The High Intensity Gamma Source for CERN:

*Physics highlights and technical challenges*

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Introduction: A lesson from the past?

- Hera and TESLA plans in the 90-ties
- The DESY “QCD-facility” proposal and its role for the future RHIC and LHC scientific programs
- “High” luminosity upgrade and closing the DESY HEP experimental program

Lesson: worthwhile do develop a new, back-up interdisciplinary program for CERN (on top of the present high-risk flagship ones – FCC, CLIC)… and based on the already existing accelerator infrastructures
The origin of the proposal
A proposal of an “unconventional” use of the LHC and its detectors for the ep(eA) collision programme

Electron beam for LHC

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Abstract

A method of delivering a small energy spread electron beam to the LHC interaction points is proposed. In this
Partially stripped ions as electron carriers

- Average distance of the electron to the large Z nucleus: $d \sim 600$ fm (sizable higher than the range of strong interactions)

- Partially stripped ion beams can be considered as independent electron and nuclear beams as long as the incoming proton scatters with the momentum transfer $q >> 300$ KeV

- Both beams have identical bunch structure (timing and bunch densities), the same $\beta^*$, the same beam emittance — the choice of collision type can be done exclusively by the trigger system (no read-out and event reconstruction adjustments necessary)
Ion striping sequence:

**BNL** & **CERN**

Lead acceleration at CERN

Gold Acceleration at the AGS in 1995 (FY96)

- 4 Booster Cycles:
  - Au$^{32+}$: 40 - 430 MeV/c/nuc
  - $h = 8 \rightarrow 4$ by bunch stacking
- 60% Stripping Efficiency:
  - RHIC
  - Au$^{77+}$: 0.43 ... 11.6 GeV/c/nuc
  - $h_{\text{inj}} = 16$
  - $h_{\text{Extr.}}$ (FEB) = 4 (1995:8)
  - $h_{\text{Extr.}}$ (SEB) = 12

Lead acceleration at CERN

- 208Pb$^{80+}$
- 208Pb$^{82+}$
- 208Pb$^{54+}$
- 208Pb$^{28+}$

From ECR
PIE@LHC*: Pb$^{81+}$(1s)-p example

- CM energy (ep collisions) = 205 GeV
- $\beta$ at IP = 0.5 m
- Transverse normalized emittance = 1.5 $\mu$ m
- Number of ions/bunch = $10^8$
- Number of protons/bunch = $4 \times 10^{10}$
- Number of bunches = 608
- Luminosity = $0.4 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

* PIE = Parasitic Ion Electron collider
High Intensity Gamma Source for CERN

…and the existing (future) light-source projects
X-ray sources

How about the quanta capable of resolving/manipulating the nuclear structure and allowing to copiously produce matter particles ($\gamma$-ray domain)?
FEL as a gamma ray source?

$\lambda_r = \frac{\lambda_u}{2\gamma^2} (1 + K^2)$,

$K = \frac{\gamma \lambda_u}{2\pi \rho} = \frac{eB_0 \lambda_u}{\sqrt{8\pi m_e c}}$

Need the low emittance electron beams spanning the beam energy range of 1-10 TeV (assuming O(10 cm) period of magnetic field)
Laser Compton Scattering as the source of MeV-range photons
The Duke University **Gamma** source
Parameters of the gamma source facilities around the world

<table>
<thead>
<tr>
<th>Project name</th>
<th>LADON³</th>
<th>LEGS</th>
<th>ROKK-1M⁴</th>
<th>GRAAL</th>
<th>LEPS</th>
<th>Hly 5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Frascati, Italy</td>
<td>Brookhaven, US</td>
<td>Novosibirsk, Russia</td>
<td>Grenoble, France</td>
<td>Harima, Japan</td>
<td>Durham, US</td>
</tr>
<tr>
<td>Storage ring</td>
<td>Adone</td>
<td>NSLS</td>
<td>VEPP-4M</td>
<td>ESRF</td>
<td>SPring-8</td>
<td>Duke-SR</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>1.5</td>
<td>2.5–2.8</td>
<td>1.4–6.0</td>
<td>6</td>
<td>8</td>
<td>0.24–1.2</td>
</tr>
<tr>
<td>Laser energy (eV)</td>
<td>2.45</td>
<td>2.41–4.68</td>
<td>1.17–4.68</td>
<td>2.41–3.53</td>
<td>2.41–4.68</td>
<td>1.17–6.53</td>
</tr>
<tr>
<td>γ-beam energy (MeV)</td>
<td>5–80</td>
<td>110–450</td>
<td>100–1600</td>
<td>550–1500</td>
<td>1500–2400</td>
<td>1–100 (158)d</td>
</tr>
<tr>
<td>Energy selection</td>
<td>Internal tagging</td>
<td>External tagging</td>
<td>(Int or Ext?) tagging</td>
<td>Internal tagging</td>
<td>Internal tagging</td>
<td>Collimation</td>
</tr>
<tr>
<td>γ-energy resolution (FWHM)</td>
<td>ΔE (MeV)</td>
<td>2–4</td>
<td>5</td>
<td>10–20</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>ΔE/E (%)</td>
<td>5</td>
<td>1.1</td>
<td>1–3</td>
<td>1.1</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>E-beam current (A)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td>Max on-target flux (γ/s)</td>
<td>5 × 10⁵</td>
<td>5 × 10⁶</td>
<td>10⁸</td>
<td>3 × 10⁹</td>
<td>5 × 10⁹</td>
<td>10⁶–5 × 10⁸</td>
</tr>
</tbody>
</table>

