ELISS2023

ELI Summer School | 29 Aug – 1 Sep 2023

Dolní Břežany, Czech Republic

ELI-NP capabilities, results and status

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ELI-NP/IFIN-HH

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Dolní Břežany, Czech Republic

eli

IMPULSE

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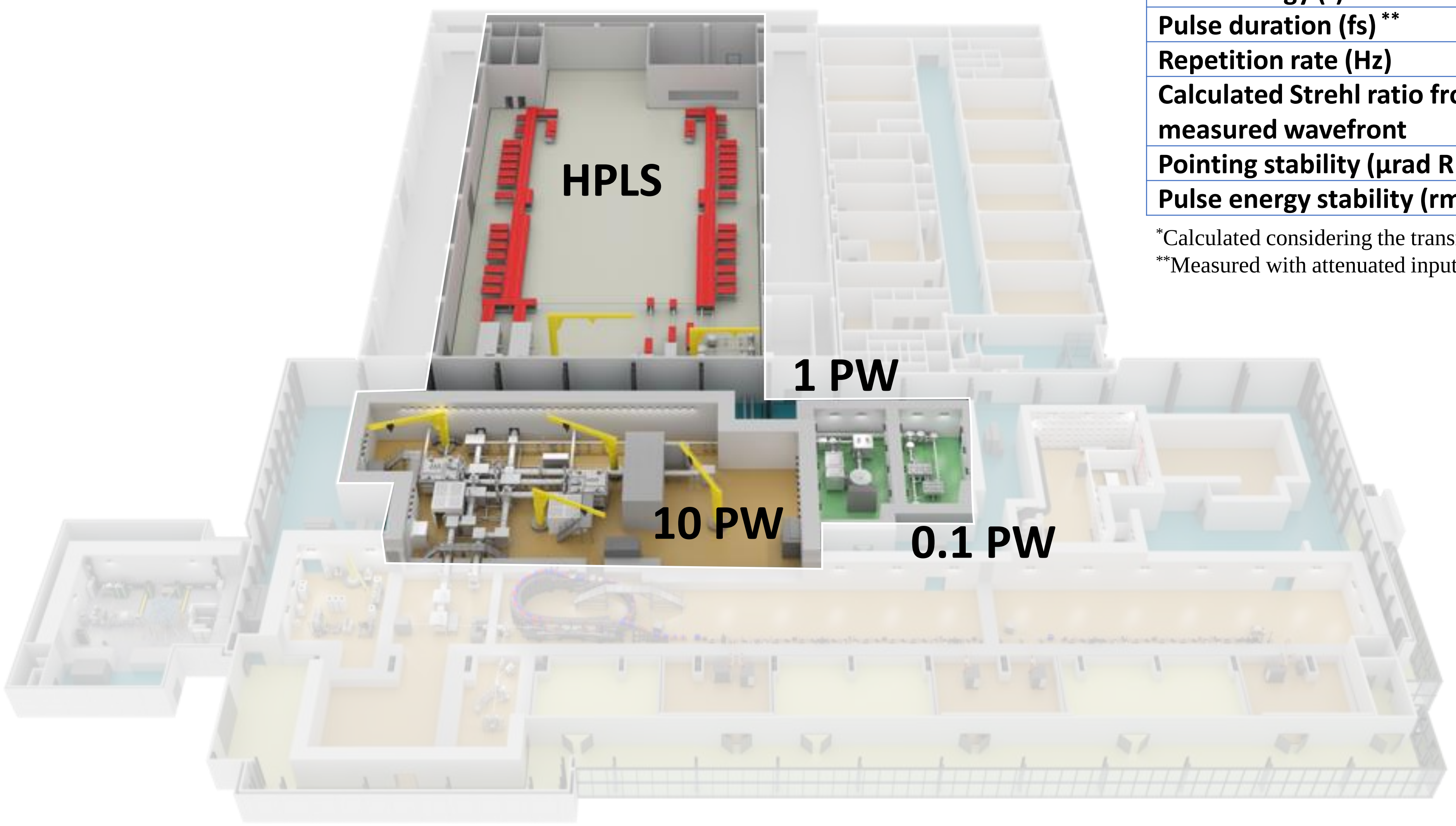
Outline

- ELI-NP laser parameters and some basics to remember
- Overview of the
  - 100 TW beamline capabilities and results
  - 1 PW beamline capabilities and results
  - 10 PW laser experiments: TNSA commissioning experiments results

    and important key parameters to look after

Experimental building layout

The HPLS and the 0.1PW, 1 PW and 10 PW areas



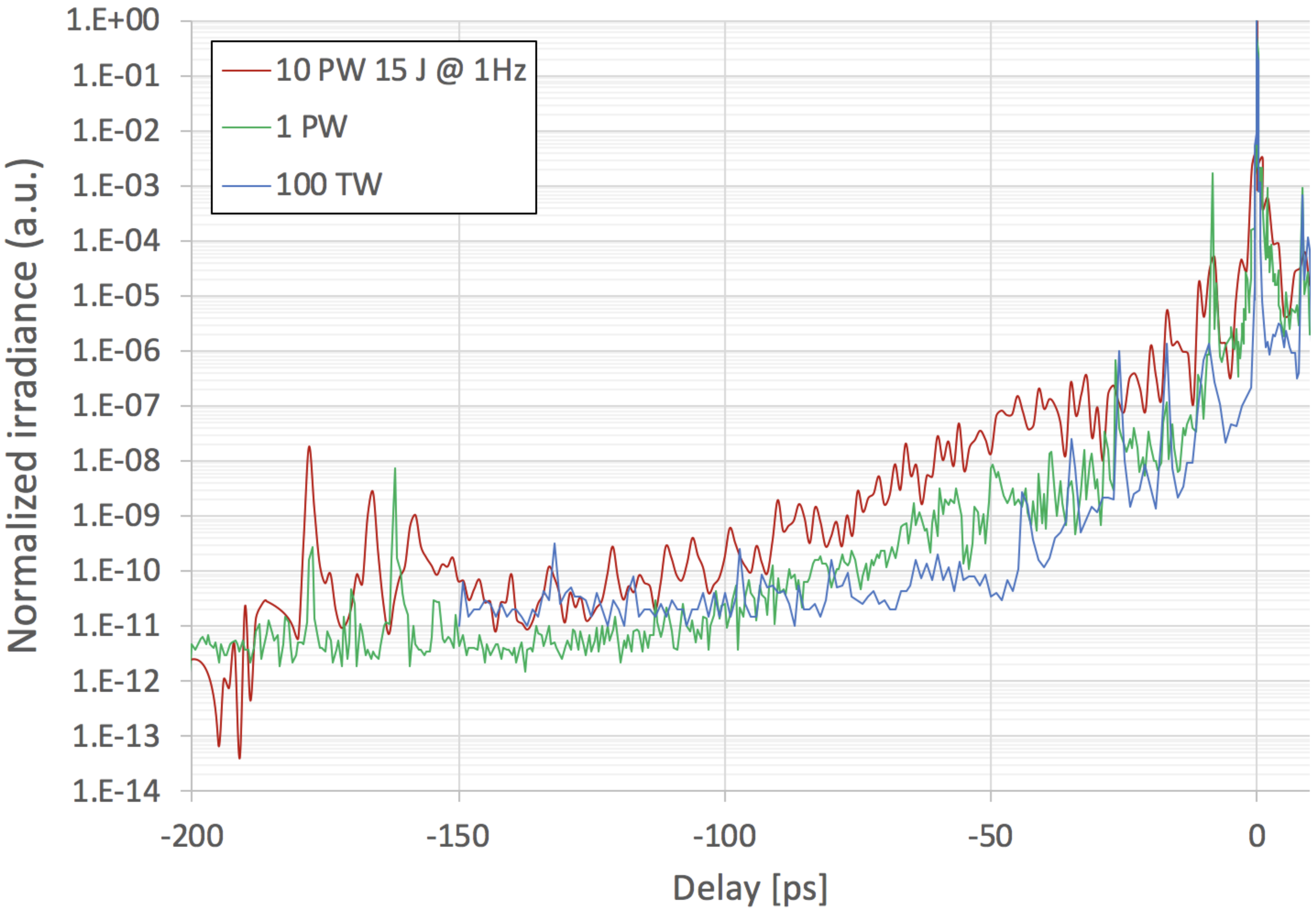
Measured parameters of the HPLS

Output type	100 TW	1 PW	10 PW
Pulse energy (J) *	2.5	24	242
Pulse duration (fs) **	< 25	< 24	<23
Repetition rate (Hz)	10	1	1/60
Calculated Strehl ratio from measured wavefront	> 0.9	> 0.9	> 0.9
Pointing stability (µrad RMS)	< 3.4	< 1.78	< 1.27
Pulse energy stability (rms)	< 2.6 %	< 1.8 %	< 1.8 %

*Calculated considering the transmission efficiency of temporal compressors

**Measured with attenuated input energy in the compressors

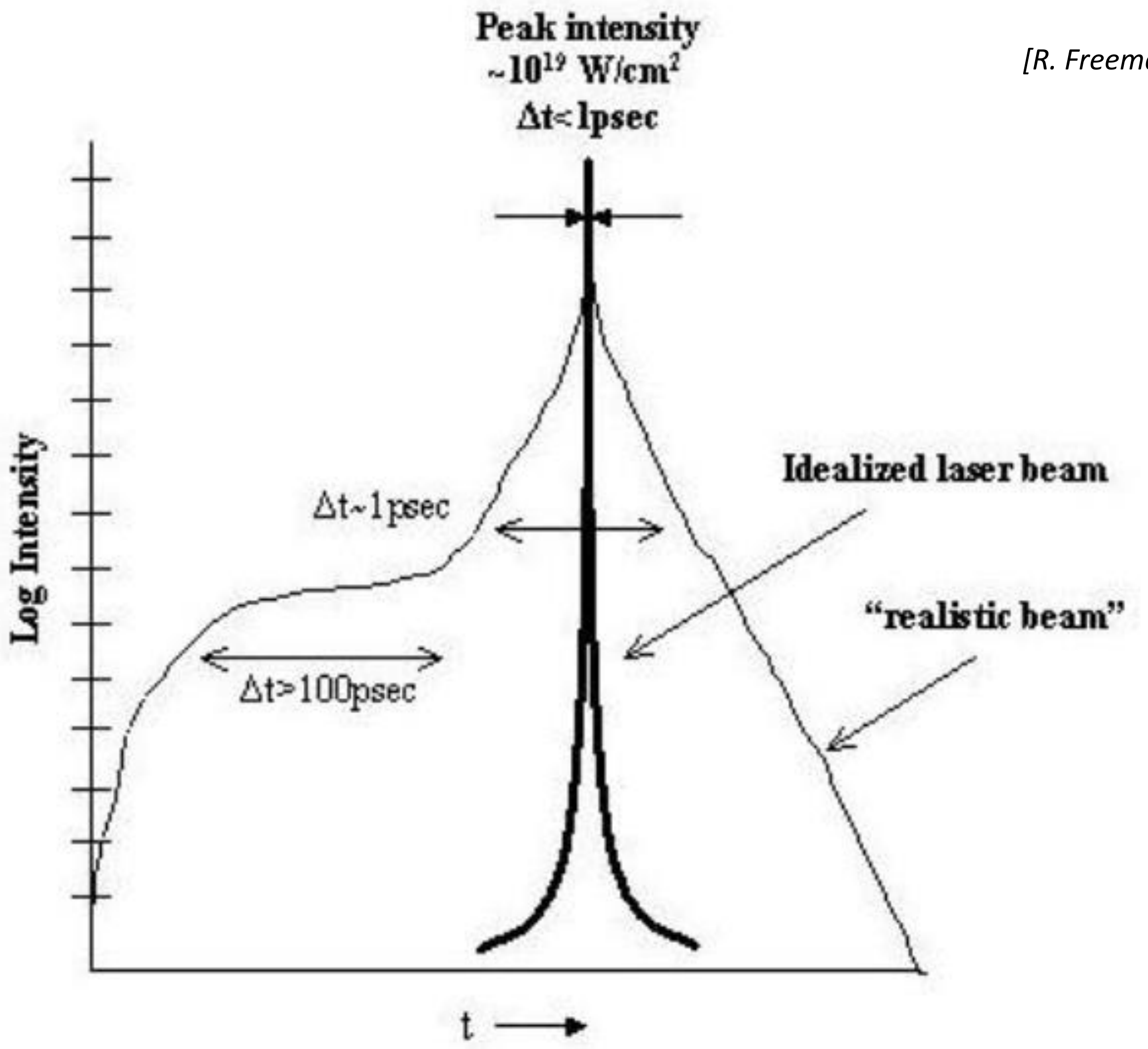
HPLS temporal intensity contrast of the 3 outputs



Contrast in May2021

Key parameter in laser-plasma solid interaction, proper measurement needed to reveal any potential pre-pulse!

Real laser pulses



[R. Freeman, Erice Summer school]

Real laser pulses span over ns in time and up to 13 orders of magnitude in amplitude even when compressed down to fs!
A real challenge also for simulating the physical processes involved

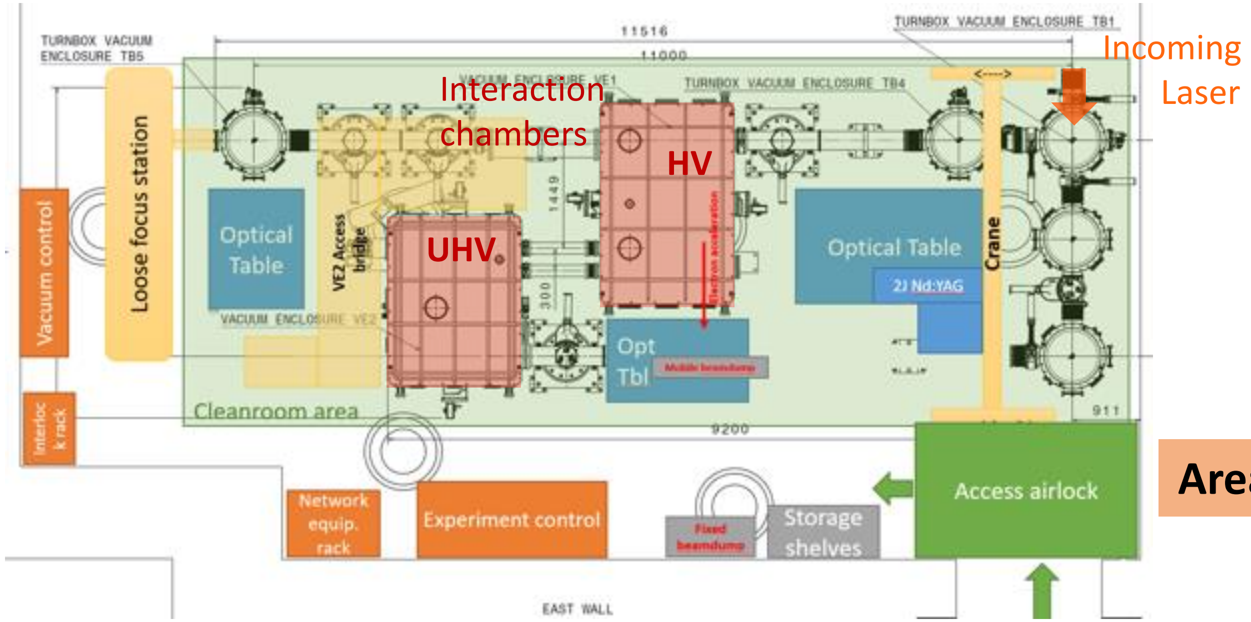
100 TW beamline:
Capabilities and e- acceleration experiment results

The 100 TW experimental area

E4: 100 TW

LGED department
(Head of LGED: Ovidiu Tesileanu)

Contact Person: Madalin Rosu
Email: madalin.rosu@eli-np.ro



100 TW area infrastructures

- 2 interaction chambers in stainless steel (**HV – VE1** and **UHV – VE2**)
- 5 turning boxes
- 10 turbomolecular pumps (maglev), 1 cryo-pump
- Integrated control system, automatic / manual modes
- VE1 typical pump time: 60 mins; venting + opening: 45 mins
- Possibility to control the vacuum level up to 10^{-6} mbar
- Large soft-wall cleanroom – equiv. ISO7
- Local Nd:YAG laser: ns pulses, max. 3J at 1064nm, 1.3J at 532nm, 0.9 J at 355 nm

Area is available to Users, 3rd ELI user call to be soon announced!

Large Optics available

- 6” flat mirrors w/ motorized mounts
- F = 1500mm off-axis parabola, AOI = 6.25°
- F = 520mm off-axis parabola, AOI = 7.5°

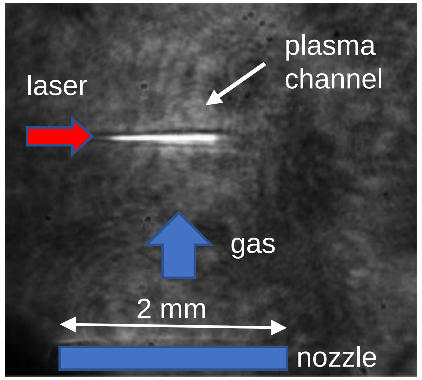
Other components for the setup

- movement stages and detectors, optical tables, optical diagnostics available on-site

https://users.eli-np.ro/experimental_facilities.php

The first 100 TW e- acceleration experiments

Electron acceleration in gas jet & betatron X-ray emission



‘Shadowgraphy’
The image of the gas jet at the interaction with the 25 fs laser pulse

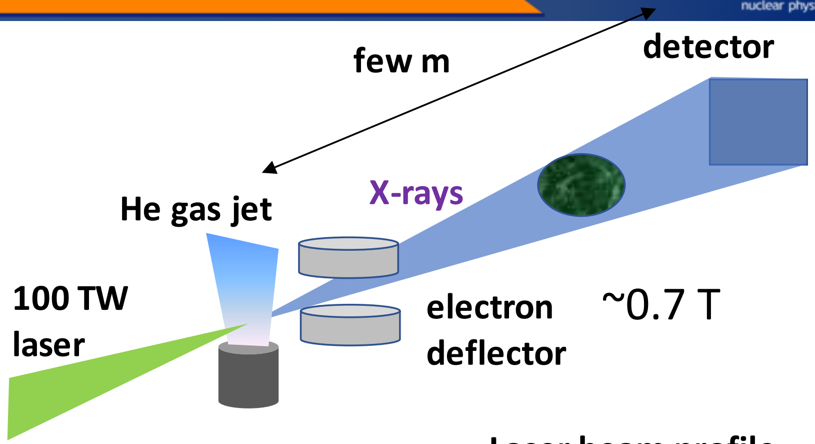
Gas: pure He or He + 2% N_2
Pressure: 10 - 20 bar

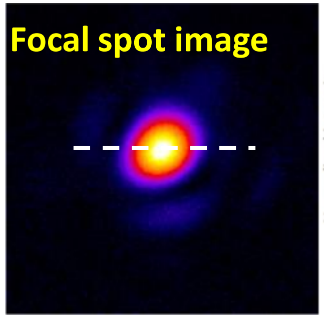
Max Energy: < 2.5 J
Pulse duration: ~ 25 fs
Central wavelength ~ 810 nm
Beam diameter: ~ 54 mm
Laser pointing fluctuation: ~ ±7 μrad

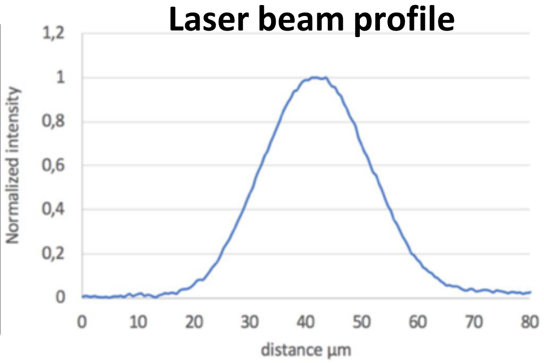
Parabolic mirror: 1.5 m focal length (F# ~28)
Spot size diameter: ~ 22±2 μm at FWHM
Encircled energy: ~ 70% @ $1/e^2$

