The **HIGS** proposal and its highlights

DESY and Zeuthen May 2015

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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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Electron beam for LHC

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Abstract

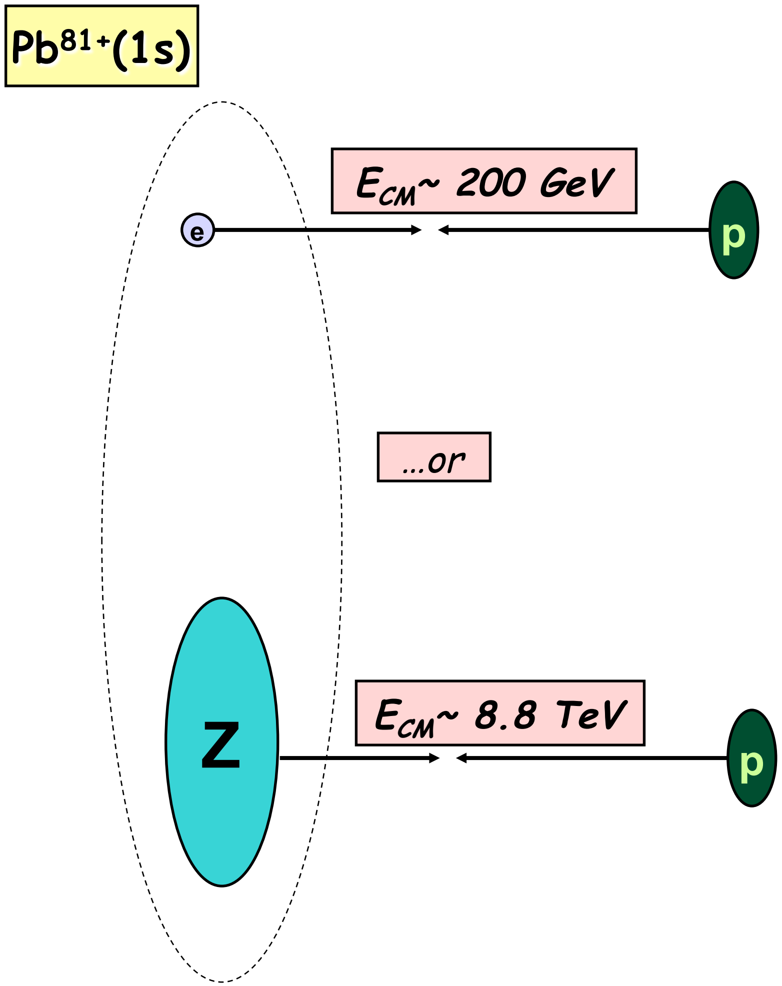
A method of delivering a small energy spread electron beam to the LHC interaction points is proposed. In this

PIE*@LHC proposal:

- CM energy (e-p collisions) -- 100- 205 GeV
- e-p luminosity ~ 10^{29} cm^{-2} s^{-1}

* PIE = Parasitic Ion Electron collider

Partially stripped ions as electron carriers



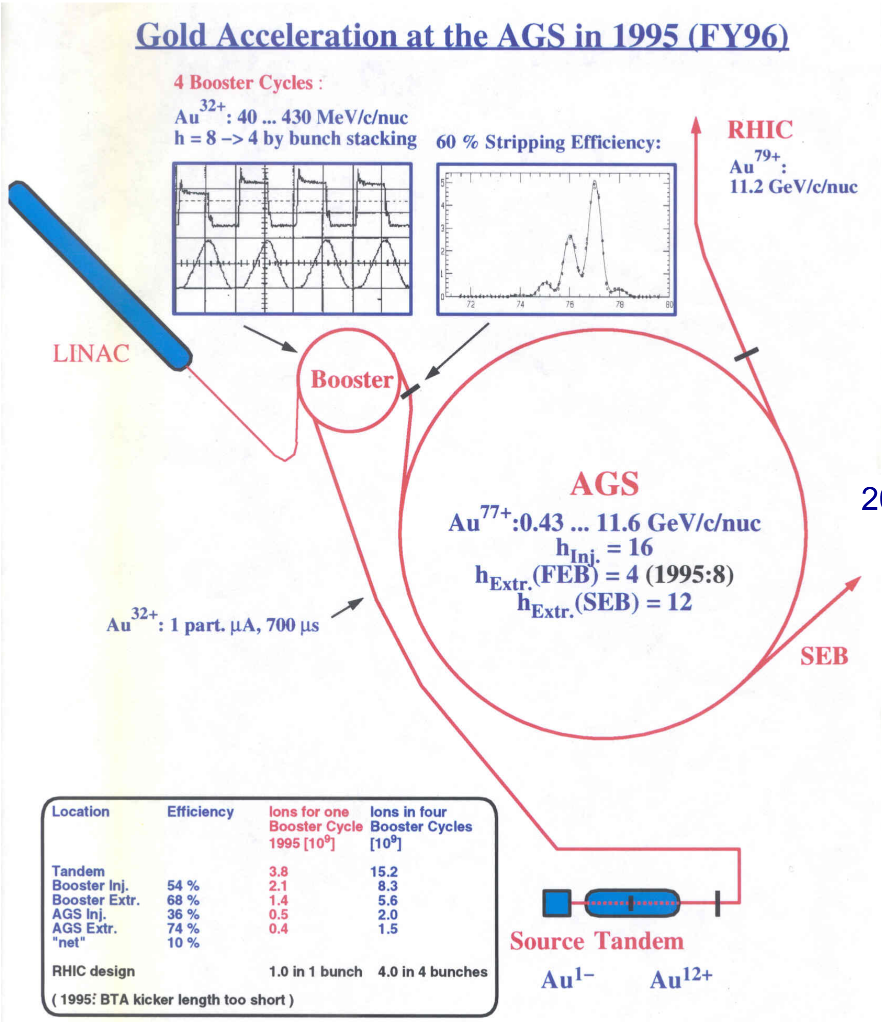
- average distance of the electron to the large Z nucleus d ~ 600 fm (sizably higher than the range of strong interactions)

- partially stripped ion beams can be considered as <u>independent electron and nuclear beams</u> as long as the incoming proton scatters with the momentum transfer q >> 300 KeV

- both beams have <u>identical bunch structure</u> (timing and bunch densities), <u>the same β^*</u>, <u>the same beam emittance</u> – the choice of collision type can be done exclusively by the trigger system (no read-out and event reconstruction adjustments necessary)

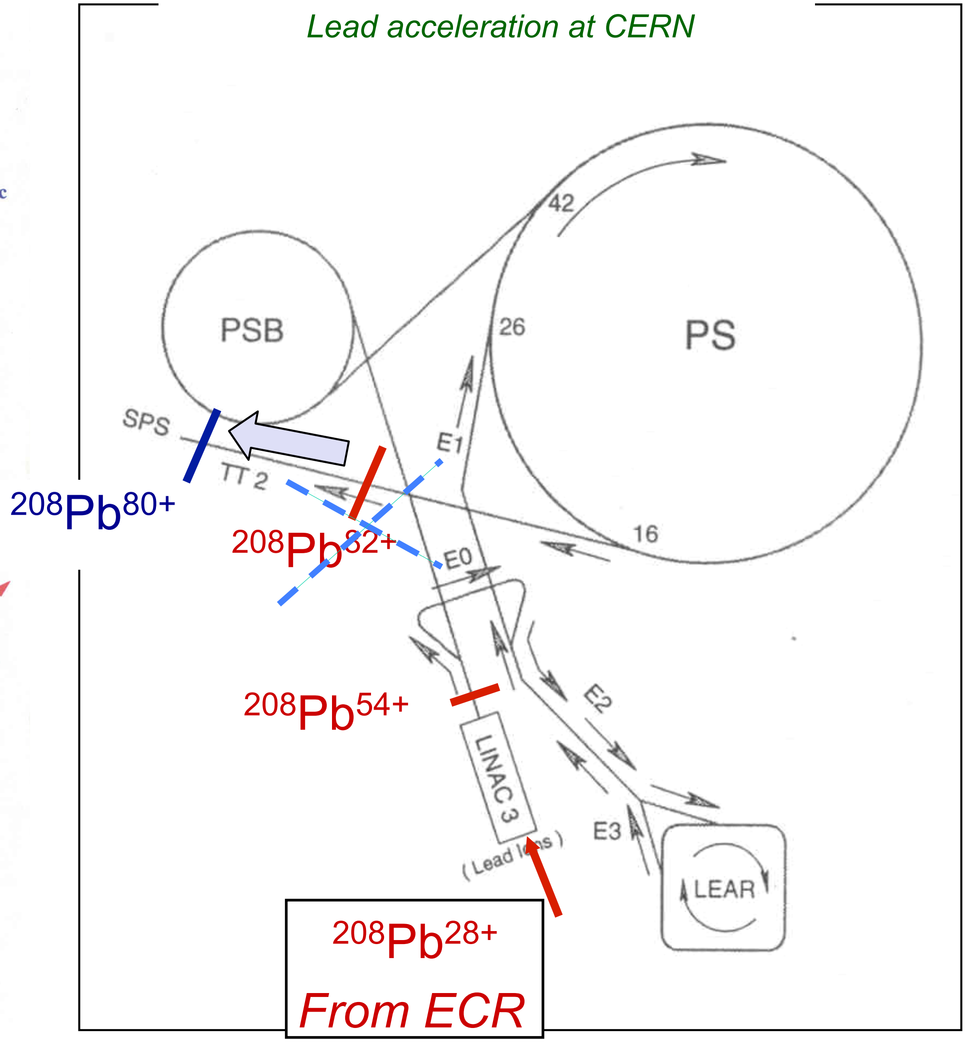
Ion striping sequence:

BNL & CERN



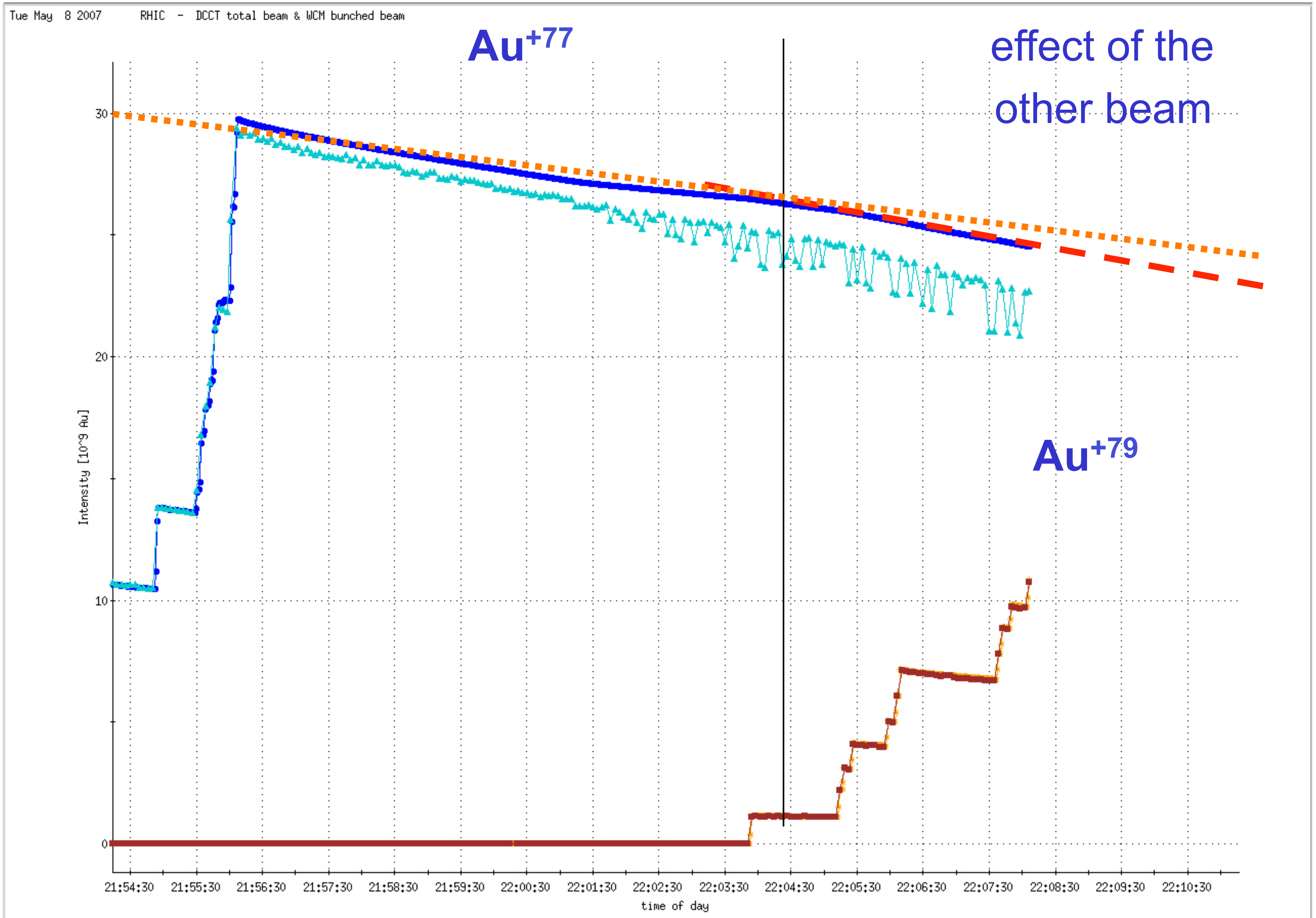
Location	Efficiency	Ions for one Booster Cycle 1995 [10^9]	Ions in four Booster Cycles [10^9]
Tandem		3.8	15.2
Booster Inj.	54 %	2.1	8.3
Booster Extr.	68 %	1.4	5.6
AGS Inj.	36 %	0.5	2.0
AGS Extr.	74 %	0.4	1.5
"net"	10 %		
RHIC design		1.0 in 1 bunch	4.0 in 4 bunches

(1995: BTA kicker length too short)



Gold with two electrons successfully stored in RHIC

Dejan Trbojevic (Apex workshop 2007)



Storage of the partially stripped ion beam is nor a science-fiction !

Survival of partially stripped ions: summary

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

- "Stark effect" in the LHC superconducting dipoles (E= 7.3 10^{10} V/m) - only high 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 collision schemes (partially stripped high Z ions can collide only with the lightest fully stripped ions: p, He, O…)

