High electron charge accelerated in the SM-LWFA regime with the LMJ-PETAL laser

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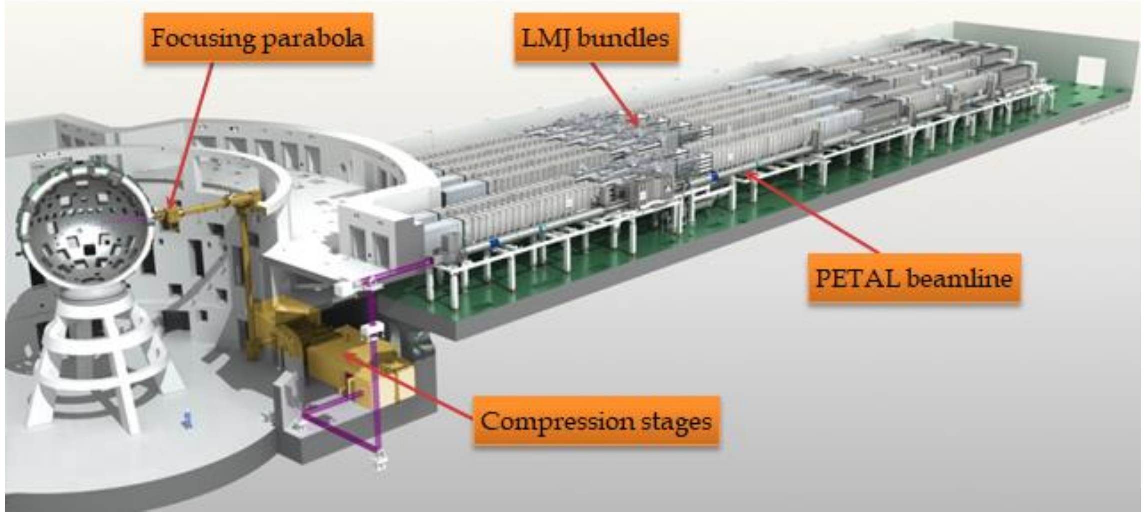
LMJ-PETAL facility

LMJ-PETAL (CEA, near Bordeaux, France)

PETAL (1 PW): ~ 400 J, ~ 700 fs, ~ 30 μm

~ 5×10^{18} W/cm^2

~ 5 shots / campaign



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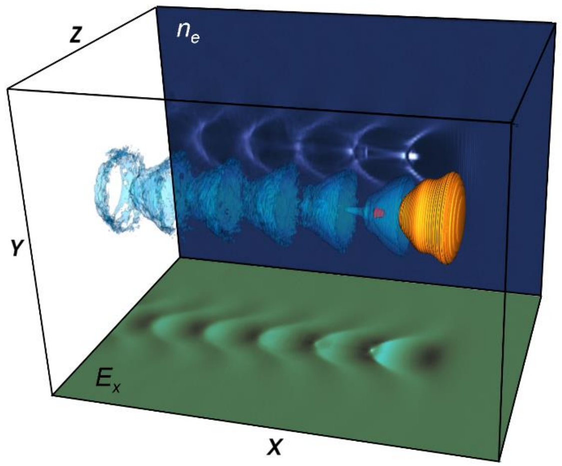
Electron wakefield acceleration on PETAL: Fundamental studies of SM-LWFA with PW laser

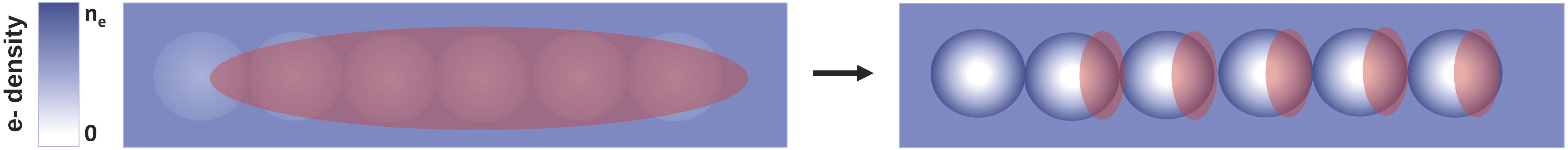
Bubble / Blowout regime

- Many results obtained in different laboratories

$\tau \sim 30$ fs



Self-Modulated LWFA regime



- Limited number of studies of the SM-LWFA regime on PW laser facilities
- Lower electron energies + broadband spectrum
- but **PW + ps** $\Rightarrow E_{laser} \sim \mathrm{kJ} \Rightarrow$ **high charge (~ µC)**

F. Albert *et al.*, Phys. Rev. Lett. 111, 235004 (2013)
F. Albert *et al.*, Phys. Rev. Lett. 118, 134801 (2017)
N. Lemos *et al.*, PPCF 60, 054008 (2018)
G. Williams *et al.*, Rev. Sci. Instr. (2018)
J.L. Shaw *et al.*, Sci. Rep 11 7498 (2021)
P. M. King *et al.*, HEDP (2022)
J. Ferri *et al.*, PRAB 19, 101301 (2016)

Electron wakefield acceleration on PETAL: Toward brilliant X- and γ-ray Sources

Sources based on large scale conventional accelerator

- Synchrotron
- FEL
- Compton sources

UHI laser-plasma interaction

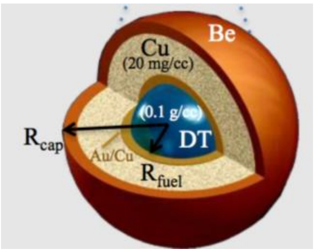
- Compact
- Ultra-short (fs) ⇒ high flux, brillance
- Synchronized with other laser beam

