Tertiary neutrino/antineutrino beams with Gamma Factory

MITP virtual workshop, Mainz, July 2020

Mieczyslaw Witold Krasny, CERN BE-ABP division,
LPNHE, CNRS-IN2P3 and University Paris Sorbonne
representing Gamma Factory study group

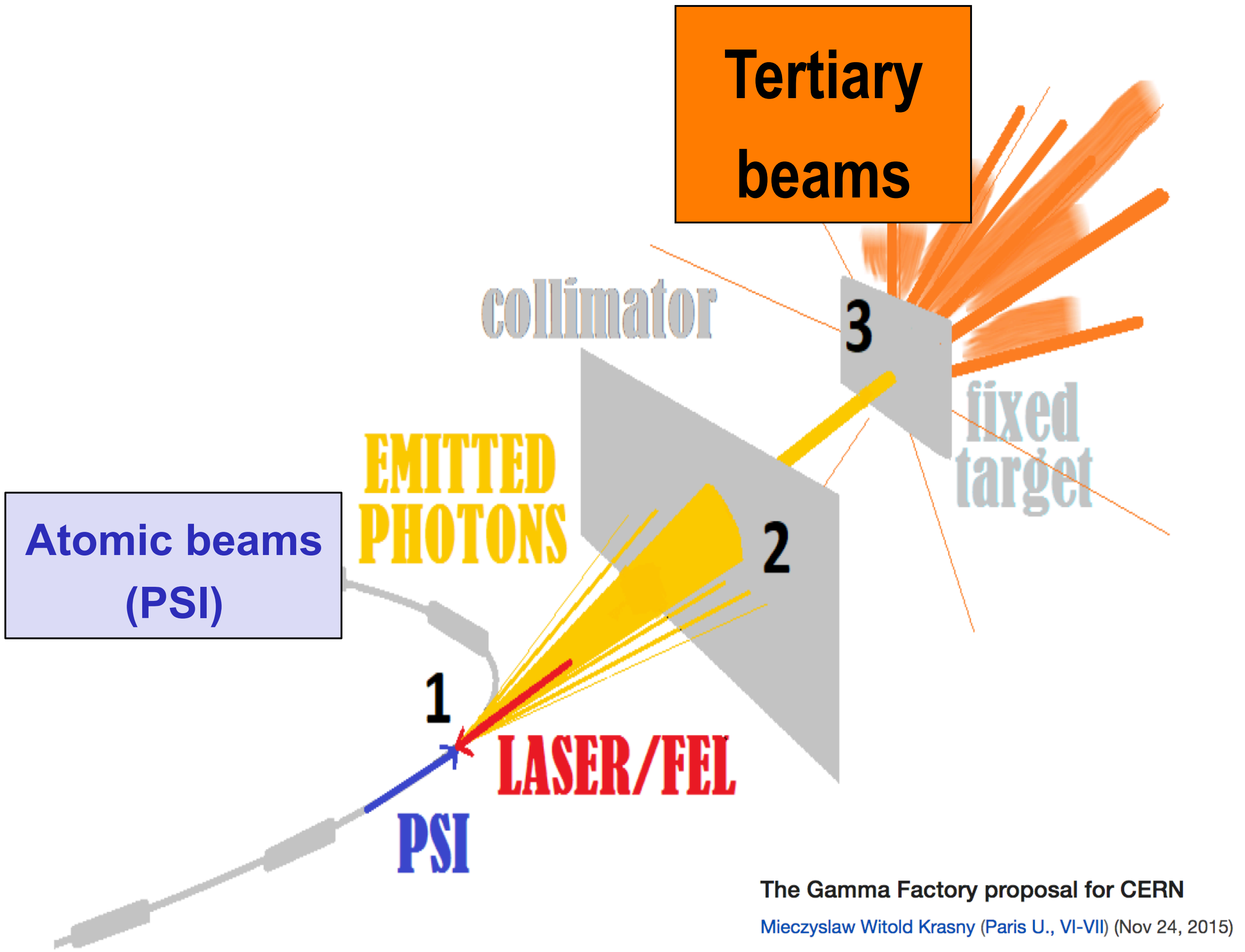
The Gamma Factory in a nutshell

1. *Accelerate and store high energy primary beams of **Partially Stripped Ions (PSI)** and excite their atomic degrees of freedom, by laser photons to form high intensity secondary beams of gamma rays and, in turn, tertiary beams of polarised leptons, neutrinos, vector mesons, neutrons and radioactive ions.*

2. *Provide a new, efficient scheme of transforming the accelerator RF power (selectively) to the above primary and secondary beams trying to achieve a leap, by several orders of magnitude, in their intensity and/or brightness, with respect to the existing facilities.*

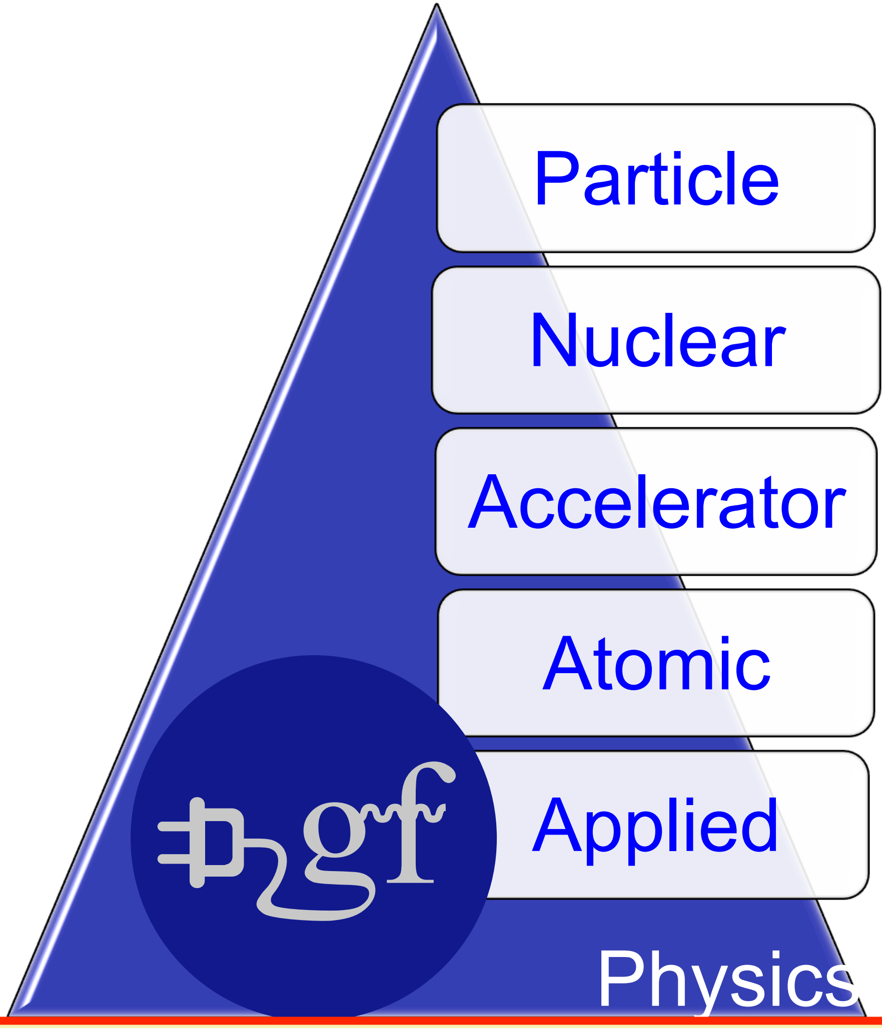
3. *Use the primary and the secondary beams as principal tools of the Gamma Factory research programme.*

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 research potential



basic symmetries, dark mater, EW precision measurements with PSI, n, μ and v beams…

nuclear charge and spin structure, neutron skin, confinement studies, photo-fission…

beam cooling, plasma wake field acc., high-int. polarized e+ & μ sources, v-sources…

physics of highly charged electronic and muonic atoms: strong EM fields, EW effects…

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…

Its context (long term vision)

- *The CERN-LHC-based research program will reach its "discovery potential saturation" (no physics gain by extending the running time) before a next large-scale infrastructure project is approved and constructed at CERN.*

- *In such a case, a strong need will arise for a novel research programme in basic (and applied) science which could re-use its existing, world-unique CERN facilities in ways and at levels that were not necessarily thought of when the machines were designed*

- ***Gamma Factory is an initiative going in this direction.***

- <u>*It requires extensive experimental and simulation studies and R&D to prove its feasibility, and to be considered as a realistic proposal (they have to be completed by the time of the next European Strategy update – in 5 years).*</u>

Its CERN-based framework

The Gamma Factory initiative (arXiv:1511.07794 [hep-ex]) was endorsed by the CERN management by creating (February 2017) the Gamma Factory study group, embedded within the Physics Beyond Colliders studies framework:

Mandate of the "Physics Beyond Colliders" Study Group

CERN Management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex and other scientific infrastructure through projects complementary to the LHC and HL-LHC and to possible future colliders (HE-LHC, CLIC, FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

An extension of the PBC mandate for the next 5 years and a substantial increase in its budget is very likely…

