INFN Proposal for ELI-NP Compton Gamma-ray Source

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• Motivations for our Proposal: Bright Mono-chromatic Compton Back-Scattering Sources need Ultra-High Phase Space Density e\(^{-}\) beams (INFN-LNF is leading in this field)

• Equivalence Gamma-ray Spectral Density / Phase Space Density of electron beam (Analytical Scaling laws)

• Extensive, unprecedented, campaign of Beam Dynamics Optimization for High Brightness Photo-Injectors (numerical scaling laws -> C-band reveals as best option)

• Lay-out for Photo-Linac and Laser (including wake-fields!) more details on scheduling, costs, etc, in Patrizio Antici’s talk
Final emittance = 0.4 μm

Matching onto the Local Emittance Max.

This brings to Ferrario's working point, adopted by LCLS and TTF - FEL II

S-band photoinjector up to 150 MeV, HOMDYN simulation

Q = 0.25 nC, L = 10ps, R = 1 mm, E_{peak} = 130 MV/m, \( \text{TW} E_{\text{acc}} = 25 \text{ MV/m} \)

ELI-NP meeting, Magurele, Aug. 18th 2011
Brief Review of Beam Dynamics in Photo-Injectors

- The beam generated at the *photocathode surface* behaves like a **Single Component Relativistic Cold Plasma** all the way up to the injector exit (150 MeV).
- It is a *quasi-laminar* beam both in *transverse* (laminar flow) and *longitudinal* plane (lack of synchrotron motion).

\[
\sigma'' + \sigma' \frac{\gamma'}{\gamma} + \sigma \frac{\Omega^2 \gamma'^2}{\gamma^2} - \frac{I(\zeta)}{2I_A \sigma \gamma^3} \approx 0
\]

\[
\gamma = \gamma_0 + \gamma'_z \quad \gamma' \equiv \frac{E_{\text{acc}}}{mc^2} \quad \sigma' \equiv \frac{d\sigma}{dz} \quad \Omega^2 = \left( \frac{eB_{\text{sol}}}{mc \gamma'} \right)^2 + \left\{ \begin{array}{l} \approx \frac{1}{8} \ SW \ \\ \approx 0 \ TW \end{array} \right\}
\]

\[
\sigma \equiv \langle x^2 \rangle \quad \text{slice} \quad \zeta = z - \beta ct
\]

Normalized focusing gradient (solenoid + RF foc.)
S.C.R.C.P. or Laminar Plasma-Beam

- Plasma launched at relativistic velocities along the propagation axis with equivalent ionization $= \frac{1}{\gamma^2}$; plasma confinement provided by external focusing (solenoids, ponderomotive RF focusing, acceleration)
- Spread in plasma frequency along the bunch $\Rightarrow$ strong time-dependent space charge effects $\Rightarrow$ inter-slice dynamics

Projected emittance (shadow) $\gg$ slice emittance (foil thickness)

$$
\varepsilon_n \equiv \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle xp_x \rangle^2} \gg \varepsilon_{nsl} \equiv \sqrt{\langle x^2 \rangle_{\xi} \langle p_x^2 \rangle_{\xi} - \langle xp_x \rangle_{\xi}^2}
$$

Liouvillian emittance $=$ foil volume
**S.C.R.C.P. or Laminar Plasma-Beam**

- **Inter-slice dynamics** brings to projected emittance oscillations which are reversible $\Rightarrow$ **emittance correction**
  
  this can be described by a multi-envelope code like HOMDYN
  
  the prescription to reach full emittance correction is to match the beam onto the **invariant envelope** (beam equilibr. mode)
  
  $\sigma_{INV} = \frac{1}{\gamma'} \sqrt{\frac{2 I(\zeta)}{I_A (1 + 4 \Omega^2)}}$

- **Intra-slice dynamics** is affected by space charge field non-linearities the prescription to avoid irreversible slice emittance growth is to use uniform cylindrical charge density distribution (flat top laser pulses, spatially uniform)
Emittance evolution for different pulse shapes