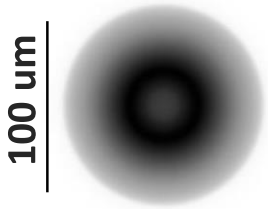
Nuclear photonic applications

Strong-field QED

Ultra-fast X- and γ-ray Imaging of dense target

1 MeV radiography simulation R. Tipton, LLNL 2017



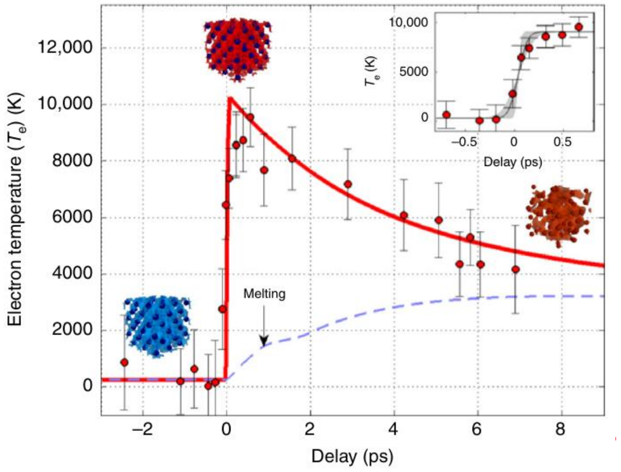


µm source size
Sub 100 ps duration

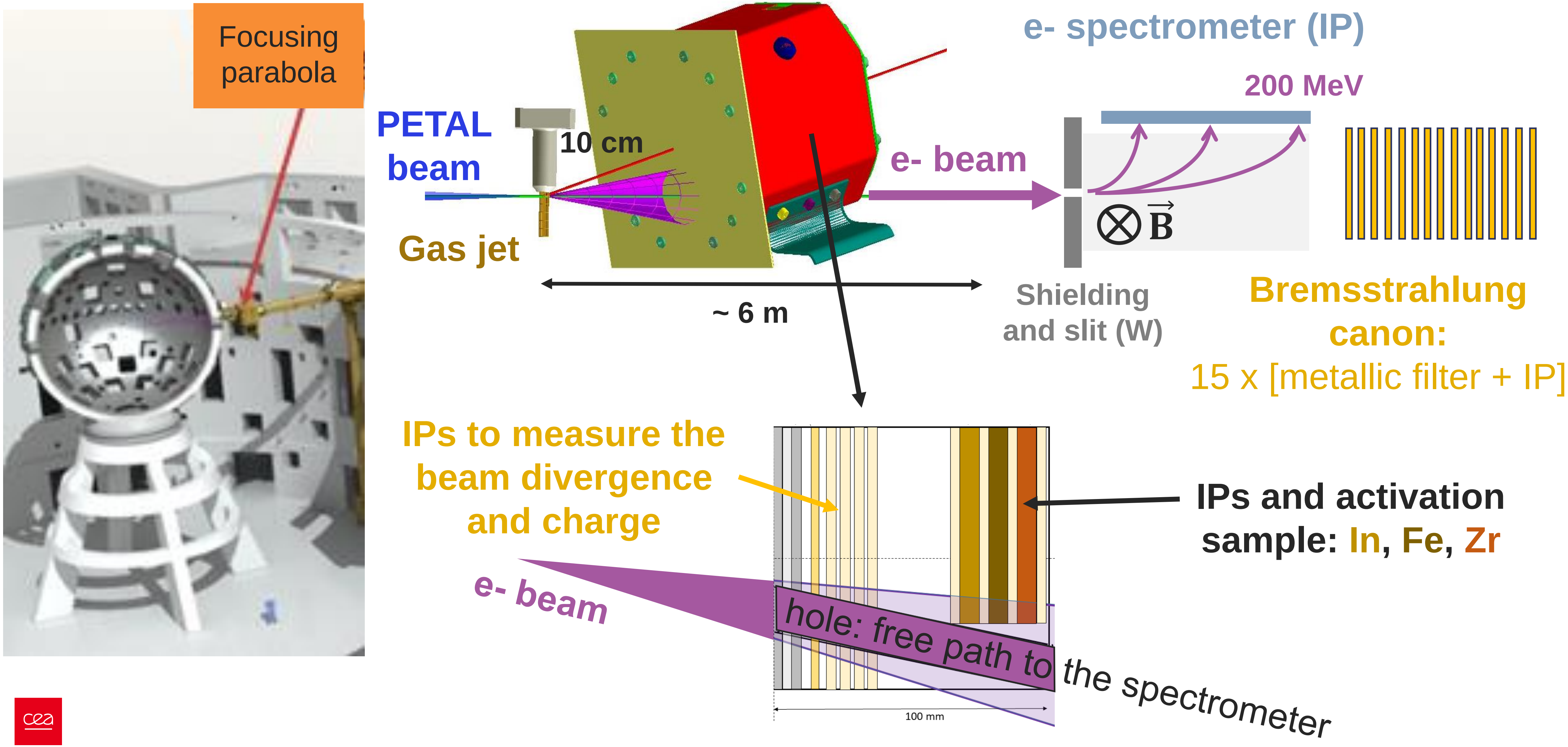
X-ray spectroscopy

Ultra-fast warm dense mater probing

B. Mahieu *et al*., Nat. Comm. **9** 3276 (2018)
