# Gamma-Factory-driven subcritical reactor – exploratory studies

Physics Beyond Colliders Annual Workshop, 9th Nov 2023

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# The context

# Electricity prices (for CERN)


M. Lamont, Oct . CERN Council meeting

**"Never let a good crisis go to waste" – opportunity for CERN to examine its long-term electricity purchasing strategy with due regard to sustainability & cost**

10 years

## Prix kWh

- Present CERN regulated price (EDF):

  **~ 0.042 euro**

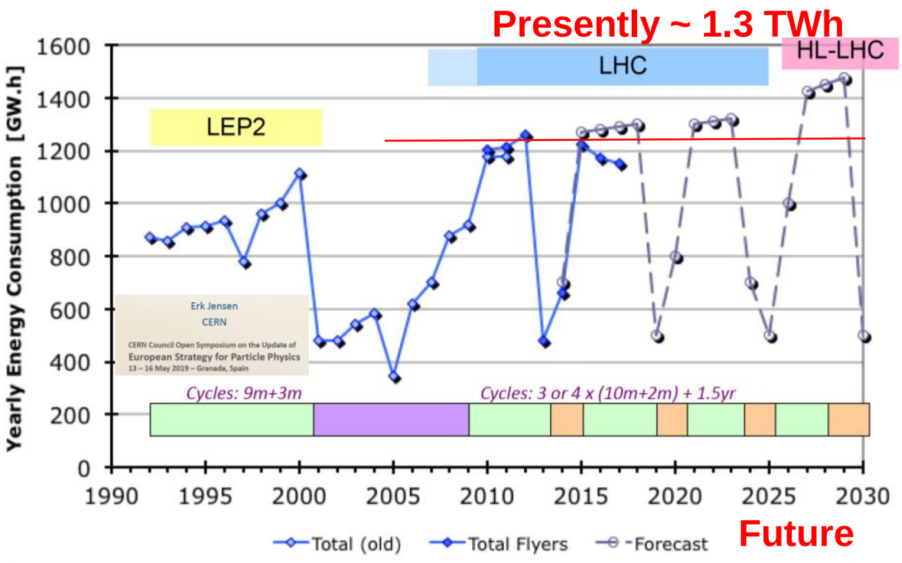
*(70% of CERN purchase with regulated tariff, till 2025)*

- "Market price"

  **~ 0.56 euro**

*(30% of CERN purchase)*

# Present and future power consumption at CERN




| Higgs factory $\sqrt{s}$ (GeV) | CLIC 380 | ILC 250 | C$^3$ 250 | CEPC 240 | FCC-ee 240 |
|---|---|---|---|---|---|
| Instantaneous power $P$ (MW) | 110 | 140 | 150 | 340 | 290 |
| Annual collision time $T$ ($10^7$ s) | 1.20 | 1.60 | 1.60 | 1.30 | 1.08 |
| Operational efficiency $\epsilon$ (%) | 75 | 75 | 75 | 60 | 75 |

| | Cost-estimate /BCHF | AC-Power /MW | Comments |
|---|---|---|---|
| Infrastructure | 5.5 | | 100km tunnel and surface infrastructure |
| FCC-ee | 5 | 260-350 | +1.1BCHF for the Top stage (365GeV) |
| FCC-hh | 17 | 580 | |

Yardsticks(yearly consumption):

- FCC-ee(240) ~ **2 TWh**
- FCC-hh ~ **3.8 TWh**
- Canton Geneva ~ **2.8 TWh**
- Mankind ~ **2 x $10^4$ TWh**

Hypothetical Electricity cost HL-LHC(FCC-hh);

- Regulated prices ~ **63 (160) x $10^6$ CHF/y**
- "Market price" ~ **840(2100) x $10^6$ CHF/y**

Present ``unitarity" bound:

**CERN yearly budget -- 1200 x $10^6$ euro /year !**

*The most stable response to the inevitable increase of the plug-power price and its present and future volatility, …and to the risks of the power cuts* ***is to produce rather than to buy*** *the CERN-requisite plug power.*

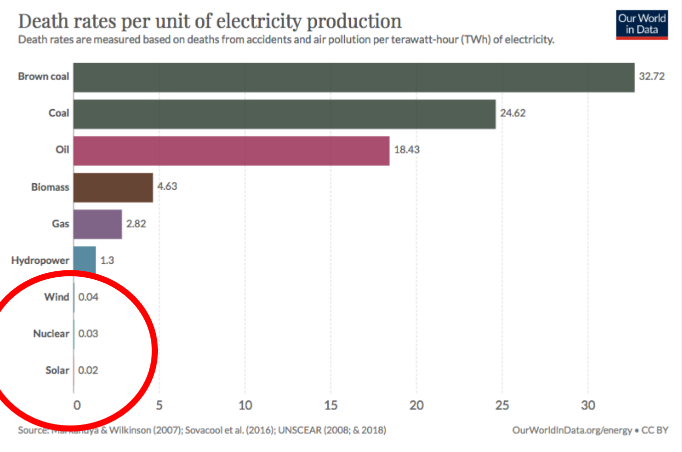
*…a "sine qua non" condition for sustainable accelerator–driven research at CERN in the more-and-more unstable external environment?*

# <u>Two necessary requirements</u>: low carbon footprint  and safe energy source

## Carbon footprint

| Options | Direct emissions | Infrastructure & supply chain emissions | Biogenic $CO_2$ emissions and albedo effect | Methane emissions | Lifecycle emissions (incl. albedo effect) |
|---|---|---|---|---|---|
| | Min/Median/Max | Typical values | | | Min/Median/Max |
| **Currently Commercially Available Technologies** | | | | | |
| Coal—PC | 670/760/870 | 9.6 | 0 | 47 | 740/820/910 |
| Gas—Combined Cycle | 350/370/490 | 1.6 | 0 | 91 | 410/490/650 |
| Biomass—cofiring | n.a.[ii] | – | – | – | 620/740/890[iii] |
| Biomass—dedicated | n.a.[ii] | 210 | 27 | 0 | 130/230/420[iv] |
| Geothermal | 0 | 45 | 0 | 0 | 6.0/38/79 |
| Hydropower | 0 | 19 | 0 | 88 | 1.0/24/2200 |
| Nuclear | 0 | 18 | 0 | 0 | 3.7/12/110 |
| Concentrated Solar Power | 0 | 29 | 0 | 0 | 8.8/27/63 |
| Solar PV—rooftop | 0 | 42 | 0 | 0 | 26/41/60 |
| Solar PV—utility | 0 | 66 | 0 | 0 | 18/48/180 |
| Wind onshore | 0 | 15 | 0 | 0 | 7.0/11/56 |
| Wind offshore | 0 | 17 | 0 | 0 | 8.0/12/35 |

## Safety




Source: The Economist

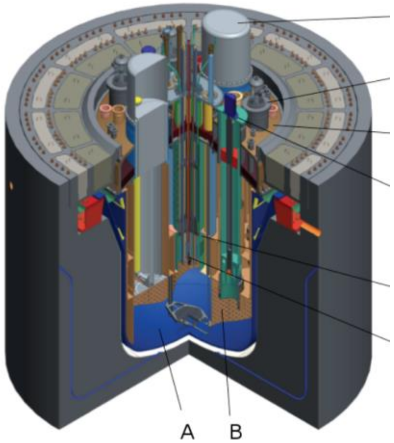
# Best use of the CERN expertise



## Accelerator driven nuclear energy (ADS)

Three conditions;

