# The Gamma Factory path to high-luminosity LHC with laser-cooled isoscalar-ion beams

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LPNHE, CNRS-IN2P3, University Paris Sorbonne and CERN BE-ABP
In collaboration with Alexey Petrenko, and Wieslaw Placzek
**and the Gamma Factory group**

The details of the proposal can be found in the review paper:

ELSEVIER

Progress in Particle and Nuclear Physics

Available online 26 May 2020, 103792

In Press, Corrected Proof ?


Review

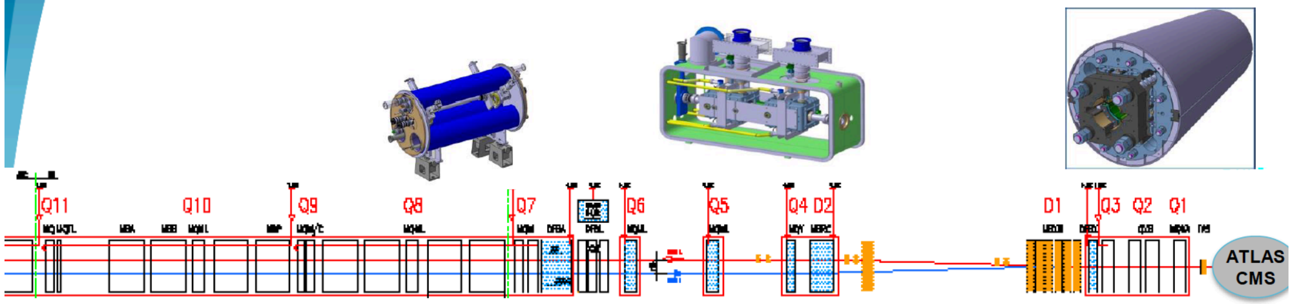
# High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams ☆

M.W. Krasny [a, b], A. Petrenko [c, b], W. Płaczek [d]

… this short presentation is bound to be restricted to the general concepts of the HL(AA)-LHC proposal…

# The on-going HL(**pp**)-LHC project

## The largest HEP accelerator in construction




**Dispersion Suppressor (DS) in P7**

**Modifications**
1. In IP2: new DS collim. in C.Cryost.
2. In IP7 new DS collimation with 11 T

**Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr… extension of infrastr.**

**Matching Section (MS)**

**Change/new lay-out**
1. TAXN
2. D2
3. CC
4. Q4
5. Correctors
6. Q5
7. Q5@1.9K in P6
8. New collimators

**Interaction Region (ITR)**

**Complete change and new lay-out**
1. TAXS
2. Q1-Q2a-Q2b-Q3
3. D1
4. All Correctors Magnets
5. Heavy shielding (W)

**> 1.2 km of LHC !!**



Levelled Luminosity: **2.5 (5) x 10$^{34}$ cm$^{-2}$s$^{-1}$**

**estimated cost ~ 1 billion euro**

Why considering a complementary high-luminosity LHC operation mode with ion (instead of proton) beams?

LHC is a collider of partonic bunches.
Why bothering with alternative partonic envelopes of: quarks, gluons and photons (nuclei, instead of protons) ?

## To answer these questions let's consider:

- Respective merits of proton and ion beams **for high-luminosity LHC research** (EW and BSM sectors).

- Feasibility of the proposed, new HL(**AA**)–LHC scheme which is based on the **laser Doppler cooling** of the ion beams.

# The principal merits of the proton beams

- *For the fixed magnetic rigidity of the LHC storage ring, twice higher partonic collision energy is accessible for pp collisions:* *($Q/M_{protons} > 2\ Q/M_{ions}$).*

- *More precise external input constraining the longitudinal momentum structure of partonic bunches confined in proton envelopes (HERA/ Tevatron data).*

- *CERN injectors delivers (at present) significantly more quarks and gluons to LHC in the proton bunches, than in the ion bunches:* *$N^{q,g}{}_{p}/N^{q,g}{}_{Pb} > 50$.*

… a natural and optimal choice for the initial LHC phase!

[complemented by short ion runs (< 10% of the running time) for studies of the large-cross-section QCD phenomena]

# The merits of the ion beams

- *Tuneable flavour and charge structure of the partonic bunches (electroweak/BSM interactions are flavour-sensitive) – special role of isoscalar ions: A=2Z.*

- *Partonic emittances (longitudinal and transverse) can be fully controlled by the LHC data alone (no precision brick-walls coming from the LHC-external data).*

- *Significantly higher precision in measuring the EW processes by using isoscalar ion beams rather than proton beams (as in earlier experiments).*

- *A $Z^4$ leap in photon fluxes – access to exclusive Higgs boson production in photon–photon collisions – unreachable for the pp running mode.*

- *Lower pileup background at equivalent (high) nucleon-nucleon luminosity.*

- *New research opportunities for EW symmetry breaking sector.*

To profit form the merits of the isocalar ion beams in the HL-LHC phase the nucleus-nucleus (AA) luminosity, the following condition must be fulfilled (equivalence of partonic luminosities):

$$\boxed{L_{AA} = L_{NN}/A^2 \approx L_{pp}/A^2}$$

Can this be achieved at a reasonable cost – say, at the MSFr level?

# The Gamma Factory path to HL(AA)-LHC

$$L_{NN} = f_0 \gamma_L n_b \frac{N_N^2}{4\pi \epsilon_n \beta^*} H\left(\frac{\sigma_z}{\beta^*}, \theta_c\right)$$

$$\frac{L_{NN}}{L_{pp}} = \frac{\gamma_L^A}{\gamma_L^p} \times \frac{A^2 N_A^2}{N_p^2} \times \boxed{\frac{\epsilon_n^p}{\epsilon_n^A}}$$

