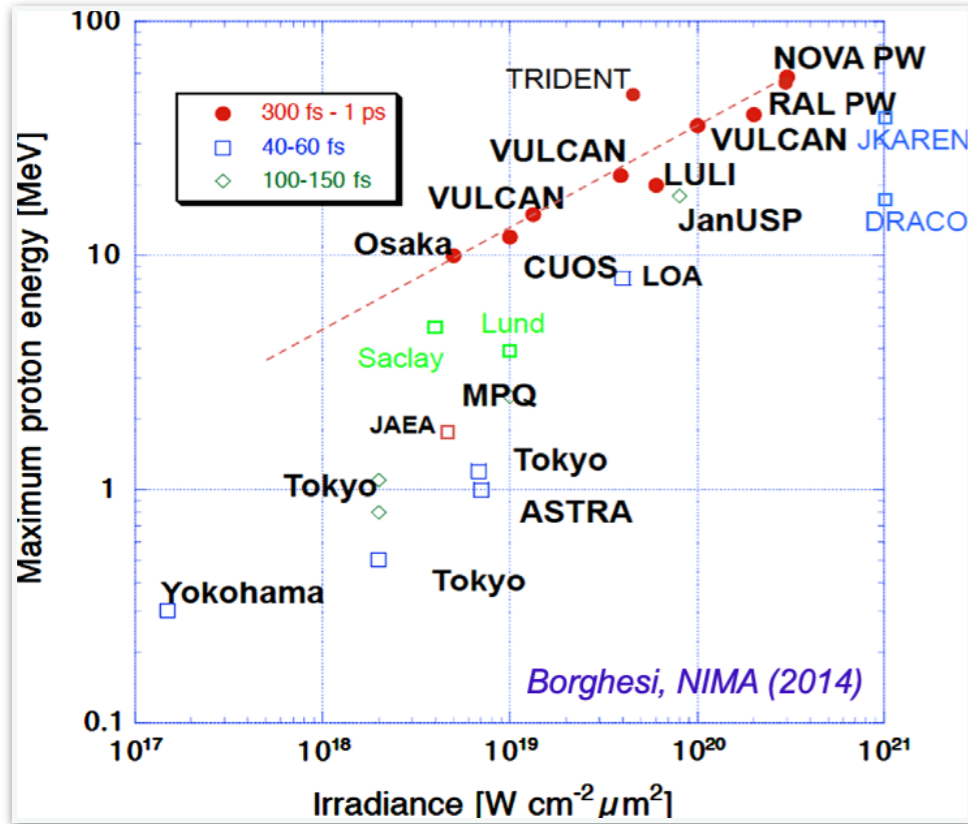
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Energy Gain: 100 MeV/ $\mu\text{m}$  (in a plasma medium)!!!

# Maximum proton energy

## experimental scaling laws (TNSA)

13



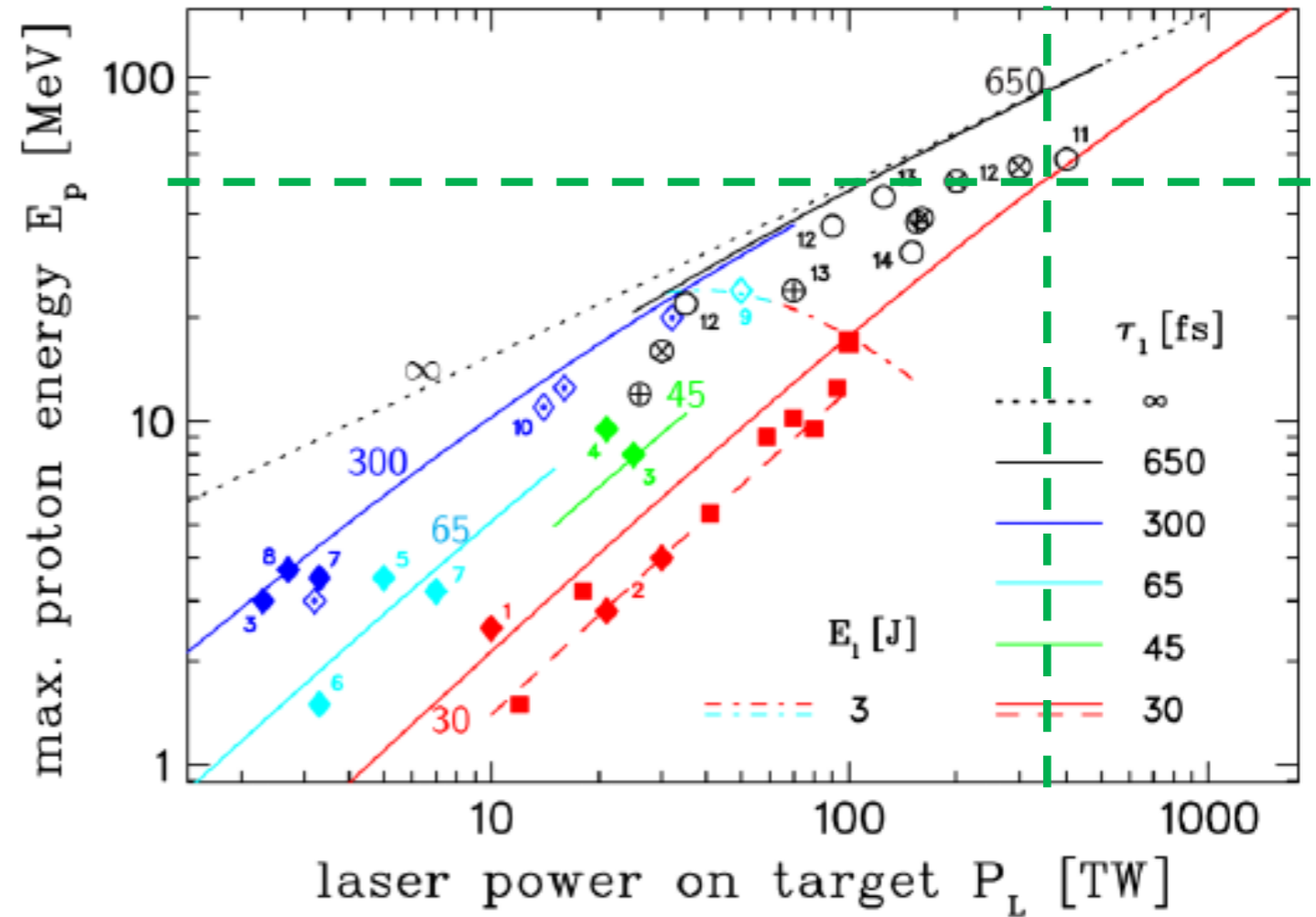
$$E \sim I_L^{1/2}$$

Intensity  $W/cm^2$   $\rightarrow$   $I \propto \frac{E_p}{\tau A}$

proton energy  $E_p$

pulse length  $\tau$

spot surface on target  $A$

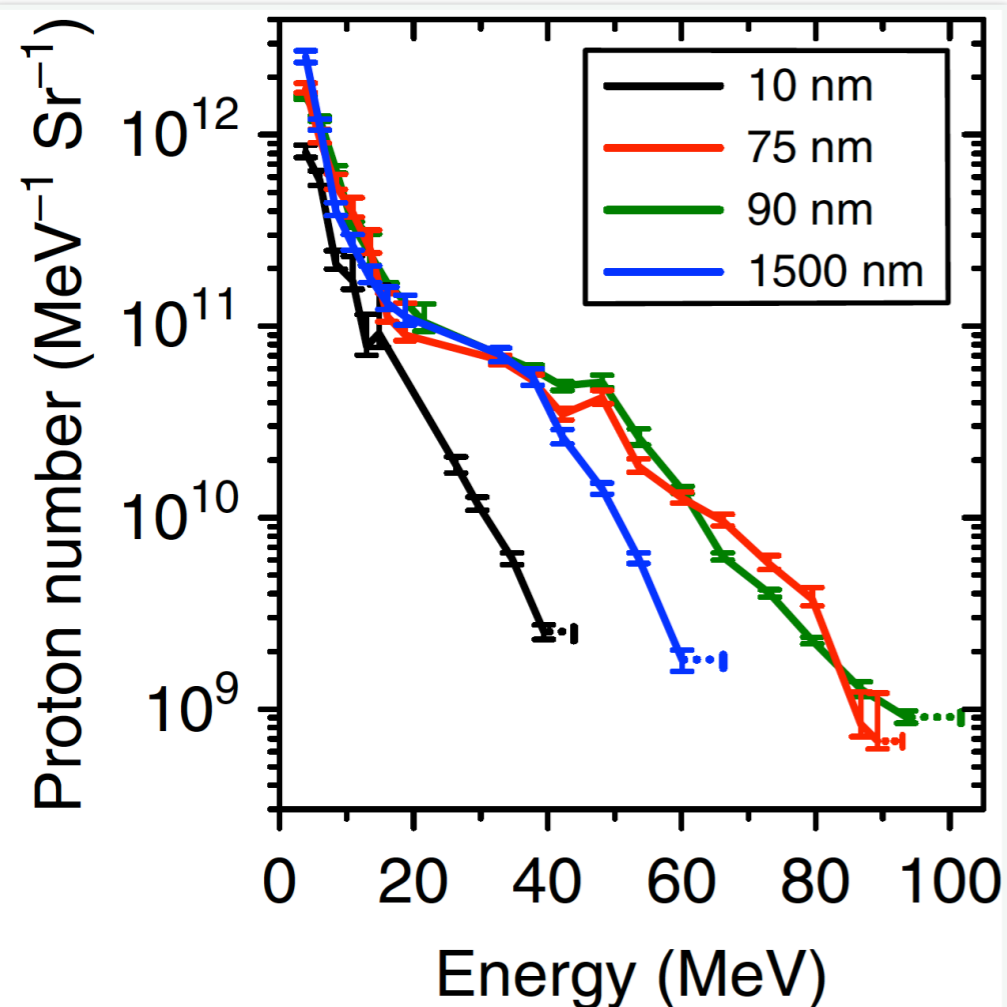


The scaling of proton energies in ultrashort pulse laser plasma acceleration  
 K Zeil et al 2010 New J. Phys. 12 045015

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

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

2018



## Vulcan laser at the Rutherford Appleton Laboratory (UK)

**Intensity** =  $\sim 10^{20} \text{Wcm}^{-2}$

Pulses of p-polarised, **1.053  $\mu\text{m}$ -wavelength**

**Pulse duration**  $\tau = (0.9 \pm 0.1) \text{ ps}$  (FWHM)

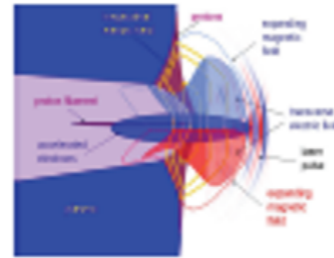
**Energy** after the plasma mirror:  $(210 \pm 40) \text{ J}$

