EUROPEAN UNION

Structural Instruments 2014-2020

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“Investing in Sustainable Development”

Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

E5, E1 and E6 Experimental areas at ELI-NP

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ELIAS2022 - 5 Oct 2022, Magurele-Bucharest (RO)

Outline

- Overview of the activities related to the HPLS
- Overview and Status of the 1 PW experimental area E5
- Commissioning experiments of the 1 PW E5 area
    - TNSA investigation
    - LWFA investigation
- Overview and Status of the 10 PW experimental areas E1 and E6
- Upcoming commissioning of the 10 PW E1 and E6 areas

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ELI-NP Experimental building

Two extreme light beam sources with unprecedented features:

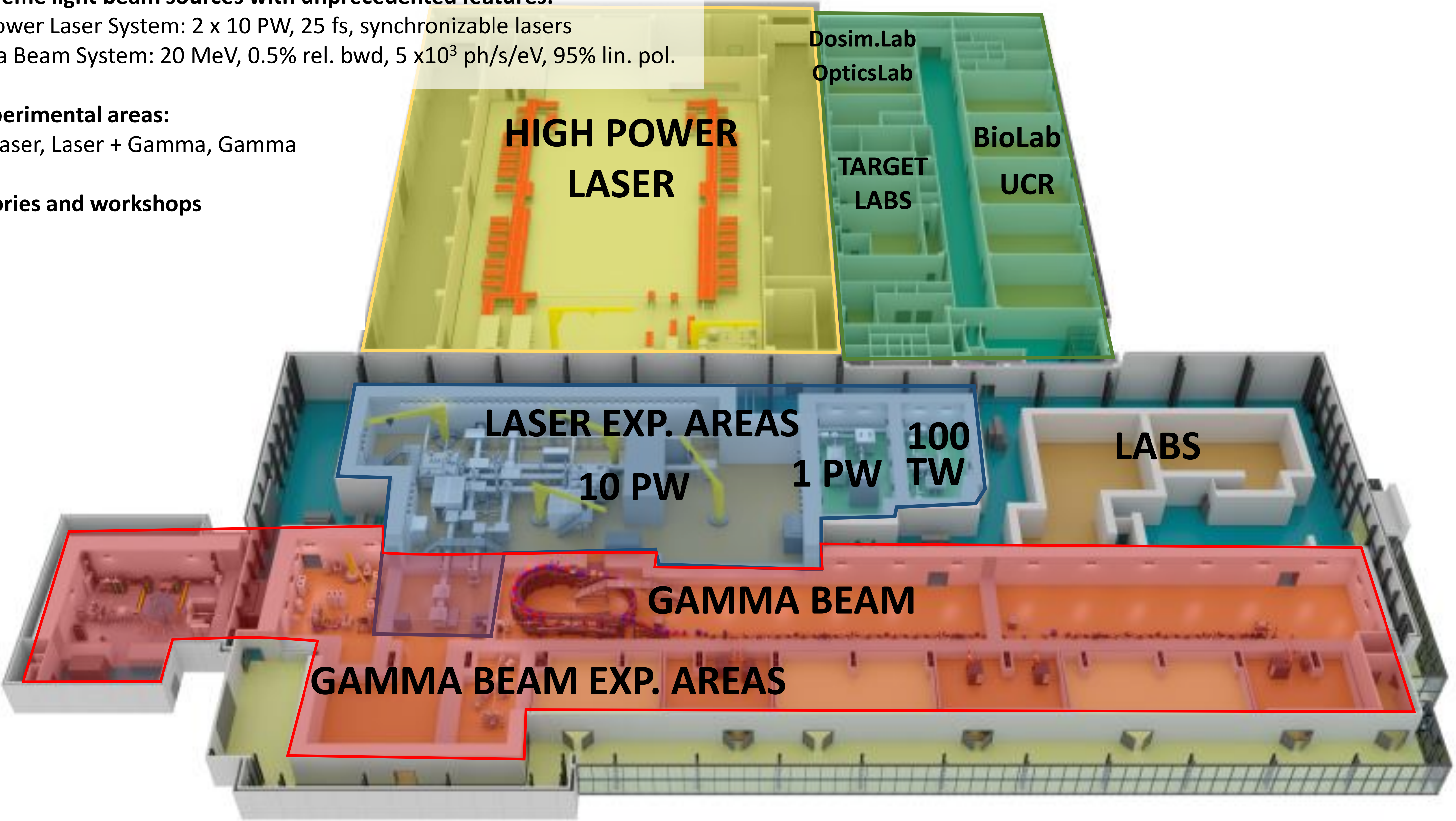
High Power Laser System: 2 x 10 PW, 25 fs, synchronizable lasers

Gamma Beam System: 20 MeV, 0.5% rel. bwd, 5 x10^3 ph/s/eV, 95% lin. pol.

Nine experimental areas:

Laser + Laser, Laser + Gamma, Gamma

Laboratories and workshops



K. A. Tanaka, et al., *Current status and highlights of the ELI-NP research program, Matter and Radiation at Extremes*, **5** (2020) 024402.

ELI-NP Experimental activities

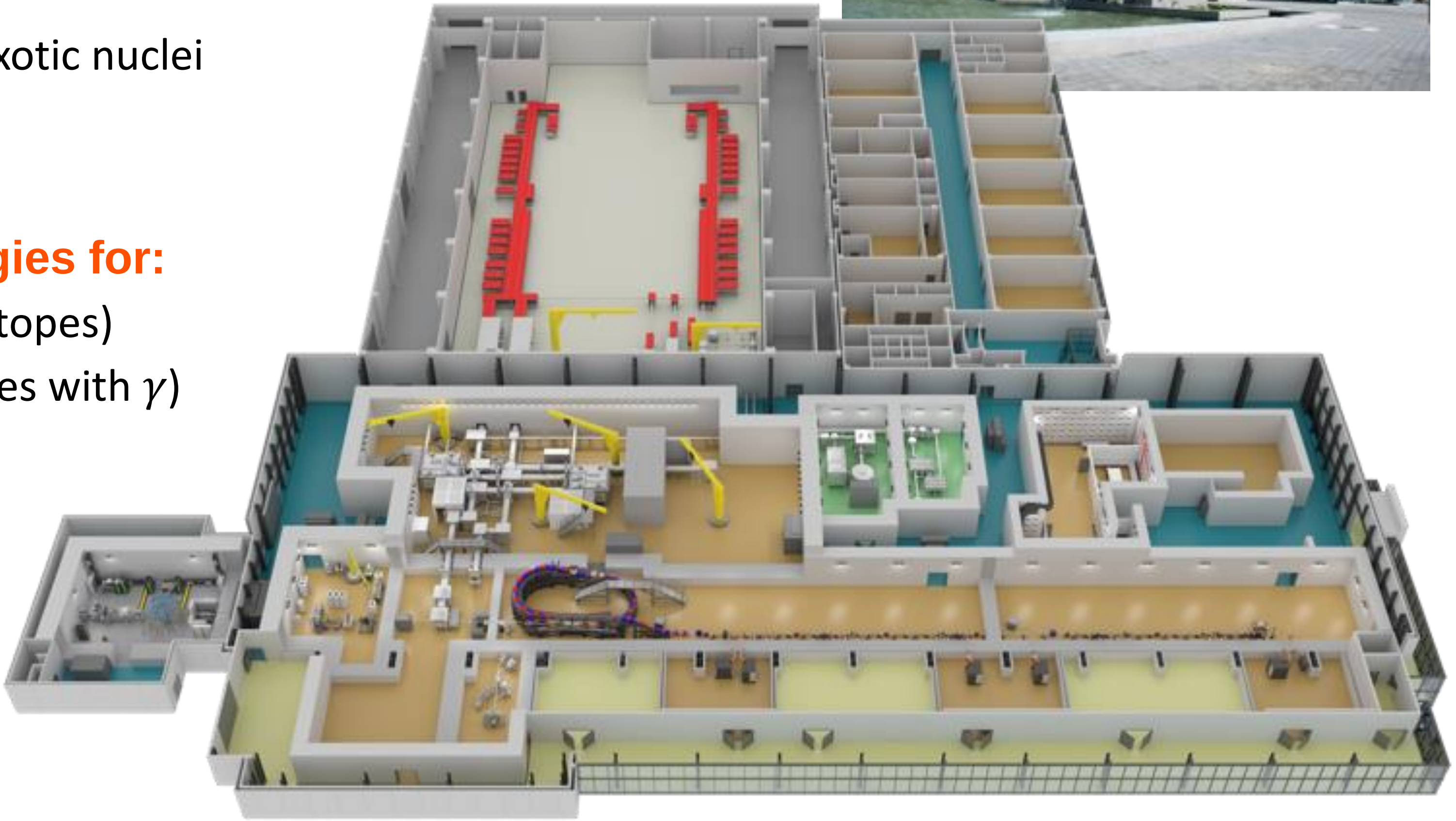
Advanced studies in basic science ...

- characterization of laser-matter interaction with nuclear methods
- particle acceleration with high power lasers
- nuclear reactions in plasma
- photonuclear reactions, nuclear structure, exotic nuclei
- nuclear astrophysics and nucleosynthesis
- quantum electrodynamics (QED)

... and applications – developing technologies for:

- medical applications (X-ray imaging, radioisotopes)
- industrial applications (non-destructive studies with γ)
- material studies with positrons
- materials in high radiation fields

Experimental building

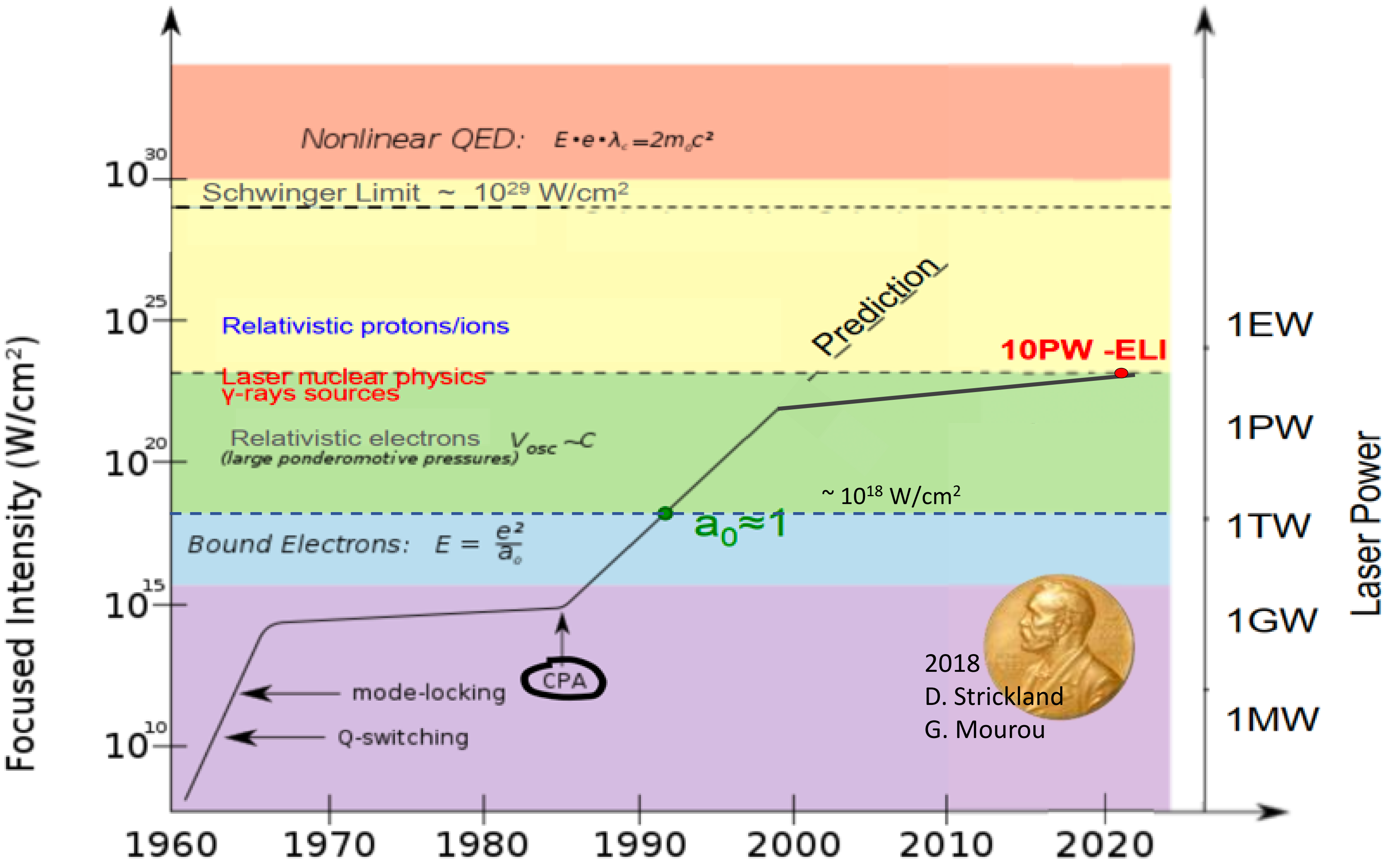


2015 Technical Design Reports
assessed by ELI-NP ISAB

Rom. Rep. Phys. Vol. 68 (2016)

K. A. Tanaka, et al., *Current status and highlights of the ELI-NP research program, Matter and Radiation at Extremes*, **5** (2020) 024402.

Laser-Driven Acceleration



$$a_0 = \frac{\overset{\text{Particle momentum}}{eE_0c/\omega}}{\underset{\text{particle rest energy}}{m_0c^2}} \sim \overset{\text{Irradiance}}{I_0^{1/2}}\lambda$$

Electron DLA (m=0.511 MeV/c²)

$\lambda_L \sim 0.81\ \mu m \Rightarrow I_0 \sim 2\cdot 10^{18}\ W/cm^2$

Proton DLA (m=938 MeV/c²)

$\lambda_L \sim 0.81\ \mu m \Rightarrow I_0 \sim 7\cdot 10^{24}\ W/cm^2$

ELI-NP

$\lambda_L \sim 0.81\ \mu m \Rightarrow I_0 \sim 10^{23}\ W/cm^2$

Other HPLS projects

- **Apollon** laser of 10 PW, CNRS-LULI, France
- Shanghai Superintense Ultrafast Laser Facility (**SULF**) 10 PW, Shanghai, China
- **LFEX** (Laser for Fast Ingnition Experiments) working for a 30-PW device, Japan
- Station of Extreme Light (**SEL**) 100 PW laser, Shanghai, China
- Exawatt Center for Extreme Light Studies (**XCELS**) for 180 PW, Russia

Chirped pulse amplification (CPA)

G. E. Cook,"Pulse Compression-Key to More Efficient Radar Transmission", IEEE Proc. IRE 48, 310 (1960)

D. Strickland and G. Mourou, “Compression of amplified chirped optical pulses”, Opt. Commun. 56, 219 (1985)

Commissioning experiments with the HPLS

Recent commissioning of 1 PW (ended in Q3 2022)

E5 1 PW:

- Benchmark TNSA proton acceleration (P.I. M. Cernaianu)
- Benchmark LWFA electron acceleration (P.I. P. Ghenuche)

Upcoming commissioning of 10 PW (from Q4 2022)

E1 10 PW solid target (P.I. D. Doria):

- Demonstrate extreme focal intensity through laser-γ conversion (“γ-flash”)
- Demonstrate 200 MeV proton acceleration
- Dense heavy ion beams for nuclear physics (time permitting)

E6 10 PW gas target (sometime in 2023):

- 10 PW laser wake-field acceleration of multi-GeV electron beams (P.I. P. Ghenuche)

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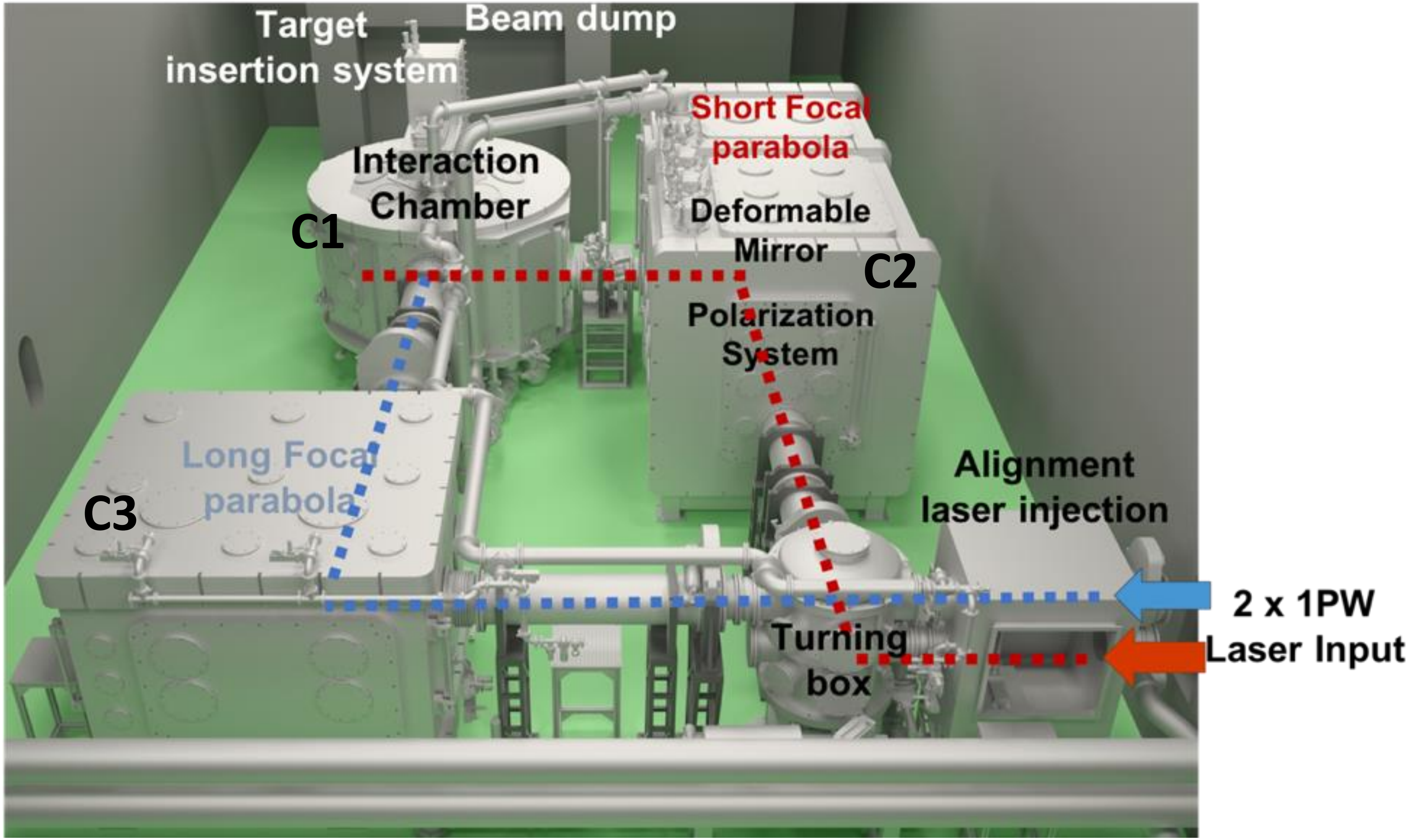
Overview of E5 area

The E5 area is **the 1 PW area** and will accommodate experiments on:

