Case 5: FEL Driven by Plasma Injector

Roxana Tarkeshian (Paul Scherrer Institut) on behalf of Group 10

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<thead>
<tr>
<th>Name</th>
<th>First Name</th>
<th>Institution</th>
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<tr>
<td>Stoll</td>
<td>Christian</td>
<td>Johannes Gutenberg-Universitaet Mainz</td>
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<tr>
<td>Ushakov</td>
<td>Andriy</td>
<td>Helmholtz Zentrum Berlin</td>
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<tr>
<td>Wei</td>
<td>Tao</td>
<td>European XFEL GmbH</td>
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<td>Winkelmann</td>
<td>Lutz</td>
<td>DESY</td>
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<td>Wissmann</td>
<td>Jan</td>
<td>Institut fuer Kernphysik</td>
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<tr>
<td>Wolff-Fabris</td>
<td>Frederik</td>
<td>European XFEL GmbH</td>
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Overview

LPAs electron beam

- High energy: 1GeV
- High peak current: 10kA
- Low emittance: 0.2mm.mrad
- Energy spread: few % level

Goal

- Development of compact FELs (radiation: GW, fs, coherence)

Overview

Challenge

- large *energy spread* of short-wavelength FEL amplification

Beam manipulation to reduce slice energy spread:

- High peak current
- Longitudinal decompression
- Transverse gradient undulator,
  (It will be presented by Tao 😊)
Laser Plasma Accelerator: laser pulses on a gas target

Gas Targets
Gas jet, gas cell, discharged guiding channel
1mm to 10cm in length
density $\sim 10^{16}-10^{18}$ cm$^{-3}$

Accelerating + focusing fields
Trapped electron orbit
Ponderomotive force

W. Leeman
Laser plasma accelerators (LPAs) are compact and produce femtosecond relativistic e-beams

- Ionization
- Ponderomotive push $\rightarrow$ charge separation
- Ions pull back electrons $\rightarrow$ charge oscillation
- Strong accelerating fields propagate w/ laser
- Electrons externally- or self-injected
- Acceleration to GeV in mm’s

B.A. Shadwick et al., IEEE PS. 2002

T. Tajima and J. Dawson, PRL, 43, 267 (1979)
Esarey et al., RMP 81, 1229 (2009)
FEL application: LPA 6D electron beam brightness comparable to conventional sources

Beam brightness: \[ B_{6D} = \frac{N}{\varepsilon_n x \varepsilon_n y \varepsilon_n z} \approx \frac{(I/I_A)}{r_e \varepsilon_n^2 \sigma_\gamma} = b_6 \lambda_c^{-3} \]

- **LPA (~cm)**
  - \( \varepsilon_N = 0.1 \) micron
  - 1 GeV
  - 1-3% energy spread
  - \( I = 3 \) kA (~10 fs)
  - \( b_6 \sim 10^{-12} \)

- **LCLS (~km)**
  - \( \varepsilon_N = 0.4 \) micron
  - 13.6 GeV
  - 0.01% energy spread
  - \( I = 3 \) kA
  - \( b_6 \sim 10^{-12} \)

- **FEL application requires post-LPA e-beam phase-space manipulation (redistribution)**
  - Emittance exchange
  - Phase-space redistribution:
    - Longitudinal decompression (with tapered undulator)
    - Transverse dispersion (with transverse gradient undulator)
The proposed electron beam and machine parameters

<table>
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<tr>
<th>Power gain model used:</th>
<th>Xie</th>
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**Beam parameters:**

- **Beam Energy [GeV]:** 0.300
- **Bunch charge [nC]:** 0.04
- **Beam size [μm]:** 26.339
- **Undulator parameters:**
  - **Type:** Hybrid with NdFeB
  - **Period [mm]:** 19
  - **Peak field [T]:** 0.718
  - **FODO period [m]:** 4
  - **Quadrupole focal length [m]:** 0.999
- **Radiation parameters:**
  - **Radiation wavelength [nm]:** 50.06

