The High Intensity Gamma Source for CERN:

Physics highlights and technical challenges

CERN, November 2015

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Introduction:

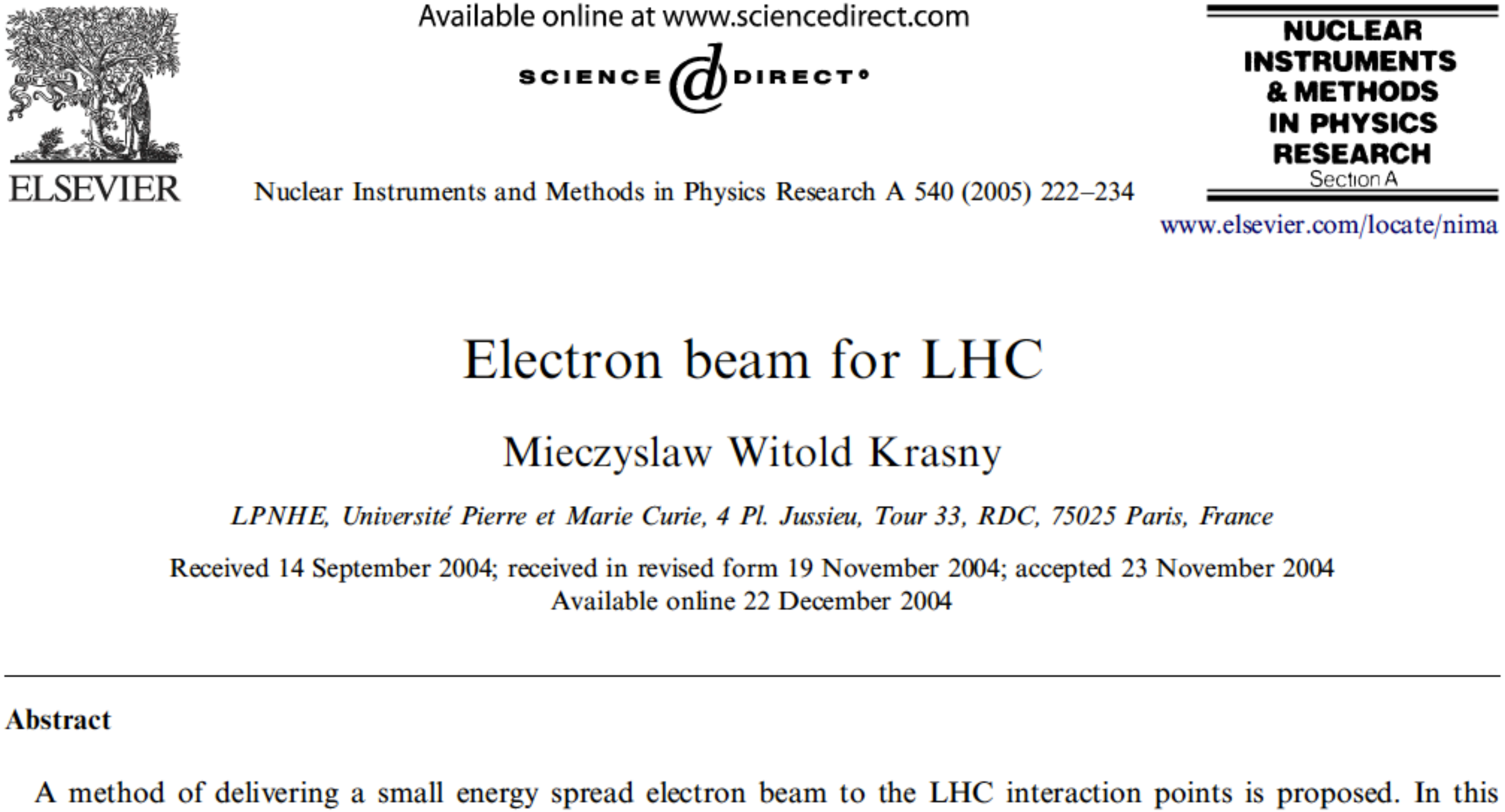
A lesson from the past ?

- Hera and TESLA plans in the 90-ties
- The DESY "QCD-facility" proposal and its role for the future RHIC and LHC scientific programs
- "High" luminosity upgrade and closing the DESY HEP experimental program

Lesson: *worthwhile do develop a new, back-up interdisciplinary program for CERN (on top of the present high-risk flagship ones – FCC, CLIC)… and based on the already existing accelerator infrastructures*

The origin of the proposal

A proposal of an “unconventional” use **of the LHC and its detectors** for the ep(eA) collision programme



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Nuclear Instruments and Methods in Physics Research A 540 (2005) 222–234

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Electron beam for LHC

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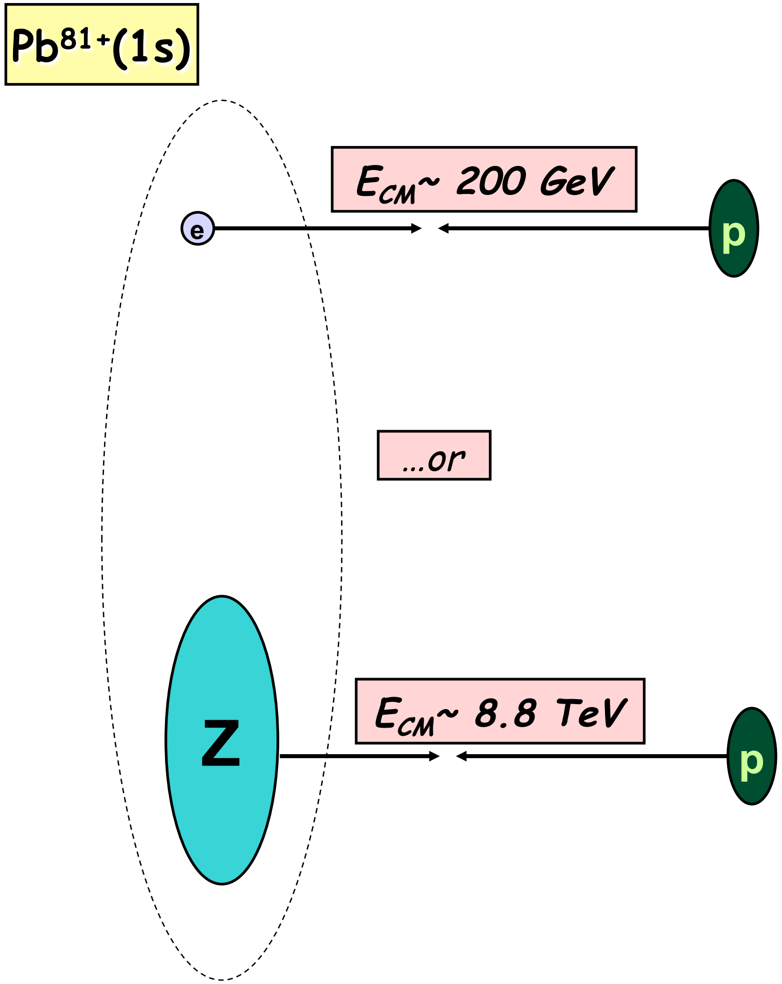
Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004
Available online 22 December 2004

Abstract

A method of delivering a small energy spread electron beam to the LHC interaction points is proposed. In this

Partially stripped ions as electron carriers



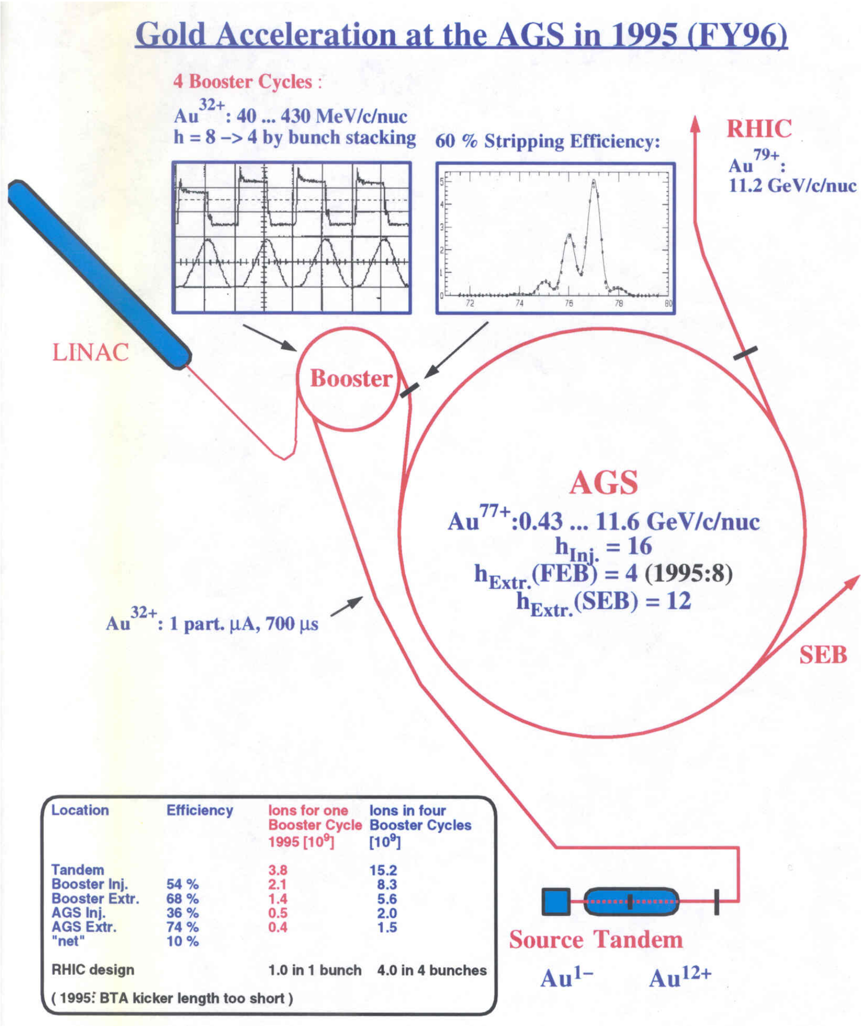
- average distance of the electron to the large Z nucleus d ~ 600 fm (sizably higher than the range of strong interactions)

- 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)

Ion striping sequence:

BNL & **CERN**



Gold Acceleration at the AGS in 1995 (FY96)

4 Booster Cycles :

Au^{32+}: 40 ... 430 MeV/c/nuc

h = 8 –> 4 by bunch stacking

60 % Stripping Efficiency:

RHIC

Au^{79+}:

11.2 GeV/c/nuc

AGS

Au^{77+}:0.43 ... 11.6 GeV/c/nuc

$h_{Inj.}$ = 16

$h_{Extr.}$(FEB) = 4 (1995:8)

$h_{Extr.}$(SEB) = 12

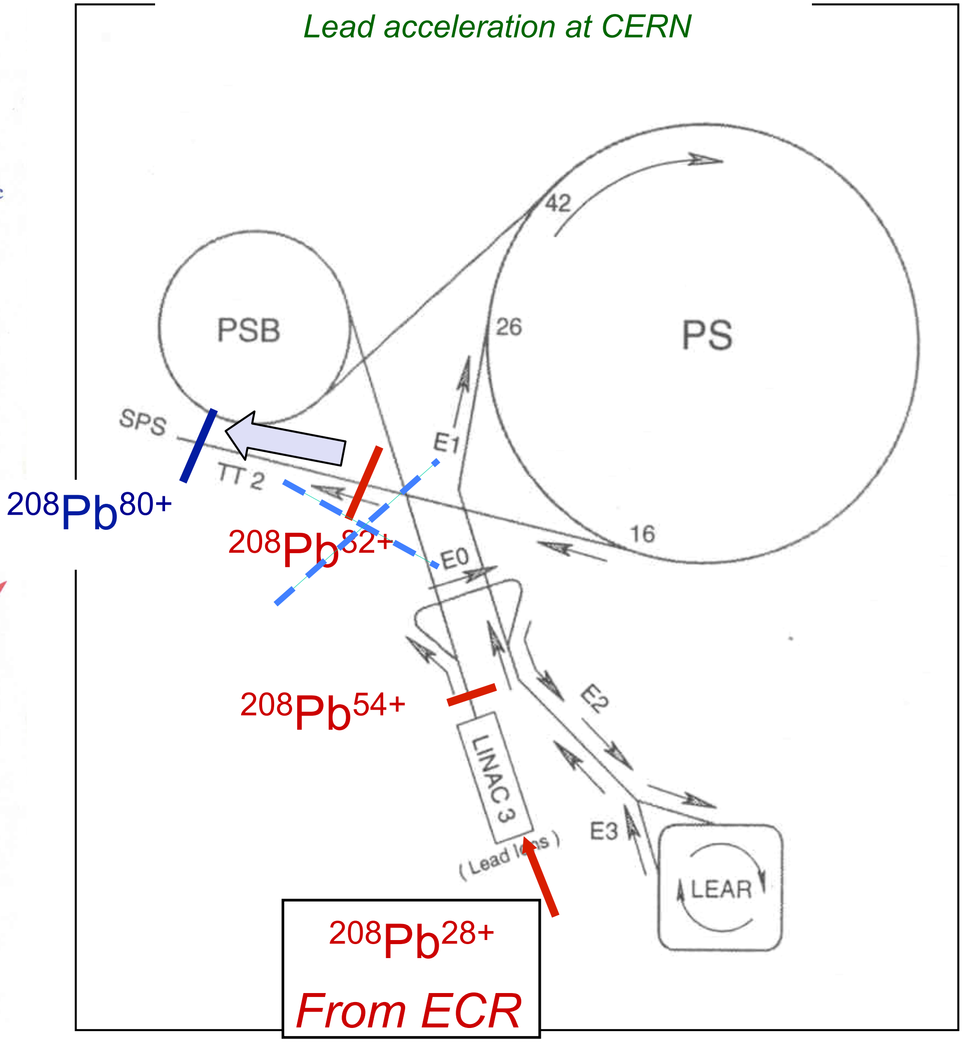
Au^{32+}: 1 part. µA, 700 µs

Source Tandem

Au^{1-} Au^{12+}

Location	Efficiency	Ions for one Booster Cycle 1995 [10^9]	Ions in four Booster Cycles [10^9]
Tandem		3.8	15.2
Booster Inj.	54 %	2.1	8.3
Booster Extr.	68 %	1.4	5.6
AGS Inj.	36 %	0.5	2.0
AGS Extr.	74 %	0.4	1.5
"net"	10 %		
RHIC design		1.0 in 1 bunch	4.0 in 4 bunches

(1995: BTA kicker length too short)



Lead acceleration at CERN

$^{208}Pb^{80+}$

$^{208}Pb^{82+}$

$^{208}Pb^{54+}$

$^{208}Pb^{28+}$

From ECR

PIE@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}

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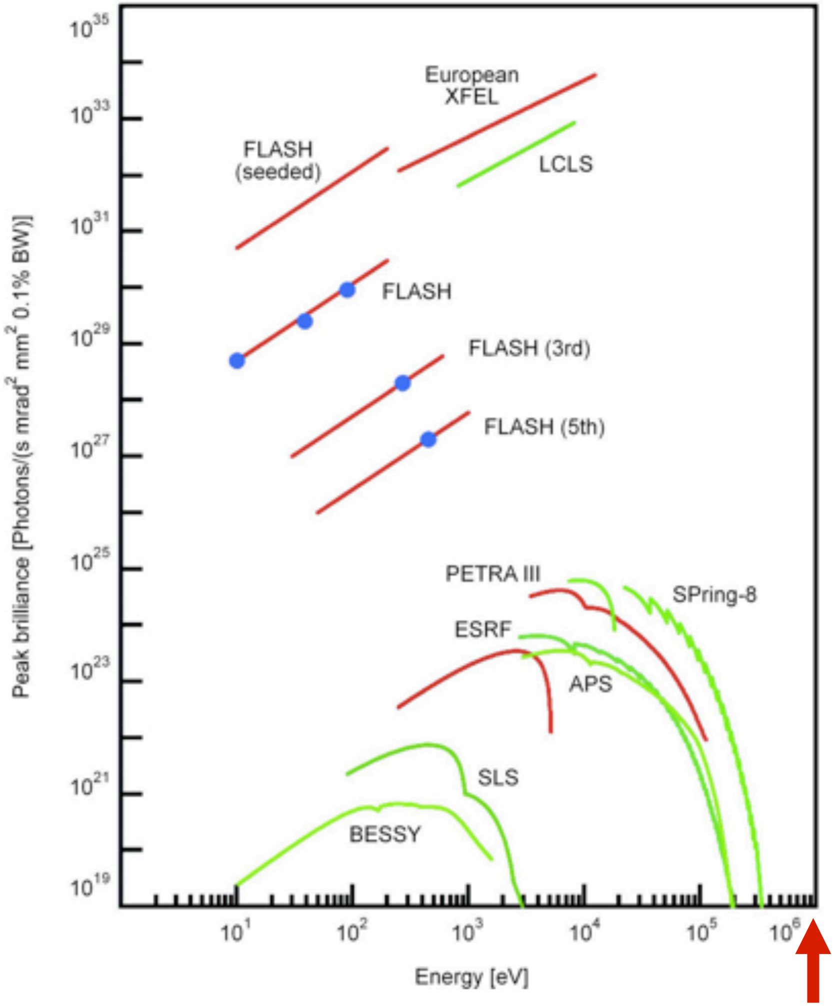
* PIE = Parasitic Ion Electron collider