The goal: achieve comparable fluxes in the MeV domain as those in the KeV domain.

For comparison: DESY FEL: photons/pulse -- 10¹¹-10¹³, pulses/second –10-5000 → (10¹² – 10¹⁷ photons/s)
The goal of the HIGS@CERN proposal

\( \text{(HIGS= High Intensity Gamma Source)} \)

Increase the intensity of the present gamma ray sources by at least 6-7 orders of magnitude

\[ E_\gamma \text{ in the range } \sim 0.1 - 400 \text{ MeV} \]
LHC as a frequency converter of $O(1-10\text{ eV})$ photons into $O(1 - 400\text{ MeV})$ $\gamma$-rays

- Energy of the laser photons tuned to a resonant frequency of an atomic transition e.g. $1s \rightarrow 2p$
- Decay length in the LAB frame $c\tau \sim \gamma L / Z^4$
  - Below 0.1 mm for $\text{Pb}^{81+}(2p) \rightarrow \text{Pb}^{81+}(1s) + \gamma$
LHC partially stripped ion beams as the light frequency converter:

\[ \nu_i \quad \rightarrow \quad (4 \gamma_L^2) \nu_i \]

\[ \gamma_L = \frac{E}{M} \] - Lorentz factor for the ion beam
Scattering of photons on ultra-relativistic atoms

\[ E_n = 1 \text{Ry} \left( \frac{Z^2}{n^2} \right) \]

\[ E_{\text{laser}} = 1 \text{Ry} \left( \frac{Z^2 - Z^2}{n^2} \right) / 2 \gamma_L \]

\[ E_{\gamma\text{-ray}} = E_{\text{laser}} \times 4 \gamma_L^2 / (1 + (\gamma_L \theta)^2) \]

Note: \((E_{\text{laser}} / m_{\text{beam}}) \times 4 \gamma_L << 1\)
Doppler Effect and Resonant Scattering

\[ r_e = 3 \times 10^{-15} \text{ m} \]

\[ \lambda \sim O(10^{-10}) \text{ m} \]
Fine tuning of gamma ray energy: $E_\gamma$

The energy of the gamma beam can be tuned by selecting the ion (Z), its storage energy ($\gamma_L$-factor), the atomic level (n), and the laser light wavelength ($E_{laser}$)

**Scenario 1 (muon production threshold):**
FEL: 104.4 nm, Pb$^{80+}$ ion, $\gamma_L=2887$, n=1→2,
$E_\gamma$ (max) = 396 MeV

**Scenario 2 (nuclear physics application):**
Erbium doped glass laser: 1540 nm, Ar$^{16+}$ ion, $\gamma_L=2068$, n=1→2, $E_\gamma$ (max) = 13.8 MeV

**Scenario 3 (SPS initial feasibility studies):**
Krypton laser: 647 nm, Xe$^{47+}$ ion, $\gamma_L=162$ (SPS), $^4S_{3/2} \rightarrow ^4P_{3/2}$
$E_\gamma$ (max) = 0.196 MeV
The comparison of the partially stripped ion beam driven LHC-based HIGS and the electron-beam driven Laser-Compton-Scattering (LCS) gamma sources
The LHC ion energies of:

1-3 TeV/nucleon

are equivalent to the energies of:

0.5-1.5 GeV

of the electron beam

Electrons:

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

\( r_e \) - the classical electron radius

Partially stripped ions:

\[ \sigma_{\text{res}} = \frac{\lambda_{\text{res}}^2}{2\pi} \]

\( \lambda_{\text{res}} \) - photon wavelength for the resonant atom excitation

Reminder:

\[ \left( \frac{E_{\text{laser}}}{m_{\text{beam}}} \right) \times 4\gamma_L \ll 1 \]
Electrons: \[ \sigma_e = 6.6 \times 10^{-25} \text{ cm}^2 \]

Partially stripped ions: \[ \sigma_{\text{res}} = 5.9 \times 10^{-16} \text{ cm}^2 \]

scenario 2, \( \lambda_{\text{laser}} = 1540 \text{ nm} \)

...cross sections in the Giga-barn range!
Example: scenario 1, \( \gamma_L = 2887 \)

Electrons:

\[
E_{\text{beam}} = 1.5 \text{ GeV}
\]

Electron fractional energy loss:
emission of 150 MeV photon:
\[
\frac{E_\gamma}{E_{\text{beam}}} = 0.1
\]

(electron is lost!)

Partially stripped ions:

\[
E_{\text{beam}} = 574 \, 000 \text{ GeV}
\]

Electron fractional energy loss:
emission of 150 MeV photon:
\[
\frac{E_\gamma}{E_{\text{beam}}} = 2.6 \times 10^{-7}
\]

(ion undisturbed!)

…stable ion beams, even in the regime of multi photon emission per turn!
Principal advantages of the ion-based light sources

Fluxes:
The Rayleigh resonant cross section for partially stripped ions is higher by a factor \((\sim \lambda_{\text{res}}/r_e)^2\) than the Thompson cross-section for electrons.

The “cross-section gain” in the \(\gamma\)-flux of the order of \(10^{7-11}\) for the same intensity of the laser light and the same beam crossing geometry as in the Duke Facility.

Beam rigidity:

Ions bunches are “undisturbed” by the light emission. Electron bunches are.
… only a partial remedy: e-beam is recycled to accelerate succeeding beam (ERL)
Principal advantages of the ion-based light sources

**Energy tunability:**
Four-dimensional flexibility of the HIGS ($E_{\text{laser(FEL)}}, \gamma_L, Z_{\text{ion}}, n.$). Easy to optimize for a required narrow band of the $\gamma$-beam energy over a large $E_\gamma$ domain. For the previous LCS sources two parameter tuning.

**Beam divergence:**
Excellent: Below 0.3 mrad

**Polarizability**
Flexible setting. Reflect, in both cases the polarization of the laser light

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**Note:**
For maximal energies (e.g. scenario 1) HIGS must be driven by a $<100$ nm FEL photons.
For lower energies standard $\sim 300$-$1500$ nm lasers and FP cavities are sufficient
Light sources based on partially stripped ions have been proposed and discussed already in several papers: thanks to Alexey Petrenko for drawing my attention to the initial ideas and earlier work in this domain...
Physics highlights
• particle physics (studies of the basic symmetries of the universe, dark matter searches, muon collider physics, neutrino-factory physics, precision-support measurements for the LHC),
• nuclear physics (confinement phenomena, link between the quark-gluon and nucleonic degrees of freedom, photo-fission research program),
• accelerator physics (beam cooling techniques, low emittance hadronic beams, high intensity photon beams, plasma wake field acceleration, high intensity polarized positron and muon sources, secondary beams of radioactive ions and neutrons, electron-ion collider, muon collider, neutrino-factory),
• atomic physics (electronic and muonic atoms),
• applied physics (AdS, transmutation of nuclear waste, fusion research, medical applications).
The use of the gamma beams

<table>
<thead>
<tr>
<th>Type of Collisions</th>
<th>Energy (E_{CM})</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ−γ collisions</td>
<td>2-800 MeV</td>
</tr>
<tr>
<td>γ−γ_L collisions</td>
<td>1-126 keV</td>
</tr>
<tr>
<td>γ−p,A collisions</td>
<td>4-60 GeV</td>
</tr>
</tbody>
</table>

Secondary beams of electrons, positrons, muons, neutrons and radioactive nuclei

Medical applications, nondestructive assay and segregation of nuclear waste, photo transmutation of nuclear waste using resonant (γ,n) transitions, γ-ray laser, nuclear fusion and fission, ADS, wake field for plasma acceleration, material science…
The expected intensity of the primary and secondary HIGS beams

