A European Proposal for the Compton Gamma-ray Source of ELI-NP

C. Vaccarezza

on behalf of the collaboration
Outline

• The European Collaboration
• The Source design
• The electron & laser beam parameters
• The Source layout
• The Photoinjector + Linac scheme
• S2e simulation results for the electron beam
• The laser system
• Future options to increase luminosity
• Conclusions
European Collaboration for the proposal of the gamma-ray source:

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

~ 80 collaborators elaborating the CDR/TDR

Covering

- Underlying physics & Best machine layout
- Technical realization
- Infrastructure concern
- Management structure
- Costs & Timing and Scheduling
- Training and education
- Implementation
The Challenge we are facing: design the *most advanced* Gamma Beam System based on *state-of-the-art* components, to be commissioned and delivered to users *by the end of year 2016*, reliable, cost-effective, compatible with present lay-out of ELI-NP building and ready for future evolutions

Warm RF Linac vs Pulsed Recirculated Laser

### Prototype of a New Generation (Light) Gamma-ray Sources:
- Bright, Mono-chromatic (0.3%),
- High Spectral Flux (> $10^4$ ph/sec/eV), Tunable (1-20 MeV),
- Highly Polarized, based on Compton Back-Scattering of High Phase Space Density Electron Beams by Lasers

### Nuclear Resonance Fluorescence
### Nuclear Photo-fission
### Isotope Detection -> toward Nuclear Photonics

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**Table 1: Summary of Gamma-ray beam Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</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 per shot within FWHM bdw.</td>
<td>$2-6 \cdot 10^5$</td>
</tr>
<tr>
<td># photons/sec within FWHM bdw.</td>
<td>$0.5-1.5 \cdot 10^9$</td>
</tr>
<tr>
<td>Source rms size</td>
<td>10 - 30 $\mu$m</td>
</tr>
<tr>
<td>Source rms divergence</td>
<td>25-250 $\mu$rad</td>
</tr>
<tr>
<td>Peak Brilliance ($N_{ph}/sec.mm^2.mrad^2.0.1%$)</td>
<td>$2.0 \cdot 10^{22} - 1.1 \cdot 10^{24}$</td>
</tr>
<tr>
<td>Radiation pulse length (rms, psec)</td>
<td>0.7-1.5</td>
</tr>
<tr>
<td>Linear Polarization</td>
<td>&gt; 95 %</td>
</tr>
<tr>
<td>Macro rep. rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td># of pulses per macropulse</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>Pulse-to-pulse separation</td>
<td>&gt; 15 nsec</td>
</tr>
</tbody>
</table>
A simple model has been derived by L. Serafini, V. Petrillo predicts the number of photons scattered within the desired bandwidth:

$$N_{\gamma}^{bw} = 1.2 \cdot 10^9 \frac{U_L [J] Q [pC] f_{RF} n_{RF}}{h \nu [eV] \sigma_x^2 [\mu m]} \Psi^2$$

scattered $- \text{ph/sec within } \Psi \equiv \gamma \vartheta$

$$\frac{\Delta \nu_{\gamma}}{\nu_{\gamma}} \approx \Psi^2$$
The spectral density (Serafini-Petrillo)

Spectral density for the considered bandwidth \( \frac{\Delta \nu}{\nu} \) :

\[
SPD = 1.67 \cdot 10^8 U_L Q f_{RF} n_{RF} \frac{\Delta \nu}{\nu} = 0.003 \quad \text{and} \quad SPD = 10^4
\]

\[
\Delta \nu = \frac{\Delta \nu}{\nu} \left( \frac{\Delta \nu}{\nu} \right)^2 - 4 \left( \frac{\Delta \nu}{\nu} \right)^2 \left( \frac{e_n}{\sigma_x} \right)^4 - \left( \frac{\Delta \nu}{\nu} \right)^2 \left( \frac{M^2 \lambda_L}{2 \pi w_0} \right)^4 - \left( \frac{a_{op}^2}{3} \right)^2
\]

\[
\gamma^2 \frac{\Delta \nu}{\nu} \left( 4 \sigma_x^2 + w_0^2 \right) \sqrt{1 + \phi^2 \left( \frac{\sigma_x^2 + c^2 \sigma_i^2}{4 \sigma_x^2 + w_0^2} \right)}
\]

