Enhanced ion acceleration using the high-energy petawatt PETAL laser

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***Enhanced ion acceleration using the high-energy petawatt PETAL laser**. D. Raffestin et al. Matter Radiat. Extremes 6, 056901 (2021)*

PETAL: an additional short-pulse (ps), high-energy beam (kJ) to the LMJ facility

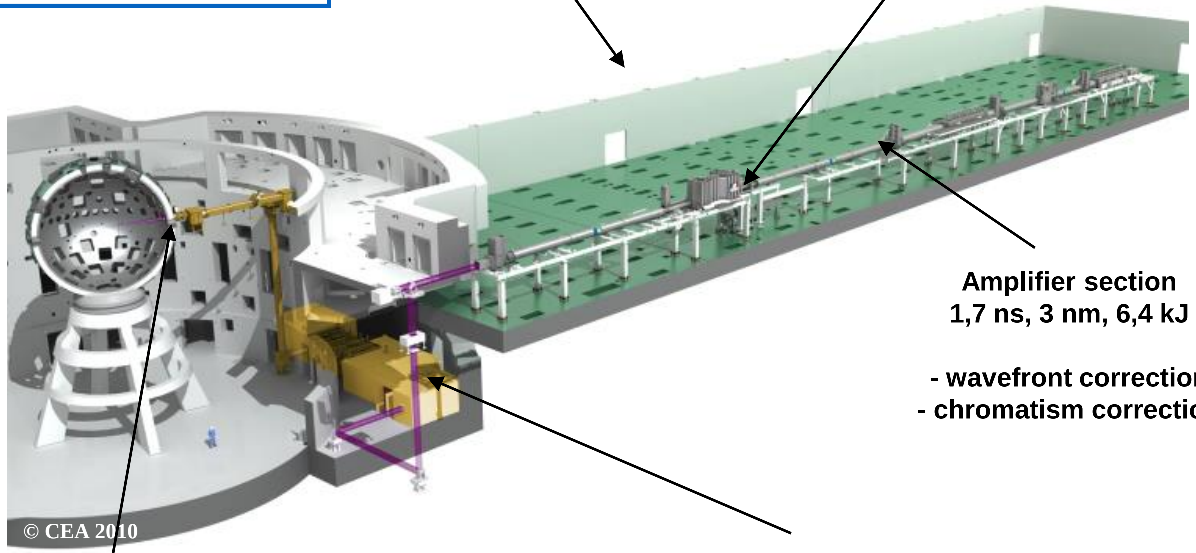
- Energy > 3 kJ*,
- Wavelength 1053 nm,
- Pulse duration between 0,5 and 10 picoseconds
- Intensity on target > 10^{18}-10^{20} W/cm²
- Intensity contrast (short pulse): 10^{-7} at -7 ps
- Energy contrast (long pulse): 10^{-3}

The Petawatt Aquitaine Laser (PETAL) facility was designed and constructed by the CEA under the financial auspices of the Nouvelle-Aquitaine Region in France (project owner), of the French Government and of the European Union.

PETAL is a part of the LMJ facility, located at CEA-CESTA (33116, le Barp, France)

Front end (oscillator, Offner)
100 fs → 9ns, 16 nm

Preamplifier Module PAM (OPCPA)
4,5 ns, 8 nm, 100 mJ



Amplifier section
1,7 ns, 3 nm, 6,4 kJ

- wavefront correction
- chromatism correction

Transport / Focusing section: (vacuum)
- pointing mirror after parabola
- 90° off-axis parabola

Compression section: 2 stages (air & vacuum)
500 fs, 3 kJ

- wavefront correction (gratings deformation)
- beam phasing instead of mosaic gratings

**** Energy was limited to 1 kJ during compression tests (1,15 PW was obtained) and to 400 J during first experiments due to mirrors damage threshold***

(current change of mirrors and parabola will allow higher energy in the near future)

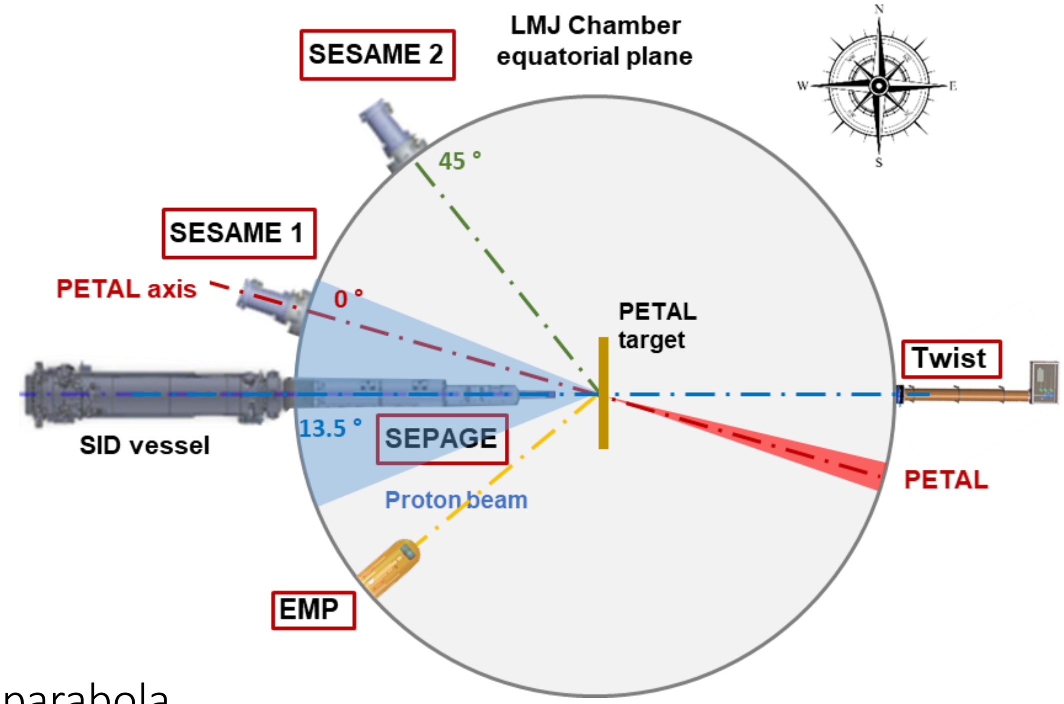
N. Blanchot et al., « 1.15 PW–850 J compressed beam demonstration using the PETAL facility”. Opt. Express 25, 16957 (2017)

