Design of the Thomson Source at SPARC/PLASMONX for incoherent and coherent X-rays

Luca Serafini - INFN/MI - on behalf of SPARC & PLASMONX Team

• The PLASMON-X Project: a marriage between the SPARC high brightness electron beam and a high intensity laser beam

  Design and acquisition of a 200 TW Ti:Sa laser system for Plasma and IFEL acceleration exp. and a Thomson Source for monochromatic X-rays
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• Coherent X-Rays at 1 Å from Thomson Sources as classical SASE-FELs or Quantum FELs (see also Maroli’s and Piovella’s talks in WG3)
• The PLASMON-X Project: a marriage between the SPARC high brightness electron beam and a high intensity laser beam for Plasma and IFEL acceleration, and a Thomson Source for monochromatic X-rays

• Coherent X-Rays at 1 Å from Thomson Sources as classical SASE-FELs or Quantum FELs (see also Maroli’s and Piovella’s talks in WG3)
(PLasma Acceleration at Sparc & MONochromatic X-rays)

IS BASED ON THE MARRIAGE BETWEEN:

High Brightness Electron Beams
(from 10’s fs to a few ps bunch length)

High Intensity Laser Beams
(30-100 fs pulses)

\[ B_n \equiv \frac{cQ_b}{\sigma_z \varepsilon_{nx} \varepsilon_{ny}} > 10^{15} \left[ \frac{A}{m^2 \text{rad}^2} \right] \]

\[ I > 10^{19} \left[ \frac{W}{cm^2} \right] \]
IS THE FIRST INGREDIENT

Under INFN responsibility

(see also Daniele Filippetto’s talk in WG4)

Under ENEA responsibility
IS THE FIRST INGREDIENT

Under INFN responsibility
(see also Daniele Filippetto’s talk in WG4)

Under ENEA responsibility

GOALS

Generation of 30-150 MeV e⁻ beams

(Q, \(\sigma_t\), \(\varepsilon_n\), \(\Delta\gamma/\gamma\))

Phase 1) 1 nC, 3 ps, 1 \(\mu\)m, \(10^{-3}\)
Phase 2) 1 nC, 300 fs, 2 \(\mu\)m, \(2\cdot10^{-3}\)
PLASMONX) 20 pC, 60 fs, 0.3 \(\mu\)m, \(2\cdot10^{-3}\)
Frascati Laser for Acceleration and Multidisciplinary Experiments (FLAME)
SPARC Building Complex
ICFA FLS-2006 Workshop - DESY, May 18th 2006

**Section view**

Canvas Tent
Storage Area

SPARC bunker
e-beam

New building

FLAME beam

HILL vacuum chamber

**Lab. 100TW**

**FLAME**

**HILL**

**Top view**

SPARC bunker

New building

LWFA with **self-injection** + Thomson scattering

LWFA with **external injection** + Thomson scattering
<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength</th>
<th>Delivered energy</th>
<th>Duration</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 CPA Ti:Sa</td>
<td>0.8 micron</td>
<td>5J</td>
<td>50fs</td>
<td>&gt;10^6</td>
</tr>
<tr>
<td>Phase 2 CPA Ti:Sa with OPCPA</td>
<td>0.8 micron</td>
<td>5J</td>
<td>30fs</td>
<td>&gt;10^8</td>
</tr>
</tbody>
</table>
Schematic layout

- Photoinjector
- RF sections
- solenoid
- quadrupoles
- dipoles
- RF deflector
- collimator

1.5 m
10.0 m
5.4 m
14.5 m
25°
11°

1-6 Undulator modules
Diagnostic
M. Ferrario, ICFA LBI-LPA 2005 Workshop, Taipei

\[ Q = 20 \text{ pC} \]

after compression \( \sigma_z = 25 \text{ \mu m} \), \( \Delta \gamma / \gamma = 0.2\% \), \( \varepsilon_{nx} < 0.3 \text{ \mu m} \)
**Bunch slicing**

- $Q = 1\,\text{nC} \implies 25\,\text{pC}$
- $L_b = 10\,\text{ps} \implies 100\,\text{fs}$
- $\sigma_x = 0.5\,\text{mm} \implies 5\,\mu\text{m}$
- $\Delta\gamma/\gamma < 0.2\%$

**Measurements**

- RF sections
- 10.0 m
- 5.4 m
- 14.5 m
- Diagnostics
- 1-6 Undulator modules
beam energy distribution at start/end of the beam line

