The **HIGS** proposal and its highlights

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Mieczyslaw Witold Krasny
LPNHE, Pierre et Marie Curie University – Paris

Introduction

(the origin of the proposal)

prolegomenon:

The expected HIGS performance estimates presented in this talk are based on the real performance figures of existing facilities:

- The LHC and BNL high energy ion colliders
- The Duke University FEL
- The ThomX laser and its F-P cavity
- The n_TOF spalation target

A 5-8 orders of magnitude progress (with respect to the existing facilities) in the performance figures discussed in this presentation is driven, *predominantly*, by new concepts, rather than by extending the present technological boundaries…

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

Mieczyslaw Witold Krasny

LPNHE, Université Pierre et Marie Curie, 4 Pl. Jussieu, Tour 33, RDC, 75025 Paris, France

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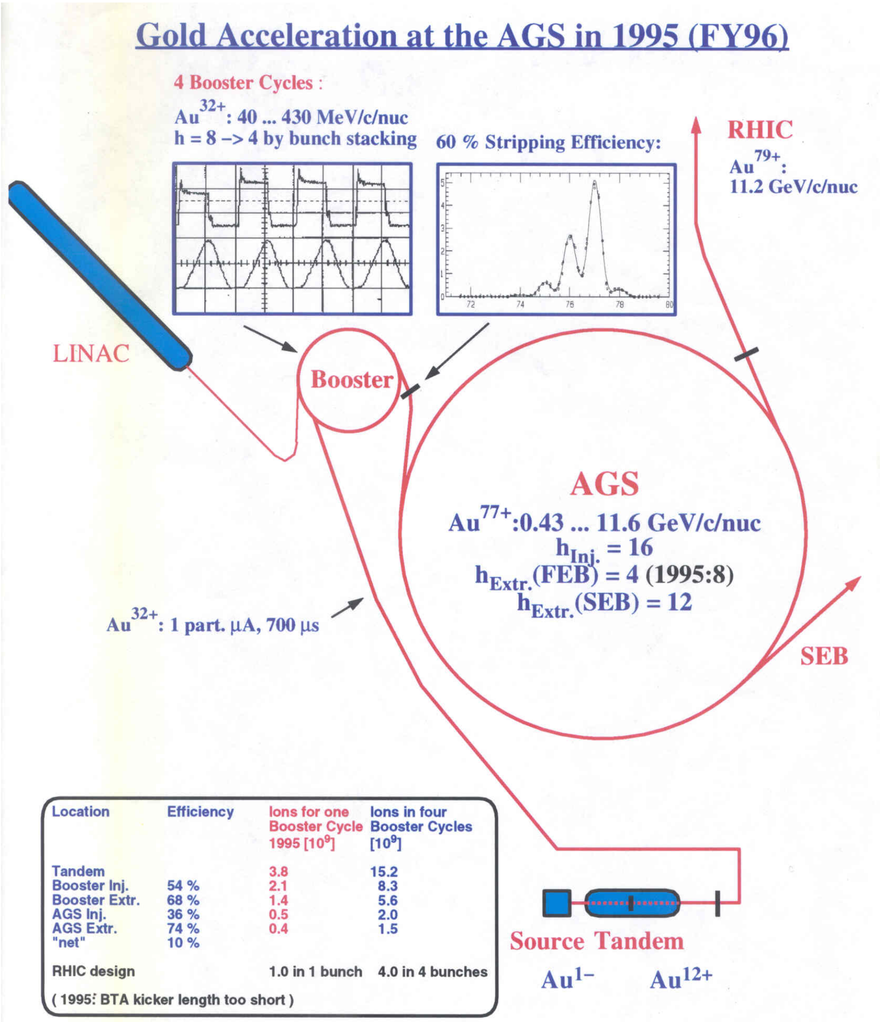
Abstract

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

Ion striping sequence:

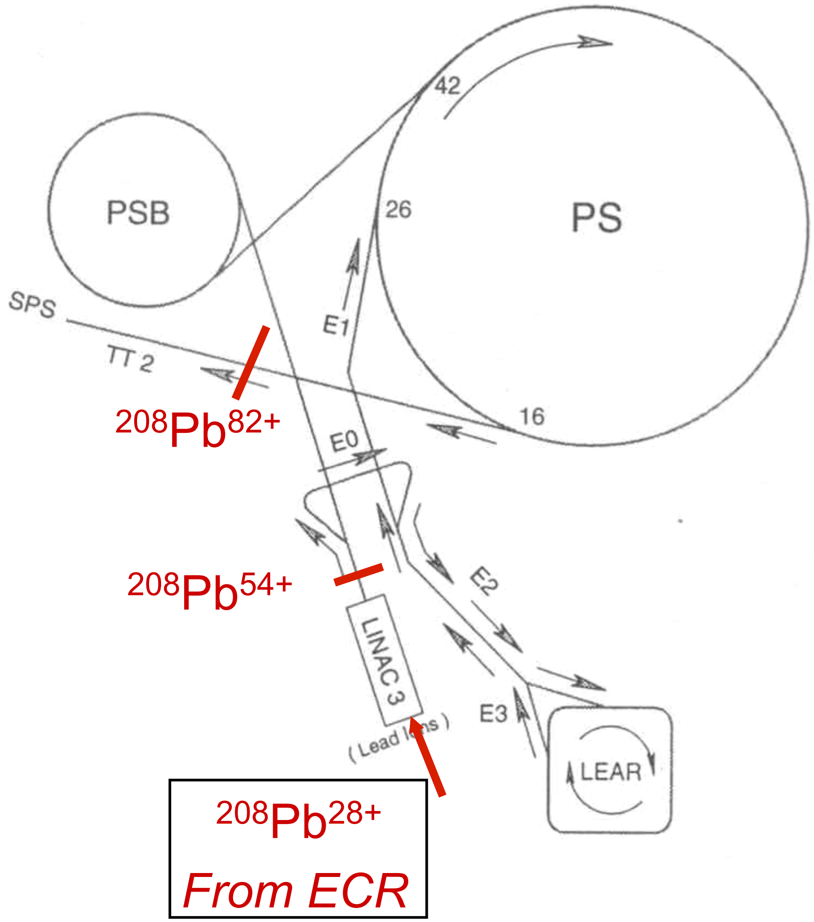
BNL & CERN



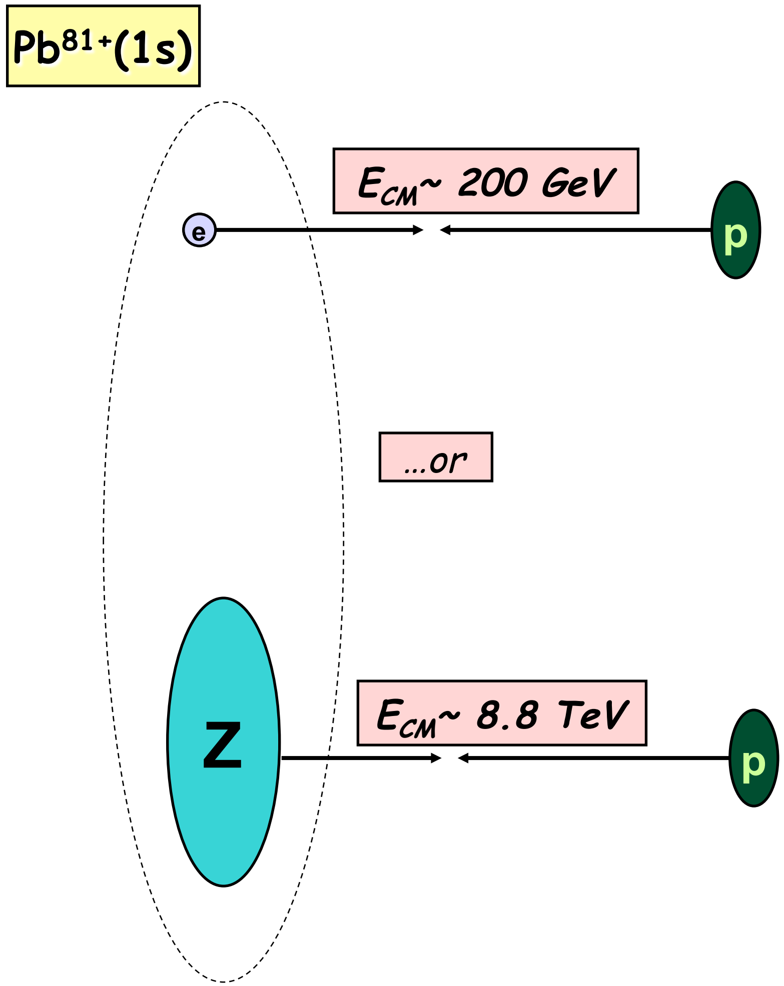
Location	Efficiency	Ions for one Booster Cycle 1995 [10^9]	Ions in four Booster Cycles [10^9]
Tandem		3.8	15.2
Booster Inj.	54 %	2.1	8.3
Booster Extr.	68 %	1.4	5.6
AGS Inj.	36 %	0.5	2.0
AGS Extr.	74 %	0.4	1.5
"net"	10 %		
RHIC design		1.0 in 1 bunch	4.0 in 4 bunches

(1995: BTA kicker length too short)