Dedicated Plasma diagnostics were developed for PETAL

Dedicated diagnostics were implemented and tested:

- Within PETAPhys project (French National Research Agency in the framework of Program IdEx Bordeaux):
  - Twist, optical imaging of the PETAL beam focal spot in the spectral range of the second and third harmonic radiation emitted from the target.
  - CRACCX, hard X-ray spectrometer consisting in a stack of imaging plates (IP) and filters.

- Within Petal+ Equipex (French National Agency for Research, coordinated by the Bordeaux University):
  - SEPAGE, an inserted diagnostic, composed of two Thomson parabola.
  - SPECTIX, an inserted diagnostic, composed of two Braggs crystals with high resolving power.
  - SESAME, an electron and proton spectrometer based on a magnetic dipole at two different angles.
- Bdot coils, to characterize strong electromagnetic pulses (EMP) produced in the interaction of the PETAL beam with target (frequency range from 50 MHz to 6 GHz)



PETAL First Qualification Experiments were performed end of 2017-spring 2018

These experiments aimed at the qualification of the dedicated plasma diagnostics and estimation of emission of X-rays, protons, electrons from targets irradiated with PETAL.

A total of 10 shots were performed during 2 campaigns: Q_PETAL1 (November 2017) and Q_PETAL2 (April - May 2018)

Date	Target	E/Dt (J/ fs)	Intensity W/cm2	Spectix	Sepage	Sesame1	Sesame 2	Twist	Cracc X	Cracc RCF
17/10/2017	Multi-layers Z/Ag/W/Au 4x20µm	336/810	4.6E+18		Non activated		Non activated		Non activated	
20/10/2017	Au 25µm	378/1020	4.5E+18		Non activated		Non activated		Non activated	
24/10/2017	Au25µm@30mm+grille	371/825	4.5E+18		Non activated		Non activated		Non activated	
17/04/2018	W 2mm	426/660	7.5E+18		Non activated			Non activated		Non activated
18/04/2018	Zn/Ag/W/Au	182/570	3.8E+18		Non activated	Non activated	Non activated	Saturated	Non activated	
20/04/2018	#176 CH50µm	450/610	7.9E+18	Non activated				No image	Non activated	
23/04/2018	#177 Parylene 10µm	409/660	7.9E+18						Non activated	
26/04/2018	Au30µm	350/11.3	5.0E+17					Saturated	Non activated	Non activated
02/05/2018	#178 Parylene 10µm	187J/610	4.9E+18						Non activated	
03/05/2018	W 2mm	406/885	5.5E+18		Non activated			Non activated		Non activated

PETAL Laser energy ranged from 100 J to 450 J and pulse duration from 600 fs to 11 ps.

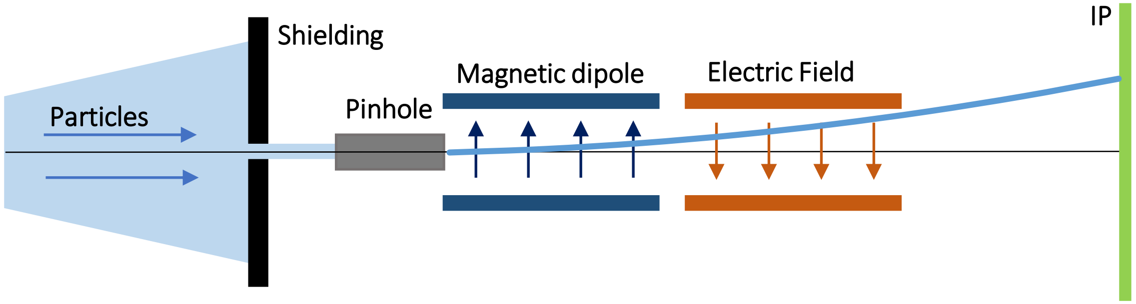
We have used either Multi-layer targets for X spectroscopy, thin targets for TNSA p+ emission and thick/high Z targets for bremsstrahlung hard X rays emission

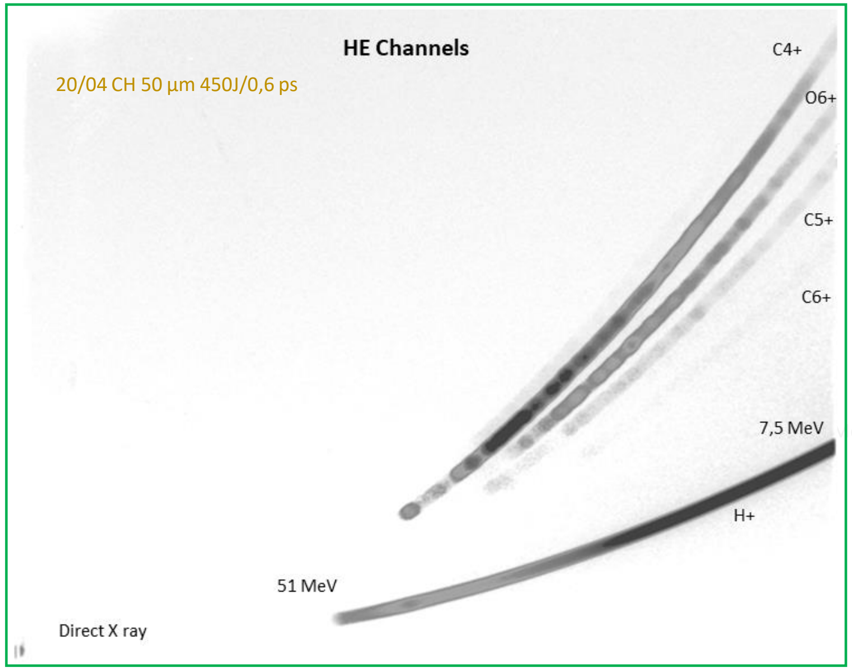
→ Focus on shots #176 #177 #178 dedicated on ions acceleration