A. Grolleau *et al*., PRL **127** 275901 (2021)

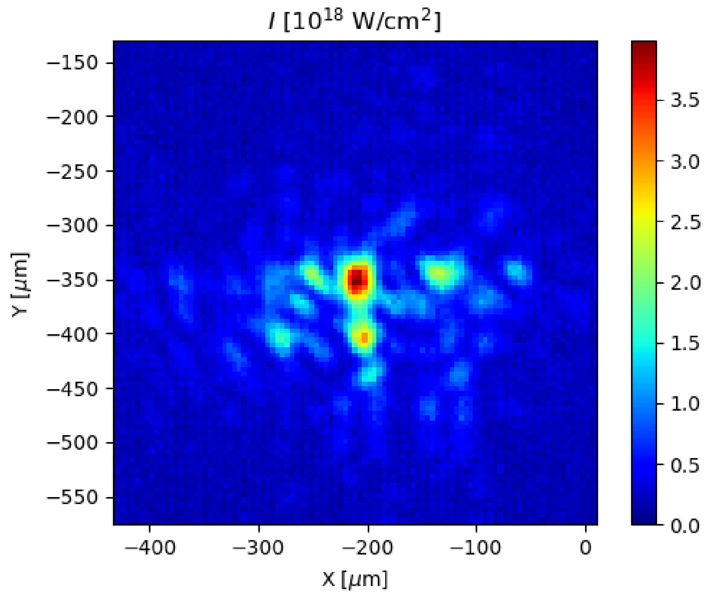


Experimental setup

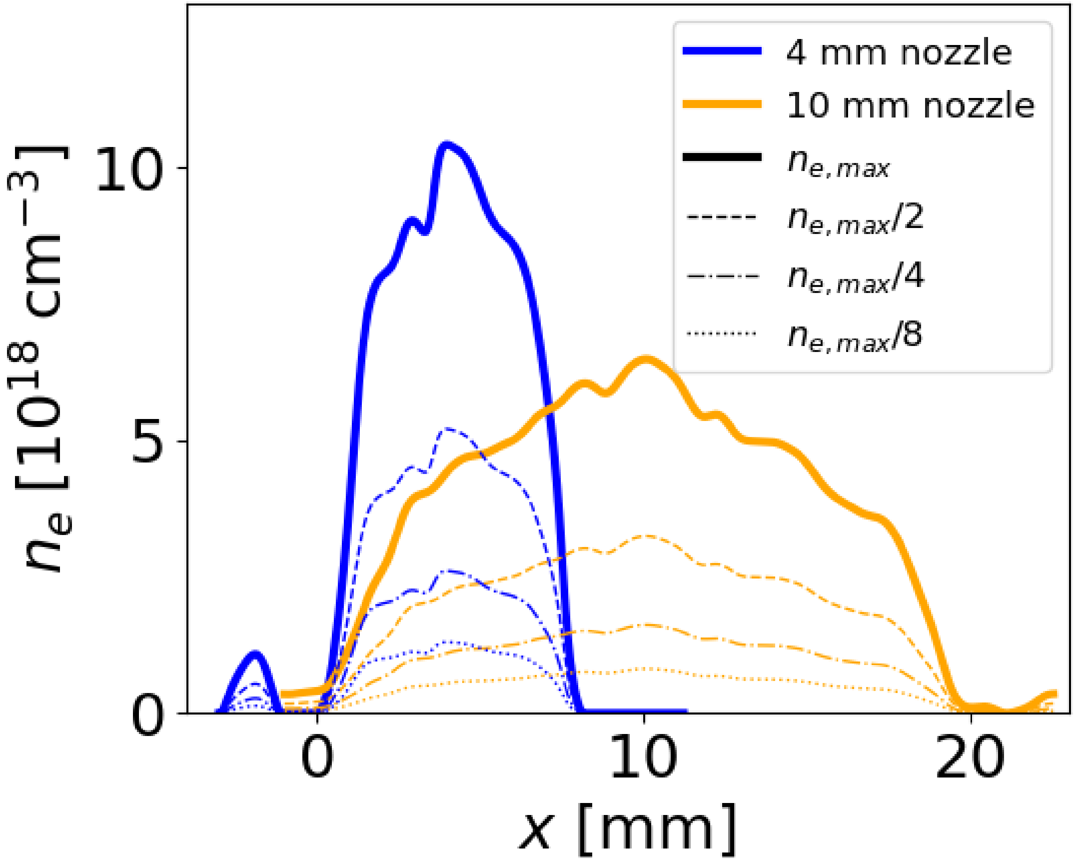


Laser and plasma target

- Typical PETAL beam
  - $\tau \sim 700$ fs
  - $\sim 5 \times 10^{18}$ W/cm^2
  - Focal spot size: ~ 30 µm
  - Full energy: ~ 350 J
  - Energy in the central spot: ~ 40 J (issue with the focal spot quality during the campaign, now solved),