High Intensity Gamma Source for CERN

…and the existing (future) light-source projects

X-ray sources

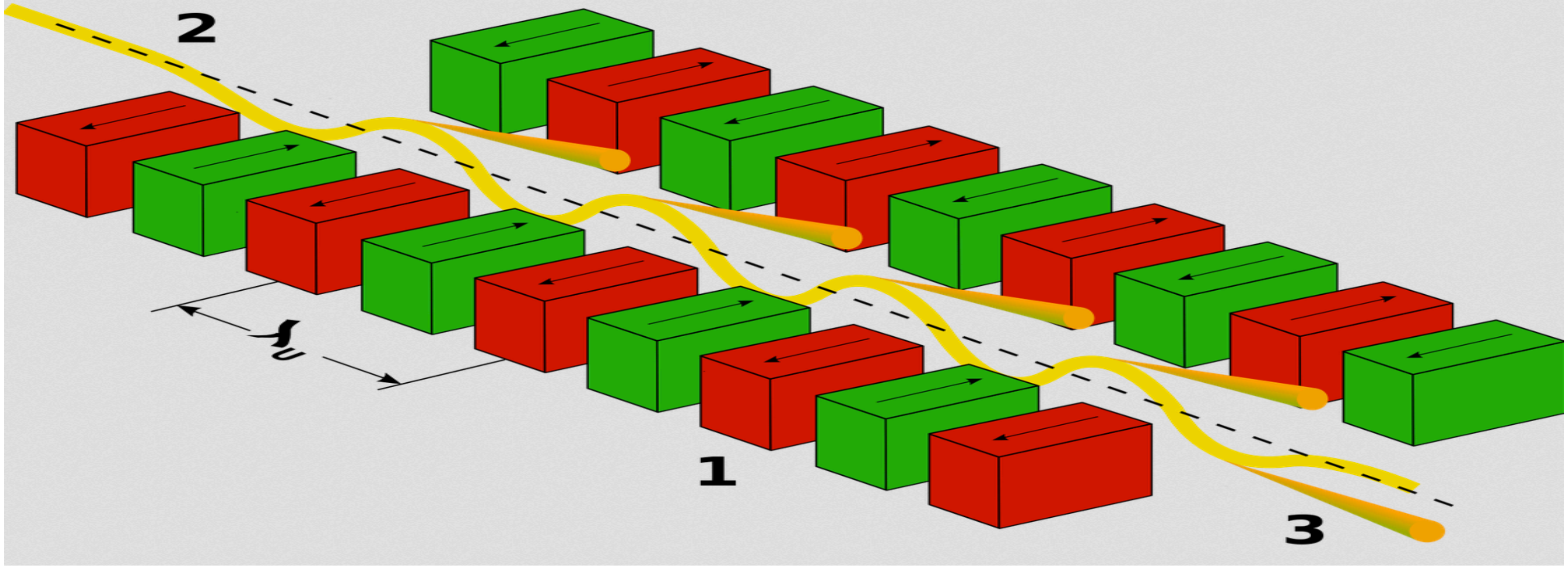


MeV

atomic structures

How about the quanta capable of resolving/manipulating the nuclear structure and allowing to copiously produce matter particles (γ-ray domain)?

FEL as a gamma ray source?

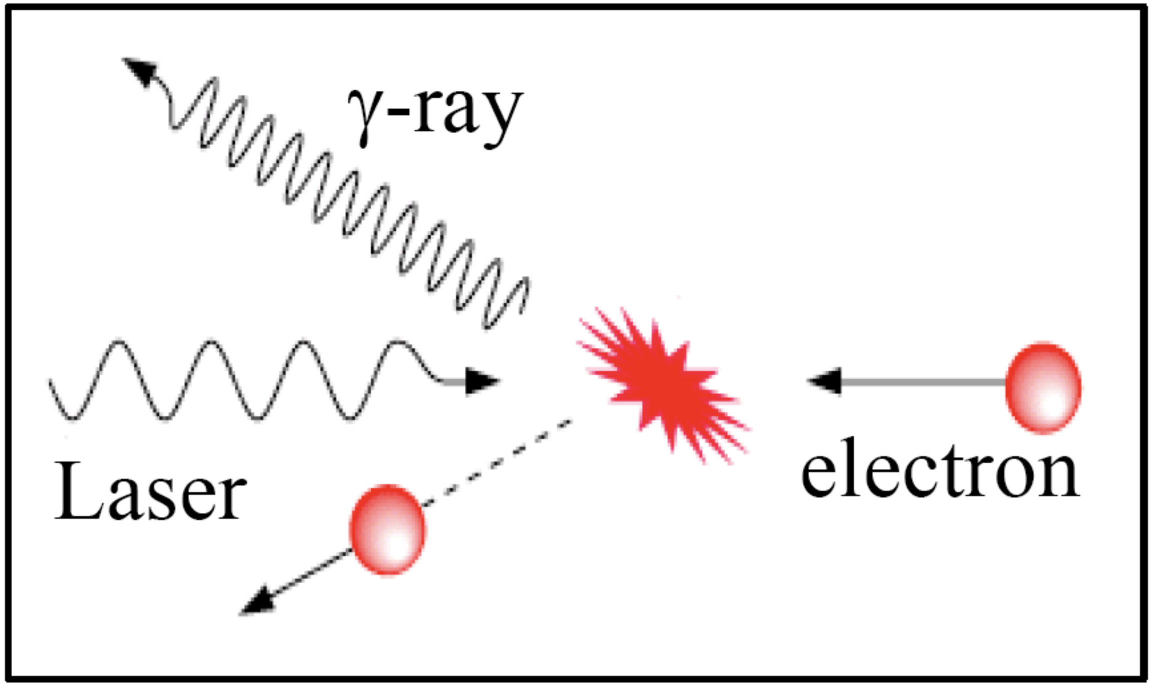


$$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + K^2),$$

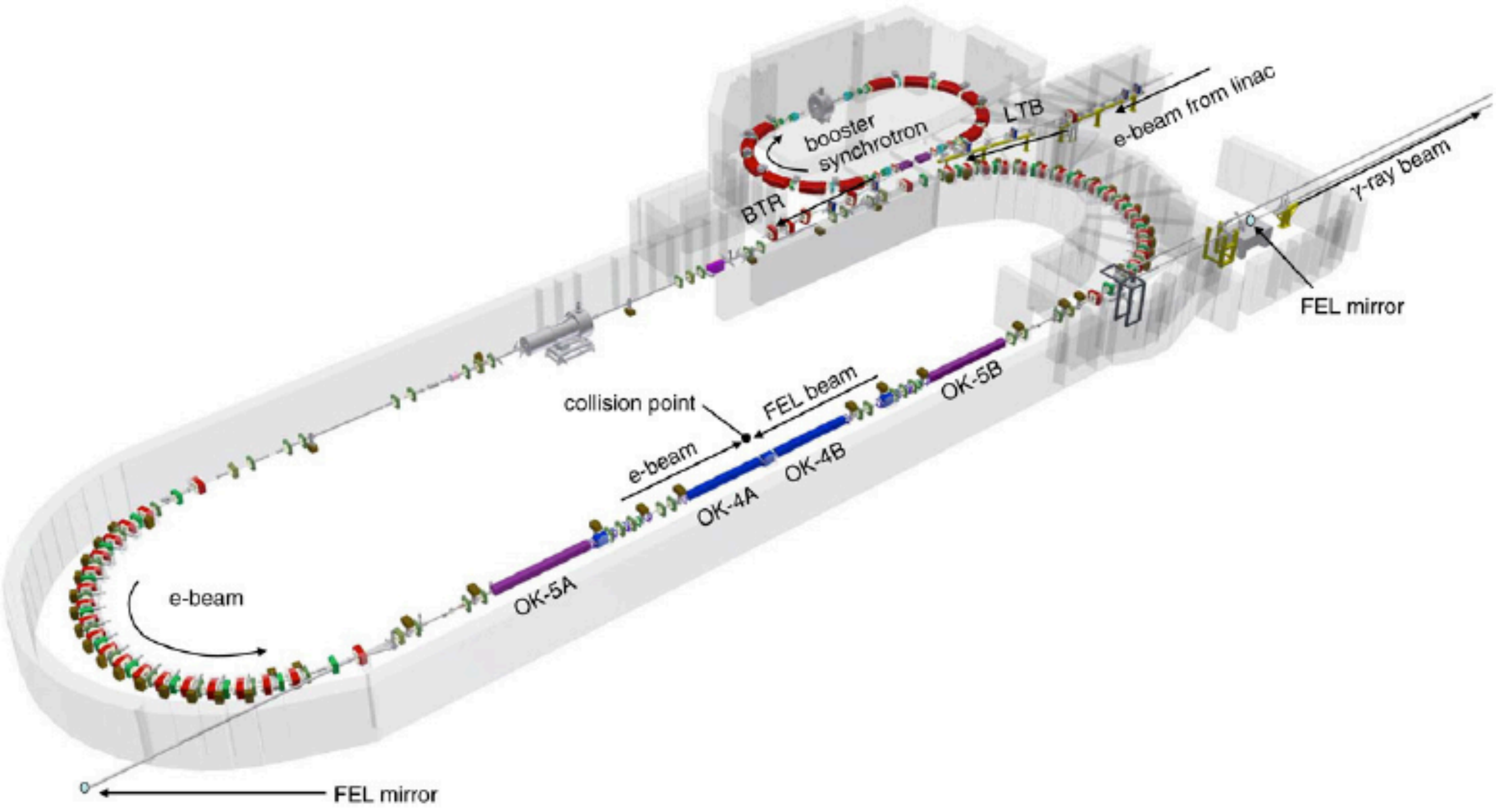
$$K = \frac{\gamma\lambda_u}{2\pi\rho} = \frac{eB_0\lambda_u}{\sqrt{8}\pi m_e c}$$

Need the low emittance electron beams spanning the beam energy range of 1-10 TeV (assuming O(10 cm) period of magnetic field)

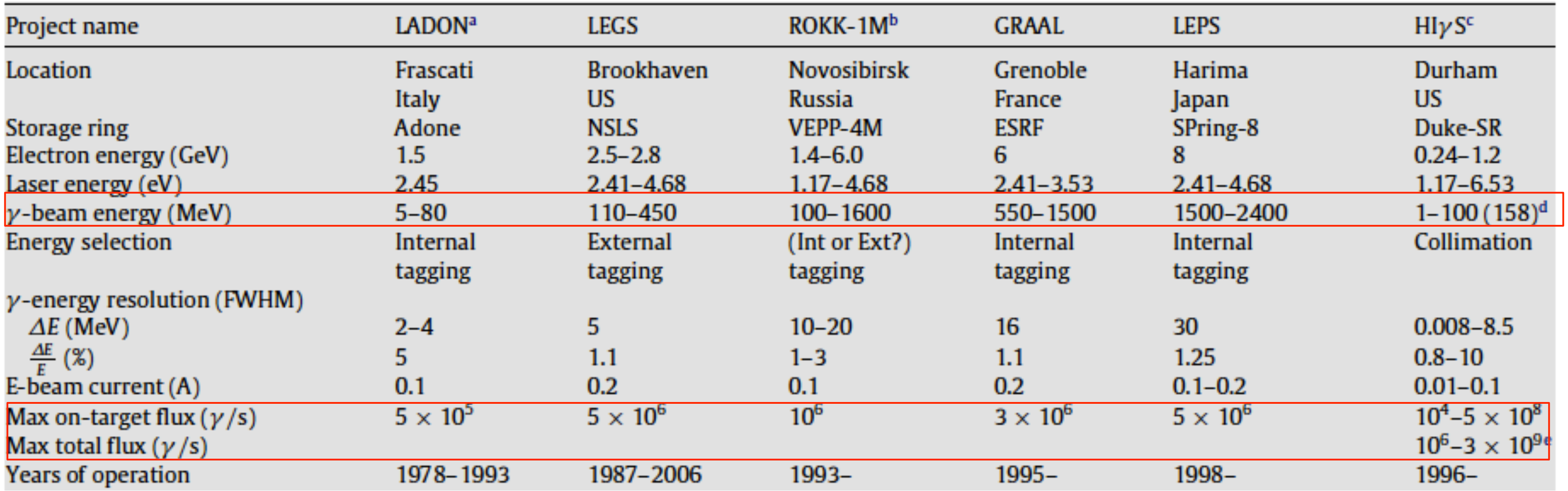
Laser Compton Scattering as the source of MeV-range photons



The Duke University Gamma source



Parameters of the gamma source facilities around the world



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–

The goal:

achieve comparable fluxes in the MeV domain as those in the KeV domain.

For comparison:

DESY FEL: photons/pulse -- 10^{11}-10^{13}, pulses/second –10-5000 → **(10^{12} – 10^{17} photons/s)**

The goal of the HIGS@CERN proposal

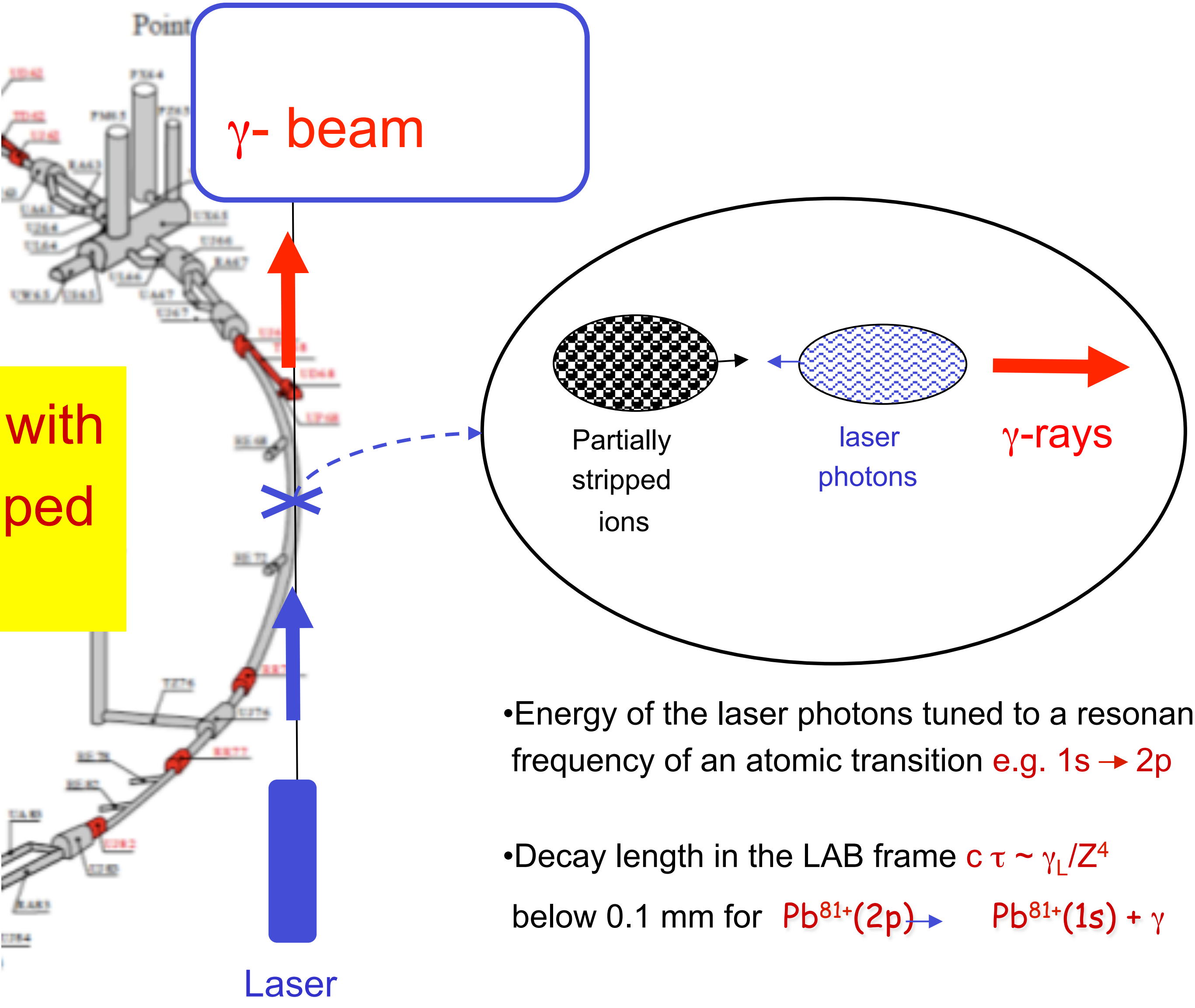
*(HIGS= **H**igh **I**ntensity **G**amma **S**ource)*

Increase the intensity of the present gamma ray sources by at least 6-7 orders of magnitude

E_γ in the range ~ 0.1- 400 MeV

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 $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

