The Abdus Salam International Centre for Theoretical Physics

IAEA

unesco

60 ICTP 1964-2024

EUROPEAN UNION

GUVERNUL ROMÂNIEI

Structural Instruments 2014-2020

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme "Investing in Sustainable Development"

eli nuclear physics

Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

IFIN-HH

Nuclear Physics Experiments with Lasers and Photons I

Joint ICTP-IAEA Workshop on Advanced Technologies in Laser-Driven Radiation Sources and Their Applications (15 - 18 April 2024)

Klaus Michael Spohr, Laser-Driven Experiments Department (LDED), ELI-NP, Bucharest-Magurele

ICTP-Trieste

Outline of Talk

1. Introduction
   - Nuclear Physics: history, fundations, experiment & theory, core questions
   - Accelerators: the drivers of nuclear physics research, towards laser-plasma driven systems
2. Laser-induced nuclear physics with PW-systems
   - (My prvate) History of laser-driven nuclear research
     - Early cross-section measurements, Medical isotope production
   - Commissioning experiments @ ELI-NP
     - Layout of ELI-NP & Target Stations, Experiments with solid targets for proton acceleration & laser-to-γ conversion, Core instrumentation
   - Planned experiments after commissioning in fundamental nuclear physics research
     - Source developemtn, Fusion-Fission, Isomer depopulation in $^{93}\mathrm{Mo}$, Cosmos in the laboratory: Production and decay studies of $^{26}\mathrm{Al}$
   - Planned programmes in applied nuclear physics research
     - Nuclear Transmutation, Laser-driven hadrontherapy
3. Summary & Outlook

Introduction

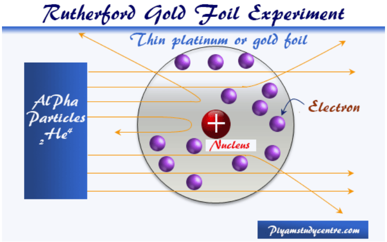
Personal Motivation for choosing this field

For me the concept of lasing, as derived by A. Einstein in 1915 and realized in the early 60’s is the biggest applied breakthrough of the last century together with the ability to harvest nuclear systems for the extraction of energy in the form of nuclear power. Being able to COMBINE both breakthroughs was a very attractive concept for me from the first day on when I got involved in that field (2002). I see a gamut of possibilities of fundamental and advanced studies that harvest the unique ability of HPLS to provide highest human made intensities. HPLS systems may allow one day a high level of control of nuclear systems including their omnipotent excited states in the same manner as we are able to control atomic states now.

Nuclear Physics: history, foundations, experiment & theory, core questions

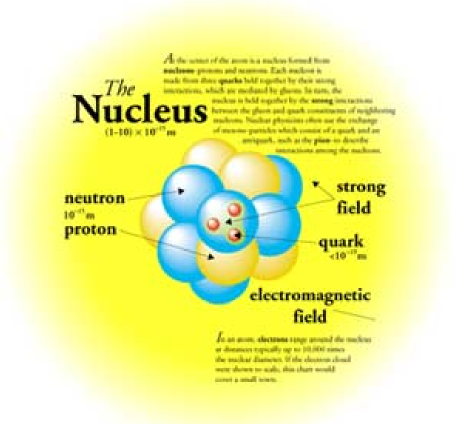
Studies atomic nuclei and their constituents (protons & neutrons) and their interactions. Effect of electrons neglected.

- 1896 Discovery of radioactivity by H. Becquerel
- 1897 Discovery of the electron, atom had internal structure by J. J. Thomson
- 1907 Characterisation of α, β and γ radiation by M. & P. Curie and E. Rutherford, and others.
- "Plum Pudding" (J J.Thomson): Atom was a (+) charged ball with smaller (-) charged electrons (Wrong, but best model at the time)
- 1911 Birth of Nuclear Physics: E. Rutherford, H. Geiger & E. Marsden fired $\alpha-$particles (helium nuclei) at a thin film of gold foil and found back-reflection of a few α's.

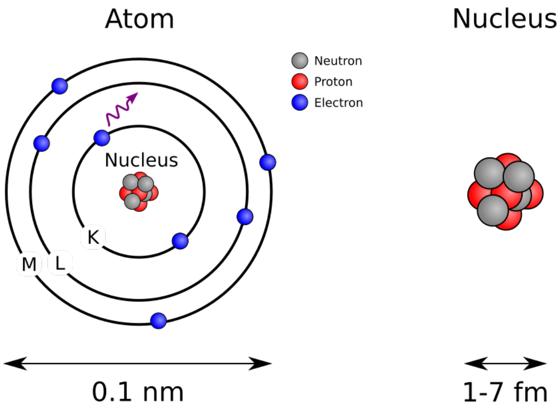


Nuclear physics, historic landmarks

- 1915 $E = mc^2$, A. Einstein (Huge energies related to nuclear systems)
- First nuclear transmutation $^{14}\mathrm{N} + \alpha \rightarrow ^{17}\mathrm{O} + \mathrm{p}$ by E. Rutherford
- 1925 Discovery of atomic spins
- 1930 Discovery of neutrons by J. Chadwick
- 1936 A. Proca 'Meson Theory' to explain nuclear binding, later formulized by H. Yukawa
- 1938 Induced nuclear fission by L. Meitner and O. Hahn



Nuclear & Atomic Physics

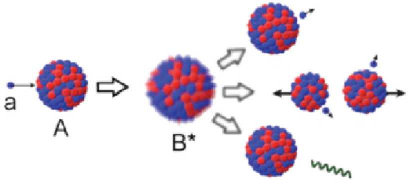


- Atomic physics determined by electrons in shells
- Electrons in quantized states
- Behaviour determined by the central Coulomb potential $V(r) \propto 1/r$
- For most phenomena the nuclear core can be neglected
- Atomic states controllable → lots of applications (Laser)

- Nuclear states determined by the interplay of protons and neutrons in shells (1948)
- Neutrons and Protons in quantized states different potentials
- Behaviour determined by complex central potential, Hamiltonian to be approximated by simplifications: Mean-Field functionals
- For most phenomena the outer electrons in their shell can be neglected

Nuclear physics *Modus Operandi*

- Early days, limited to observe the decay of natural radioactive isotopes.
- With the emergence of DC- and RF-based accelerators in the 1920's, human-made induction of nuclear reactions by the impact of an accelerated and energetic (kinetic) beam projectile on a selected target.
- Nuclear reactions, such as transmutations are achieved and the instantaneous $\sim 10^{-15}\,\mathrm{s}$ process creates highly excited states within the freshly created reaction products.
- Reaction probability defined by the cross-section σ, unit 1 b= 10^{-24} cm^{-2} (several orders of magnitude smaller compared those relevant to atomic processes)
- Threshold energies required for ions to trigger transmutation reactions. For example $E_\mathrm{p} > 3 - 5\mathrm{MeV}$ to overcome Coulomb-threshold.

