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

J. FERRI¹,²,³, S. CORDE³, A. DÖPP⁴, A. LIFSCHITZ³, A. DOCHE³, C. THAURY³, K. TA PHUOC³, B. MAHIEU³, I. ANDRIYASH⁵, V. MALKA³,⁶, X. DAVOINE²

¹Department of Physics, Chalmers University of Technology, SE-41296 Göteborg, Sweden
²CEA DAM DIF, 91297 Arpajon, France
³LOA, ENSTA ParisTech, CNRS, Ecole polytechnique, Université Paris-Saclay, 91762 Palaiseau, France
⁴Ludwig-Maximilians-Universität München, Fakultät für Physics, Am Coulombwall 1, Garching 85748, Germany
⁵Synchrotron SOLEIL, l’Orme des Merisiers, Saint Aubin, 91192 Gif-sur-Yvette, France
⁶Department of Physics and Complex Systems, Weizmann Institut of Science, Rehovot, Israel

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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


tomography

INTRODUCTION

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How can we further improve these sources?

\[ E_c, N_X \]

\[ E_c \text{ [keV]} = 5.2 \times 10^{-21} \gamma^2 n_e [\text{cm}^{-3}] r_\beta [\mu\text{m}] \]

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- DLA enhancement

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- Blowout regime
  \[ L_{depl} = L_{deph} \]
  density is imposed

Problem for betatron!
• **One stage acceleration**: impossible to both optimize electron energy and density.

  ![arrow] Compromise has to be found in the experiment

• **Our proposition**: Decouple electron acceleration and X-ray emission in two different stages.
A TWO-STAGE SCHEME FOR BETATRON EMISSION

- **One stage acceleration**: impossible to both optimize electron energy and density.
  
  Compromise has to be found in the experiment

- **Our proposition**: Decouple electron acceleration and X-ray emission in two different stages.
  
  - 1st stage: low density
  
  - 2nd stage: high density $\gamma n_e$

![Diagram showing two stages of acceleration with density and distance labels.](image)
• **One stage acceleration**: impossible to both optimize electron energy and density.

  Compromise has to be found in the experiment

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

  • 2nd stage: high density

  - laser depletion: \( L_d \propto 1/n_e \)

  - High energy laser?

  Plasma wakefield regime

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

15 J, 30 fs laser pulse

15 mm-long, low-density plasma
\[ n_e = 1.75 \times 10^{18} \text{ cm}^{-3} \]

Laser-driven Plasma Accelerator

3.3 mm-long, high-density plasma
\[ n_e = 1.1 \times 10^{20} \text{ cm}^{-3} \]

Electron Beam-driven Plasma Radiator

PWFA

MeV betatron source

Weakened electron beam
**1ST STAGE: LWFA WITH A 0.5 PW LASER**

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

Scaling laws of the blowout regime

<table>
<thead>
<tr>
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<td>$E_0 = 15$ J</td>
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- Results after 1.5 cm:
  - Quasi-monoenergetic beam
  - Energy ~ 1.8 GeV
  - Charge ~ 5 nC > 350 MeV
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
- $W_0 = 23$ $\mu$m
- $\tau_0 = 30$ fs
- $a_0 = 6$
- $n_e = 1.75 \times 10^{18}$ cm$^{-3}$
2^{nd} STAGE: GENERATION OF A PLASMA WAKEFIELD

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

- Scaling laws of the blowout regime

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

- $n_e < n_{beam}$

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<td>$\tau_0$</td>
<td>30 fs</td>
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<tr>
<td>$a_0$</td>
<td>6</td>
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1^{st} stage

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

2^{nd} stage

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

charge ~ 5 nC

$\lambda_p \sim 7 \mu$m
High-amplitude wakefield

$E_z > 2.5$ TeV/m

Modulation of the phase-space

Enhancement of the transverse motion in the 2$^{nd}$ stage
After 3.3 mm in the 2\textsuperscript{nd} 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\textsuperscript{-1}/mm\textsuperscript{2}/mrad\textsuperscript{2}/0.1\%BW
Comparison with a reference case:
- single stage
- \( n_e = 1 \times 10^{19} \text{ cm}^{-3} \)
- 5 mm target

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<thead>
<tr>
<th>Setup</th>
<th>1 stage</th>
<th>2 stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_c )</td>
<td>240 keV</td>
<td>9 MeV</td>
</tr>
<tr>
<td>( E_{rad} )</td>
<td>7.5 mJ</td>
<td>140 mJ</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.05 %</td>
<td>0.9 %</td>
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CONCLUSION

• Improvement of the betatron source energy
  ➡️ Emission in the multi-MeV domain with sub-PW class lasers
  ➡️ New applications for betatron sources (gammagrapy…)

• 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**

<table>
<thead>
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</tr>
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<tbody>
<tr>
<td>Box size (cells)</td>
<td>$800 \times 200 \times 200$</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>$0.5 \ c/\omega_0$</td>
</tr>
<tr>
<td>$\Delta x, \Delta y$</td>
<td>$0.5 \ c/\omega_0$</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>$0.288 \omega_0^{-1}$</td>
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**CALDER Circ**

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<tr>
<td>$\Delta z$</td>
<td>$0.25 \ c/\omega_0$</td>
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<tr>
<td>$\Delta r$</td>
<td>$4 \ c/\omega_0$</td>
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<td>$\Delta t$</td>
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- Laser: 11 J
- 7 mm-thick bones
- time exposure: 2h
MOTIVATIONS: HOW TO IMPROVE THE BETATRON SOURCE

- Medical applications (radiography for cancer detection)
- Thicker tissues
- Shorter time exposure
- Laser: 11 J
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- time exposure: 2h
- Higher photon energy
- Higher number of photons
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