- solid targets

- and gas targets

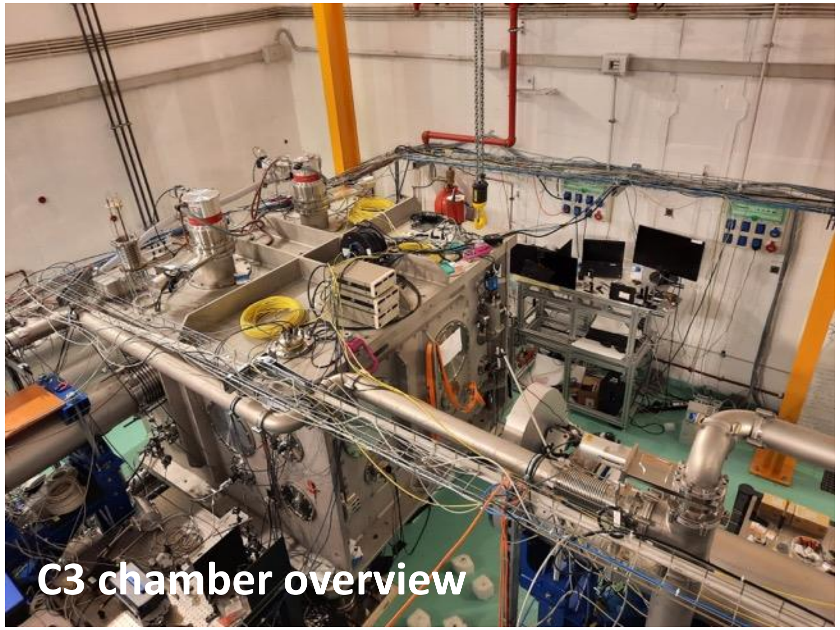


1 PW experimental area (E5)

E5 Overview

1 PW experimental area (E5)


C3 chamber


C3 chamber overview

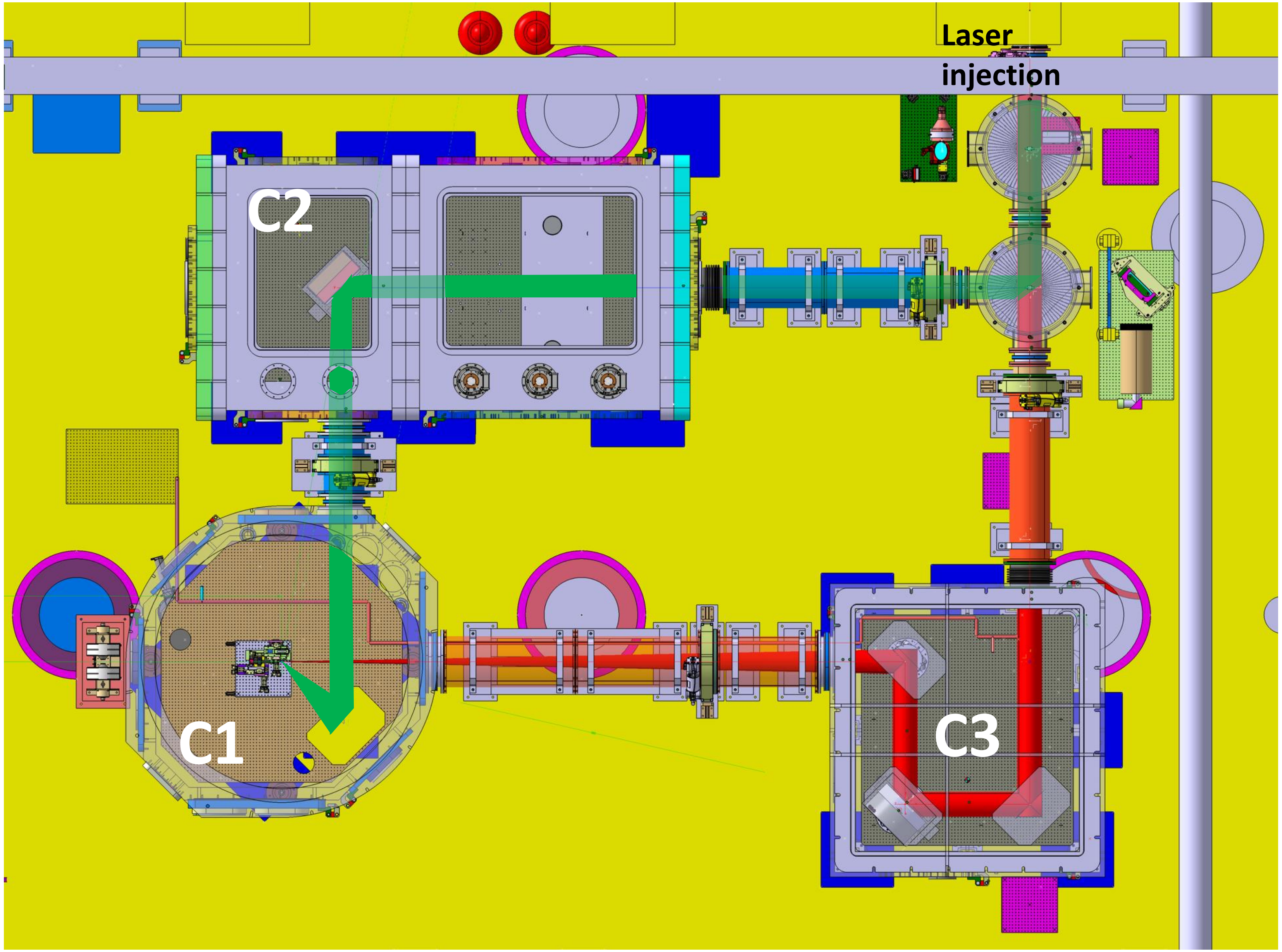

Cleanroom


C1 chamber

1 PW area infrastructures

- 1 main interaction chamber (C1) in Aluminium
- 2 turning boxes + 2 large chambers (C2, C3) in stainless steel
- 9 turbomolecular pumps (1 cryo-pump on demand may be possible)
- Integrated control system, automatic/ manual modes
- C1 typical pump time: 90 mins; venting + opening: 60 mins
- Vacuum level up to 10^{-6} mbar
- Small soft-wall cleanroom – equiv. ISO7

Overview of E5 area



Large Optics available

- 12”x8’’ rectangular flat mirrors w/ motorized mounts
- F = 5000mm off-axis parabola, AOI = 45°
- F = 710mm off-axis parabola, AOI = 22.5°

Other tools

- Internal Injection Alignment Laser: CW 632-800nm, 150mm dia.
- Linear/Circular Polarization: large Mica waveplates
- 5X –40X objectives alignment system,
- Alignment system: 1µm spatial resolution motion
- Deformable Mirror

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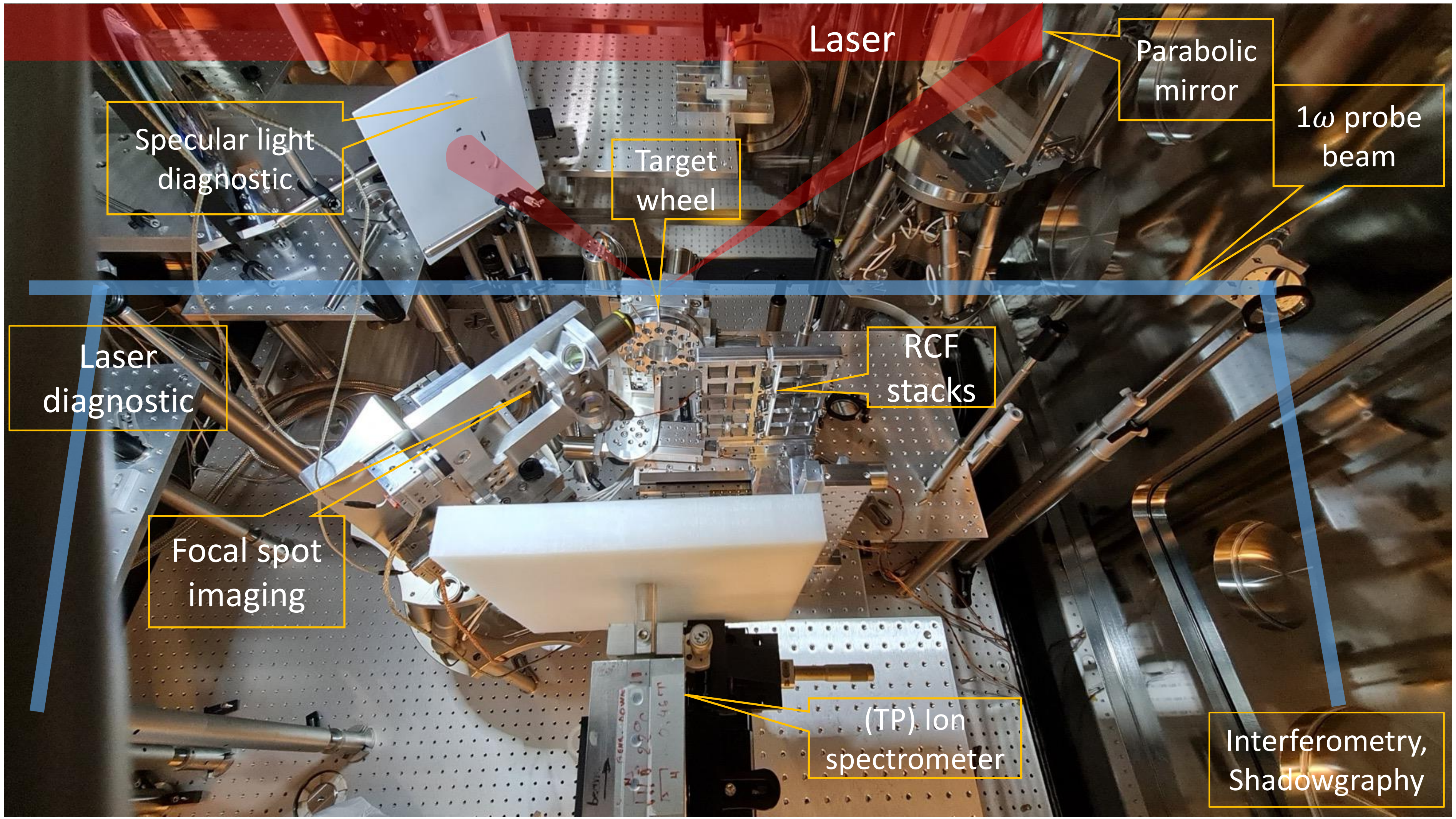
1 PW commissioning: solid targets



Main diagnostics:

- 16 RCF stacks
- TP Ion spectrometer: online Lanex readout or IP plates.
- Laser specular and back reflection energy measurement
- Specular and back reflected laser spectrum
- Laser near field (full aperture), Far field, Energy, Spectrum (pick-up) on-shot
- Plasma probing: Shadowgraphy, Interferometry
- Pulse duration (Laser bay and Experimental area)
- Temporal Contrast measurement

1 PW commissioning with solid targets (TNSA investigation)

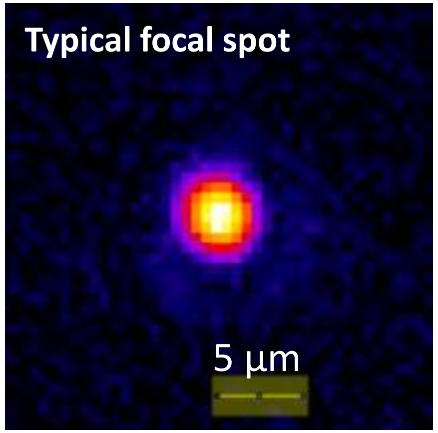
Laser characteristics with the shot focal mirror

Parabolic mirror: 710 mm focal length (F# ~3.7)

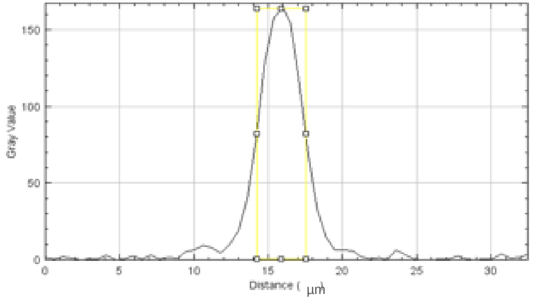
Spot size diameter: ~ 3.6 ± 2 μm at FWHM

Encircled energy: ~ 65% @ $1/e^2$ (ideal Gaussian beam is 86%)

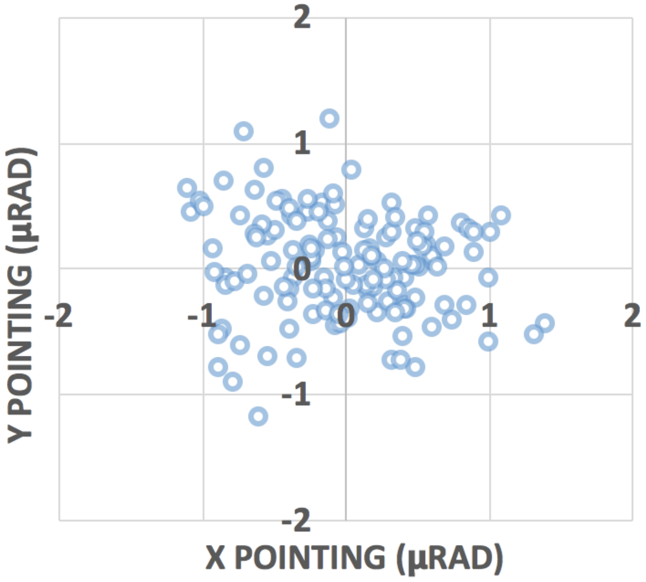
Laser energy stability at full power: ±2%
Laser pointing stability on target: < 2 μrad



Laser beam profile



Pointing fluctuation

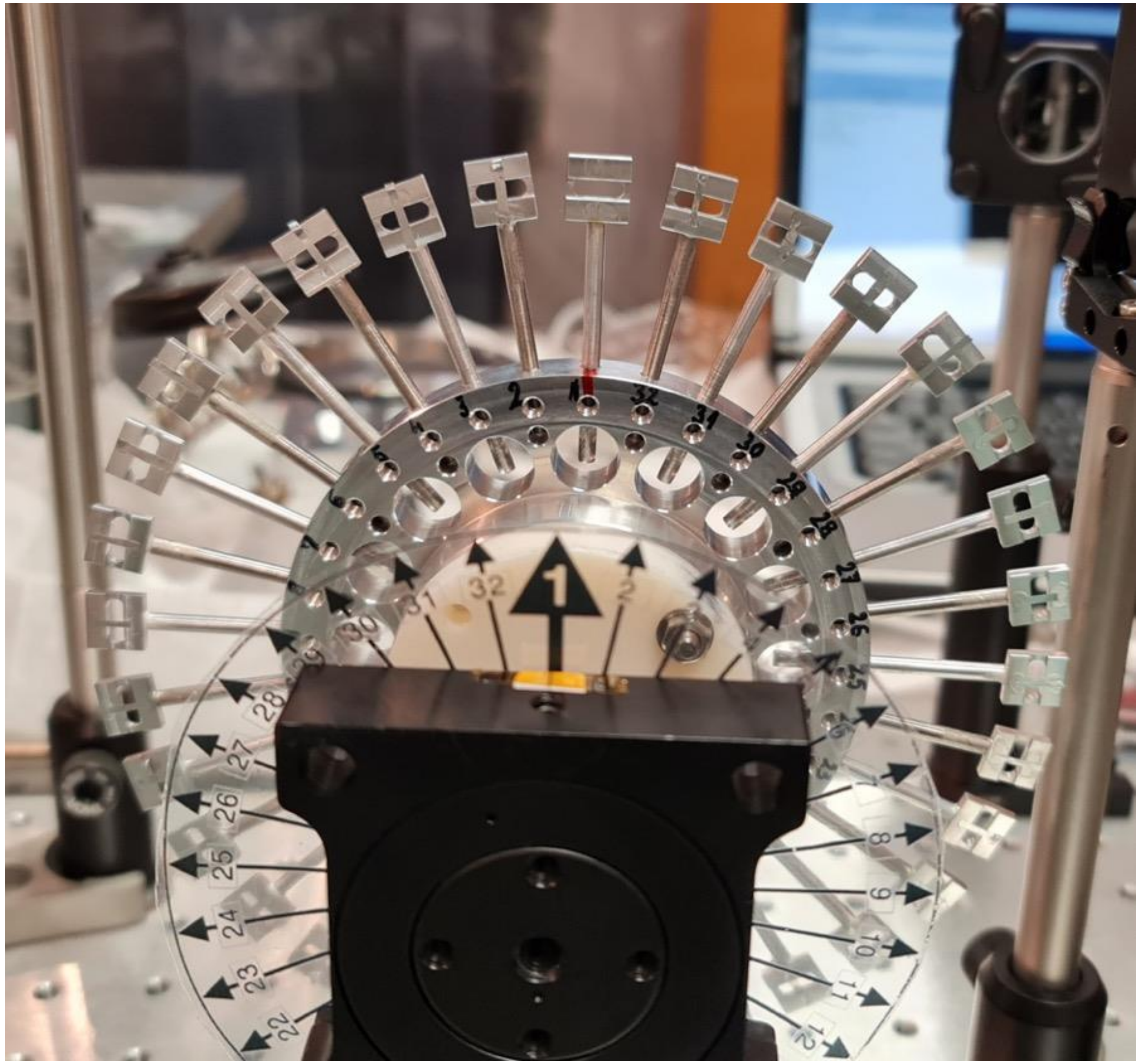



Typical NF image of fully amplified laser attenuated to 25 μJ

1 PW commissioning with solid targets (TNSA investigation)

Targetry and target alignment

32 targets individually aligned for a day of shooting

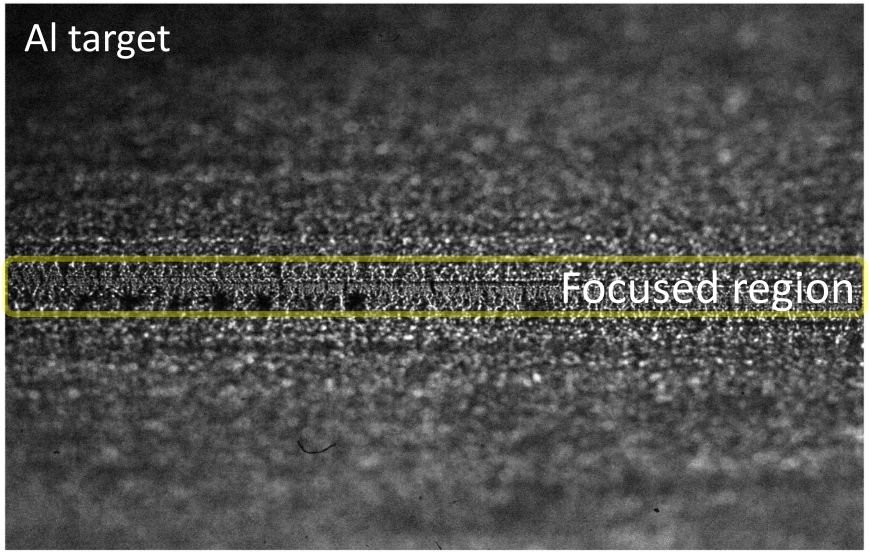


Al target foils mounted on holder

Before shot

After shot - exploded

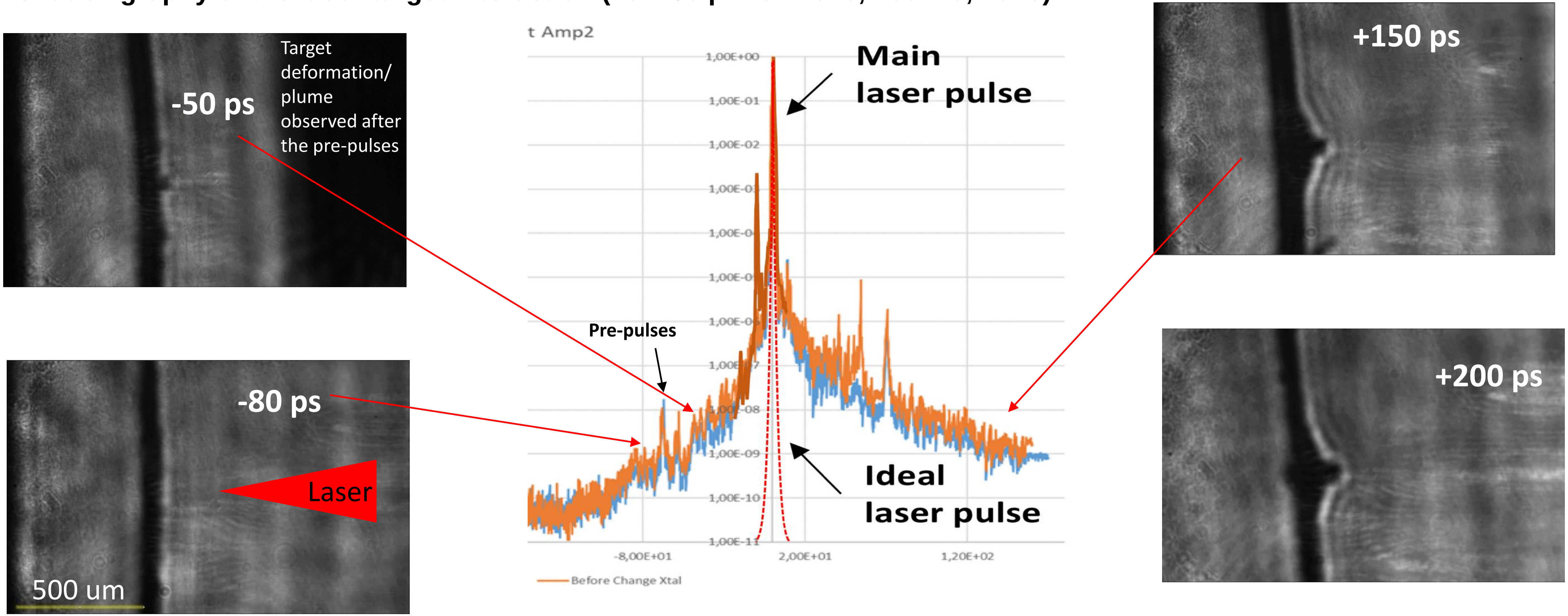
Targets aligned in focus before shooting



1 PW commissioning with solid targets (TNSA investigation)

Laser contrast investigation

Shadowgraphy of the laser-target interaction (15 – 30 µm CH foils, 400 mJ, 25 fs)

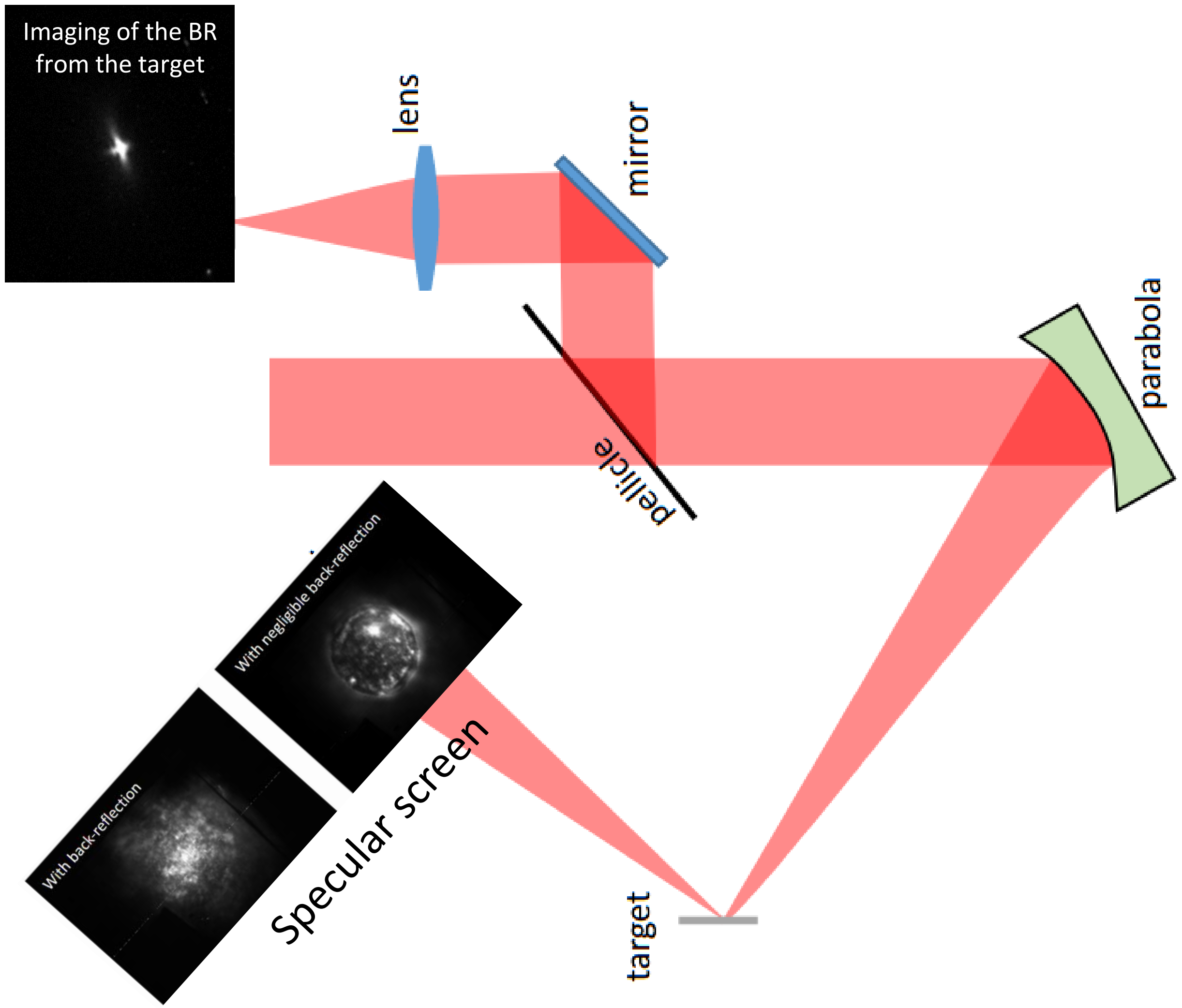


- The pre-pulses issue has been solved during the commissioning.
- The contrast due to the pedestal is at the moment of the order of 10^{-8} at about -20 ps.
- Further, improvement of the pedestal is in progress.