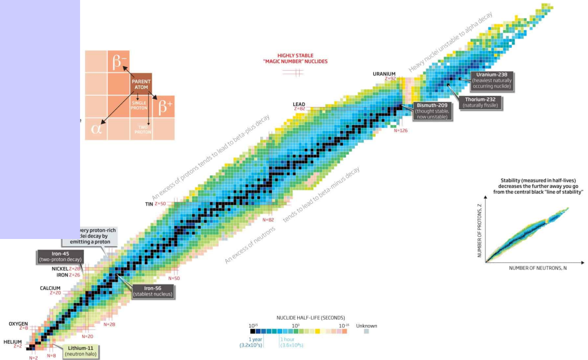


Schematics of a nuclear reaction with A the beam particle, and B the target

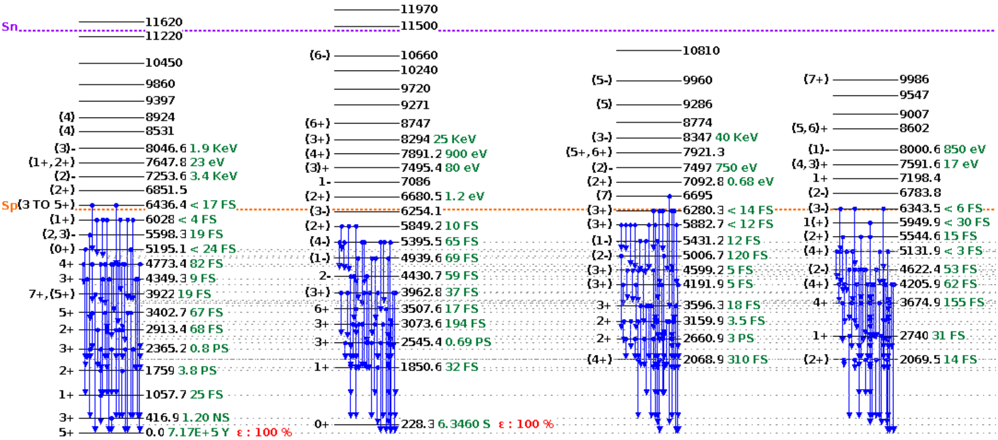
Nuclear physics, brief overview of the experimental status

- Study of the properties of the nuclei formed by a certain amount of protons, Z and neutrons, N (isotope) and bound together by the strong nuclear force to a quantum mechanical system of $A = N + Z$ nucleons
  - Identifying isotopes and elements, their masses m, spins I, magnetic moments μ, excitation levels E_{i} and associated γ decay, shapes (spherical, prolate, oblate, pear-shaped), magic numbers, abundances in the Universe, ...
  - Measuring radioactive decay, α, β, γ, SF, ...
  - Applications with societarian benefit (medical physics, energy)
  - Informing nuclear astrophysics (creation of elements, r-process, s-process), astrophysics (neutron stars), atomic & particle physics

+ $\sim$3500 known isotopes
+ Potentially $\sim$6000! more
+ Only 252 stable (black)
+ $\sim$40 very long lived
+ $10^{-21}\,\mathrm{s} < \tau < 10^{15}\,\mathrm{s}$
+ $\sim$180000 nuclear levels
+ Heaviest: $^{294}_{118}\mathrm{Og}$ (oganesson)



Nuclear physics, brief overview of the experimental status



Example: Partial level-scheme of $^{26}\mathrm{Al}$. Blue arrows are observed $\gamma-$transitions.

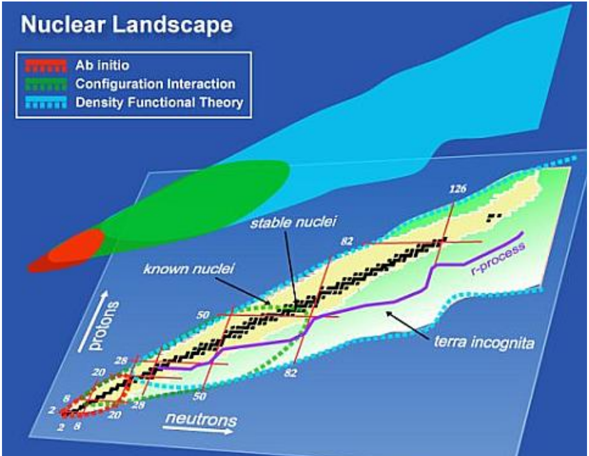
Nuclear physics, the core questions

- What are the limits of nuclear existence and how do nuclei at those limits live and die?
- What do regular patterns in the behavior of nuclei divulge about the nature of nuclear forces and the mechanism of nuclear binding?
  - Nuclear structure: Explaining all properties of nuclei and nuclear matter and their interaction
- What is the nature of extended nucleonic matter?
  - Quark-gluon plasma: “melted” nuclei allow an inside the nature of those quarks and gluons that are the constituent particles of nuclei
  - Hadron structure: characterizing the strong force and the various mechanisms by which the quarks and gluons interact and result in the properties of the protons and neutrons that make up nuclei
- How can nuclear structure and reactions be described in a unified way?
  - fundamental symmetries, unravel limitations of the Standard Model and to provide some of the understandings upon which a new, more comprehensive Standard Model will be built.
- What can we learn about the universe by the study of atomic nuclei?
  - Nuclear astrophysics: Exploring objects and events in the universe shaped by nuclear reactions
- How can we use nuclear physics for applied technological concept for the benefit of mankind
  - Highest energy-mass ratio available: nuclear power, nuclear battery?
  - Smart medical applications e.g. in oncology and radiography

Nuclear physics, brief overview on state-of-the-art theory

- Nuclear force, potential has no central potential V that can be used in the describing Hamiltonian $\hat{T} + \hat{V} = \hat{\mathcal{H}}\Psi = E\Psi$, very different to atomic physics!
  - Approximations on $\hat{V}$, self-consistent fields
  - Single particle like interaction with average $\hat{V}$ Shell Model, leading to magic numbers, 2,8,20,28,50,82,126 (strong $\mathbf{L} \cdot \mathbf{S}$-coupling)
  - But, also collective effects leading to deformed nuclei
  - Unified Nuclear Energy Density Functional (UNEDF)