Gamma Factory PBC study group

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80 scientists

33 institutes

13 countries

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

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 25th of September 2019.*

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

symmetry
dimensions of particle physics

topics ▾ follow +

A joint Fermilab/SLAC publication

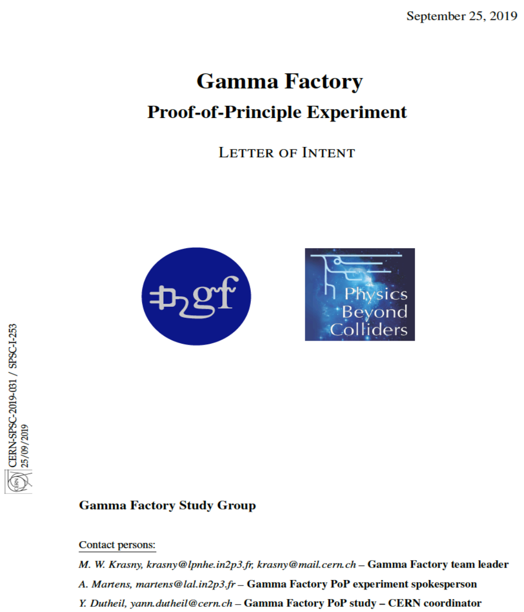
LHC accelerates its first "atoms"

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

Proof of principle of the proposed scheme-- the Gamma Factory PoP experiment at the SPS (…in the approval process)



September 25, 2019

Gamma Factory

Proof-of-Principle Experiment

LETTER OF INTENT

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

Gamma Factory Study Group

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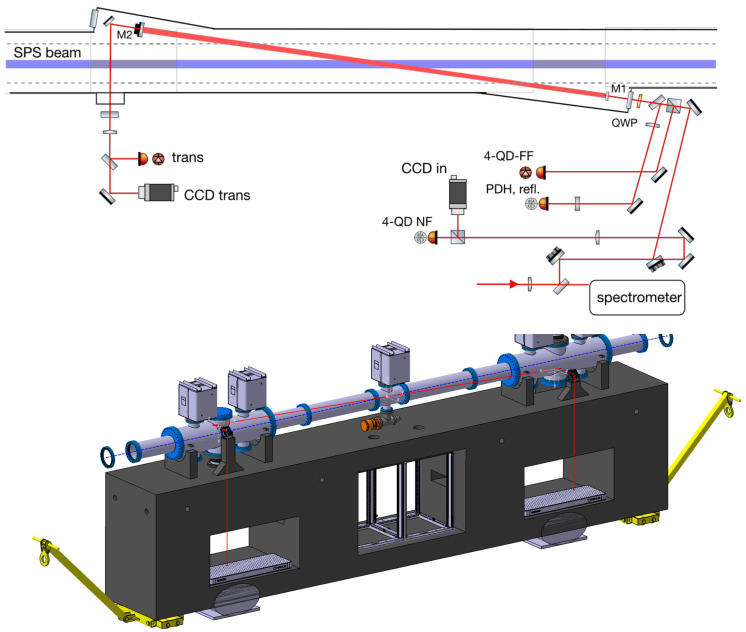
Y. Dutheil, yann.dutheil@cern.ch – **Gamma Factory PoP study – CERN coordinator**



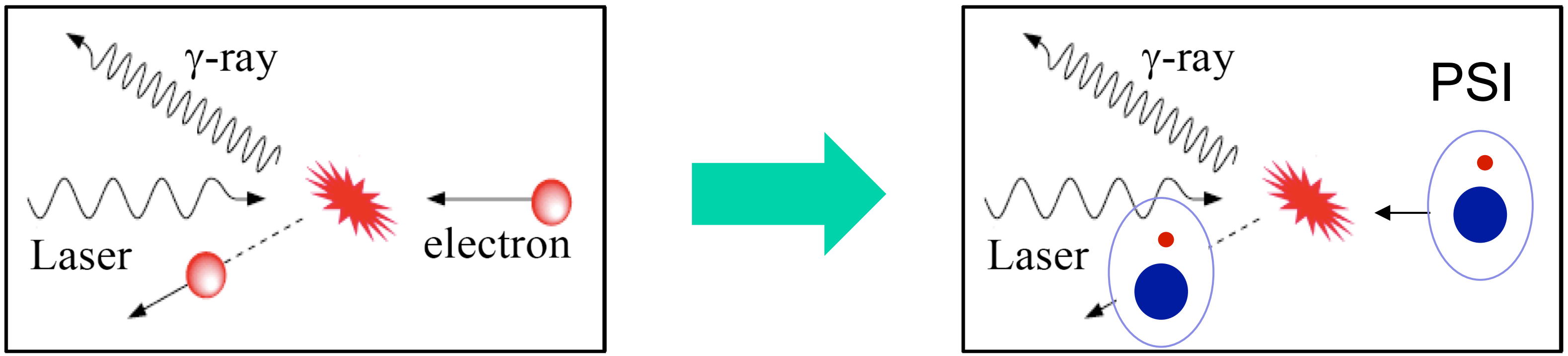
Cost of the experiment (2.4 MSFr). Delay in its consideration and approval process due to Covid virus and the corresponding delay in publishing the European Strategy Update .

The public presentation of the proposal in the open SPSC session in September!

Gamma Source

The gamma ray source for Gamma Factory

The idea: *replace an electron beam by a beam of highly ionised atoms:*
Partially Stripped Ions ***(PSI)***



K.A. ISPIRIAN, A.T. MARGARIAN, N.G. BASOV, A.N. ORAEVSKI, B.N. CHICHKOV. A. BOGACZ E.G. BESSONOV, K-J. KIIM, M.W. KRASNY…

The expected magnitude of the γ-source intensity leap

Electrons:

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

r_e - classical electron radius

Partially Stripped Ions:

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

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

Electrons:

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

Partially Stripped Ions:

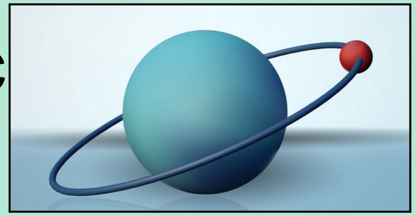
$$\sigma_{res} = 5.9 \times 10^{-16}\ \mathrm{cm}^2$$

Numerical example: $\lambda_{laser} = 1540$ nm

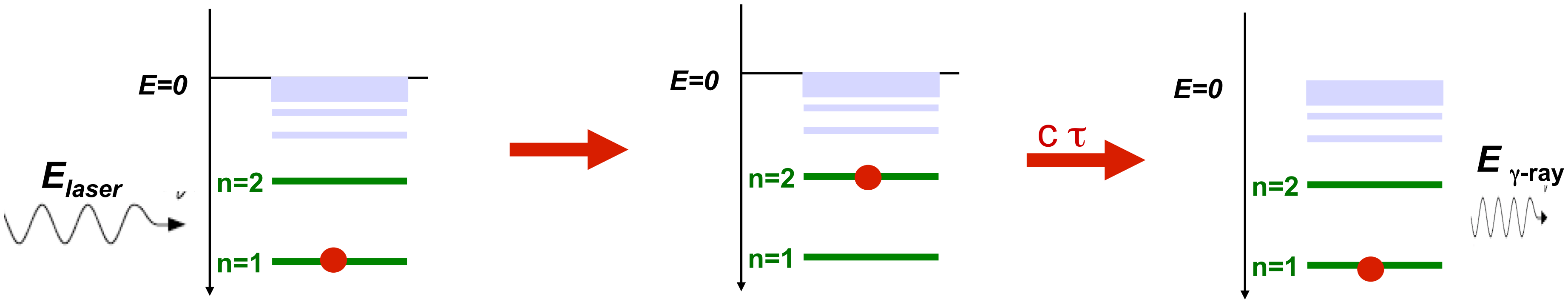
~ 9 orders of magnitude difference in the cross-section