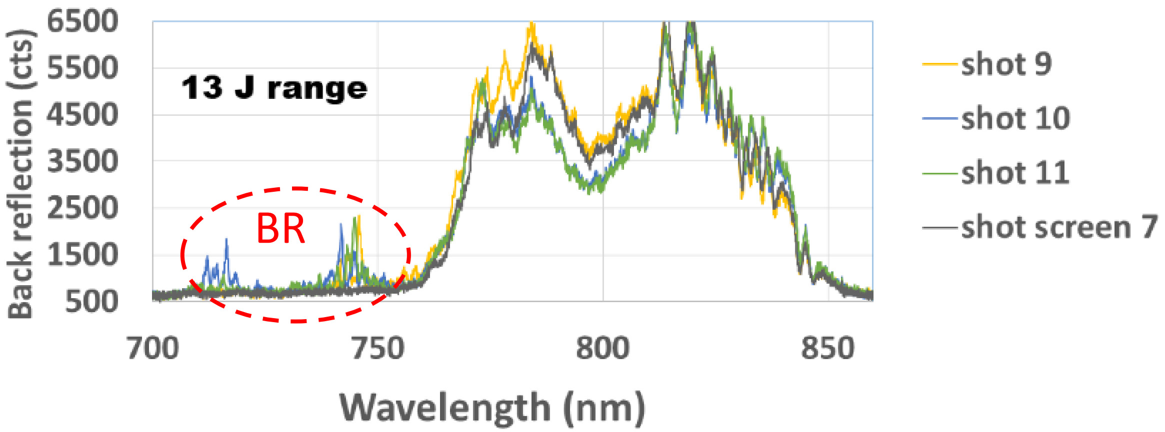
1 PW commissioning with solid targets (TNSA investigation)

Laser specular and back reflection measurements

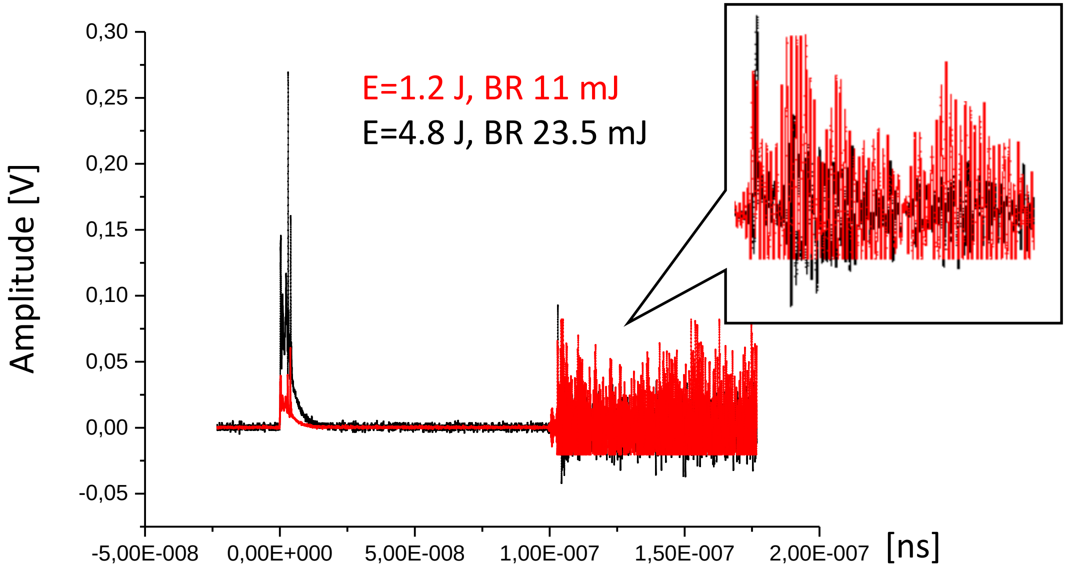
Laser pre-pulses induced strong laser back-reflections



13J laser pulse spectrum (right) and BR pulse (left) for several shots



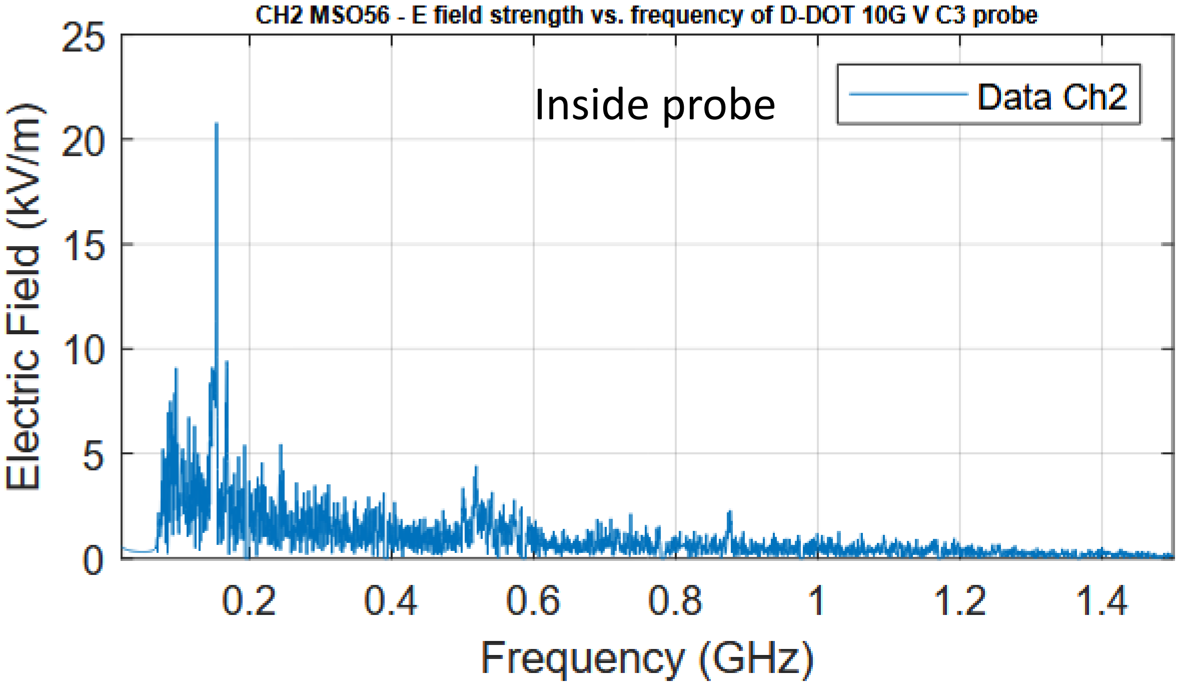
Fast photodiode diagnostic of the back-reflected pulse



BR attenuation measured in different conditions: w/o prepulse, plasma mirror

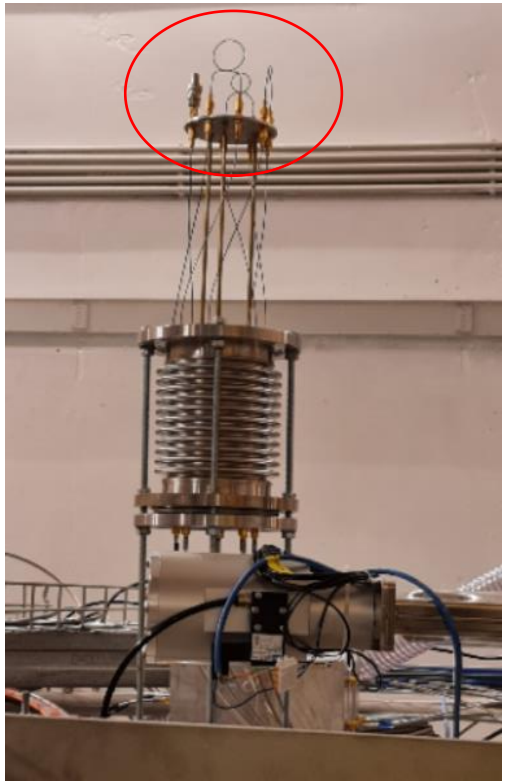
1 PW commissioning with solid targets (TNSA investigation)

EMP measurement



Inside probe

Outside probe



Measurements by M. Gugiu

EMP values of ~tens of kV/m were measured inside the vacuum chamber

1 PW commissioning: solid targets

First operation in 2021 – ion acceleration from solid targets

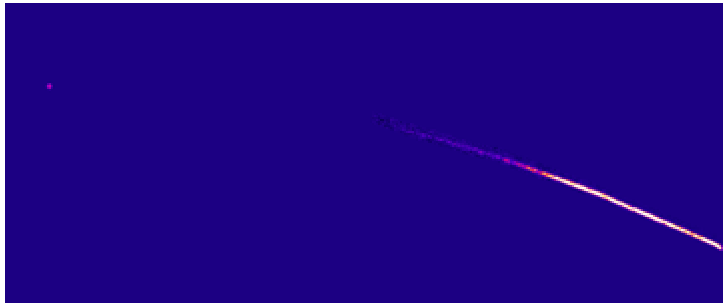
Thick and thin foils (e.g. Al, CH, DLC)

F=707mm parabola

We have started with 20 TW laser power, then we went gradually up to 100s of TW, and then finally to full power of 1 PW.

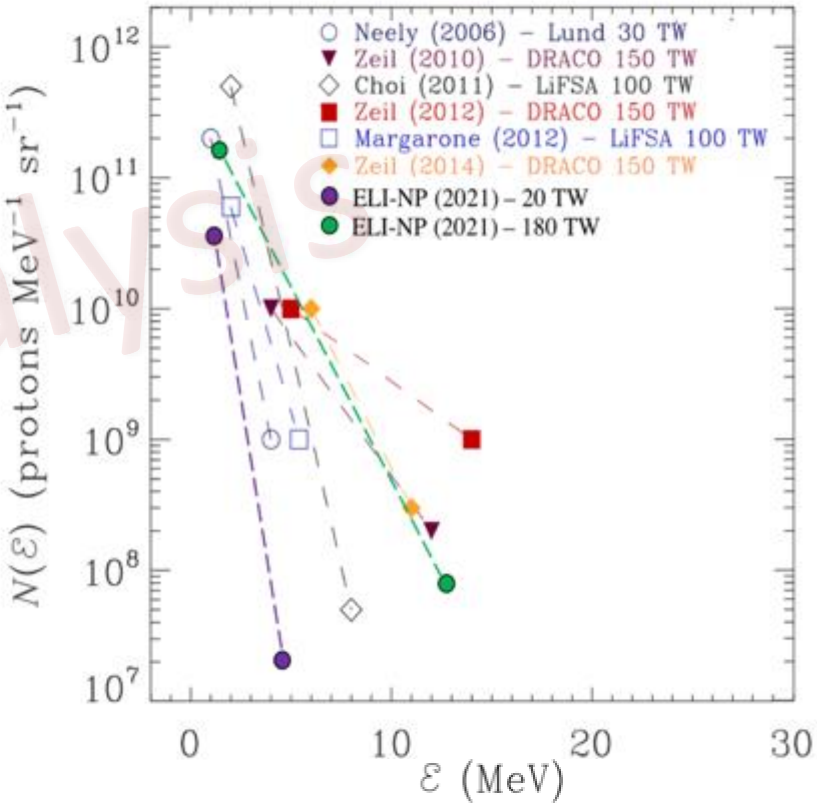
2 sample shots from the 1 PW campaign

Thomson Parabola

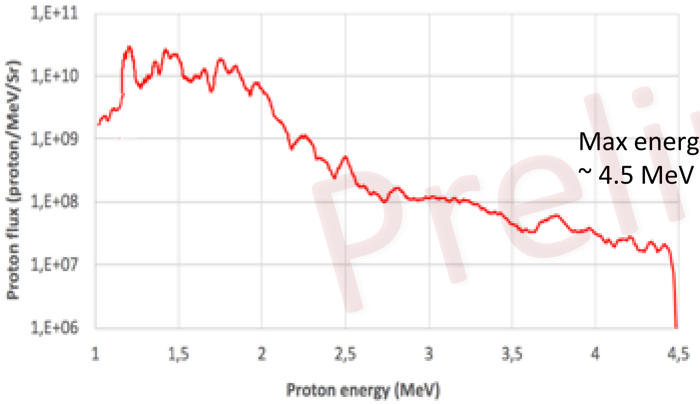


Radiochromic film stack

Comparison with the literature: results are consistent

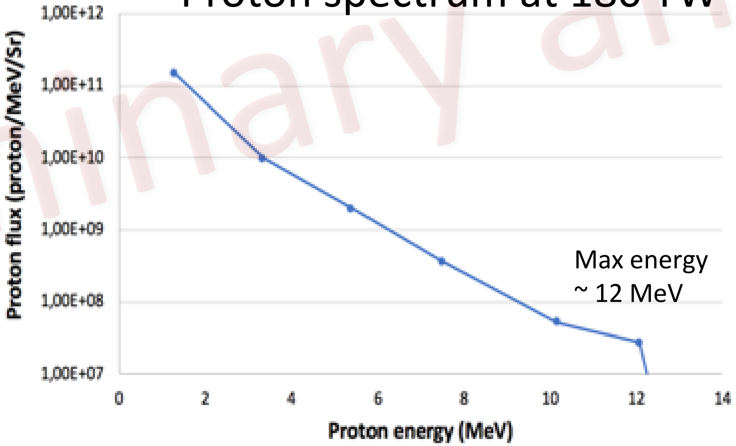


Proton spectrum at 20 TW



Max energy
~ 4.5 MeV

Proton spectrum at 180 TW



Max energy
~ 12 MeV

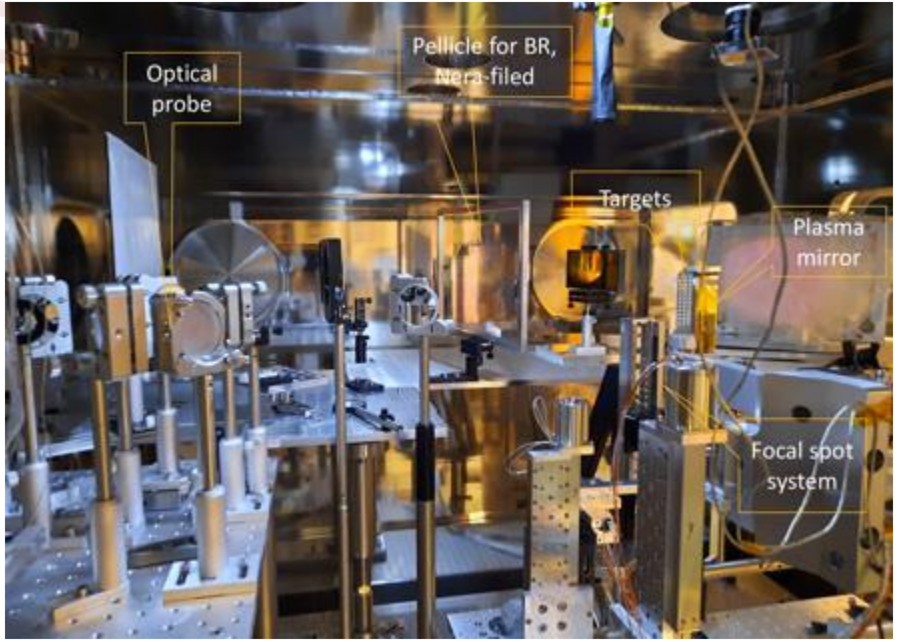
1 PW commissioning with solid targets (TNSA investigation)

Some result of TNSA

First operation in 2021 – ion acceleration from solid targets

- Thick and thin foils (e.g. Al, CH, DLC)
- F=710mm parabola
- Max. proton energy attained of 50 MeV with SPM
- Max. ion energy attained: carbon ion 15 MeV/n from DLC target by using a SPM.

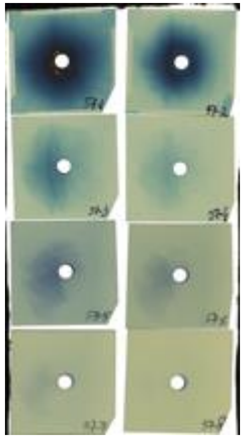
Experimental setup with PM



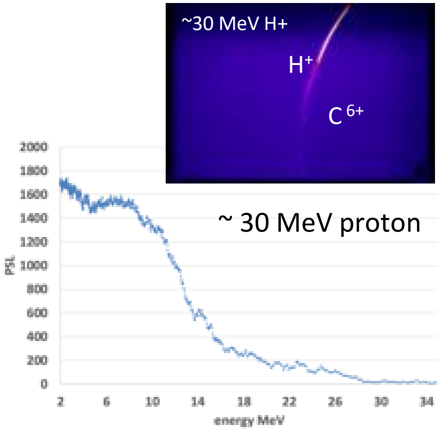
Shot parameters with plasma mirror

Laser beam power:
23.1 J, ~26 fs ➔ 880 TW
Intensity on target: ~ 4 x10^{21} W/cm^2
Target: 1.5 µm Al foil

Radiochromic film stack

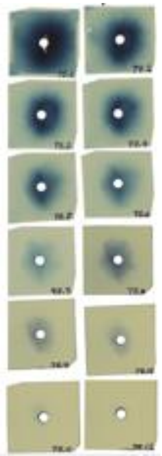


Thomson parabola data

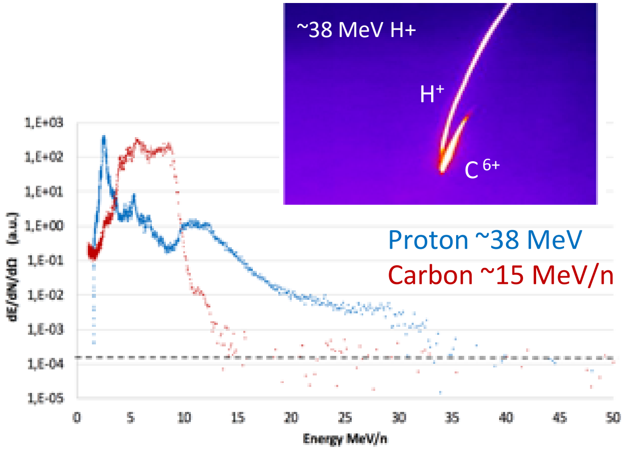


Laser beam power:
19 J, ~75 fs ➔ 250 TW
Intensity on target: ~ 1 x10^{21} W/cm^2
Target: 380nm DLC (built in house)

