HIGH-BRILLIANCE BETATRON GAMMA-RAY SOURCE POWERED BY LASER-ACCELERATED ELECTRONS

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[6]Department of Physics and Complex Systems, Weizmann Institut of Science, Rehovot, Israel

CHALMERS UNIVERSITY OF TECHNOLOGY

EAAC, 26 September 2017

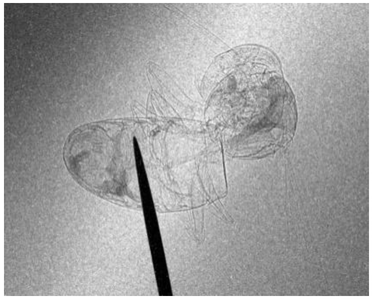
INTRODUCTION

Betatron sources with laser-plasma accelerators:

- Compact setup
- Ultra-short (fs)
- Ultra-small (µm)
- Broadband spectra (keV-10’s keV)

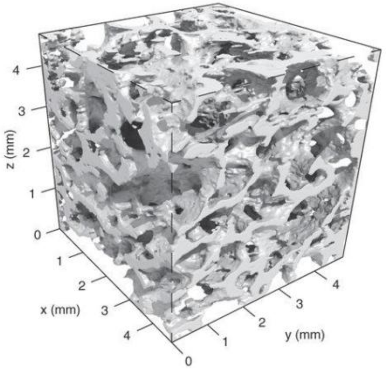
→ Applied for ultra-high resolution imagery

Phase contrast imagery



Fourmaux, S. et al, Opt. Lett. ***36****, 2426 (2011)*

tomography



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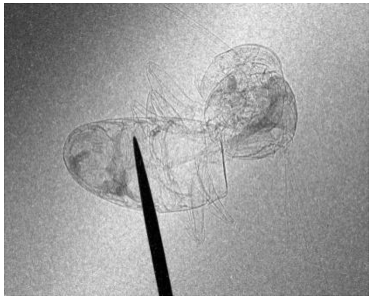

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How can we further improve these sources ?

$$E_c, N_X$$

$$E_c\ [\mathrm{keV}] = 5.2 \times 10^{-21} \gamma^2 n_e[\mathrm{cm}^{-3}] \boldsymbol{r}_\beta[\mu\mathrm{m}]$$

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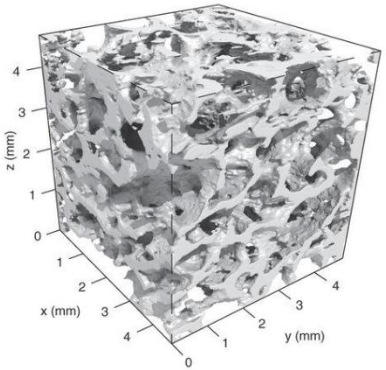

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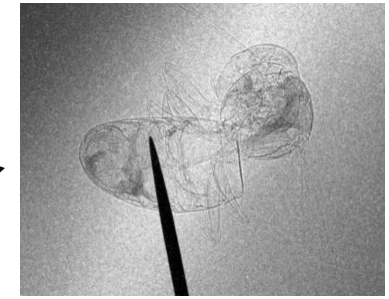

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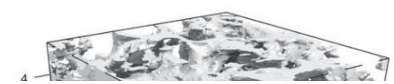

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K. Nemeth et al. Phys. Rev. Lett. ***100*** *095002 (2008)*

- Density step

K. Ta Phuoc et al. Phys. Plasmas ***15****, 063102 (2008)*

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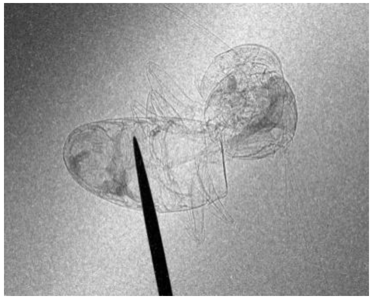

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- Blowout regime

$$L_{depl} = L_{deph}$$

→ density is imposed

Problem for betatron!

A TWO-STAGE SCHEME FOR BETATRON EMISSION

- **One stage acceleration**: impossible to both optimize electron energy and density.

  → Compromize has to be found in the experiment

- **Our proposition**: Decouple electron acceleration and X-ray emission in two different stages.