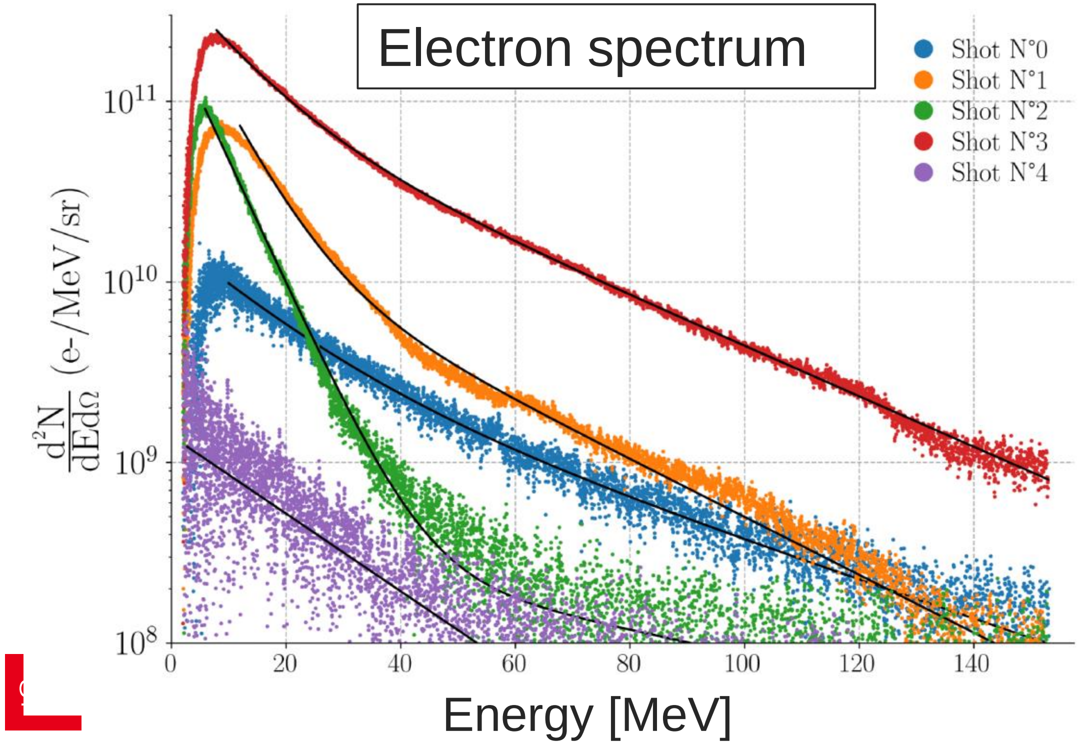


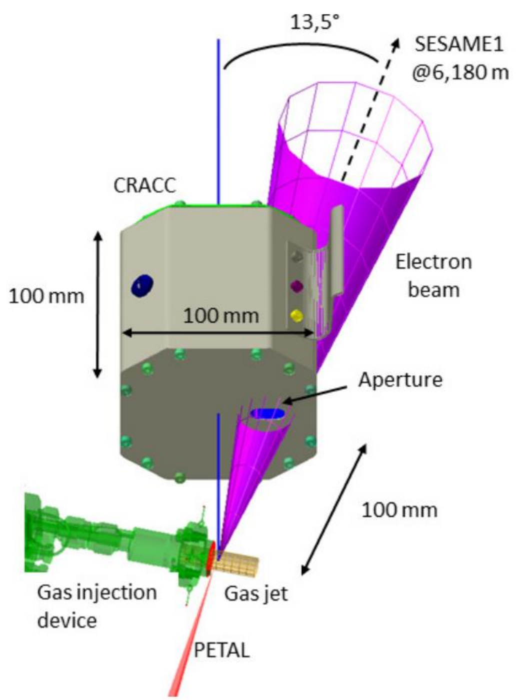
- 2 gas jets
  - 4 mm and 10 mm nozzles
  - With He only, $n_e \leq 10^{19}$ cm^{-3}

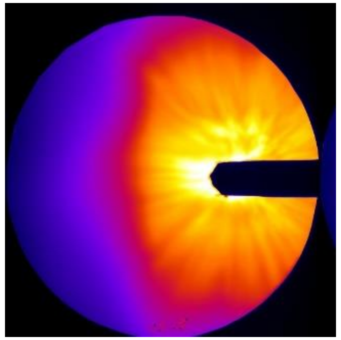


Experimental results

Laser Energy	Laser Duration	Laser Intensity	Nozzle	Density
347 J	0.64 ps	$4.4 \times 10^{18}\ \mathrm{W/cm^2}$	4 mm	$10^{19}\ \mathrm{cm^{-3}}$
313 J	0.92 ps	$4.3 \times 10^{18}\ \mathrm{W/cm^2}$	4 mm	$10^{19}\ \mathrm{cm^{-3}}$
352 J	4 ps	$8 \times 10^{17}\ \mathrm{W/cm^2}$	10 mm	$5 \times 10^{18}\ \mathrm{cm^{-3}}$
351 J	0.82 ps	$4.6 \times 10^{18}\ \mathrm{W/cm^2}$	10 mm	$5 \times 10^{18}\ \mathrm{cm^{-3}}$
278 J	0.62 ps	$5.2 \times 10^{18}\ \mathrm{W/cm^2}$	10 mm	$2.5 \times 10^{18}\ \mathrm{cm^{-3}}$



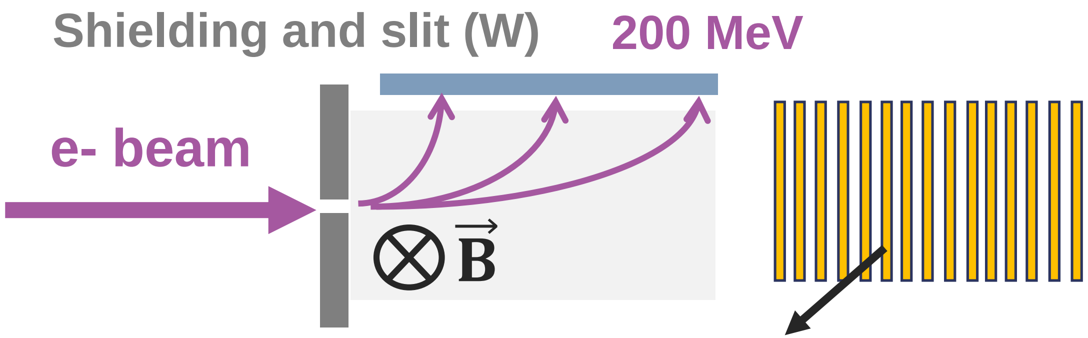




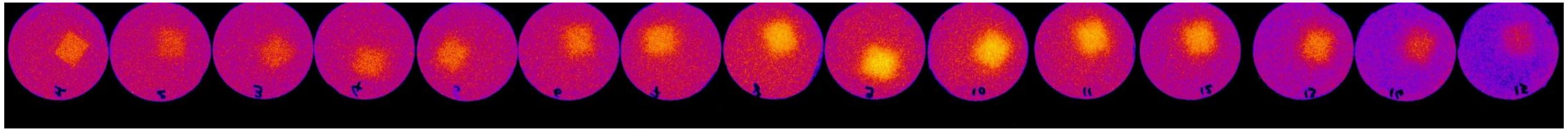
- Divergence: ~100 mrad
- Charge
  - Shot 3: ~ 1 μC > 1 MeV

