Physics Beyond Colliders Kickoff Workshop

6-7 September 2016
CERN
Europe/Zurich timezone

Mandate of the "Physics Beyond Colliders" Study Group

Scientific goal

The main goal of the Study Group is to explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world. These experiments would typically: *(i)* enrich and diversify the CERN scientific program, *(ii)* exploit the unique opportunities offered by CERN's accelerator complex and scientific infrastructure, *(iii)* complement the laboratory's collider programme (LHC, HL-LHC and possible future colliders). Examples of physics objectives include searches for rare processes and very-weakly interacting particles, measurements of electric dipole moments, etc.

350 participants,

64 abstracts submited, 15 retained for oral presentation

https://indico.cern.ch/event/523655/overview

The Gamma Factory Initiative

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...for the executive summary see: https://indico.cern.ch/event/523655/overview

e-Print: arXiv:1511.07794 ***[hep-ex]***

Three paths of progress in experimental science

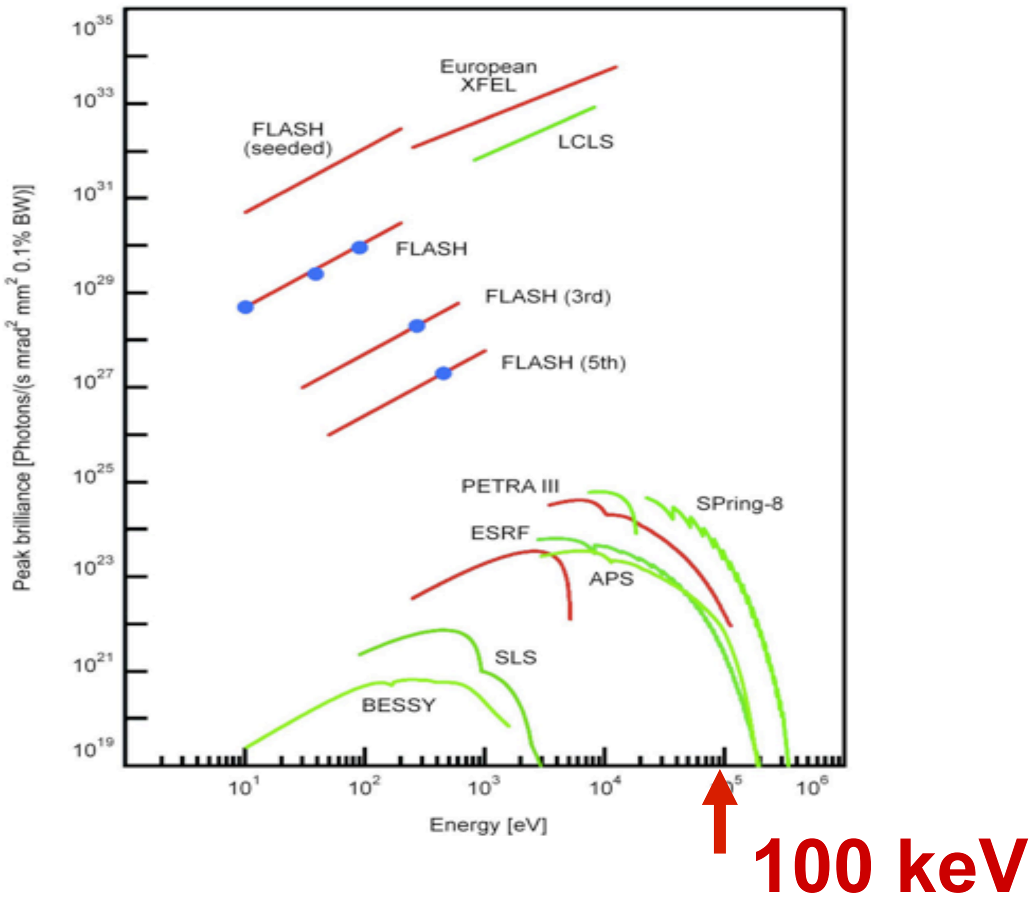
1. Increasing precision of canonical measurements to test established theories and models (e.g. ~40 years of investigation of the SM).

2. Theoretical ideas (40 years of the "Supersymmetry Discovery Guide").

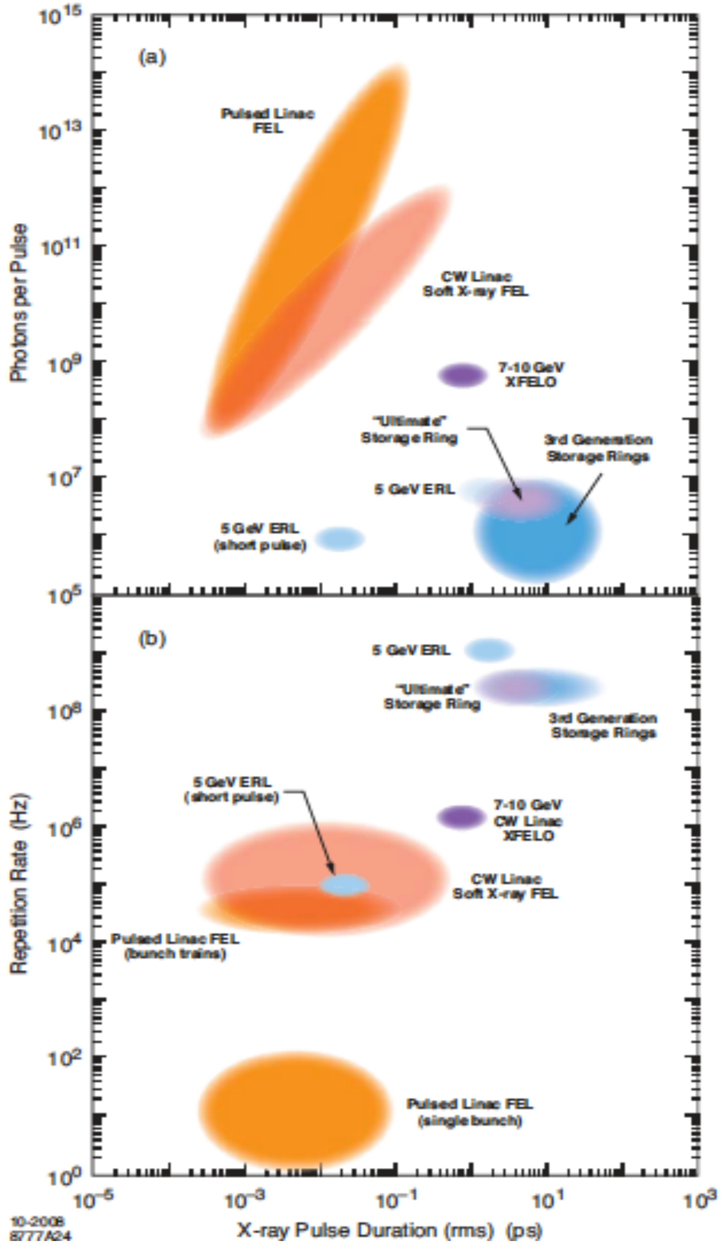
3. A technological jump, opening multiple research tools of new type … or increasing the precision of the existing ones by several orders of magnitude (of particular interest if achieved with relatively modest investments – measured in MCHF rather than GCHF units).

(an attempt going in this direction is presented in this talk) →

X-ray factories

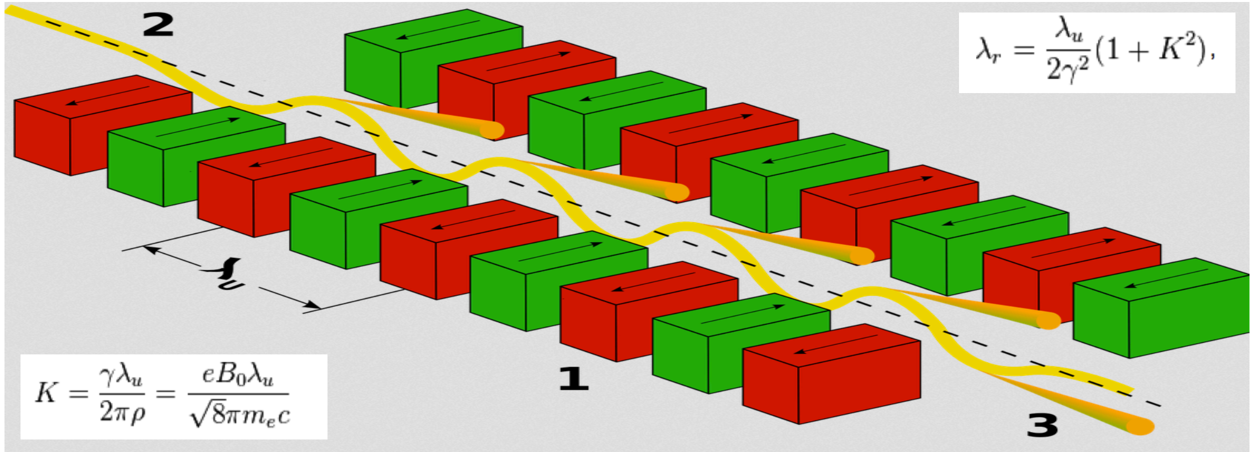


Energies up to ~ 100 keV



Intensities up to ~ **10^{16} ph/s**

Could this technology be extended from the X-ray to γ-ray domain (100 keV – 400 MeV)?



No, unless low emittance electron beams in TEV energy range of are available – not realistic in the foreseeable future…

At present, only ***the Laser-Electron beam scattering sources of γ-rays.***

Parameters of the present Electron Beam driven γ-ray sources

Project name	LADON[a]	LEGS	ROKK-1M[b]	GRAAL	LEPS	HIγS[c]
Location	Frascati Italy	Brookhaven US	Novosibirsk Russia	Grenoble France	Harima Japan	Durham US
Storage ring	Adone	NSLS	VEPP-4M	ESRF	SPring-8	Duke-SR
Electron energy (GeV)	1.5	2.5–2.8	1.4–6.0	6	8	0.24–1.2
Laser energy (eV)	2.45	2.41–4.68	1.17–4.68	2.41–3.53	2.41–4.68	1.17–6.53
γ-beam energy (MeV)	5–80	110–450	100–1600	550–1500	1500–2400	1–100 (158)[d]
Energy selection	Internal tagging	External tagging	(Int or Ext?) tagging	Internal tagging	Internal tagging	Collimation
γ-energy resolution (FWHM)						
ΔE (MeV)	2–4	5	10–20	16	30	0.008–8.5
$\frac{\Delta E}{E}$ (%)	5	1.1	1–3	1.1	1.25	0.8–10
E-beam current (A)	0.1	0.2	0.1	0.2	0.1–0.2	0.01–0.1
Max on-target flux (γ/s)	5×10^5	5×10^6	10^6	3×10^6	5×10^6	10^4–5×10^8
Max total flux (γ/s)						10^6–3×10^9[e]
Years of operation	1978–1993	1987–2006	1993–	1995–	1998–	1996–

Achieved so far γ-ray fluxes ~ 10^5 – 10^9 γ/s *(ELI in constr. phase)*

Could the energy range and the intensity of the γ-ray source be increased by an unconventional use of the already existing accelerators?

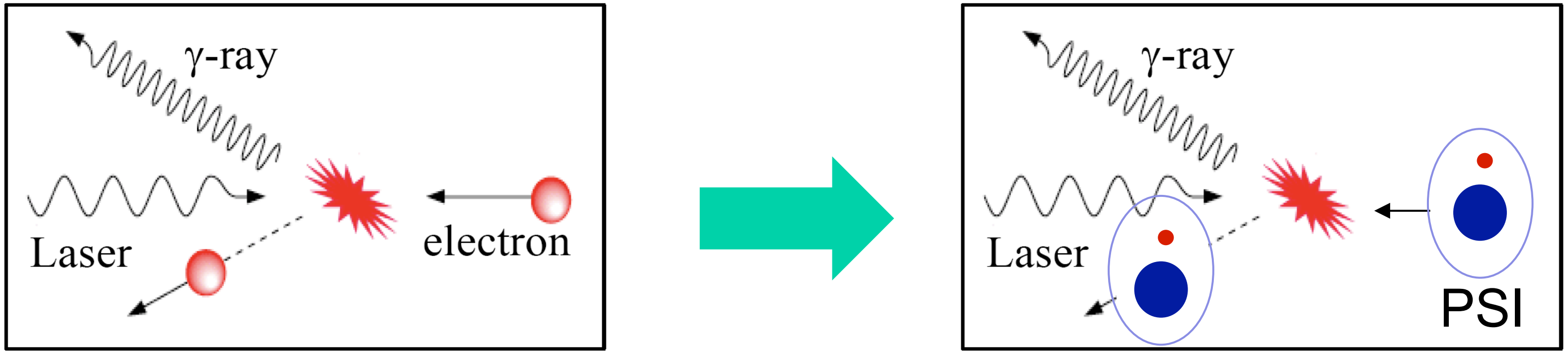
CERN as a unique place in the world to host a project, which is capable to increase the intensity of the present γ-ray sources of up to 7 orders of magnitude in the 3 orders of magnitude wide range of the γ-ray energies.

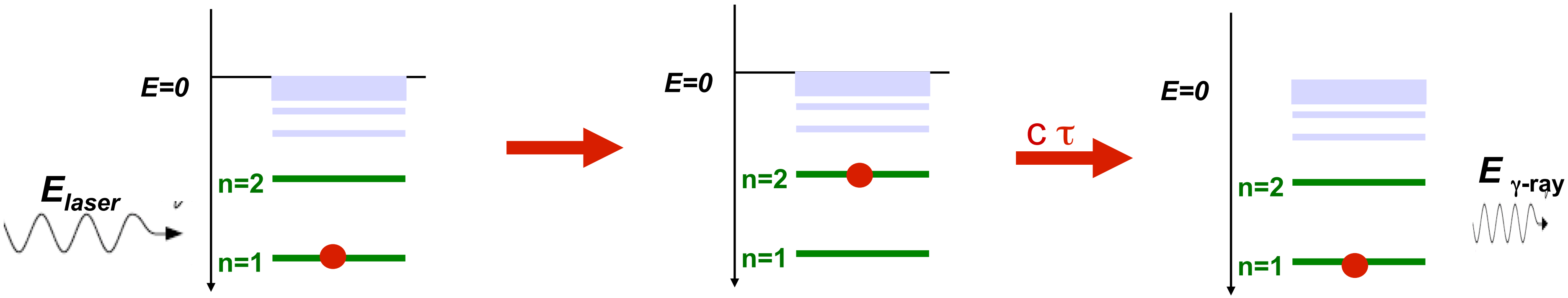
New research opportunities in many domains of particle, nuclear and atomic physics could be opened at CERN.

The rest of this talk:

How this could be done …and what purpose?