The HIGS proposal

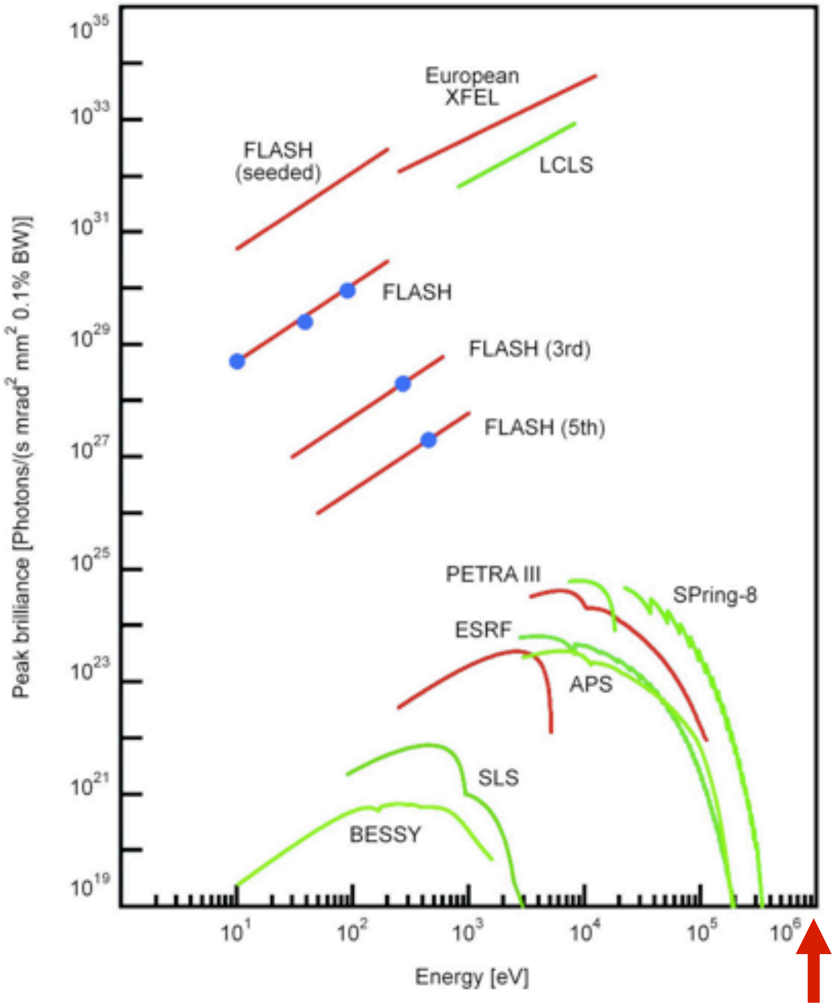
The goal of the HIGS proposal

*(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

X-ray sources



MeV

atomic structures

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

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–

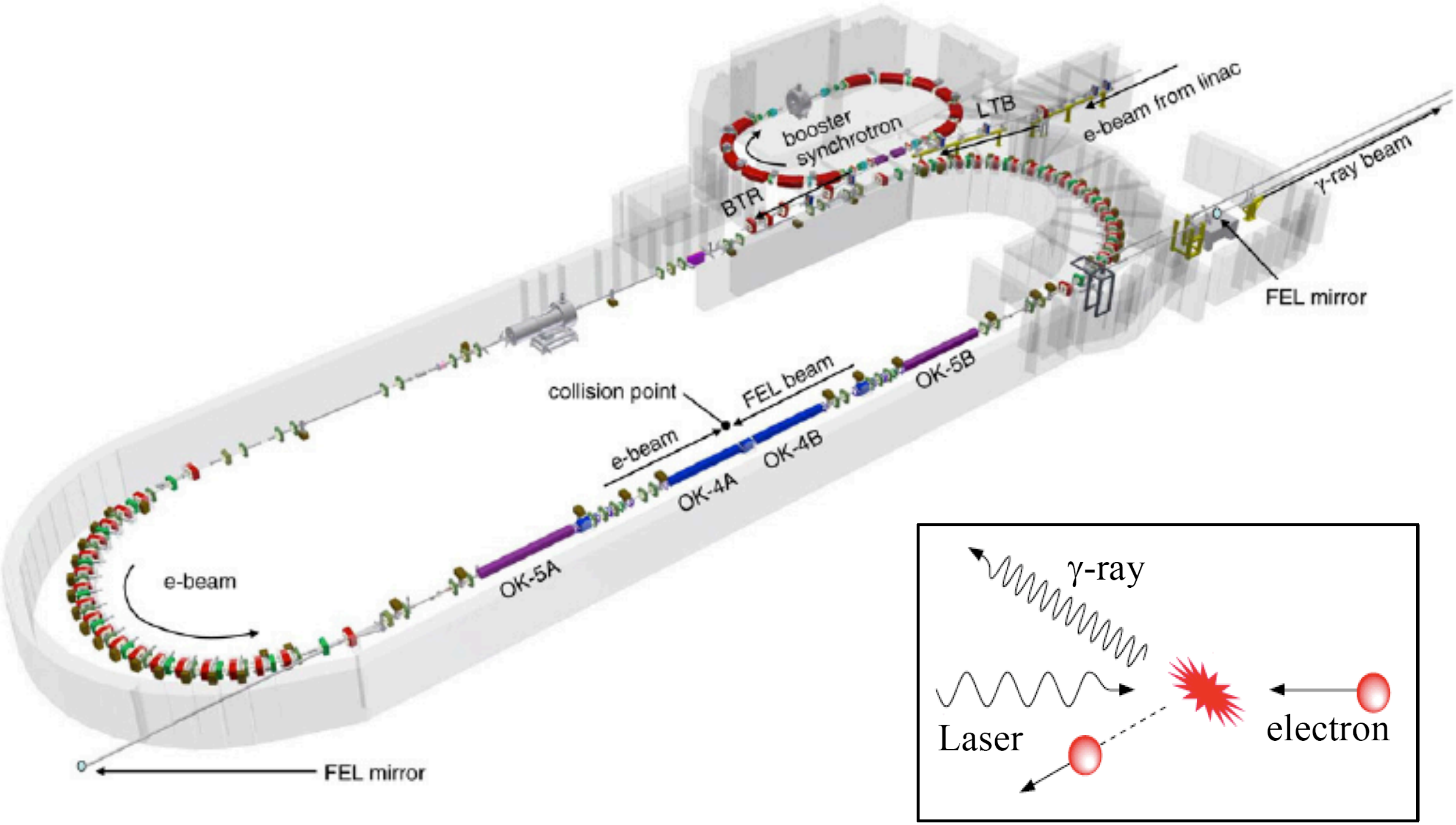
The quest:

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

For comparison:

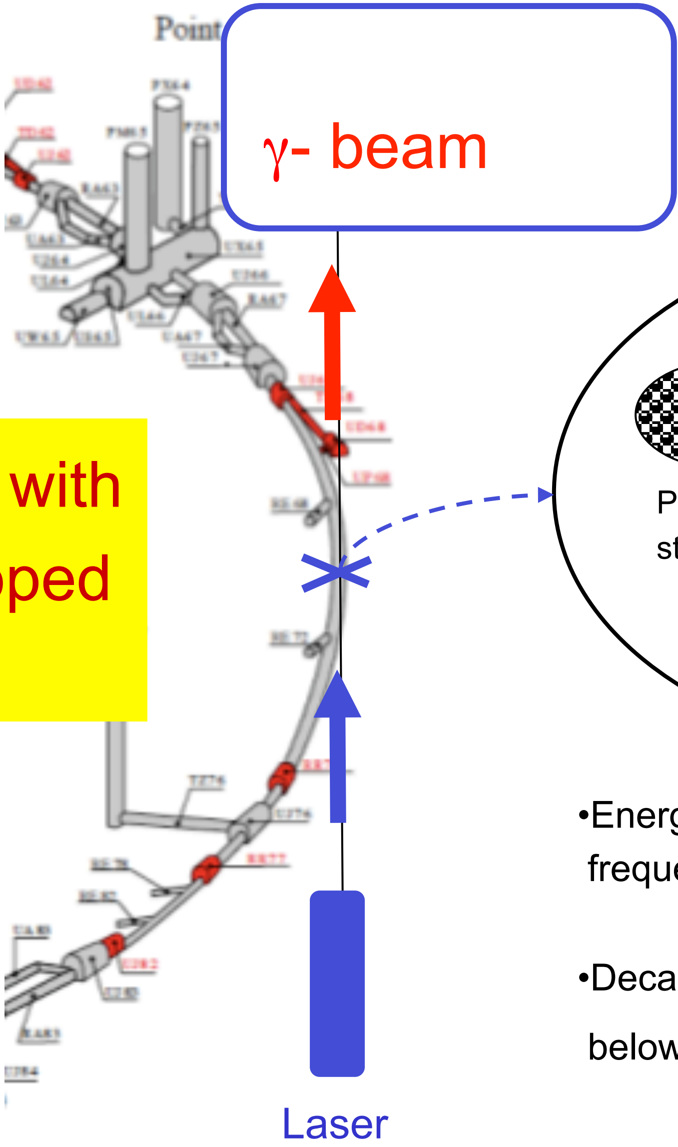
DESY FEL: photons/pulse -- 10^{11}-10^{13}, pulses/second --10—5000 →**(10^{12} – 10^{17} photons/s)**

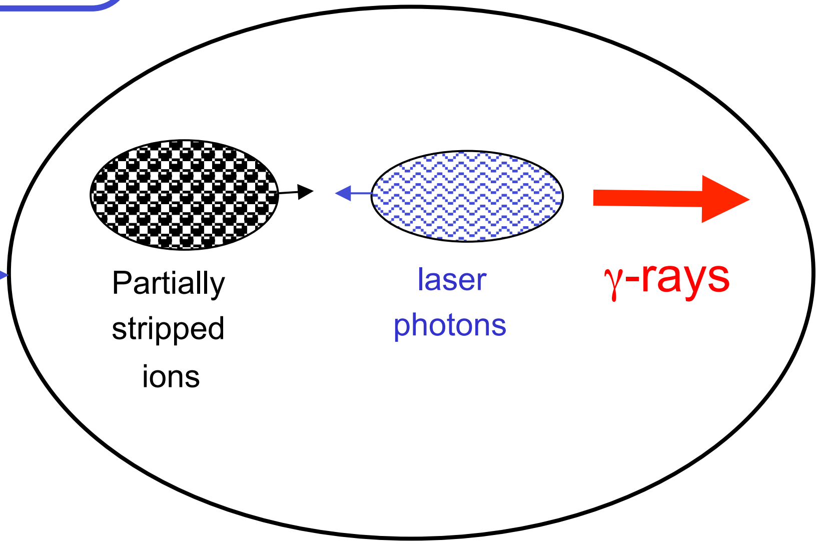
The Duke University Gamma source



The HIGS proposal: 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 → 2s

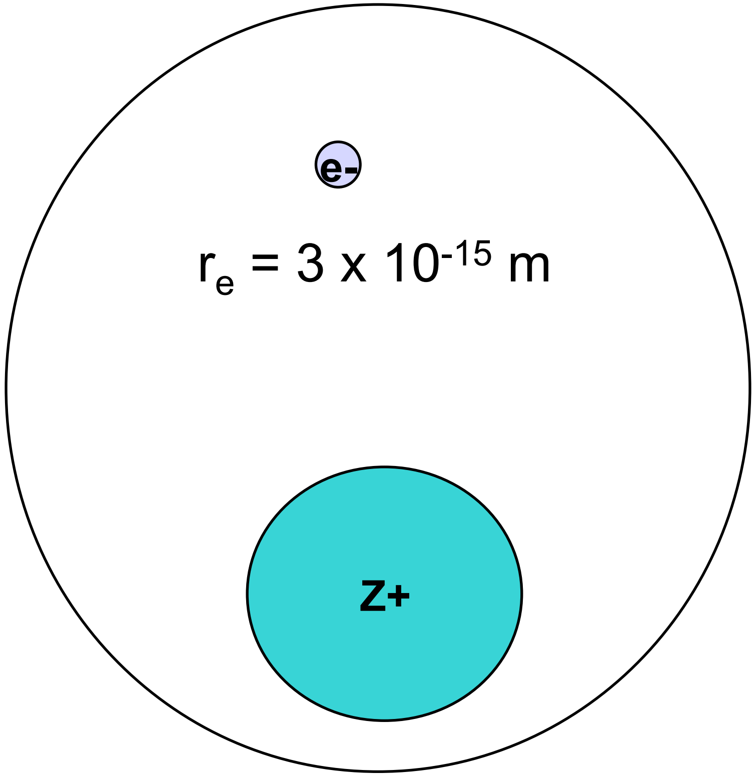
- Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$ below 0.1 mm for $Pb^{81+}(2s) \rightarrow Pb^{81+}(1s) + \gamma$

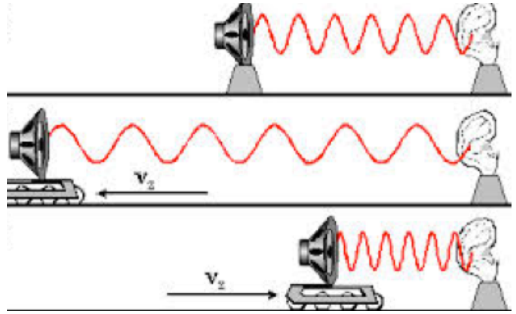
LHC partially stripped ion beams as the light frequency converter:

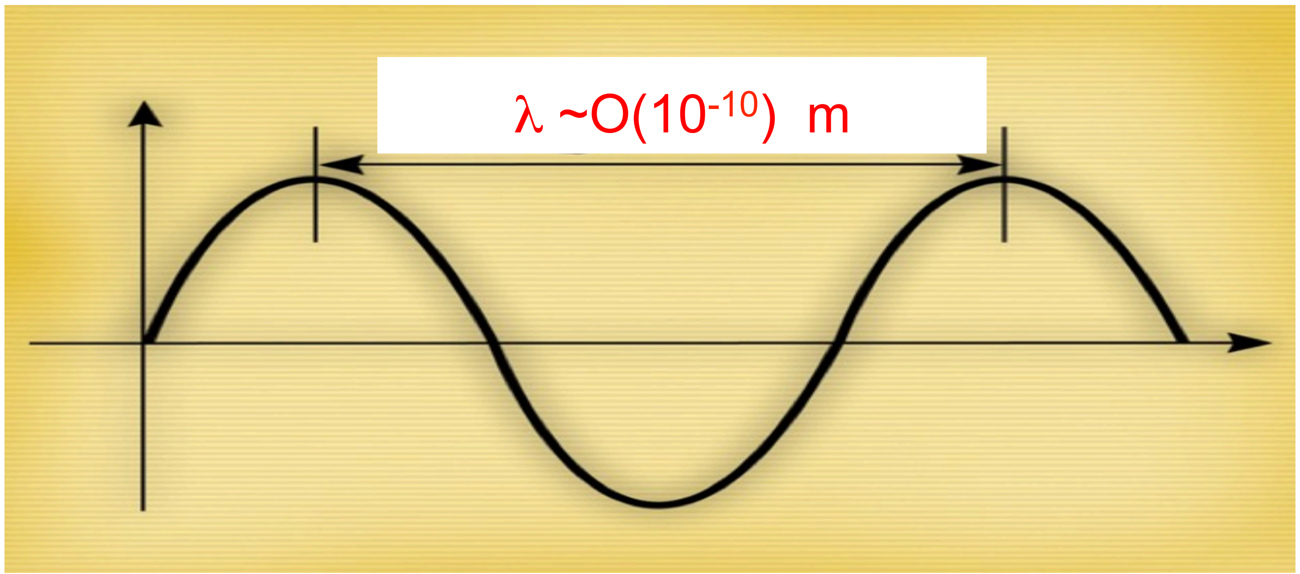
$$\nu_i \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

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

Doppler Effect and Resonant Scattering

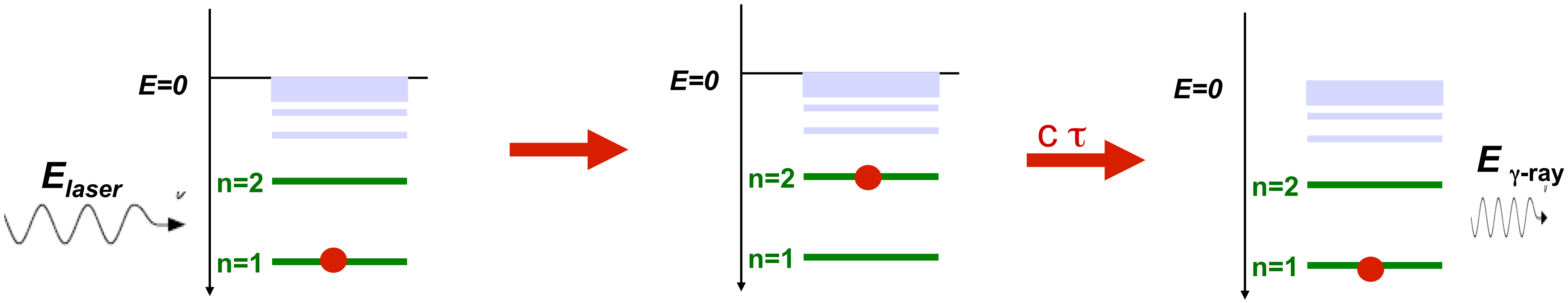






Scattering of photons on ultra-relativistic atoms

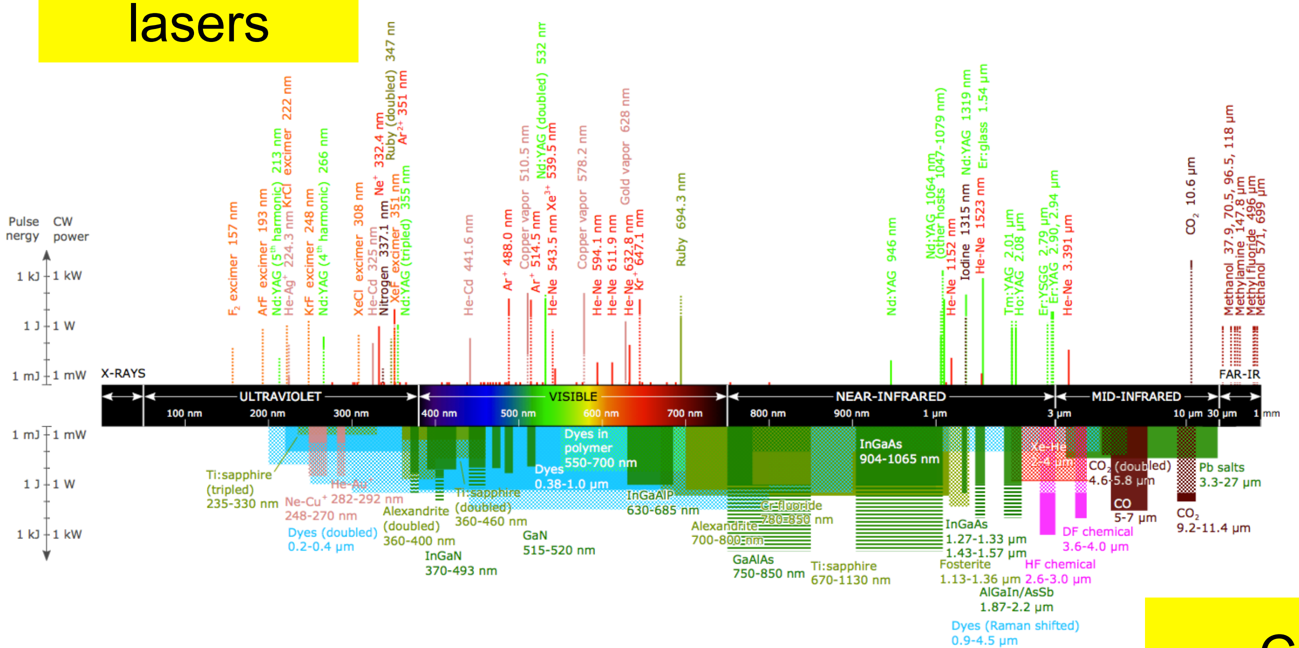
$-E_n = 1Ry\ Z^2/n^2$



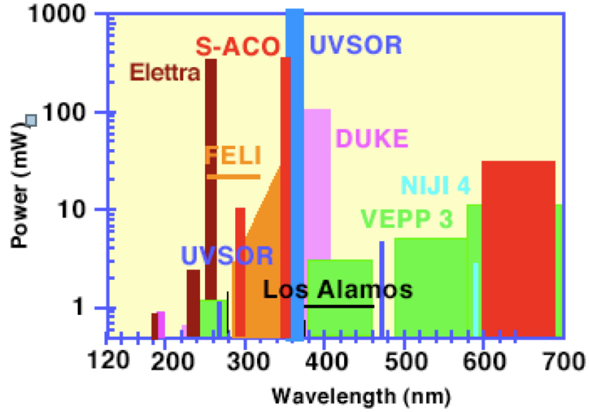
$E_{laser} = 1Ry\ (Z^2 - Z^2/n^2)/2\gamma_L$ → $E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^2/(1+(\gamma_L\theta)^2)$