Lead acceleration at CERN



Partially stripped ions as electron carriers

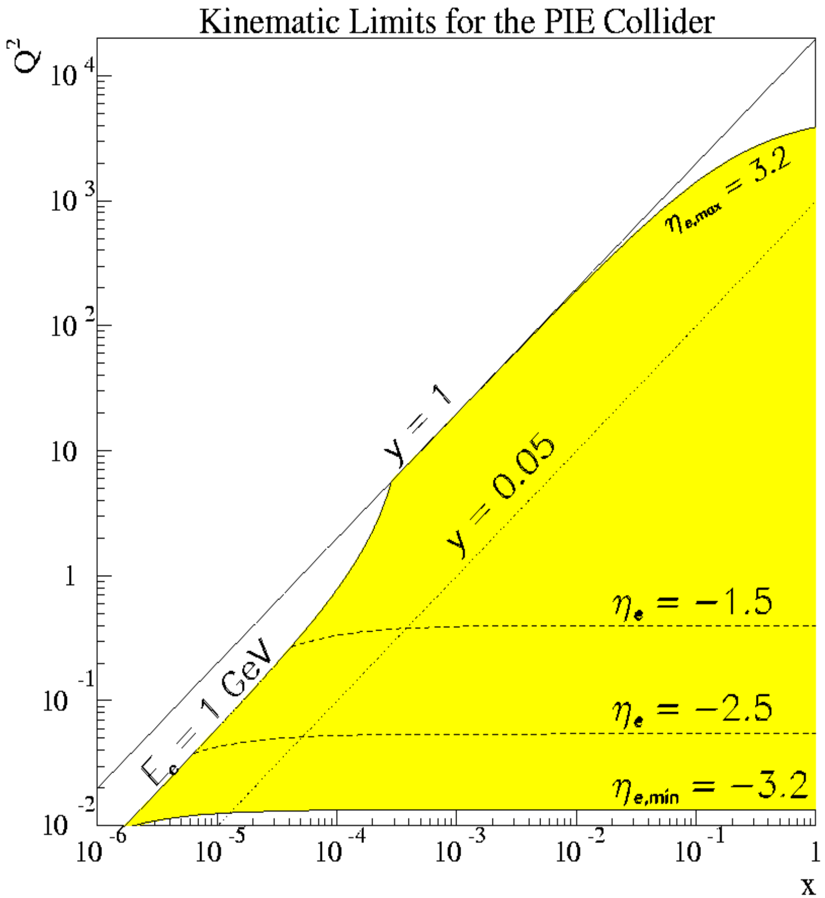


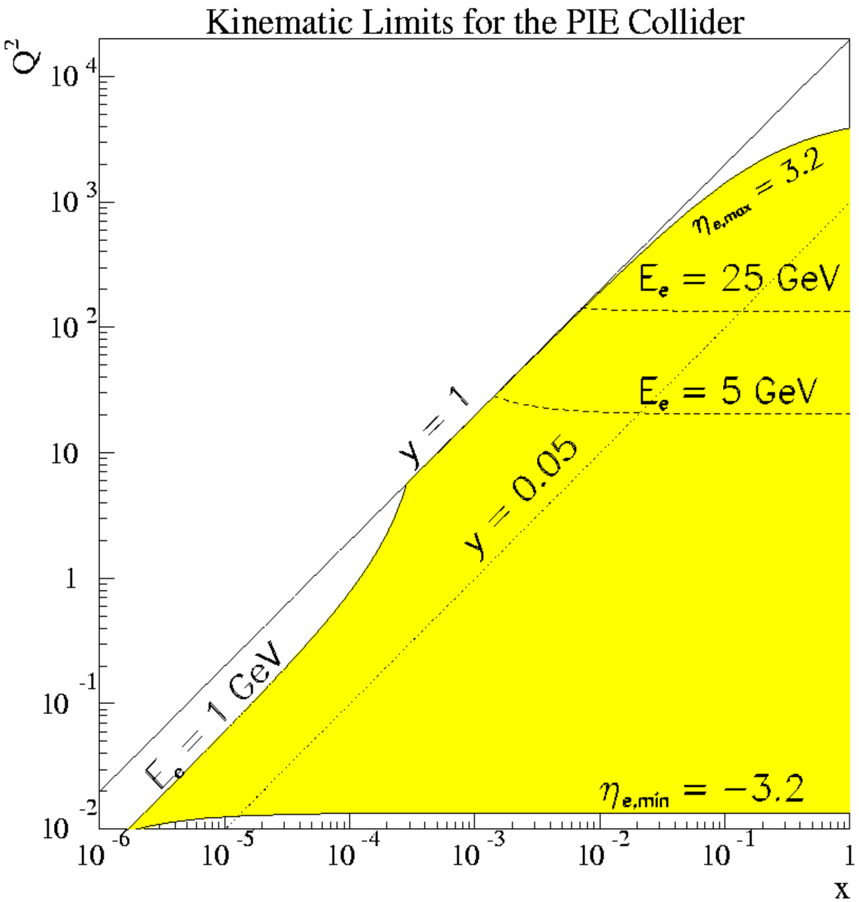
- average distance of the electron to the large Z nucleus d ~ 600 fm (sizably higher than the range of strong interactions)

- 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)

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: summary

- Bunch temperature $T_b << 1$ Ry $\times Z^2$ 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

(HIGS= High Intensity Gamma Source)

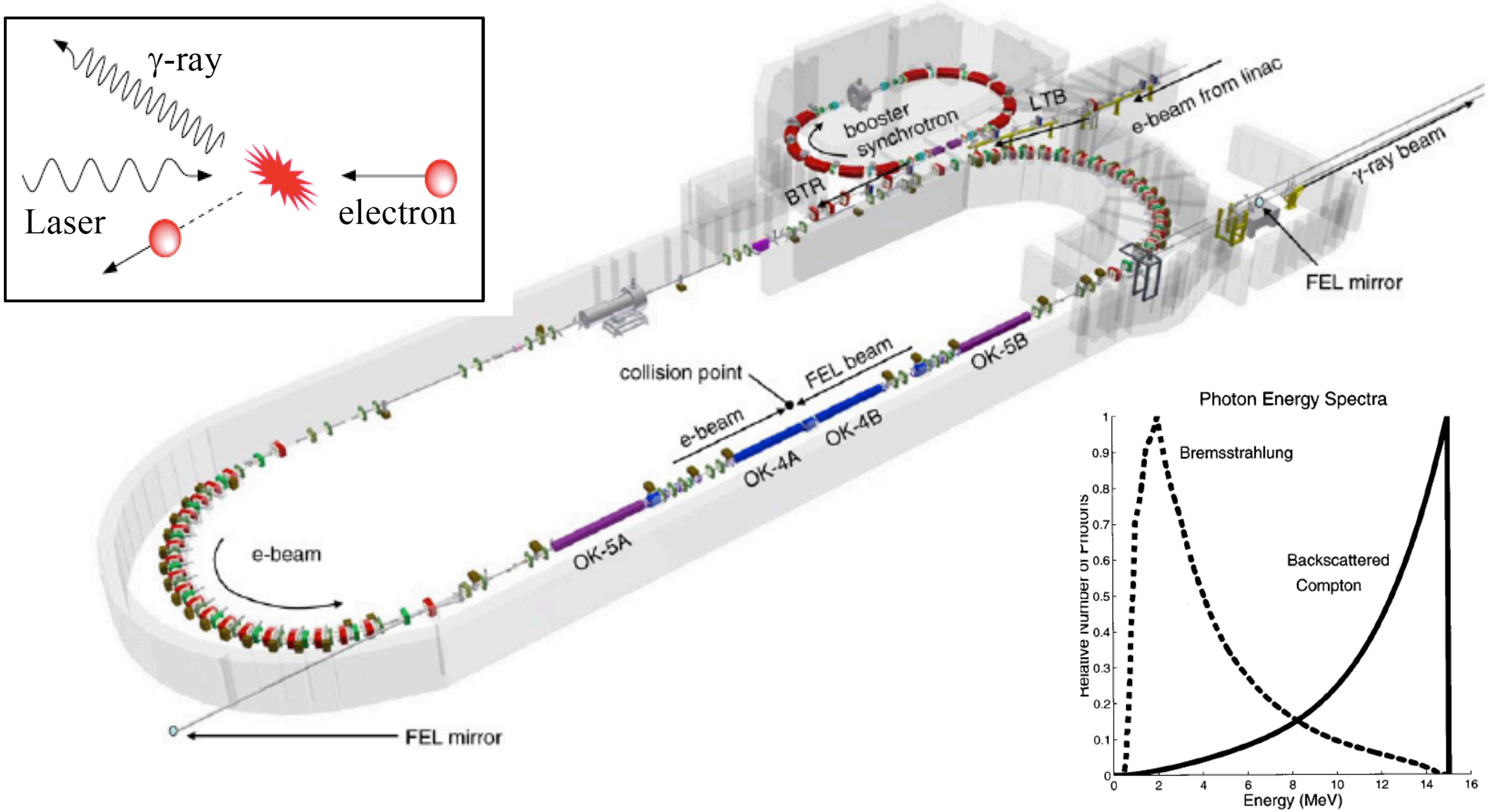
E_γ in the range 1 - 400 MeV

Parameters of the gamma 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–

How to increase the fluxes
by several orders of magnitude?