**Target:** thin planar plastic foil with thickness in the range 10 nm-1.5  $\mu\text{m}$

# Laser-driven ion acceleration mechanisms: laser intensity vs target density

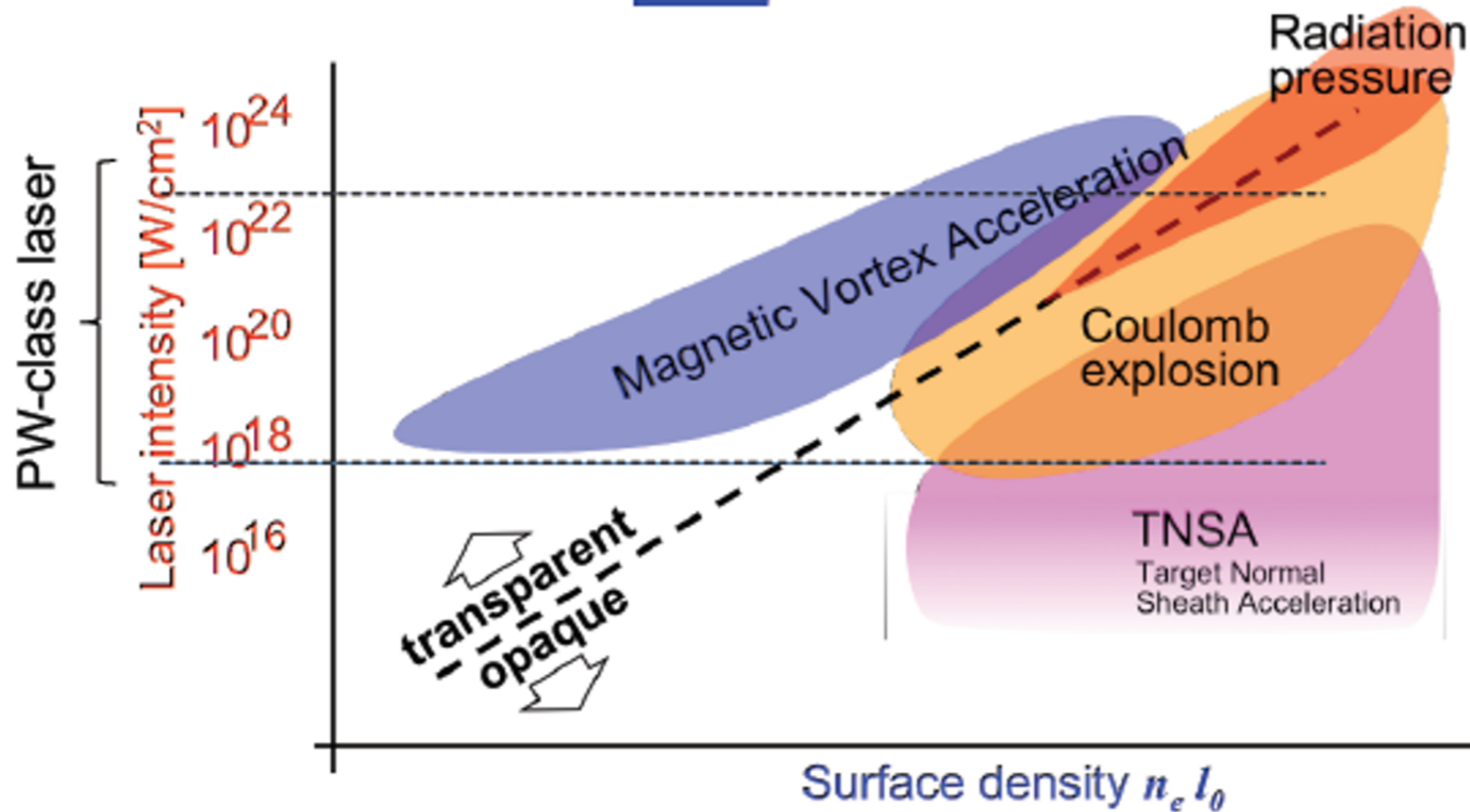
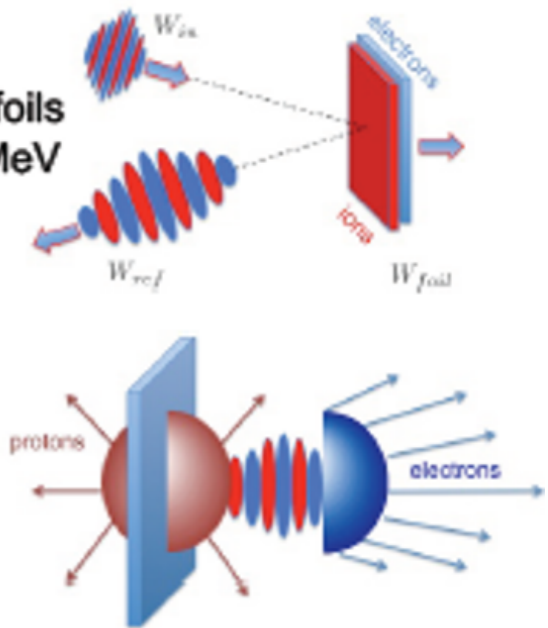
### MVA

Laser: High Intensity  
Target: Near Critical Density slab  
Ion Energy: hundreds of MeV to GeV



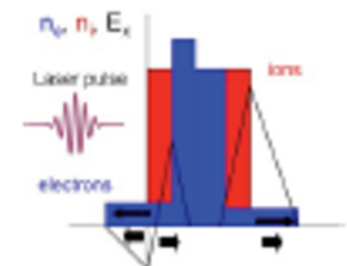
### RPA & CE

Laser: High Intensity  
Target: Thin solid density foils  
Ion Energy: hundreds of MeV



### TNSA

Laser: Low Intensity  
Target: Thick solid density foils  
Ion Energy: ~100 MeV



Courtesy of S Bulanov



I-LUCE at INFN-LNS



## **INFN Laser indUCED radiation production**

Goal: realisation of a new European laser facility for new beams, new physics and new Users





Roma TV, LNF, Pisa CNR, LNS  
15 M€

7.9 M€ **WP3 High-Power lasers**

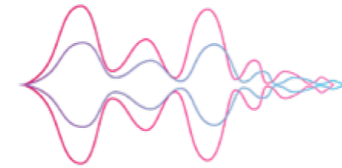
Infrastructure

Laser system and interaction chamber

Electrons and ion acceleration



LUC



Advanced technologies for Human  
Centred Medicine

# Anthem

23 Istituti; Spoke 4: Caserta, Pavia, INFN

1.3 M€

Electron acceleration for conventional and ultra high  
dose rate beams nell'accelerazione di elettroni e UHDR

## INFN Laser induced radiation production



0.8 M€

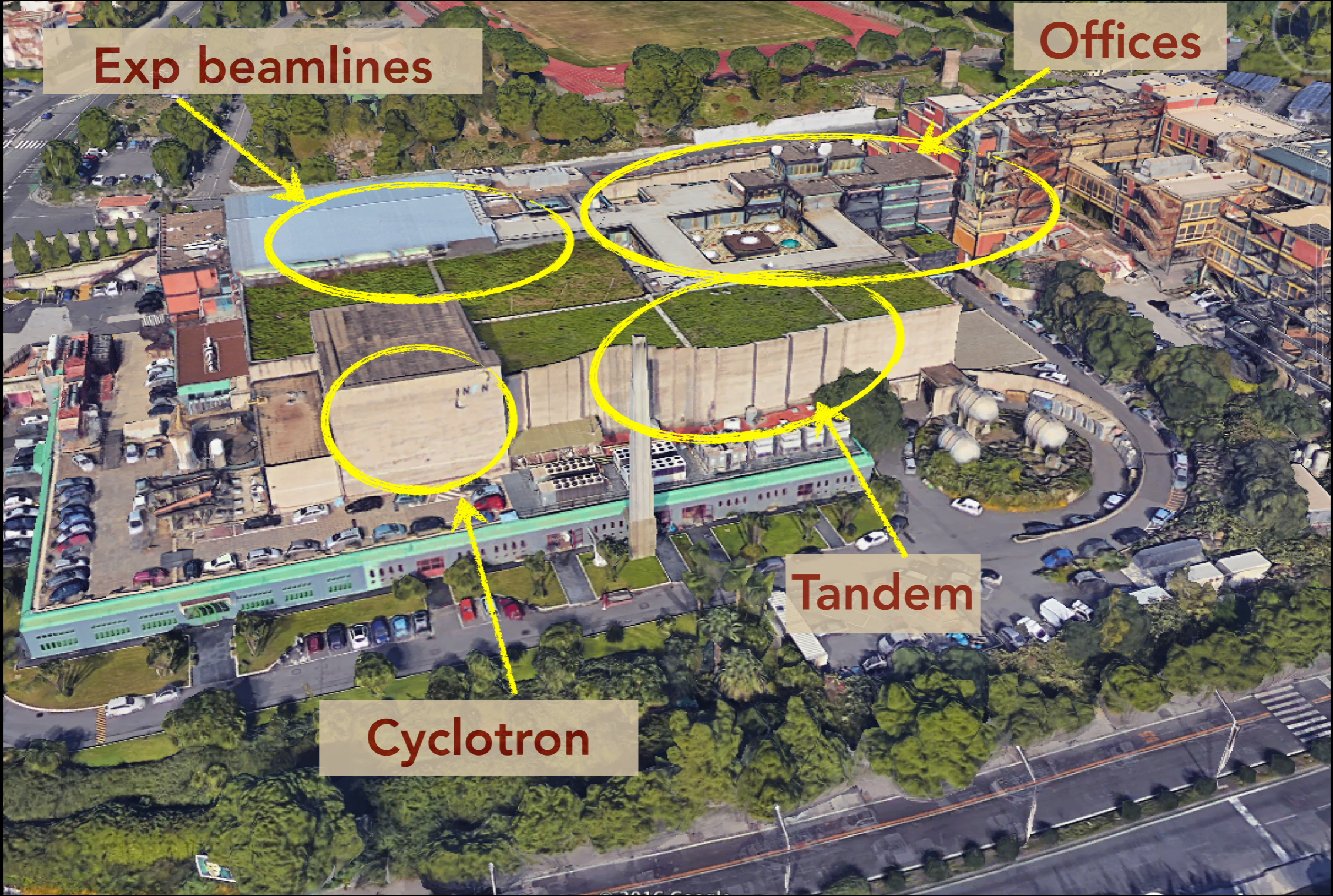
Demonstration of a micro-acceleration system for  
laser-driven proton beams