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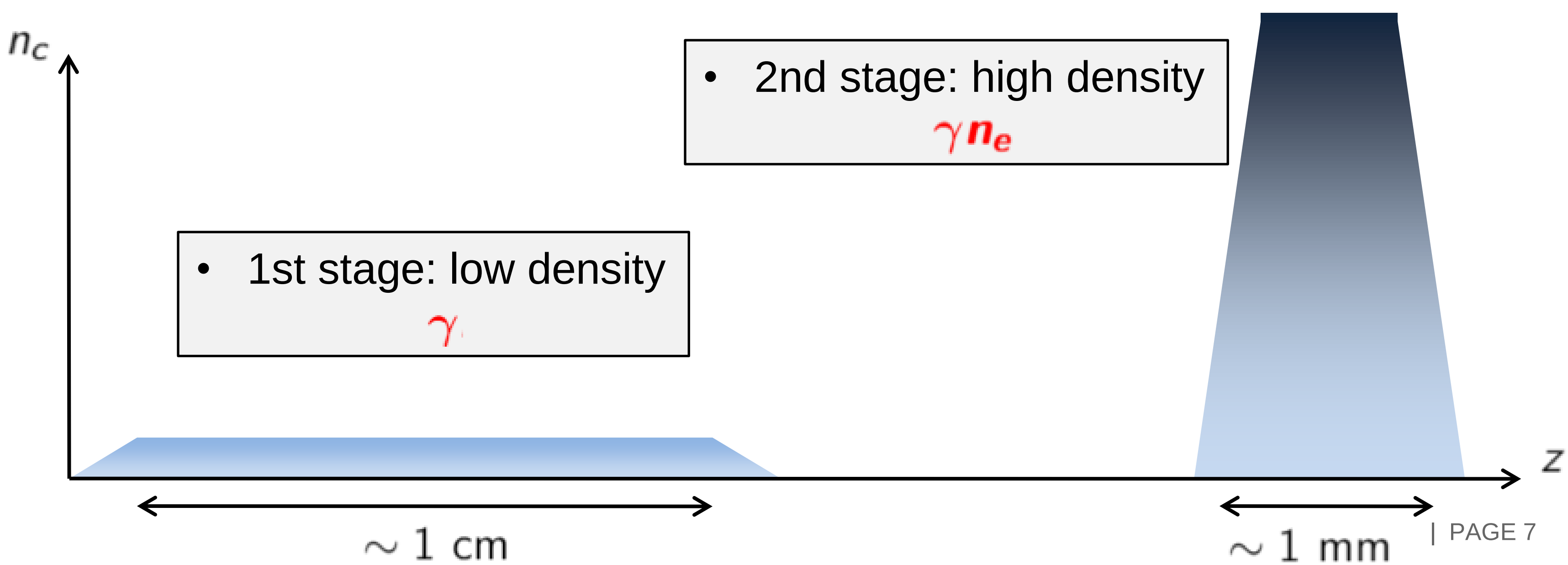

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- 2nd stage: high density

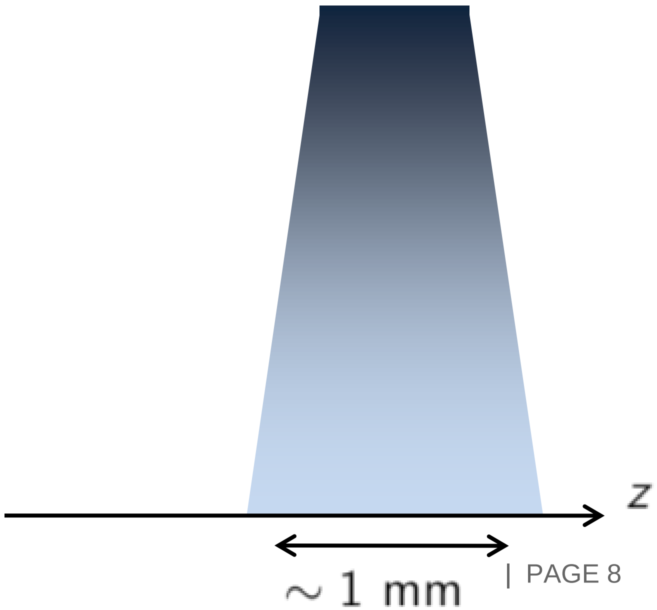
  → laser depletion: $L_d \propto 1/n_e$

