Laser plasma acceleration of high charge >200 MeV electrons at LMJ-PETAL

F. Albert[1], X. Davoine[2,3], W. Cayzac[2], D. Batani[4], N. Blanchot[5], G. Boutoux[2,5], T. Caillaud[5], S. Debesset[5], R. De Mollerat Du Jeu[5], R. Diaz[5], A. Duval[2] , M. Ferri[5], J. C. Kieffer[6], I. Lantuejoul[2], N. Lemos[1], L. Le-Déroff[5], B. Mahieu[2], R. Parreault[5], L. Ribotte[2], C. Rousseaux[2], K. Ta Phuoc[7], B. Vauzour[2]

[1]NIF and Photon Sciences, LLNL, Livermore, California 94550, USA
[2]CEA, DAM, DIF, 91297 Arpajon, France
[3]Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France
[4]CELIA, Université de Bordeaux–CNRS–CEA, UMR 5107, 33405 Talence, France
[5]CEA, DAM, CESTA, F-33114 Le Barp, France4
[6]INRS-EMT, Université du Québec, Varennes J3X 1S2, Québec, Canada
[7]LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France

albert6@llnl.gov, xavier.davoine@cea.fr, witold.cayzac@cea.fr

08/06/2023

Plan

1. **Motivation**

   Production of energetic electrons on the LMJ-PETAL facility in the SM-LWFA regime

   Generation of secondary X-ray sources

2. **Simulation of the expected electron beam**

3. **Experimental setup and first experimental results**

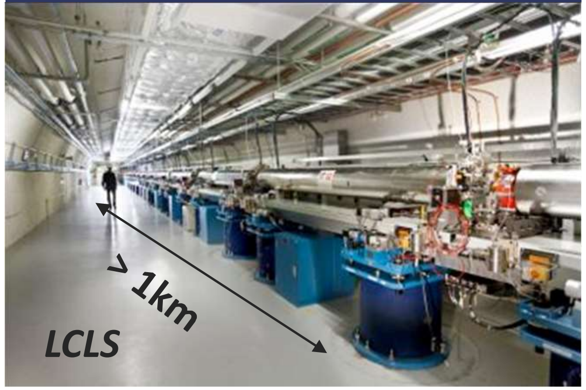
Motivation

- Development of brilliant X- and γ-ray sources on the LMJ-PETAL facility
- Fundamental study of the self-modulated laser wakefield acceleration (SM-LWFA) regime with PETAL.

Brilliant X-ray Sources:
Development of compact plasma based sources

Synchrotron

Free Electron Laser

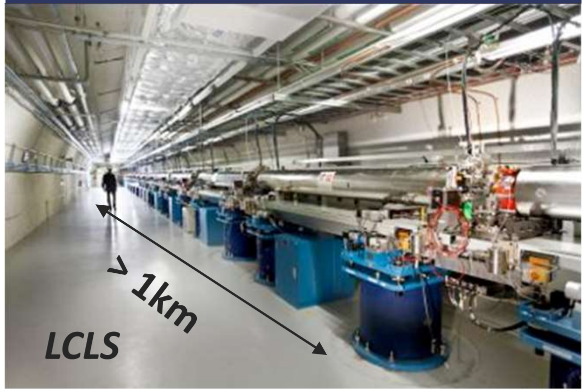


UHI laser-plasma interaction

Brilliant X-ray Sources:
Implementation of these sources on LMJ-PETAL

Synchrotron

Free Electron Laser

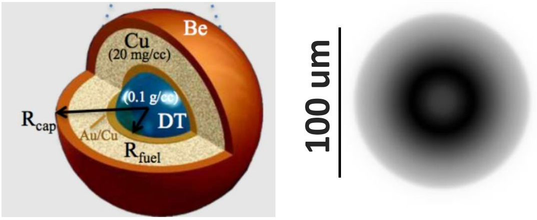


UHI laser-plasma interaction

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

1 MeV radiography simulation

R. Tipton, LLNL 2017

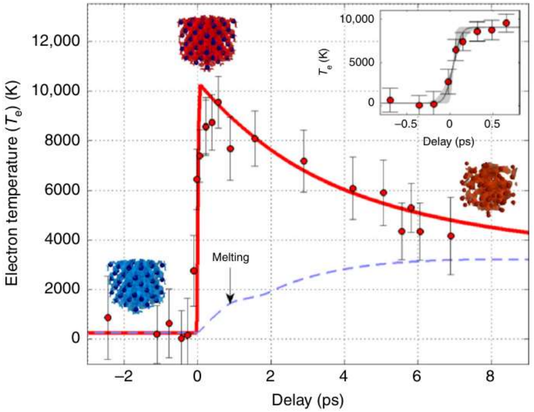


µm source size
Sub 100 ps duration

X-ray spectroscopy

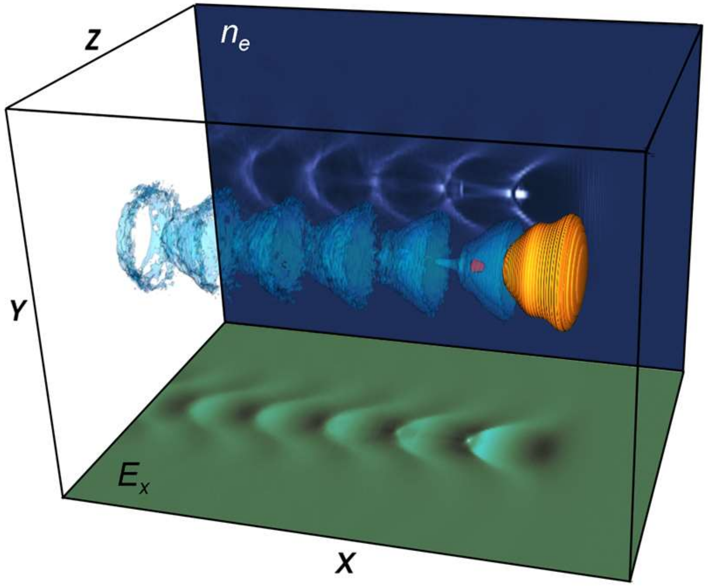
Ultra-fast warm dense mater probing

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



Laser wakefield acceleration (LWFA): Generation of secondary radiation sources

LWFA



$I > 10^{18}\ \mathrm{W/cm^2}$
$\tau \sim 30\ \mathrm{fs}$

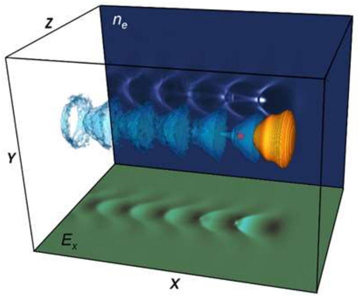
mm long gas jet
$n_e \sim 10^{19}\ \mathrm{cm^{-3}}$

$\sim 100\ \mathrm{GeV/m}$
$\sim \mathrm{MeV} - \mathrm{GeV}$

X/γ-ray sources from a LWFA:

- **Betatron sources ($\sim \mathbf{1 - 10\ keV}$)**
- Compton ($\sim 10\ \mathrm{keV} - 1\ \mathrm{MeV}$)
- Bremsstrahlung ($> 100\ \mathrm{keV}$)

Fundamental studies of SM-LWFA with PW laser



$\tau \sim 30$ fs

$c\tau \sim 10\ \mu m \sim \lambda_p = \dfrac{2\pi c}{\omega_p} \propto n_e^{-1/2}$

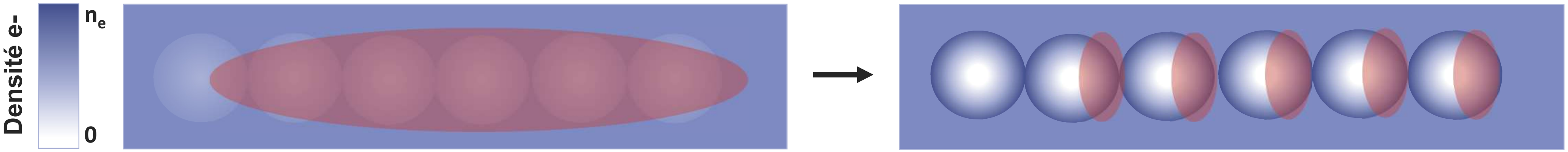
$E_{laser} \sim$ a few J

Bubble / Blowout regime

- Many results obtained in different laboratories

Self-Modulated LWFA regime: $c\tau \gg \lambda_p$

- The laser envelop is first modulated at λ_p during the beginning of the propagation
- Then an efficient wakefield is generated and electron acceleration occurs



- Limited number of studies of the SM-LWFA regime on PW laser facilities
- Lower electron energies + broadband spectrum
- but **PW + ps** $\Rightarrow E_{laser} > 100$ J $\Rightarrow$ **high charge (~ µC)** !