Optimum injection in to the linac with:

\[ \sigma' = 0 \]

\[ \gamma' = \frac{eE_{acc}}{mc^2} = \frac{2}{\sigma} \sqrt{\frac{I}{2\gamma A}} \]

ELI-NP meeting, Magurele, Aug. 18th 2011
Phase space reconstruction with SPARC
Emittance meter
phase space - simulation and measurements
Flat top vs gaussian pulse shape

- Charge: 0.74 nC
- Pulse length (FWHM): 8.7 ps
- Rise time: 2.6 ps
- RMS spot size: 0.31 mm
- RF phase ($\phi - \phi_{\text{max}}$): $-8^\circ$

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Emittance measurements with the selected solenoid current $I=198 \, \text{A}$
Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the Sparc High-Brightness Photoinjector

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In this Letter we report the first experimental observation of the double emittance minimum effect in the beam dynamics of high-brightness electron beam generation by photoinjectors; this effect, as predicted by the theory, is crucial in achieving minimum emittance in photoinjectors aiming at producing electron beams for short wavelength single-pass free electron lasers. The experiment described in this Letter was performed at the SPARC photoinjector site, during the first stage of commissioning of the SPARC project. The experiment was made possible by a newly conceived device, called an emittance meter, which allows a detailed and unprecedented study of the emittance compensation process as the beam propagates along the beam pipe.

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Analysis methodology of movable emittance-meter measurements for low energy electron beams

High brightness electron beam emittance evolution measurements in an rf photoinjector
A. Cianchi et al., PRST-AB to be published March 2008

ELI-NP meeting, Magurele, Aug. 18th 2011
FEL lasing in SASE and Seeding mode from 45 nm to 530 nm
200 fs electron bunch with low emittance demonstrated at SPARC!

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The optimal conditions to achieve maximum phase space density in a photo-LINAC are set by the invariant envelope theory (see ref. \textsuperscript{15}), describing the electron beam as a single component relativistic plasma propagating paraxially from the photo-cathode placed inside the RF gun up to the LINAC exit, under the effect of its own space charge field, the RF focusing of accelerating sections and the acceleration damping due to the strong field gradient applied. The main parameter of interest is the Cauchy invariant \( \Lambda \), defined as
\[
\Lambda \equiv \frac{J}{\gamma'}^2 \propto \frac{Q}{E_{cat}^2 \sigma_{cat}^2 \sigma_z^2}
\]
where \( J \) is the beam current density launched at the photocathode, \( \gamma' = \frac{d\gamma}{dz} \) the accelerating gradient. In more practical quantities, the Cauchy invariant is expressed vs. the bunch charge \( Q \), the peak electric RF field applied at the photocathode surface \( E_{cat} \), the cathode emitting spot size \( \sigma_{cat} \) and the length of the laser pulse \( \sigma_z \) illuminating the photocathode for electron bunch production.