Modern and Future Colliders

V. Shiltsev
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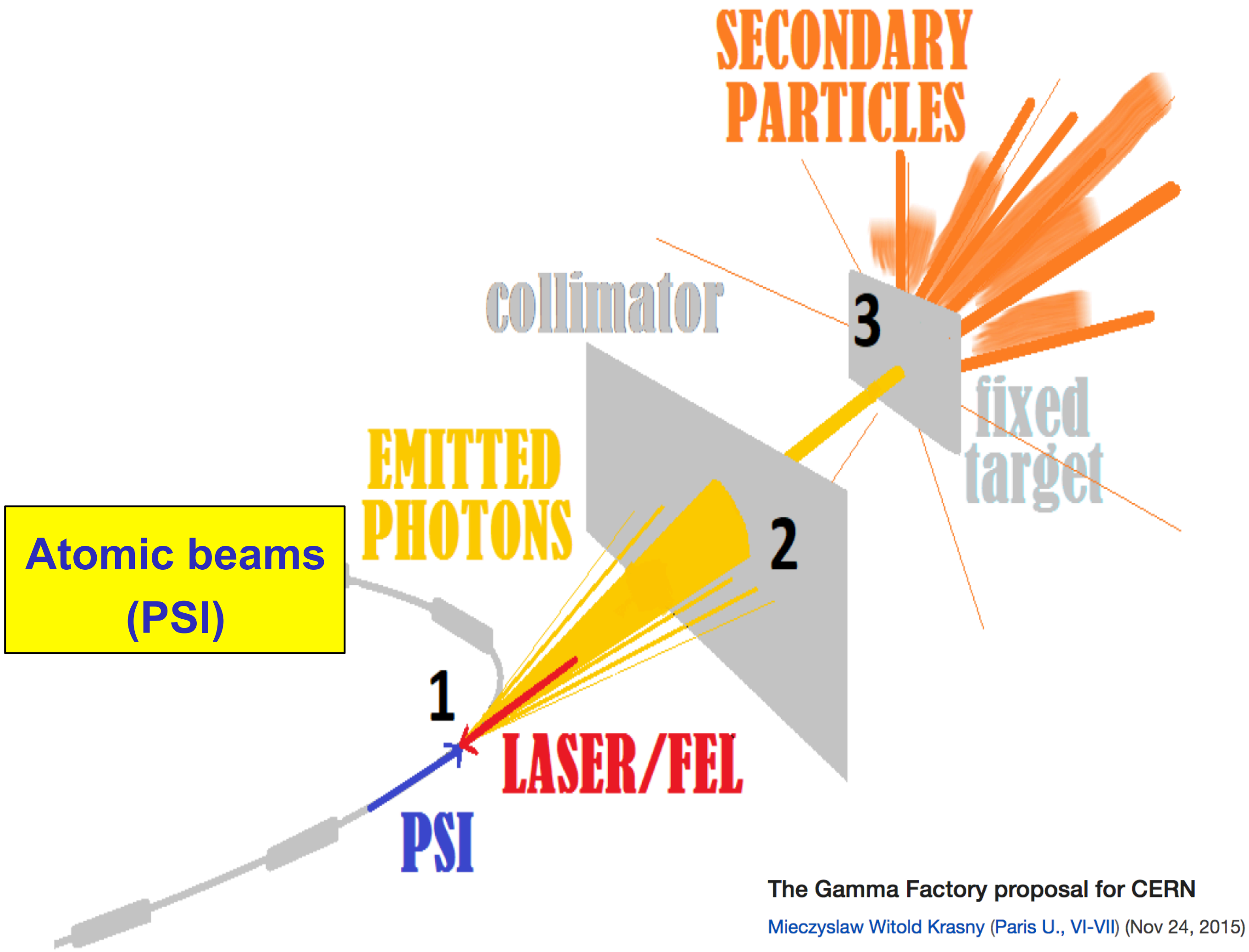
F. Zimmermann
*European Organization for Nuclear Research, CERN, 1211 Geneve, Switzerland*

Three ways to increase the nucleon-nucleon (NN) luminosity in nuclear collisions (for the fixed IR optics and bunch crossing frequency):

1. ***Increase the number of ions per bunch (not discussed in this talk).***
2. ***Decrease the transverse emittance of colliding bunches by efficient beam cooling*** → **Gamma Factory project**
3. ***Both (not discussed in this talk).***

# GAMMA FACTORY




The Gamma Factory proposal for CERN
Mieczyslaw Witold Krasny (Paris U., VI-VII) (Nov 24, 2015)
e-Print: 1511.07794 [hep-ex]

# Gamma Factory (PBC) study group

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80 physicists
33 institutes
13 countries

*GF group is open to everyone willing to contribute to this initiative!*

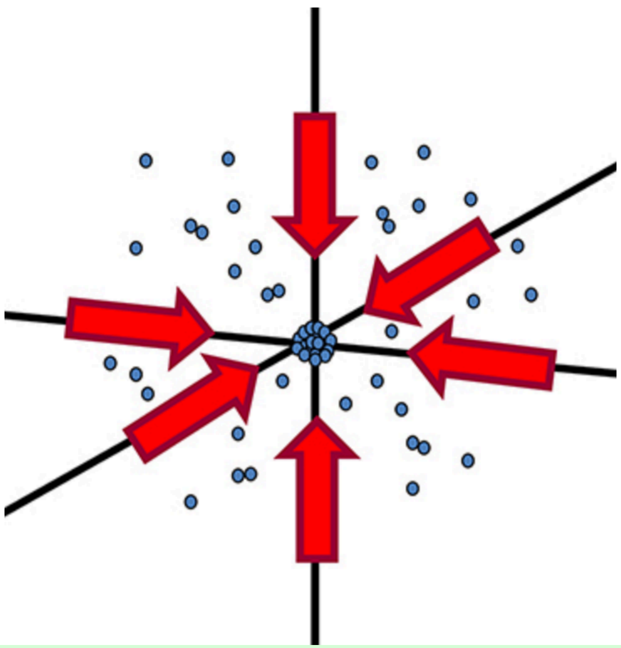
# Gamma Factory research potential

| Physics | |
|---|---|
| Particle | *basic symmetries, dark mater, EW precision measurements with PSI, n, μ and ν beams…* |
| Nuclear | *nuclear charge and spin structure, neutron skin, confinement studies, photo-fission…* |
| Accelerator | ***beam cooling**, plasma wake field acc., high-int. polarized e+ & μ sources, ν-sources…* |
| Atomic | *physics of highly charged electronic and muonic atoms: strong EM fields, EW effects…* |
| Applied | *accelerator driven energy sources , cold & warm fusion, medical isotope production…* |

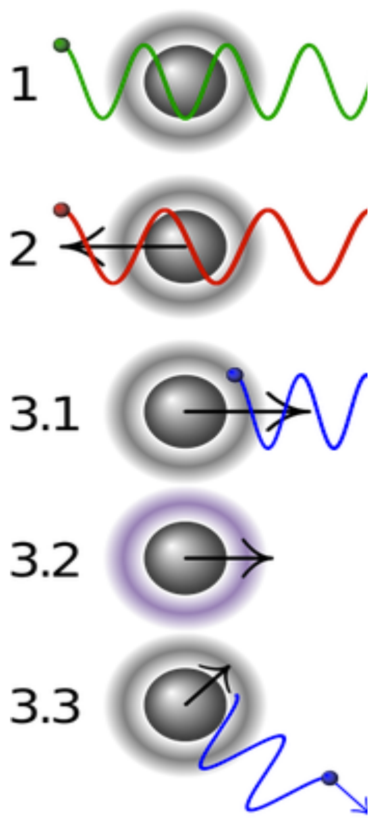


**Opening new research domains and a leap in the measurement precision in existing research domains – a paradise for creative physicists…**

# Doppler laser cooling in atomic physics (stationary atoms)



Six "red –detuned" laser beams
(optical molasses)




Simplified principle of Doppler laser cooling:

1. A stationary atom sees the laser neither red- nor blue-shifted and does not absorb the photon.
2. An atom moving away from the laser sees it red-shifted and does not absorb the photon.