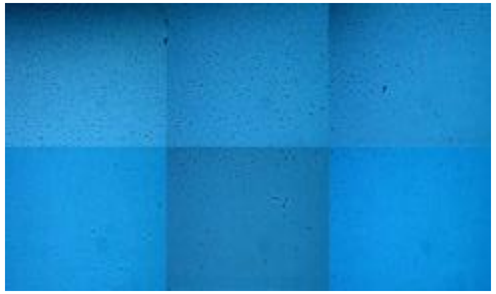
Radiochromic film stack



Thomson parabola



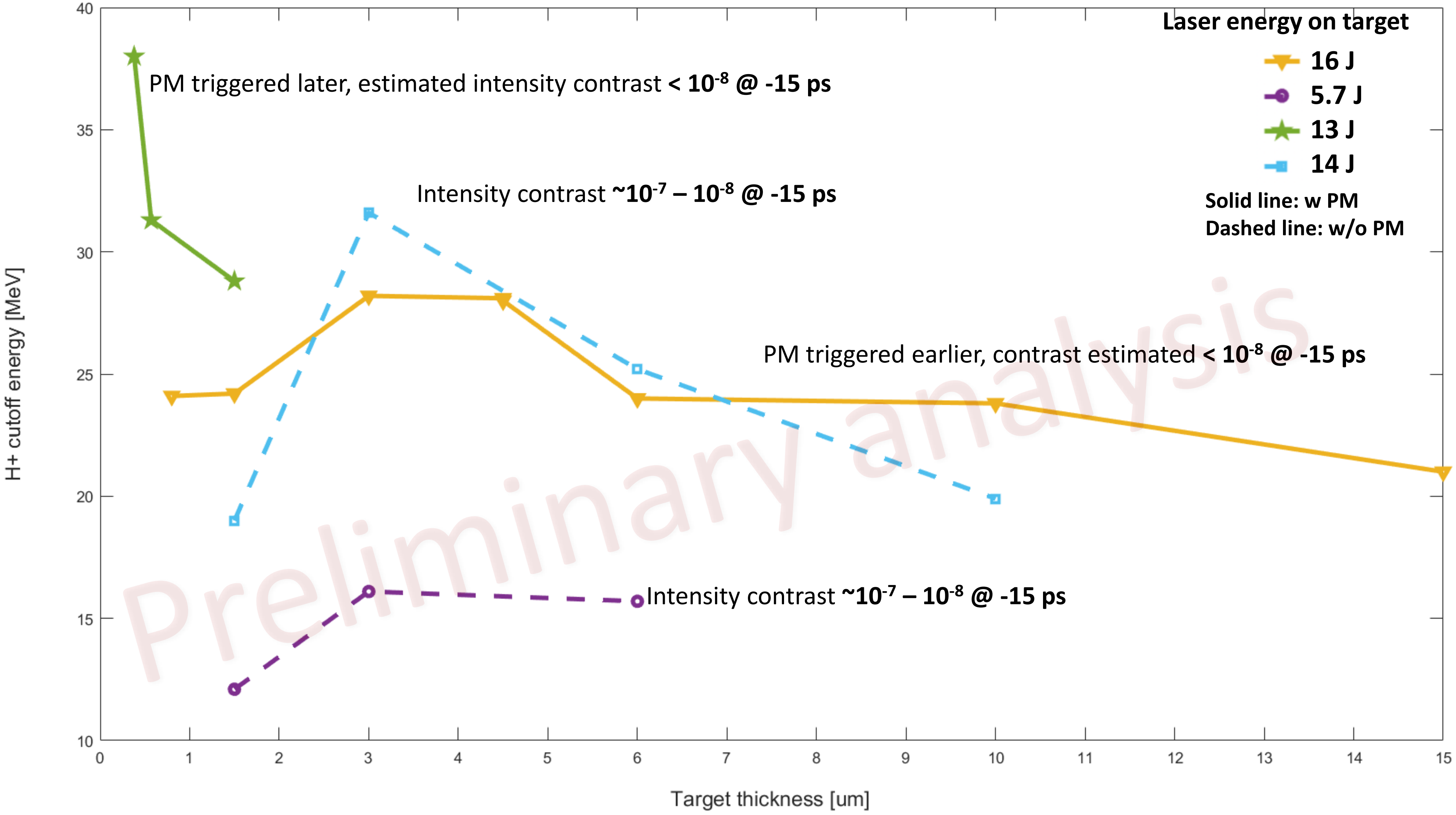
CR-39 show E_p > 50 MeV



Proton density ~ 10^3 protons /cm^2

1 PW commissioning with solid targets (TNSA investigation)

Scan of maximum proton energy with target thickness, and laser energy with different temporal contrast



PM triggered later, estimated intensity contrast **< 10^{-8} @ -15 ps**

Intensity contrast **~10^{-7} – 10^{-8} @ -15 ps**

PM triggered earlier, contrast estimated **< 10^{-8} @ -15 ps**

Intensity contrast **~10^{-7} – 10^{-8} @ -15 ps**

Solid line: w PM
Dashed line: w/o PM

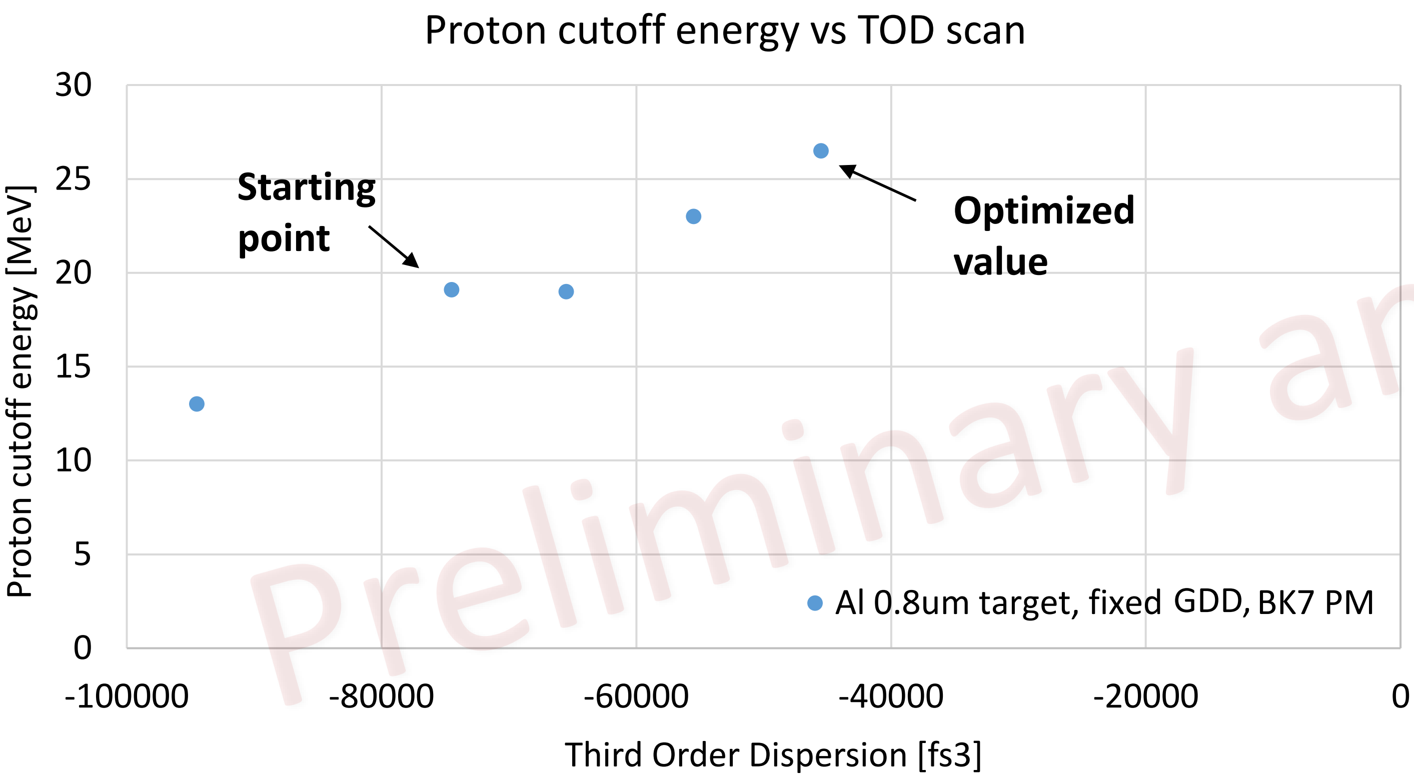
Temporal contrast improvement allowed the increasing of the cutoff energy for thin targets

1 PW commissioning with solid targets (TNSA investigation)

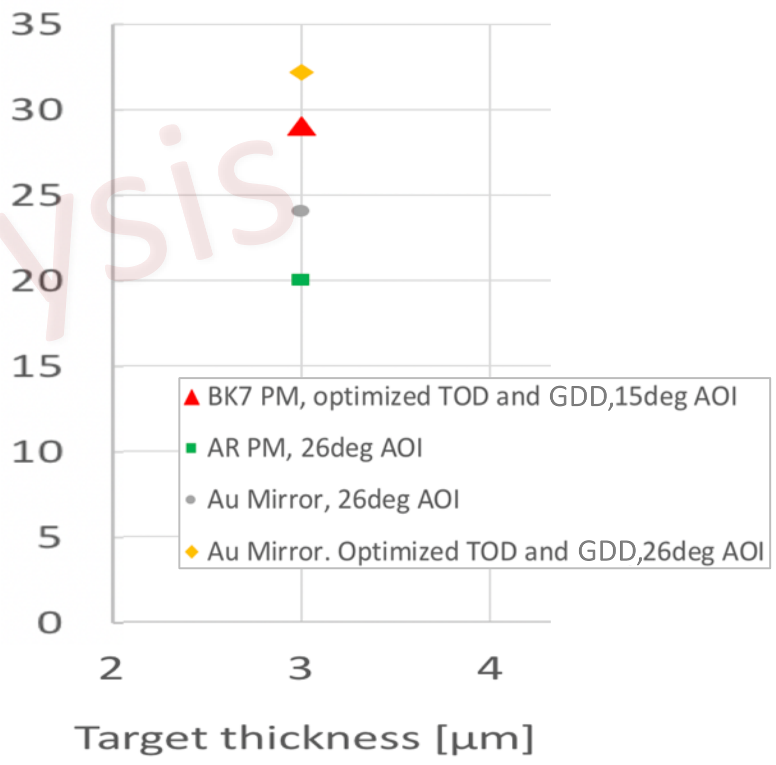
Further improvement through TOD optimization

Scan of TOD and GDD to optimize the laser-target interaction

Laser energy on target ~ 12 J



Laser shots on 3 µm Al varying TOD and PM type



Third order dispersion (TOD) optimization yielded to an increase of ~40% of the proton cutoff energy

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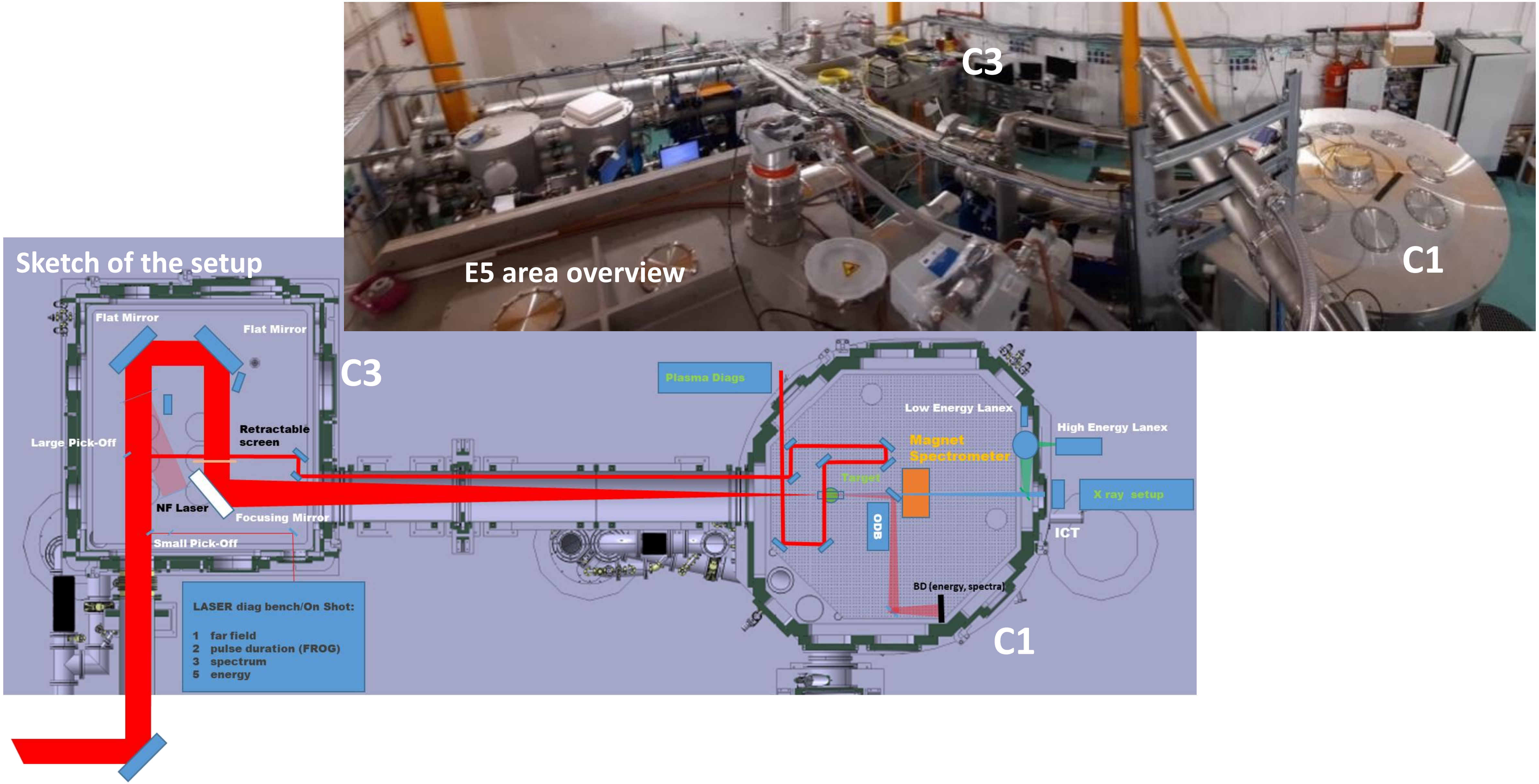
1 PW commissioning with gas targets (LWFA investigation)

First operation in 2021 – Electron acceleration in gas targets

Setup for LWFA with 1 PW laser beam in E5



E5 area overview

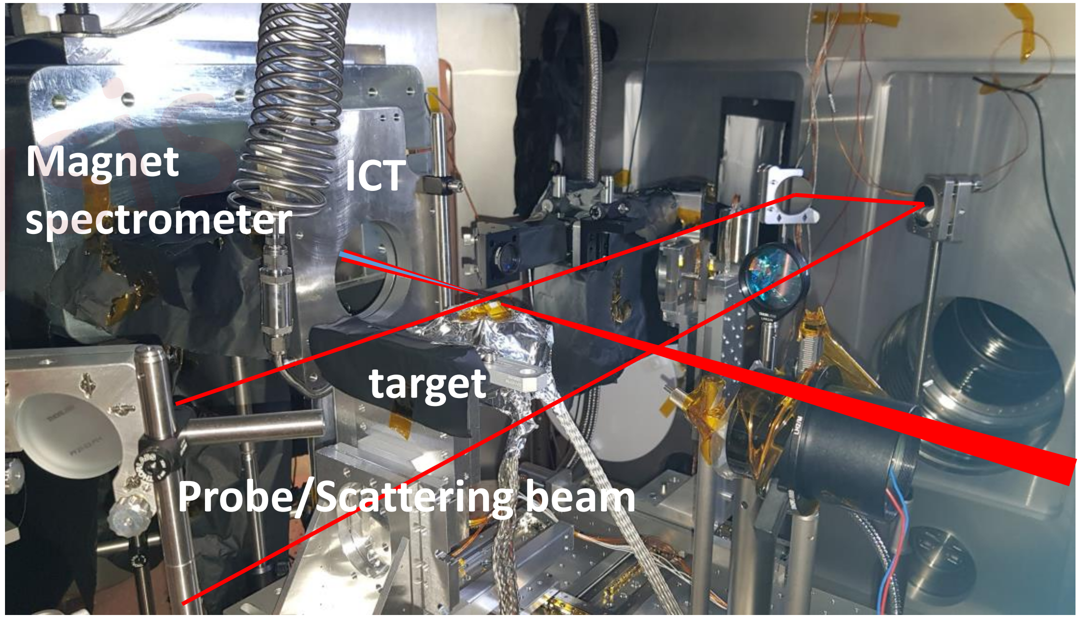
Sketch of the setup

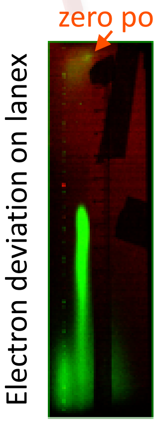
1 PW commissioning with gas targets (LWFA investigation)

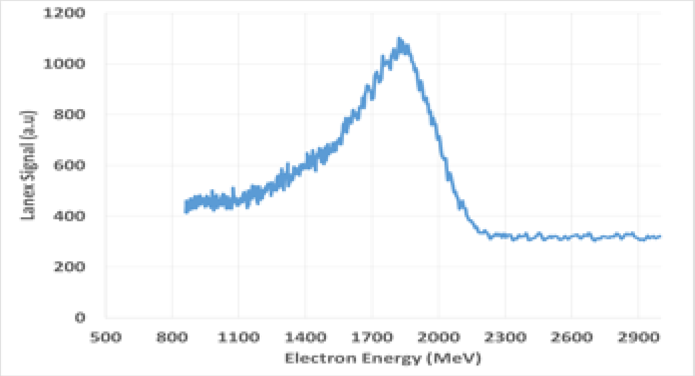
Setup and results

- Gas jet target and gas cell from 2mm to 2 cm long
- SourceLab variable metal gas cell, fix 3D printed gas cell, 2 mm metal gas jet
- Pure He and mixture He +2% N_2 were used
- F=5000mm parabola
- Max. electron energy attained with both Helium gas and admixture of ≈ 2 GeV
- Electron diagnostics: spectrometer (up to 3 GeV) – 30 cm long dipole magnet with 3 cm gap and ~1 T B-field, and a Lanex screen

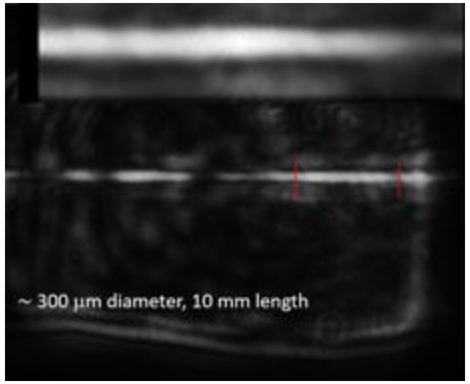
Pic of experimental setup



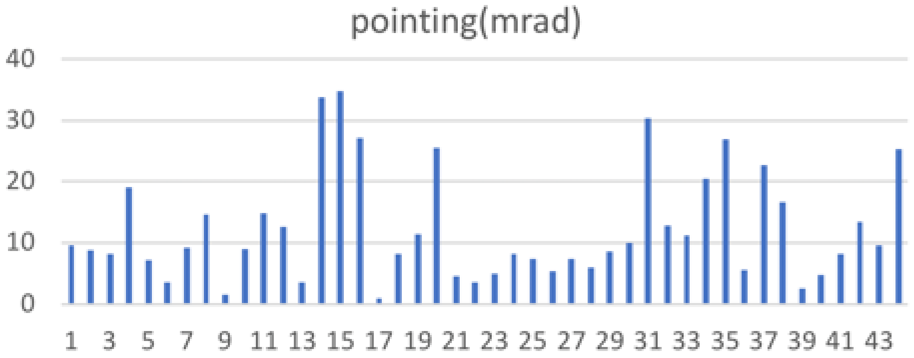




Electron Beam Energy Spectra for pure He



Shadowgraphy and WFS (plasma channel)



Electron Beam Pointing in a typical day from gas admixture

State of the art >2 GeV electron beam obtained with 2 cm gas cell
Data under evaluation and paper in preparation