  → *High energy laser?*

  ↓

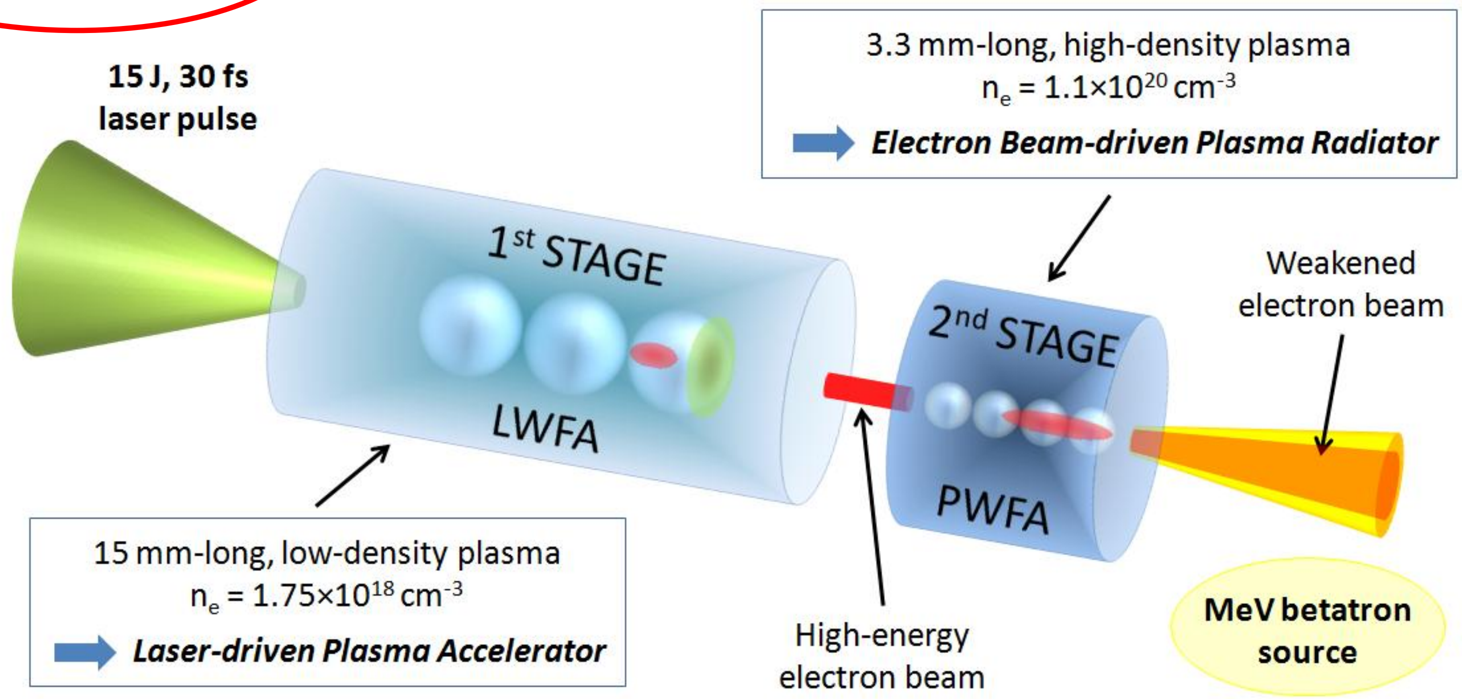
Plasma wakefield regime

S. Chou et al. Phys. ReV. Lett. ***117****, 144801 (2016)*



A TWO-STAGE SCHEME FOR BETATRON EMISSION

0.5 PW APOLLON



- 1st stage: low density, electron acceleration
  → Laser wakefield, blowout regime
- 2nd stage: high density, X-ray emission
  → Plasma wakefield

1^{ST} STAGE: LWFA WITH A 0.5 PW LASER

1^{st} stage: Laser wakefield acceleration of electrons (CALDER-Circ, ~ 1.5 cm)

→ Scaling laws of the blowout regime

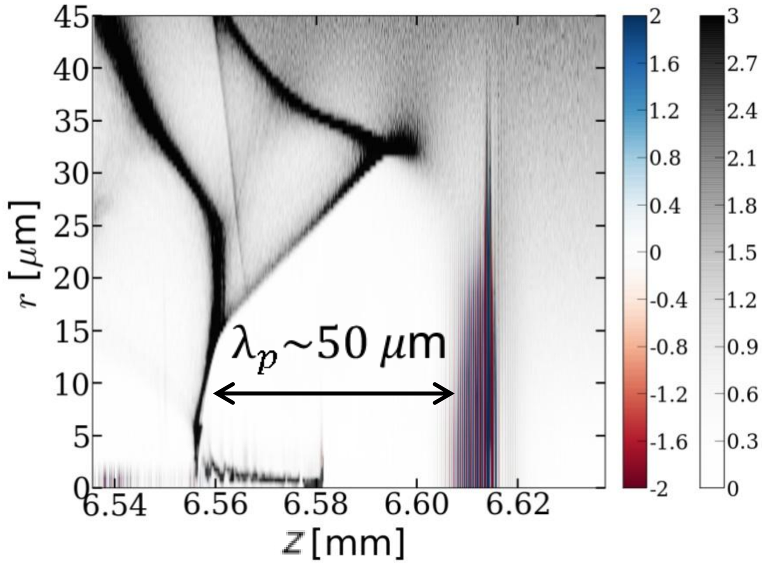
PARAMETERS

$E_0 = 15$ J $\quad W_0 = 23\ \mu$m

$\tau_0 = 30$ fs $\quad a_0 = 6$

1^{st} stage

$n_e = 1.75 \times 10^{18}$ cm^{-3}



- Results after 1.5 cm:
  - Quasi-monoenergetic beam
  - Energy ~ 1.8 GeV
  - Charge ~ 5 nC > 350 MeV

1^{ST} STAGE: LASER DEPLETION AND TRANSITION TO PLASMA WAKEFIELD

1st stage: Laser wakefield acceleration of electrons (CALDER-Circ, ~ 1.5 cm)

→ Scaling laws of the blowout regime

1.5 cm: depletion of the laser pulse
Slow transition toward plasma wakefield regimes