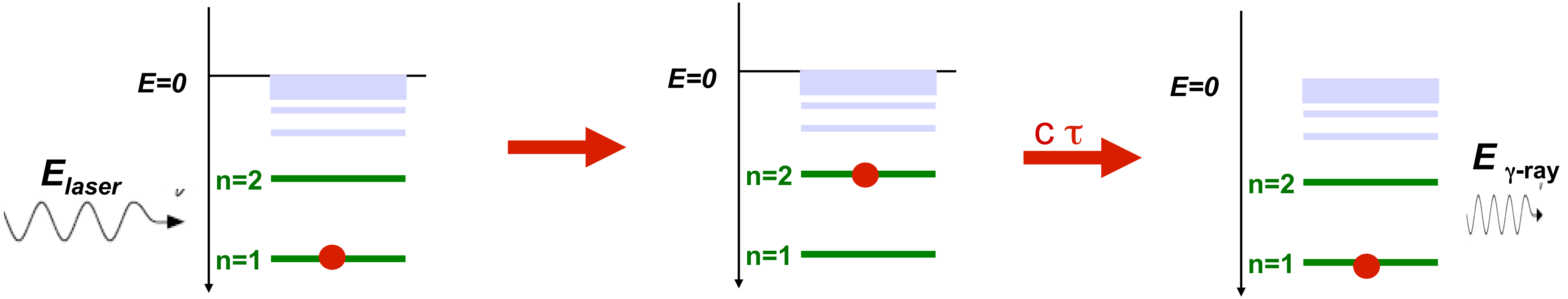
LHC partially stripped ion beams as the light frequency converter:

$$\nu_i \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

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

Scattering of photons on ultra-relativistic atoms

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

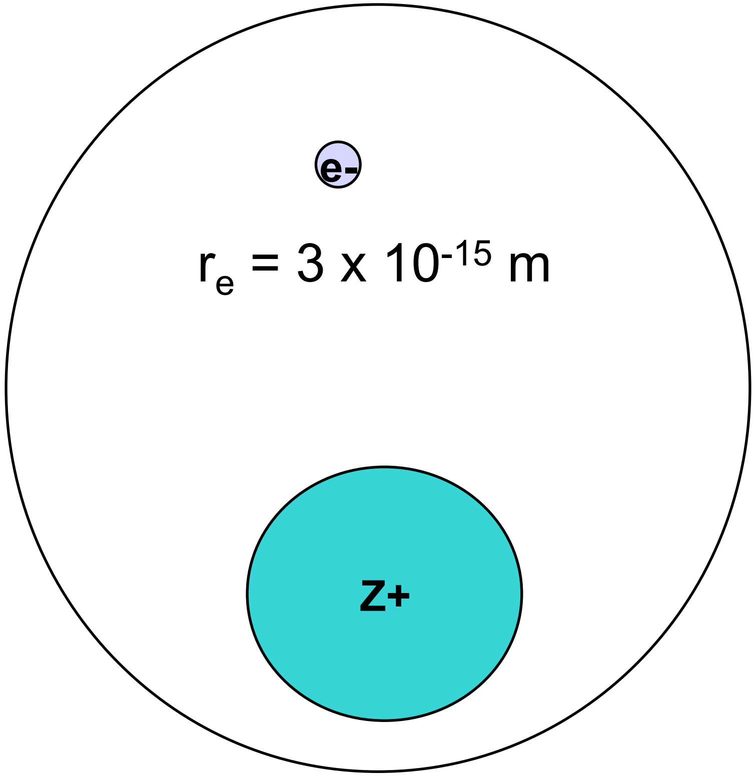


$E_{laser} = 1Ry\ (Z^2 - Z^2/n^2)/2\gamma_L$

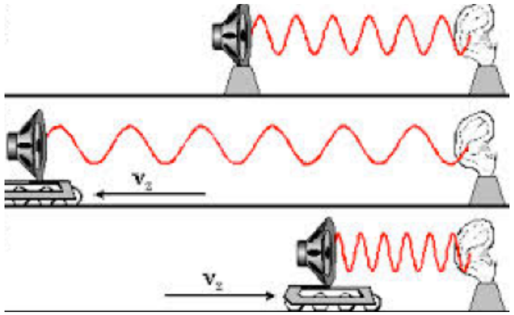
$E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^2/(1+(\gamma_L\theta)^2)$

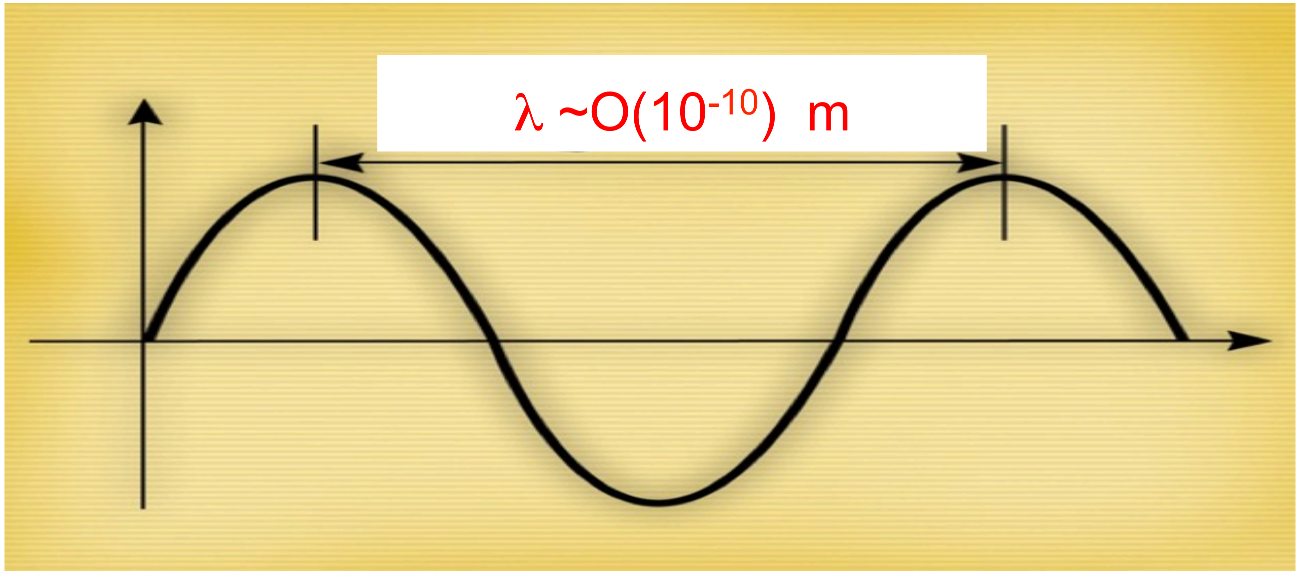
Note: $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

Doppler Effect and Resonant Scattering



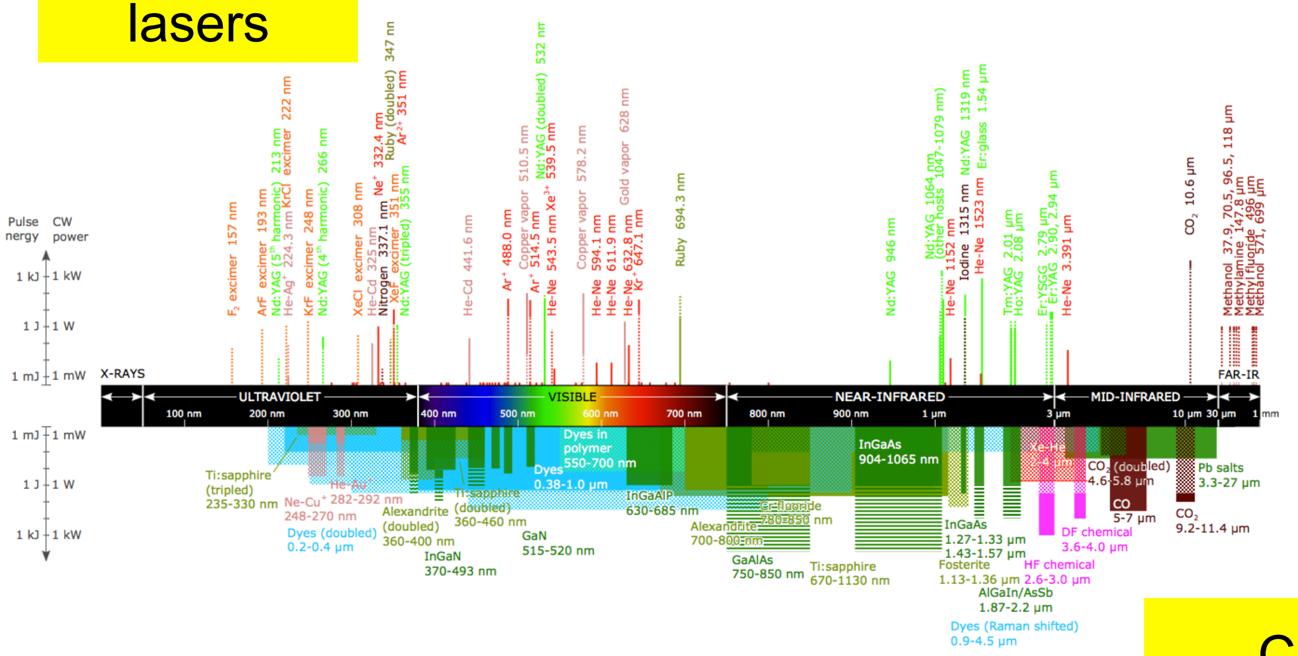
$r_e = 3 \times 10^{-15}$ m



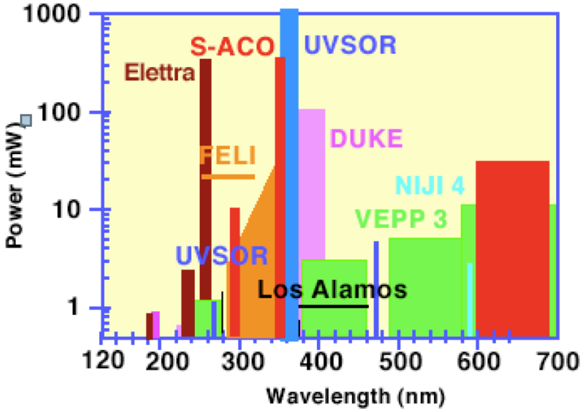


$\lambda \sim O(10^{-10})$ m

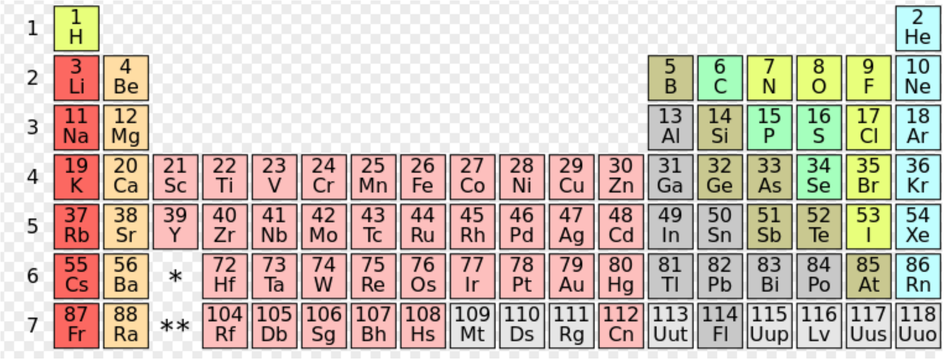
lasers



mirrors

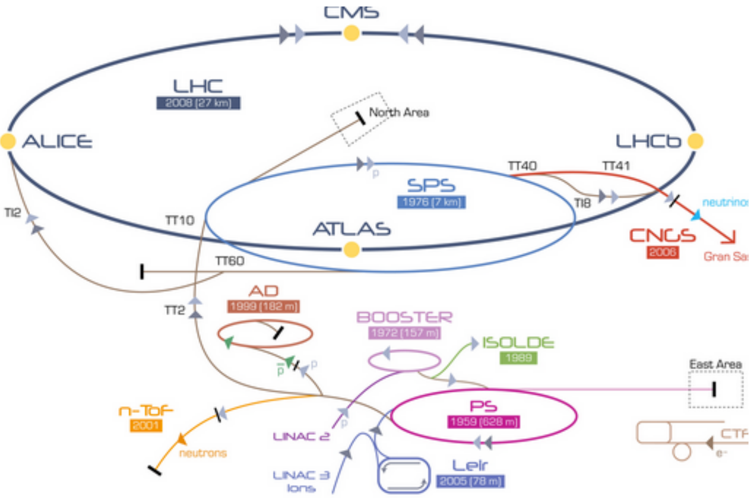


Ions



1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

CERN accelerators



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*, $\gamma_L=2887$, $n=1\rightarrow2$,

E_γ (max) = 396 MeV

Scenario 2 (nuclear physics application):

Erbium doped glass laser: 1540 nm, Ar^{16+} *ion*, $\gamma_L=2068$, $n=1\rightarrow2$, E_γ (max) = 13.8 MeV

Scenario 3 (SPS initial feasibility studies) :

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

E_γ (max) = 0.196 MeV

The comparison of the partially stripped ion beam driven LHC-based HIGS and the electron-beam driven Laser-Compton-Scattering (LCS) gamma sources

Beam energy equivalence

The LHC ion energies of:

1-3 TeV/nucleon

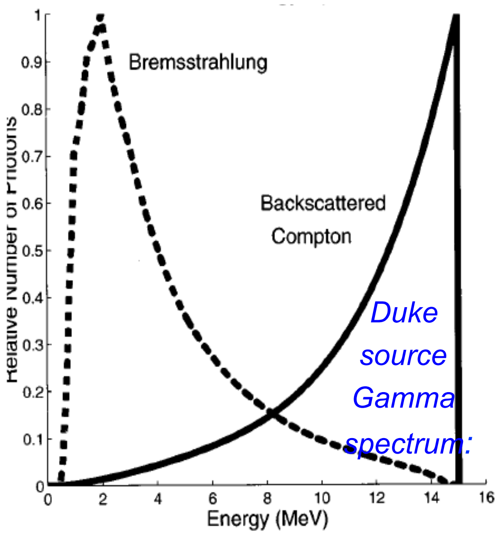
are equivalent to the energies of:

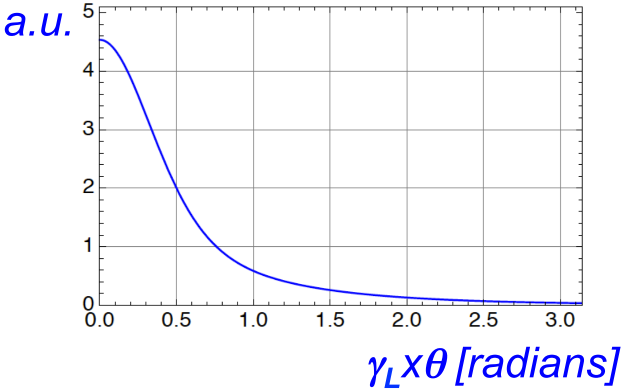
0.5-1.5 GeV

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

Fine tuning of gamma ray energy: *E* $_\gamma$

scenario 2, λ_{laser} = 1540 nm

Electrons:

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

Partially stripped ions:

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

…cross sections in the Giga-barn range!

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!

Principal advantages of the ion-based light sources

Fluxes:

The Rayleigh resonant cross section for partially stripped ions is higher by a factor $(\sim\lambda_{res}/r_e)^2$ than the Thompson cross-section for electrons

The "cross-section gain" in the γ-flux of the order of 10^{7-11} for the same intensity of the laser light an the same beam crossing geometry as in the Duke Facility

Beam rigidity:

Ions bunches are "undisturbed" by the light emission. Electron bunches are.