Information on the radiation environment: to be analyzed

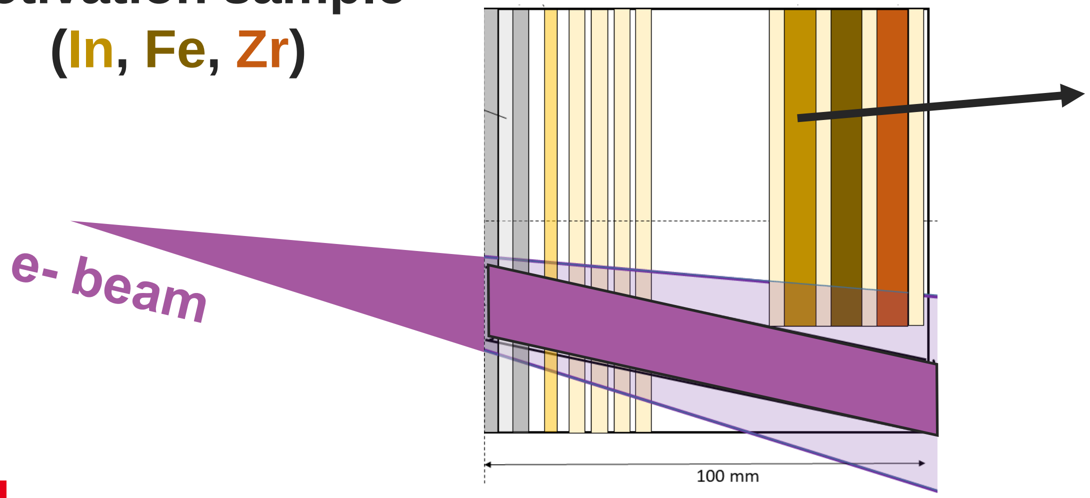
Bremsstrahlung Canon (behind the electron spectrometer)

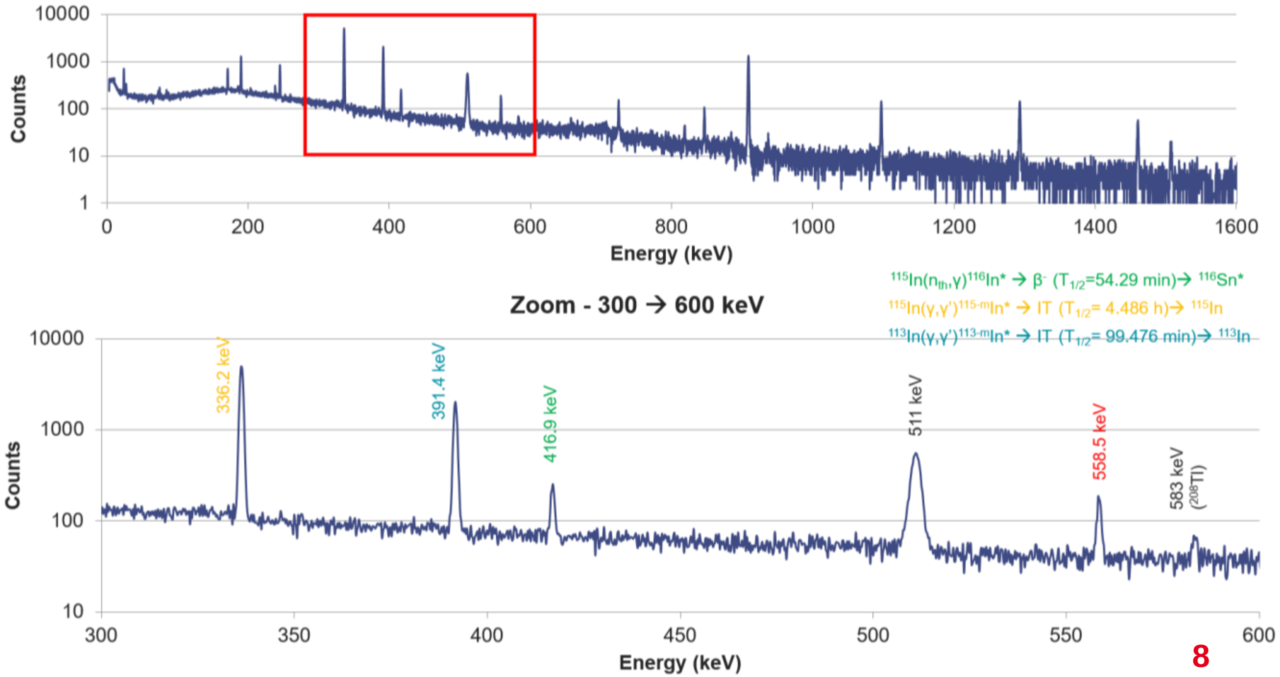


Bremsstrahlung canon: 15 x [metallic filter + IP]



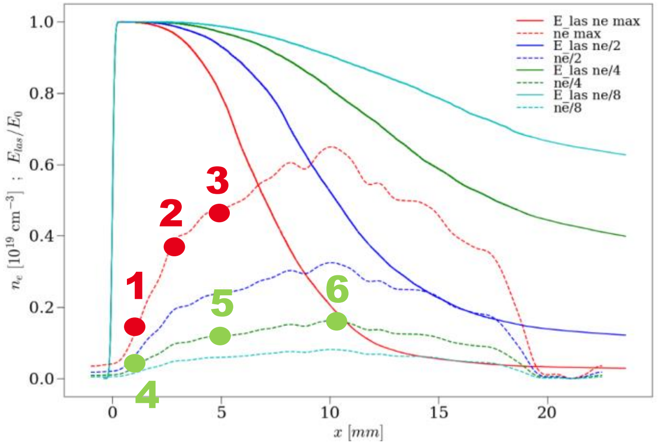
Activation sample (In, Fe, Zr)