+ Light nuclei (red): nucleon-nucleon, three nucleon forces
+ Medium nuclei (green): Interacting Shell Model
+ Heavy nuclei (blue): Self consistent Mean Field Theory
+ 50 million core hours
+ Largest theoretical collaboration in the history of nuclear physics



Accelerators: the drivers of nuclear physics research, towards laser-plasma driven systems

Accelerators: the role for laser-driven accelerators

Where do HPLS systems fit into nuclear research?
HPLS systems can widen our horizon of nuclear research as they provided the highest human-made intensity beam pulses of accelerated ions, neutrons and $\gamma-$rays and, maybe, above all, the chance of collective acceleration of ions. As such they can complement and extend current DC-RF based technology. As typical field strength for acceleration processes can be reached within a 1000$\times$ smaller acceleration path compared to that of conventional technology, we hope that our research will finally lead to a compactification of existing accelerator technology. The ultrafast beam-pluses allow, in principle, research into the timing regime that is in the same order of magnitude of nuclear processes in the fs-regime which can add a new dimension to nuclear physics. A unique chance is that those short pulses allow a higher degree of manipulation of nuclear states, thus leading to an enhanced control of nuclear phenomena besides the tremendously enhanced time resolution inherently given by the sub-ps pulses. The challenges however are manifold. As of 2024 HPLS technology only can deliver 4-5 orders of magnitude less overall beam current over a typical macroscopic beam-time of 1-2 weeks. Besides that, new concepts of detection systems have to be devised to deal with the ultrashort snapshots that emerge from HPLS systems, and which will saturate any conventional, electronics based detector system and related acquisitions.
More details in subsequent slides

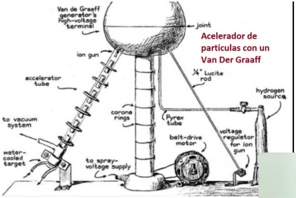
Accelerators: the drivers of nuclear physics research

Progress in our understanding of nuclear and astrophysical phenomena as well in the application of nuclear reactions for medical purposes has ALWAYS been driven by accelerator technologies as those provide the short-lived nuclei *via* dedicated nuclear reactions

An accelerator is an sophisticated transformer with the aim to amplify energies and connected intensities into a desired regime. Accelerators use electromagnetic fields to propel single charged particles **individually** to very high speeds and energies bundling them in beams. Laser Plasma based acceleration techniques are a disruptive technology and as such potential 'Game-Changers' in this fields, as they provide acceleration of **collective bunches** of ions (Veksler, 1956)

Traditional DC- and RF-based accelerators:

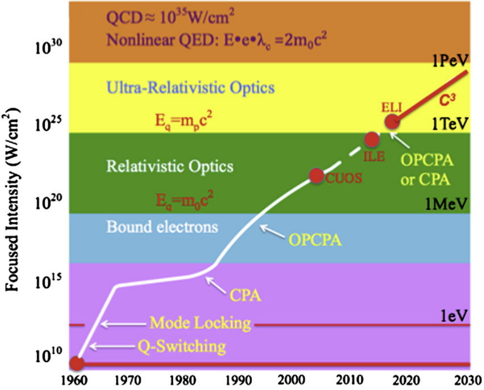
- Worldwide ~30000 in operation
- LHC CERN, 13 TeV, RHIC Brookhaven, Tevatron Illinois
- Electrostatic (DC)
  - 1930s: Van de-Graff, Cockroft-Walton
- Electrodynamic
  - Betatrons (electron)
  - Linear accelerators
  - RF-based: Synchrotrons, cyclotrons, storage rings

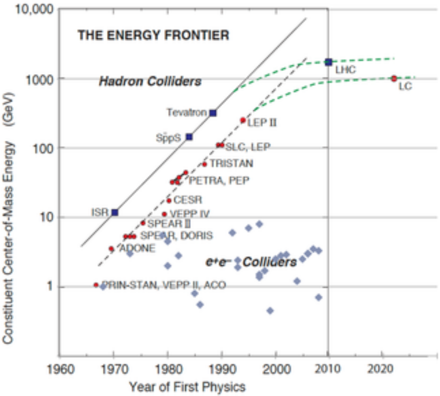


Accelerators: towards laser-plasma acceleration

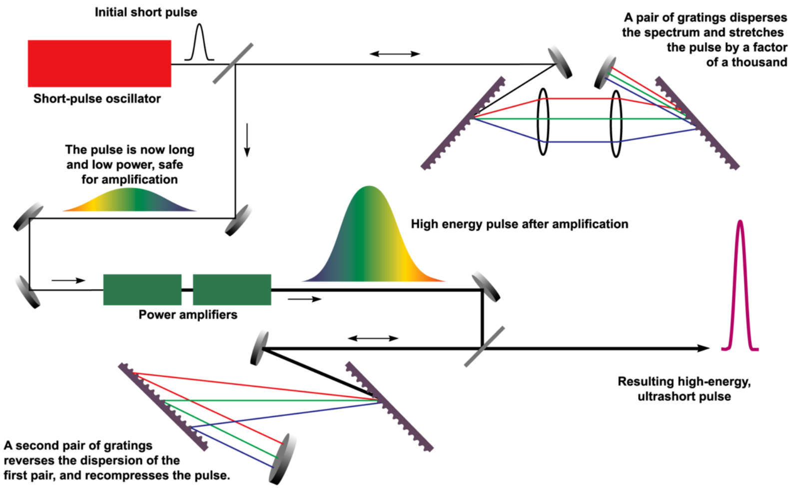
The development of laser-plasma based accelerators was enabled by the invention of the Chirped Pulse Amplification (CPA) by Strickland and Mourou, Physics Nobel Laureates 2018

Disruptive technology that led to an increase of 5-6 orders of magnitude for the laser intensity I_0 as it allows to exploit the innermost structure and high electromagnetic fields via the disturbance of an atom to create plasma. At such high intensities, laser plasma can induce particle acceleration and the production of MeV γ radiation, thus indirectly triggering high-energy processes such as nuclear fusion and fission or particle acceleration.





