Настольные лазерно-плазменные ускорители электронов и их применение

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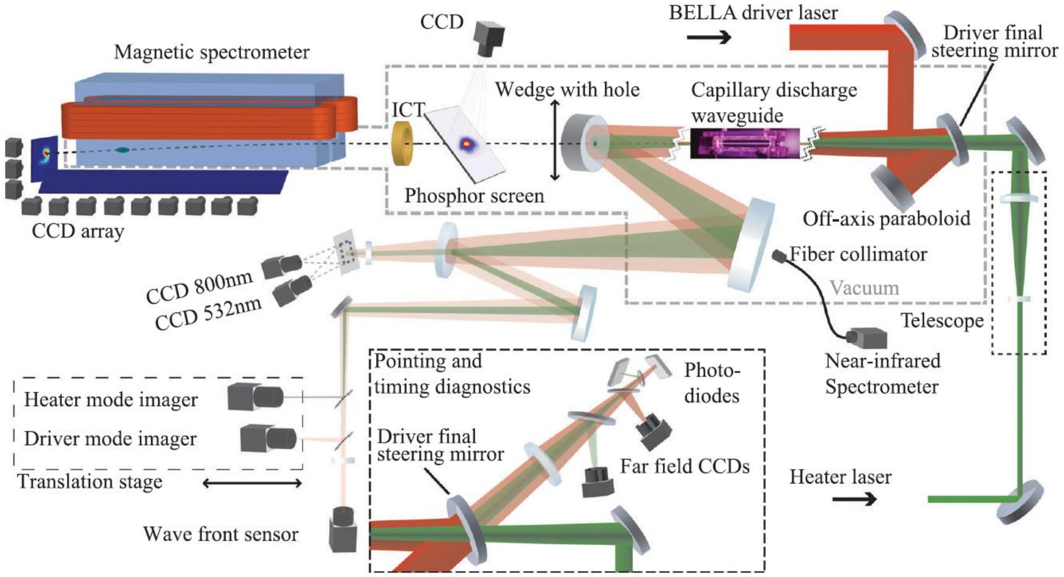
План

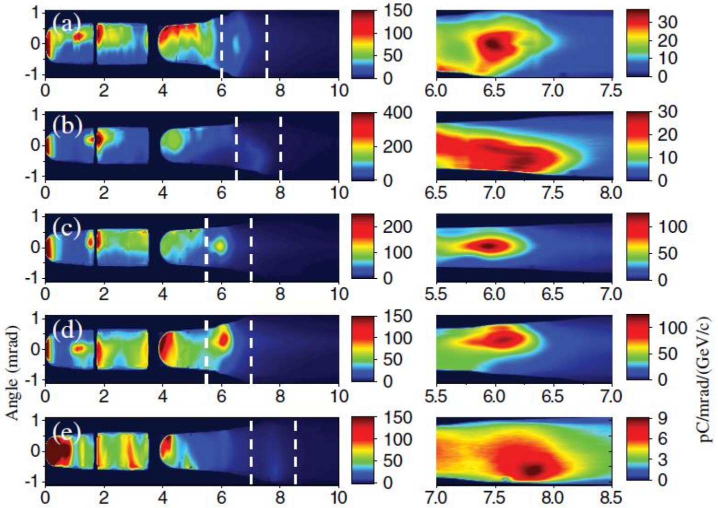
- *Что дает лазерное ускорение?*
- *Ускорение с использованием взрывающейся тонкой пленки*
- *Ускорение в газовой струе с использованием ударной волны*
- *Фотоядерные реакции*
- *Когерентное переходное излучение электронного пучка*

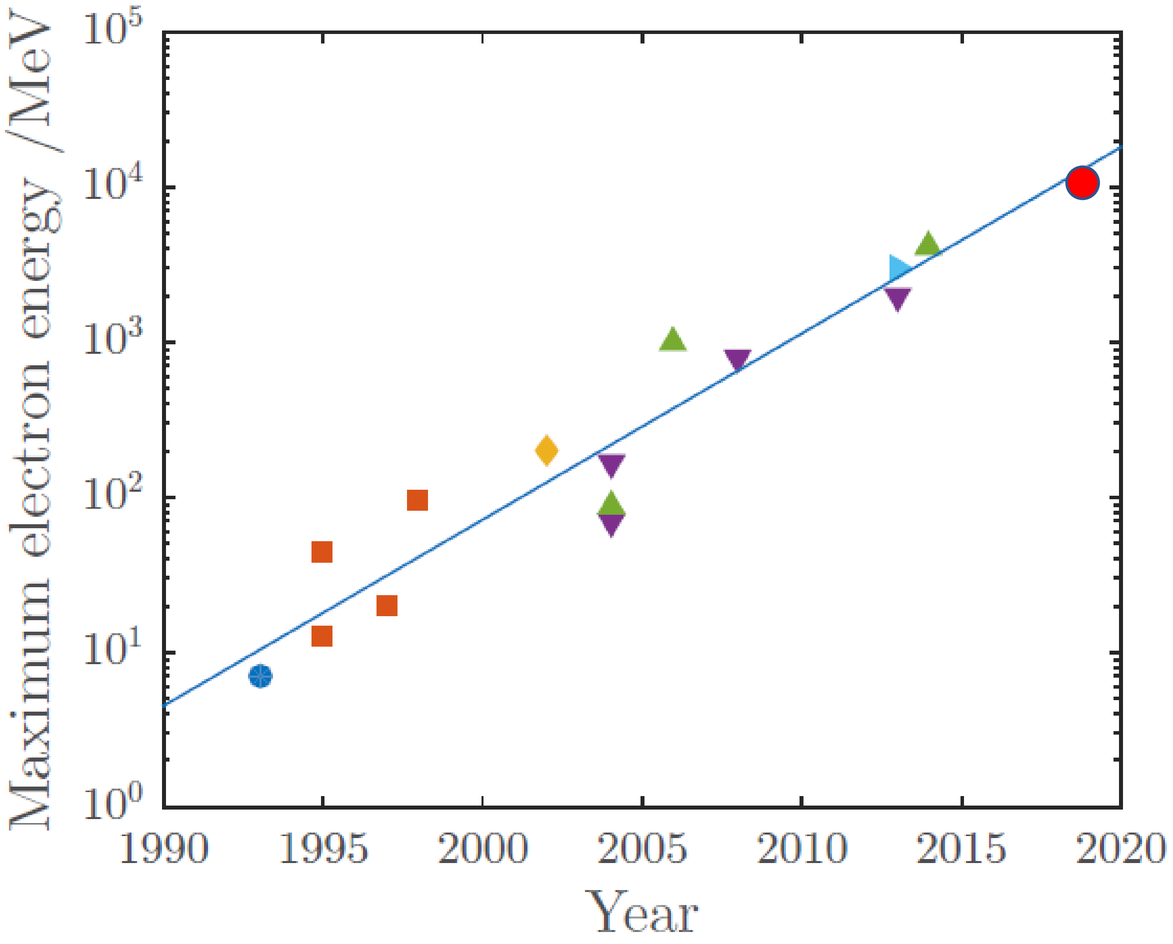
8 GeV monoenergetic



35 fs, 31 J, 850 TW, a_0=2.2

20 cm acceleration length in capillary





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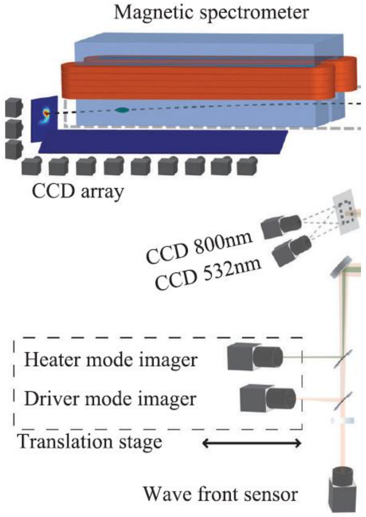

35 fs, 31 J, 850
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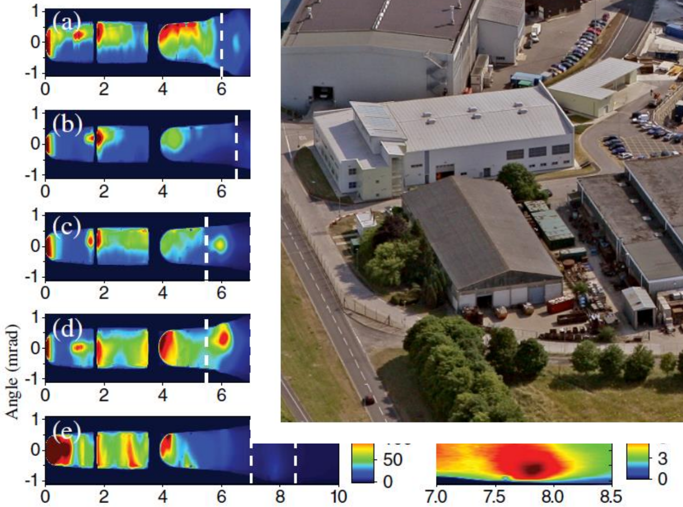
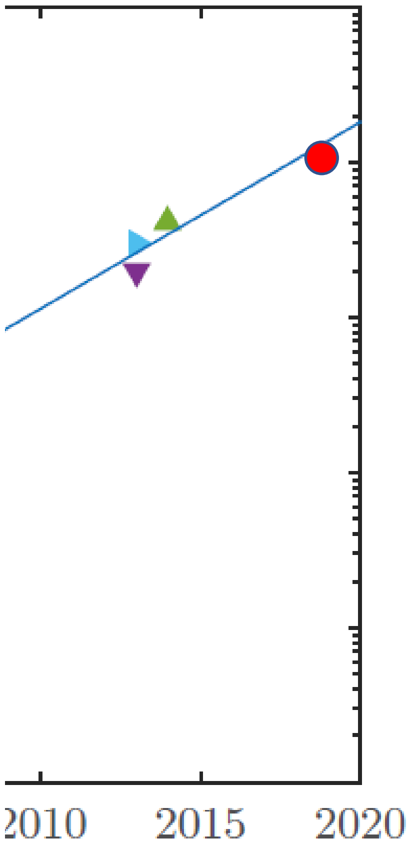


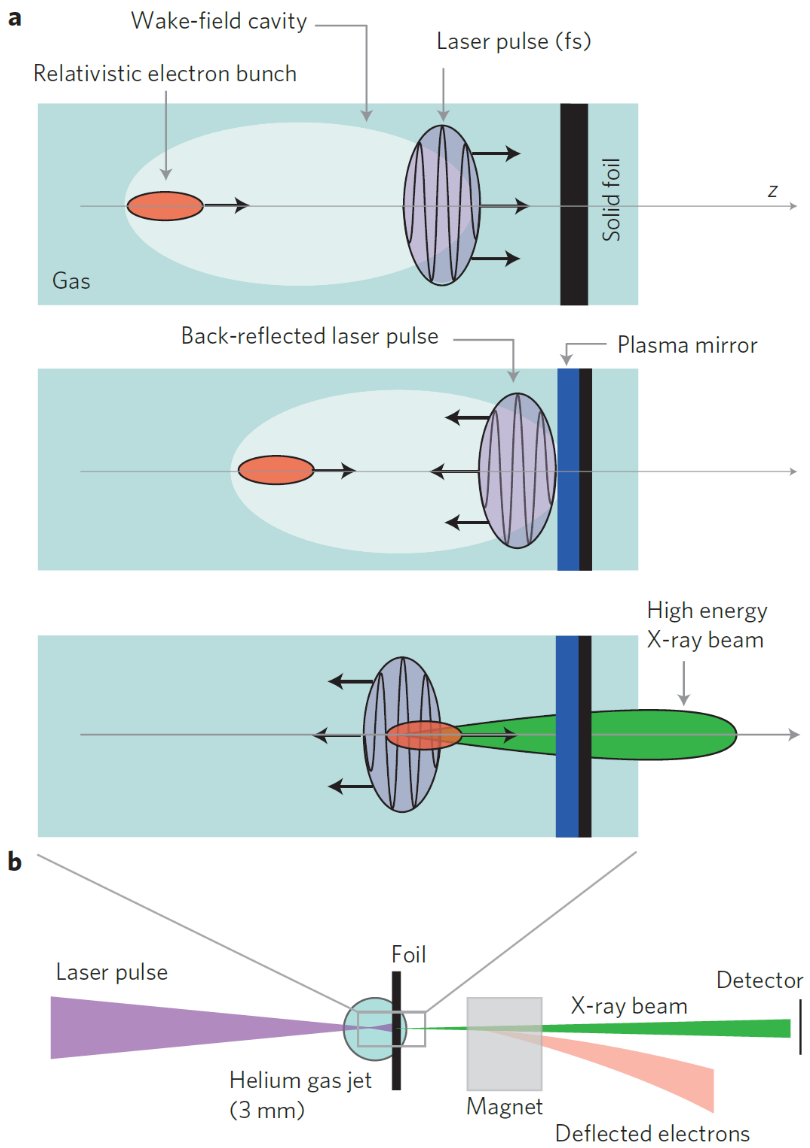
Rutherford Appleton Laboratory

Diamond light source
£300 million
3 GeV
4 football pitches

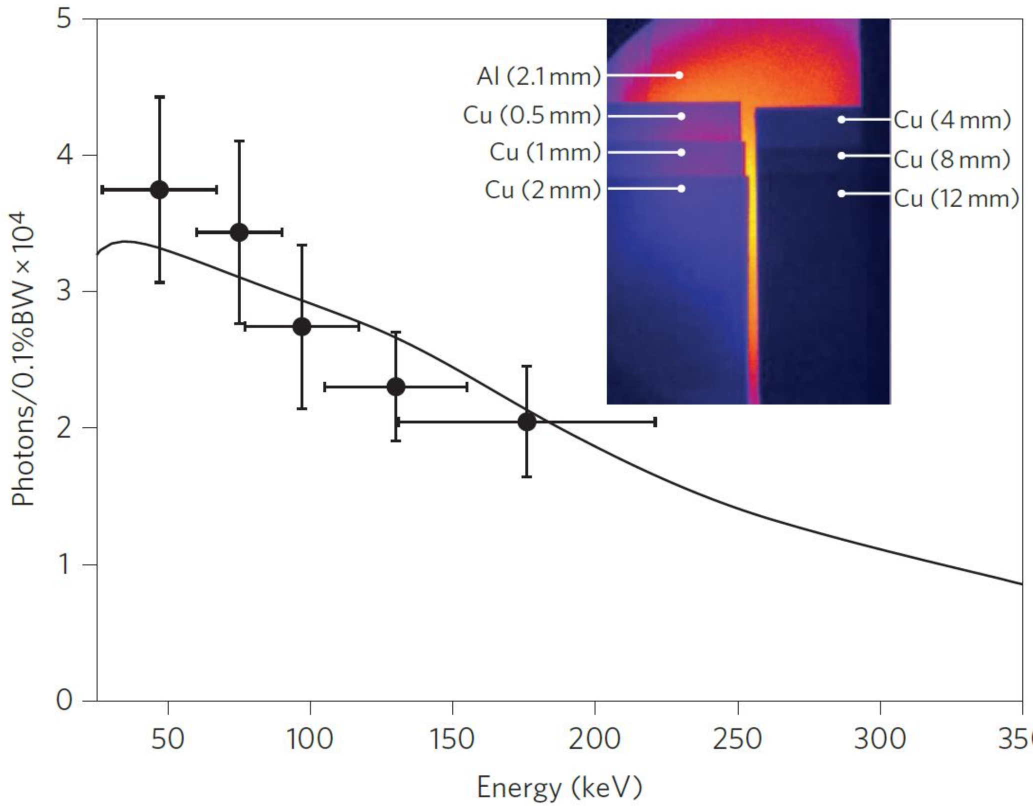
Astra-Gemini laser
£5 million
2 GeV
1 squash court