… only a partial remedy: e-beam is recycled to accelerate succeeding beam (ERL)

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

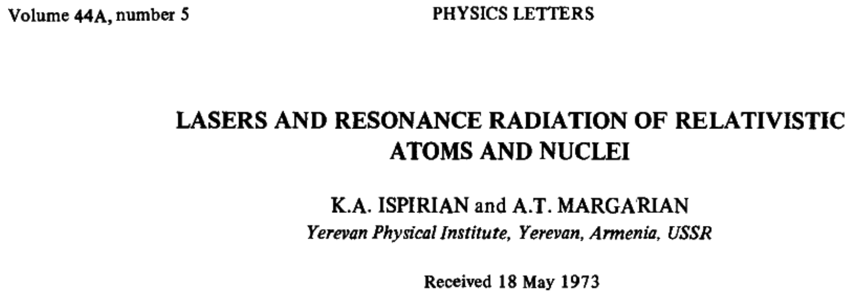
Flexible setting. Reflect, in both cases the polarization of the laser light

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

Light sources based on partially stripped ions have been proposed and discussed already in several papers:

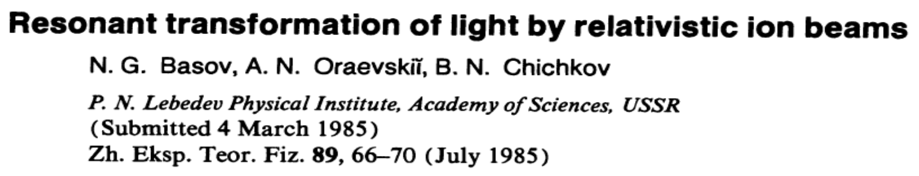


Volume 44A, number 5 PHYSICS LETTERS

LASERS AND RESONANCE RADIATION OF RELATIVISTIC ATOMS AND NUCLEI

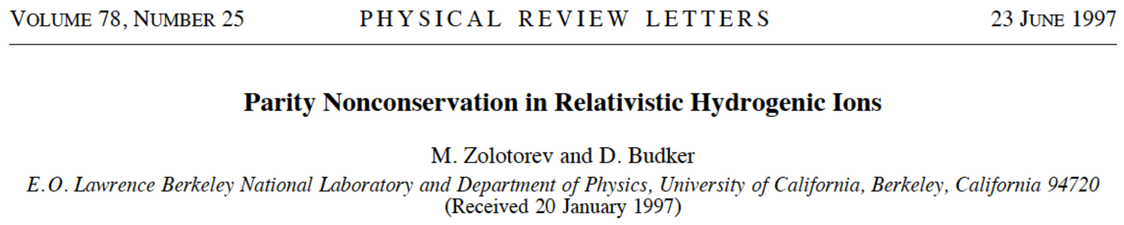
K.A. ISPIRIAN and A.T. MARGARIAN
Yerevan Physical Institute, Yerevan, Armenia, USSR

Received 18 May 1973



Resonant transformation of light by relativistic ion beams

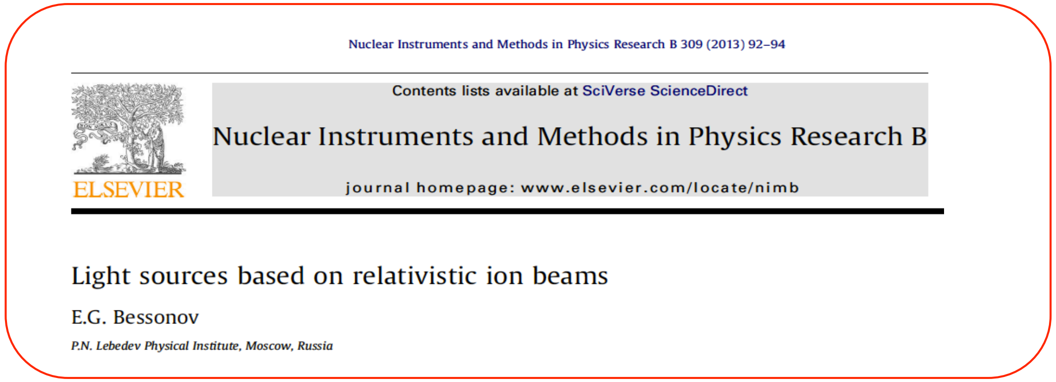
N. G. Basov, A. N. Oraevskiĭ, B. N. Chichkov
P. N. Lebedev Physical Institute, Academy of Sciences, USSR
(Submitted 4 March 1985)
Zh. Eksp. Teor. Fiz. **89**, 66–70 (July 1985)



VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker
E.O. Lawrence Berkeley National Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 20 January 1997)



Nuclear Instruments and Methods in Physics Research B 309 (2013) 92–94

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

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Light sources based on relativistic ion beams

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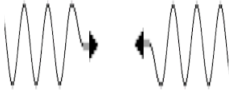
P.N. Lebedev Physical Institute, Moscow, Russia

…thanks to **Alexey Petrenko** for drawing my attention to the initial ideas and earlier work in this domain…

Physics highlights

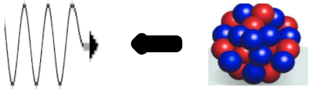
- **particle physics** (studies of the basic symmetries of the universe, dark matter searches, muon collider physics, neutrino-factory physics, precision-support measurements for the LHC),
- **nuclear physics** (confinement phenomena, link between the quark-gluon and nucleonic degrees of freedom, photo-fission research program),
- **accelerator physics** (beam cooling techniques, low emittance hadronic beams, high intensity photon beams, plasma wake field acceleration, high intensity polarized positron and muon sources, secondary beams of radioactive ions and neutrons, electron-ion collider, muon collider, neutrino-factory),
- **atomic physics** (electronic and muonic atoms),
- **applied physics** (AdS, transmutation of nuclear waste, fusion research, medical applications).

The use of the gamma beams



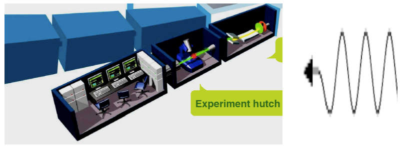
$\gamma-\gamma$ collisions, E_{CM} =2-800 MeV

$\gamma-\gamma_L$ collisions, E_{CM} =1-126 keV



γ−p,A collisions, E_{CM} =4-60 GeV

secondary beams of electrons, positrons, muons, neutrons and radioactive nuclei



Medical applications, nondestructive assay and segregation of nuclear waste, photo transmutation of nuclear waste using resonant (γ,n) transitions, γ-ray laser?, nuclear fusion and fission, ADS, wake field for plasma acceleration, material science…

The expected intensity of the primary and secondary HIGS beams

Disclaimer: The presented below initial estimation of the achievable fluxes are preliminary. For the LHC-based partially stripped ion based gamma source the intensity limits are driven predominantly by the present circumferential voltage of the LHC ring and by the stability of the ion beams, rather than by the laser power and the collision geometry (electron beam driven sources).

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:

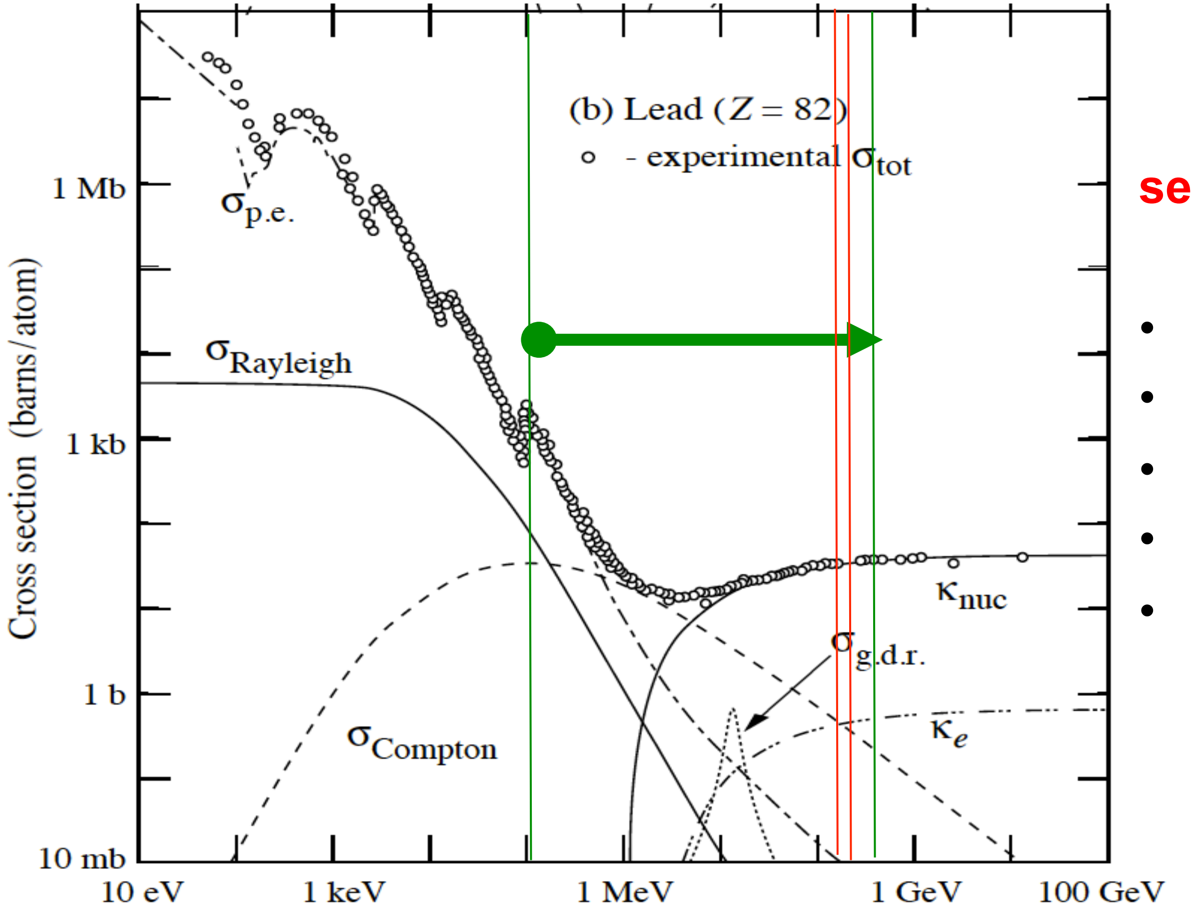
Erbium doped glass laser: 1540 nm, Ar^{16+} *ion*, γ_L=2068,

n=1→2, $E_\gamma^{(max)}$ = 13.8 MeV, **N^{max}_γ ~ 3 x 10^{17}** [1/s]

Comments:

1. $N^{\gamma}_{max} = N^{ion}_{bunch} \times N_{bunches} \times f\,[1/s] \times RF\,[MV] \times Z / \langle E_\gamma\,[MeV]\rangle$.

2. For scenario 2, where $c\tau_{exited\ ion}$ = 1.2 cm, the effect of the double photon absorption process, and the beam life-time remains to be calculated… if necessary it ccould be circumvented by using a pulsed laser beam



secondary beams:

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

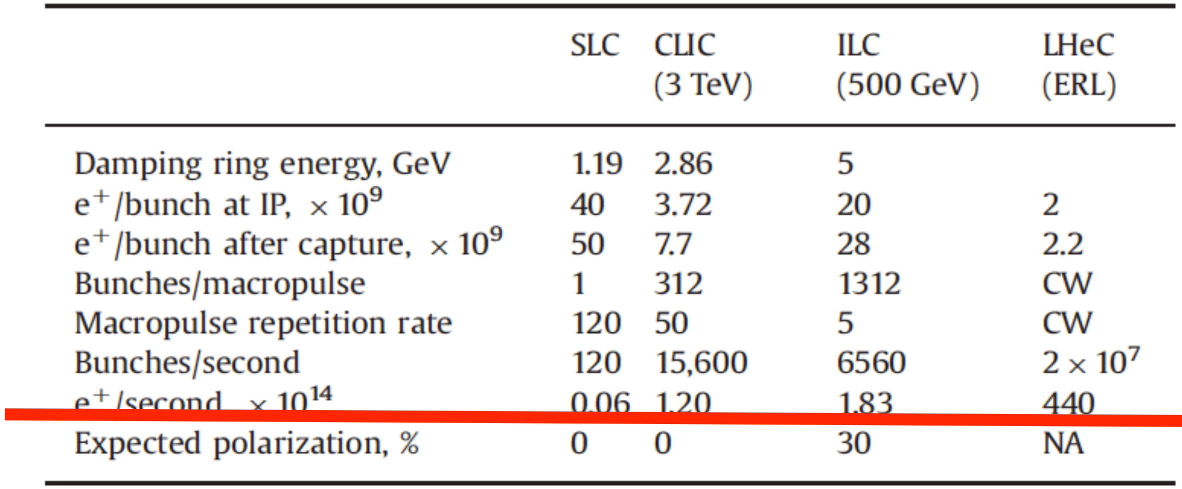
$\sigma_{p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited
$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair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

HIGS as a source of high intensity secondary beams

- *High Intensity highly polarised electron and positron beams (~10^{17} 1/s)*
- *Polarized muon and neutrino beams (~10^{12} 1/s and 4x10^{19} 1/year)**
- *High intensity monochromatic neutron beams (GDR in heavy nuclei as s a source of neutron beam: γ + A →A-1 + n) (~10^{15} 1/s)*
- *High intensity radioactive beams (~10^{14} 1/s)*
  (photo-fission of heavy nuclei:($\gamma + A \rightarrow A_1 + A_2$ + neutrons)

**) for the quoted 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.*

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



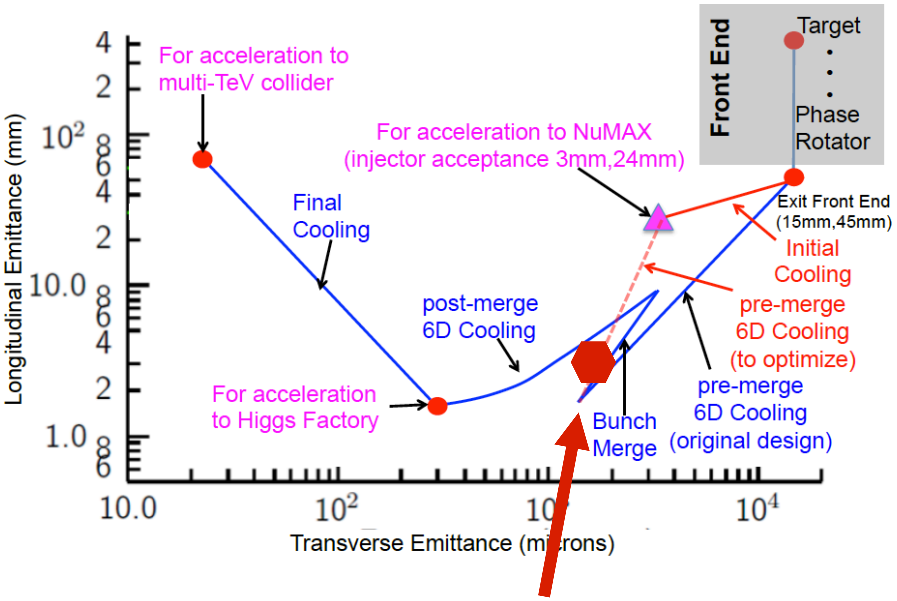
	SLC	CLIC (3 TeV)	ILC (500 GeV)	LHeC (ERL)
Damping ring energy, GeV	1.19	2.86	5	
e^+/bunch at IP, $\times 10^9$	40	3.72	20	2
e^+/bunch after capture, $\times 10^9$	50	7.7	28	2.2
Bunches/macropulse	1	312	1312	CW
Macropulse repetition rate	120	50	5	CW
Bunches/second	120	15,600	6560	2×10^7
e^+/second, $\times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

Bonus: polarization (>80%)

For scenario 2: the flux of ~10^{17} N^{e+e-} /s can 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



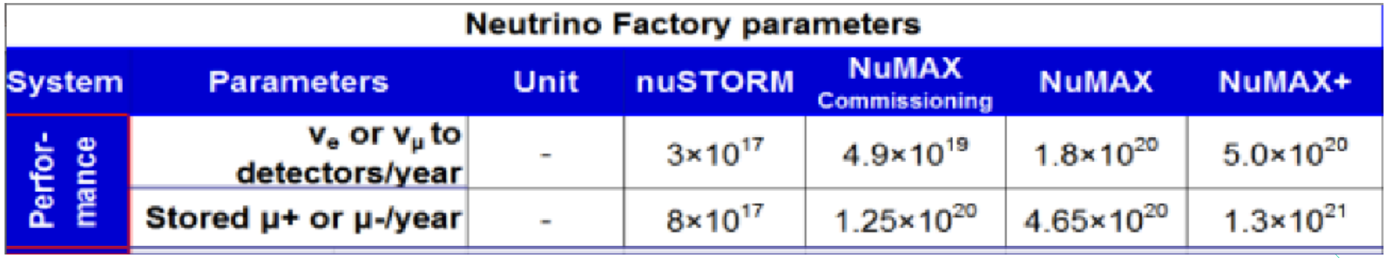
HIGS muon flux (factor 10 lower than required)up to 10^{12} polarized μ+μ^- pairs [1/s] for 4MW RF power of the LHC cavities (For comparison: TLEP RF power ~300MW)