Fundamental studies of SM-LWFA with ps laser

Titan, LLNL	OMEGA-EP, LLE	NIF – ARC, LLNL	LMJ – PETAL, CEA
			

2015 › 2016 › 2017 › 2018 › 2019 › 2020 › 2021 › 2022

Titan
SMLWFA electrons
Betatron radiation

Titan
Compton scattering/Bremsstahlung

Titan
Radiography

OMEGA-EP
SMLWFA electrons

OMEGA-EP
X-ray sources

OMEGA-EP
Radiography

NIF - ARC
SMLWFA electrons

NIF - ARC
X-ray sources

LMJ – PETAL
SMLWFA electrons

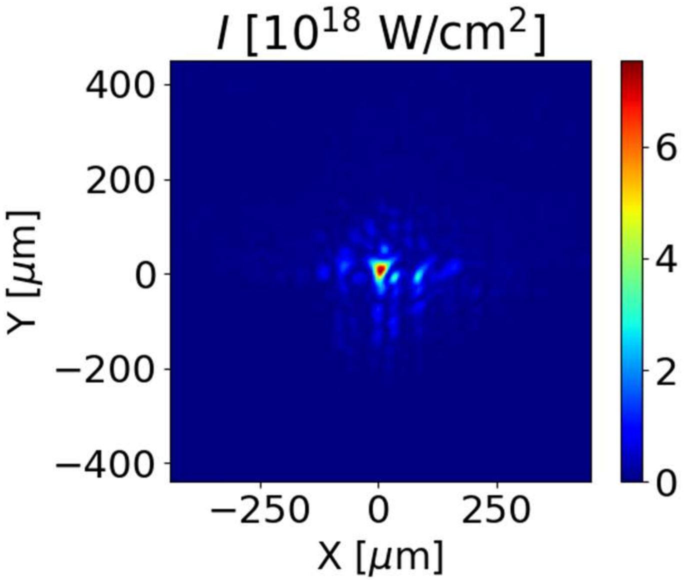
F. Albert *et al.*, Phys. Rev. Lett. 111, 235004 (2013)
F. Albert *et al.,* Phys. Rev. Lett. 118, 134801 (2017)
N. Lemos *et al.*, PPCF 60, 054008 (2018)
G. Williams *et al.*, Rev. Sci. Instr. (2018)
J.L. Shaw *et al.*, Sci. Rep 11 7498 (2021)
P. M. King *et al.*, HEDP (2022)
J. Ferri *et al.*, PRAB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

Simulation

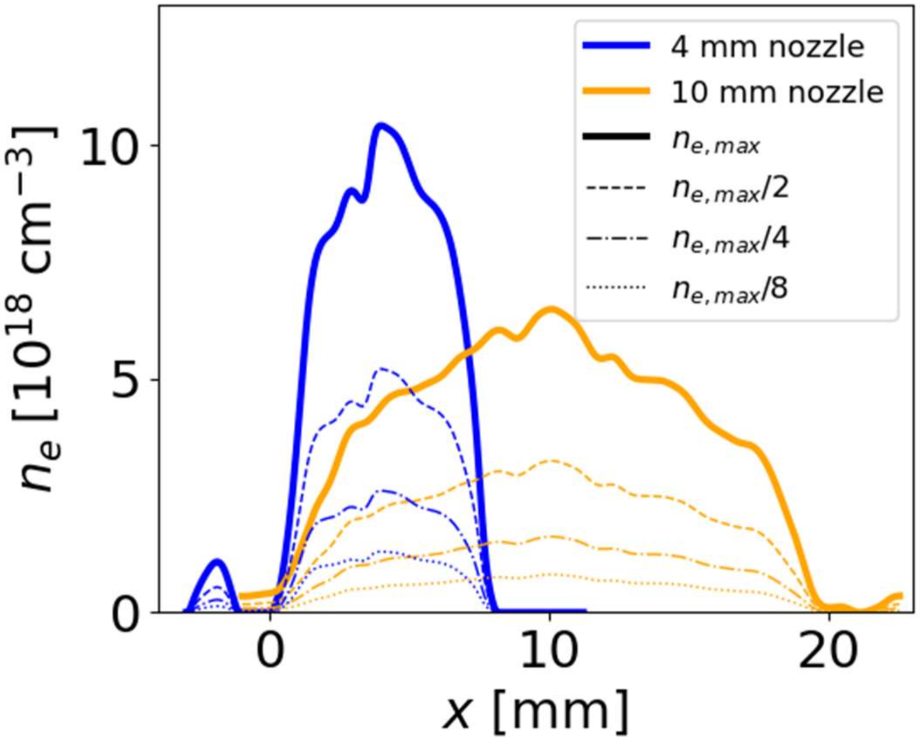
- 2D simulation run before the experiment.
- Used to design the setup.

Laser and plasma target

- PETAL beam (typical shot in 2022)
  - $\tau = 660$ fs
  - 7.5×10^{18} W/cm$^2 \Rightarrow a_0 = 2.33$
  - Focal spot size: 26 μm
  - Full energy: ~ 330 J
  - Energy in the central spot: ~ 40 J

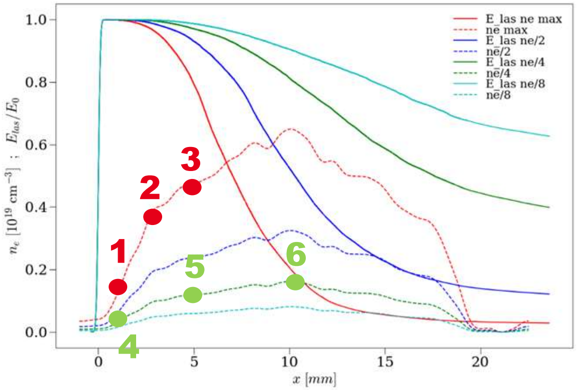


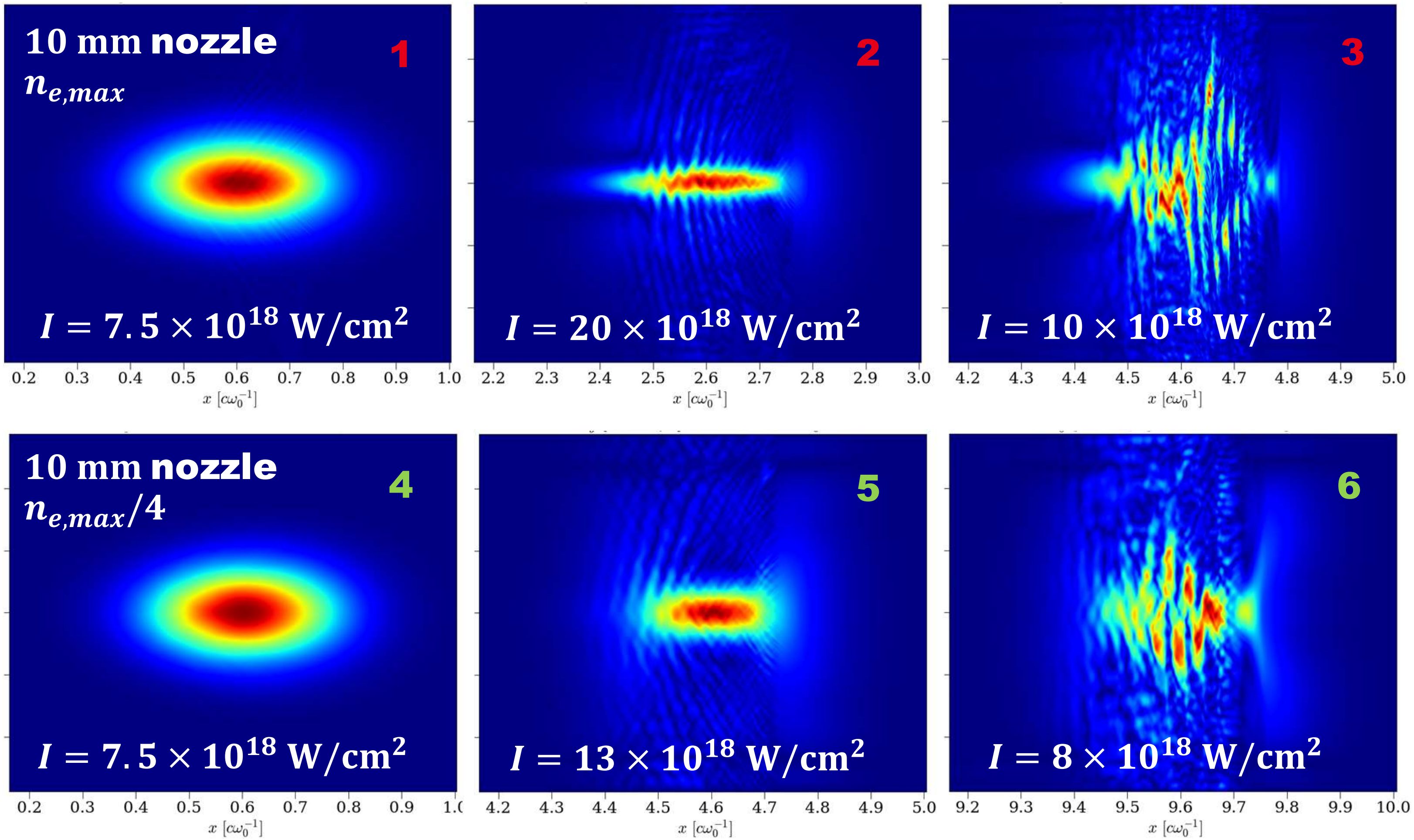
- 2 gas jets
  - 4 mm and 10 mm nozzles
  - He