$I_0 \sim 10^{19}$ W/cm^2

→ acceleration field of ~1 GV/cm

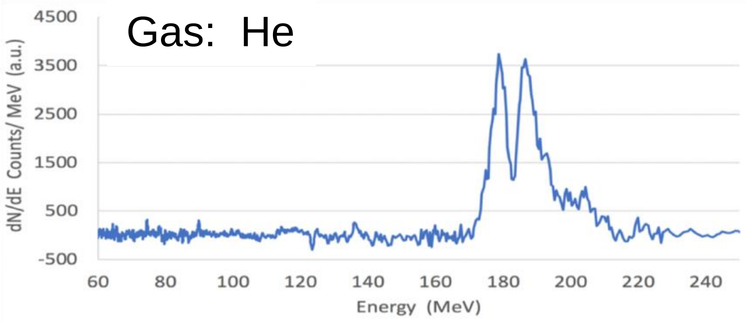


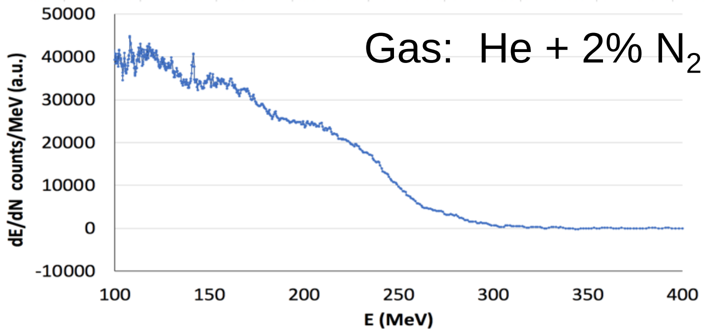




LWFA electron acceleration

courtesy of D. Doria, P. Ghenuche, M. Cernaianu

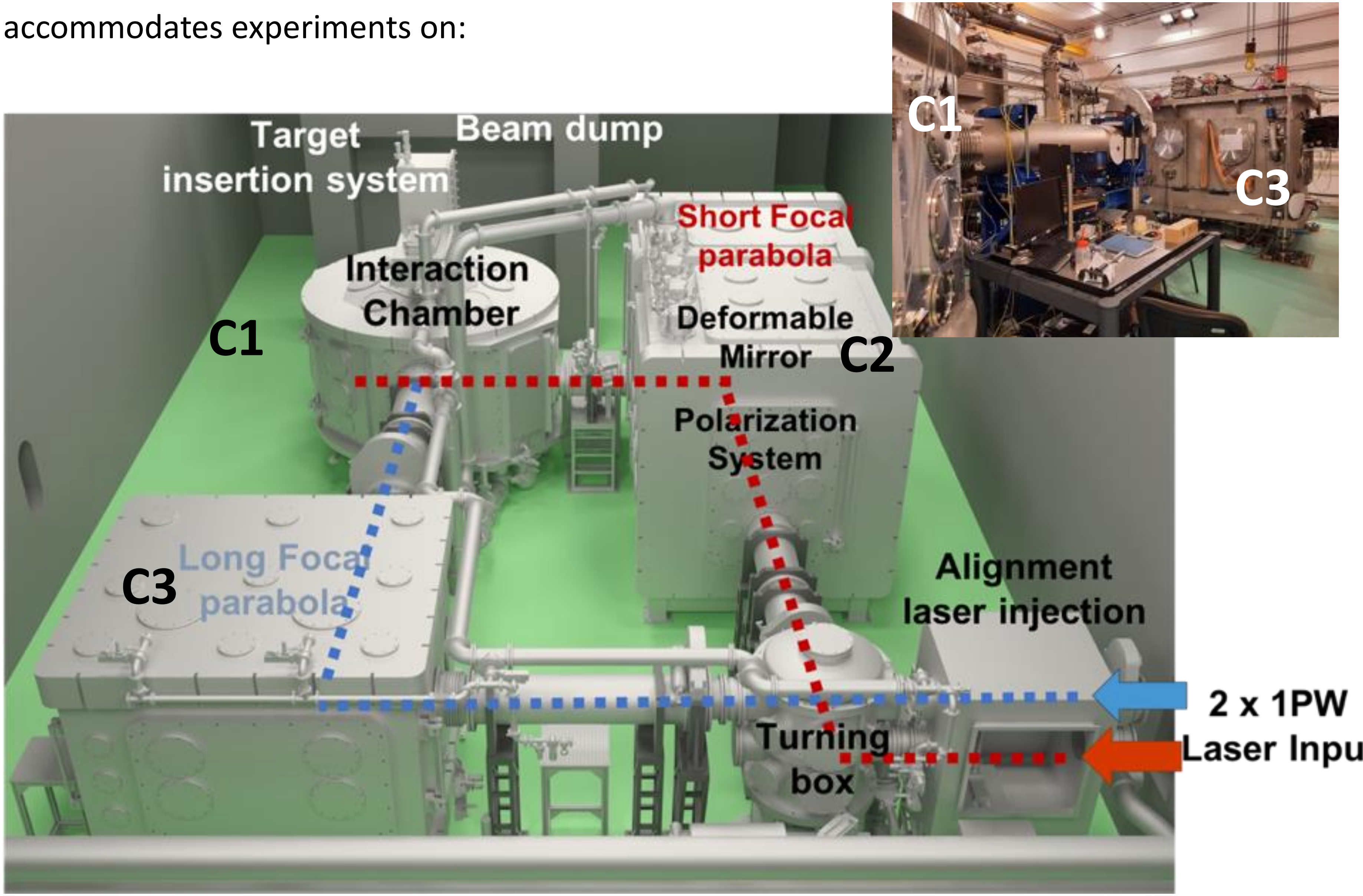




1 PW experimental area:
Capabilities and results from ion and e- acceleration experiments

Overview of the 1 PW experimental area E5

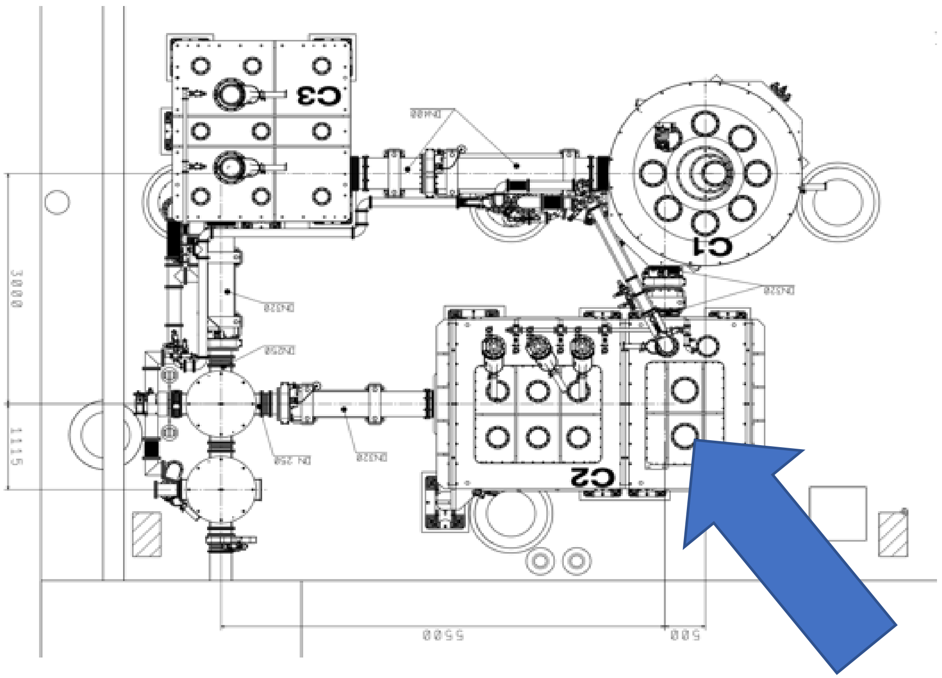
The E5 area is **the 1 PW area** and accommodates experiments on:
- **solid targets**
- **and gas targets**



Area infrastructure

- 1 main interaction chamber (C1) in Aluminium
- 2 turning boxes + 2 large chambers (C2, C3) in stainless steel
- 9 turbomolecular pumps (1 cryo-pump)
- Integrated control system, automatic /manual modes
- C1 typical pump time: 40 mins; venting + opening: 30 mins
- Vacuum level up to 10^{-6} mbar
- Small soft-wall cleanroom – equiv. ISO7

Focusing configurations and equipment in the 1 PW experimental area E5



Three experimental chambers allowing multiple configurations and further upgrades

Beam characteristics:

- **Unique 2 x 1 PW laser beams (810 nm, 25 fs, 25 J, 190 mm beam, 1 Hz), synchronizable**
- Short focal parabolic mirror ~ F/3.5
- Long focal parabolic mirror ~ F/24

Laser, alignment and target manipulation

- Internal Injection Alignment Laser: CW 632-800nm, 190mm dia.
- Laser Diagnostics: (FF, NF, laser energy at full power, FROG, back-reflection)
- Circular Polarization System: Mica waveplates (permanent system upgrade to come)
- 5X –20X objectives alignment system, 1µm spatial resolution motion
- Deformable Mirror: 52 actuators, 400 mm dia. membrane
- Shack-Hartmann wavefront sensor λ/100 R.M.S. 32x40 px
- Target insertion system

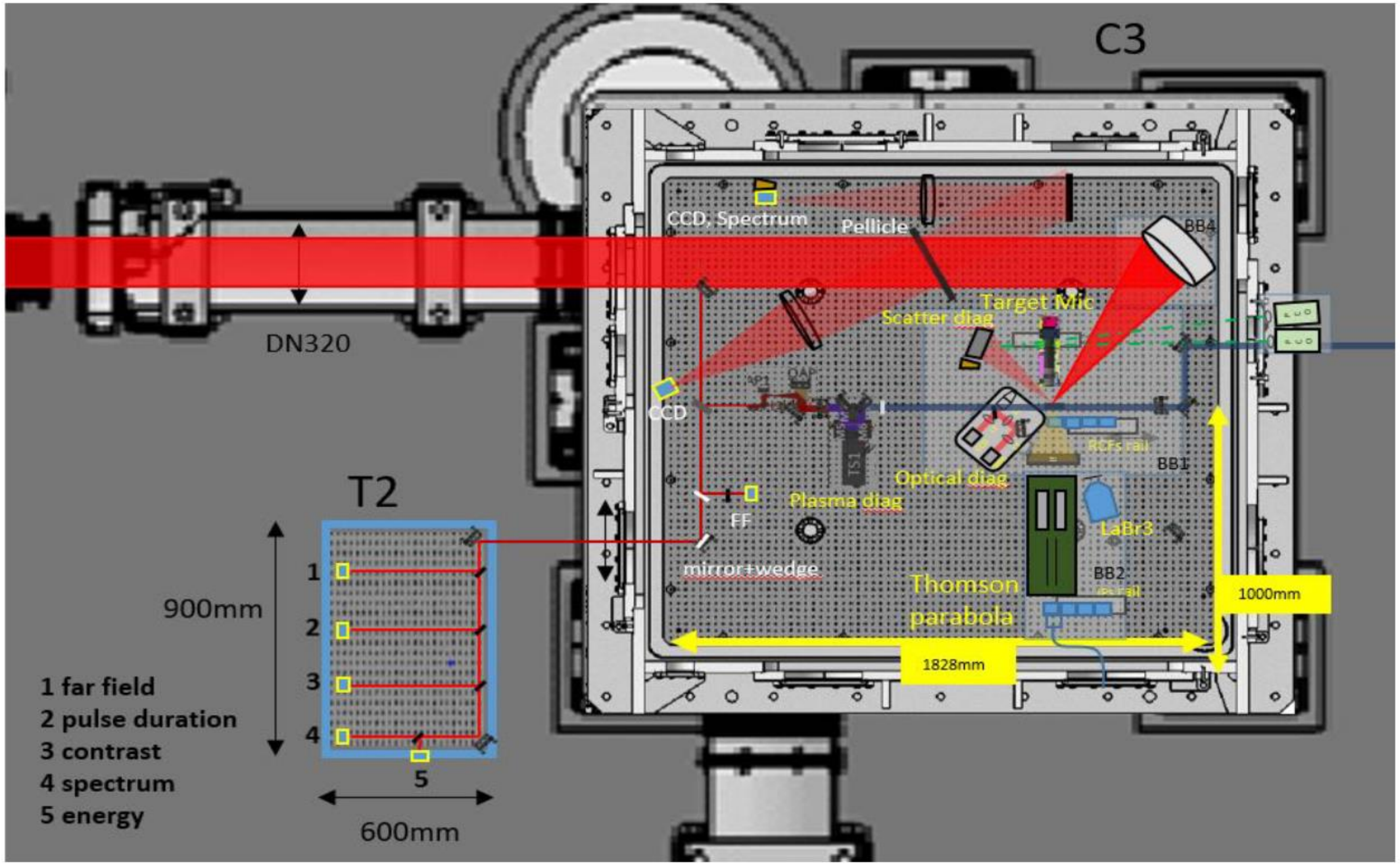
Laser diagnostics:

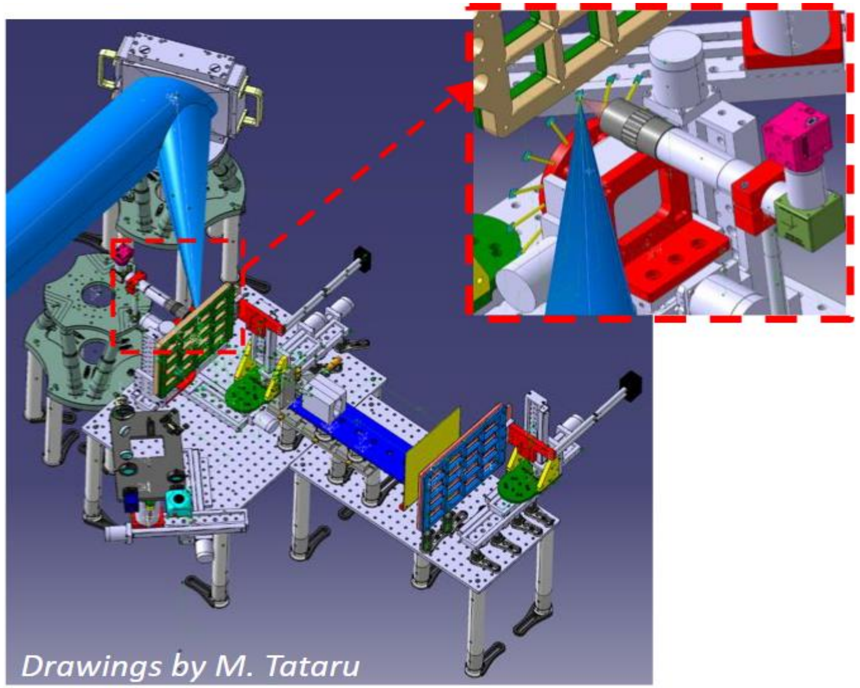
- On-shot measurement of pulse duration, spectrum, energy on sub-aperture
- Contrast measurement on sub-aperture

Secondary sources detection

- Radiochromic Film Stack: 1’’x 1’’, 2’’x 2’’up to 100 MeV proton, CR39
- Thomson Parabola: up to 60 MeV, 8% res. @ 60 MeV , optically coupled optional (online)
- Optical plasma probe: up to 100 mJ, 2w,1’’ dia., ~ µm res., Interferometry, Shadowgraphy.
- H+ Spectrometer: up to 100 MeV, 5% res. @ 100 MeV optically coupled optional (online)
- e- Spectrometer: up to 2 GeV
- Streak camera: VIS, 1 ps resolution
- Optical spectrometer: ANDOR Shamrock (VIS)
- La2Br3 detector with secondary activation targets

Typical TNSA setup for proton acceleration with PW beams



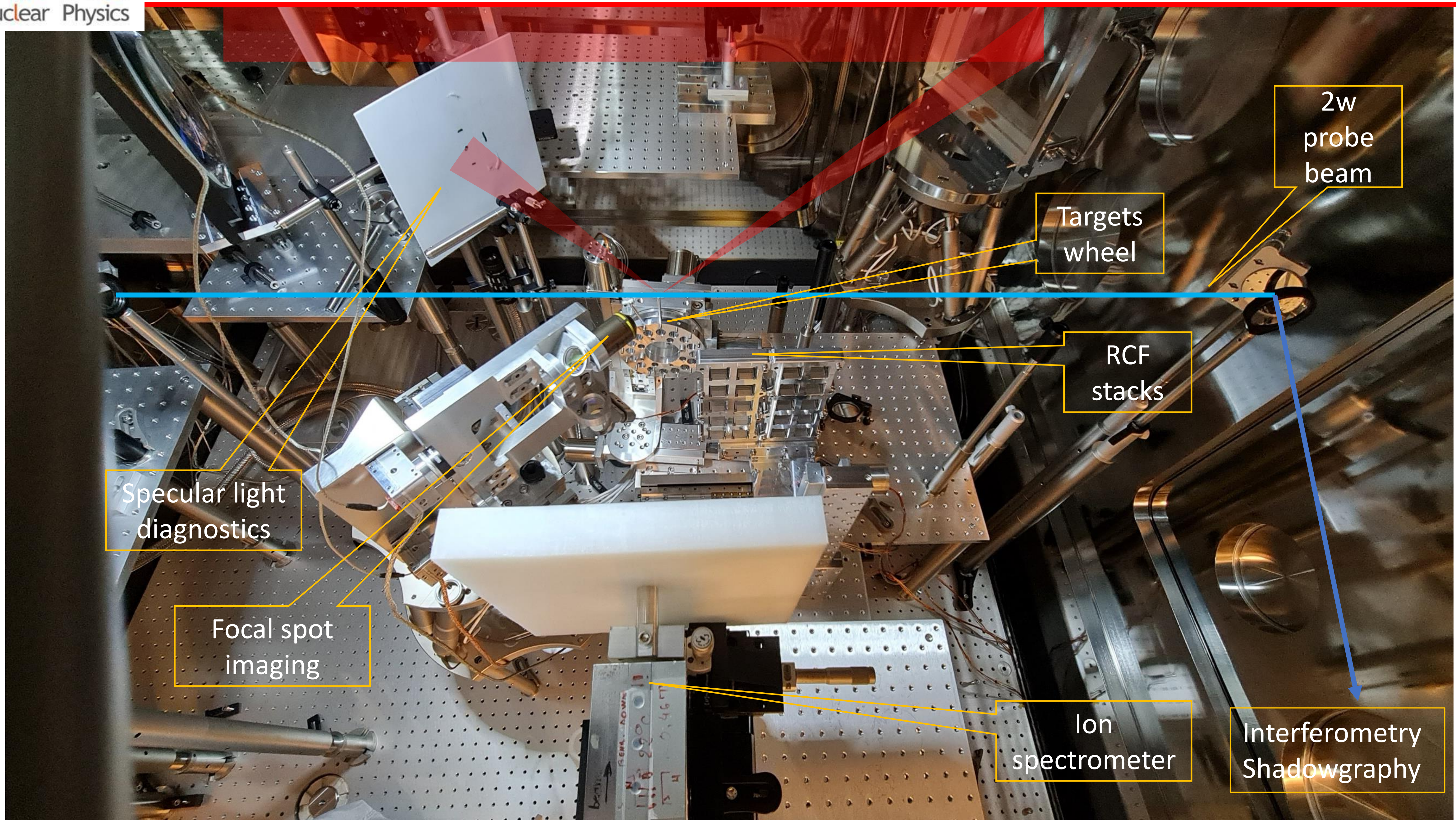


Drawings by M. Tataru

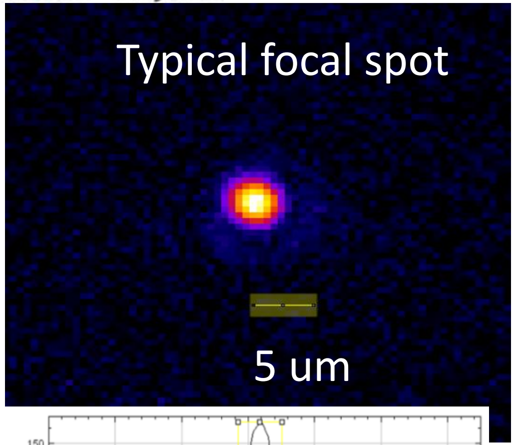
Main diagnostics

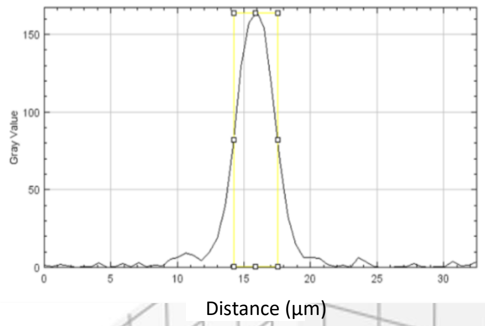
- Optical probe
- Specular reflection
- Back reflection monitor
- Radiochromic film stack
- Thomson Parabola
- Near and far-field on full power shot
- Laser characterization at full power shot

