GF-CAIN

Wiesław Płaczek

JAGIELLONIAN UNIVERSITY
IN KRAKÓW

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Outline

CAIN

- Stand-alone Monte Carlo program for simulations of **beam–beam interactions** involving **high-energy electrons, positrons and photons.**
  - → Includes interactions of high-energy **electron beam** with **laser field**.
- Written by K. Yokoya *et al.*, KEK, Japan, 1984–2011.
- Code is a mixture of FORTRAN 77 and FORTRAN 90/95, ∼ 45 000 lines in ∼ 400 files
  → not well documented, comments in code scarce.
- Dedicated, elaborate *meta-language* for defining Input (65 pages of description in *User Manual*).

GF-CAIN: Modification of routines for linear Compton

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

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

  where: $\vec{k}$ - photon wave vector, $\vec{p}$ – PSI momentum,
  $n_p(x,y,z,k,t)$ – local density of laser-photon beam,
  $\sigma_{\mathrm{tot}}(\vec{p},\vec{k})$ – 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**
  ⇒ **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-in.
- Included **time-delay** between photon **absorption** and **spontaneous emission** plus **stimulated emission**.

  → 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** $\rightarrow$ **energy spread** added in **PSI-defining routines!**

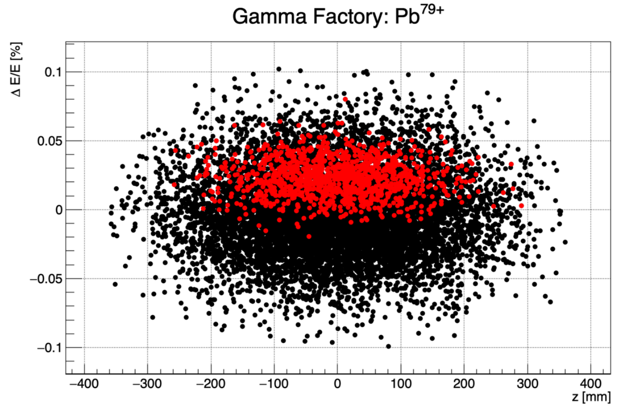
Lithium-like Pb ion for PoP (beam-cooling mode)

- **PSI beam:** ${}^{207}_{82}\mathrm{Pb}^{79+}$ → mass $M_i = 193.687\,\mathrm{GeV/c^2}$
  - transition energy and lifetime: $\hbar\omega_0 = 230.76\,\mathrm{eV},\ \tau_0 = 74\,\mathrm{ps}$
  - ion energy: $E_i = 18.68908\,\mathrm{TeV}$
  - ion energy relative spread: $\sigma_E = 3 \cdot 10^{-4}$
  - relativistic Lorentz factor: $\gamma_i = 96.491$
  - number of ions per bunch $N_i = 2 \cdot 10^8$
  - r.m.s transverse beam size: $\sigma_x = 1.051\,\mathrm{mm}, \sigma_y = 1.171\,\mathrm{mm}$
  - r.m.s. bunch length $\sigma_z = 12\,\mathrm{cm}$
  - normalised emittance: $\epsilon_n = 2 \cdot 10^{-6}\ \mathrm{m \cdot rad}$
- **Laser:** Gaussian profiles, energy 2σ below resonance
  - angle between laser and PSI beams: 2°
  - photon energy: $E_\gamma = 1.195795\,\mathrm{eV}$,
  - photon energy relative spread: $\sigma_\omega = 1.5 \cdot 10^{-4}$
  - photon wavelength: $\lambda_\gamma = 1036.84\,\mathrm{nm}$
  - pulse energy: $W_l = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}\,\mathrm{mJ}$
  - beam waist: $w_0 = \{1, 2, 3, 4, 5, 6\}\,\mathrm{mm}$
  - r.m.s. puls length: $l_l = 1.1092\,\mathrm{mm}$