- requisite power for the present and future CERN scientific programme
- operation safety **(a subcritical reactor)**
- efficient transmutation of nuclear waste (**very important societal impact if demonstrated at CERN – given its reputation** )



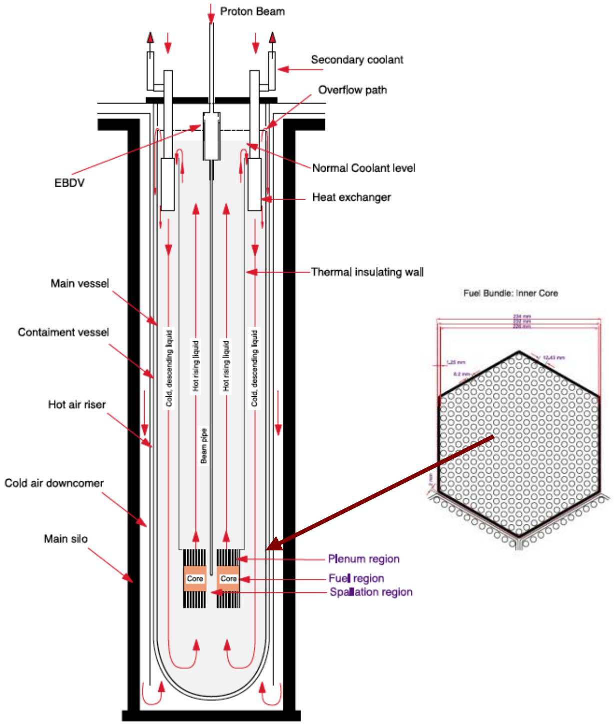
# Proton-beam-driven subcritical reactor studies

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN / AT / 95-44 (ET)

**CONCEPTUAL DESIGN OF A FAST NEUTRON OPERATED HIGH POWER ENERGY AMPLIFIER**

C. Rubbia, J.A. Rubio, S. Buono[1)], F. Carminati, N. Fiétier[2)], J. Galvez, C. Gelès, Y. Kadi, R. Klapisch, P. Mandrillon[2)], J.P. Revol and Ch. Roche




- ➢ Required proton beam power > 10 MW.
  (presently operating accelerators deliver up to 1 MW beams)
- ➢ Can photon beams be used instead of proton beams?

# The challenge

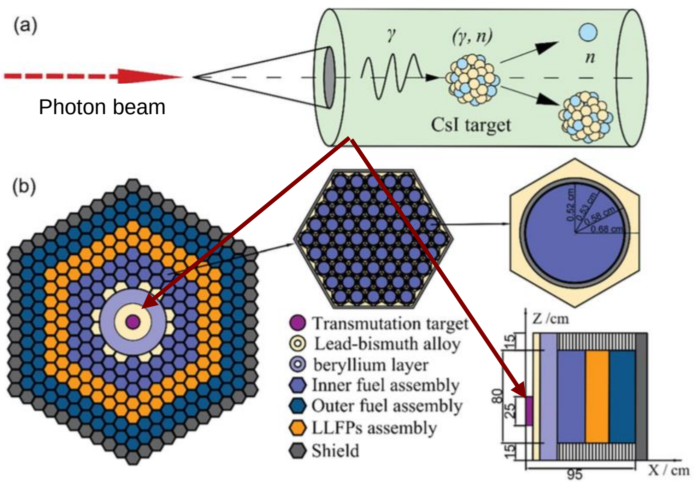
# Recent ``Nature" paper: Photon-beam-driven subcritical reactor

Article | Open Access | Published: 09 February 2022

## Transmutation of long-lived fission products in an advanced nuclear energy system

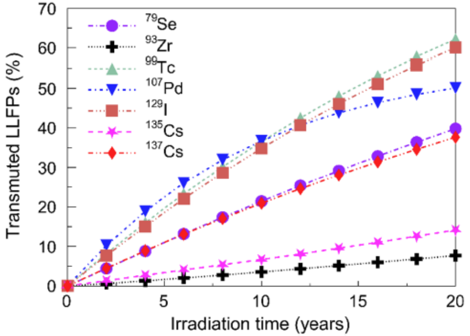
X. Y. Sun, W. Luo, H. Y. Lan, Y. M. Song, Q. Y. Gao, Z. C. Zhu, J. G. Chen & X. Z. Cai

Scientific Reports 12, Article number: 2240 (2022) | Cite this article




| Main parameters | Data used in this study |
|---|---|
| Type of fuel | $UO_2$ |
| Thermal power (MWt) | 500 |
| Electric power (MWe) | 200 |
| Core height (mm) | 1100 |
| Core diameter (mm) | 1050 |
| Number of fuel assemblies | 60/102 (inner/outer) |
| Number of pins in each of fuel assembly | 61 |
| Pin diameter (mm) | 5.8 |
| Pellet diameter (mm) | 5.2 |
| $^{235}U$ enrichment (%) | 23.3 |
| Number of LLFPs assemblies | 78 |
| Number of pins in each of LLFPs assembly | 61 |
| Number of shield assemblies | 60 |

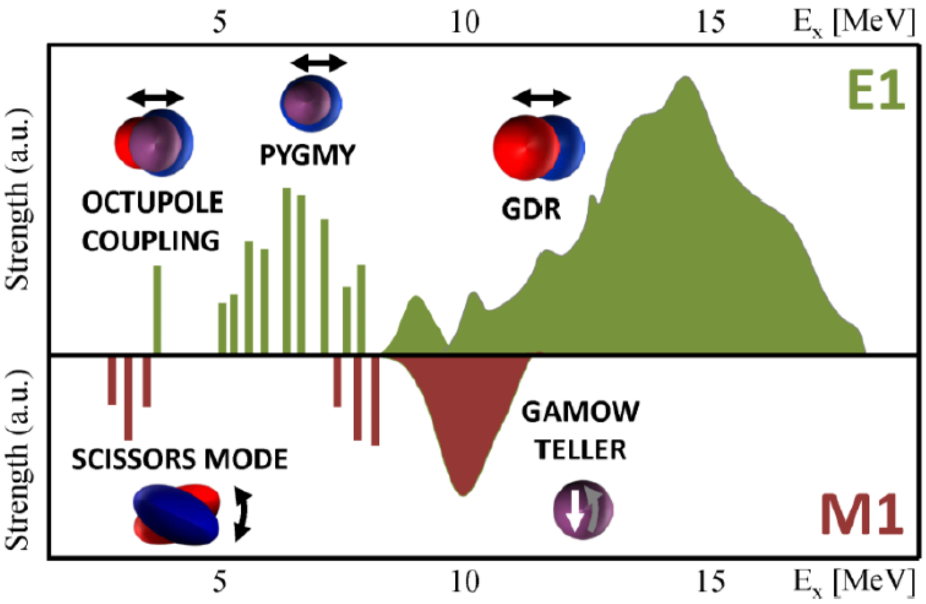
| Physical quantity | Value |
|---|---|
| Effective multiplication factor ($k_{eff}$) | 0.979 |
| Reactivity ($\rho$) | −0.019 |
| Effective multiplication factor for prompt neutrons ($k_p$) | 0.977 |
| Eigenvalue ($\alpha$) | −0.003 |
| Effective delayed neutron fraction ($\beta_{eff}$) | 0.007 |
| Neutron generation time ($\Lambda$) (μs) | 0.523 |
| Neutron worth of PNS ($\varphi$) | 1.319 |
| Sub-critical effective multiplication factor ($k_s$) | 0.984 |