Simple Idea: replace an Electron beam by a Partially Stripped Ion (PSI) beam





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

Note: $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

Partially Stripped Ion (PSI) beams as the light frequency converters:

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

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

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

Fine tuning of gamma ray energy: E_{γ}

The energy of the gamma beam can be tuned by selecting the ion (Z), its storage energy (γ_L-factor), the atomic level (n), and the laser light wavelength (E_{laser})

Scenario 1 (muon production threshold) :

FEL: 104.4 nm, Pb^{80+} *ion,* γ_L=2887, n=1→2,

E_{γ} (max) = 396 MeV

Scenario 2 (nuclear physics application):

Erbium doped glass laser: 1540 nm, Ar^{16+} *ion,* γ_L=2068, n=1→2, E_{γ} (max) = 13.8 MeV

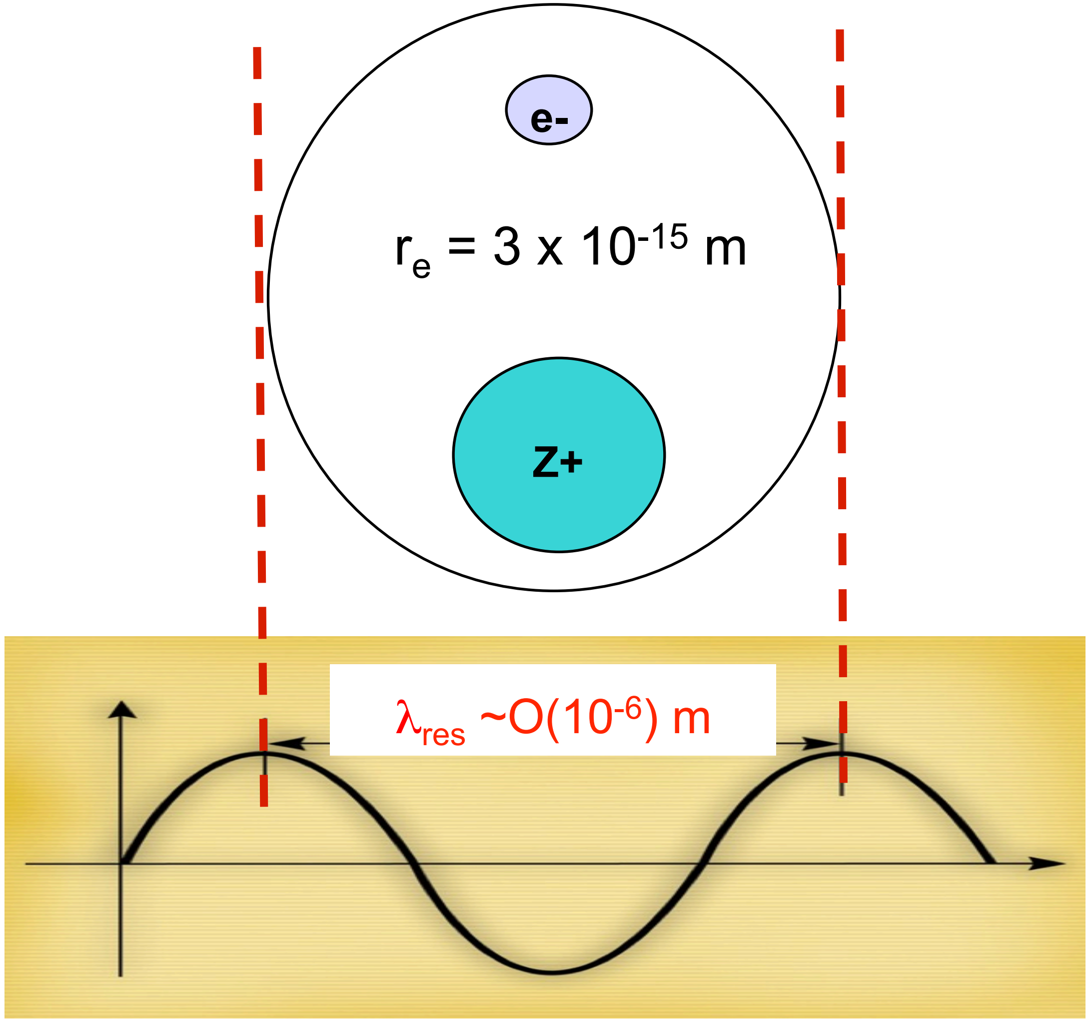
Scenario 3 (SPS initial feasibility studies) :

Krypton laser: 647 nm, Xe^{47+} *ion,* γ_L=162 (SPS), $^4S_{3/2} \rightarrow {}^4P_{3/2}$

E_{γ} (max) = 0.196 MeV

The origin of the γ-beam intensity jump

(matching the size of the target to the laser wavelength)



The origin of the γ-beam intensity jump:

Electrons:

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

r_e - the classical electron radius

Partially Stripped Ions:

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

λ_{res} - photon wavelength for the resonant atom excitation

Numerical example: λ_{laser} = 1540 nm – 9 orders of magnitude difference

Electrons:

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

Partially Stripped Ions:

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

For the LHC/SPS -based partially stripped ion based gamma source the intensity limits are driven predominantly by the acceleration and storage aspects of the PSI beams, rather than by the laser power and the collision geometry (the existing gamma/X sources require more advanced laser beam technologies with respect to e.g. the ELI and HIγs projects).

Initial estimates of the achievable γ-fluxes for the two LHC scenarios

Scenario 1 :

FEL: 104.4 nm, Pb^{80+} *ion*, γ_L=2887, n=1→2, $E_\gamma^{(max)}$ = 396 MeV, N^{max}_γ **~ 6 x 10^{15}**[1/s] for the present LHC RF system

Scenario 2:

Erbium doped glass fiber laser: 1540 nm, Ar^{16+} *ion*, γ_L=2068, n=1→2, $E_\gamma^{(max)}$ = 13.8 MeV, **N^{max}_γ ~ 3 x 10^{17}** [1/s]

Comments:

1. N^{γ}_{max} [1/s] = N^{ion}_{bunch} x $N_{bunches}$ x f [1/s] x RF [MV] x Z[e] / <E_γ [MeV]>.

2. The effect of the double photon absorption process, in particular for scenario 2 becomes important -- this effect could be circumvented by using a pulsed laser beam, long interaction region, or a special mirror system

Principal difference of the Electron and PSI beam driven gamma sources: beam rigidity

Example: scenario 1, γ_L = 2887

Electrons:

E_beam = 1.5 GeV

Electron fractional energy loss:
emission of 150 MeV photon:
$E_\gamma/E_{beam} = 0.1$
(electron is "lost")

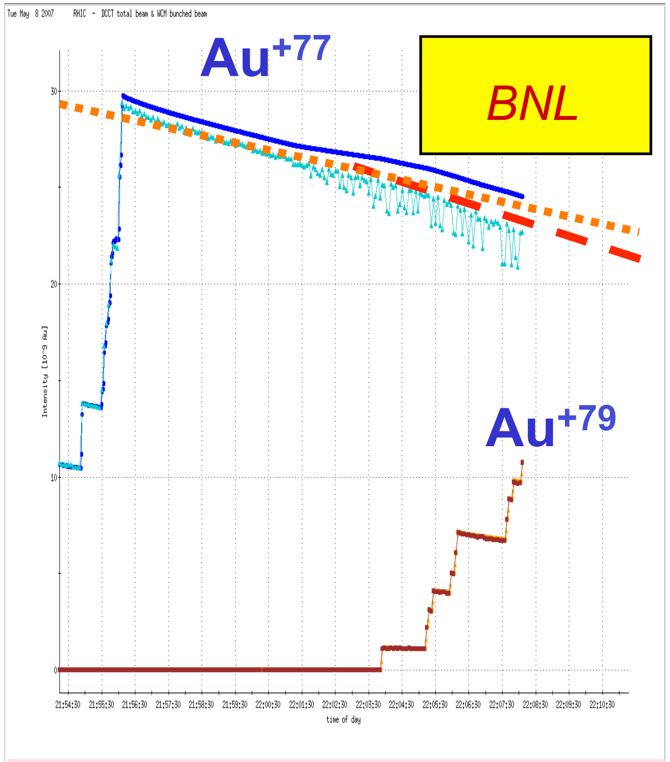
Partially stripped ions:

E_beam = 574 000 GeV

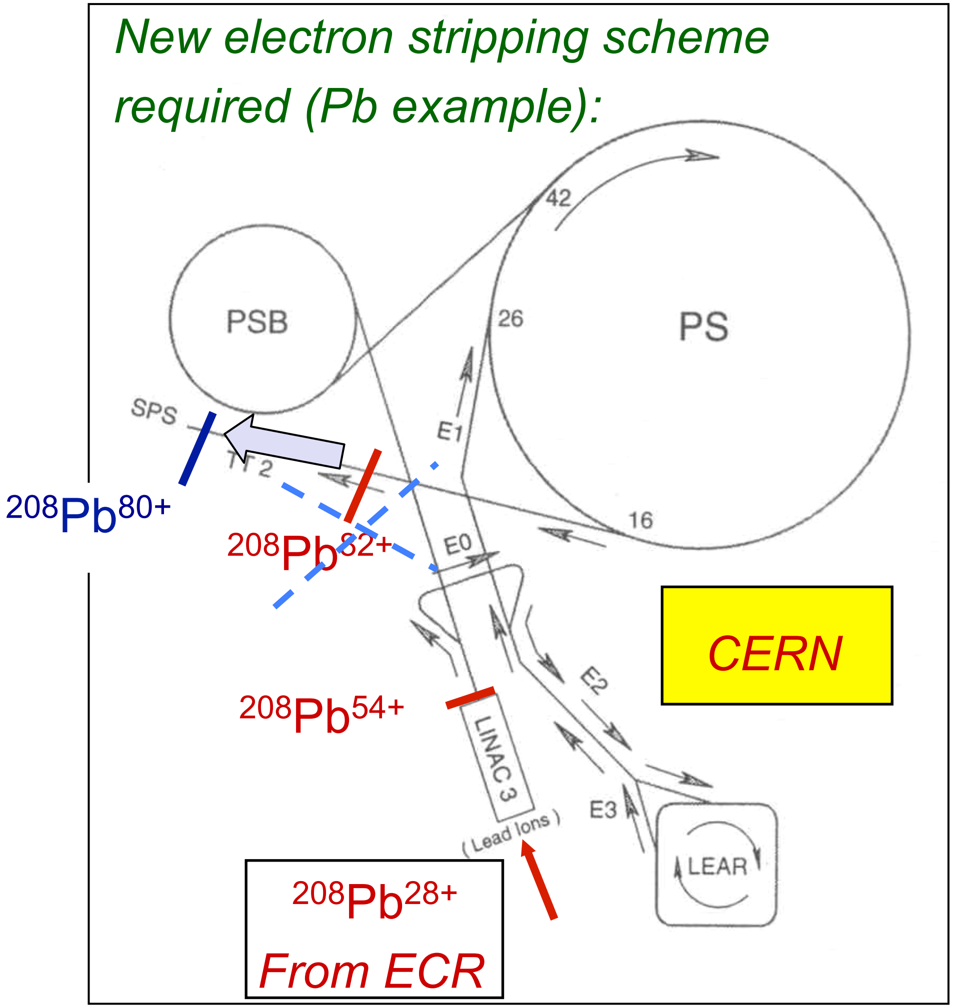
Electron fractional energy loss:
emission of 150 MeV photon:
$E_\gamma/E_{beam} = 2.6 \times 10^{-7}$
(ion undisturbed!)

…stable ion beams, even in the regime of multi photon emission per turn!

Acceleration and storage of PSI beams



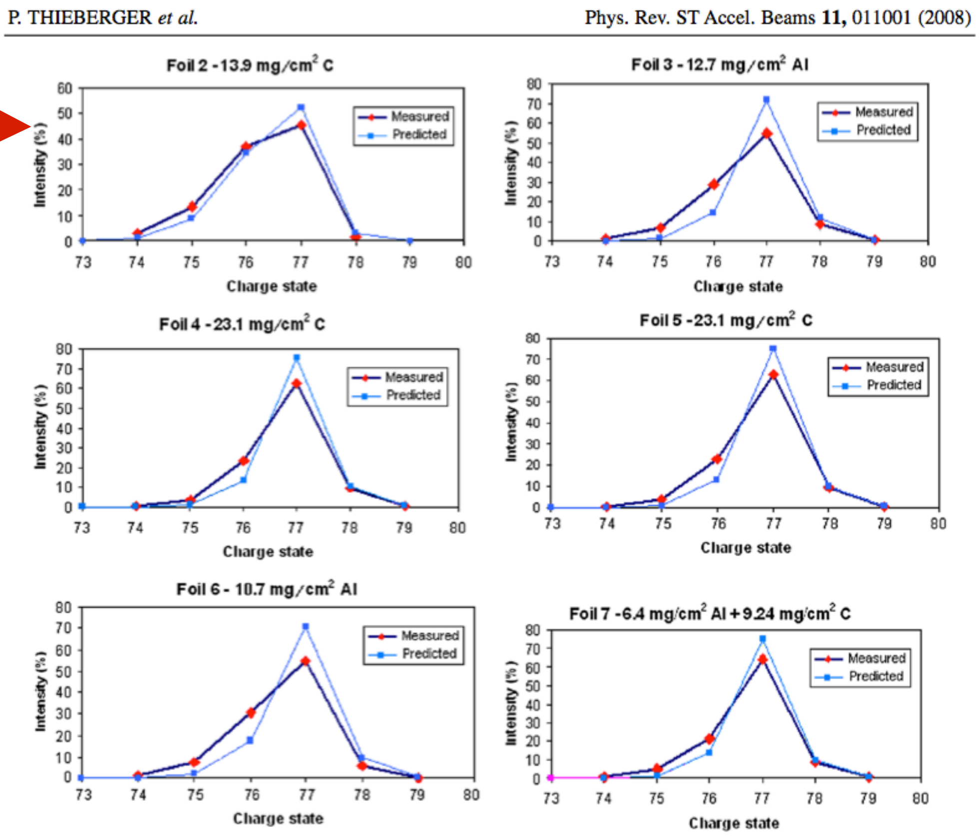
PSI beams were already accelerated and stored in AGS and in RHIC !