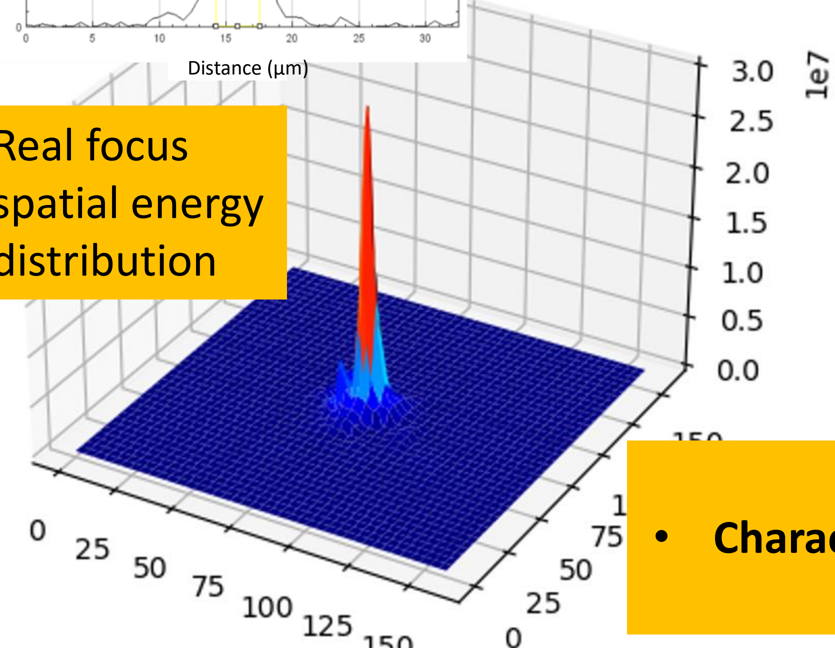
1 PW commissioning experimental setup



Laser characteristics



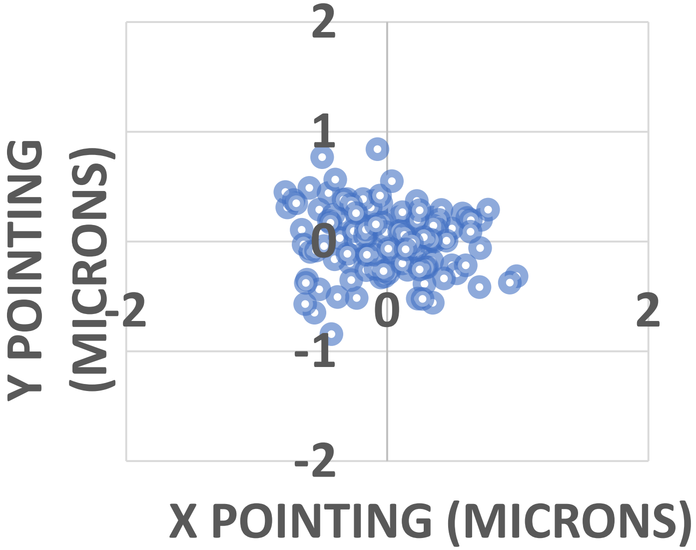


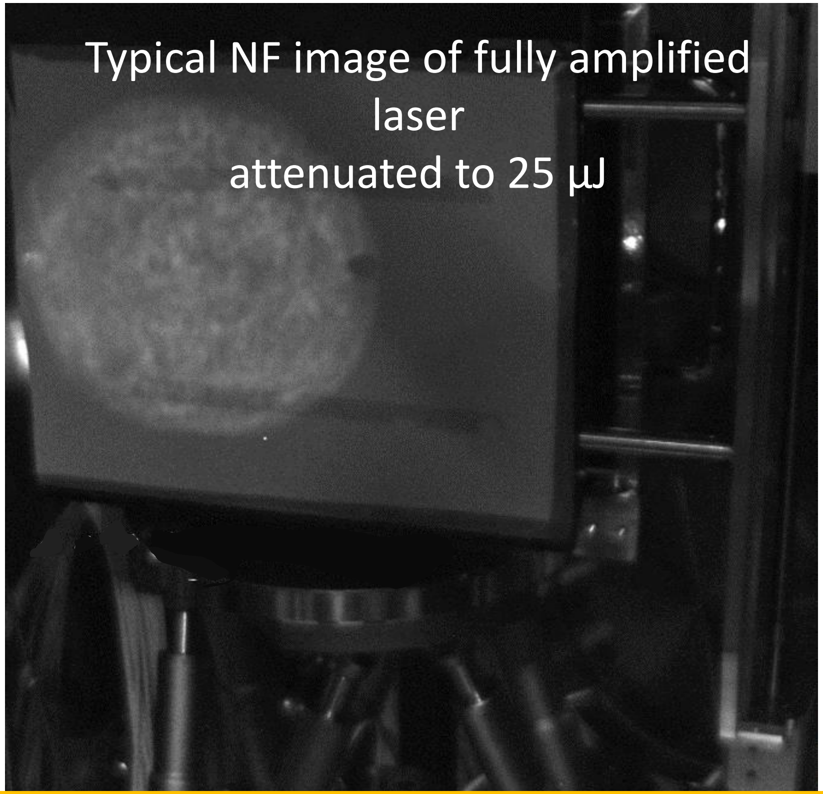


Real focus spatial energy distribution

Laser focal spot, daily optimized:

- Typical focal spot size of 3.3 – 3.6 µm FWHM
- Encircled energy
  - ~70% @ $1/e^2$ when represented over 12 bit CCD dynamic range
  - ~50% in $1/e^2$ (ideal Gaussian beam is 86%) over ~4 orders of magnitude
- Laser energy stability at full power: ±2%
- Pointing jitter: ±1 µm



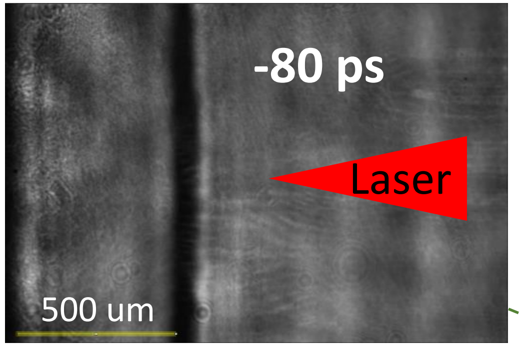


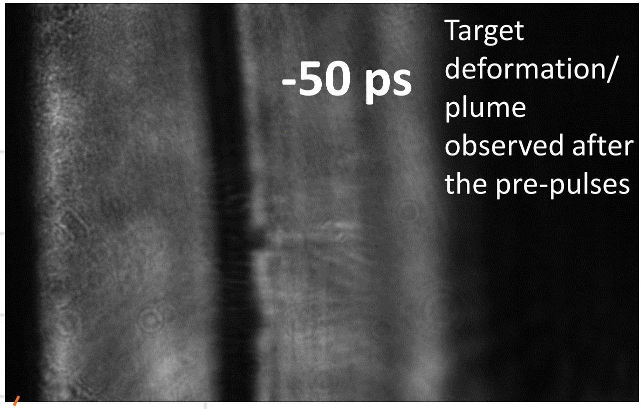
- **Best focal spot obtained after wavefront and spatial chirp adjustment**
- **Characterization needed over few orders of magnitude to calculate real encircled energy**
- **Again with huge impact over PIC simulations**

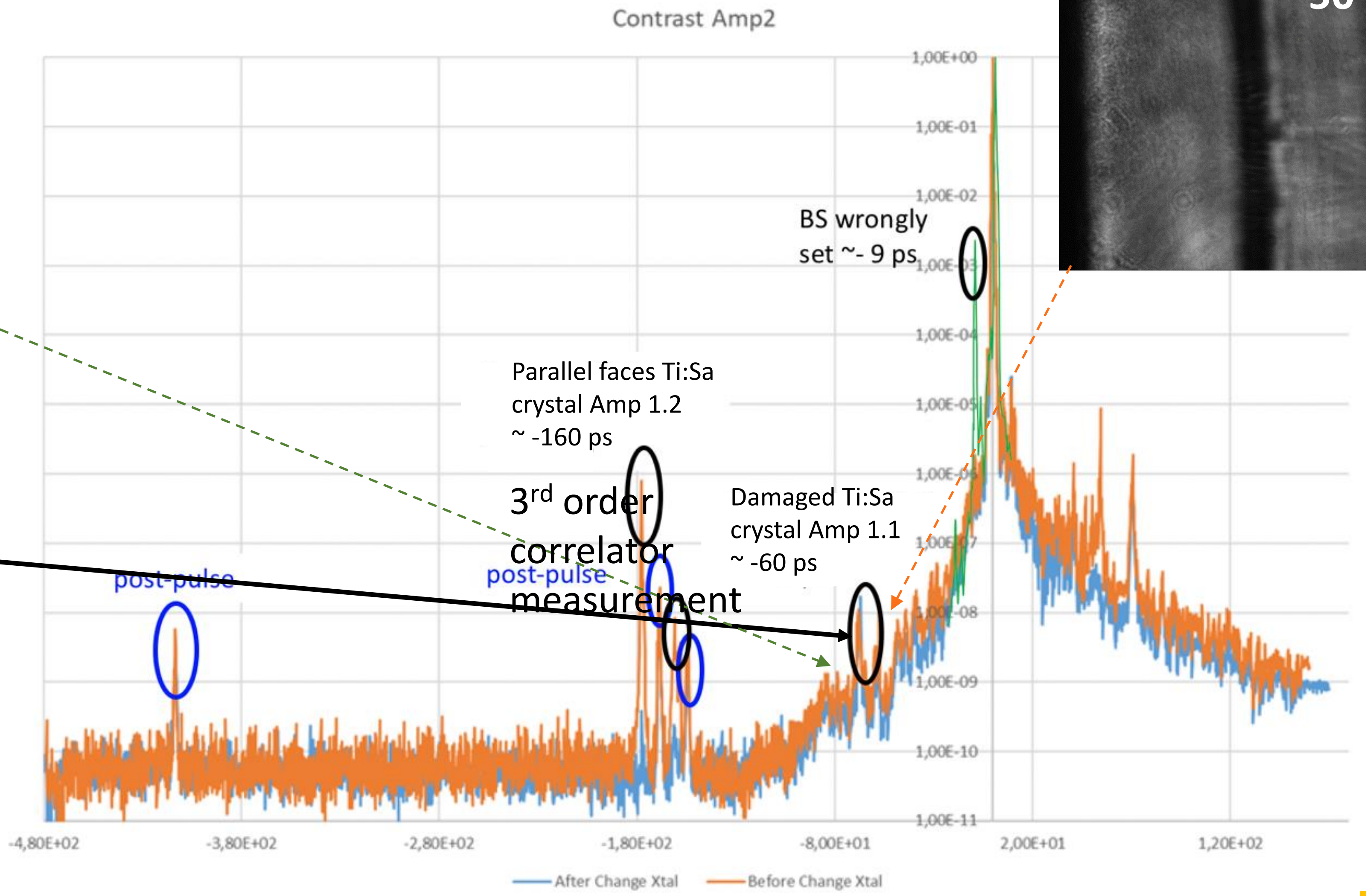
Laser pre-pulses diagnosis using plasma imaging and 3rd order correlator

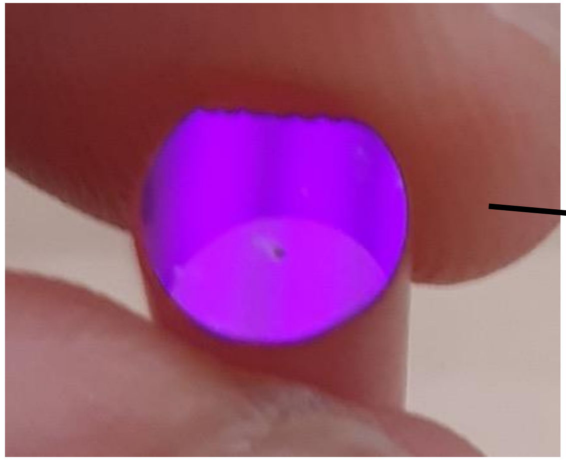
Laser contrast investigation in the 100 ps regime

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







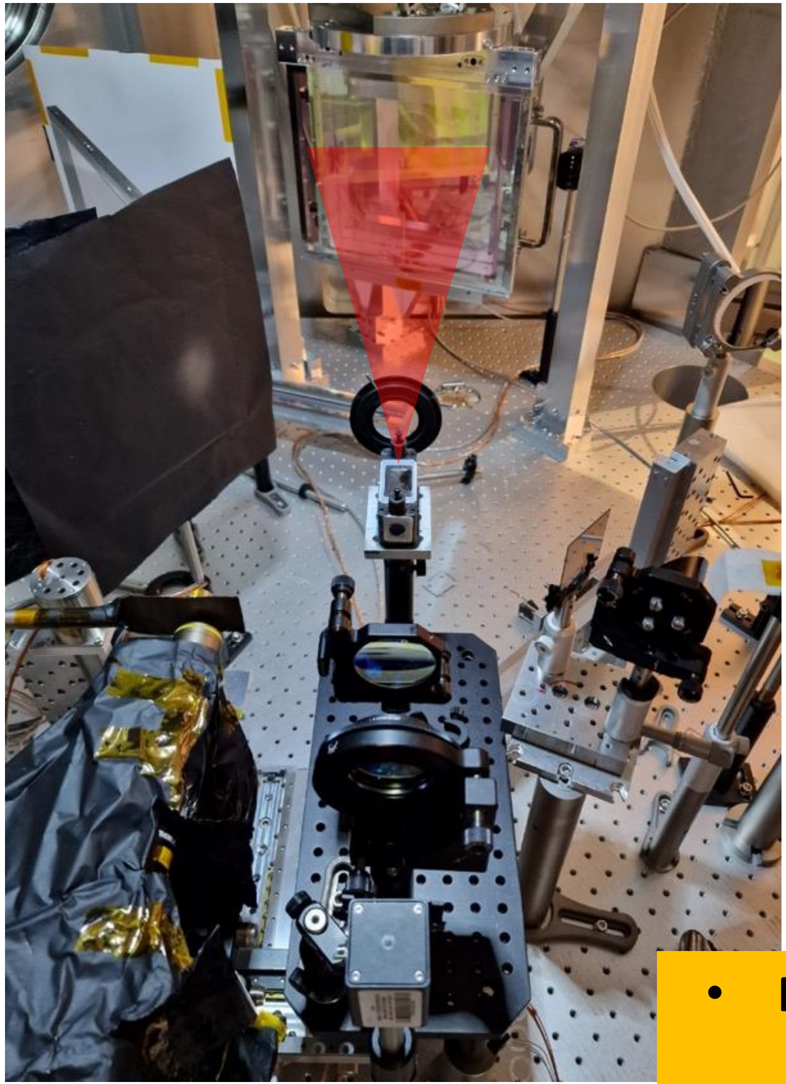


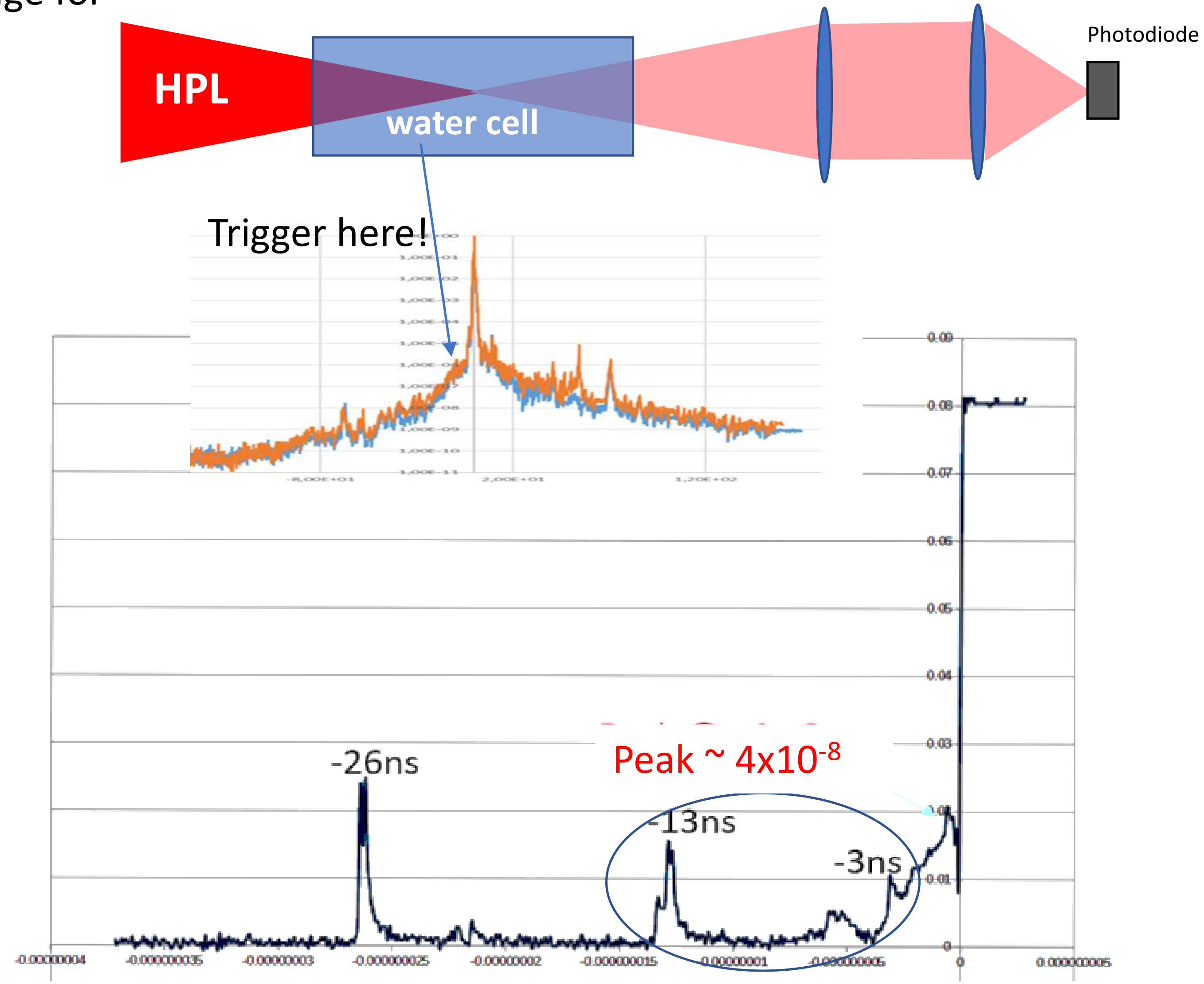
- Most of the pre-pulse sources have been identified and solved during the first 3 weeks of the commissioning
- The contrast due to the pedestal is at the moment of the order of 10^{-8} at about -20 ps.

How to characterize the long temporal profile of a high energy, compressed laser pulse?

Need to tune diagnostic for the required dynamic range for measuring peaks typically below 1E-8 contrast ratio

Again work in the plasma regime

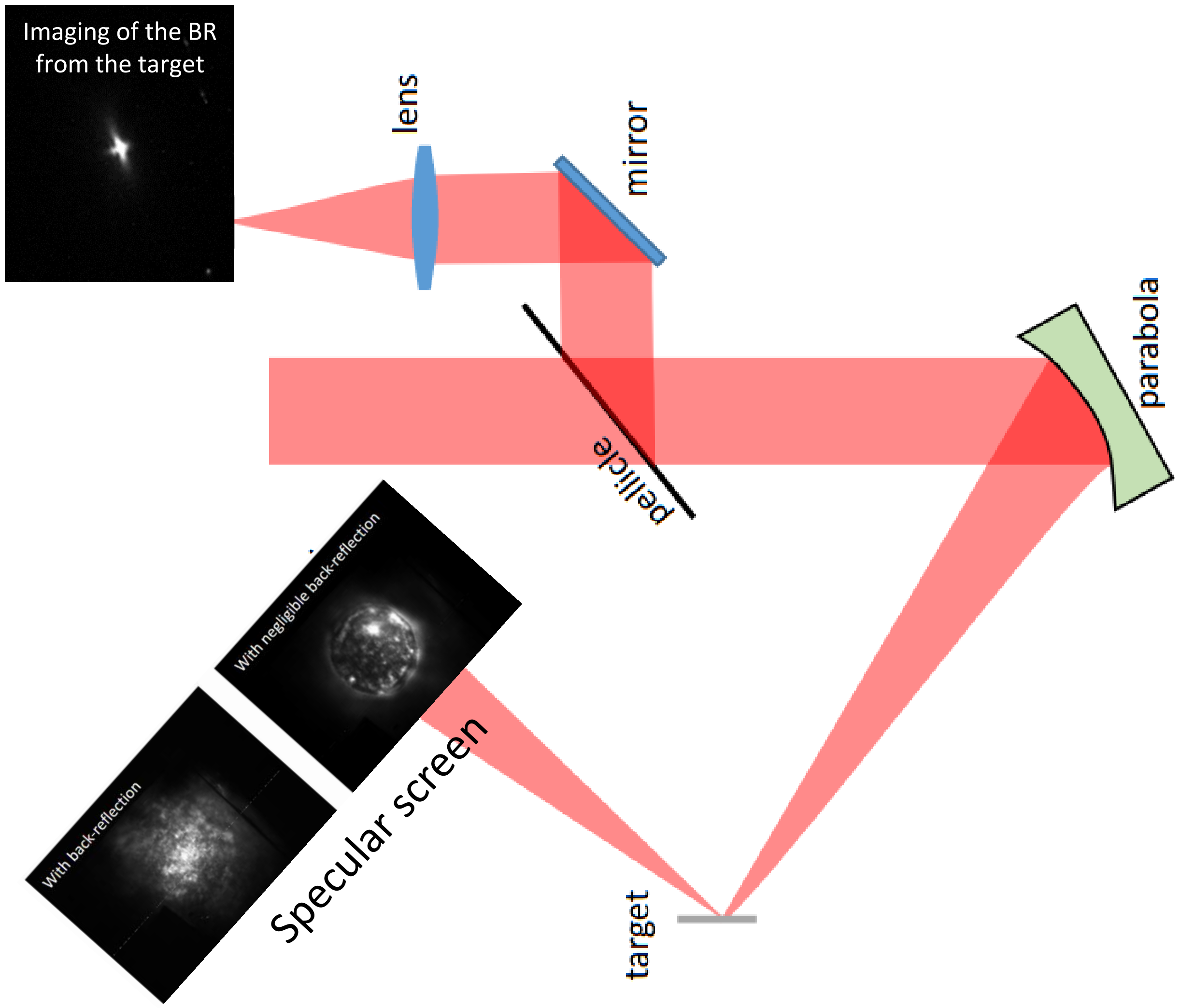




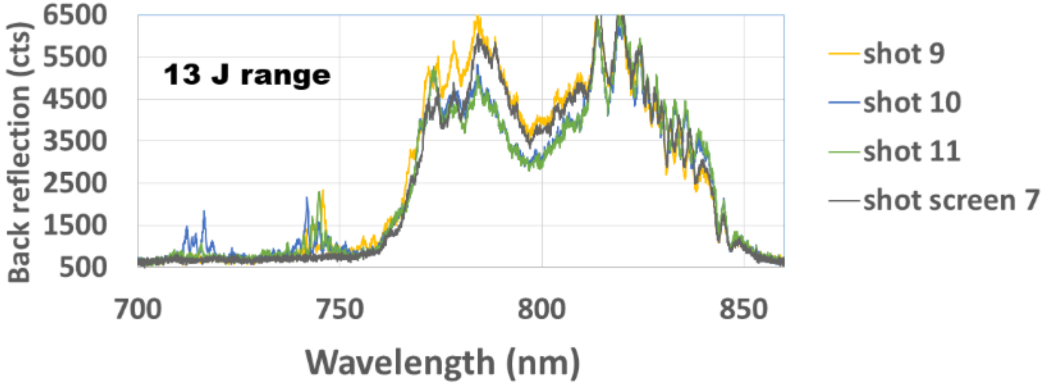
- **Pre-pulses identified with water cell (dynamic range ~10^9) and removed**
- **Boost of H+ cutoff energy achieved**