Schematics of the CPA



Ion acceleration regimes, collective acceleration *via* RPA

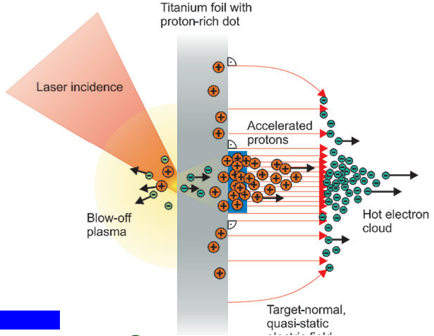
- Strong function of ℓ_{T} and I_{L} and dimensionless laser parameter a_0,

$$a_0 = \sqrt{\frac{I_0\lambda^2}{1.37\times 10^{18}\,\mathrm{Wcm}^{-2}(\mu\mathrm{m}/\lambda)^2}} > 30$$

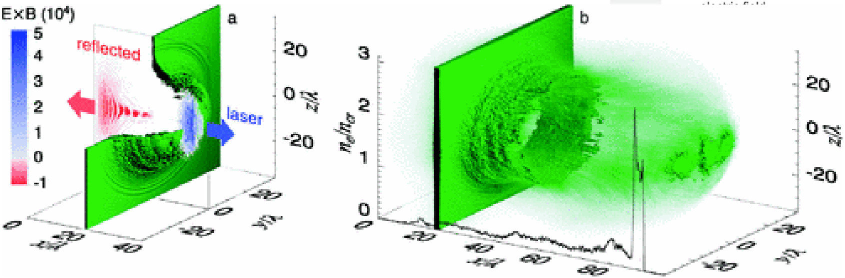
- TNSA well investigated, Maxwell-Boltzmann E_{p} distribution, currently: $\sim$ 100 MeV, Higginson *et al.* Nat. Comm. **9**, 724 (2018)
- Radiation Pressure Acceleration promises "mono-energetic" GeV protons
- Possibility of polarized protons

TNSA

Schlenvoigt *et al.*, Adv Sol St Las doi:10.5772/7965 (20



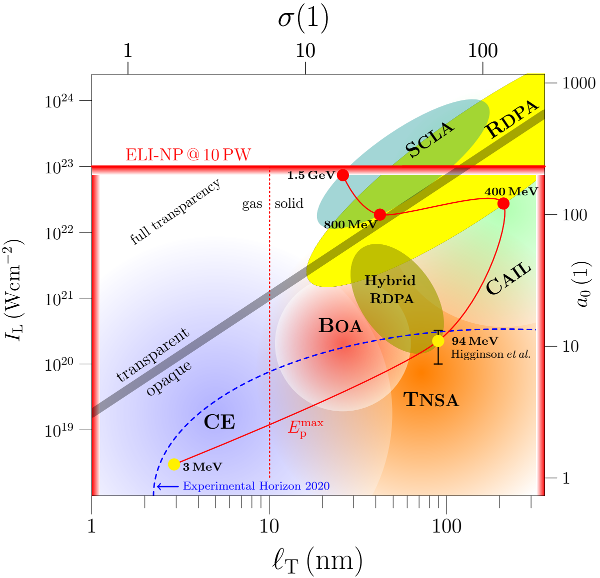
RPA



Esirkepov *et al.*, PRL **92**, 175003 (2004)

Laser-plasma Acceleration Regimes

- The chance for ELI-NP
- SCLA (Single Laser Pulse Acceleration, Mourou 2014)



Laser-driven acceleration, steering and control

An unnamed Professor at a Conference

"You have a non mono-energetic beam with a repetition rate of 1 Hz and an aperture of 30°*. What kind of 'beam' is that?"*

Me, in reply

A fast one!

Fast transposes into the high intensity of incoming particle beams in MA - GA regime, the onset of QED effects that will induce coherent betatron radiation and alter nuclear processes, reaction cross-section, and yields and induce the emergence of new reaction processes (NEEC). Collective effects of nuclear de-excitation may appear and novel applications for nuclear medicine and transmutation will become accessible in the far future. The quest to explore new acceleration regimes may lead to TeV proton beams.

High Intensity/Low Repetition rate $\longleftrightarrow$ Low Intensity/High Repetition rate

Comparison: electromagnetic *vs* laser-plasma acceleration

- Challenge: Diametrically opposed features:

Accelerator System	$t_{\mathrm{pulse}}^{\mathrm{min}}$	$\mathrm{d}N_{\mathrm{p}}/\mathrm{d}t$ (1/s)	f_{rep}
conv. electrostatic	$> \mu\mathrm{s}$ - DC	$< 10^{15}$	kHz-MHz
Laser plasma driven	$30 - 50\,\mathrm{fs}$	$\sim 10^{25}$	mHz-10 Hz

– Lower overall yield for comparable experiment duration ($10^5\times$ to $10^8\times$ reduced)
– One 10 PW shot per minute, 1 Hz at 1 PW, 10 Hz at 100 TW
– Development of radiation hardened detector systems necessary
+ Highest temporal production intensities & yields, nono-linear effects
+ Production and Irradiation times in the time spans of nuclear decays (isomers & even prompt decay), time resolution
+ Production (*via* ion acceleration) and probing with X-ray flux of nuclear system can be done in coincidence *in-situ*!
+ Astrophysical (quasi) entropy conditions in the
+ Unique chance of laser-plasma systems: collective acceleration (Paradigm shift in accelerator technology)
+ Unique Ability to deliver simultaneously mixed beams of ions, electrons and $\gamma-$radiation, *e.g.* ion-beam cocktail to mimick space radiation.

PW-class HPLS systems worldwide as of 2022

The future is bright!

Currently worldwide: 65 1 PW to 10 PW systems build or commissioned. Asia and Europe leading the way. Big additional push now in the US who were leading the field till the early 2000s

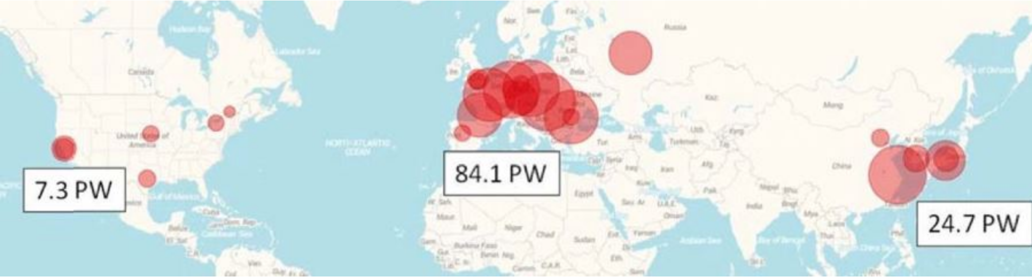


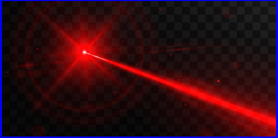
Fig. – PW laser systems 2022

Lasers in nuclear physics, the quest for control

Current high power laser systems allow nuclear physics experiments, indirectly via the creation of laser-induced radiation. A direct manipulation of nuclear states needs $I > 10^{25}\,\mathrm{Wcm}^{-2}$