### BCT

*Breast Cancer  
Therapy*

2.0 M€

Ottimizzazione nella selezione di  
fasci di protoni per applicazioni  
mediche

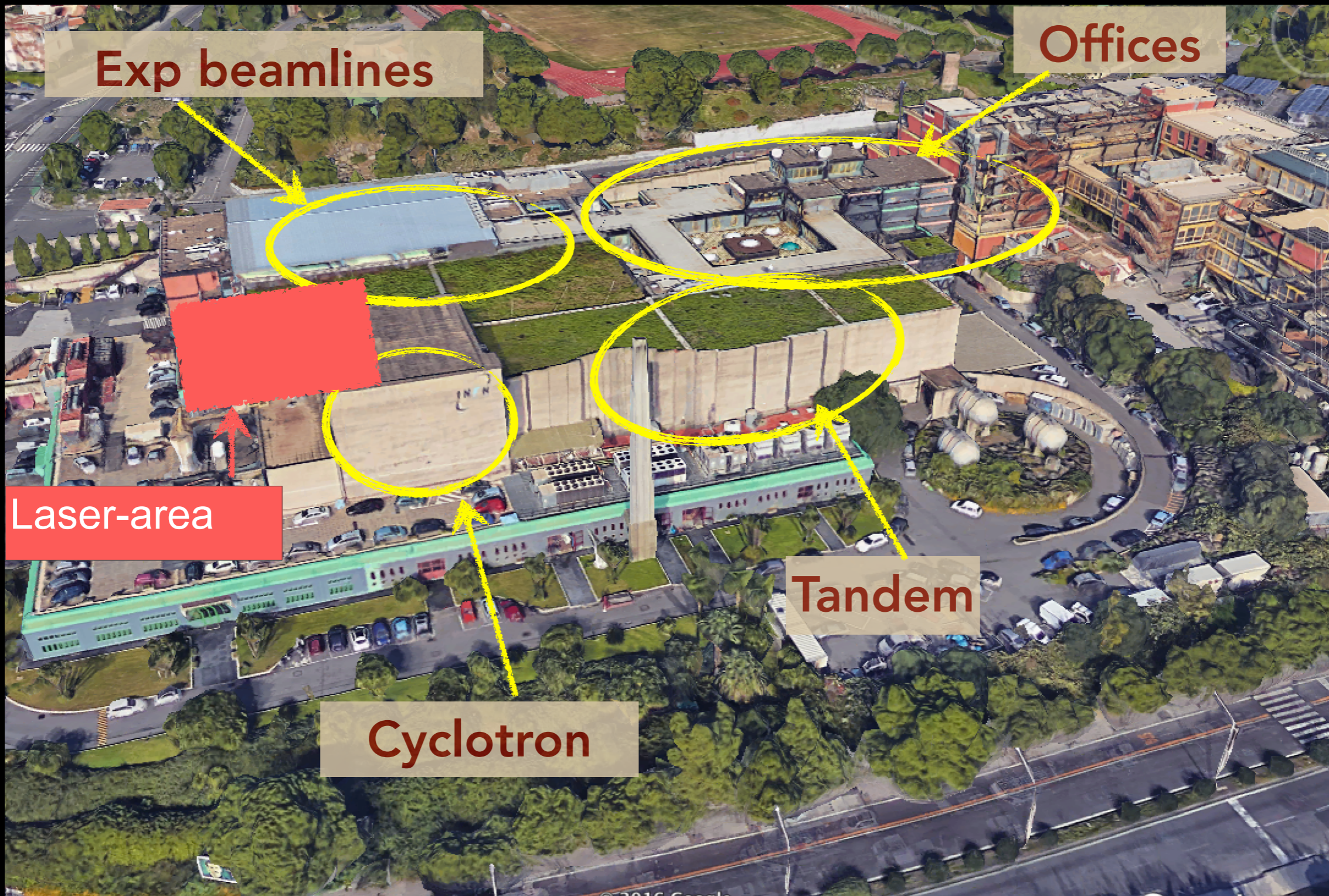


**Exp beamlines**

**Offices**

**Tandem**

**Cyclotron**



Exp beamlines

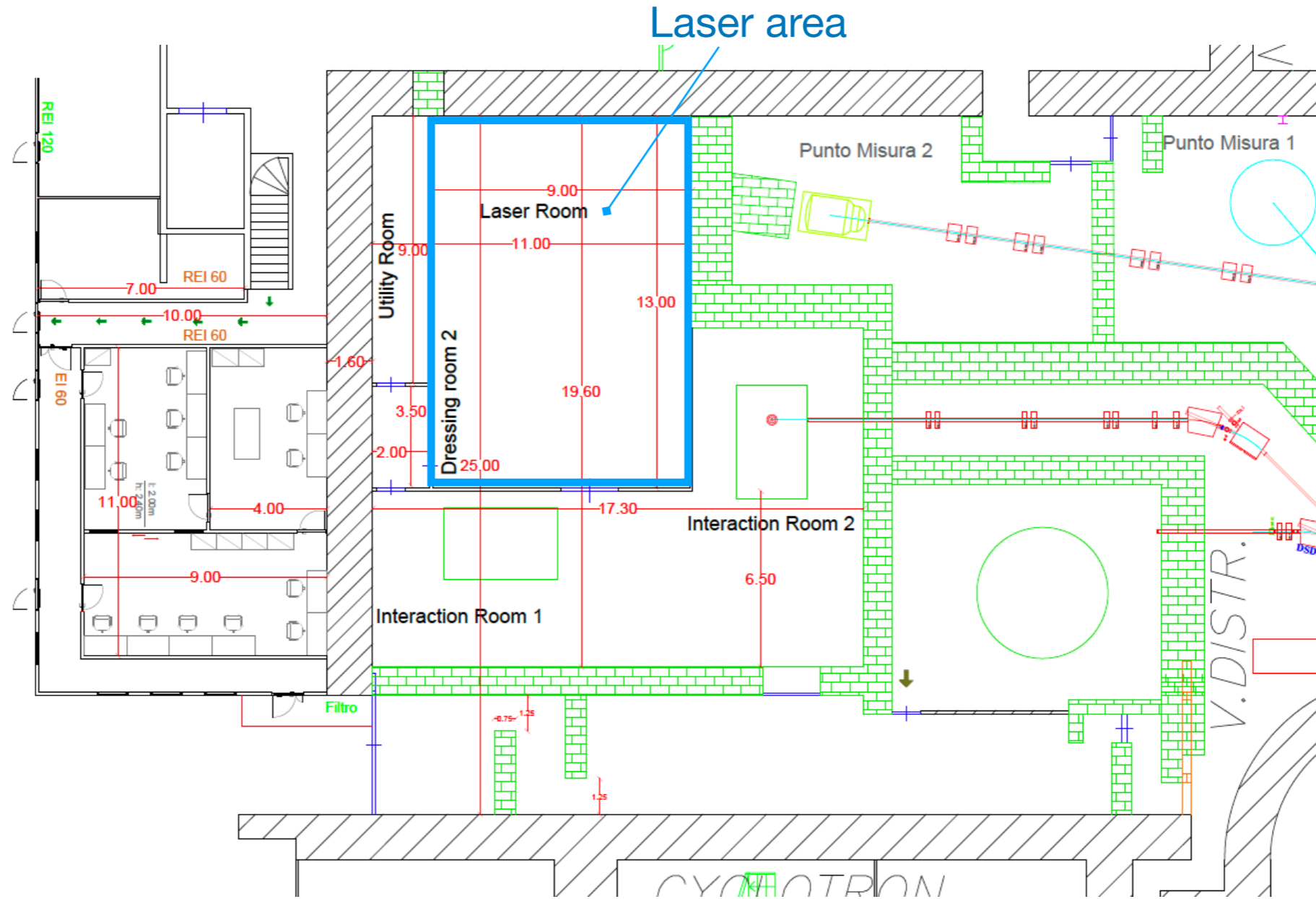
Offices

Laser-area

Tandem

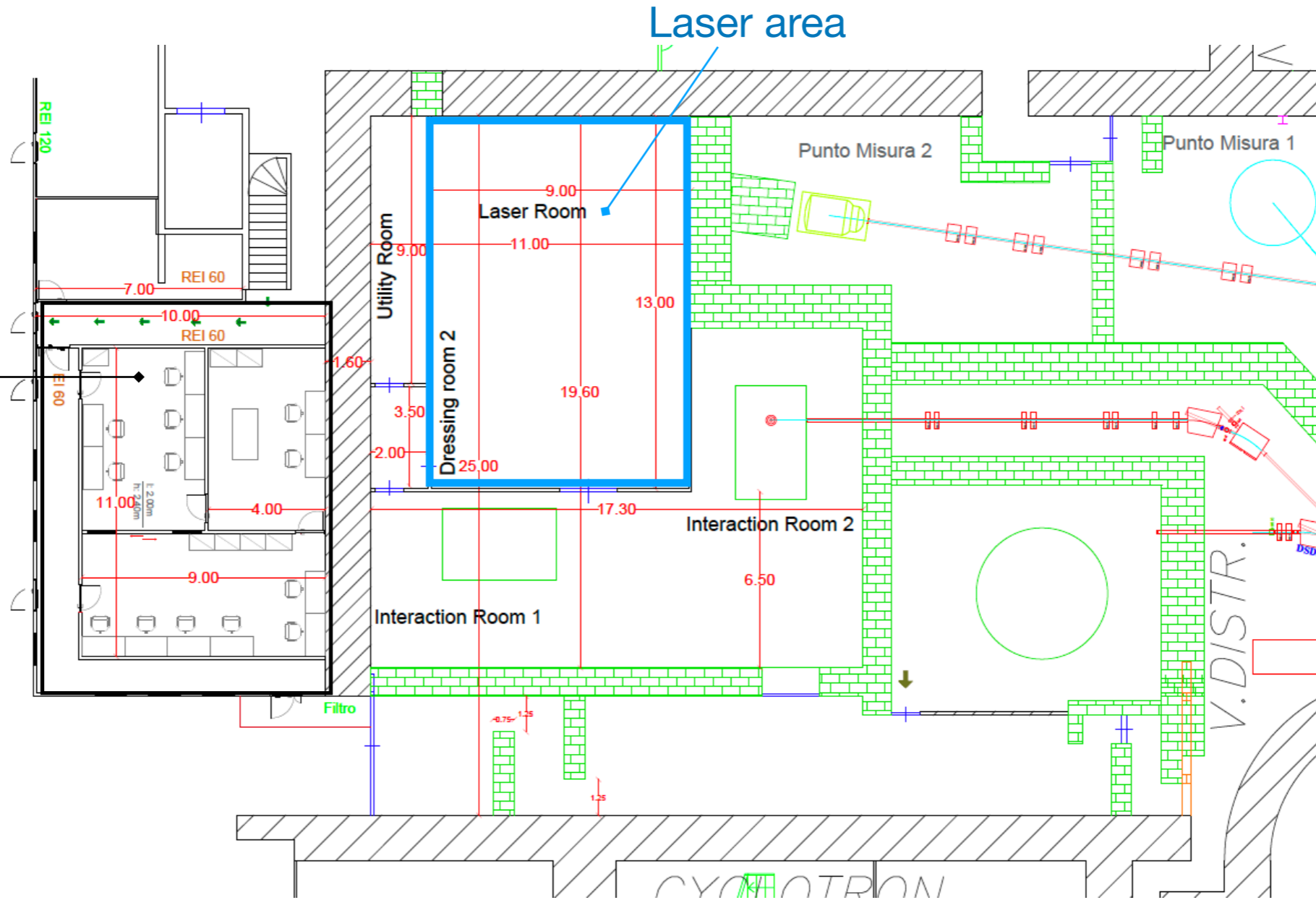
Cyclotron

# I-LUCE layout

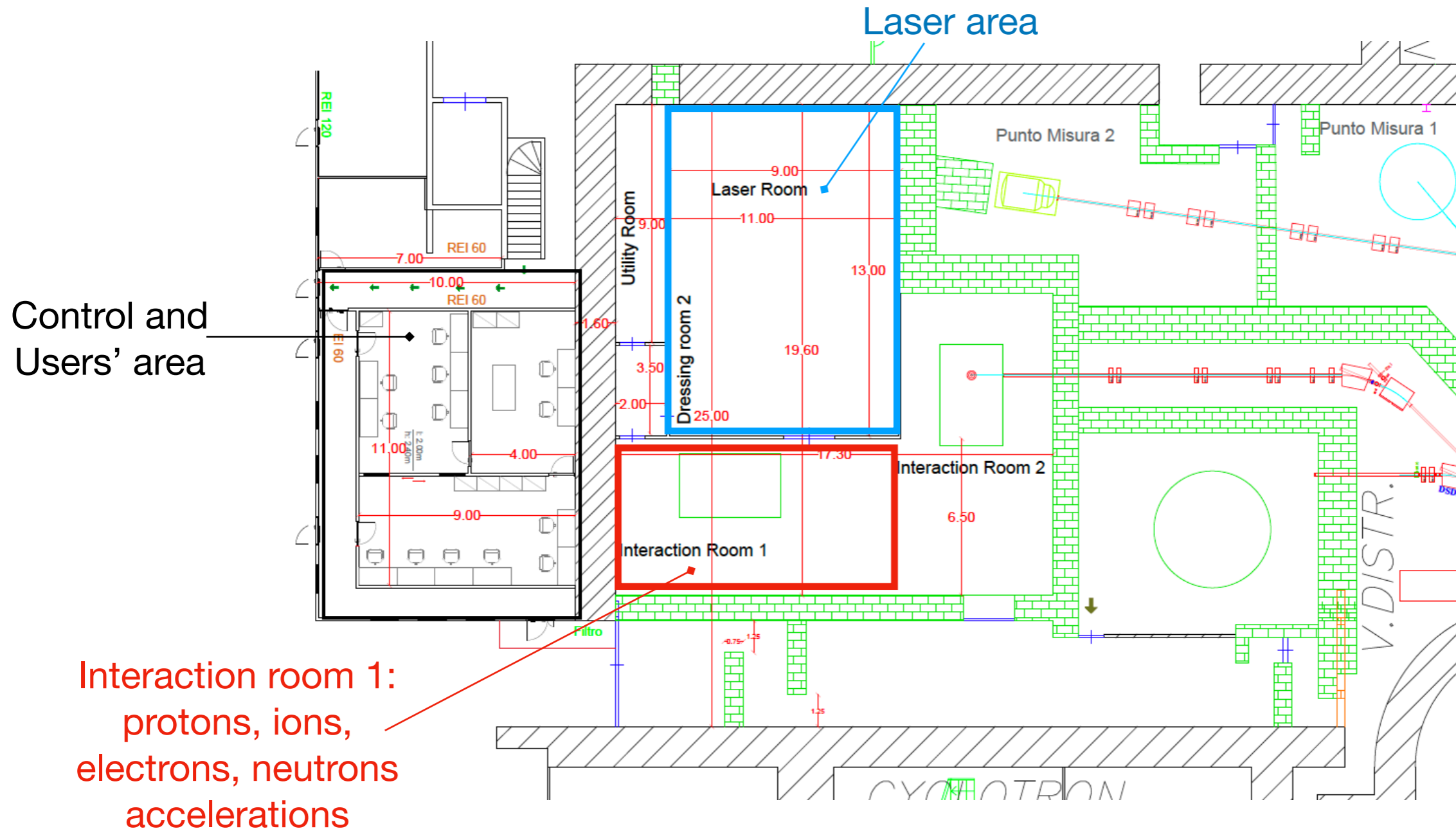


# I-LUCE layout

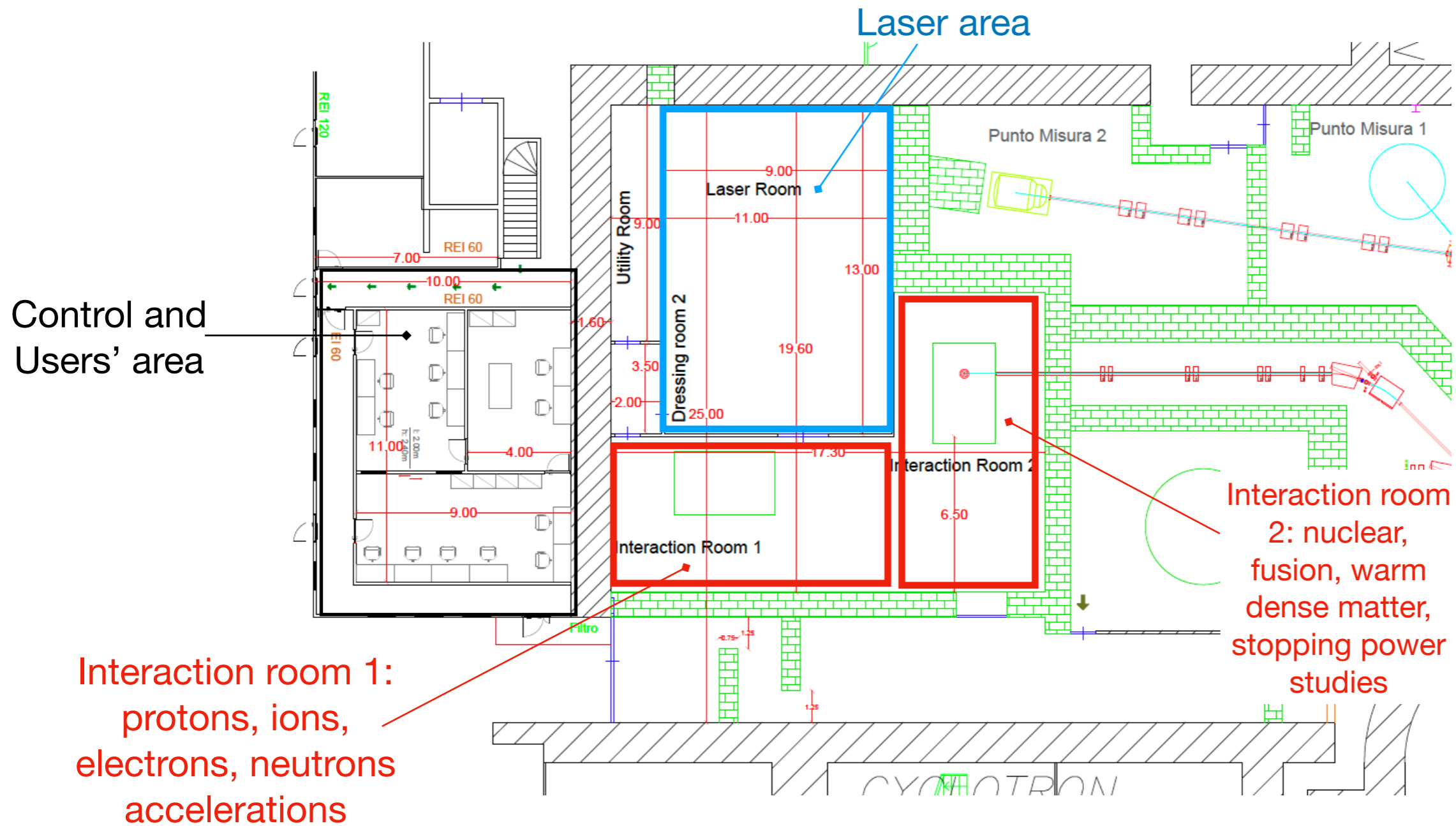
Control and Users' area



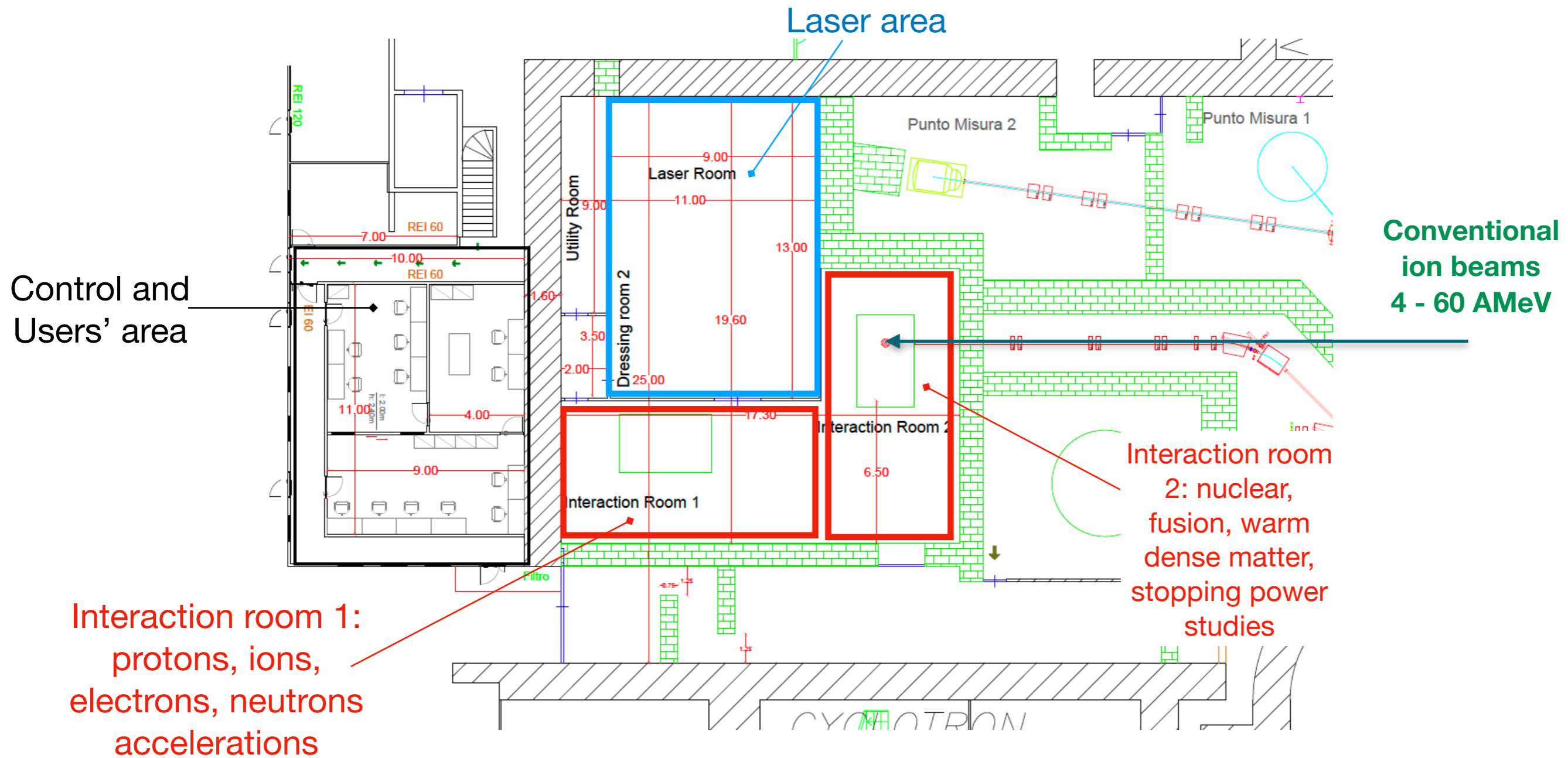
# I-LUCE layout



# I-LUCE layout

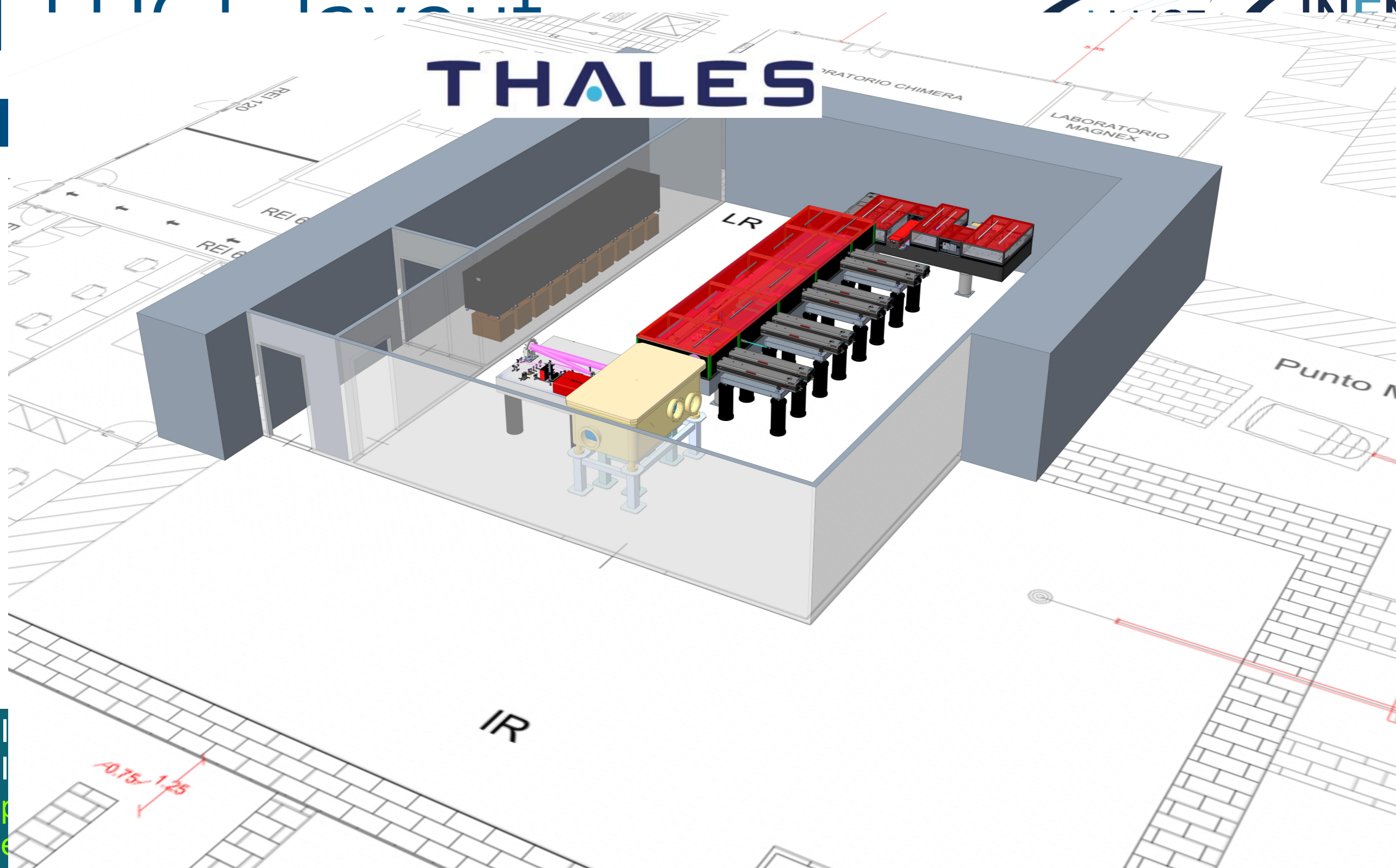


# I-LUCE layout





THALES