2013 – The Duke University HIγS facility has the highest γ-beam intensity in the world ~10^9 γ/s



Main limitation of the electron-beam generated gamma beams:

Compton scattering cross section is small ~O(10^{-25}) cm^2

…technological brick walls in:

- ERLs (e-bunches recycled to accelerate subsequent ones)
- High power FELs (to increase the energy of the initial light quanta)
- High Power lasers
- Cavities (to stack laser pulses)
- High energy, large current and small emittance electron beams

Alternative idea – the departure point for the HIGS proposal:

Use partially stripped ion beams as the light frequency converter to bypass the technological brick-walls specific to electron beams:

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

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

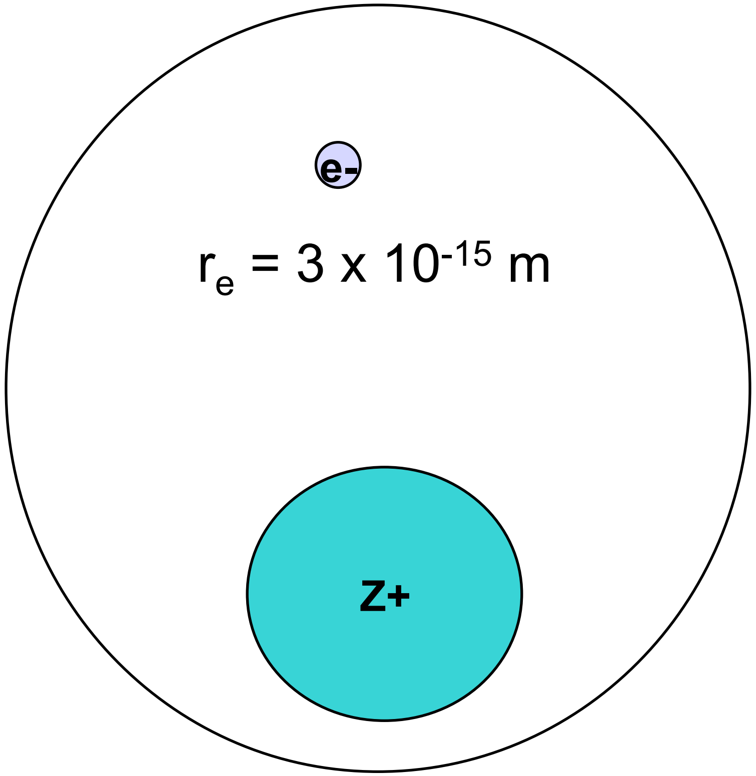
Doppler

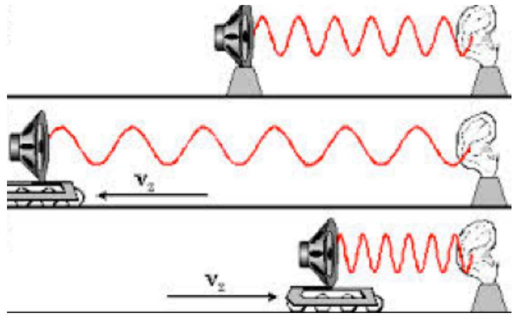
Effect

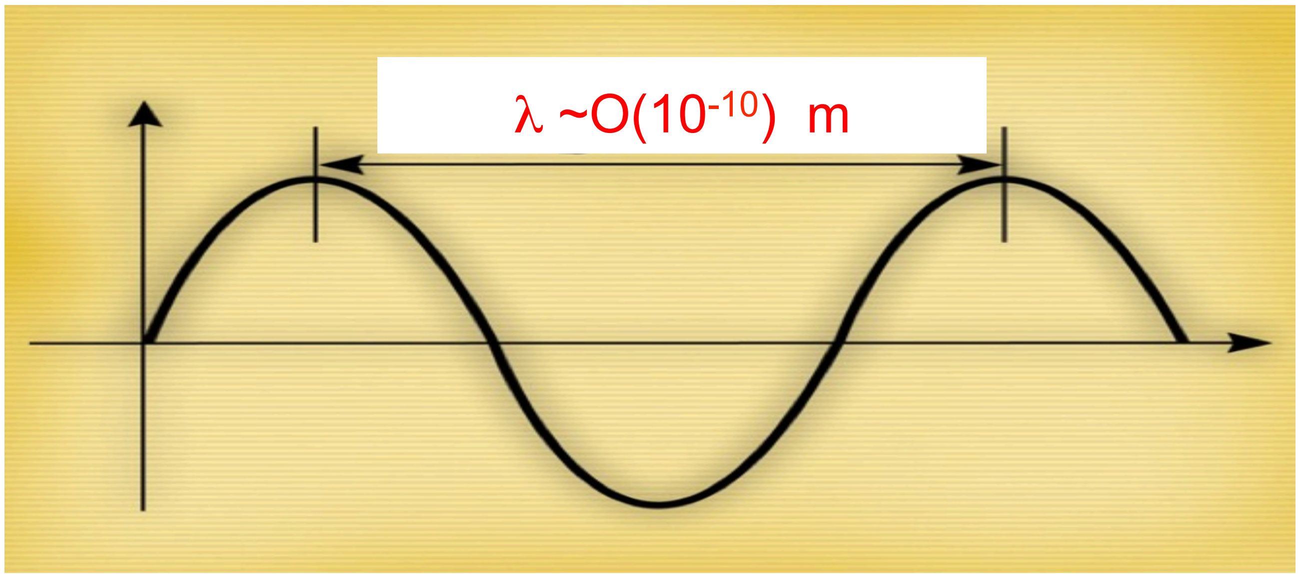
and

Resonant

Scattering

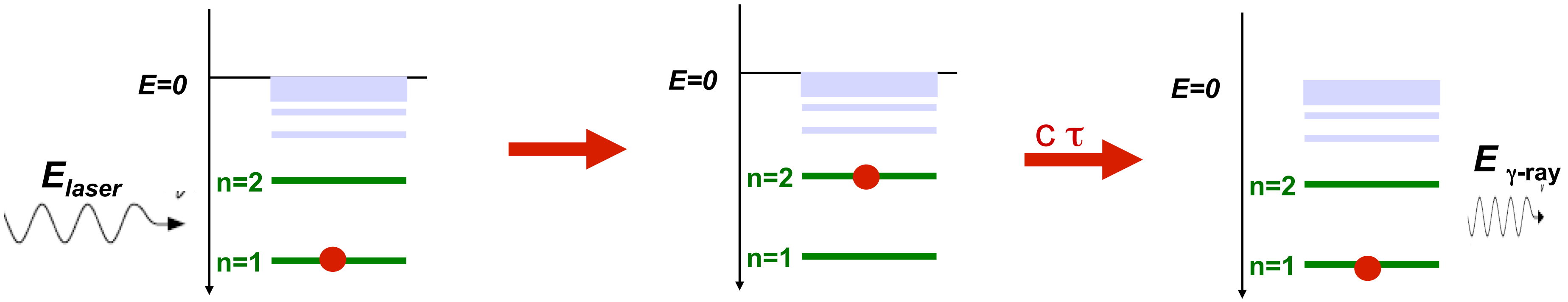






Quantum optics of ultra-relativistic atoms

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



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

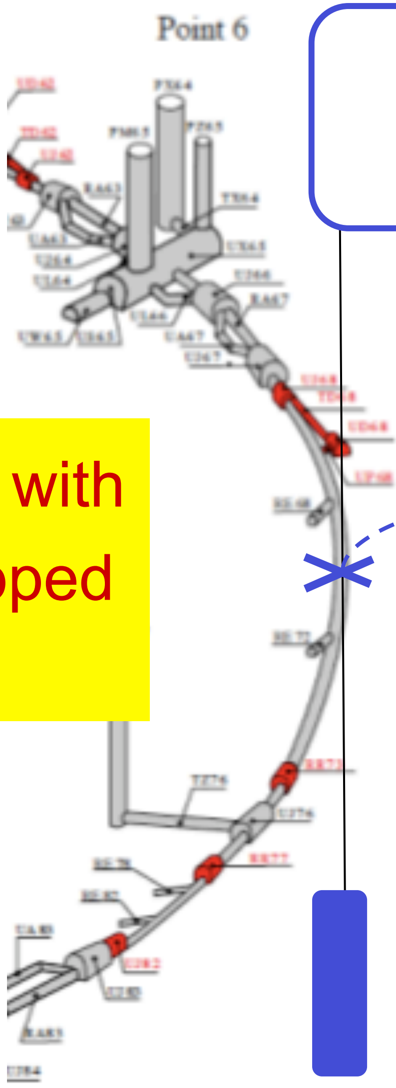
Note: $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

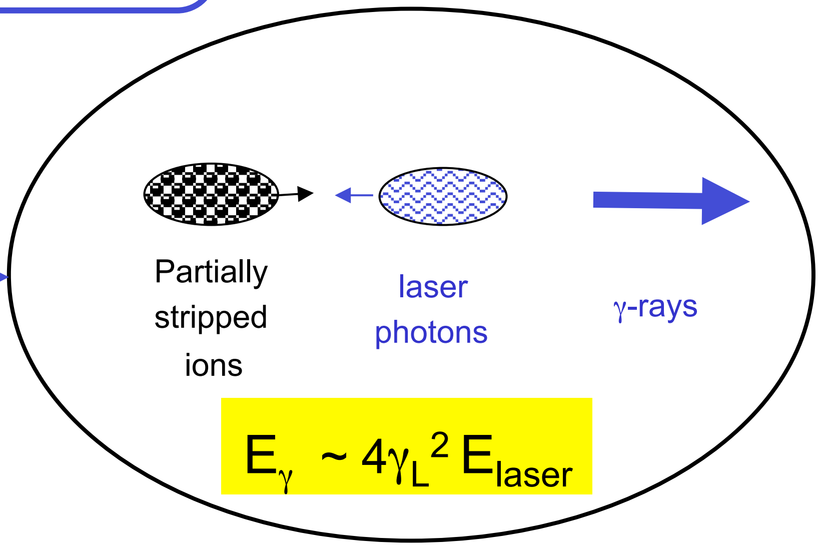
Note: 1Ry= 13.6 eV; γ_L=E/M ~2740 for Pb^{81+} at the LHC

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

γ- beam

LHC filled in with partially stripped ion beams





$$E_\gamma \sim 4\gamma_L^2 E_{laser}$$

- 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 1 mm for both $Ag^{45+}(2s) \rightarrow Ag^{45+}(1s) + \gamma$ and $Pb^{81+}(2s) \rightarrow Pb^{81+}(1s) + \gamma$

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})

Example1:

Pb^{81+} *ion at the top LHC energy* , n=2, $E_{FEL}=12.2$ *eV,*

E_γ (max) = 366 MeV

Example2:

Argon laser $E_{laser}=3.53$ *eV,* Ag^{45+} *ion,* $\gamma=2925$, n=2,

E_γ (max) = 121 MeV

Example3:

ThomX laser $\lambda=1030$ *nm,* Ca^{20+} *ion,* $\gamma=2460$, n=2,

E_γ (max) = 20 MeV

The comparison of the LHC-based HIGS and previous LCS gamma sources

Fluxes:

The Rayleigh resonant cross section for partially stripped ions is higher by a factor $(\lambda_{res}/r_e)^2$ than the Thompson cross-section for electrons ($r_e = 3 \times 10^{-15}$ m)