~ 7 orders of magnitude increase of gamma fluxes

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



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



$$E_{laser} = 1Ry\ (Z^2 - Z^2/n^2)/2\gamma_L$$

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

Partially Stripped Ion beam as a light frequency converter

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

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

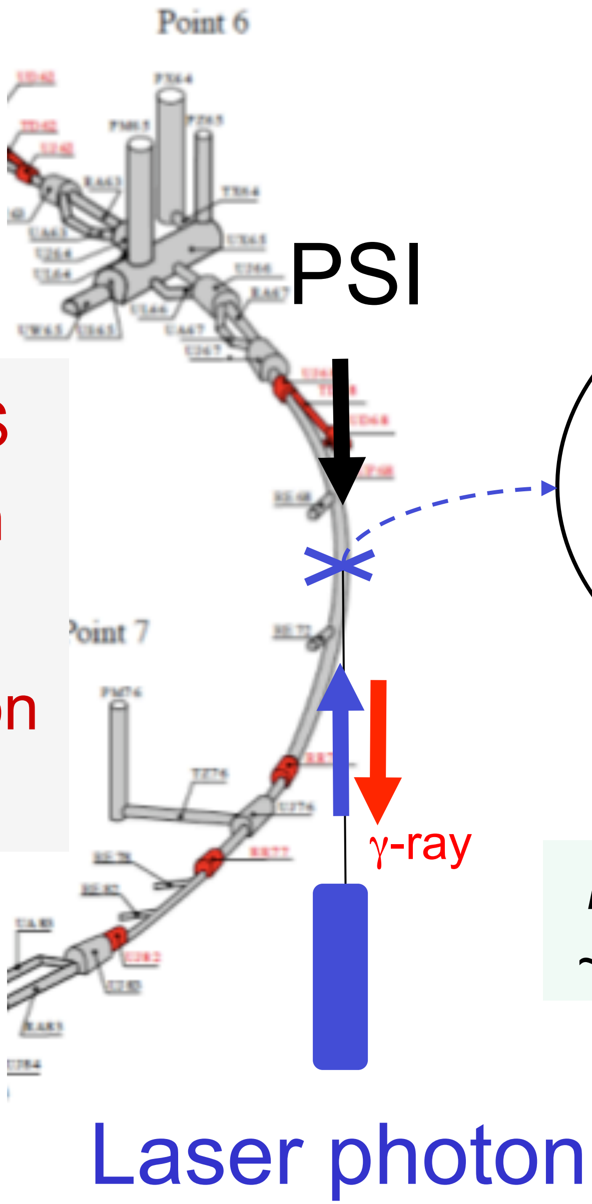
The tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy, at CERN, in the energy domain of 40 keV – 400 MeV.

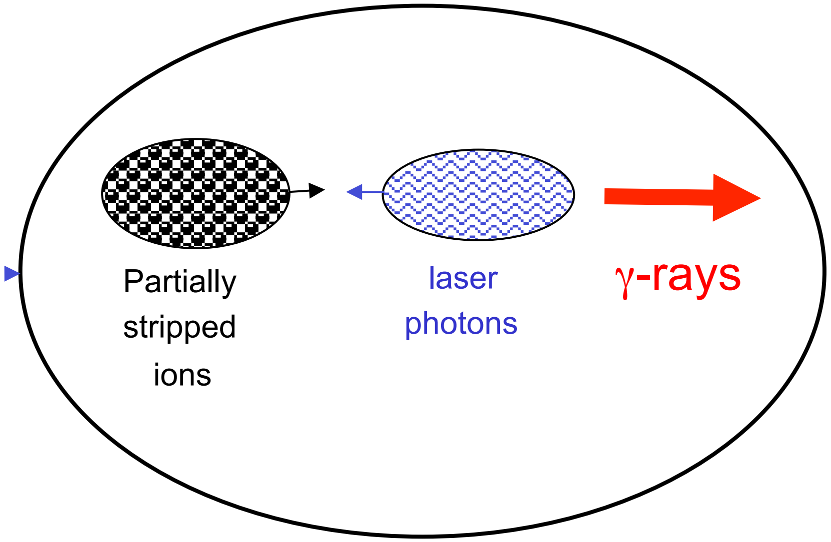
Example (maximal energy):

LHC, Pb^{80+} *ion,* $\gamma_L = 2887$, $n=1 \rightarrow 2$, $\lambda = 104.4$ nm, E_γ (max) = 396 MeV

The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches





Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$
~ 0.04 mm for $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

Principal advantages of the ion-based light sources

Energy tunability:

Four dimensional flexibility of the HIGS ($E_{laser(FEL)}$, γ_L,Z_{ion},n.). Easy to optimize for a required narrow band of the γ-beam energy over a large E_γ 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

---

Note:

For maximal energies (e.g. scenario 1) HIGS must be driven by a <100 nm FEL photons.

For lower energies standard ~300-1500 nm lasers and FP cavities are sufficient

Gamma Factory beams and collision schemes

primary beams:

- **partially stripped ions**
- **electron beam (for LHC)**

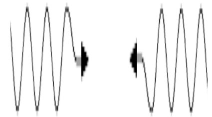
secondary beam:

- **gamma rays**

tertiary beam sources:

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

collider schemes:



$\gamma-\gamma$ collisions,

E_{CM} = 0.1 – 800 MeV

$\gamma-\gamma_L$ collisions,

E_{CM} = 1 – 100 keV

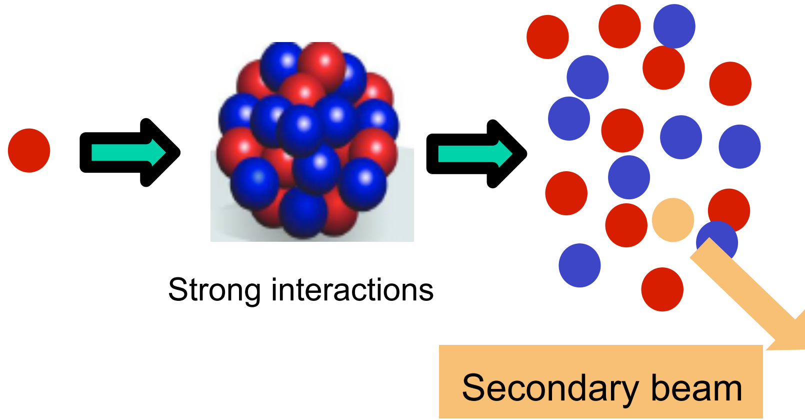
γ–p(A), ep(A) collisions,

E_{CM} = 4 – 200 GeV

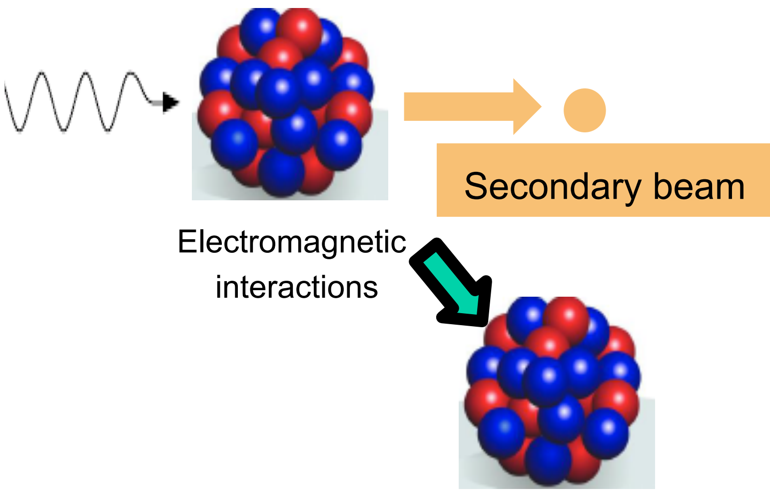
Gamma Factory tertiary beams

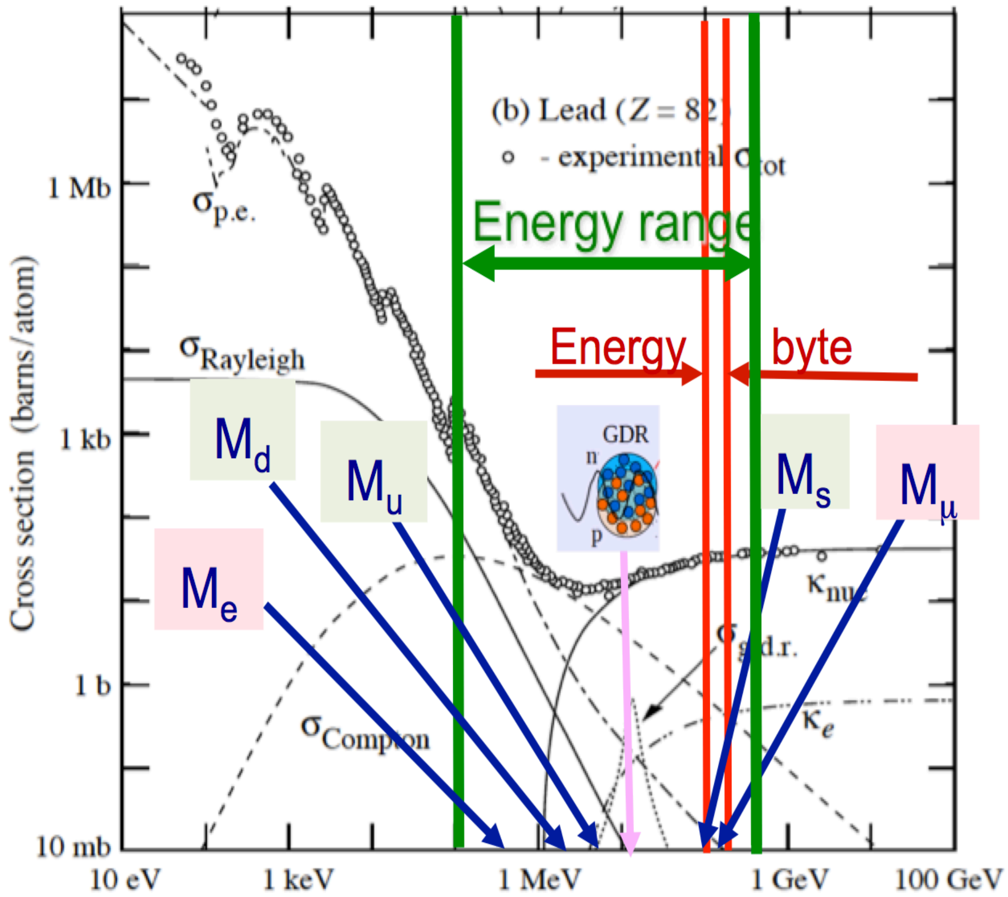
("mining" paradigm and "production-by-demand" paradigm)