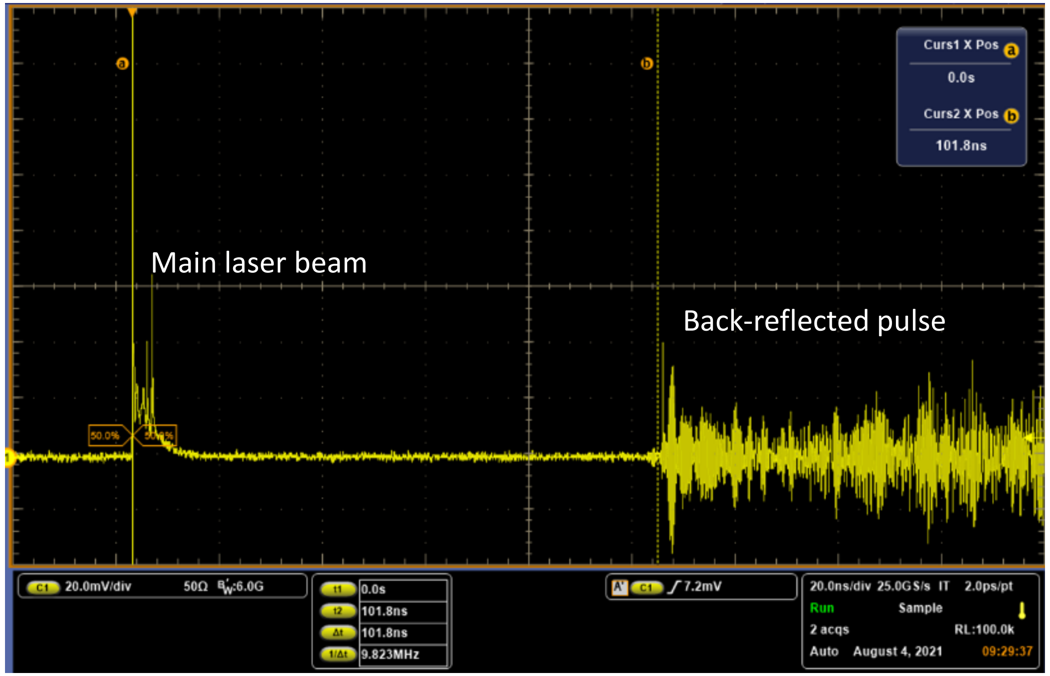
Back-reflection monitoring

Laser pre-pulses can also induce high energy laser back-reflections



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





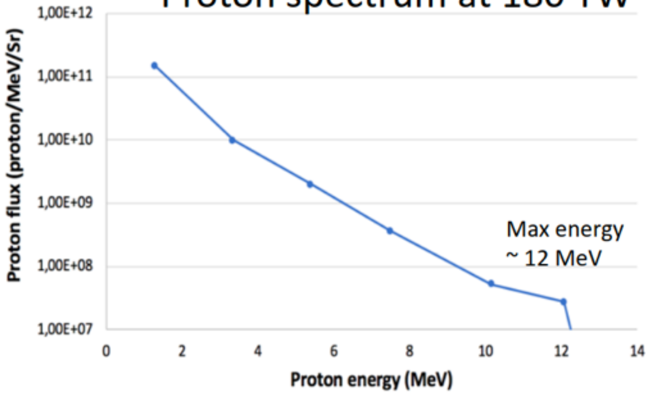
Fast photodiode diagnostic of the back-reflected pulse

First 1 PW experiments with solid targets at ELI-NP (TNSA investigation)

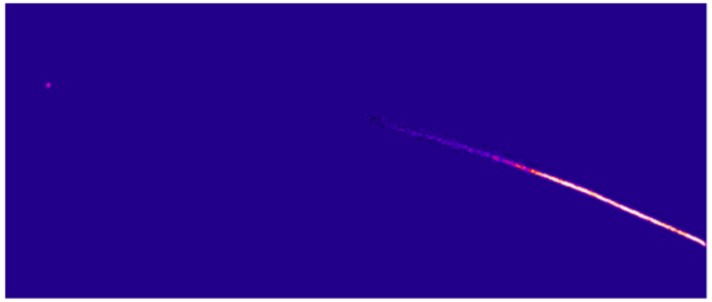
First shots on target with low power

Radiochromic film stack

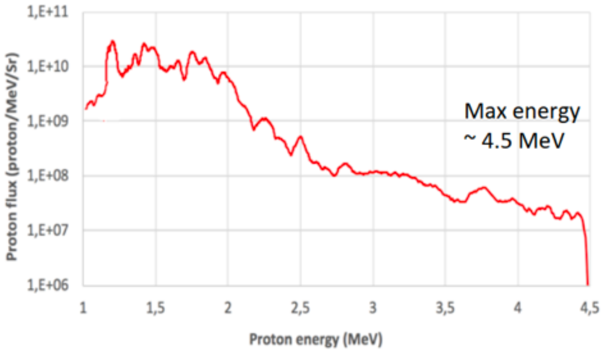
Proton spectrum at 180 TW



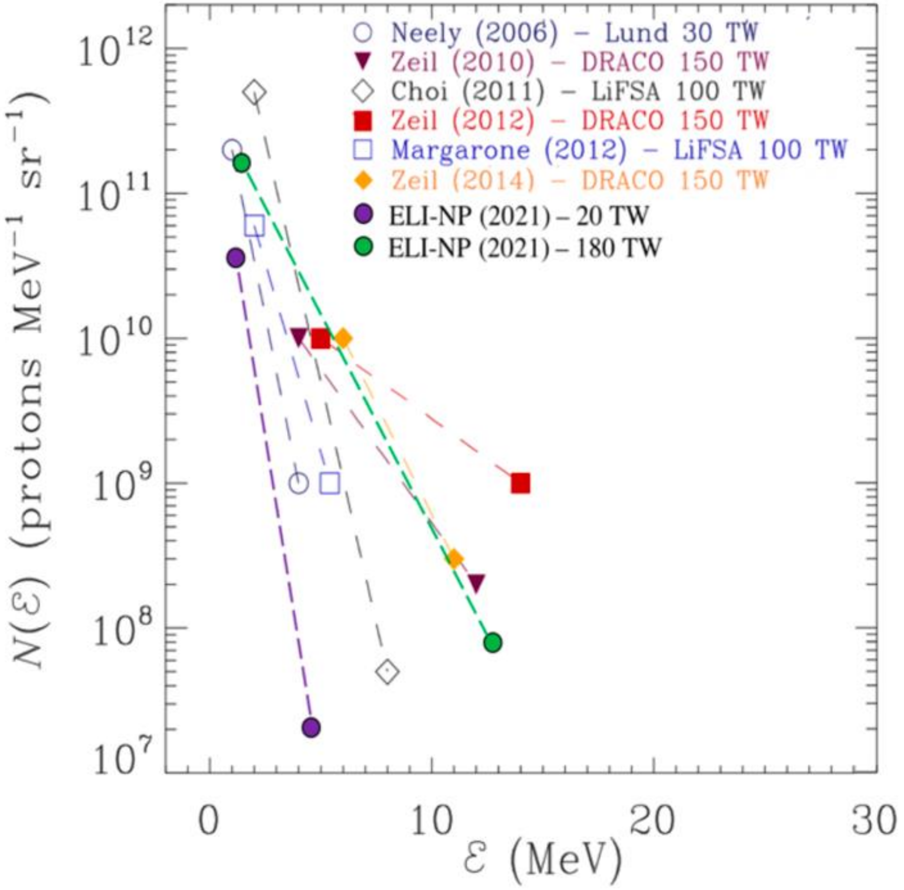
Thomson parabola



Proton spectrum at 20 TW

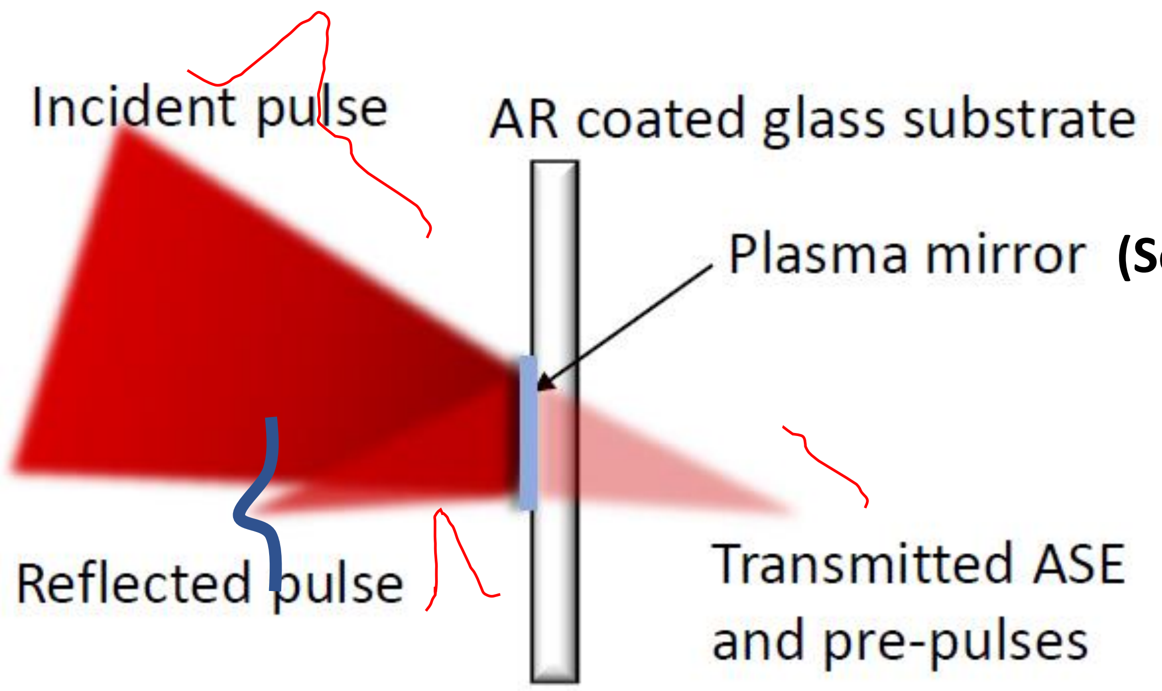


Comparison with literature:
Results are consistent



Shots with ~ 0.5 PW on 4.5µm Al foil: more than 20 MeV proton energy cut-off

Typical plasma mirror to further improve the temporal contrast



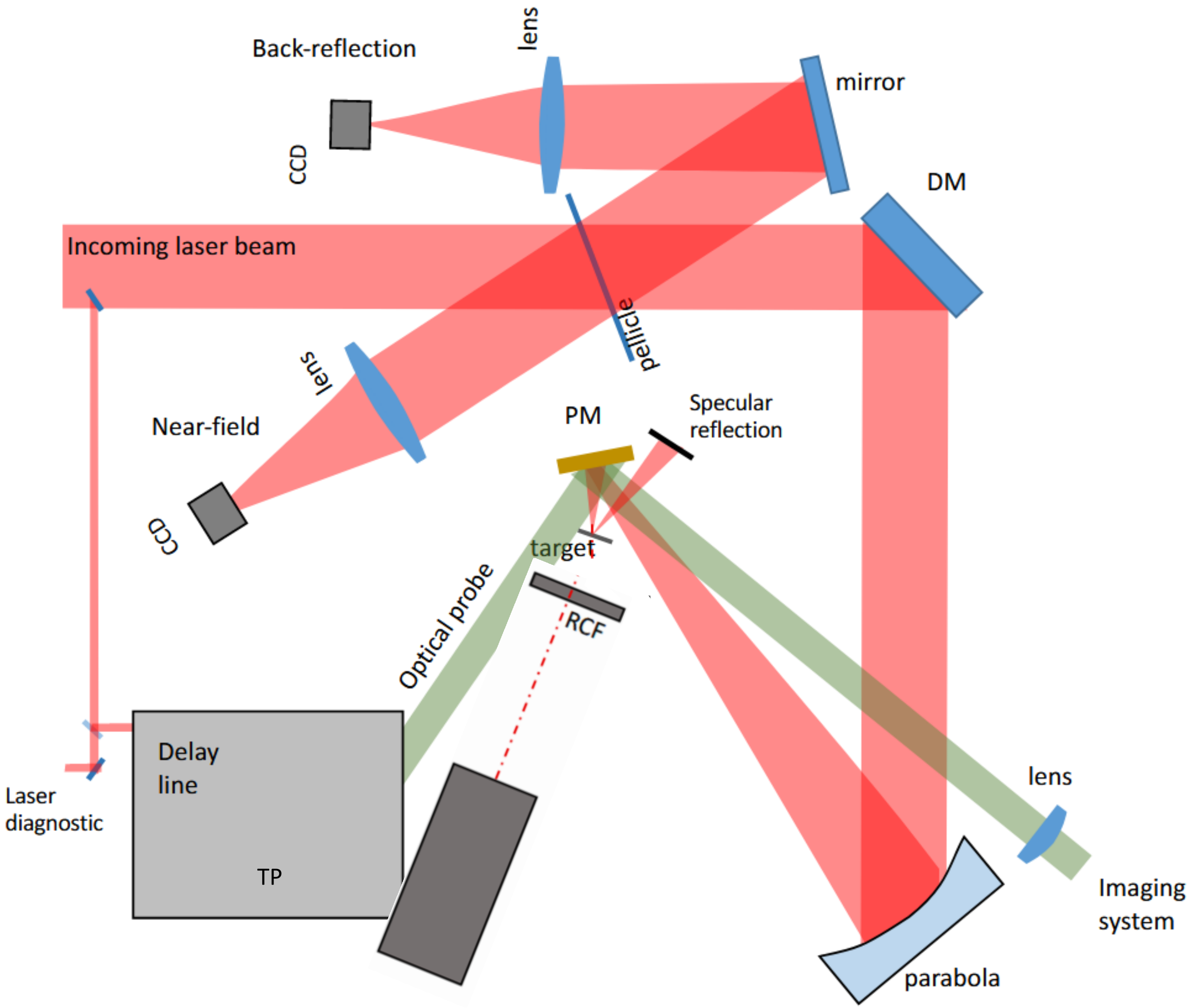
(Solid or liquid)

Conventional single or double PM configurations lie in the laser transport system, very expensive, no debris protection

PM close to target:

- Debris protection
- Back-reflection protection
- Increase temporal contrast

TNSA experiments with improved contrast



Main diagnostics
- Optical probe
- Specular reflection
- Back-reflection monitor
- Radiochromic film stacks, CR39
- Thomson Parabola
- On-shot near and far-field
- On-shot laser characterization
- EMP

1 PW experiment with solid targets (TNSA investigation) and improved contrast

Employing plasma mirrors

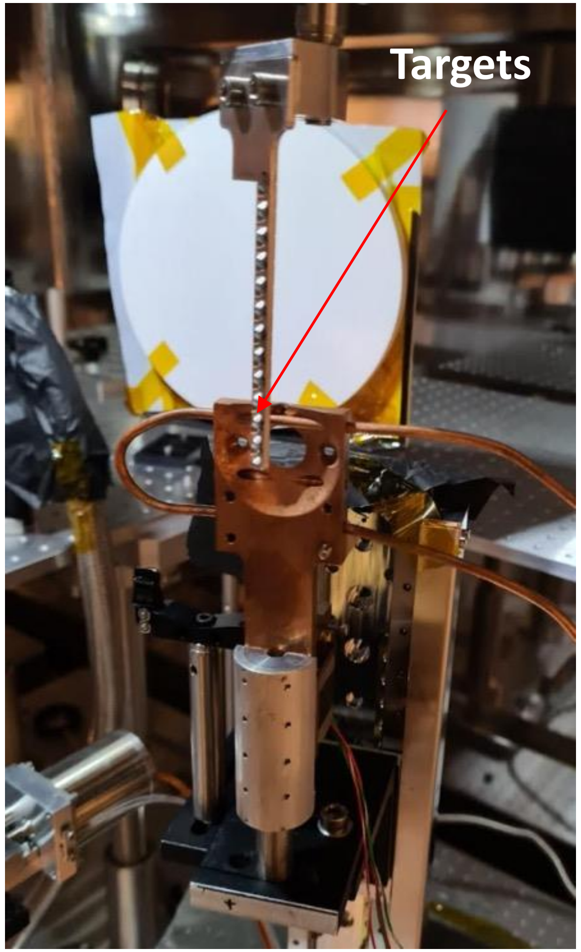
Goals:
- Contrast improvement
- Investigation of back-reflection protection
- Preparation of 10 PW experiment

Conventional PM

Gold coated

AR, FS, BK7

Liquid Crystal PM investigation at 1 PW (collaboration with D. Schumacher, OSU)

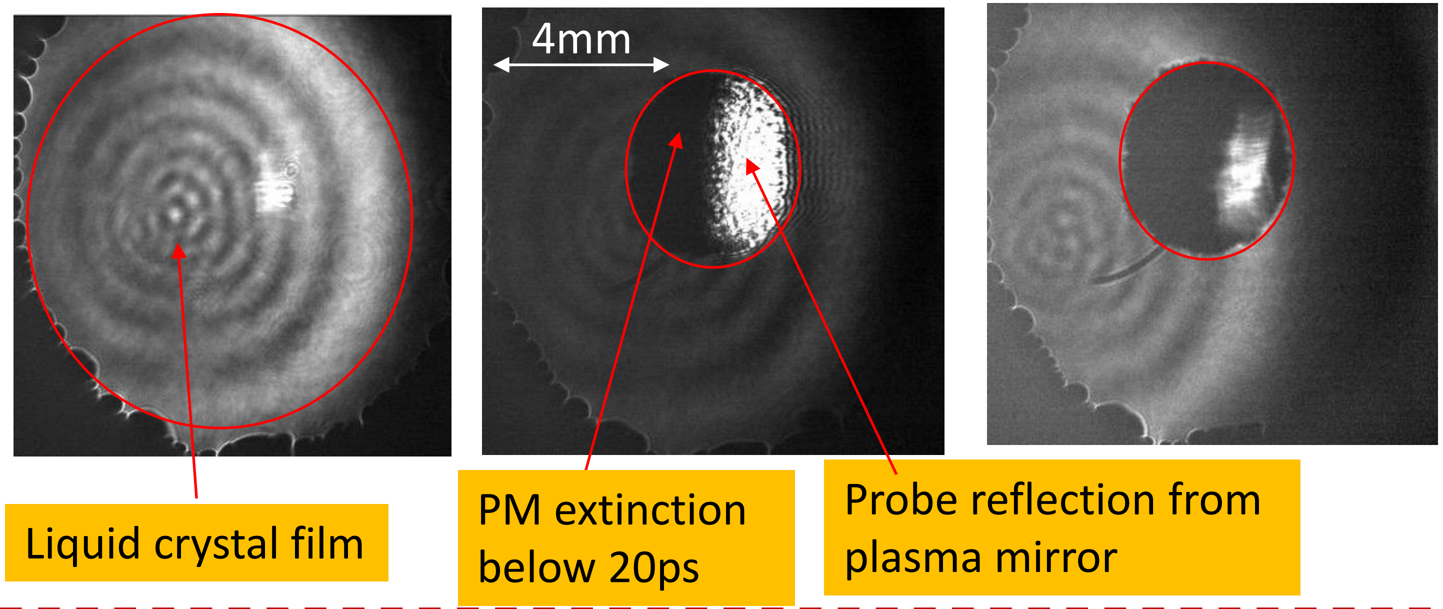


LC for contrast improvement and shutter

Imaging of liquid crystal film by optical probe reflection: varying intensity I ~10^{14} Wcm^{-2} to 10^{17} Wcm^{-2} and PM spot