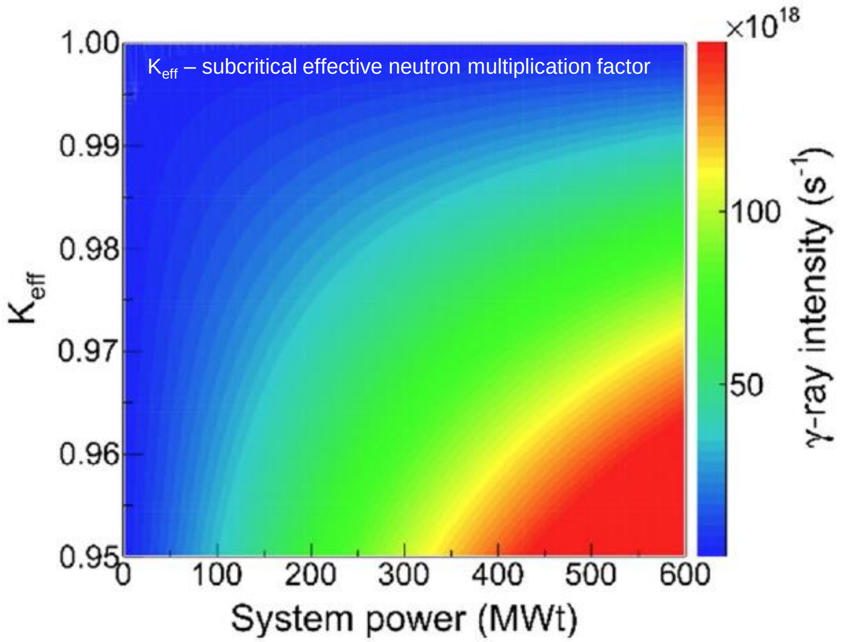



| LLFPs | Transmutation in CsI target (g/year) | | |
|---|---|---|---|
| | in photon field | in neutron field | in hybrid field |
| $^{129}I$ | $1.88\times10^3$ | $1.24\times10^3$ | $3.12\times10^3$ |
| $^{135}Cs$ | $3.85\times10^2$ | $-0.70\times10^2$ | $3.15\times10^2$ |
| $^{137}Cs$ | $9.25\times10^2$ | $-1.07\times10^2$ | $8.18\times10^2$ |

**LLFP loaded material:** Uranium dioxide pellets-fast breeder reactor core at 50 GWd/t
**Fuel:** $^{235}U$

# Two principal gamma beam requirements



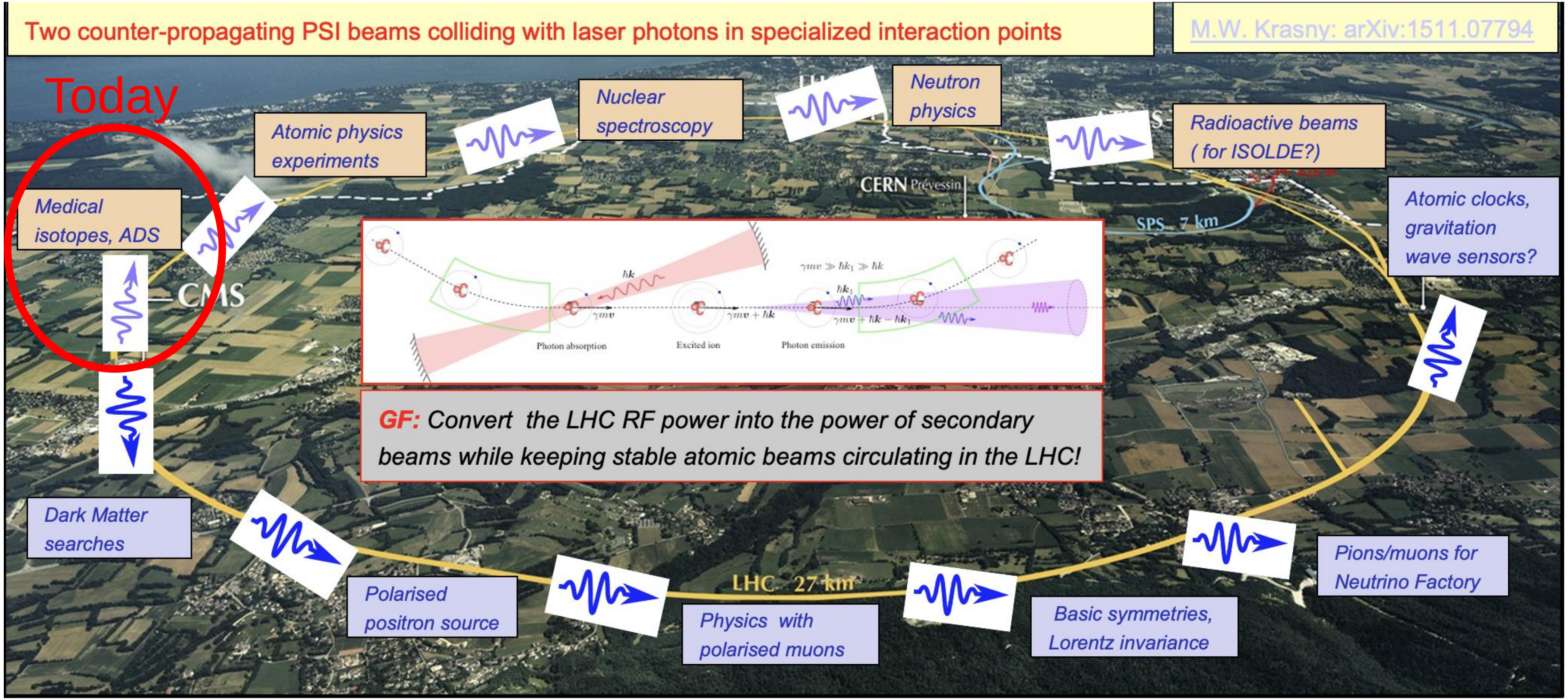




Required photon-beam energy:
5-20 MEV -- He(H)- like Ca or Kr beams + comercial ~ 1 μm lasers

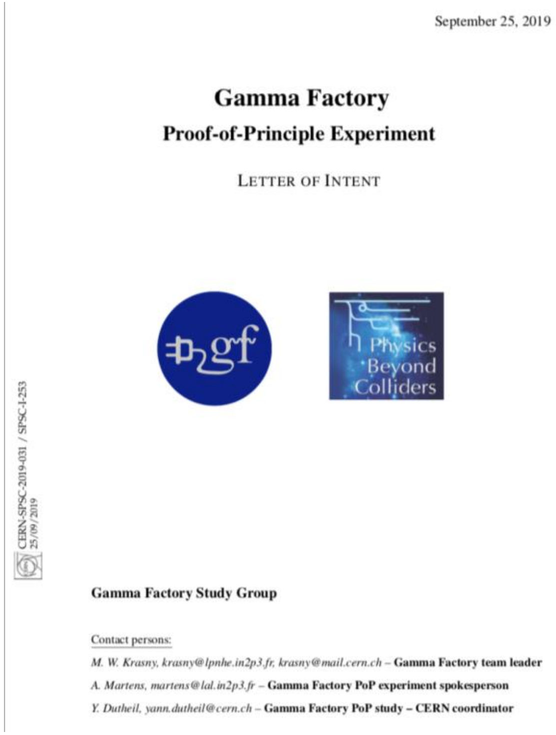
Required beam intensity:
O(10 MW) power

Can Gamma Factory deliver such a beam?