PARAMETERS

$E_0 = 15$ J $\quad W_0 = 23\ \mu$m

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1st stage

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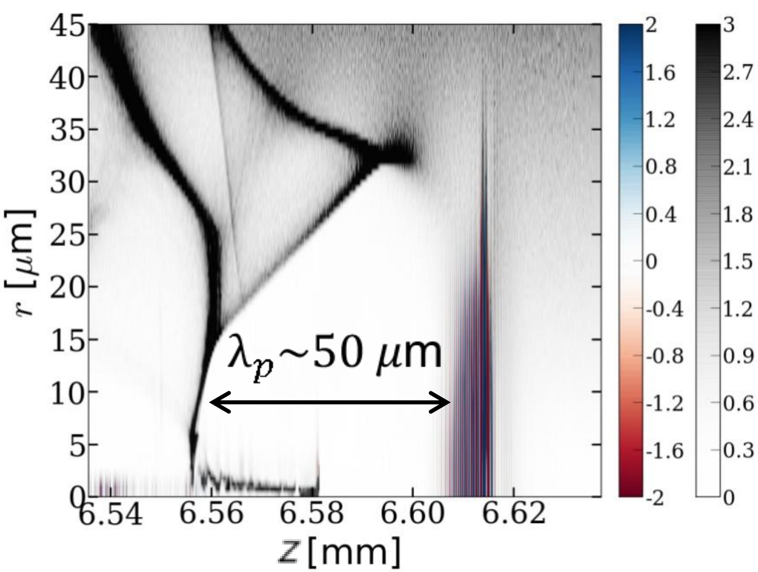
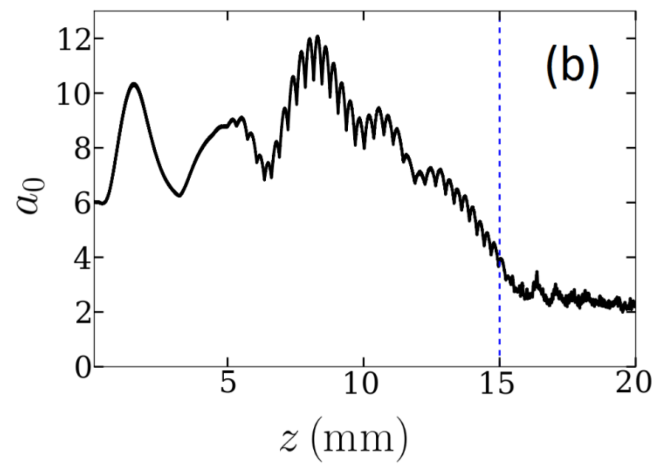




2^{ND} STAGE: GENERATION OF A PLASMA WAKEFIELD

1st stage: Laser wakefield acceleration of electrons (CALDER-Circ, ~ 1.5 cm)

→ Scaling laws of the blowout regime

2nd stage: X-ray emission in a plasma wakefield regime (CALDER 3D, ~ 3 mm)