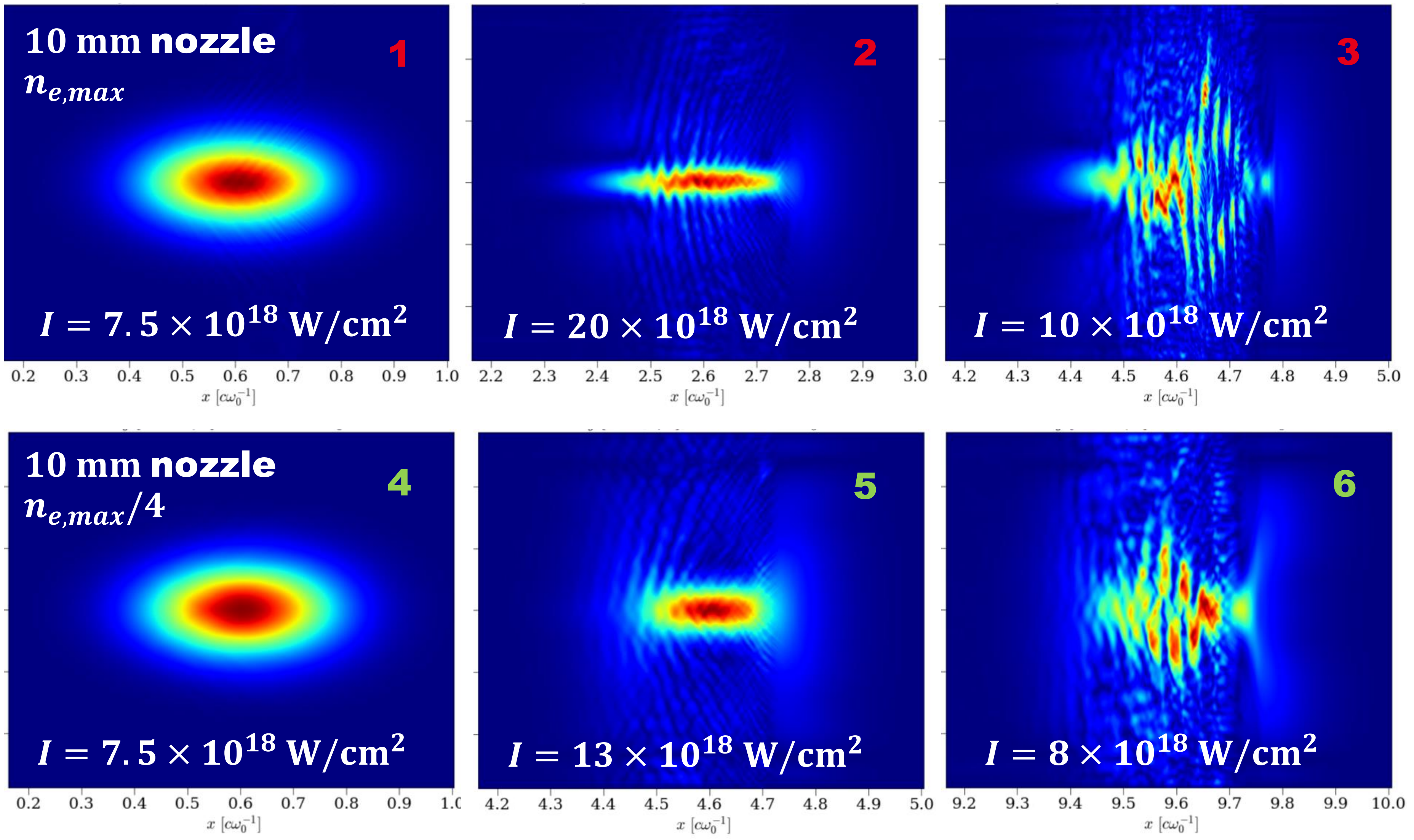




Preliminary 2D simulation (CALDER): laser focusing and self-modulation

Laser energy – 10 mm nozzle



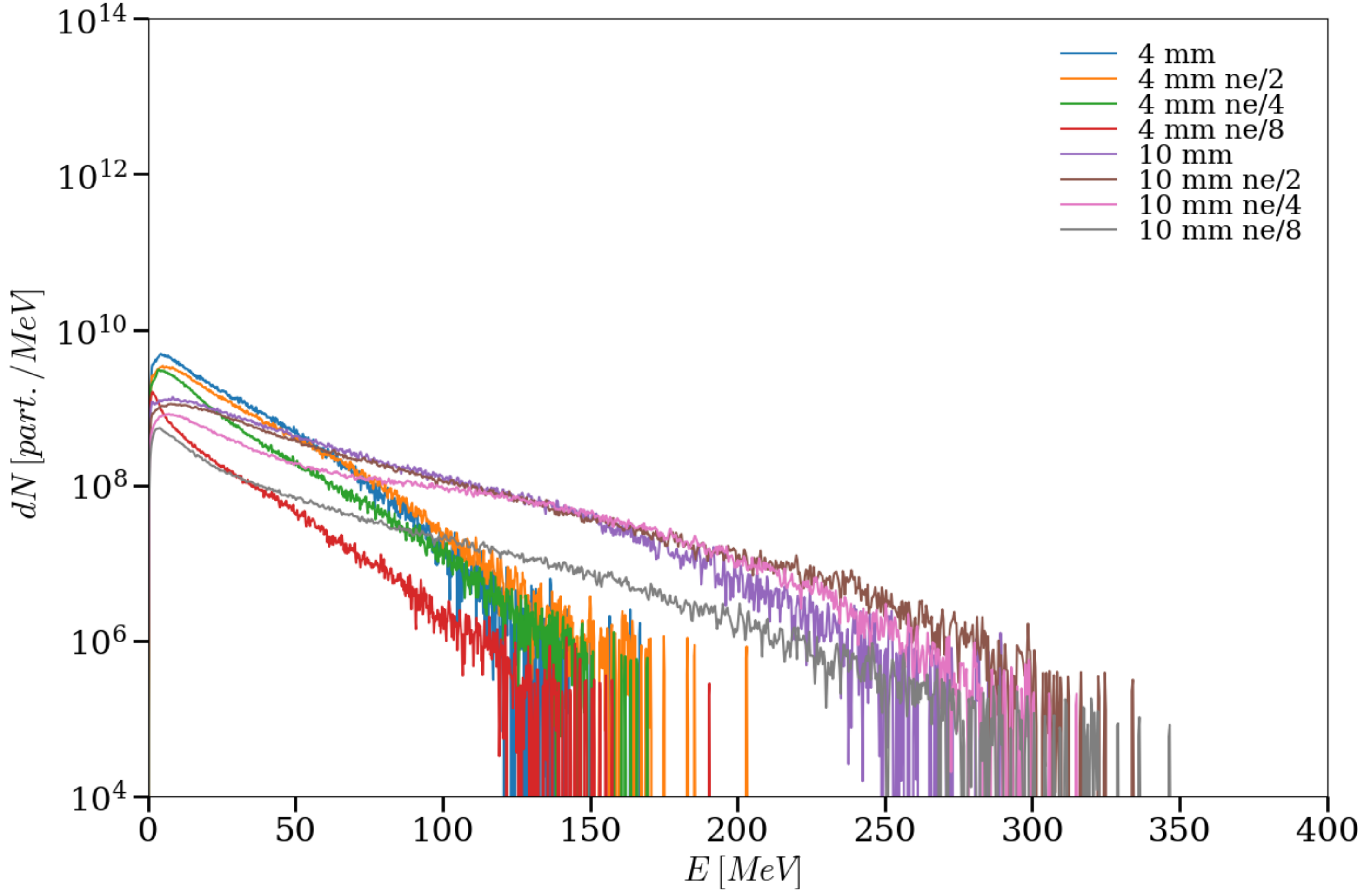


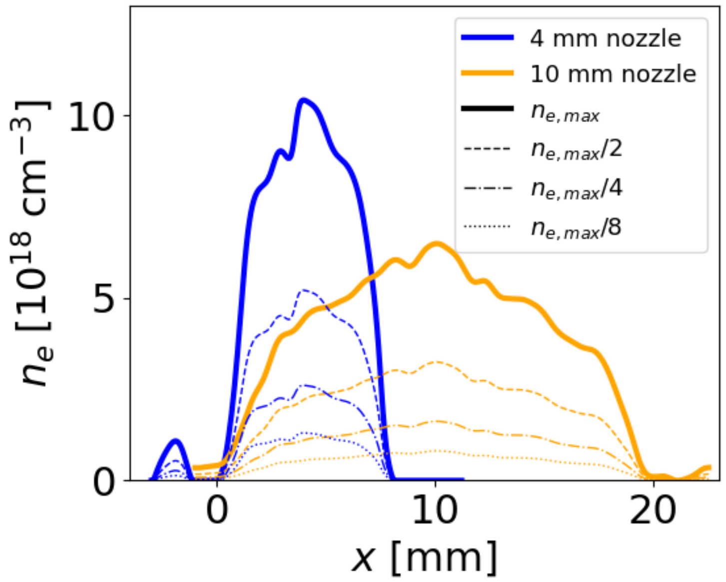
Lower plasma density:

- Lower self-focusing
- Slower laser evolution