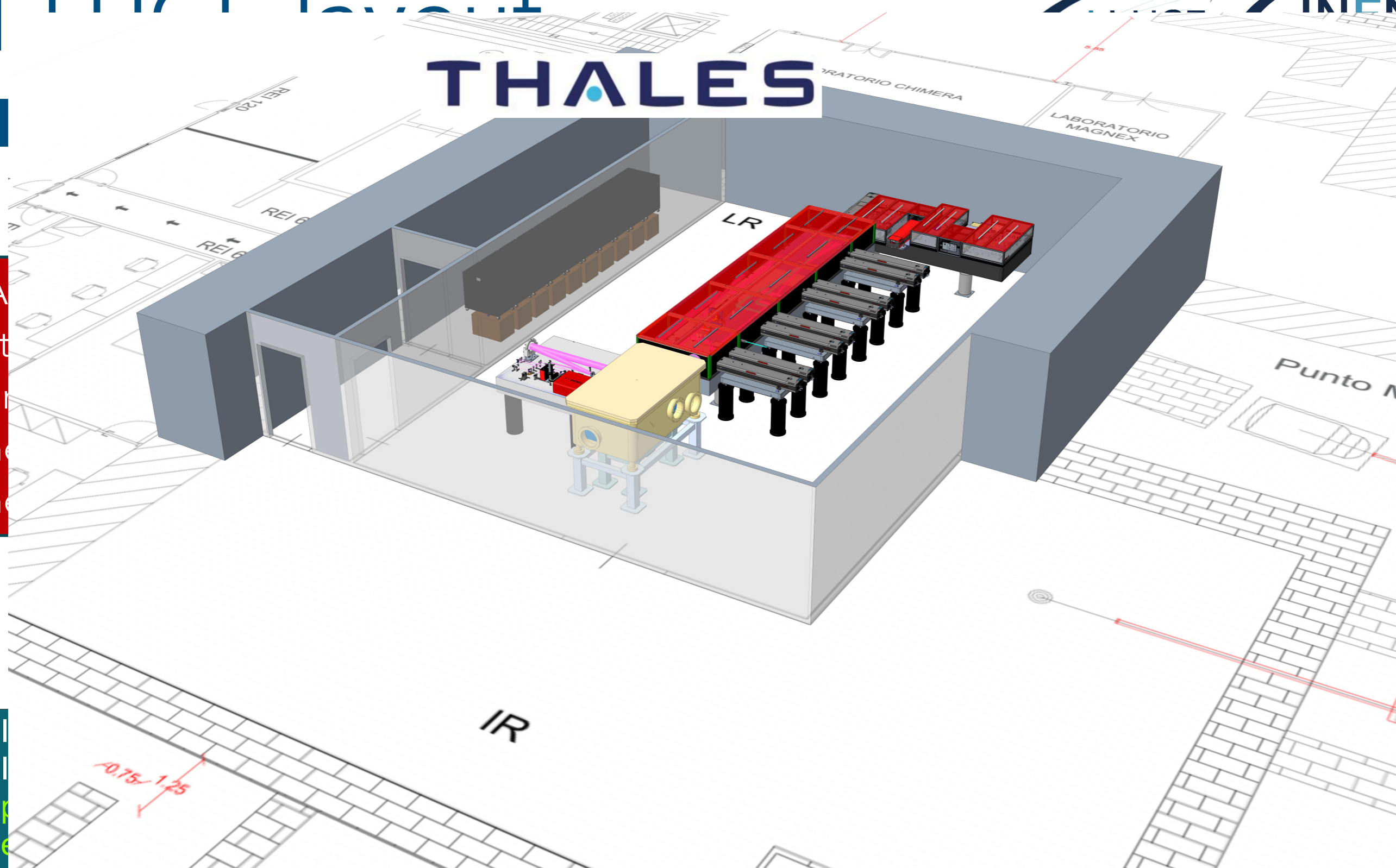
production

In-air irradiation station

Conventional ions:  
from TANDEM and  
Cyclotron

THALES

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production

In-air irradiation station

Conventional ions:  
from TANDEM and  
Cyclotron

## Two interaction chambers

- 1) **Interaction Chamber n.1:** Radiation production (protons/ions, electrons, neutrons, gamma, etc.)
  - One in-air irradiation station for multidisciplinary studies
- 2) **Interaction Chamber n.2:** Warm Dense Matter studies (WDM)
  - Nuclear physics in plasma
  - Interaction of conventional ion beams with laser-generated plasma
  - Nuclear physics fusion studies in plasma
  - .....

