The Gamma Factory project for CERN
(new research tools made from light)

Workshop on Connecting Insights in Fundamental Physics

Corfu, September, 2019

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LPNHE, CNRS-IN2P3 and University Paris Sorbonne

Introduction

symmetry
dimensions of particle physics

topics

follow +

A joint Fermilab/SLAC publication

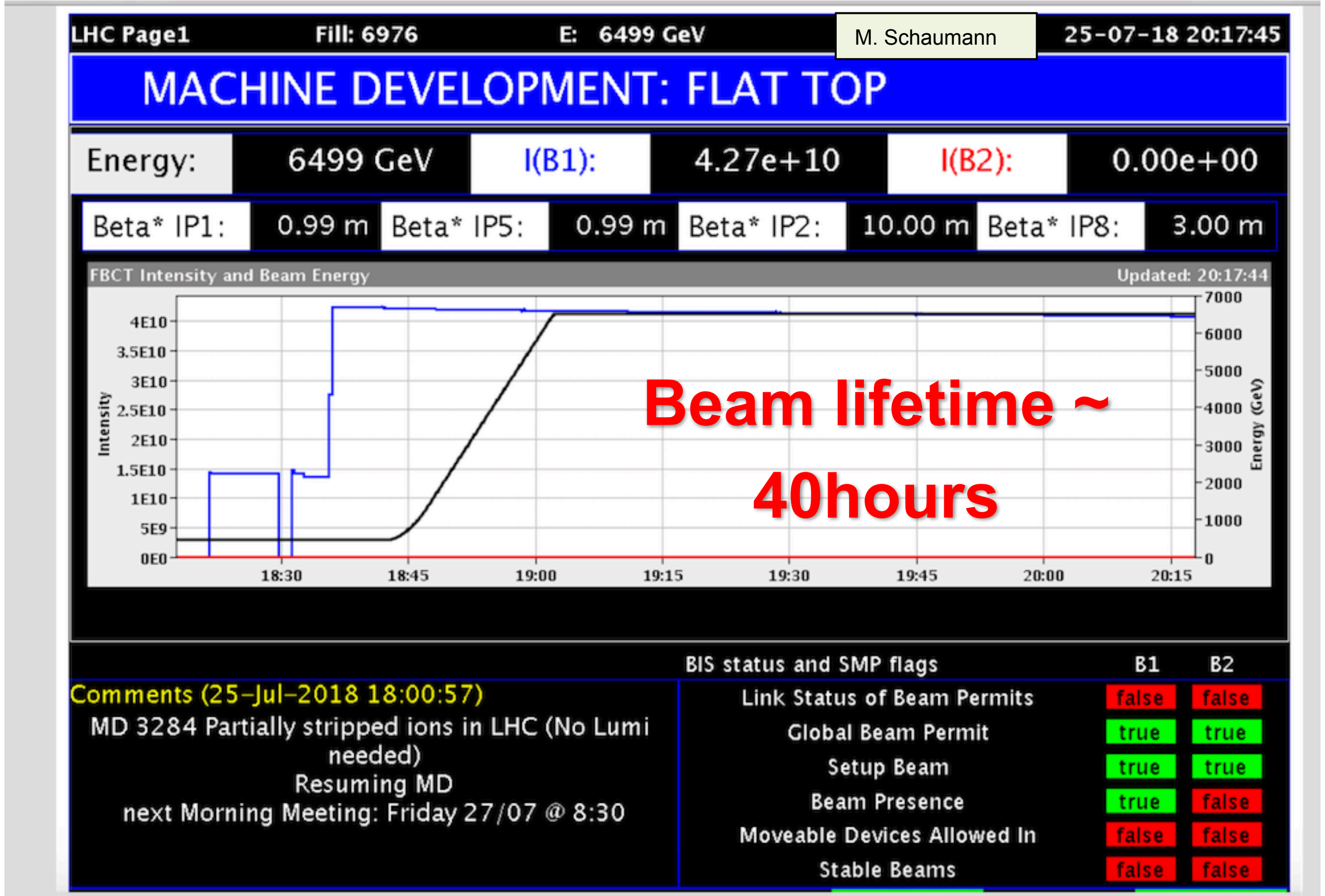
LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

Lead atoms with a single remaining electron circulated in the Large Hadron Collider.

https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html
https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms
https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time
https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms
https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html
https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

July 2018 – Successful production, injection, ramp and storage of the **Hydrogen-like lead beam in the LHC!**



intensity/bunch (~7 x 10^9), 6 bunches circulating

The Gamma Factory proposal for CERN †

Abstract

This year, 2015, marks the centenary of the publication of Einsteins Theory of General Relativity and it has been named the International Year of Light and light-based technologies by the UN General Assembly It is thus timely to discuss the possibility of broadening the present CERN research program by including a new component based on a novel concept of the light source which could pave a way towards a multipurpose Gamma Factory. The proposed light source could be realized at CERN by using the infrastructure of the existing accelerators. It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of 10^{17} photons/s, in the particularly interesting γ-ray energy domain of $1 \leq E_{photon} \leq 400$ MeV. This domain is out of reach for the FEL-based light sources. The energy-tuned, quasi-monochromatic gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. The Gamma Factory could open new research opportunities at CERN in a vast domain of uncharted fundamental physics and industrial application territories. It could strengthen the leading role of CERN in the high energy frontier research territory by providing the unprecedented-brilliance secondary beams of polarized muons for the TeV-energy-scale muon collider and for the polarized-muon-beam based neutrino factory.

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2017:

Creation of the Gamma Factory PBC study group

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† An Executive Summary of the proposal addressed to the CERN management.

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Gamma Factory group

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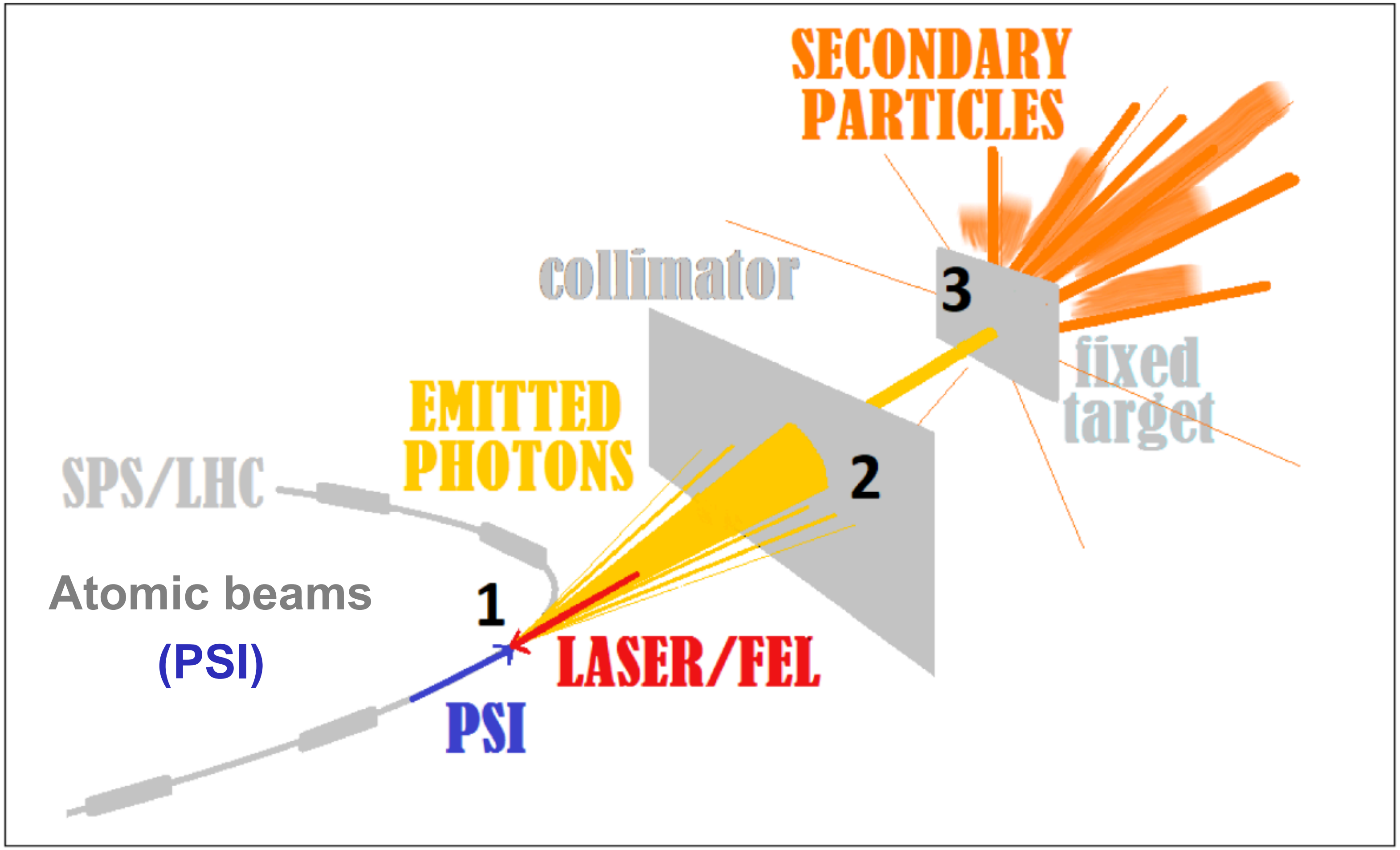
Today:
66 scientists
20 institutes
9 countries

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

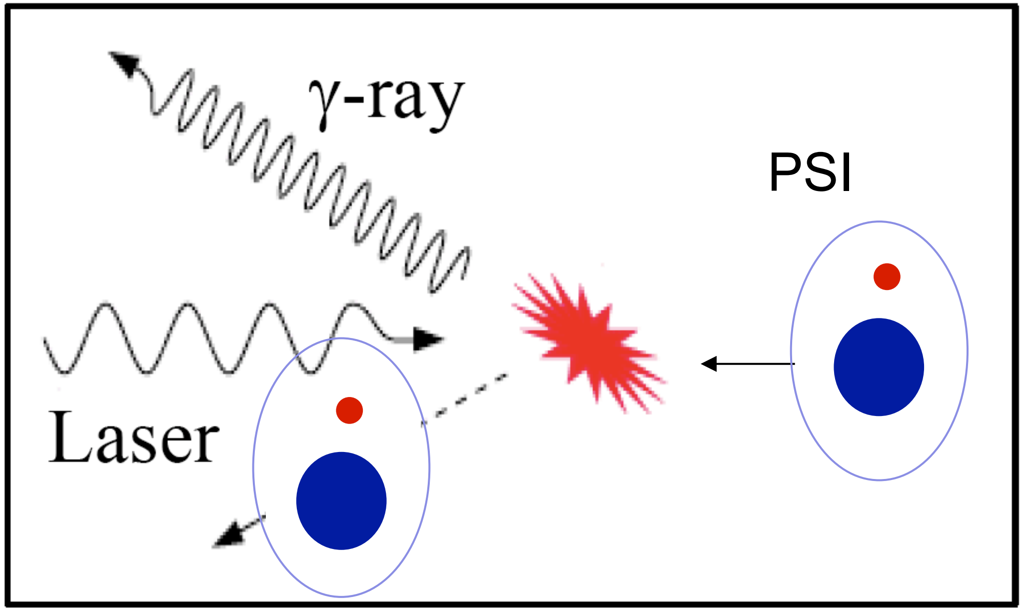
Gamma Factory Principles

Gamma Factory

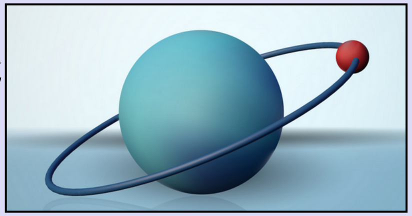


The underlying ideas:

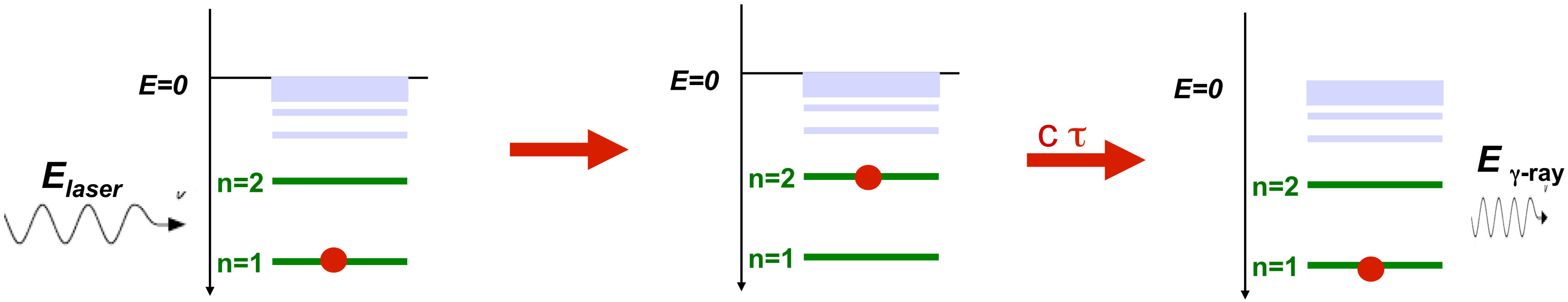
- *Use, for the first time at the LHC, atomic beams of Partially Stripped Ions (PSI)*
- *Collide atomic beams with laser pulses to produce high intensity gamma beams.*
- *Use gamma beams to produce secondary beams.*



Scattering of photons on ultra-relativistic hydrogen-like, Rydberg atoms (Bohr)



$-E_n = 1Ry\ Z^2/n^2$



$E_{laser} = 1Ry\ (Z^2 - Z^2/n^2)/2\gamma_L$ → $E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^2/(1+(\gamma_L\theta)^2)$

Large γ_L - Highly charged, high-Z, atoms can be excited by ordinary lasers - efficient manipulation of atomic beams and a high yield gamma-ray source

Partially Stripped Ion beam as a light frequency converter

...enjoy relativistic magic twice

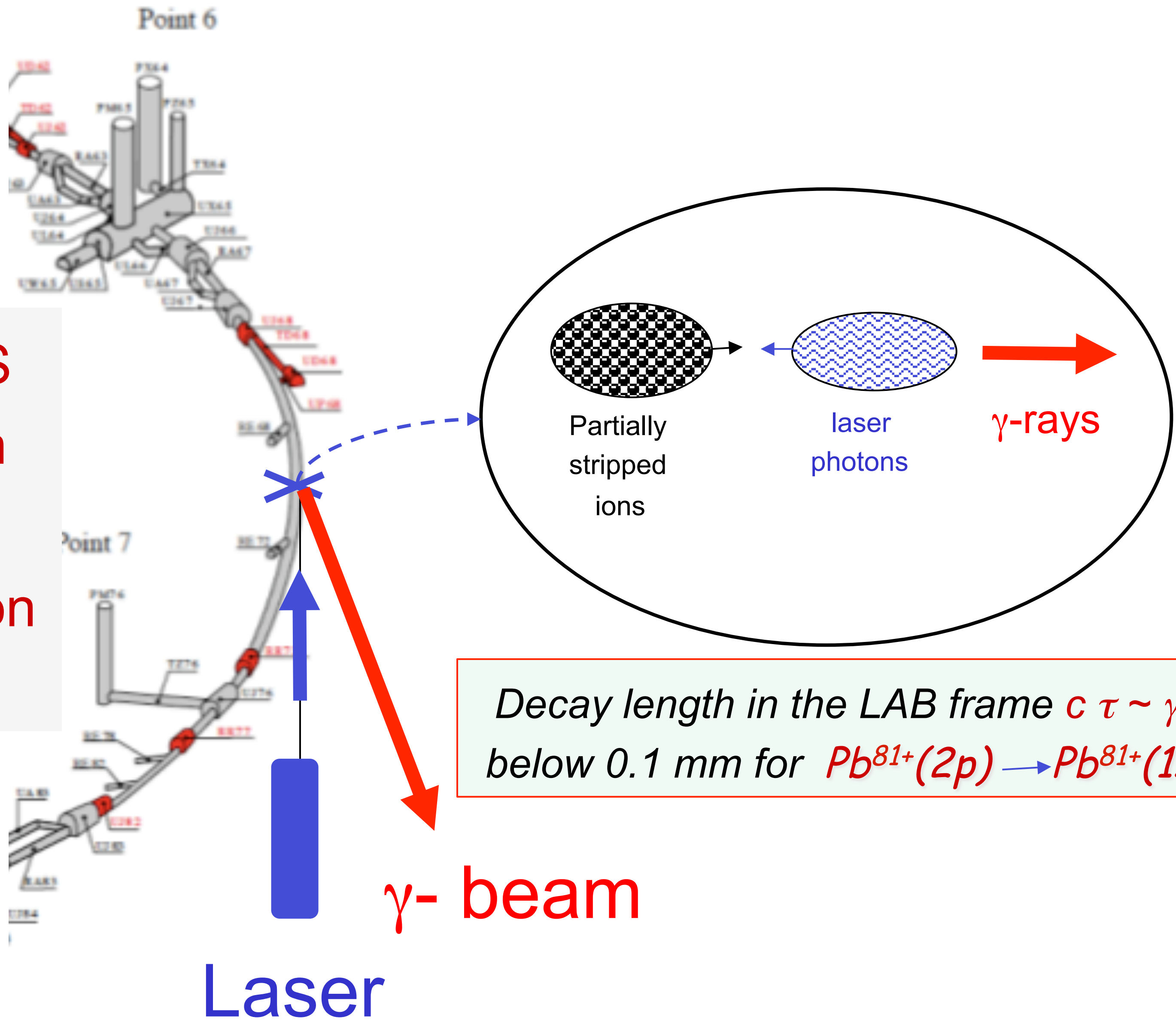
$$\nu^{max} \longrightarrow (4\,\gamma_L^{\,2})\,\nu_i$$

γ_L =E/M - Lorentz factor for the ion beam

The tuning of the beam energy (SPS or LHC), the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy at CERN in the energy domain of 100 keV – 400 MeV

The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches

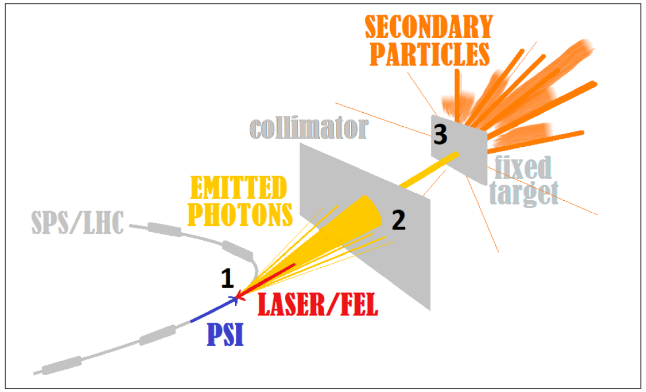


Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$ *below 0.1 mm for* $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

GF research tools: primary and secondary beams

primary beams:

- partially stripped ions
- electron beam (for LHC)
- gamma rays



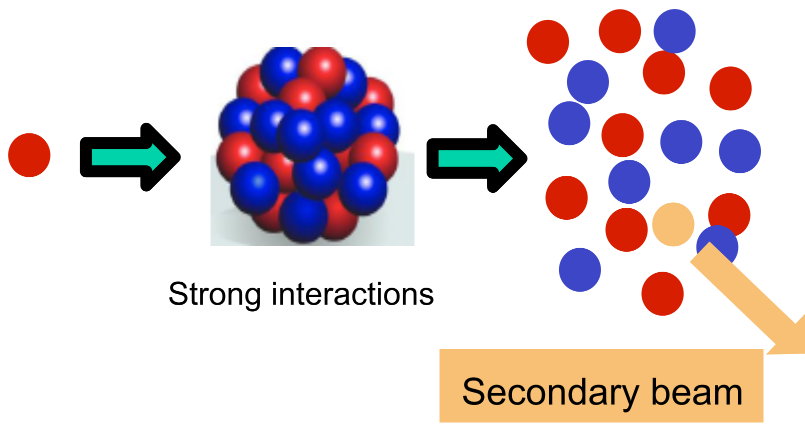
secondary beams:

- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

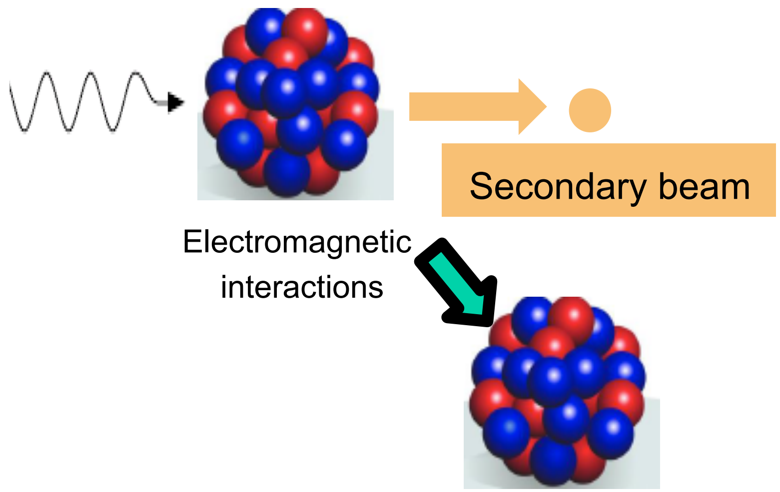
Secondary beams

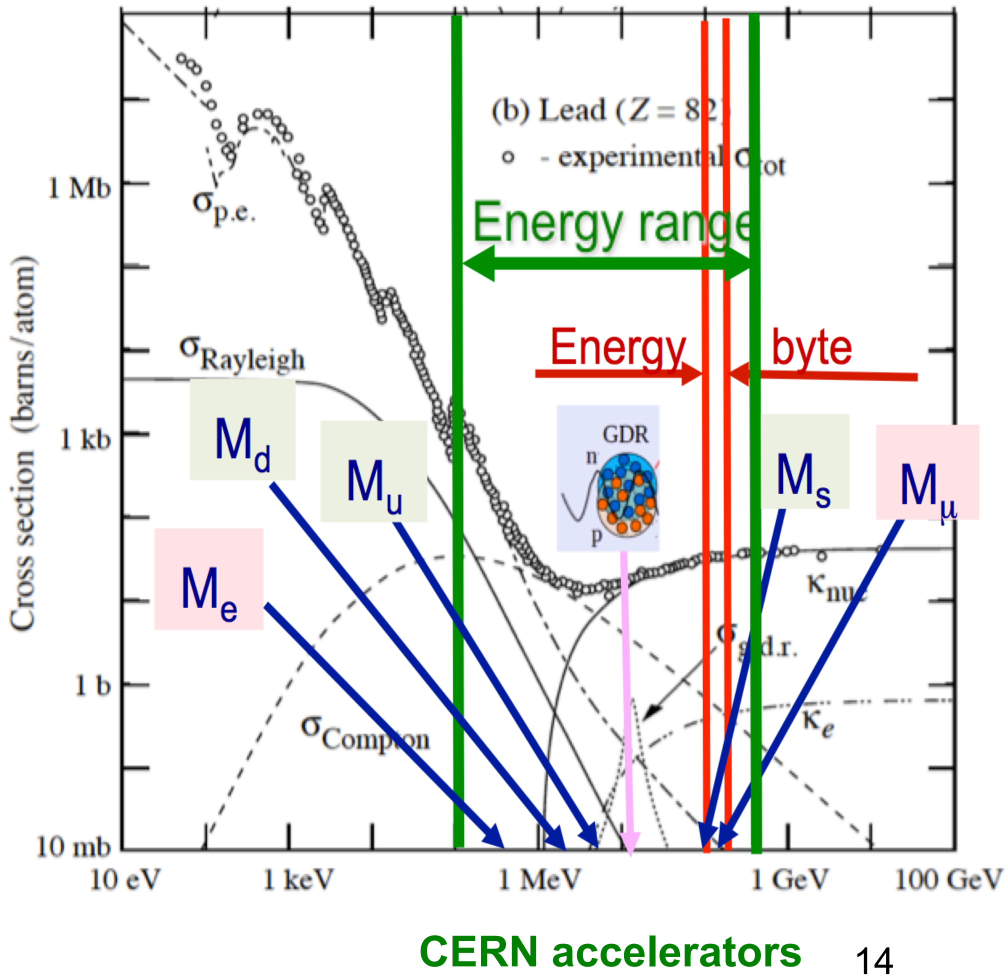
(from "mining" paradigm to "production-by-demand" paradigm)

"mining" paradigm:



"production" paradigm:





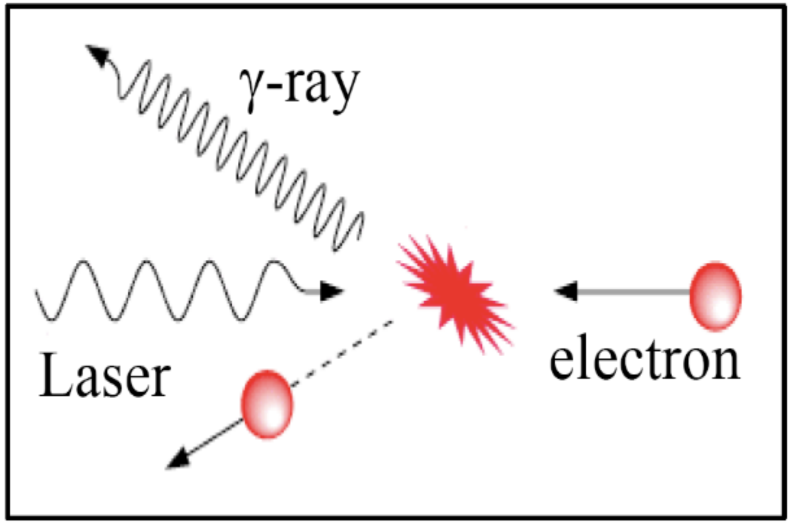
Gamma Factory beam-intensity targets

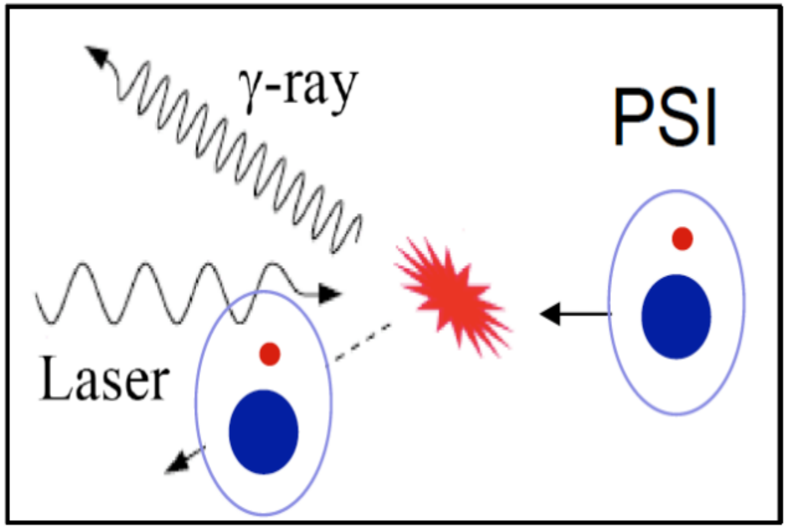
- ***Photons*** *– up to factor of* ***10^7*** *gain in* ***intensity*** *w.r.t. present* ***gamma*** *sources.*
- ***Polarised positrons*** *– up to factor of* ***10^4*** *gain in* ***intensity*** *w.r.t. KEK* ***positron*** *source.*
- ***Polarised muons*** *– up to factor* ***10^3*** *gain in* ***intensity*** *w.r.t. to PSI* ***muon*** *source (****low emittance*** *beams → **muon collider**, high purity neutrino beams).*
- ***Neutrons*** *– up to factor of* ***10^4*** *in flux of primary* ***neutrons*** *per 1 kW of driver beam power.*
- ***Radioactive ions*** *– up to a factor* ***10^4*** *gain in intensity w.r.t. to e.g. ALTO.*

The source of the γ-source intensity leap

Conventional source

Gamma Factory source





Cross-sections

Electrons:

$$\sigma_e = 8\pi/3 \times r_e^2$$

r_e - classical electron radius

Partially Stripped Ions:

$$\sigma_{peak} = \lambda_{res}^2 / 2\pi$$

λ_{res} - photon wavelength in the ion rest frame

Electrons:

$$\sigma_e = 6.6 \times 10^{-25}\ \text{cm}^2$$

Partially Stripped Ions:

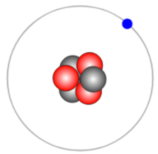
$$\sigma_{peak} = 1.7 \times 10^{-15}\ \text{cm}^2$$

Numerical example: $\lambda_{laser} = 1034$ nm, $\gamma_L^{PSI} = 1000$

$\gamma_L^{PSI} = E/M$ - Lorentz factor for the ion beam

Inventory of the Gamma Factory research tools

1. Hydrogen-, Helium-like, high Z atomic beams



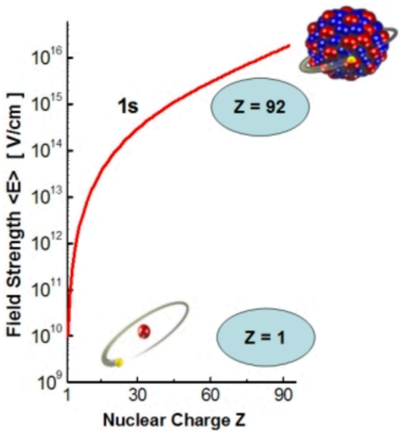


TABLE I. Z dependence of atomic characteristics for hydrogenic ions. In the given expressions, α is the fine structure constant, $\hbar = c = 1$, m_e is the electron mass, G_F is the Fermi constant, θ_w is the Weinberg angle, and A is the ion mass number.

Parameter	Symbol	Approximate Expression
Transition energy	$\Delta E_{n-n'}$	$\frac{1}{2}(\frac{1}{n^2} - \frac{1}{n'^2})\alpha^2 m_e Z^2$
Lamb shift	ΔE_{2S-2P}	$\frac{1}{6\pi}\alpha^5 m_e Z^4 F(Z)^{a}$
Weak interaction Hamiltonian	H_w	$i\sqrt{\frac{3}{2}}\frac{G_F m_e^3 \alpha^4}{64\pi}\{(1 - 4\sin^2\theta_w) - \frac{(A-Z)}{Z}\}Z^5$
Electric dipole amplitude $(2S \to 2P_{1/2})$	$E1_{2S\to 2P}$	$\sqrt{\frac{3}{\alpha}}\, m_e^{-1} Z^{-1}$
Electric dipole amplitude $(1S \to 2P_{1/2})$	$E1$	$\frac{2^7}{3^5}\sqrt{\frac{2}{3\alpha}}\, m_e^{-1} Z^{-1}$
Forbidden magn. dipole ampl. $(1S \to 2S)$	$M1$	$\frac{2^{5/2}\alpha^{5/2}}{3^4}\, m_e^{-1} Z^2$
Radiative width	Γ_{2P}	$(\frac{2}{3})^8 \alpha^5 m_e Z^4$

[a]The function $F(Z)$ is tabulated in [1]. Some representative values are $F(1) = 7.7$; $F(5) = 4.8$, $F(10) = 3.8$; $F(40) = 1.5$.

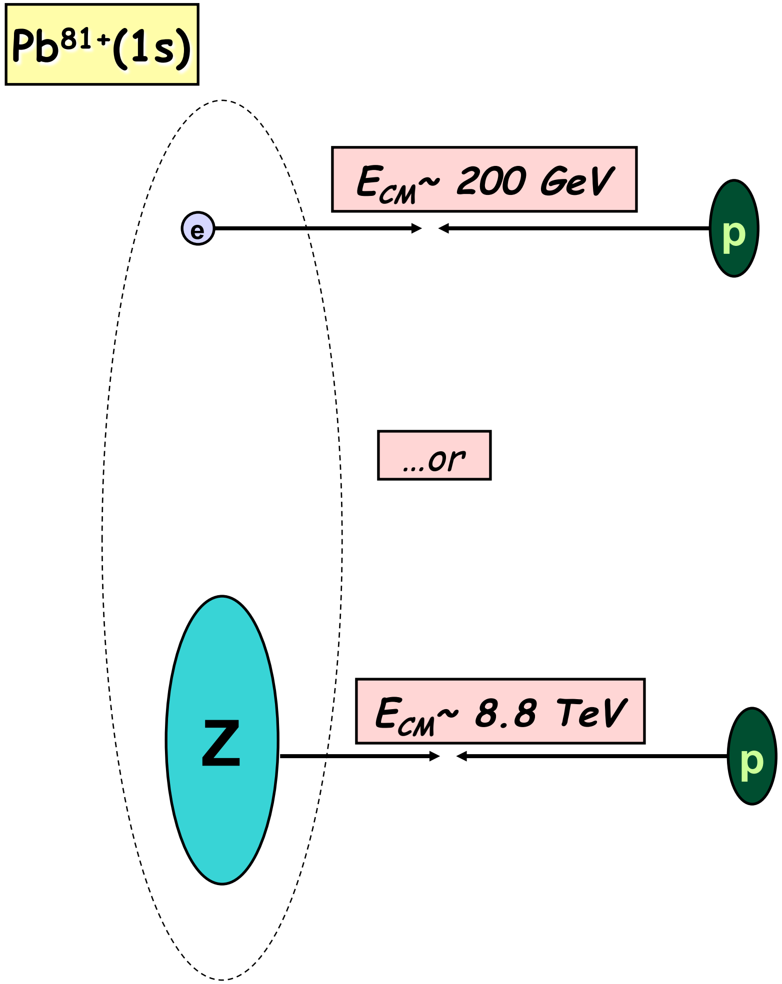
Main advantages of the hydrogen(helium)-like high-Z beam:

- *Very strong electric field (high sensitivity to the QED-vacuum effects)*
- *Weak effects rise strongly with Z*
- *Hydrogen-like atoms - calculation precision and simplicity*
- *Atomic degrees of freedom can be excited by ordinary laser owing to large γ_L*
- *Small statistical errors (large $N_{ion/bunch}$ and repetition rate)*

High Z atomic beams – Atomic, Molecular and Optical (AMO) physics research highlights

The AMO research highlights include: (1) studies of the basic laws of physics: e.g. Lorenz invariance, the Pauli exclusion principle; (2) studies of CPT symmetries; (3) precise measurement of $\sin^2\theta_W$ in the large-distance regime; (4) measurements of the nuclear charge radius and neutron skin depths in high-Z nuclei, and (5) searches for dark matter particles using the AMO detection techniques which are complementary to those used in Particle Physics.