60 fs bunch (initially uncompressed) -> 10 fs with RF compression, i.e. by combining velocity bunching and bunch-slicing
Experimental set-up for the generation of tunable X-ray radiation via Thomson scattering of optical photons by relativistic electron bunches.
THOMSON BACK-SCATTERING

\begin{align*}
\nu_T &= \nu_0 \frac{1-\beta \cos \alpha_L}{1-\beta \cos \theta} \approx \nu_0 \frac{4\gamma^2}{1+\theta^2\gamma^2} \approx 4\gamma^2 \nu_0 \\
for \quad \alpha_L = \pi \quad and \quad \theta << 1 \quad or \quad \theta = 0
\end{align*}

\begin{align*}
e^- \ (1 \text{ GeV}); \quad \lambda_0 &= 1\mu m, \ E_0 = 1.24 \text{ eV} \\
&\quad \ E_T = 20 \text{ MeV} \\
&\quad \lambda_T = 6 \times 10^{-8}\mu m, \\
\end{align*}

\begin{align*}
e^- \ (200 \text{ MeV}); \quad \lambda_0 &= 1\mu m, \ E_0 = 1.24 \text{ eV} \\
&\quad \ E_T = 800 \text{ KeV} \quad \rightarrow \\
&\quad \lambda_T = 1.56 \times 10^{-6}\mu m, \\
\end{align*}

\begin{align*}
e^- \ (29 \text{ MeV}); \quad \lambda_0 &= 0.8\mu m, \ E_0 = 1.5 \text{ eV} \\
&\quad \ E_T = 20 \text{ KeV} \quad \rightarrow \\
&\quad \lambda_T = 0.5 \times 10^{-4}\mu m, \\
\end{align*}
In the 2005 simulation (autumn), playing especially with the injection phase of the II TW structure (involved in the linear correlation correction) have been possible obtain a bunch of about 3ps (~1mm) shorter, with a denser core.
Angular and spectral distribution of the TS radiation in the case of an unguided 3 ps laser pulse (12.5 µm beam waist)
High Flux operation mode
High Flux operation mode

**Current best working point**

**Bunch**
- 2.5nC
- 8ps long (full size)
- 13μm rms tr. Size
- 1.5 mm mrad norm emittance
- 0.1% energy spread

**Pulse**
- TEM00
- 5J in 6ps
- \( w_0 = 15 \, \mu m \)
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
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Brilliance of X-ray radiation sources

SASE-FELs will allow an unprecedented upgrade in Source Brilliance

Covering from the VUV to the 1 Å X-ray spectral range: new Research Frontiers

Compact Thomson Sources extend SR to hard X-ray range allowing Advanced Radiological Imaging inside Hospitals
FEL resonance condition

\[ \lambda = \lambda_w \frac{\left(1 + a_w^2\right)}{2\gamma^2} \]  
(magnetostatic wiggler)

Example: for \( \lambda = 1 \text{A}, \ \lambda_w = 1 \text{cm}, \ E = 3.5 \text{GeV} \)

\[ \lambda = \lambda_{\text{pump}} \frac{\left(1 + a_w^2\right)}{4\gamma^2} \]  
(electromagnetic wiggler)

Example: for \( \lambda = 1 \text{A}, \ \lambda_{\text{pump}} = 1 \text{\mu m}, \ E = 25 \text{MeV} \)
Toward Coherent X-rays: exploring coherent emission mechanisms (FEL-like) in Thomson Sources

COLLECTIVE EFFECTS IN THE THOMSON BACK-SCATTERING BETWEEN A LASER PULSE AND A RELATIVISTIC ELECTRON BEAM

A. Bacci, L. Serafini INFN-Sezione di Milano, Via Celoria, 16, 20133 Milano (Italy) C. Maroli, V. Petrillo Dipartimento di Fisica dell'Università di Milano e INFN-Sezione di Milano, Via Celoria, 16, 20133 Milano (Italy) M. Ferrario INFN-LNF, Via Fermi 40, 00044 Frascati (RM), Italy

Laser pulse characteristics:
- Wavelength $\lambda=0.8 \mu m$, power 1TW, time duration $T=5$ ps
- Circular polarization, focal spot diameter $w_0>50$ micron