## Two working modalities

- 1) Low power: 50 TW/23fs/10Hz
- 2) High power: 350 TW/23fs/1Hz

Upgrade from 350 TW to 500 TW  
(0.5 M€)

# I-LUCE first phase

EUAPS  
I-LUCE @ LNS

## Two interaction chambers

### 1) Interaction Chamber

neutrons, gamma

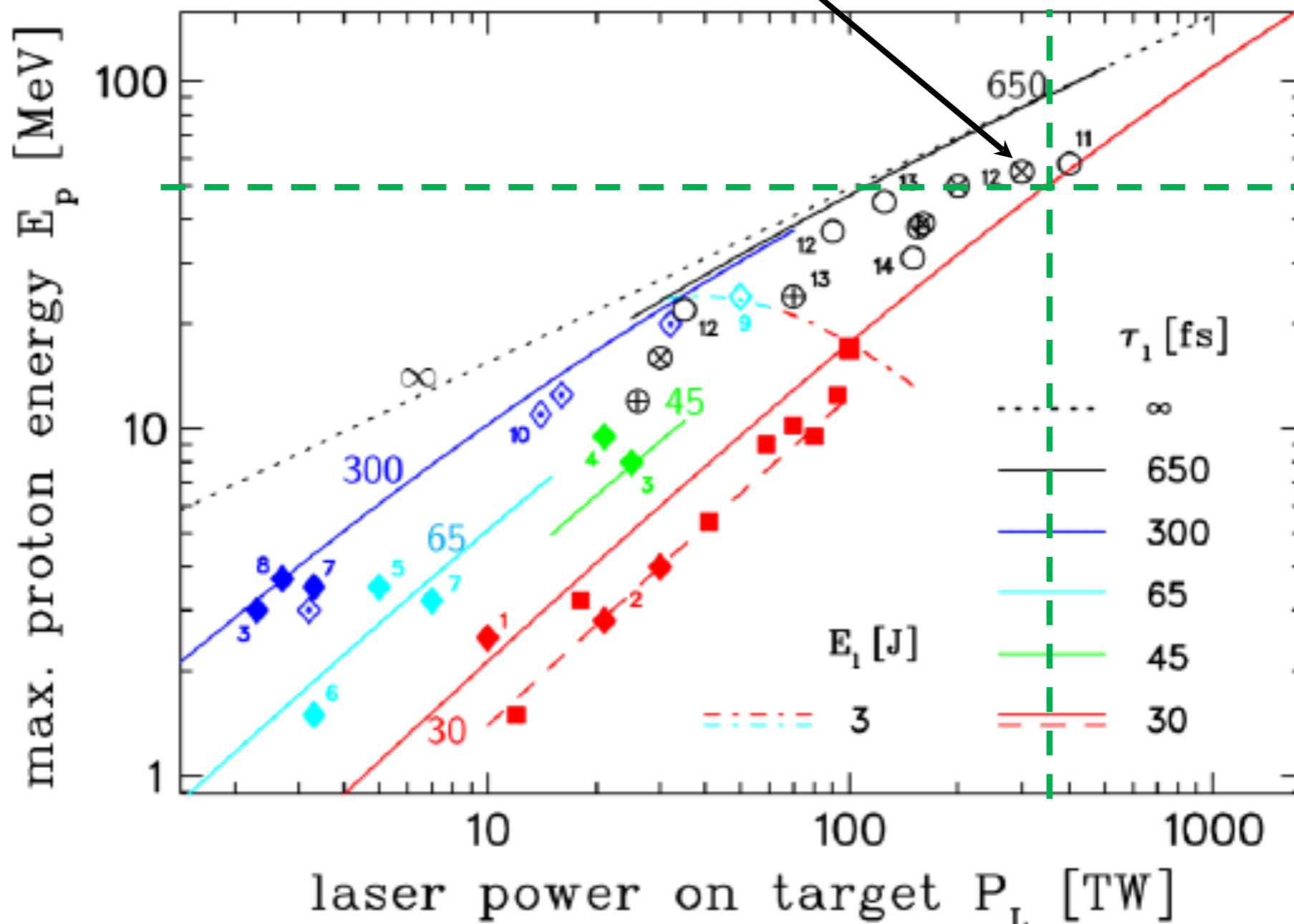
- One in-air

### 2) Interaction Chamber

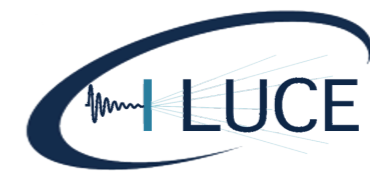
- Nuclear physics
- Interaction
- Nuclear physics
- .....

## Two working points

- 1) Low power: 50 TW
- 2) High power: 350 TW



# Low power modality: 50 TW



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22

Laser Power		$\geq 50$ TW
Energy per pulse		$\geq 1$ J
Pulse duration		$\leq 23$ fs
Focusing surface		$36 \mu\text{m}^2$
Max power density (at the target)		$1.21 \cdot 10^{20}$
$I \cdot \lambda^2$		$7.72 \cdot 10^{19}$
Contrast ratio @100 ps (ASE)		$> 10^{10}$
Repetition rate		$\geq 10$ Hz
Protons Ions	Max energy	4 MeV
	Particle per pulse (at 2 MeV)	$10^{11} \text{ MeV}^{-1} \text{ Sr}^{-1}$
	Energy spread	100%
	Beam divergency (max)	$\pm 20^\circ$
Eletrons	Max energy	0.1 GeV
	Particles per pulse	$10^9$
	Beam divergency (max)	$\pm 20$ mad
Neutrons	Max energy	TBD
	Particles per pulse	
	Energy spread	
	Beam divergency	
Gamma X-beams	Synchrotron radiation of the electrons inside the plasma or breemsstrahlung	
	Energy	up to 20 MeV
	Beam divergency	Directionality in the beam propabgation direction

*Fusion studies,  
nuclear studies,  
radioisotopes production,  
.....*

*Acting on the compression  
procedure, the **pulse  
duration can  
be increased up to 1/10 ps:***

$$\implies 2.78 \cdot 10^{18} \text{ W/cm}^2$$

$$2.78 \cdot 10^{17} \text{ W/cm}^2$$

$$\implies i\lambda^2 = 1.77 \cdot 10^{18}$$

$$i\lambda^2 = 1.77 \cdot 10^{17}$$

**Longer plasma expansion times:**

- Decay studies
- Stopping powers studies
- WDM characterisation

**Power densities** can be improved  
reducing the focusing spot:  
— shorter focusing parabola  
— but issues related to the: target  
degree, back reflection, ...

# High-power modality: 350 TW

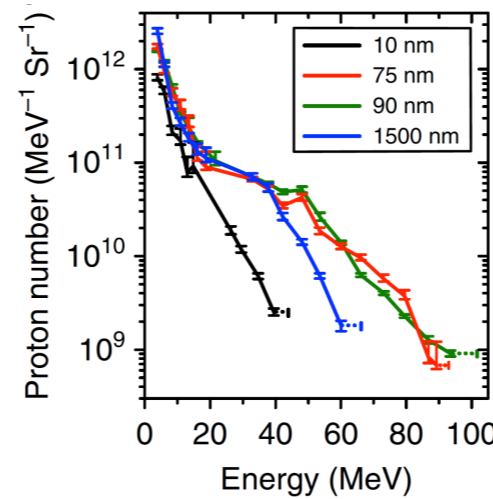


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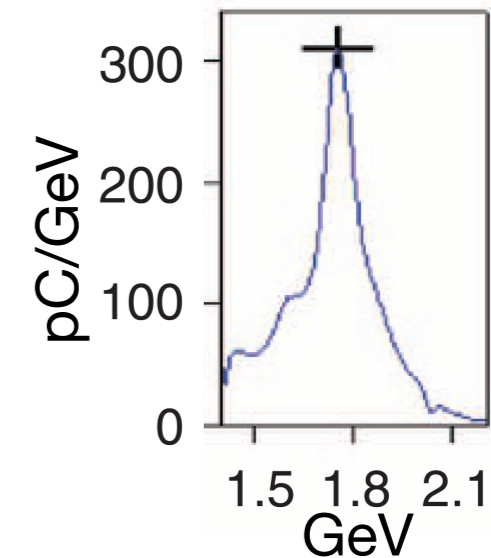
23

Laser Power	350 TW	
Energy per pulse	>7 J	
Pulse duration	≤ 25 fs	
Focusing surface	36 μm <sup>2</sup> or better	
Max power density (at the target)	$8.82 \cdot 10^{20}$	
$I \cdot \lambda^2$	$5.64 \cdot 10^{20}$	
Contrast ratio @100 ps (ASE)	> 10 <sup>10</sup>	
Repetition rate	1 Hz	
Protons Ions	Max energy	50 MeV
	Particle per pulse (at 30 MeV)	10 <sup>11</sup> MeV <sup>-1</sup> Sr <sup>-1</sup>
	Energy spread	100%
	Beam divergency (max)	±20°
Eletrons	Max energy	3 GeV
	Particles per pulse	10 <sup>9</sup>
	Beam divergency (max)	± 20 mad
Neutrons	Max energy	20 MeV
	Particles per pulse	10 <sup>10</sup>
	Energy spread	100
	Beam divergency	Isotropic
Gamma X-beams	Synchrotron radiation of the electrons inside the plasma or	
	Energy	up to 80 MeV
	Beam divergency	Directionality in the beam

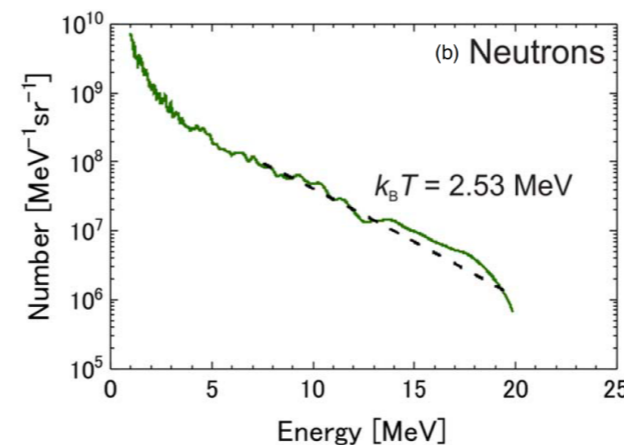
**Protons spectra** from A. Higginson et al. "Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme", NATURE COMMUNICATIONS | (2018) 9:724



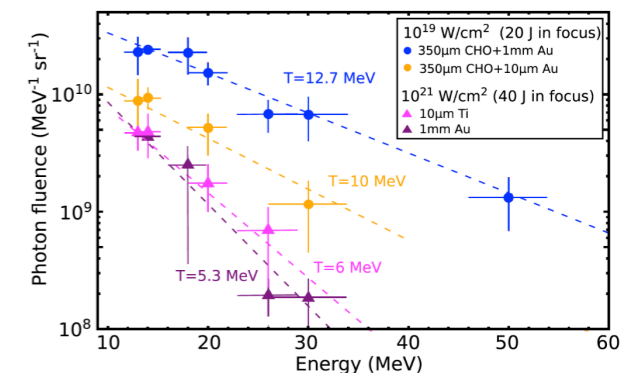
**Electrons spectra** from X. Wang et al. "Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV", NATURE COMMUNICATIONS, 4:1988 2018 DOI: 10.1038/ncomms2988



**Neutrons spectra** from A.Yogo et al. "Single shot radiography by a bright source of laser-driven thermal neutrons and x-rays", Applied Physics Express 14, 106001 (2021)



**Gamma spectra** from M. M. Günther et al "Forward-looking insights in laser-generated ultraintense γ-ray and neutron sources for nuclear application and science" NATURE COMMUNICATIONS | (2022) 13:170