**3.1** An atom moving towards the laser sees it blue-shifted and absorbs the photon, slowing the atom.

**3.2** The photon excites the atom, moving an electron to a highe quantum state.

**3.3** The atom re-emits a photon. As its direction is random, there is no net change in momentum over many absorption-emission cycles.

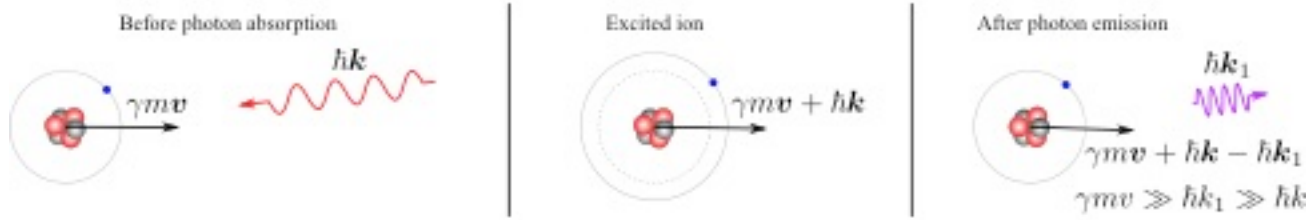
## Doppler laser cooling of relativistic atomic beams


[9] S. Schroder *et al.*, Phys. Rev. Lett. **64** (1990) 2901, doi:10.1103/PhysRevLett.64.2901.

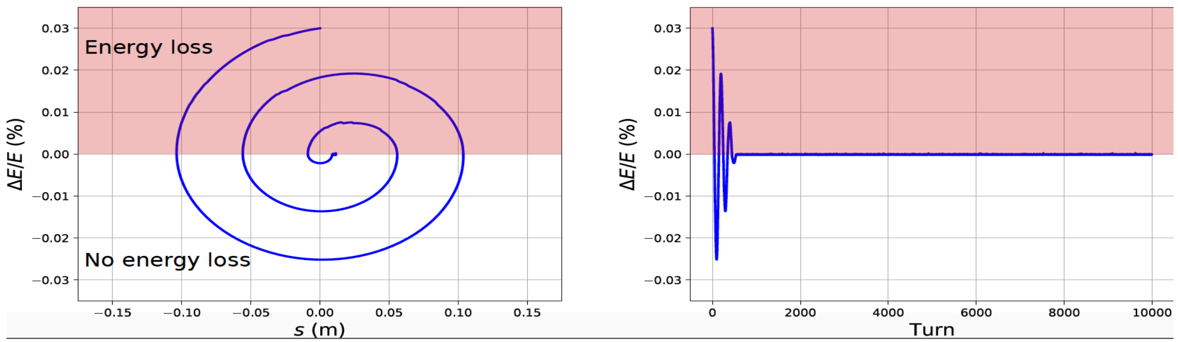
[10] J.S. Hangst, M. Kristensen, J.S. Nielsen, O. Poulsen, J.P. Schiffer and P. Shi, Phys. Rev. Lett. **67** (1991) 1238, doi:10.1103/PhysRevLett.67.1238.

[11] I. Lauer *et al.*, Phys. Rev. Lett. **81** (1998) 2052, doi:10.1103/PhysRevLett.81.2052.

# …and its extension to highly-relativistic atomic beams of partially stripped ions




*The laser cooling mechanism is similar to that of the synchrotron-radiation cooling for the electron beam. The most notable difference is that while the latter is a spontaneous (random) process, the former can be stimulated and precisely controlled by the suitable **tuning of the laser pulse parameters, such as its power, the photon-wavelength spread and offset, the photon transverse spot size and its offset with respect to the ion-beam spot**. This allows to selectively manipulate a chosen fraction of ions within their bunches with an unprecedented precision.*




*An example of the longitudinal cooling speed of the SPS bunches: the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

# The proposed scheme of the beam cooling

- *Leave couple of electrons attached to their parent nuclei in the SPS acceleration phase (in the canonical SPS heavy ion operation all electrons are already stripped off).*

- *Cool the atomic beam with the specialised laser system at the top SPS energy to reduce its emittance (longitudinal and the transverse cooling).*

- *Strip the electrons in the SPS-to-LHC transfer line.*

- *Accelerate and collide fully stripped ion beams in the LHC.*

The GF path is restricted to a narrow range of nuclei!

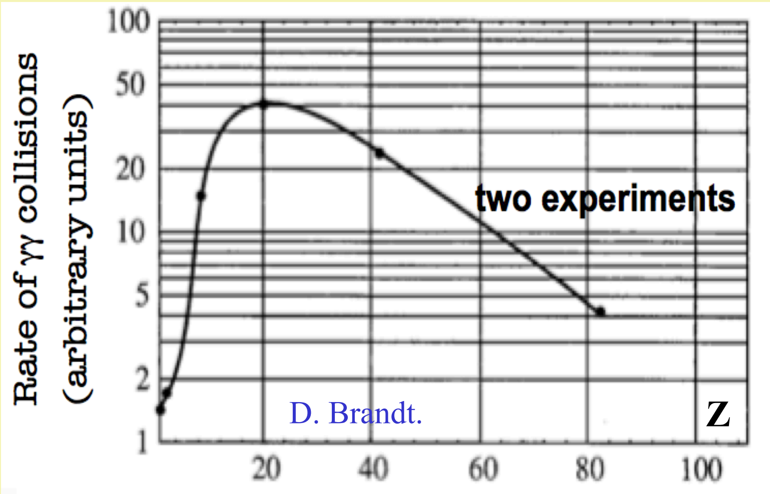
(see our published paper for details)

1. *Ion Source.*
2. *Space-charge tune shift* $\sim Z^2 N_{ion} / A\gamma_L{}^3$.
3. *Electron stripping pattern.*
4. *Laser constraints.*
5. *Lifetime of atomic beams in the SPS.*
6. *IBS:* $\alpha_{IBS}{}^{A} = Z^3/A^2\ \alpha_{IBS}{}^{p}$.
7. *Beam collimation.* $\xi_{x,y} = \frac{r_0 N \beta^*_{x,y}}{2\pi\gamma\sigma^*_{x,y}(\sigma^*_x + \sigma^*_y)}$
8. *Beam-beam parameter.*
9. *Parasitic beam burning*