# Gamma Factory



# The FP cavity of the GF PoP experiment as a demonstrator


September 25, 2019

**Gamma Factory**

**Proof-of-Principle Experiment**

LETTER OF INTENT

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

**Gamma Factory Study Group**

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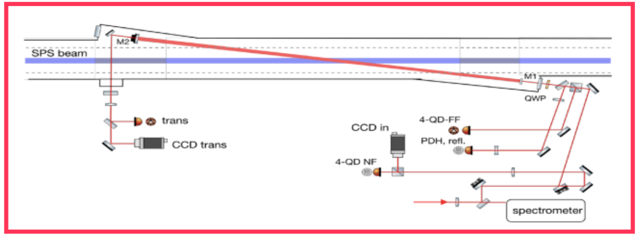
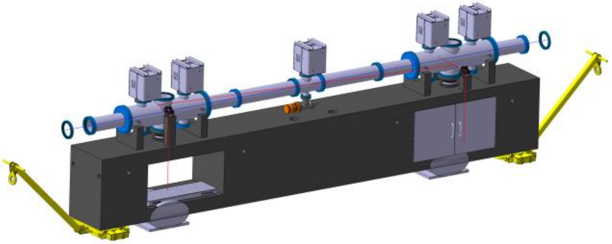
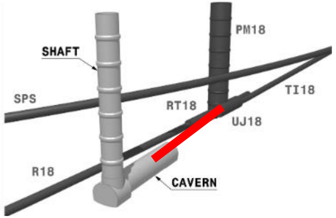
*A. Martens, martens@lal.in2p3.fr* – **Gamma Factory PoP experiment spokesperson**

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

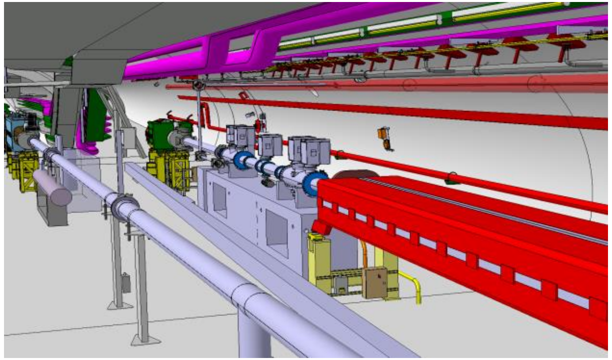



***GF SPS –PoP: F-P cavity length – 3.75 m***

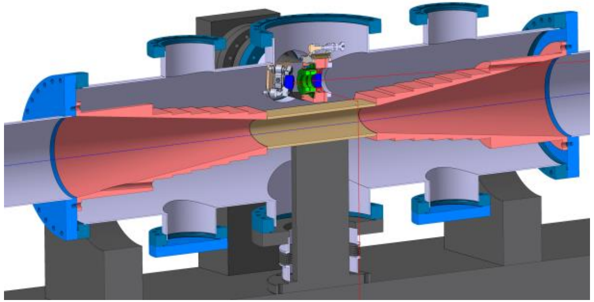





*LHC implementation*



***GF F-P cavity integration – SPS ring***



*Cost estimate: Laser + F-P – ~ 1 MCHF*

*More: Yann's talk this morning…*

# Three principal technical requirements

## LHC RF power and circumferential voltage

◆ Present RF power generated by sixteen 300kW/400MHz klystrons = 4.8 MW.

→ For the 10 MW photon beam the number of klystrons would have to be increased by a factor of 3

NB. At LEP 2 forty four klystrons, each of 1.3 MW power → 57 MW total power

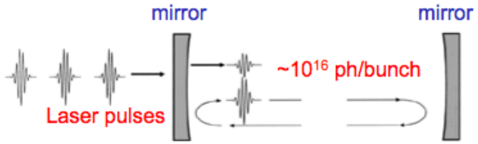
◆ Present LHC circumferential voltage, cv, delivered by 8 cavities (two cryomodules) -- **cv = 16 MV**

→ For the 10 MW photon beam of <E$\gamma$> =10 MeV, driven by He-like Ca ions, the cv over the LHC ring would have to be increased to: **cv ~ 180 MV**

NB. At LEP 2, **cv = 3650 MV** to compensate for the average ~ 3 GeV energy loss of each of the beam electron/positron per turn

## Integrated laser pulses power

GF PoP FP Cavity:
5mJ pulses @ 40MHz, (200kW photon beam – commercial lasers)



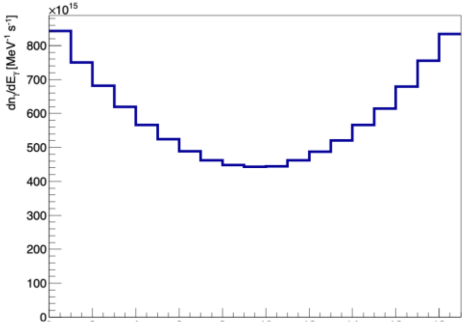

For the ideal case of 5mJ "Erbium laser" photon pulses (1550 nm), zero-degree crossing geometry, $10^9$ Ca+18 ions/bunch, and 500 ps long laser pulses GF – the maximal achievable photon rate would be ~$10^{18}$ 1/s (10 MW beam of <E$\gamma$> =10 MeV photons requires 6.3 x $10^{18}$ $\gamma$/s )

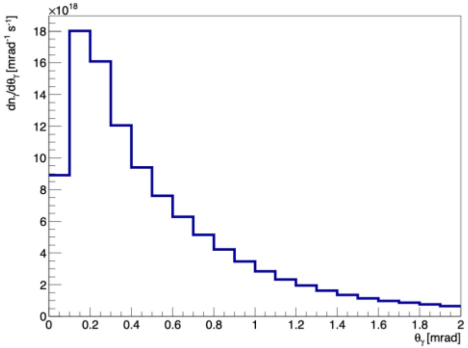
➢ For 10 MW photon beam the number of laser-pulse-PSI-beam crossing points over the LHC straight section would have to be increased…

→ special design and its full simulation needed

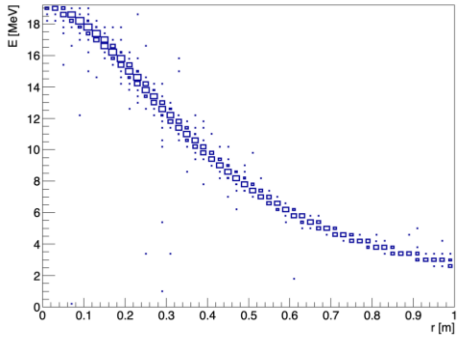
# Optimisation studies: GF beam and laser pulses parameters and their collision optics