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

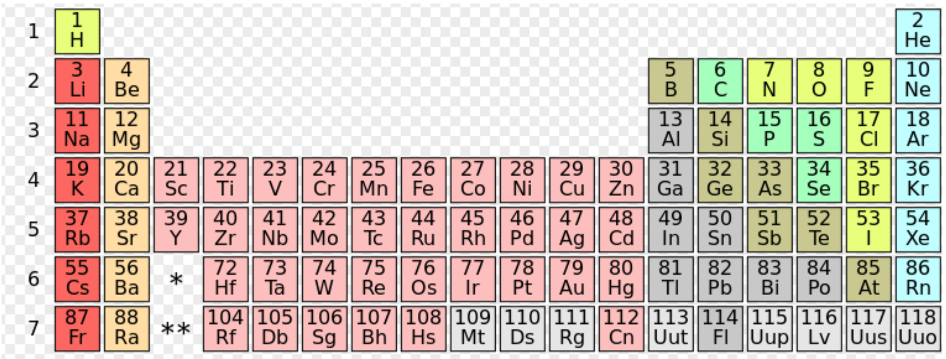
lasers



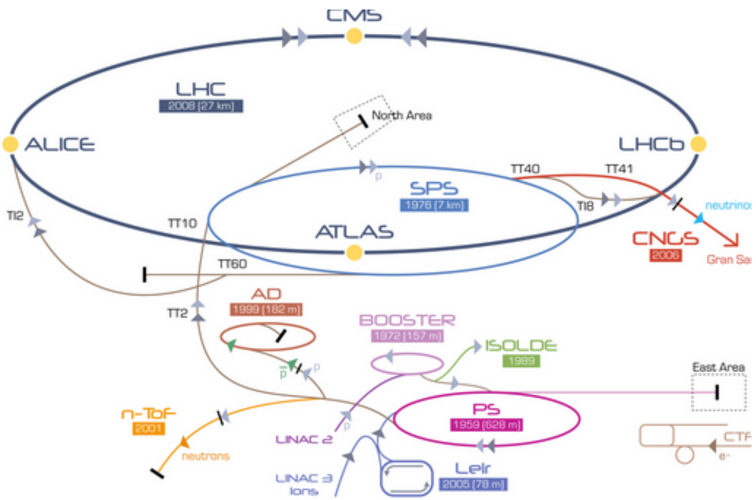
mirrors



Ions



CERN accelerators



Fine tuning of $E_{\gamma\text{-beam}}$

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 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

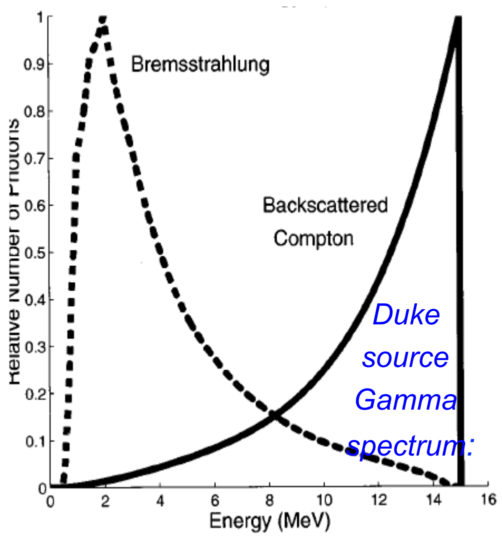
of the electron beam

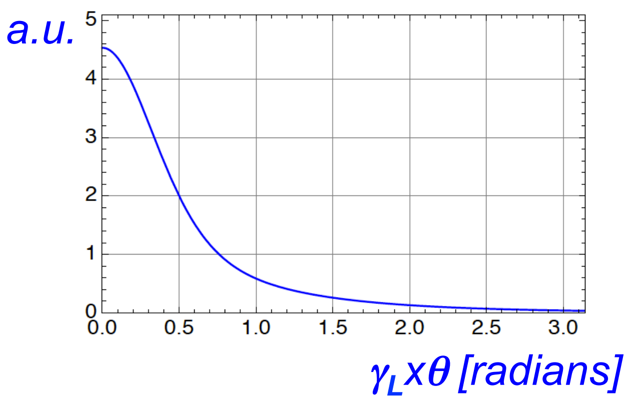
…however, the fraction: of the beam particle energy transferred to the 150 MeV gamma-ray for the 1.5 GeV electron and for the 3 TeV/ nucleon Pb ion:

x = 0.1 (electron)
x = 3 x 10 $^{-7}$ (ion)

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

Example: 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

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

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)

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

Technological challenges

For maximal energies HIGS must be driven by a <100 nm FEL photons.

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

The primary and secondary HIGS beams

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

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} (~10^{17})** [1/s] for the present (LEP-like) RF system

Scenario 2:

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

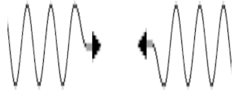
n=1→2, $E_\gamma^{(max)}$ = 13.8 MeV, **N^{max}_γ ~ 3 x 10^{17}** [1/s]

Comments:

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

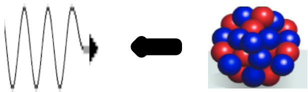
2. For scenario 2, where $c\tau_{exited\ ion}$ = 1.2 cm, the effect of the double photon absorption process, and the beam life-time remains to be calculated

The use of the gamma beams

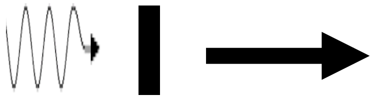


$\gamma-\gamma$ collisions, E_{CM} =2-800 MeV , L^{max} ~10^{32} 1/(s*cm^2)

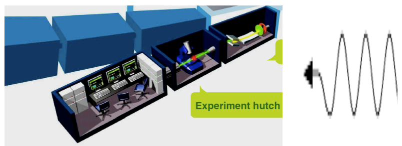
$\gamma-\gamma_L$ collisions, E_{CM} =1-126 keV , L^{max} ~10^{34} 1/(s*cm^2)



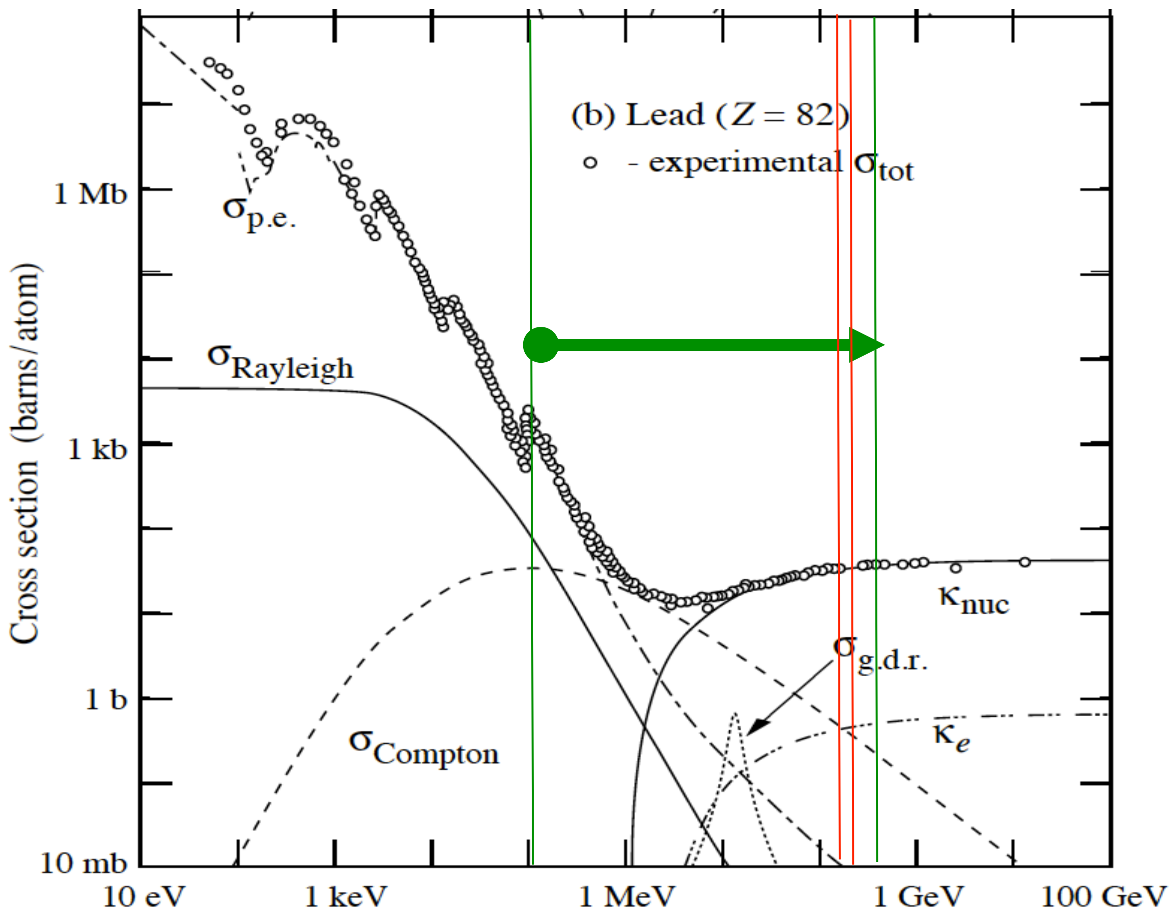
$\gamma-$p,A collisions, E_{CM} =4-60 GeV , L^{max} ~ 10^{30} 1/(s*cm^2)



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



Medical applications, nondestructive assay and segregation of nuclear wastes, 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…



$\sigma_{\text{p.e.}}$ = 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

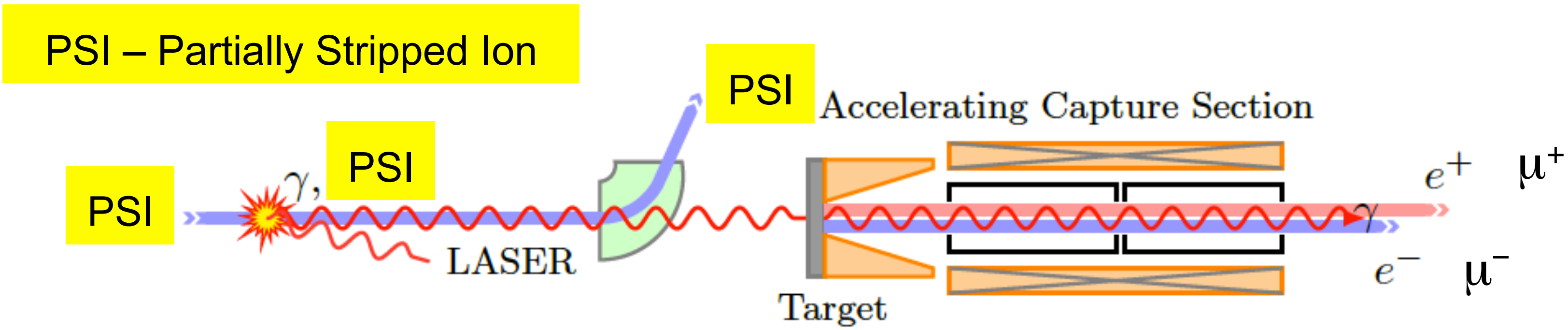
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance
In these interactions, the target nucleus is broken up.

HIGS as a source of high intensity secondary beams

- High Intensity highly polarised electron and positron beams
- Polarized muon and neutrino beams
- High intensity monochromatic neutron beams (GDR in heavy nuclei as s a source of neutron beam: $\gamma + A \rightarrow A\text{-}1 + n$)
- High intensity radioactive beams (photo-fission of heavy nuclei:($\gamma + A \rightarrow A_1 + A_2$ + neutrons)

Secondary beams of polarized:

e^+, e^-, μ^+, μ^-



Achievable fluxes (assuming that all produced leptons are collected):

e+, e- : < 10^{17} [1/s] (scenario 2) , μ^+,μ^- : <10^{12} [1/s] (scenario 1)

…a factor of ~10^5 (10^4) higher then the the KEK positron source (the Zurich muon source). No longer a necessity to stack the positrons in the pre damping or damping ring for the CLIC and ILC designs! Muon beams attractive for the neutrino programme (charge symmetry, and precise control of the energy spectra for ν_e, ν_μ and their antiparticles)!.

Important note: for the maximal flux of the muons the LHC circumferential voltage would need to be increased from the present value of RF=16 MV to the "LEP-like" value of RF=3560 MV

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

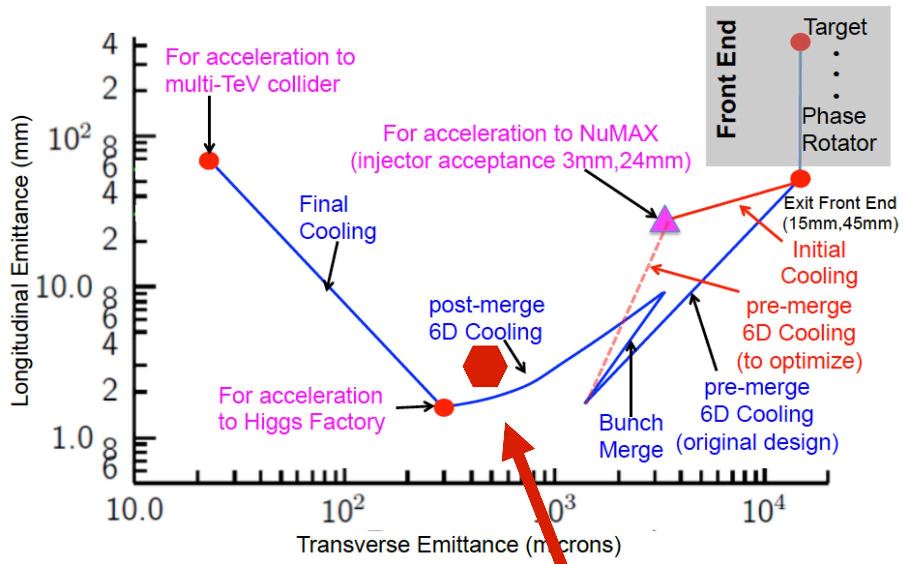
	SLC	CLIC (3 TeV)	ILC (500 GeV)	LHeC (ERL)
Damping ring energy, GeV	1.19	2.86	5	
e^+/bunch at IP, $\times 10^9$	40	3.72	20	2
e^+/bunch after capture, $\times 10^9$	50	7.7	28	2.2
Bunches/macropulse	1	312	1312	CW
Macropulse repetition rate	120	50	5	CW
Bunches/second	120	15,600	6560	2×10^7
e^+/second, $\times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

Bonus: polarization (80-90%)

For scenario 2: the flux of $\sim 10^{17}$ N^{e+e-}/s can be achieved with the nominal LHC RF voltage. Note: the beam power which has to be handled by the conversion target is 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)

~10^{12} polarized μ+μ- pairs [1/s]

muon beam emittance (factor 10000 better)

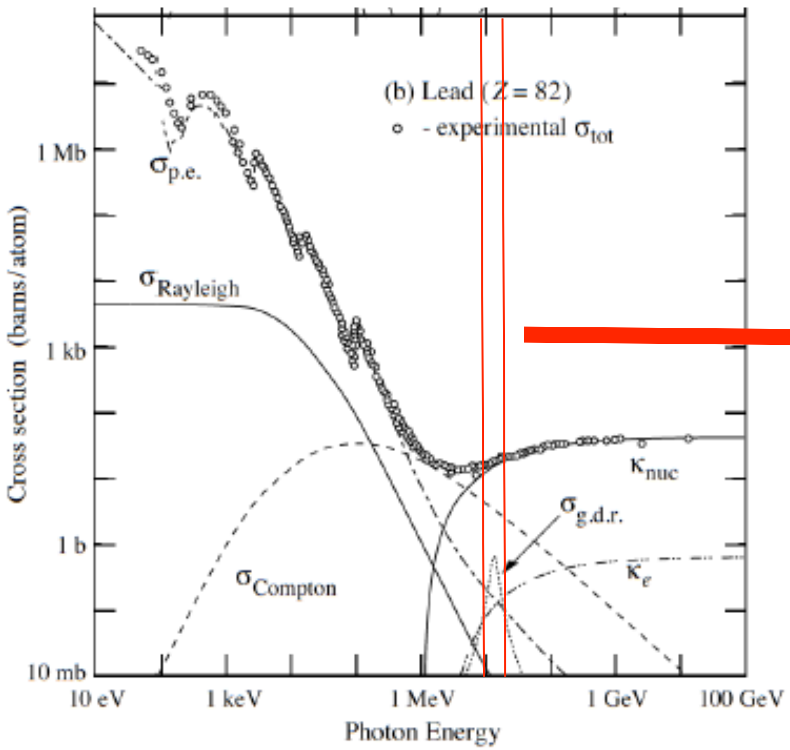
ε_L ~ 5 mm ε_T ~ 500

Note, the timing structure of the initial HIGS muon beam requires a continuous stacking of the ERL accelerated muon bunches into ~ 7 bunches circulating in the R=50 m storage ring!

1. The circumferential RF voltage of the LHC would need to be upgraded to the "LEP" level.

2. $(m_\mu/m_e)^2 = 4 \times 10^4$ - the beam energy efficiency smaller by a factor 100 w.r.t "pion-beam" scheme.

