Simulation of a brilliant betatron gamma-ray source from a two-stage wakefield accelerator

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Laser
\[10^{19} \text{ W/cm}^2\]
5 fs – 100 fs
> 1J – 10 TW

gas target
(mm – cm)

Electron beam
MeV – GeV
pC – nC
short (fs)
Small size (µm)

LWFA generates X-ray Betatron source
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Betatron source
- Synchrotron-type radiation
- $K \gg 1 \Rightarrow$ Broadband spectrum
- keV – few keV
- Short (fs)
- Small source size ($\mu$m)
- High brilliance
Betatron source: principle and motivations

**Laser**
- $10^{19}$ W/cm²
- 5 fs – 100 fs
- > 1J – 10 TW

**Gas target** (mm – cm)

**Phase contrast imaging**


**Tomography**


**Time-resolved X-ray spectroscopy**

B. Mahieu et al., submitted
Betatron source: Interest for a 2-stage scheme

\[
\begin{align*}
P_{rad} & \propto K^2 \gamma n_e \\
E_c & \propto K \gamma \sqrt{n_e} \\
F_y & \propto r n_e
\end{align*}
\]
Laser Wakefield accelerator: $\Delta E \propto n_e^{-1}$

=> a compromise on the density used is needed

**idea**: the source performance could benefit from a decoupling between the acceleration (low $n_e$) and radiation (high $n_e$) parts => 2-stage scheme.

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\end{align*}$$
Two-stage scheme with a beam-driven plasma radiator to boost the betatron radiation

15 J, 30 fs laser pulse

1st STAGE

LWFA

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

Electron Beam-driven Plasma Radiator

2nd STAGE

PWFA

High-energy electron beam

Weakened electron beam

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

Laser-driven Plasma Accelerator

Simulation with CALDER CIRC

Acceleration optimization (low $n_e$)

Radiation optimization (High $n_e$)

Simulation with CALDER 3D

J. Ferri et al., PRL 120, 254802 (2018)
Simulation of the two-stage scheme: Efficient beam-driven regime in the second stage

**Laser:**
- $a_0 = 6$
- $\tau_0 = 30$ fs
- $W_0 = 23 \mu m$
- $E_0 = 15$ J

**Beam:**
- Acc. on 1.5 cm
- $\sim 1.8$ GeV
- $\sim 5$ nC ($> 350$ MeV)

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

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

Laser:

\[ E_{\text{las}} \left( \frac{m_c \omega_0}{e} \right) \frac{n_e}{n_c} \]

Beam:

\[ a_0 = \text{peak amplitudes} \]

\[ E(z) - \text{energy profile} \]

\[ E(z) > 2.5 \text{ TeV/m} \]
Production of a MeV-photon source with short duration and small source size

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
$n_e \times 60 \rightarrow$ radiated power boosted by 3 orders of magnitude

$$P_{\text{rad}} \propto K^2 \gamma n_e$$

$$K \equiv \frac{p_{\text{max}}}{m_e c} \propto \sqrt{\gamma n_e r_{\text{max}}}$$

$$P_{\text{rad}} \propto r_{\text{max}}^2 \gamma^2 n_e^2$$

Best case: $L_{\text{grad}} \ll \lambda_{\beta}$

$\lambda_{\beta} \sim 300 \, \mu m$ @ 1.5 GeV

$L_{\text{grad}} = 25 \, \mu m$

$L_{\text{grad}} \gg \lambda_{\beta} \Rightarrow P_{\text{rad}} \propto n_e \Rightarrow$ Lower gain

$n_e \times 60 \Rightarrow P_{\text{rad}} \times 60^2$
Improved performances compared with a 1-stage case

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

<table>
<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>
</tr>
</tbody>
</table>
Limit: high beam density required

High current and tightly focused beam needed.

\[ Q \sim 5 \text{ nC} \quad \sigma_x \sim 30 \text{ \(\mu\)m} \quad \sigma_r \sim 1 \text{ \(\mu\)m} \]

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\[ I \sim 50 \text{ kA} \quad \& \quad n_b \sim 3.3 \times 10^{20} \text{ cm}^{-3} = 3n_e \]

Condition for an efficient beam-driven regime (2\textsuperscript{nd} stage):

\[ n_e < n_b \]
Brilliant MeV betatron source from a 2-stage WFA.

2nd stage: beam-driven (PWFA) blowout regime
- High current needed \((n_b > n_e)\)

Proof-of-principle simulation (15 J, 30 fs)
- \(E_c = 9 \text{ MeV}\)
- \(B = 4 \times 10^{23} \text{ s}^{-1} \text{mm}^{-2} \text{mrad}^{-2}/0.1\% \text{BW} \quad @ \ 1 \text{ MeV}\)
- High efficiency (0.9 %)

New applications for betatron sources
- Gammagraphy
- Photo-nuclear reactions
- ...

J. Ferri et al., PRL 120, 254802 (2018)