"mining" paradigm:



"production" paradigm:

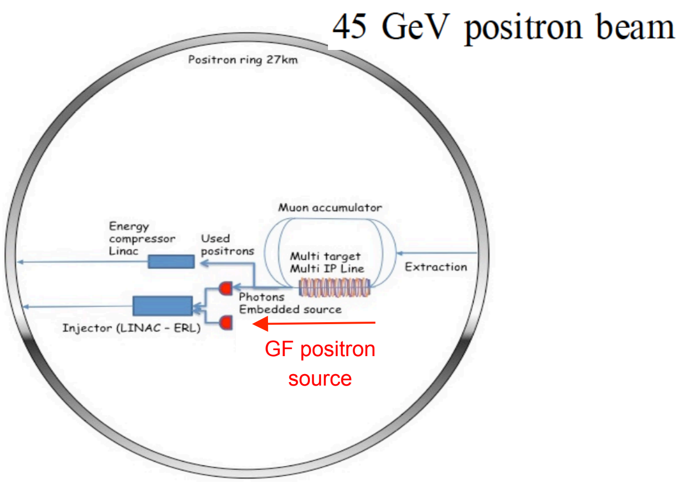




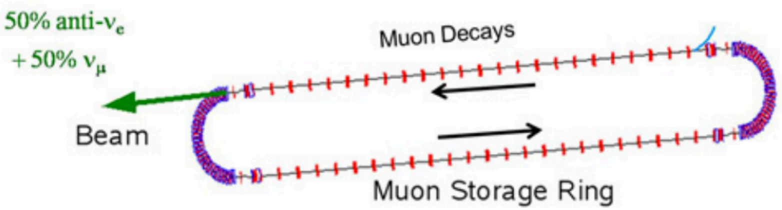
CERN accelerators

Gamma-Factory-based neutrino/antineutrino beams production schemes

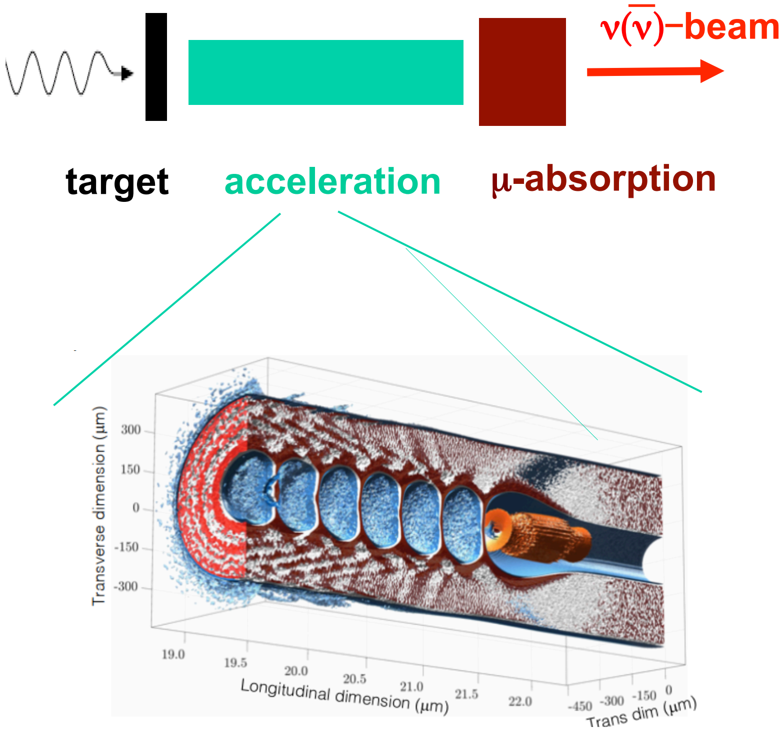
"LEMMA" scheme



Therefore, the efficiency of a 0.3 X_o Beryllium target is $\mathbf{1.3 \times 10^{-6}} \mu/\mathbf{e}^{+}$ $(674 \times 10^{3} \mu / 5 \times 10^{11} e^{+})$.



Direct muon production scheme



Nanostructure Accelerators

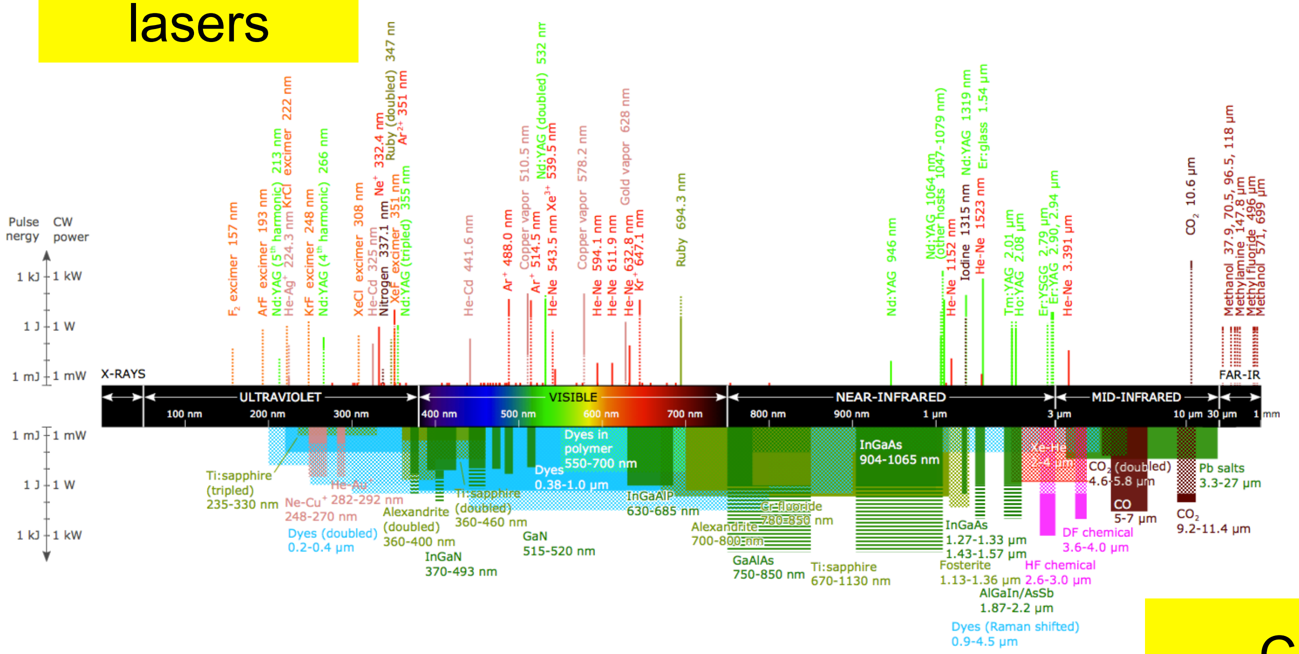
Novel concept and path to its realization

*A. Sahai *, M. Golkowski (Univ. of Colorado Denver), F. Zimmermann (CERN), J. Resta-Lopez (Univ. of Liverpool & Cockcroft Inst.), T. Tajima (UC Irvine), V. Shiltsev (Fermilab)*

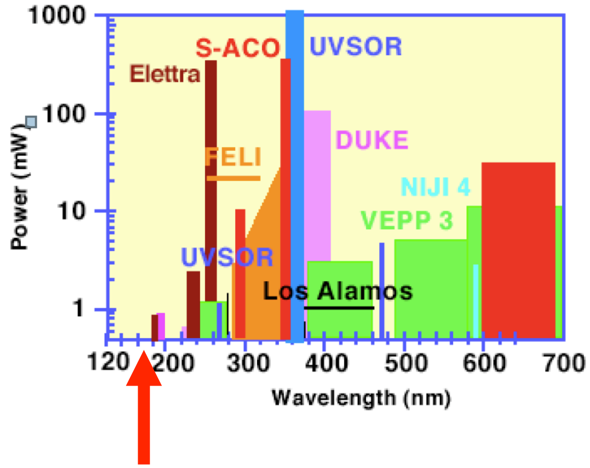
multidimensional GF configuration space:

- ion types available at CERN (sources)
- ion charges
- ion beam energies (CERN accelerators)
- atomic excitation level – transition energy
- atomic excitation level – life time
- stripping scheme
- beam lifetime (SPS)
- beam lifetime (LHC)
- laser parameters (wavelength, power)
- beam cooling time