Disclaimer: The presented below initial estimation of the achievable fluxes are preliminary. For the LHC-based partially stripped ion based gamma source the intensity limits are driven predominantly by the present circumferential voltage of the LHC ring and by the stability of the ion beams, rather than by the laser power and the collision geometry (electron beam driven sources).
Initial estimates of the achievable $\gamma$-fluxes for the two LHC scenarios

Scenario 1:
FEL: 104.4 nm, Pb$^{80+}$ ion, $\gamma_L=2887$, $n=1\rightarrow2$, $E_{\gamma}^{(\text{max})}=396$ MeV, $N_{\gamma}^{\text{max}} \sim 6 \times 10^{15} [1/s]$ for the present LHC RF system

Scenario 2:
Erbium doped glass laser: 1540 nm, Ar$^{16+}$ ion, $\gamma_L=2068$, $n=1\rightarrow2$, $E_{\gamma}^{(\text{max})}=13.8$ MeV, $N_{\gamma}^{\text{max}} \sim 3 \times 10^{17} [1/s]$

Comments:
1. $N_{\gamma}^{\text{max}} = N_{\text{ion bunch}} \times N_{\text{bunches}} \times f [1/s] \times RF [MV] \times Z / <E_{\gamma} [MeV]>.$
2. For scenario 2, where $c\tau_{\text{exited ion}} = 1.2$ cm, the effect of the double photon absorption process, and the beam life-time remains to be calculated… if necessary it could be circumvented by using a pulsed laser beam
secondary beams:
- electrons,
- positrons,
- muons,
- neutrons
- radioactive nuclei

\[ \sigma_{\text{p.e.}} = \text{Atomic photoelectric effect (electron ejection, photon absorption)} \]
\[ \sigma_{\text{Rayleigh}} = \text{Rayleigh (coherent) scattering–atom neither ionized nor excited} \]
\[ \sigma_{\text{Compton}} = \text{Incoherent scattering (Compton scattering off an electron)} \]
\[ \kappa_{\text{nuc}} = \text{Pair production, nuclear field} \]
\[ \kappa_{e} = \text{Pair production, electron field} \]
\[ \sigma_{\text{g.d.r.}} = \text{Photonuclear interactions, most notably the Giant Dipole Resonance} \]
In these interactions, the target nucleus is broken up.
HIGS as a source of high intensity secondary beams

- **High Intensity highly polarised electron and positron beams** ($\sim 10^{17}$ 1/s)

- **Polarized muon and neutrino beams** ($\sim 10^{12}$ 1/s and $4 \times 10^{19}$ 1/year) *

- **High intensity monochromatic neutron beams** *(GDR in heavy nuclei as a source of neutron beam: $\gamma + A \rightarrow A-1 + n$) ($\sim 10^{15}$ 1/s)

- **High intensity radioactive beams** ($\sim 10^{14}$ 1/s)
  *(photo-fission of heavy nuclei: $\gamma + A \rightarrow A_1 + A_2 + \text{neutrons}$)

*) for the quoted flux of the muons/neutrinos the LHC circumferential voltage would need to be increased from the present value of RF=16 MV and/or the number of stored ions (bunch population and bunch frequency) would have to be increased by e.g the factors of 2, 2 and 3. The power of the gamma-beam for the quoted fluxes would be $\sim 4$ MW.
For scenario 2: the flux of $\sim 10^{17}$ $N_{e^+e^-}/s$ can be achieved with the nominal LHC RF voltage. Note: the beam power which has to be handled by the photon conversion target would be of the order of 100 kW.
**μ⁺-μ⁻ collider requirements**