Secondary Neutron and Radioactive Beams



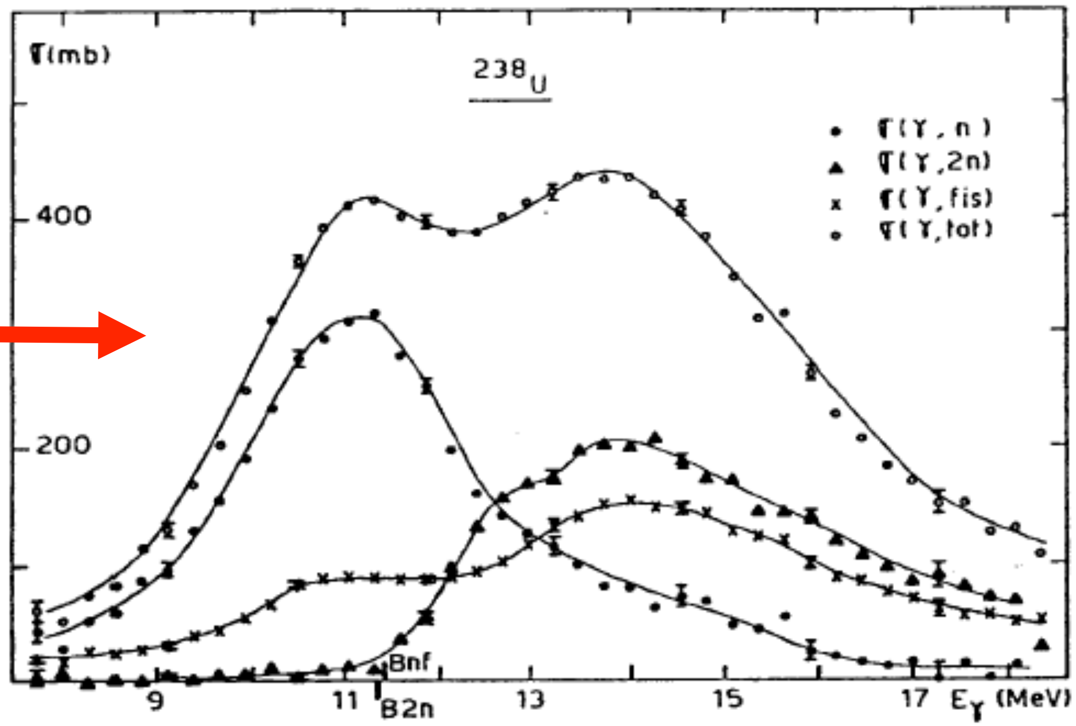
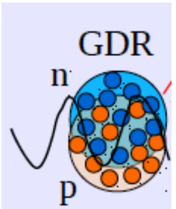
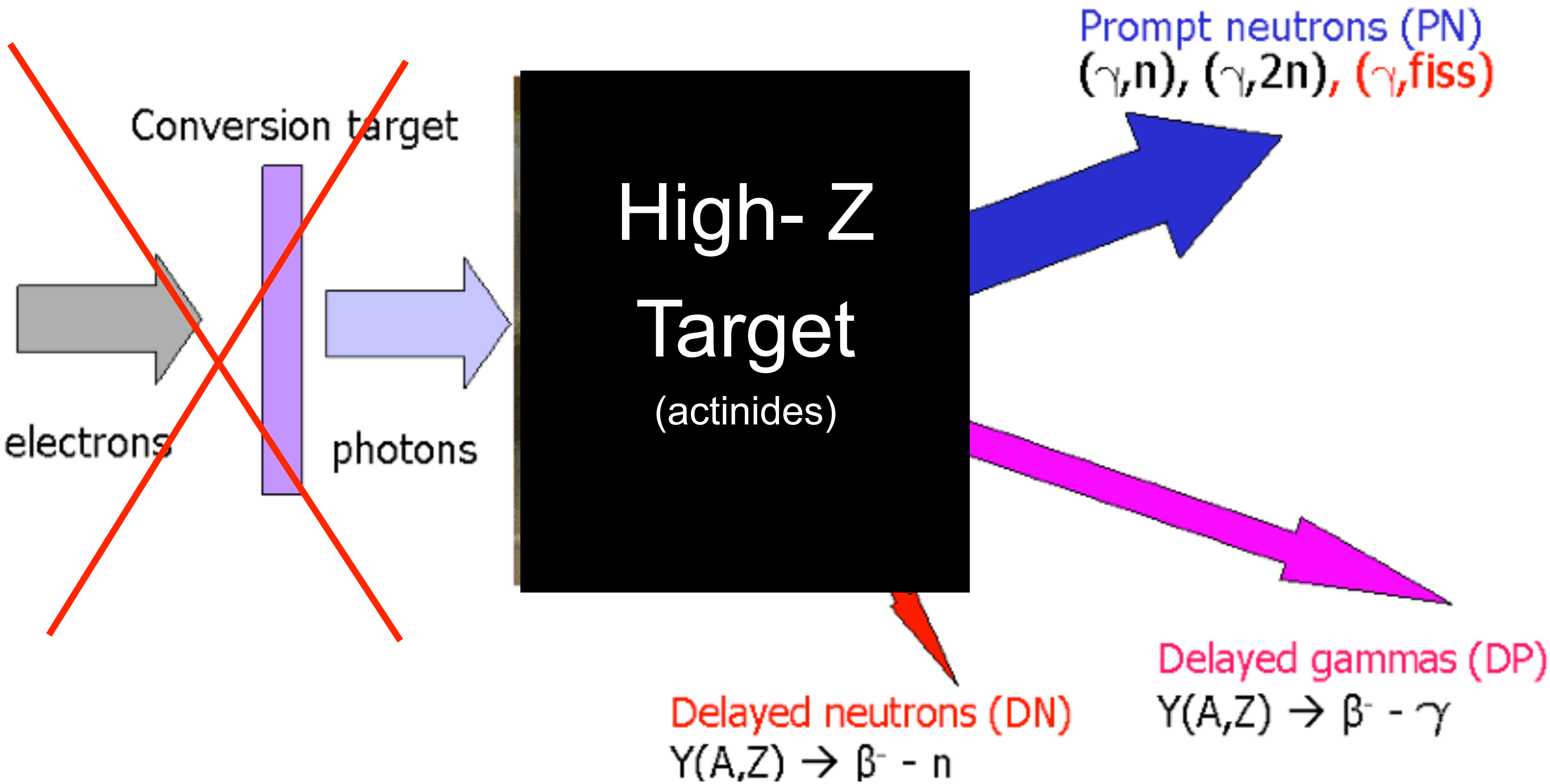


Figure 1. Partial and total photonuclear cross sections (γ,n), (γ,2n), (γ,f), and (γ,tot) for U^{238}.

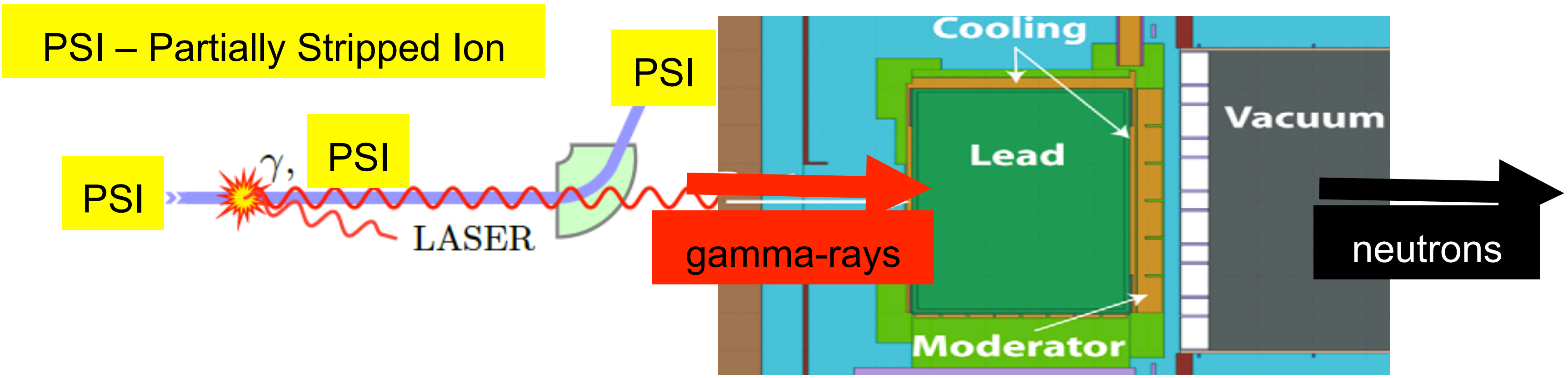


S.S.Dietrich, B.L.Berman
At.Data Nucl. Data
Tables **38** (1988) 199

GDR=Giant Dipole Resonance


Prompt neutrons (PN)
(γ,n), (γ,2n), (γ,fiss)
Conversion target
High- Z
Target
(actinides)
electrons
photons
Delayed gammas (DP)
Y(A,Z) → β- - γ
Delayed neutrons (DN)
Y(A,Z) → β- - n

Secondary Neutron Beams



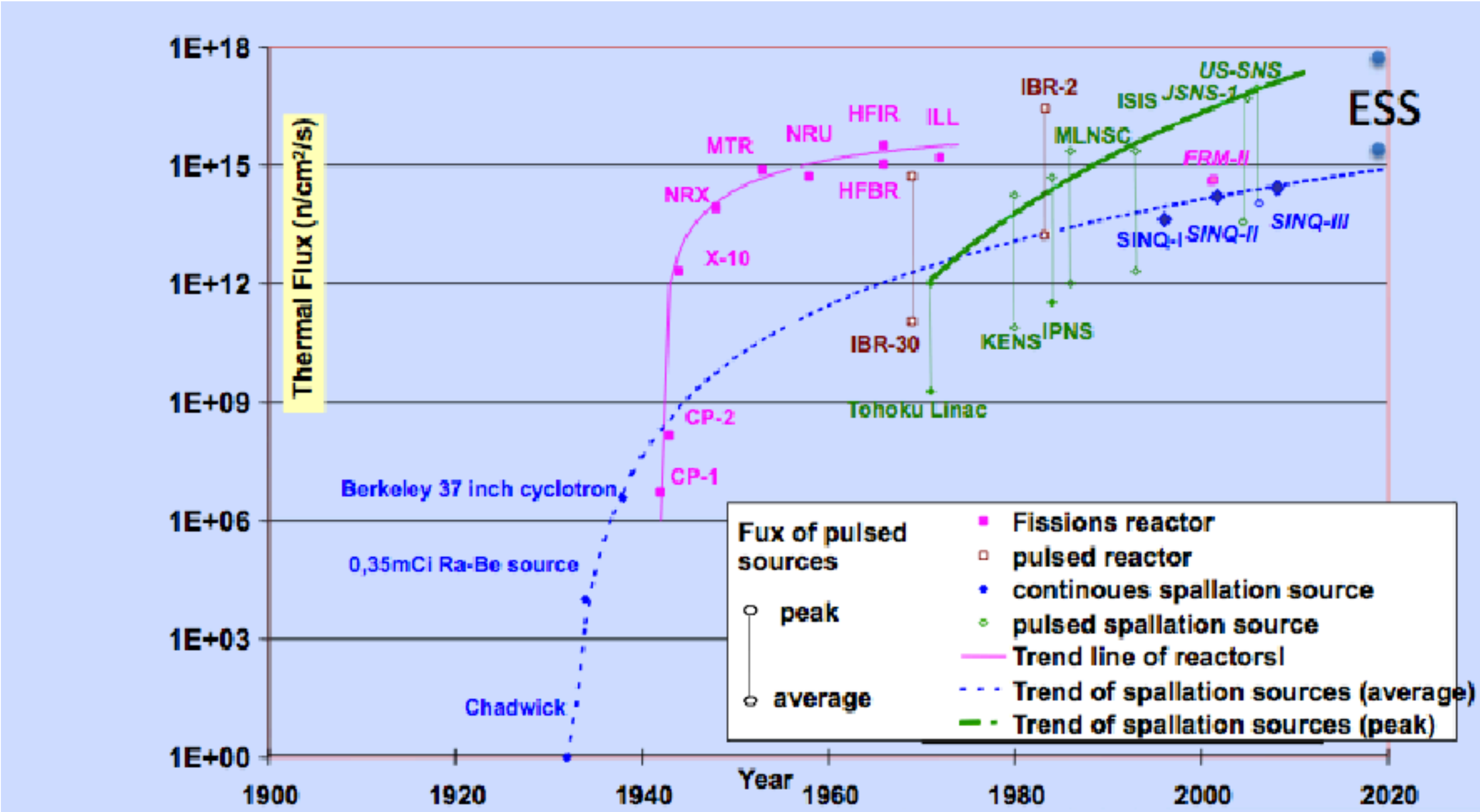
<u>Achievable production rate of primary neutrons:</u>

neutrons ~10^{15} 1/s

(If the HIGS tuned to the Giant Dipole Resonance wavelength)

<u>Note,</u> High efficiency of transforming the RF power of the accelerator cavities into the neutron flux ($N_{neutron}$/kW of beam power)

…one 10 GeV proton produces ~ 20-30 thermal neutrons



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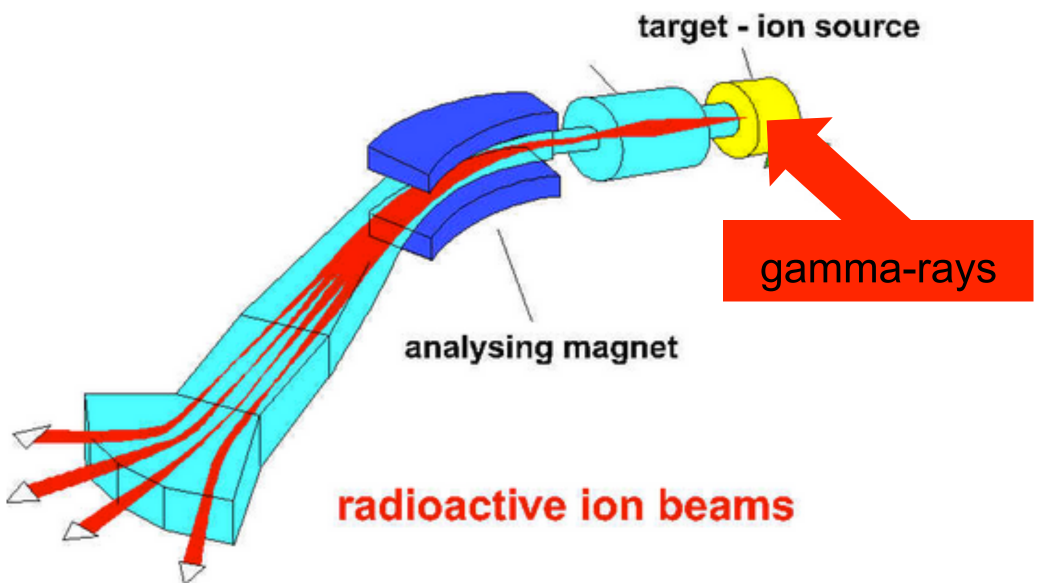
Questions:

- *What could be the rate of thermal neutrons produced by ~10^{15}, MeV-energy neutrons (using a moderator and a fissionable target material ?*
- *Can the " proton-beam based spallation neutron source requirements" be met by the gamma-beam driven spallation neutron source?*

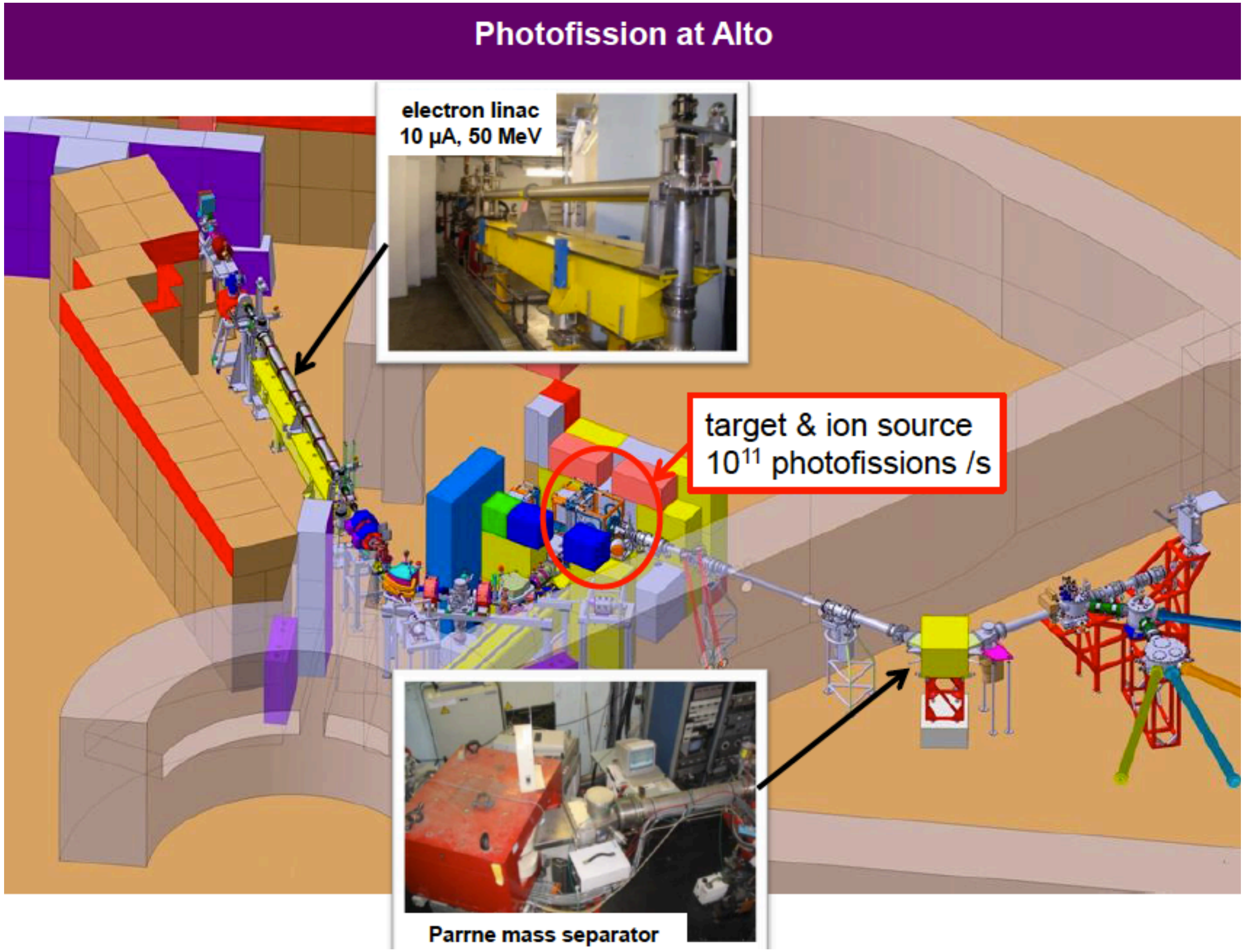
Secondary Radioactive Beams



<u>Achievable photo-fission rate</u> **:**

Number of photo-fissions ~10^{14} 1/s

(If the HIGS beam is tuned to the photo-fission-sensitive wavelength-band)



.