- But acceleration on a longer distance ⇒ higher electron energy

Preliminary 2D simulation (CALDER): Electron beam spectrum

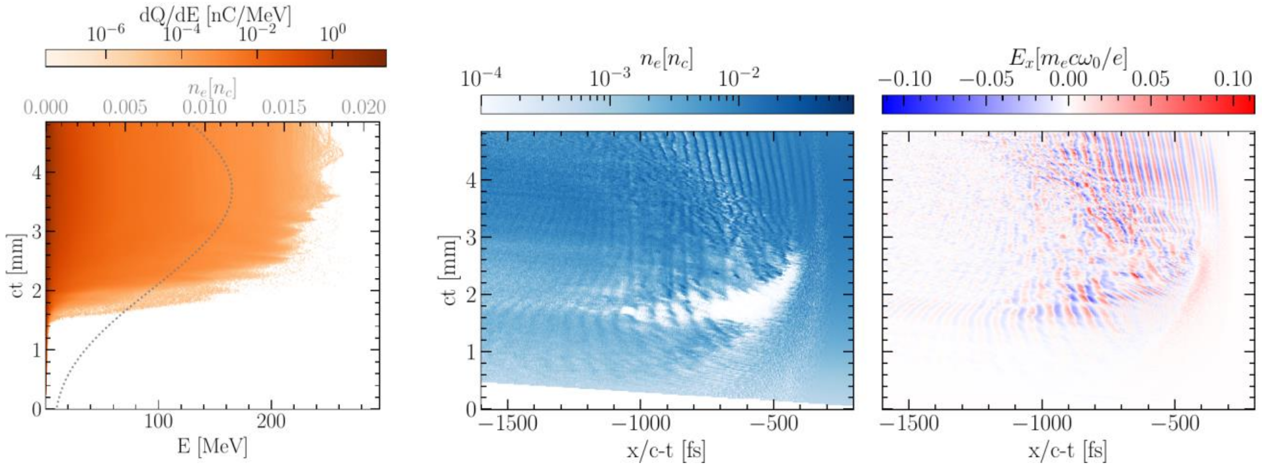
- Higher electron energies obtained with the 10 mm nozzle (up to 300 MeV)
- Lower beam charges obtained with the lower plasma densities