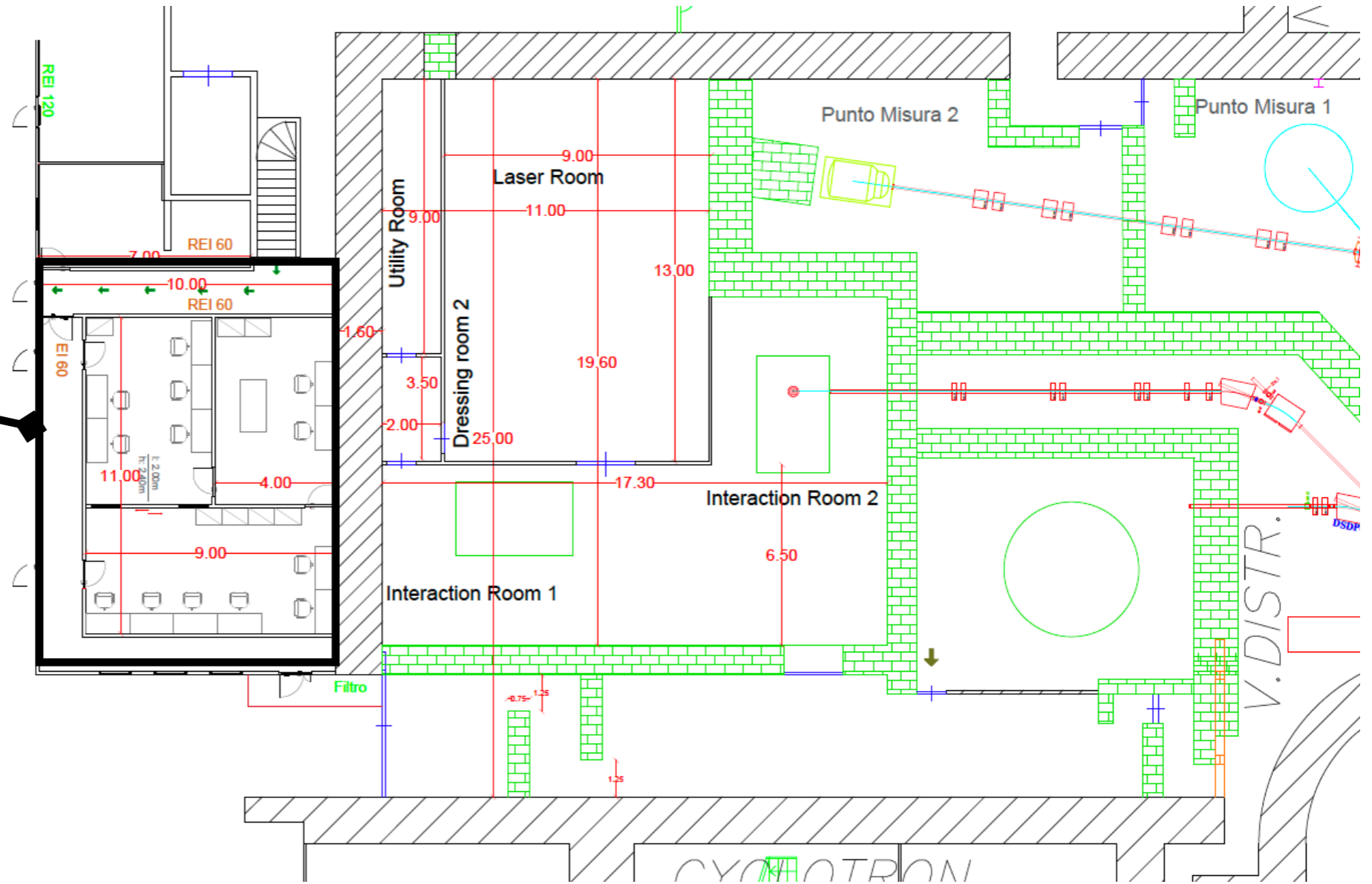


# I-LUCE current status

24



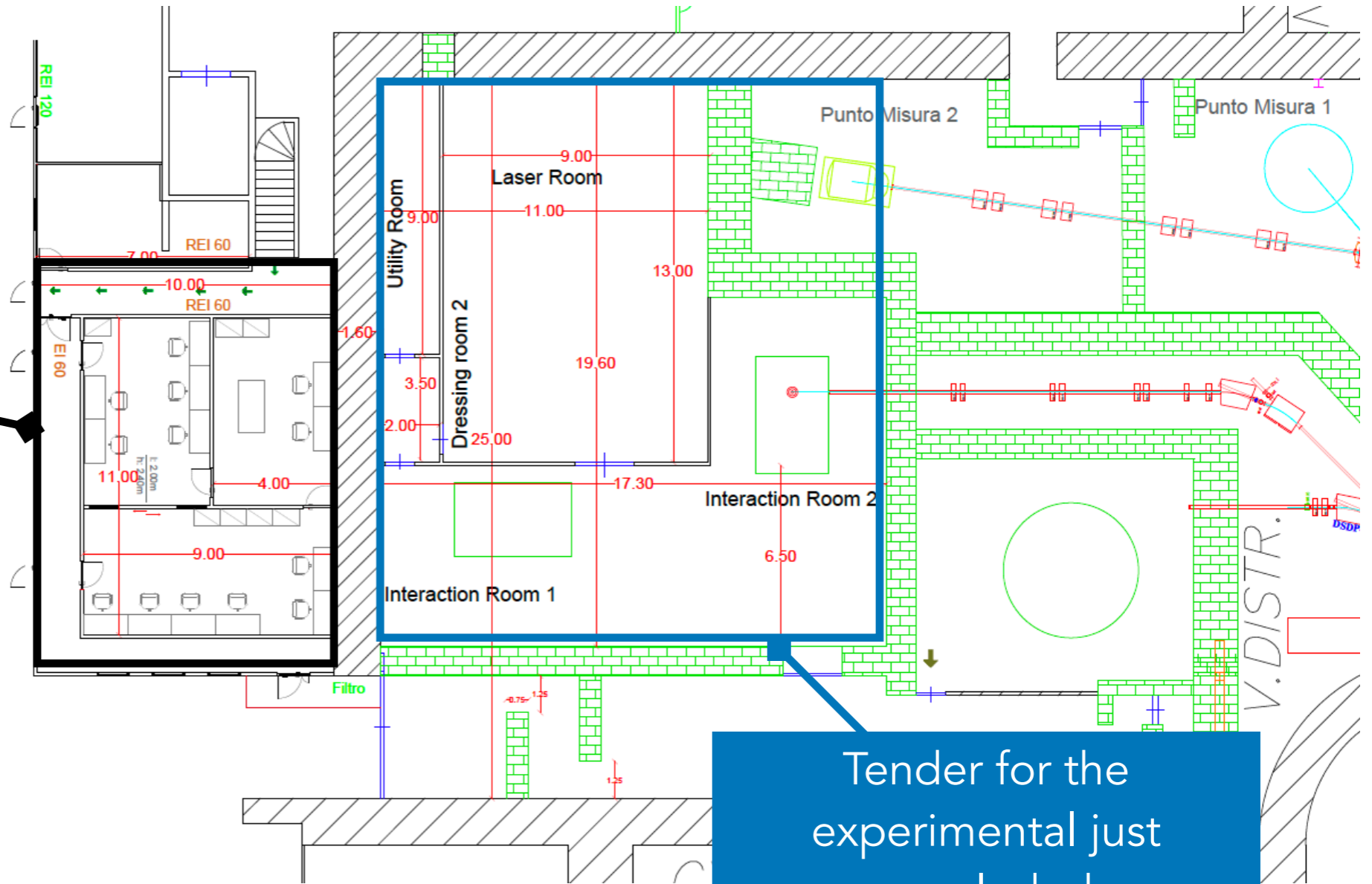
Control area  
under  
construction



# I-LUCE current status



Control area under construction



Tender for the experimental just concluded



# I-LUCE current status



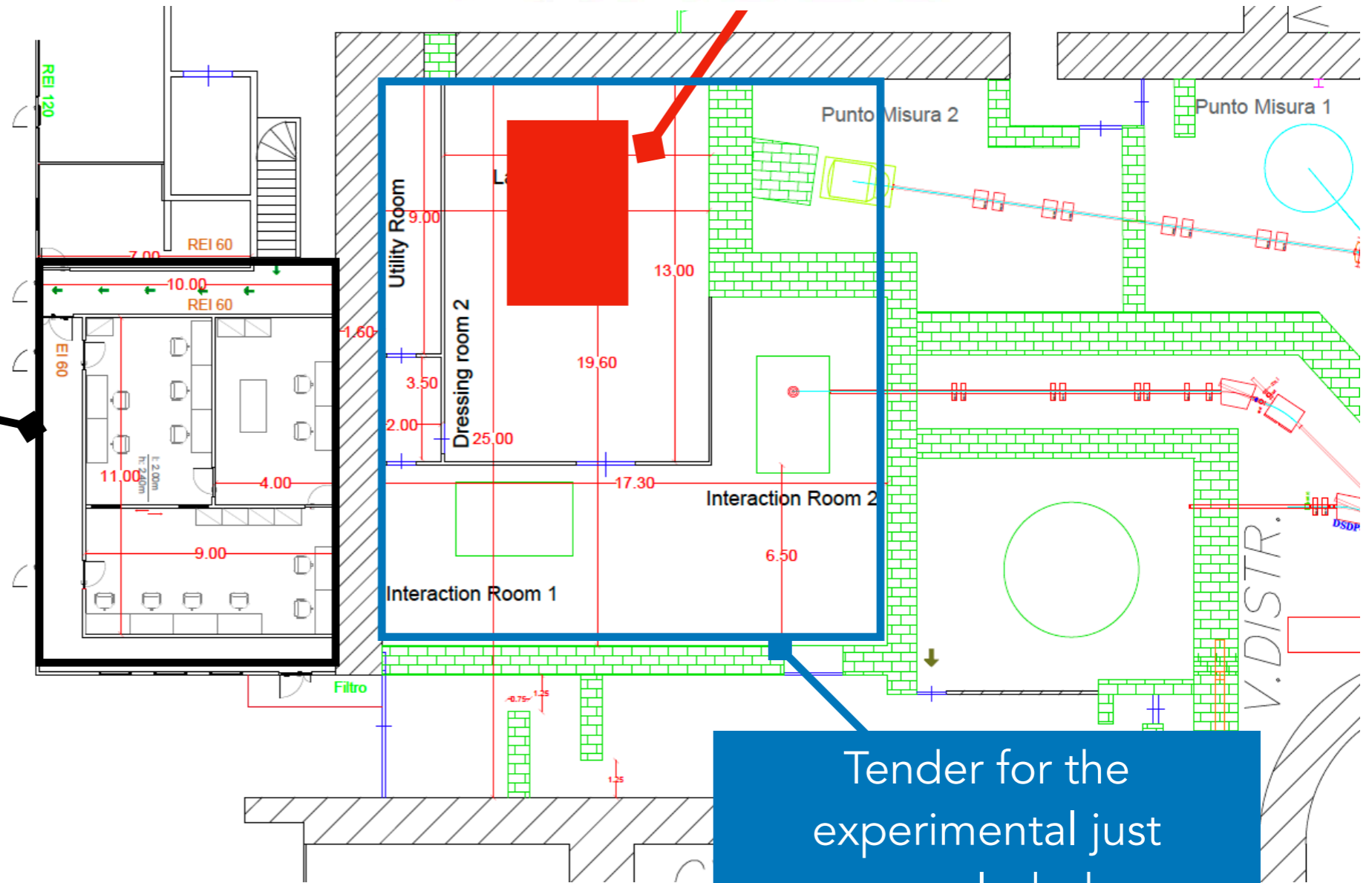
Istituto Nazionale di Fisica Nucleare

24

Laser tender concluded  
Contract to be signed



Control area  
under  
construction



Tender for the  
experimental just  
concluded

# I-LUCE current status



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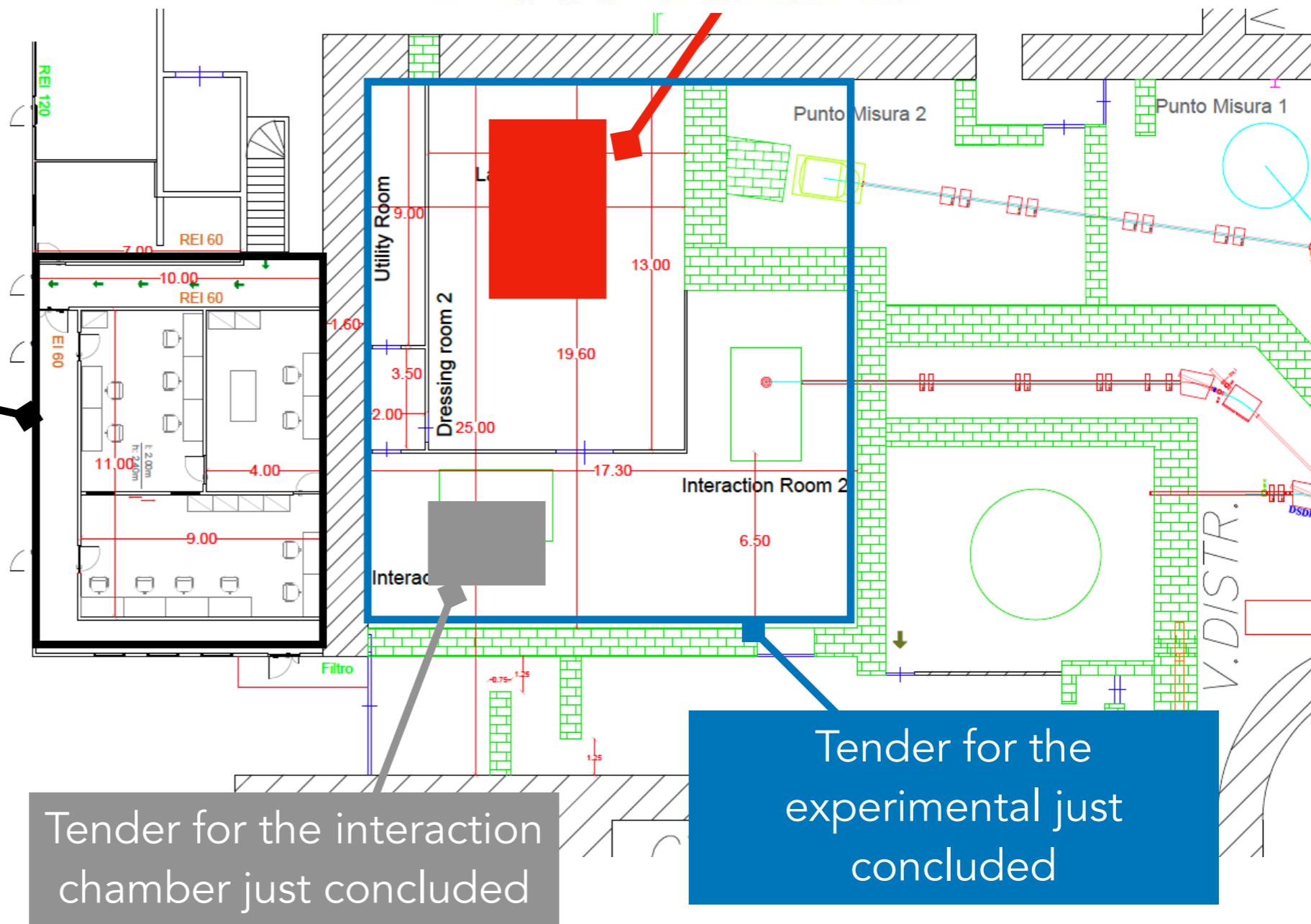
24

Laser tender concluded  
Contract to be signed

# THALES



Control area  
under  
construction



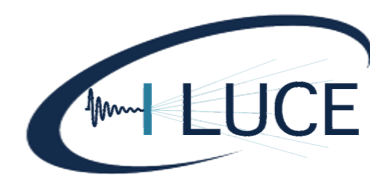
Tender for the interaction  
chamber just concluded