The parameter \( \Lambda \) is useful when we want to transform a specific configuration of photo-LINAC, found by numerical studies and optimized for a certain RF frequency, bunch charge and RF cathode field, into another one, working at different frequency, bunch charge, etc. The simple criterion is: keeping invariant the selected value of \( \Lambda \), while transforming individual quantities, allows to find an equivalent beam which still preserves an optimized behavior, i.e. minimum emittance and maximum phase space density. As an example, if we want to scale with the RF frequency \( \omega_{RF} \), we will have to scale all beam dimensions with \( \lambda_{RF} \propto \frac{1}{\omega_{RF}} \) (in order to respect the geometrical scaling of beam with the RF environment), i.e. \( \sigma_{cat} \propto \sigma_z \propto \frac{1}{\omega_{RF}} \), scale bunch charge like \( Q \propto \frac{1}{\omega_{RF}} \), and RF peak field like \( E_{cat} \propto \omega_{RF} \) (as already discussed in ref. \textsuperscript{16}).
This example of ideal scaling with RF frequency implies a very tight requirement on the scaling of RF field vs. frequency: a RF gun operated at 120 MV/m peak field on the cathode at S-band (3 GHz) would have to be scaled to 240 MV/m for operation at C-band (6 GHz). But at a premium of a beam emittance scaling like $\varepsilon_n \propto \frac{1}{\omega_{RF}}$. In fact, in a well optimized photo-LINAC (the one whose layout is according to the so-called M. Ferrario working point [17], which tunes the beam propagation according to an invariant envelope of minimum emittance at the LINAC exit, see ref. 18), the final emittance is very close to the thermal one at the cathode, which scales like the cathode emissive spot size $\sigma_{cat}$. Hence, $\varepsilon_n \propto \sigma_{cat} \propto \frac{1}{\omega_{RF}}$. Applying this scaling, we would find a quality factor $\eta$ for spectral density scaling like $\eta \propto \frac{Q}{\varepsilon_n^2} \propto \omega_{RF}$. ImPLYing that the spectral density of the

But unfortunately pure RF scaling is technologically impossible
Scattered photons in collision

- Scattered flux
  \[ N_\gamma = L \sigma_T \]

- Luminosity as in HEP collisions
  - Many photons, electrons
  - Focus tightly
  - Short laser pulse; <few psec (depth of focus)

\[ \sigma_T = \frac{8 \pi}{3} r_e^2 \]

- Thomson X-section
  \[ \sigma_T = 0.67 \cdot 10^{-24} \text{cm}^2 = 0.67 \text{ barn} \]

\[ L = \frac{N_L N_e f}{4 \pi \sigma_x^2} \]

- U_L = 5 J ; Q = 1 nC \implies N_L = 2 \cdot 10^{19} \quad N_e = 6.3 \cdot 10^9

\[ \sigma_x = 10 \mu m \implies \langle L \rangle = \frac{N_L N_e f}{4 \pi \sigma_x^2} \approx 10^{34} \text{ f cm}^{-2} \text{s}^{-1} \]

- \[ N_\gamma = 7 \cdot 10^9 \text{ f s}^{-1} \] (full spectrum)
Energy-angular Spectral distribution

For a bunch the energy spread of the collected photons depends on

- Collecting angle $\theta_M$
- Bunch energy spread
- Transverse emittance

\[ \frac{\Delta E_X}{E_X} \approx 2 \frac{\Delta \gamma}{\gamma} + (\gamma \mathcal{G}_M)^2 + 2 \left( \frac{\varepsilon_n}{\sigma_\perp} \right)^2 + \frac{a_0^2}{1 + a_0^2} \]

\[ \Psi = \bar{\gamma} \mathcal{G} \approx (\bar{p}_\perp / mc) \approx (\varepsilon_n / \sigma_\perp) \]

**Optimized Bandwidth**

\[ \approx 2 (\varepsilon_n / \sigma_\perp)^2 \]

**Optimized Spectral Density**

\[ \propto \frac{Luminosity}{(\varepsilon_n / \sigma_\perp)^2} \propto \frac{Q}{\varepsilon_n^2} \]
Including thermal emittance
0.6 mm·mrad per mm of cathode spot-size (Cu cathode)