Electron beam characteristics:
- Counterpropagating respect the laser pulse
- Energy 15 MeV ($\gamma=30$), spot size $\sigma_0=10 \mu m$, length $L_b=100-200 \mu m$, charge $Q=1$ nC

Radiation characteristics:
- Wavelength $\lambda=2.2$ Ang
Conditions to operate a Thomson Source in FEL mode

\[ \lambda_R = \lambda \frac{1 + a_0^2}{4 \gamma^2} \]
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Conditions to operate a Thomson Source in FEL mode

- **Laser length**
  \[ c \tau = 10L_g \]
  \[ R_0 = 2\sigma_0 \quad c \tau \leq 2Z_0 \]

- **Beam-laser overlap**
  \( \frac{\Delta}{a_0} = \frac{2a_0^2}{1+a_0^2} \)
  \[ \Delta \leq \rho \frac{1+a_0^2}{2a_0^2} \]

- **Laser bandwidth**
  \[ \frac{\Delta \lambda_R}{\lambda_R} = \frac{\Delta \lambda}{\lambda} = \frac{c \tau}{\lambda} \]
  \[ c \tau \geq \frac{\lambda}{\rho} \]
Conditions to operate a Thomson Source in FEL mode

**FEL bandwidth broadening due to beam emittance**

\[
\frac{\Delta \lambda_R}{\lambda_R} \approx \frac{\gamma^2 \theta^2}{1 + a_0^2} \approx \frac{4 \varepsilon_n^2}{\sigma_0^2} \left\{ \begin{array}{l}
\frac{\Delta \lambda_R}{\lambda_R} \leq \alpha \rho \\
\alpha \geq 1
\end{array} \right.
\]

\[
L_g = \frac{\lambda}{4 \pi \rho} \quad Z_R = \frac{4 \pi \sigma_0^2}{\lambda_R}
\]

\[
\varepsilon_n \leq \sqrt{\alpha} \sqrt{\frac{Z_R}{L_G}} \frac{\lambda_R \gamma}{2 \sqrt{2 \pi}}
\]

**Generalized Pellegrini criterion**

\[
\lambda_R = \lambda \frac{(1 + a_0^2 + \gamma^2 \theta^2)}{4 \gamma^2}
\]

\[
\rho = \frac{Z_R}{L_G} \frac{\lambda_R \lambda}{8 \pi^2 \sigma_0^2}
\]
Generalized Pellegrini criterion

\[ \varepsilon_n \leq \sqrt{\alpha} \sqrt{\frac{Z_R}{L_G}} \frac{\lambda_R \gamma}{2\sqrt{2\pi}} \]

**LCLS**

\[ \lambda_R \cong 1 \text{ Angstrom} \]
\[
\gamma = 3 \cdot 10^4 \\
\lambda_w = 2.5 \text{ cm} \\
L_g \cong Z_R \cong 10 \text{ m} \\
\varepsilon_n < \frac{3 \cdot 10^4 10^{-10}}{4\pi} \cong 0.25 \text{ \(\mu m\)}
\]

**FEL-Thomson**

\[ \gamma = 30 \]
\[ \lambda = 1 \text{ \(\mu m\)} \]
\[ L_g \cong 100 \text{ \(\mu m\)} \quad ; \quad Z_R \cong 10 \text{ m} \]
\[ \varepsilon_n < \sqrt{\frac{10^5}{2\sqrt{2\pi}}} \frac{30 \cdot 10^{-10}}{2\sqrt{2\pi}} \cong 0.11 \text{ \(\mu m\)} \]
Satisfying all conditions above implies:

\[ \varepsilon_n = \frac{\lambda}{5.62} \]

\[ U = 47 \lambda / \Delta^2 \]

\[ P = 3.1 \cdot 10^9 / \Delta \]

\[ a_0 = 1.12 \]

\[ \gamma = 0.068 \sqrt[3]{\frac{I}{\Delta^2}} \]

\[ \lambda_R = 120 \lambda \sqrt[3]{\frac{\Delta^4}{I^2}} \]

\[ \tau = 1.5 \cdot 10^{-8} \lambda / \Delta \]

\[ \alpha = 0.18 \Delta \]

\[ \beta_0 = 0.018 \lambda \sqrt[3]{\frac{I}{\Delta^5}} \]

\[ \sigma_0 = 0.21 \lambda / \sqrt[3]{\Delta} \]

\[ L_G = 0.44 \lambda / \Delta \]