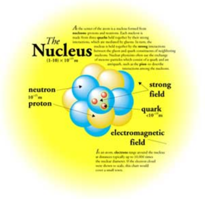
- For $I_0 \sim 10^{23}\,\mathrm{Wcm}^{-2}$ *indirect* interaction via laser induced radiation
  - Resonant coupling of electric and nuclear transitions (10 PW ELI-NP)
- Theory: $I_0 > 10^{25}\,\mathrm{Wcm}^{-2}$ onset of *direct* interaction of laser fields with nuclei
  - As laser (EM) – nuclear matrix elements become of significant amplitude.
- Modify or even control the nuclear dynamics and processes
- Nuclear quantum optics, the ability to 'play' with nuclear transitions in the keV-regime in the same way as with atomic transitions in the eV-regime with a laser, leading to many applications

Amplification and full fine-tuned control



Energy generation, failures in control

Full 'nuclear' control?



Laser-induced nuclear physics with PW-systems

History of laser-driven nuclear research

History of laser-driven nuclear research

- Nuclear physics exploiting ion acceleration and hard X-ray generation *via* laser-plasma $I > 10^{19}\,\mathrm{Wcm}^{-2}$
- Nuclear reactions
- Isotope/isomer production with ultra-intense accelerated electron/ion and radiation beams, reaction studies
- Applied (medical) and fundamental (astrophysics) experiments

- First acceleration of ions (protons) with NOVA laser 1996
- First nuclear transmutation created by a laser, K. W. D. Ledingham, founding father of laser-induced nuclear physics,
  - Ledingham, K. W. D. *et al.* *"Photonuclear physics when a multiterawatt laser pulse interacts with solid targets"*, Phys. Rev. Lett. **84**(5), 899 (2000).
  - Snavely R. A. *el al.* *"Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids"*, Phys. Rev. Lett. **85**(14), 2945 (2000)
- Photonuclear cross-sections measurements σ^{int}
- Production of isotopes for medical research.
  - Spohr, K. M. *et al.* "*Study of photo-proton reactions driven by bremsstrahlung radiation of high-intensity laser generated electrons*"; New Journal of Physics **10**, 043037, 2008."Best of IoP Papers Selection Award",
  - First time high power laser research ADDED new data to nuclear physics database.

Nuclear Experiments: Primary & secondary target

- Primary target = production of ion beam or radiation
- Secondary target = Reaction production target

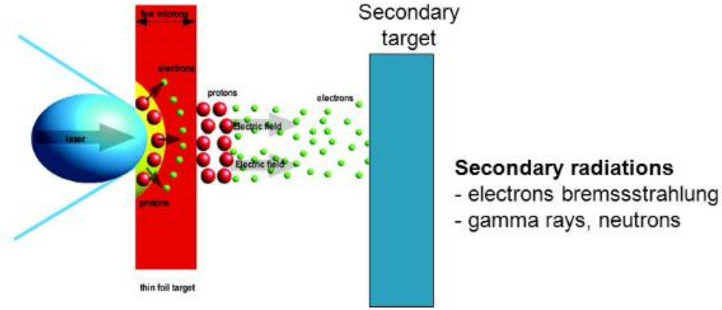


Fig. – Primary & secondary target arrangements in a laser plasma nuclear experiment

cross-section measurements to inform nuclear technology

- 30 TW, f=10 Hz Lasersystem: IOQ Jena.
- Laser-accelerated electrons $\rightarrow$ Bremsstrahlung ($\mathrm{k}T = 3.0\,\mathrm{MeV}$).
- Bremsstrahlung induces nuclear reaction, (γ,n) (γ,p), (γ,α), ...
- Measurement of $\sigma_{\mathrm{int}}(\gamma,\mathrm{p})$ for 6 different isotopes which are present in nuclear power plants.

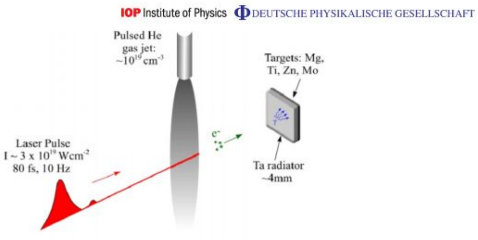


Figure 1. Schematic view of the experimental set-up. The target was placed in direct contact with the tantalum converter to narrowly confine the activated volume.

Fig. – Schematics of experiment

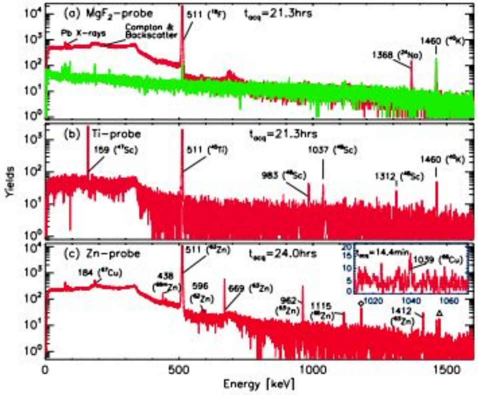


Fig. – Activity measured with Ge-Detector

Production of ^{99m}Tc for medical use

- ^{99m}Tc **most important isomer** for medical treatments worldwide, $\sim$ 50 m treatments per year!
- Supply has declined dramatically from 2017 onwards, but recovered in 2020
  - van Noorden, R. "*Radioisotopes: The medical testing crisis*", Nature 504, **202**, (2013).
- Production: $^{100}_{42}\mathrm{Mo}\,(\gamma,\mathrm{n})\,^{99}_{42}\mathrm{Mo} \xrightarrow{\beta^-\ \ t_{1/2}=66\,\mathrm{h}} {}^{99m}_{43}\mathrm{Tc}$, **first time with a laser** $\sim$ 50 kBq
  - Treatment dose: $\sim$ 500 MBq