All-in-one laser Compton source



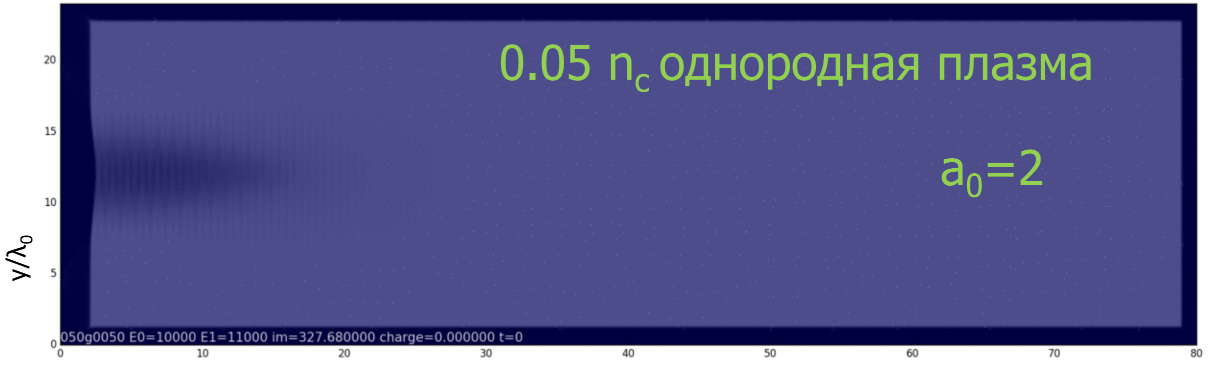
30 TW laser
100 MeV, 120 pC



X-ray source size – 1.5 μm

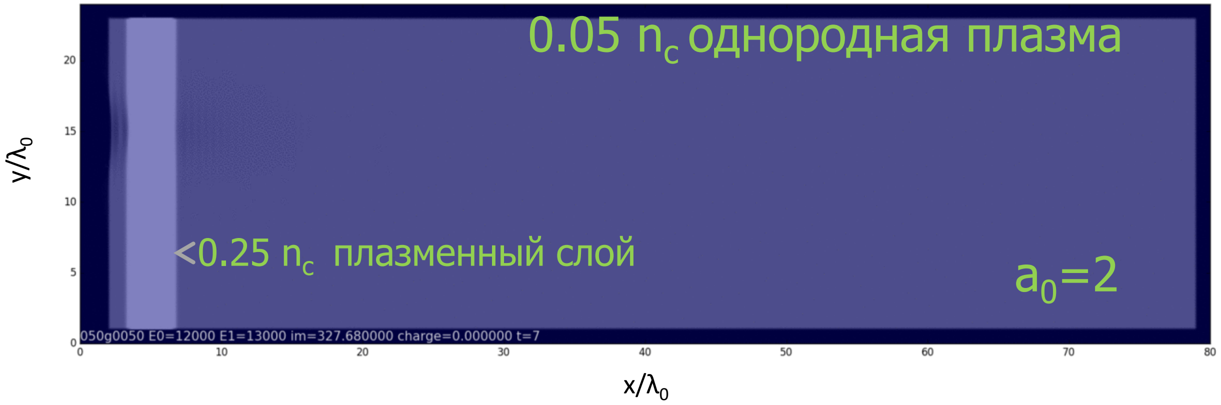
Ta Phuoc, K., Corde, S., Thaury, C. *et al.* All-optical Compton gamma-ray source. *Nature Photon* **6**, 308–311 (2012)

Формирование коллимированных электронных пучков с большим зарядом в режиме DLA



Белым показана электронная концентрация; нет электронов с энергиями >4mc^2

x/λ_0



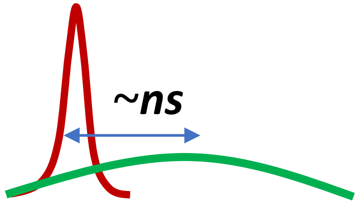
Белым показана электронная концентрация, красным – электроны с E>20mc^2

Схема с инжекцией в плазменный канал за счет распада волн параметрических неустойчивостей в тонком слое более плотной плазмы

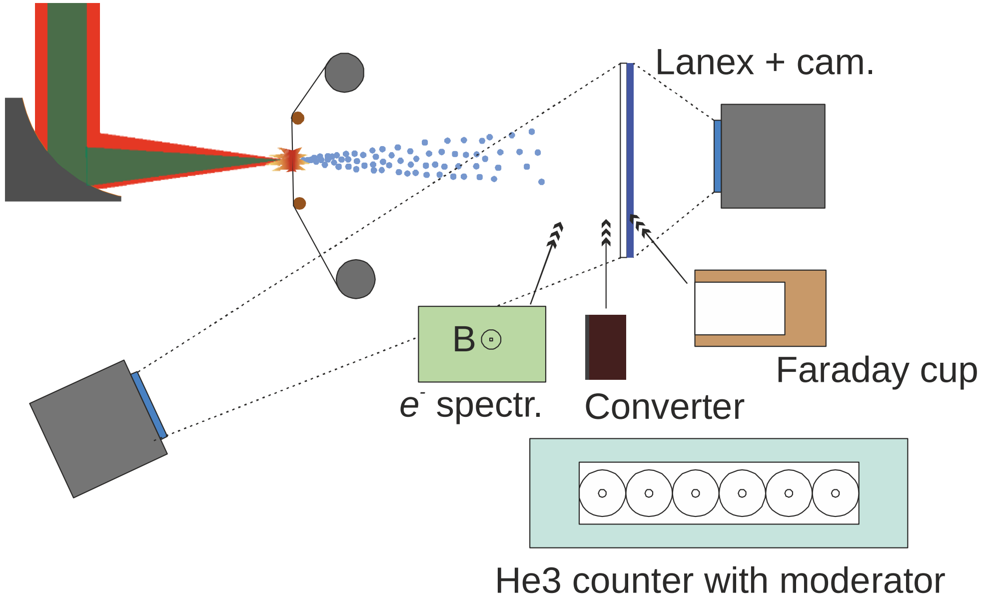
Plasma Phys. Control. Fusion. 2019. Vol. 61, № 7. P. 075016
Plasma Phys. Control. Fusion. 2021. Vol. 62, № 2. P. 02201
Physical Review E 2020, 102(6), 063206

e^- bunch generation with ablated tape target

Double-pulsed interaction with thin tape target



Nanosecond prepulse
1064 nm, 10 ns, I_{peak}~10^{13} W/cm^2
Femtosecond pulse:
50 fs, 1TW, I_{peak}=3-5x10^{18} W/cm^2