→ $n_e < n_{beam}$

PARAMETERS

$E_0 = 15$ J $\quad W_0 = 23\ \mu$m

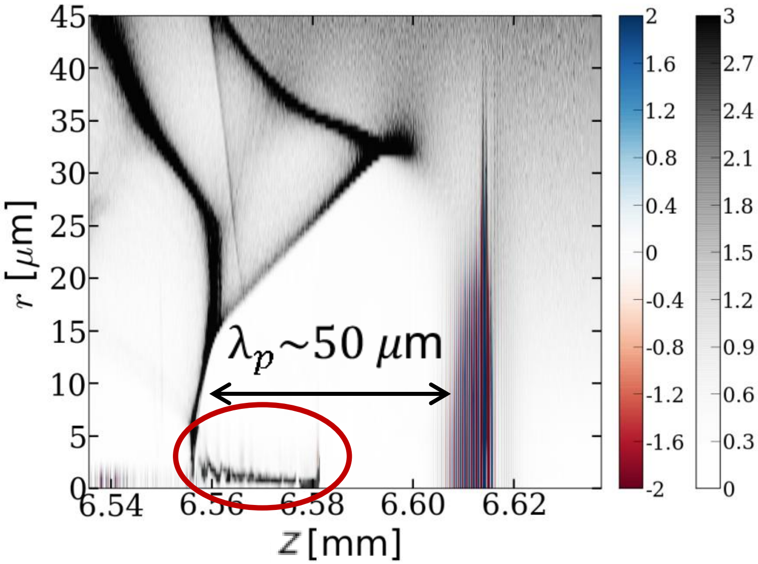
$\tau_0 = 30$ fs $\quad a_0 = 6$

1st stage

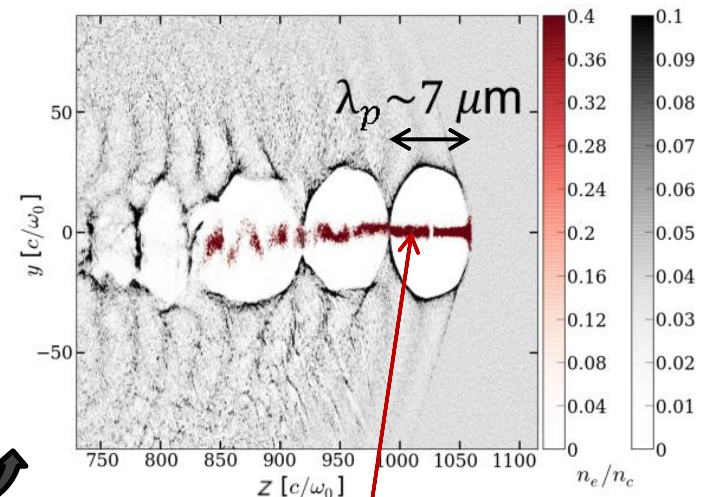
$n_e = 1.75 \times 10^{18}$ cm^{-3}

2nd stage

$n_e = 1.1 \times 10^{20}$ cm^{-3}

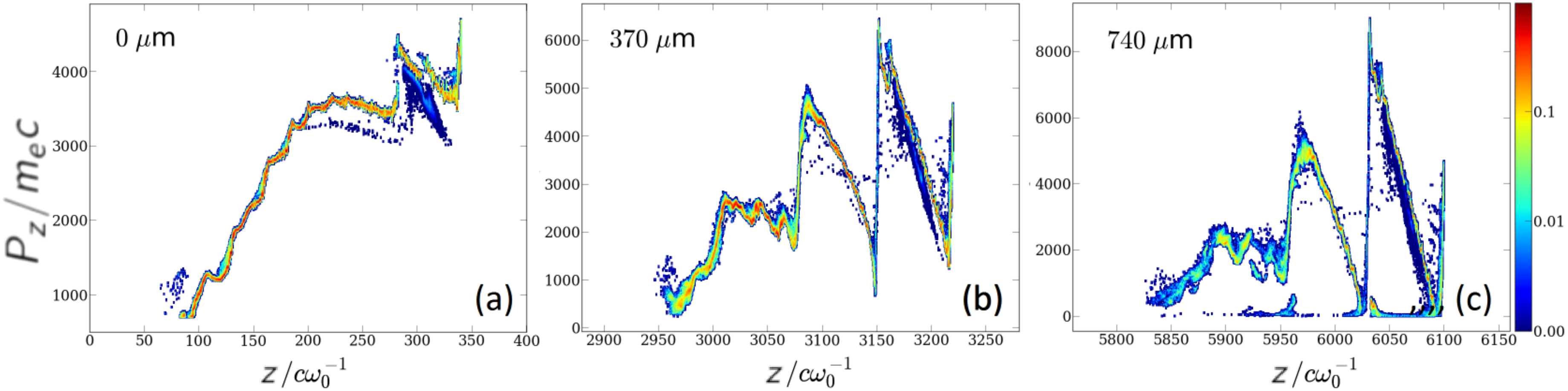


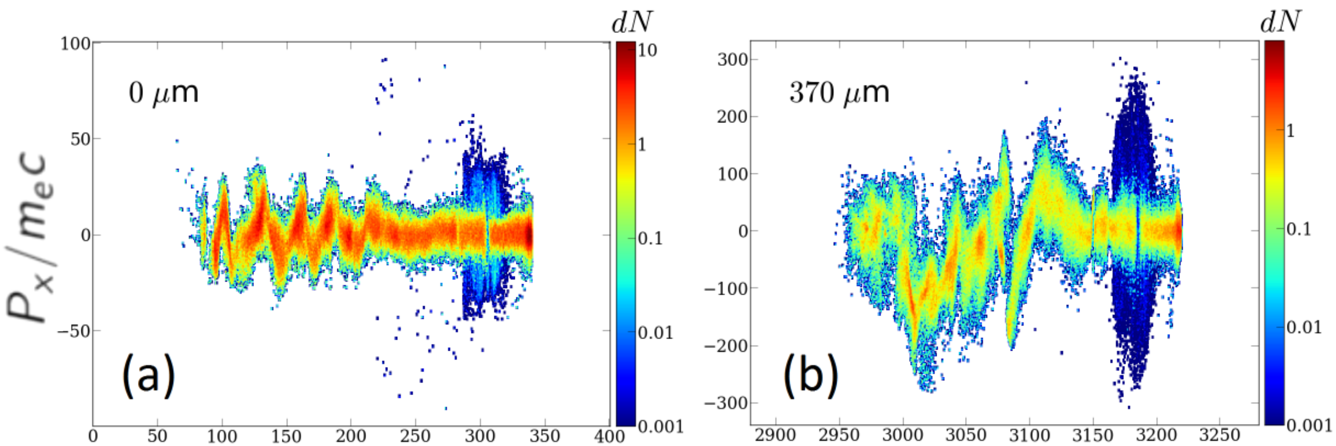
$n_e \times 60$



charge ~ 5 nC