For ELI - NP must be \( \frac{\Delta \nu}{\nu} = 0.003 \) and \( SPD = 10^4 \)

\( f_{RF} = 100 \text{ Hz} \)

\( U_L = \text{Laser pulse energy (J)} \)

\( h \nu = \text{laser photon energy=2.4 eV} \)

\( n_{RF} = \text{bunches per RF pulse} \)

\( Q = \text{el. bunch charge (pC)} \)

\( \phi = \text{collision angle} \)

\( \sigma_x = \text{e- beam focal rms spot size in \( \mu m \)} \)

\( W_0 = \text{laser focal spot size in \( \mu m \)} \)
Analytical model vs. classical/quantum simulation

Number of photons vs. bandwidth.

(a) CAIN (quantum MonteCarlo) Run by I.Chaichovska and A. Variola
(b) TSST (classical) Developed by P. Tomassini
Comp_Cross (quantum semianalytical) Developed by V.Petrillo

V. Petrillo
### Table 2: Electron beam parameters at Interaction Points: general characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>all values are rms</strong></td>
<td></td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>200-720</td>
</tr>
<tr>
<td>Bunch charge (pC)</td>
<td>25-400</td>
</tr>
<tr>
<td>Bunch length (µm)</td>
<td>100-450</td>
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<tr>
<td>ε_{n,x,y} (mm-mrad)</td>
<td>0.2-0.8</td>
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<tr>
<td>Bunch Energy spread (%)</td>
<td>0.04-0.08</td>
</tr>
<tr>
<td>Focal spot size (µm)</td>
<td>10-30</td>
</tr>
<tr>
<td># bunches in the train</td>
<td>&lt; 25</td>
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<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>
</tr>
<tr>
<td>Pointing jitter (µm)</td>
<td>1</td>
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**Table 3: Laser beam parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Energy Interaction</th>
<th>High Energy Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy (J)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Wavelength (eV)</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>FWHM pulse length (ps)</td>
<td>2-4</td>
<td>2-4</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>( M^2 )</td>
<td>&lt; 1.2</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>Focal spot size ( w_0 ) (µm)</td>
<td>25-40</td>
<td>20-35</td>
</tr>
<tr>
<td>Bandwidth (rms)</td>
<td>0.05 %</td>
<td>0.05 %</td>
</tr>
<tr>
<td>Pointing Stability (µrad)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Synchronization 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>
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</table>
Baseline for the Linac

Accelerator Layout Schematic

N. Bliss
The hybrid scheme for the Linac

**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

**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%)
Linac & TL

Low Energy

High Energy

Twiss parameters for eli_lowen_double_WP_28_3

Twiss parameters for eli_highen_double_WP_28_3

IPAC 2012, May 21-25 2012, New Orleans
WP_{ref} from the photoinjector

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

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

\[ x / \text{mm} \]

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

\[ \Delta E / \langle E \rangle / \% \]

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

\[ E_{\text{gun}} = 120 \, \text{MV/m} \]

\[ E(S1) = E(S2) = 21 \, \text{MV/m} \]

\[ Q = 250 \, \text{pC} \]

C. Ronsivalle
SB-Transverse beam size & distribution

Lowen

$E_0 = 0.36$ GeV

$\sigma_x = 0.0145$ mm

$\sigma_y = 0.017$ mm

$\sigma_x^{\text{rms}} = \sigma_y^{\text{rms}} = 15 \mu$ mm

Highen

$E_0 = 0.72$ GeV

$\sigma_x = 0.0115$ mm

$\sigma_y = 0.0119$ mm

$\sigma_x^{\text{rms}} = \sigma_y^{\text{rms}} = 12 \mu$ mm
Lowen

Highen
Wake on $\Delta x = 500 \, \mu m$

Transverse wake of a single cell from:

$$W = ae^{-t/\tau} \sin(\omega_{RF} \tau) \frac{V}{C/m}$$

with: $a = 245 \frac{V}{p \cdot C/m}$, $\omega_{RF} = 2\pi \cdot 8.398 \times 10^9$