Questions:

- *Would it be useful to increase the photo-fission rate by 4 or more orders of magnitude?*
- *Relative merits of photo-fission RIBs and spallation RIBs?*

The achievable intensity of the HIGS generated Secondary Neutron and Radioactive Beams outnumber, by several orders of magnitude, the intensity of the present beams (e.g. the CERN n_TOF or TSL Uppsala neutron beam or the ISOLDE or ALTO-facility radioactive beams)

The neutron emission and the photo-fission rate could, potentially, be increased by 1-2 orders of magnitude if the LHC could be equipped with the "LEP-like" beam RF power.

Beam-Power handling limit?

Physics highlights and…

…industrial and medical applications

Fundamental physics

- Fundamental QED measurements (elastic $\gamma\gamma$ scattering)
- Dark matter searches (dark photon and neutron portals)
- QED vacuum properties
- Understanding of the QCD confinement ($\gamma\gamma$, γp, γA, ep, eA) collisions
- Study of basic symmetries of the Universe (neutron dipole moment, neutron-antineutron oscillations, rare muon decays)
- A support for the LHC EW precision programme

Nuclear physics

- Development of QGP diagnostic tools
- Physics with radioactive beams
- Energy tagged neutron beam physics
- …

Industrial applications

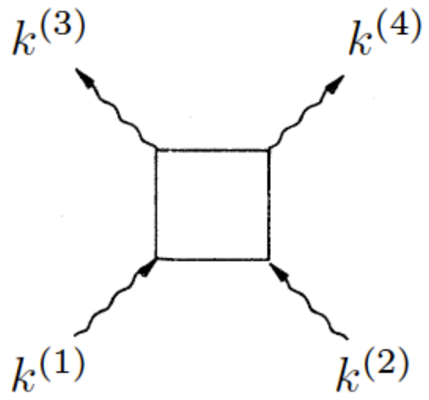
- Transmutation of nuclear waste
- Muon catalysed, cold fusion R&D
- Gamma beam catalysed, hot fusion R@D
- ADS and Thorium based “Energy amplifier” research
- Nondestructive assay and segregation of nuclear wastes
- Material studies (thick objects)
- …

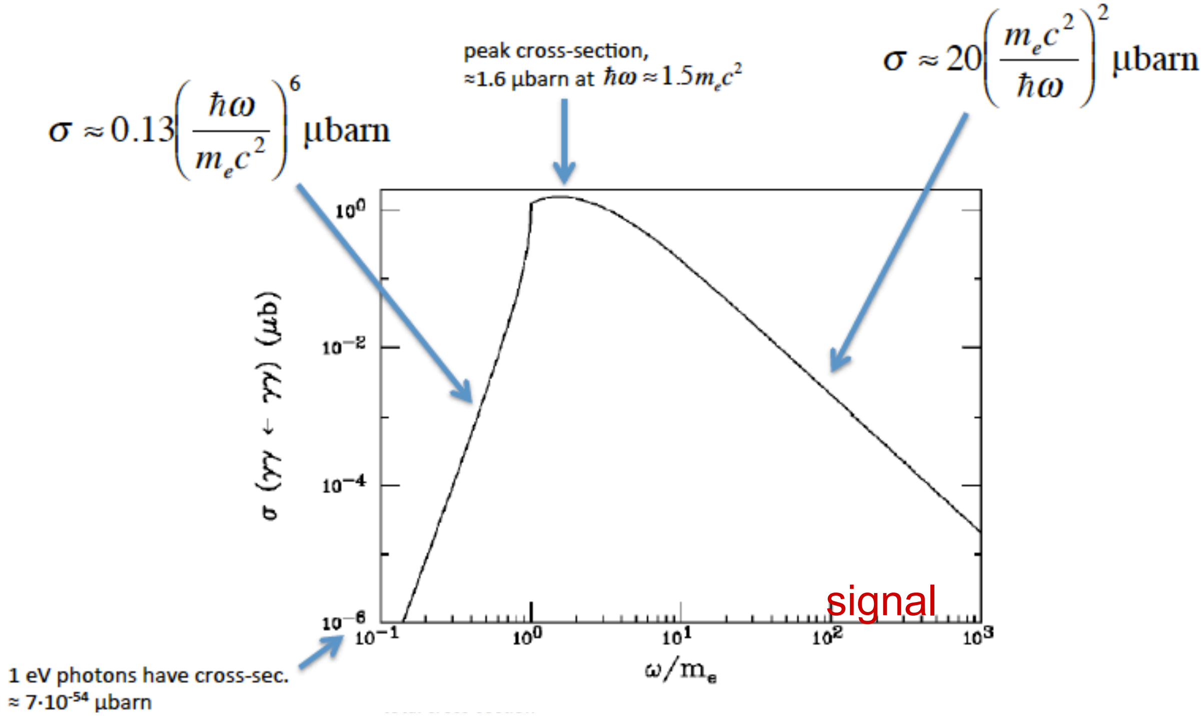
Medical applications

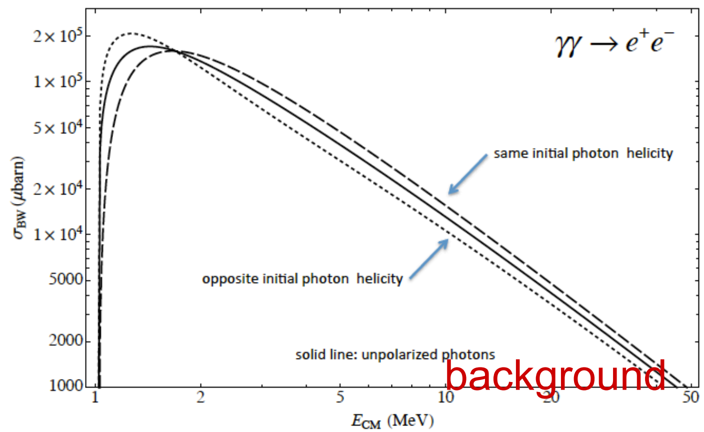
- Production of ions for PET
- Conventional cancer treatment
- Selective cancer-cell killers (production of α−emitters)
- …

Couple of examples

Elastic light-by-light scattering (never measured)







Two measurements:

γ–γ collisions, for $E_{CM} > 2m_e$

and (background free)

γ–γ_L collisions, for $E_{CM} < 2m_e$

~1000 events/s expected, to be compared to ~20 events/year at the LHC

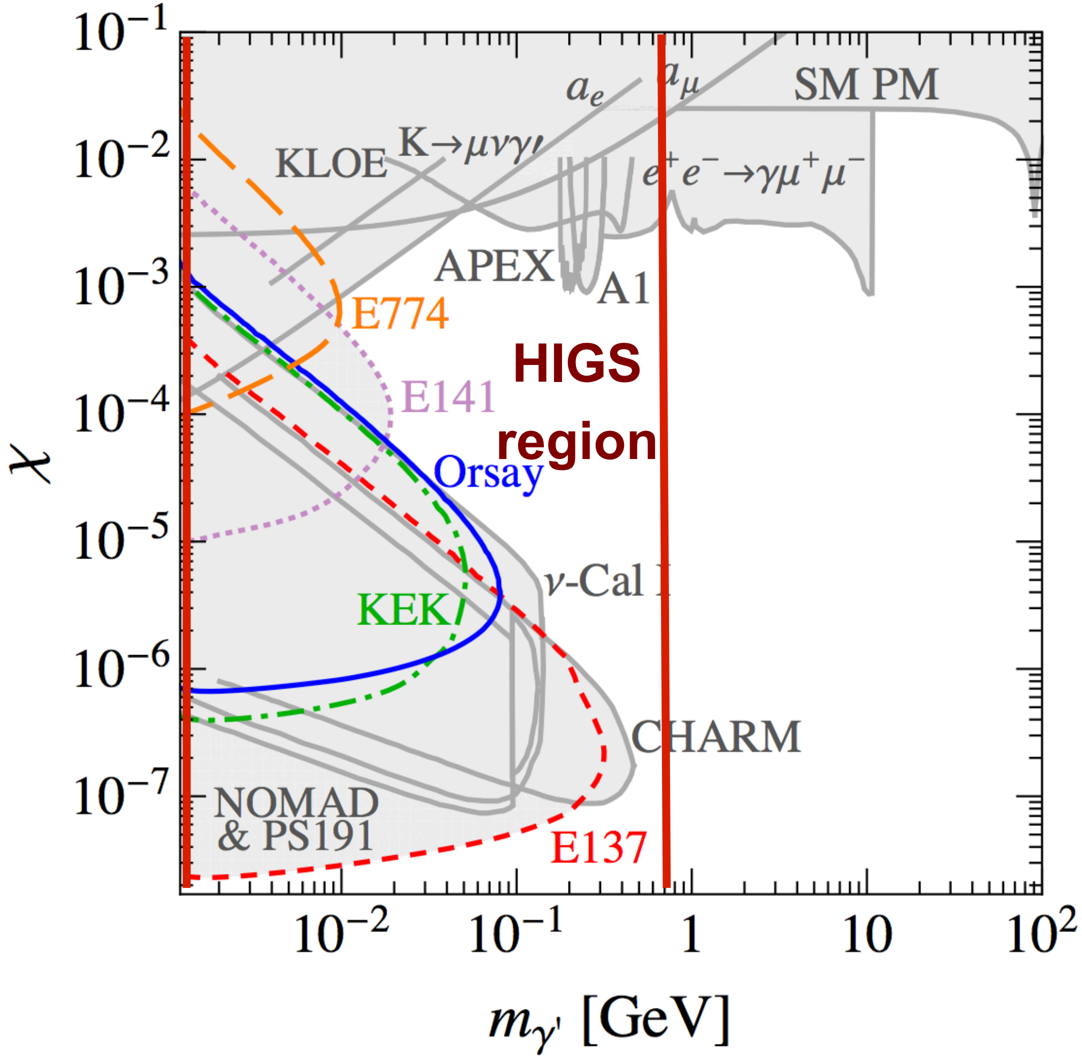
Dark Gauge Forces

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

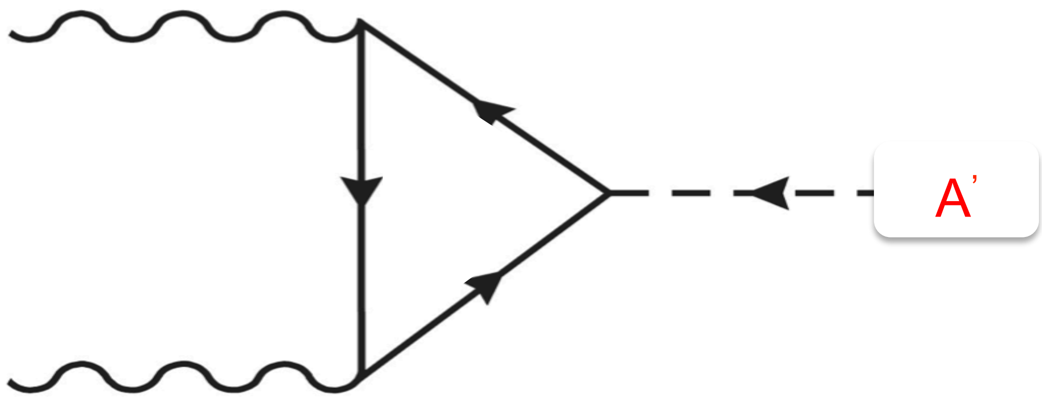
where $\mathcal{L}_{\rm SM}$ is the Standard Model Lagrangian, $F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$, and A' is the gauge field of a massive dark $U(1)'$ gauge group [1]. The second term in (3) is the kinetic

Present status

courtesy Andreas Ringwald)

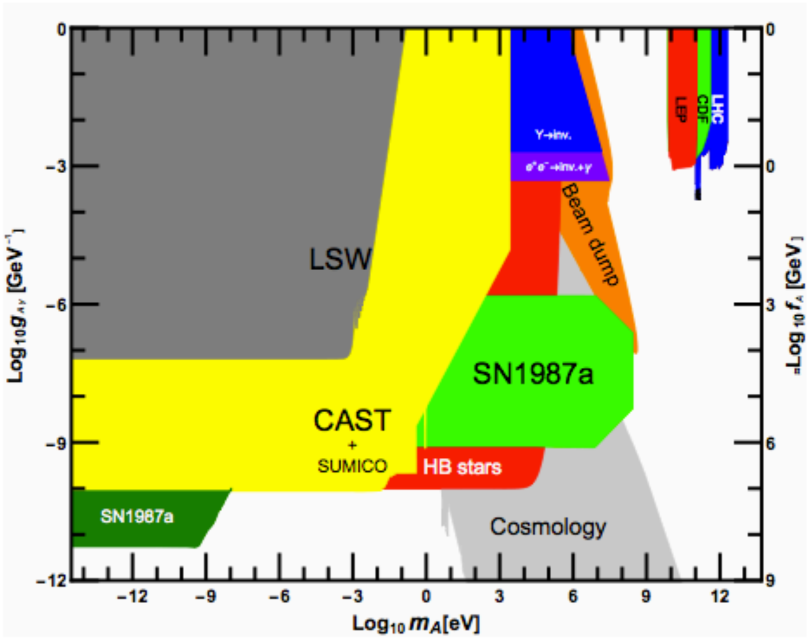


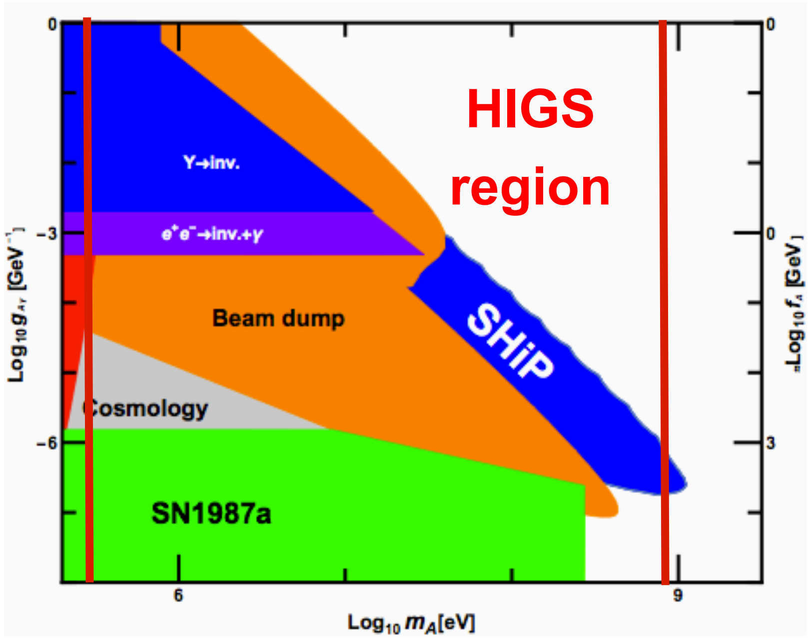
Resonant production of ALPs via Primakoff process



A very wide mass region(1 KeV - 700 MeV) and a wide range of the production cross-sections (down to the O(1) fb region) can be explored

HIGS and ALPs





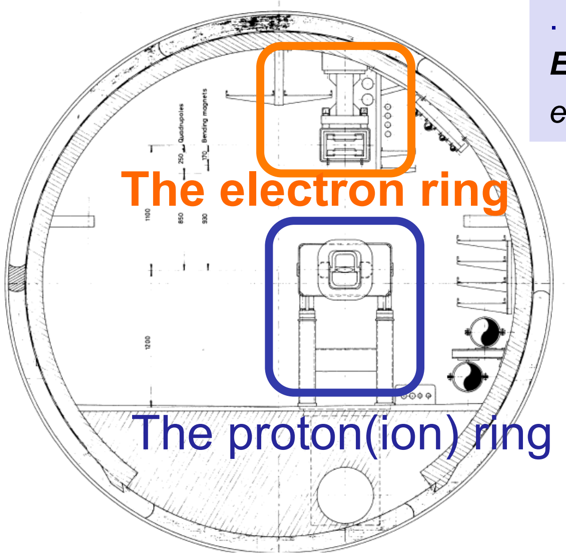
CERN-SPSC-2015-017 (SPSC-P-350-ADD-1)