Two prerequisite “proof of principle” steps

•*Short SPS test run with the “BNL-type stripping target” (measurement of the beam life time, and time-dependent emittance of the beam of the Partially Stripped Ion beam in SPS*

•*If successful, measurement of the life-time of the partially stripped lead ion beam in the LHC*



Target type and thickness optimisation for the BNL Au^{77+} beams (two electrons attached)

Research Tools of the Gamma Factory

1. *Primary, Partially Stripped Ion (PSI) beams*

2. *High intensity, energy-tuned, γ-beams (produced in the collisions of the laser light with the PSI beams)*

3. *Secondary beams of polarised electrons, polarised positrons polarised muons, neutrons and radioactive ions (produced in the collisions of the γ-beams with stationary targets)*

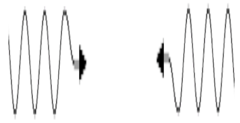
Physics highlights – PSI beams

1. *New (no cost) operation mode of the LHC as the electron-proton and electron-ion colliders (for details see M.W. Krasny, Nucl.Instr.Meth. A540 (2005) 222))*

2. *Precision electroweak measurements and searches for physics beyond the standard model with Relativistic high-Z, Hydrogen-like ions (marrying the simplicity of the H-like atoms with ~Z^5 increase of sensitivity to EW phenomena) (for details see e.g. M.Zolotorev, D.Budker , Phys.Rev.Lett.7825 (1997) 4117))*

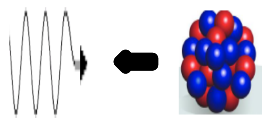
3. *Potentially a large (factor 100?) increase of the acceleration gradient [GeV/m] of the plasma-wakefield acceleration of a witness beam using low emittance, laser-cooled PSI beams (for details see A. Petrenko, forthcoming paper)*

Physics highlights – γ-beams



γ−γ collisions,
E_{CM} = 0.1 – 800 MeV

$\gamma-\gamma_L$ collisions,
E_{CM} = 1 – 100 keV

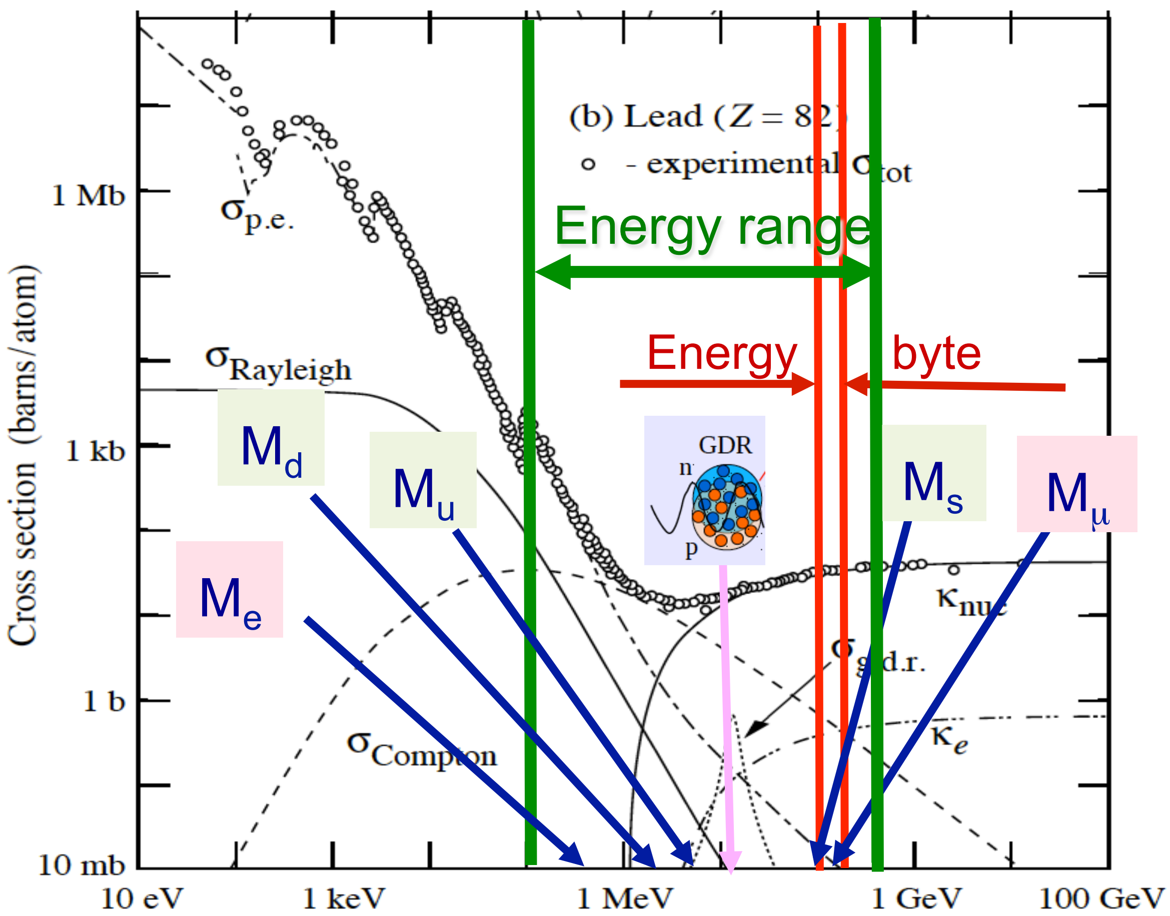


γ−p,A collisions,
E_{CM} = 4 – 60 GeV

1. *Precision QED measurements. Beam dump and direct searches of Dark Matter particles (e.g. WISPs, axions, ALPs, …), in the high luminosity γγ collisions over a large mass domain of ~ 1 keV – 800 MeV*

2. *Precision study of colour confinement phenomena*

3. *QCD studies of photon-nucleon and photon-nucleus collisions (CM energy range ~ 4 – 60 GeV)*



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

Physics highlights – secondary beams

secondary beams:

- **polarised electrons,**
- **polarised positrons,**
- **polarised muons,**
- **neutrons**
- **radioactive nuclei**

A potential to sizably increase the intensity and/or beam quality with respect to the present sources…

1. *High intensity polarised positron and muon sources capable to open new research roads towards a TeV muon collider, neutrino-factory, lepton-proton(ion) collider*
2. *High intensity monochromatic neutron source for the precision measurement of neutron dipole moment, neutron-antineutron oscillations*
3. *High intensity neutron-rich radioactive ion source (ISOLDE program)*
4. *BSM searches with high intensity muon beam*
5. *Medical (isotopes) and technological (ADS, EA) applications.*

The way forward

- *CERN (given its accelerator infrastructure) is the only place where the Gamma Factory programme could be realised.*
- *The technical "proof of principle" of the proposed scheme can be performed almost entirely at the SPS (in parallel to the present LHC physics programme).*
- *The presented initiative requires "in depth" studies before it could be considered as a proposal.*
- *To embark on detailed studies the institutional CERN interest and support is a "sine qua non" condition (both of the CERN management and of the CERN accelerator experts).*

Conclusions

- *The idea underlying the Gamma Factory proposal is to use, for the first time, atomic degrees of freedom, in forming very high intensity beams of photons, polarised leptons, neutrons and radioactive ions.*

- *The CERN-based Gamma Factory scheme provides a very efficient scheme of transforming accelerator RF power to the power of the (γ, e, μ, ν, n, radioactive ion) secondary beams (beam rigidity, efficient cooling).*

- *In many cases the proposed scheme may lead to a leap, by several orders of magnitude, in their intensity.*

- *Handling powerful beams of photons/electrons and neutrons represents an important technological challenge. The potential bonuses of addressing such a challenge are, however, numerous:*

1. *Possible application to the high energy frontier (muon colliders, wakefiled acceleration) and high intensity frontier (i.e. the SPS based ep(eA) collider, $\gamma\gamma$ colliders and neutrino factories).*

2. *Opening new research domains in Fundamental Physics (including high sensitivity dark matter searches, investigation of the basic symmetries of the universe with high precision,…).*

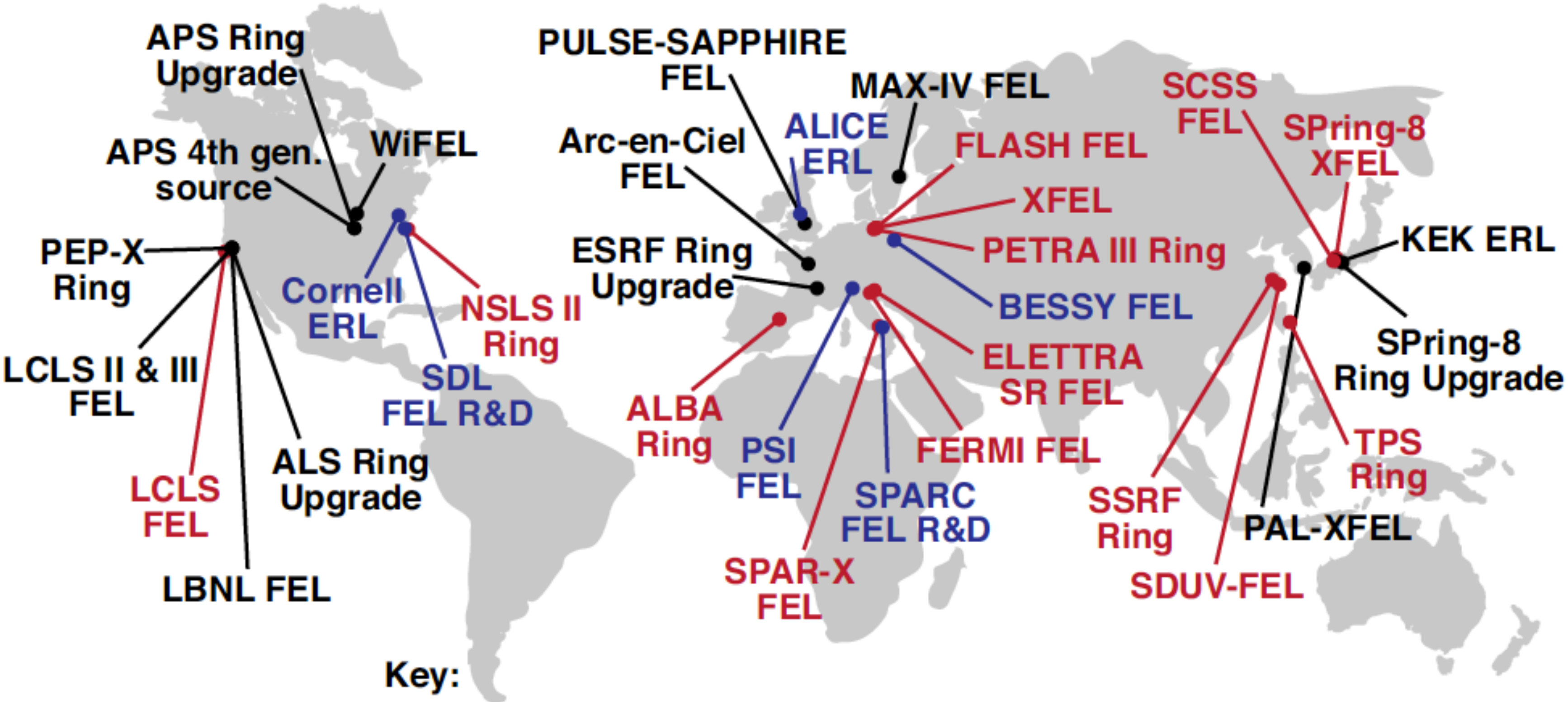
3. *Extending the experimental program in Nuclear Physics (with neutron rich radioactive isotopes and with neutron beams).*

4. *New research opportunities for Atomic Physics (precision measurements with high Z hydrogen-like atoms and muonic atoms).*

5. *Industrial and medical applications (energy production, the research on nuclear reactors with reduced nuclear waste, production of isotopes for the selective cell killing techniques).*

Extra transparencies

X-ray sources



Key:

Red - funded (operational or under construction)

Blue - funded R&D program

Black - concepts and proposals

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Selected technical challenges:

acceleration, storage and cooling of partially stripped ion beams

Life-time of partially stripped ion beams

- Bunch temperature $T_b << 1$ Ry × Z^2 at all the acceleration stages - (radiative cooling, evaporation cooling, laser Doppler cooling)

- "Stark effect" in the LHC superconducting dipoles (E= 7.3 10^{10} V/m) - only high and medium Z ions allowed to be the electron carriers at the LHC

- Ionization process

  -realistic requirement on the LHC vacuum (concentration of CH_4 is critical - must be kept below ~$6x10^{11}$ mol/m^3 (circumference averaged) to achieve the $Pb^{81+}(1s)$ beam life-time larger that 10 Hours)

  - stringent requirements on the allowed beam collision schemes (only partially stripped high Z ions can collide only with the lightest fully stripped ions: p, He, O…)

Survival of partially stripped ions:

Ionization losses

- A dominant process leading to losses of partially stripped ions is the ionization process in beam-beam and beam-gas collisions (note a quantum jump in magnetic rigidity of the beam particles)

Ionization cross-sections

Anholt and Becker, Phys.Rev.A36(1987)

Coulomb contribution:

$\sigma_{Coul} = s(Z_t,Z_p)\,(Z_t/Z_c)^2\,10^4$ [barn/electron]

Transverse contribution:

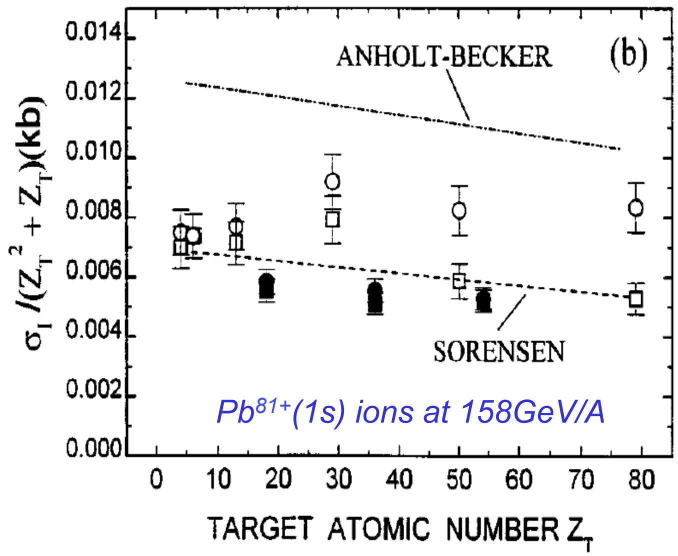
$\sigma_{Tran} = t(Z_t,Z_p)\,(Z_t/Z_c)^2\,10^4\,\ln(\gamma^2)$ [barn/electron]

Where: $s(Z_t,Z_p)$, $t(Z_t,Z_p)$ are slowly (logarithmically) varying functions of the electron carrier Z_c and target Z_t, and γ is the Lorenz factor

Note:
- *spin-flip contribution is neglected*
- *coherent bunch contribution is neglected*

Experimental cross-check

Krause et al., Phys.Rev.A63(2001)



Survival of partially stripped ions: beam-gas collisions

Collisions of $Pb^{81+}(1s)$ ions with the residual gas in the LHC beam pipe – how long can they survive?

- Calculate maximal allowed concentration of molecules to achieve the 10 hour lifetime of the beam

$$\tau^{-1} = \sigma_i \times \rho_i \times c$$

- Compare with the estimated densities for the gas molecules in the interaction regions by Rossi and Hilleret, LHC project rapport 674 (2003): (H_2 – 1.3×10^{12}; CH_4 – 1.9×10^{11}; … CO_2 – 2.8×10^{11} mol/m^3)

Result: The safety factor varies between 30 (for the H_2 molecules) and 2 (for the CO_2 molecules). Better vacuum in arcs.