23J, I ~ 8×10^{15} Wcm^{-2}, 20 nm liquid crystal plasma mirror

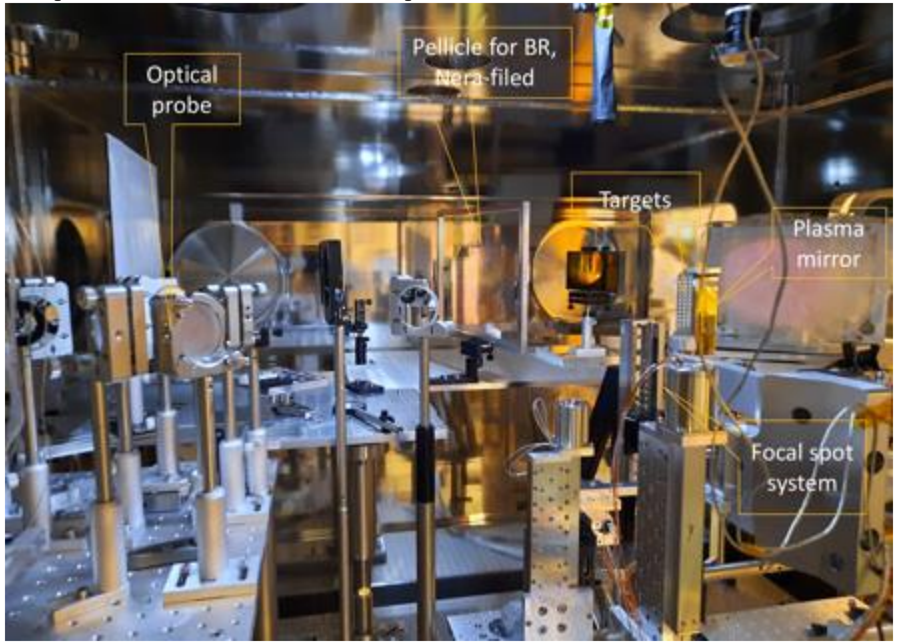
Probe @T0 – 20ps | Probe @T0 | Probe T0 + 420ps



Some result of TNSA

- 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.
- RCF and Ion spectrometer (Thomson Parabola) to fully characterize the ion beam

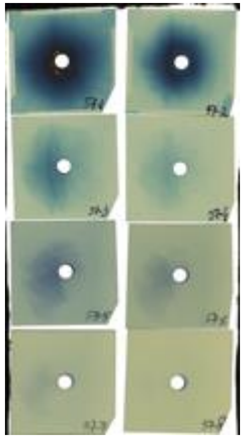
Experimental setup with PM



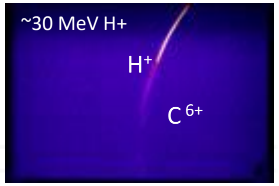
Shot parameters with plasma mirror

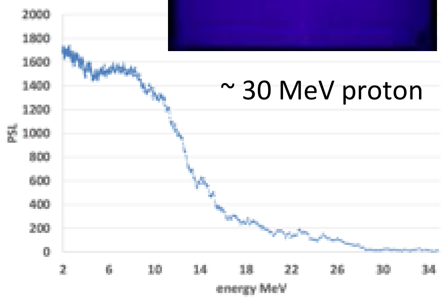
Laser beam power:
23.1 J, ~26 fs ➔ 880 TW
Intensity on target: ~ 4 x10^{21} W/cm^2
Target: 1.5 µm Al foil

Radiochromic film stack



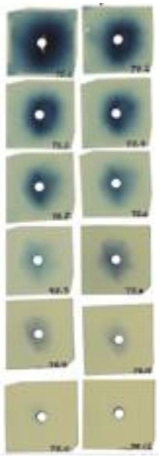
Thomson parabola data



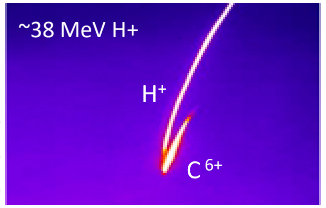


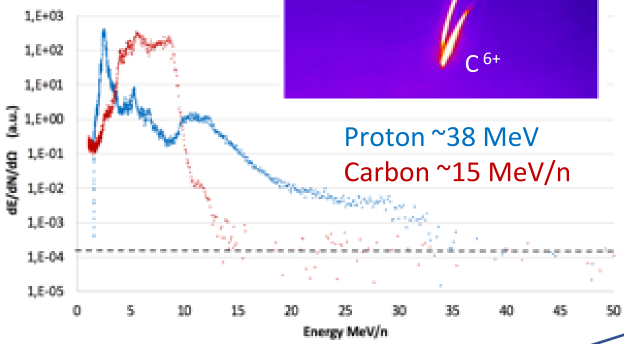
Laser beam power:
19 J, ~75 fs ➔ 250 TW
Intensity on target: ~ 1 x10^{21} W/cm^2
Target: 380nm DLC (built in house)

Radiochromic film stack

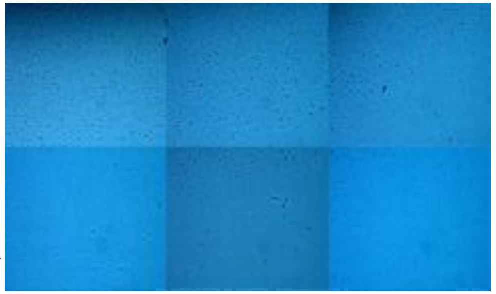


Thomson parabola





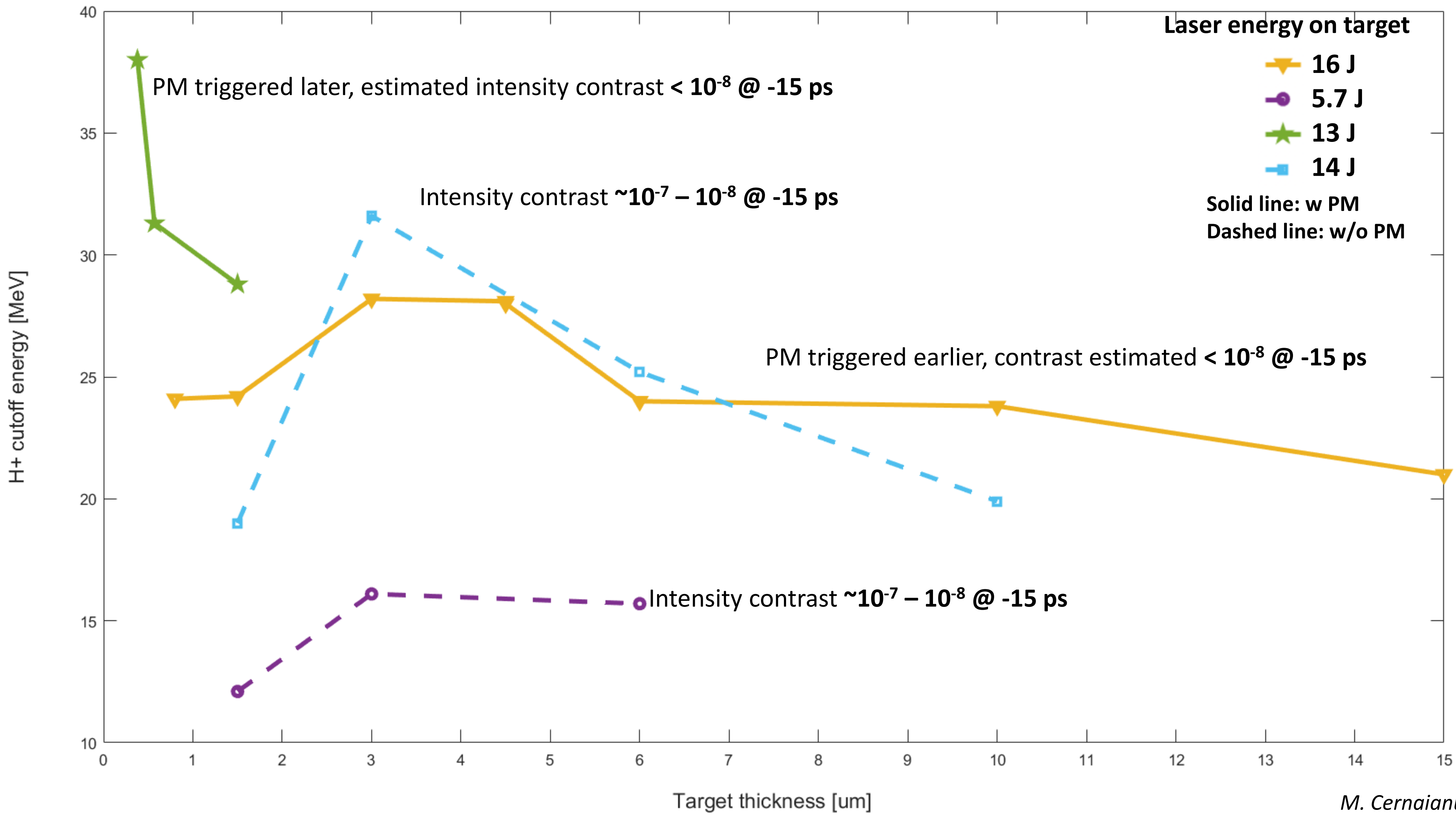
CR-39 show E_p > 50 MeV



Proton density ~ 10^3 protons /cm^2

1 PW commissioning with solid targets (TNSA investigation)

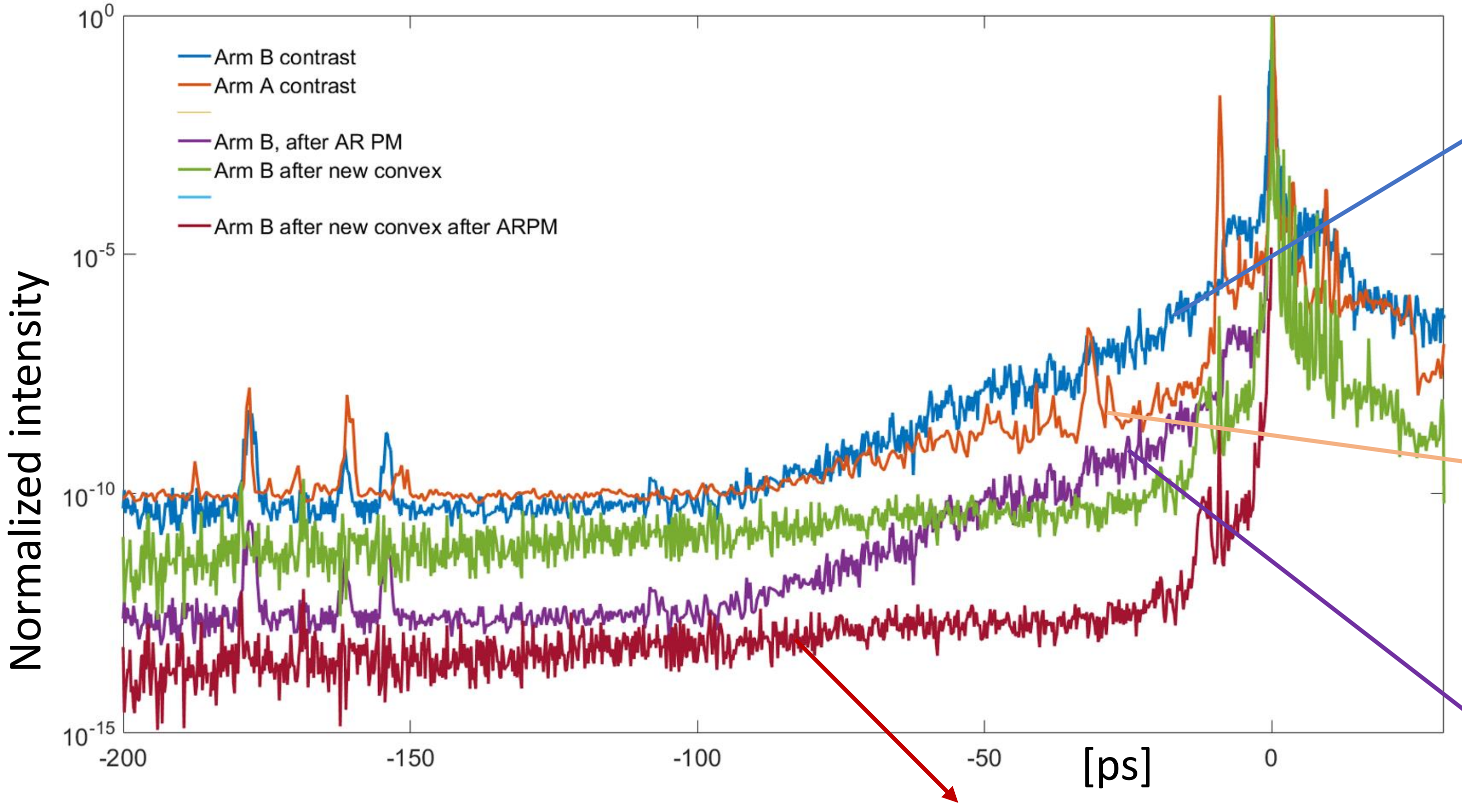
Scan of maximum proton energy with target thickness, and laser energy with different temporal contrast

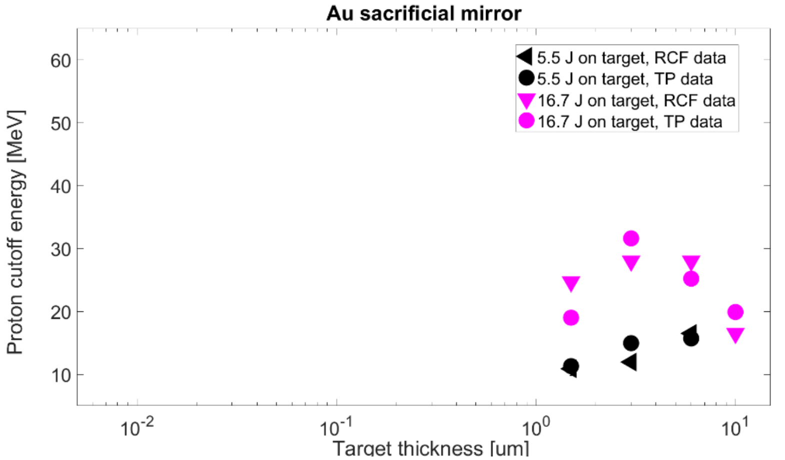


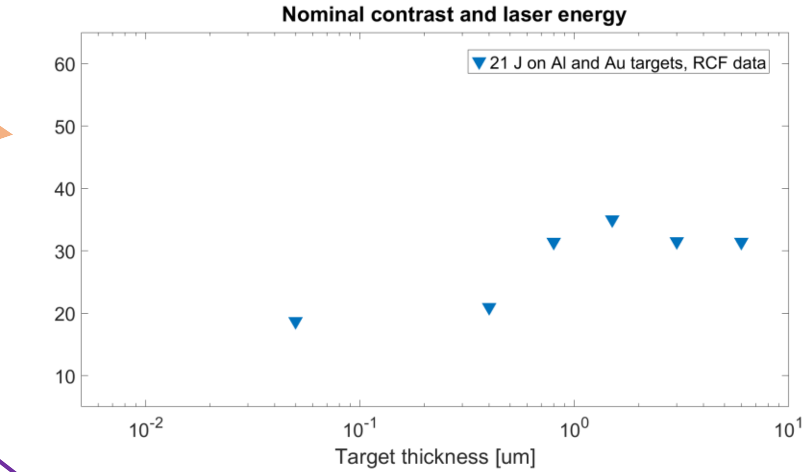
M. Cernaianu et al., in prep

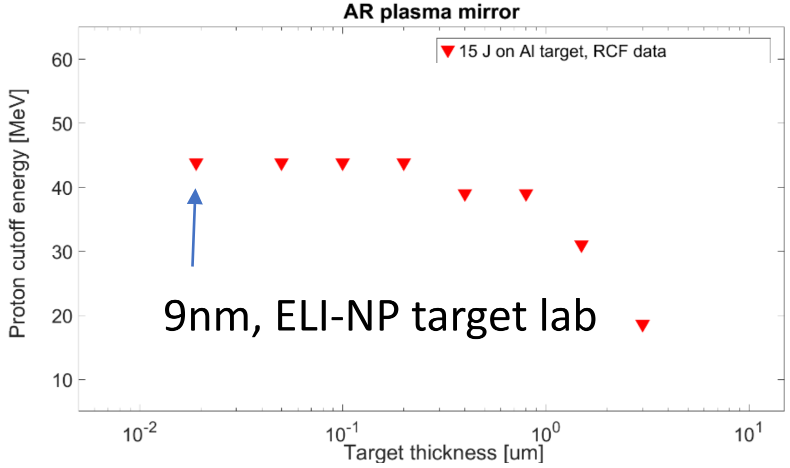
Temporal contrast improvement allowed the increasing of the cutoff energy for thin targets

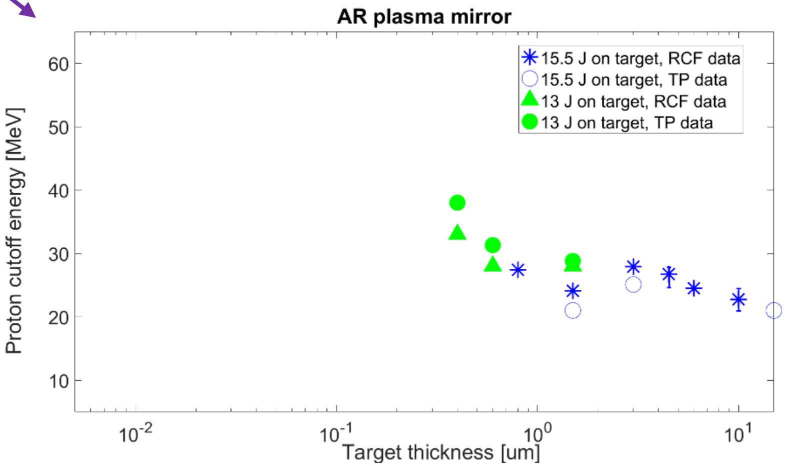
Effects of different laser temporal contrasts





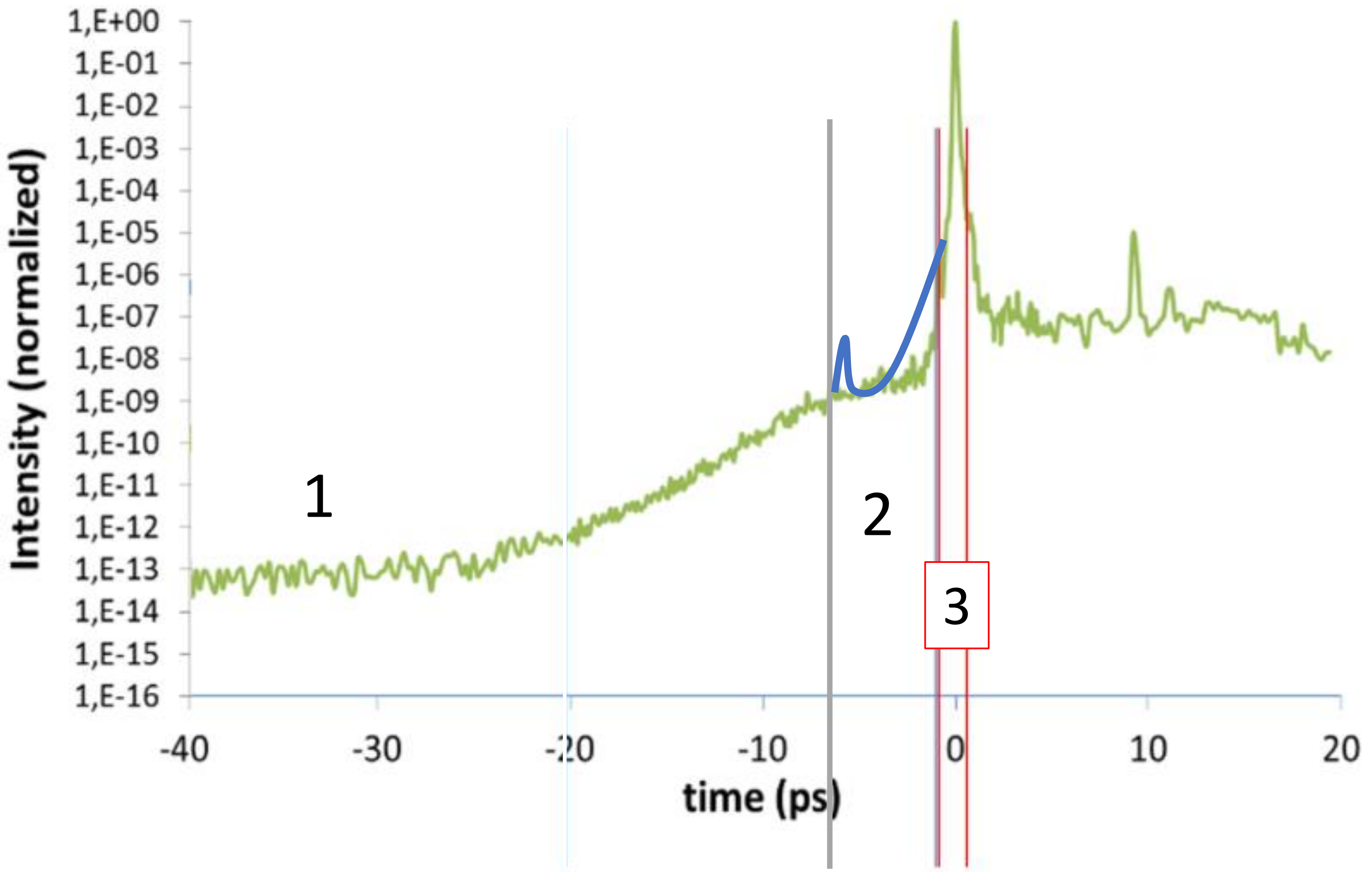






Improved temporal contrast allows to accelerate protons up to ~45 MeV from ultra-thin films

How do we simulate the processes involved in laser –plasma interaction?