Laser focusing and self-modulation

Laser energy – 10 mm nozzle



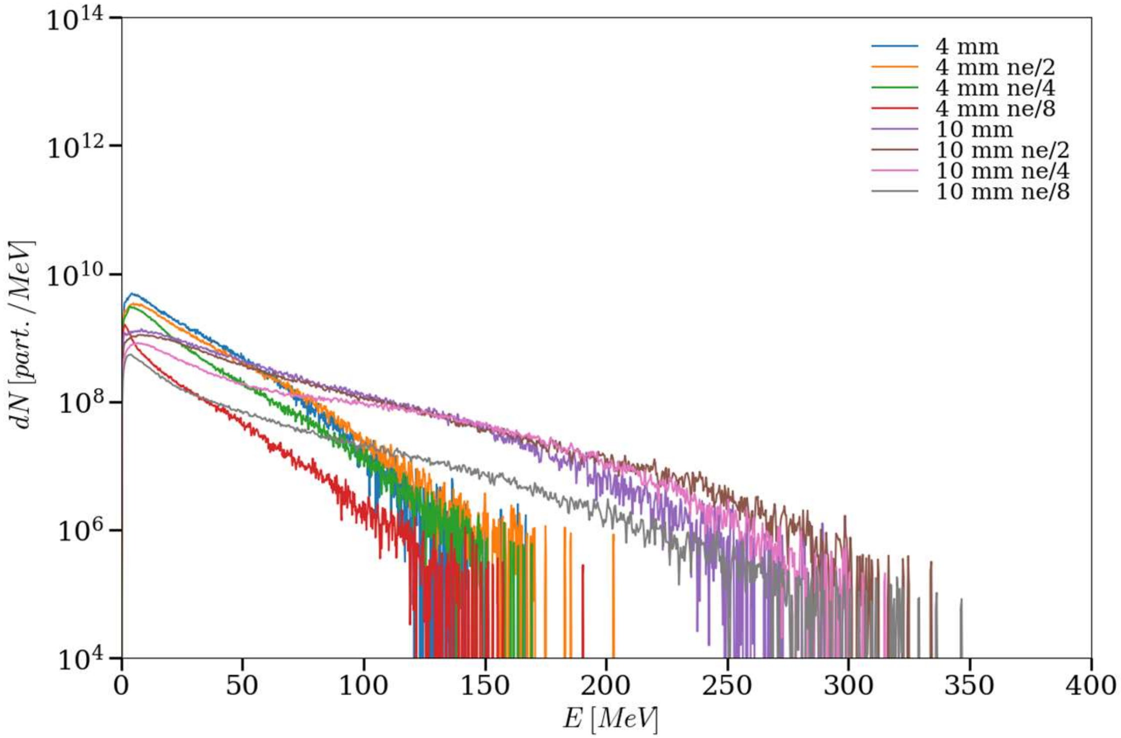


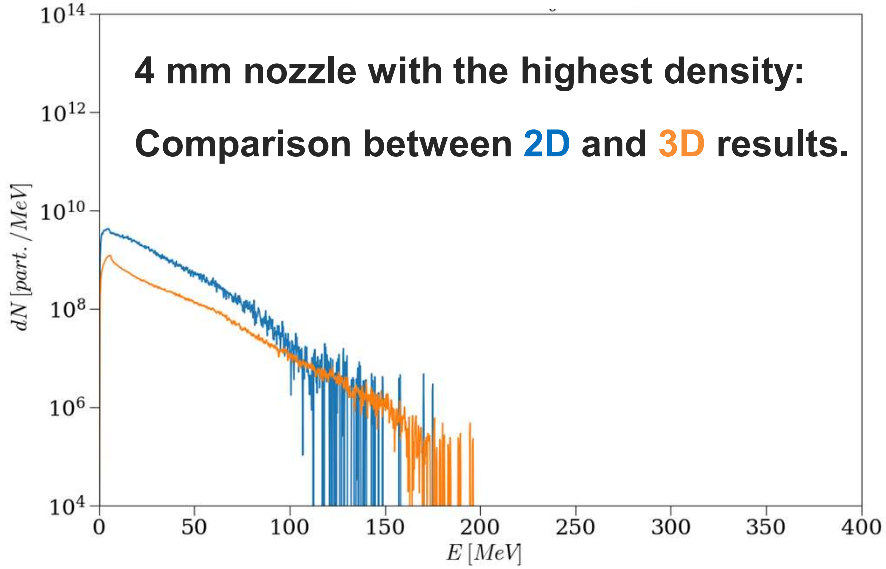
Lower plasma density:

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

Electron beam spectrum

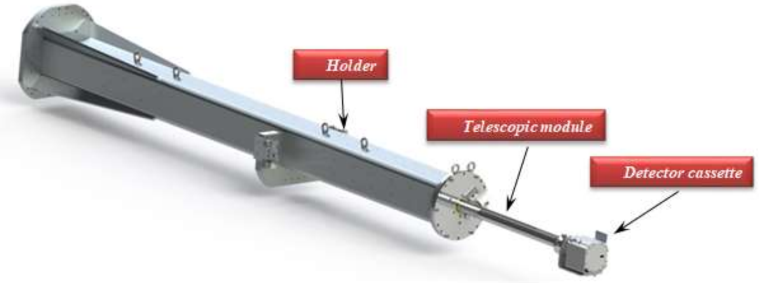
- Higher electron energies obtained with the 10 mm nozzle (up to 300 MeV)
- Lower beam charges obtained with the lower plasma densities





Experimental results

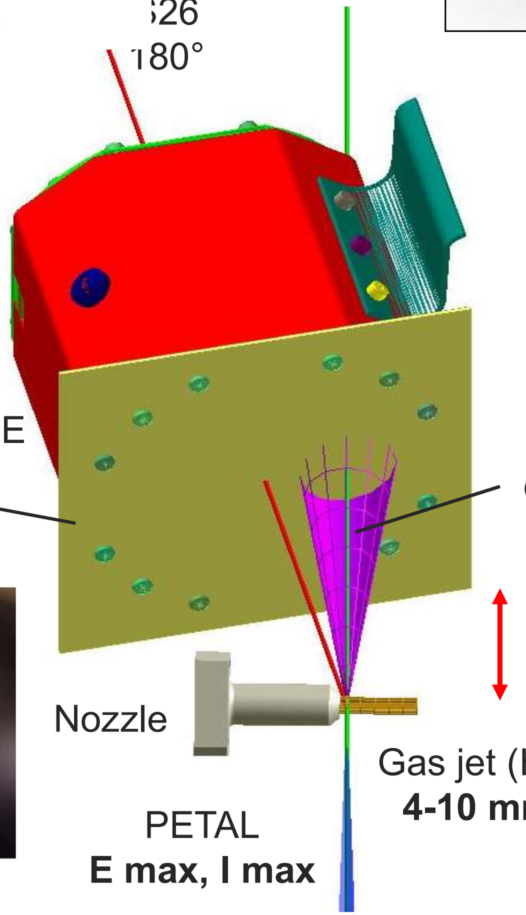
Overview of the experimental configuration



SESAME1
166.5°
@ 6.18 m

CRACC cassette with SESAME line-of-sight (CRACC in S26)

IP stack with SESAME line-of-sight



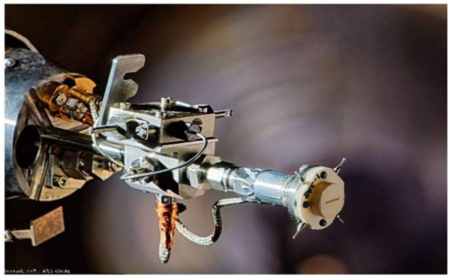
Electron beam divergence
≈ 100 mrad

10 cm

Nozzle

Gas jet (He)
4-10 mm

PETAL
E max, I max



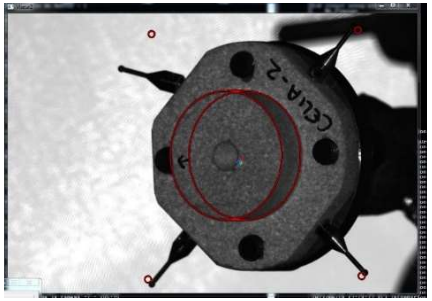
Diagnostics	
SESAME1	Magnetic spectrometer: e- spectrum
	Bremsstrahlung canon: betatron spectrum
CRACC-IP	IP stack: electron beam spatial profile + charge
CRACC-ACTIVATION	**Activation samples (In, Fe, Zr) inside the CRACC cassette**
TWIST	3w imaging