1 PW commissioning: Simulation of LWFA with 1 PW

Expected results for He pure gas

LWFA in the pure bubble + self injection regime

Laser parameters

$$E \geq 18J$$

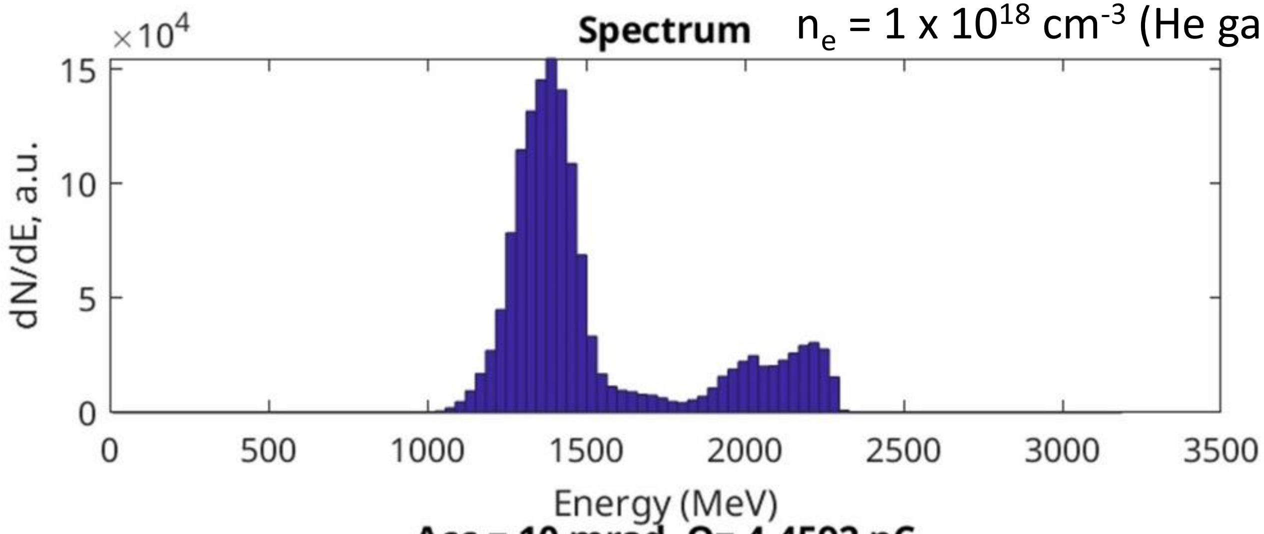
$$T = (24 \pm 1) fs$$

$$w_0 = (22.5 \pm 1) \mu m$$

$$Z_R \simeq 1.8mm$$

$$P = 750\, TW; \;\; I = 9 \times 10^{19} W/cm^2; \;\; a_0 = 6.6$$

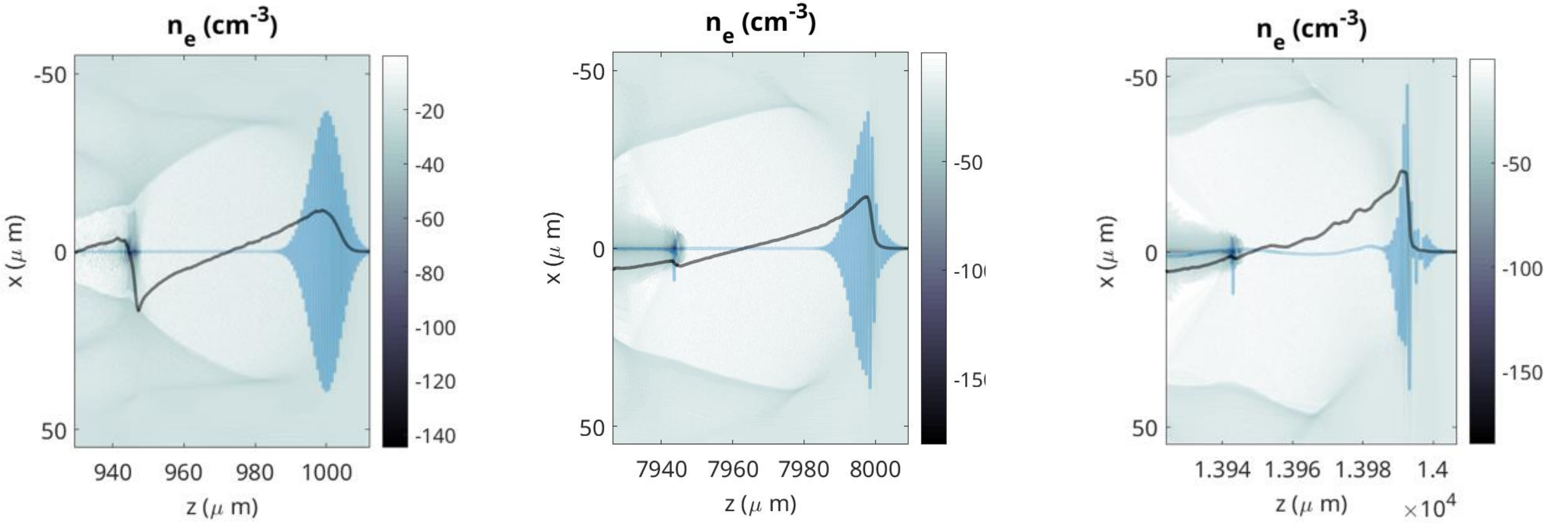
Simulated spectrum



$n_e = 1 \times 10^{18}$ cm^{-3} (He gas)

Acc.= 10 mrad, Q= 4.4592 nC

Bubble charge density and E-field



Dephasing begins

Simulation support by
P. Tomassini (LDED) and
A. Berceanu (LGED)

Ongoing Quasi-3D sims on UPB cluster and
3D PIConGPU simulations

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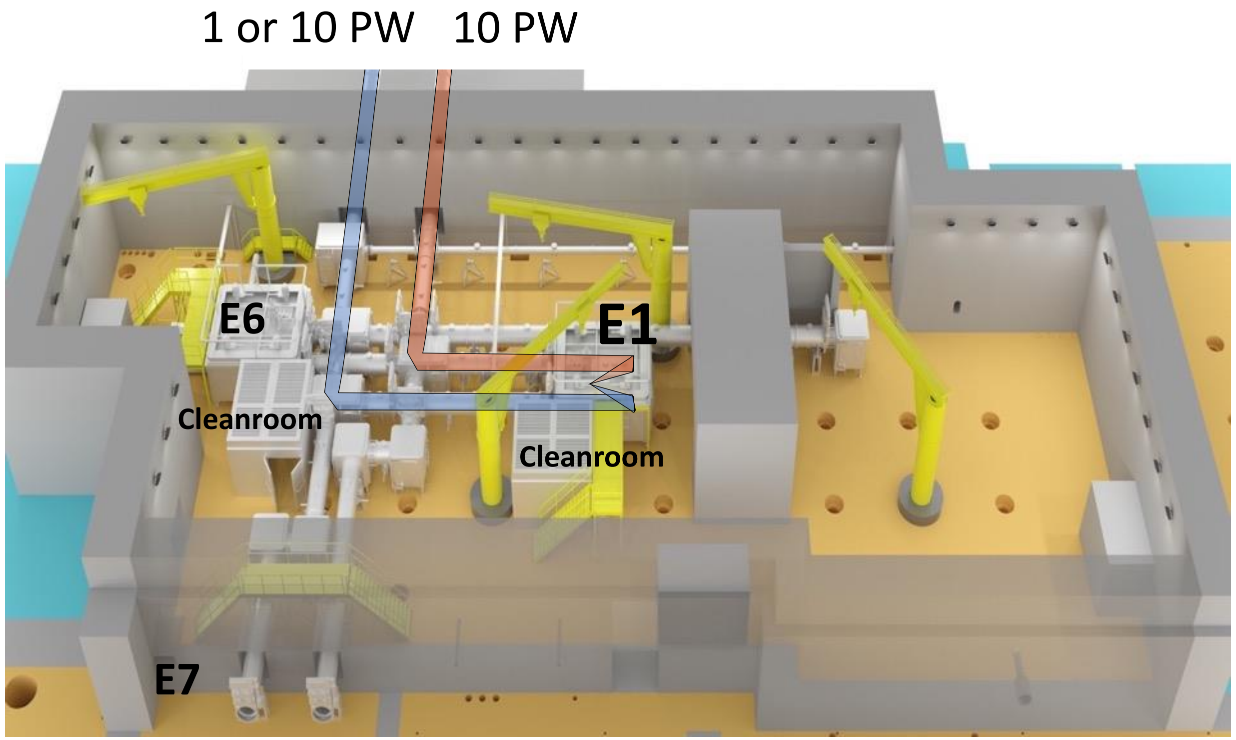
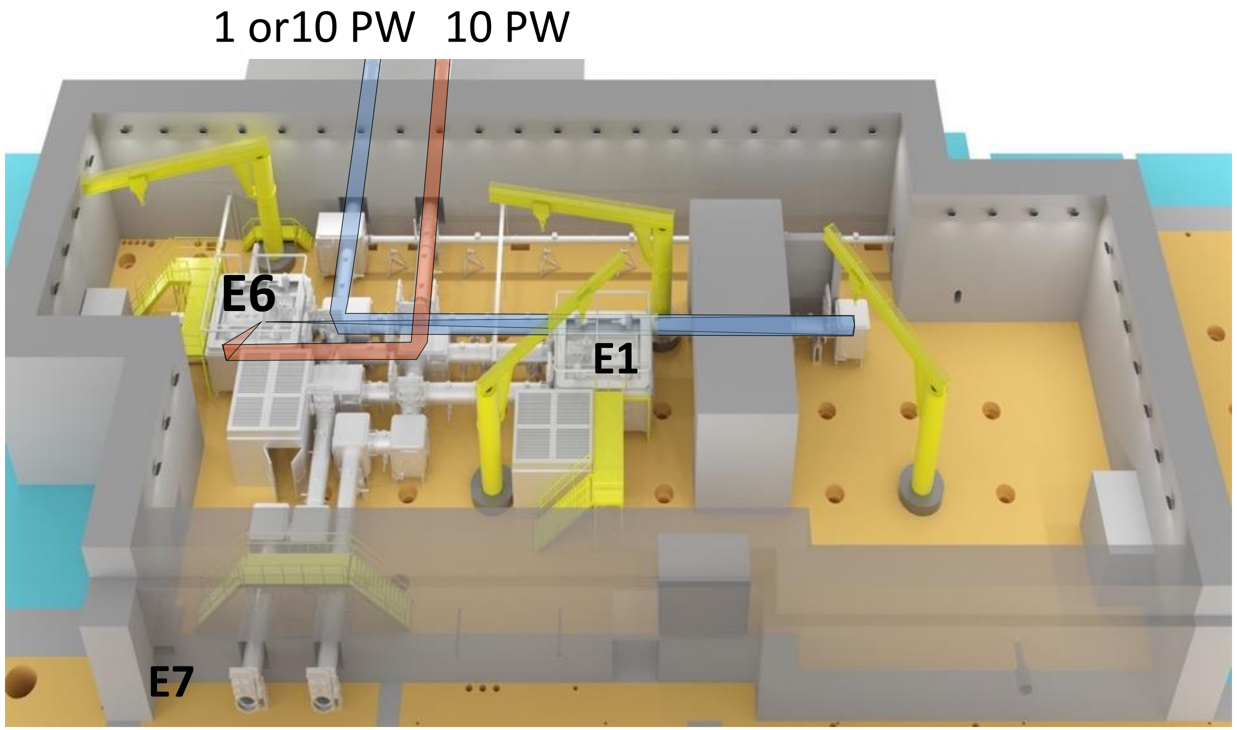
10 PW experimental hall

E1 target area configuration (solid targets, nuclear physics)



E6 target area configuration (gas targets, QED)



E1 target area (solid target experiments)

- 2 x 10 PW laser beams: 240 J, 23 fs, 810 nm, ~ 45 cm dia. FWHM (or 10 PW @ 1/60 Hz and 1 PW @ 1 Hz)
- 2 Shot focal parabolic mirrors F2.7
- 1 Plasma mirror
- 1 Cleanroom
- Experimental chamber: L x W x H of 4000 x 3300 x 1780 mm^3

E6 target area (gas target experiments)

- 2 x 10 PW laser beams: 240 J, 23 fs, 810 nm, ~ 45 cm dia. FWHM (or 10 PW @ 1/60 Hz and 1 PW @ 1 Hz)
- 1 Shot focal - parabolic mirrors F2.7
- 1 Long focal ~30 mt. - spherical mirror ~F60 @ 10 PW (~F160 @ 1 PW)
- 1 Plasma mirror
- 1 Cleanroom
- Experimental chamber: L x W x H of 4000 x 3300 x 1780 mm^3

10 PW experimental hall

LBTS

E1

Long focal mirror

Overview

E6

Large Optics

- 2 x 30 m focal spherical mirror (0 deg, Enhanced silver coating, LIDT > 0.3 J/cm^2), 630mm aperture on 3 motorized axis: tip/tilt/focus.
- 4 x 1.5 m short focal off-axis parabolas (45 deg, Enhanced silver coating, LIDT > 0.3 J/cm^2) on 2 hexapods (custom Zondas by Symetrie)

The installation of the short focal mirror in E1 area is done along with full diagnostic benches

The long focal has been tested recently

Outline

- Overview of the activities related to the HPLS
- Overview and Status of the 1 PW experimental area E5
- Commissioning experiments of the 1 PW E5 area
    - TNSA investigation
    - LWFA investigation
- Overview and Status of the 10 PW experimental areas E1 and E6
- Upcoming commissioning of the 10 PW E1 and E6 areas

10 PW experimental areas (E1 and E6)

10 PW commissioning with solid targets started in September 2022

Goals of the 10 PW area commissioning

E1 (solid targets)

- Demonstrate **200 MeV proton** acceleration
- Demonstrate extreme focal intensity through laser-γ conversion (“**γ-flash**”)
- **Dense heavy ion beams** for nuclear physics (time permitting)

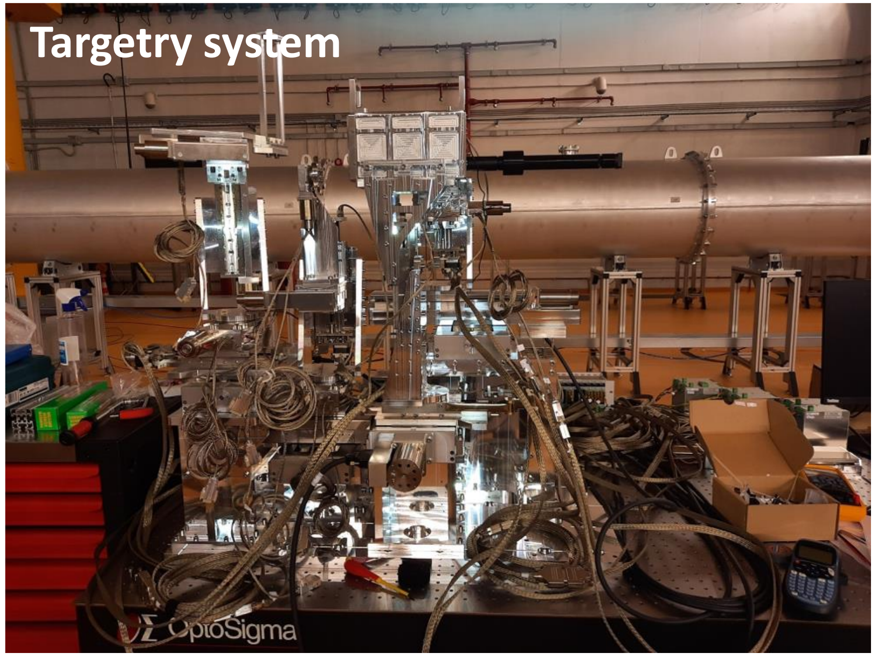
10 PW commissioning with gas targets is planned for the second half of 2023

E6 (gas targets)

- 10 PW LWFA of **multi-GeV electron** beams

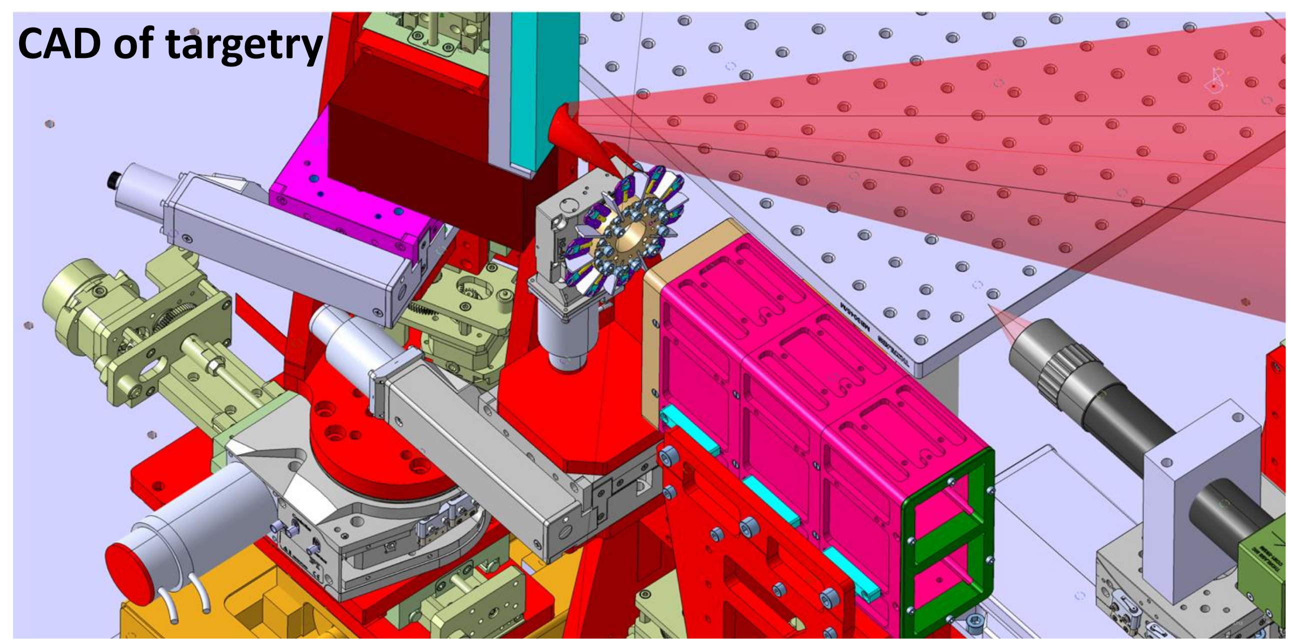
10 PW E1 experimental area commissioning (from 26 Sept 2022)


10 PW E1 area overview


Targetry system


Targetry system


E1 interaction chamber


CAD of targetry

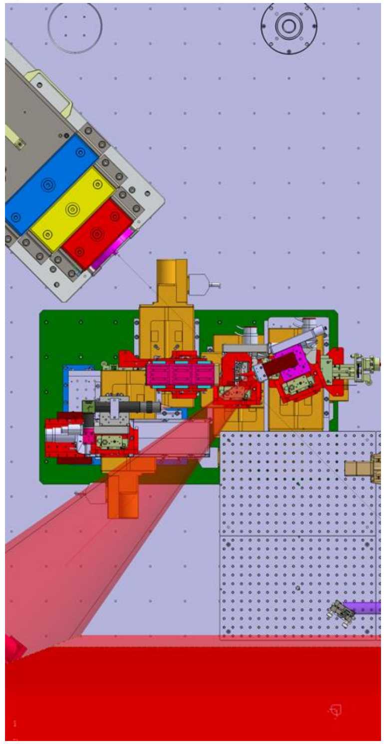

Target wheel

10 PW E1 experimental area commissioning (from 26 Sept 2022)

Commissioning goals:

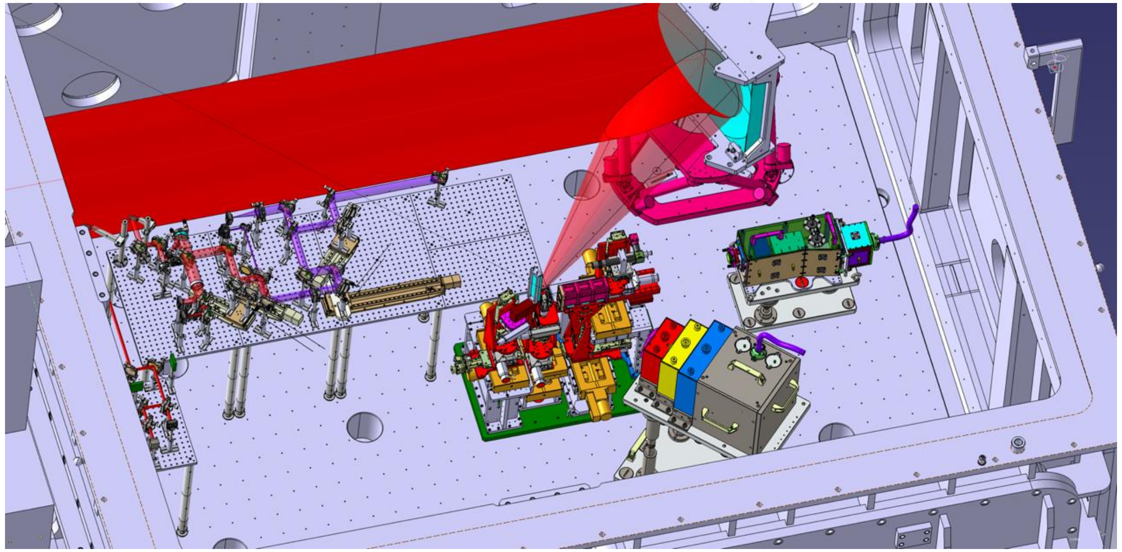
TNSA >200 MeV protons,
Gamma flash scaling ,
TNSA/RPA high-Z bulk acceleration

CAD by Eng. M. Tataru



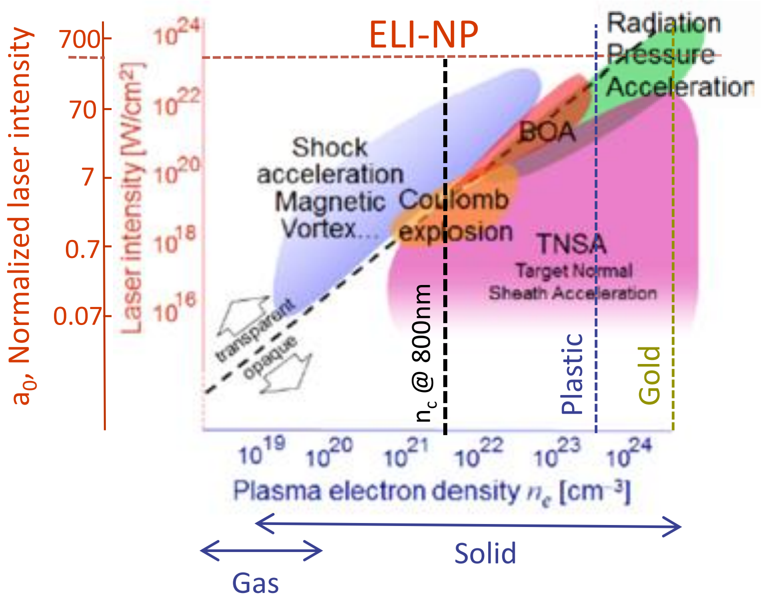
List of diagnostics of E1

Laser Diagnostics
Targetry and Alignment System
Radiochromic films stack (>100MeV), CR39
Thomson Parabola (~60MeV and ~500MeV proton)
Forward Compton gamma spectrometer (up to 50MeV)
e−/ e+ Pair Spectrometer 100MeV
Angle Resolved Gamma Spectrometer/Calorimeter (CsI:Tl)
Optical Probe/Pump (100mJ)