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

Neutrino-factory requirements



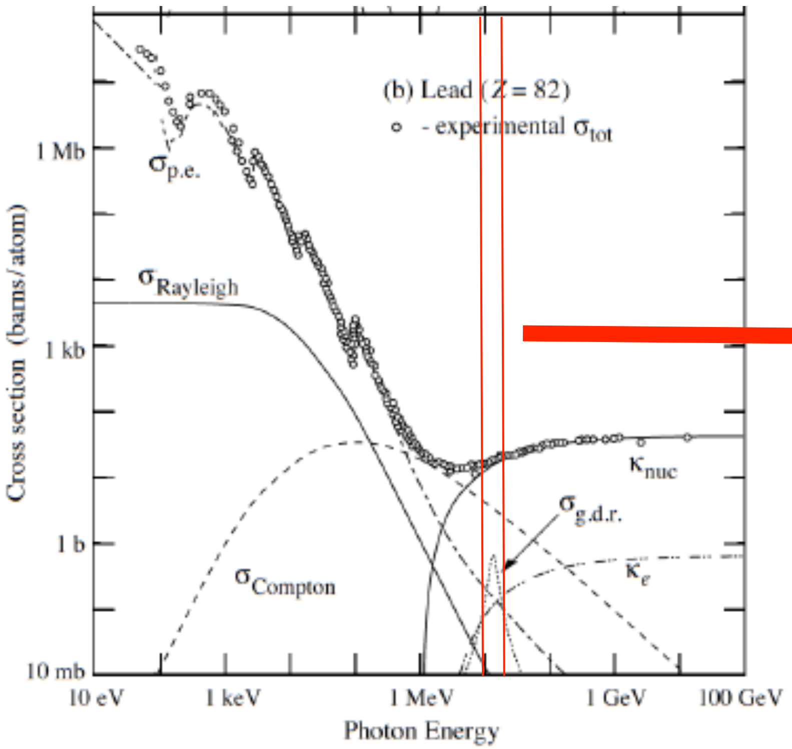
Neutrino Factory parameters

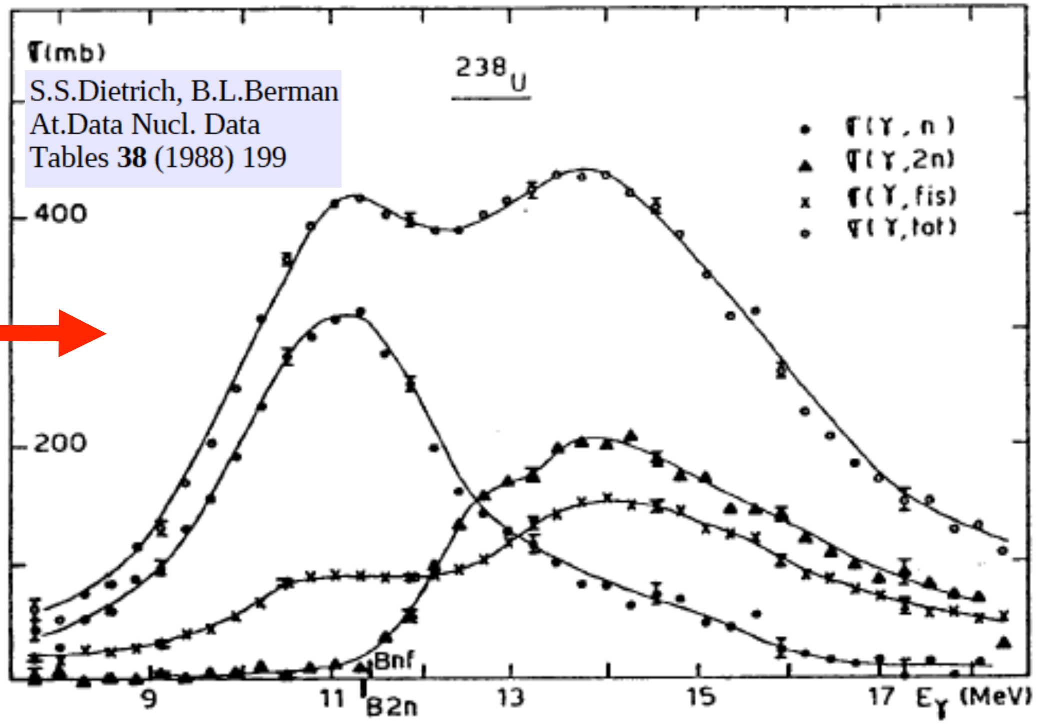
System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Perfor-mance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}

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)

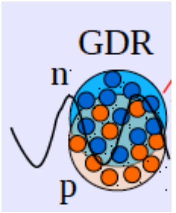
Secondary Neutron and Radioactive Beams





S.S.Dietrich, B.L.Berman
At.Data Nucl. Data
Tables **38** (1988) 199

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 **$\sim 10^{15}$ 1/s**
- fission products **$\sim 10^{14}$ 1/s**

Selected technical challenges

Meeting these challenges is anything but easy – the feasibility of Gamma Source concept is far from being proven, it needs detailed studies – what will be shown in the following are all preliminary ideas/calculations

… the input of the accelerator experts (your input) is a *sine qua non* condition to move forward with this project

1. Life-time of partially stripped ion beams

- Bunch temperature $T_b << 1$ Ry × Z^2 at all the acceleration stages - (radiative 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

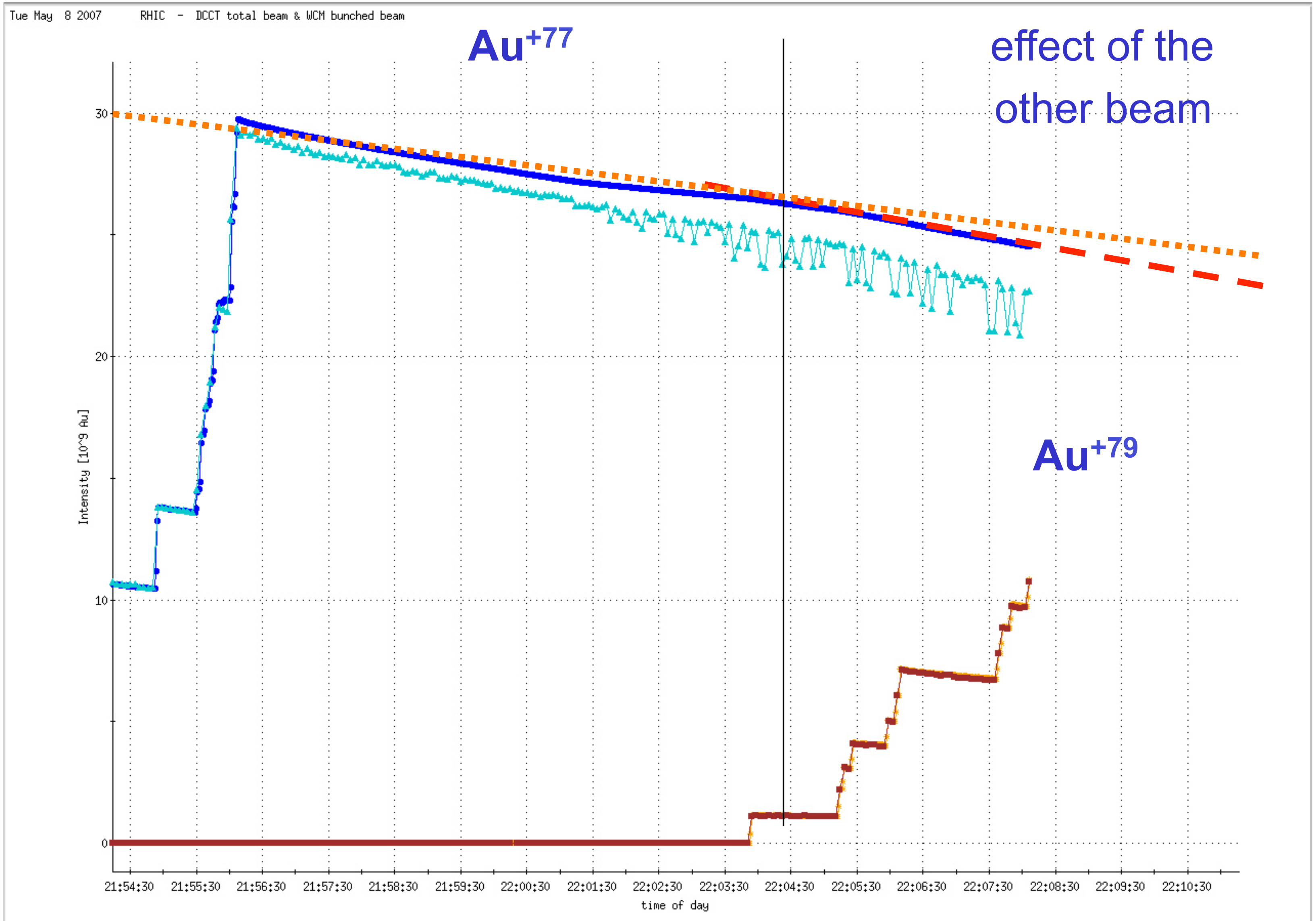
- Ionization process

  -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…)

Gold with two electrons successfully stored in RHIC

Dejan Trbojevic (Apex workshop 2007)



Au^{+77}

effect of the other beam

Au^{+79}

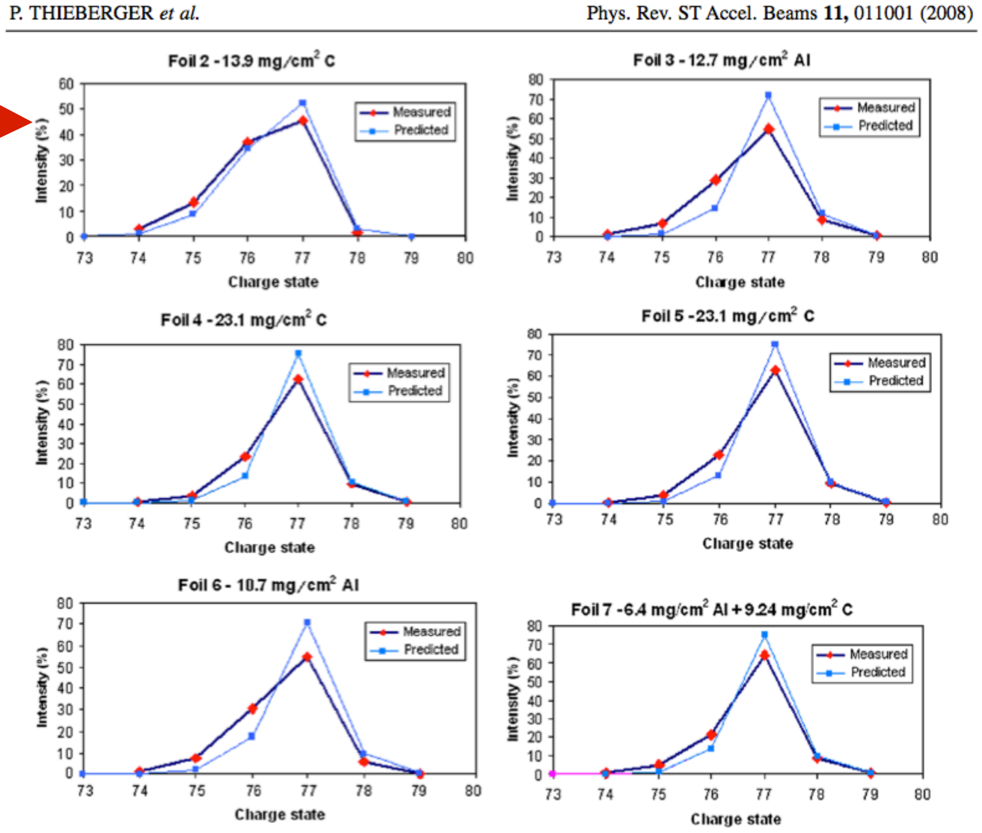
Storage of the partially stripped ion beam is not a science-fiction !

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?

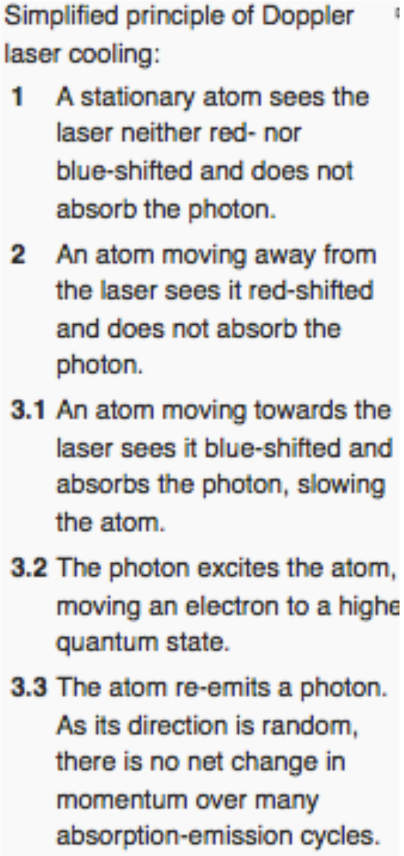
- If successful measurement of the life-time of the partially stripped lead ion beam in the LHC?

- If successful first ep, eA collisions in ATLAS, CMS, ALICE &LHCb


P. THIEBERGER *et al.* Phys. Rev. ST Accel. Beams **11,** 011001 (2008)

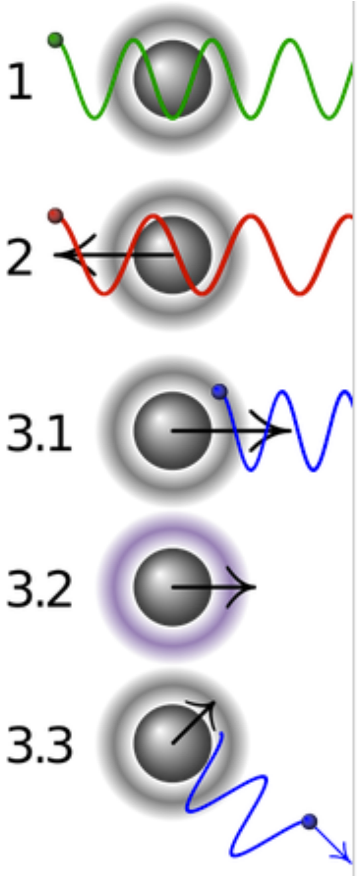
Target type and thickness optimisation for the BNL Au^{77+} beams (two electrons attached)

2. Beam cooling (methods of atomic physics)



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.



Crystalline beams created by atomic physics using laser cooling techniques

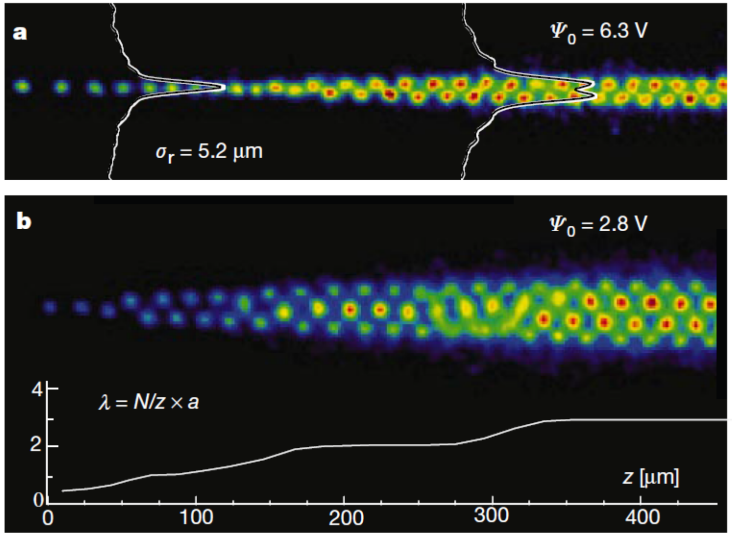


Figure 1 Images of ion crystals at rest in PALLAS. False colours reflect the fluorescence intensity of individual ions. The ions are longitudinally confined in a weak static potential[12] which is generated by the two drift tubes, highlighted in Fig. 2. The crystal becomes more complex when the linear ion density $\lambda = (N/z) \times a$, N denoting the number of particles and a the Wigner–Seitz radius[19], increases with lowered confining potential ψ_0 from **a** to **b** or when it increases stepwise along the axis z because of the weak longitudinal confinement, as illustrated in **b**. The radius $\sigma_r = 5.2$ µm of the linear ion string mainly reflects the overall spatial resolution (integration time 0.4 s).

Two 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 $\varepsilon_x = 3 \times 10^{-15}$ mrad (E.G. Bessonov)

2. Enhanced cooling

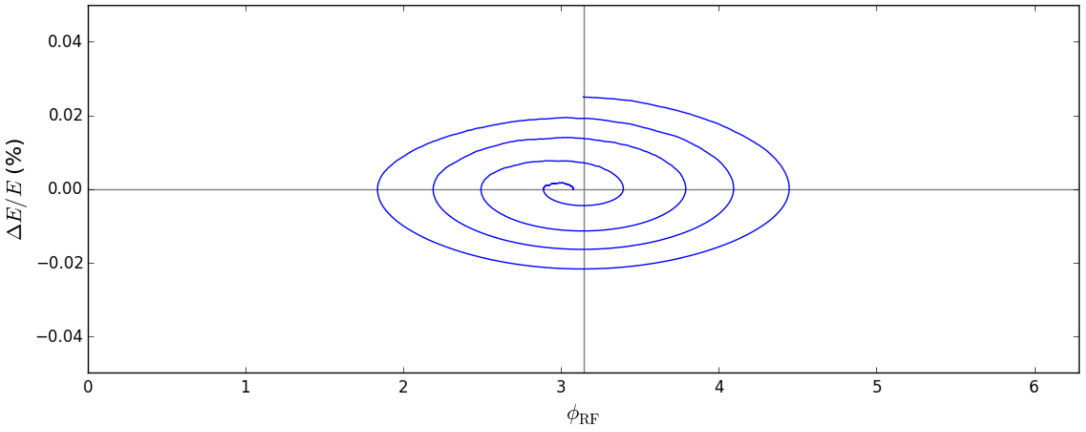
Linear rise of the laser beam power in the frequency interval within the a fraction of a broad bam region (previous case)

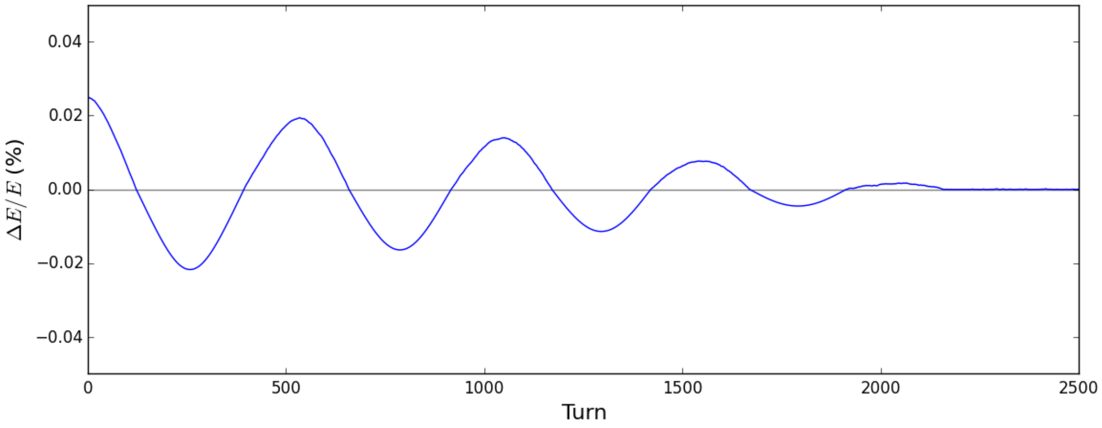
The dumping time is reduced to t =0.1 s (note cooling mainly in longitudinal direction, emittance exchange schemes must be applied..)