<table>
<thead>
<tr>
<th>C of m Energy</th>
<th>1.5</th>
<th>3</th>
<th>6</th>
<th>TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>0.92</td>
<td>3.4</td>
<td>0.9</td>
<td>10^{34}\ cm^2\sec^{-1}</td>
</tr>
<tr>
<td>Beam-beam Tune Shift</td>
<td>≈0.087</td>
<td>≈0.087</td>
<td>≈0.087</td>
<td></td>
</tr>
<tr>
<td>Muons/bunch</td>
<td>2 (1.44 ?)</td>
<td>2</td>
<td>2</td>
<td>10^{12}</td>
</tr>
<tr>
<td>Total muon Power</td>
<td>9</td>
<td>15</td>
<td>3.7</td>
<td>MW</td>
</tr>
<tr>
<td>Ring &lt;bending field&gt;</td>
<td>6</td>
<td>8.4</td>
<td>8.4</td>
<td>T</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>2.6</td>
<td>4.5</td>
<td>9</td>
<td>km</td>
</tr>
<tr>
<td>β* at IP = σ₂</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
<td>mm</td>
</tr>
<tr>
<td>rms momentum spread</td>
<td>0.1 (0.3 ?)</td>
<td>0.1</td>
<td>0.1</td>
<td>%</td>
</tr>
<tr>
<td>Required depth for ν rad</td>
<td>≈20</td>
<td>≈200</td>
<td>≈200</td>
<td>m</td>
</tr>
<tr>
<td>Proton Energy</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>GeV</td>
</tr>
<tr>
<td>Muon per proton</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Muon per pulse</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>%</td>
</tr>
<tr>
<td>protons/pulse</td>
<td>187 (134 ?)</td>
<td>200</td>
<td>240</td>
<td>Tp</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>15 (21 ?)</td>
<td>12</td>
<td>1.5</td>
<td>Hz</td>
</tr>
</tbody>
</table>

**HIGS muon flux** (factor 10 lower than required) up to 10^{12} polarized μ⁺-μ⁻ pairs [1/s] for 4MW RF power of the LHC cavities (For comparison: TLEP RF power ~300MW)

beam emittance (factor >10^4 improvement* possible, counterbalance lower intensity?)

*) the theta/energy correlation of the muons produced by the photon conversions on high Z target would have to be exploited in the beam forming section
Neutrino-factory requirements

Achievable neutrino flux  (a factor 10 lower that of NuMAX, a factor 50 higher than that of nuSTORM)

...but, if the initial muon polarization is preserved in the acceleration process → ultra pure $\nu_\mu$ ($\bar{\nu}_\mu$) beams of precisely equal fluxes (e.g. CP – violation measurements in the neutrino sector)
Secondary Neutron and Radioactive Beams

Achievable production rate of:
- primary neutrons $\sim 10^{15} \text{ 1/s}$
- fission products $\sim 10^{14} \text{ 1/s}$

GDR=Giants Dipole Resonance

Figure 1. Partial and total photonuclear cross sections $(\gamma,n)$, $(\gamma,2n)$, $(\gamma,f)$, and $(\gamma,\text{tot})$ for $^{238}\text{U}$. 
Selected technical challenges

Meeting these challenges is anything but easy – the feasibility of Gamma Source concept is far from being proven, it needs detailed studies – what will be shown in the following are all preliminary ideas/calculations

… the input of the accelerator experts (your input) is a sine qua non condition to move forward with this project
1. Life-time of partially stripped ion beams

- Bunch temperature $T_b \ll 1 \text{ Ry} \times Z^2$ at all the acceleration stages - (radiative evaporation cooling, laser Doppler cooling)

- “Stark effect” in the LHC superconducting dipoles ($E = 7.3 \times 10^{10} \text{ V/m}$) - only high and medium Z ions allowed to be the electron carriers at the LHC

- Ionization process
  - realistic requirement on the LHC vacuum (concentration of $\text{CH}_4$ is critical - must be kept below $\sim 6 \times 10^{11} \text{ mol/m}^3$ (circumference averaged) to achieve the $\text{Pb}^{81+}(1s)$ beam life-time larger than 10 Hours)
  - stringent requirements on the allowed beam collision schemes
    (only partially stripped high Z ions can collide only with the lightest fully stripped ions: $p$, $He$, $O$…)

40
Gold with two electrons successfully stored in RHIC

Dejan Trbojevic (Apex workshop 2007)

Storage of the partially stripped ion beam is not a science-fiction!
Two prerequisite “proof of principle” steps

- Short SPS test run with the “BNL-type stripping target” (measurement of the beam life time, and time-dependent emittance of the beam of the Partially Stripped Ion beam in SPS?
- If successful measurement of the life-time of the partially stripped lead ion beam in the LHC?
- If successful first ep, eA collisions in ATLAS, CMS, ALICE & LHCb

Target type and thickness optimisation for the BNL Au$^{77+}$ beams (two electrons attached)
2. Beam cooling (methods of atomic physics)

