OPTIMIZING RF LINACs AS DRIVERS FOR INVERSE COMPTON SOURCES: THE ELI-NP CASE

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Outline:

• The High Brightness Beam Experience:
  • The Photoinjector Optimization
  • The bunch compression

• The ELI-NP Gamma Beam System
  • The RF LINAC design
  • The GBS layout
The High Brightness Beam Experience

The Brightness parameter is written as:

$$B = \frac{2I}{\varepsilon_n^2}$$

for the SASE Fel its relevance comes from the Pierce parameter $\rho$ defined in the ideal 1-D model as *:

$$\rho = \left[ \left( \frac{I}{I_A} \right) \left( \frac{\lambda_w A_w}{2\pi \sigma_x} \right)^2 \left( \frac{1}{2\gamma_0} \right)^3 \right]^{1/3}$$

where the current density $I / 2\pi \sigma_x^2$ appears and that gives the highest possible Fel gain (shortest length), being:

$$L_g = \lambda_w / 4\pi \sqrt{3} \rho \quad \text{and} \quad P_{sat} \approx \rho P_{beam}$$

* Ming Xie, Proc. Of PAC 95, p. 183
The Photoinjector Optimization

- Focusing solenoid at the exit of the photoinjector

- Proper matching of the transverse space of the electron beam injected in the downstream accelerating sections (booster) to control the transverse emittance oscillations during the acceleration
  (L. Serafini and J. Rosenzweig, Phys. Rev. E 55, 7565 (1997))
The matching condition:

Serafini-Rosenzweig showed that the rms normalized transverse emittance
\[ \varepsilon_n = \sqrt{\langle x^2 \rangle \langle \beta \gamma x' \rangle^2 - \langle x \beta \gamma x' \rangle^2} \]
oscillates with frequency \( \sqrt{2K_r} = k_p \) if the bunched beam is rms matched in a focusing channel of gradient \( K_r \) (Brillouin flow equilibrium) and that the oscillations are damped under the invariant envelope condition:

\[ \sigma_{\text{inv}}(\zeta) = \frac{2}{\gamma'} \sqrt{\frac{I(\zeta)}{I_0 \gamma}}, \text{ with } \gamma' = eE_{\text{acc}}/m_e c^2 \text{ and } \zeta = z - \beta ct + z_0 \]

so the key point is to inject the beam into an accelerating section at a laminar waist:

\[ \sigma' = 0 \text{ with } \gamma' = \frac{2}{\sigma_w} \sqrt{\frac{\hat{i}}{2I_0 \gamma}} \]

that gives the invariant envelope condition for a TW accelerating field.
The Bunch Compression

High peak currents are required by several applications such as short wavelengths free electron lasers, plasma wake field accelerators, and so on:

- Magnetic compressors
- Velocity bunching
The velocity bunching technique

If the bunch is injected into the wave at zero phase at an energy lower than the synchronous one ($\gamma_r$) it will slip back in phase and go up in energy (accelerated by the wave); extracting the beam from the wave at the time it reaches the resonant $\gamma_r$ (i.e. when it is synchronous with the wave) the bunch undergoes a quarter of synchrotron oscillation and is compressed in phase.

To control the emittance dilution the RF compression process has to be integrated with the emittance compensating invariant envelope matching condition, as successfully demonstrated at SPARC. (M. Ferrario et al., Phys. Rev. Lett. 104, 054801, 2010)

Measured envelopes and PARMELA simulations (left plot). Emittance evolution along the linac, PARMELA simulations (right plot). No compression (curves a), compression with long solenoids off (curves b), same compression with long solenoids set to 450 G (curves c)

Phase space plots of a slow RF wave ($\gamma_r$ finite) showing the basics of the VB
The ELI-NP Gamma Beam System
ELI-NP: F-I-UK Project

European Collaboration for a new generation gamma-ray source:

- Italy: INFN, Sapienza
- France: IN2P3, Univ. Paris Sud
- UK: ASTeC/STFC

Covering:

- Underlying physics & Best machine layout
- Technical realization
- Infrastructure concern
- Management structure
- Training and education
- Implementation
New generation γ-source