HIGS: gain in the γ-flux of the order of ~ 10^8 for the same intensity of the laser light (even if one assumes that only a small fraction of the laser light of 10^{-2} can be absorbed resonantly (beam divergence, momentum spread, Γ_{atomic})

Beam rigidity:

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

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

The comparison of the LHC-based HIGS and LCS 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

Technological challenges

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

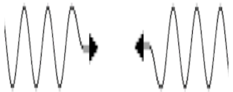
For lower energies standard 100-1000 nm lasers (e.g. CAN lasers) + FP cavities are sufficient

Highlights of the physics opportunities of the HIGS proposal

An increase (with respect to present facilities) of the intensity of the γ-beam by $\mathcal{O}(8)$ orders of magnitude, in conjunction with its unprecedently broad $\mathcal{O}(1\text{-}400)$ MeV and tuneable energy opens a vast domain of new physics and technological opportunities

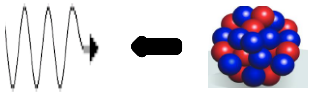
The HIGS Beams

Collision modes

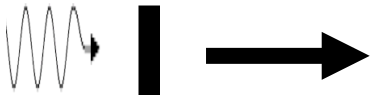


$\gamma-\gamma$ collisions, E_{CM} =2-800 MeV , L > 10^{32} 1/(s*cm^2)

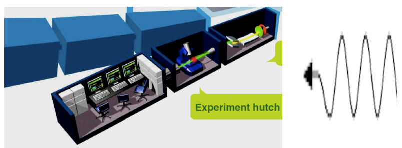
$\gamma-\gamma_L$ collisions, E_{CM} =1-126 keV , L> 10^{34} 1/(s*cm^2)



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



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



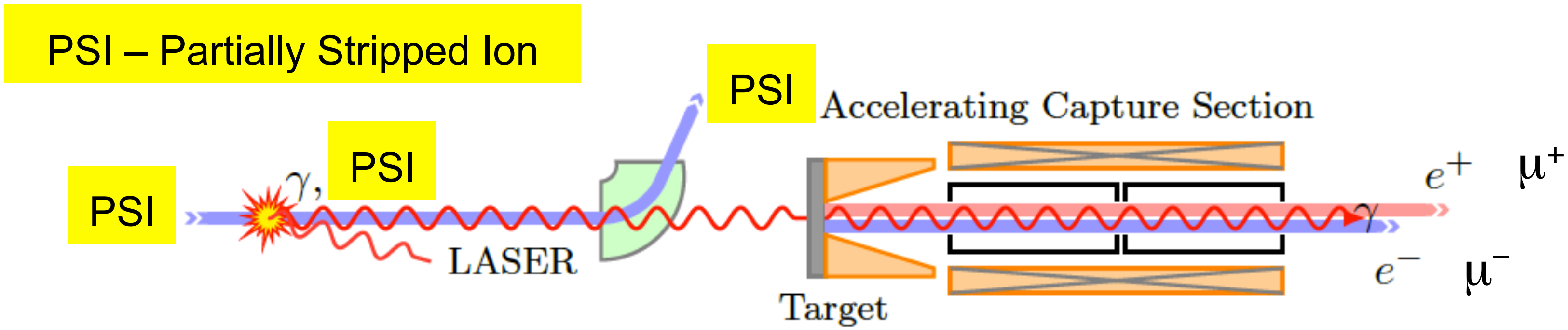
Medical applications, nondestructive assay and segregation of nuclear wastes, photo transmutation of nuclear waste using resonant (γ,n) transitions, γ-ray laser?, nuclear fusion and fission, ADS, wakefield for plasma acceleration, material science…

γ-beams as a source of high intensity secondary beams

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

Secondary beams of polarized:

e^+, e^-, μ^+, μ^-



Achievable fluxes:

$e+$, $e-$: $>10^{17}$ 1/s, μ^+,μ^- : $>10^{13}$ 1/s (low emittance) (bunch structure reflect the LHC ones)

…a factor of $>10^5$ higher then the the KEK positron source and the the Zurich muon source. Note, no longer a necessity to stack the positrons in the pre damping or damping ring for the CLIC and ILC designs! This scheme opens new possibility for designing a viable high luminosity lepton collider!

e^+e^- collider requirements

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

Bonus: polarization

$\mu^+\mu^-$ collider requirements

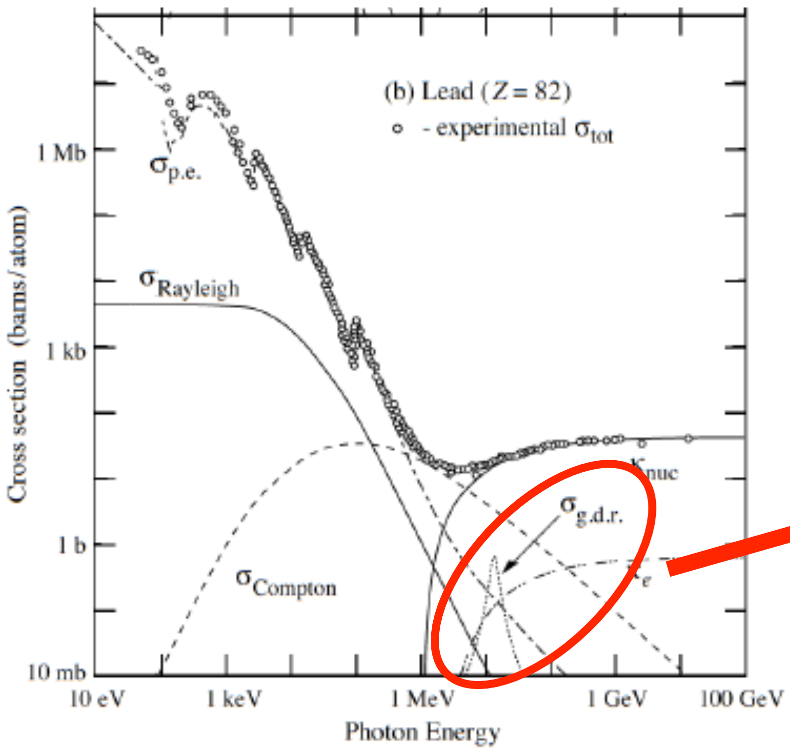
C of m Energy	1.5	3	6	TeV
Luminosity	0.92	3.4	0.9	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	≈0.087	≈0.087	≈0.087	
Muons/bunch	2 (1.44 ?)	2	2	10^{12}
Total muon Power	9	15	3.7	MW
Ring <bending field>	6	8.4	8.4	T
Ring circumference	2.6	4.5	9	km
β^* at IP $= \sigma_z$	10	5	2.5	mm
rms momentum spread	0.1 (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

The low emittance and high intensity HIGS-driven polarized muon beams offer an extremely cost effective jump into a ~5 TeV energy lepton collider with the SPS-size rings!!!

- low power consumption,
- no pion decay tunnel,
- no horns to improve beam divergence,

+ a high intensity low emittance neutrino beam as a bonus!

Secondary Neutron and Radioactive Beams



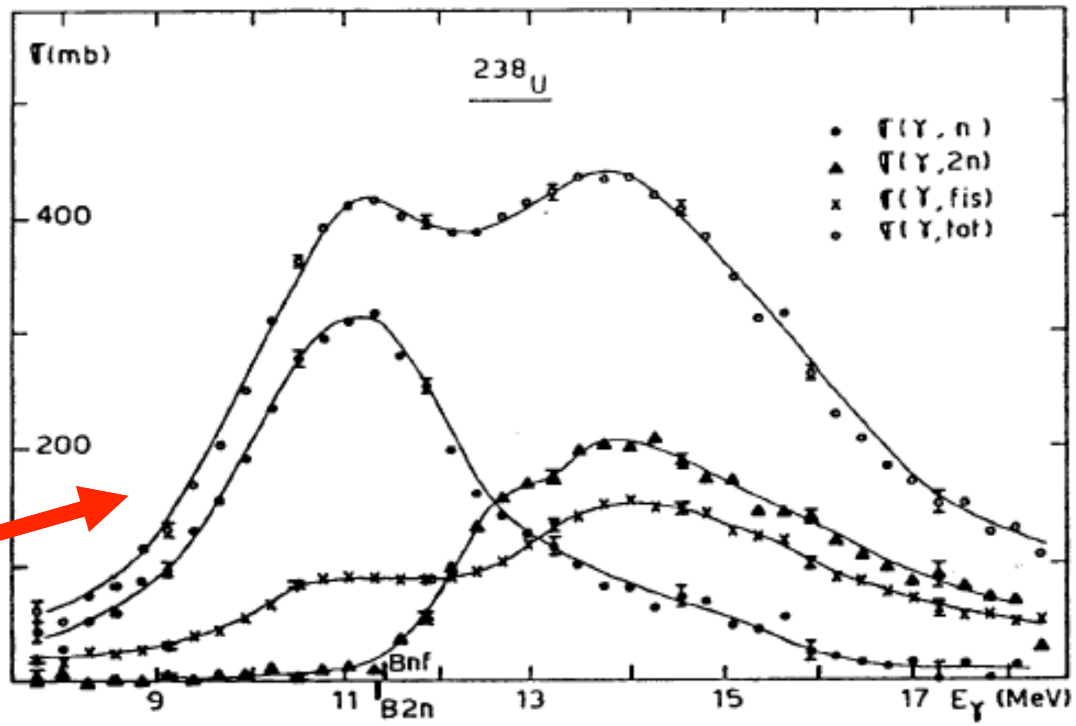
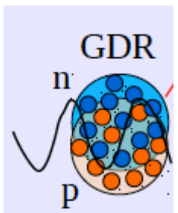


Figure 1. Partial and total photonuclear cross sections (γ,n), (γ,2n), (γ,f), and (γ,tot) for U^{238}.