Two beam cooling methods:

1. Radiative ion cooling (broad-band-laser cooling) – faster beam particles lose more energy than slower ones and all gain the same energy in the accelerating cavity

$$\Delta\omega/\omega_L = (\Delta\psi)^2/4 + \Delta\gamma/\overline{\gamma}.$$

Laser bandwidth covers the angular and momentum dispersion of the ion beam

For Scenario 1 the dumping time is t =52 s and the equilibrium horizontal emittance is ε_x= 3 x 10^{-15} mrad (E.G. Bessonov)

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2. Enhanced cooling

Linear rise of the laser beam power in the frequency interval within the a fraction of a broad beam region (previous case)

The dumping time is reduced to t =0.1 s (note cooling mainly in longitudinal direction, emittance exchange schemes must be applied..) (E.G. Bessonov)

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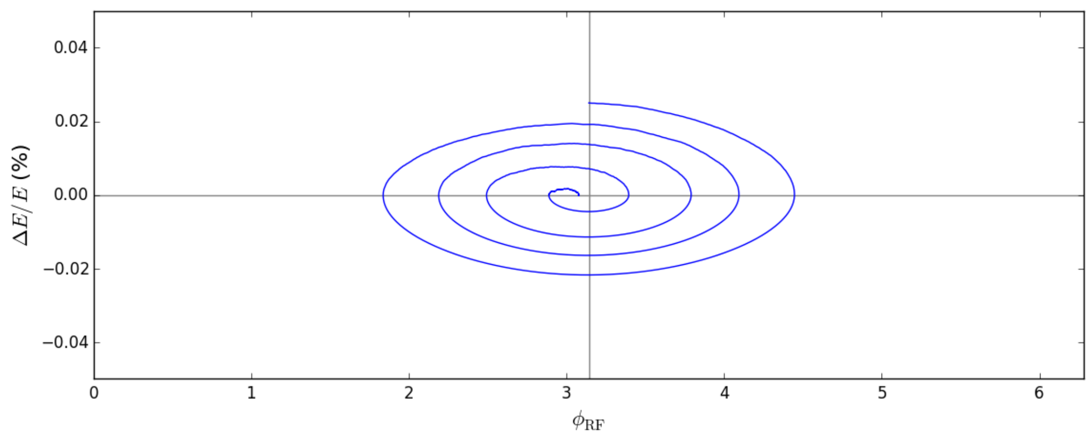
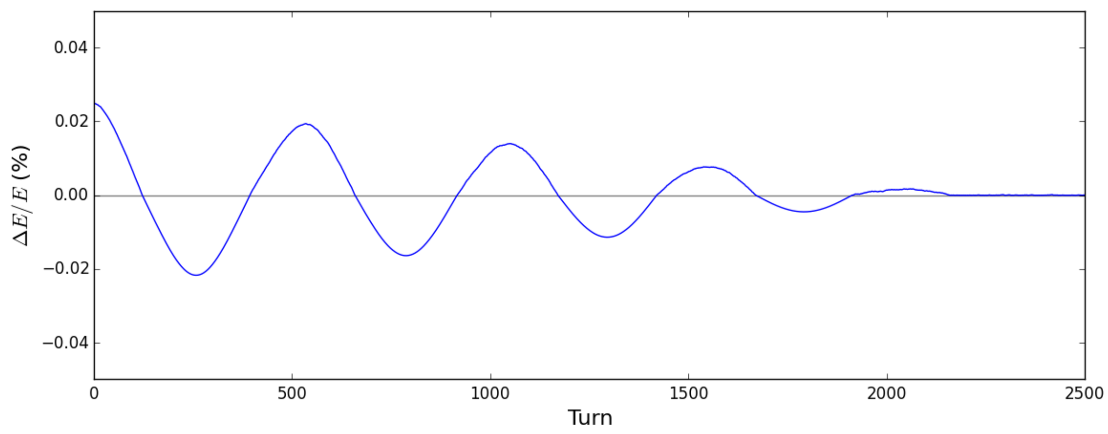
[1] E.G.Bessonov, Kwang-Je Kim, Radiative cooling of ion beams in storage rings by broad band lasers, Phys. Rev. Lett., 1996, v.76, No 3, p.431-434; Preprint LBL -37458, UC-414, June 1995.

PSI beam-cooling:

initial simulations of the ions in the LHC lattice by Alexey Petrenko



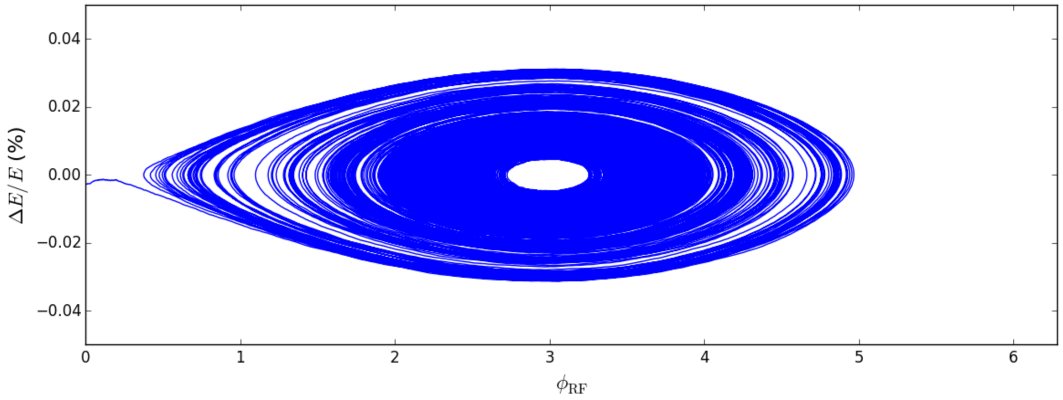


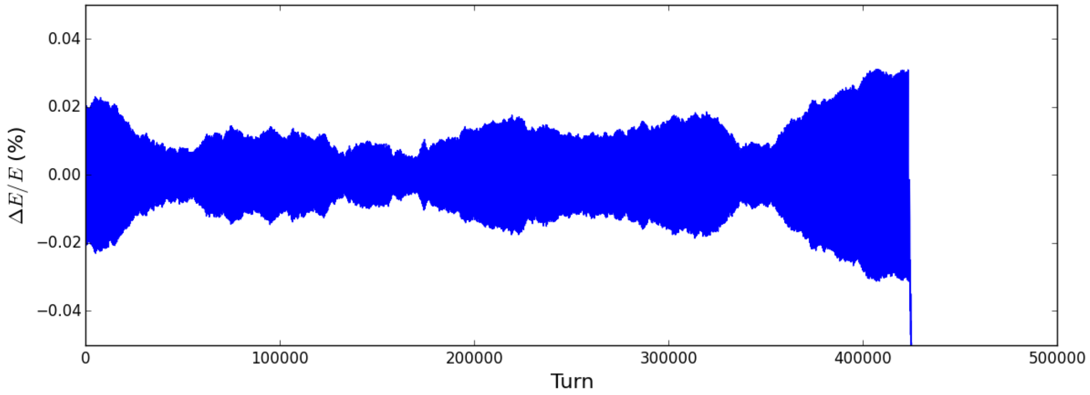
Scenario 1:

Laser frequency band covers the $\Delta E > 0$ energies (negative ΔE out of the resonance)

Low power laser: each ion is radiating with probability of 50% over every turn)

Initial simulations of the ions in the LHC lattice by Alexey Petrenko





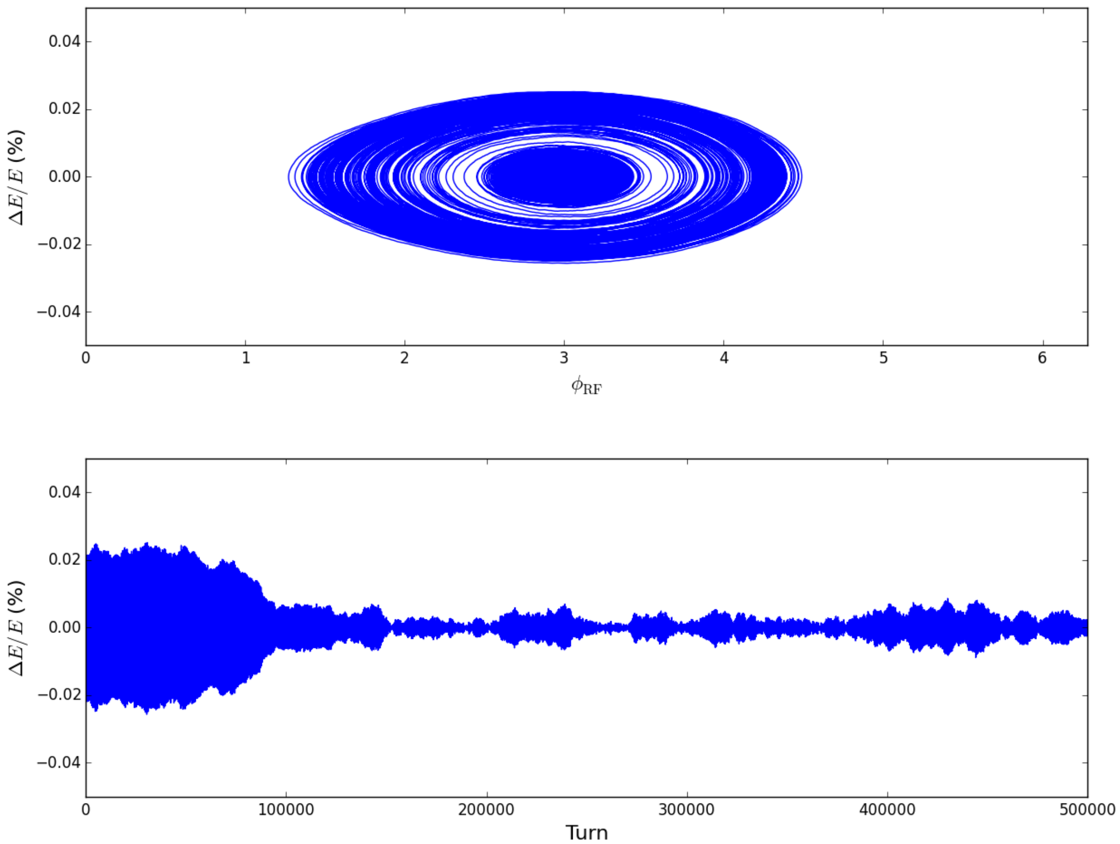
Scenario 1:

Full laser power covering uniformly the LHC ion energy bandwidth.

No beam cooling.

Ion is lost from the bucket

Initial simulations of the ions in the LHC lattice by Alexey Petrenko



Instability disappears

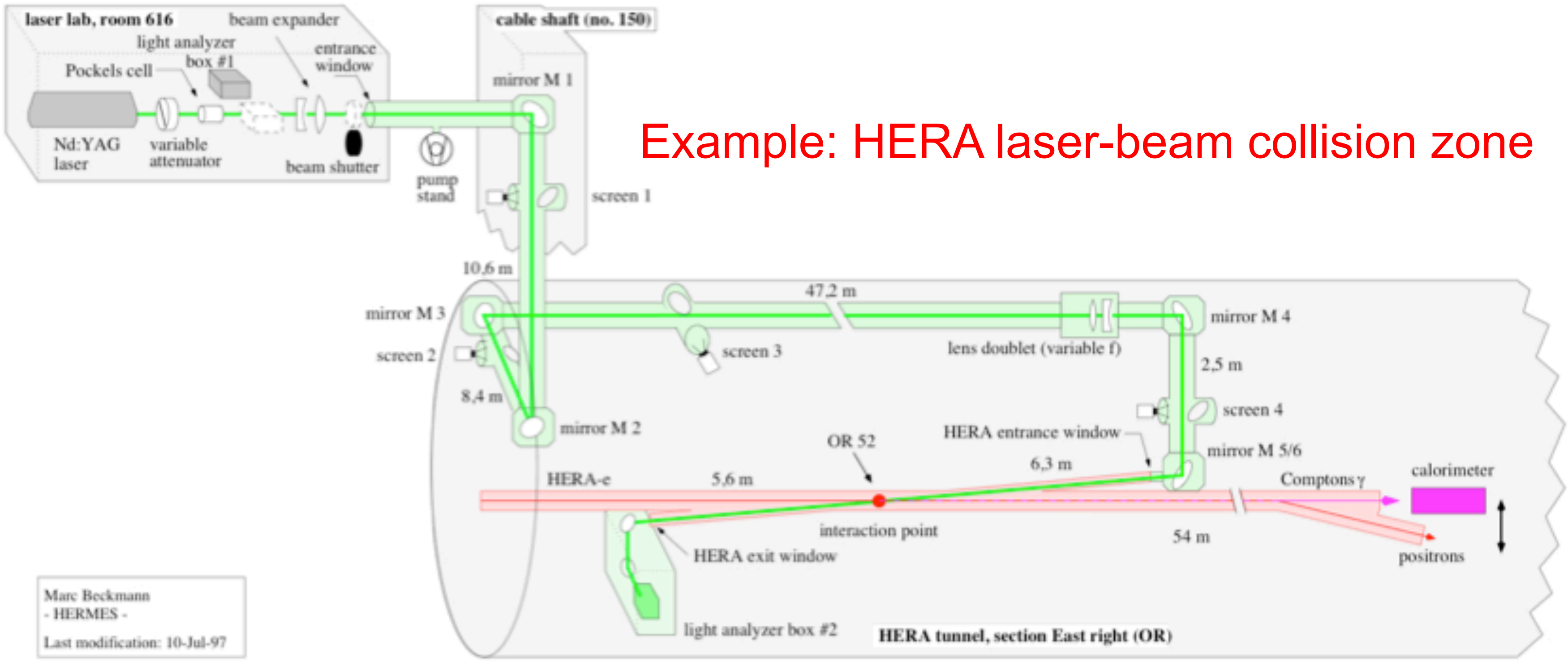
Scenario 1:

Gamma-beam generating laser (full power)covering uniformly the LHC initial ion energy bandwidth

+

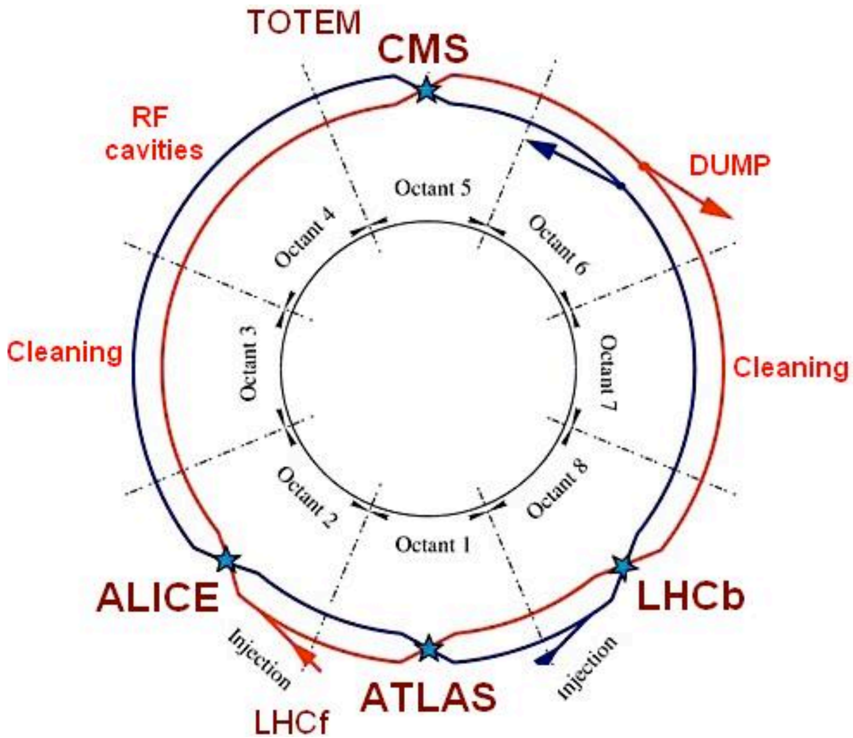
Beam cooling, low power laser with frequency band covering the $\Delta E > 0$ resonant collisions