- Bright
- Mono-chromatic
- High Spectral Flux
- Tunable
- Highly Polarized

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy</td>
<td>1-20 MeV</td>
</tr>
<tr>
<td>Spectral density</td>
<td>$&gt; 10^4$ ph/sec.eV</td>
</tr>
<tr>
<td>Bandwidth (rms)</td>
<td>$&lt;0.3%$</td>
</tr>
<tr>
<td># photons/sec within FWHM bdw.</td>
<td>$0.5 \div 1.5 \times 10^9$</td>
</tr>
<tr>
<td>Linear Polarization</td>
<td>$&gt;95%$</td>
</tr>
</tbody>
</table>

- Nuclear Resonance Fluorescence
- Nuclear Photo-fission
- Isotope Detection -> toward Nuclear Photonics
The electron-photon collider approach

The rate of emitted photons is given by:

\[ N_\gamma = \Sigma_T L = \Sigma_T \frac{N_{el} N_{las}}{2\pi \left( \sigma_x^2 + \frac{w_0^2}{4} \right)} f \cdot n_{RF} \cdot \delta \phi \]

leading to:

\[ N_\gamma = 4.2 \times 10^8 \frac{U_L[J] Q[pC] f \cdot n_{RF} \cdot \delta \phi}{h\nu[eV] \left( \sigma_x^2[\mu m] + \frac{w_0^2[\mu m]}{4} \right)} \]

with \( h\nu = 2.4 \text{ eV}, Q = 250 \text{ pC}, U_L = 0.4 \text{ J}, \sigma_x \approx 15 \mu m, w_0 \approx 28 \mu m, \) and \( f = 100 \text{ Hz}, \) over the entire solid angle we have a gamma ray flux:

\[ N_\gamma \approx 3 \times 10^9 \text{ s}^{-1}. \]
Within the desired bandwidth:

The frequency $\nu_\gamma$ of the radiation emitted within a small angle of scattering and electron incidence $\theta_c$ is:

$$\nu_\gamma = \nu_L \frac{4\gamma^2}{1 + \gamma^2 \theta_c^2 + a_0^2/2} (1 - \Delta)$$

and the rms bandwidth is:

$$\Delta \nu_\gamma \approx \sqrt{\left(\frac{\gamma^2 \theta_c^2}{2}\right)^2 + \left(2 \frac{\Delta \gamma}{\gamma}\right)^2 + \left(\frac{2\varepsilon_n^2}{\sigma_x^2}\right)^2 + \left(\frac{\Delta \nu}{\nu}\right)^2 + \left(\frac{M^2 \lambda_L}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1 + a_0^2/2}\right)^2}$$

so within the bandwidth we have:

$$N_{\nu_\gamma}^{bw} = 1.4 \times 10^9 \frac{U_L[J]Q[pC]f}{h \nu [eV]} \frac{n_{RF} \delta_\phi}{\left(\sigma_x^2 [\mu m] + \frac{w_0^2 [\mu m]}{4}\right)} \cdot \sqrt{\left(\frac{\Delta \nu_\gamma}{\nu_\gamma}\right)^2 - \left(2 \frac{\Delta \gamma}{\gamma}\right)^2 - \left(\frac{2\varepsilon_n^2}{\sigma_x^2}\right)^2 - \left(\frac{\Delta \nu}{\nu}\right)^2 - \left(\frac{M^2 \lambda_L}{2\pi w_0}\right)^4 - \left(\frac{a_0^2/3}{1 + a_0^2/2}\right)^2}$$
The required spectral density:

\[ S = \frac{N_{yw}}{\sqrt{2\pi} h \Delta \nu_{\gamma}} \quad \Rightarrow \quad S_r(eV^{-1}) = \frac{0.35 \times 10^9 E_L Q \Psi^2}{h \omega \nu_L \left( \sigma_x^2 + \frac{w_0^2}{4} \right)} \frac{1}{\sqrt{2\pi h \Delta \nu_{\gamma}} \left[ \frac{\Delta \nu_{\gamma}}{\nu_{\gamma}} \right]} . \]

needs from the RF linac the maximum for the parameter

\[ Q \]

\[ \sigma_x^2 \left[ \Delta \gamma / \gamma + \left( 2 \epsilon_n / \sigma_x \right)^2 \right] \]

with no further bunch compression we can optimize separately the energy spread and transverse emittance i.e. the 4D transverse phase space density of the electron beam:

\[ \eta \equiv \frac{Q}{\epsilon_n^2} . \]
ELI-NP requirements:

State of the art + Compact = S-band Photoinjector + C-band linac
ELI-NP GBS:

r.t. RF linac vs pulsed laser source

<table>
<thead>
<tr>
<th>Electron beam parameter at IP</th>
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<tbody>
<tr>
<td>Energy (MeV)</td>
<td>80-720</td>
</tr>
<tr>
<td>Bunch charge (pC)</td>
<td>25-400</td>
</tr>
<tr>
<td>Bunch length (µm)</td>
<td>100-400</td>
</tr>
<tr>
<td>$\varepsilon_{n,x,y}$ (mm-mrad)</td>
<td>0.2-0.6</td>
</tr>
<tr>
<td>Bunch Energy spread (%)</td>
<td>0.04-0.1</td>
</tr>
<tr>
<td>Focal spot size (µm)</td>
<td>&gt;10</td>
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<tr>
<td># bunches in the train</td>
<td>32</td>
</tr>
<tr>
<td>Bunch separation (nsec)</td>
<td>16</td>
</tr>
<tr>
<td>energy variation along the train</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Energy jitter shot-to-shot</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Emittance dilution due to beam breakup</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>Time arrival jitter (psec)</td>
<td>&lt; 0.5</td>
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<tr>
<td>Pointing jitter (µm)</td>
<td>1</td>
</tr>
</tbody>
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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Pulse energy (J)</td>
<td>0.2</td>
<td>2×0.2</td>
</tr>
<tr>
<td>Wavelength (eV)</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>FWHM pulse length (ps)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$M^2$</td>
<td>□1.2</td>
<td>□1.2</td>
</tr>
<tr>
<td>Focal spot size $w_0$ (µm)</td>
<td>&gt; 28</td>
<td>&gt; 28</td>
</tr>
<tr>
<td>Bandwidth (rms)</td>
<td>0.1 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Pointing Stability (µrad)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sinchronization to an ext. clock</td>
<td>&lt; 1 psec</td>
<td>&lt; 1 psec</td>
</tr>
<tr>
<td>Pulse energy stability</td>
<td>1 %</td>
<td>1 %</td>
</tr>
</tbody>
</table>
The ELI-NP RF Linac design:

- **Operation criteria:**
  - Long bunch at cathode for high phase space density:
    \[ \frac{Q}{\varepsilon_n}^2 > 10^3 \text{ pC}/(\mu\text{rad})^2 \]
  - Short exit bunch (280 µm) for low energy spread (~0.05%)

- **Advantages:**
  - Moderate risk (state of art RF gun, reduced multibunch operation problems respect to higher frequencies, low compression factor<3)
  - Economic
  - Compact (the use of the C-band booster meets the requirements on the available space)
  - Possibility to use SPARC as test stand
Ref from the photoinjector (Tstep tracking)

\[ \gamma \varepsilon_x = 0.407 \mu m \]

\[ x' / \text{mrad} \]

\[ x / \text{mm} \]

\[ \sigma_z = 0.280 \text{ mm}, \sigma_E/\langle E \rangle = 1.747\% \]

\[ \Delta E(E)/\% \]

\[ \langle E \rangle = 79.663 \text{ MeV} \]

Egun=120 MV/m
E(S1)=E(S2)=21 MV/m
Q=250 pC
The beam loading effect and the Beam break UP (BBU) instability have been extensively studied to guarantee the multibunch operation feasibility. In particular the beam loading in the structures will be compensated with a modulation of the input power to maintain the required energy spread along the bunch train.
Central cells

For the BBU a strong damping solution has been adopted for which each cell of the structure has four waveguides that allows the excited HOMs to propagate and dissipate into loads.
Mitigation of multibunch effect with damped structure

C-band non damped SPARC energy upgrade

D. Alesini
The machine layout

ELI

ELI-NP infrastructure

N. Bliss
Linac & Transfer lines

Low energy

High Energy
SB-Transverse beam size and distribution (Elegant tracking)

Low energy

High energy
from CAIN simulation:

- with 600 MeV electron beam
- in the 0.5 % bw
- within 88 mrad collimation angle
- $2.8 \times 10^5$ photons/shot obtained
Conclusions

• The key parameters of the new generation Compton source have been described together with the main common features with the high brightness beam expertise.

• A C-band RF linac has been presented based on the requirements of the gamma-ray source in the framework of the ELI-NP project.