1) ns to ps scale – MHD simulations
2) “grey” area: 10^{15} W/cm2 – 10^{18} W/cm2 – estimation, hydro, PIC, …
3) ps – fs : Particle-in-Cell simulations

Pre-pulse hydrodynamic simulations example

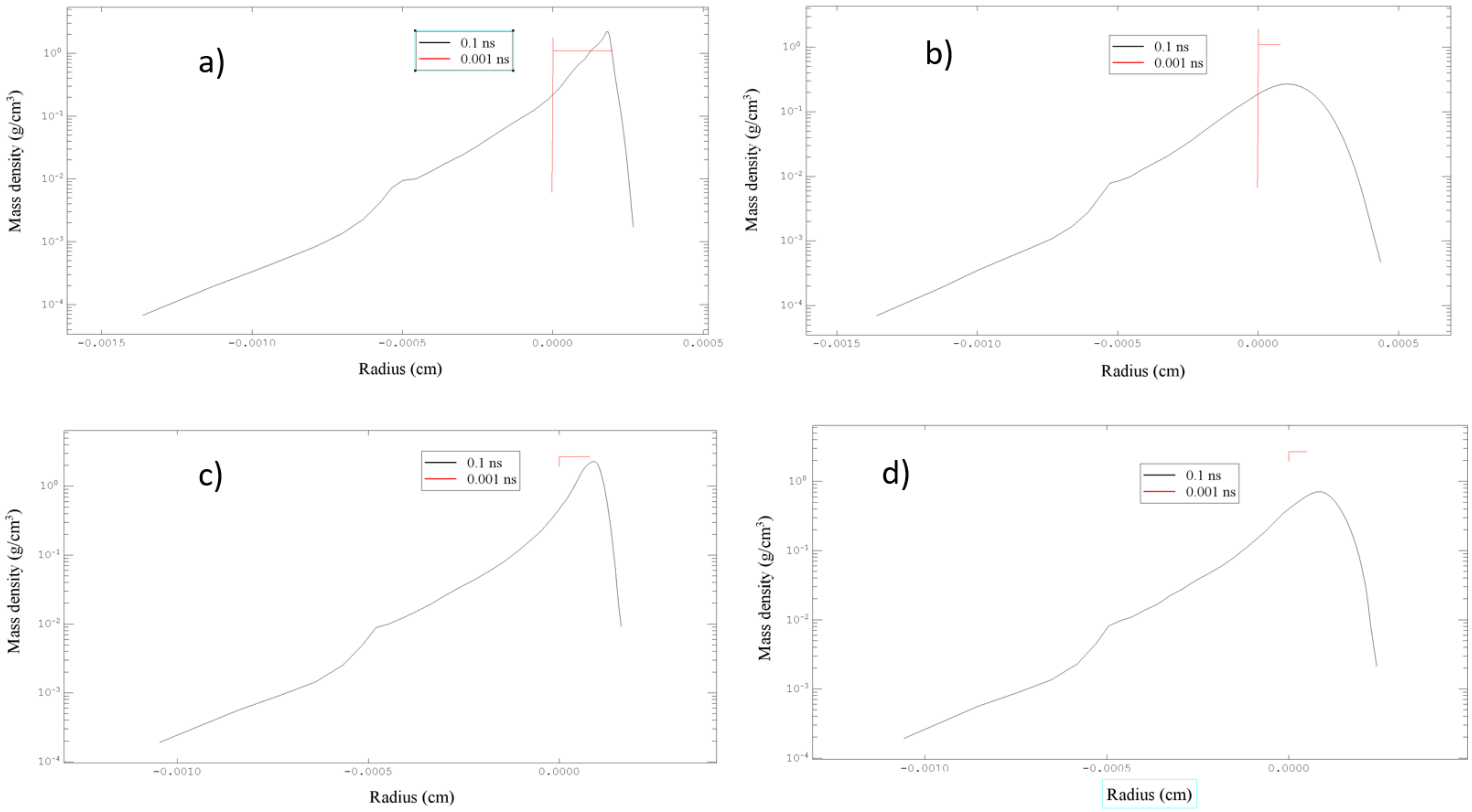
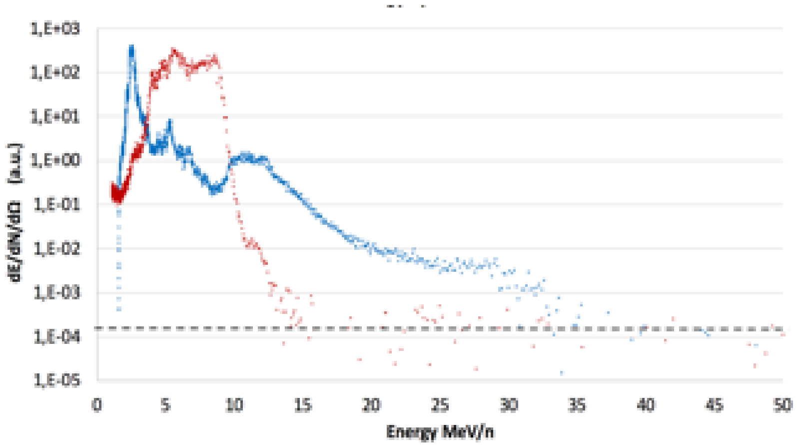
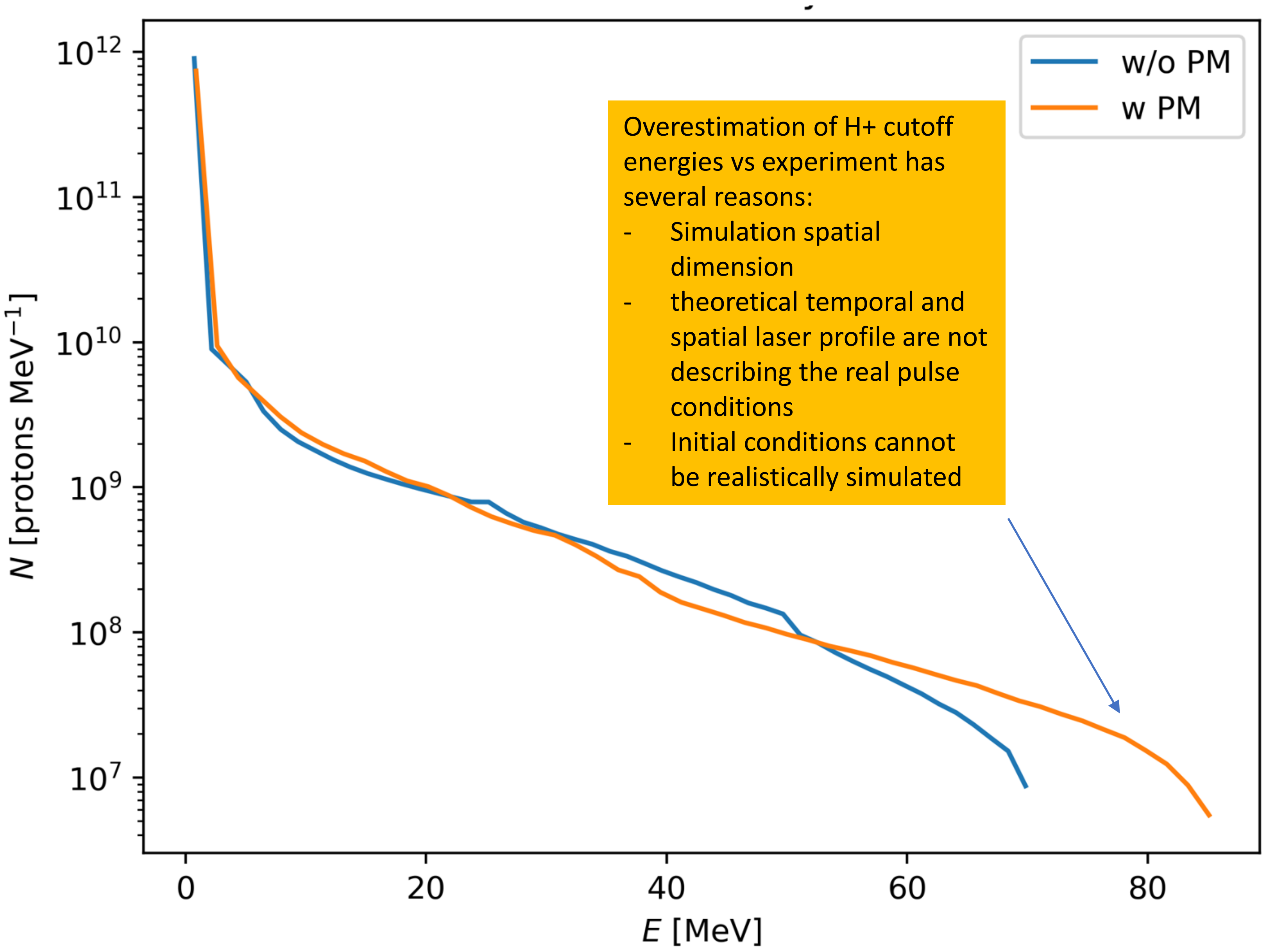


Figure 3 Simulated targets (a) CH 2 µm thick, b) CH 0.8 µm thick, c) Al 0.8 µm thick, d) Al 0.5 µm) density profiles before the pre-pulse interaction (0.001ns) and after 110 ps of pre-pulse interaction. The latter corresponds to the point when the main pulse interacts (peak intensity 8x10^20 W/cm2) with each target. Laser is incident from the left side.

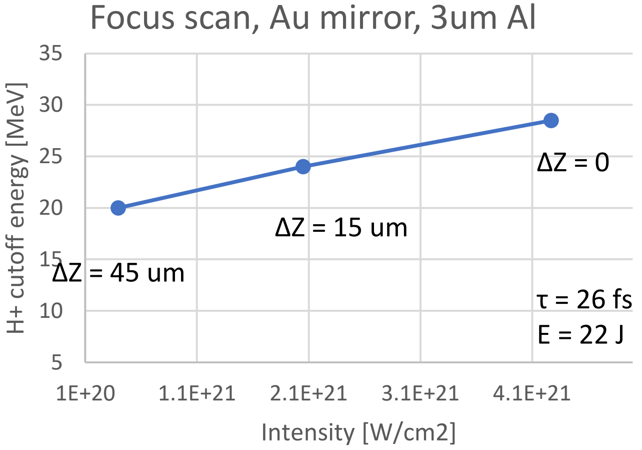
Simulation of the interaction in PIC codes

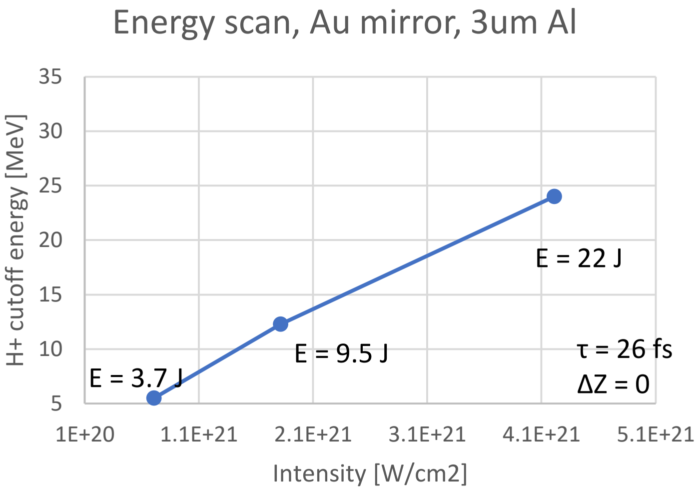
EPOCH 2D, peak I= 1E21 W/cm^2, Al 1.5um, P polarization, initial plasma conditions from hydro code

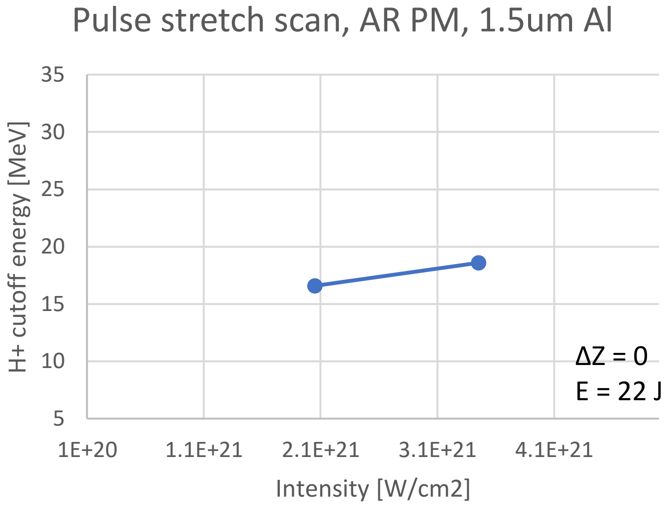


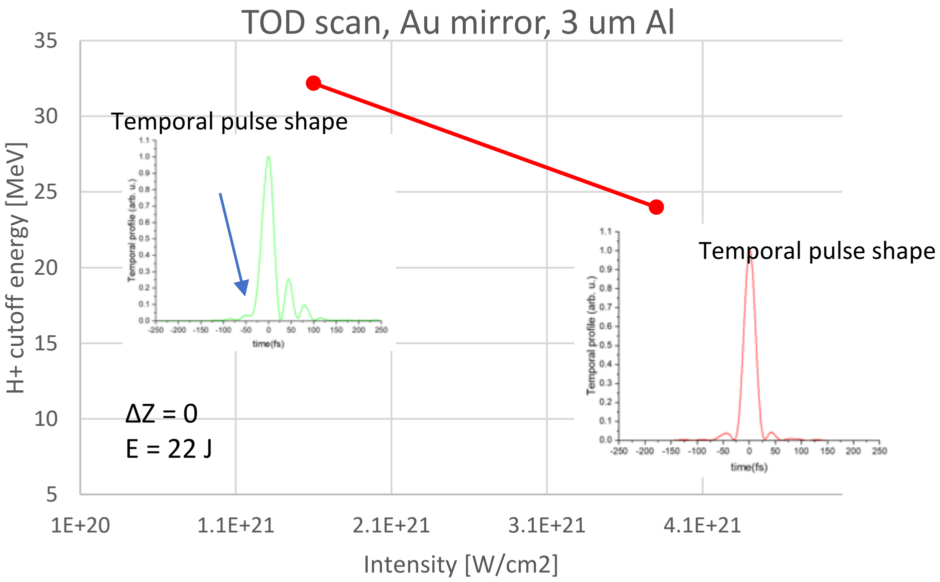


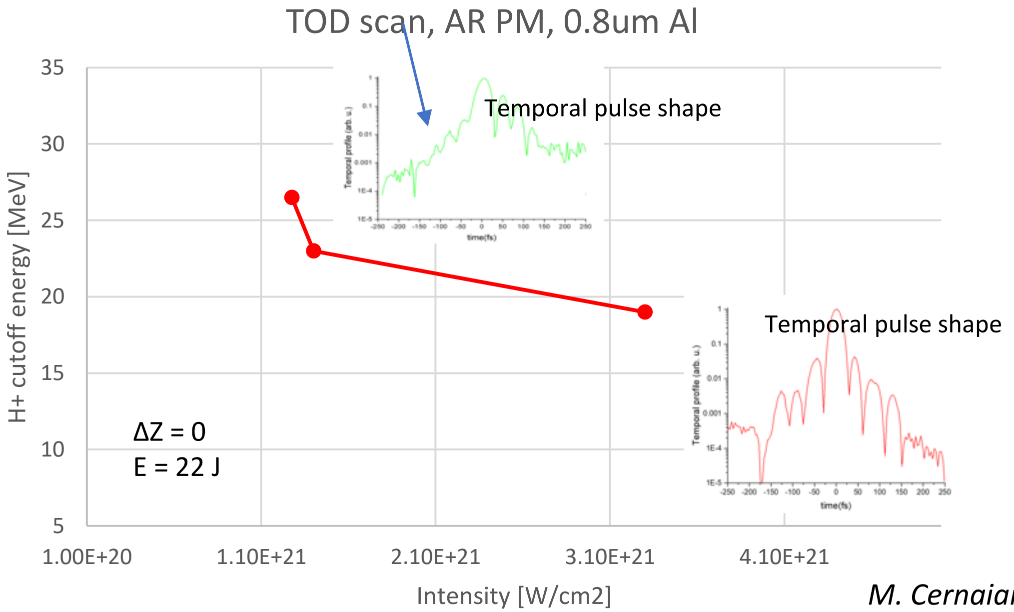
Further improvement through Third Order Dispersion optimization











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TOD optimization yields a lower peak intensity on target and a gain for the proton cutoff energy

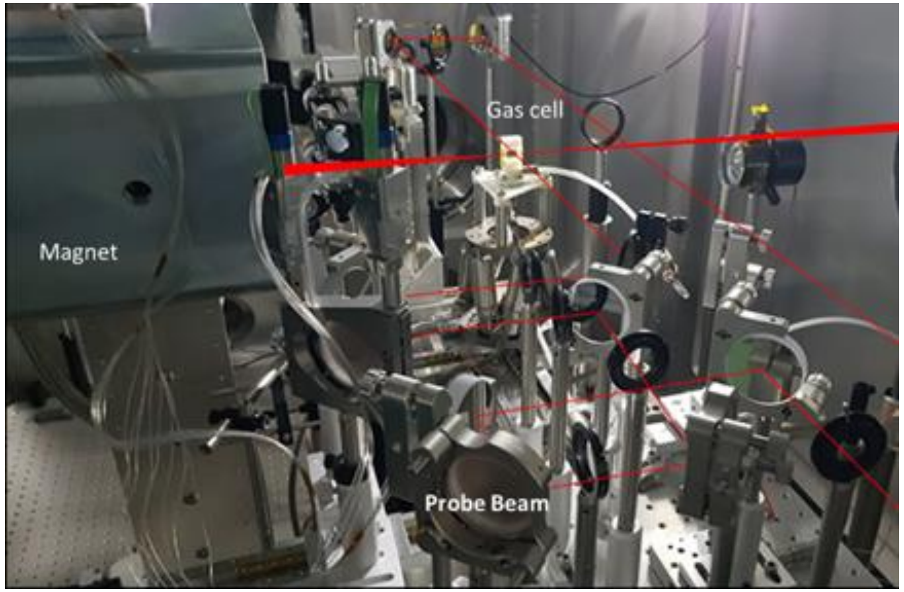
1 PW experiments with gas targets (LWFA investigation)

First operation in 2021 – Electron acceleration in gas targets (P.I. P. Ghenuche)

Setup for LWFA with 1 PW laser beam in E5

- Gas jet target and gas cell from 2mm to 1.5 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
- 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

Experimental setup



Results of the LWFA run from Nov – Dec 2021

Analysis status

- Data analysis started for 1 PW LWFA

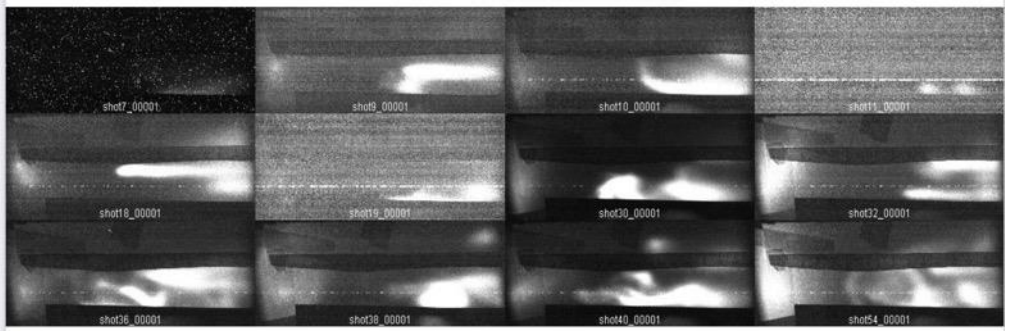
Goals

- Obtain > 1GeV electron beams
- Optimize electron beam properties (stability, energy, bandwidth)
- Test additional diagnostics and targets (including for the 10 PW commissioning campaign)

Results

- **Good Start and Good Cut-off (>2GeV/1.5cm cell)**
- **Stability and diagnostics issues**

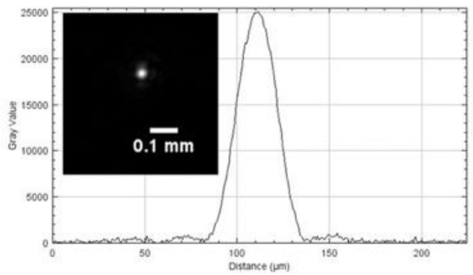
Out of 55 shots



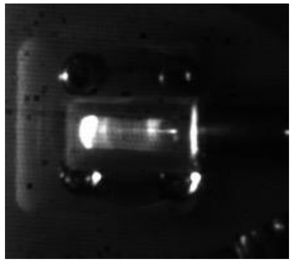
Collaborations:

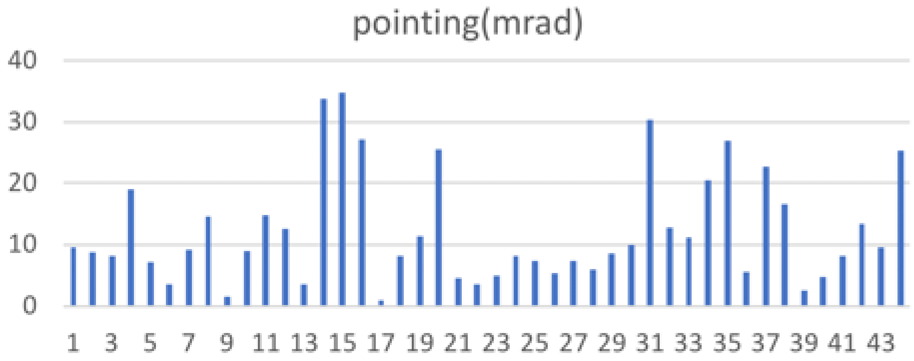
Prof. G. Sarri, QUB UK and Leo Gizzi INO IT

~25 µm FWHM focal spot

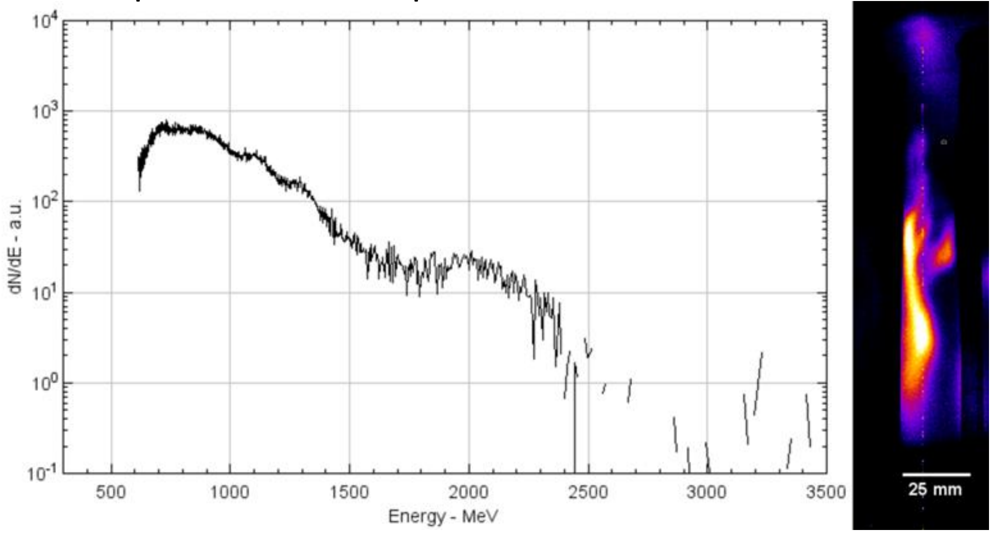


Gas-cell





Example of electron spectrum

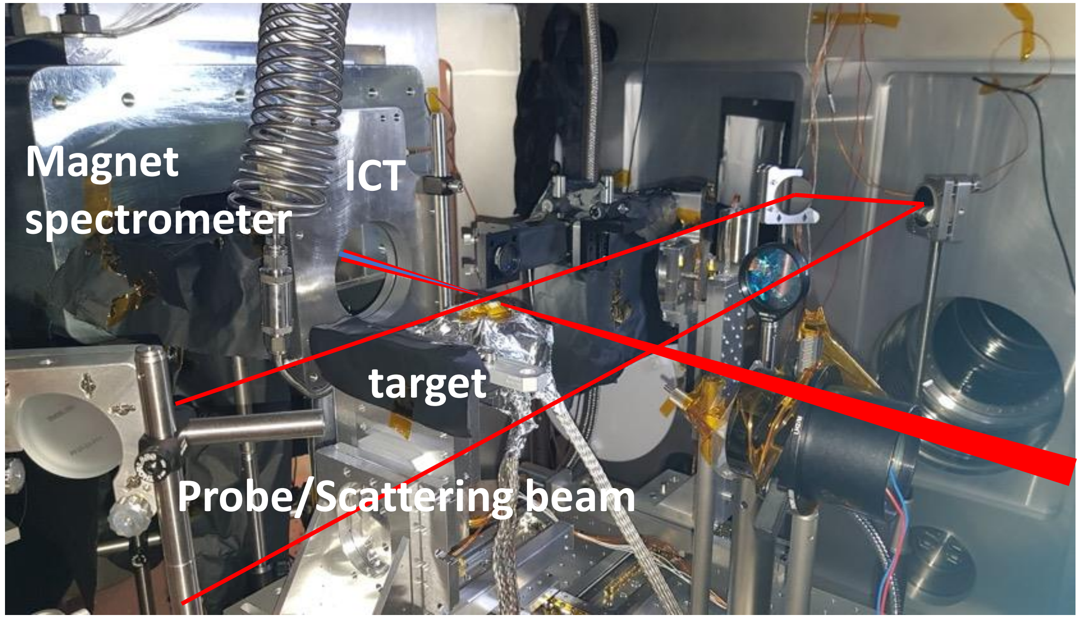


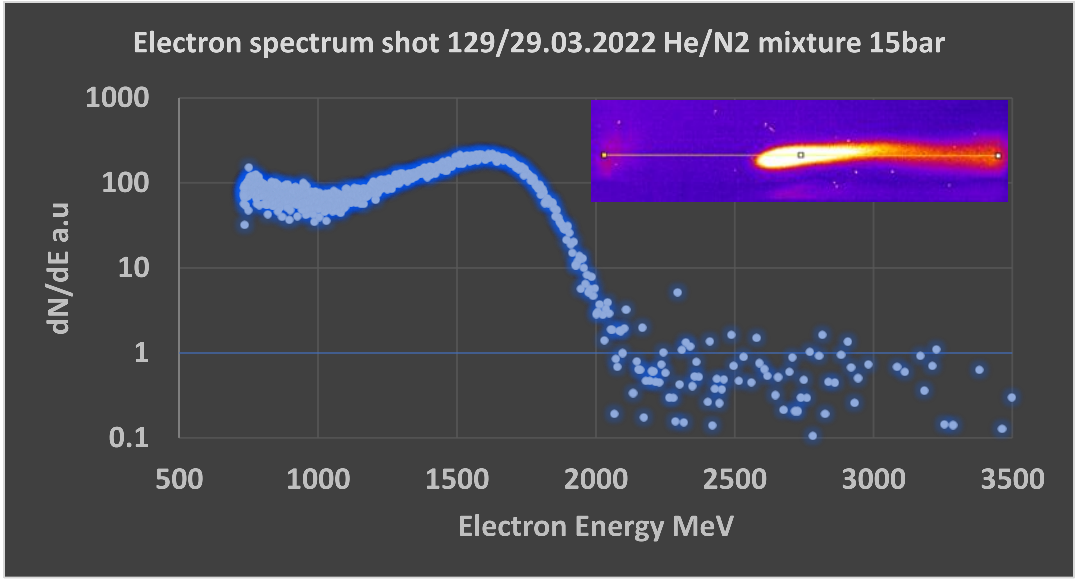
LWFA goals and results

- Optimize electron beam properties (stability, energy, bandwidth)
- Test additional diagnostics and targets (including for the 10 PW upcoming campaign)

Challenges: Additional care must be dedicated to the target's operation and handling.

C1 LWFA Experimental setup (2022)





Other type of laser beams: complex wavefronts

Helical laser beam (Laguerre-Gaussian beam)

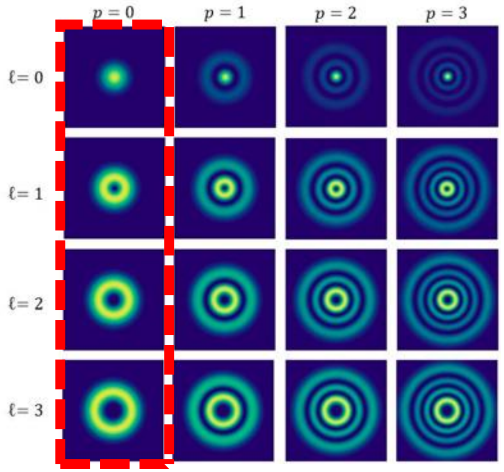
$$u(r,\phi,z) = C_{lp}^{LG} \frac{w_0}{w(z)} \left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|} \exp\left(-\frac{r^2}{w^2(z)}\right) L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right) \exp\left(-ik\frac{r^2}{2R(z)}\right) \exp(-il\phi) \exp(i\psi(z)).$$

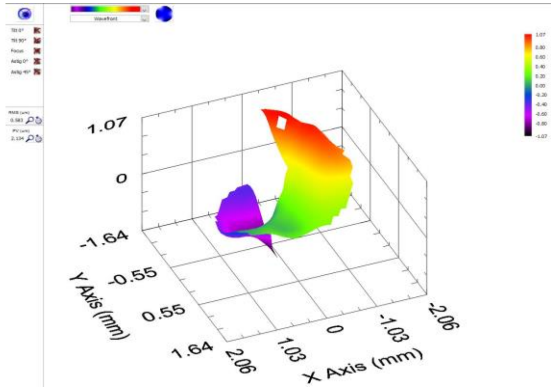
where L_p^l are the generalized Laguerre polynomials

$$C_{lp}^{LG} = \sqrt{\frac{2p!}{\pi(p+|l|)!}} \Rightarrow \int_0^{2\pi} d\phi \int_0^{\infty} r dr |u(r,\phi,z)|^2 = 1$$

with a twist index l and radial index p

Laguerre modes

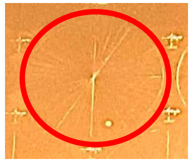


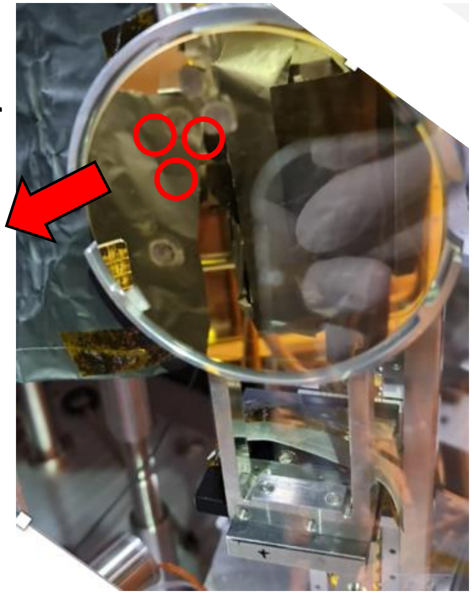


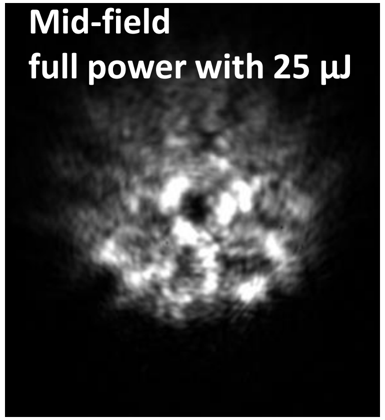
Helical wavefront

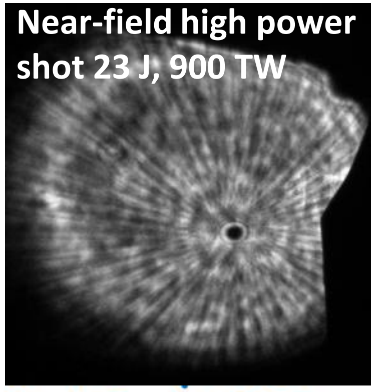
Helical PM, novel technique

Helical mirror element









Experimental results
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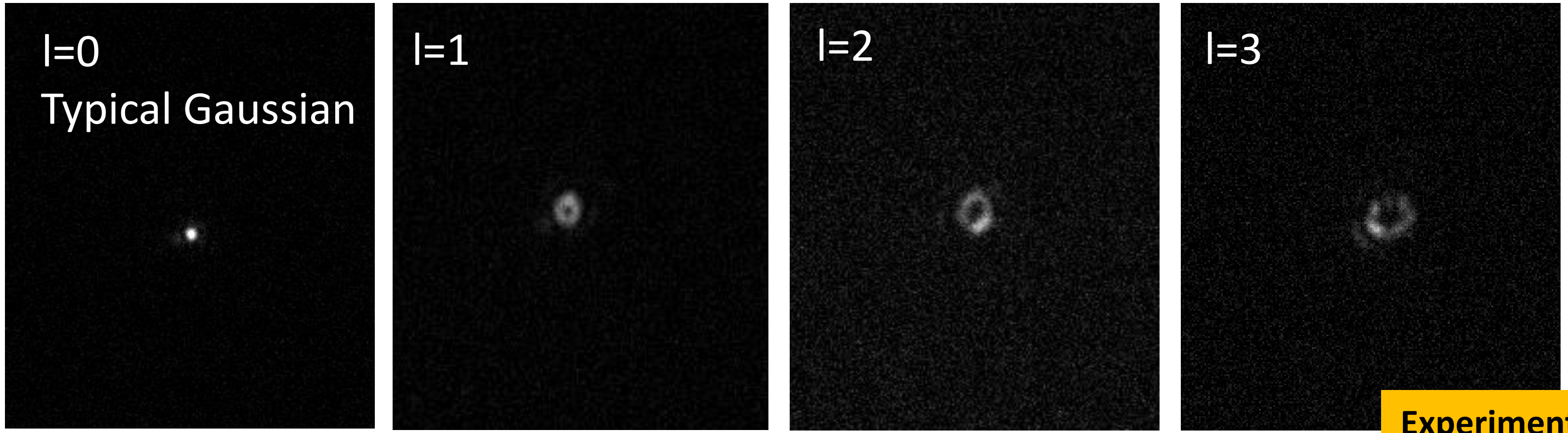
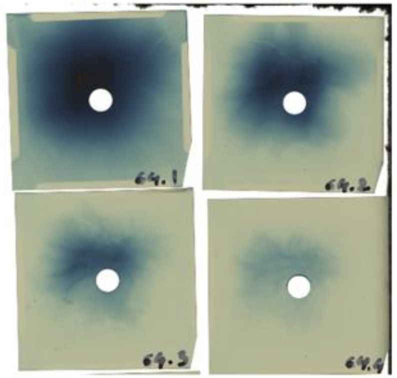
(far-field: focal spot at full power with but 25 µJ)

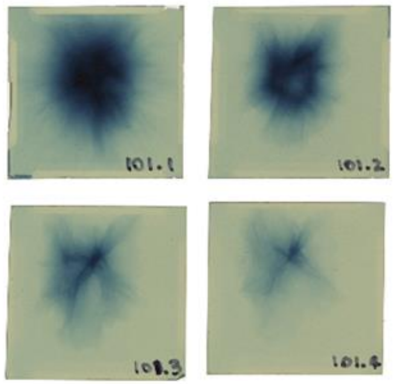


Some shots

E27, Al 1.5um, Gauss, 7.13J



C31, Al 1.5um, CP-L3,7.09J



Experiments show a dose redistribution dependence on helical order

10 PW experimental area:
Ion acceleration experiments results

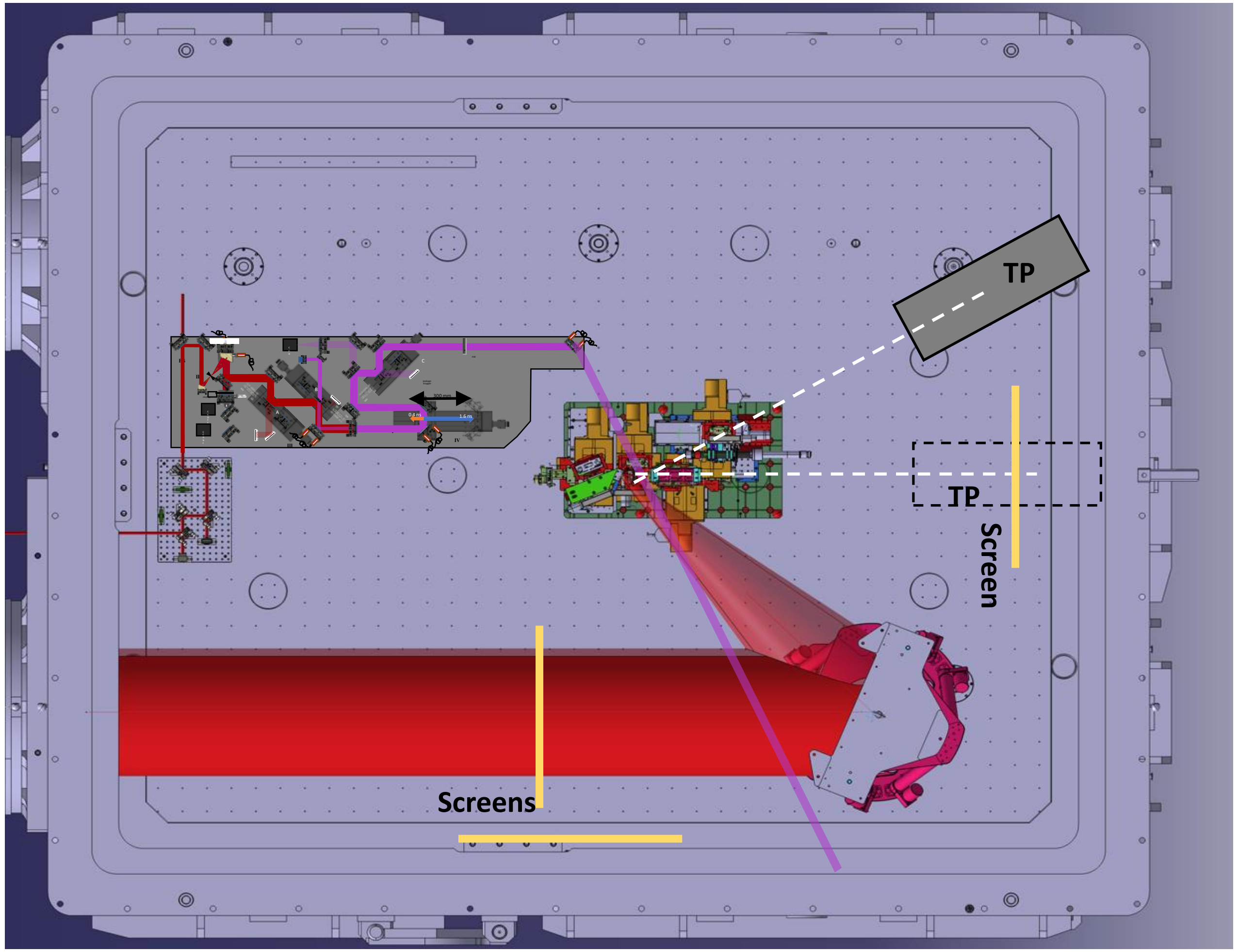
10 PW E1 experimental area commissioning (from 26 Sept 2022)

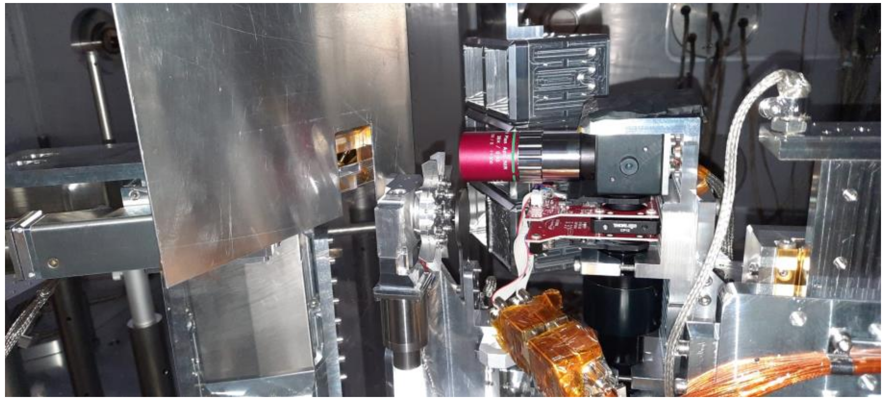
Commissioning goals:

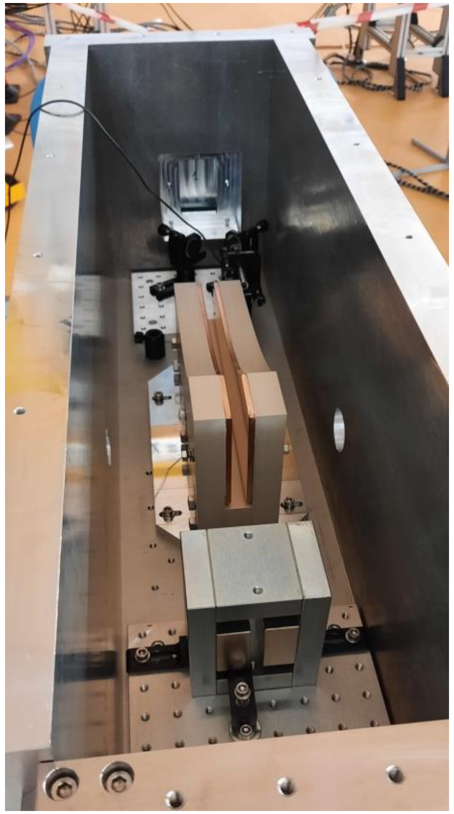
TNSA >200 MeV protons,
RPA high-Z bulk acceleration