### Table 5: S-band photo-LINAC at 120 MV/m peak field on photocathode

<table>
<thead>
<tr>
<th>Q [pC]</th>
<th>( \epsilon_n [\mu m] )</th>
<th>( \frac{Q}{\epsilon_n^2} ) [pC/\mu m^2]</th>
<th>( \Lambda [KA] )</th>
<th>( B_n [A/m^2] ) (I [A])</th>
<th>( \sigma_x [mm] )</th>
<th>( T_{laser} [ps] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.76</td>
<td>1731</td>
<td>18.1</td>
<td>2.1e14 (56)</td>
<td>0.385</td>
<td>20.33</td>
</tr>
<tr>
<td>750</td>
<td>0.63</td>
<td>1889</td>
<td>16.0</td>
<td>2.2e14 (43)</td>
<td>0.355</td>
<td>20.26</td>
</tr>
<tr>
<td>575</td>
<td>0.55</td>
<td>1901</td>
<td>19.4</td>
<td>2.3e14 (35)</td>
<td>0.291</td>
<td>19.07</td>
</tr>
<tr>
<td>500</td>
<td>0.537</td>
<td>1734</td>
<td>20.1</td>
<td>2.6e14 (38)</td>
<td>0.309</td>
<td>14.20</td>
</tr>
<tr>
<td>425</td>
<td>0.468</td>
<td>1935</td>
<td>17.9</td>
<td>2.3e14 (25)</td>
<td>0.253</td>
<td>20.25</td>
</tr>
<tr>
<td>350</td>
<td>0.426</td>
<td>1929</td>
<td>18.67</td>
<td>2.5e14 (26)</td>
<td>0.238</td>
<td>18.05</td>
</tr>
<tr>
<td>250</td>
<td>0.361</td>
<td>1918</td>
<td>22.99</td>
<td>2.7e14 (17)</td>
<td>0.192</td>
<td>16.09</td>
</tr>
</tbody>
</table>
Table 7: C-band photo-LINAC at 200 MV/m peak field on photocathode

<table>
<thead>
<tr>
<th>Q [pC]</th>
<th>$\varepsilon_n [\mu m]$</th>
<th>$Q/\varepsilon_n^2$ [pC/\mu m^2]</th>
<th>$\Lambda$ [KA]</th>
<th>$B_n$ [A/m^2] (I [A])</th>
<th>$\sigma_x$ [mm]</th>
<th>$T_{laser}$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.433</td>
<td>2667</td>
<td>18.1</td>
<td>5.2e14 (49)</td>
<td>0.208</td>
<td>12.58</td>
</tr>
<tr>
<td>350</td>
<td>0.355</td>
<td>2777</td>
<td>17.5</td>
<td>6.2e14 (39)</td>
<td>0.191</td>
<td>10.74</td>
</tr>
<tr>
<td>250</td>
<td>0.29</td>
<td>2972</td>
<td>18.7</td>
<td>6.7e14 (28)</td>
<td>0.156</td>
<td>10.80</td>
</tr>
<tr>
<td>100</td>
<td>0.18</td>
<td>3086</td>
<td>33.1</td>
<td>9.7e14 (16)</td>
<td>0.092</td>
<td>7.0</td>
</tr>
<tr>
<td>50</td>
<td>0.126</td>
<td>3149</td>
<td>32.3</td>
<td>1.1e15 (8)</td>
<td>0.066</td>
<td>6.67</td>
</tr>
</tbody>
</table>

Table 9: X-band photo-LINAC at 200 MV/m peak field on photocathode

<table>
<thead>
<tr>
<th>Q [pC]</th>
<th>$\varepsilon_n [\mu m]$</th>
<th>$Q/\varepsilon_n^2$ [pC/\mu m^2]</th>
<th>$\Lambda$ [KA]</th>
<th>$B_n$ [A/m^2] (I [A])</th>
<th>$\sigma_x$ [mm]</th>
<th>$T_{laser}$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.578</td>
<td>1497</td>
<td>51.4</td>
<td>4.8e14 (81)</td>
<td>0.185</td>
<td>5.58</td>
</tr>
<tr>
<td>350</td>
<td>0.41</td>
<td>2082</td>
<td>49.5</td>
<td>7.7e14 (64)</td>
<td>0.163</td>
<td>5.22</td>
</tr>
<tr>
<td>250</td>
<td>0.317</td>
<td>2488</td>
<td>56.7</td>
<td>9.2e14 (46)</td>
<td>0.131</td>
<td>5.04</td>
</tr>
<tr>
<td>100</td>
<td>0.19</td>
<td>2770</td>
<td>62.0</td>
<td>1.4e15 (25)</td>
<td>0.095</td>
<td>3.51</td>
</tr>
<tr>
<td>20</td>
<td>0.085</td>
<td>2768</td>
<td>92.9</td>
<td>2.4e15 (8.6)</td>
<td>0.050</td>
<td>1.69</td>
</tr>
</tbody>
</table>
Fit to the numerical Data

\[ \eta = \frac{Q}{\varepsilon_n^2} \]