High Luminosity **ep (eA) colliders** under consideration

	ENC@FAIR (GSI)	MEIC (TJNAF)	eRHIC (BNL)	iCHEEP (CERN)	LHeC (CERN)
E_{CM} range [GeV]	14	10-65	45-175	14-230	800-1300
Peak Lumi [10^{33} cm $^{-2}$ s^{-1}]	0.2 (0.6)	14.2	9.7	10	1-1.7
Polarisation, p,e [%,%]	80,80	70,80	70,80	0.8-0.9	0,90
Adequacy of collider parameters for the quest to understand QCD	***	****	*****	*****	***
Attractiveness to the nuclear physics community	****	****	****	****	**
New observables and new physics questions	***	*****	*****	*****	***
Importance for the LHC experimental programme	**	***	****	*****	****
Challenging accelerator R&D	***	*****	*****	*****	*****
Financing probability/cost	****	***	***	*****	**

1 to be confirmed

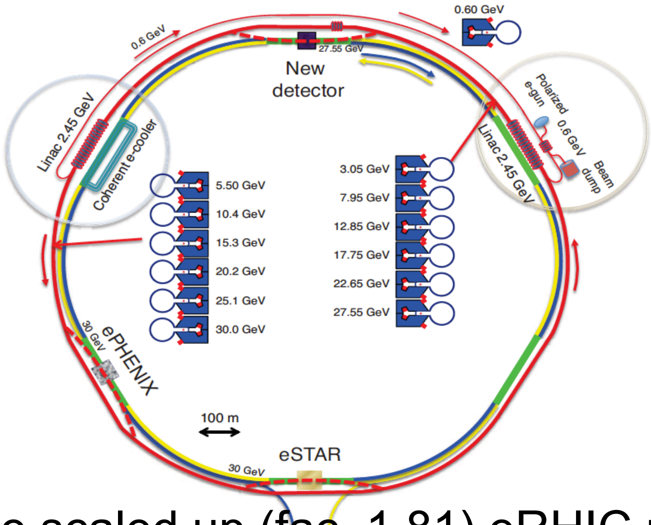
High intensity polarized electron and positron source for the “iCHEEP” ep(eA) collider in the SPS tunnel -- an optimal facility to study the confinement phenomena



.
***Exploring Confinement**, Mieczyslaw Witold Krasny (Paris U., VI-VII). Aug 2012.*
e-Print: arXiv:1208.3764 [physics.acc-ph]

→ **2.45 GeV ERLs**
(no bypasses necessary)

6 vertically stacked recirculation passes in the arcs : 5.5, 10.4, 15.3, 20.2, 25.1, 30.0 GeV

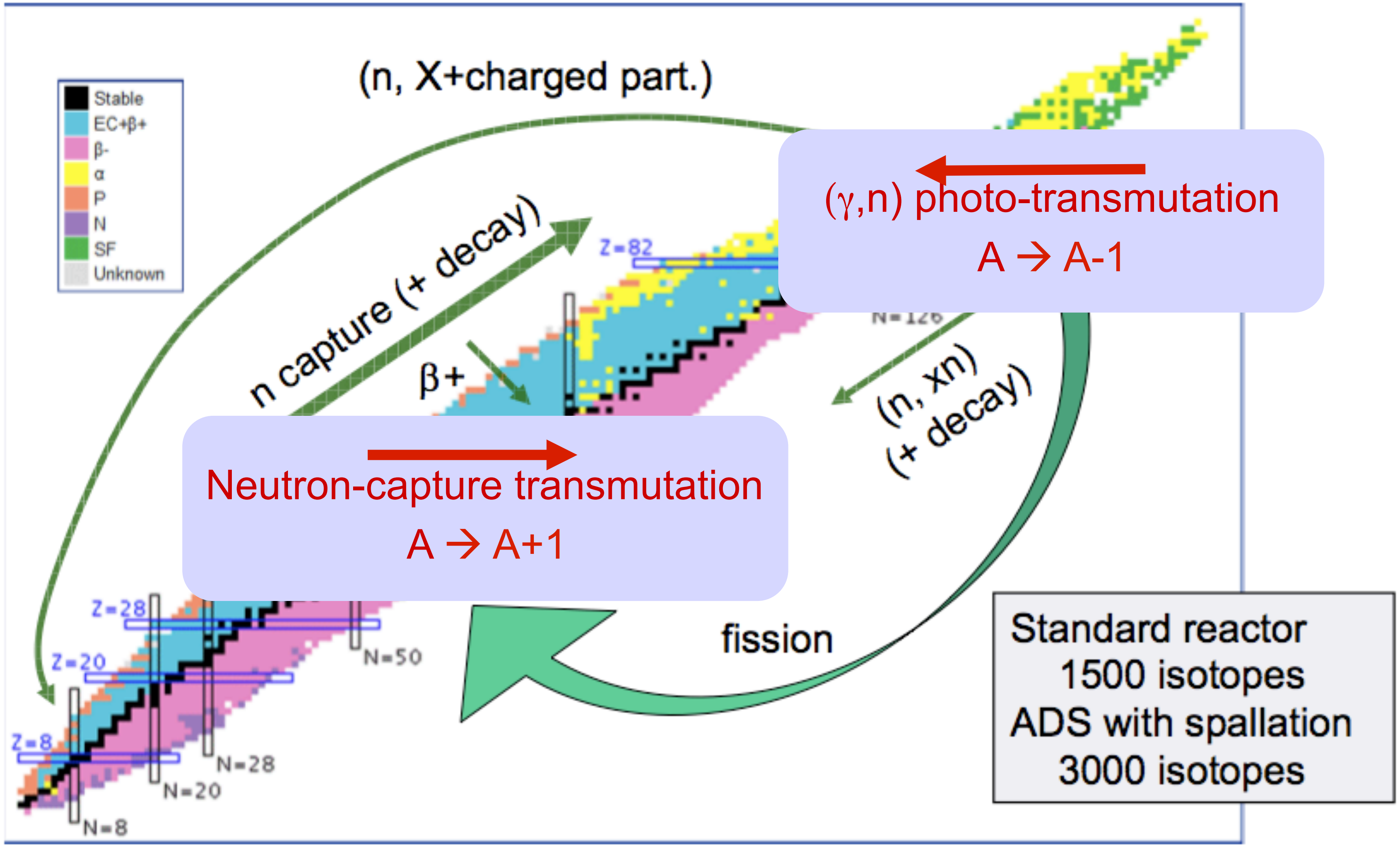


The scaled up (fac. 1.81) eRHIC project

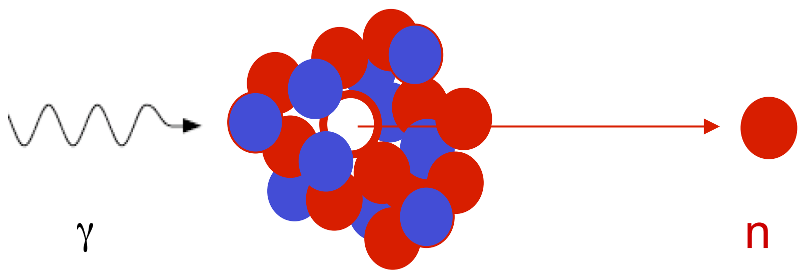
→ **E_{CM}(ep/eA) = 14-230 GeV**

(covers the energy range of eRHIC, MEIC and ENC@FAIR, overlap with PIE@LHC – easy cross-normalisation of the iCHEEP and LHC cross-sections)

Transmutation



γ-ray surgery of nuclear waste

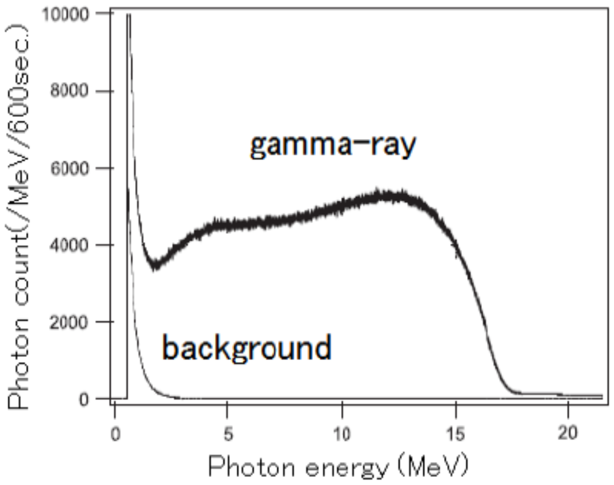


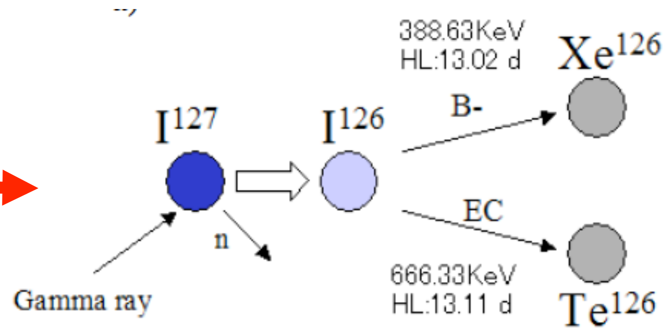
Example: (γn) transmutation of a nuclear waste 126Sn with a high life-time of 100 00 years into 125Sn with a life-time 9.64 days

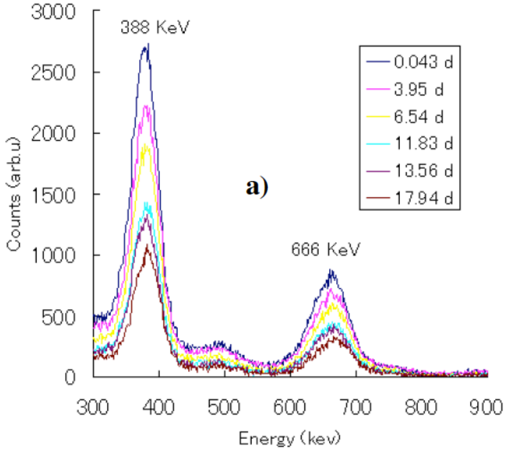
… γ-transmutation not taken (so far) seriously because of lack of high-intensity mono-energetic γ-sources in the range 5-20 MeV…

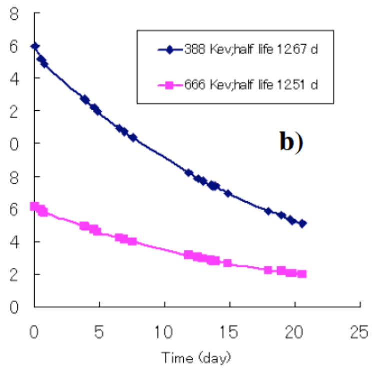
…no longer the case for the HIGS beams?

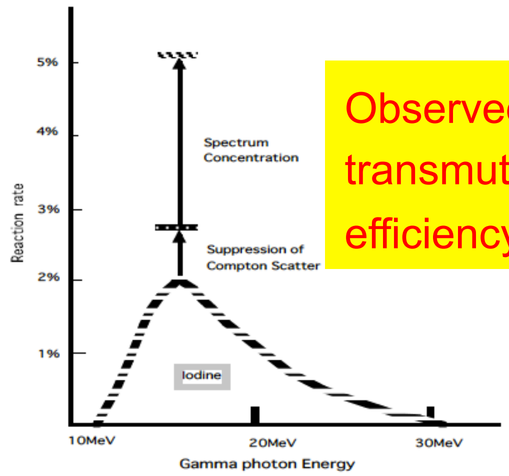
Transmutation efficiency







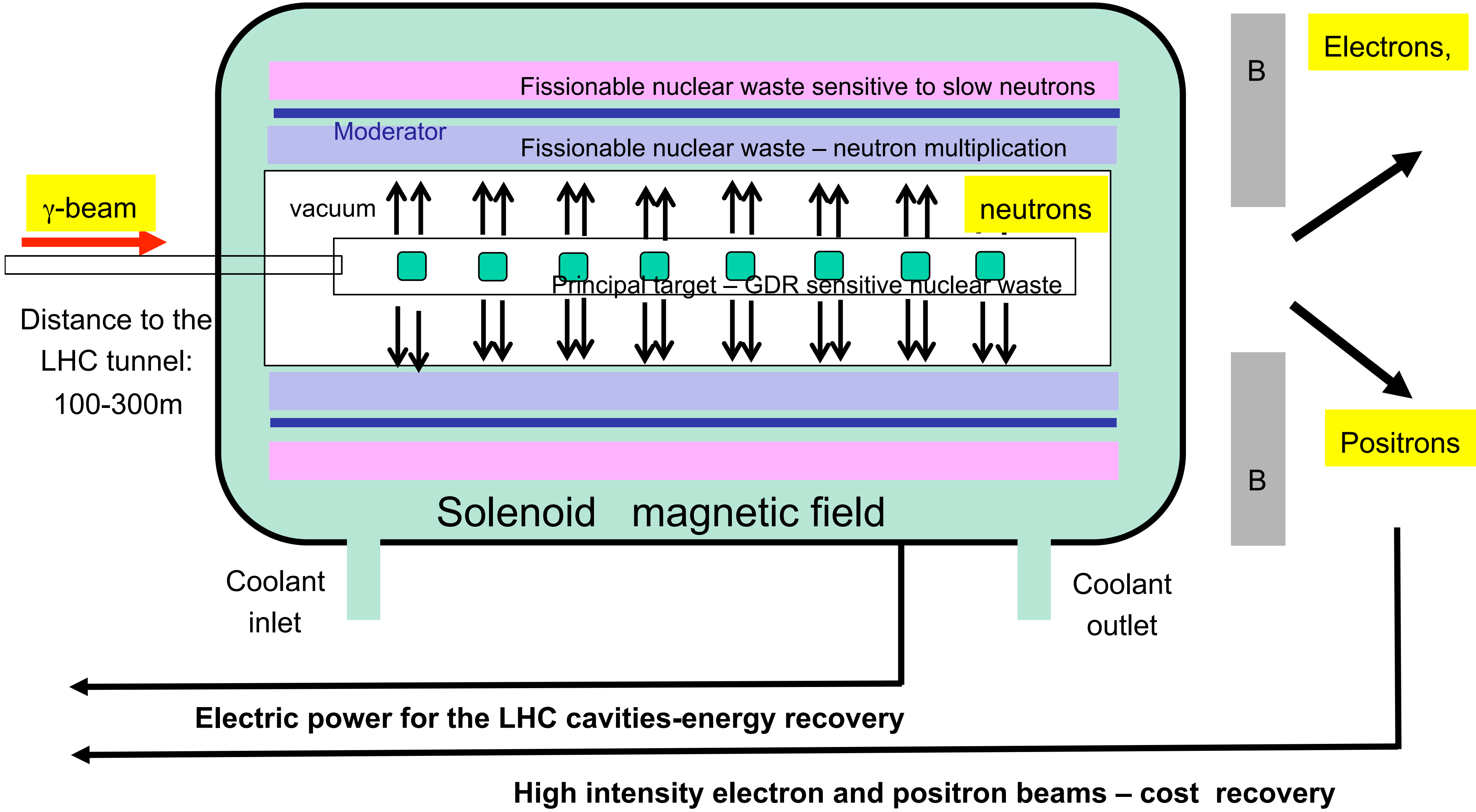




Observed transmutation efficiency: ~5%

Dazhi LI , Kazuo IMASAKI , Ken HORIKAWA , Shuji MIYAMOTO , Sho AMANO & Takayasu MOCHIZUKI(2009) SUBARU facility, Journal of Nuclear Science and Technology, 46:8, 831-835, DOI 10.1080/18811248.2007.9711592.

