GF-CAIN – progress report

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Outline

1. What is CAIN?
2. MC simulations of laser-photon–PSI collisions
3. Numerical results
4. Summary

CAIN

- Stand-alone Monte Carlo program for similations of **beam–beam interactions** involving **high-energy electrons, positrons and photons**.
- Written by K. Yokoya *et al.*, KEK, Japan, 1984–2011.
- Code is a mixture of FORTRAN 77 and FORTRAN 90/95, $\sim$ 45 000 lines in $\sim$ 400 files
  $\rightarrow$ not documented, comments in code scarce.
- Dedicated, elaborate *meta-language* for defining Input (65 pages of description in *User Manual*).
- Output in form of text files with all particle information and TopDrower histograms (no well-defined event record).

ABEL→CAIN history

- It started with program called **ABEL** for **beam–beam interactions** (deformation due to Coulomb field and beamstrahlung) in e^+e^- **linear colliders**.
- Then, after adding interactions with **laser** beams it was renamed to **CAIN**.
- **CAIN 2.0** was written **from scratch** and allowed for **any mixtures** of e^+, e^-, γ and lasers, and **multiple-stage** interactions (input data format completely refreshed).
- Newest version: **CAIN 2.42**, 27 June 2011, available at: https://ilc.kek.jp/∼yokoya/CAIN/Cain242/

Physical processes in CAIN 2.42

1. Classical interactions (orbit deform.) due to Coulomb field.
2. Luminosity between beams (e^+, e^-, γ).
3. Synchrotron radiation by electrons/positrons (beamstrahlung) and (coherent) pair creation by high-energy photons due to beam field.
4. Interactions of high-energy photon or **electron**/positron beams with **laser field**, including non-linear effects of field strength.
5. Classical and Quantum interact. with const. external field.
6. Incoherent e^+e^--pair creation by photons, electrons and positrons.
7. Transport of charged particles through magnetic beamline.
8. Polarisation effects can be included in most interactions.

Output of CAIN

- Output data (particle properties, luminosities, statistics, etc.) can be written in specified files at any moment of job → **Can be huge!**
- Graphical output is written only in **TopDrawer** format → **Obsolete!**

▷ How to use CERN **ROOT** system for data analysis?

1. For **low** statistics:
   Write particle properties in **CAIN output file** and read them by **ROOT** data analysis program (in C++).
2. For **high** statistics:
   Transmit **CAIN output** to **input** of **ROOT** data analysis program (run concurrently) through UNIX **FIFO pipes**.

CAIN ⟶ **FIFO** ⟶ **ROOT data analysis program**

▷ Small problem: Fortran decimal exponent D → E of C++

GF-CAIN: Modification of routines for linear Compton

- **Scattering probability** in time step Δt:

$$P(\vec{r},\vec{p},\vec{k},t) = \sigma_{\rm tot}(\vec{p},\vec{k})\,(1-\vec{\beta}\cdot\vec{k}/|\vec{k}|)\,n_p(x,y,z,k,t)c\Delta t,$$

where: $\vec{k}$ - photon wave vector, $\vec{p}$ – PSI momentum,
$n_p(x,y,z,k,t)$ – local density of laser-photon beam,
$\sigma_{\rm tot}(\vec{p},\vec{k})$ – total cross section for photon–PSI scattering.

- **Monte Carlo generation** – two stages:
  1. According to probability $P(\vec{r},\vec{p},\vec{k},t)$ **scattering event** is sampled using **von Neumann rejection method.**
  2. When scattering event occurs **emitted photon** is generated, i.e. its **energy** and **angles** are generated in **PSI rest-frame** according to differential cross section, and then event is **Lorentz-transformed** to **LAB** frame.

  ▷ The above is repeated for **each macroparticle**, and then generation moves to the **next** time moment, i.e. $t+\Delta t$, ...

GF-CAIN: Modification of routines for linear Compton

- Total photon–PSI scattering cross section [Bessonov&Kim]:

$$\sigma_{\rm tot}(\vec{p},\vec{k}) = \frac{2\pi r_e c f \Gamma}{[\gamma\omega(1-\beta\cos\psi)-\omega_0]^2+\Gamma^2},$$

r_e – classical electron radius, f – oscilator strength,
γ, β – relativistic factor and velocity of PSI,
ω – incoming photon frequency,
ψ – angle between incoming photon and PSI,
ω_0 – PSI transition frequency between states 1 and 2,
$\Gamma = \omega_0^2 r_e f g_1/(c g_2)$ – spontaneous emission half-linewidth,
where $g_{1,2}$ – degeneracy factors of states 1 and 2, resp.