---

[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.

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





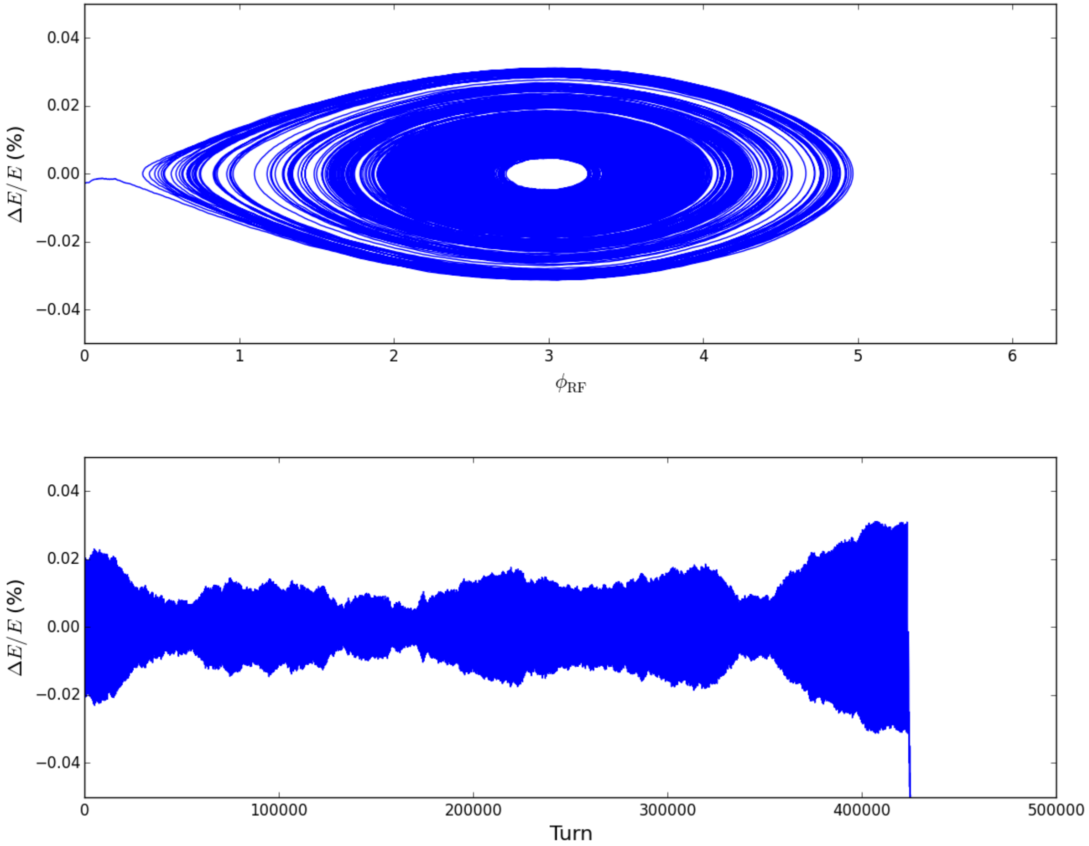
Scenario 1:

Laser frequency band covers the ΔE >0 energies (negative ΔE out of the resonance)

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

Possible use of the ultra-cold ion beam in Wake-field plasma acceleration?

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



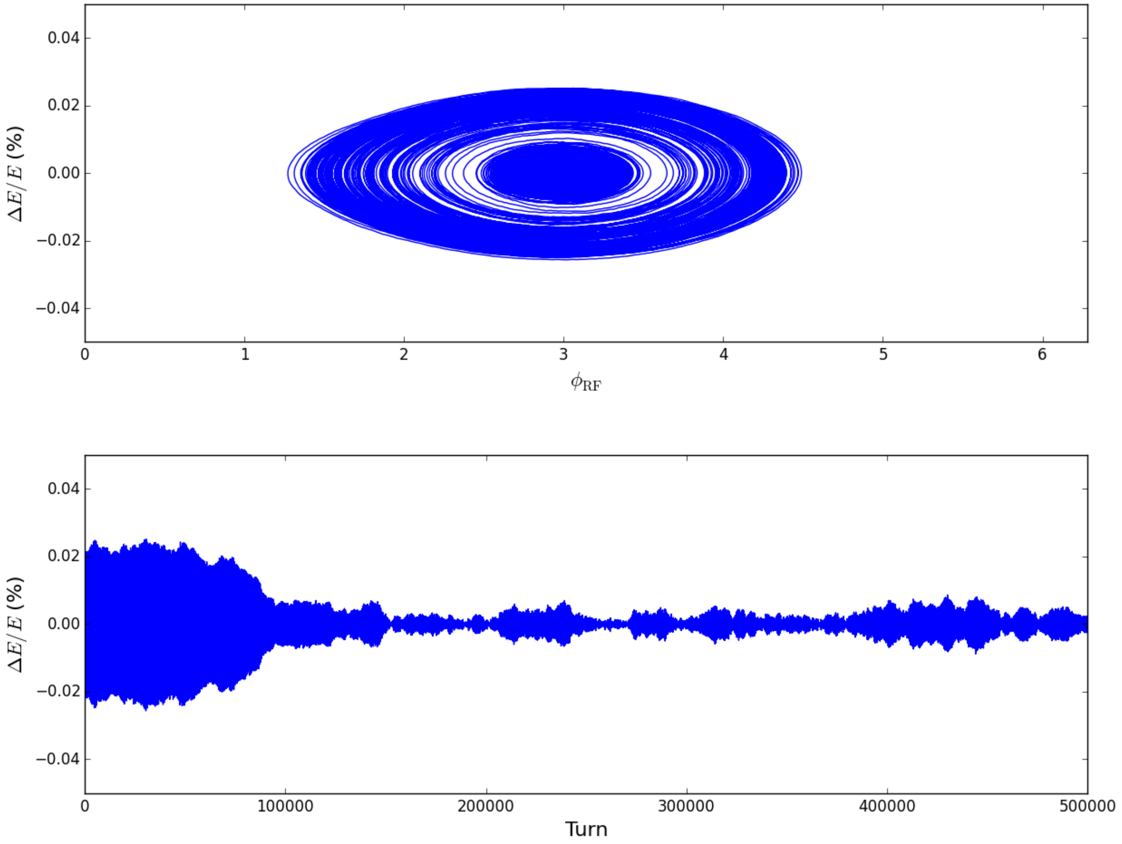
Scenario 1:

Full laser power covering uniformly the LHC ion energy bandwidth.

No bam cooling.

Ion is lost from the bucket

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



Instability disappears

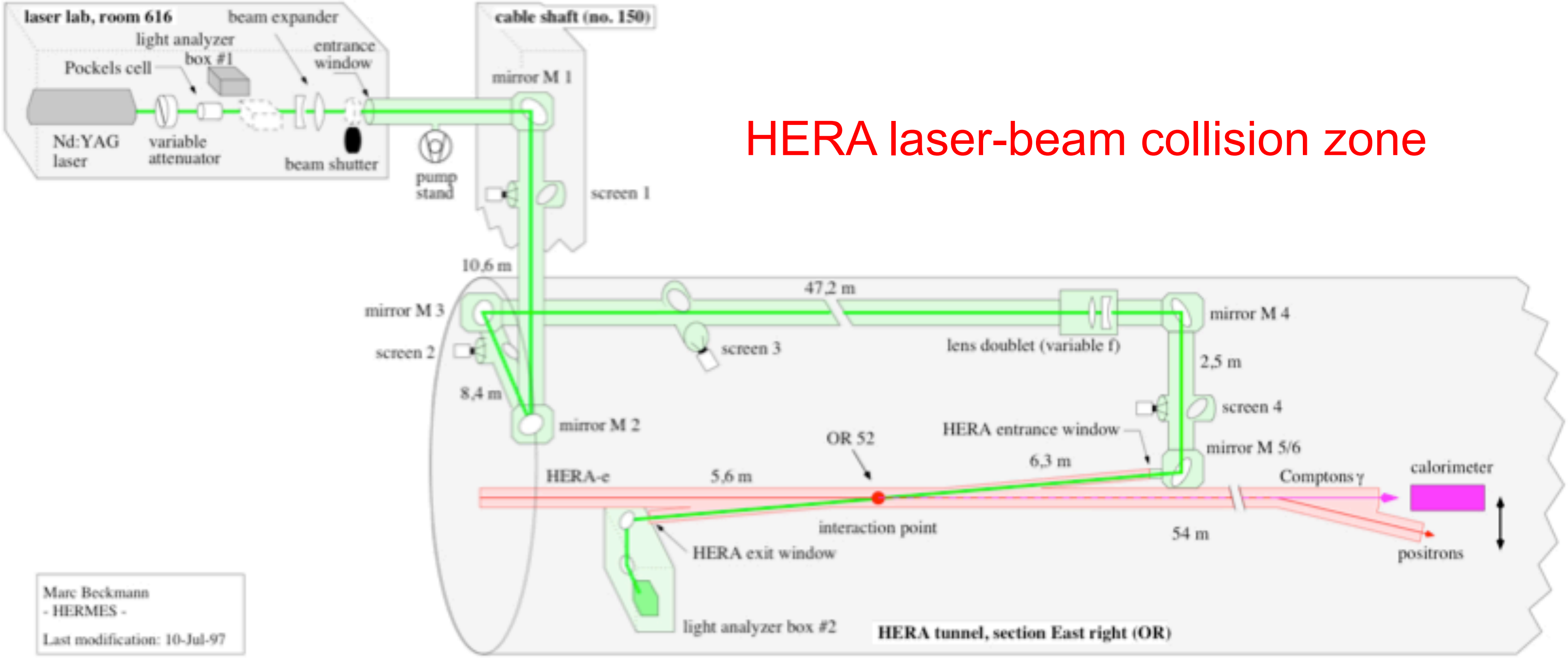
Scenario 1:

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

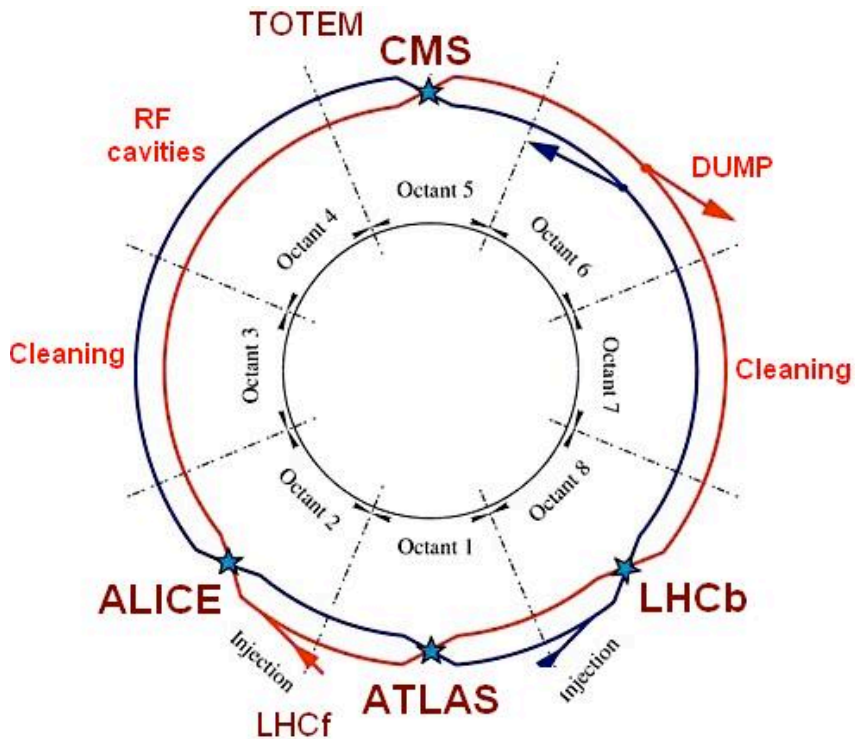
\+

Beam cooling, low power laser with frequency band covering the ΔE >0 resonant collisions

3. Laser system and the gamma beam extraction


HERA laser-beam collision zone

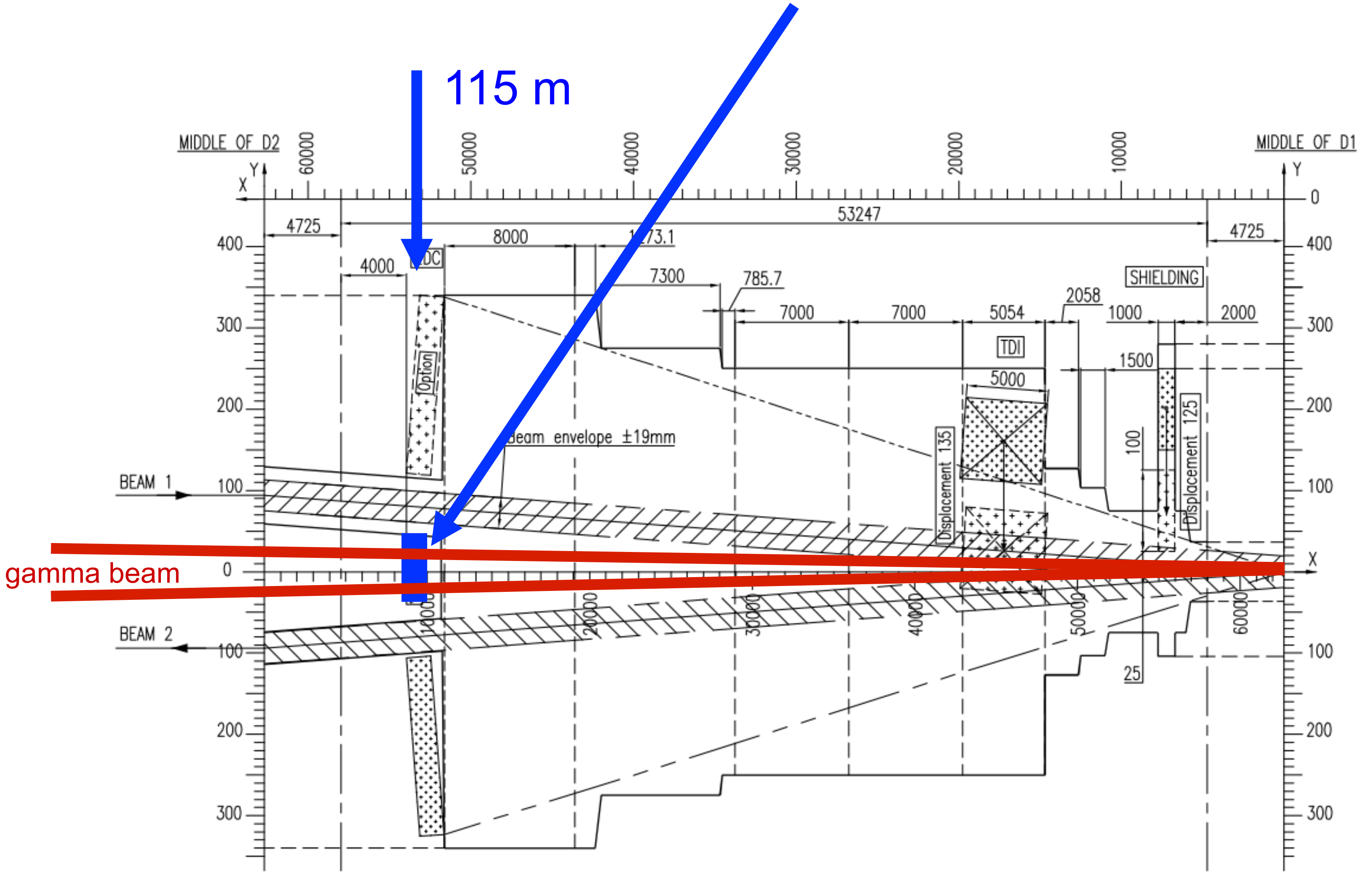
- Nd:YAG laser - 3ns x 100 mJ @ 100 Hz
- Pockels cell converts linear (>99%) light to circularly polarised light



Is there a technical possibility to install the laser system in the octants 3/7 or maybe in octant 6 (external ring)?…

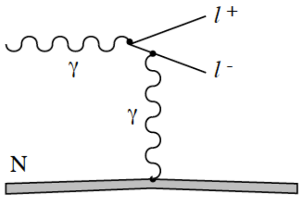
..less attractive solution is to install it in one of the IPs..