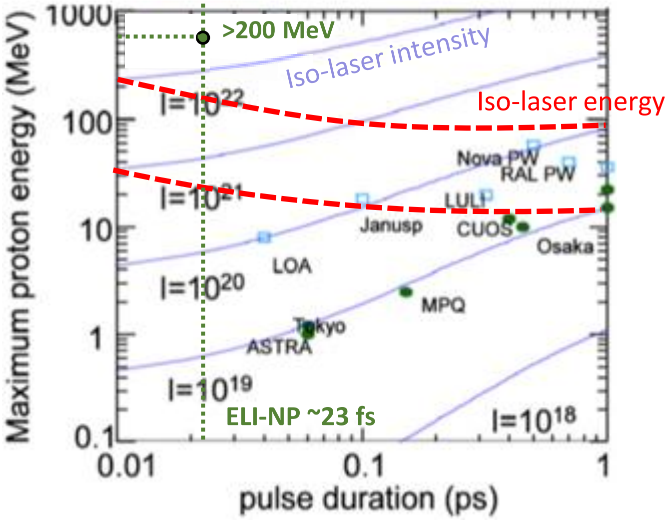


E1 10 PW commission goals: TNSA > 200 MeV

Target Normal Sheath Acceleration (TNSA) scaling law



Adapted from P. Mckenna et al.,

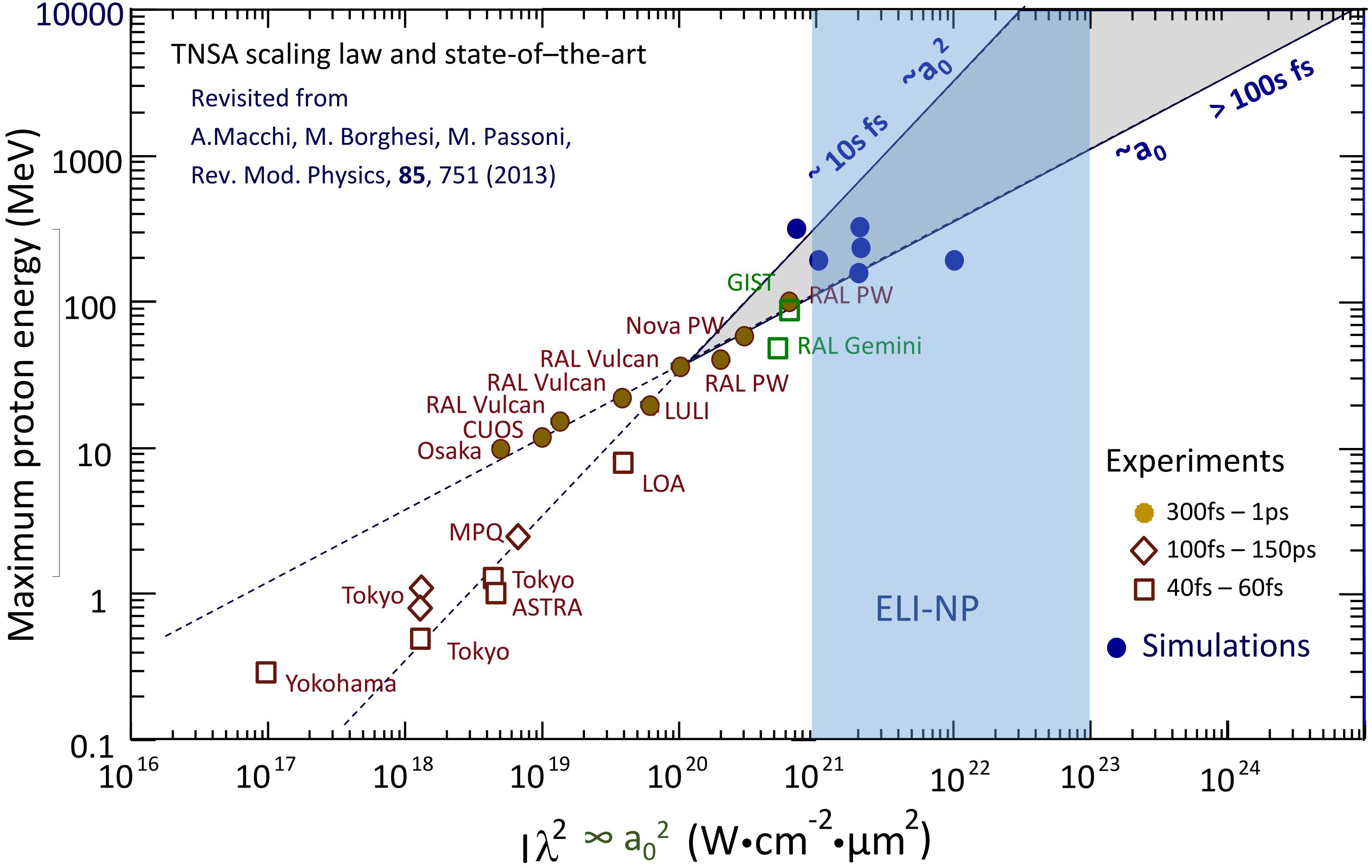


Adapted from J. Fuchs et al., Nature Physics 2, 48 (2006)

Theoretical acceleration regimes for solid targets

- In the interval of laser amplitudes $1 < a_0 < 10$ TNSA
- For $10 < a_0 < 70$ TNSA-RPA hybrid schema
- For $70 < a_0$ RPA may be significant

ELI-NP laser intensity ~10^{23} W/cm² (10 PW: 240J, 24fs) -> $a_0 \sim 215$ @ LP



TNSA scaling law and state-of–the-art

Revisited from

A.Macchi, M. Borghesi, M. Passoni,

Rev. Mod. Physics, **85**, 751 (2013)

E1 10 PW commission goals: γ-flash emission

Gamma ray emission

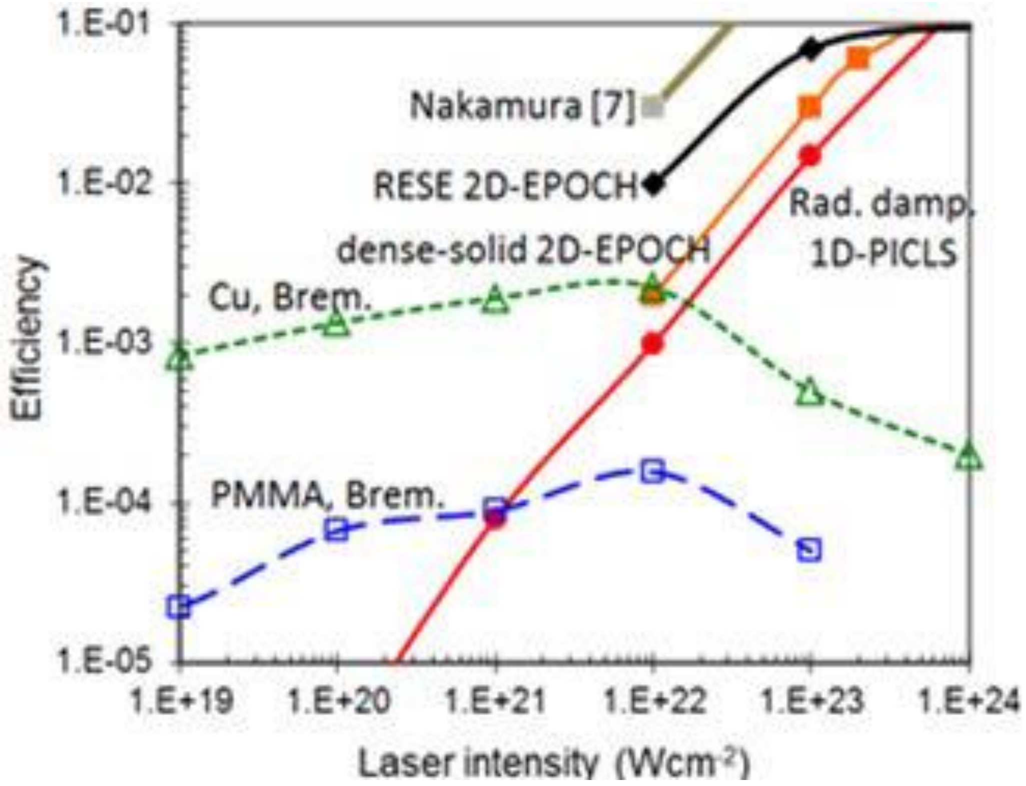


Fig. 1 – Efficiency of laser-to-γray conversion as a function of laser intensity. The radiation damping calculations (filled symbols) are from PICLS simulations, calculations by Nakamura *et al*. 2012 and 2D-EPOCH simulations for solid density and RESE mechanisms. Open symbols are bremsstrahlung calculations for Cu and PMMA plastic. (Credits: I.C.E. Turcu *et al., RRP, 68, 2016*)

Type of emission

- The **bremsstrahlung radiation (BR) scales as ~ Z^2** (material type) and linearly with the areal density of the target.
- On the contrary, **the synchrotron-like radiation (SR) is independent of the material**, as it is created by the free electrons interacting with the laser field and it has a different scaling law.

Scaling of Synchrotron-like Radiation (SR)

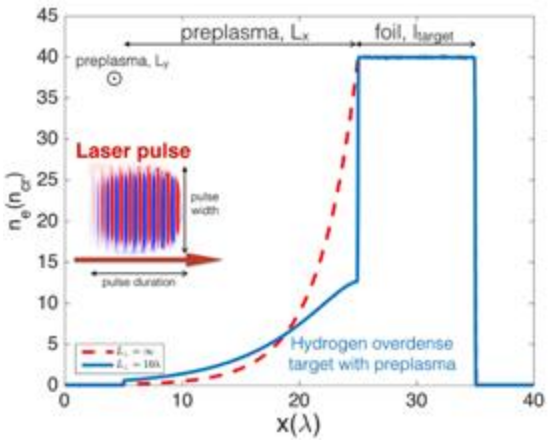
- For laser intensities **below 10^{21} W/cm^2**, the conversion efficiency from **laser-to-gamma power scales as $P\gamma \sim P_L^2$**;
- while for laser intensities **above 10^{21} W/cm^2** the **scaling becomes linear up to sub-10^{23} W/cm$^{2.}$**

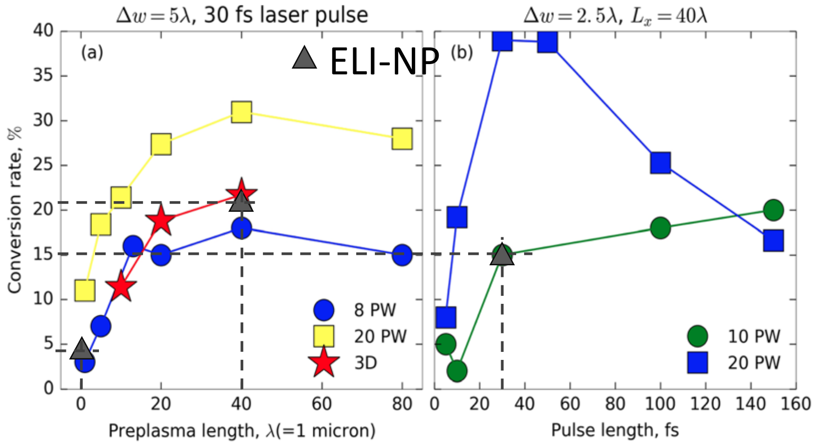
E1 10 PW commission goals: γ-flash emission

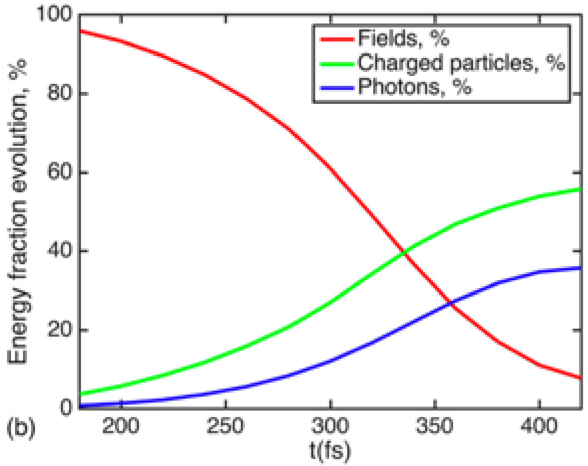
PHYSICS OF PLASMAS 25, 123105 (2018)

High power gamma flare generation in multi-petawatt laser interaction with tailored targets

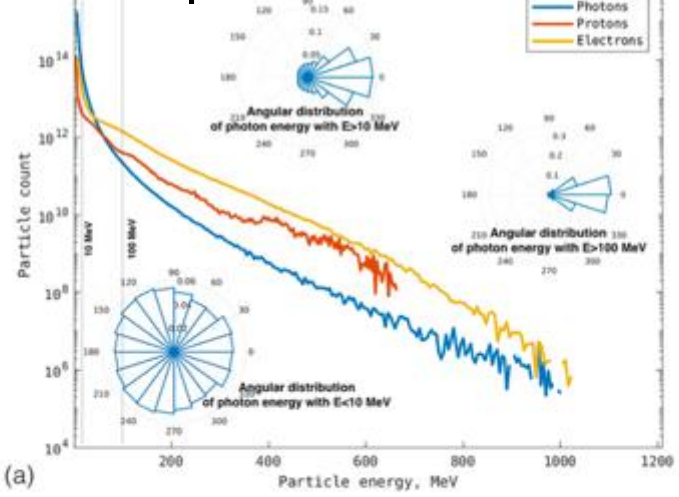
K. V. Lezhnin,[1,2] P. V. Sasorov,[3,4] G. Korn,[4] and S. V. Bulanov[4,5,6]







1e13 photons total



Gamma-ray power scaling

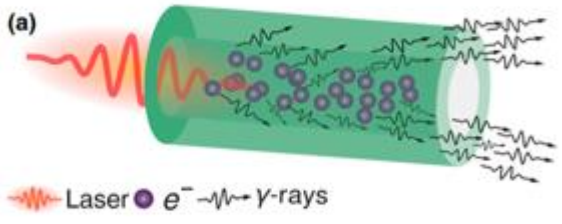
$P_\gamma \sim P_L^2$ for $P_L<1$ PW

$P_\gamma \sim P_L$ for $P_L>1$ PW

PHYSICAL REVIEW APPLIED 13, 054024 (2020)

Power Scaling for Collimated γ-Ray Beams Generated by Structured Laser-Irradiated Targets and Its Application to Two-Photon Pair Production

T. Wang,[1,2] X. Ribeyre,[3] Z. Gong,[4] O. Jansen,[1] E. d'Humières,[3] D. Stutman,[5,6] T. Toncian,[7] and A. Arefiev[1,2,*]



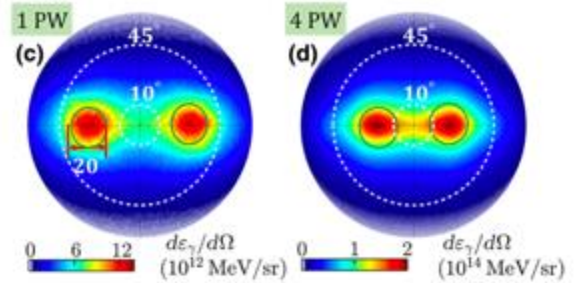
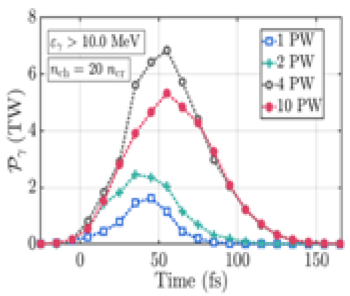
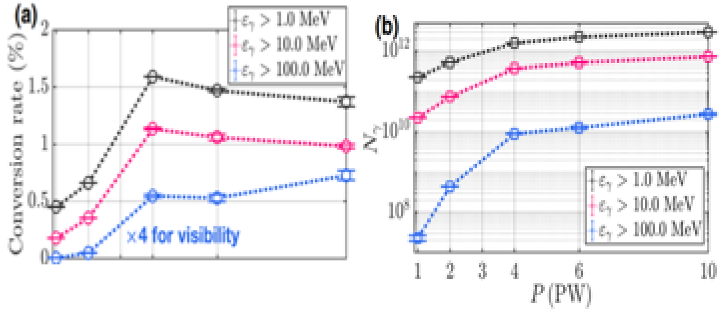


TABLE I. Parameters used in the 3D PIC simulations.

Laser pulse	
Pulse energy	37, 75, 149, 223, and 373 J
Peak intensity	5×10^{22} W/cm^2
a_0	190
Wavelength	$\lambda = 1\ \mu m$
Power	$P = 1, 2, 4, 6,$ and 10 PW
Location of focal plane	$x = 0\ \mu m$
Pulse profile (transverse and longitudinal)	Gaussian
Pulse duration (FWHM of intensity)	35 fs
Focal-spot size (FWHM of intensity)	$w_0 = 1.3, 1.9, 2.7, 3.2$ and 4.2 μm
Plasma	
Composition	Carbon ions and electrons
Bulk density	$n_{bulk} = 100 n_{cr}$
Bulk thickness	$d_{bulk} = 3.0\ \mu m$
Channel density	$n_{ch} = 20 n_{cr}$
Ionization state of carbon	Fully ionized
Channel radius	$R_{ch} = 0.7 w_0$
Channel length	$L_{ch} = 45\ \mu m$
General parameters	
Spatial resolution	$30/\mu m \times 30/\mu m \times 30/\mu m$
No. of macroparticles per cell	
Electrons	15
Carbon ions	5

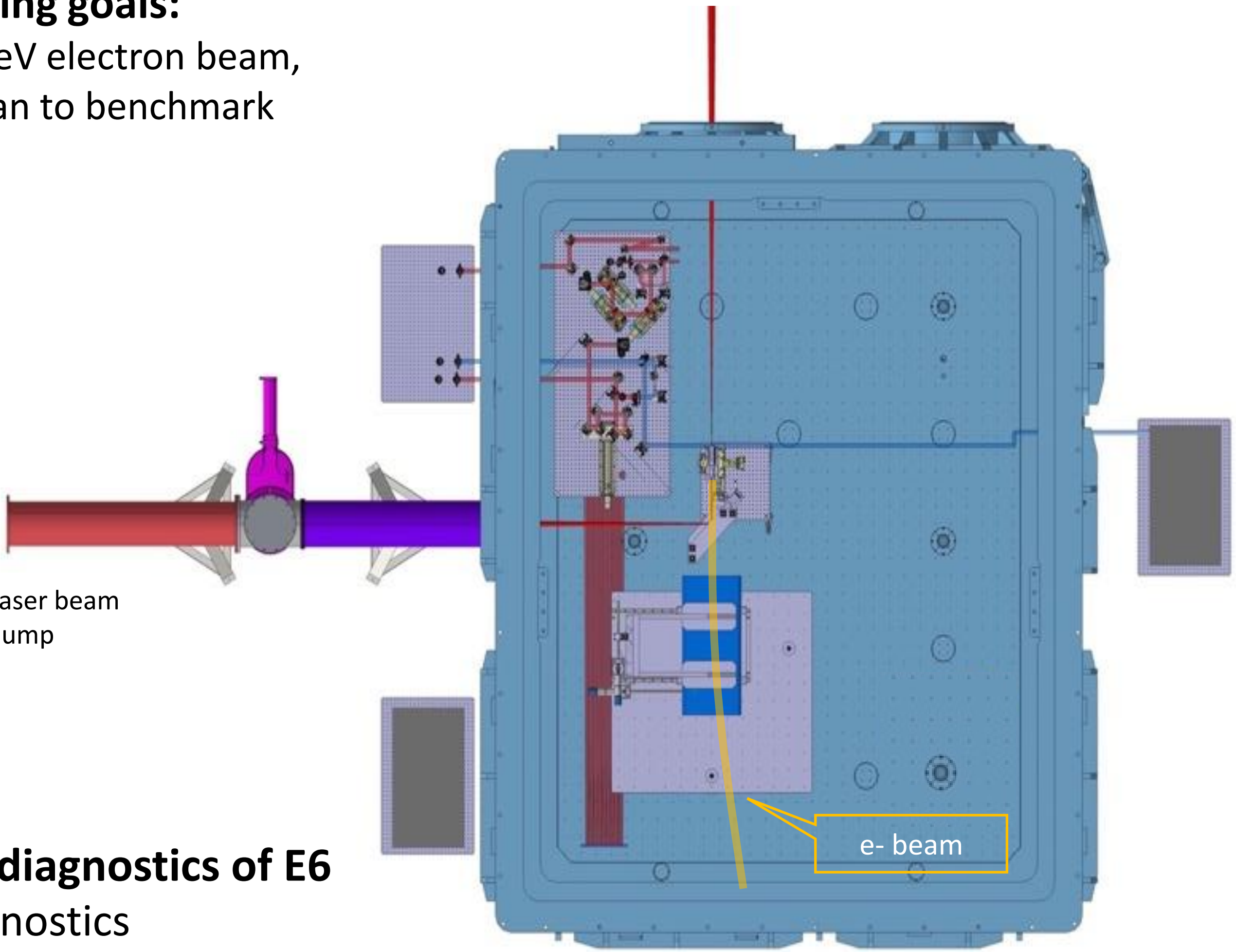


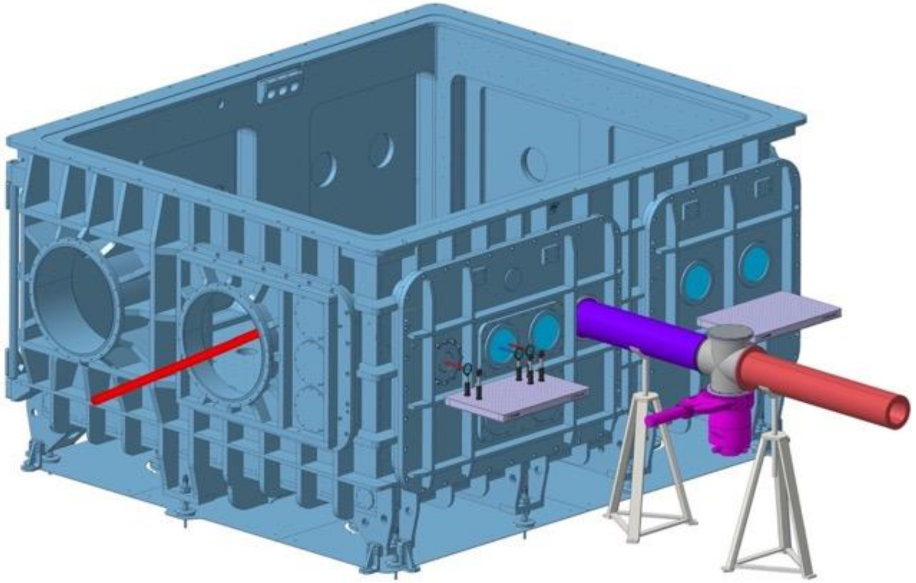


E6 experimental area commissioning (from July 2023)