**Input data set:** none

**Input data set:** none

**Energy Spread [MeV]:** 3

- **Beam Power [TW]:** 3
- **#Bunches/sec.:** 1
- **Geometry:** planar
- **Length [m]:** 4
- **Bessel factor J0-J1:** 0.876
- **Quadrupole Length [m]:** 0.1
- **beta_max/beta_min:** 120.783

**Average beta-function [m]:** 2.033

**Photon Energy [eV]:** 24.776

- **1D gain length [m]:** 0.06
- **3D gain length [m]:** 0.173
- **Saturation power [GW]:** 8.481
- **Effective Energy spread:** 3.927
- **Divergence (FWHM) [μrad]:** 356.18
- **Photons per Pulse:** 0.043E14
- **Peak Brilliance:*:** 3.415E30
- **Average Brilliance:*:** 0E21
- **SR Energy spread [MeV]:** 0

**Saturation length [m]:** 3.48

**Power at undulator exit [GW]:** 8.511

- **Diffraction parameter:** 2.1
- **Bandwidth (FWHM) [%]:** 1.19
- **Autocorrelation time [fs]:** 9.329
- **Pulse Energy [mJ]:** 0.017

**1D rho parameter (Bonifacio):** 0.01441

- **3D rho parameter:** 0.005046
- **Shotnoise power [W]:** 140.641
- **Electrons per wavelength:** 10429167
- **Spotsize at exit (FWHM) [μm]:** 62.02
- **Pulse duration (FWHM) [fs]:** 1.88
- **Peak Flux [#/sec.]:** 21.394E26
- **Average Flux [#/sec.]:** 0E18
- **SR Energy loss [MeV]:** 0.00001
Higher peak current to overcome the impact of 1% energy spread

Disadvantage: Space charge force!
Space charge effect

• The major space-charge induced effect on the bunch scale is the buildup of a longitudinal energy chirp.
• Electrons at the bunch head get accelerated while electrons at the bunch tail get decelerated. This energy modulation can reduce the efficiency of the FEL process.
• To maintain the FEL performance the width of the detuning range traversed by a photon during one gain length has to be smaller than the Pierce parameter.
Dispersion of e-beam will mitigate slice energy spread

Key requirements
- Sub-% energy spread required for lasing slice
- Disperse/stretch electron beam
  (although, gain length $\sim I_{pk}^{-1/3} \sim n^{1/3}$)

DESY (Germany), LUNEX5 (France), LBNL (USA), and others

Transverse Gradient Undulator

TGU to reduce the sensitivity to electron energy variation for FEL oscillator

Higher energy electrons are dispersed to the higher field region to match FEL resonant condition.
Stretching the bunch transversely

- Such a big energy spread cause different wavelength;
- How to compensate? K varied with energy also.

\[ \lambda_r = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right) \]

- Transverse Gradient Undulator (TGU) introduced at dispersion section. Resonance can be satisfied for all beam energies if

\[ x = \eta \frac{\Delta \gamma}{\gamma_0} \]

\[ \frac{\Delta K}{K_0} = \alpha x \]

\[ \eta = \frac{2 + K_0^2}{\alpha K_0^2} \]
• The influence of energy spread can be well compensated by TGU placed at finite dispersion;

• But the beam cross sectional area changed. In comparison with energy spread, such an impact is more slightly;

\[ \rho = \frac{1}{2\gamma} \left[ \frac{I}{I_A} \left( \frac{\lambda_u K f_B}{2\pi \sigma_x} \right)^2 \right]^{1/3} \]