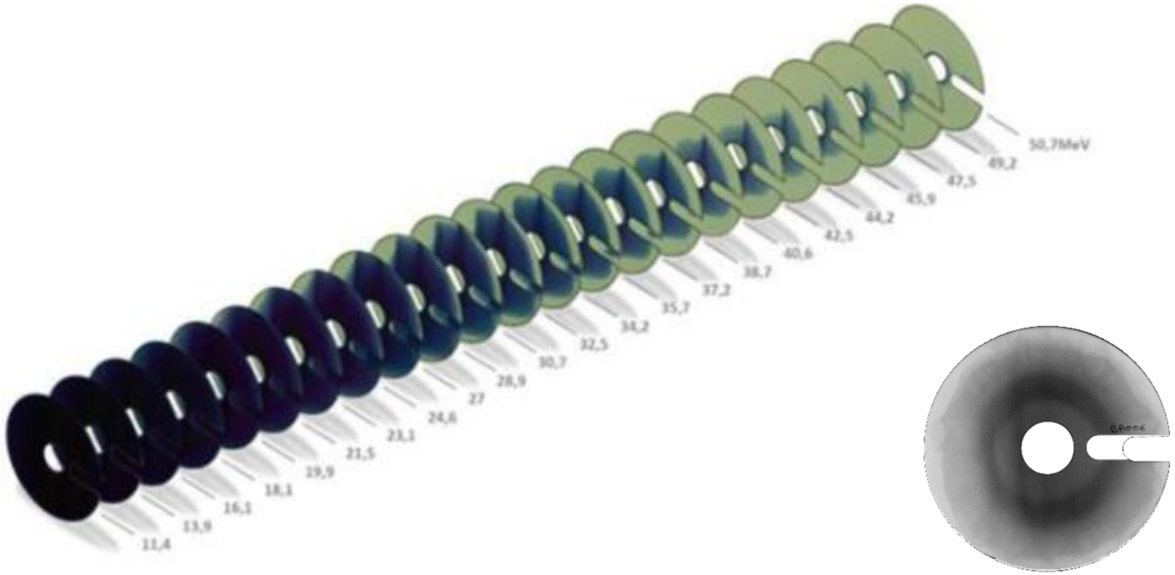
SEPAGE (Spectromètre Electrons Protons A Grandes Energies) is dedicated to the measurement of charged particles generated by experiments using PETAL

SEPAGE is based on the Thomson parabola principle

- Two TP channels (High and Low energies)
  - p+: 0.1 MeV to 20 MeV / 8 MeV to 200 Mev
  - e-: 0.1 MeV to 150 MeV.
- Cassette with RCF Stack for spatial and spectral resolution of the p+ beam
- Passive Detectors (Imaging Plates)
- Inserted diagnostic (using SID+)