\[ \bar{\rho} = 6 \cdot 10^{11} \lambda \sqrt[3]{\frac{\Delta^5}{I}} \]

\[ Z_0 = 2.2 \lambda / \Delta \]
For the case of a Ti:Sa laser we derive:

\[ \varepsilon_n = 0.14 \ \mu m \]

\[ U = 0.37/\Delta^2 \ [J] \]

\[ P = 0.31/\Delta \ [TW] \]

\[ \lambda_R = 2063\Delta^3 \sqrt{\frac{\Delta}{I^2}} \ [\text{Angstrom}] \]

\[ \gamma = 1.47 \frac{\sqrt{I}}{\Delta^2} \]

\[ \rho = 1.8 \cdot 10^{-3} \Delta \]

\[ \rho = 1.8 \cdot 10^{-3} \Delta \]

\[ a_0 = 1.12 \]

\[ \sigma_0 = 1.7/\sqrt{\Delta} \ [\mu m] \]

\[ \Delta \ [%] ; \ I \ [A] \]

\[ L_G = 35/\Delta \ [\mu m] \]

\[ \bar{\rho} = 222\Delta^3 \sqrt{\frac{\Delta^2}{I}} \]

\[ Z_0 = 0.18/\Delta \ [mm] \]

\[ \beta_0 = \frac{0.03 \sqrt{I}}{\Delta^2} \ [mm] \]
Setting $\Delta = 0.5 \%$ and $I = 1700 \, A$

**Classical SASE**

$\varepsilon_n = 0.14 \, \mu m$

$U = 1.5 \, J$

$P = 3.1 \, TW$

$a_0 = 1.12$

$\gamma = 28$

$\lambda_R = 5.7 \, \text{Angstrom}$

$\tau = 2.4 \, ps$

$\rho = 9 \cdot 10^{-4}$

$\sigma_0 = 2.4 \, \mu m$

$L_G = 70 \, \mu m$

$\bar{\rho} = 6$

$Z_0 = 0.36 \, mm$

$\beta_0 = 1.14 \, mm$
Setting $\Delta = 0.1 \%$ and $I = 2500 \, A$

**Quantum FEL**

$\varepsilon_n = 0.14 \, \mu m$

$U = 37 \, J$

$P = 0.6 \, TW$

$a_0 = 1.12$

$\gamma = 93$

$\lambda_R = 0.52 \, \text{Angstrom}$

$\tau = 12 \, ps$

$\rho = 1.8 \cdot 10^{-4}$

$\sigma_0 = 5.4 \, \mu m$

$L_G = 350 \, \mu m$

$\bar{\rho} = 0.35$

$Z_0 = 1.8 \, mm$

$\beta_0 = 18.8 \, mm$
up to $2 \cdot 10^{10}$ photons per pulse @ 6 keV, emitted in a coherent diffraction limited radiation beam, $\Delta \theta = 3 \ \mu \text{rad}$ (cmp. $10^9$ ph/pulse in $\Delta \theta = 3 \ \text{mrad}$ of incoherent Thomson radiation)
Compact Thomson Sources extend SR to hard X-ray range allowing Advanced Radiological Imaging inside Hospitals

Coherent Thomson Sources will push the achievable brilliance if laser pulses with \( \Delta I/I < \Delta \omega/\omega = 2 \times 10^{-3} \) will be made available.
**GeV-class IFEL design:**

- Application of IFEL scheme as 4th generation light source driver
- Compact-size accelerator
- ESASE benefits intrinsic
  - Exponential gain length reduction
  - Absolute timing synchronization with external laser
  - Control of x-ray radiation pulse envelope
- Advanced Accelerator driven light source
- Design exercise aimed to extend the energy and wavelength reach of planned SPARC linac

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial e-beam energy (γ value)</td>
<td>210 MeV</td>
</tr>
<tr>
<td>Initial e-beam intrinsic energy spread</td>
<td>0.1% (1σ)</td>
</tr>
<tr>
<td>Initial e-beam current</td>
<td>1 kA</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>800 nm</td>
</tr>
<tr>
<td>Laser peak power</td>
<td>20 TW</td>
</tr>
<tr>
<td>Nominal length of wiggler, ( L_w )</td>
<td>200 cm</td>
</tr>
</tbody>
</table>
**Final output parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.7 GeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>&lt;0.8 %</td>
</tr>
<tr>
<td>Microbunch length</td>
<td>250 as</td>
</tr>
<tr>
<td>Peak current</td>
<td>&gt; 6 kAmp</td>
</tr>
<tr>
<td>Avg. gradient</td>
<td>750 MeV/m</td>
</tr>
</tbody>
</table>