PETAL request	
Pulse length	Minimum duration (0,7 ps)
Energy	Maximum (350-400 J)
Intensity	Maximum (5x10^{18}-10^{19} W/cm²)
Pointing	**Transversal:** 3 mm from nozzle exit **Longitudinal:** 0.5 mm after half of the rising edge of the density profile

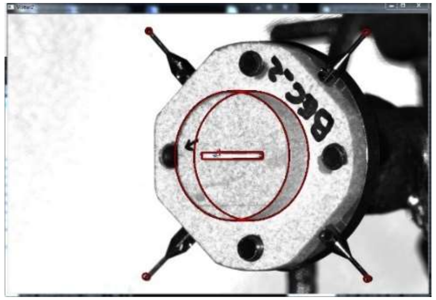
Nozzles and gas jet

- First-time ever gas jet (He) on LMJ-PETAL, with two different nozzles succesfuly fielded:

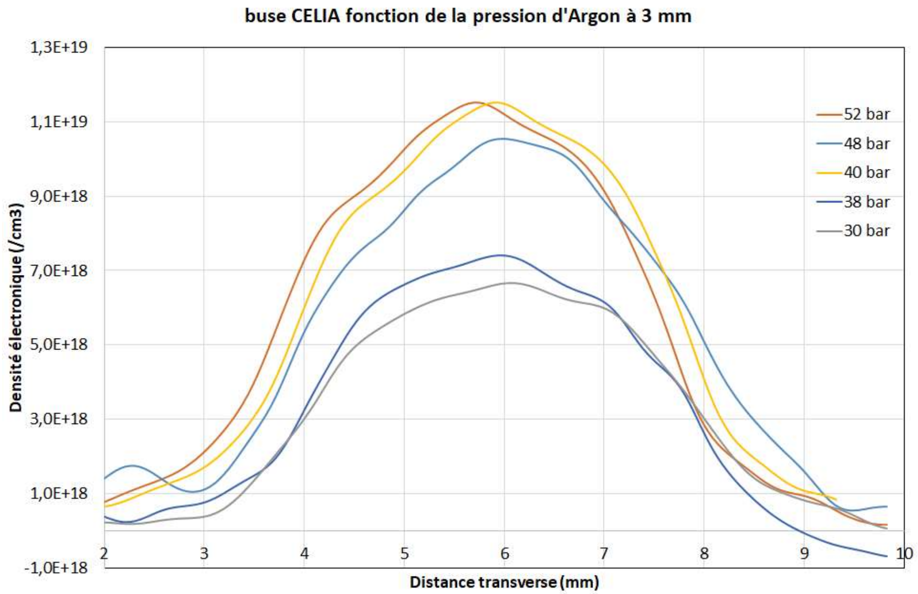
Cylindrical nozzle Ø 4mm

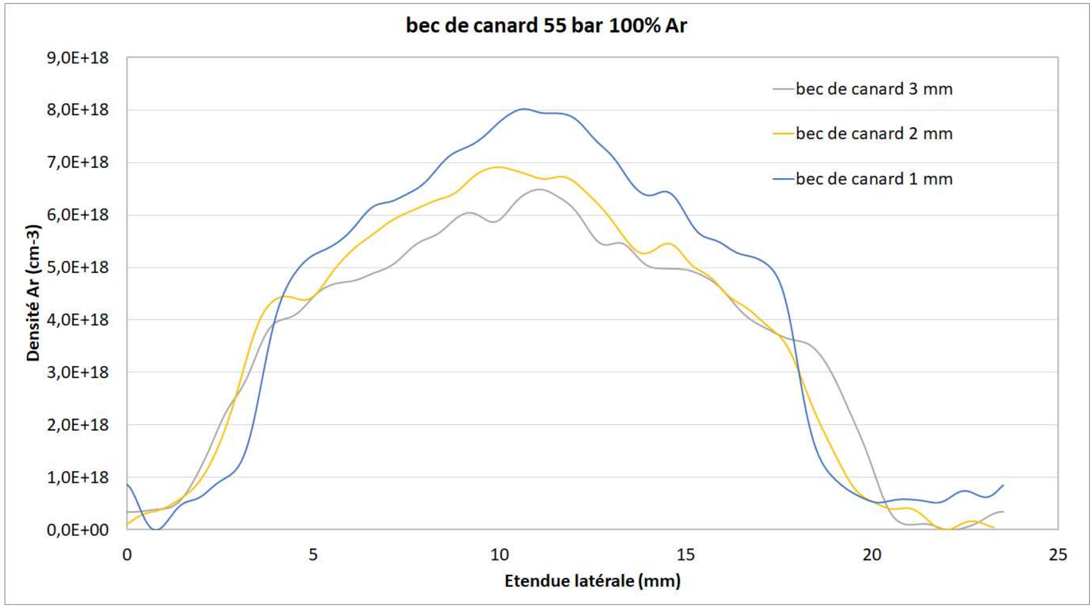


« Duck beak » nozzle 10mm x 1 mm



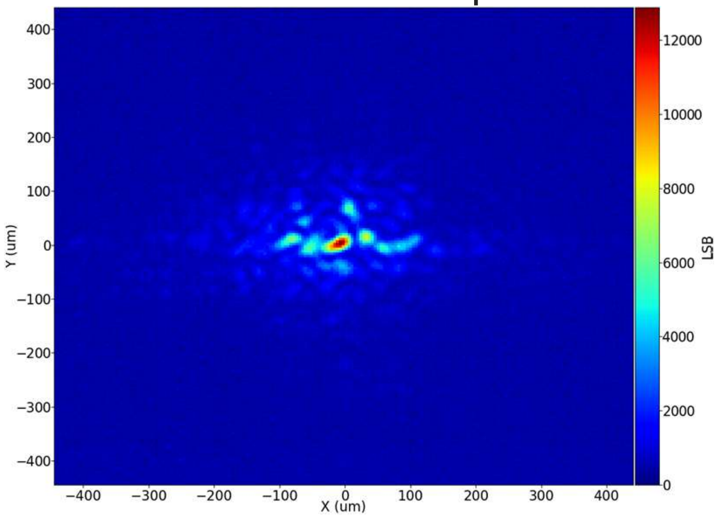
- Jet characterization at CEA-CESTA using argon gas and Mach-Zehnder interferometry for electron density measurements