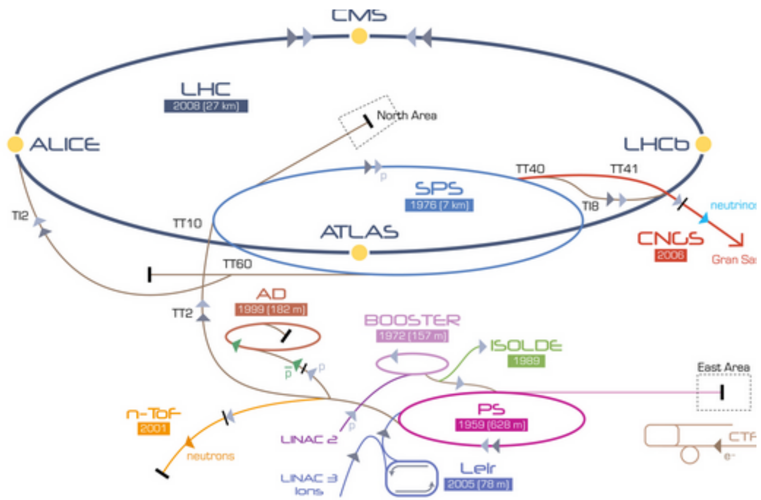
lasers



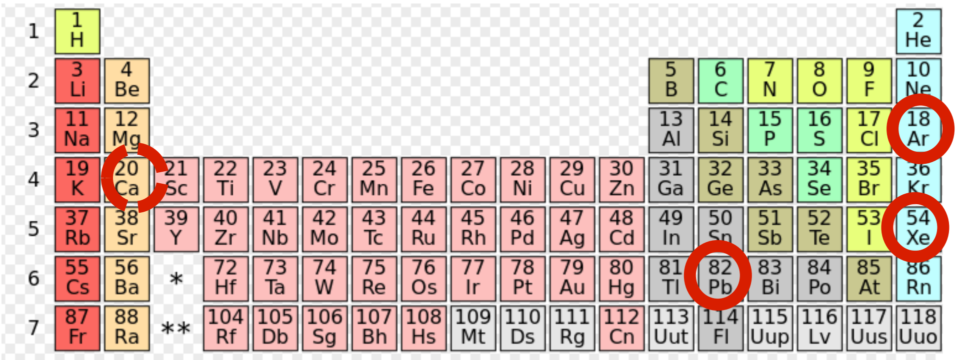
mirrors



CERN accelerators

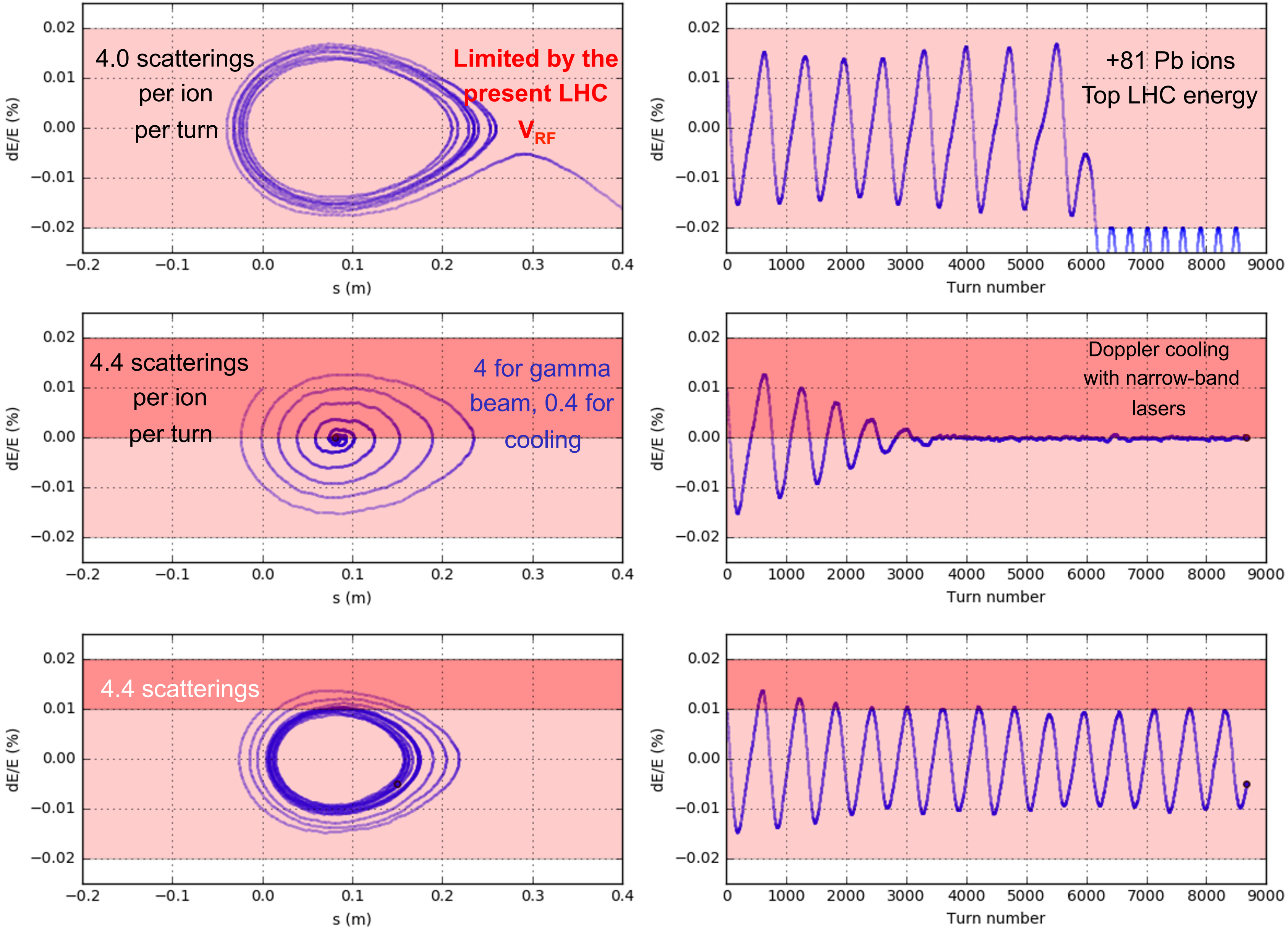


Ions



Ion	O^{6+}	O^{7+}	Ar^{12+}	Ar^{16+}	Ar^{17+}	Ca^{12+}	Ca^{14+}	Xe^{30+}	Bi^{30+}	Bi^{41+}	U^{36+}	U^{40+}
I, eμA	3000	1400	1400	350	50	670	270	320	710	100	150	20

PSI beam stability studies and cooling simulations



http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

Optimisation of the GF-photon beams for positron and muon production

Towards optimal gamma sources to maximise production of polarised positrons and muons

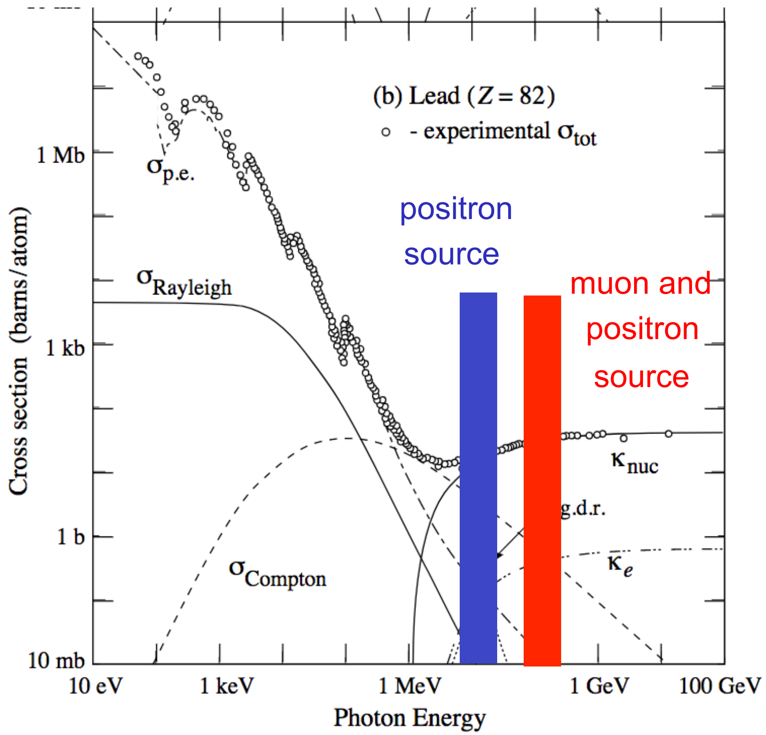


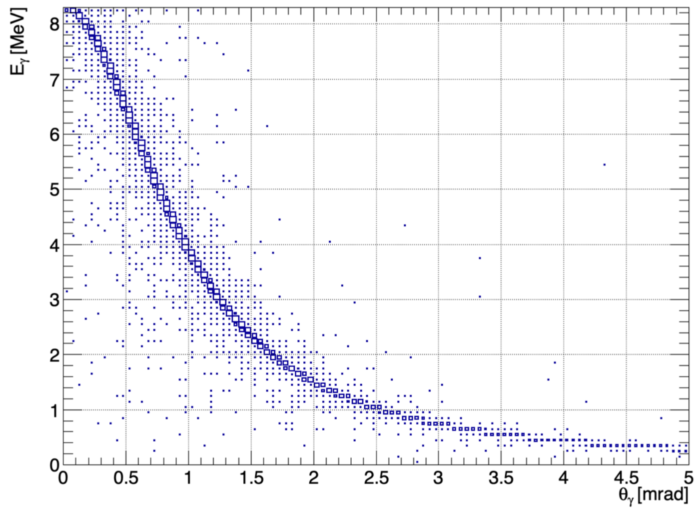
Figure 33.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [51]:

$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

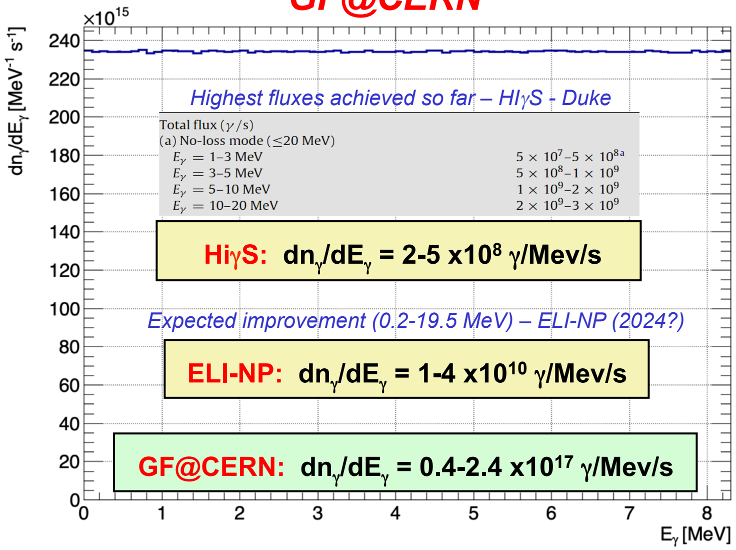
A concrete implementation scenario for the GF positron source

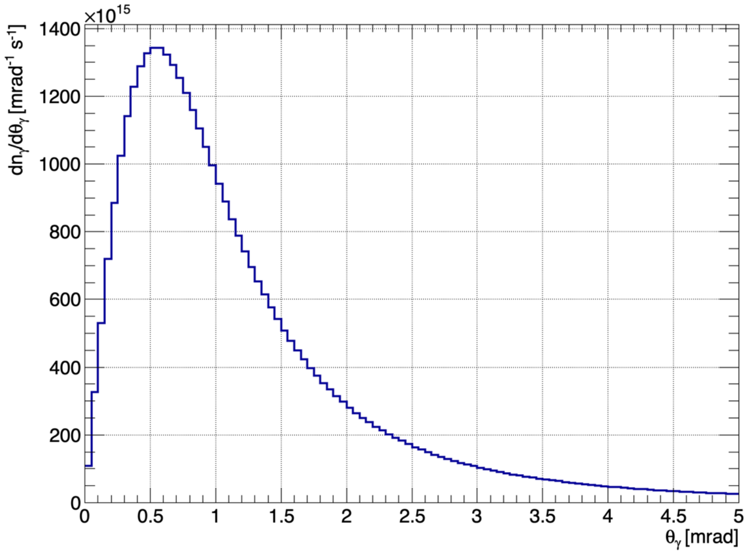
(includes an option of an efficient transmutation of nuclear waste)

```
+++ Laser parameter defined
   Interact with Right going beam only
   Wavelength                               0.67610 micron
   Photon energy                           1.833824 eV
   Peak power density                     1.129D+13 Watt/m**2
   Maximum Xi parameter                     0.00000
   Focus (t,x,y,s)              0.000D+00 0.000D+00 0.000D+00 0.000D+00 meter
   Direction of e1 vector                  1.000000  0.000000  0.000000
   Direction of e2 vector                  0.000000 -1.000000  0.000000
   Propagation direction (e3 vector)       0.000000  0.000000 -1.000000
   Flush energy (num.integ. at z=)        -5.246D-01 0.000D+00 5.246D-01 m
                                          0.000D+00 0.000D+00 0.000D+00 Joule
   Flush energy (analytic)                1.995D-03 Joule
   Stokes parameter                      (  0.00000  0.00000  0.00000)
   Time profile of pulse                 Gaussian
   R.m.s. pulse length                     149.8962 mm
   Longitudinal Gaussian tail cutoff          3.500 sigmas
   Spatial profile of pulse              Gaussian
   Rayleigh length in e1,e2 direction      418.1996  418.1996 mm
   Transverse Gaussian tail cutoff            3.500 sigmas
   Emittance dilution (x,y)                 1.00000   1.00000 TDL
   Rms beam size (x,y) at focus              150.00    150.00 micron
```