Crystalline beams created by atomic physics using laser cooling techniques

Figure 1 Images of ion crystals at rest in PALLAS. False colours reflect the fluorescence intensity of individual ions. The ions are longitudinally confined in a weak static potential which is generated by the two drift tubes, highlighted in Fig. 2. The crystal becomes more complex when the linear ion density \( \lambda = (N/z) \times a \), \( N \) denoting the number of particles and \( a \) the Wigner–Seitz radius, increases with lowered confining potential \( \psi_p \) from a to b or when it increases stepwise along the axis \( z \) because of the weak longitudinal confinement, as illustrated in b. The radius \( \sigma_r = 5.2 \mu m \) of the linear ion string mainly reflects the overall spatial resolution (integration time 0.4 s).
Two cooling methods:

1. Radiative ion cooling (broad-band-laser cooling) – faster beam particles lose more energy than slower ones and all gain the same energy in the accelerating cavity.

\[ \frac{\Delta \omega}{\omega_L} = \frac{\Delta \psi}{4} + \frac{\Delta \gamma}{\gamma}. \]

Laser bandwidth covers the angular and momentum dispersion of the ion beam.

For Scenario 1 the dumping time is \( t = 52 \text{ s} \) and the equilibrium horizontal emittance is \( \varepsilon_x = 3 \times 10^{-15} \text{ mrad} \) (E.G. Bessonov).

2. Enhanced cooling

Linear rise of the laser beam power in the frequency interval within the a fraction of a broad band region (previous case).

The dumping time is reduced to \( t = 0.1 \text{ s} \) (note cooling mainly in longitudinal direction, emittance exchange schemes must be applied..)

Initial simulations of the ions in the LHC lattice by Alexey Petrenko

Scenario 1:

Laser frequency band covers the $\Delta E > 0$ energies (negative $\Delta E$ out of the resonance)

Low power laser: each ion is radiating with probability of 50% over every turn)

Possible use of the ultra-cold ion beam in Wake-field plasma acceleration?
Initial simulations of the ions in the LHC lattice by Alexey Petrenko

Scenario 1:

Full laser power covering uniformly the LHC ion energy bandwidth.

No bam cooling.

Ion is lost from the bucket
Initial simulations of the ions in the LHC lattice by Alexey Petrenko

Scenario 1:

Gamma-beam generating laser (full power) covering uniformly the LHC initial ion energy bandwidth + Beam cooling, low power laser with frequency band covering the $\Delta E > 0$ resonant collisions

Instability disappears
3. Laser system and the gamma beam extraction

- Nd:YAG laser - 3ns x 100 mJ @ 100 Hz
- Pockels cell converts linear (>99%) light to circularly polarised light
Is there a technical possibility to install the laser system in the octants 3/7 or maybe in octant 6 (external ring)?…

..less attractive solution is to install it in one of the IPs..
ALICE Zero Degree Calorimeter (ZDC) zone as an example...

115 m

gamma beam

Vertical bump necessary...
4. Polarised electron/positron and muon source

Principal gains of a HIGS driven positron source:

- High positron/electron flux (no necessity to stack the positrons in the pre damping or damping ring)
- Highly polarized electrons/positrons (circular gamma polarisation)
- Significantly lower target heat load per produced positron
- Precious admixture of muon pairs ($E_\gamma$ above muon production threshold)

Replace Primary Electrons by Polarised Gamma

Replace the 4.5 X0 Converter by a ~1X0 converter – only primary conversions
Problems which need to be solved:

- For e.g. $E_\gamma \sim 300$ MeV, muons constitute only a small ($\sim 10^{-5}$) fraction of all the photon conversion pairs. 
  How to filter them out?

- Muons produced mainly at significantly larger angles than electrons and may be emitted at large angles ($\gamma_e >> \gamma_\mu$). 
  How to collect them to preserve the small longitudinal and transverse bunch sizes of the parent photon bunches?
The conversions, especially on high Z material lead to a simple relation between the outgoing muon energy and angle:

Electrons are relativistic, muons are not:

\[ \beta_e = 1, \langle \beta_\mu \rangle \sim 0.5 \]

20 ns following the collision of the photon bunch with the conversion target, electron and muon bunches are separated by (on average) 200 cm allowing for their efficient separation.
initial ideas...

- Electrons and positrons
- Muons
- \( \gamma \)-beam
- Momentum equalisation zone
- Focusing zone
- Electron and muon bunches separation zone

Muon collider
Neutrino factory

Electron-ion collider

$\sim 3 \text{ m bunch separation}$
$\text{over the time span of}$
$\sim 20\text{ns}$
A possible use of the HIGS polarized lepton source – the high luminosity energy recovery Electron-Ion Collider (EIC) … and/or a 3 TeV muon collider in the SPS tunnel

The SPS tunnel

Muon collider ring?