## 20 GF-PoP –like FP cavities




Number of photons with energy, Eγ, in the interval of 6-19 MeV:




Energy- radius correlation at 1 km distance from the photon-beam production point

**$N_\gamma$ = 7.24027 x $10^{18}$ 1/s**
**(11,5 MW GF beam)**

$N_\gamma$/day / $N_{Avogadro}$ ~ 1

$N_A$ = 6,023·$10^{23}$

**+ Ca+18 beam parameters at IP**

- Energy 9.107D+13 eV
- **Number of ions/bunch 1.0000D+09**
- Transverse Distribution Gaussian
- **Beta (x,y) 5.000D+01 5.000D+01 m**
- Emittance (x,y) 3.000D-10 3.000D-10 rad.m
- **R.m.s. beam size (x,y) 125.5 125.5 μm**
- Gaussian tail cut off 3.50 3.50 sigma
- R.m.s. Bunch length 1.500D-02 m
- E distribution Gaussian
- Relat. energy spread 2.000D-04

**+ Laser parameters at IP (Erbium laser)**

- **Wavelength 1.55000 micron**
- Photon energy 0.799898 eV
- Peak power density 3.527D+13 Watt/m**2
- **Pulse energy (FP) 4.987D-03 Joule**
- Time profile of pulse Gaussian
- **R.m.s. pulse length 29.9792 mm**
- Spatial profile of pulse Gaussian
- Rayleigh length 729.6602 mm
- **R.m.s beam size at focus 300.00 300.00 μm**

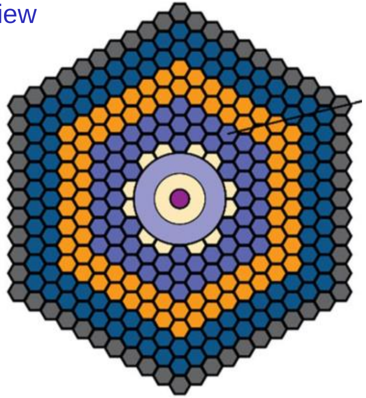
**+ PSI-bunch – laser pulse crossing angle 1 deg**

Alternative scenario: Ytterbium laser - second harmonics of the PoP laser, He -like Krypton beam, $E_{max}$ = 28 MeV

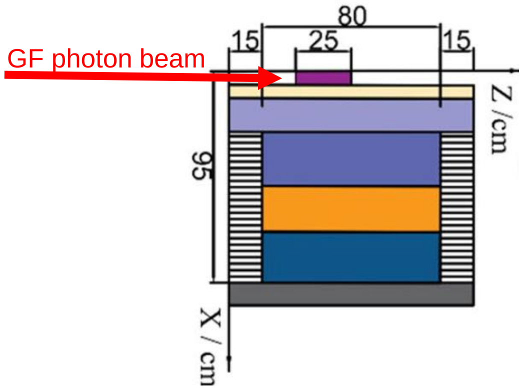
# Next steps

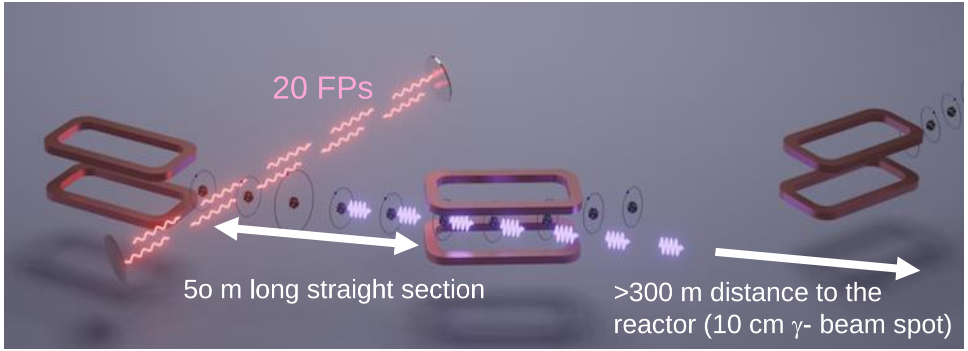
# Optimisation of the GF-beam-driven reactor – on-going simulation studies

Front view



Side view




- *Optimisation of the overall layout of the system*
- *Optimisation of photo-neutron source*
- *Neutron transport*
- *Transmutation efficiencies*

**Collaboration with Prof. Wen Luo group:**
School of Nuclear Science and Technology, University of South China, Hengyang

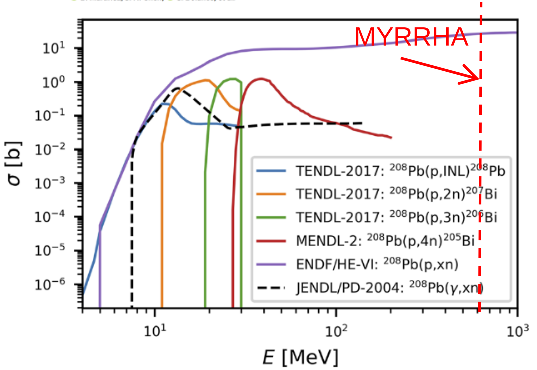
# Why photons rather than protons?

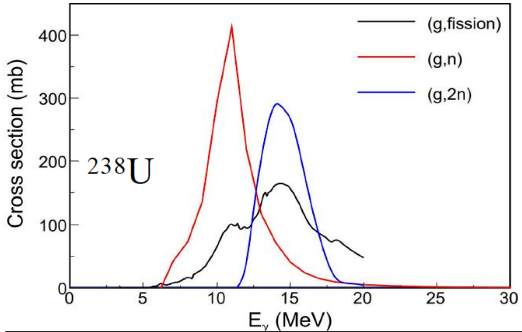
# Proton-beam-driven and photon-beam driven subcritical reactors:

## (1) transmutation potential

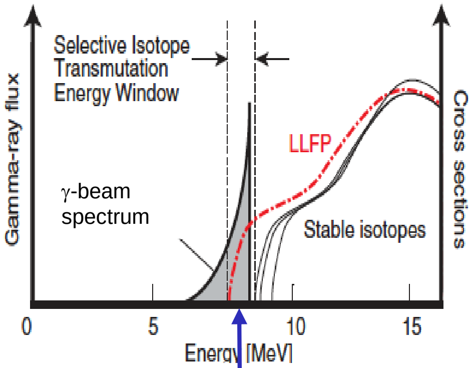
Cite as: Matter Radiat. Extremes 7, 024401 (2022); https://doi.org/10.1063/5.0060582
Submitted: 20 June 2021 • Accepted: 30 November 2021 • Published Online: 27 December 2021

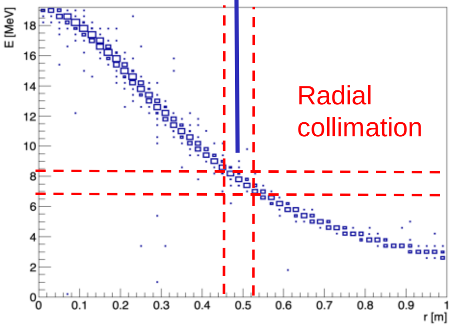
B. Martinez, S. N. Chen, S. Bolaños, et al.