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



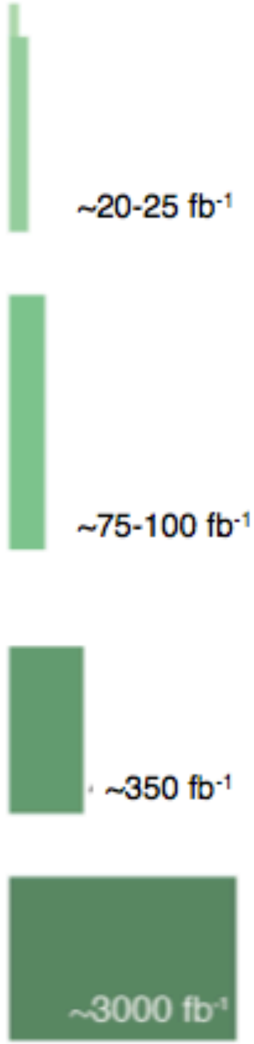
The way forward

Two parallel paths:

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

Schedule assumption (today)

2009		✧ LHC startup, $\sqrt{s}$ = 900 GeV
2010–2012		$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns
2013–2014	LS1	Go to design energy, nominal luminosity (**Phase-0**)
2015–2017		$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
2018	LS2	Injector and LHC **Phase-1** upgrade to full design luminosity
2019–2021		$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
2022	LS3	**HL-LHC Phase-2** upgrade, IR, crab cavities?
2023 … 2030?		$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling



>2030? **HE-LHC: $\sqrt{s}$ = 33 TeV, 300-3000 fb^{-1}**

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
- (2016-2017?) Short SPS test run with “BNL-type stripping target” (measurement of the beam life time, and time-dependent emittance of the beam of PSI in SPS?
- (2017?) At the end of the LHC Run2   measurement of the life-time of the partially stripped lead ion beam in the LHC?
- (2018?) 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)

Conclusions

The history of our discipline shows that a big technological leaps resulted in 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 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, potentially , the most efficient scheme of transforming accelerator RF power to the power of the (γ, e, μ, ν, n, radioactive ion) secondary beam(no "π,K energy dissipation")**

- **The HIGS initiative may lead to a leap, by several orders of magnitude, in the increase of their intensity.**

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

1. **Possible contributions to the high energy frontier (lepton colliders) and high intensity frontier (i.e. the iCHEEP ep(eA) collider, $\gamma\gamma$ colliders and neutrino factories)**

2. **Opening new research domains in Fundamental Physics (including the dark matter searches domain)**

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 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:**

  - the LHC can be envisaged to be used as HIGS facility only after finalizing its high luminosity phase (> 2021)
  - a wide community must be interested in the HIGS driven research programmes

…here, your contribution is highly desired ….

extra transparencies

Facts – nuclear waste

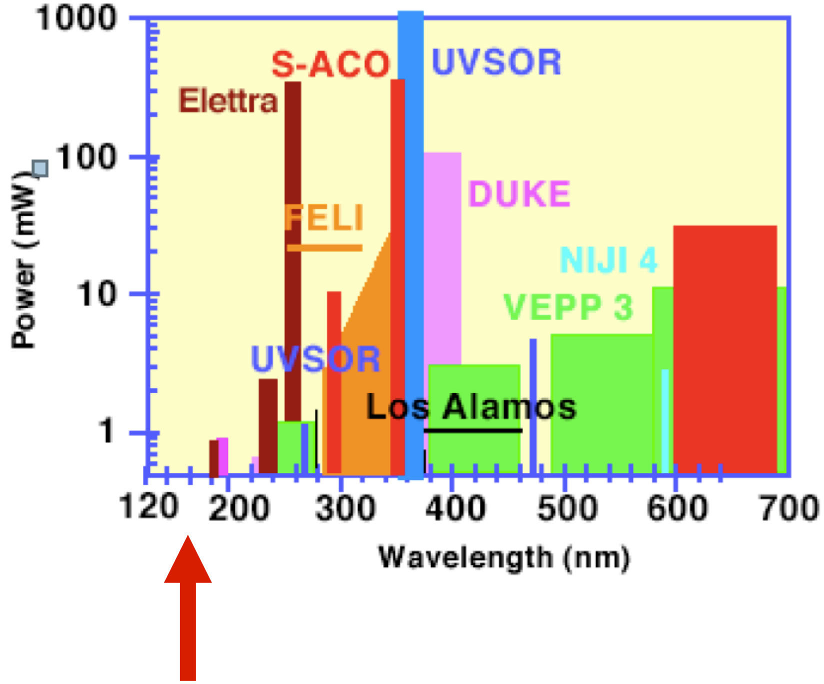
With 145 operating reactors (2001) with a total power of 125 GW, the resulting electrical energy generation in Europe is of about 850 TWh per year and represents ~35% of the total electricity consumption of the European Union.

Most of the hazard from the spent fuel stems from only a few chemical elements - *plutonium, neptunium, americium, curium*, and some *long-lived fission products such as e.g iodine and technetium* at concentration levels of grams per ton.

Approximately 2500 tons of spent fuel are produced annually in the EU, containing about 25 tons of plutonium and 3.5 tons of the "minor actinides" neptunium, americium, and curium and 3 tons of long-lived fission products (the long term > 100 years radio-toxicity is dominated by the actinides).

Technological challenges

Need optical cavities for (100 nm - 400 nm) wavelength. Multilayer mirrors using high refraction index materials (AL2O3, HFO2, ZRO2) and low refraction index material (SiO2) deposited on silicium or sapphire. The roughness must be controlled to better than 1 angstrom. Very recent technological progress: Mackowski- Lyon, Jena (Germany)*



* private communication: Fabian Zomer and Raphael Roux

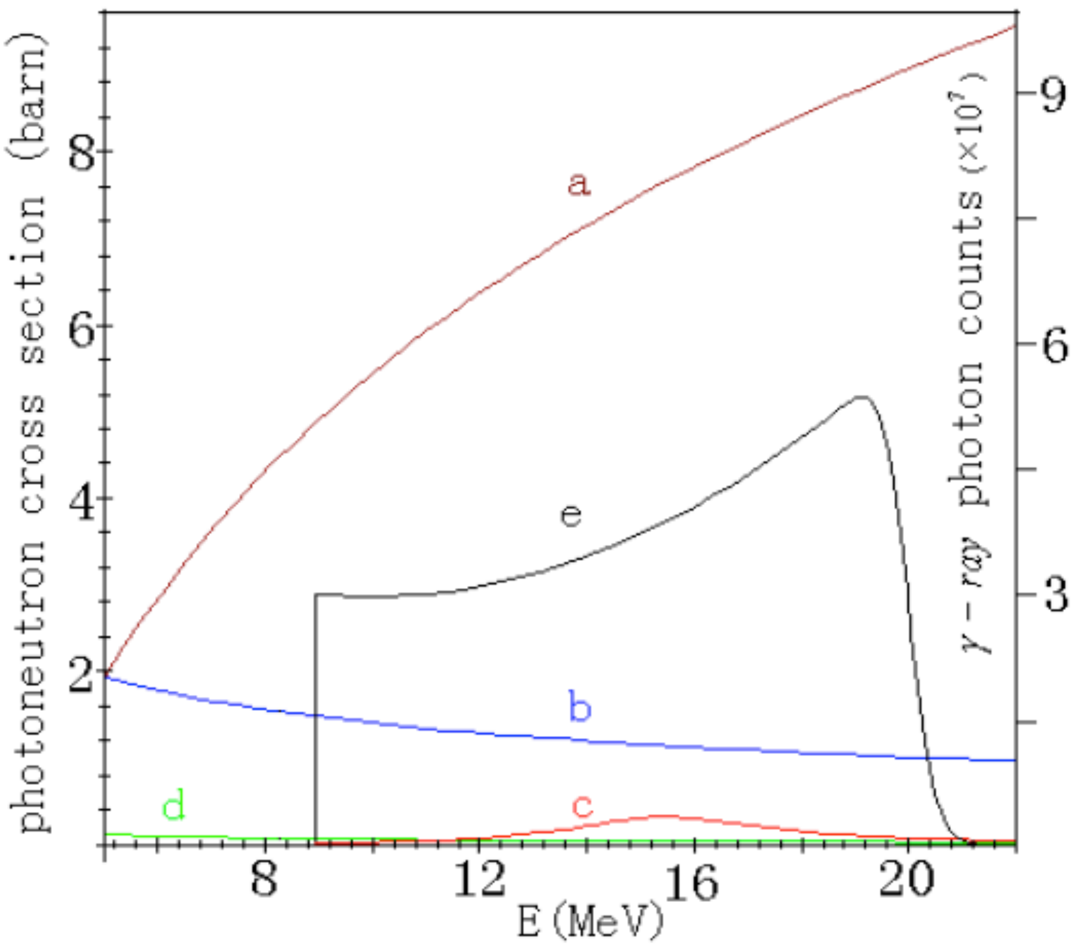


Fig.3. Coupling of γ ray to nuclear giant resonance of ^{129}I. Crosssections of gamma ray photon for the typical target interactions is indicated. Curve a shows pair creation, and b corresponds to Compton scatter by target atom electron and c corresponds to giant resonance and d corresponds to photo-electron effect. Curve e denotes γ ray photon by Compton scattering.

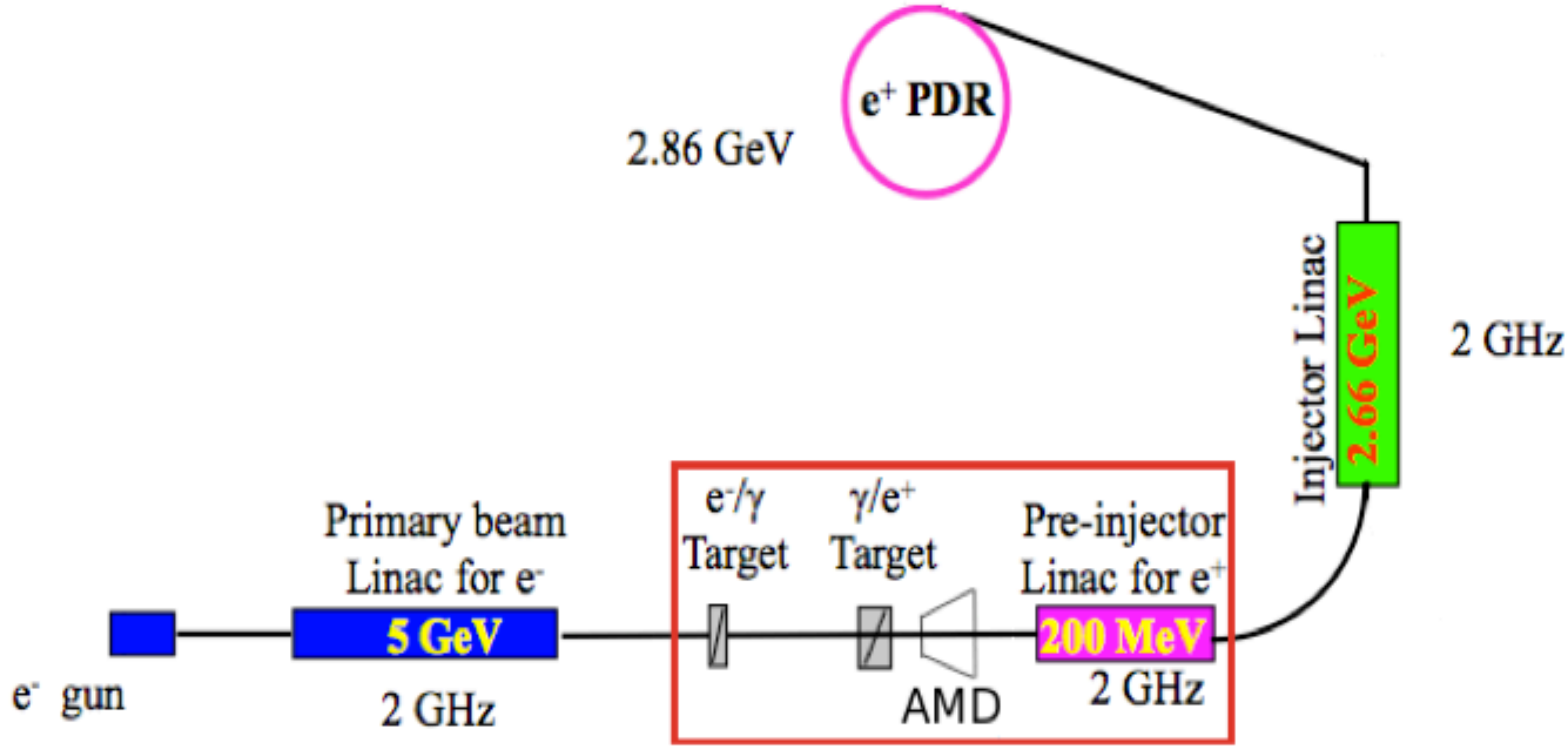


Figure 1: Layout of the CLIC positron source. Red box show the part which concerns the positron production and capture (zoomed in Figure 2).

Medium lived elements

$$^{137}_{55}Cs\ (\tau = 30.1\ y) + n \Rightarrow {}^{138}_{55}Cs \xrightarrow{\beta^-\ (33.2\ m)} {}^{138}_{56}Ba\ (stable)$$

$$^{134}_{55}Cs\ (\tau = 2.06\ y) + n \Rightarrow {}^{135}_{55}Cs\ (\tau = 2.6 \times 10^{6}\ y)$$

$$^{90}_{38}Sr\ (\tau = 29.1\ y) + n \Rightarrow {}^{91}_{38}Sr \xrightarrow{\beta^-\ (6.63\ h)} {}^{91}_{39}Y \xrightarrow{\beta^-\ (58.51\ d)} {}^{91}_{40}Zr\ (stable)$$

$$^{90}_{39}Y\ (\tau = 64.1\ h) + n \Rightarrow {}^{91}_{39}Y \xrightarrow{\beta^-\ (58.51\ d)} {}^{91}_{40}Zr\ (stable)$$

Long lived elements

$$^{135}_{55}Cs\ (\tau = 2.6 \times 10^{6}\ y) + n \Rightarrow {}^{136}_{55}Cs \xrightarrow{\beta^-\ (13.16\ d)} {}^{136}_{56}Ba\ (stable)$$

$$^{129}_{53}I\ (\tau = 6.6 \times 10^{7}\ y) + n \Rightarrow {}^{130}_{53}I \xrightarrow{\beta^-\ (12.36\ h)} {}^{130}_{54}Xe\ (stable)$$

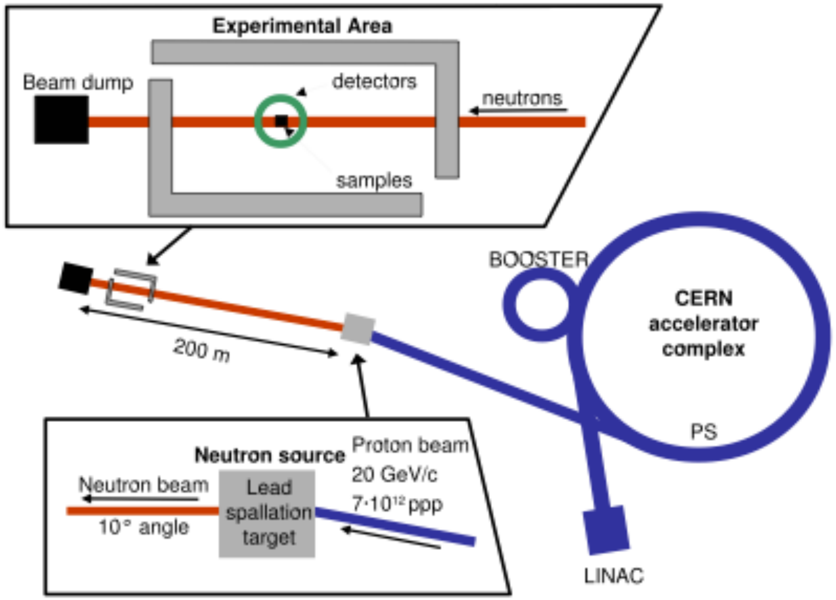
$$^{126}_{50}Sn\ (\tau = 1.0 \times 10^{5}\ y) + n \Rightarrow {}^{127}_{50}Sn \xrightarrow{\beta^-\ (12.4\ m)} {}^{127}_{51}Sb \xrightarrow{\beta^-\ (3.85\ d)} {}^{127}_{52}Te \xrightarrow{\beta^-\ (9.35\ h)} {}^{127}_{53}I\ (s$$

$$^{99}_{43}Tc\ (\tau = 2.1 \times 10^{5}\ y) + n \Rightarrow {}^{100}_{43}Tc \xrightarrow{\beta^-\ (15.8\ s)} {}^{100}_{44}Ru\ (stable)$$

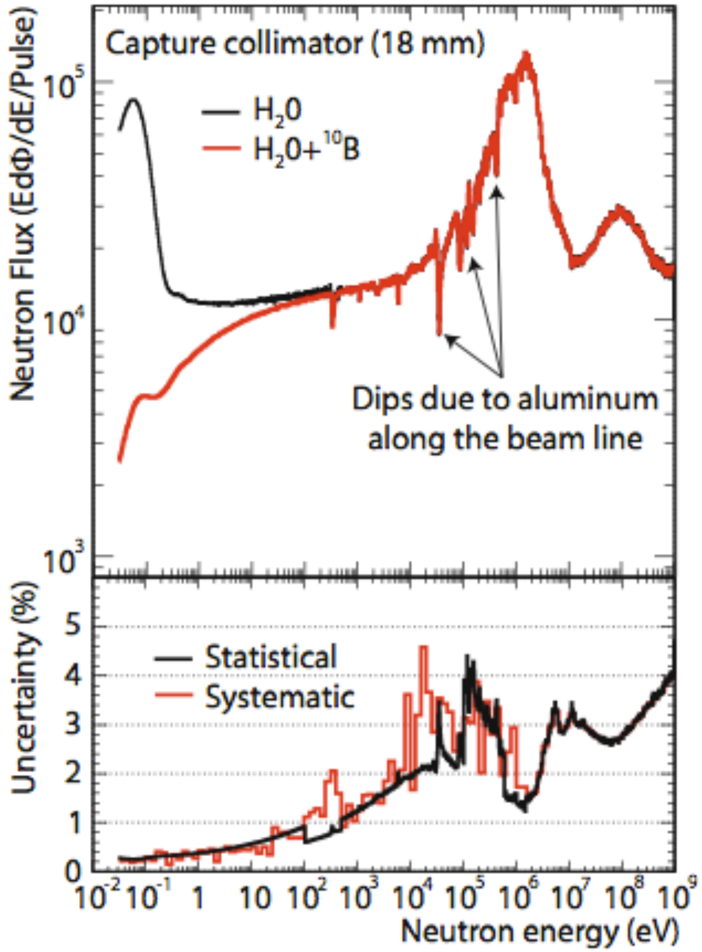
$$^{93}_{40}Zr\ (\tau = 1.5 \times 10^{6}\ y) + n \Rightarrow {}^{94}_{40}Zr\ (stable)$$

$$^{79}_{34}Se\ (\tau = 6.5 \times 10^{4}\ y) + n \Rightarrow {}^{80}_{34}Se\ (stable)$$

n_TOF



Experimental Area
Beam dump
detectors
neutrons
samples
BOOSTER
CERN accelerator complex
200 m
PS
Neutron source
Proton beam
20 GeV/c
7·10^12 ppp
Neutron beam
10° angle
Lead spallation target
LINAC