**Longitudinal phasespace**

*Resonant energy (MeV)*

*Distance along the undulator (m)*

*Resonant energy (MeV)*

*Phase distribution*

*Energy distribution*

*Longitudinal phasespace*

*Phase distribution*

*Distance along the undulator (m)*

*Resonant energy (MeV)*

*Phase distribution*
Conclusions

• Among laser accelerators, the IFEL offers best control of the longitudinal phase space.
• Preserving ultrashort pulse structure in the radiation output requires some precautions in the design of the FEL amplifier (slippage problems) but can be done.
• Path towards ultrashort probe beams pass through a synergy between laser and accelerator worlds.

Sending such a beam into an undulator
  FEL radiation @ $\lambda = 3$ nm (water window). Peak power 1 GW in 300 attoseconds
Best result in 2004: $\sigma = 8.7 \mu$m (1 nC Solenoid lens)

The results seem to be good especially for the very low longitudinal energy spread. Keeping in consideration that the beta in the focal spot is about 5 mm, the principal limitation is due to bunch length.
Triplet configuration:
Ideal +1 -2 +1
Q-length = 1.46 cm
Q-Gradient = 300 T/m

σ-x = 10 µm

σ-x = 25 µm
Triplet configuration:
Q1-length = 1.00 cm ; Q2-length = 2.00 cm ; Q3-length = 2.00 cm
Gradient = +300 ; -300; +300 (T/m)
Position, Q1 = 12.0968 m; Q2 = 12.12305 m; Q3 = 12.1511 m

σ-x = 10 µm

σ-x = 18 µm
Triplet configuration for the final focus system - Permanents magnets (1nC – Bunch)  C-case

Triplet configuration - thin lens:
Ideal +1 -2 +1
Q-length = 1.00 cm
Q-Gradient = 645 T/m

σ-x = 10 µm

σ-x = 35 µm
Best result in 2004: \( \sigma_x = 8.7\mu\text{m} \) (1nC Solenoid lens)

2005 best results (1nC Solenoid lens):

Best results with triplet (1nC Solenoid lens) – ONLY X PROJECTION

ICFA FLS-2006 Workshop – DESY, May 18th 2006
Two additional beam lines at SPARC for plasma acceleration and monochromatic X-ray beams

30-50 fs synchr.
Ti:Sa 200-TW Laser System

1 J, 10 ps gaussian
2 nC, 10 ps

1 J, 100 fs gaussian
500 μJ
20 mJ, 10 ps flat top

20 pC, 10-60 fs
ε_n=2 μm, σ=5 μm, Δγ/γ=4·10^{-4}

ε_n=0.2 μm, σ=10 μm

ε_n=1 μm
1 nC, 10 ps
A 3D Model View of the buildings from outside

- CANVAS TENT
- STORAGE AREA
- CONTROL ROOM
- MODULATOR & KLYSTRON HALL
- UNDERGROUND BUNKER
- ACCESS TO UNDERGROUND BUNKER
- ACCELERATOR