The proton(ion) ring
“EIC with the SPS protons and ions”

The scaled down ERL of the LHeC project
5. Polarized positron source and the Energy and cost recovery scheme

Fissionable nuclear waste sensitive to slow neutrons

Moderator

Fissionable nuclear waste – neutron multiplication

Principal high Z target

Vacuum

Neutrons

Solenoid magnetic field

Distance to the LHC tunnel: 100-300m

~10 MeV $\gamma$-beam

High intensity electron and positron beams – cost recovery

Electric power for the LHC cavities-energy recovery

Electrons,

Positrons

… a preliminary idea of the secondary beam producing station with the electric power and cost recovery.
**Direct pair production: (the idea presented yesterday)**
Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s} \sim 0.212\text{GeV}$) in asymmetric collisions (to collect $\mu^+$ and $\mu^-$)

- **References:**
  - M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, “Novel proposal for a low emittance muon beam using positron beam on target”, NIMA online
  - Investigation of this idea by SLAC team:
    - Simulations study by SLAC: L. Keller, J. P. Delehaye, T. Markiewicz, U. Wienands, MAP workshop 2014
    - **Presentation in Snowmass 2013**, Minneapolis (USA) July 2013:
      [M. Antonelli and P. Raimondi, Snowmass report (2013)] also [LNF-Note]
Schematic Layout

- 6 km positron ring \( (\rho = 0.6 \text{ km}) \)
- \( \text{Nb}=100 \) (200 ns bunch spacing)
- \( I_{\text{tot}}(e^+) = 240 \text{ mA} \)
- \( 3 \cdot 10^{11} e^+ \) per bunch
- \( 1.5 \cdot 10^{18} e^+ \) /s on target

**Positron ring**
- \( \mu^+ \) accumulator
- \( \mu^- \) accumulator

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**Key point:**

Positron source requirements strictly related to the momentum acceptance

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<td>( B ) [T]</td>
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<td>( E_{\text{critical}} ) [keV]</td>
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<td>( e^+ ) rate [Hz]</td>
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<td>( &lt; N_\gamma &gt; )</td>
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<td>( U_0 ) [GeV]</td>
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<td>( P_{\text{tot}} ) [MW]</td>
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The way forward

Two parallel paths:

1. Detailed evaluation of the physics and industrial and medical applications opportunities of the HIGS proposal.
2. The technical feasibility studies.
The first critical steps

- Present the proposal to potentially interested communities (evaluate interest)

- Develop the tools and precision calculations of the intensity, emittances and spot sizes of the primary gamma-rays and secondary beams for realistic ion, laser (FEL) F-P choices and realistic Partially Stripped Ion (PSI) beam parameters

- Short SPS test run with “BNL-type stripping target” (measurement of the beam lifetime, and time-dependent emittance of the beam of PSIs in the SPS?)

- At the end of the LHC Run2 (or earlier?) measurement of the life-time of the partially stripped lead ion beam in the LHC?

- A proposal to SPSC for a test experiment to study the collisions of F-P cavity photons, driven by a laser system, with the (extracted) PSI beams (Ar ions –scenario 3)
**LHC roadmap: according to MTP 2016-2020**

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- **LS2**: Starting in 2019 => 24 months + 3 months BC
- **LS3**: LHC starting in 2024 => 30 months + 3 months BC
- **Injectors**: in 2025 => 13 months + 3 months BC

**Legend:**
- **Physics**
- **Shutdown**
- **Beam commissioning**
- **Technical stop**

**Phase 1:** 2015-2028

**Phase 2:** 2029-2035

**HL-LHC installation**
Conclusions
The history of our discipline shows that a big technological Leaps led to important discoveries -- at least as frequently as the research guided by verification of the theoretical models of a priori defined discoveries – the dominant paradigm in HEP these days.

Large laboratories, like CERN, may be forced to diversify further their research domain – focussed at present mainly on the high energy frontier (a lesson from the “dinosaur’s extinction”) -- and use existing infrastructure to enlarge the research scope.

The high energy storage rings (HERA, Tevatron, LHC) are costly – we may be confronted with the need to extend their life time before a new costly infrastructure is build.
• The idea underlying the HIGS@CERN proposal is to use, for the first time, atomic degrees of freedom, in forming very high intensity beams of photons, leptons, neutrons and radioactive ions.