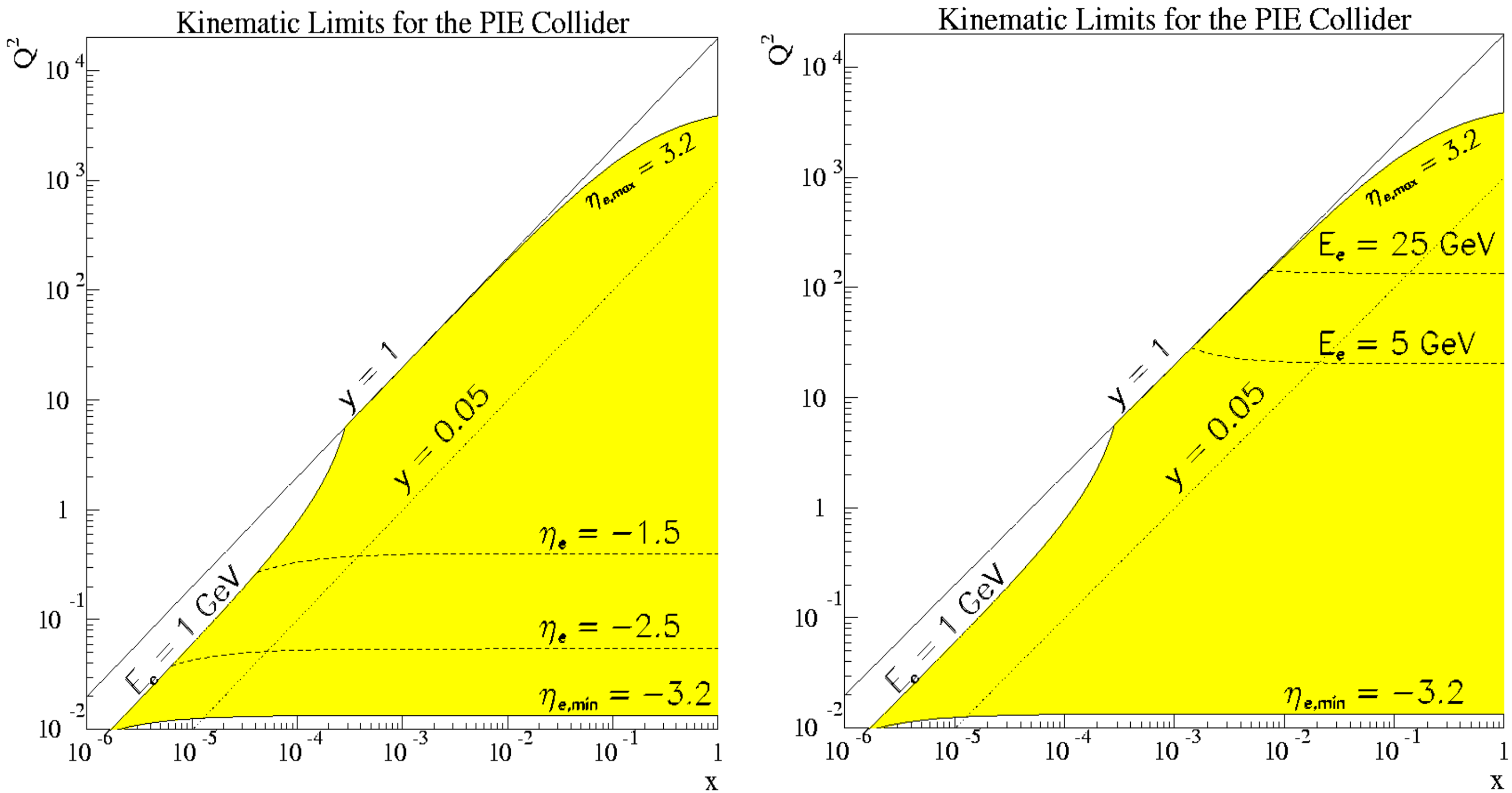
Capture collimator (18 mm)
$H_2$0
$H_2$0+^{10}B
Dips due to aluminum along the beam line
Neutron Flux (EdΦ/dE/Pulse)
Uncertainty (%)
Statistical
Systematic
Neutron energy (eV)

The ThomX Project

Injector	
Charge	1 nC
Laser wavelength and pulse power	266 nm, 100 µJ
Gun Q and Rs	14400, 49 MW/m
Gun accelerating gradient	100 MV/m @ 9.4 MW
Normalized r.m.s emittance	8 π mm mrad
Energy spread	0.36%
Bunch length	3.7 ps
Laser and FP cavity	
Laser wavelength	1030 nm
Laser and FP cavity Frep	36 MHz
Laser Power	50 - 100 W
FP cavity finesse / gain	30000 / 10000
FP waist	70 µm
Source	
Photon energy cut off	46 keV (@50 MeV), 90 keV (@ 70 MeV)
Total Flux	10^{11}-10^{13} ph/sec
Bandwidth	1 % - 10%

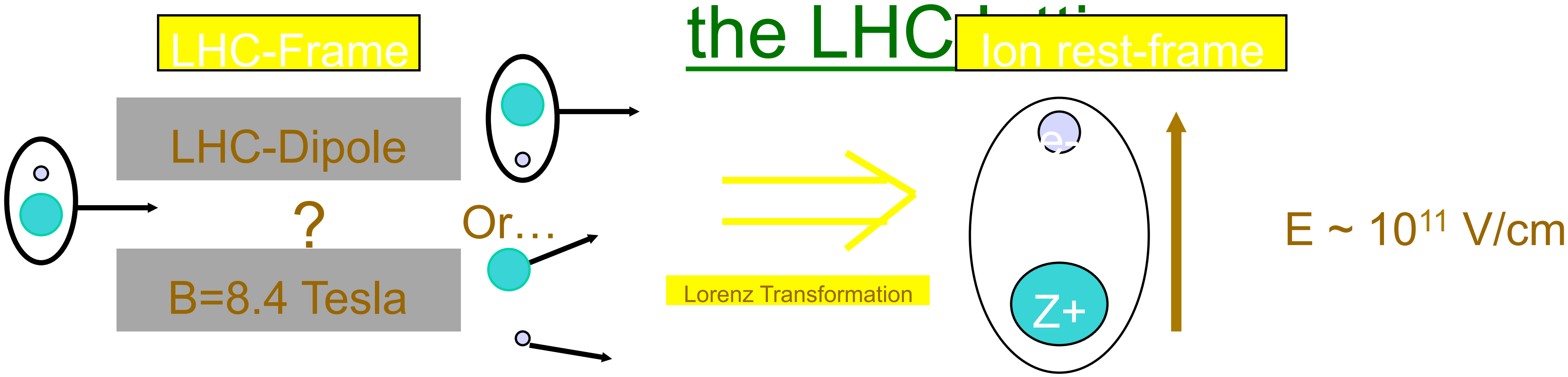
Ring	
Energy	50 MeV (70 MeV possible)
Circumference	16.8 m
Crossing-Angle (full)	2 degrees
$B_{x,y}$ @ IP	0.2 m
Emittance x,y (without IBS and Compton)	3 10^{-8} m
Bunch length (@ 20 ms)	30 ps
Beam current	17.84 mA
RF frequency	500 MHz
Transverse / longitudinal damping time	1 s /0.5 s
RF Voltage	300 kV
Revolution frequency	17.8 MHz
σ_x @ IP (injection)	78 mm
Tune x / y	3.4 / 1.74
Momentum compaction factor α_c	0.013
Final Energy spread	0.6 %

Kinematical region of PIE@LHC



Note: The ep luminosity used in the first measurement of the Structure Function F_2 at HERA could be collected in two 10 hour-long Pb $^{80+}$ - p collision runs at LHC

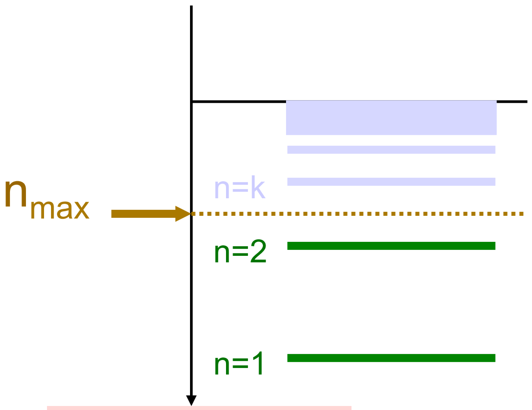
Survival of partially stripped ions:



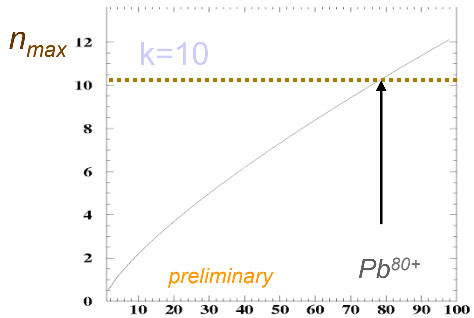
Binding energy of Rydberg-like atoms

Ionization of Rydberg-like atoms

Bethe-Salpeter,:"Quantum mechanics Of One- and Two- Electron Atoms



$E = 1Ry\ Z^2/n^2$



$B=7.3\ T, \gamma=2964, \beta=1$

LOW-Z ions cannot survive!

$10^5 Z^2/k^2 > E/15620(n/Z)(n1-n2)$

…tunneling effects …

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:

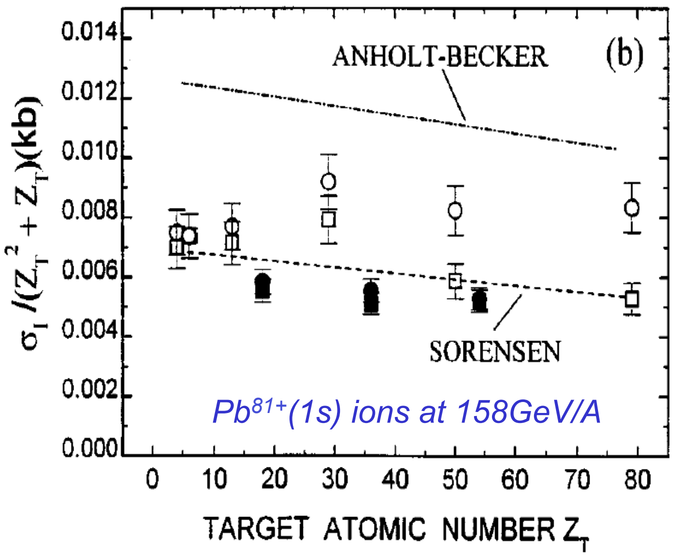
$\sigma_{Tran} = t(Z_t,Z_p)\,(Z_t/Z_c)^2\,10^4\,\ln(\gamma^2)$ [barn/electron]

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

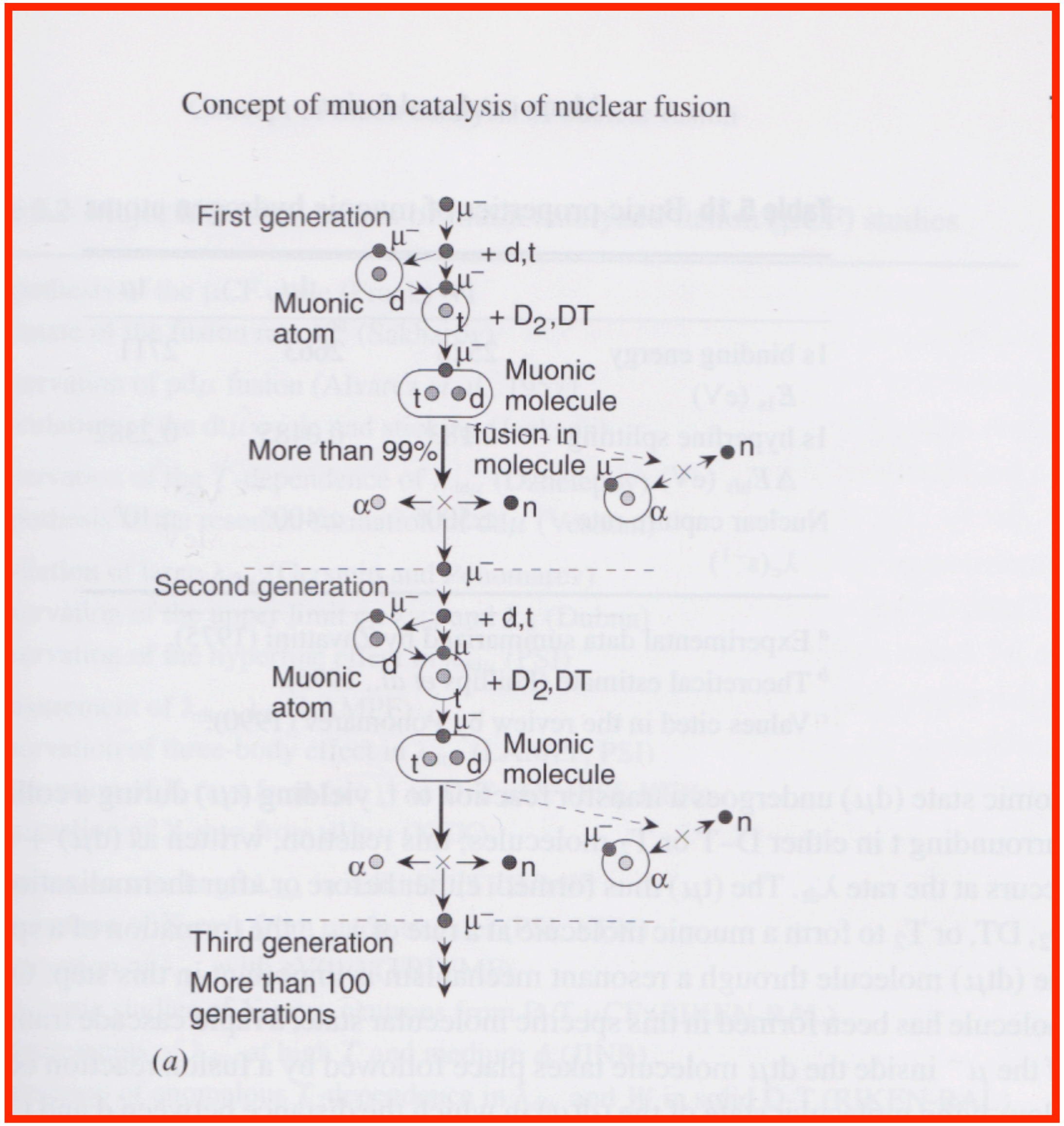
Collisions of $Pb^{81+}(1s)$ ions with the residual gas in the LHC beam pipe – how long can they survive?

- 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 – $1.3\text{x}10^{12}$; CH_4 – $1.9\text{x}10^{11}$; … CO_2 – $2.8\text{x}10^{11}$ mol/m^3)

Result: The safety factor varies between 30 (for the H2 molecules) and 2 (for the CO2 molecules). Better vacuum in arcs.


Concept of muon catalysis of nuclear fusion
First generation
μ⁻
+ d,t
Muonic atom
d
t
+ D2,DT
Muonic molecule
fusion in molecule
More than 99%
α
n
Second generation
Third generation
More than 100 generations
(a)

	OK-4 FEL	OK-5 FEL
Polarization	Horizontal	Circular/Linear
FEL wigglers		
No. of wigglers	2	4 (2 installed)
No. of regular periods	33	30
Wiggler periods (m)	0.10	0.12
Wiggler gap (mm)	25	40×40
Max. magnetic field (T) (at 3 kA)	0.536	0.286
FEL resonator cavity		Same as OK-4 FEL
Length (m)	53.73	
Rayleigh range (m)	4.44–5.52	
Wavelength (nm)	1064–190[a]	
Optical beam size ($\sigma = \sqrt{\frac{\lambda Z_R}{4\pi}}$) (mm)	0.61–0.68 at 1064 nm 0.26–0.29 at 190 nm	
Round-trip loss (%)	0.3–2	
Electron beam at collision point		Same as OK-4 FEL
Horizontal beam size ($\sigma_x = \sqrt{\epsilon_x \beta_x}$) (mm)	0.14–0.40	
Vertical beam size ($\sigma_y = \sqrt{\epsilon_y \beta_y}$) (mm)	0.02–0.07	
Horizontal angular spread ($\sigma_x' = \sqrt{\epsilon_x / \beta_x}$) (mrad)	0.035–0.10	
Vertical angular spread ($\sigma_x' = \sqrt{\epsilon_y / \beta_y}$) (mrad)	0.006–0.02	

	LHC @ injection									
Variable, convention & units	Beam int. [ions/B]	Loss [%]	$\beta\gamma\varepsilon_{H,V}$ RMS [µm]	Kin. E. [GeV/n]	ε_z ($4\pi\sigma_E\sigma_T$) [eVs/n]	Bunch len. 4 RMS [ns]	$\Delta p/p$ RMS [-]	no. of B. [-]	max. $\Delta Qsc_{H,V}$ [-]	[-]
LHC design rep.	7.0E+07 1.)	N/A	1.4 1.)	176.4 1.)	0.280 1.)	1.8 26.)	3.2E-04 26.)	592 1.)	-1.9E-04 18.)	-2.4E-04 18.)
Achieved 2013	**1.4E+08** 9.)	N/A	**0.9** 9.), 10.)	**176.4** 2.)	**0.2...0.52** 11.)	**0.9...1.4** 11.)	**1.1...1.6E-4** 11.)	**358** 17.)	**-1.0E-03** 18.)	**-1.1E-03** 18.)
LIU Ions	1.2E+08 (max. 1.5E8), 14.)	N/A	**0.9** 14.)	176.4 14.)	0.351 23.)	1.8 14.)	3.5E-04 20.)	1248 3.)	-3.7E-04 18.)	-4.6E-04 18.)