SPARC_LAB recent results
Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams
Massimo.Ferrario@LNF.INFN.IT
Ti:Sa FLAME laser
Linac and FEL

S-band Gun

Velocity Bunching

Diagostic and Matching

150 MeV S-band linac

Long Solenoids

S-band Gun

Seeding

Undulators

$\lambda_u = 2.8 \text{ cm}$

$K_{max} = 2.2$

$\lambda_p = 500 \text{ nm}$

Spectrometer

Linac and FEL

Ministere dell' Universita e della Ricerca

Consiglio Nazionale delle Ricerche

ENEA

INFN

University
HB photo-injector with Velocity Bunching
Undulator chain
Thomson back-scattering source
SPARC_LAB: Some achievements

Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the SPARC High-Brightness Photoinjector
M. Ferrario et al., PRL 99, 234801 (2007)

Experimental Demonstration of Emittance Compensation with Velocity Bunching
M. Ferrario et al., PRL 104, 054801 (2010)

Self-Amplified Spontaneous Emission Free-electron Laser with an Energy-Chirped Electron Beam and Undulator Tapering
L. Giannessi et al., PRL 106, 144801 (2011)

High-Gain Harmonic-Generation and Superradiance Free-electron Laser Seeded by Harmonics Generated in Gas
M. Labat et al., PRL 107, 224801 (2011)

High-Order Harmonic Generation and Superradiance in a Seeded Free-electron Laser
L. Giannessi et al., PRL 108, 164801 (2012)

Superradiant Cascade in a Seeded Free-electron Laser
L. Giannessi et al., PRL 110, 044801 (2013)
NEW: TWO COLORS SASE FEL

Two bunches with a two-level energy distribution and time overlap (Laser COMB tech.) produce two wavelength SASE–FEL radiation with time modulation.

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

\[ \frac{\Delta \lambda_r}{\lambda_r} = 2 \frac{\langle \gamma_1 \rangle - \langle \gamma_2 \rangle}{\langle \gamma \rangle} \]

\[ \Delta t = \frac{\lambda_u \left( 1 + K_{\text{rms}}^2 \right)}{4c \langle \gamma \rangle \langle \gamma_1 \rangle - \langle \gamma_1 \rangle} \]
Electron beam requirements

two bunches with a two-level energy distribution and time overlap (Laser COMB tech.)

Lasing condition:

• To prevent mode competition:

\[
\frac{\delta \gamma_{1,2}}{\langle \gamma_{1,2} \rangle} < \rho
\]

\[
\frac{\langle \gamma_1 \rangle - \langle \gamma_2 \rangle}{\langle \gamma \rangle} > \rho
\]

Single spike condition:

\[
l_b \approx L_{coop} = \frac{\lambda_r}{4\pi\sqrt{3}\rho}
\]
Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

Fig. 1. Evolution of a six bunch electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation $\Delta E$ (MeV).

Laser Pulse Train Generation

\[ \Delta T = \left| \frac{1}{v_{ge}} - \frac{1}{v_{go}} \right| L_{\text{crystal}} \]

**Diagram Description:**
- **LASER** is the input source.
- **Crystal 4 ps** processes the input to produce a UV pulse.
- **UV pulses** are shown in the graph on the left.
- **Crystal 2 ps** further processes the UV pulses, resulting in shorter pulses.
- **UV pulses** are shown in the graph on the right.

**Graphs:**
- The first graph shows the UV pulses with time on the x-axis and arbitrary units on the y-axis.
- The second graph shows a different set of UV pulses with time on the x-axis and arbitrary units on the y-axis.

**Streak Camera:**
- The diagrams include streak cameras at the end of the process.
Electron beam diagnostics

- Long Solenoids
- Beam energy: 90 – 180 MeV
- Bunch charge: 50 – 500 pC
- Rep. rate: 10 Hz
- $\varepsilon_n < 2 \text{ mm-mrad}$
- $\sigma_\gamma 0.05\% - 1\%$
- Laser Pulse length: 200 fs – 5 ps (FWHM)

Seeding THz Source

DIPOLE

Quadrupoles

RF DEFLECTOR

... to the undulator

... to the dogleg

Beam Screens
Measured 2 bunches distance versus VB phase

Compression phase (deg)

Time separation (ps)
Achieved Electron Beam Performances

Whole beam
- Peak current: 300 A (with 160 pC)
- Bunch duration: 300 fs
- Normalized emittance: 1.7 (0.1) mm mrad
- Energy spread: 0.6%
- Energy: 93.04 (0.03) MeV