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



Vertical bump necessary…

4. 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

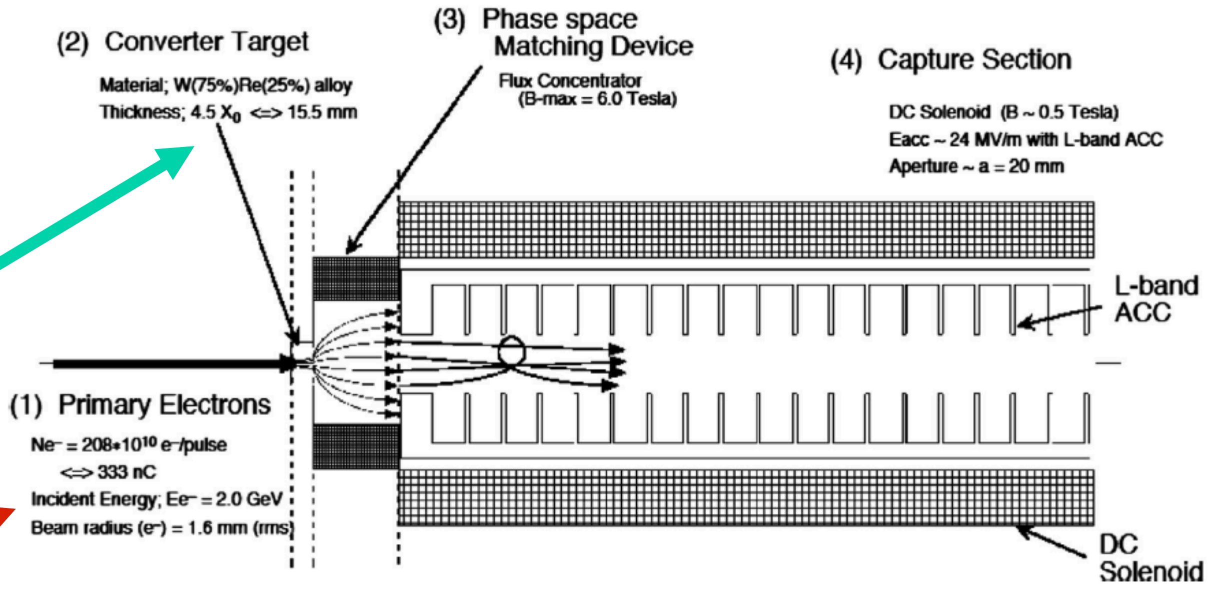


Fig. 2. Layout of the CLIC e^+ source with a single target.

Principal gains of a *HIGS* 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.

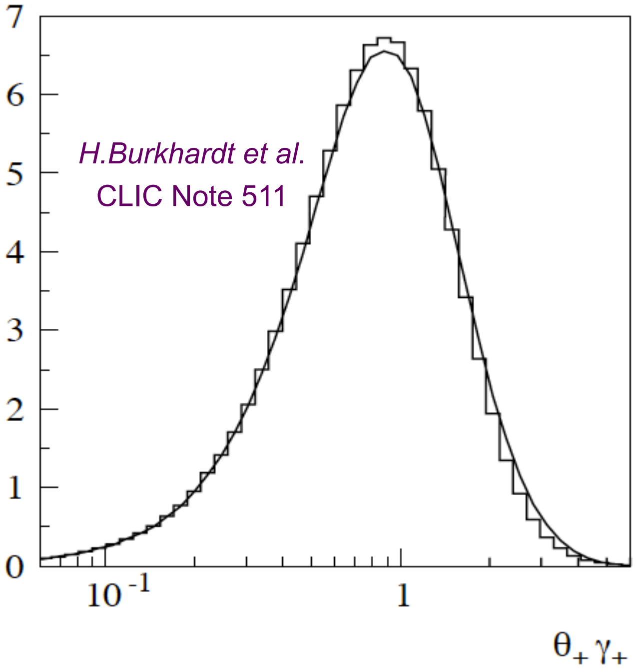
  How to filter them out?

- 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:



H.Burkhardt et al.

CLIC Note 511

Hint2

Electrons are relativistic, muons are not:

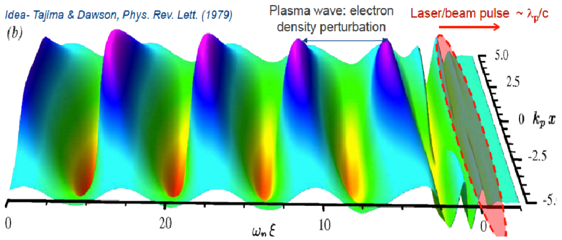
$\beta_e = 1$, $\langle\beta_\mu\rangle \sim 0.5$

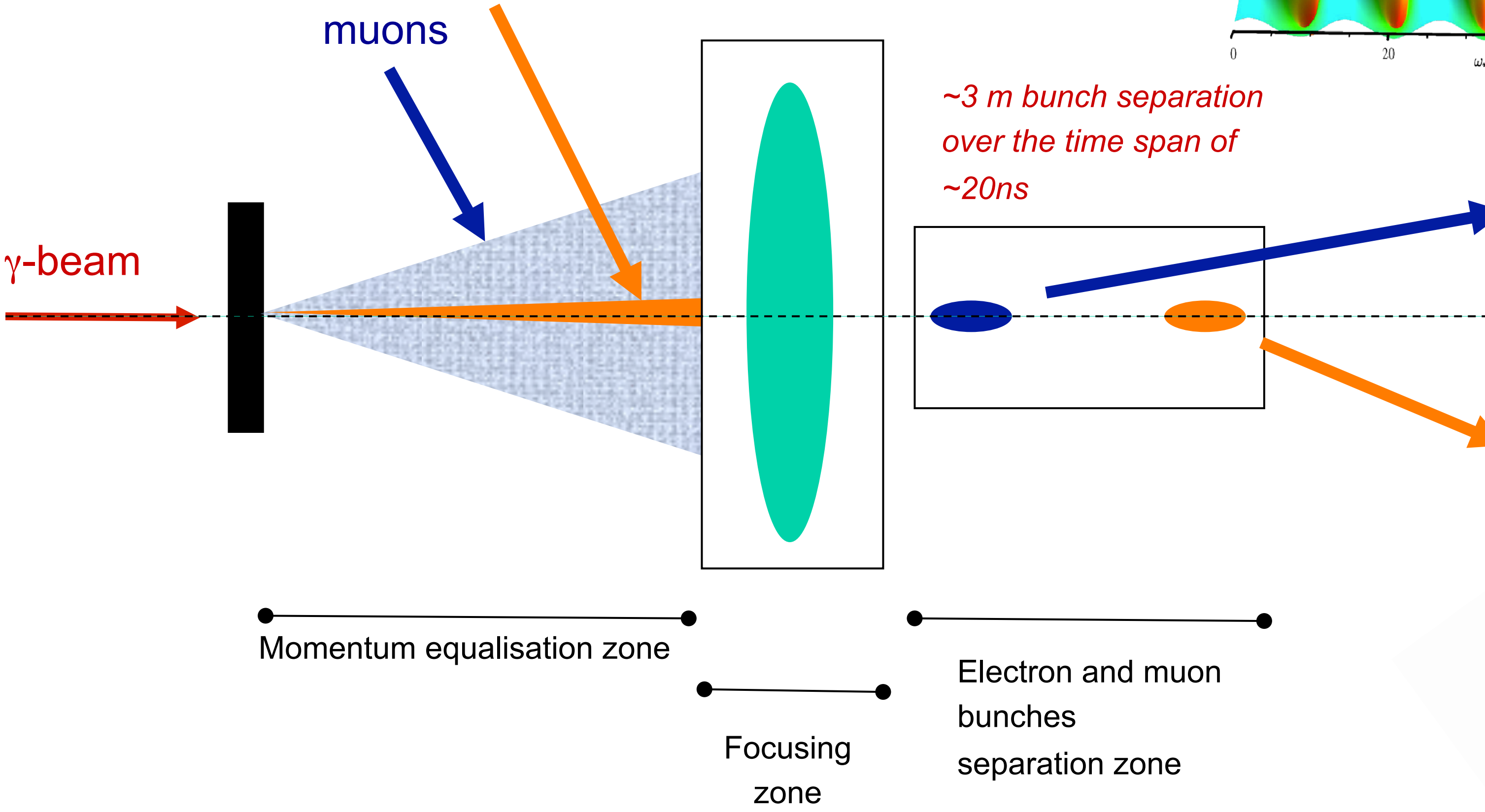
20 ns following the collision of the photon bunch with the conversion target, electron and muon bunches are separated by (on average) 200 cm allowing for their efficient separation

initial ideas…

muon collider
neutrino factory

Plasma Waves





Electrons and positrons

muons

γ-beam

~3 m bunch separation over the time span of ~20ns

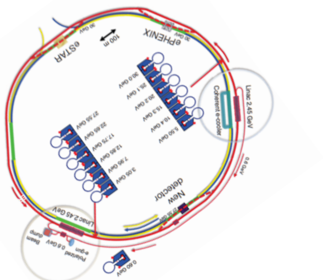
Momentum equalisation zone

Focusing zone

Electron and muon bunches separation zone

muon acceleration

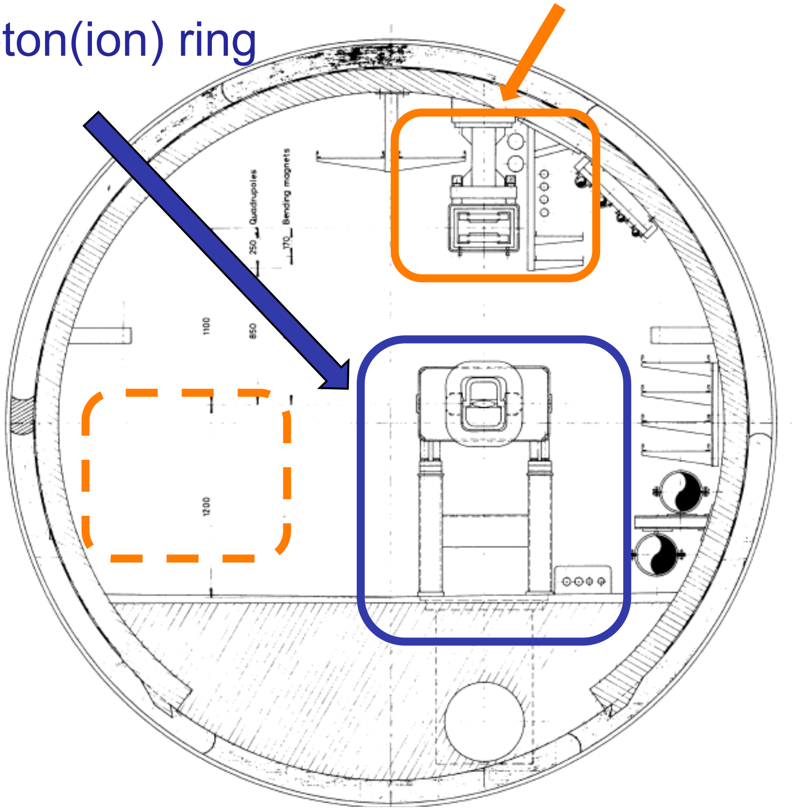
electron acceleration



electron-ion collider

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

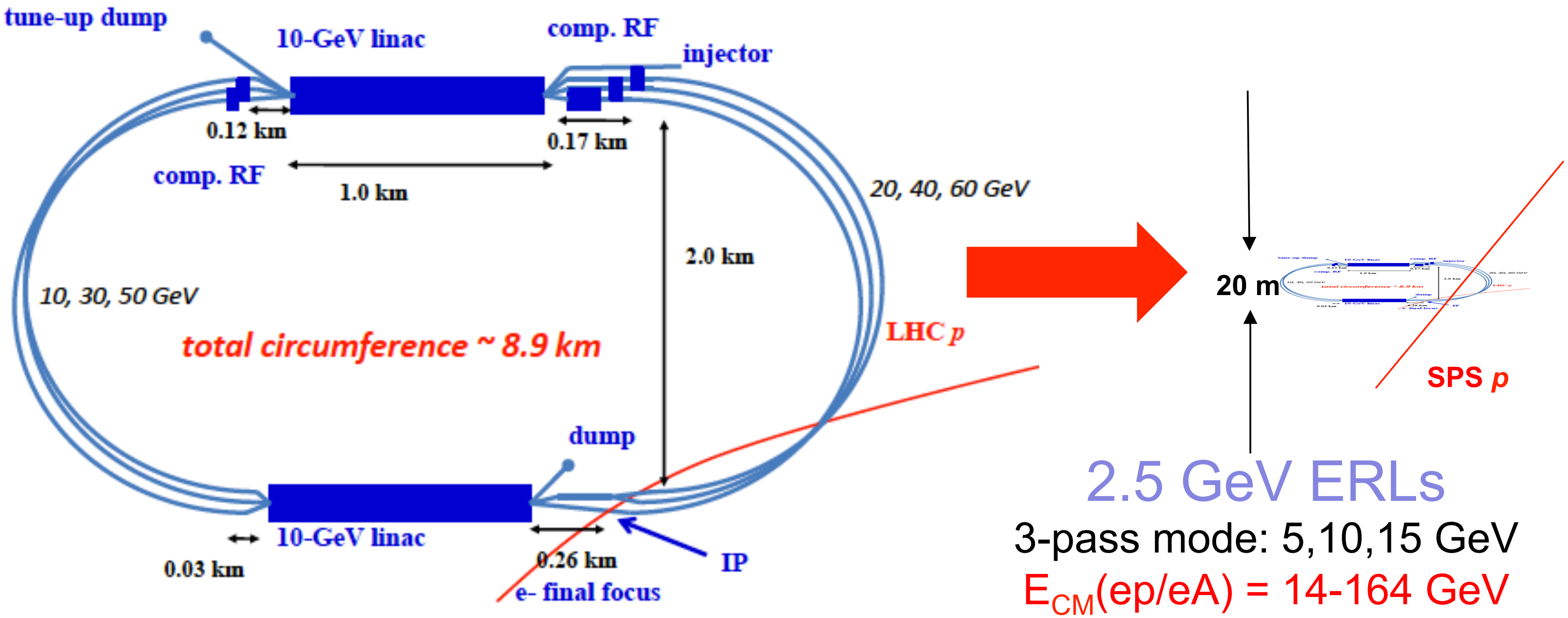
The SPS tunnel



Muon collider ring?

The proton(ion) ring

“EIC with the SPS protons and ions”



2.5 GeV ERLs

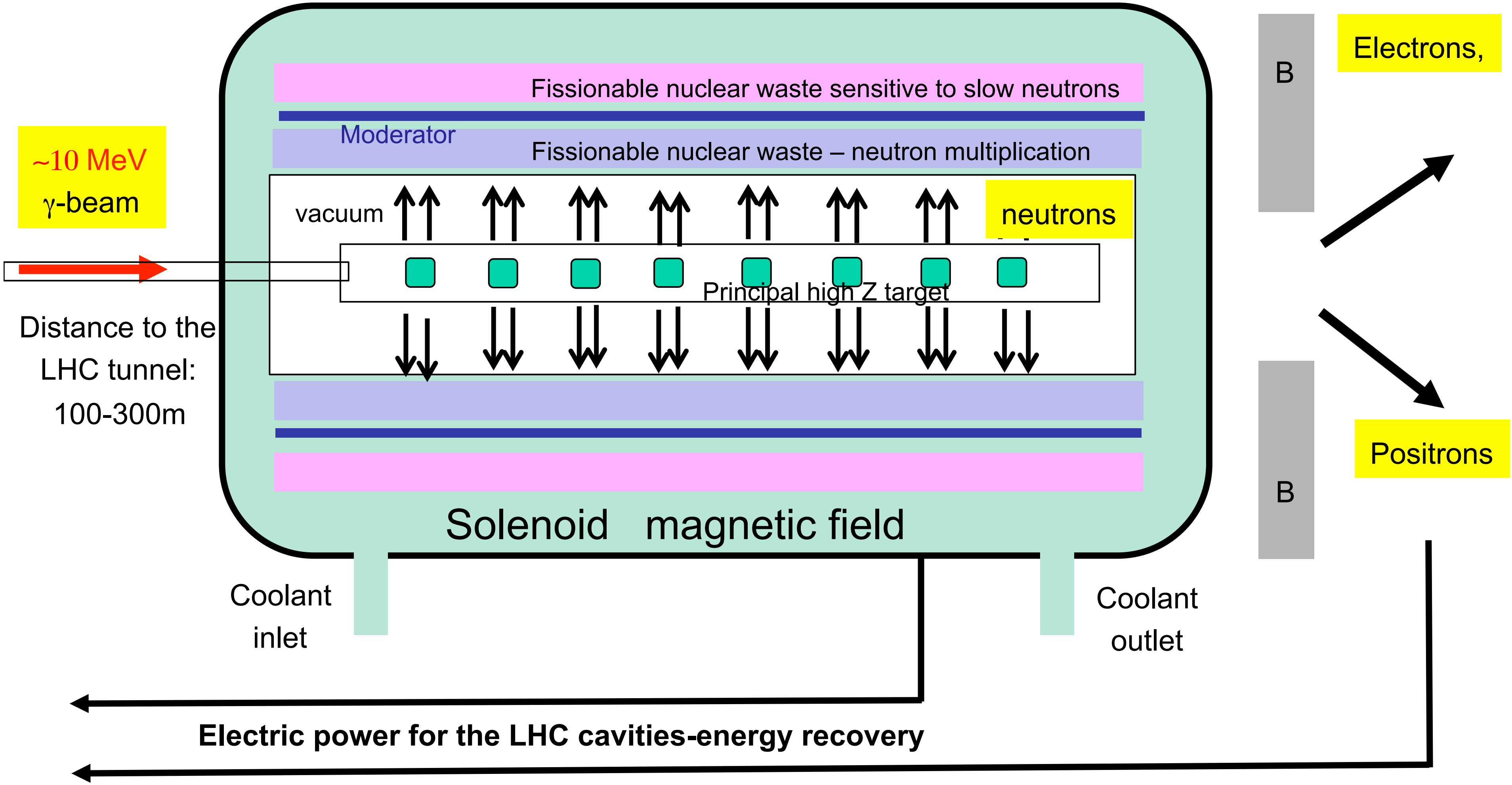
3-pass mode: 5,10,15 GeV

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

5. Polarized positron source and the Energy and cost recovery scheme



Fissionable nuclear waste sensitive to slow neutrons

Moderator

Fissionable nuclear waste – neutron multiplication

vacuum

neutrons

Principal high Z target

~10 MeV
γ-beam

Distance to the
LHC tunnel:
100-300m

Solenoid magnetic field

Coolant
inlet

Coolant
outlet

B

B

Electrons,

Positrons

Electric power for the LHC cavities-energy recovery

High intensity electron and positron beams – cost recovery

… a preliminary idea of the secondary beam producing station with the electric power and cost recovery..