Commissioning goals:

LWFA multi-GeV electron beam,
Parametric scan to benchmark



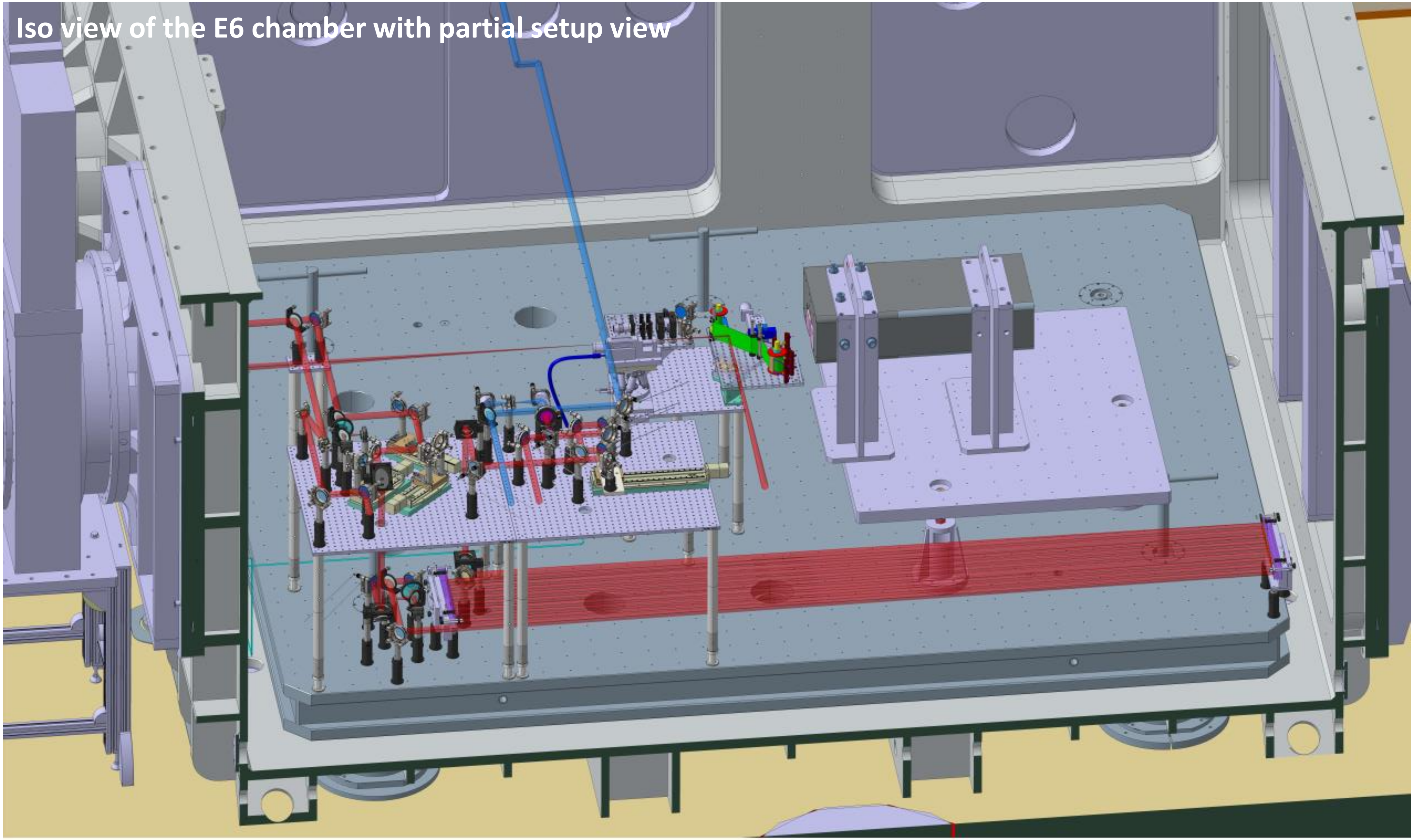


E6 CAD drawings by Eng. M. Risca

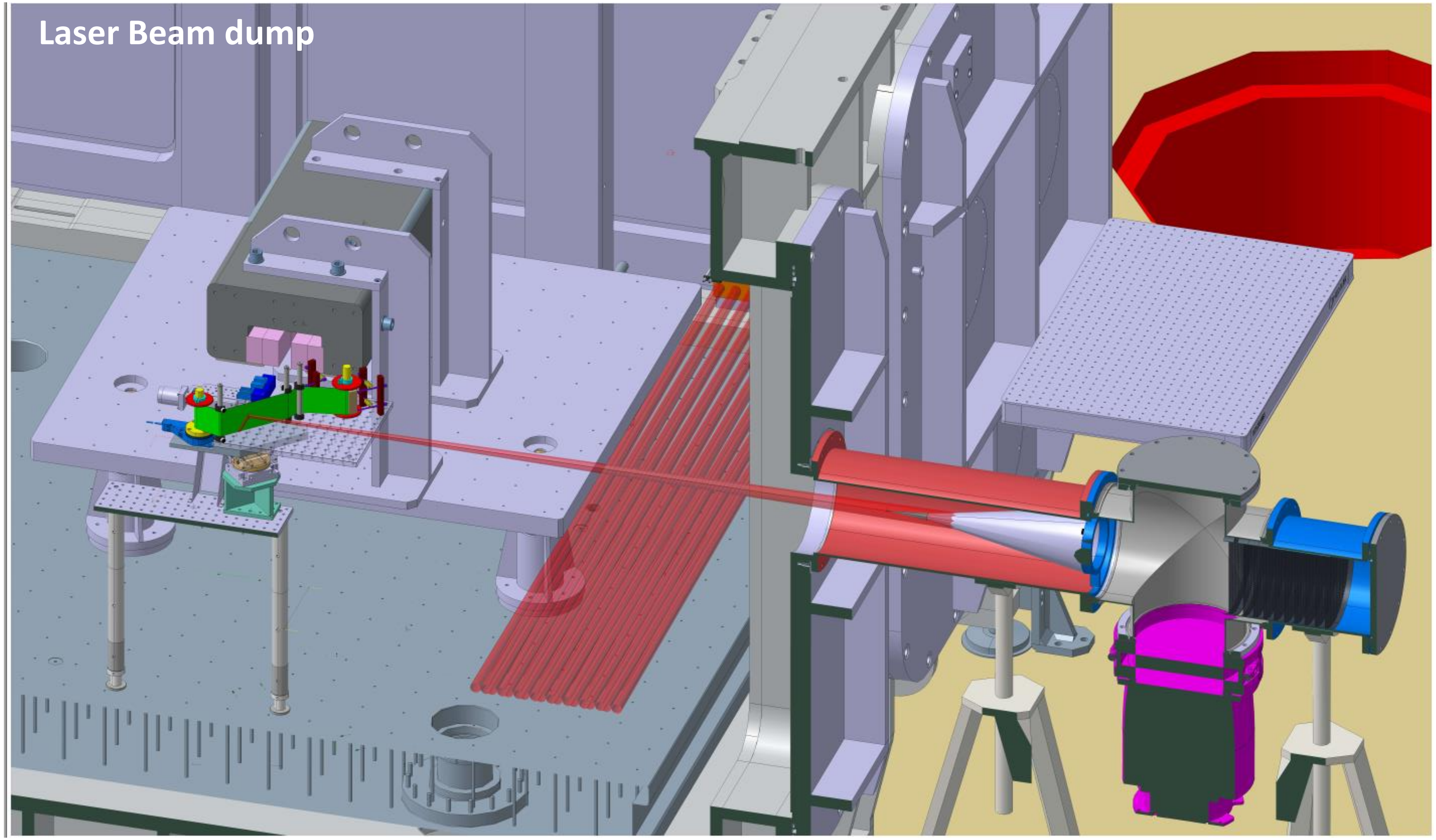
List of main diagnostics of E6

- Laser Diagnostics
- Targetry and Alignment Systems
- Laser Beam Dump
- e−/ e+ Pair Spectrometer
- e- spectrometer in vacuum up to 5GeV, with planned upgrades to 20GeV
- Optical Probe/Pump

E6 10 PW experimental area


Iso view of the E6 chamber with partial setup view

E6 10 PW experimental area



Laser beam dump design almost completed

It is made of a ribbon of aluminum 50-100 µm think and a pipe with a system of a cone and degraders to dump the beam and avoid relevant back reflection

e-/e+ spectrometer

The magnet dipoles has arrived and the detection system too.

We have 3 magnets: 2x 800mm long 0.9 T, and 1 x 300 mm long 0.9T, all with 30mm gap

Gas target

The gas target system: 5cm carriable cell and jet are at ELI, and at the moment under testing.
The target system is completed

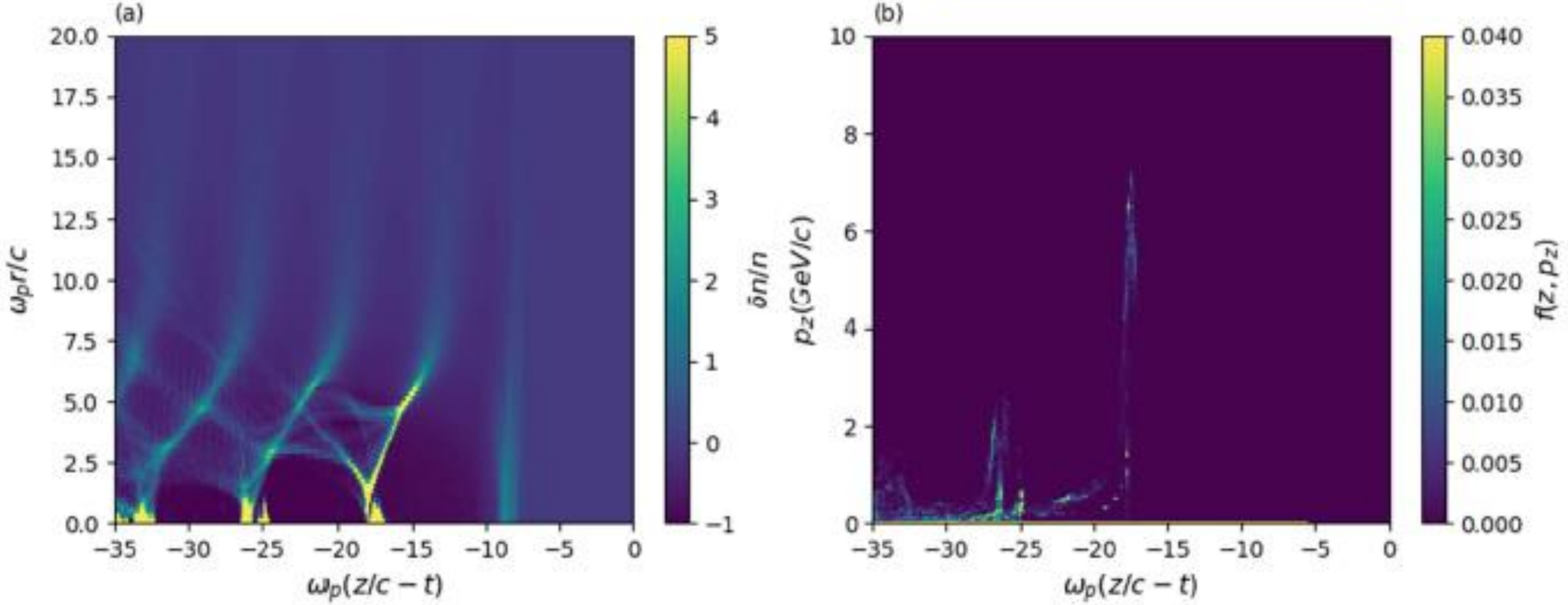
E6 10 PW commission goals

Goal: demonstrating multi-GeV electron

LWFA at ELI-NP with 5cm long gas cell

At optimum condition with 10 PW and 5cm gas cell

~ 7 GeV electron energy



D Gordon, NRL, State Department Science Fellows Program
Wake and Beam Phase Space after 5 cm LWFA at 10 PW

Collaborations with NRL, Michigan U, Johns Hopkins U, UCSD

Multi-neutron capture: r-process

S-process

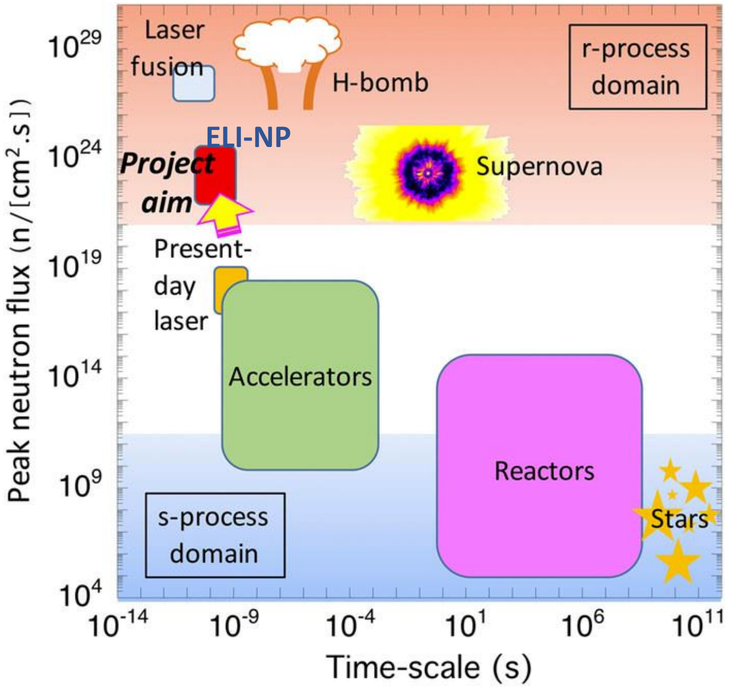
$$^{209}Bi + n \rightarrow {}^{210}Bi \rightarrow {}^{210}Po + \beta^-$$

$$^{210}Po \xrightarrow{138d} {}^{206}Pb + \alpha$$

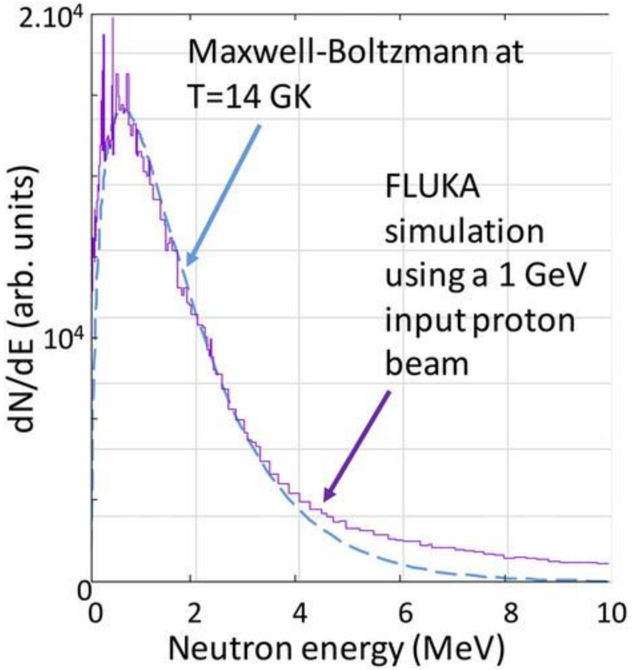
R-process can occur only under an extremely high neutron flux [>10^{20} $n/(cm^2\ s)$]

ELI-NP should generate >10^{12} neutrons in the output of the Pb converter via spallation

The estimations give a peak flux of $\sim 10^{22}–5 \times 10^{23}\ n/(cm^2\ s)$



Peak neutron flux vs time scale of neutron sources produced in various astrophysical sites and in facilities on Earth, showing the parameters at which the s(low)- and r(apid)-processes of nucleosynthesis take place.



Simulated **neutron** spectrum obtained by spallation in a **2 cm thick Pb target** of a laser-driven proton beam, using FLUKA. The **spallation yield is 10 neutrons/proton**. The dashed line represents the thermal spectrum, indicating that the spectral shape is not far from the conditions expected for the r-process.

S. Chen, *et al.*, Matter and Radiation at Extremes, 2019, 4, 5, 054402, (2019)

Laser-Driven Nuclear Physics

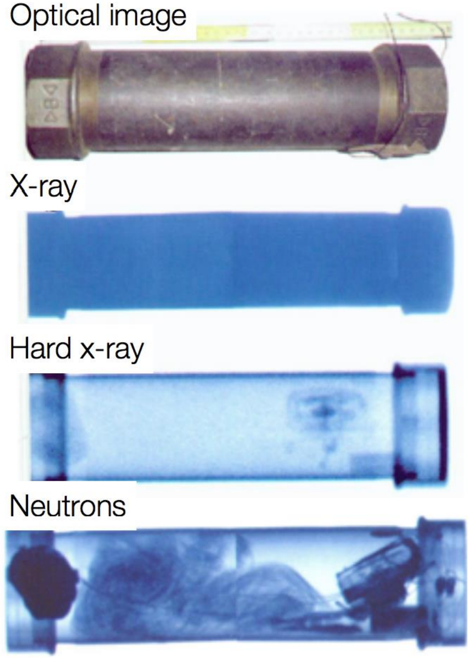
Probing with laser-generated neutron beams

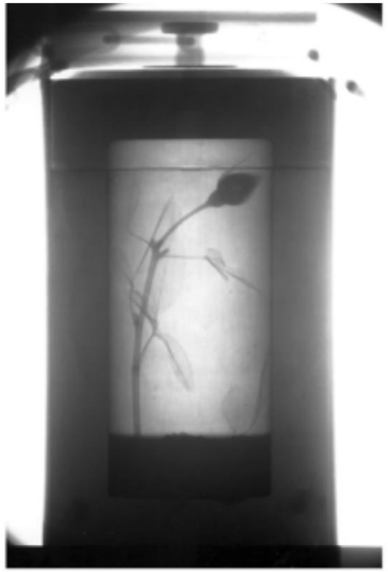
Laser-accelerated proton can be easily generated with a large flux (up to 10^{12} proton in a single laser shoot)

Proton can be converted into neutron with a flux up to 10^{9} n/Sr in the same setup using a converter, and the energy can be tuned using a moderator.

Probing through very dense material as lead

Security



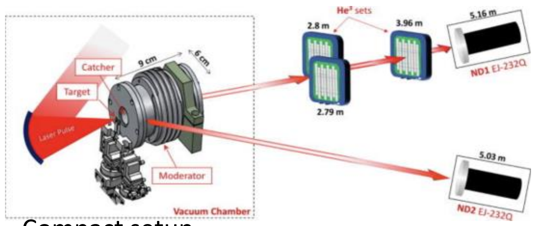


AIP Applied Physics Letters

A miniature thermal neutron source using high power lasers

Appl. Phys. Lett. **116**, 174102 (2020); https://doi.org/10.1063/5.0003170

S. R. Mirfayzi[1,a)], H. Ahmed[1], D. Doria[1,b)], A. Alejo[1,c)], S. Ansell[2], R. J. Clarke[3], B. Gonzalez-Izquierdo[4], P. Hadjisolomou[1,d)], R. Heathcote[3],



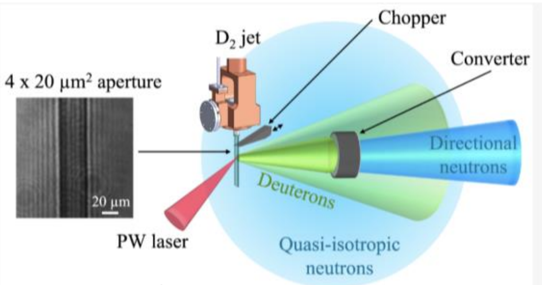
Compact setup

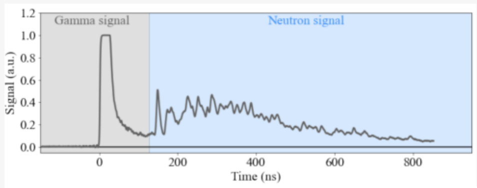
	N_F (n/sr)	N_{Th} (n/sr)	N_{Ep} (n/sr)
	$E_n \geq 1$ MeV	≤ 0.5 eV	0.5 eV $\leq E_n \leq 65$ eV
H_2O	$\sim 1.7 \times 10^9$	$(1.4 \pm 0.1) \times 10^6$	$(1.9 \pm 0.3) \times 10^6$
D_2O	$\sim 1.3 \times 10^9$	$(3.4 \pm 0.5) \times 10^5$	$(4.6 \pm 0.1) \times 10^5$
HDPE	$\sim 8.9 \times 10^8$	$(2.3 \pm 0.4) \times 10^5$	$(9.9 \pm 0.2) \times 10^5$

Open Access Article

Towards High-Repetition-Rate Fast Neutron Sources Using Novel Enabling Technologies

by Franziska Treffert [1,2,*], Chandra B. Curry [1,3], Todd Ditmire [4], Griffin D. Glenn [1,5], Hernan J. Quevedo [4], Markus Roth [2], Christopher Schoenwaelder [1,6], Marc Zimmer [2], Siegfried H. Glenzer [1] and Maxence Gauthier [1]





Liquid jet of Deuterium

Laser Boron Fusion Reactor

H. Hora *et al.*, "Laser Boron Fusion Reactor With Picosecond Petawatt Block Ignition," in *IEEE Transactions on Plasma Science*, vol. 46, no. 5, pp. 1191-1197, May 2018, doi: 10.1109/TPS.2017.2787670.