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

GDR=Giant Dipole Resonance

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)

Table 1. High intensity proton sources: existing, under construction, and proposed (Snowmass 2001 survey)

Machine	Flux (10^{13}/pulse)	Rep Rate (Hz)	Flux† (10^{20}/year)	Energy (GeV)	Power (MW)
Existing:					
RAL ISIS	2.5	50	125	0.8	0.16
BNL AGS	7	0.5	3.5	24	0.13
LANL PSR	2.5	20	50	0.8	0.064
ANL IPNS	0.3	30	9	0.45	0.0065
Fermilab Booster (*)	0.5	7.5	3.8	8	0.05
Fermilab MI	3	0.54	1.6	120	0.3
CERN SPS	4.8	0.17	0.8	400	0.5
Under Construction:					
ORNL SNS	14	60	840	1	1.4
JHF 50 GeV	32	0.3	10	50	0.75
JHF 3 GeV	8	25	200	3	1
Proton Driver Proposals:					
Fermilab 8 GeV	2.5	15	38	8	0.5
Fermilab 16 GeV	10	15	150	16	4
Fermilab MI Upgrade	15	0.65	9.8	120	1.9
BNL Phase I	10	2.5	25	24	1
BNL Phase II	20	5	100	24	4
CERN SPL	23	50	1100	2.2	4
RAL 15 GeV (**)	6.6	25	165	15	4
RAL 5 GeV (**)	10	50	500	5	4
Other Proposals:					
Europe ESS (**)	46.8	50	2340	1.334	5
Europe CONCERT	234	50	12000	1.334	25
LANL AAA	-	CW	62500	1	100
LANL AHF	3	0.04	0.03	50	0.003
KOMAC	-	CW	12500	1	20
CSNS/Beijing	1.56	25	39	1.6	0.1

One proton produces ~ 20-30 thermal neutrons

…comparable to those expected for the dedicated spallation sources…

Note, a significantly higher efficiency of HIGS neutron source (a factor of 10-100 in $N_{neutron}$/kW of beam power)

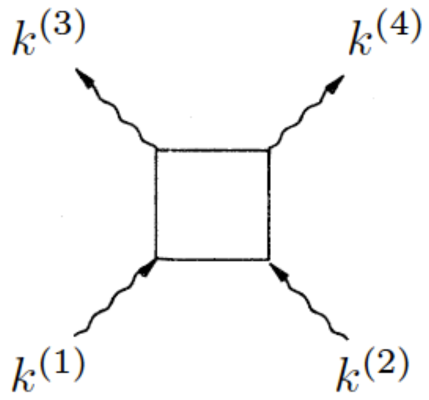
The HIGS physics opportunities

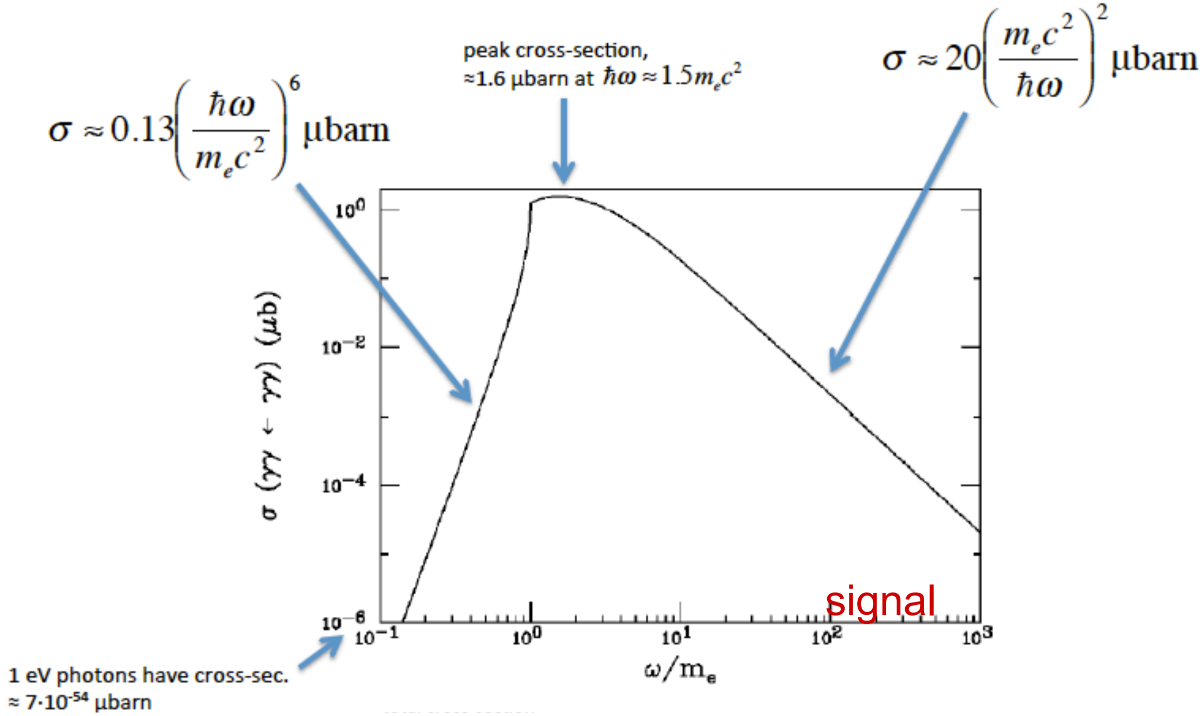
Fundamental physics

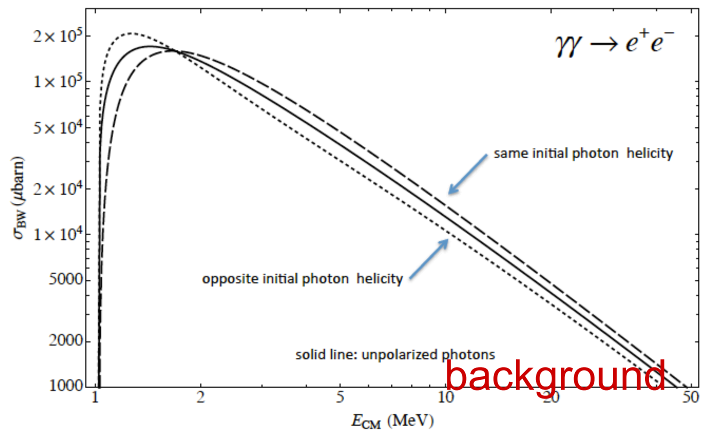
- Fundamental QED measurements (elastic $\gamma\gamma$ scattering)
- QED vacuum properties
- Dark matter searches (dark photon and neutron portals)
- Origin of baryon-antibaryon asymmetry in the Universe
- CPT symmetry
- Rare decays in the lepton sector
- Understanding of the QCD confinement ($\gamma\gamma$, γp, γA, ep, eA collisions – a base for the iCHEEP proposal)
- ...

(today)

Elastic light-by-light scattering (never measured)







Two measurements:

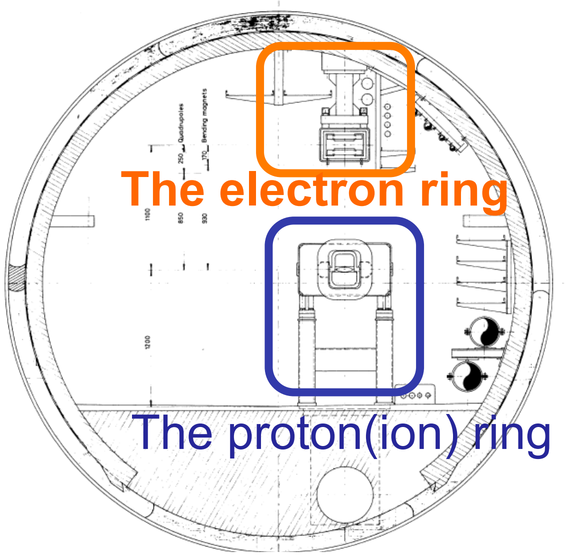
γ–γ collisions, for $E_{CM} > 2m_e$

and (background free)

γ–γ_L collisions, for $E_{CM} < 2m_e$

> 100 events/s expected, to be compared to ~20 events/year at the LHC

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



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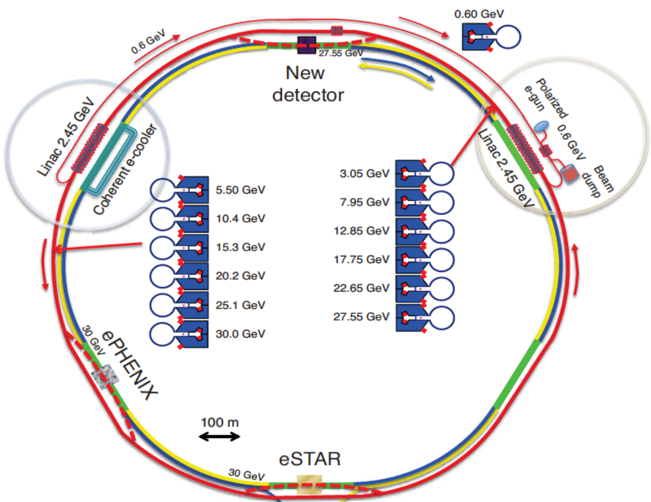
Exploring Confinement, Mieczyslaw Witold Krasny (Paris U., VI-VII). Aug 2012. 12 pp.
e-Print: arXiv:1208.3764 [physics.acc-ph]

→ **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)

iCHEEP evaluation attempt

	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	0,80	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	****	***	***	*****	**