Direct pair production: (the idea presented yesterday)

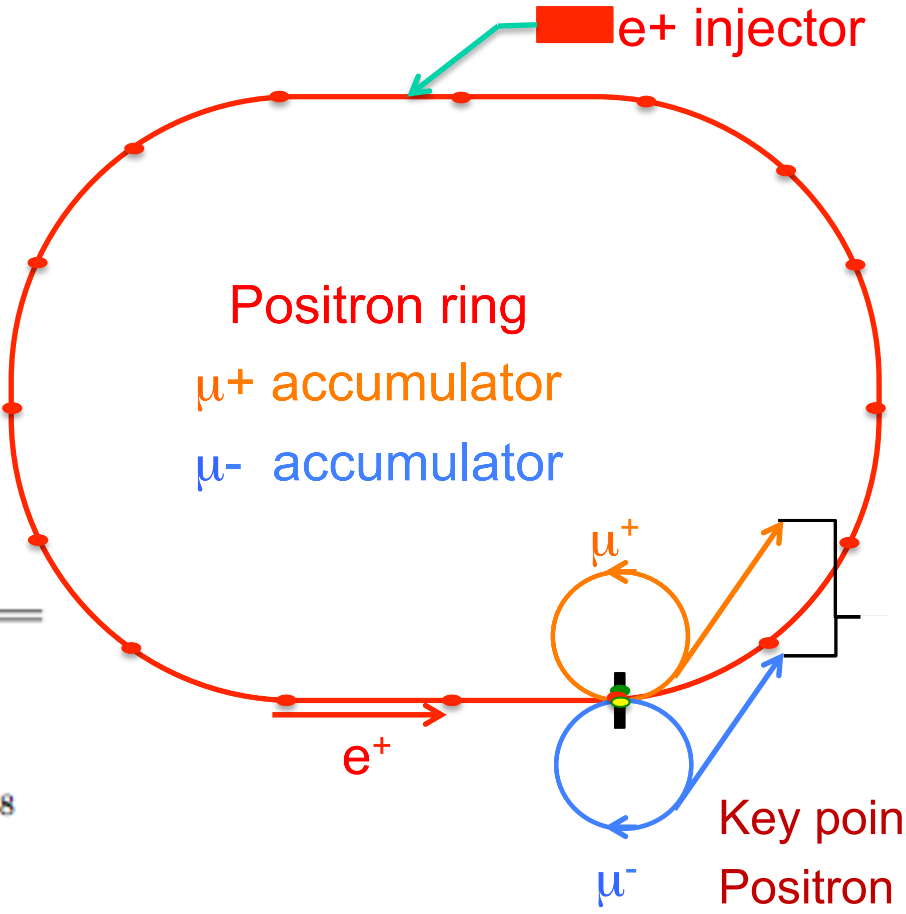
Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s}$~0.212GeV) in asymmetric collisions (to collect μ^+ and μ^-)

- 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



$$n_b = \sum_{i=1}^{N_T} e^{-\Delta t (N_T - i)/\tau_\mu^{lab}}$$

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

The way forward

Two parallel paths:

1. Detailed evaluation of the physics and industrial and medical applications opportunities of the HIGS proposal.
2. The technical feasibility studies.

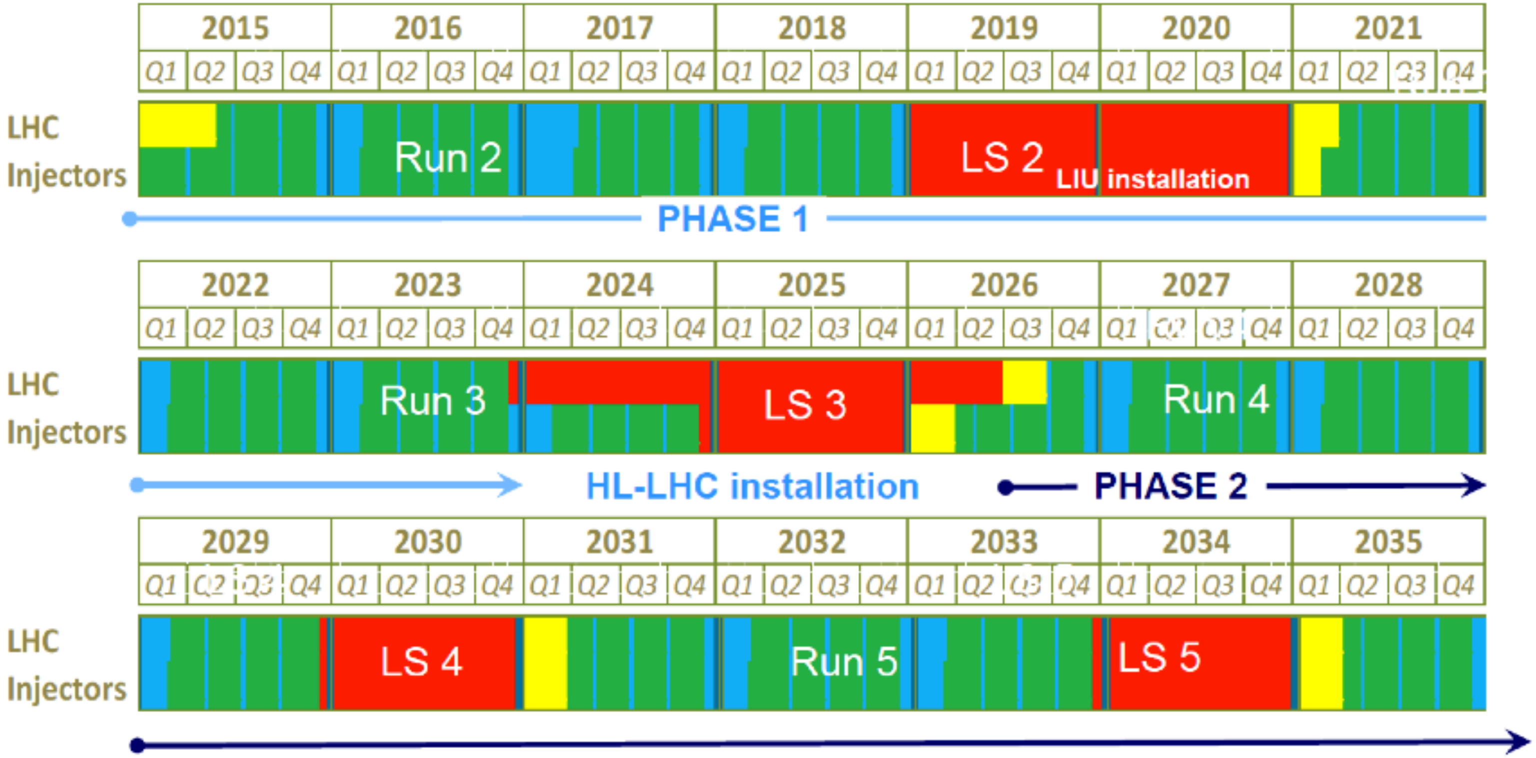
The first critical steps

- **Present the proposal to potentially interested communities (evaluate interest)**
- Develop the tools and precision calculations of the intensity, emittances and spot sizes of the primary gamma-rays and secondary beams for realistic ion, laser (FEL) F-P choices and realistic Partially Stripped Ion (PSI) beam parameters
- Short SPS test run with “BNL-type stripping target” (measurement of the beam life time, and time-dependent emittance of the beam of PSIs in the SPS?
- At the end of the LHC Run2 (or earlier?) measurement of the life-time of the partially stripped lead ion beam in the LHC?
- A proposal to SPSC for a test experiment to study the collisions of F-P cavity photons, driven by a laser system, with the (extracted) PSI beams (Ar ions –scenario 3)

LHC roadmap: according to MTP 2016-2020

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- 🟩 Physics
- 🟥 Shutdown
- 🟨 Beam commissioning
- 🟦 Technical stop



Conclusions

The history of our discipline shows that a big technological Leaps led to important discoveries -- at least as frequently as the research guided by verification of the theoretical models of a priori defined discoveries – the dominant paradigm in HEP these days.

Large laboratories, like CERN, may be forced to diversify further their research domain – focussed at present mainly on the high energy frontier (a lesson from the “dinosaur’s extinction”) -- and use existing infrastructure to enlarge the research scope

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.

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

- **The HIGS scheme provides a very efficient scheme of transforming accelerator RF power to the power of the (γ, e, μ, ν, n, radioactive ion) secondary beam**

- **In some cases the HIGS scheme may lead to a leap, by several orders of magnitude, in the increase of 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) and high intensity frontier (i.e. the SPS based ep(eA) collider, γγ colliders and neutrino factories)

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

3. (Extending?) the experimental program in Nuclear Physics

4. Industrial applications (energy production, the research on nuclear reactors with significantly reduced nuclear waste, etc.)

5. Medical applications (including production of isotopes for the selective cell killing techniques).

- **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).**

- **Its positive outcome is the necessary but not sufficient condition for the HIGS proposal to be considered at CERN…**

- **Since this project is bound to use the full LHC infrastructure two necessary conditions must, in addition, be fulfilled:**

  - a support of the CERN accelerator experts and the CERN management for the initial feasibility studies
  - a wide multidisciplinary interest and support (including funds) (particle physics, atomic physics, nuclear physics, applied physics)

extra transparencies

Future: ELI-NP (under construction)

An intense (up to $10^{13}\gamma$/s), brilliant γ beam, 0.1 % band-width, with Eγ > 19 MeV, which is obtained by incoherent Compton back scattering of a laser light off a very brilliant, intense, classical electron beam (Ee > 700 MeV) produced by a warm linac.

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:

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

Transverse contribution:

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

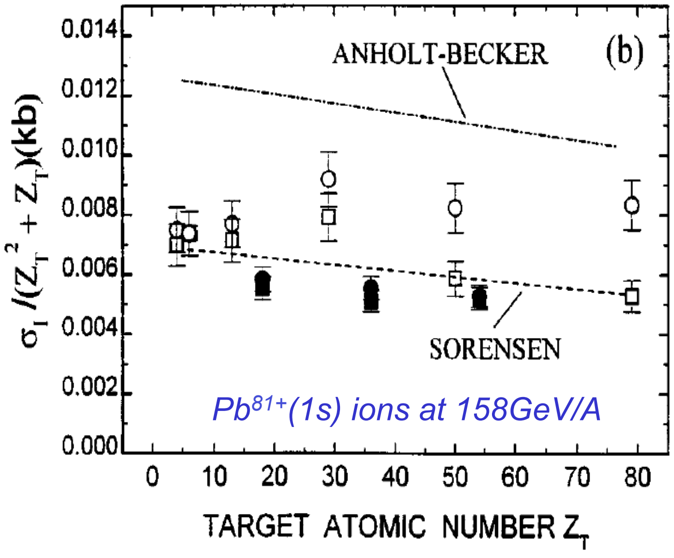
Note:

- spin-flip contribution is neglected

- coherent bunch contribution is neglected

Experimental cross-check

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



$Pb^{81+}(1s)$ ions at 158GeV/A

Survival of partially stripped ions: beam-gas collisions

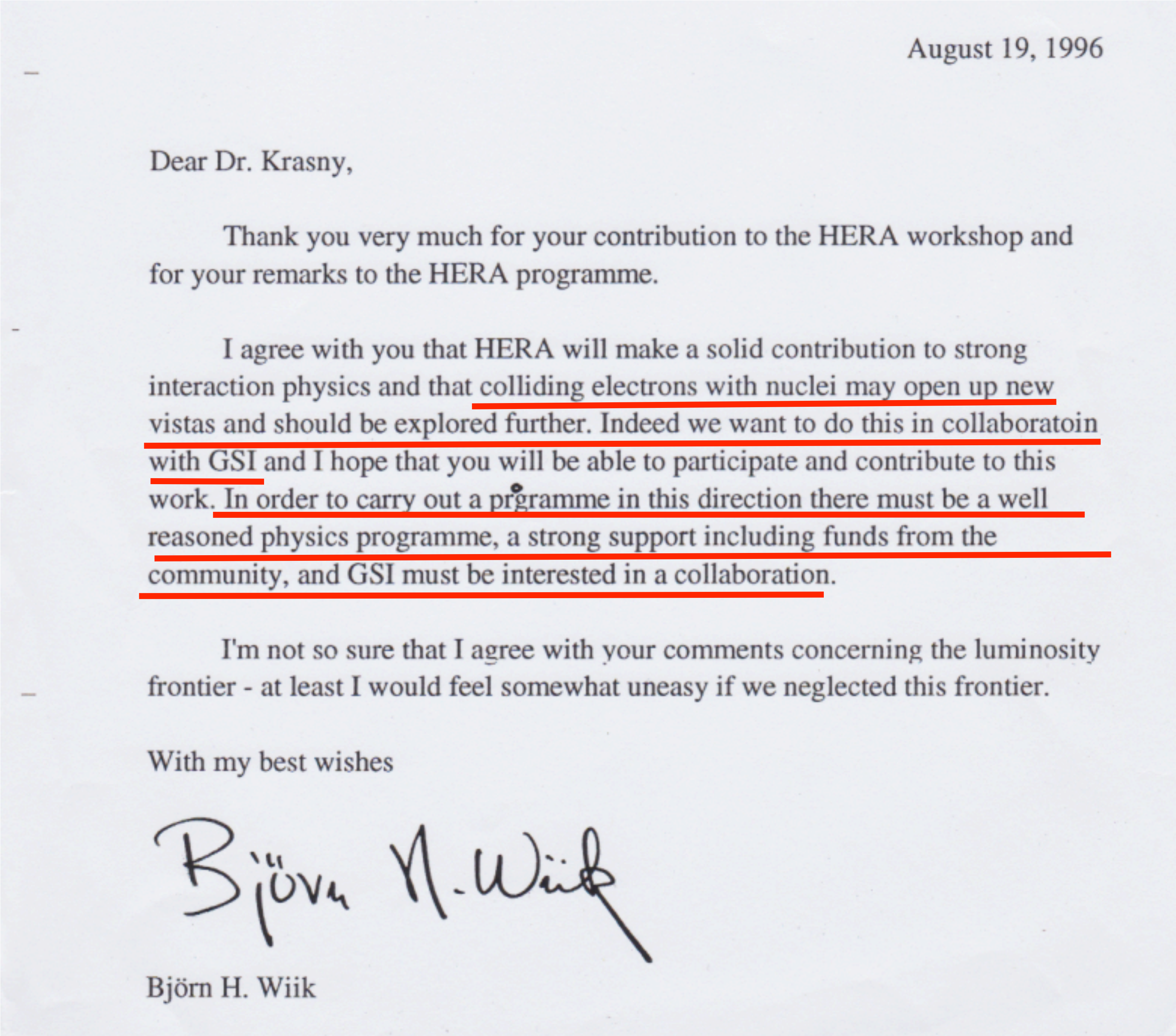
Collisions of $Pb^{81+}(1s)$ ions with the residual gas in the LHC beam pipe – how long can they survive?

- 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 H2 molecules) and 2 (for the CO2 molecules).
Better vacuum in arcs.



August 19, 1996

Dear Dr. Krasny,

Thank you very much for your contribution to the HERA workshop and for your remarks to the HERA programme.

I agree with you that HERA will make a solid contribution to strong interaction physics and that colliding electrons with nuclei may open up new vistas and should be explored further. Indeed we want to do this in collaboratoin with GSI and I hope that you will be able to participate and contribute to this work. In order to carry out a programme in this direction there must be a well reasoned physics programme, a strong support including funds from the community, and GSI must be interested in a collaboration.

I'm not so sure that I agree with your comments concerning the luminosity frontier - at least I would feel somewhat uneasy if we neglected this frontier.

With my best wishes

Björn H. Wiik

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