ICFA FLS-2006 Workshop - DESY, May 18th 2006
**LASER SYSTEM**

*Custom-laser*

purch. from Coherent

**Flat Top**

*Time Profile*

rise time < 1 ps

---

**Pumps**

- **Verdi**
  - Nd:YVO₄

**Seed Line**

- **Mira**
  - Ti:Sa Oscillator
  - 800 nm
  - 10 nJ
  - 80 MHz
  - 100 fs

**Pulse Shaping developed in house**

- **DAZZLER**
  - TeO₂

**Synchro Lock**

- PLL

RF-laser jitter < 0.5 ps

---

**RF Reference**

- R&S 2,856 GHz

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**RGA + 2 MP**

---

**Hidra**

- CPA Ti:Sa Amplifier
- RGA + 2 MP

**THG**

- 800 nm
- 50 mJ
- 10 Hz
- 100 fs

---

**UV Stretcher**

- 266 nm
- 4 mJ
- 10 Hz
- 100 fs

---

**Evolution**

- Nd:YLF

**Continuum**

- Nd:Yag

---

**Verdi**

- Nd:YVO₄

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**Continuum**

- Nd:Yag
## Schedule of the planned PLASMONX activity

<table>
<thead>
<tr>
<th>Activity/YEAR</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set up cluster for parallel computing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Test experiments @ CEA -Saclay</td>
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<tr>
<td>Development of m.w. PIC codes</td>
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<tr>
<td>Modelling of acceleration schemes</td>
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<tr>
<td>Modelling of T.S.</td>
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<tr>
<td>Design of Laser System</td>
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<tr>
<td>Set up LASER LABORATORY at LNF</td>
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<tr>
<td>Set up Phase 1: 30fs, 0.1TW</td>
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<td>Set up I II amplification stage</td>
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<td>Development of the OPCPA amplifiers</td>
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<td>Installation of Laser diagnostics</td>
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<td>Phase 2: 1TW compression test</td>
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<td>IV amplification stage</td>
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<td>Phase 3: 100 TW compression test</td>
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<td>Self injection LWFA experiments</td>
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<td>External injection LWFA test</td>
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<td>Set up additional beam-line at LNF</td>
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<td>Set up laser beam transport to LINAC</td>
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<td>Set up laser beam-electron bunch interaction</td>
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<td>Synchronization R&amp;D and setup</td>
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<td>Thomson source test</td>
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<td>TS beam users (MA MB O, etc)</td>
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### 2.5 Meuro bid is ongoing for the FLAME laser

QFEL experiment under study with PLASMONX facility
With these parameters, \[ \rho = \frac{1}{\gamma_0} \left( \frac{\omega_P^2 \alpha_{L0}^2}{16 \omega_L^2} \right)^{\frac{1}{3}} = 10^{-4}. \]

The gain length \( L_g = 110 \) micron, and the system is classic

\[
A_L(\mathbf{r}, t) = \frac{a_{L0}}{\sqrt{2}} \left( g(\mathbf{r}, t) e^{-i(k_L z + \omega_L t)} \hat{e} + cc \right) + O\left( \frac{A_L}{w_0} \right)
\]

with

\[
\hat{e} = \frac{(e_x + i e_y)}{\sqrt{2}}
\]

And with envelope

\[
g(\mathbf{r}, t) = \Phi(z + ct) \frac{1 + i \frac{z}{z_0}}{1 + \frac{z^2}{z_0^2}} \exp \left[ -4 \frac{x^2 + y^2}{w_0^2 (1 + \frac{z^2}{z_0^2})} - 4i \frac{x^2 + y^2}{w_0^2 \left( \frac{z}{z_0} + \frac{z_0}{z} \right)} \right]
\]
The 3 dimensional collective equations that describes the collective effects are similar to the FEL equation with the SVEA approximation.

\[
\frac{d}{dt} \mathbf{F}_j(\mathbf{r}) = \rho \frac{\mathbf{P}_j(\mathbf{r})}{\gamma_j(\mathbf{r})} \\
\frac{d}{dt} P_{\perp j}(\mathbf{r}) = -\frac{a_{L0}^2}{2 \rho \gamma_0^2 \gamma_j} \left[ \frac{\partial}{\partial \mathbf{z}} \left| g \right|^2 \right]_{\mathbf{x}=\mathbf{r}_j} - \frac{2}{\gamma_j} \text{Re \, al} \left[ (g^* \overline{A})_{\mathbf{x}=\mathbf{r}_j} e^{i\theta_j(\mathbf{r})} \right] + \ldots \\
\frac{d}{dt} P_{\parallel j}(\mathbf{r}) = -\frac{a_{L0}^2}{2 \rho \gamma_0^2 \gamma_j} \left[ \nabla_{\perp} \left| g \right|^2 \right]_{\mathbf{x}=\mathbf{r}_j} - \frac{4 k_L \rho}{k} \frac{1}{1 + \frac{k_L}{k} \gamma_j} \text{Im} \left[ (\nabla_{\perp} (g^* \overline{A}))_{\mathbf{x}=\mathbf{r}_j} e^{i\theta_j(\mathbf{r})} \right] + \ldots \\
\left( \frac{\partial}{\partial t} + \frac{\partial}{\partial \mathbf{z}} \right) \overline{A}(\mathbf{x}, \mathbf{r}) - i \frac{k_L}{k} \rho \nabla_{\perp}^2 \overline{A} = b
\]