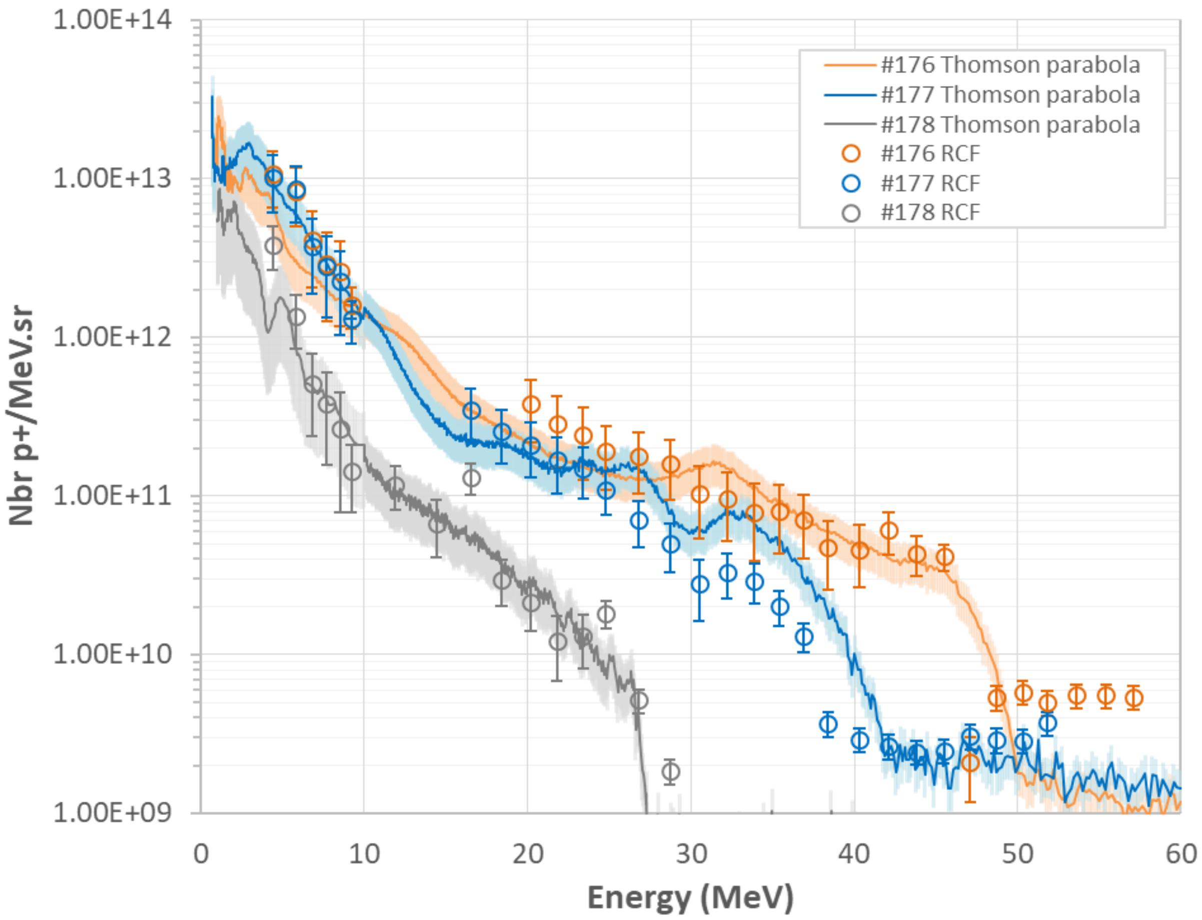


Radiochromic film images (EBT3) due to protons obtained in shot #176: 450J/610 fs on a 50 µm thick plastic target (CH+1µm Al). Right: annular distribution pattern on HDV2 radiochromic film (protons around 9 MeV)

I. Lantuéjoul et al. "SEPAGE: a proton-ion-electron spectrometer for LMJ-PETAL" Proc. SPIE 10763

Absolute distribution were infered from both TP and RCF. Maximum of 51 MeV p+ were recorded

Proton spectra obtained on the SEPAGE TP and RCF stacks for shots #176, #177, and #178



→ Very good agreement between TP and RCF

On shot #176 (CH 50µm+Al, 450 J, 610 fs, 8E18 W/cm2) up to 51 MeV p+ were recorded

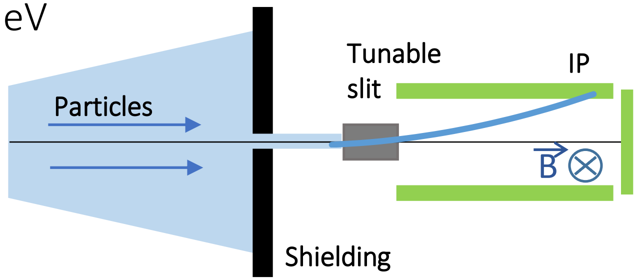
Energy conversion efficiency of the laser into protons ranges from 1.3 % for the lowest energy shot (#178) to 3.3 % for shot #176, with total number of protons above 7 MeV of 6.1×10^{12}, 4.2×10^{12} and 9.5×10^{11} for shots #176, #177, and #178

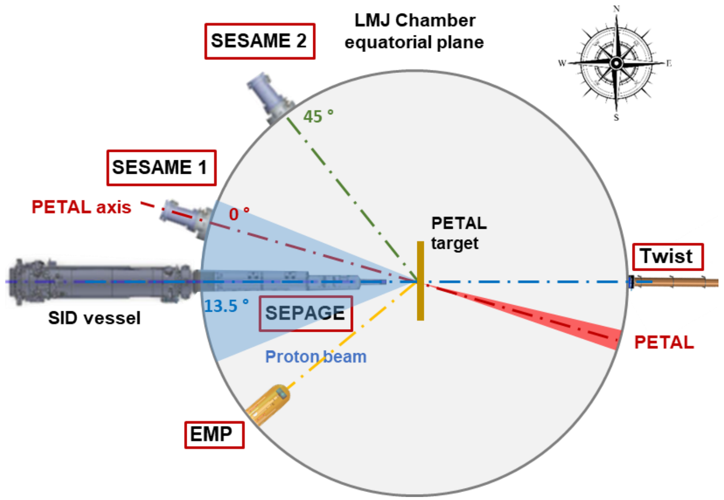
SESAME is dedicated to the measurement of p-/e- at two angles. Measured hot electron temperature exceed prediction

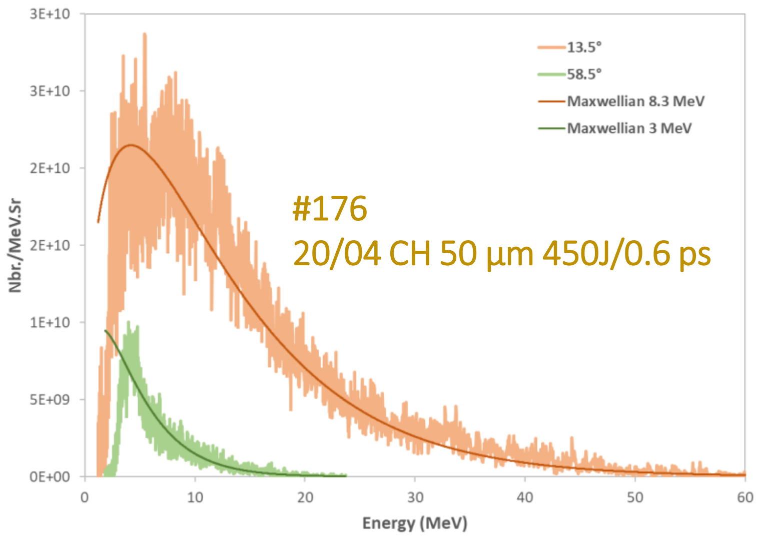
SESAME is based on the deflection of e-/p+ by a magnetic dipole

- Two modules on the target chamber wall
  - 0° and 45 ° from the axe of PETAL (13.5° and 58.5° from target side)
  - Energy range: 5 MeV to 150 MeV