Q [pC]

num. artifact
Nicely uncorrelated transv. phase space – thermal emittance dominant – no bifurcations

Figure 13: Longitudinal and transverse phase space distributions
At the very last minute (just this night, thanks to A. Bacci) we obtained, blending vel. Bunch. with X-band RF curvature correction (1 X-band)

$$\varepsilon_n = 0.33 \ \mu m \quad T_{laser} = 5 \ ps \quad \sigma_x = 0.27 \ mm \ \Delta T = 557 \ keV \ for \ T = 585\ MeV$$

uncompensated rms energy spread is 15 keV at 550 MeV, implying $$\Delta \gamma / \gamma = 2.7 \cdot 10^{-5}$$ (nicely confirming something well known: photo-LINACs for high brightness beams deliver very small uncorrelated energy spreads, usually quite lower than $$10^{-4}$$, which is the usual target for slice energy spread in FEL drivers).
Using the code TS2 (described in [13, 15]) we scan over the parameter space of the laser and electron beam focusing. Using a 1 J laser pulse 10 ps long (gaussian time and transverse profile) at 500 nm wavelength, colliding with the electron beam described above, focused down to $\sigma_x = 30 \ \mu m$, we find the spectrum intensity distribution shown in Figure 17.

Figure 17: Spectrum intensity distribution vs electron energy
Pushing the correction of correlated energy spread we can go down to \( \Delta T/T = 2 \cdot 10^{-4} \), therefore achieving \( \sigma_E < 10 \, keV \)
Last… but not least… Wake-fields!

One important issue in the electron beam dynamics is the effect of longitudinal and transverse wake-fields in degrading the beam quality in the transversal of the Linac. Wake-fields are mainly generated by the iris-coupled accelerating structures, alternating in their geometry small aperture irises to much larger cavity cells, where the RF field couples to the RF structure to set up the typical TM_{010} 2π/3 mode used for accelerating the beam. Iris radius (i.e. the iris aperture) is the main parameter characterizing these wake-fields, usually referred as geometrical wakes. At S-band a=10 mm, for our C-band cavities (described below) a=7 mm, typical SLAC X-band cavities have a=3 mm. The longitudinal wake potential, which is the energy loss imparted on a witness electron, experiencing the wake-field, following a drive electron, exciting the wake, scales like 1/a^2, while the transverse wake potential, representing a transverse kick due to a misalignment between the witness and driving particles with respect to the accelerating cavity, scales like 1/a^4. Longitudinal wakes impact mainly the correlated energy spread of the electron bunch, while transverse wakes can induce an emittance growth due to correlated transverse kicks along the bunch, which is seen in the transverse phase space as a dilution of its density, and in the (x,z) plane as a banana-shaped effect on the bunch profile, so that the bunch centroid wiggles or drifts away from the linac symmetry axis, and bunch head and tail wiggle and/or drift by different amounts.
Figure 15: rms misalignment

Figure 16: Centroid drift versus accelerator length (for both axis)
Figure 15. The beam was transported and accelerated through the linac without trying to applying an orbit correction, and its centroid drifted out of the reference symmetry axis by different amounts in the two planes: at the Linac exit the x misalignment was only 12 microns, while the y misalignment reached 86 microns (as shown in Figure 16). The rms transverse emittance increases by a quantity 0.5 mm.mrad in the y plane, while stays almost unaltered in the x plane, indicating that we can have a significant emittance dilution when the beam offset reaches values comparable to the unperturbed beam spot size, which is almos 300 microns in our reference case (see figure 12). In this situation we would have an unacceptable growth of emittance indicating a severe loss of beam quality in terms of its phase space density.