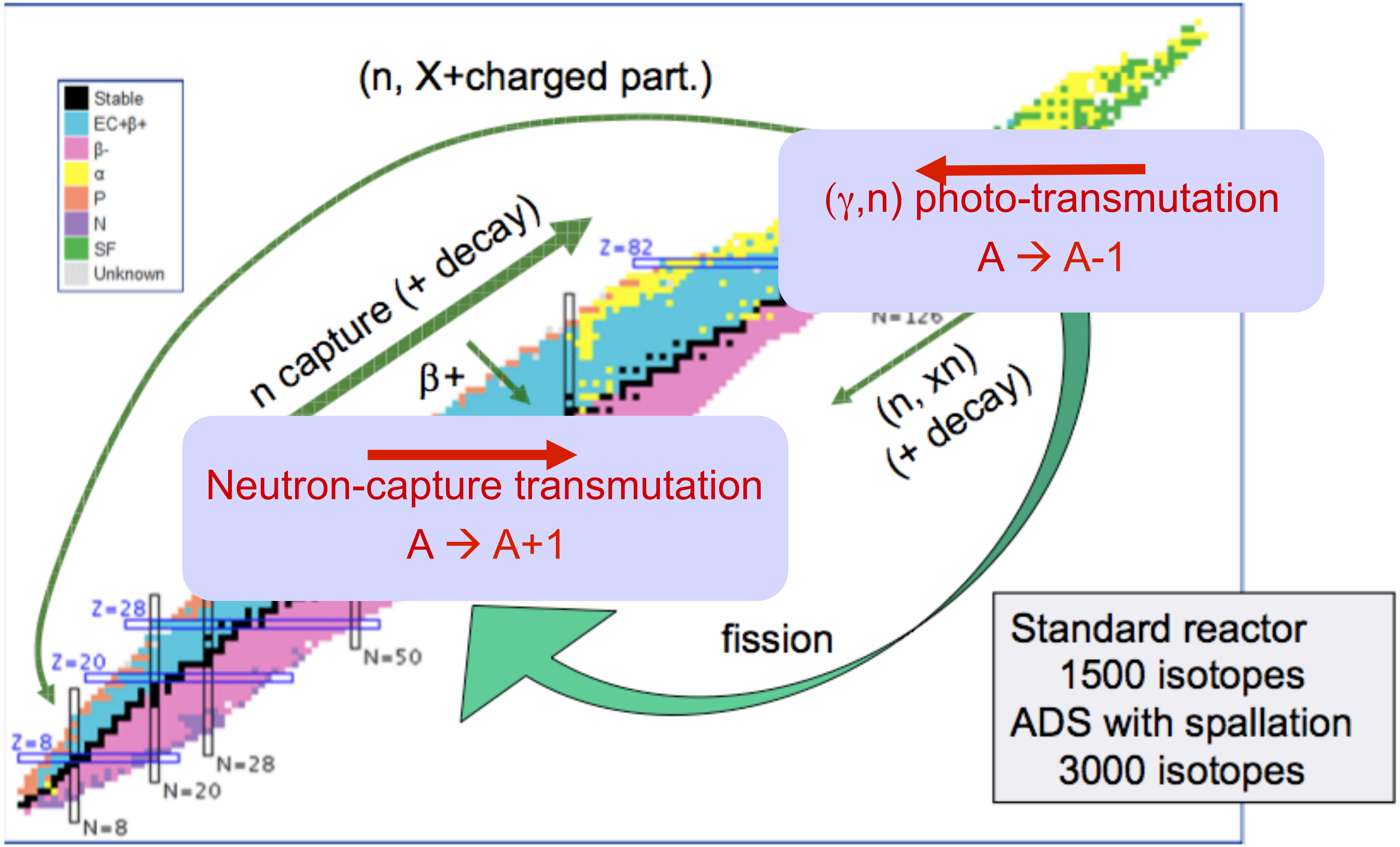
1 to be confirmed

Nuclear physics

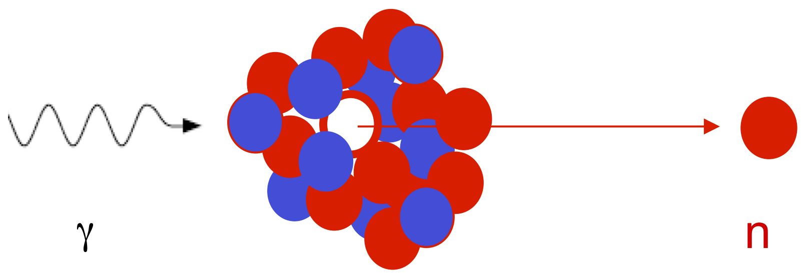
- Quark-gluon degrees of freedom in nucleons and nuclei
- Development of QGP diagnostic tools
- Photo-fission processes
- Radioactive beams (ISOLDE) physics
- Energy tagged neutron beam (n_TOF) physics
- Investigating the structure of nuclei far from stability
- GDR physics
- …

Industrial applications

- Transmutation of nuclear waste
- ADS and Thorium based “Energy amplifier” research
- Nondestructive assay and segregation of nuclear wastes
- Material studies (thick objects)
- …


(n, X+charged part.)
Stable
EC+β+
β-
α
P
N
SF
Unknown
n capture (+ decay)
β+
Z=82
N=126
(γ,n) photo-transmutation
A → A-1
(n, xn)
(+ decay)
Neutron-capture transmutation
A → A+1
fission
Z=28
Z=20
Z=8
N=50
N=28
N=20
N=8
Standard reactor
1500 isotopes
ADS with spallation
3000 isotopes

γ-ray surgery of nuclear waste

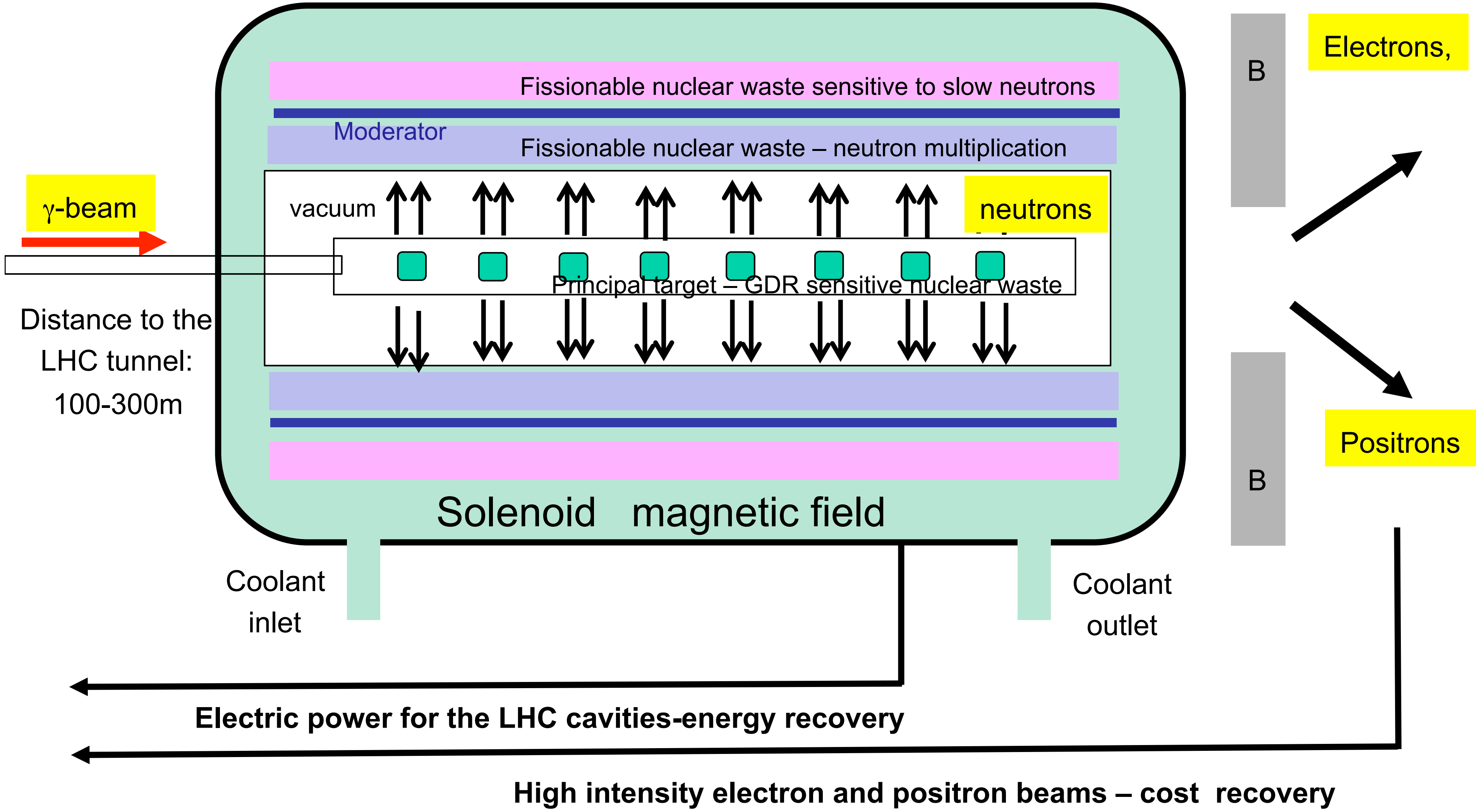


Example: (γn) transmutation of a nuclear waste 126Sn with a high life-time of 100 00 years into 125Sn with a life-time 9.64 days

… 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!

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



Medical applications

- Production of ions for PET
- Conventional cancer treatment
- Selective cancer-cell killers (γA -→ A-4 + α process)
- gamma tomography
- …

A sketch of the initial-phase road map

- (2015) Present the proposal to potentially interested communities
- (2015) LOI and getting a support from CERN for the initial feasibility studies
- (2015) Develop the specialized Monte-Carlo addressing mainly the issue of handling the powerful beam of gamma rays
- (2016) The short SPS test run with "BNL-type stripping target"
- (2017) At the end of the LHC Run2 Measurement of the life-time of the partially stripped ion beam in the LHC
- (2017) A colliding mode run with detection of monochromatic gamma rays at zero angle (upgrade of the 0-degree neutron detector → gamma detector)

Conclusions

In the present phase of HEP characterized by :

- **no clear hint where to go, in the energy, intensity and precision frontiers**
- **prohibitive cost cost of re-utilizing old ideas and technologies to extend, even by a tiny bit, these frontiers (size-scaling)**

unorthodox ideas by individuals should be considered and evaluated on equal footing as the “community-driven” ones.