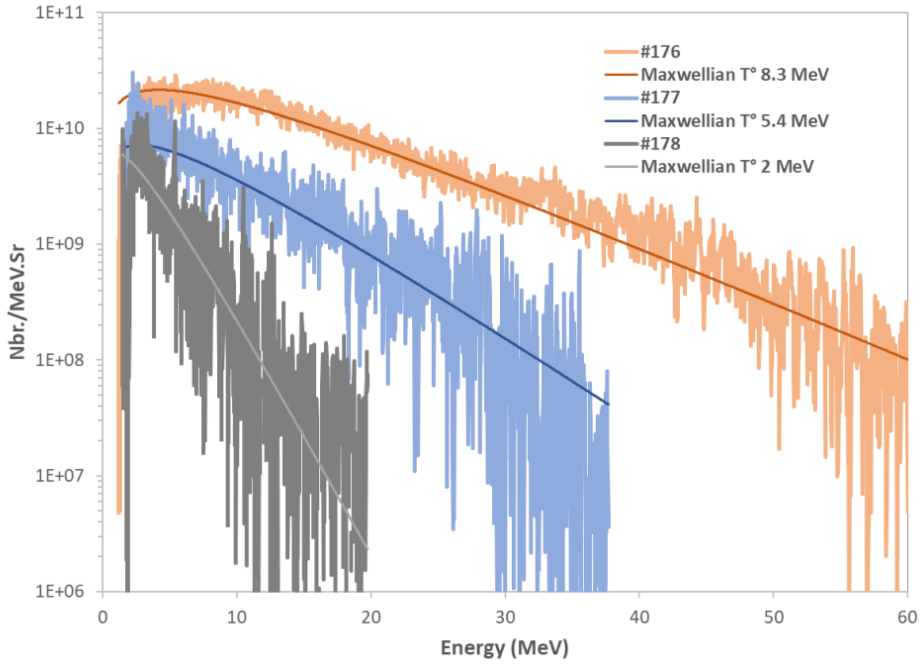
- Passive Detectors (Imaging Plates)
- Fixed diagnostic







Electrons spectra at 13.5° and 58.5° from the rear target normal shot #176



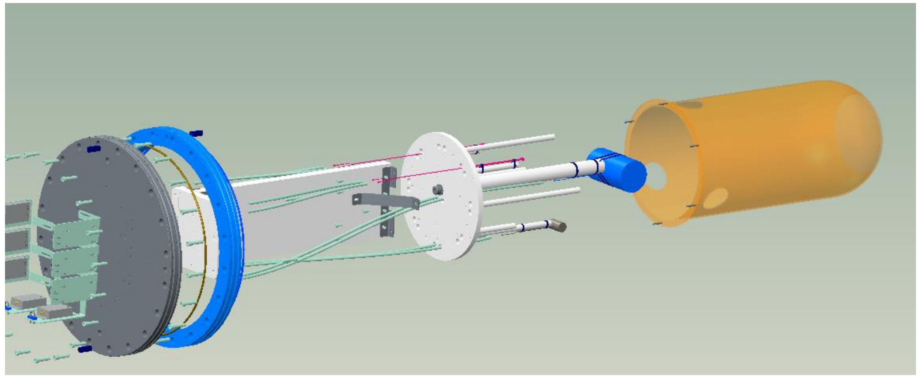
Electrons energy spectra measured at 13.5°

Ponderomotive scaling (Wilks et al.) give maximum temperature of about 1 MeV

Shot number	Maximum Intensity (W/cm²)	Hot electron temperature (MeV)	Number of electrons above 2.5 MeV
#176	7.9×10^{18}	8.3	2×10^{12}
#177	6.6×10^{18}	5.4	3×10^{11}
#178	3.3×10^{18}	2.0	4×10^{10}

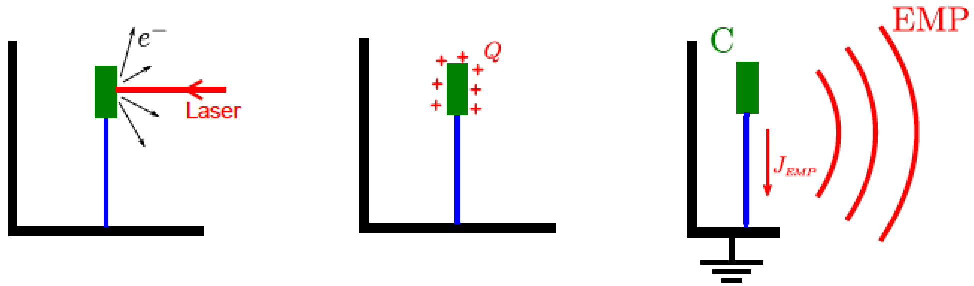
Total number of ejected electron can be infer from EMP diagnostic

J.L Dubois



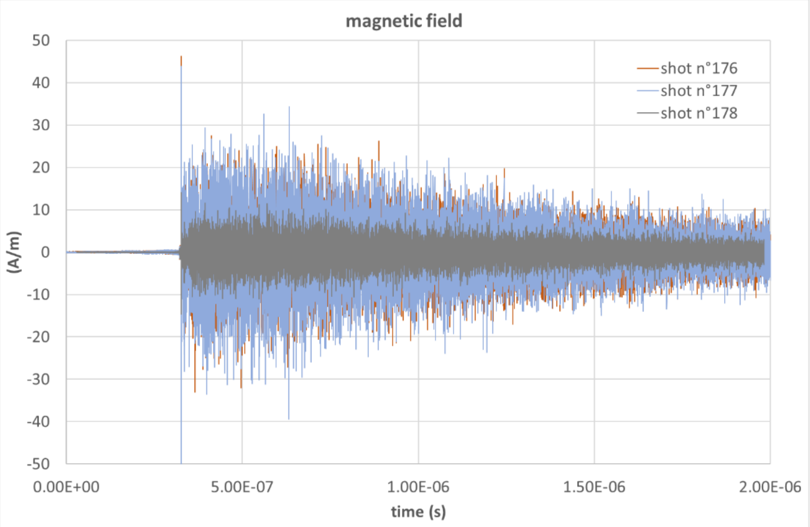
Description of EMP:

1) The laser ejects electron from the target
2) The target is charged
3) The target holder acts as an antenna and emits EMP



$$dE = \frac{Q^2}{2\pi\varepsilon_0 c}\left[\frac{1}{\beta}\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\right]d\nu$$