This preliminary evaluation points out that a special care must be taken to correct the beam orbit to avoid emittance dilution due to transverse wake-fields, and that alignment requirements on accelerating structures are very demanding: the beam centroid should be taken under control at the level of 10-20 microns by beam orbit correctors. It also points out that at X-band, for the same beam and misalignment conditions, the effect would be 19.8 times stronger than at C-band (scaling as the ratio of iris aperture to fourth power, times the ratio of the two linac lengths, scaling roughly like 40/60 MV/m).

Not an issue at S-band....
In the following we present a LINAC design, based on C-band technology, with a Gun and accelerating structures. As can be seen in Figure 20, the general layout can be divided in several sections:

A first section with the Gun (that includes the photocathode laser), a first accelerating section that includes 3 LINACs (Booster), reaching 360 MeV. In order to separate the induced bremsstrahlung, we insert a Chicane. Angles for the chicane have been takes as optimized for the PLASMONX project. After the first half-chicane, a first interaction point is foreseen at lower energy (360 MeV). After the full chicane, the electron beam can be further accelerated to higher energies (720 MeV) before reaching the second interaction point.

**Figure 20:** General layout of the accelerator. Approximate distances are indicated in the shaded box, global minimum distances on top of the sections.
Figure 21: a) Schematic of the C-band Gun; b) SUPERFISH Field maps of the Gun with optimized parameters: $a$, $t$, $\text{ellipse}_r$, $R_{\text{arc}}$, $e = t/\text{ellipse}_r$, $t = 0.45$ cm, $\text{ellipse}_r = 0.765$ cm, $e = 0.558$, $a = 0.8$ cm, $R_{\text{arc}} = 0.4$ cm

Experimental measurements on 50 cm accelerating section prototype (travelling wave) have obtained a peak surface field about $\sim140$ MV/m [25], we are therefore confident to achieve in our standing wave gun a $\sim200$ MV/m field on the cathode. We have therefore taken this as reference value for the simulations indicated in the section “Theory, scientific background and numerical analysis”.

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Figure 23: HFSS (3D FEM) Simulation showing the power coupling.
5.3.5 The C-band prototype

A 50 cm long prototype has been manufactured by an Italian firm. It consists of 20 RF cells that are brazed in the high vacuum furnace available at LNF. The prototype has been vacuum and low power tested and, after that, high power tested in the KEK C-band test stand (JP). Figure 28 shows a CAD drawing of the prototype. The calculated main parameters of the prototype are listed in Table 17.

Figure 28: CAD drawing of the C-band prototype.
CONCLUSIONS

• Best RF freq. for a photo-Linac driving a Compton gamma-ray Source: the one achieving highest peak field on the photo-cathode inside RF Gun, the one assuring weakest wake-fields in Linac (and having available higher RF bands for RF curv. corr. -δT scales like 1/n² -> 1/4 from C to X, 1/16 from S to X)

• To work on optimum photo-Linac configuration (inv. envelope with M. Ferrario working point) -> C-band for photo-injector (90 MeV) followed by S-band photo-Linac

• Evolutionary approach: start with S-band (tomorrow! at 130 MV/m), substitute first 90 MeV with C-band later (to get 200-240 MV/m), save one X-band structure for en. spread corr.
Production of 13 MeV gamma rays

Electron beam: Emittance=0.9 mm mrad, \( \sigma_x=4 \mu m, \sigma_y=9 \mu m \)
Energy= 750 MeV
Energy spread=0.225 MeV
Charge =1 nC

Laser parameters
Energy 5J
Waist(diam)=10 \mu m
Temp. Dur.= 6ps

Total photon number=7.7 \times 10^8
Bandwidth=2.1%
Spectr. dens. = 3 \times 10^4 ph/sec\cdot eV

Total number vs beam transverse dimension

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