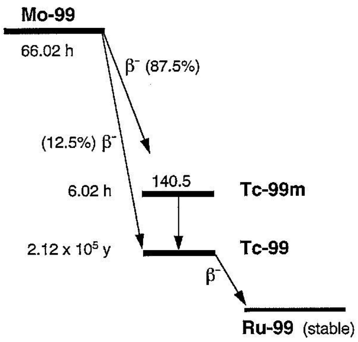


Fig. – Decay-Scheme

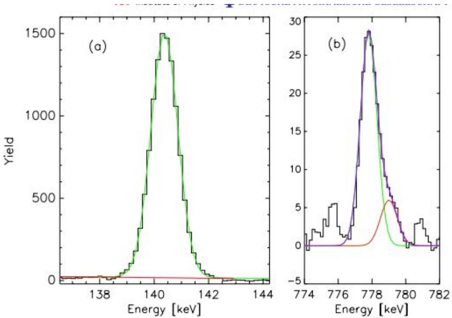


Fig. – Identification of ^{99m}Tc

Commissioning experiments @ ELI-NP

Layout of ELI-NP & Target Stations

ELI-NP, March 13, 2019: 10.88 PW World Record

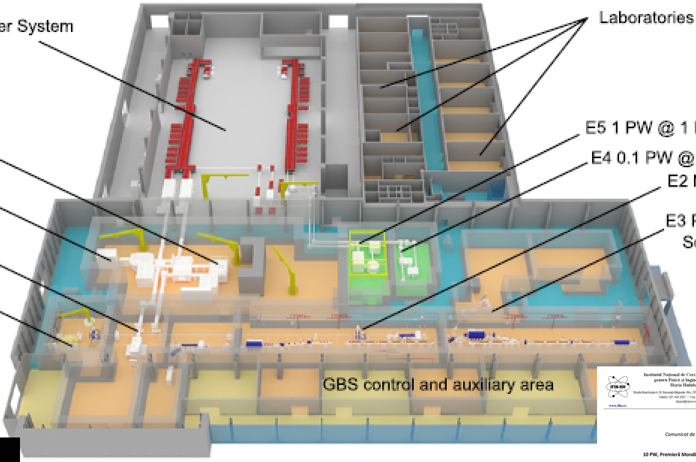
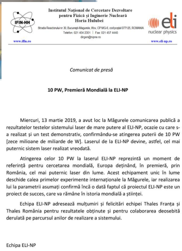


Fig. – The ELI facility



Institutul Național de Cercetare Dezvoltare pentru Fizică și Inginerie Nucleară Horia Hulubei

Strada Reactorului nr 30, București-Magurele, Ilfov, CP MG-6, cod poștal 077125, ROMANIA
Telefon: 021 404 2301 | Fax: 021 457 4440
drgen@nipne.ro

www.ifin.ro www.eli-np.ro

Comunicat de presă

10 PW, Premieră Mondială la ELI-NP

Miercuri, 13 martie 2019, a avut loc la Măgurele comunicarea publică a rezultatelor testelor sistemului laser de mare putere al ELI-NP, ocazie cu care s-a realizat și un test demonstrativ, confirmându-se atingerea puterii de 10 PW [zece milioane de miliarde de W]. Laserul de la ELI-NP devine, astfel, cel mai puternic sistem laser realizat vreodată.

Atingerea celor 10 PW la laserul ELI-NP reprezintă un moment de referință pentru cercetarea mondială, Europa deținând, în premieră, prin România, cel mai puternic laser din lume. Acest echipament unic în lume deschide calea primelor experimente internaționale la Măgurele, iar realizarea lui la parametrii asumați confirmă încă o dată faptul că proiectul ELI-NP este un proiect de succes, care va rămâne în istoria mondială a științei.

Echipa ELI-NP adresează mulțumiri și felicitări echipei Thales Franța și Thales România pentru rezultatele obținute și pentru colaborarea deosebită derulată pe parcursul anilor de realizare a sistemului.

Echipa ELI-NP

The 10 PW target station E1 & E6 at ELI-NP

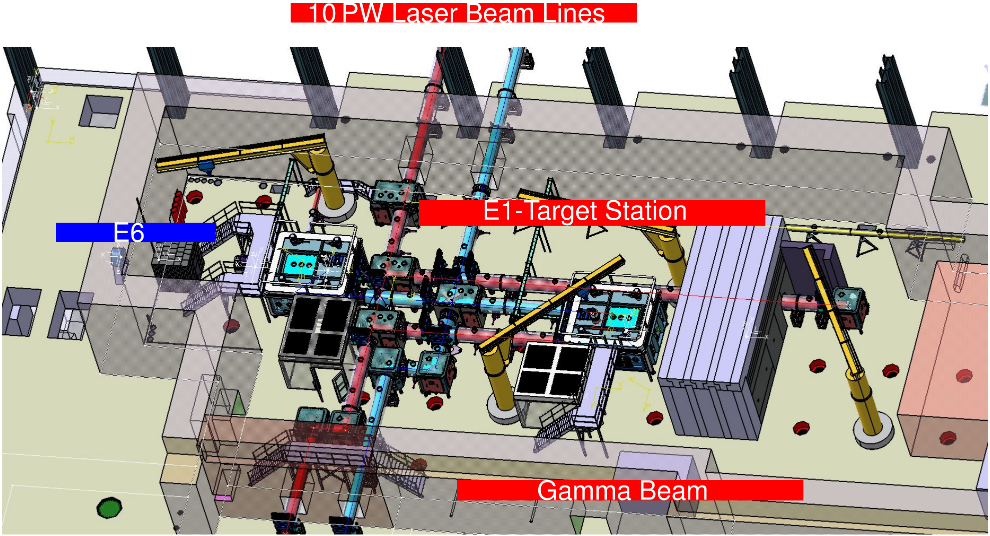


Fig. – Overview of E1 & E6

Commissioning nuclear experiments with solid targets

Commissioning nuclear experiments with solid targets

Core rationale

Harvesting nuclear/quantum electrodynamic (QED) effects emerging at the high fields ($\mathrm{E} \sim 10^{15}\,\mathrm{Vm}^{-1}$) provided by the high laser light intensities $I_\mathrm{L} \sim 10^{23}\,\mathrm{Wcm}^{-2}$ in laser-matter interaction with the 10 PW) :$\mathrm{E}_\mathrm{laser} \sim 250\,\mathrm{J}$, $t_\mathrm{pulse} \sim 25\,\mathrm{fs}$