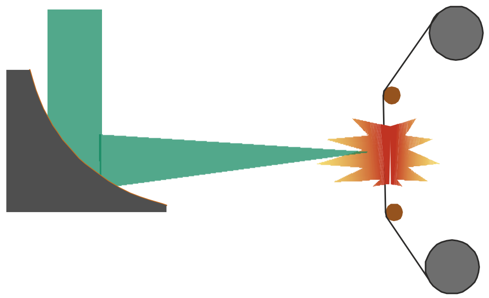
~15 micron thick rewindable tape

Ablation of tape target

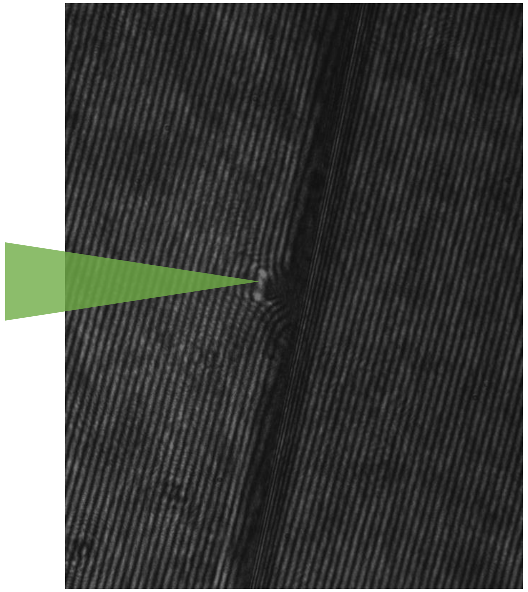
Plasma density profile evolution

Nanosecond prepulse

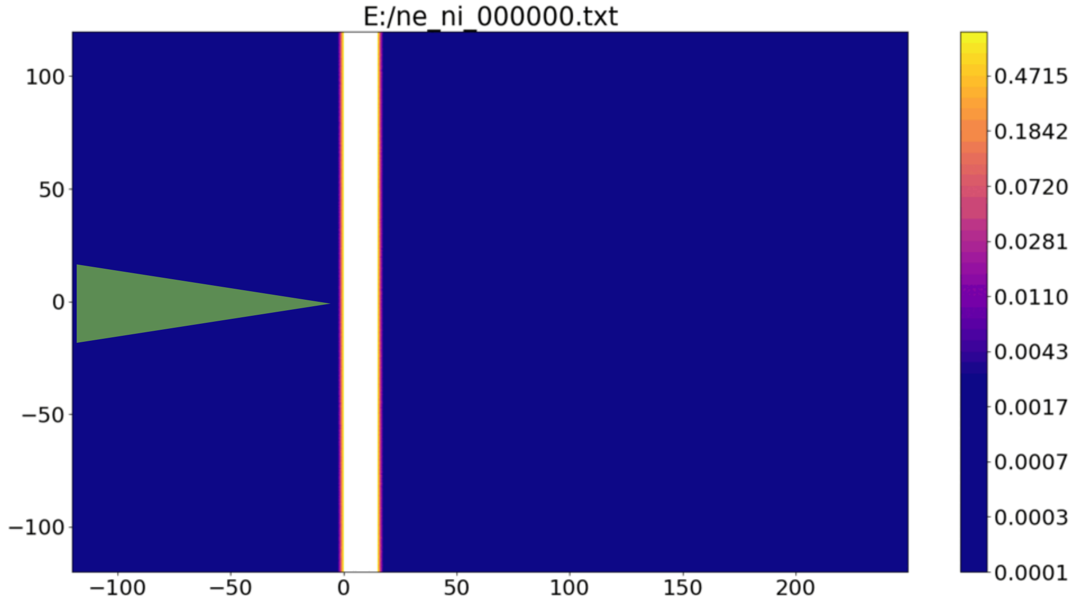
1064 nm, 10 ns, I_{peak}>10^{12} W/cm^2



Experiment



Hydrodynamic simulations



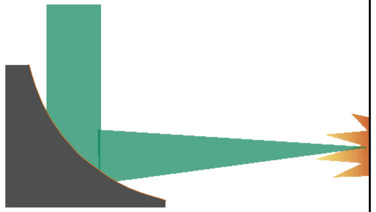
Ablation of tape target

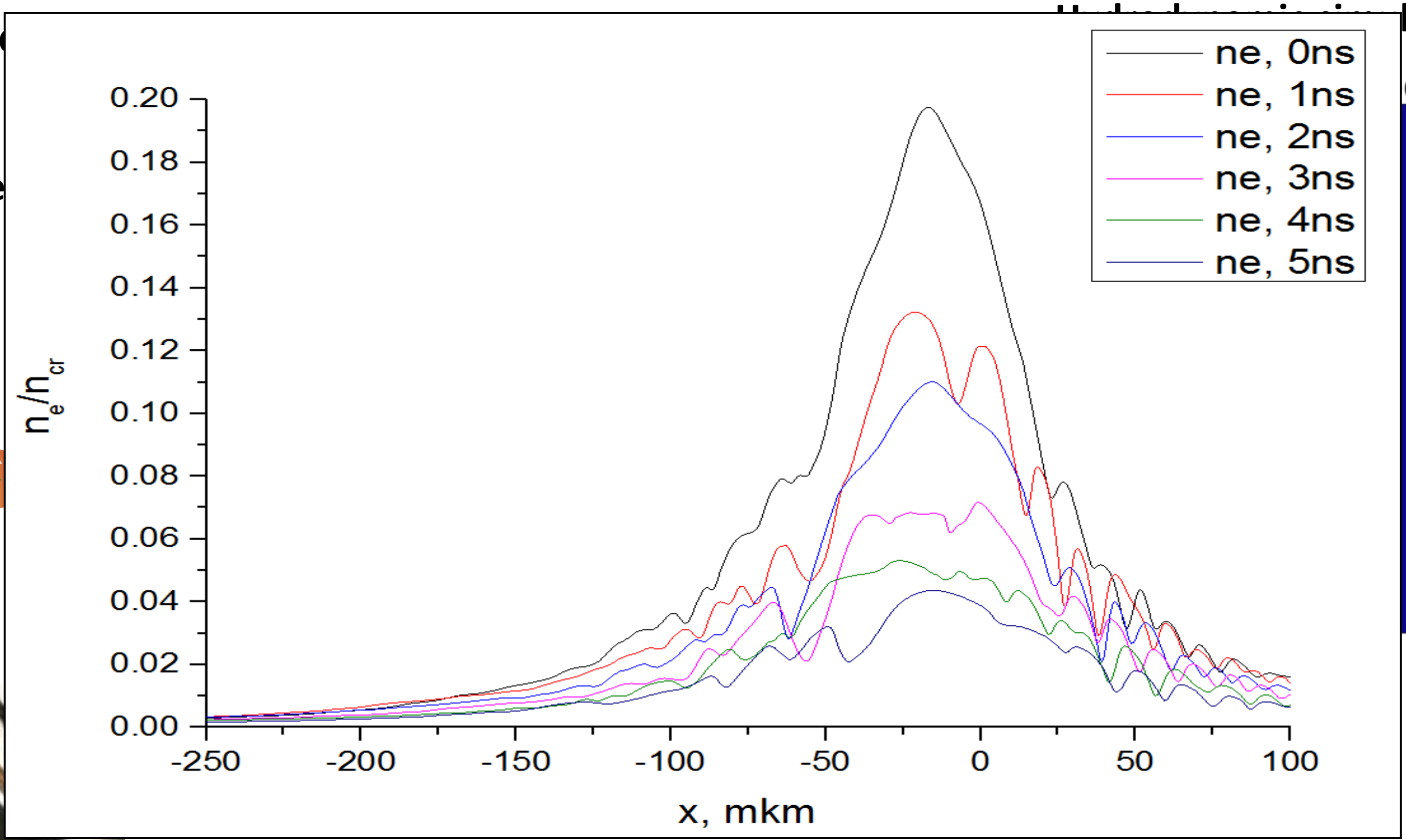
Plasma density profil

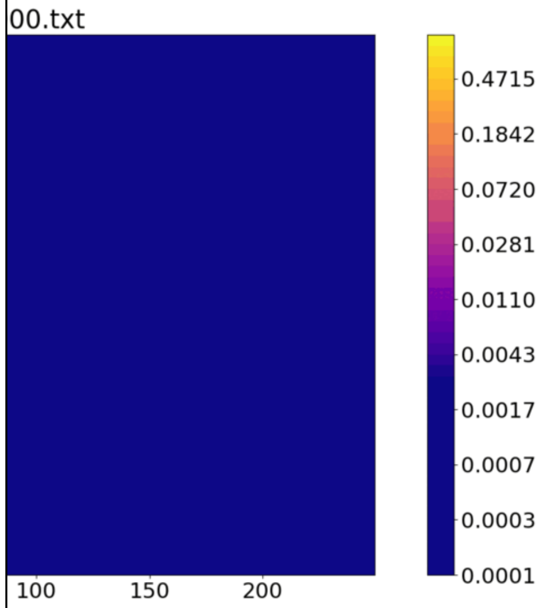
lations

Nanosecond prepulse

1064 nm, 10 ns, I_{peak}>



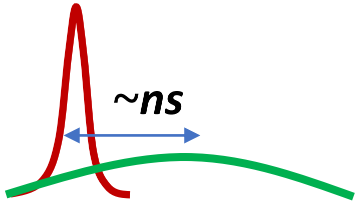




Evolution of axial density profile

e^- bunch generation with ablated tape target

Double-pulsed interaction with thin tape target



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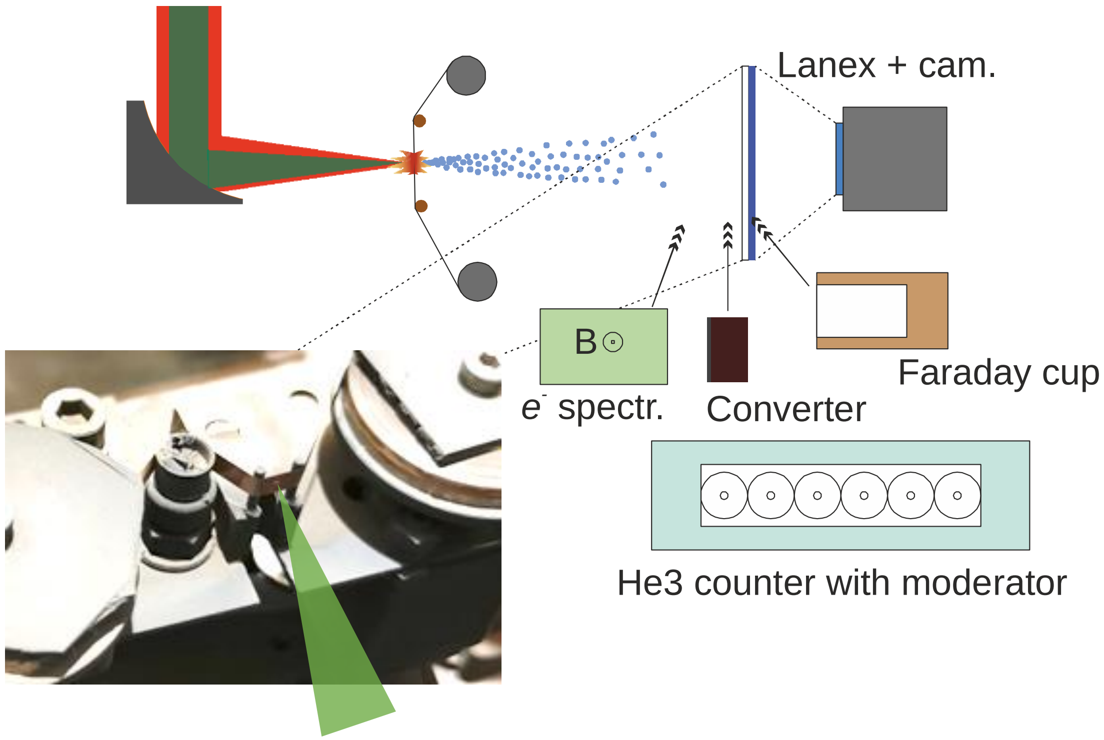
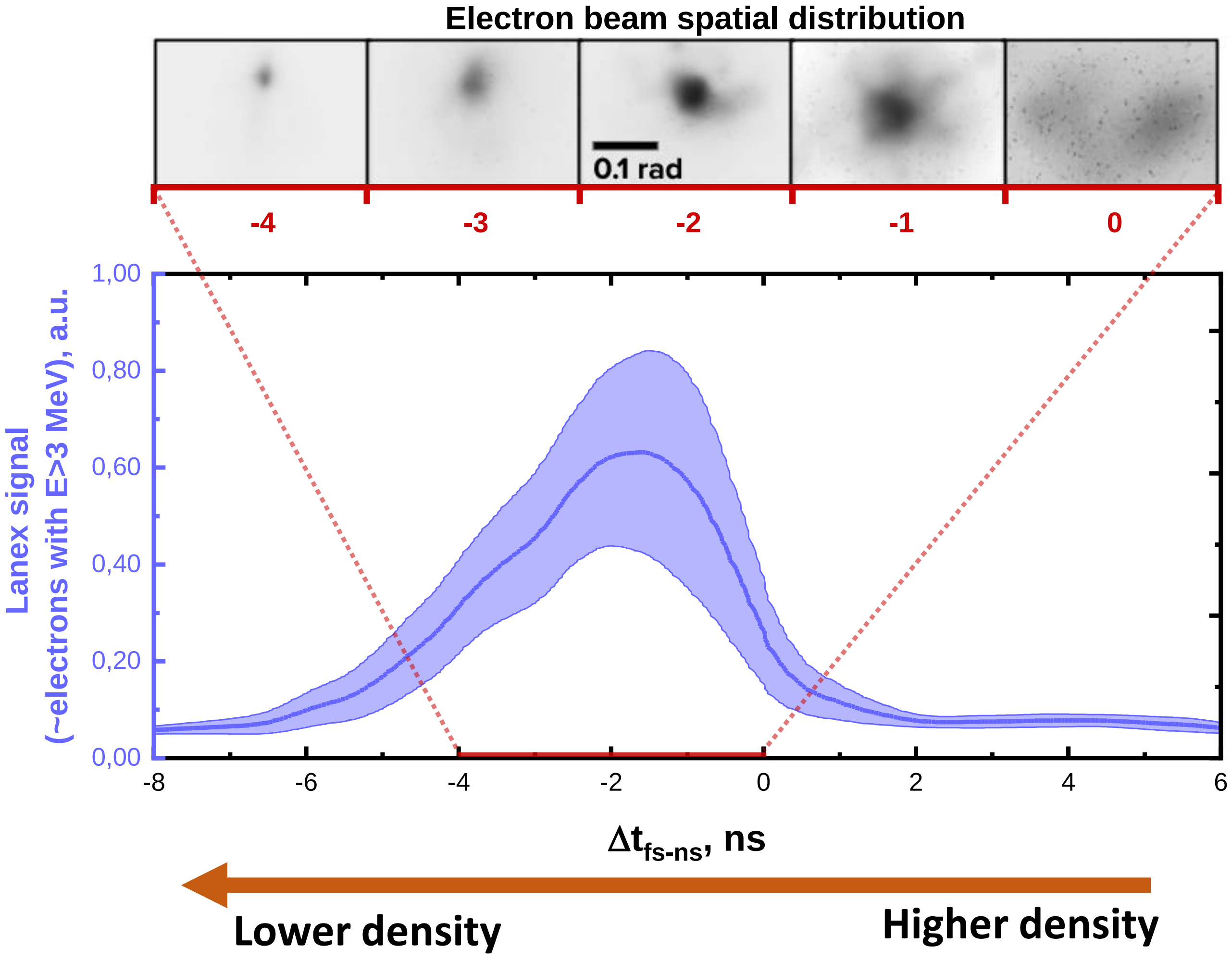
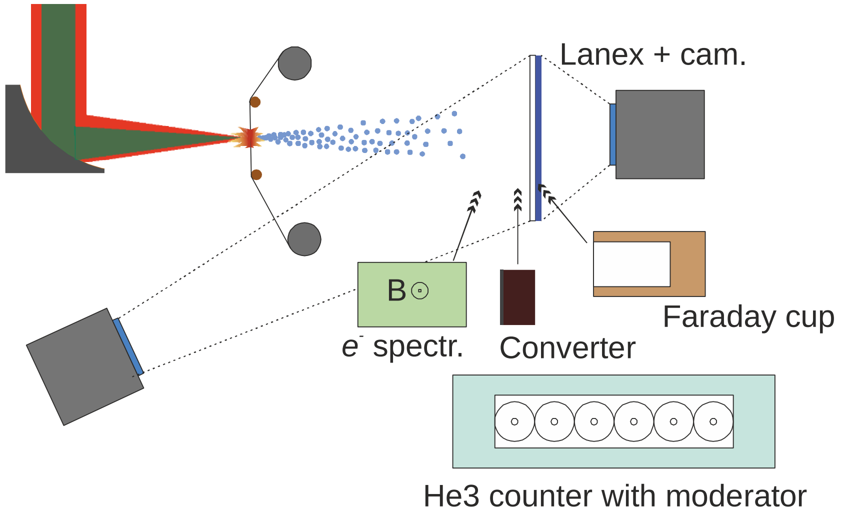
50 fs, 1TW, I_{peak}=3-5x10^{18} W/cm^2





Characterization of the e^- beam

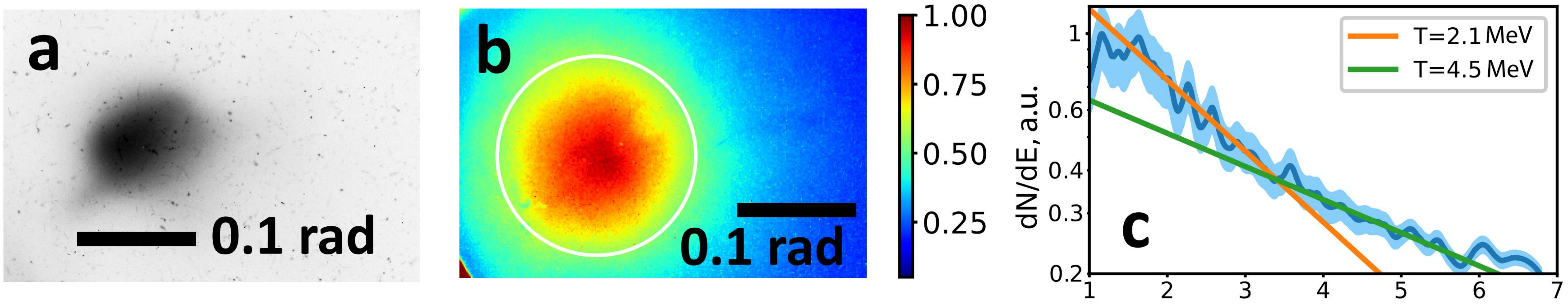
Divergence and stability



Charge measurement

Charge, pC	E>1 MeV	>2 MeV	>3 MeV	>4 MeV
Faraday cup	100 +-10	50 +-12	25 +-7	13 +-3

Full charge > 0.5 nC (10 nC/J)



3D PIC simulations

SMILEI 3D3V

Target – C atoms

~plastic target

Immobile ions

1 particle per cell

Laser:

τ_{FWHM}=50 fs **a_0=1.5**

r_{FWHM}=4λ

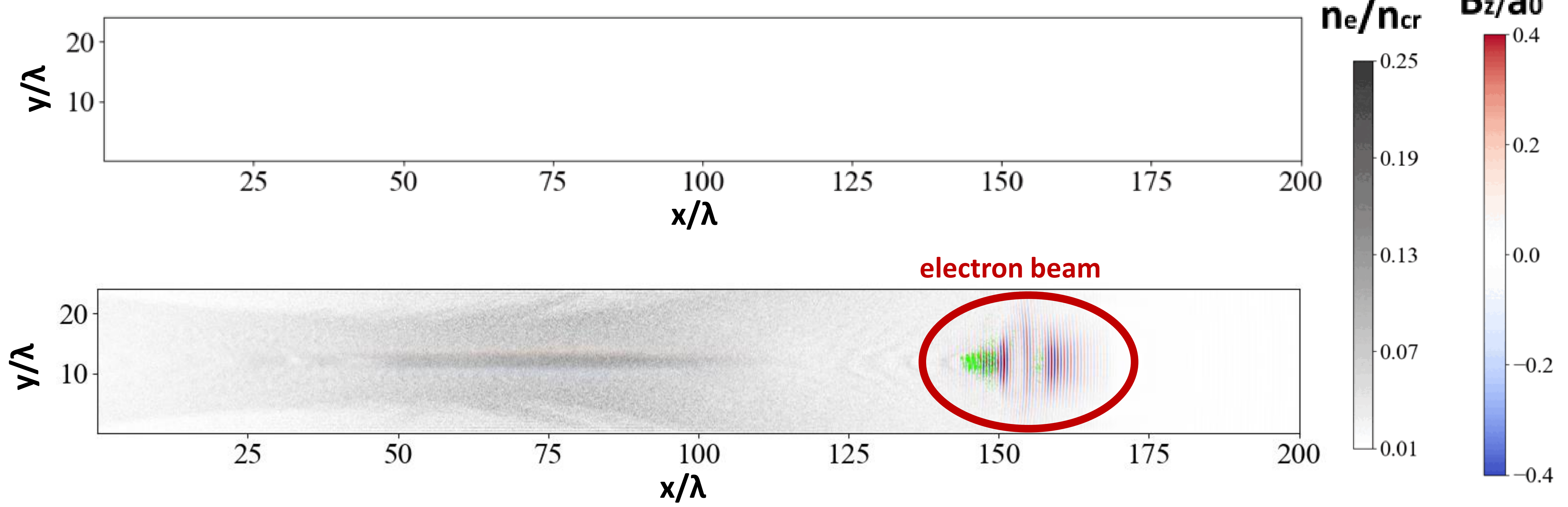
Simulation box: 200λ×24λ ×24λ

Focus: x=60λ, y,z=12λ

Grid steps: x: λ/32, y,z: λ/4, τ/36

For ionization: λ=0.8 μm

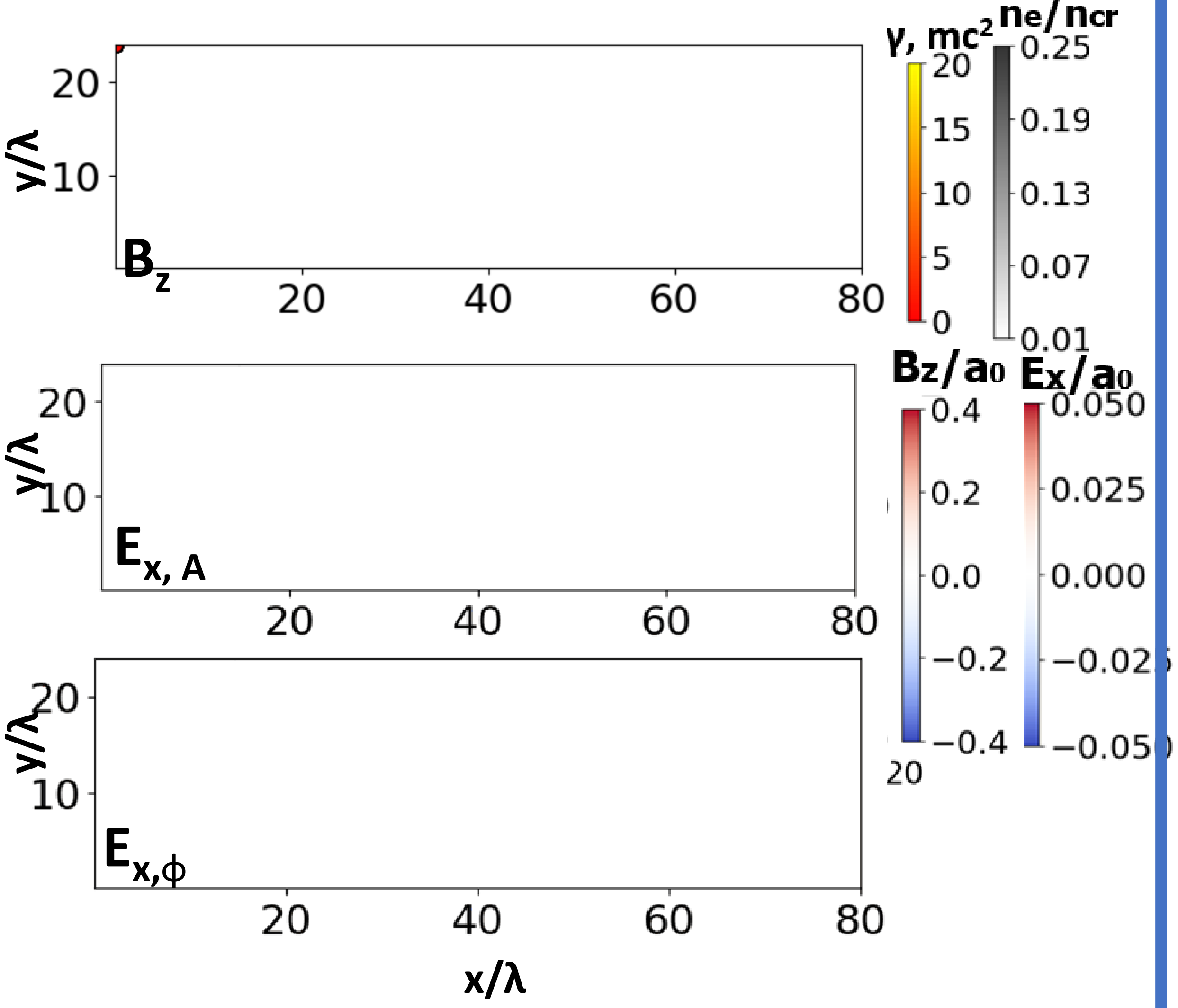
Green – electrons with E>2 MeV



Acceleration mechanisms

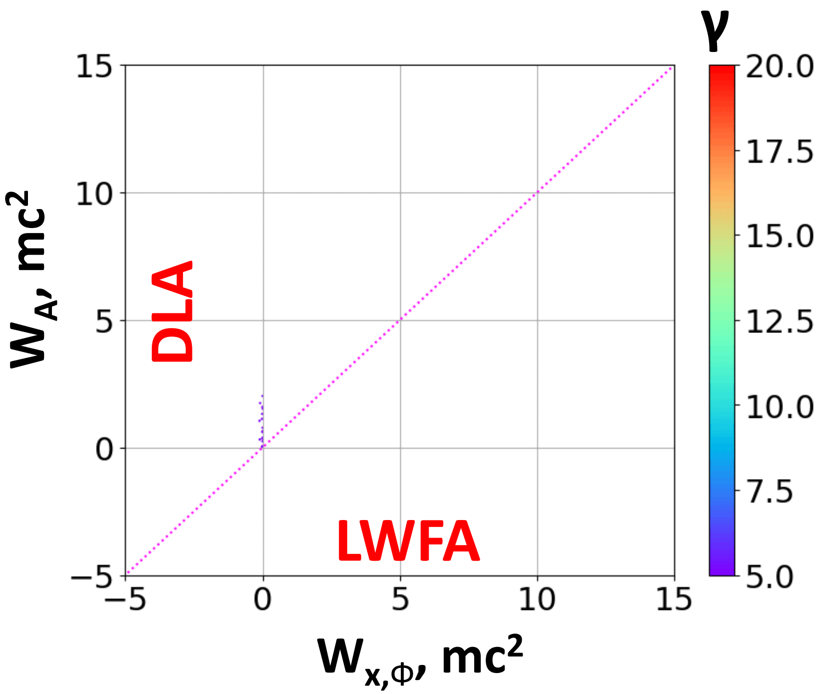
$n_{e_{MAX}}/n_{cr} = 0.1$

$\Delta t_{fs\text{-}ns}$= -3 ns, LP



$$W_j = -e\int_0^t E_j v_j dt$$

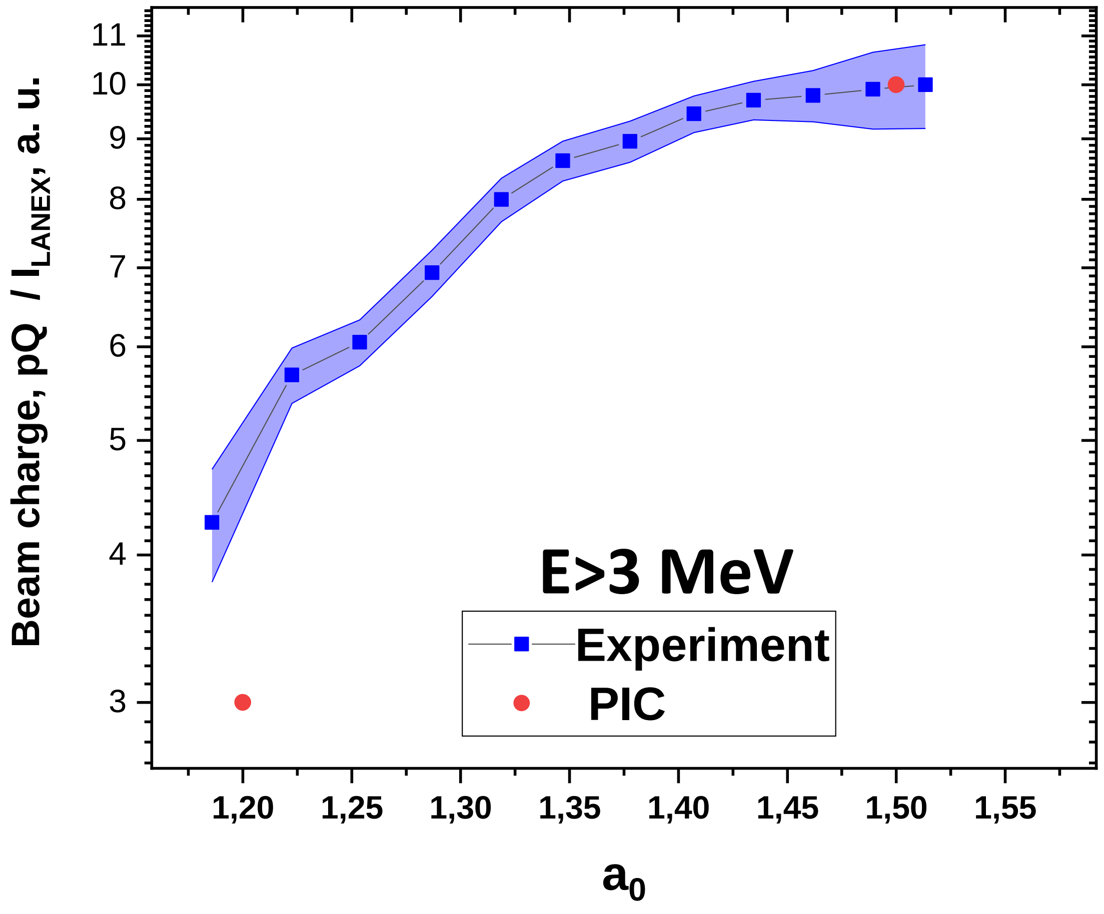
Work via different mechanisms:

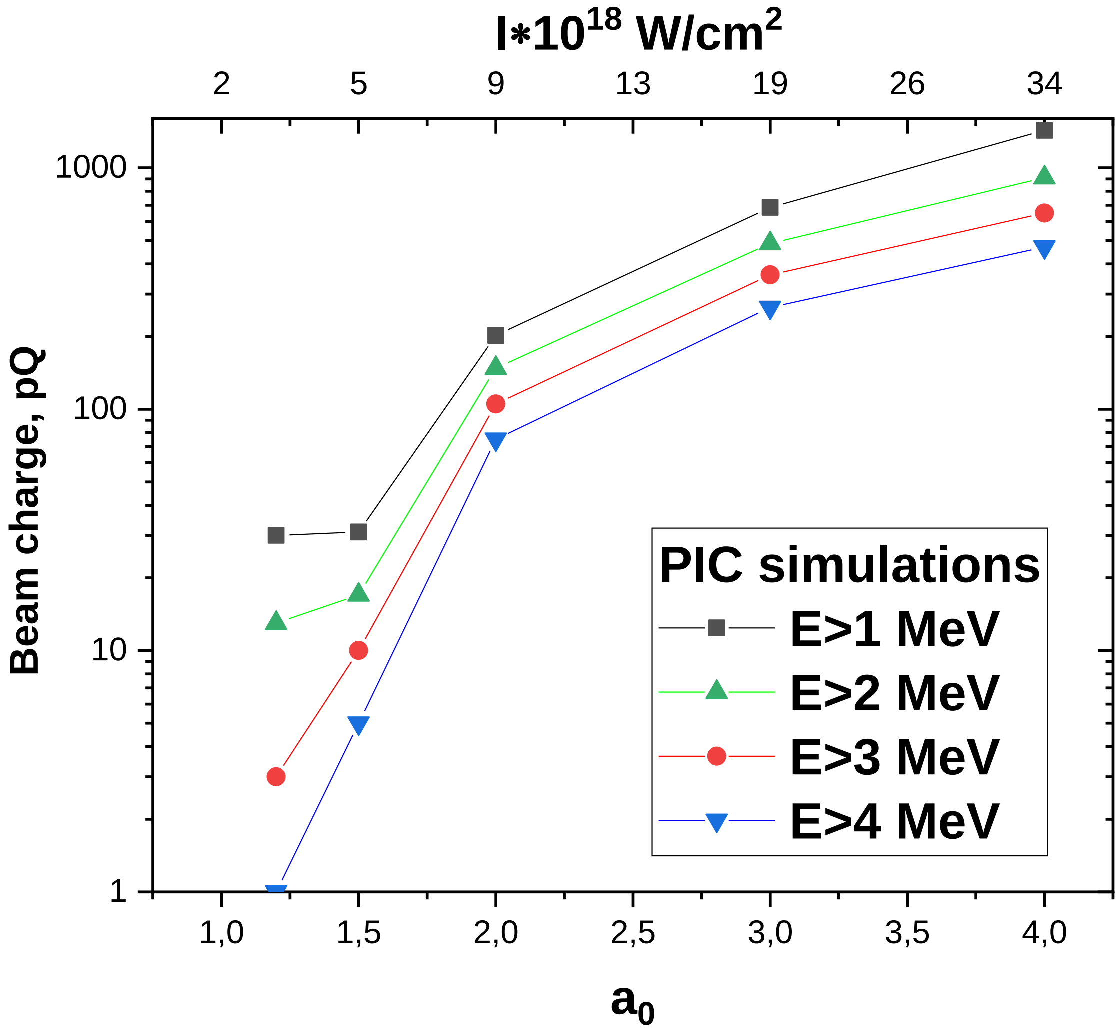


$E_{A,(x,y,z)}$ – **laser pulse** (DLA)