Tender for the  
experimental just  
concluded



# Physics cases at I-LUCE

# What we will have at disposal?



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26

An high power laser: 8J/23fs/1Hz

A plasma generated by the laser:

Temperature: 2 eV - 200 eV

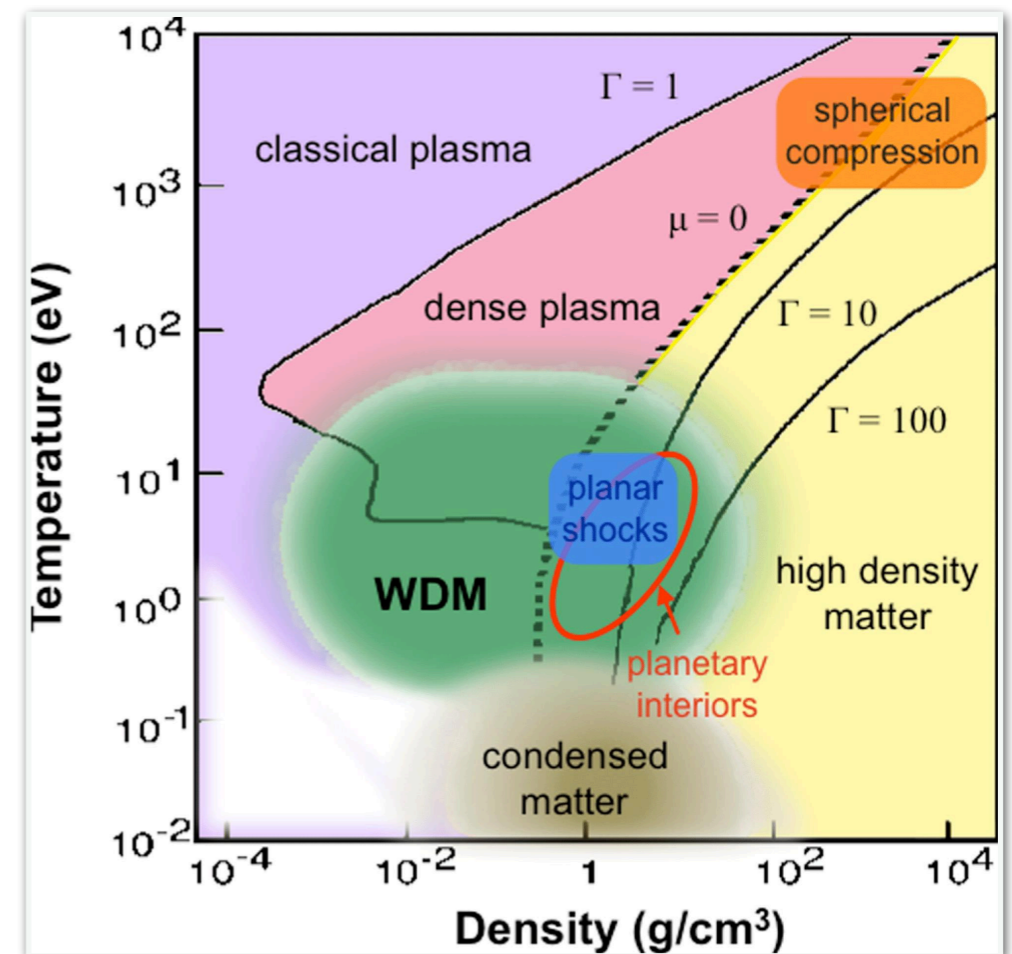
$$T \approx \left( \frac{I}{1.37 \times 10^{16} \text{ W/cm}^2} \right)^{1/2}$$

$$n \approx \frac{I}{e^2 T}$$

Density:  $10^{25} \text{ m}^{-3}$

$$n \approx \frac{\epsilon_0 m_e \omega_p^2}{e^2}$$

Ion beams in a wide Z range and energy up to 70 AMeV



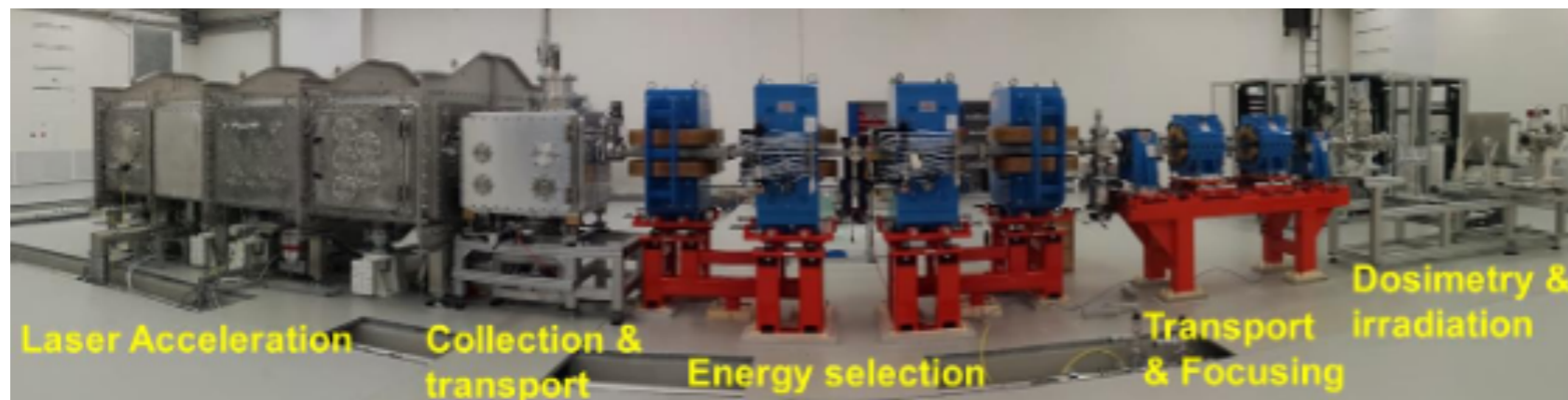
Use of ions/electrons beams for radiobiology studies

....for radioisotope production

... for hydrogen production

....for cultural heritage applications

... for inertial confinement studies



ELIMED/LIMAIA beamline th ELI-Beamlines facility (CZ)



Review

### ELIMAIA: A Laser-Driven Ion Accelerator for Multidisciplinary Applications

Daniele Margarone <sup>1,\*</sup>, G. A. Pablo Cirrone <sup>1,2</sup>, Giacomo Cuttone <sup>2</sup>, Antonio Amico <sup>2</sup>, Lucio Andò <sup>2</sup>, Marco Borghesi <sup>3</sup>, Stepan S. Bulanov <sup>4</sup>, Sergei V. Bulanov <sup>1</sup>, Denis Chatain <sup>5</sup>, Antonín Fajstavr <sup>1</sup>, Lorenzo Giuffrida <sup>1</sup>, Filip Grepl <sup>1</sup>, Satyabrata Kar <sup>3</sup>, Josef Krasa <sup>1</sup>, Daniel Kramer <sup>1</sup>, Giuseppina Larosa <sup>2</sup>, Renata Leanza <sup>2</sup>, Tadzio Levato <sup>1</sup>, Mario Maggiore <sup>6</sup>, Lorenzo Manti <sup>7</sup>, Guliana Milluzzo <sup>2,3</sup>, Boris Odlozilik <sup>1</sup>, Veronika Olsovcova <sup>1</sup>, Jean-Paul Perin <sup>5</sup>, Jan Pipek <sup>2</sup>, Jan Psikal <sup>1</sup>, Giada Petringa <sup>2</sup>, Jan Ridky <sup>1</sup>, Francesco Romano <sup>2,8</sup>, Bedřich Rus <sup>1</sup>, Antonio Russo <sup>2</sup>, Francesco Schillaci <sup>1,2</sup>, Valentina Scuderi <sup>1,2</sup>, Andriy Velyhan <sup>1</sup>, Roberto Versaci <sup>1</sup>, Tuomas Wiste <sup>1</sup>, Martina Zakova <sup>1</sup> and Georg Korn <sup>1</sup>

# Nuclear astrophysics

28

## THE COULOMB EXPLOSION PARADIGM

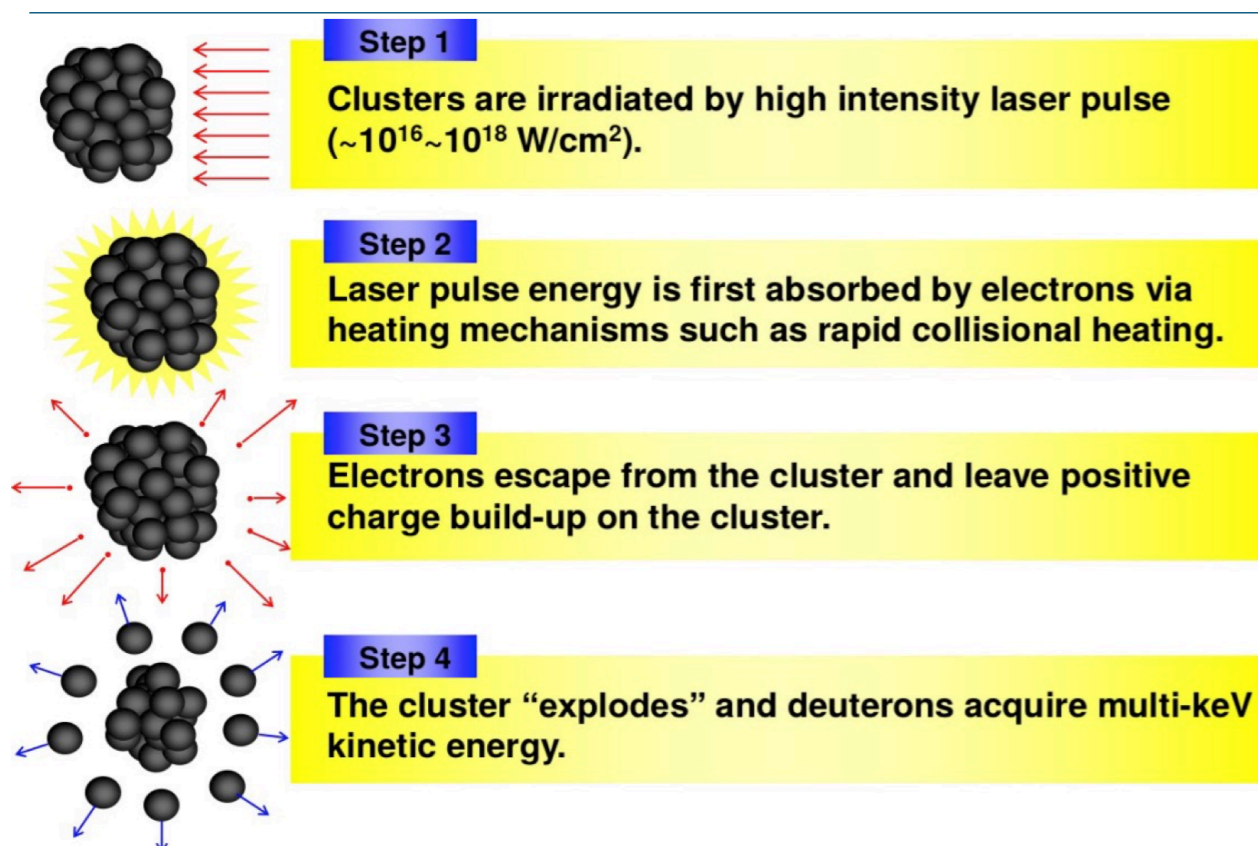
The interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber causes the formation of **plasmas with multi-keV temperature**. These energies overlap with the typical temperatures of stellar environments **where thermonuclear reactions occur**, thus making this paradigm a perfect scenario for nuclear astrophysics research.