GF-CAIN: Modification of routines for linear Compton

- MC generation of **emitted photon** in **PSI rest-frame**
  $\Rightarrow$ **Unpolarised case so far!**
  1. azimuthal angle ϕ:
  $$\phi \in \mathcal{U}(0,1),$$
  where $\mathcal{U}$ denotes **Uniform** distribution,
  2. polar angle θ:
  $$\cos\theta \in \mathcal{U}(-1,1),$$
  3. angular frequency ω' ($\rightarrow$ energy $E' = \hbar\omega'$):
  $$\omega' \in \mathcal{L}(\omega'_{min}, \omega'_{max}),$$
  where $\mathcal{L}$ – **Lorentzian** distribution with prob. density funct.:
  $$\rho_{\omega_0,\Gamma}(\omega';\omega'_{min},\omega'_{max}) = \mathcal{N}\,\frac{\Gamma}{(\omega'-\omega_0)^2+\Gamma^2},$$
  with $\mathcal{N}^{-1} = \arctan([\omega'_{max}-\omega_0]/\Gamma) - \arctan([\omega'_{min}-\omega_0]/\Gamma)$.

GF-CAIN: H-like and Li-like Pb atoms

- PSI's cannot be defined by **CAIN** input – they are implemented in **CAIN** routine LNCPGN:
  - Lithium-like Pb^{79+} in file lncpgn-Pb_Li-like.f
  - Hydrogen-like Pb^{81+} in file lncpgn-Pb_H-like.f
- They are copied into the **CAIN** file lncpgn.f with the help of Makefile when the corresponding PSI-run is chosen by a make command, e.g.
  - `make run-PbLi`
  - `make run-PbH`

  and then an appropriate input file is read.
- **Spontaneous** emission **delay** and **stimulated** emission have been added – important for PoP experiment Pb^{79+}
  → appropriate modifications of **CAIN** **event record**
  as well as *drift* routines were necessary.
- Other PSI's can be implemented in a similar way – not elegant, but easier than modifying complicated **CAIN** input!

GF-CAIN input

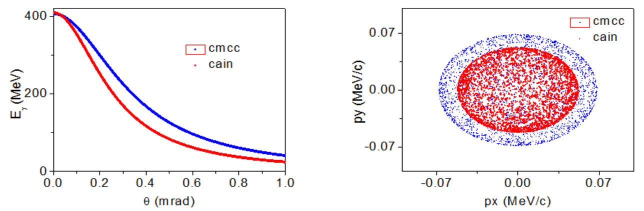
- Main **PSI beam bunch** input parameters:
    - Number of real particles and number of macroparticles (each macroparticle represents some number of real particles),
    - Energy and its relative r.m.s. spread,
    - Twiss parameters $(\alpha_{x,y}, \beta_{x,y})$, r.m.s. geometric emittance (ϵ_x, ϵ_y) and r.m.s. bunch length σ_t.
- Main **laser-pulse** input parameters:
    - Wavelenght λ_L,
    - Peak power density P_{00} [Watt/m^2].
    - Time profile: Gaussian (r.m.s. time length) or trapezoidal (total pulse length),
    - Spatial profile: Gaussian (Rayleigh length) or donut-shape,
    - Two unit vectors: parallel and perpendicular to laser beam,
    - Stokes parameters for polarisation.

  ▷ Laser in **CAIN** is **monochromatic** → **energy spread** added in **PSI-defining routines!**

Bug in CAIN laser implementation

- **Wrong angular** distributions of outgoing **photons** with **newer** Fortran compilers, e.g. on CERN Linux CC7, macOS 10.14, Windows 10.
- **OK** with **older** compilers, e.g. on CERN Linux SLC6.

▷ First noticed by Camilla Curatolo:



▷ Confirmed by my comparisons between results from SLC6, CC7 and macOS systems in November 2018 (CERN).