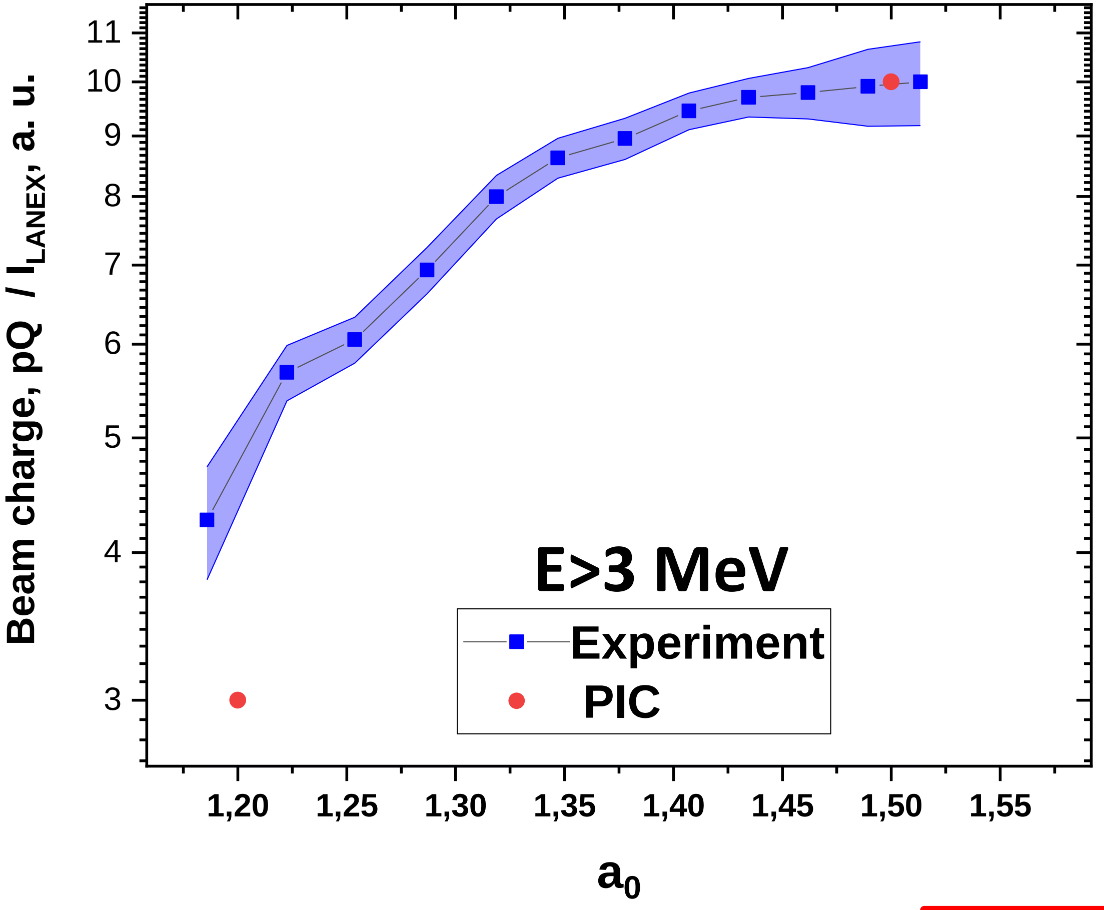
$E_{\Phi,x}$ – **plasma waves (LWFA)**

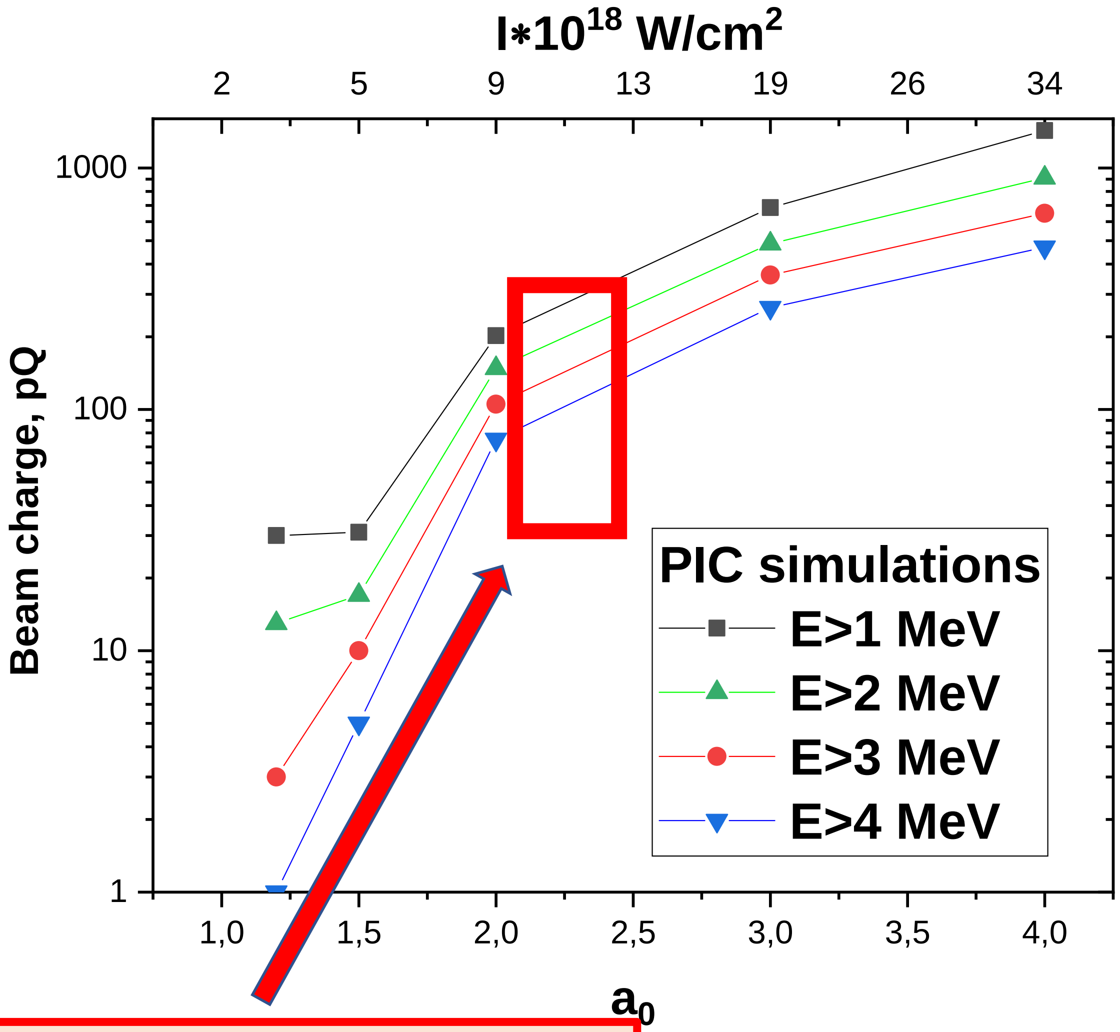
Energy scaling





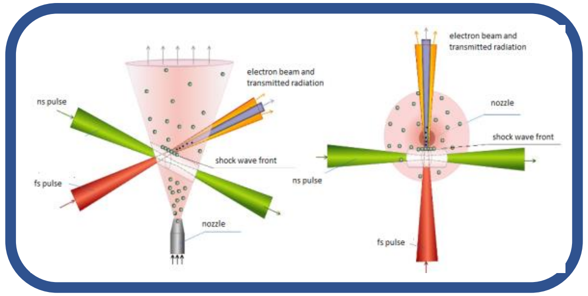
Energy scaling





2x laser pulse energy = 10x beam charge

e^- bunch generation with gas target

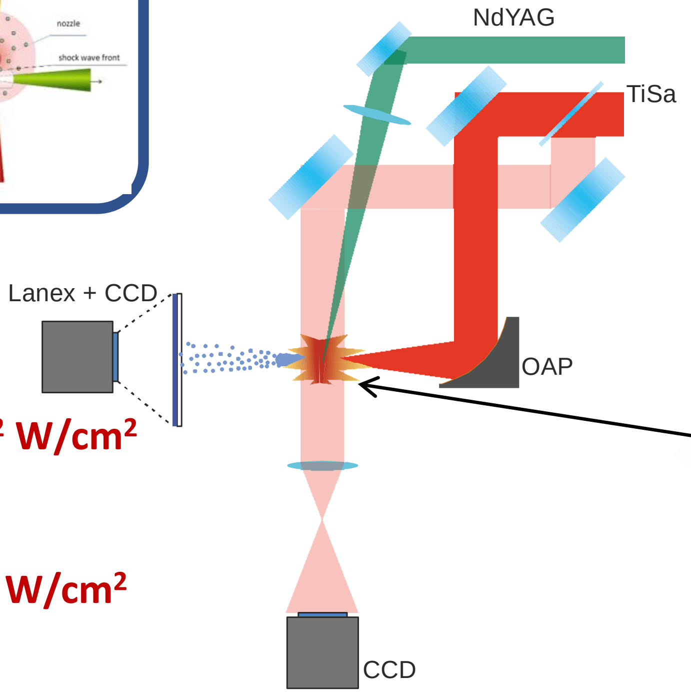


Nanosecond pulse

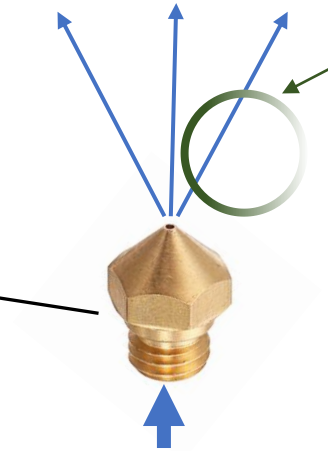
1064 nm, 10 ns, I_{peak}>10^{12} W/cm^2

Femtosecond pulse:

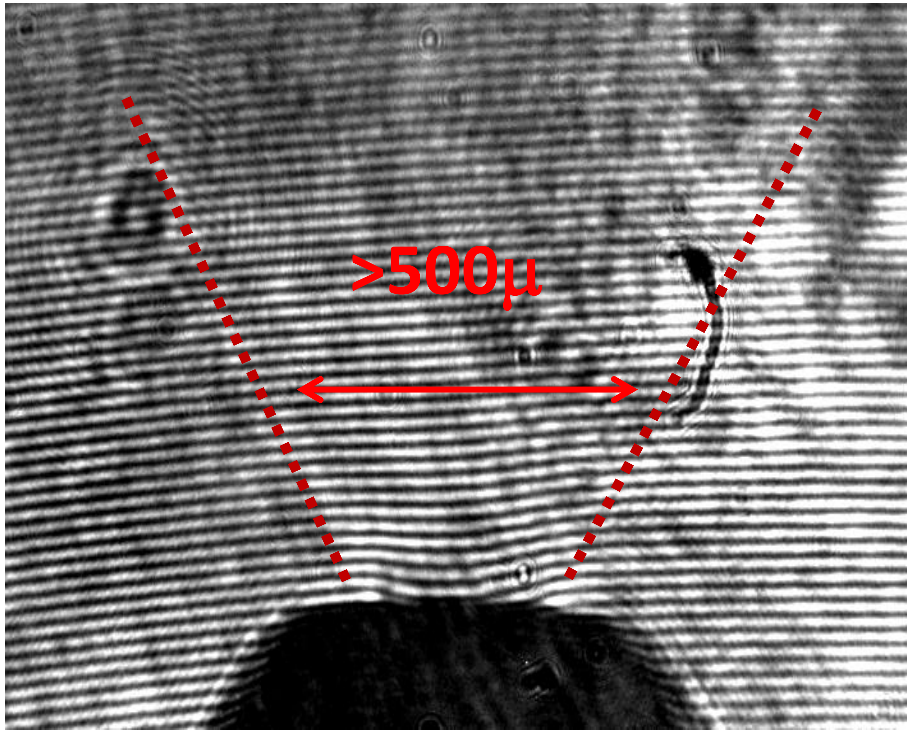
50 fs, 1TW, I_{peak}=3-5x10^{18} W/cm^2

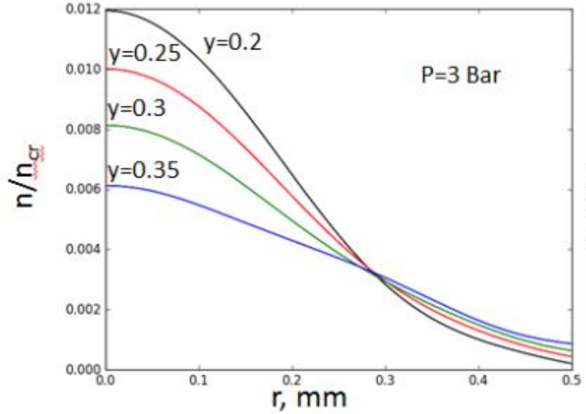


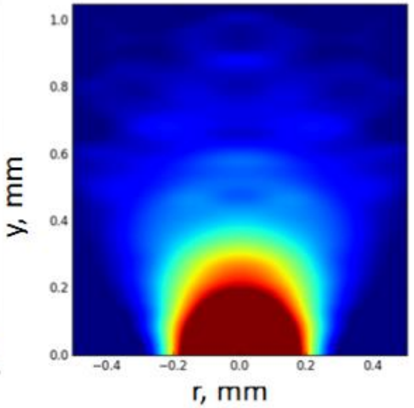
NdYAG induced shock wave



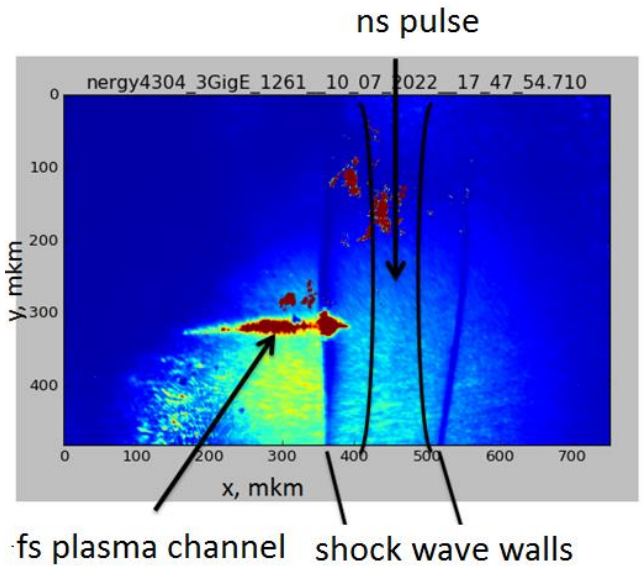
Continuous Nitrogen flow at 3-5 bar, 0.4mm orifice