Laser system and the gamma beam extraction



Example: HERA laser-beam collision zone

- Nd:YAG laser - 3ns x 100 mJ @ 100 Hz
- Pockels cell converts linear (>99%) light to circularly polarised light

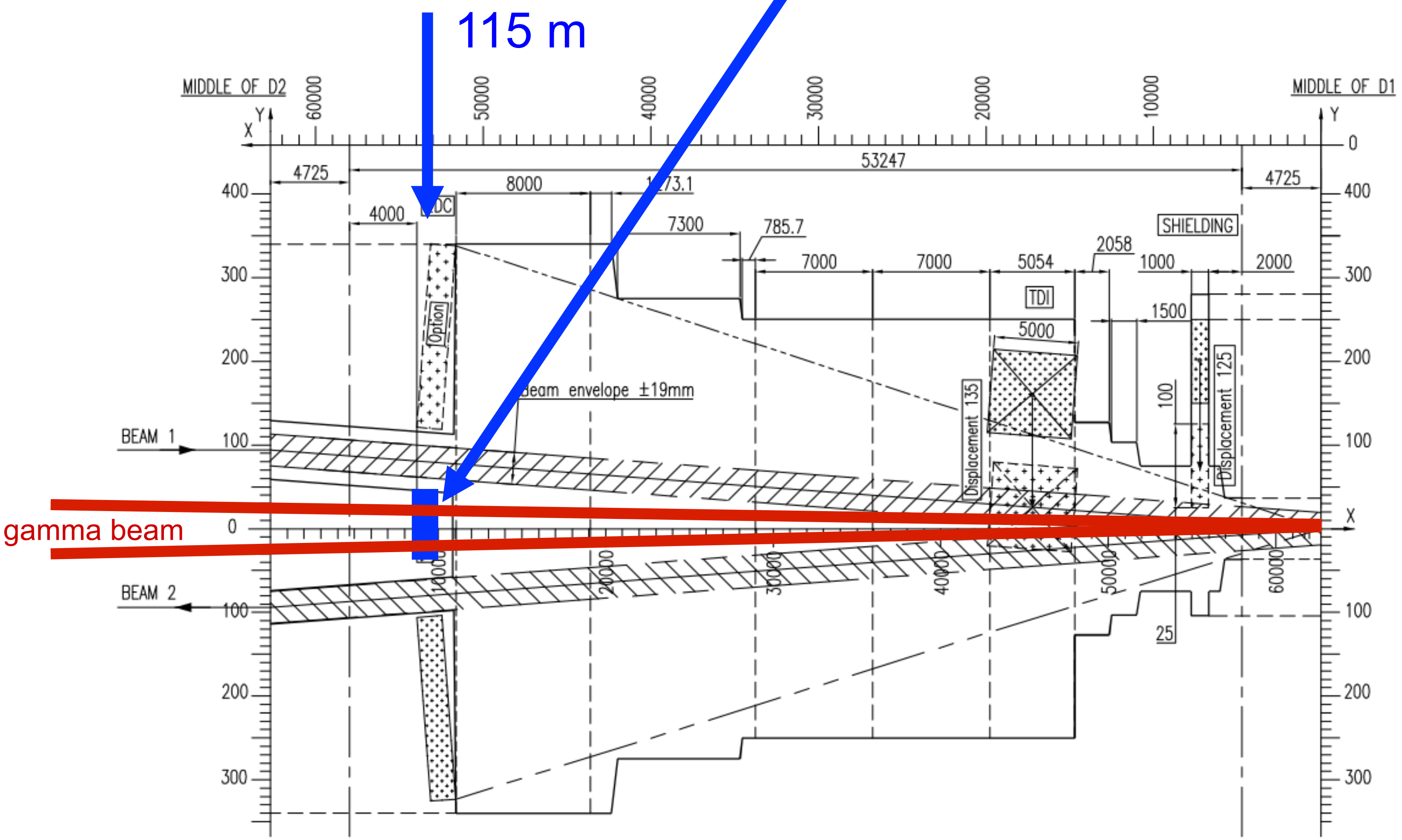


… a technical possibility to install the laser system

in the octants 3/7 or maybe in octant 6 (external ring)?…

..less attractive solution is to install it in one of the IPs..

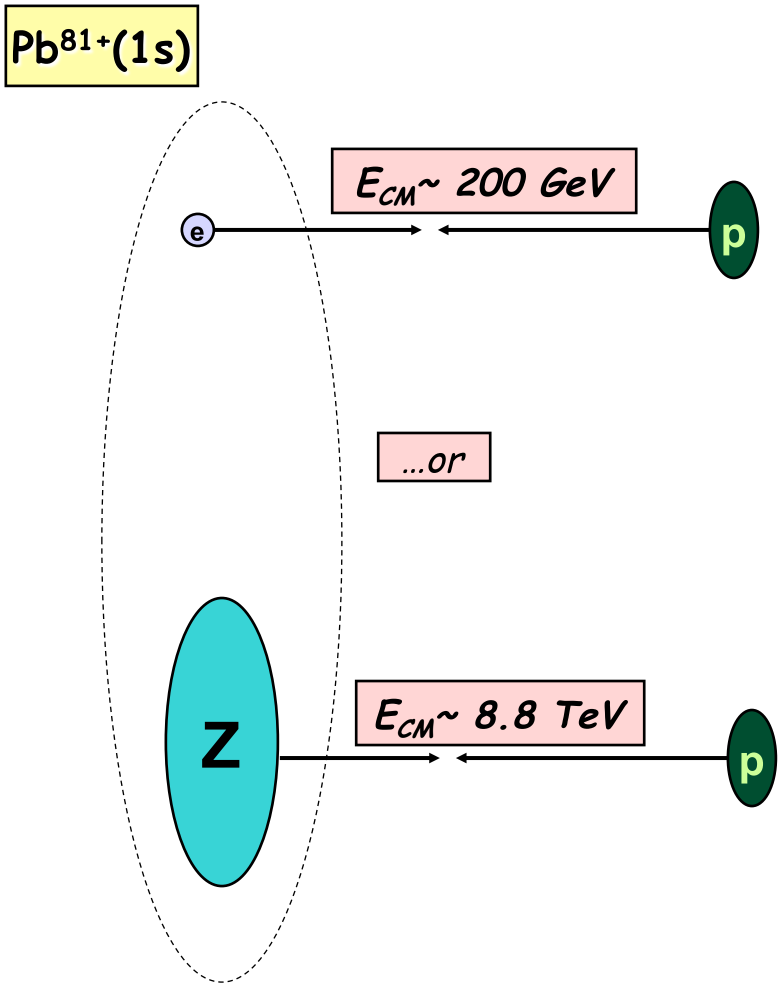
ALICE Zero Degree Calorimeter (ZDC) zone as an example…



Vertical bump necessary…

Electron-proton and electron-ion collisions at the LHC with the LHC detectors.

Partially stripped ions as electron carriers



• 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)

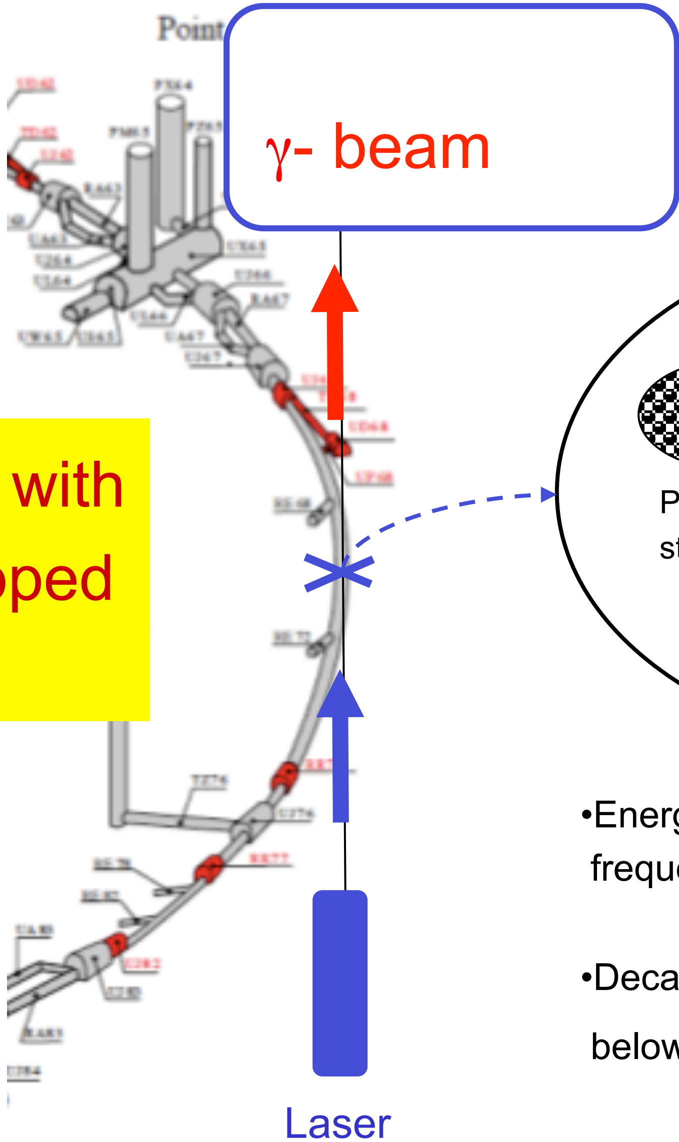
ep@LHC: Pb^{81+}(1s)-p example

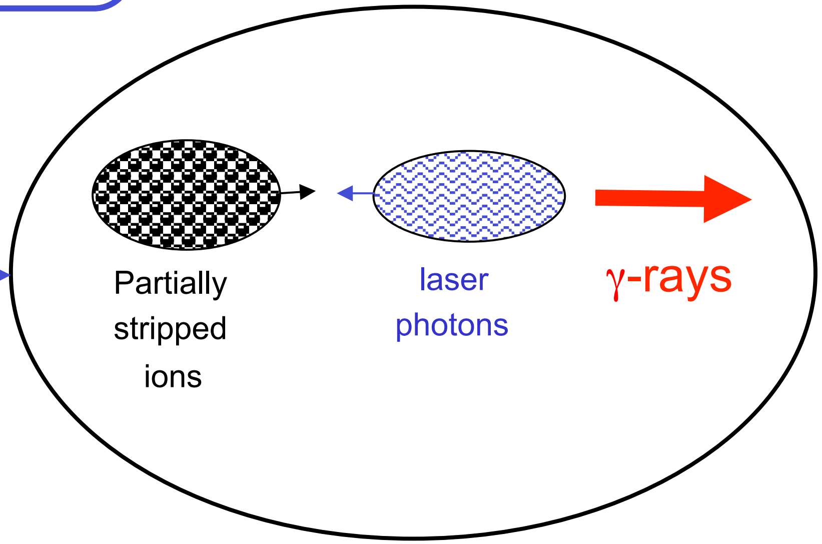
- CM energy (ep collisions) = 205 GeV
- β at IP = 0.5 m
- Transverse normalized emittance = 1.5 μ m
- Number of ions/bunch = 10^8
- Number of protons/bunch = 4×10^{10}
- Number of bunches = 608
- Luminosity = 0.4×10^{30} cm^{-2} s^{-1}

Gamma Factory: γ-beams

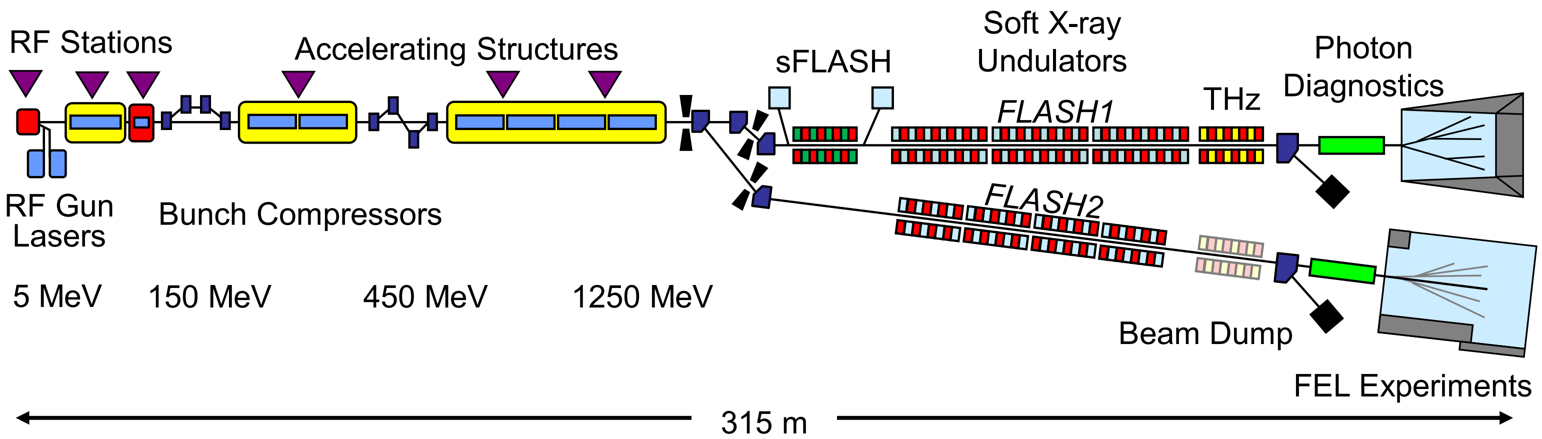
LHC as a frequency converter of O(1 - 10 eV) photons into O(1 - 400 MeV) γ-rays