- First shots with the short and dense gas jet to maximize the electron detection

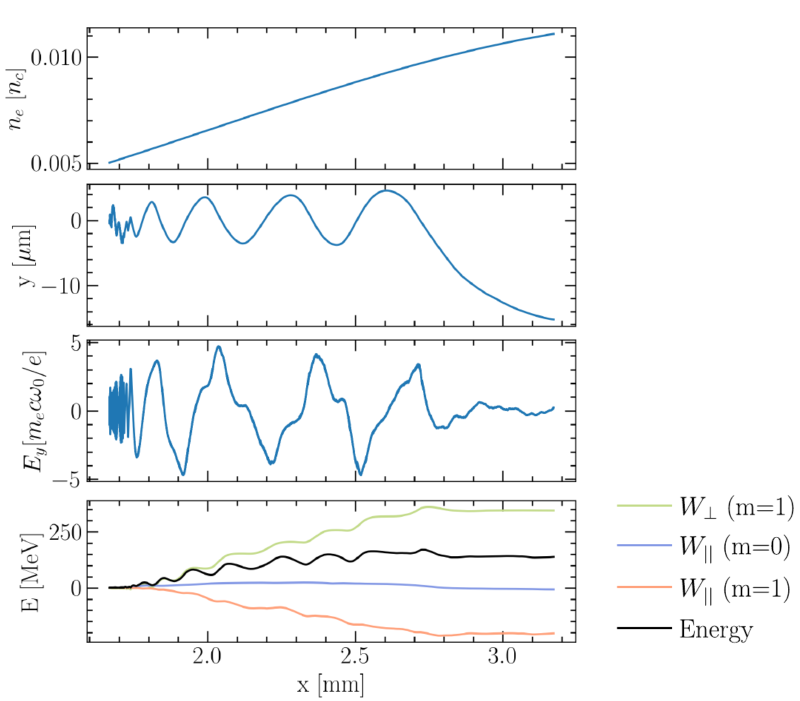
Quasi-3D simulation (OSIRIS): competition between SM-LWFA and DLA

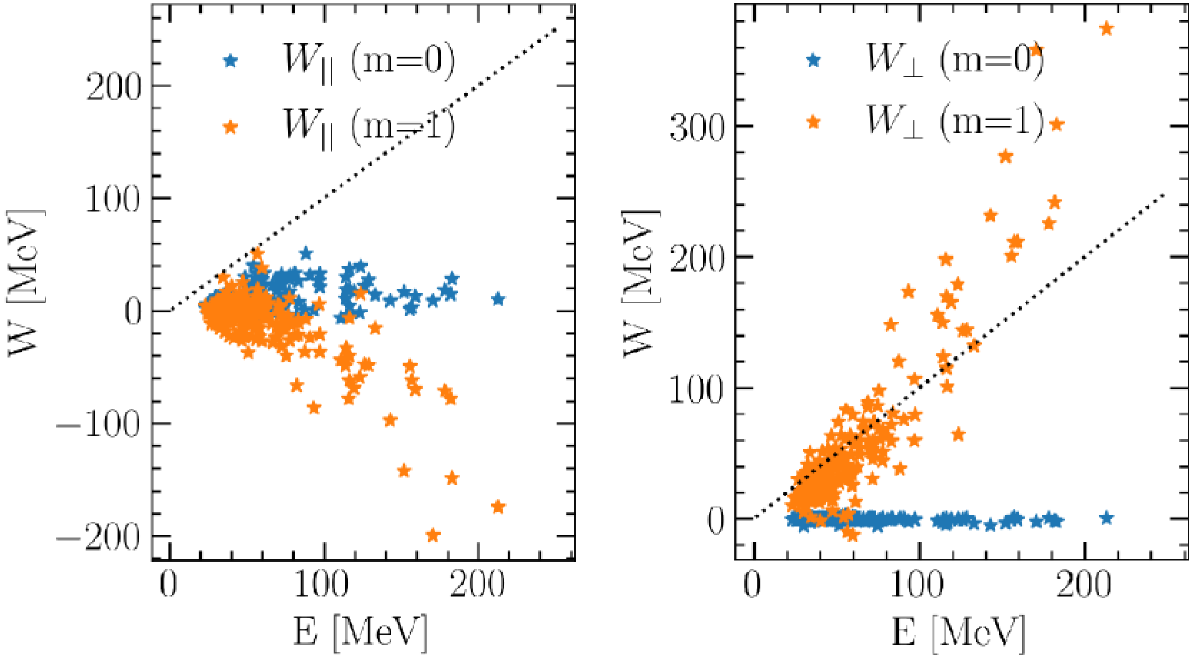


- At low density: wakefield acceleration is dominant. a_0 and n_e are too low for efficient DLA.

  R. Babjak et al., New J. Phys. **26** (2024) 093002

- At higher density: DLA is dominant. DLA is boosted due to the pre-acceleration in the wakefield.





Conclusions

- First experiment of wakefield acceleration in the self-modulated regime on PETAL
  - First use of a gas jet on LMJ-PETAL
  - Production of electrons > 150 MeV (Maxwellian-like spectrum)
  - Charge > 1 MeV up to µC level
  - Charge > 10 MeV up to several 10's of nC
  - Even at low n_e and a_0, DLA can occur due to pre-acceleration in the wakefield

- Possibility to enhance these sources in the coming years
  - Project to upgrade the PETAL energy to 800 J and 1 kJ in the next years
  - Improvement of the laser beam (contrast, focal spot) and optimization of the setup
  - Use of energetic electrons produced in the gas jet to trigger Bremsstrahlung and (γ,n) reactions in a convertor to study photonuclear reactions and produce alternative neutron sources

- These results pave the way to the applications with the energetic particle sources produced on PETAL.