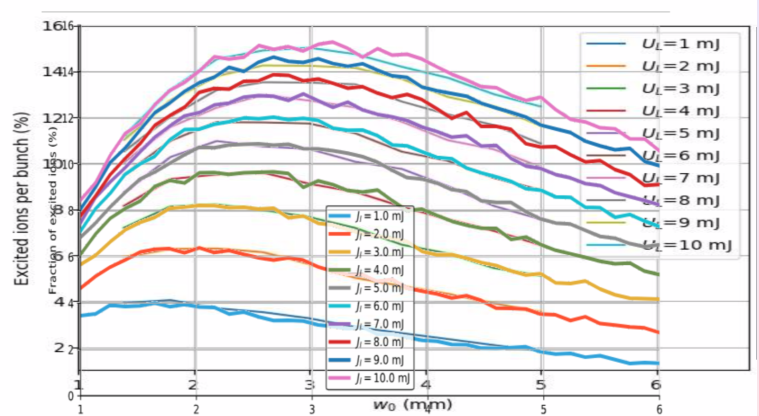
Doppler cooling of PSI beam

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

● excited ions ● other ions



Alexey’s talk, GF meeting at CERN, 26 Feb. 2019



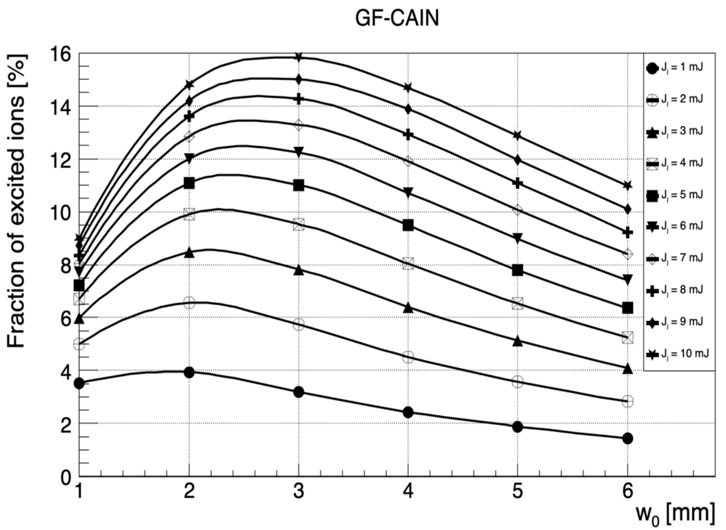
- Perfect agreement between programs of **Alexey Petrenko** and **Camilla Curatolo** (both based on balance equation)!

→ What about **GF-CAIN**?

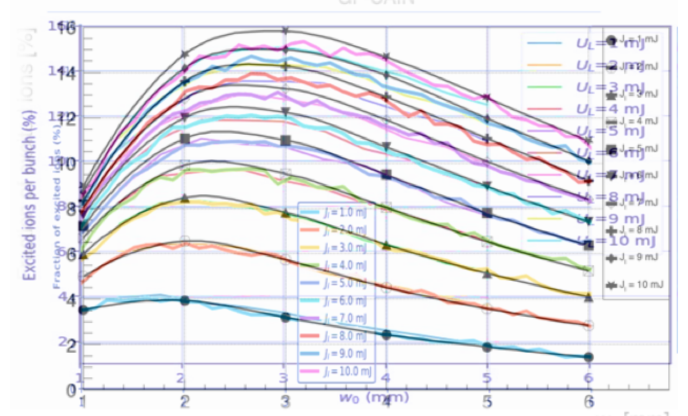
GF-CAIN: fraction of excited ions – table

Excited ions [%]	Laser-beam waist w_0 [mm]					
Pulse energy [mJ]	1	2	3	4	5	6
1	3.52	3.94	3.18	2.43	1.89	1.45
2	4.99	6.56	5.73	4.52	3.58	2.83
3	6.00	8.47	7.82	6.39	5.14	4.10
4	6.71	9.90	9.53	8.03	6.53	5.24
5	7.23	11.08	11.00	9.48	7.79	6.36
6	7.70	12.00	12.24	10.71	8.98	7.41
7	8.04	12.84	13.28	11.91	10.06	8.41
8	8.35	13.59	14.27	12.91	11.09	9.22
9	8.72	14.19	14.99	13.87	11.97	10.09
10	8.97	14.79	15.81	14.67	12.85	10.98

GF-CAIN: fraction of excited ions – plot



Comparisons with Alexey’s and Camilla’s codes



→ **Good agreement** for **lower** pulse energy (< 5 mJ).

→ For **higher** pulse energy and **smaller** beam waist **more** excited ions from **GF-CAIN** (differences within 1%).

Summary

- **CAIN** Monte Carlo program **debugged** and **adapted** to **laser-photon pulse** collisions with **PSI beams** of Pb^{81+} and Pb^{79+} (**Gamma Factory**) $\Rightarrow$ **GF-CAIN**.
- **Spontaneous** emission **delay** and **stimulated** emission implemented $\rightarrow$ **important for PoP experiment.**
- **Good agreement** for number of **excited ions** with **Alexey's** and **Camilla's** codes for **lower laser-pulse energy** (< 5 mJ), while for **higher** laser-pulse energy and **smaller** beam-waist **GF-CAIN** gives slightly **higher rates**.

→ **FYI:** I had a presentation on **Gamma Factory** at the XXV Cracow **Epiphany Conference**, 8–11 Jan. 2019, and submitted a contribution to proceedings (to appear in Acta Physica Polonica B); arXiv:1903.09032 [physics.acc-ph] (authors list taken from our current YR draft).