2. Cost-less electron beam for electron-proton collisions at the LHC



• *average distance of the electron to the large Z nucleus d ~ 600 fm (sizably 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 β^*, 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)*

ep@LHC*: Pb^{80+}(1s)-p example

- CM energy (ep collisions) = 205 GeV
- β at IP = 0.5 m
- Transverse normalized emittance = 1.5 μ m
- Number of ions/bunch = 10^8
- Number of protons/bunch = 4 x 10^{10}
- Number of bunches = 608
- Luminosity ~ 10^{30} cm^{-2} s^{-1}

* PIE = Parasitic Ion Electron collider

3. Low emittance hadronic beams

(the Gamma Factory path to a high luminosity LHC)

$$\mathscr{L} = f_{\text{coll}} \frac{n_1 n_2}{4\pi \sigma_x^* \sigma_y^*}$$

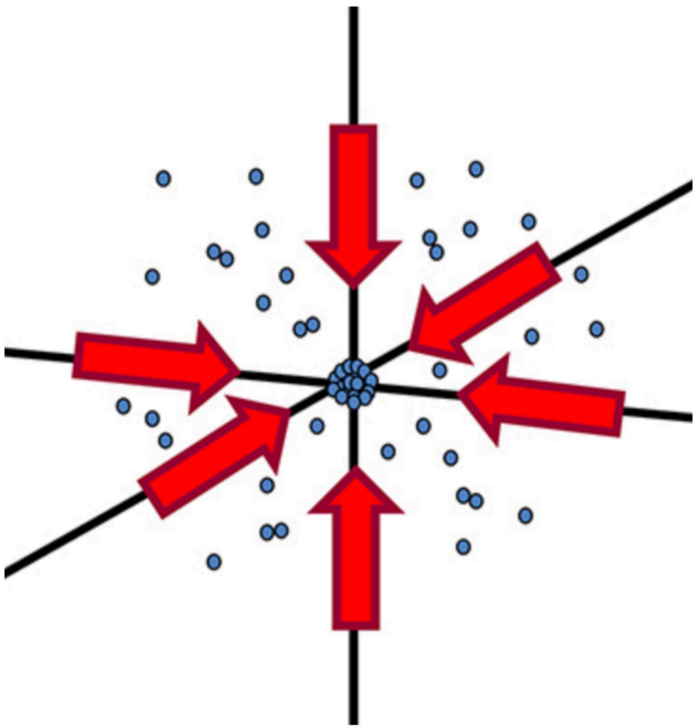
The beam width σ can be expressed in terms of the β parameter describing beam focussing strength in the interaction point and a beam emittance ε.

$$\varepsilon_x \equiv \frac{\sigma_x^2}{\beta_x}, \quad \longrightarrow \quad \mathscr{L} = f \frac{n_1 n_2}{4\pi \sqrt{\epsilon_x \, \beta_x^* \, \epsilon_y \, \beta_y^*}}$$

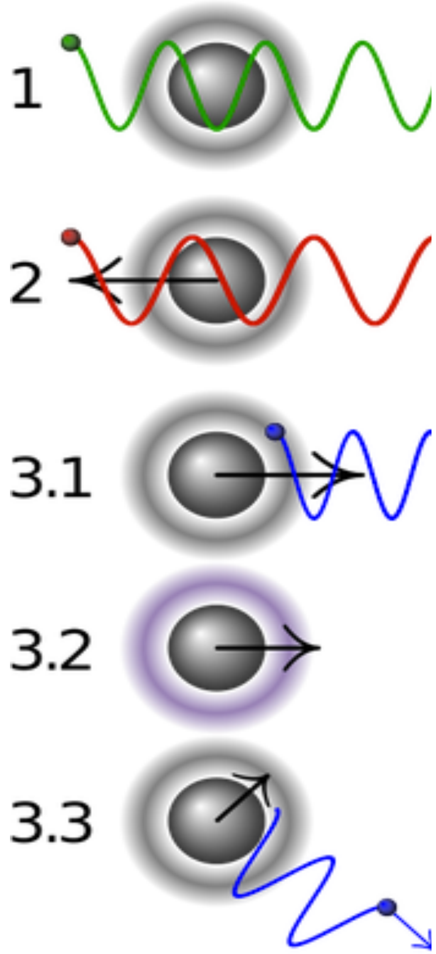
Two complementary ways to increase the machine luminosity --
increase the focusing strength (HL-LHC), or reduce the beam emittance

*(a low-emittance particle beam is a beam where the particles are confined to a small distance and have nearly the same momentum – **cold beams**)*

Doppler cooling – in atomic physics



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.

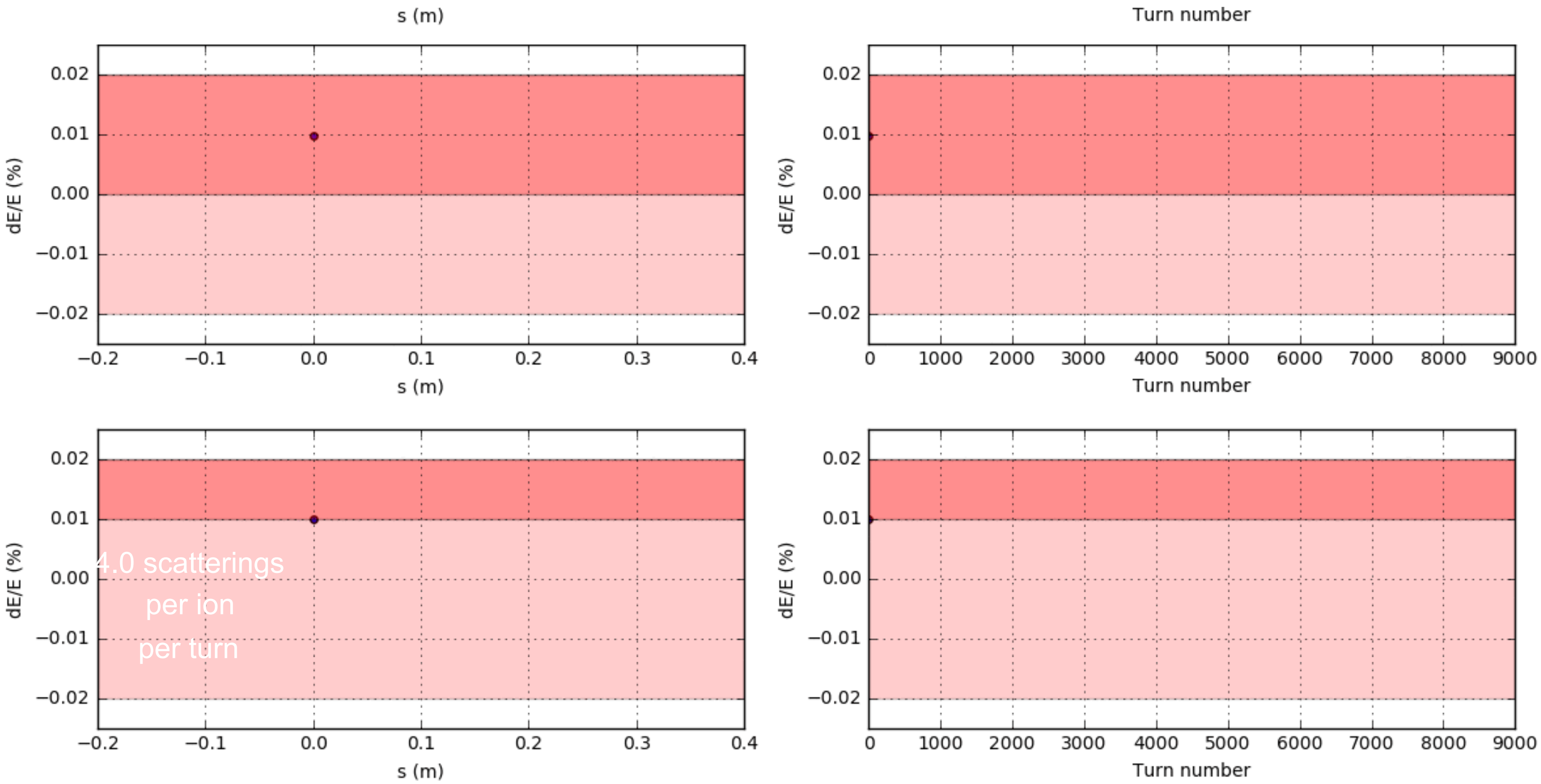
3.1 An atom moving towards the laser sees it blue-shifted and absorbs the photon, slowing the atom.

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.

Gamma Factory beam cooling technique to reduce the beam emittance

(principle borrowed from atomic physics)



Application 1: Cooled beams as for precision EW physics at the LHC

The canonical LHC pp collision programme (including HL-LHC) cannot improve the precision of the measurement of the EW model parameters (missing external PDF measurement input)*

…high luminosity ($L_{AA} \sim L_{pp}/A^2$) nuclear collisions of isoscalar ions are important

Proposal to cool the beams in the SPS, strip the remaining electrons in the SPS-LHC transfer line, inject, accelerate and collide them in the LHC.

For the quantification of these statements see e.g..:

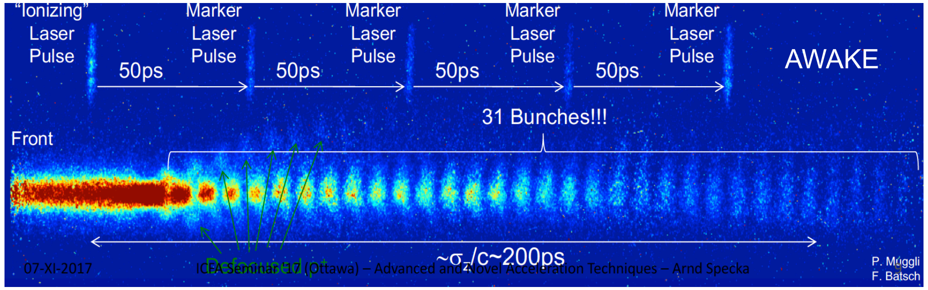
M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C69 (2010) 379-397.*
F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, *Eur.Phys.J. C63 (2009) 33-56.*
M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C51 (2007) 607-617.*
M.W. Krasny, S. Jadach, W. Placzek, *Eur.Phys.J.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

Merits of the isoscalar (Z=A/2) beams

- Isoscalar beams $u^{(v)} = d^{(v)}$ and $u^{(s)} = d^{(s)}$ cancel the majority of W^+, W^- and Z production differences (Z as a standard candle)
- The measurement of the W-boson charge asymmetry constrain directly the s-c distribution
- Analysis restricted to forward lepton pseudorapidities reduces errors due to b distribution uncertainty

Drastic reduction of systematic errors of modelling the W and Z production and decay processes!