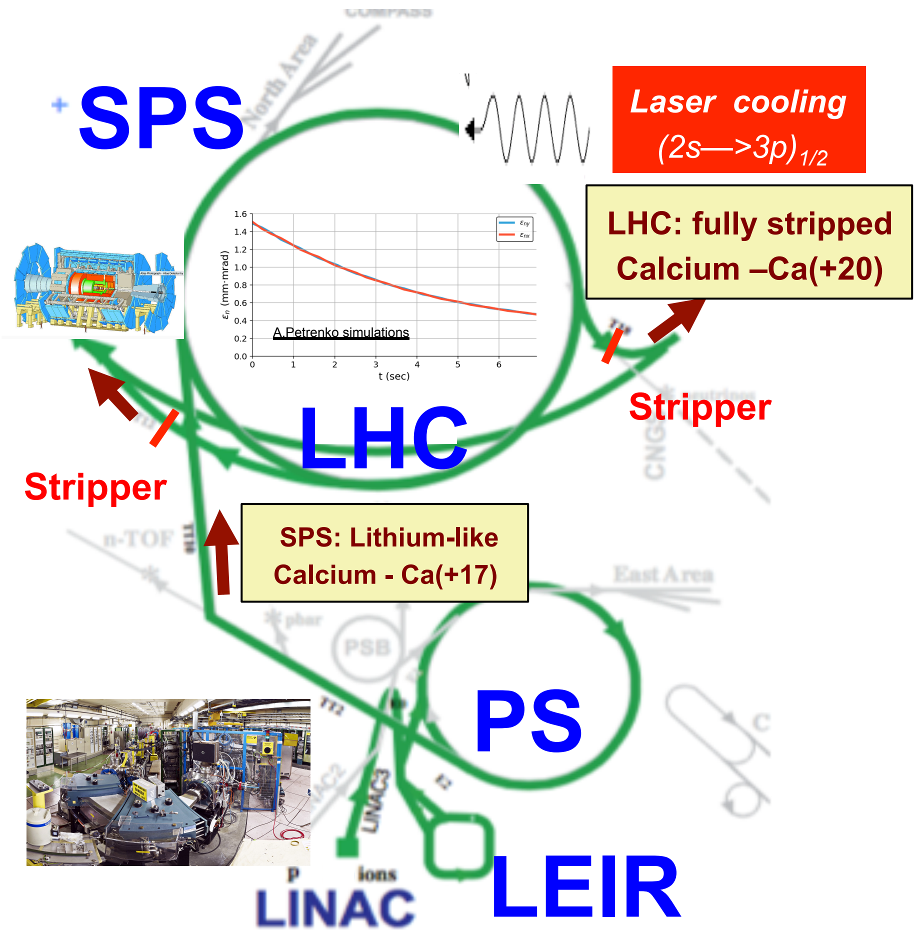
   *(e+e- production* $\sim Z^7$ *and*

   *nucleus dissociation* $\sim[(A-Z)Z^3/A^{2/3}]$.

***Ca(+20) beam turns out to be the best candidate to be the HL(AA)-LHC "parton carrier"** – it has a stable isoscalar isotope and maximises photon-photon luminosity in AA collisions.*



# Gamma Factory path to HL(AA)-LHC:
## An implementation scheme with Ca beams

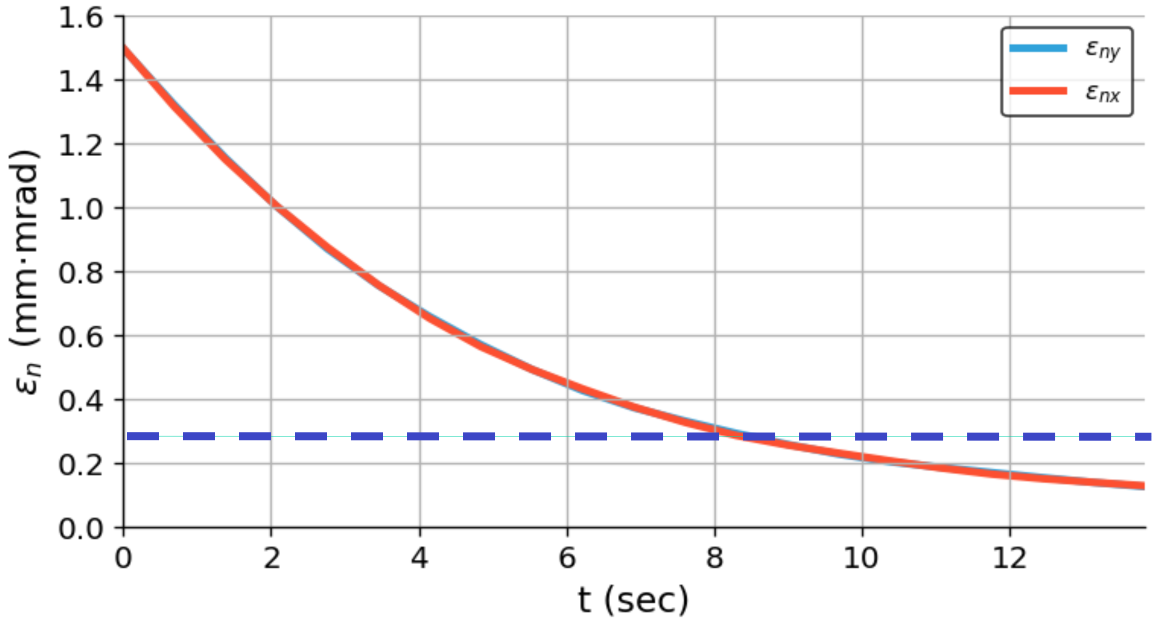



**Ion Source + Linac:** Charge state after stripping:
Ca(+17), evaporation temperature 80 K lower than Pb!

| Parameter | Value |
|---|---|
| $s^{1/2}$ [TeV] | 7. |
| $\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$ | $5 \times 10^{-5}$ |
| $\sigma_{had}(Ca)/\sigma_{tot}(Ca)$ | 0.6 |
| $N_b$ | $3 \times 10^{9}$ |
| $\varepsilon_{(x,y)n}$ [μm] (1) | **0.3** → |
| IBS [h] | 1-2 |
| β* [m] | 0.15 |
| $L_{NN}$ [cm-2s-1] | **$4.2 \times 10^{34}$** |
| Nb of bunches | 1404 |
| Collisions/beam crossing | 5.5 |

(1) Optical stochastic cooling time for the Ca beam, if necessary at the top energy – 1.5 hours (V. Lebedev)

## Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: transverse emittance evolution.