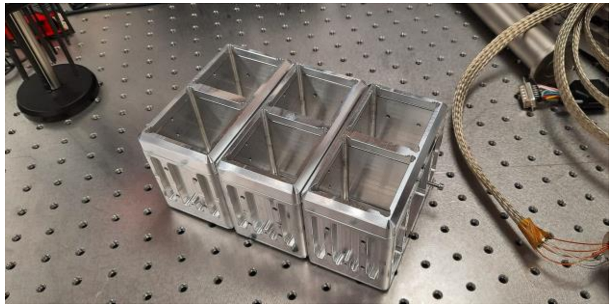
List of diagnostics of E1

Laser Diagnostics
Targetry and Alignment System
Radiochromic films stack, CR39 (< 200 MeV)
Thomson Parabola (~100 MeV and ~500 MeV proton)
Optical Probe/Pump (< 2 J)



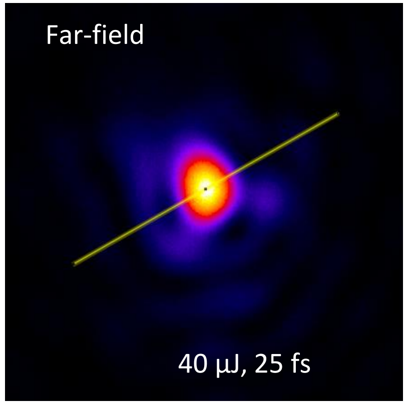


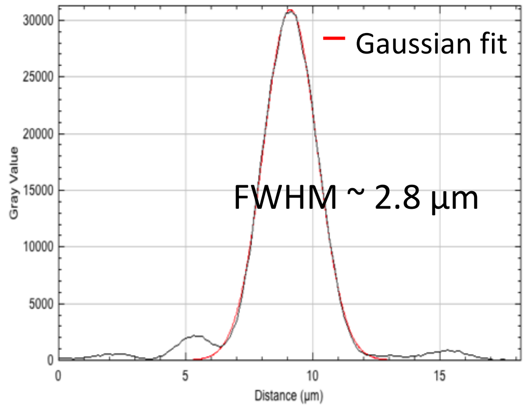




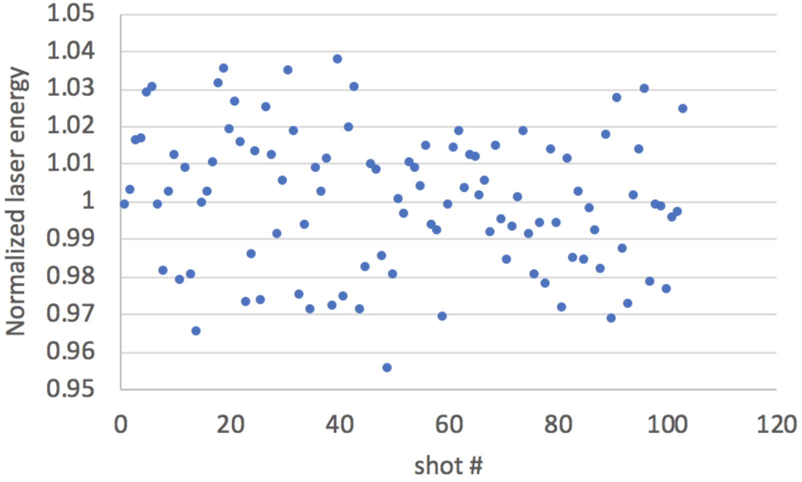
HPLS at low power (PW amplification)

Best focal spot

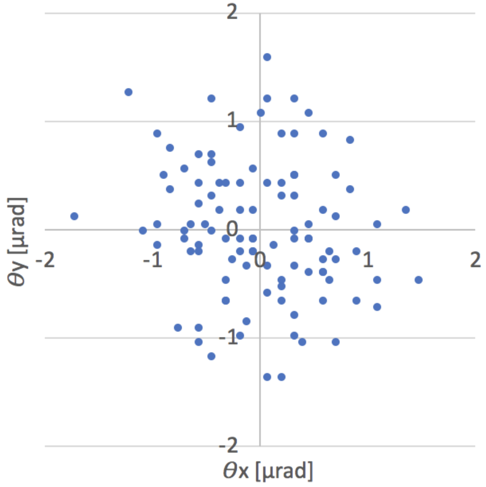




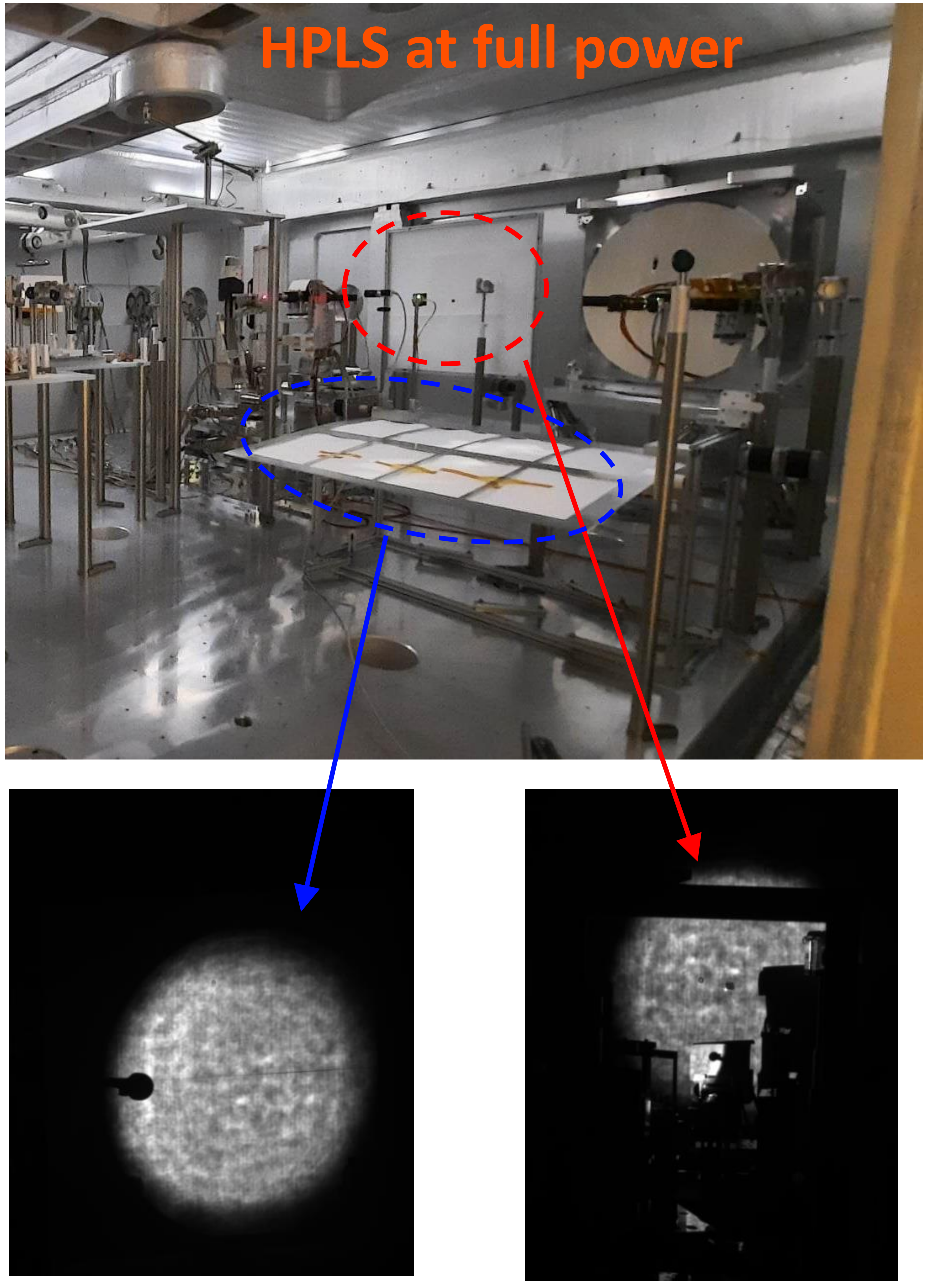
Laser energy fluctuation ~2%



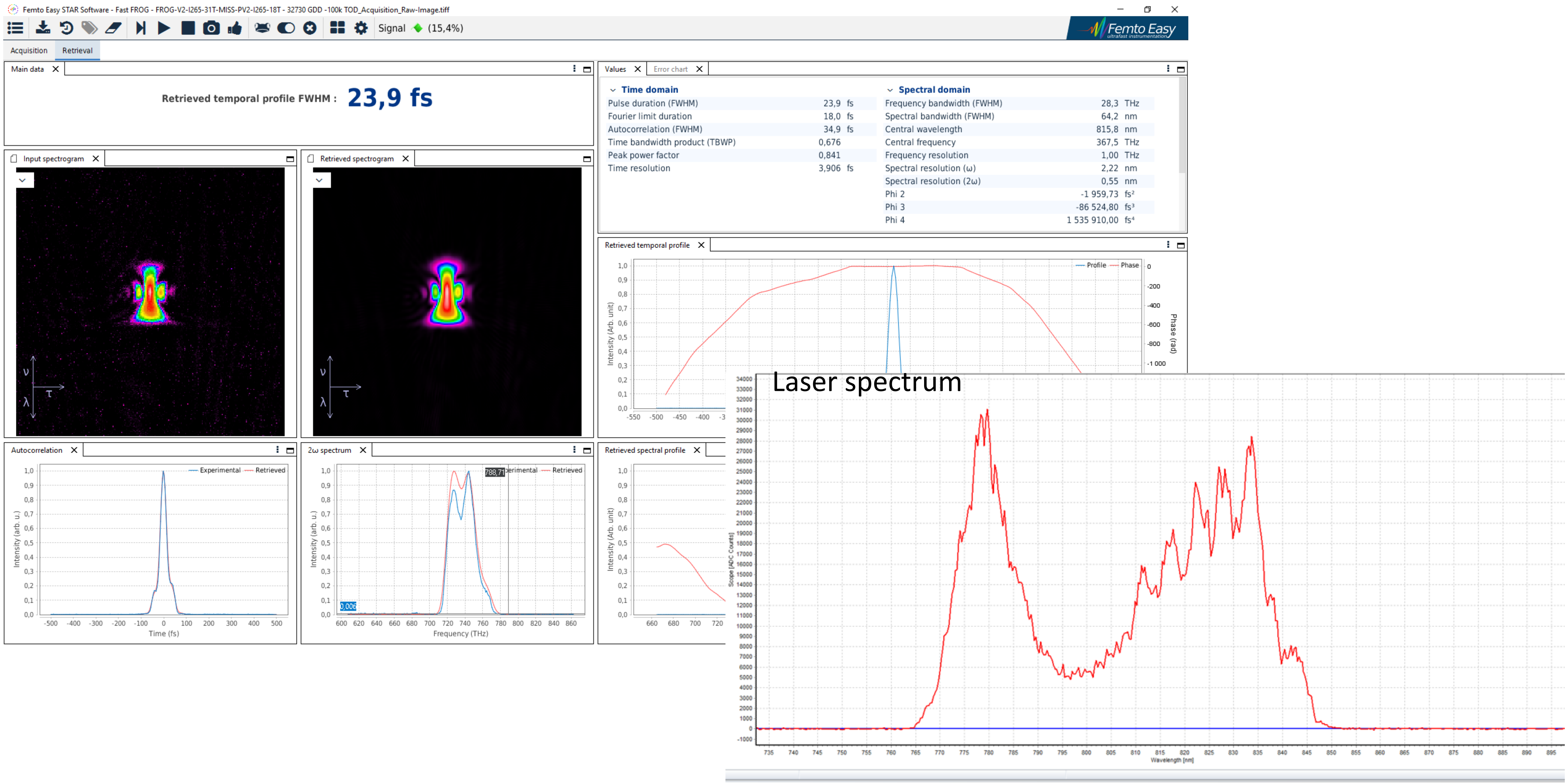
Pointing fluctuation [µrad]



HPLS at full power



Laser pulse duration measurement with FROG, confirmed with Wizzler



First 10 PW shots

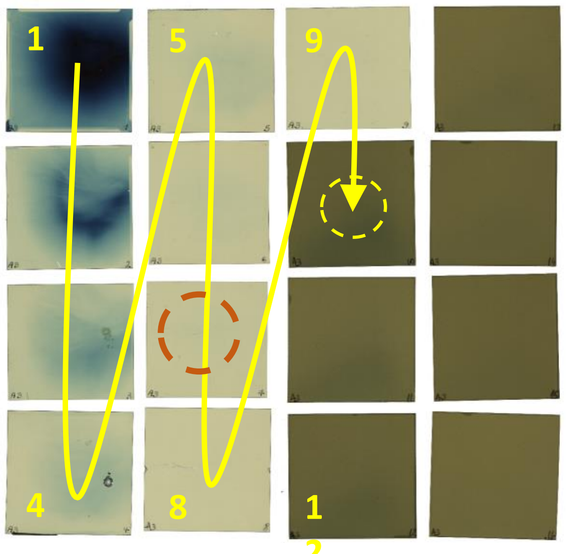
10 PW shots started from Apr 2023 on RCF

Laser energy 221-240 J
Pulse duration ~24 fs
Focal spot 2.8-4 µm FWHM
Encircled energy ~ 50%
Single PM ~ 75%

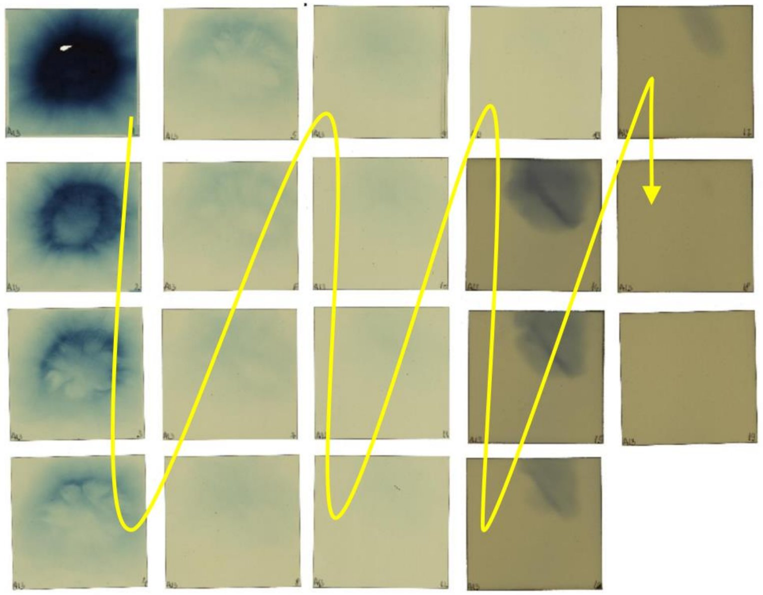
→ Power shot ~ 10 PW
Laser intensity range on target ~ 1 - ~ 4 x 10^{22} Wcm^{-2}

→ Target Al foils:
6, 3, 1.5, 0.8, 0.4, 0.1 µm thick
Au: 0.4, 0.2 µm
Ni: 1 µm
CH: 0.5 µm

Preliminary results on Radiochromic film stack

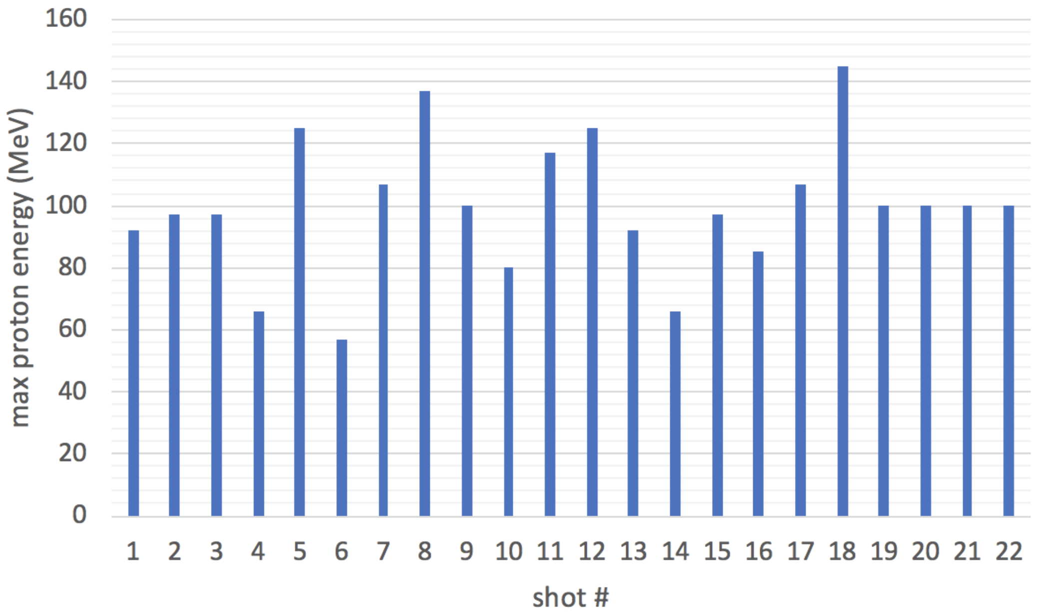


240 J → 10 PW 6 µm Al
61 to 92 MeV



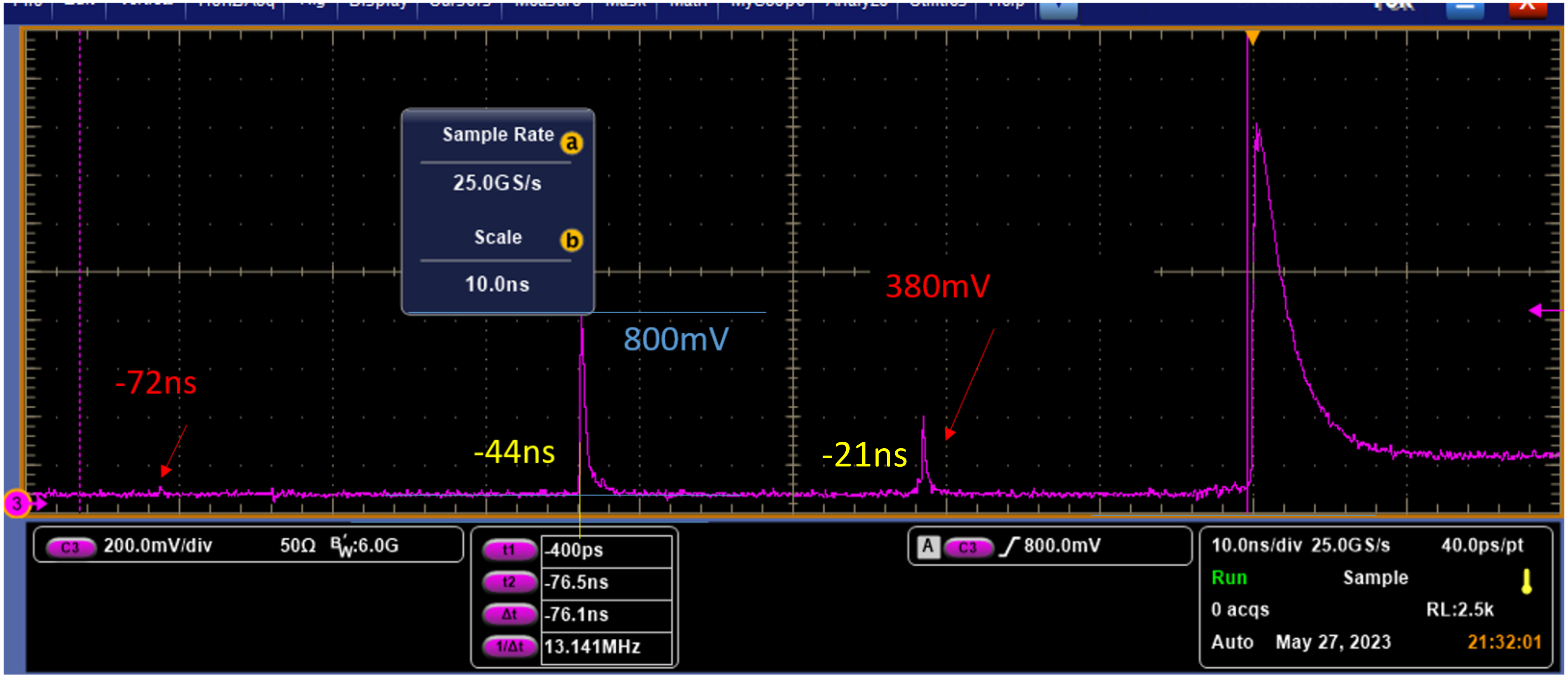
Al 0.4 microns Exceding 120MeV proton

H+ cutoff energy from Al and Au targets < 1.5 µm



- Temporal contrast improvement allowed to increase the accelerated H+ cutoff energy
- Double plasma mirror runs to start from next week

Temporal contrast measurement and improvement at 10 PW power



- Temporal profile measurement and analysis needed to understand the interaction of the entire laser pulse with the target!
- Existent pre-pulses can damage the target and pre-expand it by the time the main pulse arrives on target

Conclusions

- 100 TW and 1 PW areas operational, awaiting users. 10 PW in near future
- Laser beam parameters need to be always carefully measured and understood to ensure the foreseen results
- Realistic input conditions for simulation codes are needed to understand the physical processes and match the experimental data

Questions?

Email @ mihail.cernaianu@eli-np.ro