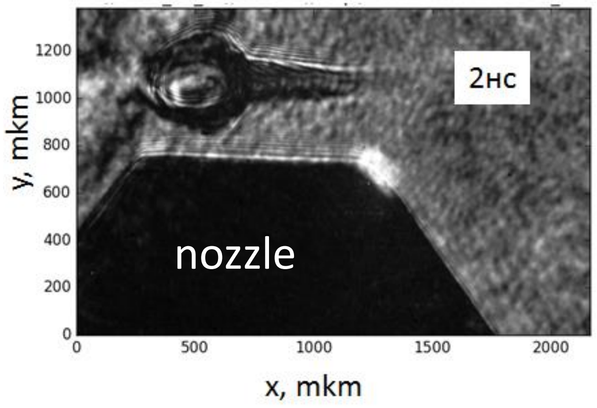


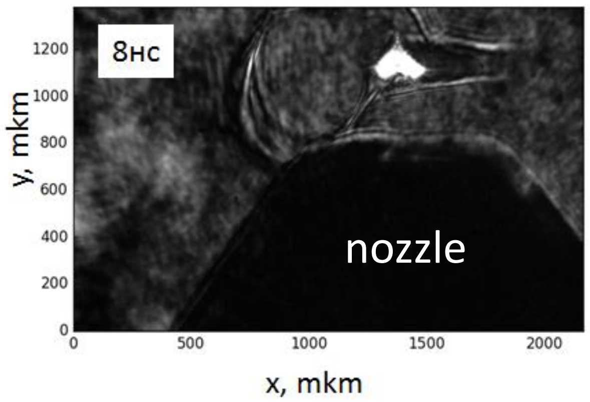


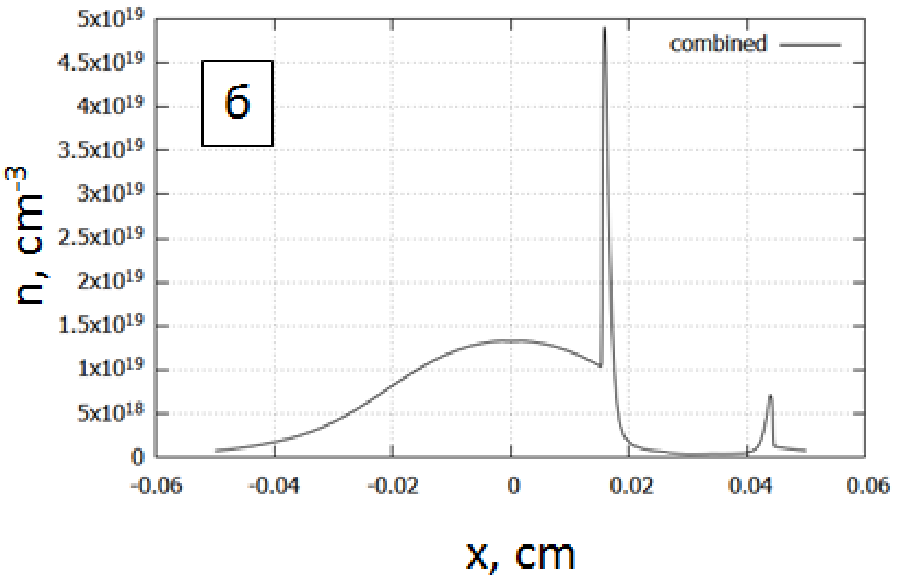


Gas target characterization





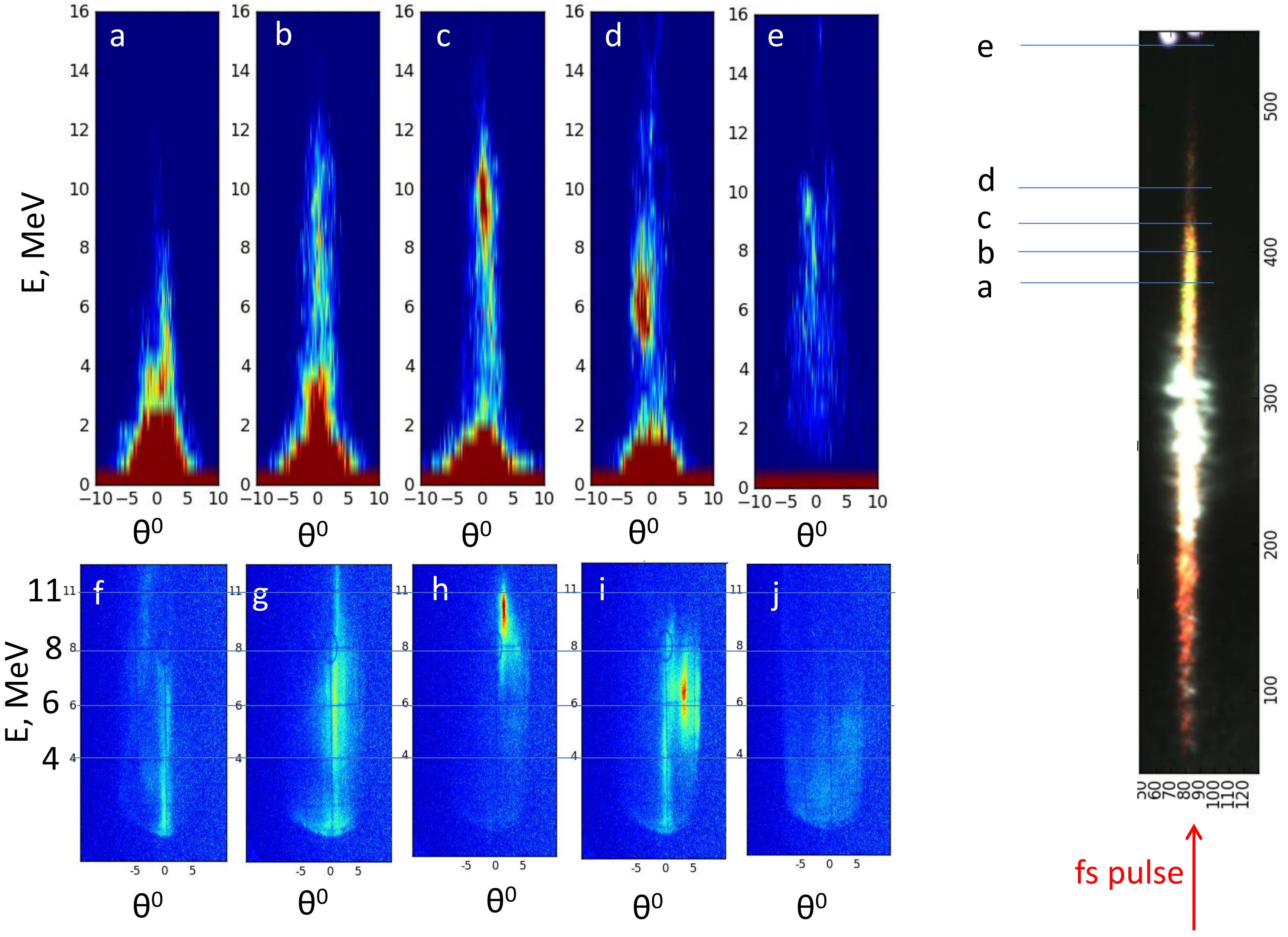




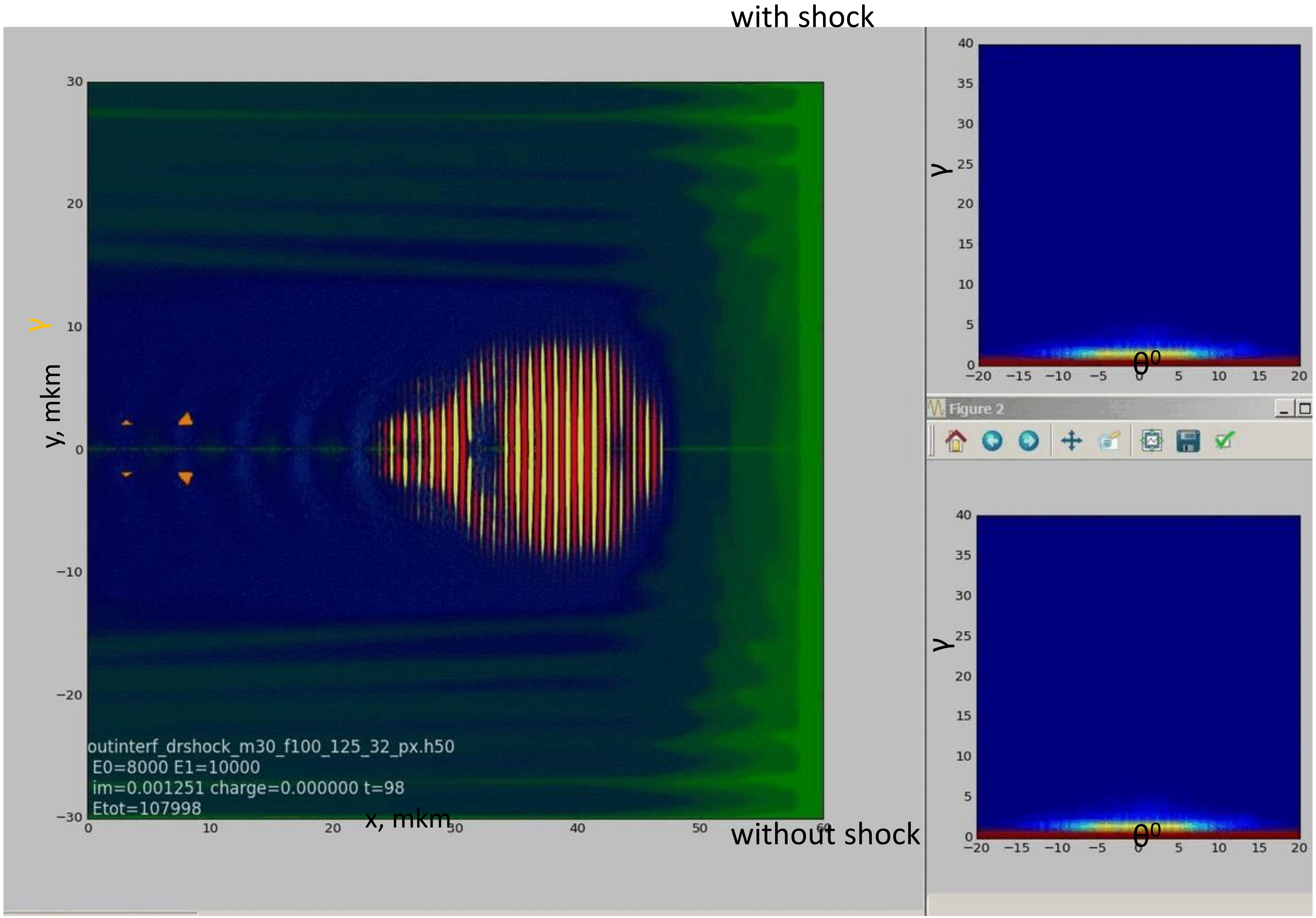
$$s(r) = \begin{cases} 5 \times \exp\left(-\left(\frac{|r-r_0|}{l_1}\right)^{1.2}\right), & r < r_0 \\ 1 + 4 \times \exp\left(-\left(\frac{|r-r_0|}{l_2}\right)^{4}\right), & r \geq r_0 \end{cases}$$

l_1 = 15 mkm, l_2 = 15 mkm for t = 2ns

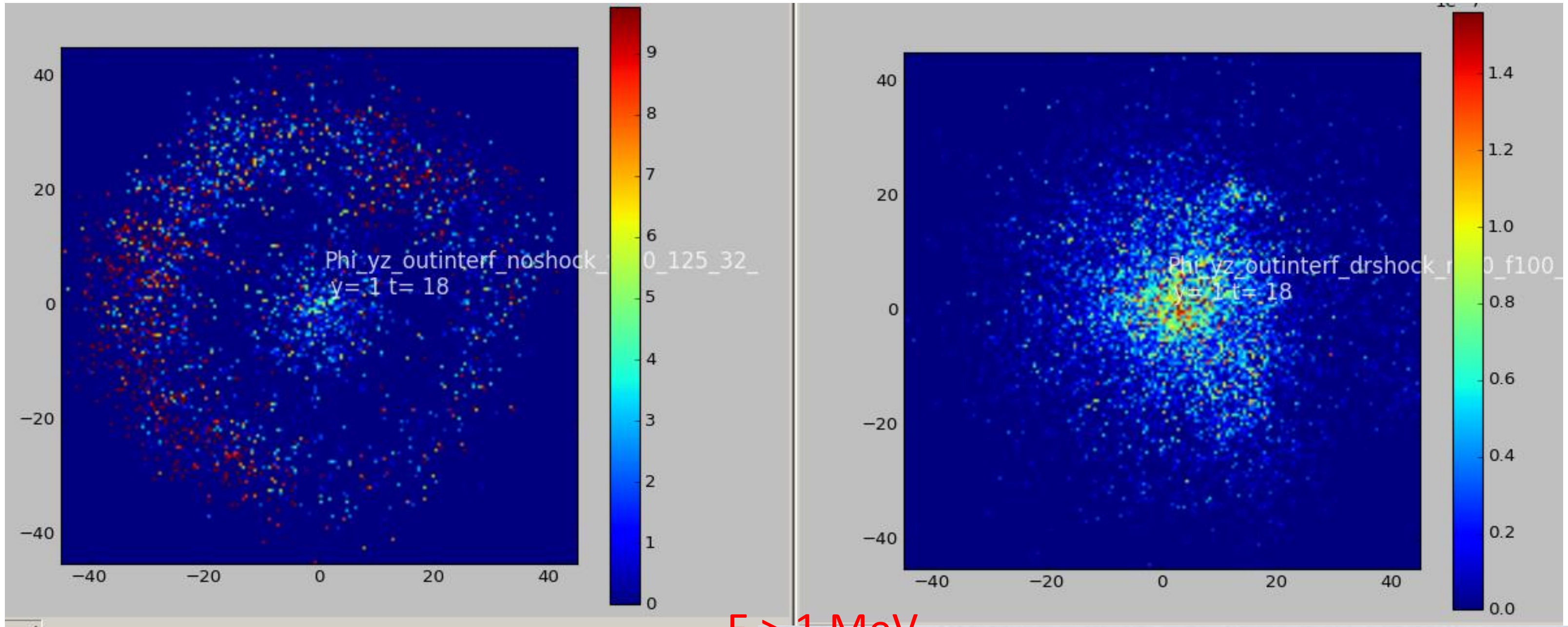
Electron energy spectrum



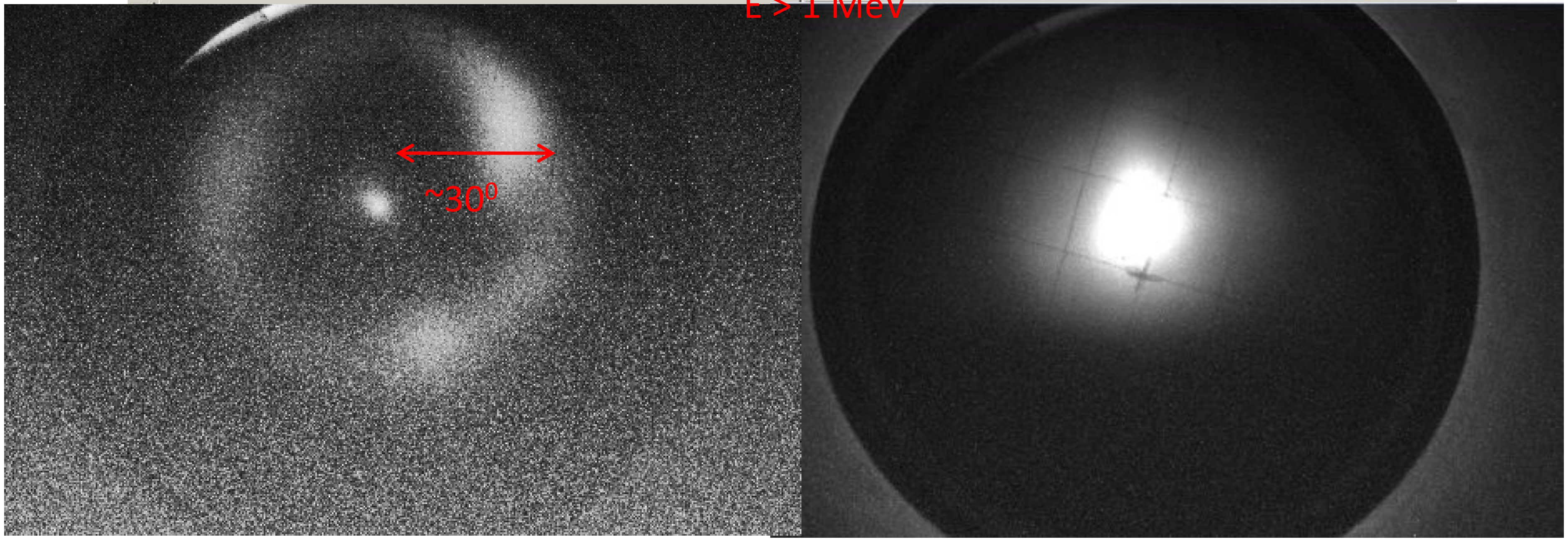
PIC simulation of dephasing reduction



Electron beam dephasing



E > 1 MeV

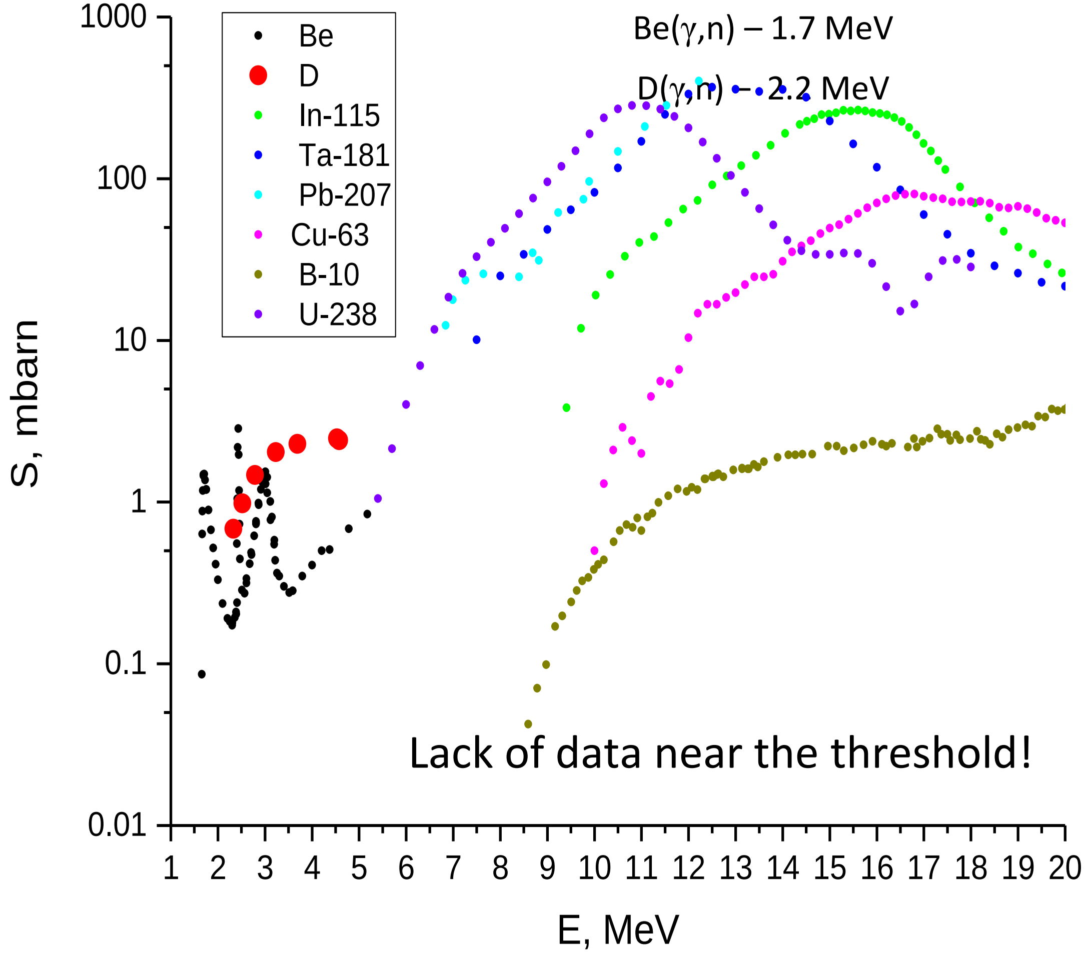


Фотоядерные реакции

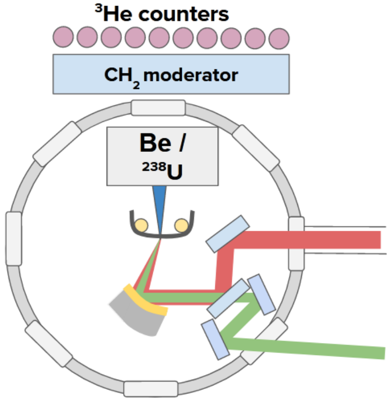
Typical reactions threshold: < 10 MeV

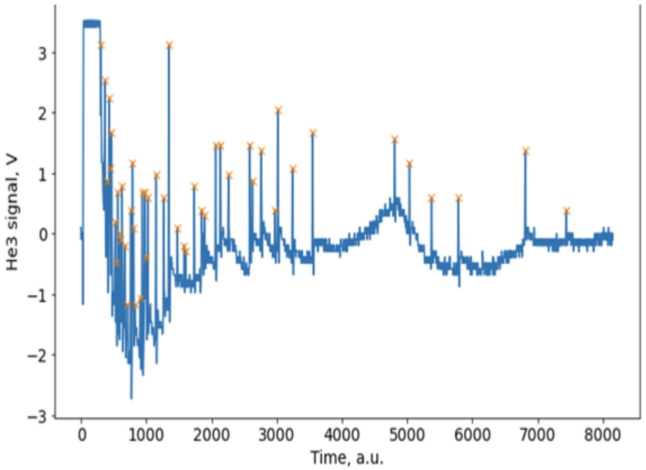
Be(γ,n) – 1.7 MeV

D(γ,n) – 2.2 MeV



Lack of data near the threshold!