Comparable neutron-driven transmutation capacity per MW of the beam power




Photon beam -- unique fission surgery tool for photon-driven transmutation

**Table 1.** Particle threshold energies and residual nuclei for even-Z elements including LLFPs.

| Isotopes | $T_{1/2}$ | $E$ (MeV) | R.I. | $T_{1/2}$ |
|---|---|---|---|---|
| $^{90}$Zr | - | 8.355(p) | $^{89}$Y | - |
| $^{91}$Zr | - | 7.195(n) | $^{90}$Zr | - |
| $^{92}$Zr | - | 8.634(n) | $^{91}$Zr | - |
| $^{93}$Zr | $1.61\times10^6$ y | 6.734(n) | $^{92}$Zr | - |
| $^{94}$Zr | - | 8.220(n) | $^{94}$Zr | $1.61\times10^6$ y |
| $^{96}$Zr | - | 7.854(n) | $^{95}$Zr | 64 d |
| $^{76}$Se | - | 9.508(p) | $^{75}$As | - |
| $^{77}$Se | - | 7.418(n) | $^{76}$Se | - |
| $^{78}$Se | - | 10.399(n) | $^{77}$Se | - |
| $^{79}$Se | $2.95\times10^5$ y | 6.914(n) | $^{78}$Se | - |
| $^{80}$Se | - | 9.914(n) | $^{79}$Se | $2.95\times10^5$ y |
| $^{82}$Se | - | 9.276(n) | $^{81}$Se | 18 m |
| $^{104}$Pd | - | 8.658(p) | $^{103}$Ph | - |
| $^{105}$Pd | - | 7.941(n) | $^{104}$Pd | - |
| $^{106}$Pd | - | 9.347(p) | $^{105}$Rh | 1.47 d |
| $^{107}$Pd | $6.5\times10^6$ y | 6.359(n) | $^{106}$Pd | - |
| $^{108}$Pd | - | 9.221(n) | $^{107}$Pd | $6.5\times10^6$ y |
| $^{110}$Pd | - | 8.861(n) | $^{109}$Pd | 13.7 h |
| $^{117}$Sn | - | 6.945(n) | $^{116}$Sn | - |
| $^{118}$Sn | - | 9.327(n) | $^{117}$Sn | - |
| $^{119}$Sn | - | 6.485(n) | $^{118}$Sn | - |
| $^{120}$Sn | - | 9.107(n) | $^{119}$Sn | - |
| $^{122}$Sn | - | 8.814(n) | $^{121}$Sn | 27 h |
| $^{124}$Sn | - | 8.488(n) | $^{123}$Sn | 40 m |
| $^{126}$Sn | $2.3\times10^5$ y | 8.193(n) | $^{125}$Sn | 9.6 d |
| $^{88}$Sr | - | 10.614(p) | $^{87}$Rb | - |
| $^{90}$Sr | 28.8 y | 7.806(n) | $^{89}$Sr | 50.6 d |

| Isotopes | $T_{1/2}$ | $E$ (MeV) | R.I. | $T_{1/2}$ |
|---|---|---|---|---|
| $^{133}$Cs | - | 6.085(p) | $^{132}$Xe | - |
| | | 8.987(n) | $^{132}$Cs | 6.5 d |
| $^{135}$Cs | $2.3\times10^6$ y | 6.751(p) | $^{134}$Xe | - |
| | | 8.762(n) | $^{134}$Cs | 2.0 y |
| $^{137}$Cs | 30 y | 7.416(p) | $^{136}$Xe | - |
| | | 8.278(n) | $^{136}$Cs | 13.2 d |
| $^{127}$I | - | 6.206(p) | $^{126}$Te | - |
| @ | | 9.143(n) | $^{126}$I | 13.1 d |
| $^{129}$I | $1.57\times10^7$ y | 6.799(p) | $^{128}$Te | - |
| | | 8.833(n) | $^{128}$I | 25 m |
| $^{99}$Tc | $2.11\times10^5$ y | 6.500(p) | $^{98}$Mo | - |
| | | 8.967(n) | $^{98}$Tc | $4.2\times10^6$ y |

**Proposal for selective isotope transmutation of long-lived fission products using quasi-monochromatic γ-ray beams**

Takehito Hayakawa, Shuji Miyamoto, Ryoichi Hajima, Toshiyuki Shizuma, Sho Amano, Satoshi Hashimoto & Tsuyoshi Misawa

# Proton-beam-driven and photon-beam driven subcritical reactors:
## (2) cost and operation aspects

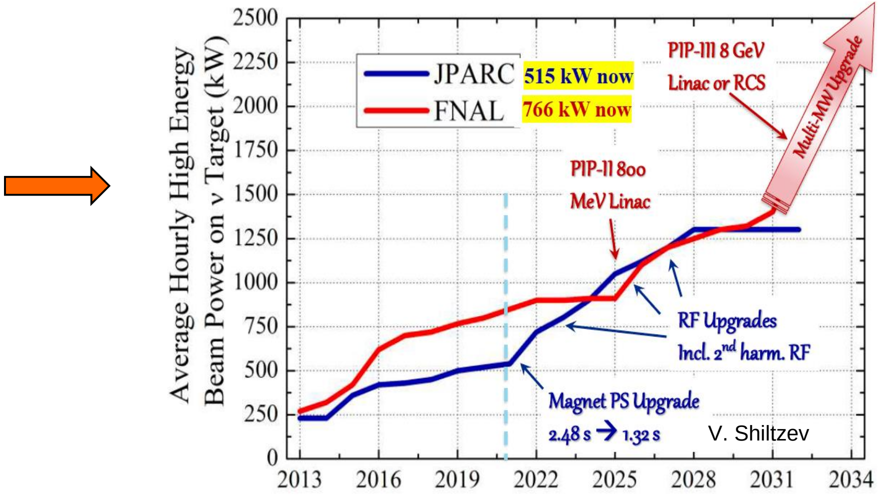
- ✓ There is no apparent showstopper to create at CERN the O(10) MW photon beam – if based on the Gamma Factory concept

- ✓ Building of O(10) MW proton accelerator driver represents a technological challenge (presently < 1 MW, up to 2.4 MW planned for the future MYRRHA project)

- ✓ Its cost (likely >$10^9$ CHF) would be comparable to the cost of a subcritical nuclear reactor construction

- ✓ The 10 MW photon beam driver accelerator already exists (LHC). Cost of the laser stations negligible… but the operation aspects by far more complicated – practical only if associated with a broad multidisciplinary research programme with the Gamma Factory photon beams?