- Efficient proton/ion acceleration $E_\mathrm{p}^\mathrm{max} > 200\,\mathrm{MeV}$ with high yield; Radiation Pressure Acceleration (RPA)?: (10^{13} (25 fs)).
- In the future: Macroscopic (!) ion-sheet acceleration (bulky bunches, Pancake-like beams) with quasi-solid density and with quasi-monoenergetic energies of 100's of MeV $\longrightarrow$ hitherto unachievable intensities of nuclear reaction products (kA-MA beam bursts). Changes in nuclear stopping (Bethe - Bloch formula)
- Ultra-intense $\gamma-$source Onset of QED 'Radiation Reaction'; large conversion efficiency for laser-to-γ ($E_\mathrm{Laser} \to E_\gamma$), predicted 20% to 50% for $I_\mathrm{L} > 10^{23}\,\mathrm{Wcm}^{-2}$
- Understanding the partitioning of the laser pulse energy E_Laser between ion and e^- acceleration & γ production to evaluate the quality and quantity of the laser-induced beams
  - Partitioning: $E_\mathrm{Laser} = f(I_\mathrm{L})$, hence t_pulse, $\varnothing_\mathrm{beam}$, $I_\mathrm{reflected}$, the target's thickness ℓ_T crucial
  - Influence of unavoidable prepulse! (Spontaneous Emission)
  - Emergence and influence of RPA is a strong function of ℓ_T

Inaugural nuclear physics experiments (solid targets)

Challenges

- High intensity - low momentum (Pancake-bursts, rather than beam), time-integrated intensity and yield more than 10^{-3} smaller than DC–RF systems
- Processes in the fs-regime, "faster than electronics" domain
- All optical detection using scintillators (Lanex Screens), optical fibres and cameras, "all-at once" measurements, no event-by-event base
- Reproducibility of conditions & Fail-safe operation of optics ((Two)Plasma Mirror(s))

Unique chances of the new technology

- Nuclear reactions with high temporal intensity and possible high efficiency & mixed beam acceleration
- Non-linear, intensity dependent effects
- Real plasma conditions, coupling of atomic, plasma and nuclear states
- Mixed beams by using mixed targets

Strategy

- Commissioning experiments: Fixed set-up, only variation E_{Laser} and ℓ_{T}
- Target wheel: 20 thin solid targets (Starform) and supported by plastic stocks to reduce Electromagnetic Pulse (Emp)
- Targets: Plastics down to $\sim 10\,\mathrm{nm}$, as well as Al and Fe $\sim 100\,\mathrm{nm} < \ell_{\mathrm{T}} < \text{few}\ \mu\mathrm{m}$. Mixed targets = Mixed beams!

TNSA *vs* RPA regime, thickness & projected energies

- Source for proton distribution at the TNSA and RPA interface with $E_p^{max} \sim 100\,\mathrm{MeV}$: Higginson *et al.*, Nature Communications **9**, 724 (2018)
  - $E = 210(40)\,\mathrm{J}$, $t_{pulse} = 0.9(1)\,\mathrm{ps}$, 30% on focal spot $I \sim 3(2) \times 10^{20}\,\mathrm{Wcm}^{-2}$
  - underpinned by EPOCH calculations
  - Optimal thickness for E_p^{max} and laser-to-proton energy efficiency (=12%) for $d_{target} \sim 100\,\mathrm{nm}$
- Onset and influence of RPA will be a strong function of I for short pulses $t_{pulse} \sim 40\,\mathrm{fs}$
- Onset of RIT for ultra-thin targets

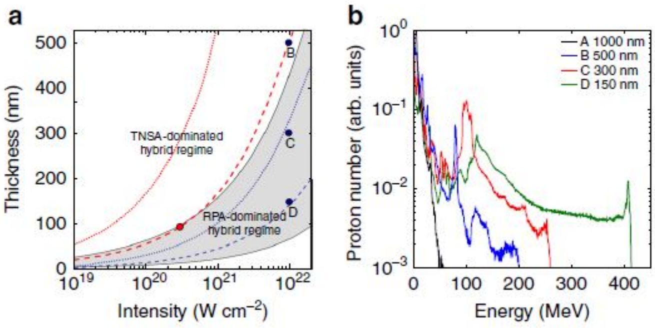


Fig. – a) TNSA/RPA regimes for 900 fs (red) 40 fs pulse (blue), dotted=maximum d_{target} for RIT onset, dashed=optimal d_{target} for plastic

E1 set-up for Commissioning experiments & core instrumentation

(K. A. Tanaka & K. M. Spohr *et al.*, Current status and highlights of the ELI-NP research program Matter and Radiation at Extremes **5**, 024402 (2020); https://doi.org/10.1063/1.5093535)

E1 set-up for Commissioning experiments & core instrumentation

HPLS: 10 PW and 1 PW for commissioning studies

Area	Motivation	Detectors	Parameters
E1	Nuclear physics experiments with *solid* targets, production of high fluxes of energetic ion beams (ideally monoenergetic) and neutrons, and intense X-ray flares	Thomson parabola, gamma spectrometer, e^--e^+ spectrometer, CsI(Tl) spectrometer, activation foils, image plates, radiochromic films, CR-39 resin, and optical plasma probe	$f/2.7$ $d^{f}_{90} \gtrsim 3.5\,\mu m$ $z_R \approx 15\ \mu m$ $a_0 \lesssim 220$
E6	QED and nuclear physics experiments with *gas* targets, production of GeV electrons at high intensity for radiation reaction studies	GeV e^- spectrometer and optical plasma probe	$f/54$ $d^{f}_{90} \gtrsim 60\,\mu m$ $z_R \approx 4$ mm $a_0 \lesssim 16$
E5	Applied experiments, medical research, production of MeV ions, and preliminary studies for 10 PW system using *gas* and *solid* targets	As for E1, but modified for E5 setup where necessary	$f_s/3.5$ and $f_\ell/24$[a] $d^{f}_{90,s} \gtrsim 5\,\mu m$ $z_{R,s} \approx 25\ \mu m$