Wake res Q 11000

Wake res Q 100
Wake on $\Delta x=500 \mu m$

SB

Wake res Q 100
RF-laser Synchronization 1ps
The laser systems

No specific development needed ➔ Industrial deliverable (Ti:sapph)

No industrial system do exist ➔ specific development

RF-laser Synchronization 1ps
Reagan et al., Colorado State Univ. CLEO 2012 (results shown last week)

This is the solution we are following:
- Already 2 beams @ 50Hz & optical switch @100Hz fits the requirement
- Pushing 50Hz → 100Hz is feasible

State of the art cryogenic amplifier around 100Hz

\[ \lambda = 1 \mu m, 1J @ 50Hz, 5ps \]
Laser request at the Compton IP

1ms (100Hz)

~15ns

~25 pulses ~0.5J/pulse

pulse@100Hz
\( \lambda \sim 1\mu m \)
\( \Delta t \sim 3ps \)

Amplifiers
\( \lambda \sim 1\mu m \)
1J@100Hz

Frequency doubling
\( \lambda \sim 0.5\mu m \)
0.5J@100Hz

25 passes optical recirculator
Solution: a laser beam recirculator made of individual spherical mirrors

Mirrors are located on 2 rings centred on the e-beam axis

Incident laser
3ps FWHM 515nm

≥ 2m \(\Rightarrow\) ≥13ns round-trip period

\(w_0=25-35\mu m\)

And another solution under study to reach 50 Round trips

F. Zomer
Future option for Luminosity increase

- Increase the number of interactions per pulse by recirculating $N_{\text{turns}}$ times the beam in a ring

$L_{\text{ring}} \geq T_{\text{pulse}}$
(one train circulating in the ring)

$10 \text{ msec}$

$T_{\text{pulse}} < 300 \text{ nsec}$

NO e- beam recirculation:
Laser beam recirculations ($N_{lr}$) = bunches in the train ($N_b$)

$N_{\text{turns}} \geq 1 \Rightarrow N_{lr} > N_b \times N_{\text{turns}}$

C. Biscari
Horizontal emittance degradation

Strong influence of bending angle
Space requirements against emittance increase

No chromatic effect correction
No shielding
6 cells: 100% increase $\varepsilon_x$
8 cells: 80%
10 cells: 5%

C. Biscari
Conclusions

• The E-Gammas-Source has been designed with his main features for feasibility, performance and cost effectiveness.
• Electron beam SB and MB beam dynamics studies have been performed and are close to be completed.
• The laser system and recirculator baseline has been defined the design finalization is on going.
• Tolerance studies have been started and their completion is on going.
• An electron recirculating ring is under study to improve luminosity.
Collimation system 1/2

Geant4 collimation line simulation

- Collimator 1 [Cu]
  \[ d = 6 \text{ m}, \ r = 0.4 \text{ mm}, \ l = 30 \text{ cm} \]
  used @ E166 (\( r = 0.425 \text{ mm} \))

- Collimator 2 & 3 [W]
  \[ d = 6.5 \text{ & 7.0 m}, \ r = 0.4 \text{ mm}, \ l = 4 \text{ cm} \]

- Beam pipe [Fe]
  \[ r = 2 \text{ cm}, \ t = 0.1 \text{ cm} \]
Other type: dual slit collimator [W]
used with 5 MeV linac X-ray beam

A solution was found with 4×2 collimators
- Collimation length greater
- Gamma yield smaller (~3 times less)

Courtesy M. Gambaccini