Single bunch
- Energy spread: 0.2% / 0.3%
- Bunch duration: 100 fs / 250 fs

Energy separation: 1.07 (0.05) MeV

Time separation: 0.42 (0.03) ps

FEL parameter $\rho$: $6.7 \times 10^{-3}$
FEL Photon Diagnostics

**Fiber Spectrometer**
- Resolution: 1.2 nm @ 800 nm
- Window: 200-840 nm

**Joulemeter**
- Minimum detected energy: 1 pJ
- Calibration: 5.96e8 V/J @ 1µm
- Optical density filters

**FROG: NIR-Grenouille**
- Time-bandwidth product: <~10
- Spectral resolution: 0.7 nm @800nm
- Single shot sensitivity: 1 µJ

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>2.8 cm</td>
</tr>
<tr>
<td>Undulator length</td>
<td>2.156.m</td>
</tr>
<tr>
<td>No of Periods</td>
<td>77</td>
</tr>
<tr>
<td>Gap (nom./min/max)</td>
<td>0.958 / 0.6 / 2.5 cm</td>
</tr>
<tr>
<td>K (nom./max/min)</td>
<td>2.145 / 3.2 / 0.38</td>
</tr>
<tr>
<td>Remanent field</td>
<td>1.31 T</td>
</tr>
<tr>
<td>Blocks per period</td>
<td>4</td>
</tr>
<tr>
<td>Block size (h x l x w)</td>
<td>2 x 0.7 x 5 cm</td>
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</tbody>
</table>
FEL Experiments: Two-levels radiation spectra

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{min}}) (nm)</td>
<td>769.8 (2)</td>
</tr>
<tr>
<td>(BW_{\lambda_{\text{min}}}) (%)</td>
<td>0.5</td>
</tr>
<tr>
<td>(\lambda_{\text{Max}}) (nm)</td>
<td>788.6 (1.3)</td>
</tr>
<tr>
<td>(BW_{\lambda_{\text{Max}}}) (%)</td>
<td>0.7</td>
</tr>
<tr>
<td>(\Delta \lambda) (nm)</td>
<td>18.8 (2.9)</td>
</tr>
<tr>
<td>(\Delta E) (MeV)</td>
<td>1.1 (0.17)</td>
</tr>
<tr>
<td>FEL Energy</td>
<td>&gt; 37 (\mu) J</td>
</tr>
</tbody>
</table>
FEL EXPERIMENTS: Two-color tunability

Δλ (nm)  20.7 (1.7)
ΔE (MeV)  1.066 (0.086)

Δλ (nm)  26 (3)
ΔE (MeV)  1.35 (0.14)
FEL Experiments: Time-modulated pulses

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (MeV)</th>
<th>En. Spread (%)</th>
<th>Length (ps)</th>
<th>Charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Beam</td>
<td>92.515 (0.033)</td>
<td>0.174 (0.005)</td>
<td>0.147 (0.002)</td>
<td>82.15 (1.58)</td>
</tr>
<tr>
<td>Second Beam</td>
<td>93.588 (0.033)</td>
<td>0.317 (0.005)</td>
<td>0.283 (0.003)</td>
<td>77.85 (1.56)</td>
</tr>
<tr>
<td>Whole Beam</td>
<td>93.038 (0.032)</td>
<td>0.631 (0.003)</td>
<td>0.305 (0.004)</td>
<td>160.00 (3.10)</td>
</tr>
</tbody>
</table>

- **Energy Separation (MeV):** 1.07 (0.05)
- **Time Separation (ps):** 0.42 (0.03)

### Simulation by GENESIS

![FROG traces](image)

<table>
<thead>
<tr>
<th>Δλ (nm)</th>
<th>BW (%)</th>
<th>RMS Time duration (fs)</th>
<th>Time separation (fs)</th>
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</thead>
<tbody>
<tr>
<td>18</td>
<td>0.86</td>
<td>80</td>
<td>110</td>
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</table>

110 fs
Expected time modulation at shorter wavelength

\[ \Delta t = \frac{\lambda^2}{c(\lambda_2 - \lambda_1)} = \frac{\lambda_u(1 + K_w^2/2)}{4c\gamma \Delta \gamma} \]

(a) SPARC case.
(b) \( \lambda = 30 \, \text{nm} \)
(c) \( \lambda = 0.15 \, \text{nm} \)
CONCLUSIONS

- Production of a two-pulse beam with **time and energy separation tunable** with linac settings
- Demonstration of the possibility to control time and energy separation
- Achievement of beam quality necessary for FEL applications
- Generation of a two-pulse beam, each pulse shorter than the $L_c$, acting as independent radiation source in a quasi-single spike regime
  - Production and characterization of a two-color FEL spectrum and of a train of short FEL pulses
- Different techniques:
  - Chirped seeding ➔ G. De Ninni et al., PRL 110, 064801 (2013)
  - Alternate K undulator ➔ A. A. Lutman et al., PRL 110, 134801 (2013)
Acknowledgement

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