LHC filled in with partially stripped ion beams



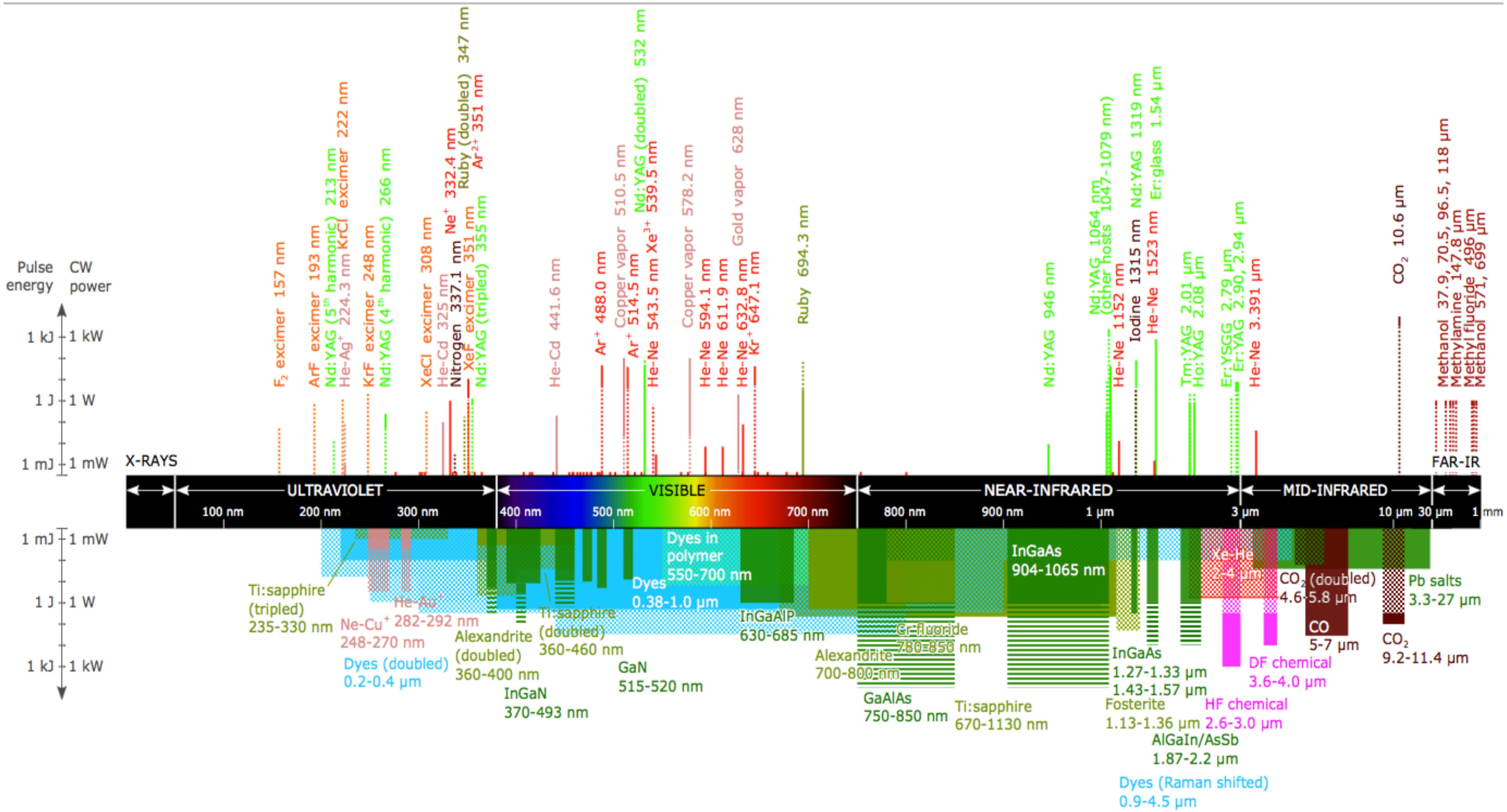


- Energy of the laser photons tuned to a resonant frequency of an atomic transition e.g. 1s → 2p
- Decay length in the LAB frame $c\tau \sim \gamma_L / Z^4$ below 0.1 mm for $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$



FEL Radiation Parameters 2016.
FLASH2 shows expected values. The unit for brilliance is B=photons/s /mrad²/mm²/0.1%bw.

Parameter	FLASH1	FLASH2
Wavelength Range (fundamental)	4.2 - 52 nm	4 - 90 nm
Average Single Pulse Energy	1 - 500 µJ	1 - 500 µJ
Pulse Duration (FWHM)	<30 - 200 fs	<10 - 200 fs
Pulses per second	10 - 6000	10 - 6000
Peak Power (from av.)	1 - 5 GW	1 - 5 GW
Average Power	up to 600 mW	up to 600 mW
Spectral Width (FWHM)	0.5 - 2 %	0.5 - 2 %
Photons per Pulse	10^{11} - 10^{13}	10^{11} - 10^{13}
Average Brilliance	10^{17} - 10^{21}B	10^{17} - 10^{21} B
Peak Brilliance	10^{28} - 10^{31} B	10^{28} - 10^{31} B


Pulse energy
CW power
1 kJ 1 kW
1 J 1 W
1 mJ 1 mW
X-RAYS
ULTRAVIOLET
VISIBLE
NEAR-INFRARED
MID-INFRARED
FAR-IR
100 nm
200 nm
300 nm
400 nm
500 nm
600 nm
700 nm
800 nm
900 nm
1 μm
3 μm
10 μm
30 μm
1 mm
F2 excimer 157 nm
ArF excimer 193 nm
Nd:YAG (5th harmonic) 213 nm
He-Ag+ 224.3 nm
KrCl excimer 222 nm
KrF excimer 248 nm
Nd:YAG (4th harmonic) 266 nm
XeCl excimer 308 nm
He-Cd 325 nm
Nitrogen 337.1 nm
Ne+ 332.4 nm
XeF excimer 351 nm
Nd:YAG (tripled) 355 nm
Ruby (doubled) 347 nm
Ar2+ 351 nm
He-Cd 441.6 nm
Ar+ 488.0 nm
Copper vapor 510.5 nm
Ar+ 514.5 nm
He-Ne 543.5 nm
Xe3+ 539.5 nm
Nd:YAG (doubled) 532 nm
Copper vapor 578.2 nm
He-Ne 594.1 nm
He-Ne 611.9 nm
Gold vapor 628 nm
He-Ne 632.8 nm
Kr+ 647.1 nm
Ruby 694.3 nm
Nd:YAG 946 nm
Nd:YAG 1064 nm (other hosts 1047-1079 nm)
He-Ne 1152 nm
Iodine 1315 nm
Nd:YAG 1319 nm
He-Ne 1523 nm
Er:glass 1.54 μm
Tm:YAG 2.01 μm
Ho:YAG 2.08 μm
Er:YSGG 2.79 μm
Er:YAG 2.90, 2.94 μm
He-Ne 3.391 μm
CO2 10.6 μm
Methanol 37.9, 70.5, 96.5, 118 μm
Methylamine 147.8 μm
Methyl fluoride 496 μm
Methanol 571, 699 μm
Ti:sapphire (tripled) 235-330 nm
Ne-Cu+ 248-270 nm
He-Au+ 282-292 nm
Dyes (doubled) 0.2-0.4 μm
Alexandrite (doubled) 360-400 nm
InGaN 370-493 nm
Ti:sapphire (doubled) 360-460 nm
GaN 515-520 nm
Dyes 0.38-1.0 μm
Dyes in polymer 550-700 nm
InGaAlP 630-685 nm
Alexandrite 700-800 nm
Cr-fluoride 780-850 nm
GaAlAs 750-850 nm
Ti:sapphire 670-1130 nm
InGaAs 904-1065 nm
InGaAs 1.27-1.33 μm 1.43-1.57 μm
Fosterite 1.13-1.36 μm
AlGaIn/AsSb 1.87-2.2 μm
Dyes (Raman shifted) 0.9-4.5 μm
Xe-He 2-4 μm
HF chemical 2.6-3.0 μm
DF chemical 3.6-4.0 μm
CO2 (doubled) 4.6-5.8 μm
CO 5-7 μm
CO2 9.2-11.4 μm
Pb salts 3.3-27 μm

Beam energy equivalence

The LHC ion energies of:

1-3 TeV/nucleon

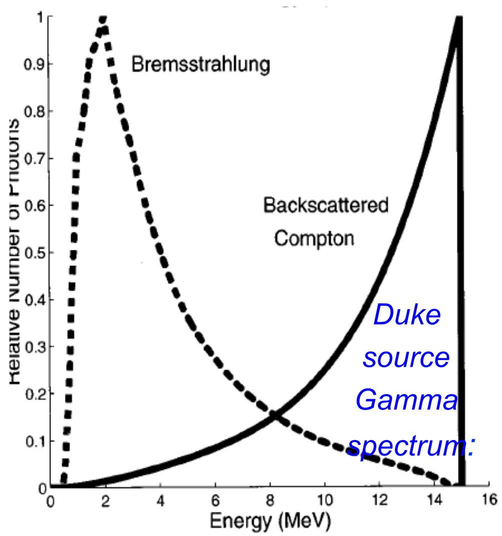
are equivalent to the energies of:

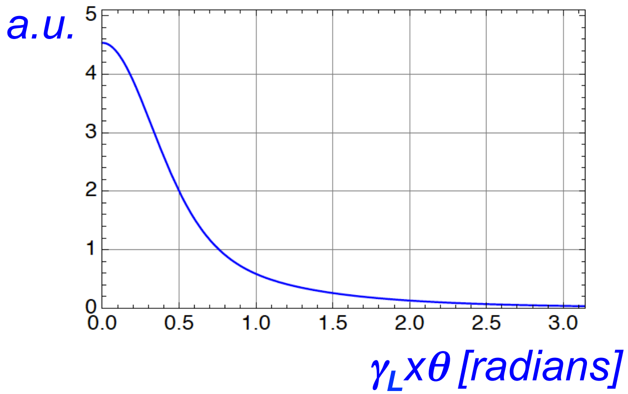
0.5-1.5 GeV

of the electron beam

The spectra equivalence

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





Photon cross sections

Electrons:

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

r_e - the classical electron radius

Partially stripped ions:

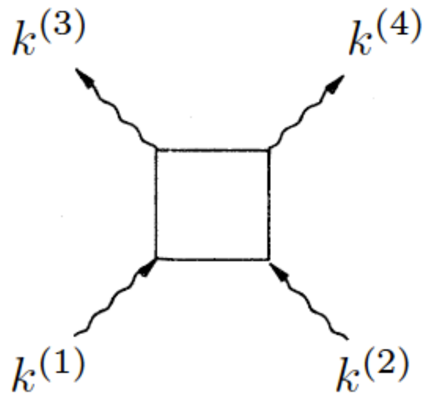
$$\sigma_{res} = \lambda_{res}^2/2\pi$$

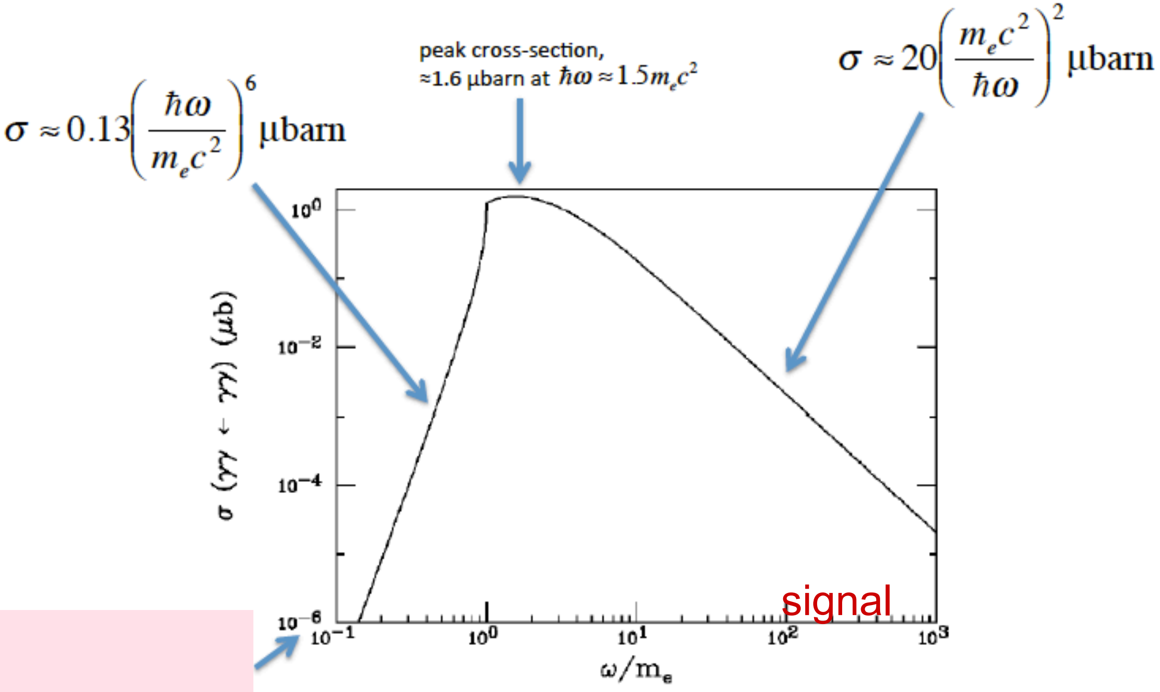
λ_{res} - photon wavelength for the resonant atom excitation

Reminder:
$(E_{laser}/m_{beam}) \times 4\gamma_L << 1$

Gamma Factory: elastic photon-photon scattering and dark matter

Elastic light-light scattering (never measured)





Two measurements:

γ−γ collisions, for $E_{CM} > 2m_e$

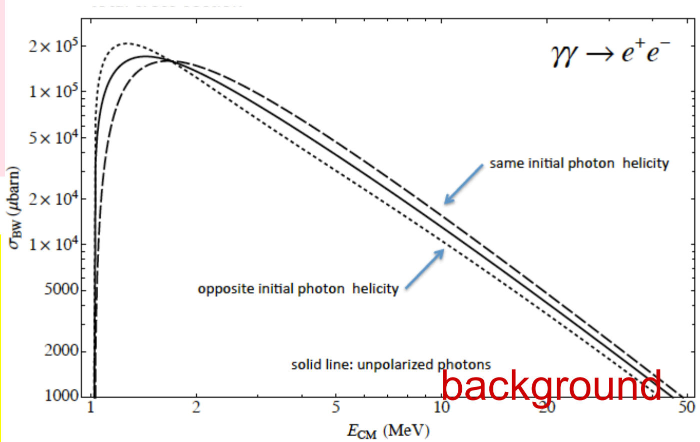
and (background free)