• The HIGS scheme provides a very efficient scheme of transforming accelerator RF power to the power of the (\(\gamma\), e, \(\mu\), \(\nu\), n, radioactive ion) secondary beam

• In some cases the HIGS scheme may lead to a leap, by several orders of magnitude, in the increase of their intensity.

• Handling powerful beams of photons/electrons and neutrons represents an important technological challenge. The potential bonuses of addressing such a challenge are, however, numerous:
1. Possible application to the high energy frontier (muon colliders) and high intensity frontier (i.e. the SPS based ep(eA) collider, γγ colliders and neutrino factories)

2. Opening new research domains in Fundamental Physics (including the dark matter searches domain, investigation of the basic symmetries of the universe with high precision, …)

3. (Extending?) the experimental program in Nuclear Physics

4. Industrial applications (energy production, the research on nuclear reactors with significantly reduced nuclear waste, etc.)

5. Medical applications (including production of isotopes for the selective cell killing techniques).
• The technical “proof of principle” of the proposed scheme can be performed almost entirely at the SPS (in parallel to the present LHC physics programme).

• Its positive outcome is the necessary but not sufficient condition for the HIGS proposal to be considered at CERN…

• Since this project is bound to use the full LHC infrastructure two necessary conditions must, in addition, be fulfilled:
  
  - a support of the CERN accelerator experts and the CERN management for the initial feasibility studies
  - a wide multidisciplinary interest and support (including funds) (particle physics, atomic physics, nuclear physics, applied physics)
extra transparencies
An intense \( \text{up to } 10^{13}\gamma/s \), brilliant \( \gamma \) beam, 0.1 % band-width, with \( E\gamma > 19 \text{ MeV} \), which is obtained by incoherent Compton back scattering of a laser light off a very brilliant, intense, classical electron beam \( (Ee > 700 \text{ MeV}) \) produced by a warm linac.
Survival of partially stripped ions:

**Ionization losses**

- A dominant process leading to losses of partially stripped ions is the ionization process in beam-beam and beam-gas collisions (note a quantum jump in magnetic rigidity of the beam particles)

**Ionization cross-sections**


\[
\sigma_{\text{Coul}} = s(Z_t, Z_p) \left(\frac{Z_t}{Z_c}\right)^2 10^4 \, [\text{barn/electron}]
\]

*Transverse contribution:*

\[
\sigma_{\text{Tran}} = t(Z_t, Z_p) \left(\frac{Z_t}{Z_c}\right)^2 10^4 \ln(\gamma^2) \, [\text{barn/electron}]
\]

*Where:* \(s(Z_t, Z_p), t(Z_t, Z_p)\) are slowly (logarithmically) varying functions of the electron carrier \(Z_c\) and target \(Z_t\), and \(\gamma\) is the Lorenz factor

*Note:*
- spin-flip contribution is neglected
- coherent bunch contribution is neglected

**Experimental cross-check**


Pb\(^{81+}(1s)\) ions at 158GeV/A
Survival of partially stripped ions: beam-gas collisions

Collisions of Pb$^{81+}(1s)$ ions with the residual gas in the LHC beam pipe – how long can they survive?

- Calculate maximal allowed concentration of molecules to achieve the 10 hour lifetime of the beam

$$\tau^{-1} = \sigma_i \times \rho_i \times c$$

- Compare with the estimated densities for the gas molecules in the interaction regions by Rossi and Hilleret, LHC project rapport 674 (2003):
  
  - H2 – $1.3 \times 10^{12}$ mol/m$^3$
  - CH4 – $1.9 \times 10^{11}$ mol/m$^3$
  - CO2 – $2.8 \times 10^{11}$ mol/m$^3$

**Result:** The safety factor varies between 30 (for the H2 molecules) and 2 (for the CO2 molecules). Better vacuum in arcs.
August 19, 1996

Dear Dr. Krasny,

Thank you very much for your contribution to the HERA workshop and for your remarks to the HERA programme.

I agree with you that HERA will make a solid contribution to strong interaction physics and that colliding electrons with nuclei may open up new vistas and should be explored further. Indeed we want to do this in collaboration with GSI and I hope that you will be able to participate and contribute to this work. In order to carry out a programme in this direction there must be a well reasoned physics programme, a strong support including funds from the community, and GSI must be interested in a collaboration.

I'm not so sure that I agree with your comments concerning the luminosity frontier - at least I would feel somewhat uneasy if we neglected this frontier.

With my best wishes

Björn H. Wiik