Bug-fix of CAIN laser implementation

- Bug found on 3rd Dec. 2018 (CERN): **lack of initialisation** of one variable to **zero** in routine LRSGEO – why treated differently by different versions of gfortran compilers???

```
*************************************************************
*** WP: There was a bug here: SUM was not initialized with 0!
*** WP: Corrected: CERN, Dec. 3, 2018.
*************************************************************
     SUM = 0D0         !  <-- This was missing!
     DO 310 I=1,3
        EV(I,1)=EVLSR(I,1,LSR)-C00*EV(I,3)
        SUM=SUM+EV(I,1)**2
 310 CONTINUE
```

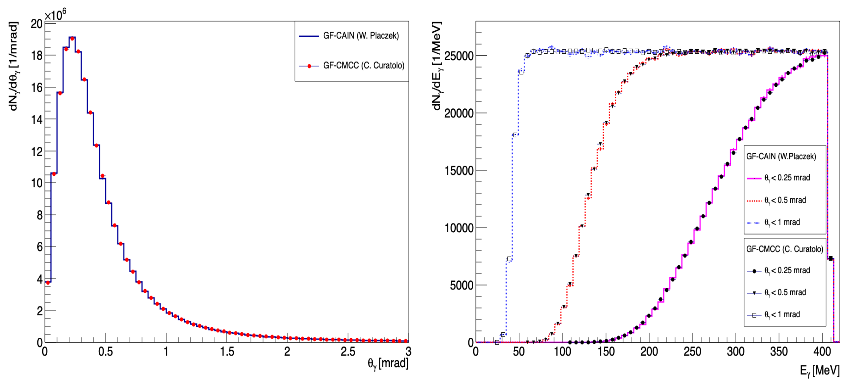
- After this **bug-fixing** results from different versions of gfortran compiler in **perfect agreement**!

Input parameters (based on E.G. Bessonov et al.)

- **PSI beam:** ${}^{207}_{82}Pb^{81+}$ → mass $M_i = 193.62938\,\mathrm{GeV/c^2}$
  - transition energy: $\hbar\omega_0 = 68.7\,\mathrm{keV}$; $f = 0.416$, $g_1 = 1$, $g_2 = 3$
  - ion energy and relative spread: $E_i = 575\,\mathrm{TeV}$, $\sigma_E = 2 \cdot 10^{-4}$
  - relativistic factor: $\gamma_i = 2970$
  - number of ions per bunch $N_i = 9.4 \cdot 10^7$
  - beta function in IR: $\beta_x = \beta_y = 0.5\,\mathrm{m}$
  - geometric emittance: $\epsilon_x = \epsilon_y = 3 \cdot 10^{-9}\,\mathrm{m\,rad}$
  - r.m.s transverse beam size: $\sigma_x = \sigma_y = 38.73\,\mu\mathrm{m}$
  - r.m.s. bunch length $\sigma_z = 15\,\mathrm{cm}$
- **Laser:** Gaussian spatial and time profiles
  - photon energy and rel. spread: $E_\gamma = 11.57\,\mathrm{eV}$, $\sigma_\omega = 2 \cdot 10^{-4}$
  - photon wavelength: $\lambda_\gamma = 107.19\,\mathrm{nm}$
  - pulse energy: $W_l = 57\,\mu\mathrm{J}$
  - peak power density: $P_{00} = 1.13 \cdot 10^{13}\,\mathrm{W/m^2}$
  - r.m.s. transverse beam size at focus: $\sigma_x = \sigma_y = 25.29\,\mu\mathrm{m}$
  - Rayleigh length: $R_{L,x} = R_{L,y} = 7.5\,\mathrm{cm}$
  - r.m.s. puls length: $l_l = 15\,\mathrm{cm}$

Comparisons: GF-CAIN vs. GF-CMCC

- Number of **macroparticles** generated in **GF-CAIN**: **10^7**
- Spontaneous emission **delay** included (small in this case)



▷ Number of emitted **photons** per **ion**: $\mathbf{N_\gamma/N_i = 0.11}$

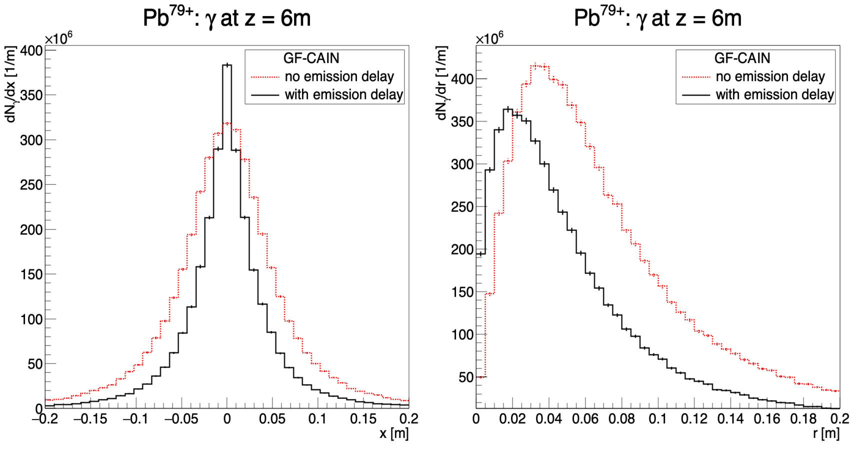
Lithium-like *Pb* ion for PoP – parameters (A. Petrenko)