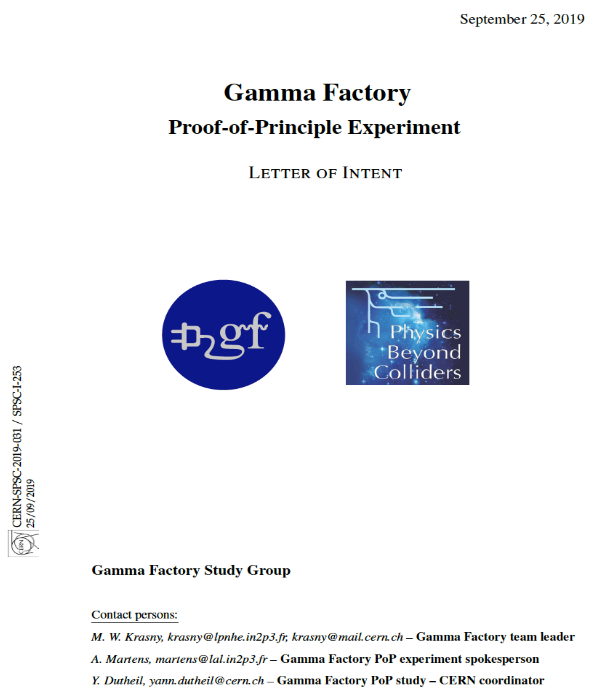



***Reduction of the transverse x,y emittances by a factor of 5 can be achieved in 9 seconds –*** *sufficiently short to avoid the CA(+17) beam losses in the SPS (driven by the ionisation of partially stripped ions in beam-gas collisions).*

## Experimental proof of the proposed laser cooling scheme:

one of the gooals the Gamma Factory PoP experiment at the SPS

(…in the SPSC approval process…)



CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

September 25, 2019

**Gamma Factory**

**Proof-of-Principle Experiment**

LETTER OF INTENT



**Gamma Factory Study Group**

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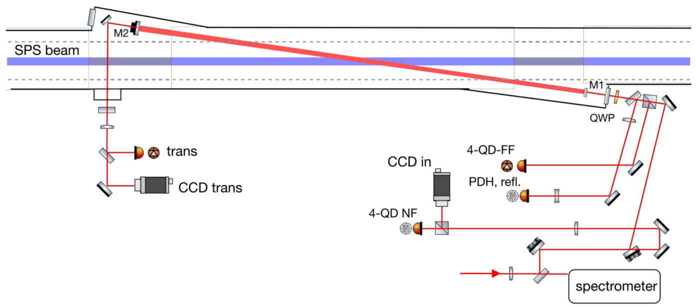
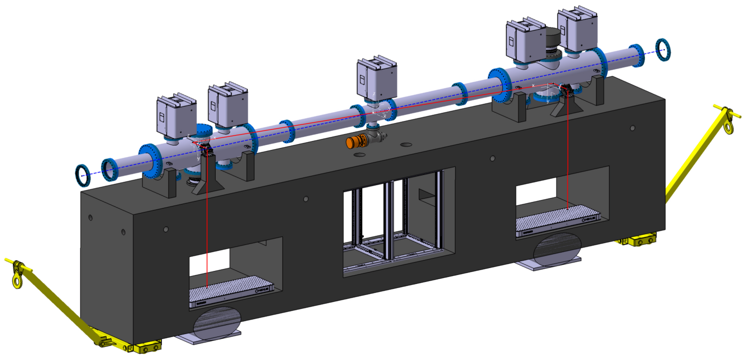






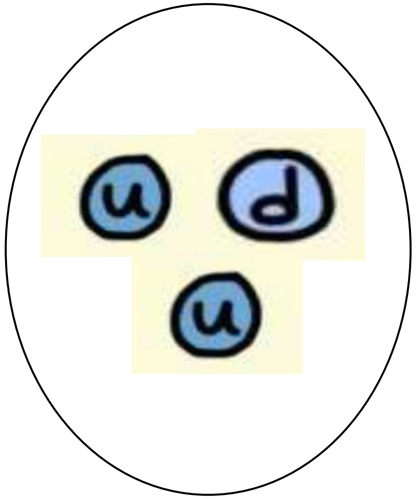
The Gamma Factory PoP experiment at the SPS (2.4 MSFr) may open a complementary path to HL-LHC (with equivalent, …or perhaps even higher partonic luminosities), by “storing” quark, gluons and photons in bunches of **“cold-nuclei”** rather than in **“hot-protons”.**

# Conclusions

- *HL(AA)-LHC with laser-cooled isoscalar ion beams appears to be an attractive option to **significantly enlarge the research potential of the LHC** collider*
- **$L_{NN}$ in AA mode ~4 x $10^{34}$ $cm^{-2}s^{-1}$, $L_{NN}$ in pp mode 2.5-5 x $10^{34}$ $cm^{-2}s^{-1}$,** *(optimal running time sharing 2/3 pp mode, 1/3 AA mode)*
- *Of particular importance, if no new phenomena are discovered over the initial phase of HL(pp)-LHC operation.*
- *The proposed scheme requires further studies (IBS, beam collimation, beam stabilization, head-tail instability, tune shift, beam-beam limit, …) and the experimental validation of the Gamma Factory laser-cooling simulations by the Gamma Factory PoP experiment at the SPS.*
- *Successful demonstration of the capacity of the CERN accelerator complex to produce, accelerate, store and to cool atomic beams can open novel research opportunities in many branches of science.*
- *It provides also a new way to maximise the partonic luminosity at the future high-energy frontier hadronic colliders.*

# Additional slides

*Significantly higher precision in measuring the EW processes by using isoscalar ion rather than proton beams – WHY?*



**u** and **d** quarks have different charges, weak isospin and vector and axial couplings.
For EW-physics: proton beams are equivalent to neutrino and electron beam mixed in not precisely known proportions

*Need to know -- to a very high precision (external input) – the composition of partonic beam -- in particular the relative momentum distributions of **u** and **d** quarks in the proton!*