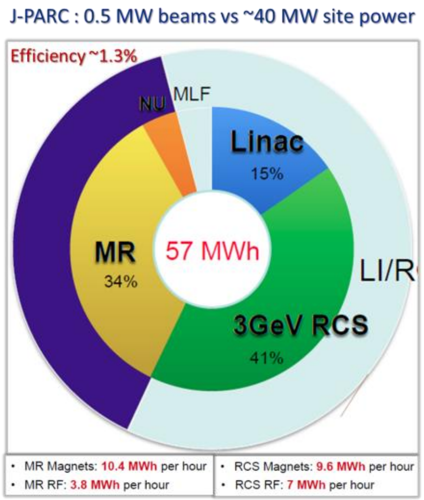
- ✓ Important aspect: GF photon beam is quasi continuous (20 MHz repetition rate) – very useful for the neutron flux stability(sub-criticality)



# Proton-beam-driven and photon-beam driven subcritical reactors:

## (3) plug power efficiency

### Proton beam J-PARC




**Efficiency = 1.3 %**

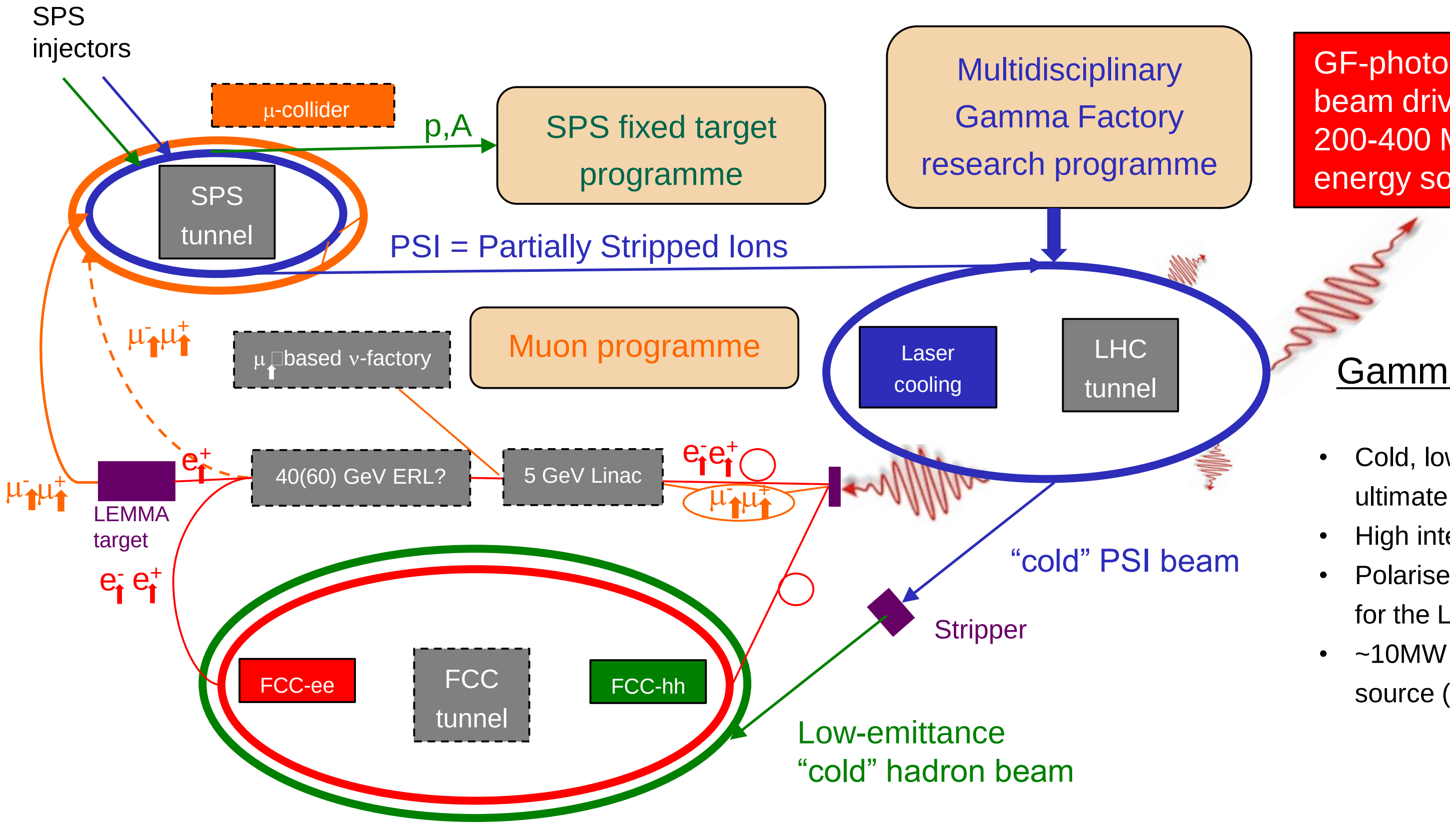
### Photon beam CERN-GF

- beam lifetime 10 h
  (plug power necessary to ramp the PSI beam to requisite energy negligible)
- beam power efficiency = beam power/ RF-power > 90 %
  NB.(DESY FEL beam power efficiency – 0.1 %)
- overall energy efficiency = beam power/(LHC cryogenic power +RF power) = 10 MW /(10MW +40MW) = 20%

**Efficiency ~ 20 %**

# Outlook

# Potential GF role in an incremental, sustainable, and multi-disciplinary development of the research infrastructure at CERN



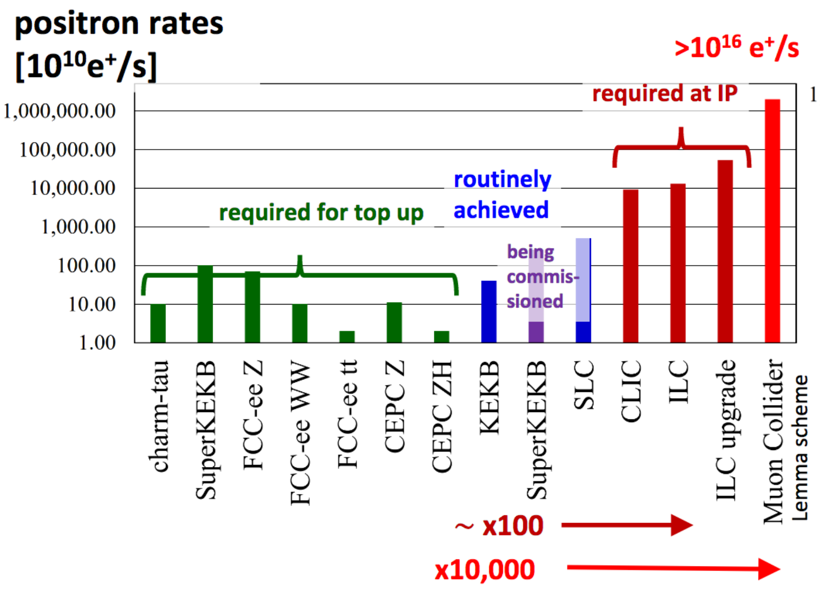

## Gamma Factory could provide:

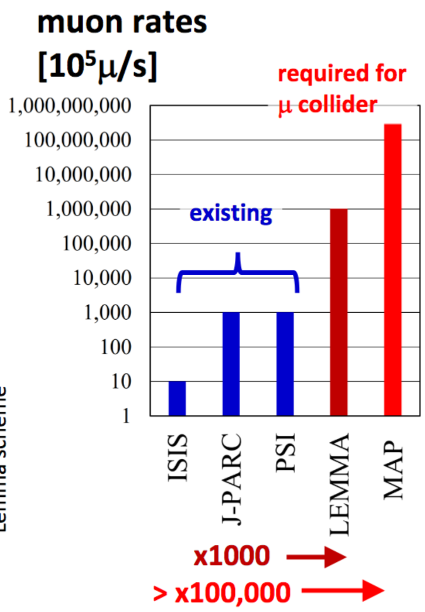
- Cold, low emittance, hadronic beam for the ultimate luminosity hadron collider
- High intensity μ source **( >10$^{13}$ μ/s/MW)**
- Polarised positron source **(>10$^{16}$ e$^{+}$/s/MW)** for the LEMMA scheme muon collider
- ~10MW driver beam for the ADS energy source (under study)