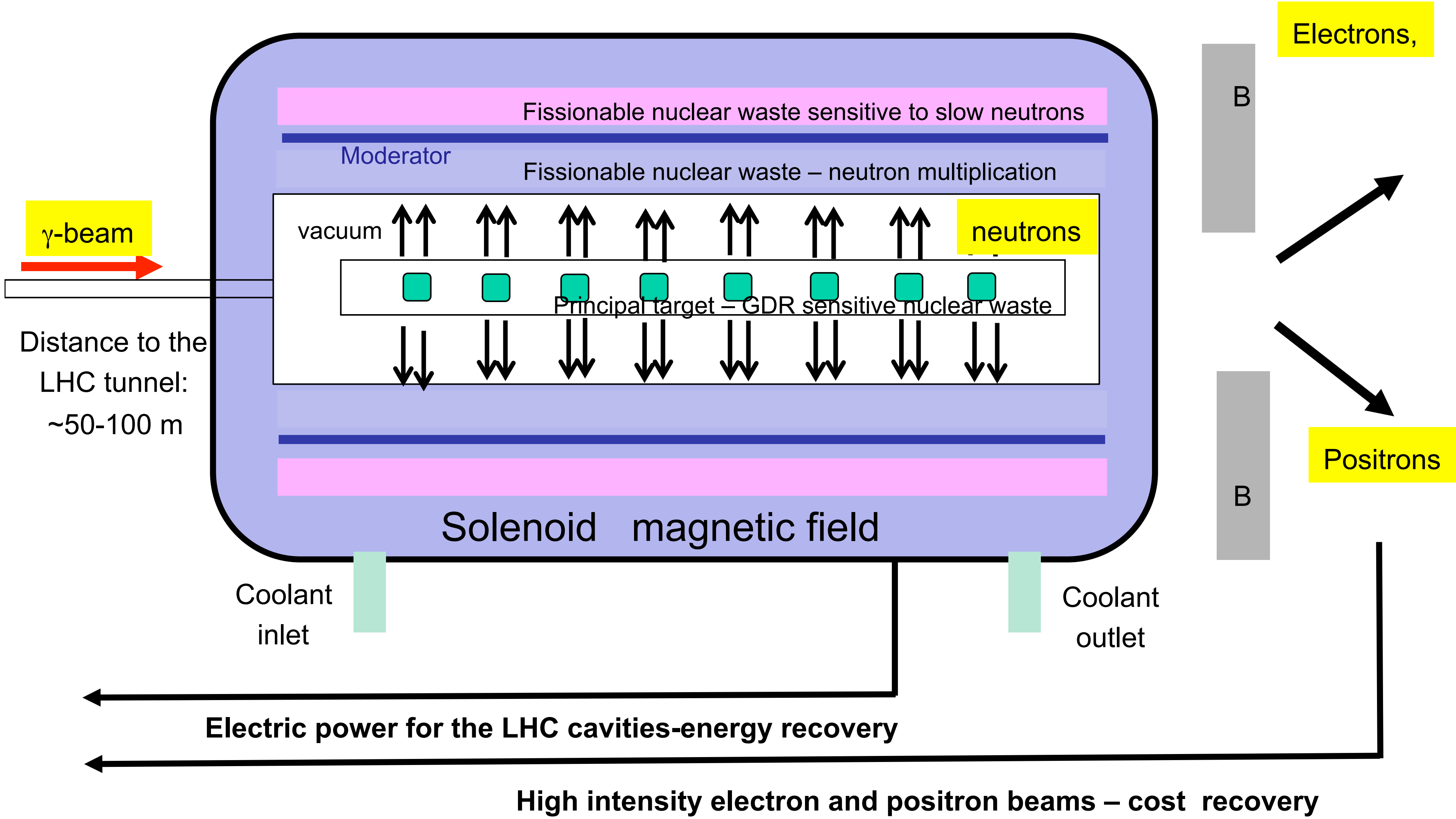


GF@CERN

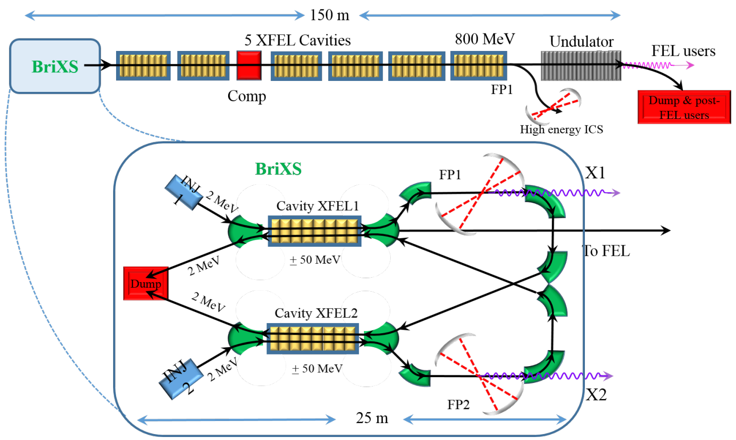


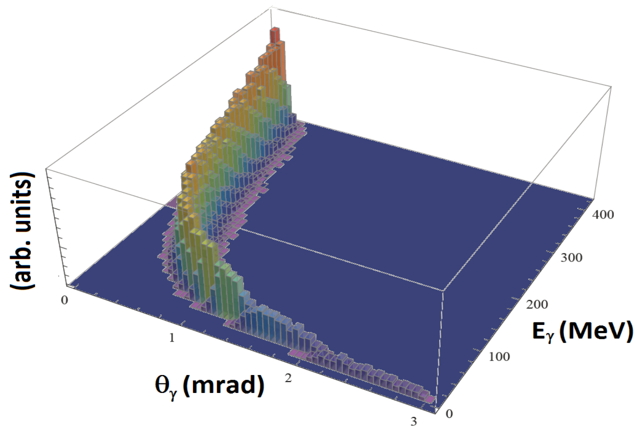


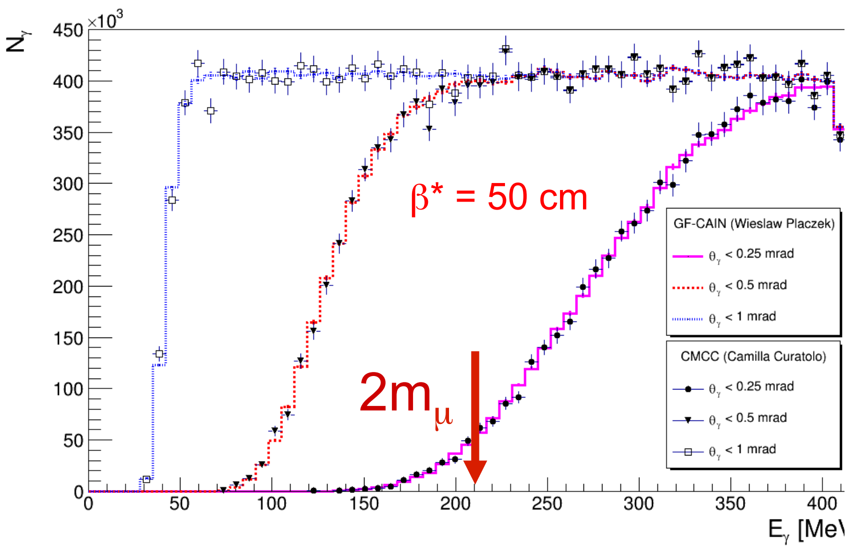
… an initial idea of the tertiary positron beam producing station with sustainable research -- the electric power and cost recovery..

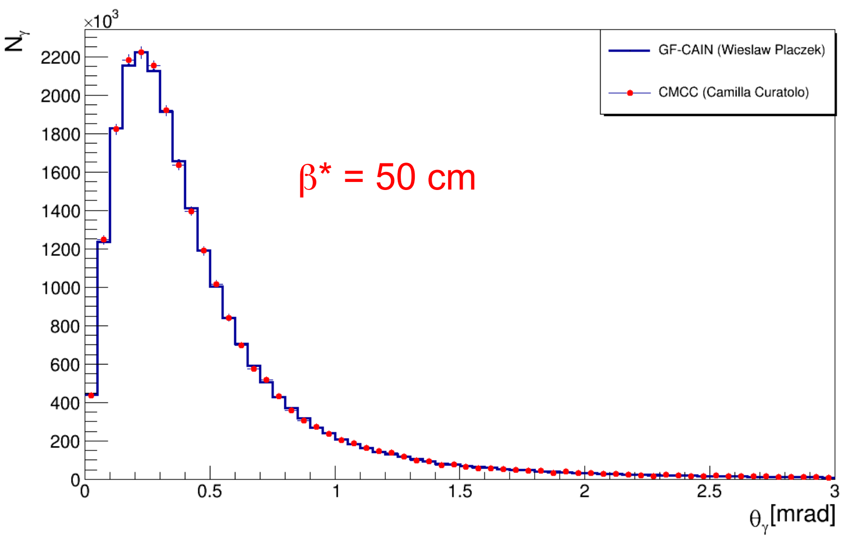


A tentative scenario for the GF moun source based on the MARIX-FEL and Hydrogen-like lead beam









Long term future – the HE-LHC scenario

HE-LHC scenario :

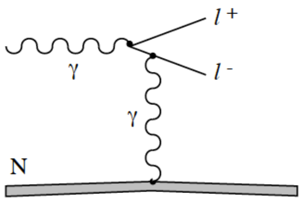
Ar laser: 488 nm, Xe^{53+} *ion*, γ_L=5866, n=1→2, $E_\gamma^{(max)}$ = 350 MeV

$N^{max}_\gamma \sim$ **2 x 10^{17}**[1/s] (already for the present LHC RF system -- 16 MV circumferential voltage, and larger if extra cavities added)

- No longer **FEL and mirror reflectivity constraints** – gamma flux limited only by the circumferential voltage of the LHC and the maximal power which can be absorbed by the photon conversion target
- Note a gain is the Xe source yield w.r.t. to Pb – less collisions per ion, per turn at fixed gamma flux

GF-based positron and muon beams

Gamma Factory based polarised lepton source



Replace the 4.5 X0 Converter by a ~1-2 X0 converter – only primary conversions

Replace Primary Electrons by Polarised Gamma

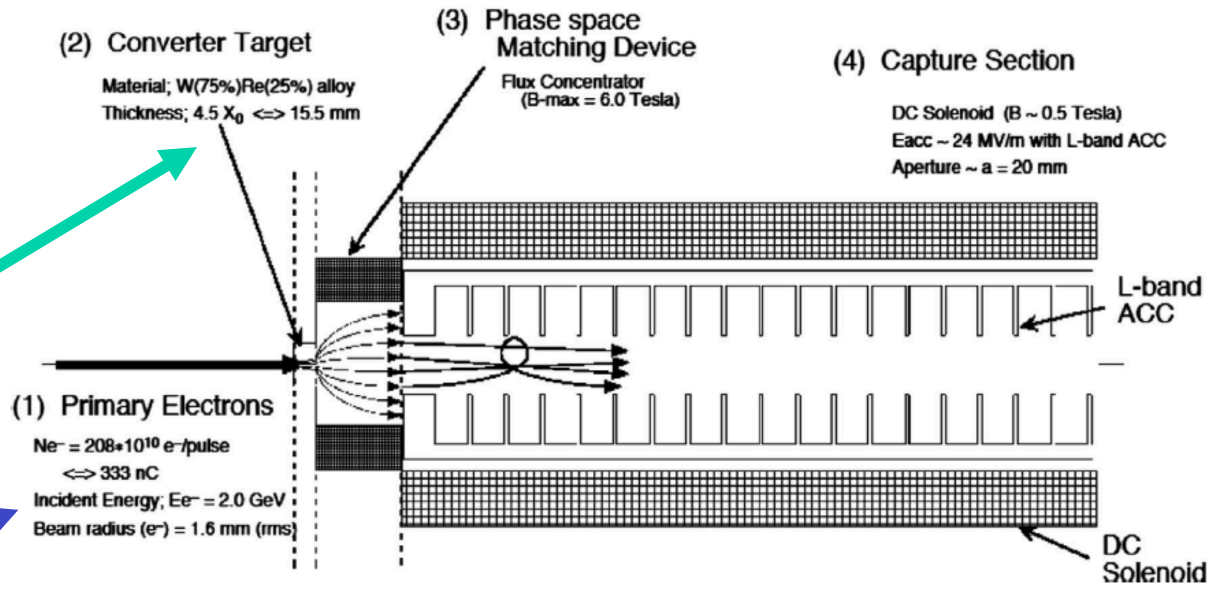


Fig. 2. Layout of the CLIC e+ source with a single target.

Principal gains of a *GF based* polarised lepton 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 (if E_γ above muon production threshold)

Problems which need to be solved:

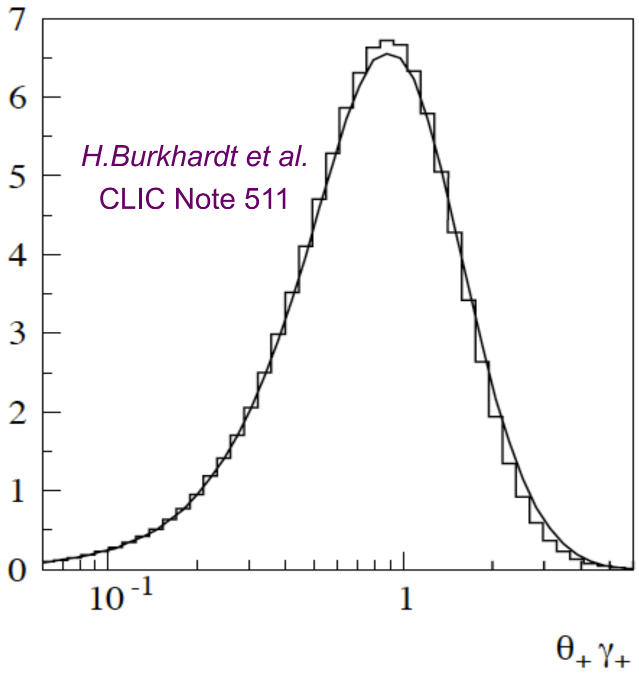
- For e.g. E_γ ~ 300 MeV, muons constitute only a small (<10^{-5}) fraction of all the photon conversion pairs.
  How to filter them out?