J. D. Jackson



Shot number	Averaged microwave emission [3 GHz – 6GHz] (J/Hz)	Typical electron energy before deceleration (MeV)	Total ejected charge (µC)	Total number of ejected electrons
#176	2×10^{-11}	8.3	1.6	10^{13}
#177	2.2×10^{-11}	5.4	1.8	1.1×10^{13}
#178	5.7×10^{-12}	2.0	1.4	7.4×10^{12}

From Sesame

A comparison with the hot electron numbers estimated from Sesame (up to 2E12) confirms that a significant number of electrons with energies less than 2.5 MeV were ejected from the target and make a dominant contribution to the EMP

Comparison with previous results

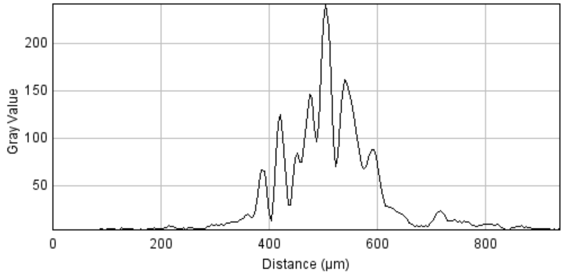
Publication	Laser energy (kJ)	Laser intensity (W/cm^2)	Laser pulse duration (ps)	Laser focal spot FWHM (µm)	Target type	Target thickness (microns)	Proton cutoff energy (MeV)	Conversion efficiency in energetic protons
Omega EP (Rochester USA) Flippo et al.	1	$4x10^{19}$	10	40	xxx	15	40	2%
LFEX (Osaka Japan) Yogo et al.	1	10^{18}	1.5-6	60	Al	5	33	5%
ARC-NIF (Livermore USA) Mariscal et al.	1-2.6	10^{18}	1-10	100	xx	xx	18	2%
This study	**0.2-0.45**	**7.9 x10^{18}**	**0.6**	**50**	**CH**	**50**	**51**	**3.3%**

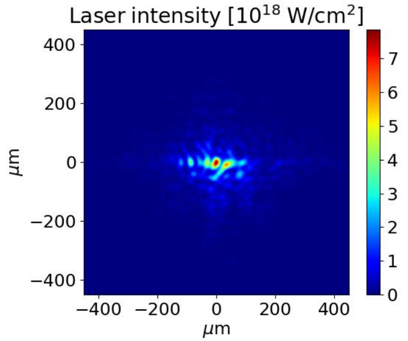
Despite the smaller energy delivered on target (reduced by at least a factor 2 compared to other experiments) and laser intensities not exceeding those achieved in previous experiment, we have obtained on PETAL significantly higher proton cut-off

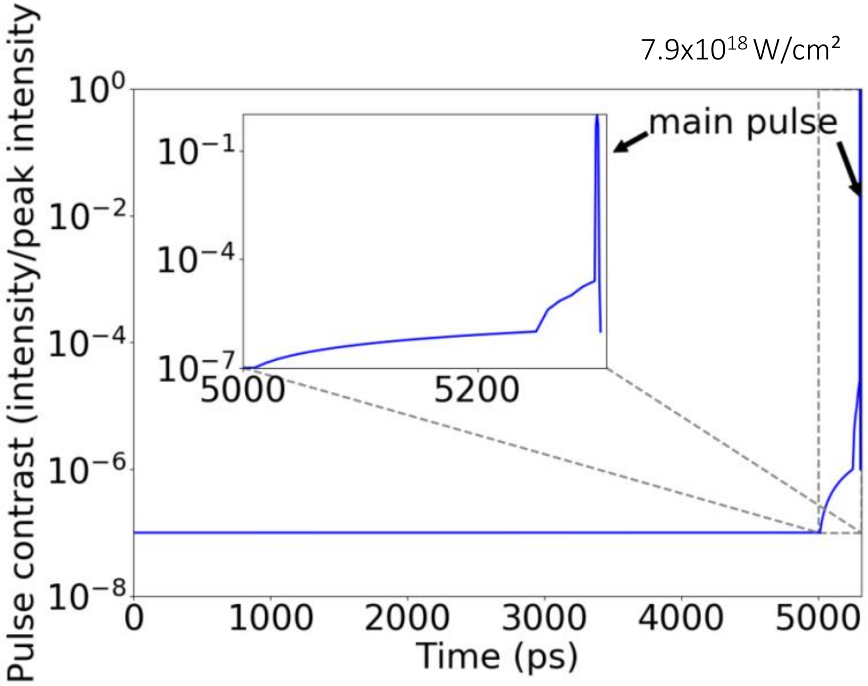
Shot #176 (CH, 450 J, 610 fs) with 51 MeV proton was simulated using TROLL and CALDER

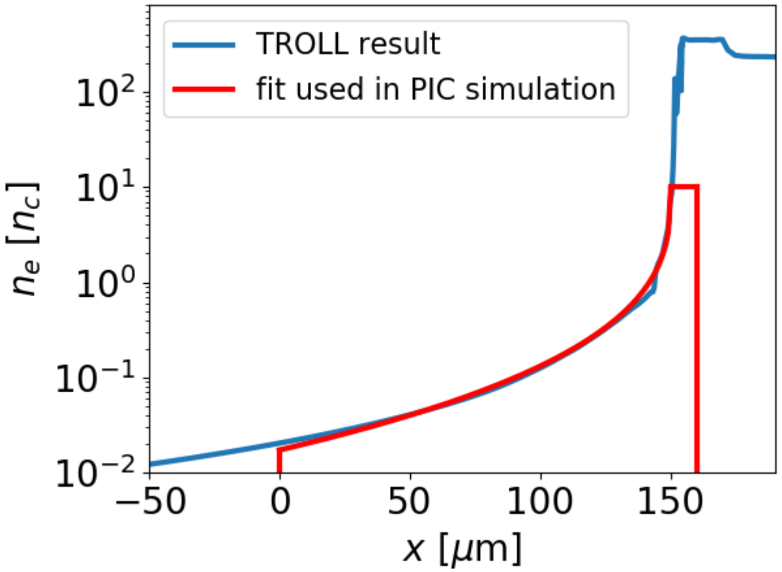
P. E. Masson-Laborde

The <u>hydrodynamic simulations (TROLL)</u> were initialized using the pulse shape and focal spot of PETAL with a homogenous cold medium at solid density, consisting of a 50 µm CH target with a 1 µm Al front layer