• The design of TGU-FEL is a compromise between FEL performance and undulator technique & beam transport.
- 5 quadrupoles + 1 bending magnet used to transport electron beam;
- 5m long transverse gradient undulator, the average beta function is \(~4.5m\), the dispersion is 0.024m;
- **External coil used to compensate 1\textsuperscript{st} and 2\textsuperscript{nd} magnetic field integral caused by the TGU.**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
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<tbody>
<tr>
<td>Beam energy (MeV)</td>
<td>300</td>
</tr>
<tr>
<td>Normalized transverse emittance (μm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak current (kA)</td>
<td>5</td>
</tr>
<tr>
<td>Rms energy spread</td>
<td>1%</td>
</tr>
<tr>
<td>Injection Twiss parameter β (m)</td>
<td>0.01</td>
</tr>
<tr>
<td>Undulator type</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Undulator length (m)</td>
<td>5</td>
</tr>
<tr>
<td>Undulator period (mm)</td>
<td>20</td>
</tr>
<tr>
<td>Average beta function in TGU (m)</td>
<td>4.5</td>
</tr>
<tr>
<td>Horizontal dispersion η in TGU (m)</td>
<td>0.024</td>
</tr>
<tr>
<td>TGU maximum transverse gradient α (m⁻¹)</td>
<td>100</td>
</tr>
<tr>
<td>External compensate field (gauss)</td>
<td>2</td>
</tr>
<tr>
<td>TGU gap adjust range (mm)</td>
<td>7.8 ~ 4.8</td>
</tr>
<tr>
<td>Undulator parameter K</td>
<td>1.2 ~ 2.2</td>
</tr>
<tr>
<td>Central peak field (T)</td>
<td>0.64 ~ 1.18</td>
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</table>
• Gain length $L_g$ calculated from Ming Xie model (without TGU);
• Gain length $L_{gT}$ calculated from the upper formula (with TGU);
• For our case, the gain length is $\sim 0.25\text{m}$, the saturation length is $\sim 5\text{m}$. 
Halbach-type hybrid undulator with cant angle

e.g., $\phi = 14$ deg, $\lambda_u = 2$ cm, $g = 7.8$ mm

$= 100 \text{ m}^{-1}$
## Summary of suggested schemes for mitigation of energy spread

<table>
<thead>
<tr>
<th>Schemes</th>
<th>Comments</th>
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<tr>
<td>Longitudinal decompression</td>
<td>Compromise between peak current drop and energy spread suppression</td>
</tr>
<tr>
<td>Higher Peak current</td>
<td>Space charge effects and loss of emittance control. Increase of FEL parameter but dependence is too weak!</td>
</tr>
<tr>
<td>Transverse decompression</td>
<td>The beam can lase independently in the different transverse locations and hence looses spatial coherence. This will lead to a multimode beam that is less focusable and has reduced coherent flux.</td>
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</table>
Thank you slide!

- Thank you Sven for fruitful discussions! 😊

Thanks for your attention!
Case 5 – FEL driven by Plasma Injector

• Goal: *Use the output from a plasma injector to drive an FEL in the UV range.*

• Background: The non-linear regime of a laser driven plasma channel can generate a relativistic electron beam with small emittance but rather large energy spread. They can potentially shorten the classical RF injector and accelerator of FEL facilities down to a few meters.

• Approach: Experiments have shown promising beam parameters with a current of hundreds of Amperes, small emittances of about 100 to 200 nm but an relative energy spread of 1% at a beam energy of several hundreds of MeV. The practical limit to apply the beam to an FEL is its large energy spread.
With an expected energy spread of about 1% discuss the methods to overcome this limitation by

1. Stretching the bunch longitudinally, where the energy spread decreases linearly with the decompression but the FEL parameter only with its cubic root
2. Stretching transversely with dispersion and apply a transverse gradient to the undulator field.

Propose possible configuration of the machine layout for both methods. Discuss possible limitation in the wavelengths with any of the methods.

An alternative approach is to generate much higher peak current to overcome the impact of 1% energy spread. What is the minimum current to allow lasing at 300 MeV and a wavelength of 50 nm. Discuss the impact on longitudinal space charge.
FEL equations

Spread in the average beam energy

- spread in resonant condition and degrading FEL gain

\[ \lambda_r = \frac{\lambda_u}{2\gamma_0^2} \left( 1 + \frac{K_0^2}{2} \right). \]

High-Gain FEL requirements:

\[ \sigma_\delta = \frac{\sigma_\gamma}{\gamma_0} \ll \rho = \left[ \frac{1}{16} \frac{I_0}{I_A} \frac{K_0^2[JJ]^2}{\gamma_0^3 \sigma_x^2 k_u^2} \right]^{1/3}, \]