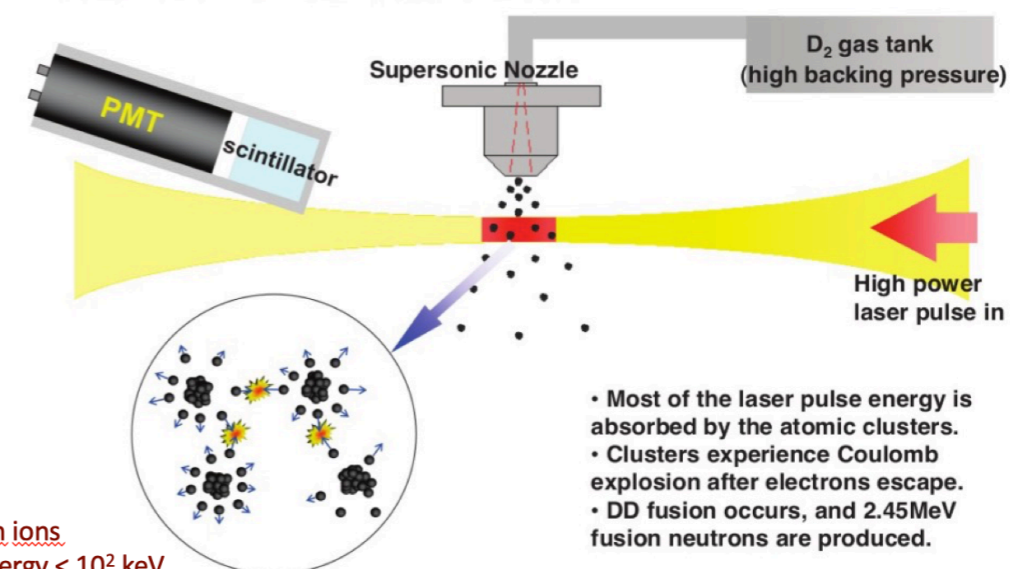
### The AsFiN laser collaboration:

A. Bonasera, G.L. Guardo, M. La Cognata, L. Lamia, D. Lattuada, A.A. Oliva, R.G. Pizzone, G.G. Rapisarda, S. Romano, D. Santonocito, A. Tumino

### Example: deuterium-deuterium fusion



### Nuclear fusion from laser-cluster interaction



deuterium ions  
Kinetic Energy < 10<sup>2</sup> keV  
Density  $\sim 10^{18}$  atoms/cm<sup>3</sup>  
10<sup>5</sup>-10<sup>7</sup> neutrons per shot

## PHYSICAL REVIEW C

covering nuclear physics

Highlights Recent Accepted Authors Referees Search Press About

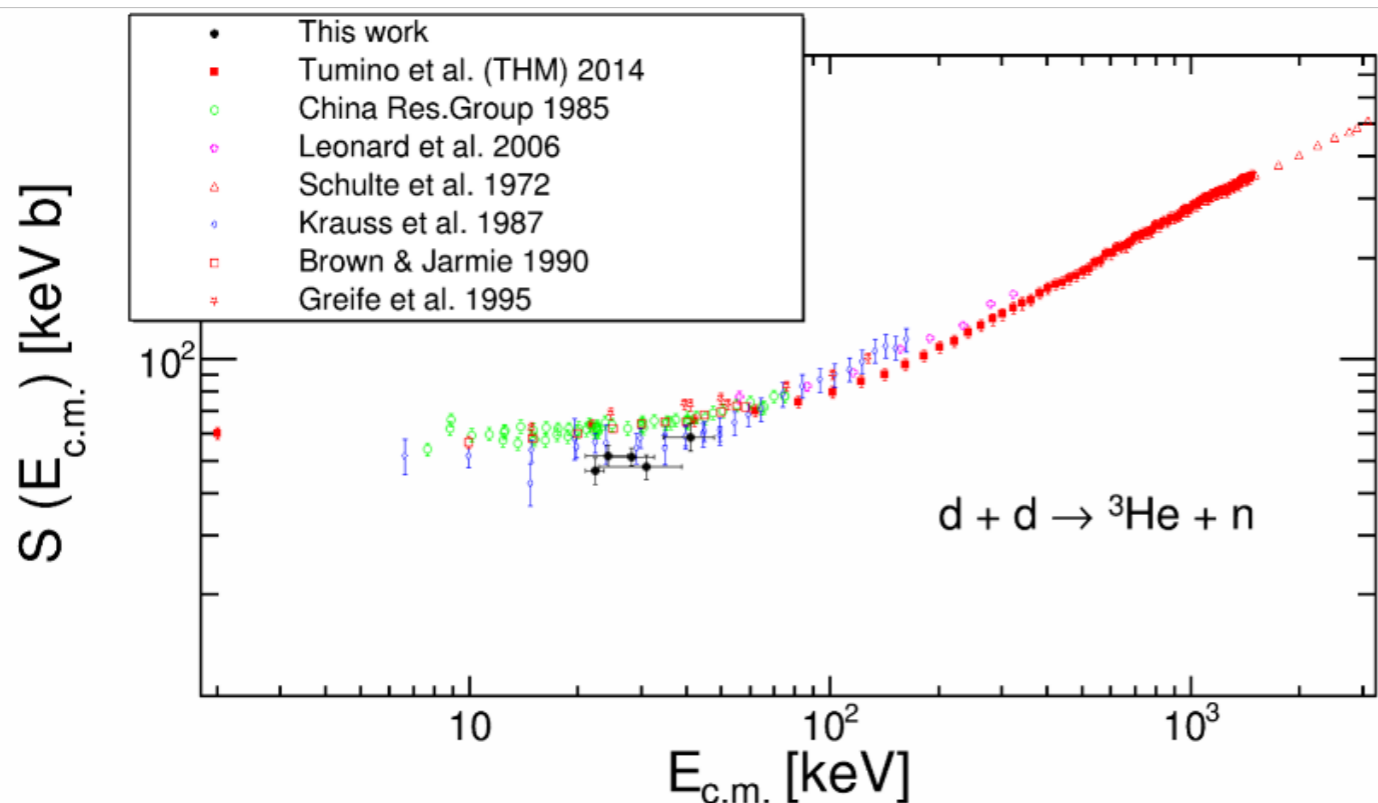
### Model-independent determination of the astrophysical $S$ factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

Phys. Rev. C **93**, 045808 – Published 19 April 2016

This method will open the way for a new approach to study nuclear astrophysics reactions such as:

- deuterium- deuterium
- deuterium- $^3\text{He}$
- proton-lithium
- proton-boron
- $^{12}\text{C}$ - $^{12}\text{C}$
- $^{16}\text{O}$ - $^{16}\text{O}$
- and much more....



Stopping power of ions in plasma is a process of fundamental importance in many applications:

- Inertial Confinement Fusion
- Astrophysics and Nuclear Astrophysics
- High-energy Density Physics
- Plasma strippers
- Solid State Physics

Characterization of ions stopping power in plasma at I-LUCE facility

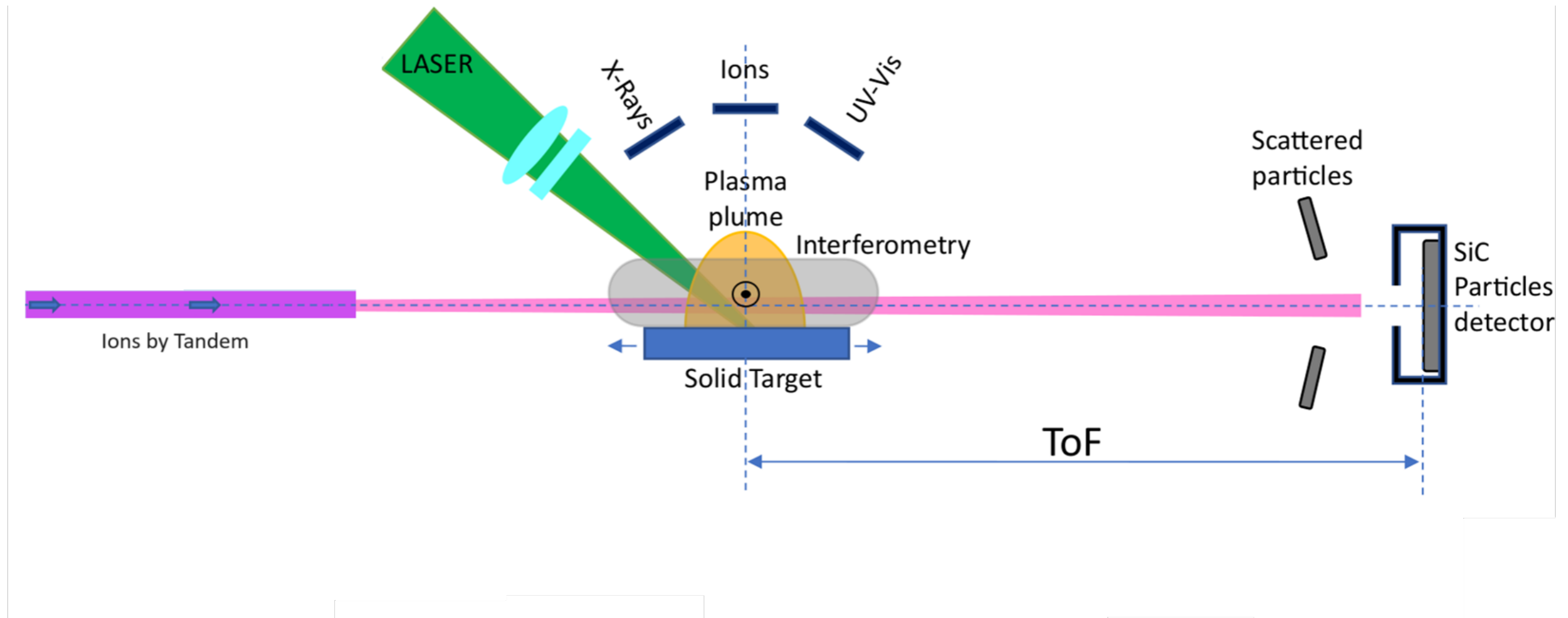
**Collaboration:** C. Altana, G. Castro, S. Cavallaro, C. Ciampi, G.A.P. Cirrone, R. De Angelis, S. De Luca, G. Lanzalone, L. Malferrari, F. Odorici, L. Palladino, G. Pasquali, A. Russo, A. Trifirò and S. Tudisco

**Participating INFN sections:**  
Catania, LNS, LNGS, Bologna, Firenze



# Stopping powers in plasma

31



LNS has the only possibility, together with GSI, to deliver a beam with low energy by Tandem accelerator that cross a plasma plume generated under vacuum by a laser beam interacting with a solid target.

# Nuclear physics mid-term plan



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32

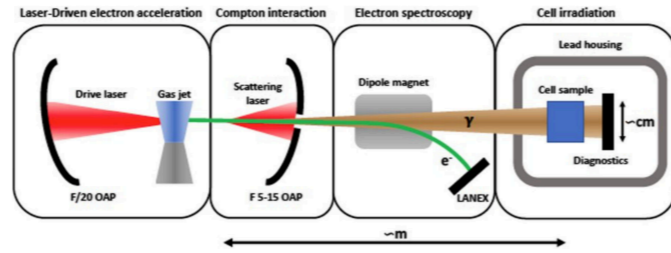
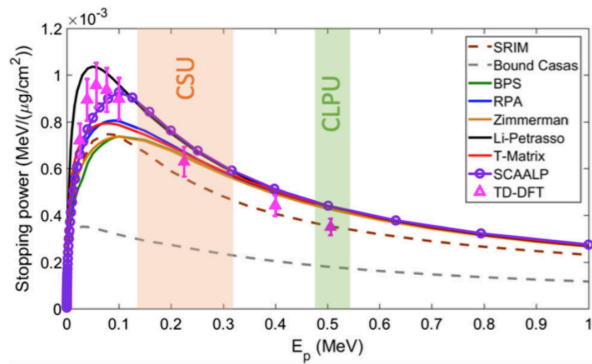
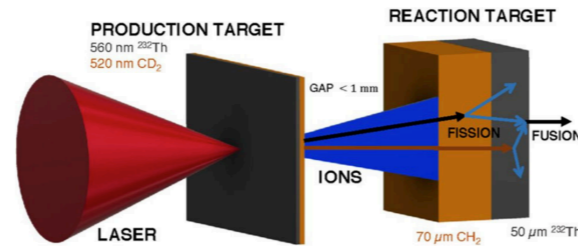


Fig. 48 Setup for the high-brilliance γ production via inverse Compton-scattering (from Sarri et al. [371])

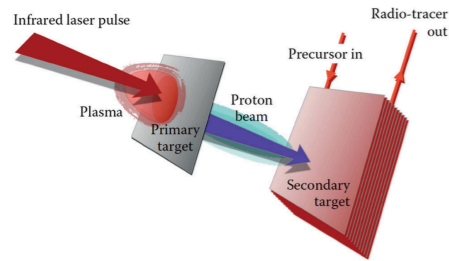
## Chapter 6.2 Laser applications

### Positrons generation

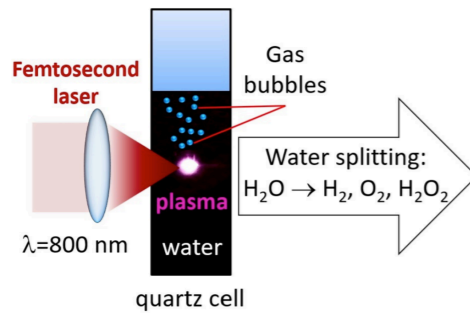


### Nuclear reaction schemes

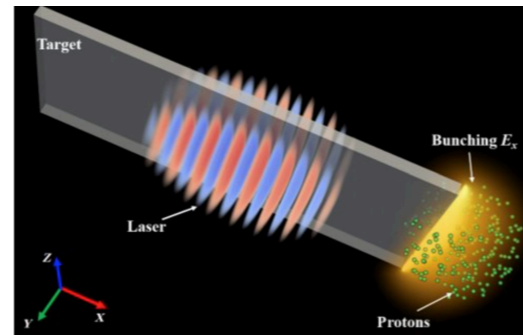
### Stopping power in plasma



### Radioisotopes



### Hydrogen generation



### Protons and electrons generation

Eur. Phys. J. Plus (2023) 138:1038  
<https://doi.org/10.1140/epjp/s13360-023-04358-7>

THE EUROPEAN  
 PHYSICAL JOURNAL PLUS

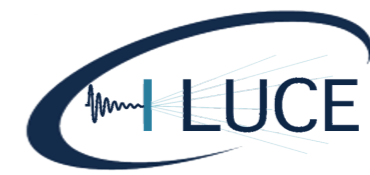
Regular Article

### Nuclear physics midterm plan at LNS

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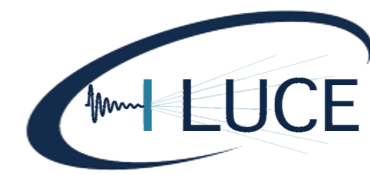
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# Take-to-home message



33

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33

New radiation beams, complementary to the existing ones

New basic physics and multidisciplinary studies (also complementary to other apparatus in realisation, i.e. PANDORA)

A new European facility with unique features

Thanks to everyone