- **PSI beam:** $^{207}_{82}Pb^{79+}$ → mass $M_i = 193.62938\,\mathrm{GeV/c^2}$
  - transition energy and lifetime: $\hbar\omega_0 = 230.16\,\mathrm{eV},\ \tau_0 = 74\,\mathrm{ps}$
  - ion energy and relative spread: $E_i = 18.64\,\mathrm{TeV}, \sigma_E = 3 \cdot 10^{-4}$
  - relativistic factor: $\gamma_i = 96.287$
  - number of ions per bunch $N_i = 2 \cdot 10^8$
  - Twiss parameters: $\alpha_x = 1.12376\,\mathrm{m},\ \alpha_y = -1.3501\,\mathrm{m},$
    $\beta_x = 53.1297\,\mathrm{m},\ \beta_y = 65.9803\,\mathrm{m}$
  - geometric emittance: $\epsilon_x = \epsilon_y = 2.077 \cdot 10^{-8}\,\mathrm{m\,rad}$
  - r.m.s transverse beam size: $\sigma_x = 1.051\,\mathrm{mm}, \sigma_y = 1.171\,\mathrm{mm}$
  - r.m.s. bunch length $\sigma_z = 12\,\mathrm{cm}$
- **Laser:** Gaussian spatial-time profiles, beam angle: 2°
  - photon energy and rel. spread: $E_\gamma = 1.196\,\mathrm{eV}, \sigma_\omega = 1.5 \cdot 10^{-4}$
  - photon wavelength: $\lambda_\gamma = 1037.03\,\mathrm{nm}$
  - pulse energy: $W_l = 5.1\,\mathrm{mJ}$
  - peak power density: $P_{00} = 2.188 \cdot 10^{13}\,\mathrm{W/m^2}$
  - r.m.s. transverse beam size at focus: $\sigma_x = \sigma_y = 2\,\mathrm{mm}$
  - Rayleigh length: $R_{L,x} = R_{L,y} = 48.46\,\mathrm{m}$
  - r.m.s. puls length: $l_l = 1.1092\,\mathrm{mm}$

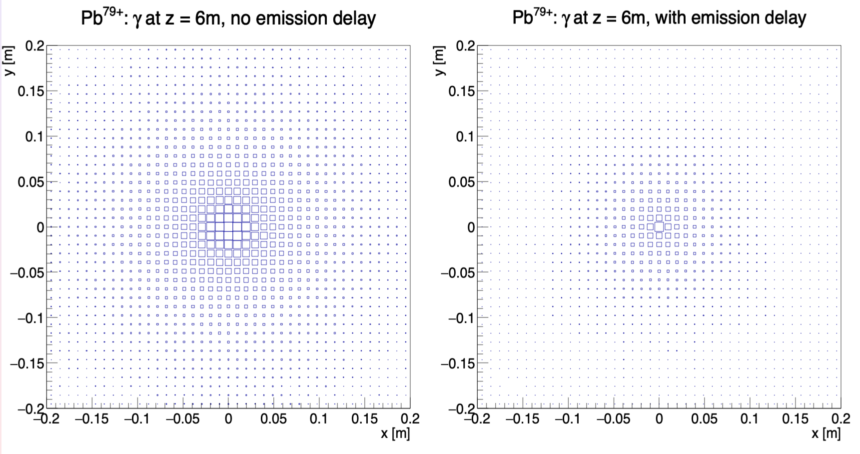
Spontaneous emission delay and stimulated emission

Number of emitted **photons per ion** at $z = 6\,\mathrm{m}$:	$\mathbf{N}_\gamma/\mathbf{N}_\mathbf{i}$
No spontaneous emission **delay**:	**20.1%**
With spontaneous emission **delay**:	**15.7%**
With spont. emission **delay** and **stimulated** emission	**13.3%**