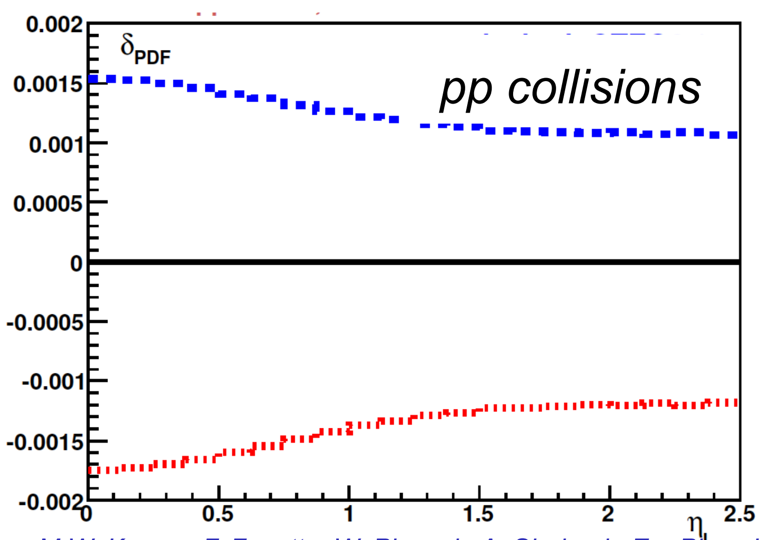
## Isoscalar (A=2Z) ion beams

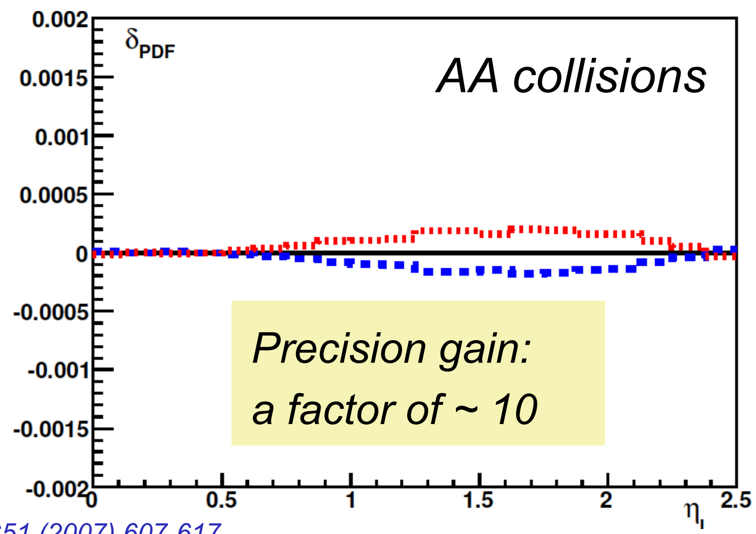
Profit from the flavour symmetry of strong interactions to to equalize the distributions of the u and d quarks: $u_{v,s}^{A=2Z,Z}(x, k_t, Q^2) = d_{v,s}^{A=2Z,Z}(x, k_t, Q^2)$


M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C69 (2010) 379-397.*
F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, *Eur.Phys.J. C63 (2009) 33-56.*
M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C51 (2007) 607-617.*
M.W. Krasny, S. Jadach, W. Placzek, *Eur.Phys.J. C44 (2005) 333-350.*

# 1. Significantly higher precision in measuring the EW processes by using isoscalar ion rather than proton beams

Example: Measurement of the pseudo-rapidity distributions of charged leptons produced in W-boson decays. Plots below show the uncertainty of the theoretical prediction reflecting the limited knowledge of the partonic composition of protons and isoscalar ions (precision-optimised measurement method).



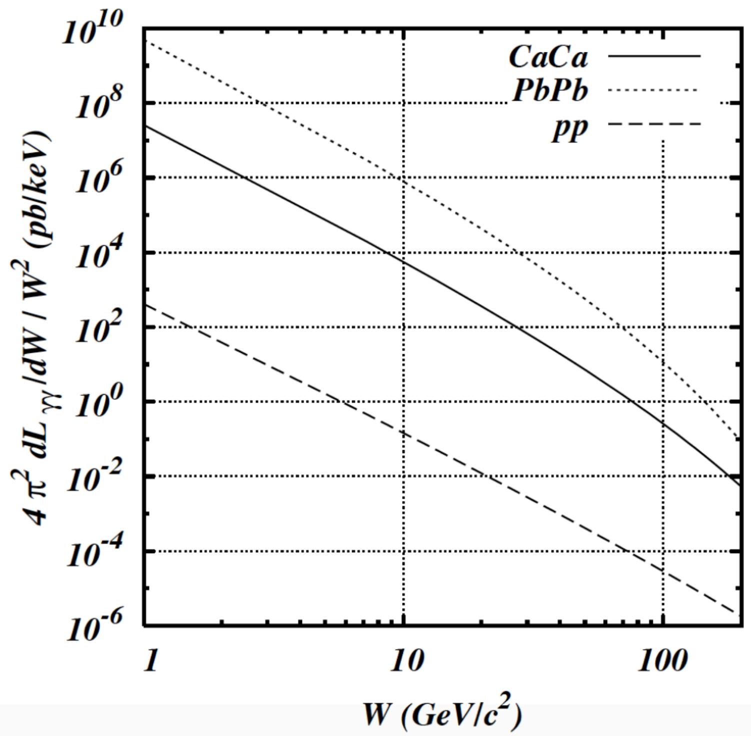

M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, Eur.Phys.J. C51 (2007) 607-617.

***Isoscalar beams provide an unique way for improving the present precision of the SM parameters such as $M_W$, $\sin^2\theta_W$,… at the LHC!***

***For nucleon-nucleon luminosity of 1000 $fb^{-1}$: $\delta(\sin^2\theta_W) < 10^{-4}$, $\delta(M_{W)} <$ 5 MeV.***

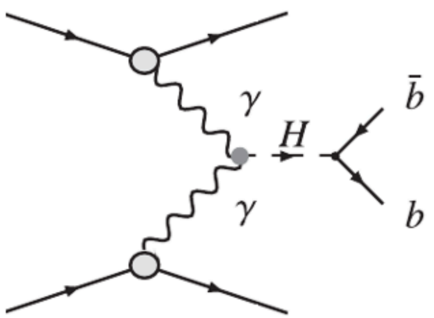
*2. A leap in photon fluxes – access to exclusive Higgs boson production in photon–photon collisions – beyond the reach for the pp running mode)*

*A factor of $Z^4$ gain in photon-photon luminosity*





[50] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky and Y. Kharlov, Phys. Rept. **364** (2002) 359, doi:10.1016/S0370-1573(01)00101-6 [hep-ph/0112211].


***For the collected nucleon--nucleon luminosity of 1000 fb$^{-1}$, the expected number of exclusively produced Higgs bosons in photon-photon collisions is ~420 per experiment – unique possibility of studies of $\gamma\gamma \rightarrow H \rightarrow$ bbar decays in clean environment.***

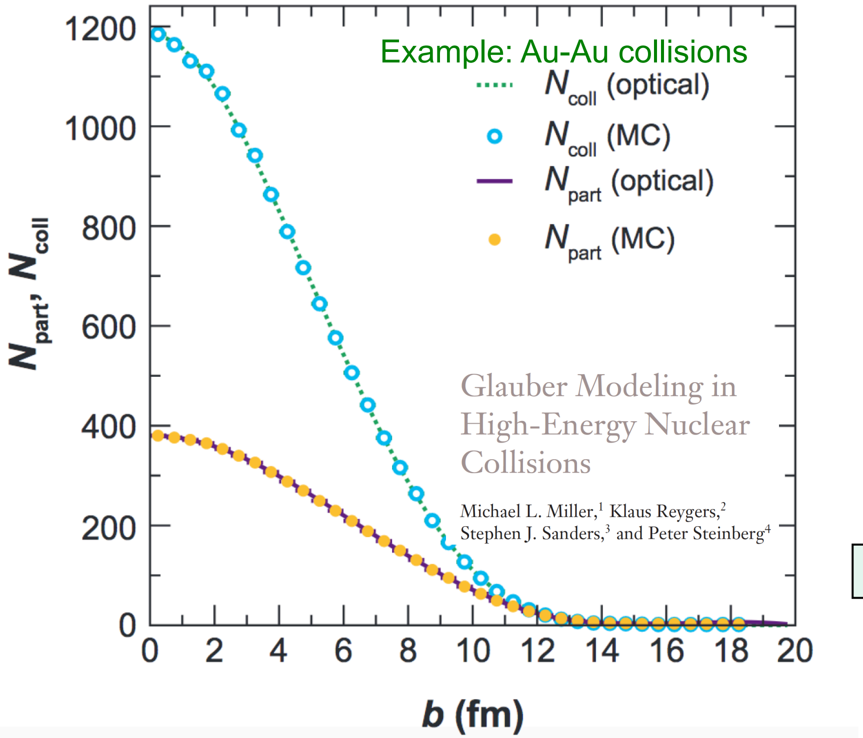

Higgs boson production in photon-photon interactions with proton, light-ion, and heavy-ion beams at current and future colliders