Conclusions

The history of our discipline shows that a big technological leaps resulted more often in important discoveries than the verification of the theoretical models of a priori defined discoveries – the present day paradigm in HEP.

Large laboratories, like CERN, need to diversify their research domain -- with balanced progress in each activity domain (not only in the high energy frontier) – learning from the “dinosaur’s case”…

Conclusions

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

The HIGS initiative proposes a viable way to make a leap by four to seven orders of magnitude in their intensity.

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

1. **Novel way of addressing the high energy frontier (e.g. a 2-6 TeV muon collider) 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 a big jump in dark matter detection sensitivity)**

3. **Extending the experimental program in Nuclear Physics**

4. **Industrial applications (including the research on nuclear reactors with significantly reduced nuclear waste).**

5. **Medical applications (including the selective cell killing techniques).**

extra transparencies

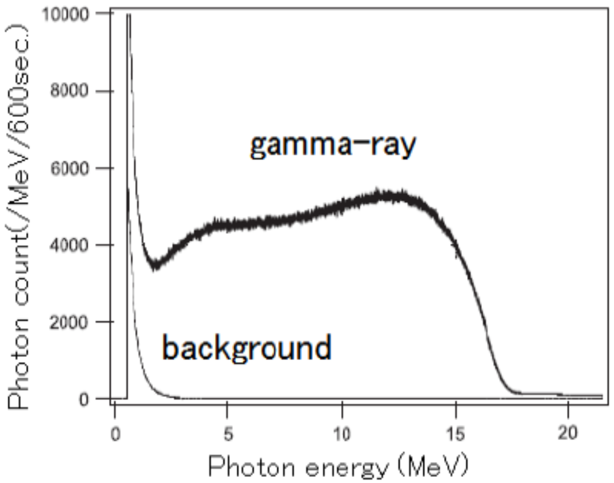
Facts – nuclear waste

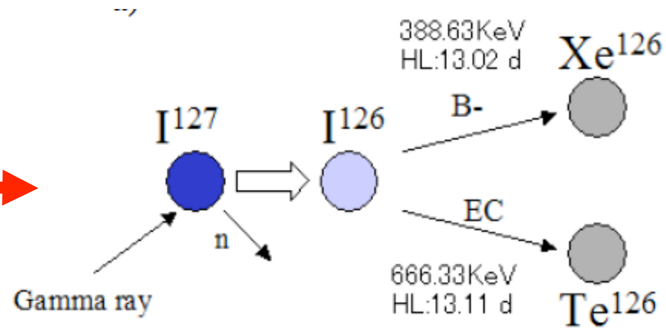
With 145 operating reactors (2001) with a total power of 125 GW, the resulting electrical energy generation in Europe is of about 850 TWh per year and represents ~35% of the total electricity consumption of the European Union.

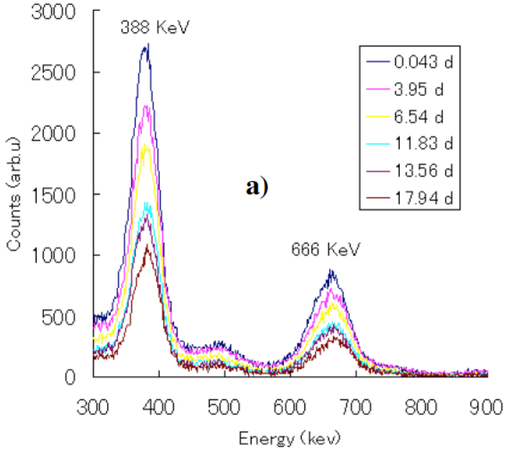
Most of the hazard from the spent fuel stems from only a few chemical elements - *plutonium, neptunium, americium, curium*, and some *long-lived fission products such as e.g iodine and technetium* at concentration levels of grams per ton.

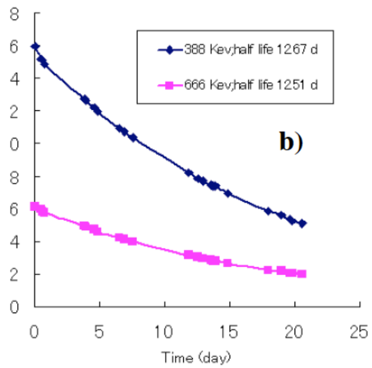
Approximately 2500 tons of spent fuel are produced annually in the EU, containing about 25 tons of plutonium and 3.5 tons of the "minor actinides" neptunium, americium, and curium and 3 tons of long-lived fission products (the long term > 100 years radiotoxicity is dominated by the actinides).

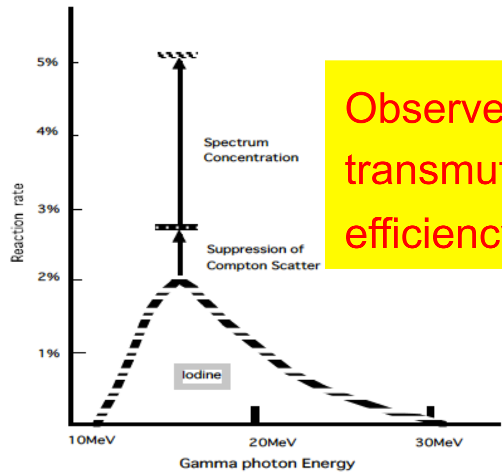
Transmutation efficiency









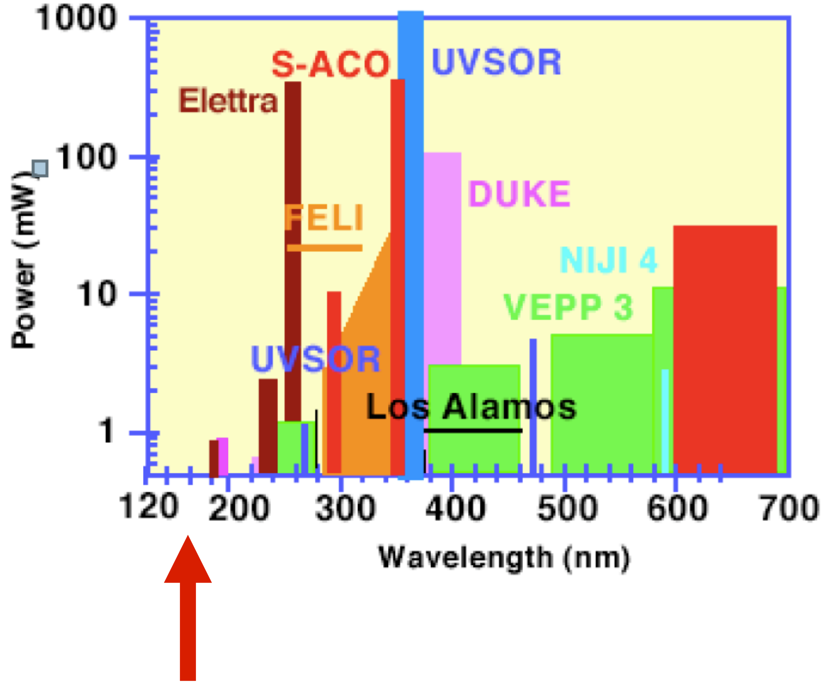


Observed transmutation efficiency: ~5%

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.

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

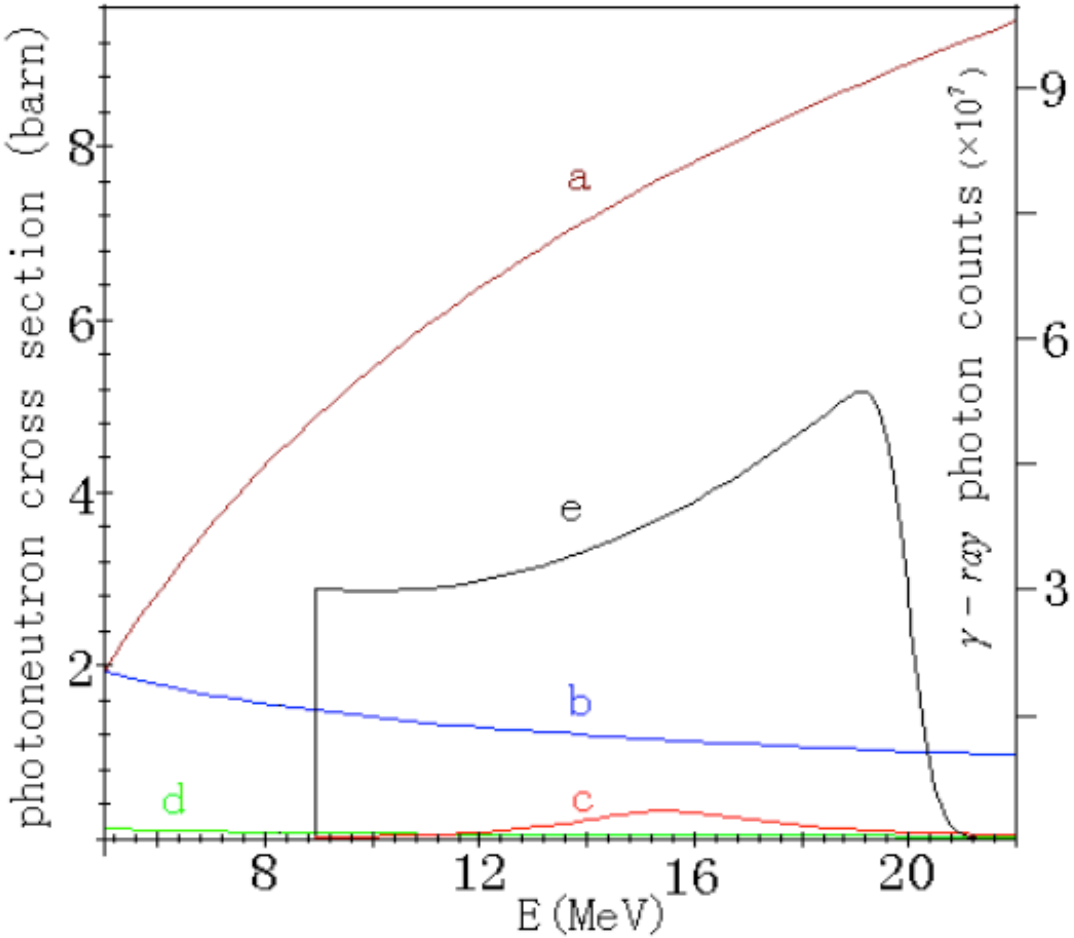


Fig.3. Coupling of γ ray to nuclear giant resonance of ^{129}I. Crosssections of gamma ray photon for the typical target interactions is indicated. Curve a shows pair creation, and b corresponds to Compton scatter by target atom electron and c corresponds to giant resonance and d corresponds to photo-electron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