<u>Application 2: Cooled beams as a low emittance drivers for Plasma Wake Field acceleration?</u>



The principal limiting factor for the Plasma Wake Field (PWF) acceleration rate is the achievable hadron beam density (driven by the beam emittance).

<u>Atomic beams can be efficiently cooled by the Doppler cooling – increase of acceleration rate and modulation of the bunch microstructure!</u>

<u>… In addition: Electrons ready to be accelerated!!!</u>

4. Photon beams

Example 1: photon-photon scattering

collider schemes:

γ–γ collisions,

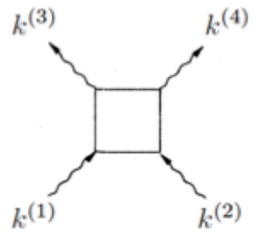
E_{CM} = 0.1 – 800 MeV

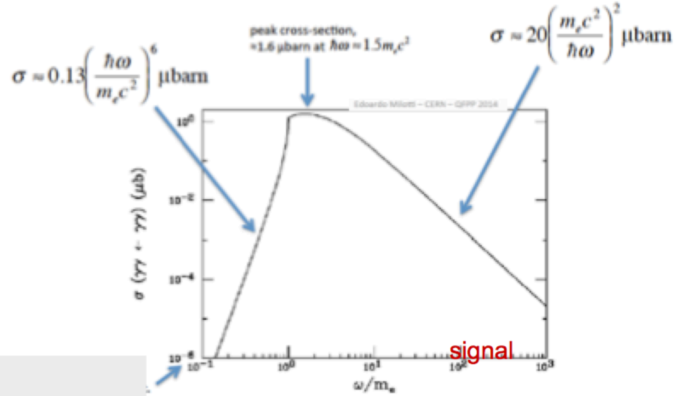
γ–γ_L collisions,

E_{CM} = 1 – 100 keV

γ–p(A), ep(A) collisions,

E_{CM} = 4 – 200 GeV



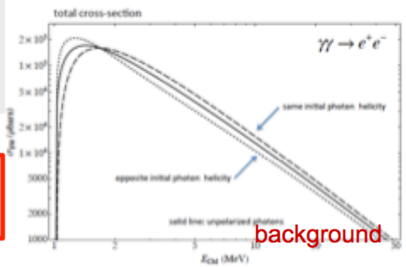


Two measurements:

γ–γ ***collisions, for $E_{CM} > 2m_e$***

and (background free)

γ–γ_L ***collisions, for $E_{CM} < 2m_e$***



Up to 1000 events/second expected*, to be compared to ~10 events/year at the LHC*

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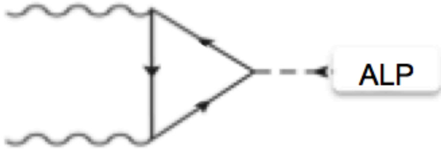
Example 2: Dark matter searches with photon beams

Principal portals accesible :

Dark Photon

Axion-like



A very wide mass region(1 keV - 800 MeV) and a wide range of the production cross sections (down to the O(1) fb region) can be explored

Search sensitivity leap:

1. *Beam intensity for the beam dump type of experiment:* ***up to 10^{24} /year of dumped photons*** *(the SHIP yardstick: 10^{19} protons/year on target)*
2. *A comfortable timing structure of gamma beams (~10 MHz)*
3. *Direct Searches with a broad-band colliding gamma beams can be followed by dedicated resonance region investigations with a very narrow band beam*

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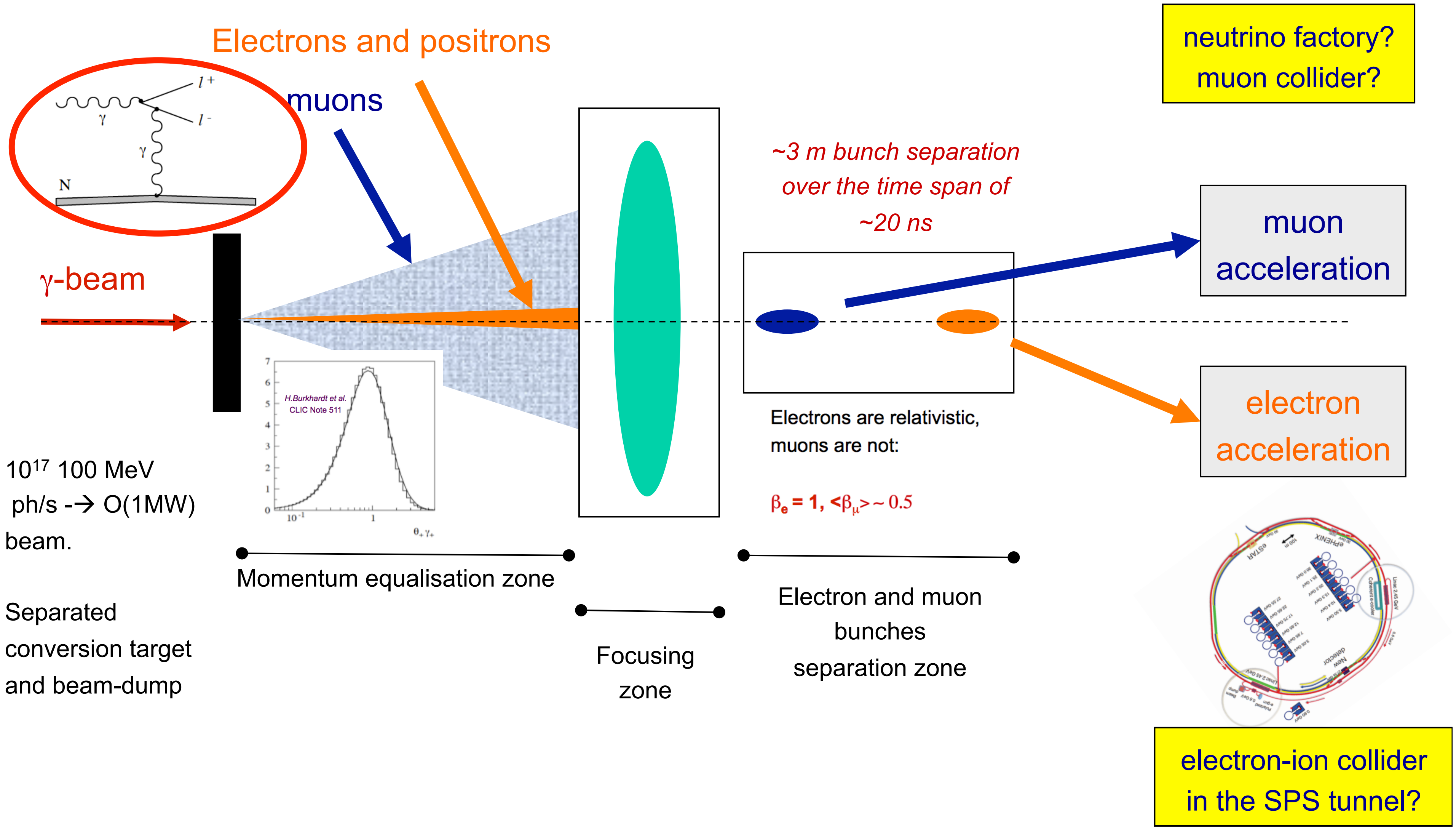
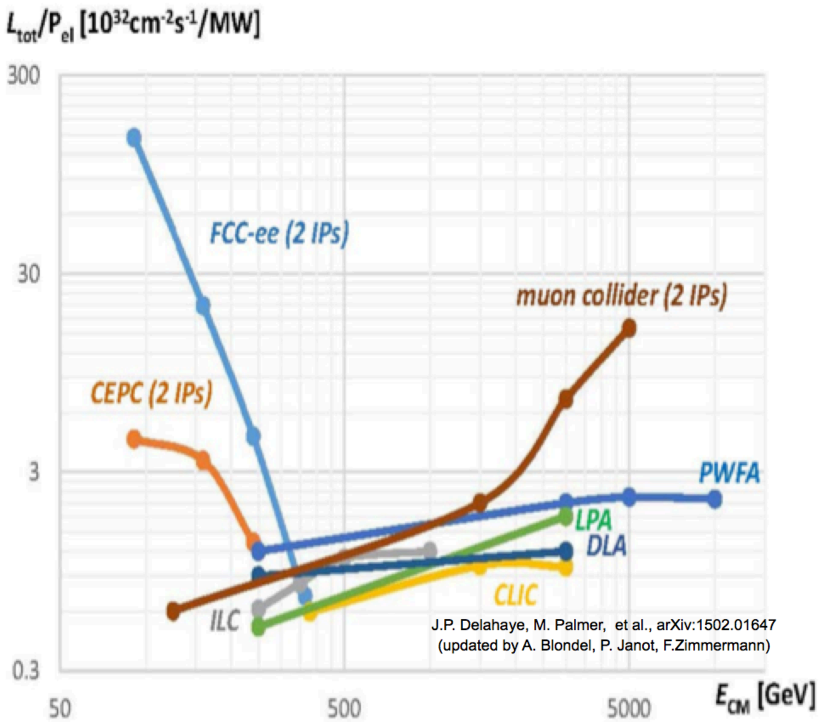
5. Secondary beams

A high intensity, low emittance, polarised lepton-beam source

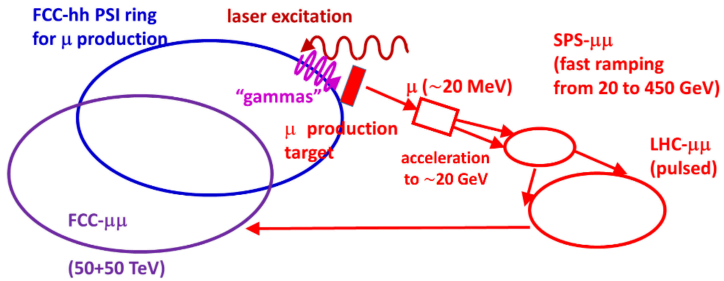


Example: Variants of a multi-TeV scale muon colliders

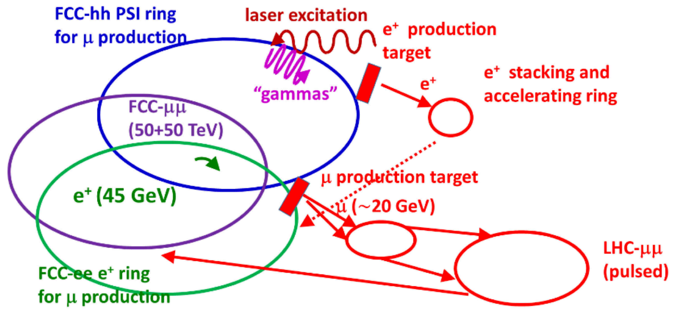
based on the Gamma Factory muon source



For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption



100 TeV μ collider FCC-μμ with FCC-hh PSI e^+ & FCC-ee $\mu^\pm$ production



LHC/FCC-BASED MUON COLLIDERS*

F. Zimmermann†, CERN, Geneva, Switzerland

The merit of the neutrino beams originating form the Gamma Factory polarised muon source