$\gamma - \gamma_L$ collisions, for $E_{CM} < 2m_e$

Up to 1000 events/s expected,

to be compared to ~20 events/year

at the LHC

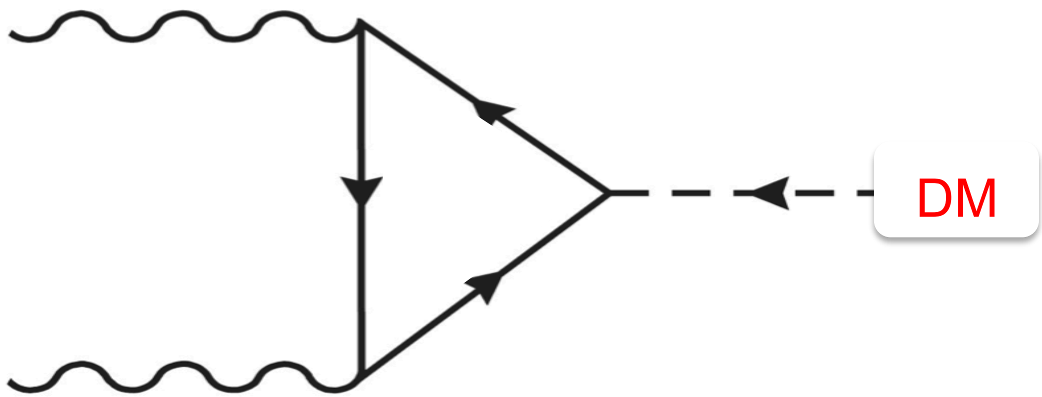


Dark Gauge Forces

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \epsilon_Y F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}, \quad (3)$$

where $\mathcal{L}_{\rm SM}$ is the Standard Model Lagrangian, $F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$, and A' is the gauge field of a massive dark $U(1)'$ gauge group [1]. The second term in (3) is the kinetic

Axions and ALPs



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

Gamma Factory: secondary beams

Gamma Factory as a source of high intensity secondary beams

- *High Intensity highly polarised electron and positron sources \ (up to 10^{17} γ->e+e- /s) Polarized muon and neutrino sources (up to 10^{12} $\gamma \to \mu^+\mu^-$ /s and 4×10^{19} 1/year)**

- *High intensity monochromatic neutron beams (GDR in heavy nuclei as s a source of neutron beam: $\gamma + A \rightarrow A-1 + n$) (up to 10^{15} 1/s)*

- *High intensity radioactive beams (up to 10^{14} 1/s) (photo-fission of heavy nuclei:($\gamma + A \rightarrow A_1 + A_2$ + neutrons)*

**) for the quoted maximal flux of the muons/neutrinos the LHC circumferential voltage would need to be increased from the present value of RF=16 MV and/or the number of stored ions (bunch population and bunch frequency)would have to be increased by e.g the factors of 2, 2 and 3). The power of the gamma-beam for the quoted fluxes would be ~4 MW. (+ionisation remedies)*

e^+-e^- and e-p collider requirements

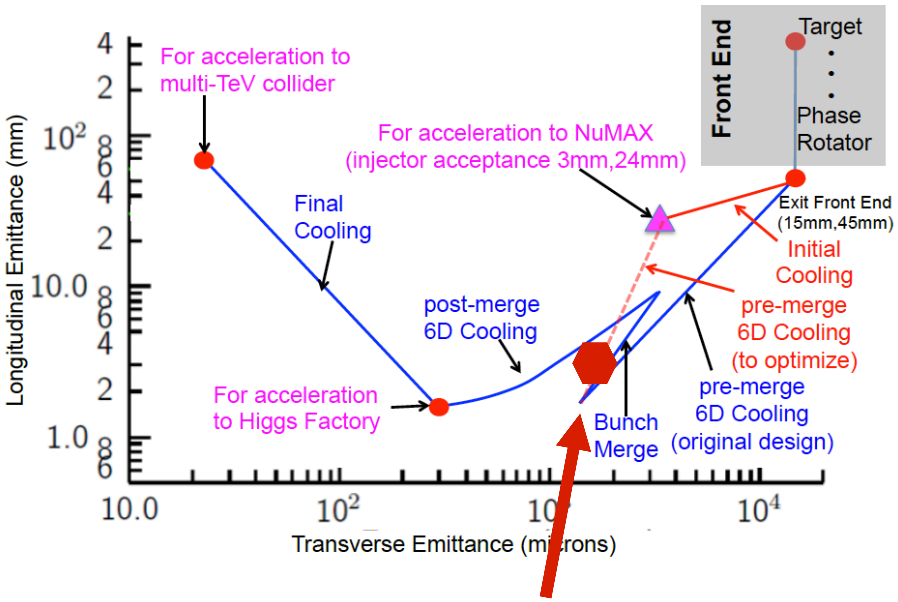
	SLC	CLIC (3 TeV)	ILC (500 GeV)	LHeC (ERL)
Damping ring energy, GeV	1.19	2.86	5	
e^+/bunch at IP, $\times 10^9$	40	3.72	20	2
e^+/bunch after capture, $\times 10^9$	50	7.7	28	2.2
Bunches/macropulse	1	312	1312	CW
Macropulse repetition rate	120	50	5	CW
Bunches/second	120	15,600	6560	2×10^7
e^+/second, $\times 10^{14}$	0.06	1.20	1.83	440
Expected polarization, %	0	0	30	NA

Bonus: polarization (>80%)

For scenario 2: 10^{17} γ -> e+e- /s could be achieved with the nominal LHC RF voltage. Note: the beam power which has to be handled by the photon conversion target would be of the order of 100 kW.

μ^+- μ^- collider requirements

C of m Energy	1.5	3	6	TeV
Luminosity	0.92	3.4	0.9	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	≈0.087	≈0.087	≈0.087	
Muons/bunch	2 (1.44 ?)	2	2	10^{12}
Total muon Power	9	15	3.7	MW
Ring <bending field>	6	8.4	8.4	T
Ring circumference	2.6	4.5	9	km
β^* at IP $= \sigma_z$	10	5	2.5	mm
rms momentum spread	0.1 (0.3 ?)	0.1	0.1	%
Required depth for ν rad	≈20	≈ 200	≈ 200	m
Proton Energy	8	8	8	GeV
Muon per proton	0.16	0.16	0.16	
Muon Survival	7	6	5	%
protons/pulse	187 (134 ?)	200	240	Tp
Repetition Rate	15 (21 ?)	12	1.5	Hz



G-F maximal muon flux (factor 10 lower than required)up to 10^{12} polarized μ+μ^- pairs [1/s] for 4MW RF power of the LHC cavities (For comparison: TLEP RF power ~300 MW)

beam emittance (factor >10^4 improvement* possible, counterbalance lower intensity?)

*) the theta/energy correlation of the muons produced by the photon conversions on high Z target would have to be exploited in the beam forming section

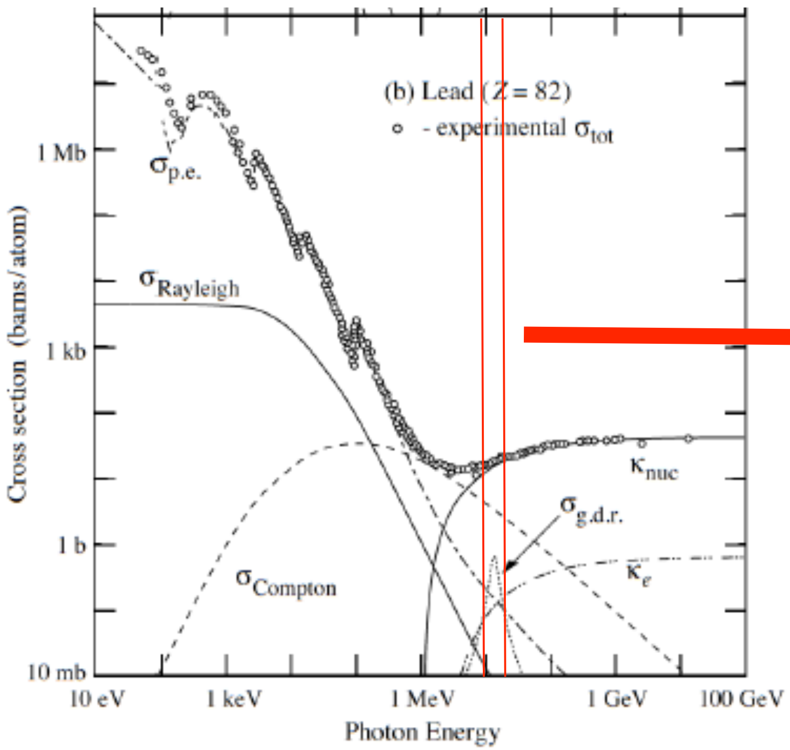
Gamma Factory and Neutrino-factory requirements

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}

Maximal achievable neutrino flux (a factor 10 lower that of NuMAX, a factor 50 higher than that of nuSTORM)

…but, if the initial muon polarization is preserved in the acceleration process → ultra pure ν_μ ($\overline{\nu_\mu}$) beams of precisely equal fluxes (e.g. CP – violation measurements in the neutrino sector)

Secondary Neutron and Radioactive Beams



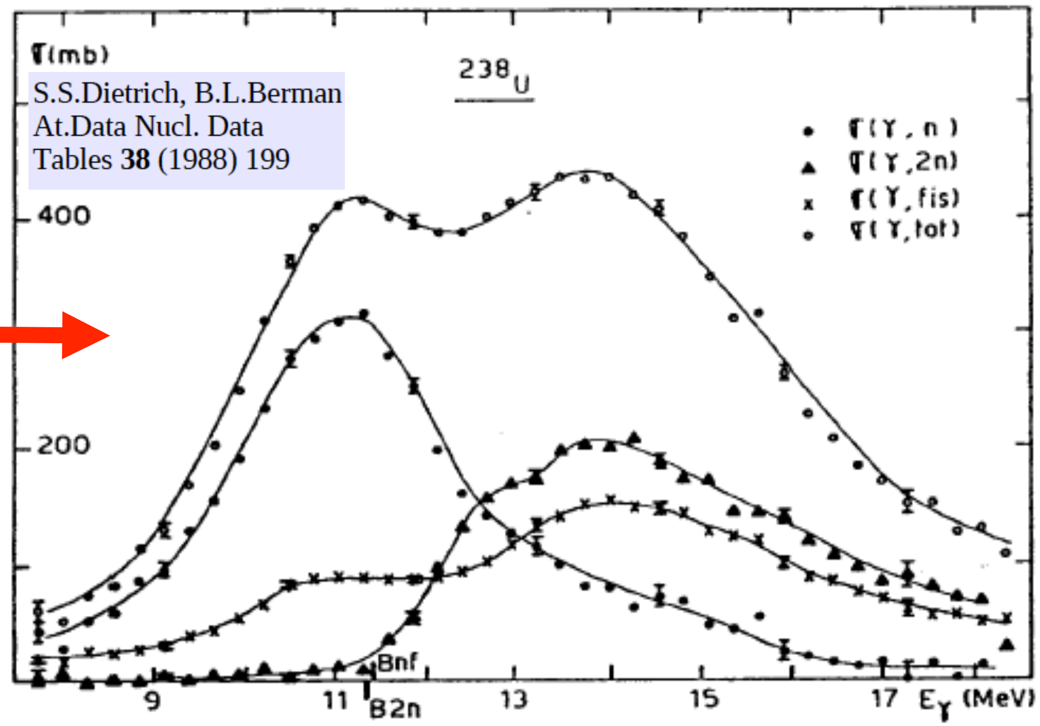
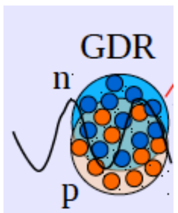


Figure 1. Partial and total photonuclear cross sections (γ,n), (γ,2n), (γ,f), and (γ,tot) for U^{238}.

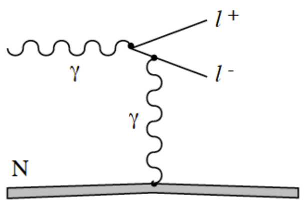


GDR=Giant Dipole Resonance

Achievable production rate of:

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

Polarised electron/positron and muon source



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

Replace Primary Electrons by Polarised Gamma

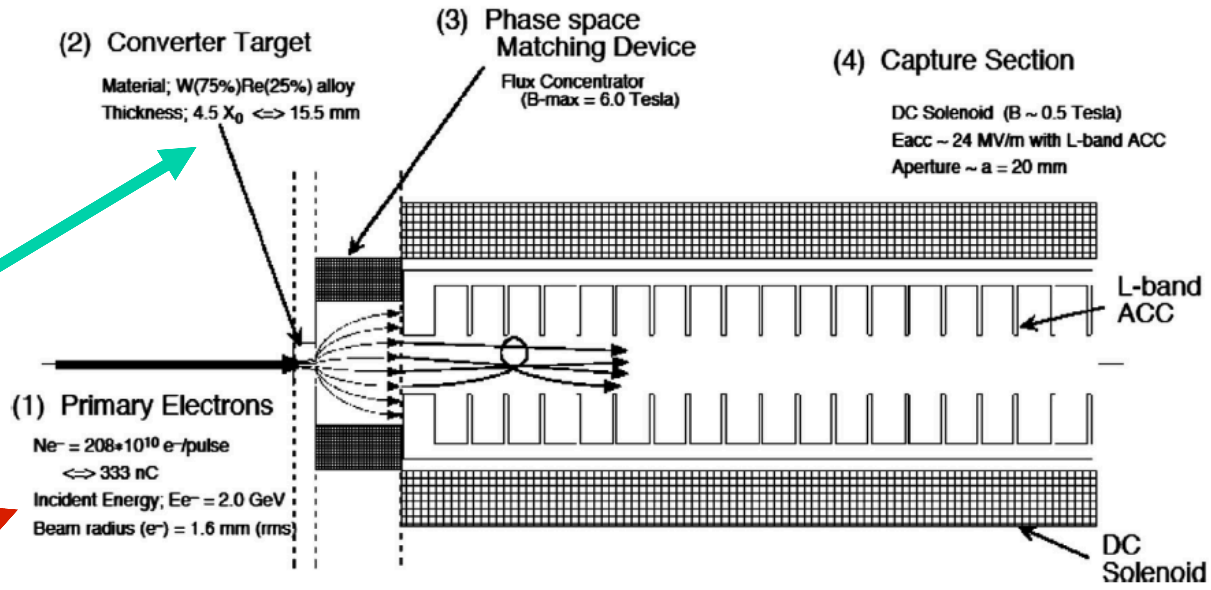


Fig. 2. Layout of the CLIC e+ source with a single target.

Principal gains of a *Gamma Factory* driven positron 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 (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.

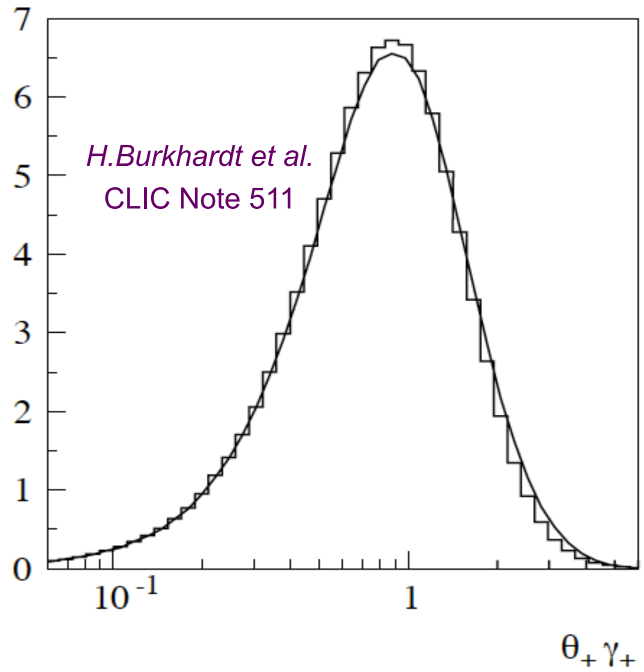
  How to filter them out?