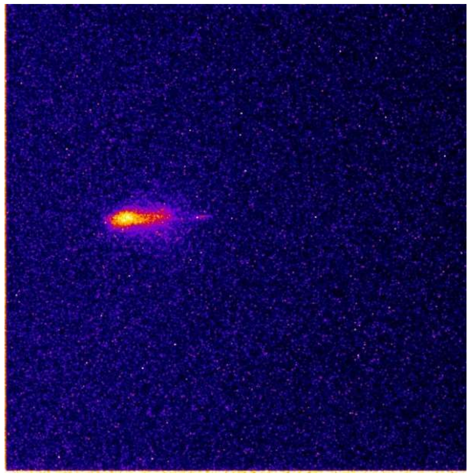


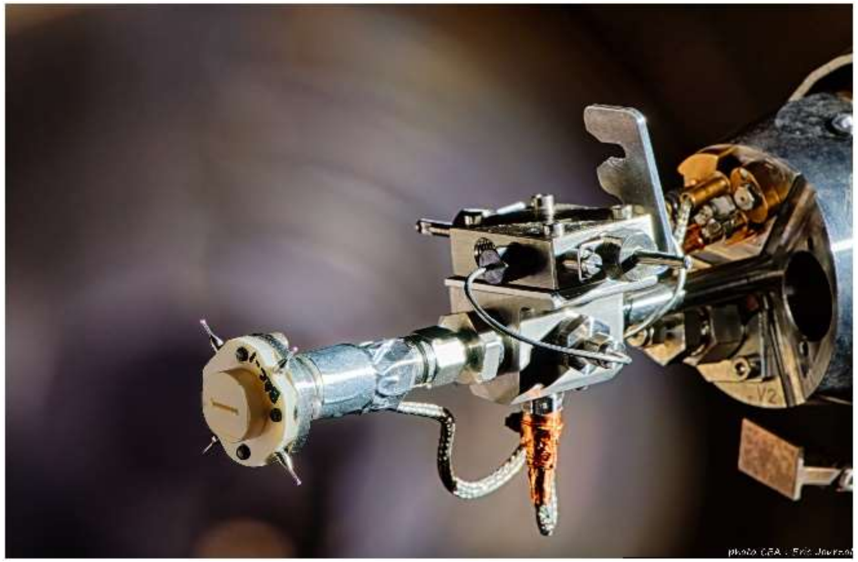
PETAL-jet interaction

PETAL focal spot



TWIST 3w emission





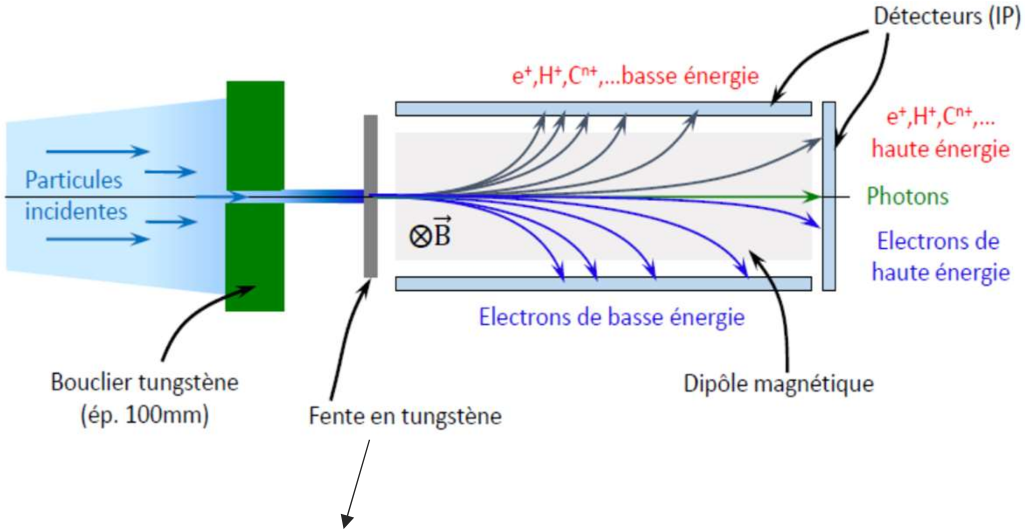
« Duck beak » nozzle and gas filling system

- The focal spot distribution varies from shot to shot and strongly impacts the results
- PETAL intensities ≈ 10^{18} – $5x10^{18}$ W/cm²
- Gas pressures of 55-60 bar were used for obtaining electron densities ≈ 10^{-19} cm^{-3}
- Expected: electron energies of hundreds MeV, betatron energies of tens keV

Experimental configuration: SESAME1

SESAME1 provides 3 measurements:

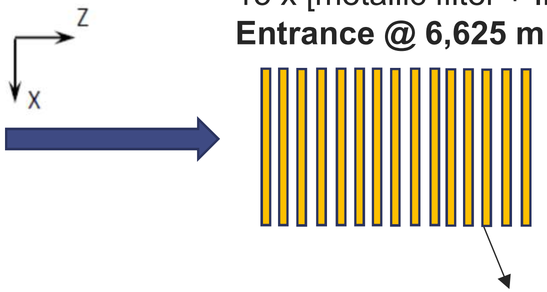
1. **IP electrons (MS type)** -> main measurement: electron spectrum **in principle between 5 and 150 MeV**
2. **IP protons (MS type)** -> not useful here
3. **Canon Bremsstrahlung** -> measurement of the X spectrum (betatron if any)



Entrance slit:

- **Dimensions 5 mm x 5 mm (maximum aperture)**
- **Thickness 29 mm**
- **Distance from TCC = 6,180 m**

Bremsstrahlung canon:
15 x [metallic filter + IP MS]
Entrance @ 6,625 m from TCC



Filter stack

Numéro du filtre	Matériau	Densité (g/cm³)	Epaisseur (mm)
1	Al	2,7	0,09
2	Ti	4,54	0,125
3	Fe	7,874	0,125
4	Cu	8,96	0,1
5	Mo	10,22	0,1
6	Ag	10,5	0,15
7	Sn	7,31	0,5
8	Ta	16,65	0,5
9	Au	19,3	1,5
10	Pb	11,35	1
11	Pb	11,35	2
12	Pb	11,35	3
13	Pb	11,35	4
14	Pb	11,35	6
15	Pb	11,35	6

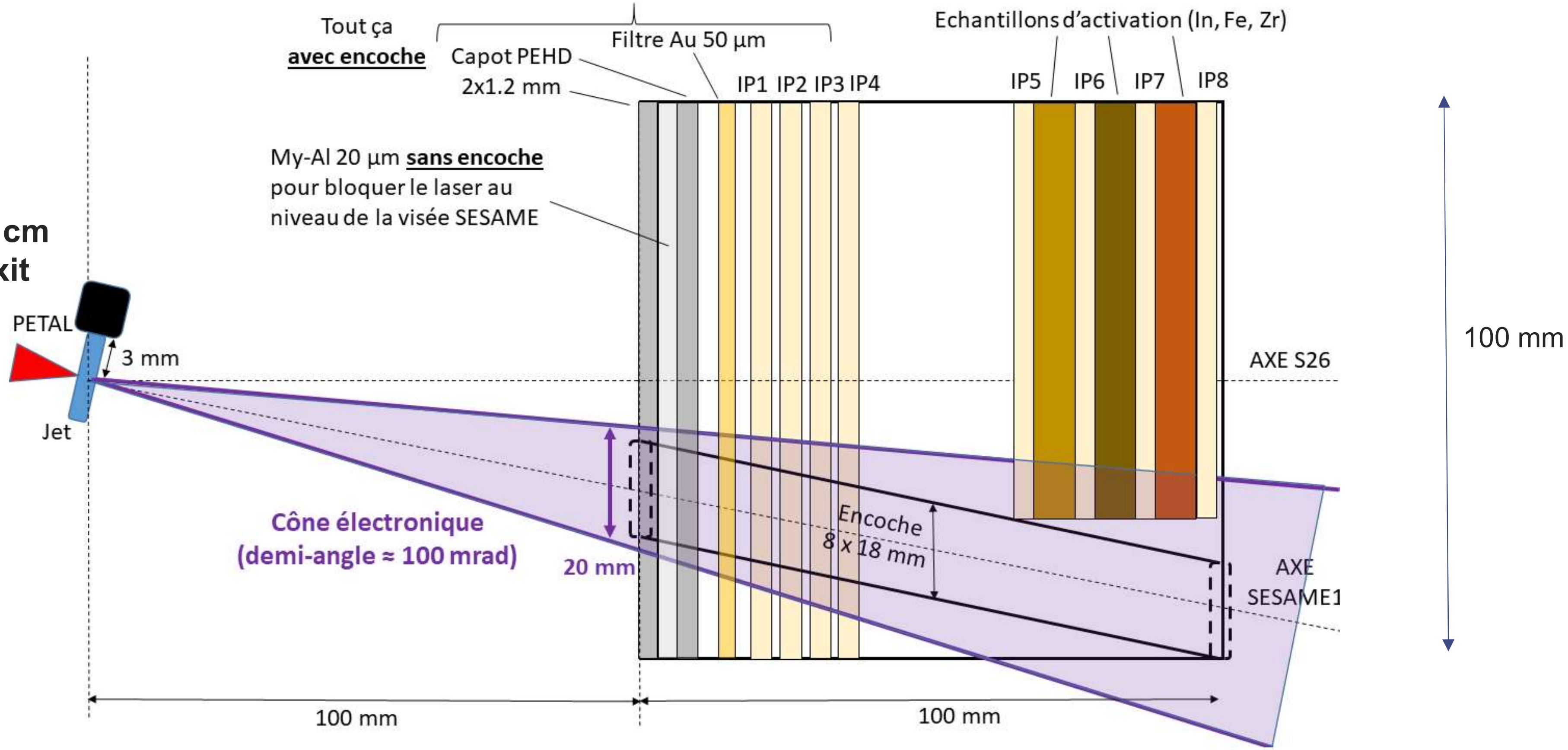
Tableau 1 : Empilement "Haute énergie"

Experimental configuration: CRACC cassette

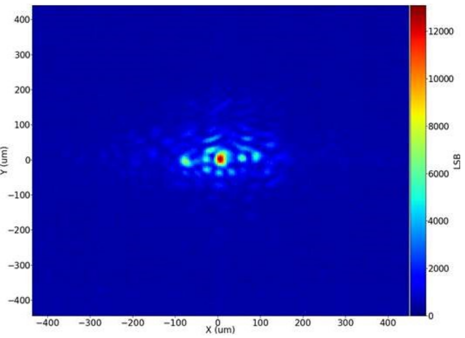
CRACC provides 3 measurements:

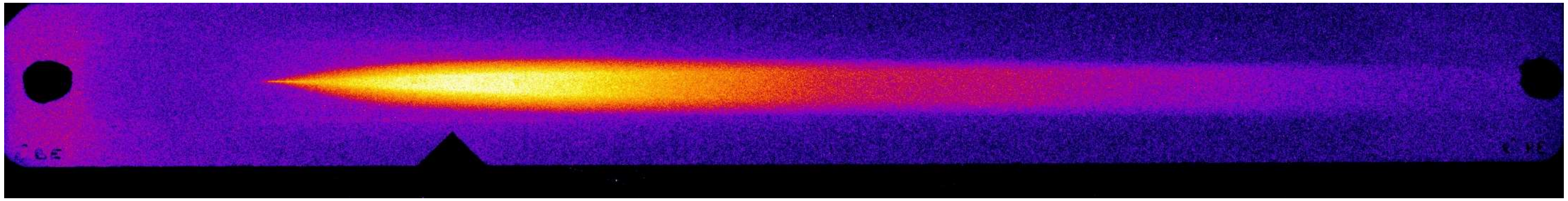
1. **IP stack on the cassette front** (IP1, IP2, IP3, IP4)
2. **IP stack on the cassette rear** (IP5, IP6, IP7, IP8)
3. **Activation measurements In, Fe, Zr**