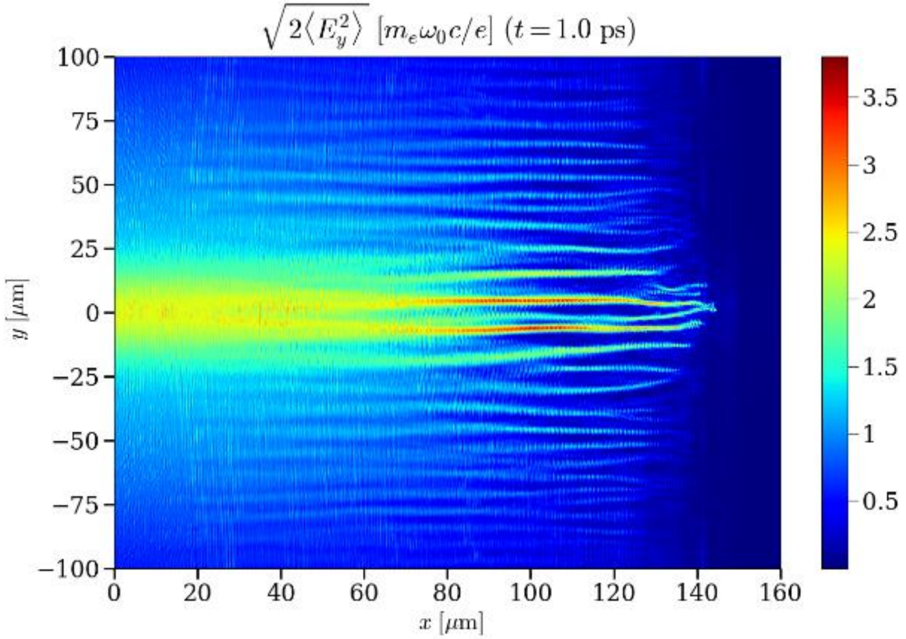


the 50 µm target rear side was not perturbed by the shock induces by the prepulse

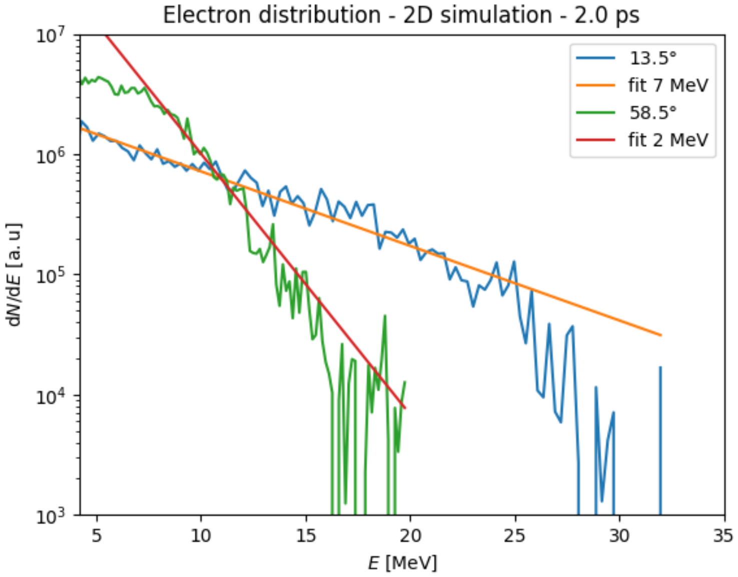
Density modulation and filamentation are observed (CALDER-2D PIC simulation)

X. Davoine

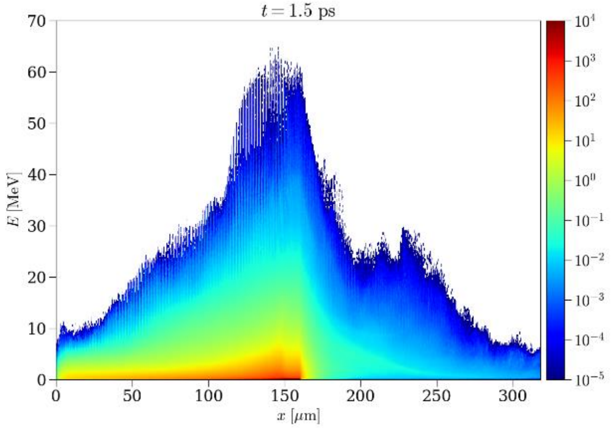
Counter-propagating field induces by SRS, interferes with the incident laser field and creates the observed modulations. The laser beam is split into several filaments in the density ramp (amplification up to 5×10^{19} W/cm^2 near high intensity part of the target)



Both the backward reflected/scattered laser field and filamentation in the density ramp boost electron acceleration and heating