PLASMA WAKEFIELD: PHASE SPACE MODULATION AND INCREASE OF THE TRANSVERSE MOTION





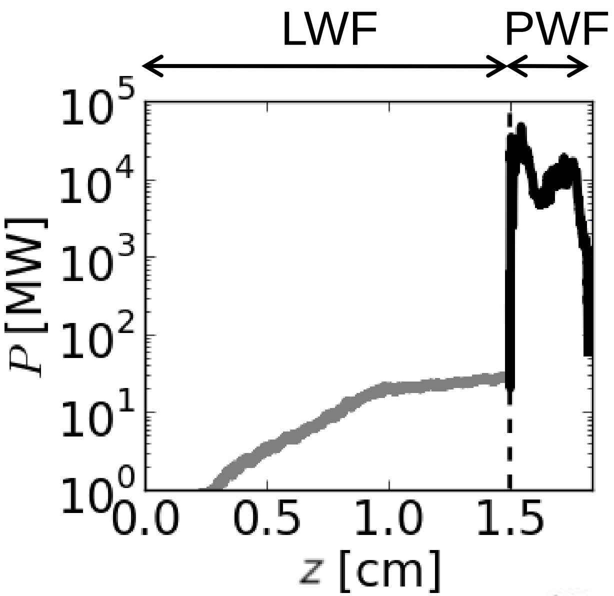
- High-amplitude wakefield

$\rightarrow$ $E_z > 2.5$ TeV/m

- Modulation of the phase-space

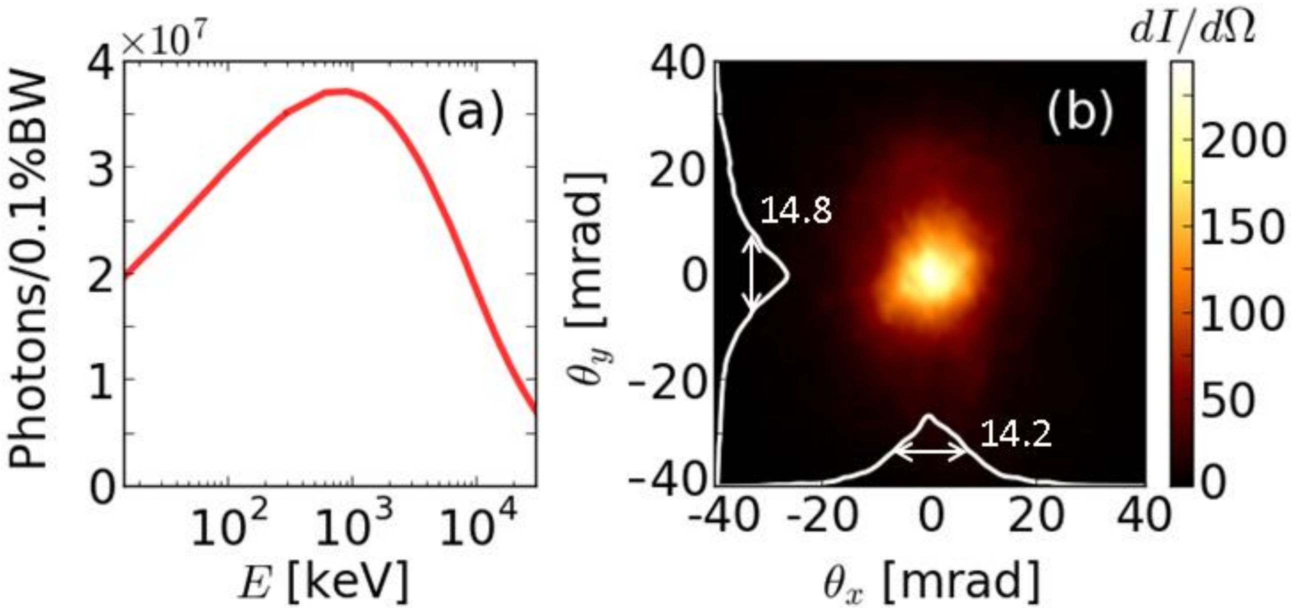
$\rightarrow$ Enhancement of the transverse motion in the 2nd stage

MEV-BETATRON SOURCE GENERATED IN THE PLASMA WAKEFIELD STAGE

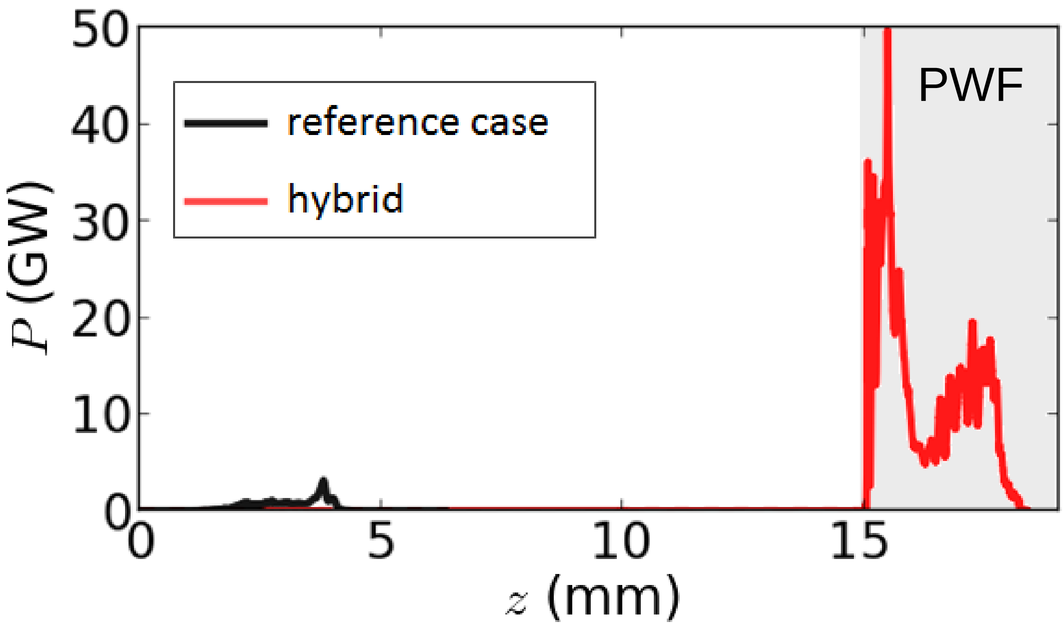


After 3.3 mm in the 2nd stage:

- 90 % of the beam energy is depleted
- P_{rad} increases by 3 orders of magnitude
- $E_c = 9$ MeV
- $B = 4 \times 10^{23}$ phot/s^{-1}/mm^2/mrad^2/0.1%BW



BETATRON SOURCE: 1 STAGE SCHEME VS 2 STAGES SCHEME



- Comparison with a reference case:
  - single stage
  - $n_e = 1 \times 10^{19}$ cm^{-3}
  - 5 mm target

Setup	1 stage	2 stages
E_c	240 keV	9 MeV
E_{rad}	7.5 mJ	140 mJ
η	0.05 %	0.9 %

CONCLUSION

- Improvement of the betatron source energy

  → Emission in the multi-MeV domain with sub-PW class lasers

  → New applications for betatron sources (gammagraphy…)

- No additionnal source of energy in the beam-driven stage

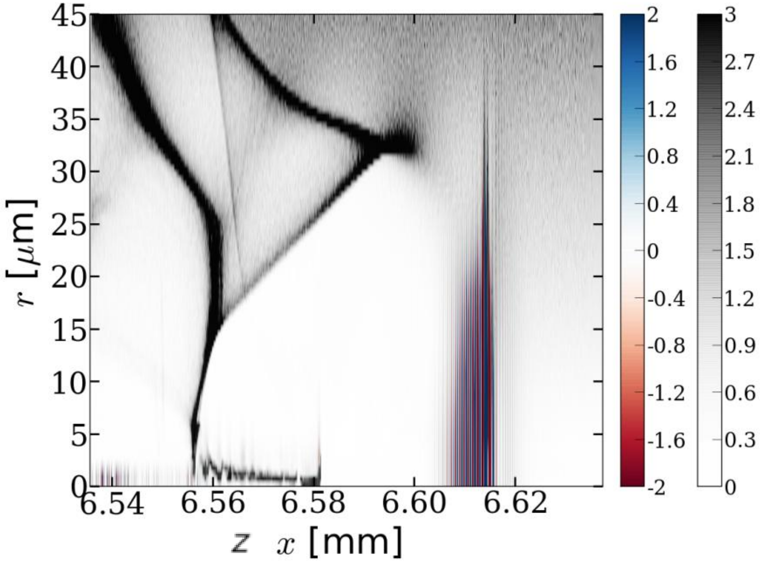
  → Increase of the betatron source efficiency

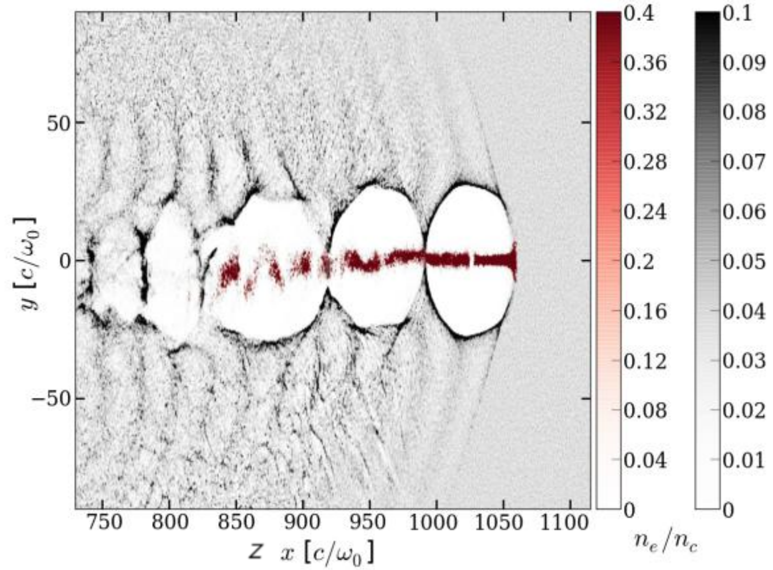
- Requirements : high current and small transverse size.

  → Laser power must be high enough

  → Lower efficiency for low-energy laser systems

NUMERICAL PARAMETERS





CALDER 3D	
Box size (cells)	$800 \times 200 \times 200$
Δz	$0.5\ c/\omega_0$
$\Delta x,\ \Delta y$	$0.5\ c/\omega_0$
Δt	$0.288\ \omega_0^{-1}$

CALDER Circ	
Box size (cells)	3200×200
Δz	$0.25\ c/\omega_0$
Δr	$4\ c/\omega_0$
Δt	$0.249\ \omega_0^{-1}$

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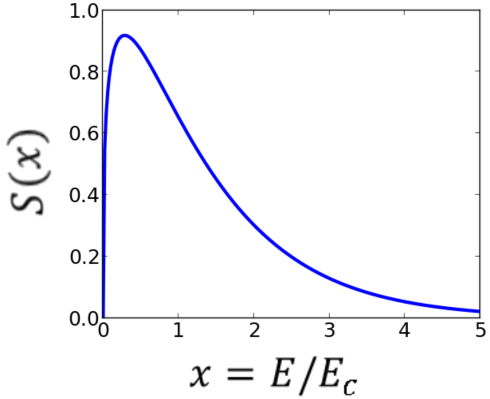