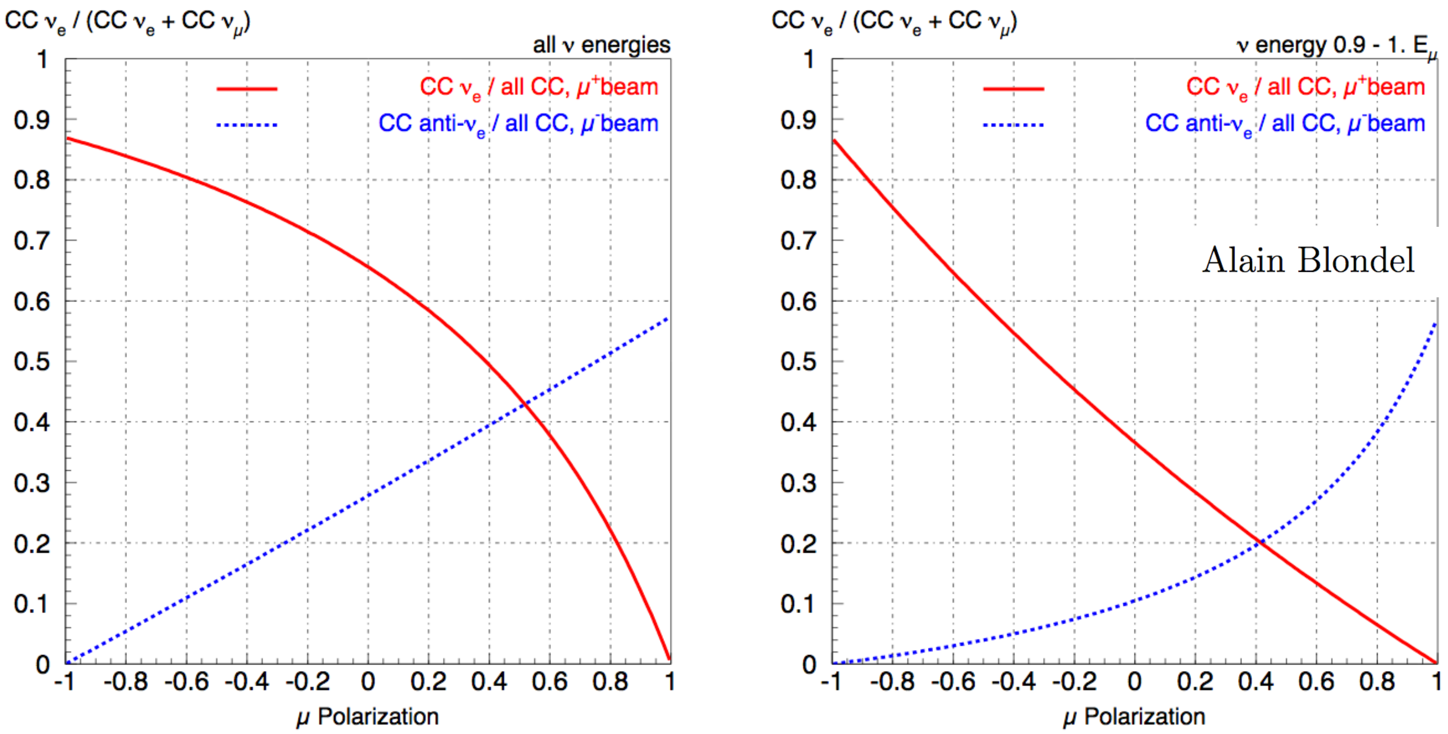
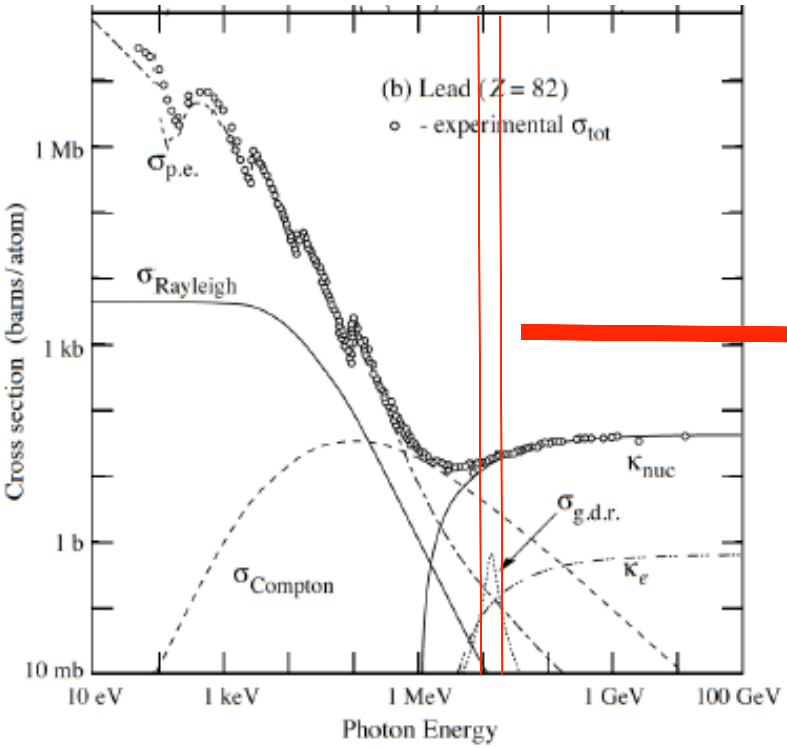


Fig. 5. *Fraction of ν_e events among all CC events as function of muon polarisation and for the two muon signs. On the left: all energies; on the right: the high energy end of the spectrum.*

Neutron and Radioactive Beams



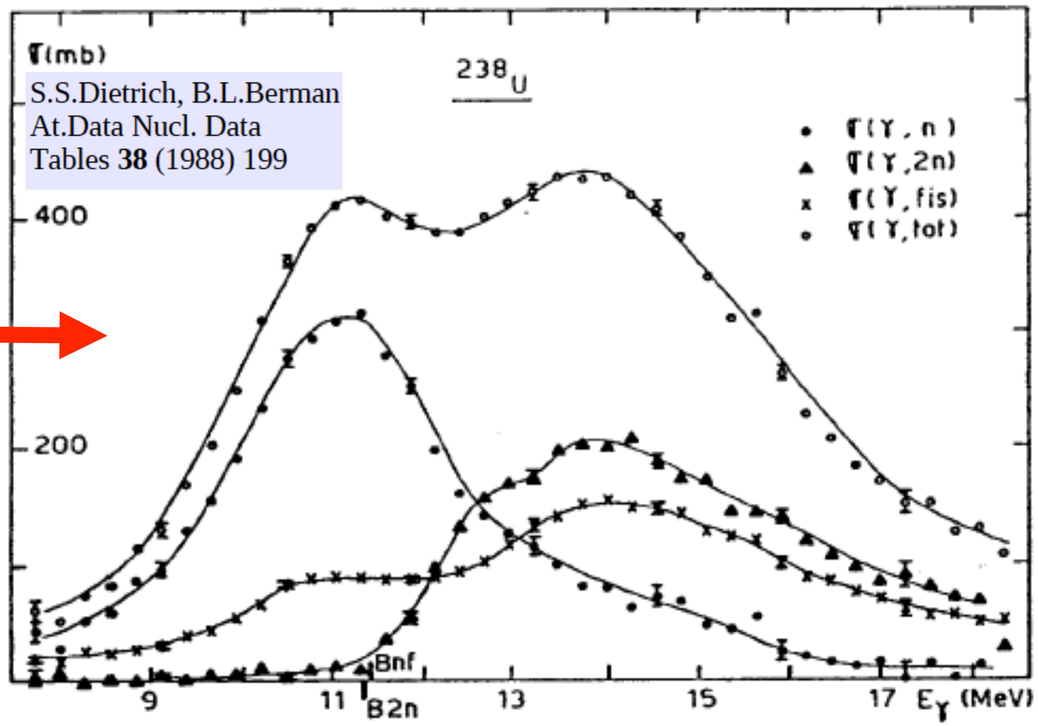
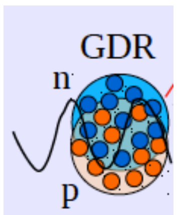


Figure 1. Partial and total photonuclear cross sections (γ,n), (γ,2n), (γ,f), and (γ,tot) for U^{238}.

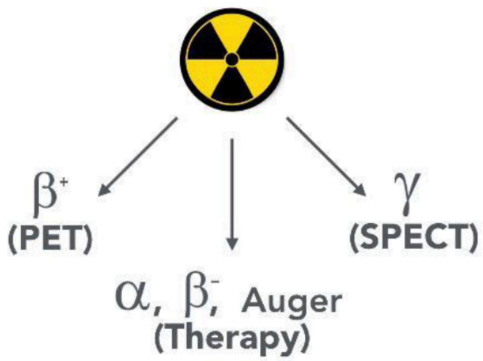


GDR=Giant Dipole Resonance

Achievable production rate of:

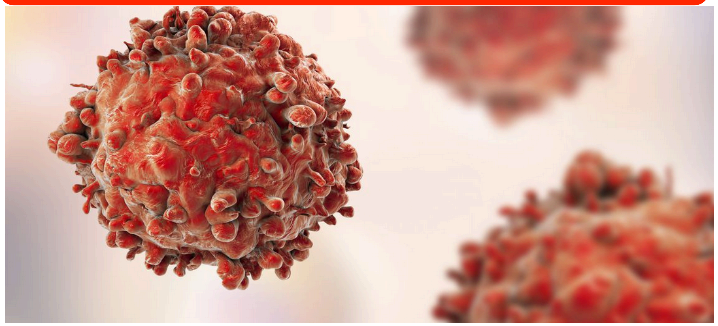
- primary neutrons **~10^{15} 1/s**
- fission products **~10^{14} 1/s**

An application example: cancer treatment



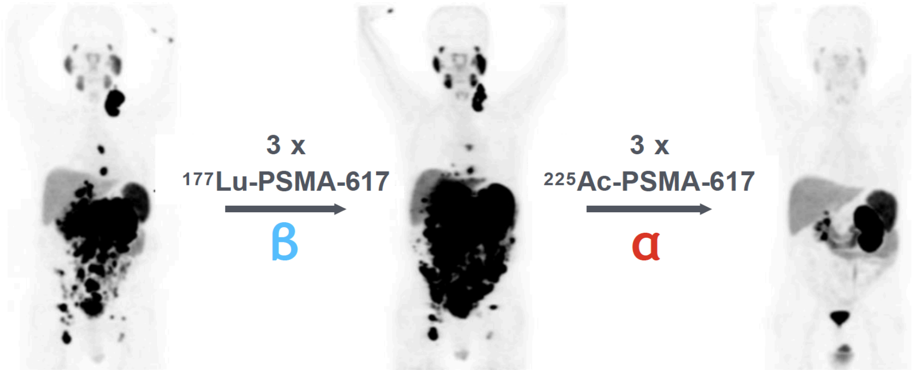
α

$\alpha-$ range 100 μm ~ 10 cells



Selective destruction of the cancer cells

When betas fail....



Kratochwil et al., 2017.

...there are always alphas!