Neutron generation

$^{9}Be + \gamma \rightarrow n + {}^{8}Be$

Up to 15 registered neutrons per pulse

Neutron flux
~10^{5}-10^{6} s^{-1}J^{-1}

$^{238}U + \gamma \rightarrow n + {}^{237}U$

Up to 4 registered neutrons per pulse

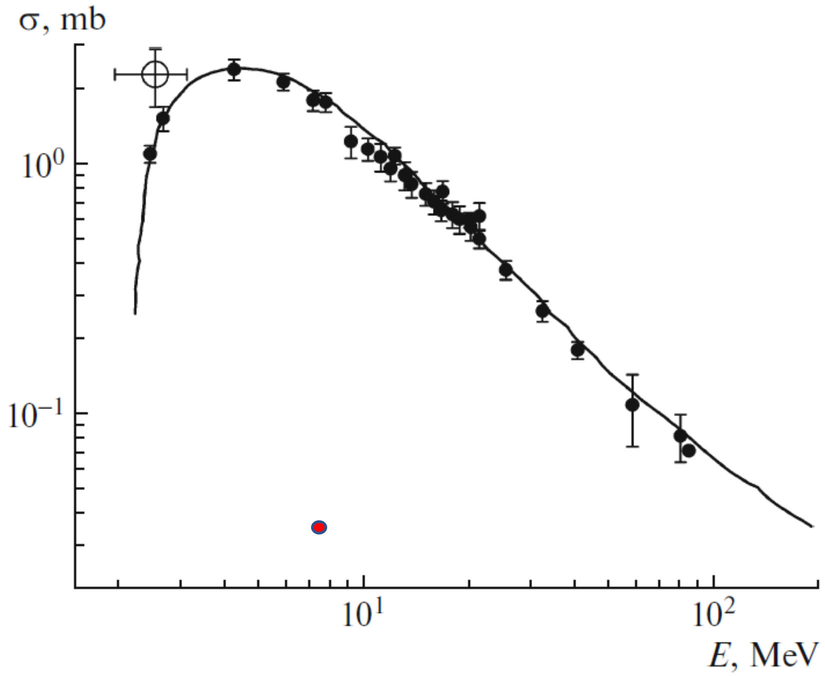
Neutron flux
~10^{5} s^{-1}J^{-1}

$^{208}Pb + \gamma \rightarrow n + {}^{207}Pb$

Up to 12 detected neutrons per pulse

Neutron flux
~ 10^{5}-10^{6} s^{-1}J^{-1}

$< \sigma_{\gamma n} > = 2{,}5 \pm 0.5$ **mbarn**



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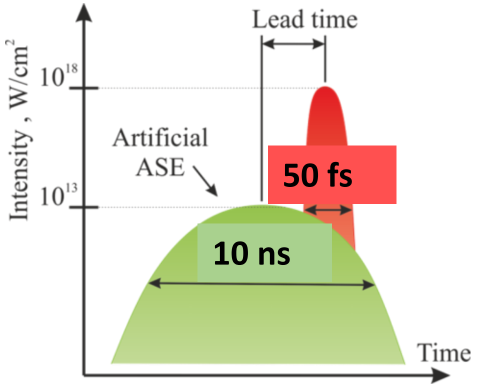
*Ishkhanov, B. S., et al. "Photonuclear reactions and astrophysics." *The Universe Evolution: Astrophysical and Nuclear Aspects" (Nova Science Publishers, New York, 2013)*

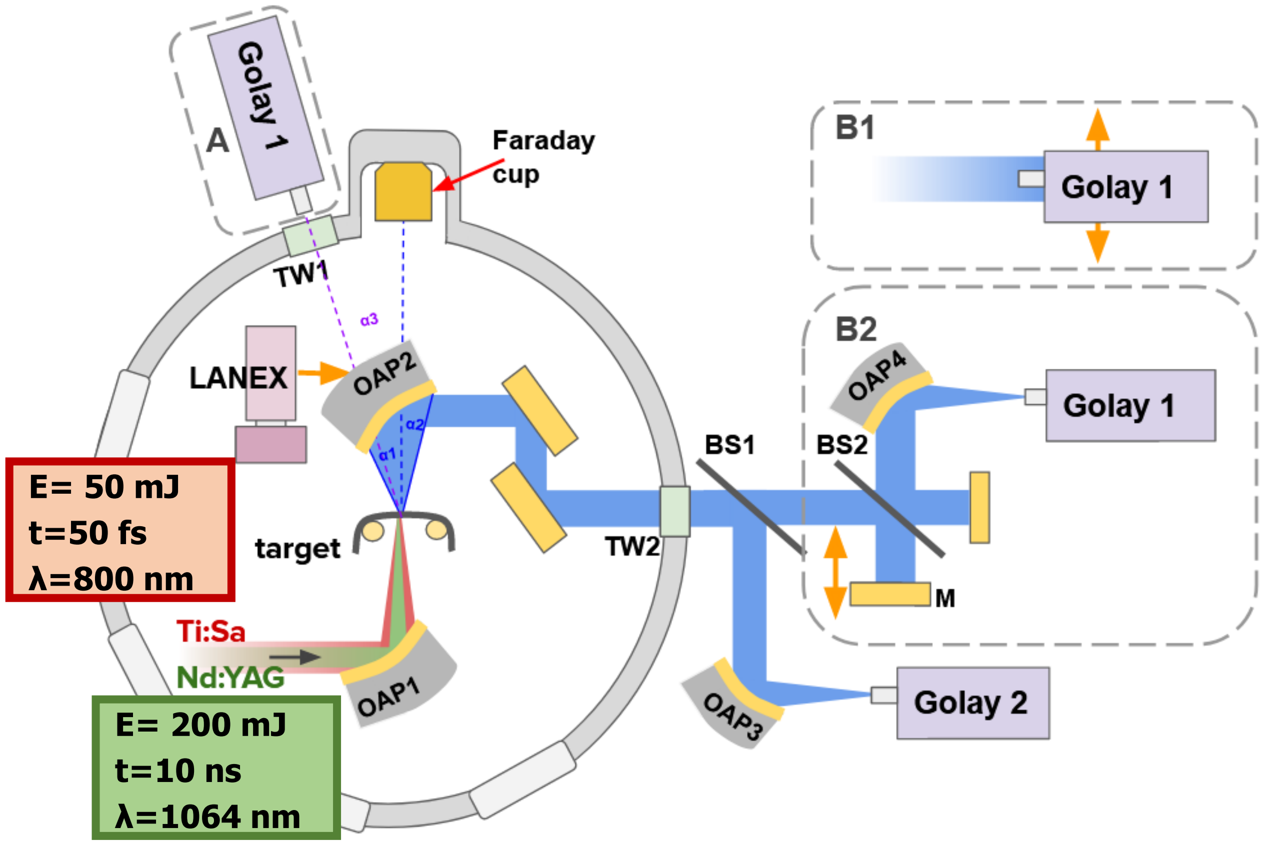
**Arnold C. W. et al. Cross-section measurement of 9 Be (γ, n) 8 Be and implications for α+ α+ n→ 9 Be in the r process //Physical Review C. – 2012. – T. 85. – №. 4. – C. 044605.

Experimental setup for the THz measurements

$I_{Ti:Sa} \sim 5 \cdot 10^{18}$ W/cm^2
$I_{Nd:YAG} \sim 10^{12}$ W/cm^2



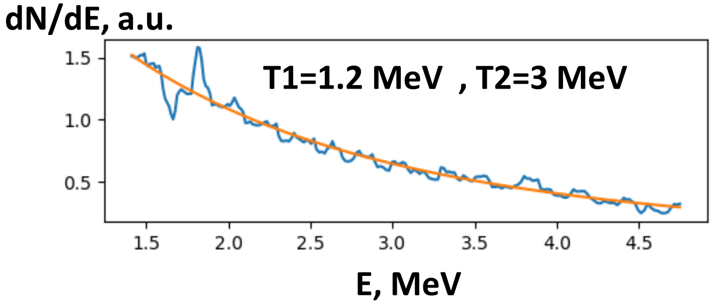
Detectors:
- LANEX screen
- Electron spectrometer
- 10 He^3 counters
- CCD cameras
- **Golay Cell**