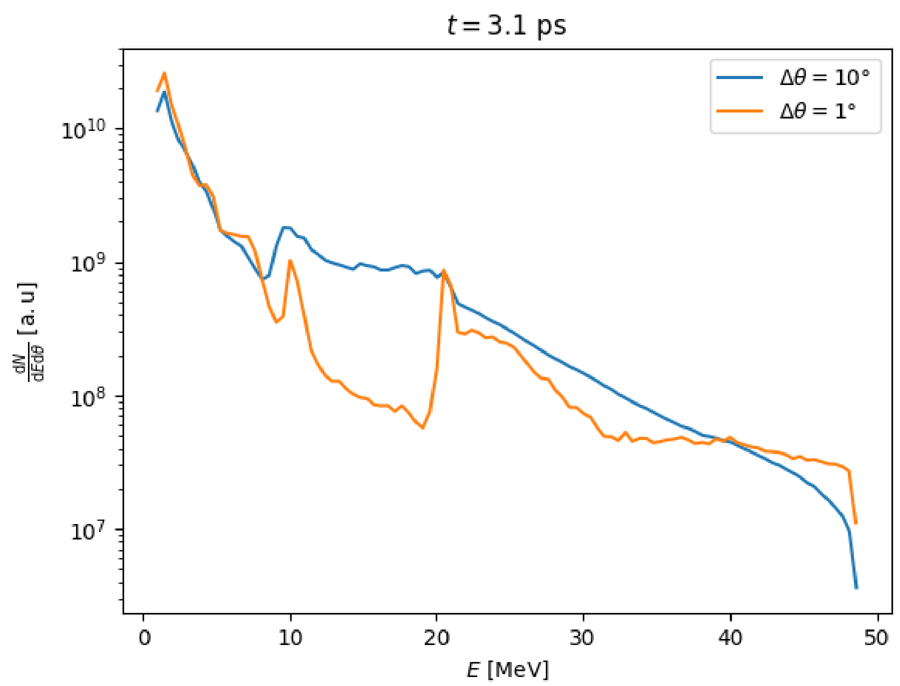


Fair agreement with the experimental values (7 and 2 MeV vs 8.3 and 3 MeV)

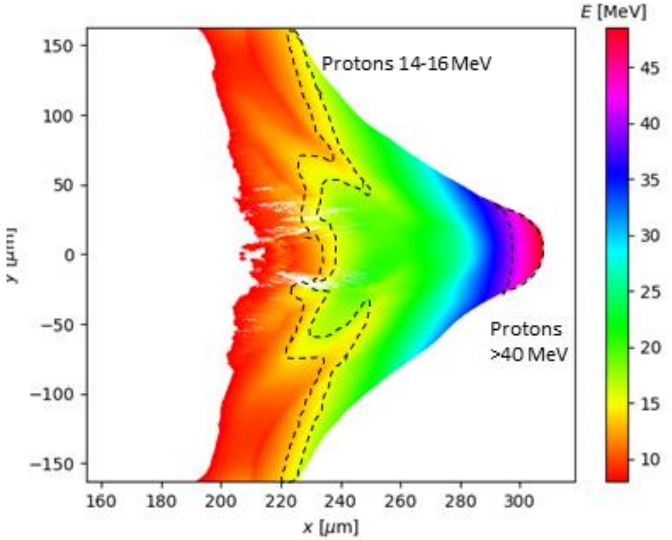


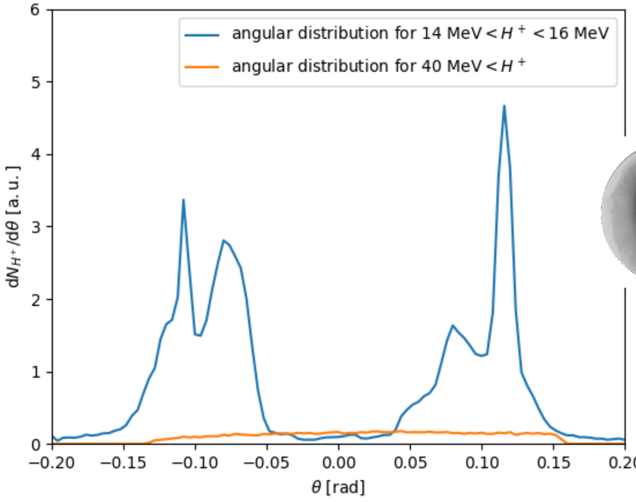
Stochastic heating and direct acceleration in the filaments may explain the measured temperature of the energetic electrons above ponderomotrice acceleration

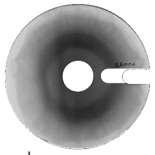
Angular and spectral distribution of simulated proton emission



An energy of 50 MeV is obtained at the end of the 2D simulation





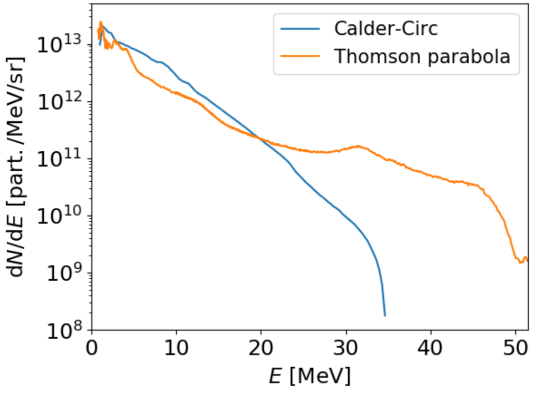


The fastest protons (> 40 MeV) form a bunch located on the axis.

Low energy p+ (off axis) are deflected by Ey fields

Quasi-3D PIC simulation (CALDER-CIRC)

Unlike in 2D, it is possible to compare directly the absolute number of accelerated ions with the experimental data



→ Total number of protons accelerated over 7 MeV is 2.2 x 10^{12} in agreement with observation (6 x 10^{12})

Conclusion

- Several diagnostics, including SEPAGE (Spectromètre Electron Proton A Grande Energie) and SESAME (Spectromètre ElectronS Angulaires Moyenne Energies), were used to characterize the energetic particle distributions that originated from plastic foil targets of varying thickness. Both electron and proton spectra were measured successfully, as well as the consistent absolute numbers of accelerated particles.

- Very high flux of protons (with temperature up to 50 MeV) were observed

- Simulations based on the actual performance of PETAL, linking hydro, PIC and Monte-Carlo codes reproduced with fair agreement the observation. The simulations revealed the importance of energetic electron production in the extended low-density preplasma at the irradiated target surface
  - Hot e- are produced through two main pathways:
    (i) stimulated backscattering of the incoming laser light, triggering stochastic electron heating in the resulting counter-propagating laser beams;
    (ii) laser filamentation, leading to local intensifications of the laser field and plasma channeling, tend to boost the electron acceleration.
  - Moreover, owing to the large waist and picosecond duration of the PETAL beam, the hot electrons can sustain a high electrostatic field at the target rear side for an extended period