Aneutronic fusion of hydrogen with the boron isotope 11, **$H^{11}B$**.

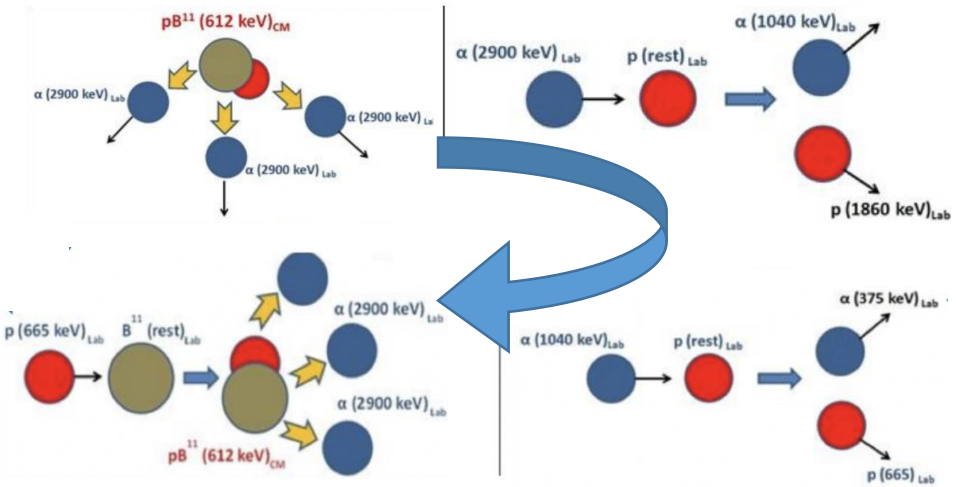
At local thermal equilibrium, is 10^{5} times more difficult than fusion of deuterium and tritium (DT)

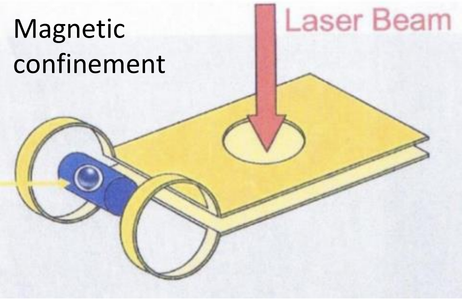
But at extreme nonequilibrium plasma conditions the fusion of $H^{11}B$ is comparable to DT fusion

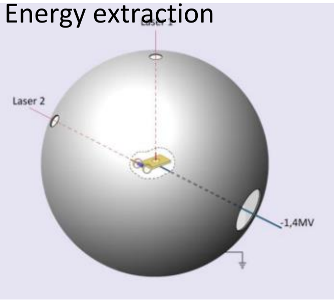
Method

- **H11B rod a cm size**
- **Main laser for driven-ignition:** 30PW laser energy and ps pulse duration
- **A second laser for magnetic field generation of ~10 kT:** 1kJ energy and ns pulse duration

Nuclear reaction schema



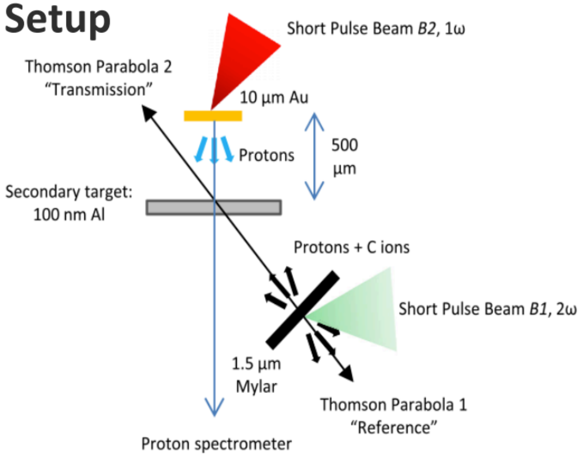




Using a container electrostatically charged to -1.4 MV, it will be possible to generate about **277 kWh** of energy per laser **shot**.

Nuclear Reaction in Plasma – screening effect

Setup

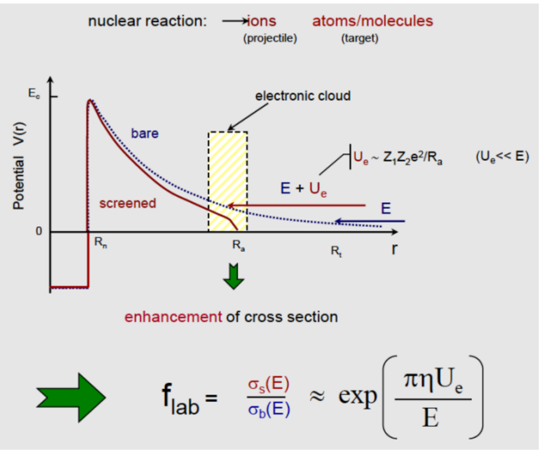


ELFIE Laser (LULI)

$I \sim 10^{19}$ W/cm^2

$\lambda \sim 1$ µm

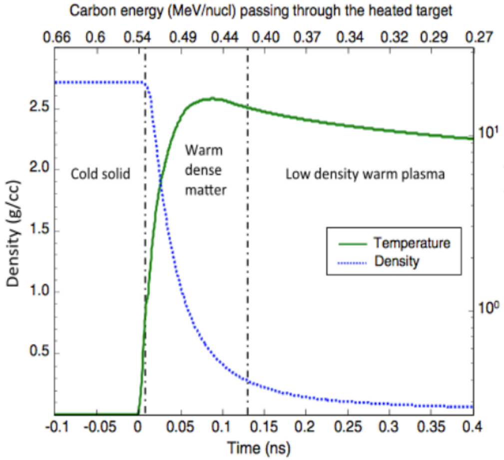
$\tau \sim 500$ fs



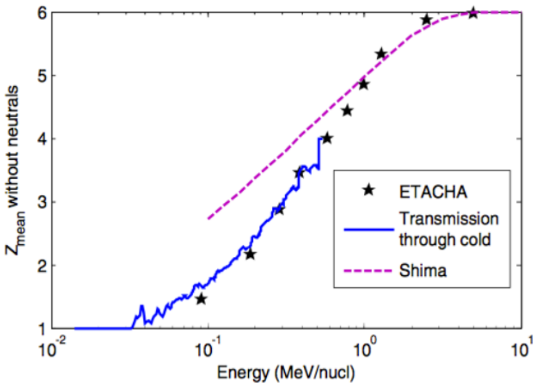
$$f_{lab} = \frac{\sigma_s(E)}{\sigma_b(E)} \approx \exp\left(\frac{\pi\eta U_e}{E}\right)$$

Salpeter formula (plasma correction):

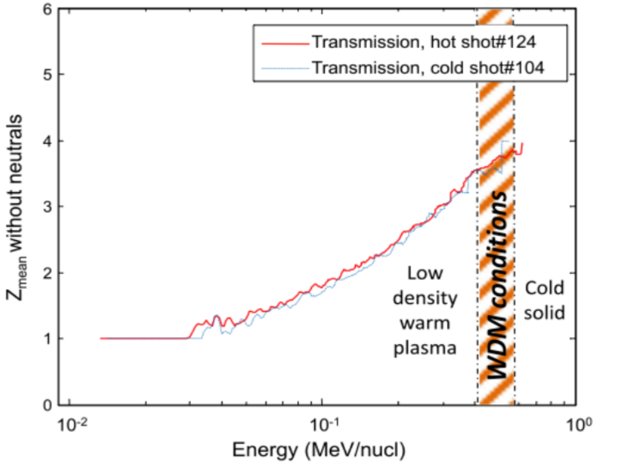
$$f = \exp\left(\frac{Z_1 Z_2 e^2}{R_D k T}\right) = \exp\left(0.188\, Z_1 Z_2\, \zeta\, \rho^{1/2}\, T_6^{-3/2}\right)$$



Density and temperature of the heated aluminum target as simulated by ESTHER using the measured heating proton parameters



Comparison between Z_{mean} from our experiment from Shima and from ETACHA.



Z_{mean} measurements through aluminum cold or heated to 1 eV.

Charge Equilibrium of a Laser-Generated Carbon-Ion Beam in Warm Dense Matter

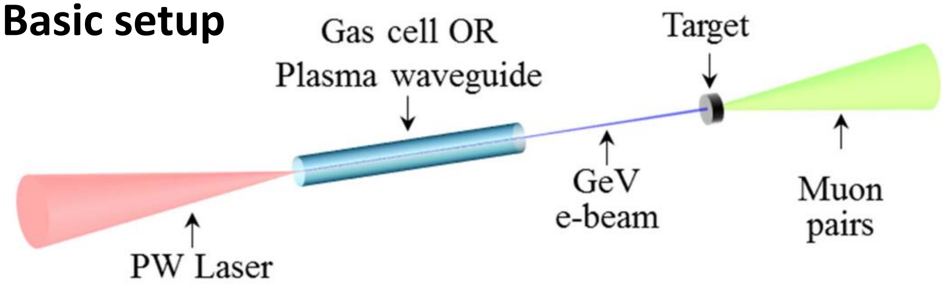
M. Gauthier, S. N. Chen, A. Levy, P. Audebert, C. Blancard, T. Ceccotti, M. Cerchez, **D. Doria**, et al. PRL. **110**, 135003 (2013)

Laser-Driven Nuclear Reactions

Muon	
Mass	~ 105.6 MeV/c^2
Mean lifetime	~ 2.2 μs
Decay into	$e^- + \bar{\nu}_e + \nu_\mu$ (most common)

Multi-GeV LWFA may enable direct generation of **muon pairs** with unique properties of high directionality, **sub-100 ps duration**, and a peak **brightness of 5×10^{17} pairs $s^{-1}cm^{-2}sr^{-1}$**.

Basic setup



Bobbili Sanyasi Rao *et al* 2018 Plasma Phys. Control. Fusion 60 095002

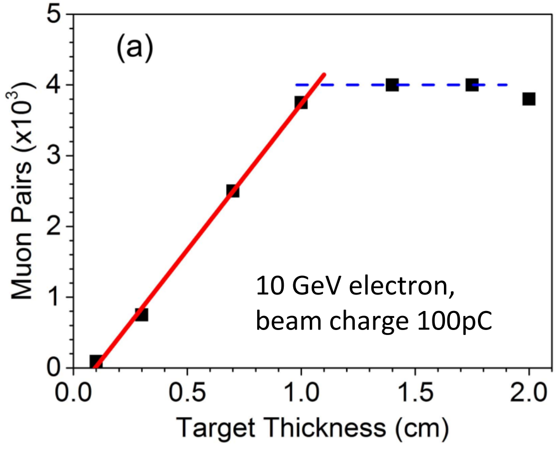
Process of generation

$$E_\gamma > 2\,m_\mu c^2 \approx 211\ \mathrm{MeV}$$

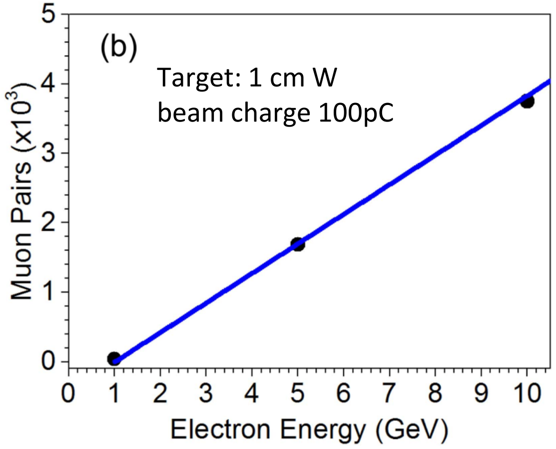
$$e^- + N \rightarrow e^{-*} + N + \gamma$$ Bremsstrahlung

$$\gamma + N \rightarrow N + \mu^- \mu^+$$ Bethe-Heitler

Monte Carlo simulations

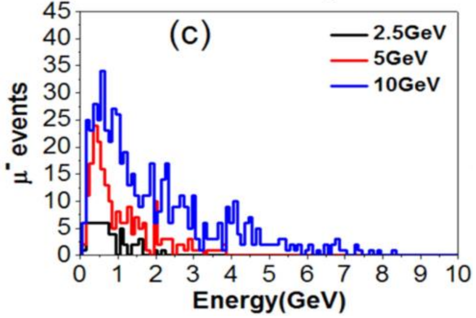


Dependence of the yield of muon pairs on target thickness

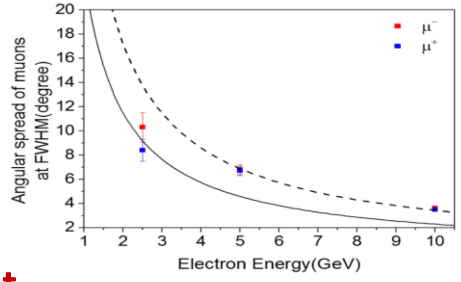


Dependence of the yield of muon pairs on electron energy

Energy distribution of μ−



Angular distribution of μ− , μ+



Muons can also be generated via proton > 500 MeV, at the rate of 10^{11} μ/shot

Laser-Driven Nuclear Reactions

QED – Radiation Reaction: L and NL Compton scattering

Accelerating charges radiate and therefore lose energy (Radiation Reaction – RR)

Relativistic and classical generalization is called the "**Abraham–Lorentz–Dirac force**". not valid at distances of roughly the **Compton wavelength** or below.

0. Classical Lorentz force

$$m\frac{du^{u}}{ds} = eF^{uv}u_{v}$$

✗ No energy loss

1. LAD Equation

$$m\frac{du^{u}}{ds} = eF^{uv}u_{v} + \frac{2}{3}e^{2}\left(\frac{d^{2}u^{u}}{ds^{2}} + \frac{du^{v}}{ds}\frac{du^{v}}{ds}u^{u}\right)$$

✓ Damping force (radiation reaction term)
✗ Classical renormalisation (point-like electron)
✗ Runaway solutions! (diverging acceleration even without external field)

2. LL Equation

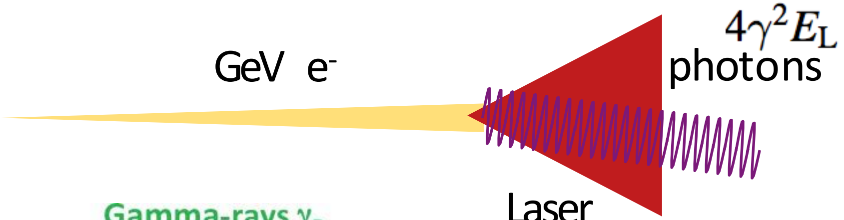
$$m\frac{du^{u}}{ds} = eF^{uv}u_{v} + \frac{2}{3}e^{2}\left(\frac{e}{m}(\partial_{\alpha}F^{uv})u^{\alpha}u_{v} - \frac{e^{2}}{m^{2}}F^{uv}F_{\alpha v}u^{\alpha} + \frac{e^{2}}{m^{2}}(F^{\alpha v}u_{v})(F_{\alpha\lambda}u^{\lambda})u^{u}\right)$$

✓ No runaway solutions
✓ Valid in classical relativity

Schwinger limit

$$E_S = \frac{m_e^2 c^3}{q_e \hbar} \simeq 1.32 \times 10^{18}\ \mathrm{V/m}$$

(or $I \sim 10^{29}$ W/cm^2)



$4\gamma^2 E_L$ photons

GeV e^-

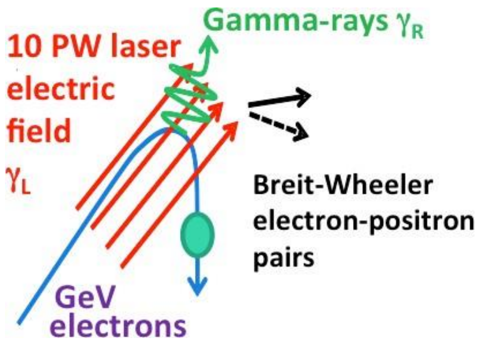
Laser
10^{23} W/cm^2

ϒ ~ 1000 for 1 GeV electron

for $I \sim 10^{23}$ W/cm^2 = $E_L \sim 10^{15}$ V/m

$\chi = E/Es \sim ϒ\, E_L/Es$

$\chi \sim 0.1$ for 1 GeV electrons
$\chi \sim 1$ for 10 GeV electrons



Laser-Driven Nuclear Reactions

QED – Radiation Reaction: L and NL Compton scattering

PHYSICAL REVIEW X

Open Access

Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser

K. Poder, M. Tamburini, G. Sarri, A. Di Piazza, S. Kuschel, C. D. Baird, K. Behm, S. Bohlen, J. M. Cole, D. J. Corvan, M. Duff, E. Gerstmayr, C. H. Keitel, K. Krushelnick, S. P. D. Mangles, P. McKenna, C. D. Murphy, Z. Najmudin, C. P. Ridgers, G. M. Samarin, D. R. Symes, A. G. R. Thomas, J. Warwick, and M. Zepf

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Schwinger limit

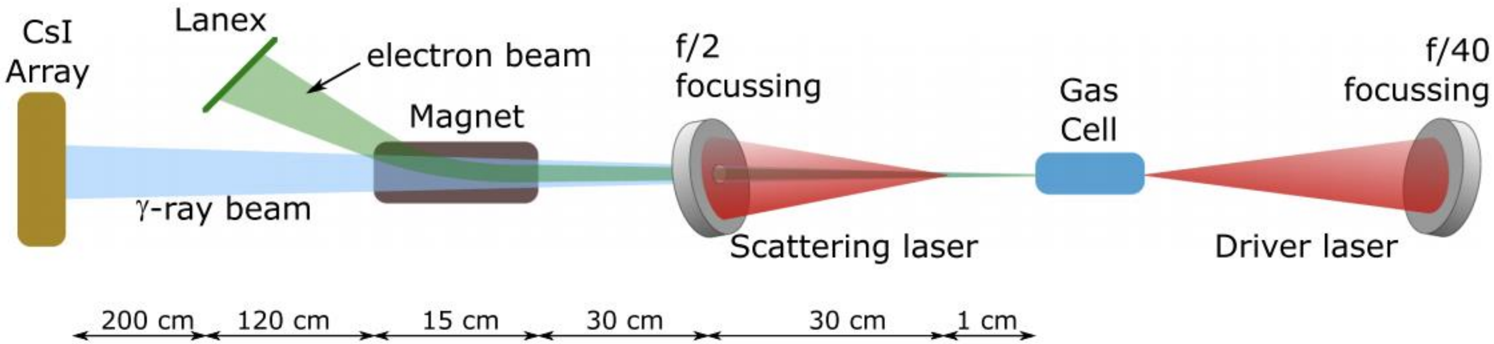
$I \sim 10^{29}$ W/cm^2 = $E \sim 1.32\ 10^{18}$ V/m

$\chi = E/E_s \sim \Upsilon E_L/E_s$

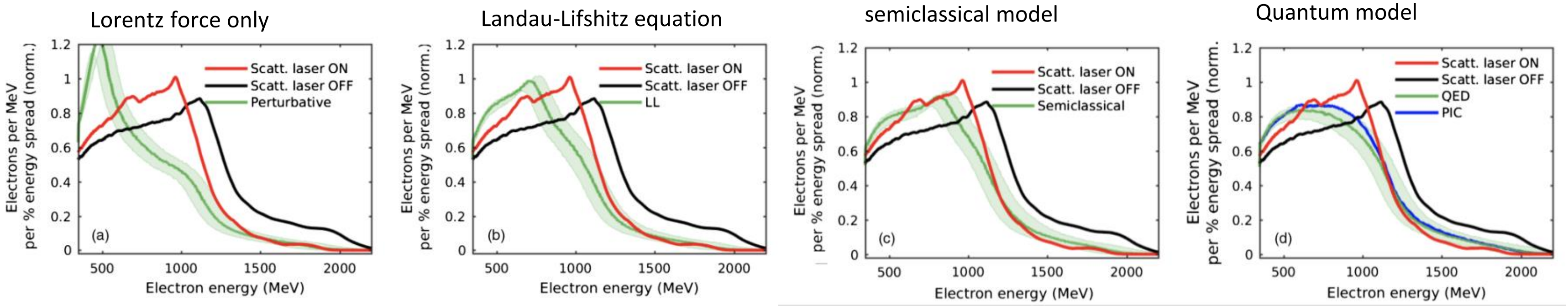
$\chi \sim 0.1$ for 1 GeV electrons

$\chi \sim 1$ for 10 GeV electrons

Typical setup LWFA



ELECTRON ENERGY LOSS: Experimental evidence and comparison with theory


Lorentz force only

Landau-Lifshitz equation

semiclassical model

Quantum model

The experimental data are best theoretically modeled by taking into account radiation reaction occurring during the propagation of the electrons through the laser field, and best agreement is found for the semiclassical correction of the Landau-Lifshitz equation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