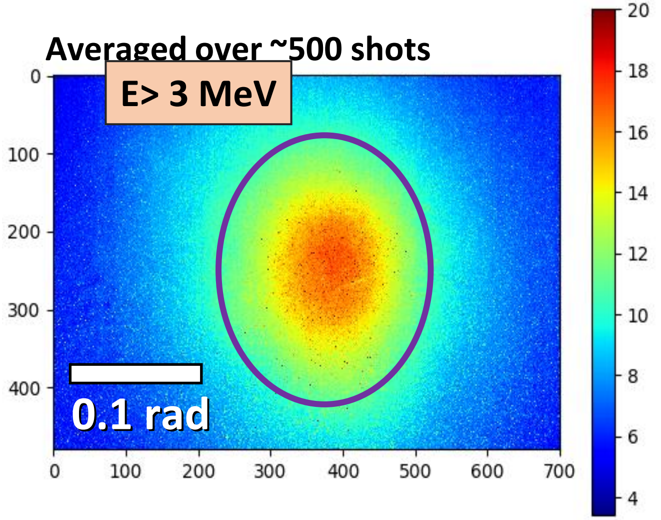


Electron beam characteristics + THz radiation

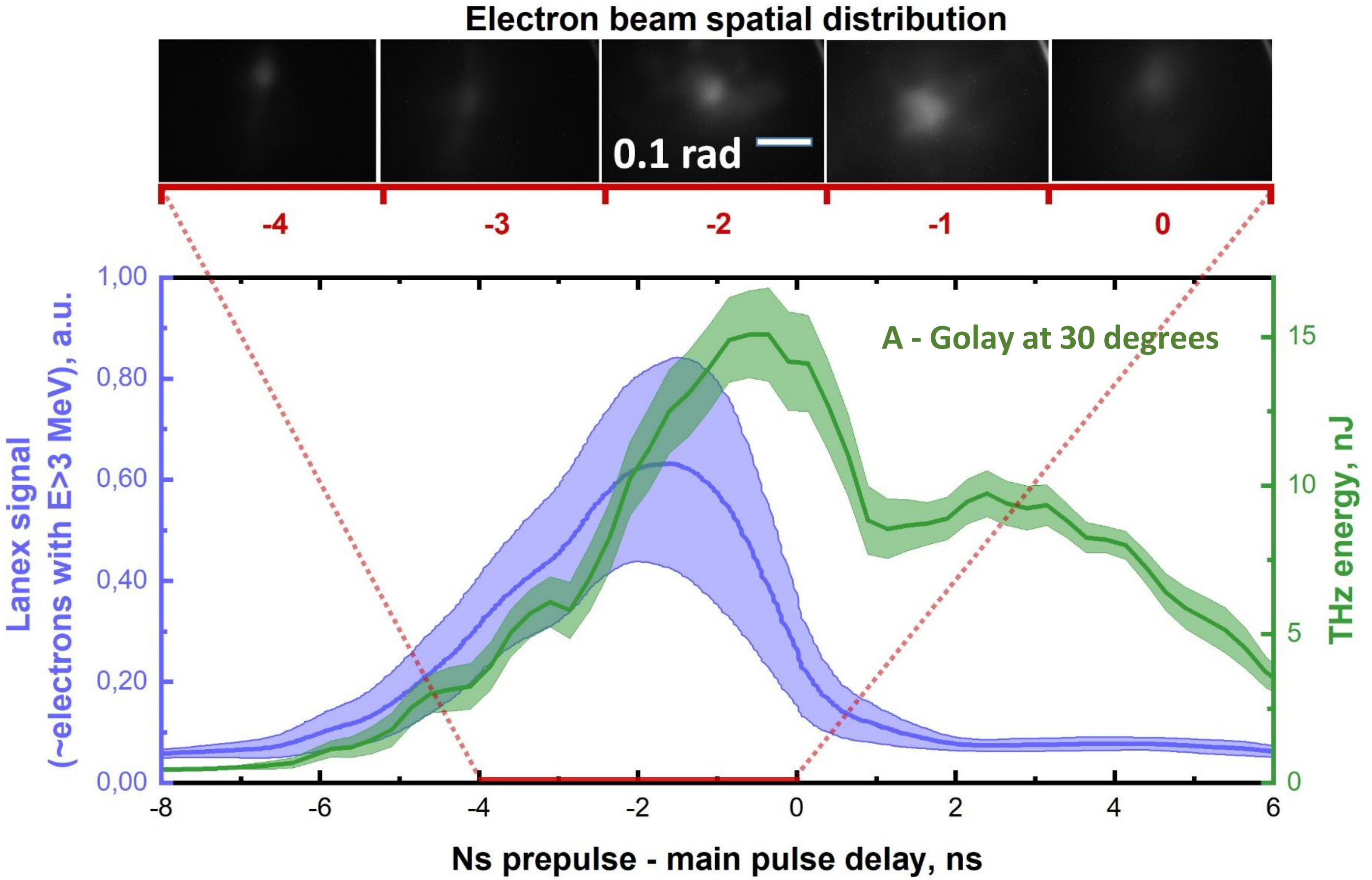
Q~50-100 pC for E>1.7 MeV

T~2-2.5 MeV



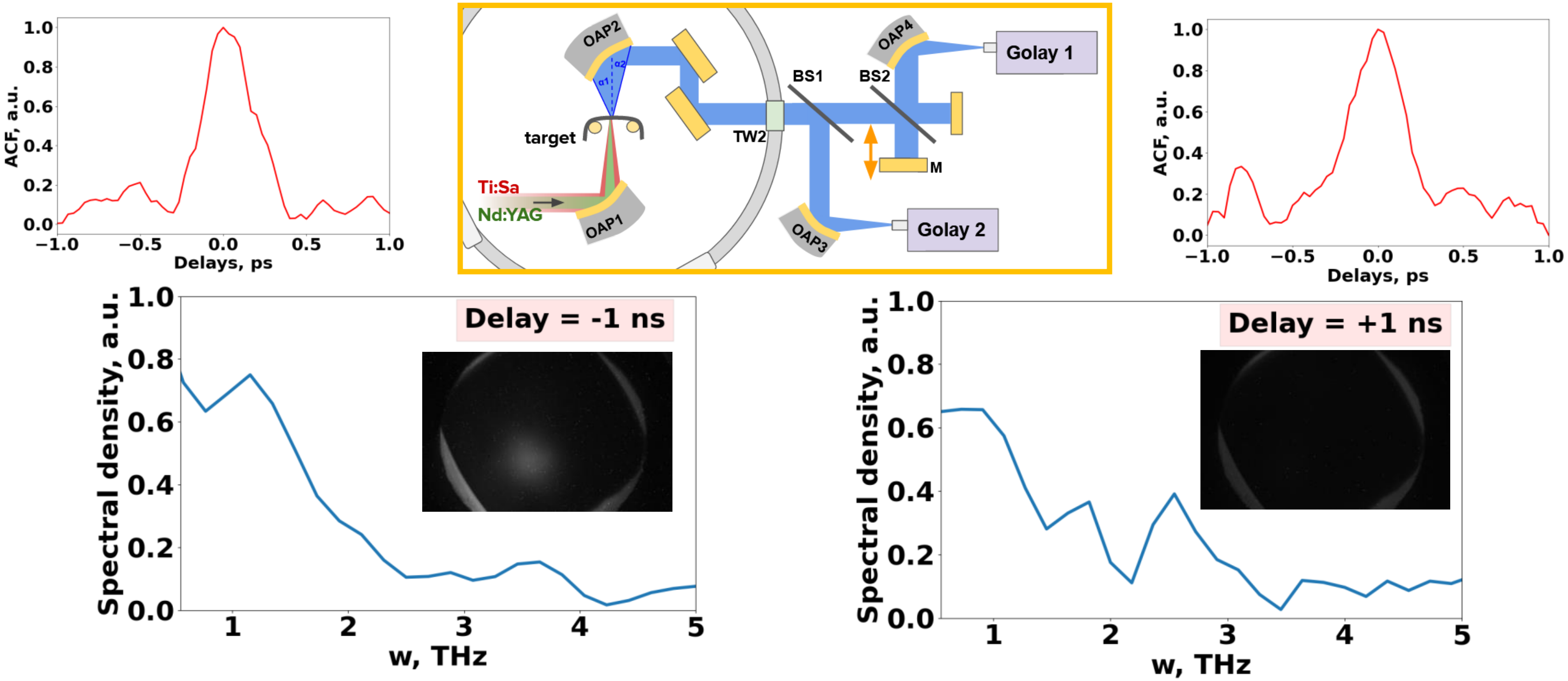


Electron beam pointing stability



D Gorlova *et al* 2022 *Laser Phys. Lett.* 19 075401

THz radiation spectrum



Collimated beam → Diffuse beam

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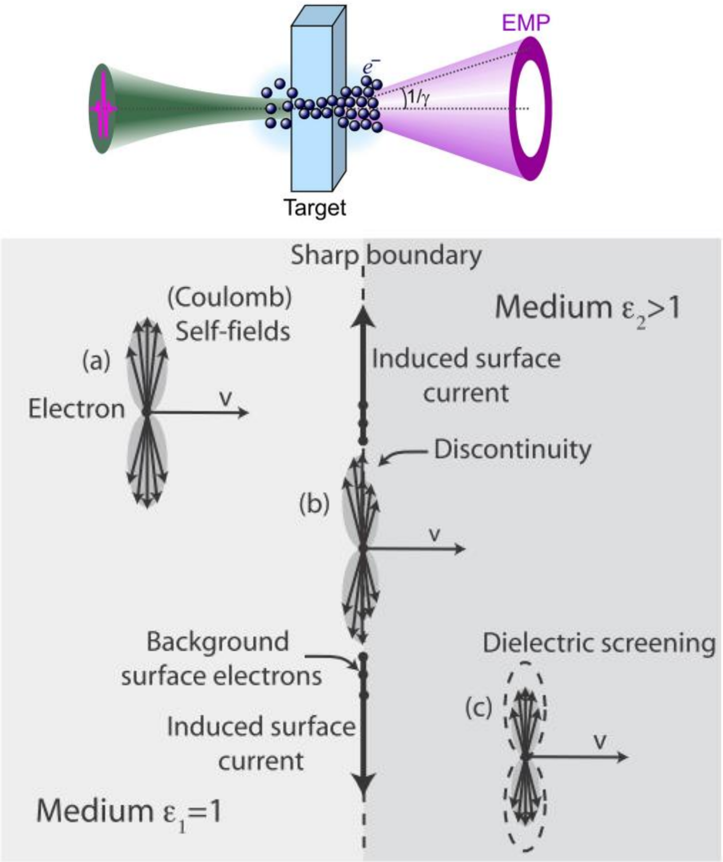
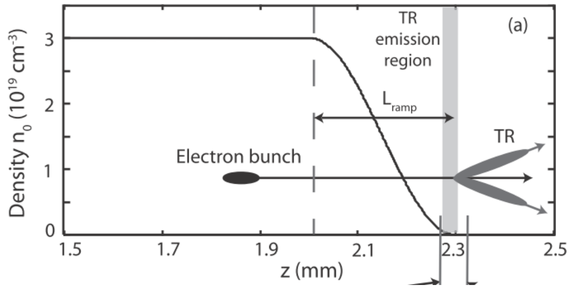
Coherent Transition Radiation (CTR)



From Van Tilborg, 2006, PhD thesis

Sharp boundary?

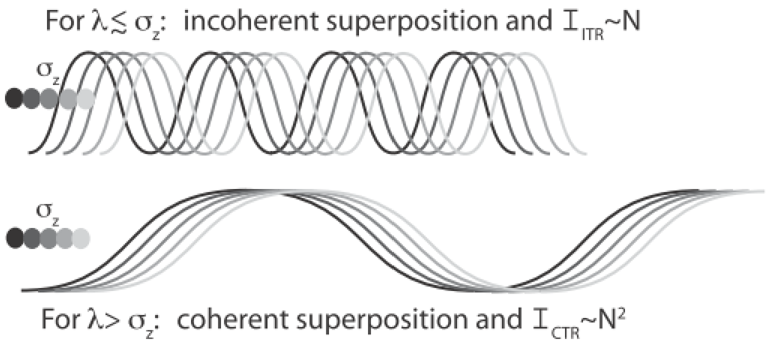


Coherency?

$\tau < 1/2\nu_{THz}$

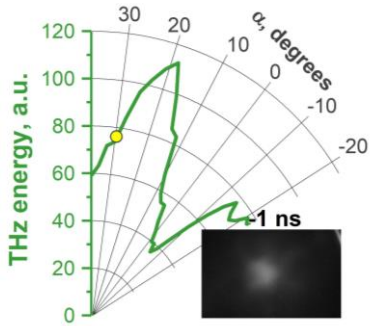
E=0.5 MeV -> v=0.87c

For 200 μm coherent up to 5 THz

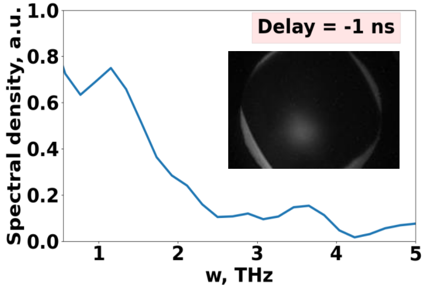


CTR calculations

Angular distribution



Spectra



From Van Tilborg, 2006, PhD thesis

$$\boldsymbol{E}(\omega, z) = i\frac{4\pi e}{\omega}\sum_{j=1}^{N}\frac{1}{\cos\theta}\mathcal{E}(\theta, u_j)D(\theta,\omega,u_j,\rho)e^{-ix_j k \sin\theta}\boldsymbol{e}_{\perp}$$

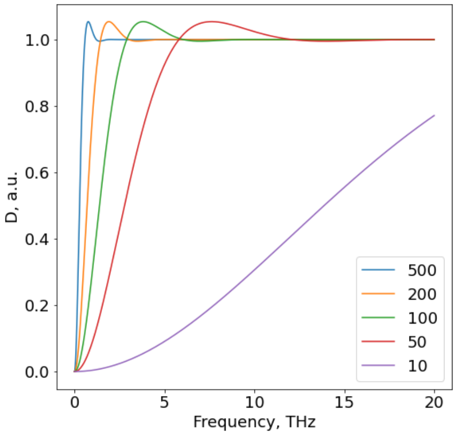
$D(\theta,\omega,u_j,\rho) = 1 - J_0(bu\sin\theta)\left[bK_1(b) + \frac{b^2}{2}K_0(b)\right] - \frac{b^2}{2}K_0(b)J_2(bu\sin\theta)$ – models radiation diffraction on the preplasma cloud with radii ρ, где $b = 2\pi\rho/u\lambda$, J – Bessel functions, K – McDonald functions

scaling ~N^2

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2}{\pi^2 c}\sum_{j=1}^{N}\sum_{m=1}^{N}\mathcal{E}_j\mathcal{E}_m D_j D_m e^{ik(x_m - x_j)\sin\theta}$$

Frequency-angular distribution of CTR radiation

Diffraction!

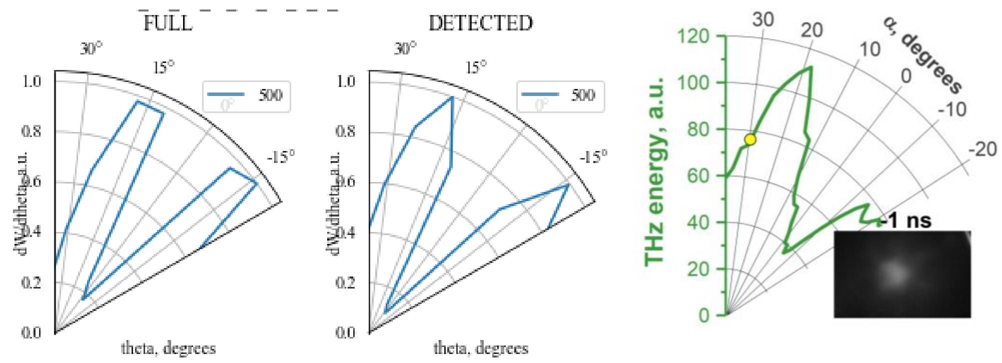


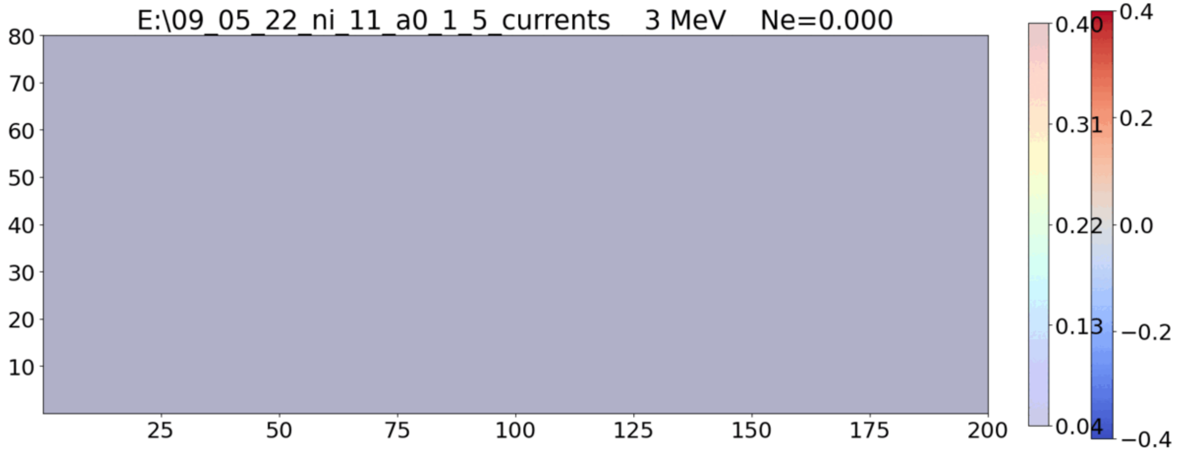
Spectra with temperature T can be simulated by an electron with energy E=T

Schroeder et.al.
PHYSICAL REVIEW E 69, 016501

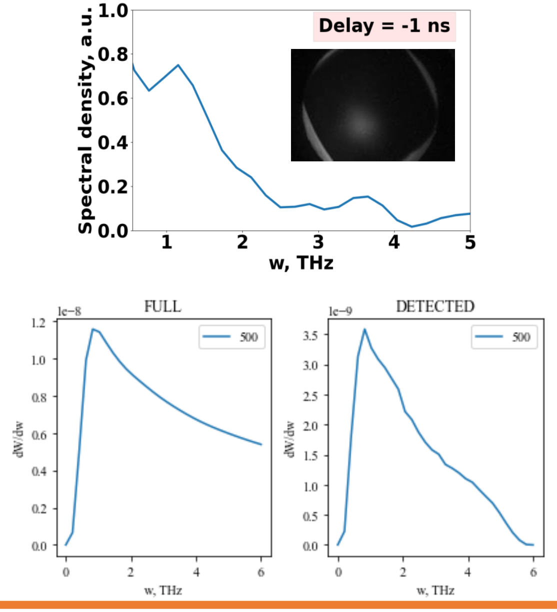
PIC simulations

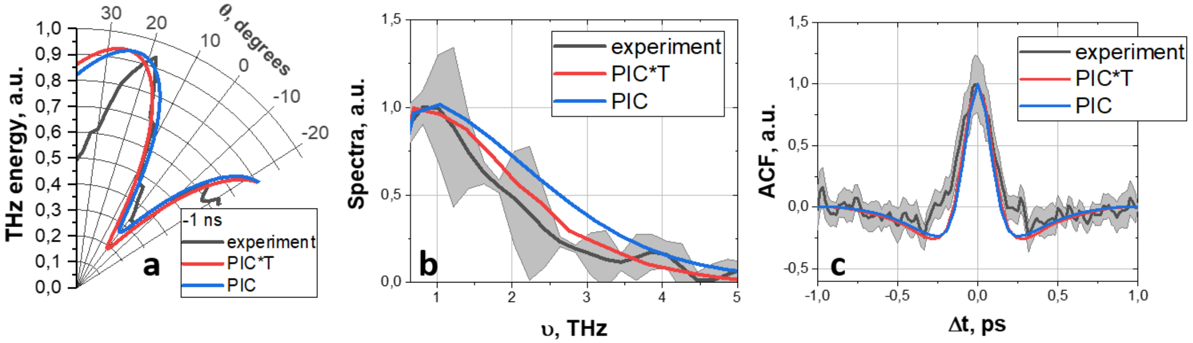
Angular distribution

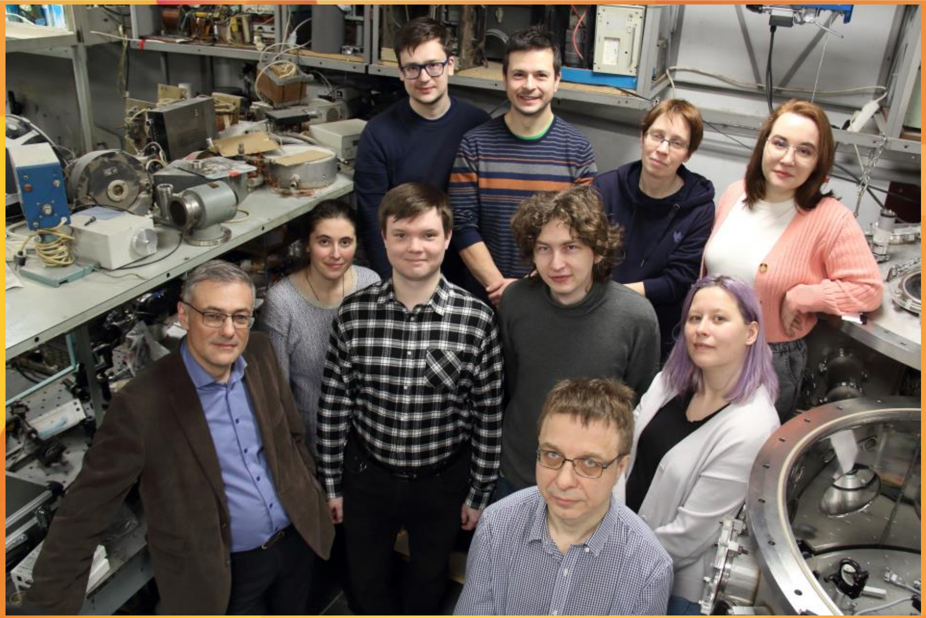




Spectrum







RLP | Laboratory of Relativistic Laser Plasma

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+ ФИАН, ИЯИ РАН, ИПМ РАН

Спасибо за внимание!