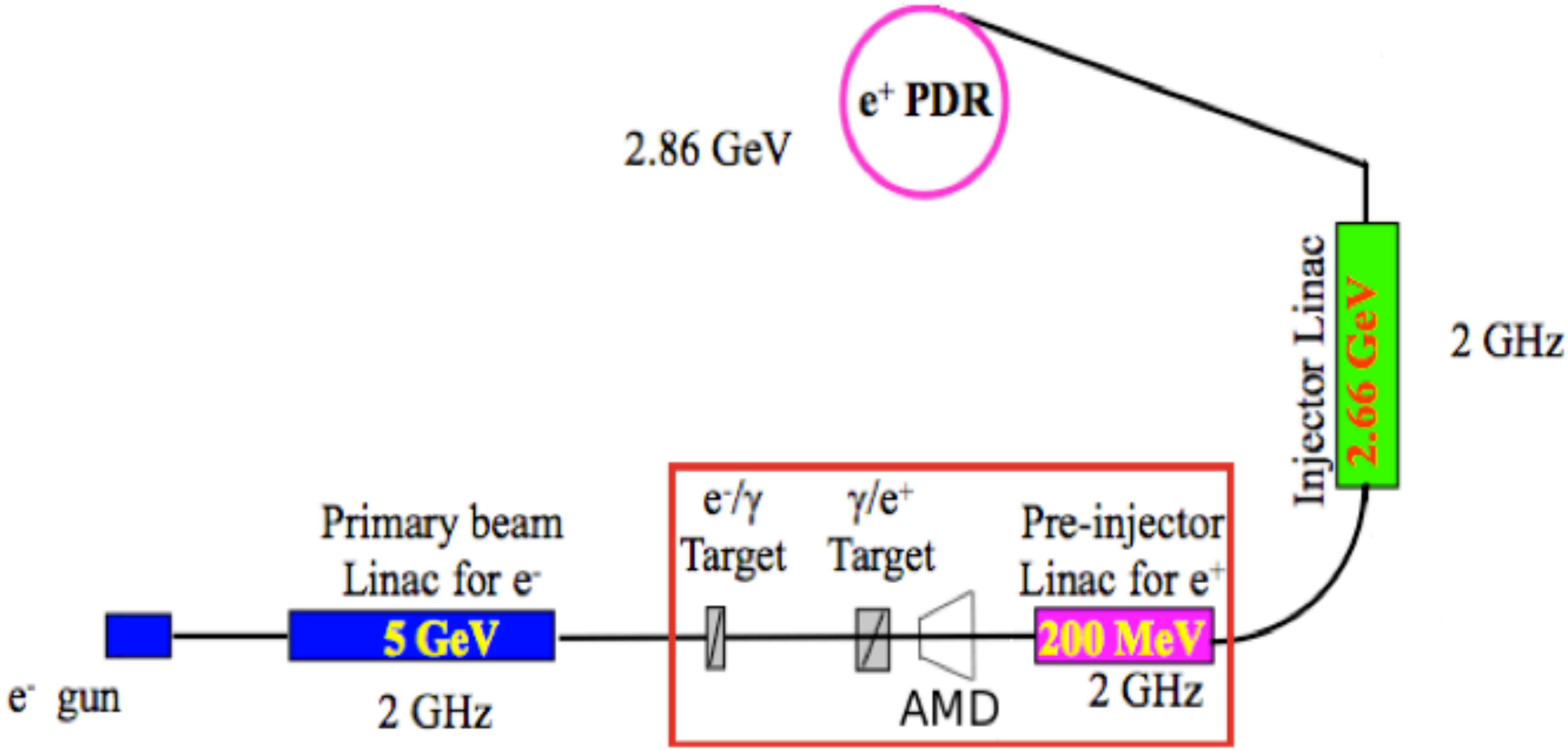


Figure 1: Layout of the CLIC positron source. Red box show the part which concerns the positron production and capture (zoomed in Figure 2).

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)

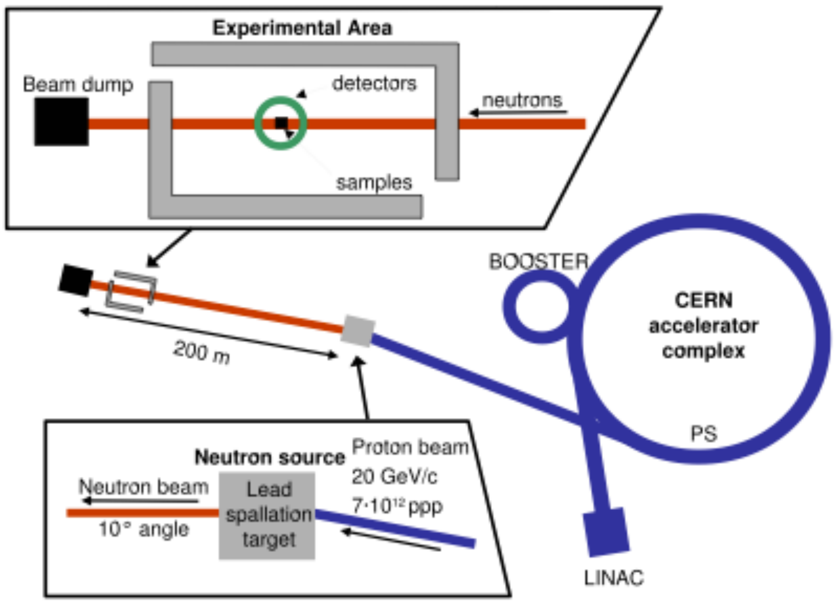
$^{126}_{50}Sn\ (\tau = 1.0 \times 10^5\ y)\ +\ n \Rightarrow\ ^{127}_{50}Sn \xrightarrow{\beta^-\ (12.4\ m)}\ ^{127}_{51}Sb \xrightarrow{\beta^-\ (3.85\ d)}\ ^{127}_{52}Te \xrightarrow{\beta^-\ (9.35\ h)}\ ^{127}_{53}I$ (s

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

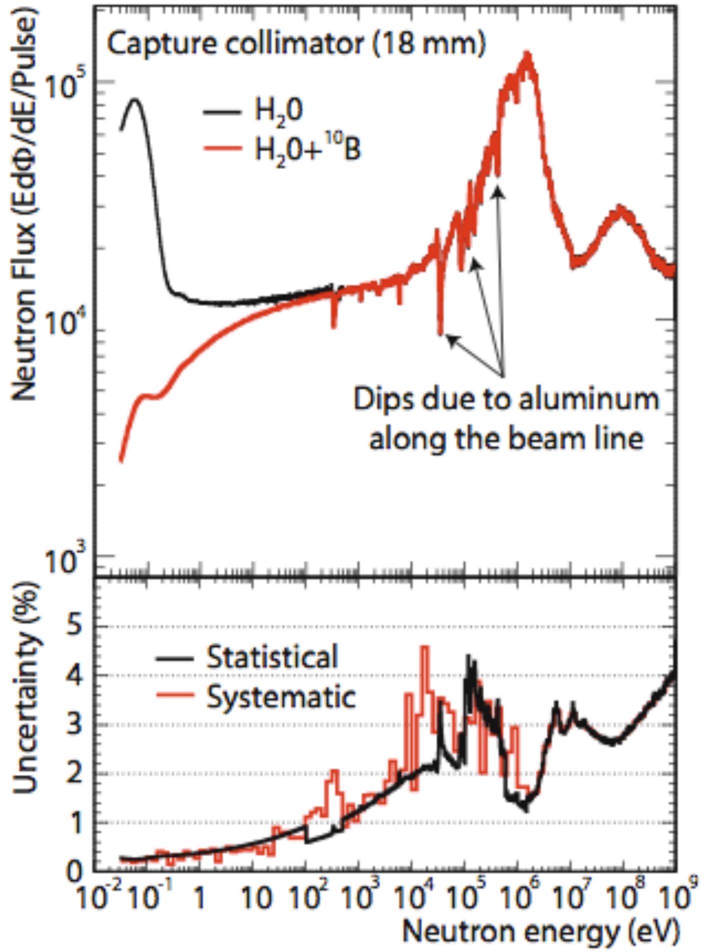
$^{93}_{40}Zr\ (\tau = 1.5 \times 10^6\ y)\ +\ n \Rightarrow\ ^{94}_{40}Zr$ (stable)

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

n_TOF



Experimental Area
Beam dump
detectors
neutrons
samples
BOOSTER
CERN accelerator complex
PS
200 m
LINAC
Neutron source
Proton beam
20 GeV/c
7·10¹² ppp
Neutron beam
10° angle
Lead spallation target



Capture collimator (18 mm)
H₂0
H₂0+¹⁰B
Dips due to aluminum along the beam line
Neutron Flux (EdΦ/dE/Pulse)
Statistical
Systematic
Uncertainty (%)
Neutron energy (eV)

PIE*@LHC proposal:

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 x 10^9
- Number of bunches = 608
- Luminosity = 0.4 x 10^{29} cm^{-2} s^{-1}

* PIE = Parasitic Ion Electron collider

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 %