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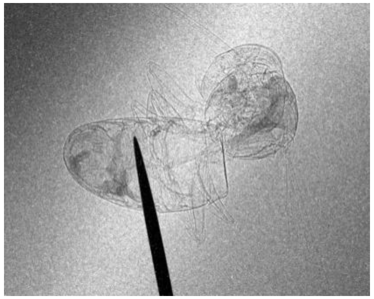

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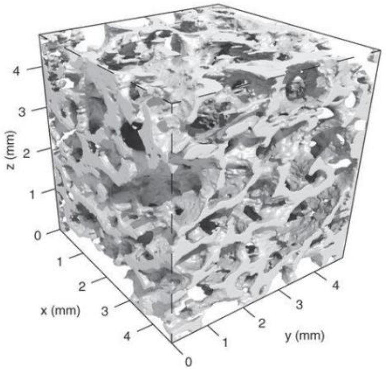

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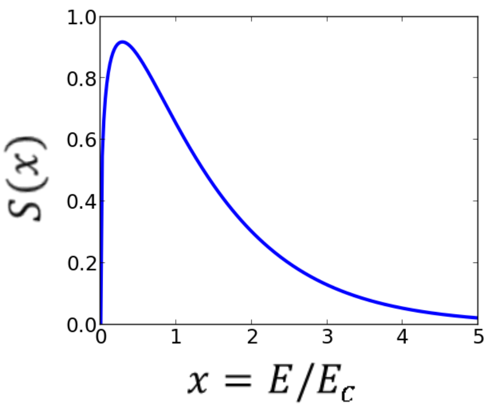

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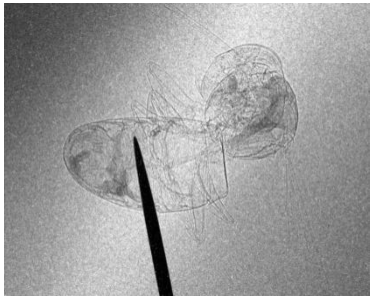

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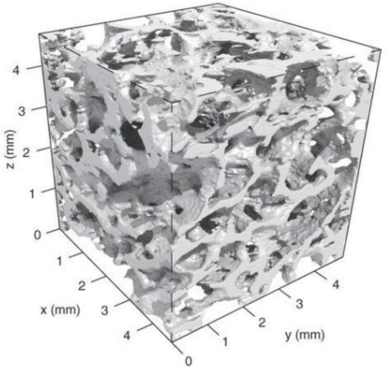

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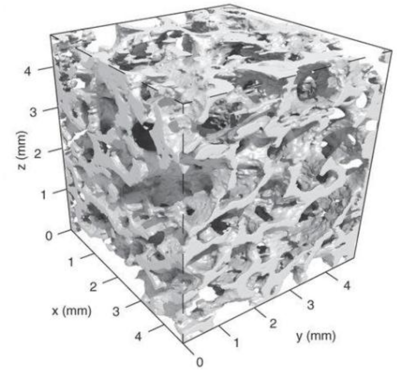

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- 7 mm-thick bones
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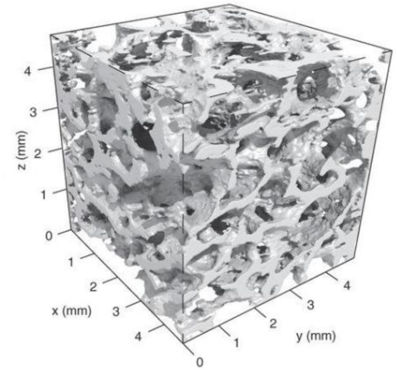

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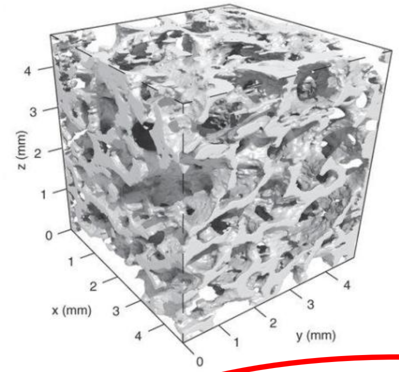

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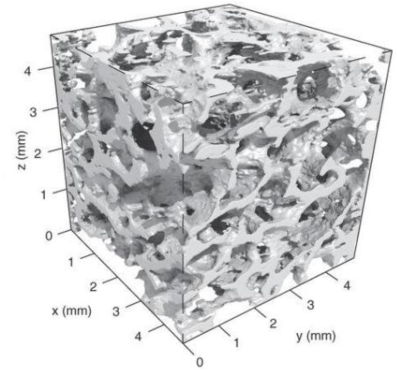

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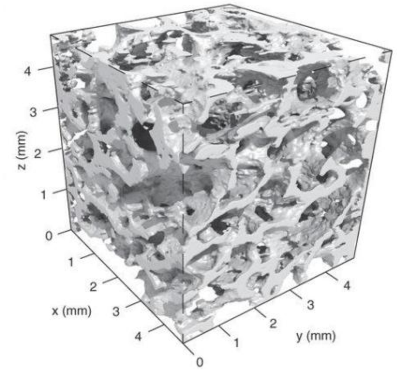

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