- The Gamma converter must be placed at a certain distance from the gamma production point (irreducible emittance growth -- recoil effect)
  How to minimise the emittance growth w.r.t that of the parent ion bunches?

- 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?

Hint1

The conversions, especially on high Z material, lead to a simple relation between the outgoing muon energy and angle:



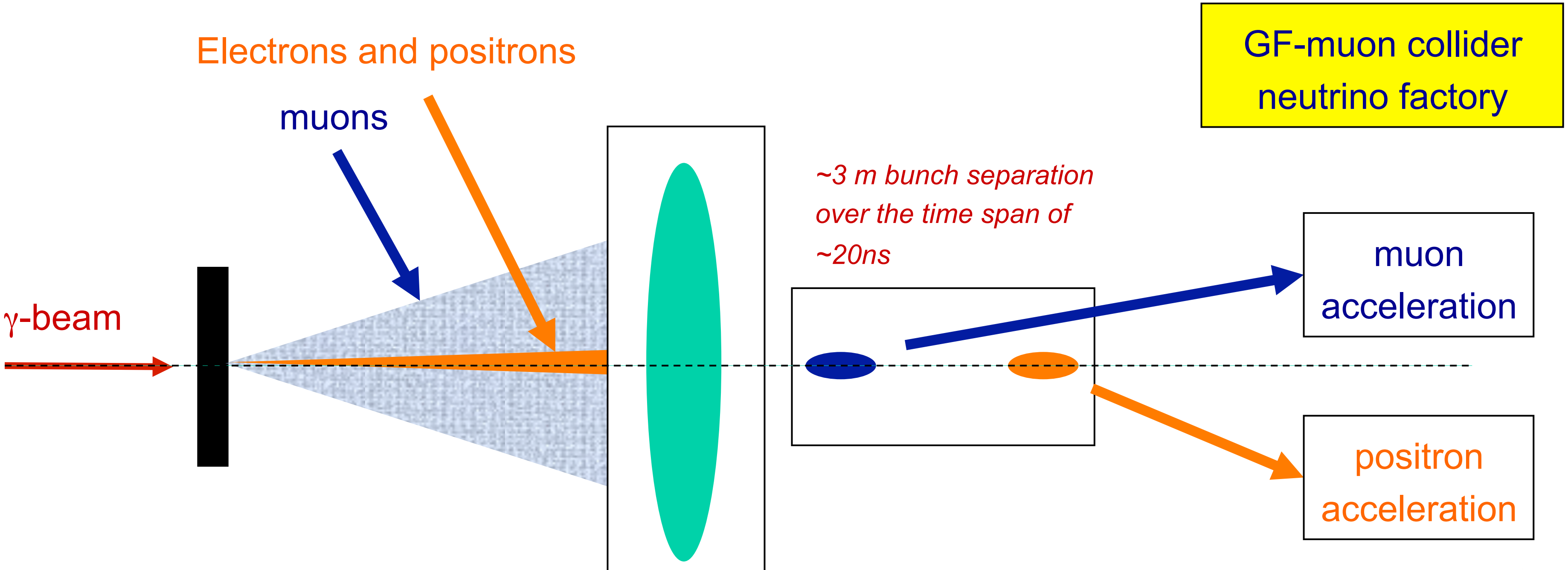
Hint2

Electrons are relativistic, muons are not:

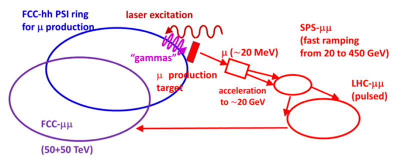
$\beta_e = 1$, $\langle\beta_\mu\rangle \sim 0.5$

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

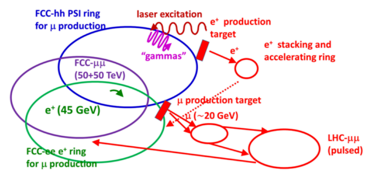
initial ideas…



100 TeV μ collider FCC-μμ with FCC-hh PSI μ± production



100 TeV μ collider FCC-μμ with FCC-hh PSI e+
& FCC-ee μ± production



The way forward

- *Development of the specialized generator for photon conversion into muon pairs close to the production threshold (done)*

- *Realistic design of the gamma production IP, gamma beam extraction, and the gamma conversion target (work on-going)*

- *Realistic design of the muon/electron beam separator and the beam transport including "muon beam emittance corrector" (work on-going)*

- *Design of the of muon beam acceleration and storage scheme (the work has not started yet)*

The principal advantages of the neutrino factory driven by the polarised muons beams

- *The muon beam source of very low initial emittance – no cooling needed. Ready to accelerate to a required energy (e.g. with the Plasma Wake Field technology?)*

- *Muon beam charge can be selected on bunch-by-bunch bases (100 ns) providing easy, bunch timing, separation of neutrino and anti-neutrino beam*

- *Circular polarisation of laser photons is reflected in circular polarisation of gamma-rays (He-like beams), and in the longitudinal polarisation of the muon source (linear acceleration preserves the initial muon polarisation) – "easy" separation of ν_e and ν_μ*

- *The perfect symmetry of the neutrino and anti-neutrino fluxes -- contrary to π/K-decay driven beams -- both controlled at per-mille level (a dream beam property for CP –violation measurements in the neutrino sector?)*

Neutrino Factory parameters

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Perfor-mance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}

***Preliminary GF estimates:* Neutrino fluxes which could be achieved by the GF are comparable to those of NuMAX (for un-polarised muons) and to , nuSTORM for the polarised muon source.**

The role of muon polarisation for the muon-beam driven neutrino factory

In the muon rest frame, the distribution of muon antineutrinos (neutrinos) and electron neutrinos (antineutrinos) in the decay $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ is given by:

$$\frac{d^2N}{dx\,d\Omega} = \frac{1}{4\pi}\left[f_0(x) \mp \mathcal{P}_\mu f_1(x)\cos\theta\right],$$

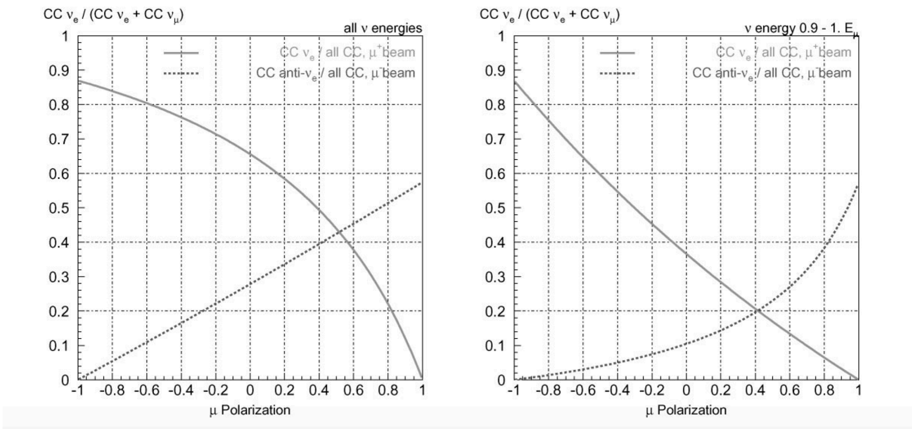
	$f_0(x)$	$f_1(x)$
ν_μ, e	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$

Table 2: Neutrino fluxes from concurrent μ^- with $\mathcal{P}_\mu = +1$ and μ^+ with $\mathcal{P}_\mu = -1$

ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	ν_e
enhanced max. flux at max. momentum	none	enhanced max. flux at max. momentum	none

F.Dydak's GF study

Alain Blondel Nuclear Instruments and Methods in Physics Research A 451 (2000) 131–137



For the measurements for which the figure of merit is "$\mathcal{P}^2$ **x Intensity"**, the Gamma Factory source has a clear advantage over pion/kaon driven sources

Conclusions:

Following the phase of its conceptual development the Gamma Factory project entered already the initial phase of its experimental tests (SPS and LHC beam studies, PoP experiment).

The goal of these tests is to provide realistic estimates of the gamma fluxes (and the corresponding intensity of the GF tertiary beams), which can be achieved using the present CERN accelerator complex (…and to define the necessary upgrades - to achieve even higher fluxes).

The Gamma Factory potential in producing low emittance beams of polarised leptons: (muons and electrons) can play an important role in development of the muon collider project and for the future neutrino factory concepts.

The studies of the achievable fluxes are on-going – stay tuned