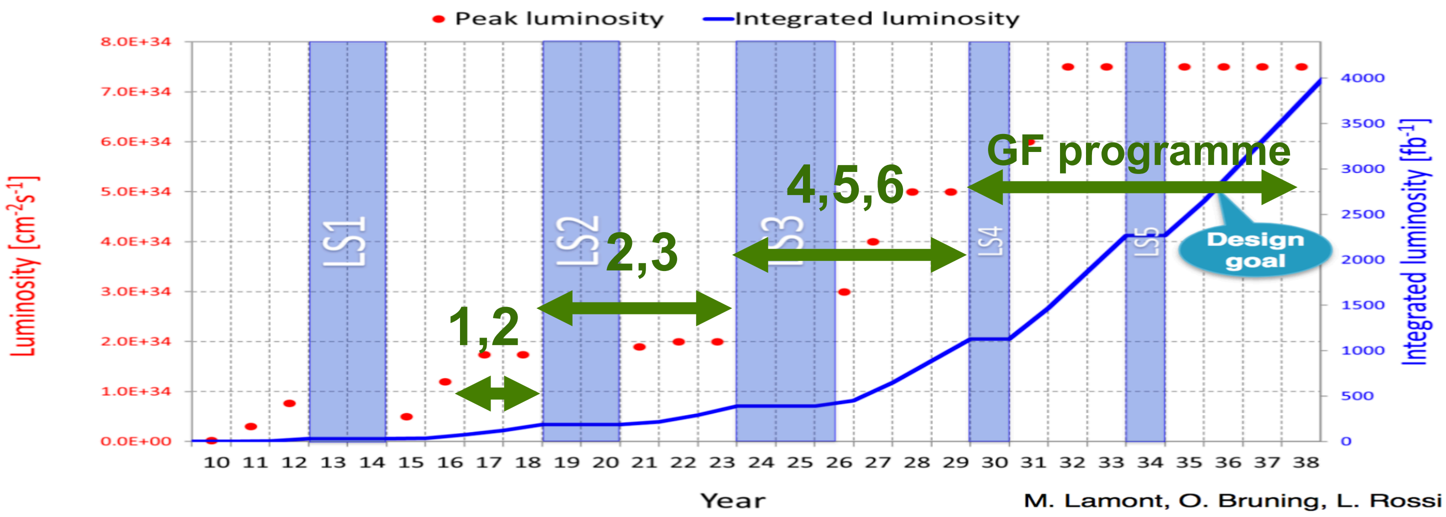
efficient scheme
of production of
radioactive ions
(alpha-emitters)

The way forward

(on the path from the GF initiative to the GF project)

Gamma Factory project milestones

1. ***Production**, **acceleration** and **storage** of **"atomic beams"** at CERN accelerator complex (2017-2018)*
2. ***Development** "ab nihilo" the requisite Gamma Factory **software tools***
3. ***Proof-of-Principle** (PoP) experiment in the SPS tunnel.*
4. ***Realistic assessment** of Gamma Factory **performance figures**.*
5. ***Physics highlights** of Gamma Factory based **research programme**.*
6. *Gamma Factory **TDR**.*



Gamma Factory Proof-of-Principle experiment

LETTER OF INTENT

… in preparation

What we want to learn/demonstrate with the PoP experiment in the SPS?

1. *How to integrate of the laser + F-P cavity into the storage ring of hadronic beam?* *(radiation hardness of the laser system, IP for high beam magnetic rigidity beam, etc…)*
2. *How to maximise the rate of atomic excitations? (matching of the characteristics of the ion bunches to those of the laser bunches, matching laser light bandwidth to the width (lifetime) of the atomic excitation, timing synchronisation, etc.) ?*
3. *How to extract the Gamma-rays from the collision zone?*
4. *How to collimate the Gamma beam?*
5. *How to monitor/measure the flux of outgoing photons?*

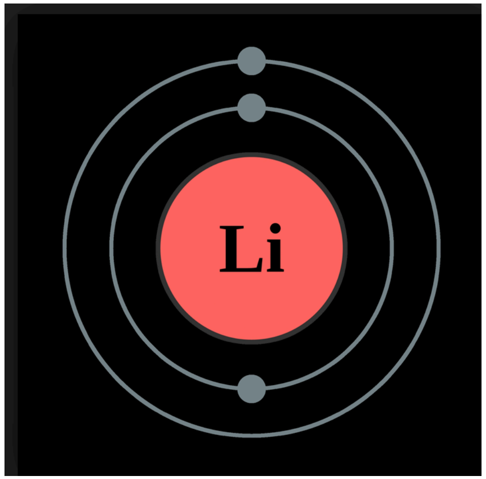
---

6. *Demonstrate new cooling method of hadronic beams (Laser Cooling)*
7. *Atomic Physics measurement programme (PNC, Lamb shift, …)*

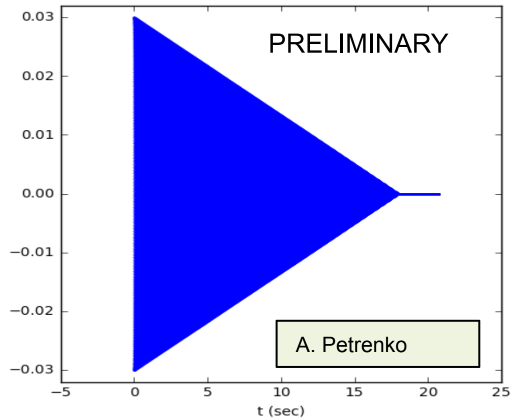
POP experiment: the choice of ion beam

Lithium-like Lead: Pb79

Atomic transition energy $2s_{1/2} — 2p_{1/2}$	eV	230.76
Excited state lifetime (ion frame)	ps	76.57
Excited state decay length (lab frame)	m	2.19
Max. emitted photon energy (lab frame)	keV	44

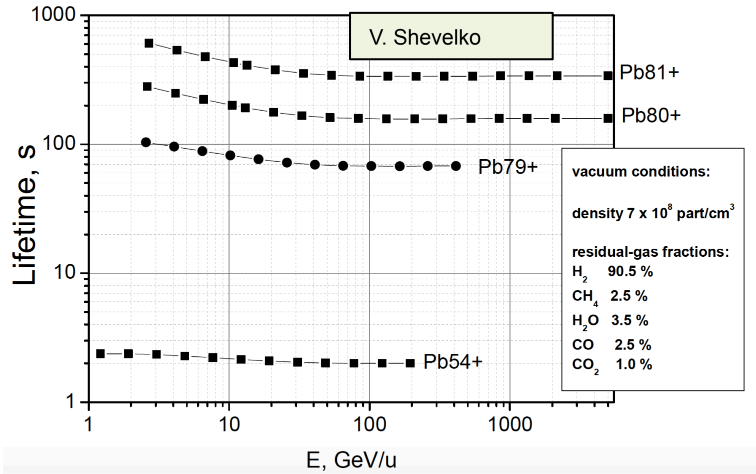


Cooling time in the SPS
(~1 ph absorption/ revolution/ion)



$\tau_{\text{cooling}} < \tau_{\text{beam}}$

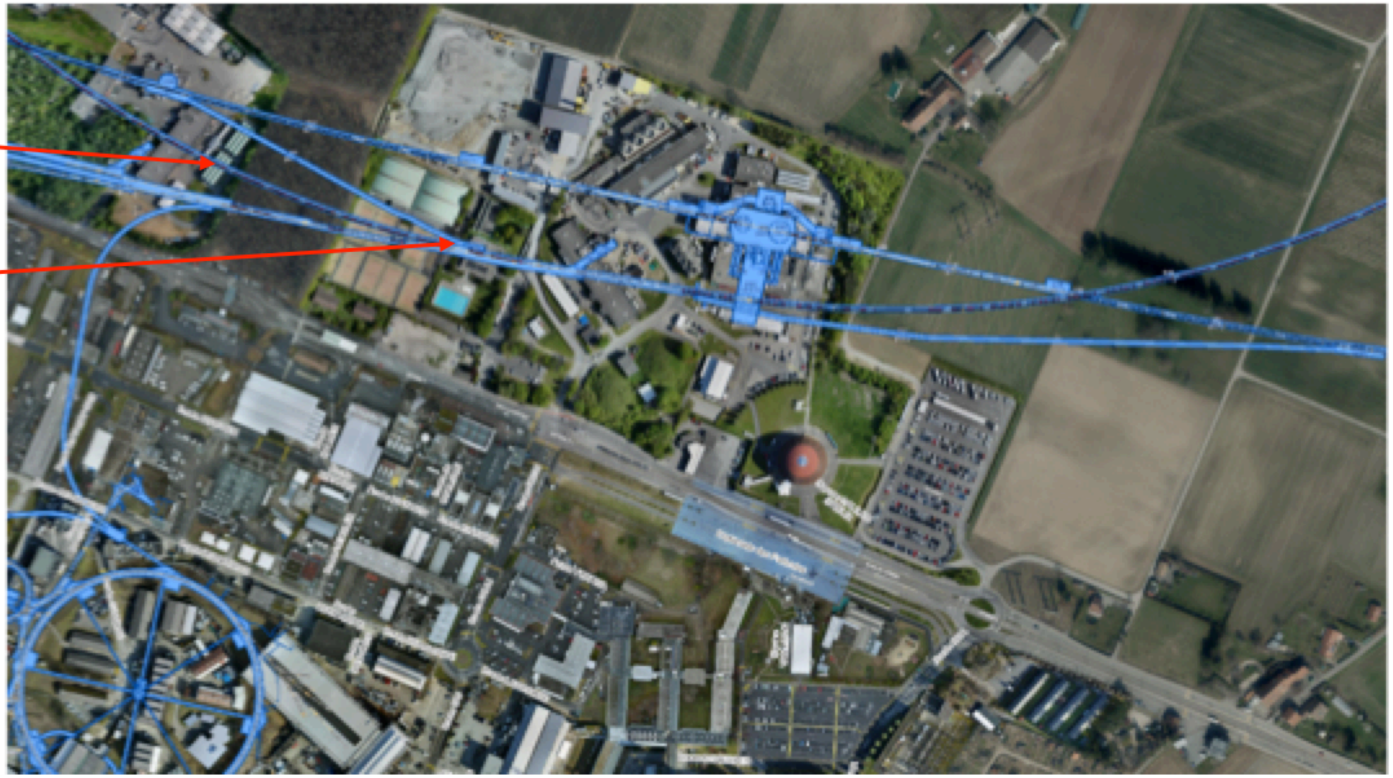
Pb+79 beam life-time in the SPS



PoP experiment: integration (LSS6)