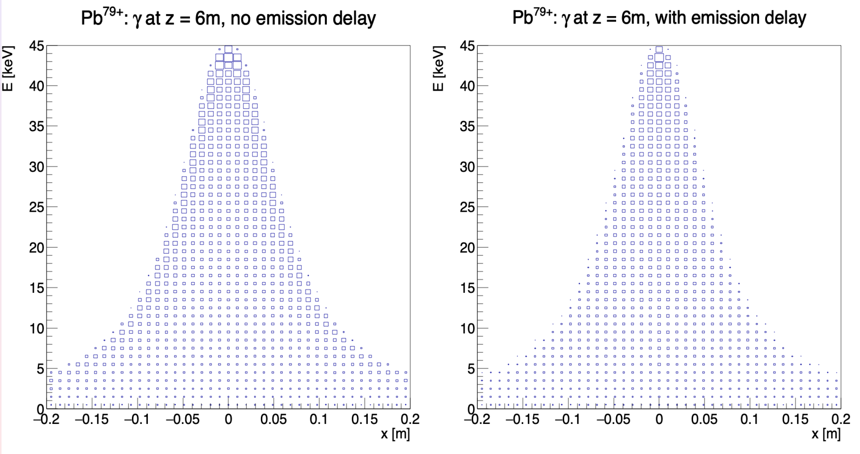
Photon *x*-coordinate and radius distributions at *z* = 6m



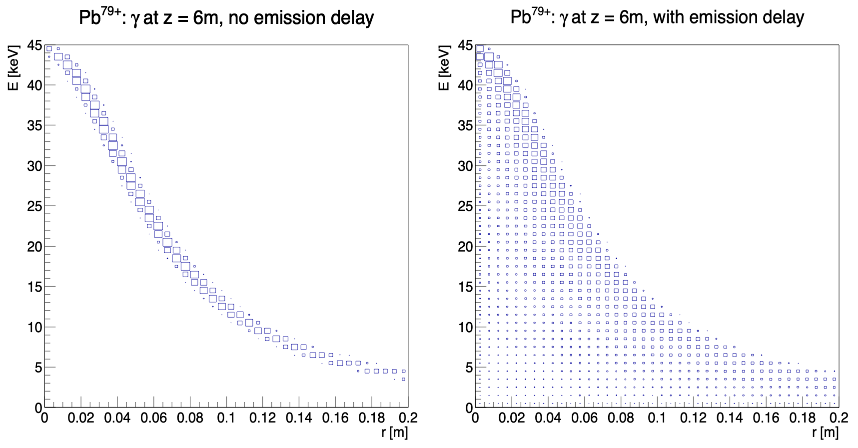
Photon *x* vs. *y* distributions at *z* = 6m



Photon *x* vs. energy distributions at *z* = 6m



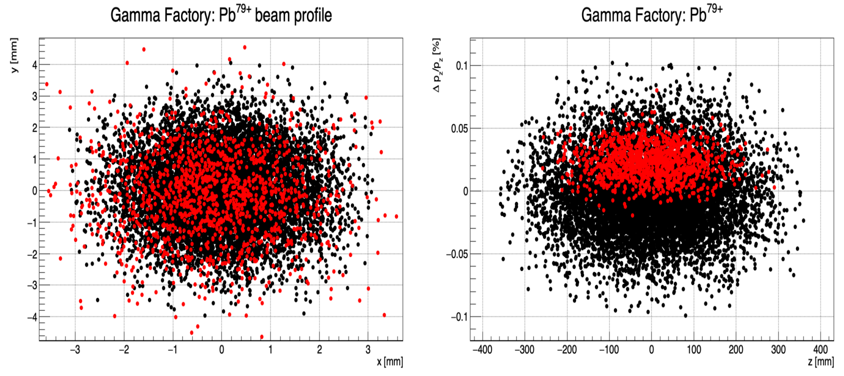
Photon radius vs. energy distributions at z = 6m



Doppler cooling of PSI beam

- Laser energy lowered by $2\sigma_\omega$ w.r.t. resonance energy

● excited ions ● other ions



▷ Fraction of excited ions: $\mathbf{N_\gamma/N_i = 9.7\%}$
(with spontaneous emission delay and stimulated emission)

Summary

- **CAIN** code has been customised to **compile** with **gfortran** (GNU Fortran) and **run** on Linux and macOS systems
  → with the use of customised Makefile
- **CAIN** Monte Carlo program has been **debugged** and **adapted** to **laser-photon pulse** collisions with **PSI beams** of Pb^{81+} and Pb^{79+} (**Gamma Factory**) ⇒ **GF-CAIN**.
- **Spontaneous** emission **delay** and **stimulated** emission have been implemented – important for PoP experiment.
- **GF-CAIN** output has been interfaced with **ROOT** data analysis program via UNIX **FIFO pipes**.
- **Good agreement** with independent Monte Carlo event generator **GF-CMCC** of Camilla Curatolo for Pb^{81+} at LHC.
- Statistics of **10^7 macroparticles** can easily be generated on medium PC.