David d'Enterria (CERN), Daniel E. Martins (UFRJ, Rio de Janeiro), Patricia Rebello Teles (Rio de Janeiro State U.) (Apr 26, 2019)

Published in: *Phys.Rev.D* 101 (2020) 3, 033009 • e-Print: 1904.11936 [hep-ph]

# 3. *Lower pileup background* *at the equivalent (and high) partonic luminosity*

$$\nu_{AA} = \nu_{pp} \times \frac{\sigma_{AA}}{\sigma_{pp}} \times A^{-2}$$



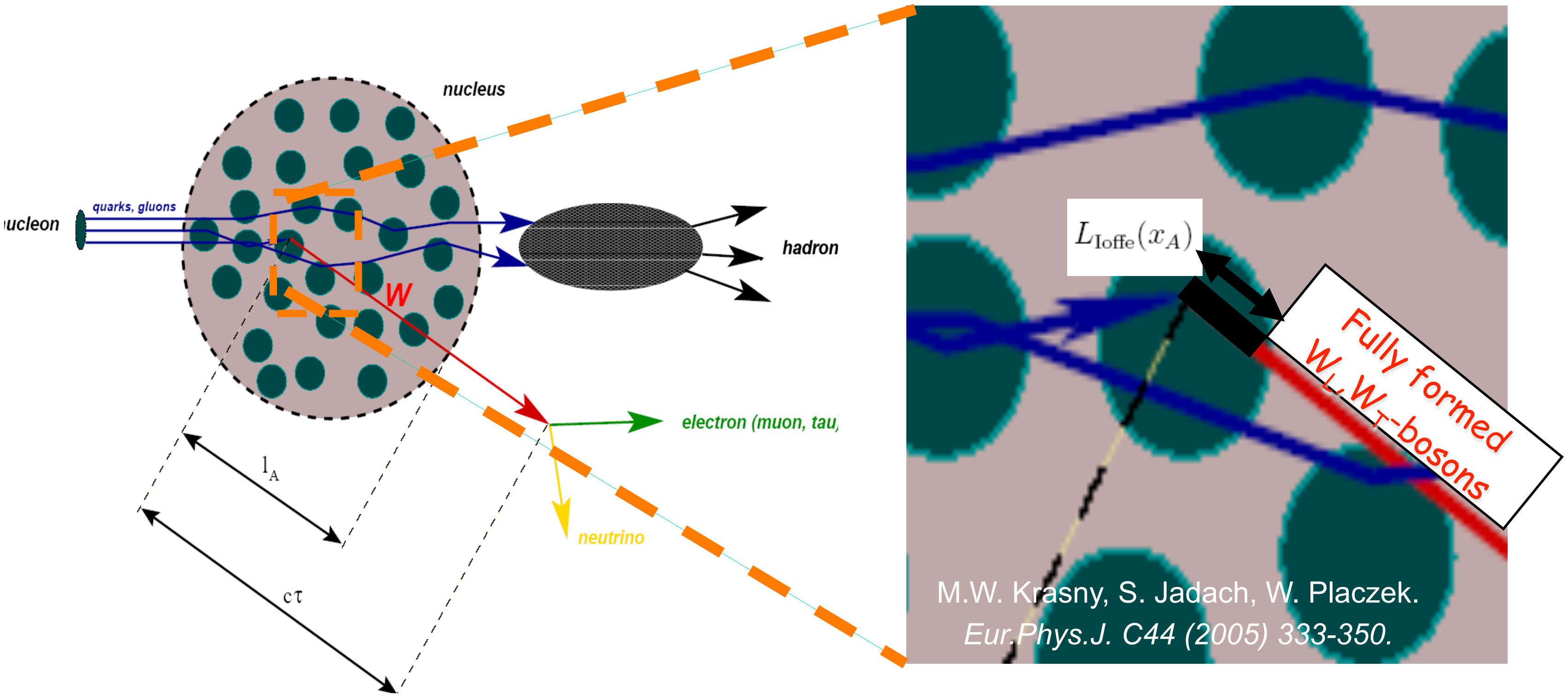

***Reduction of the average number of beam particle collisions per bunch crossing, at the same partonic luminosity by** a factor of 40, 136, 650 and 1260 for OO, CaCa, XeXe and PbPb collisions (opens a possibility of studying exclusive processes).*

***Reduction of the multiplicity of the soft, pileup particles** (opens a possibility to run the LHC detectors (trackers) at higher partonic luminosity w.r.t. HL(pp)-LHC).*

**$N_{pileup}$ (pp) ~ $N_{coll}$, $N_{pileup}$ (AA) ~ $N_{part}/2$**

*(stripping-off of soft partons and the nucleus surface)*

# 4. New research opportunities for EW symmetry breaking sector
## (interactions of longitudinally and transversely polarized W and Z bosons)




**Quantum uncertainty of the Longitudinal position of W-production**

$$L_{\rm Ioffe}(x_A) = \frac{1}{2M_A x_A}$$

**Quantum formation lengths of W-boson**

$$\delta z = \gamma_W / M_W$$

# Gamma Factory milestones – where we are?

1. *Demonstration of efficient production, acceleration and storage of "atomic beams" in the CERN accelerator complex.*
2. *Development "ab nihilo" the requisite Gamma Factory software tools.*
3. ***Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.***
4. *Building up the physics cases for the LHC-based GF research programme and attracting wide scientific communities to use the GF tools in their respective research.*
5. *Extrapolation of the PoP experiment results to the LHC case and realistic assessment of the performance figures of the GF programme.*
6. *Elaboration of the TDR for the LHC-based GF research programme.*