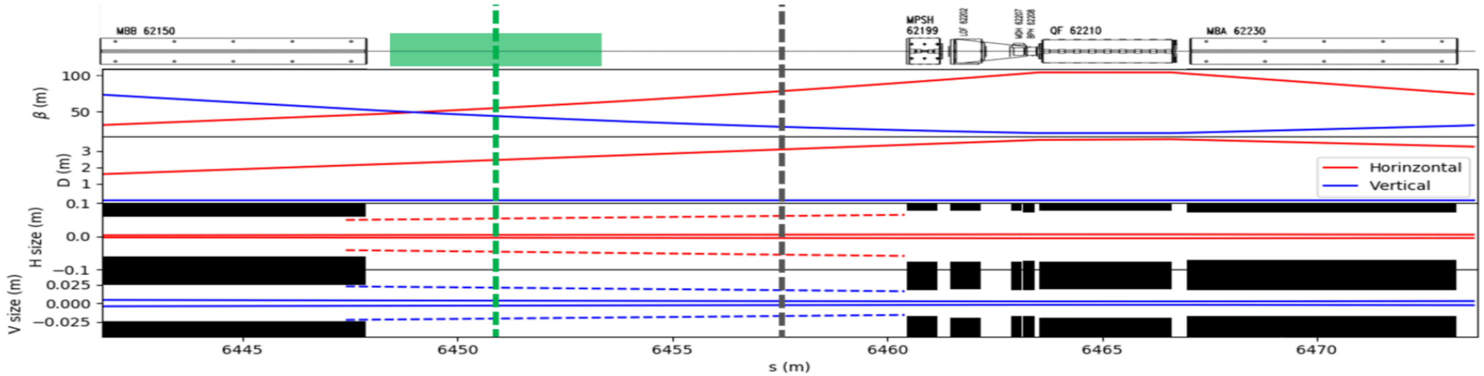
SPS

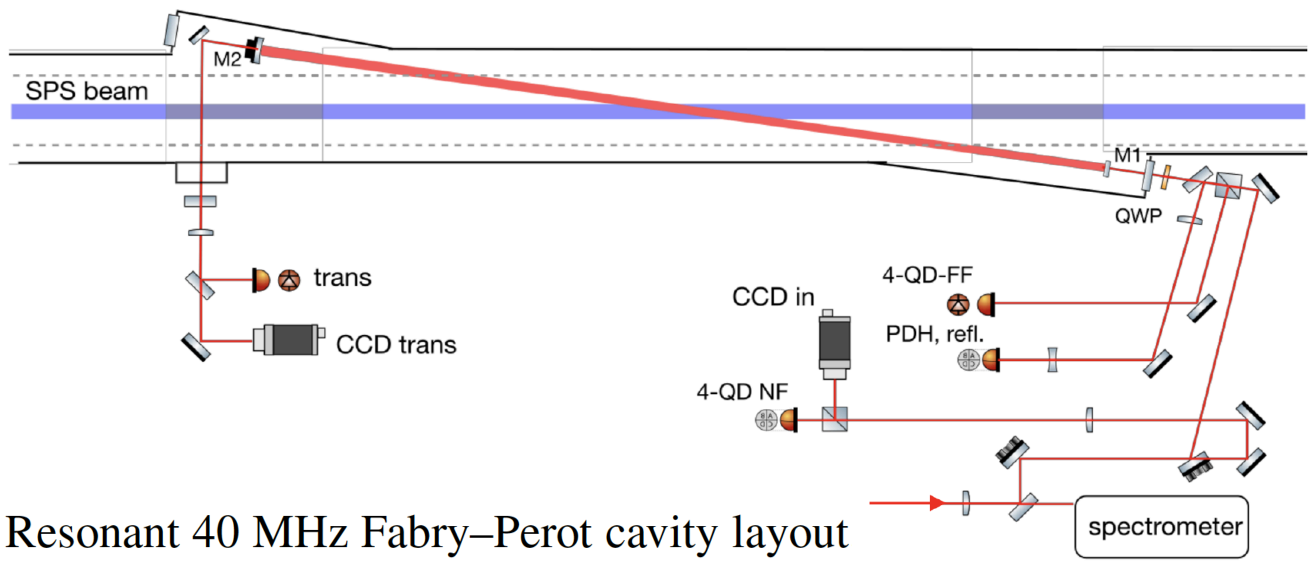
PoP location



PoP experiment: layout

Layout, optical functions and beam sizes with aperture limits around the interaction region.

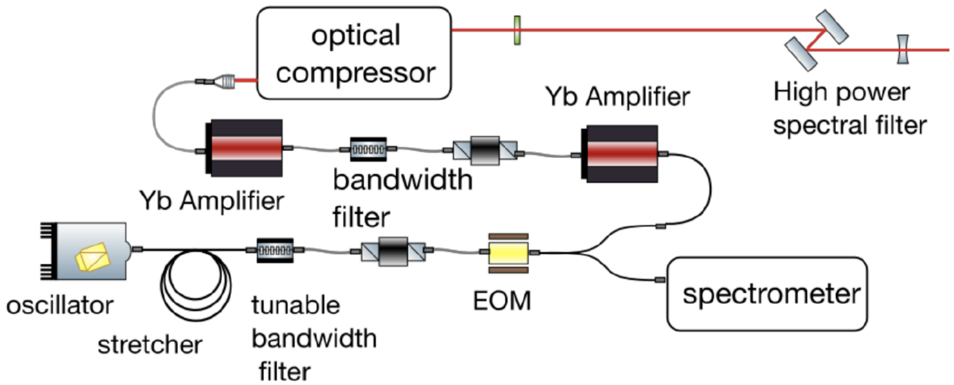




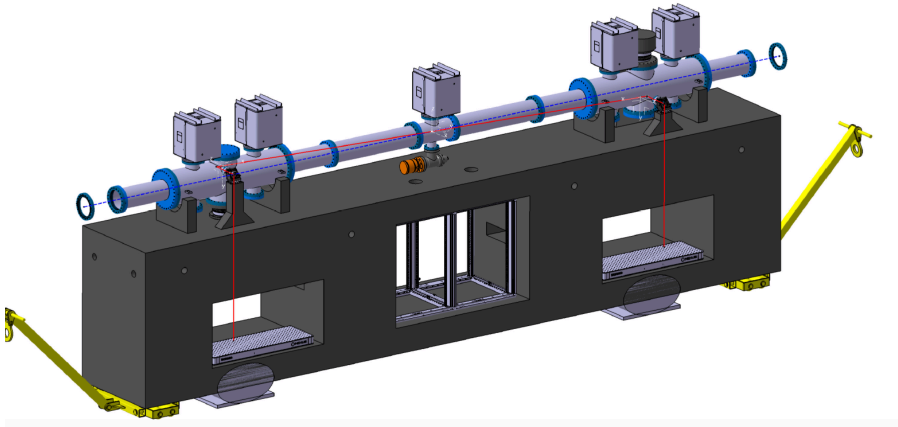
Resonant 40 MHz Fabry–Perot cavity layout

PoP experiment: Laser + Fabry-Perot cavity

Laser system



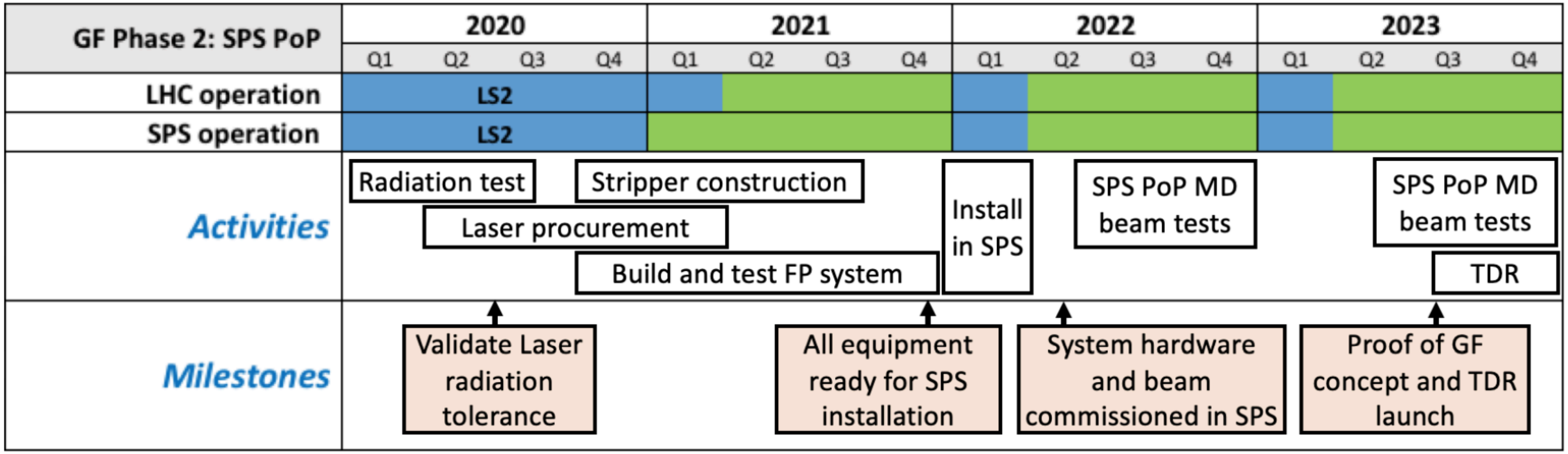
Mechanical frame of the Fabry–Perot cavity



PoP experiment: Laser parameters

Parameter	Unit	FP cavity	Single-pass
Laser repetition frequency	MHz	40	0.0434
Laser output pulse energy	μJ	5000	5000
Average laser power	W	40	> 217
F_{rev} (Pb_{208}^{79+} $\gamma 86$)	Hz	43,373	
Atomic transition energy $2s_{1/2} — 2p_{1/2}$	eV	230.76	
Excited state lifetime (ion frame)	ps	76.57	
Excited state decay length (lab frame)	m	2.19	
Max. emitted photon energy (lab frame)	keV	44	
Laser - PSI beam crossing angle	deg	2.6	
Laser wavelength	nm	1034	
PSI relativistic γ		96.3	
RMS momentum spread in bunch		2×10^{-4}	
Laser pulse energy at IP	mJ	5	

PoP experiment: Timeline of the Phase 2 of the Gamma Factory project



Conclusions

Over the last 2 years the Gamma Factory initial ideas developed into a well defined project involving a group of around ~70 physicists.

Progress has been impressive. The next steps are clear.

The target of the GF initiative is to develop the potential of a variety of novel research tools which could potentially open new opportunities in a broad domain of basic and applied science.

It's an interesting phase for accelerator based HEP research – with no strong theoretical guidance for the mass scale of new physics, nor a mature, affordable technology for a leap into high energy "terra incognita" – high risk, high gain initiatives become important.

This what we should be doing!

Gamma Factory research potential - summary

- ***particle physics*** *(studies of the basic symmetries of the universe, dark matter searches, precision QED studies, rare muon decays, neutrino-factory physics, precision-support measurements for the LHC - DIS physics, muon collider physics)*
- ***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, plasma wake field acceleration, high intensity polarized positron and muon sources, secondary beams of radioactive ions and neutrons, neutrino-factory)*
- ***atomic physics*** *(electronic and muonic atoms), Pauli principle, parity violation, Lamb shift, …*
- ***applied physics*** *(accelerator driven energy sources , cold and warm fusion research, isotope production: e.g alpha-emitters for medical applications, …).*

Photon beams: a concrete LHC scenario

Stripping sequence: Xe+39 → Xe+53 (PS-SPS transfer line)

Beam life time (SPS) ~ 250 s

Beam life time (LHC) ~ 20 h

Transition energy (ion rest frame) ~ 34 KeV (using Z^2 scaling)

τ_excited state = 0.16 fs (using Z^4 scaling)

$\gamma_L(max) = 3040$

$E_L(min) = 5.2$ eV

$\lambda_L(max) = 238$ nm

$E_\gamma(max) = 182$ MeV

N_γ (scaled) ~ N_γ^{PoP} x $[\lambda_L^*(LHC)/\lambda_L^*(PoP)]^2$ x $[\Gamma_{xe}(1s\text{->}2p)/\Gamma_{Pb}(2s\text{->}2p_{1/2})]$ x$[N_{Xe}/N_{Pb}]$ ~ 20 x 4 x N_γ^{PoP}

Gamma flux may be limited by laser power (fifth harmonic) (l_{decay} = 0.14 mm) and double photon absorption.

Laser: e.g. the same as for PoP (5th harmonic.)

8

Example: Gamma ray production spectra for +81 Pb beam collisions with photon bunches at the top LHC energy (two generators being developed)