PETAL pointing 3 cm from the nozzle exit



SESAME electron spectra – example shot 1



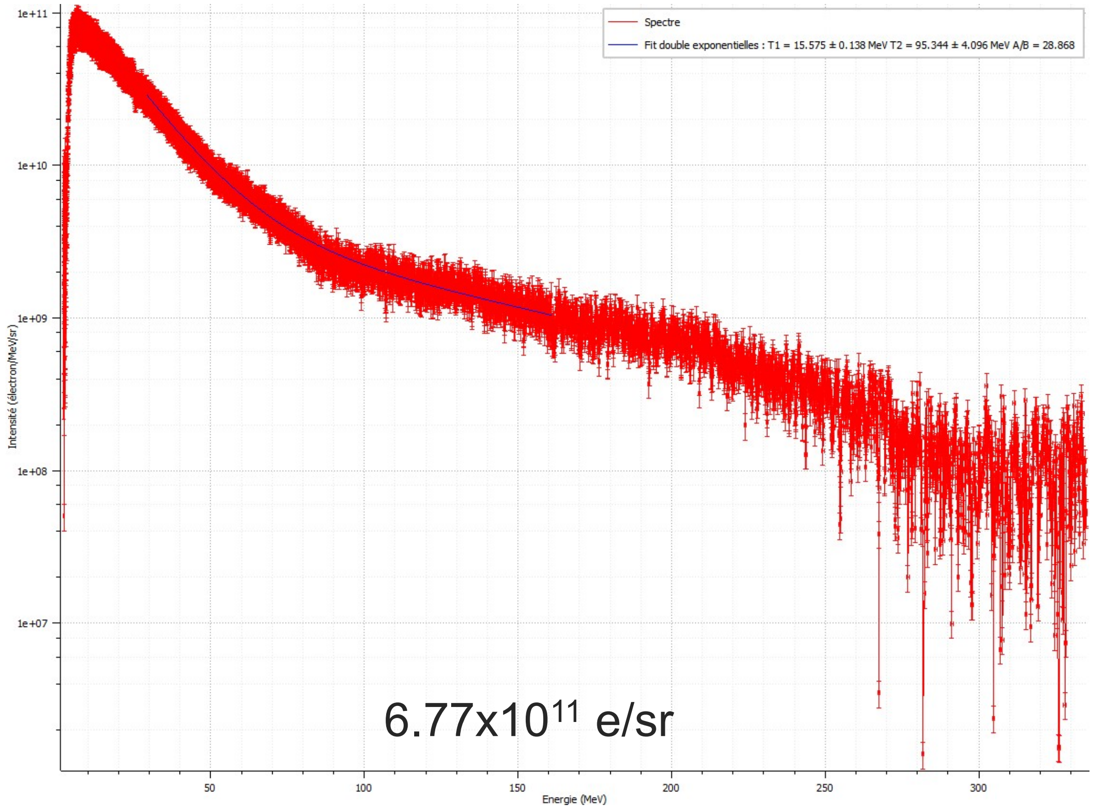


Energy

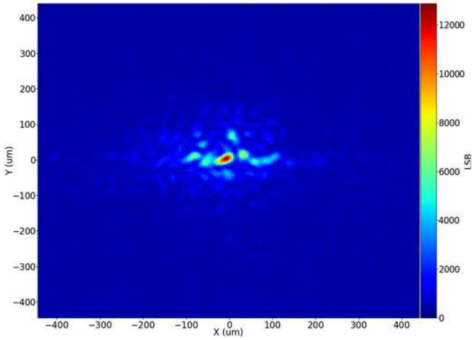
A max ≈ 10^{11} e/MeV/sr

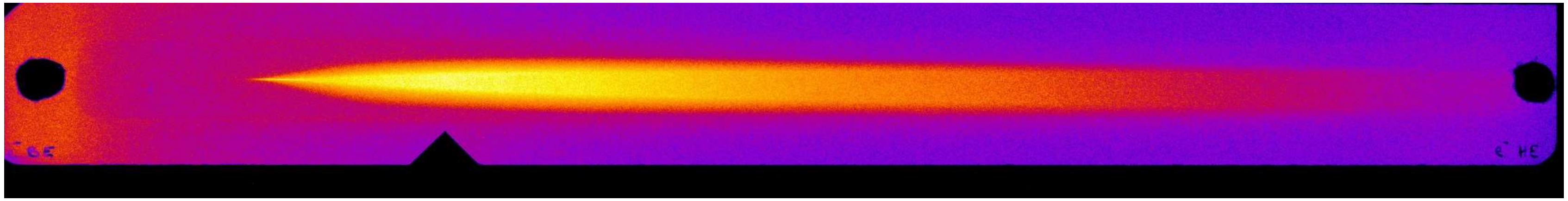
E max ≈ 150-200 MeV

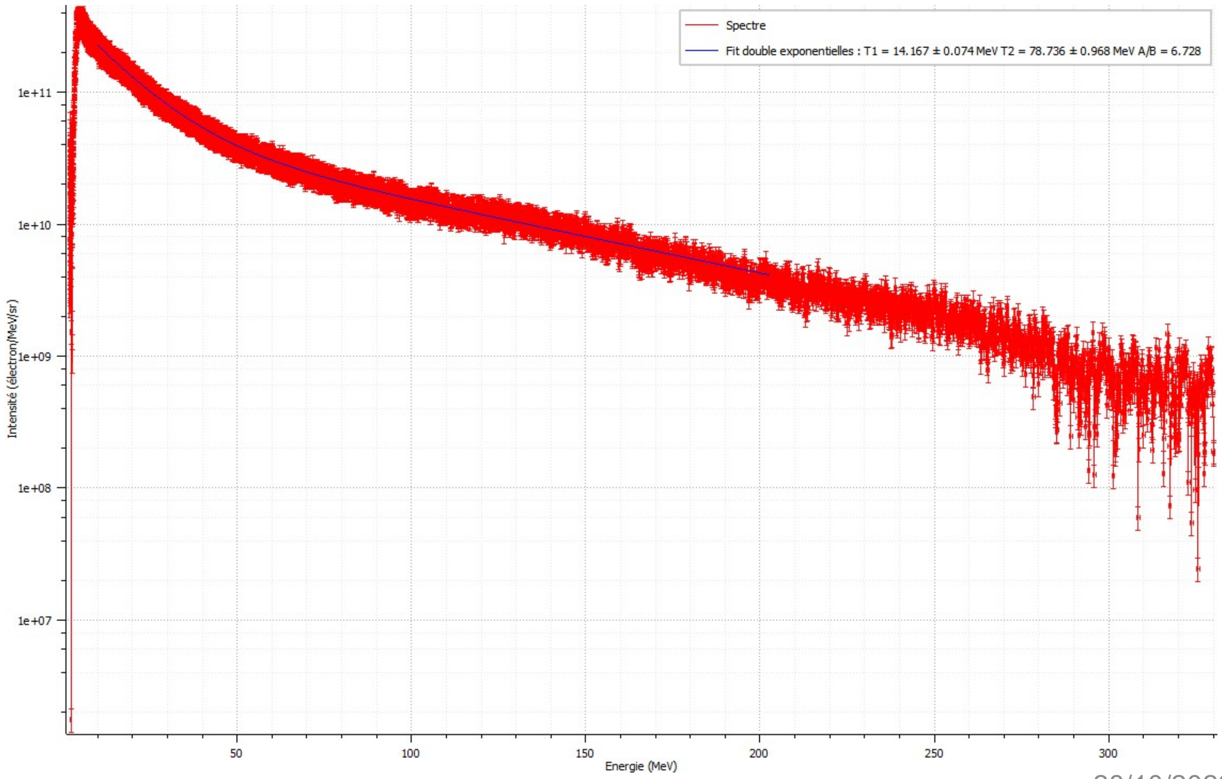
T1 = 16 MeV
T2 = 95 MeV



SESAME electron spectra – example shot 3





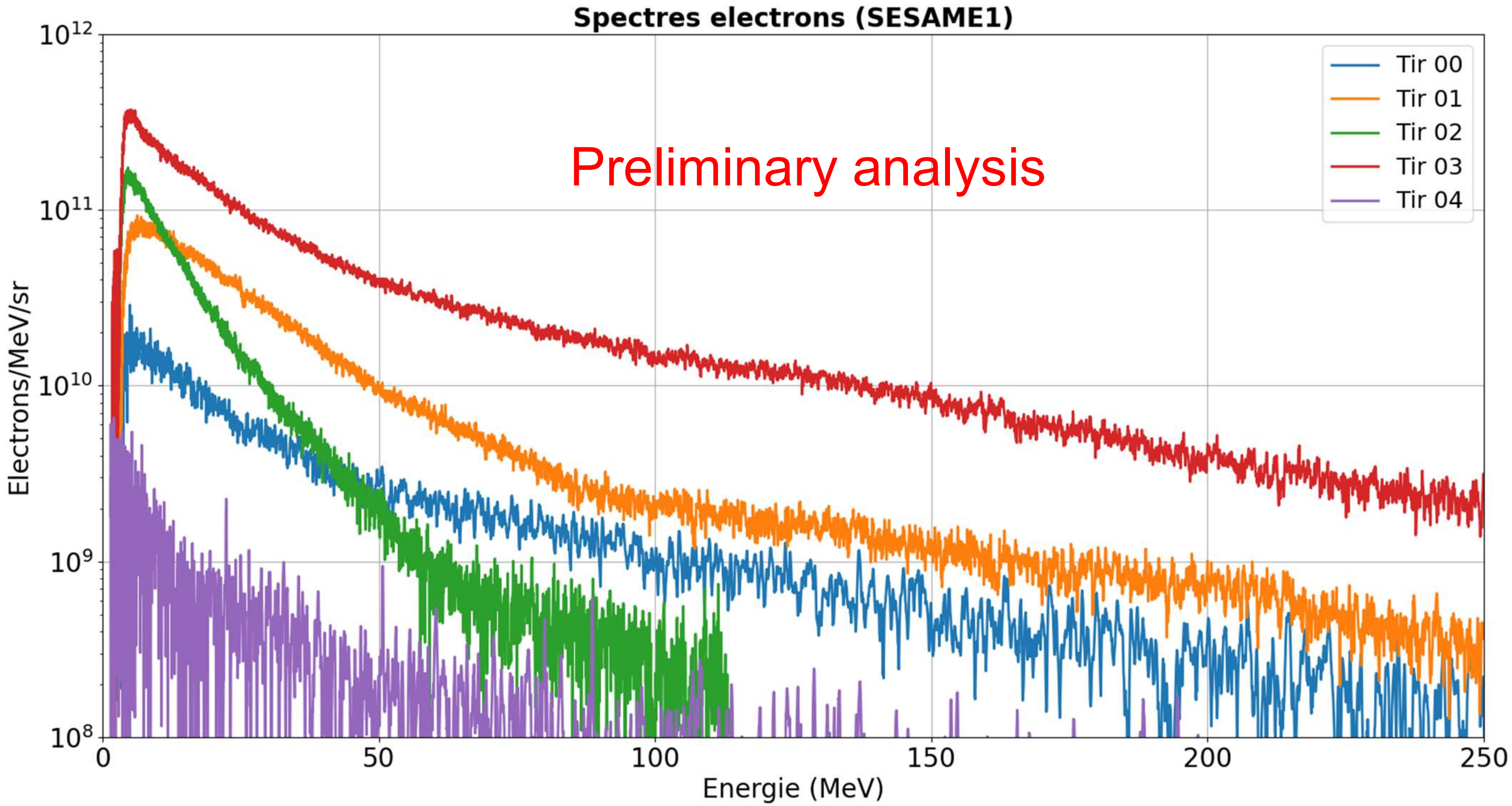


A max ≈ 4×10^{11} e/MeV/sr

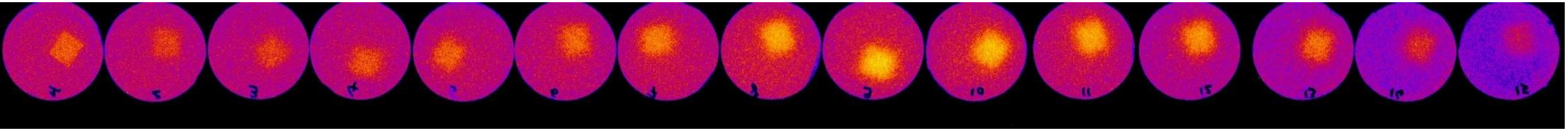
E max ≈ 250 MeV

T1 = 14 MeV
T2 = 79 MeV

Electron spectra - overview



Bremsstrahlung canon

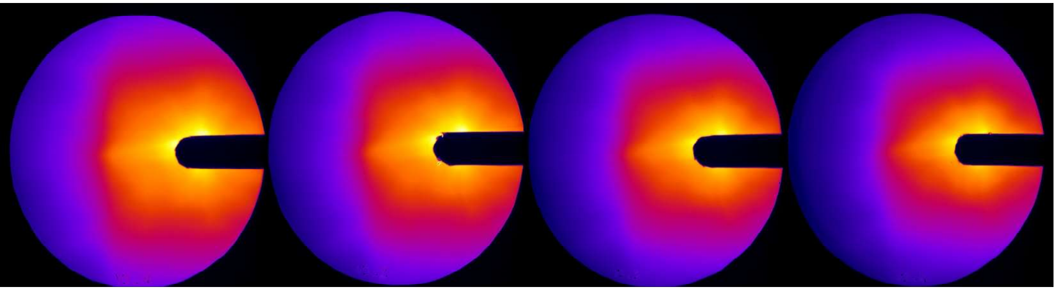


- Strong signals on all IP, most intense from 8th-9th IP
- Square shape comes from entrance slit 5x5 mm
- Not characteristic of betatron -> simulations ongoing to understand these signals
  - Bremsstrahlung noise arriving on SESAME ?
  - Pairs @511 keV generated by interaction between Bremsstrahlung avec high-Z filters within the canon filter stack ?