- 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:



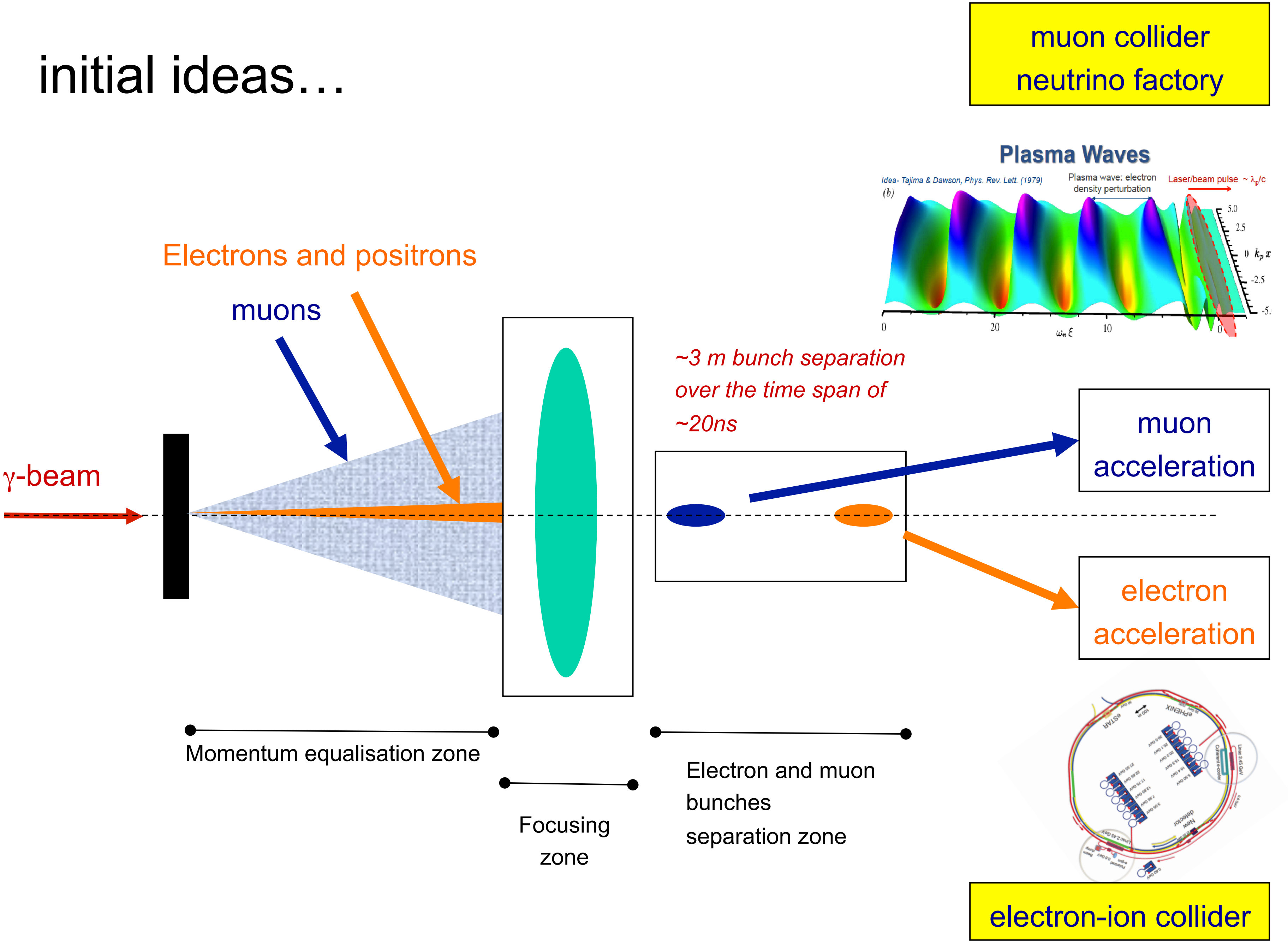
Hint2

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…



Colliders which could be based on the Gamma Factory

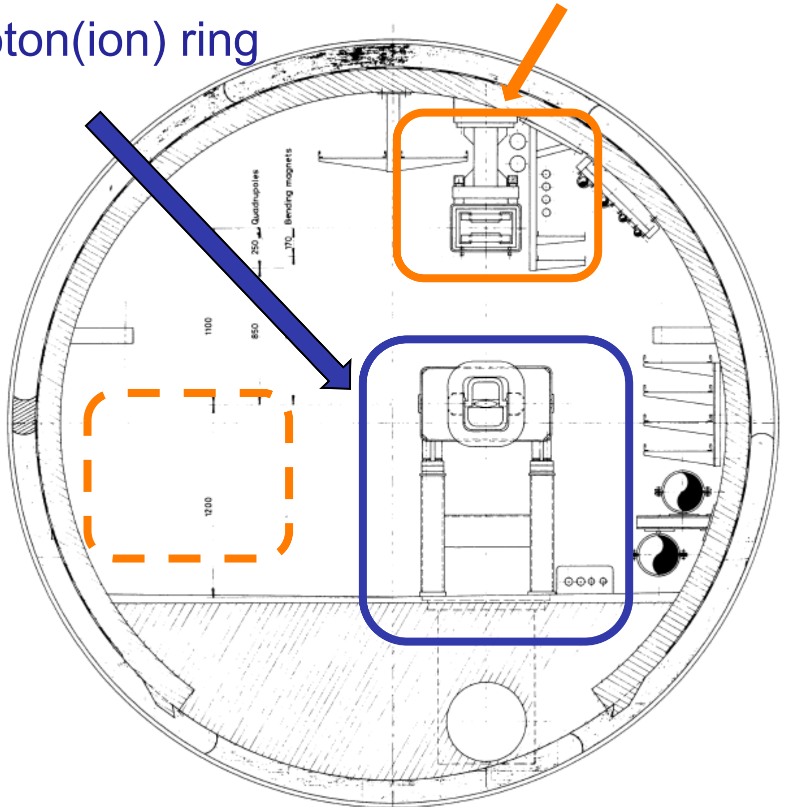
secondary beam sources

A possible use of the Gamma Factory polarized lepton source – the high luminosity energy recovery Electron-Ion Collider (EIC) … and/or a 3 TeV muon collider in the SPS tunnel

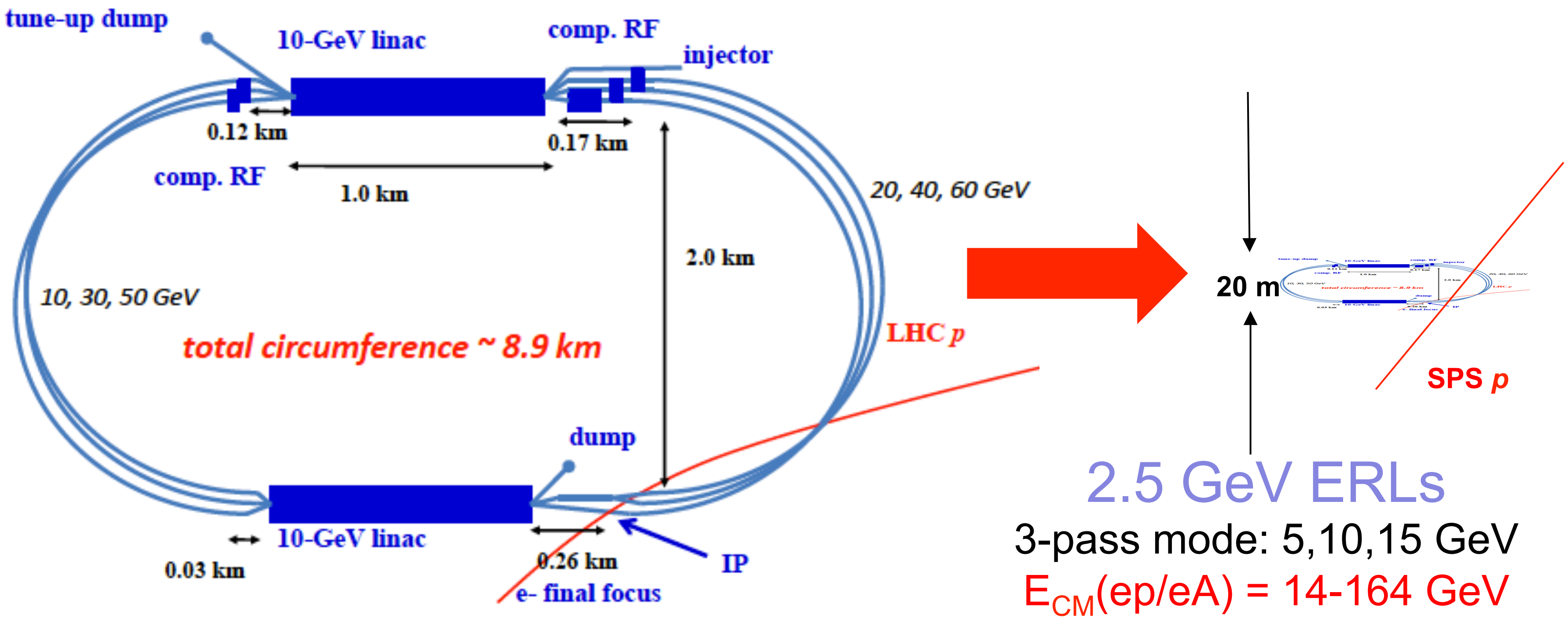
The SPS tunnel

Muon collider ring?

The proton(ion) ring



“EIC with the SPS protons and ions”



2.5 GeV ERLs

3-pass mode: 5,10,15 GeV

E_{CM}(ep/eA) = 14-164 GeV

(covers the energy range of eRHIC, MEIC and ENC@FAIR)

The scaled down ERL of the LHeC project

Muon collider based on a very intense positron source:

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s} \sim 0.212$GeV) in asymmetric collisions

(to collect μ^+ and μ^-)

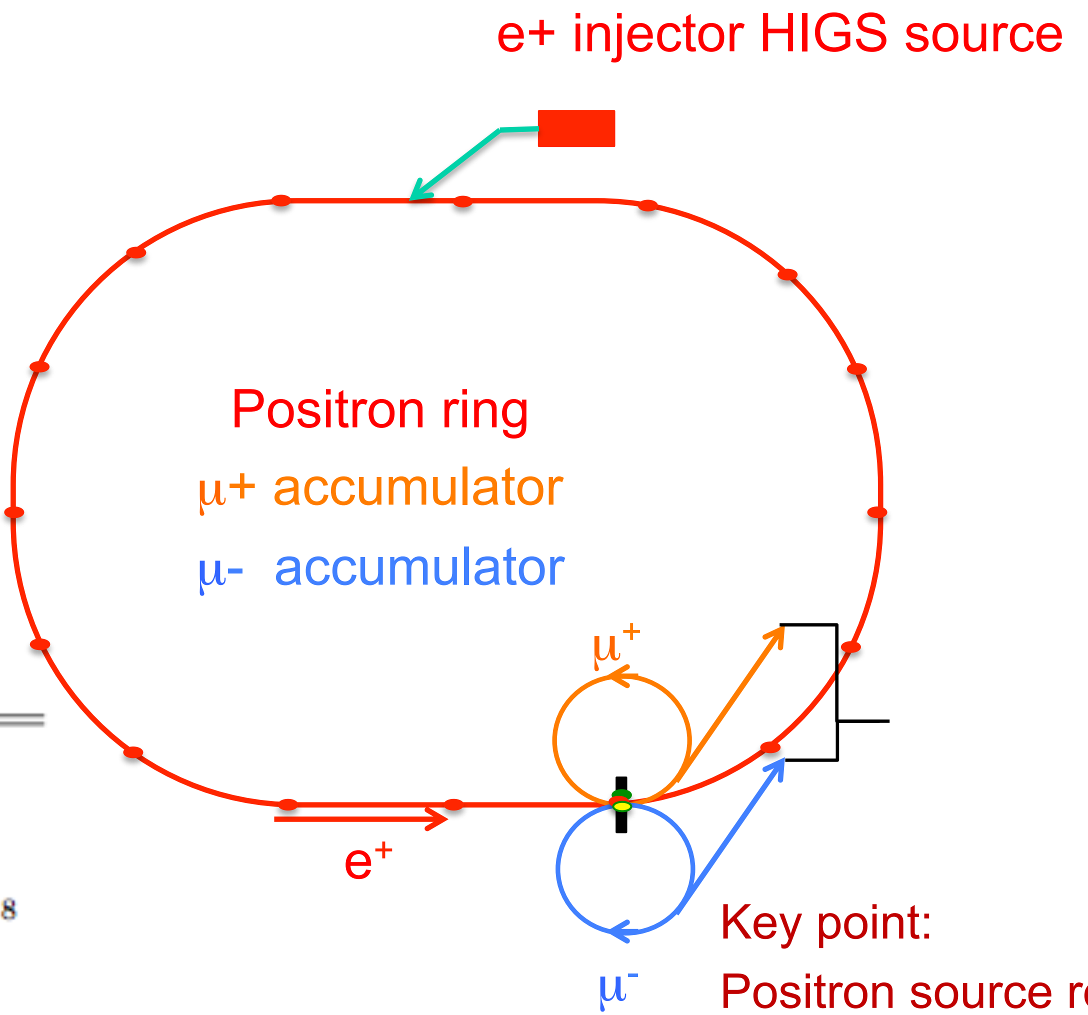
- References:
  - M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, "Novel proposal for a low emittance muon beam using positron beam on target", NIMA online http://www.sciencedirect.com/science/article/pii/S0168900215013364

  Investigation of this idea by SLAC team:

  – Simulations study by SLAC: L. Keller, J. P. Delehaye, T. Markiewicz, U. Wienands, MAP workshop 2014

  – **Presentation in Snowmass 2013**, Minneapolis (USA) July 2013: [M. Antonelli and P. Raimondi, Snowmass report (2013)] also [LNF-Note]

Schematic Layout



B [T]	0.245
$E_{critical}$ [keV]	315
e^+ rate [Hz]	$1.5 \cdot 10^{18}$
$< N_\gamma >$	5763
U_0 [GeV]	0.578
P_{tot} [MW]	139

Key point:
Positron source requirements strictly related to the momentum acceptance

Gamma Factory: Closing remarks

Conclusions

- *The history of our discipline shows that a big technological leaps led to important discoveries – more frequently than the research guided by verification of the theoretical-model's discovery scenarios.*

- *Large laboratories, like CERN, may be soon forced to diversify further their research domains – focussed at present mainly on the high energy frontier – with the existing accelerator infrastructure.*

- *The high energy storage rings (HERA, Tevatron, LHC) are costly – we may be confronted with the need to extend their life time before a new costly infrastructure is build.*