*Documented in Vol.1 of the the Gamma Factory Yellow Report.*

*LoI submitted to the SPSC on the 25$^{th}$ of September 2019.*

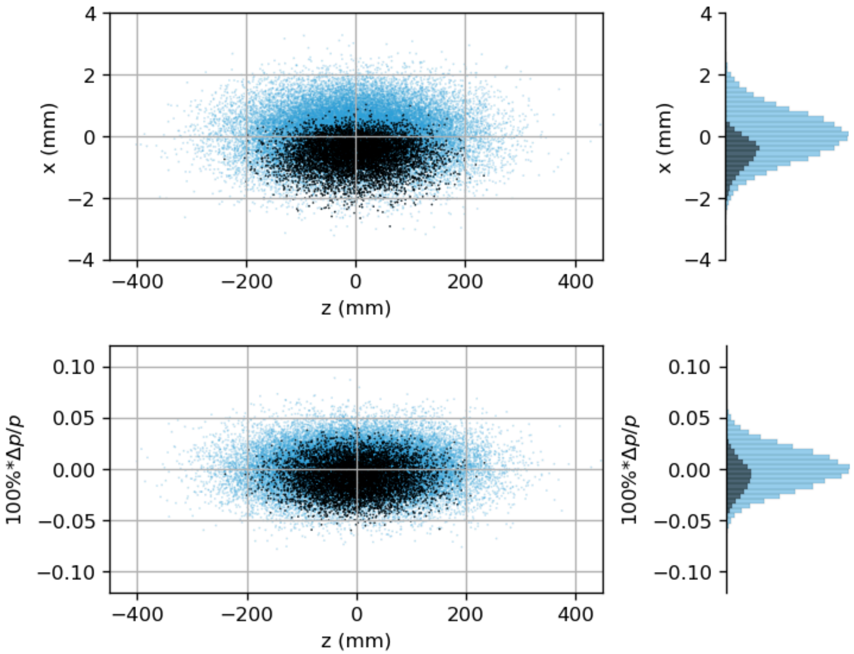
*Documents summarising highlights of the GF research potential in the domains of Atomic and Nuclear physics in preparation.*

# Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS – input parameters

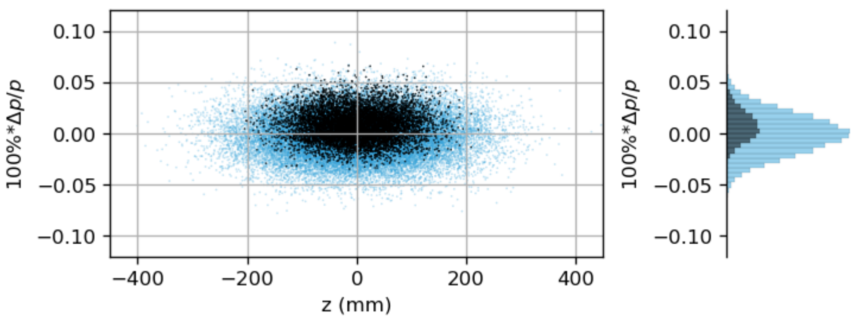
Table 1: Parameters of the calcium-beam cooling configuration in the SPS.

| | |
|---|---|
| Ion beam | $^{40}\mathrm{Ca}^{17+}$ |
| $m$ – ion mass | 37.21 GeV/c$^2$ |
| $E$ – mean energy | 7.65 TeV |
| $\gamma_L = E/mc^2$– mean Lorentz relativistic factor | 205.62 |
| $N$ – number ions per bunch | $4 \times 10^9$ |
| $\sigma_E/E$ – RMS relative energy spread | $2 \times 10^{-4}$ |
| $\epsilon_n$ – normalised transverse emittance | 1.5 mm mrad |
| $\sigma_x$ – RMS transverse size | 0.80 mm |
| $\sigma_y$ – RMS transverse size | 0.57 mm |
| $\sigma_z$ – RMS bunch length | 10 cm |
| Dispersion function | 2.44 m |
| Laser | pulsed Ti:Sa (20MHz) |
| $\lambda$ – wavelength ($\hbar\omega$ – photon energy) | 768 nm (1.6 eV) |
| $\sigma_\lambda/\lambda$ – RMS relative band spread | $2 \times 10^{-4}$ |
| $U$ – single pulse energy at IP | 2 mJ |
| $\sigma_L$ – RMS transverse intensity distribution at IP ($\sigma_L = w_L/2$) | 0.56 mm |
| $\sigma_t$ – RMS pulse duration | 2.04 ps |
| $\theta_L$ – collision angle | 1.3 deg |
| Atomic transition of $^{40}\mathrm{Ca}^{17+}$ | $2s \rightarrow 3p$ |
| $\hbar\omega_0'$ – resonance energy | 661.89 eV |
| $\tau'$ – mean lifetime of spontaneous emission | 0.4279 ps |
| $\hbar\omega_1^{\max}$ – maximum emitted photon energy | 271 keV |

# Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: laser pulse tuning



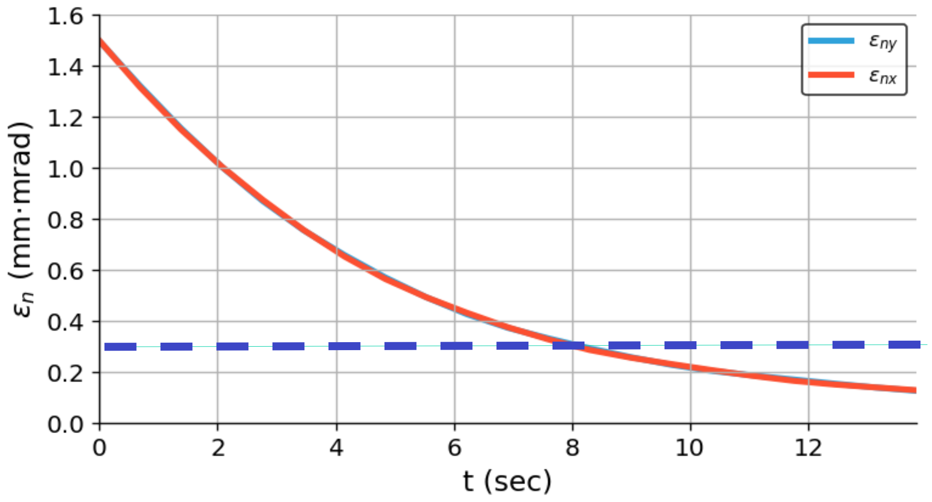

*Horizontal positions and momenta of the ions interacting with the pulse of the first laser in the momentum-dispersive region. Excited ions are shown as black dots while non-excited ions are shown as blue dots. The shift of the laser pulse by 1.4 mm provides an optimal coupling of horizontal betatron oscillations to synchrotron oscillations.* ***17 % of all ions are excited in each bunch crossing!***




*Momentum and longitudinal positions of the ions interacting with the photon-pulse of the second laser. The laser pulse focal point is aligned with the ion beam centre but its frequency band is shifted to excite the higher-momentum ions.*

# Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: transverse emittance evolution

*The betatron tunes are set to the same value: $\nu_x=\nu_y=26.13$ (the design values are only slightly different: $\nu_x = 26.13$ $\nu_y = 26.18$). The transverse coupling is introduced with a single 1 m long skew quadrupole with a field strength which is ~ 10 times lower than that for the typical SPS quadrupole. The resulting width of the coupling resonance (tune separation) is 0.0078. The vertical betatron oscillations are transferred into the horizontal oscillations in about 100 turns.*




**Reduction of the transverse x,y emittances by a factors of 3 can be achieved in 5 seconds, by a factor of 5 in 9 seconds.**