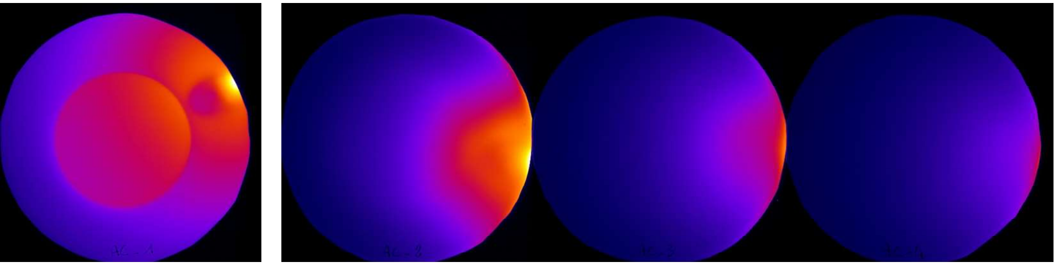
Beam profiles on CRACC

Shot 1

IP 1-2-3-4

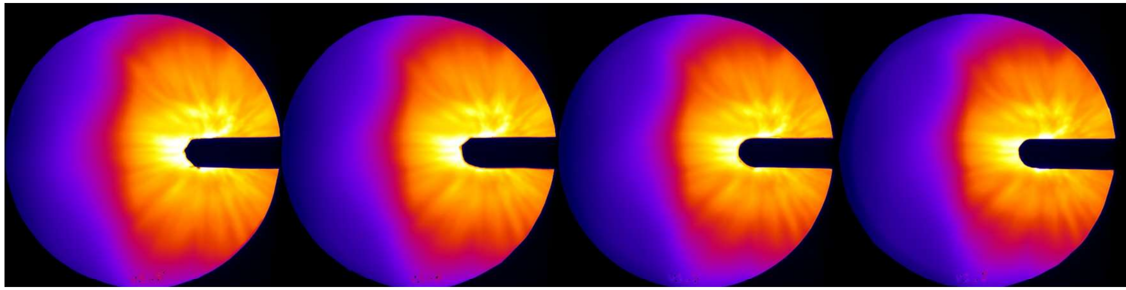


IP 5-6-7-8

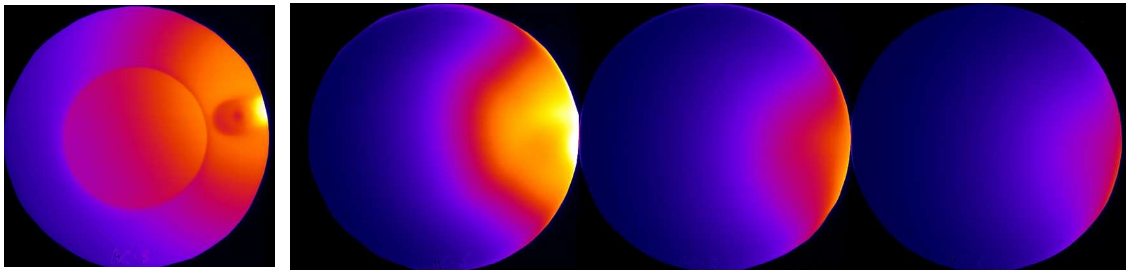


Shot 3

IP 1-2-3-4



IP 5-6-7-8



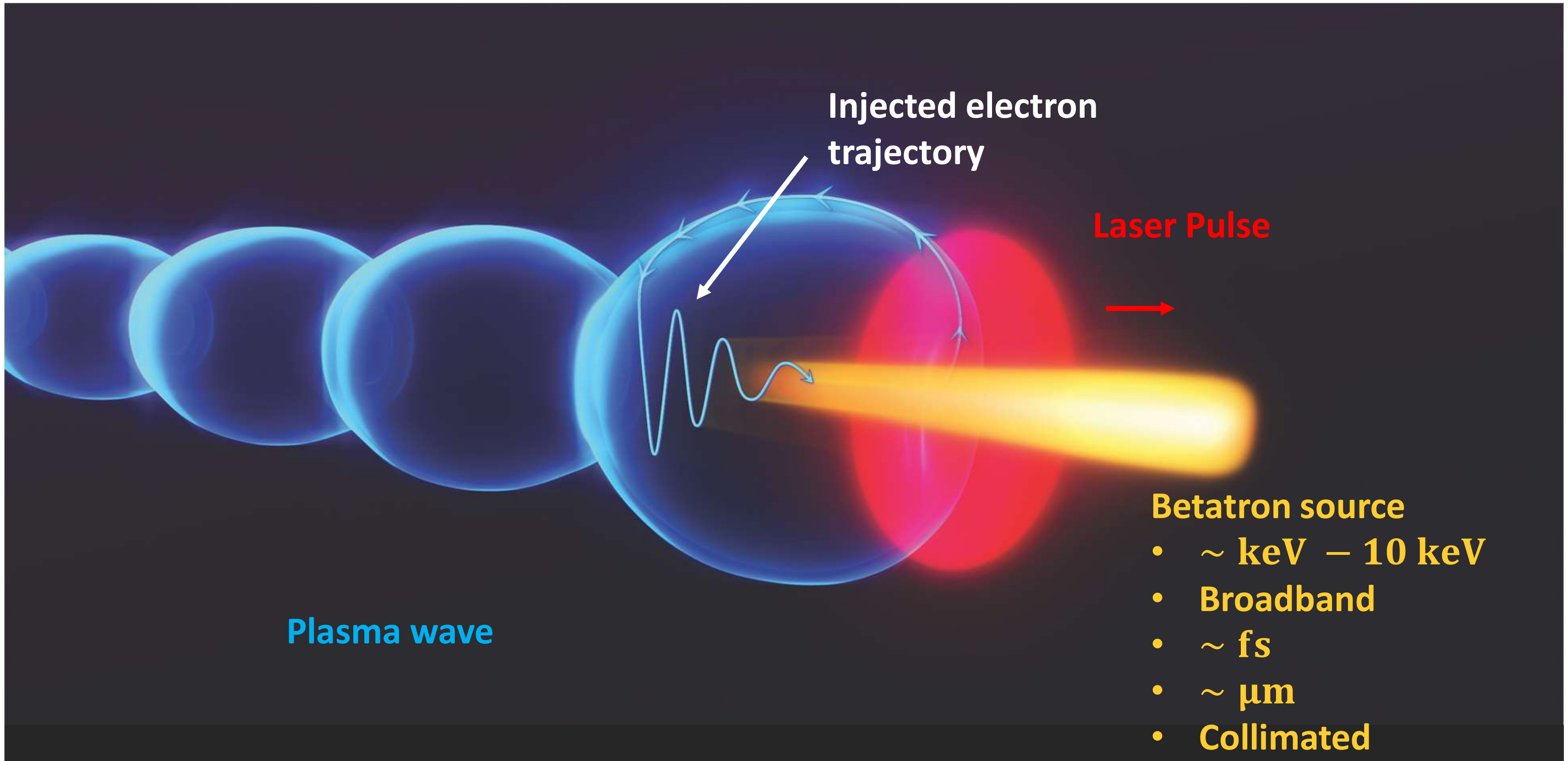
Ongoing analysis to deduce the beam charge

Conclusions

- Gas jet successfully tested on LMJ-PETAL
- Successful SESAME and CRACC measurements of electron spectra and spatial profiles
- Electronic spectra seem to exceed 200-250 MeV, results to be confirmed
- Spatial measurements obtained with CRACC give access to the total generated electronic charge
- Interesting activation measurements for complementary electron spectrum information, ongoing analysis

- Future work possibilities:
    - Betatron measurements (need of a detector closer to the target chamber center)
    - Higher electron energies (PETAL energy upgrade, SESAME magnet upgrade)
    - Application of electron beam for Bremsstrahlung (γ sources) and pair creation
    - Application of betatron radiation for X-ray radiography, contrast imaging,…

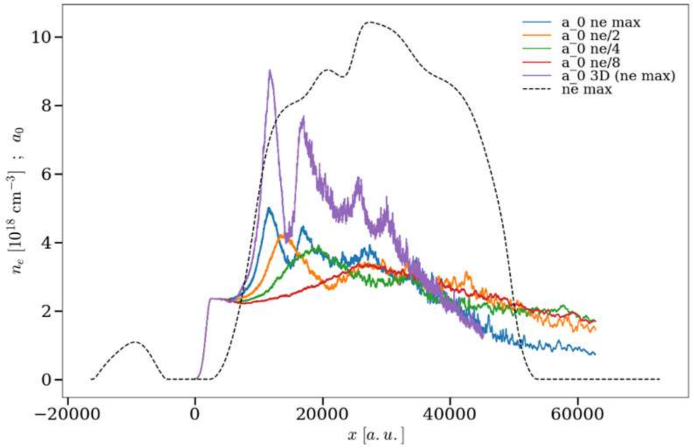
Betatron source principle



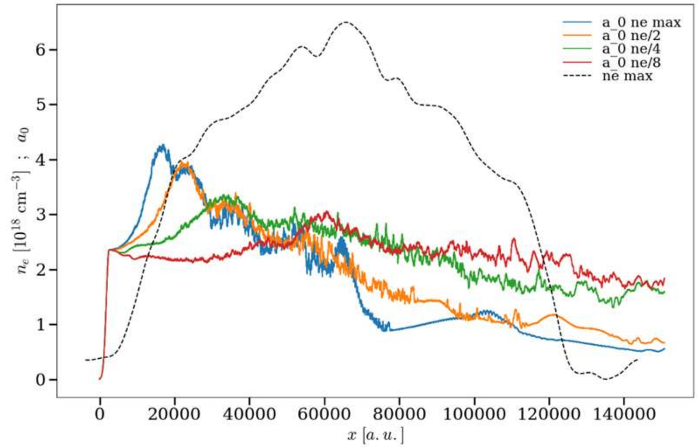
F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)

Laser self-focusing and energy depletion

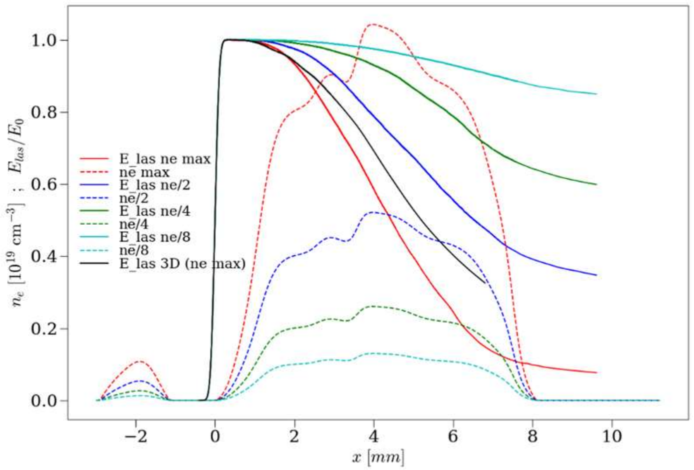
a_0 – 4 mm nozzle



a_0 – 10 mm nozzle



Laser energy – 4 mm nozzle



Laser energy – 10 mm nozzle