# Supplementary slides

GF – presently the only technology capable to deliver the requisite power polarised positron source for the CLIC, ILC and for the Lemma scheme muon collider

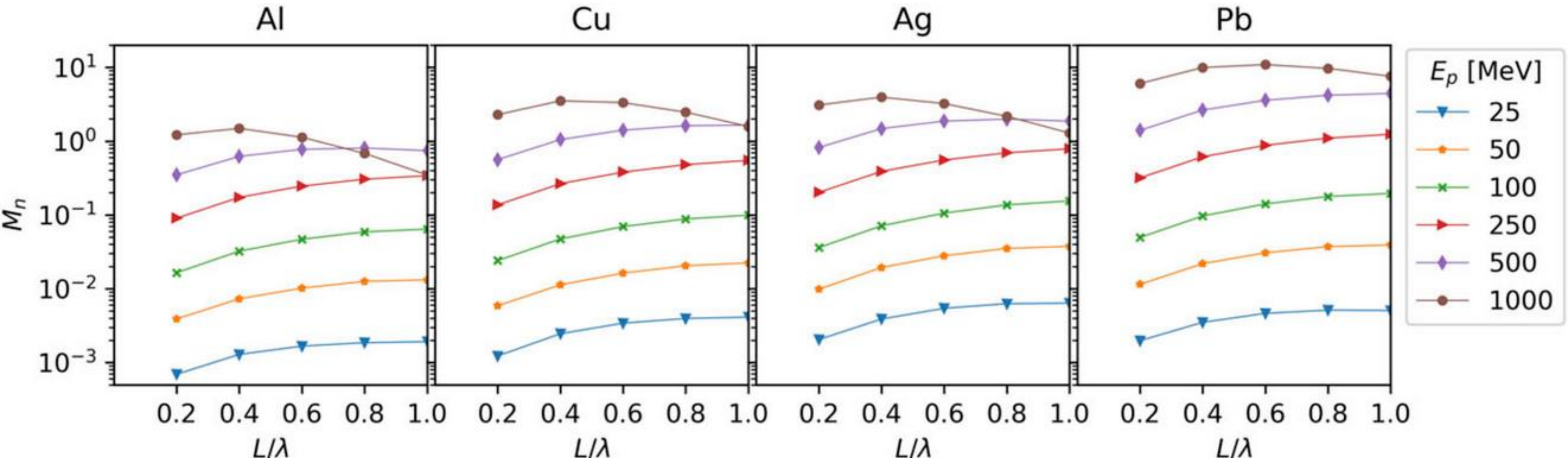
*Frank Zimmermann – CERN seminar on challenges for future colliders*




Gamma Factory: $N_{e+} > 10^{16}$ 1/s/MW, $N\mu+ = N\mu- > 10^{13}$ 1/s/MW

# Neutrons per proton



# Energy footprint of photon beams : DESY-XFEL example

DESY-XFEL

- Wall-pug power – 19 MW
- Driver beam power consumption – 600 kW
- Photon beam power 600 W
- **beam power efficiency ~ 0.1 %**
- **overall plug-power consumption efficiency ~ 0.003 %**

  (thanks to Andrea Latina for these numbers)

| Element | Isotope | Relative composition (wt%) | Natural half-life ($T_{1/2}$) | Neutrons capture cross section at 0.025 eV (barn) | (γ, n) parameters | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $E_{th}$ (MeV) | $\Gamma$ (MeV) | $E_{max}$ (MeV) | $\sigma_{max}$ (mbarn) |
| Se | $^{76}$Se | $1.4\times10^{-4}$ | Stable | 85.02 | 11.15 | 7.0 | 15.01 | 107 |
| | $^{77}$Se | 0.032 | Stable | 41.33 | 7.52 | 5.2 | 17.04 | 141 |
| | $^{78}$Se | 0.064 | Stable | 50.02 | 10.50 | 6.0 | 16.01 | 122 |
| | $^{79}$Se | 0.096 | $3.27\times10^{5}$ a | 11.81 | 6.96 | 5.0 | 17.04 | 150 |
| | $^{80}$Se | 0.190 | Stable | 0.59 | 9.91 | 5.0 | 16.01 | 128 |
| | $^{82}$Se | 0.410 | Stable | 0.04 | 9.28 | 4.0 | 16.00 | 142 |
| Zr | $^{90}$Zr | 0.190 | Stable | 0.01 | 11.97 | 4.5 | 17.00 | 192 |
| | $^{91}$Zr | 6.790 | Stable | 1.30 | 7.19 | 4.5 | 17.00 | 182 |
| | $^{92}$Zr | 8.060 | Stable | 0.23 | 8.63 | 3.2 | 16.01 | 159 |
| | $^{93}$Zr | 8.590 | $1.53\times10^{6}$ a | 2.24 | 6.73 | 4.0 | 15.00 | 141 |
| | $^{94}$Zr | 8.750 | Stable | 0.05 | 8.22 | 3.0 | 15.03 | 130 |
| | $^{95}$Zr | 0.940 | 64.032 d | 8.11 | 6.46 | 3.5 | 14.99 | 134 |
| | $^{96}$Zr | 8.940 | $2.0\times10^{19}$ a | 0.02 | 7.85 | 4.5 | 14.98 | 103 |
| Tc | $^{99}$Tc | 8.370 | $2.11\times10^{5}$ a | 22.80 | 8.97 | 3.7 | 15.99 | 202 |
| Pd | $^{104}$Pd | $7.6\times10^{-5}$ | Stable | 0.65 | 10.00 | 4.8 | 16.00 | 220 |
| | $^{105}$Pd | 2.480 | Stable | 21.08 | 7.09 | 4.2 | 15.98 | 221 |
| | $^{106}$Pd | 0.800 | Stable | 0.30 | 9.56 | 4.0 | 15.98 | 228 |
| | $^{107}$Pd | 0.820 | $6.5\times10^{6}$ a | 9.53 | 6.54 | 4.0 | 15.98 | 232 |
| | $^{108}$Pd | 0.380 | Stable | 8.57 | 9.22 | 4.1 | 15.98 | 194 |
| | $^{109}$Pd | 0.120 | 13.701 h | 24.20 | 6.15 | 3.8 | 16.01 | 208 |
| I | $^{127}$I | 0.590 | Stable | 6.15 | 9.14 | 5.0 | 15.03 | 253 |
| | $^{129}$I | 1.870 | $1.57\times10^{7}$ a | 30.29 | 8.99 | 5.0 | 15.56 | 300 |
| Cs | $^{133}$Cs | 14.200 | Stable | 30.36 | 9.00 | 5.0 | 15.50 | 314 |
| | $^{134}$Cs | 0.520 | 2.065 a | 140.02 | 6.99 | 4.5 | 15.10 | 312 |
| | $^{135}$Cs | 13.200 | $2.30\times10^{6}$ a | 8.41 | 8.78 | 4.5 | 15.00 | 316 |
| | $^{136}$Cs | 0.012 | 13.16 d | 13.36 | 6.83 | 4.0 | 15.02 | 322 |
| | $^{137}$Cs | 13.500 | 30.08 a | 0.27 | 8.30 | 3.5 | 15.00 | 325 |

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