E1 set-up for Commissioning experiments & core instrumentation

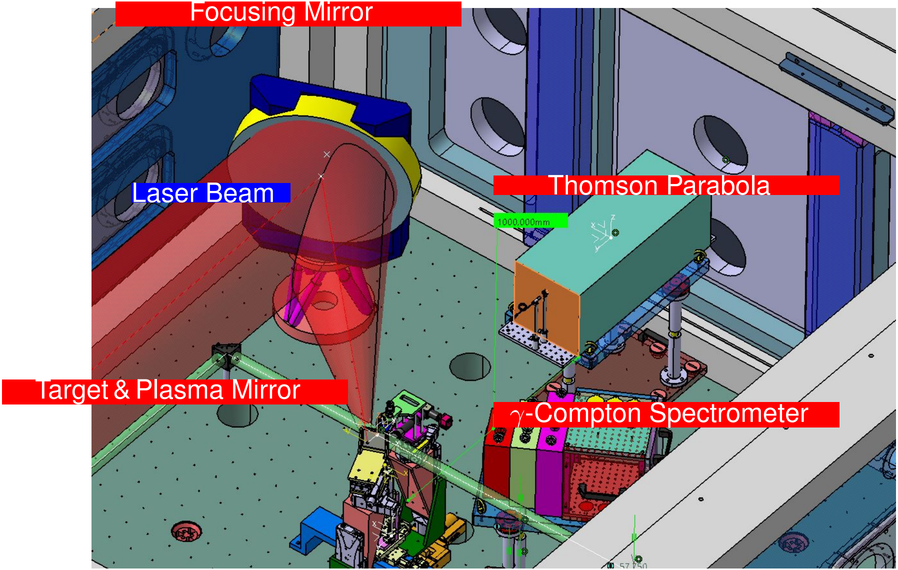
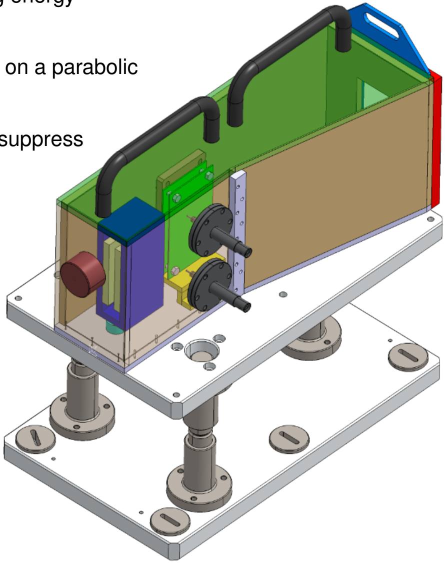


Fig. – Planned E1 set-up with Thomson Parabola or γ-Compton Spectrometer/Electron Spectrometer

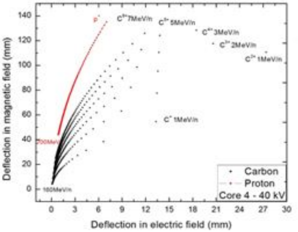
Thomson Parabola for $E_p > 200\,\mathrm{MeV}$

- Established, robust instrument for ion separation acc. to their charge-to-mass ratio & deriving energy distribution
- Static electromagnetic field forces ions on a parabolic curve
- Small entry pinhole ($\Omega = 0.2\,\mathrm{mrad}$) to suppress background
- Optical readout from Lanex

Design



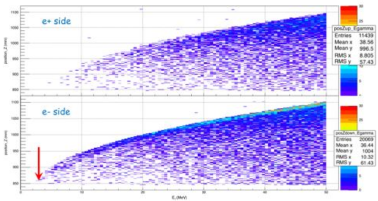
Ion Deflect.



Electron & Positron Spectrometer / $\gamma-$Compton

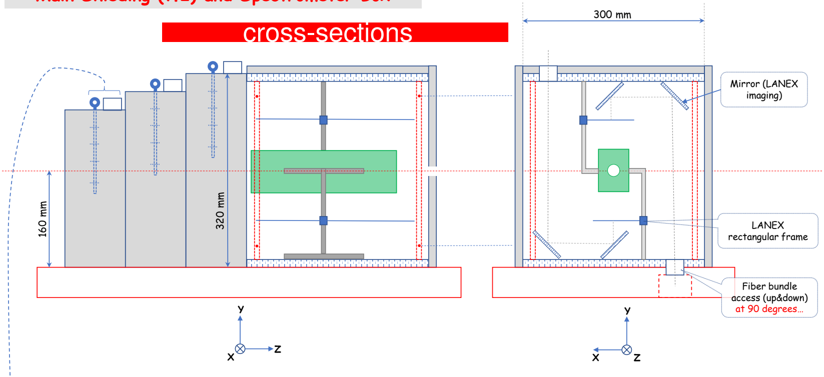
- Forward Compton Gamma Spectrometer' (FCGS) (5 MeV to 50 MeV) and the 'Electron-positron' pair spectrometer (5 MeV to 100 MeV with 10-15% resolution)
- A 2.5 cm Li-converter at FCGS which converts γ into electrons
- Magnets: 20 mm $\times$ 55 mm; B=0.55 T
- Optical readout from Lanex

Upper and Lower Lanex



Main Shieding (v.2) and Spectrometer Box

cross-sections

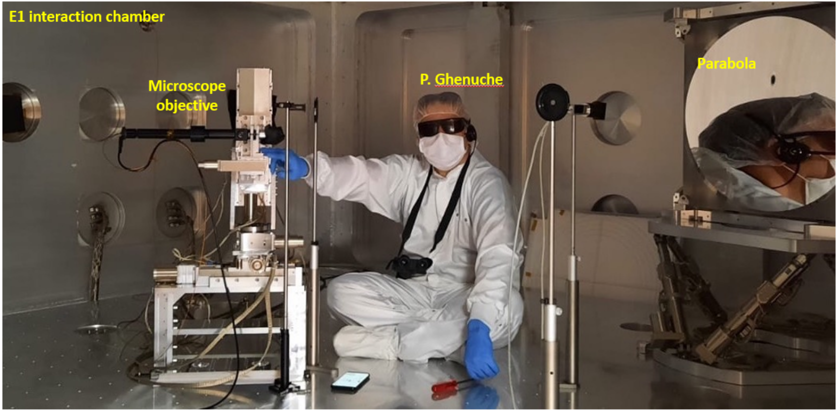


ELI-NP, Impressions of 10 PW HPLS commissioning at E1

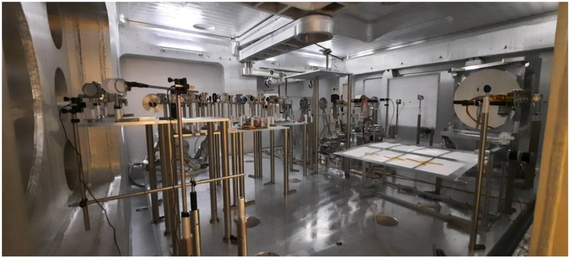
ELI-NP, Impressions of 10 PW HPLS commissioning at E1

10 PW E1 experimental area commissioning (from 26 Sept 2022)

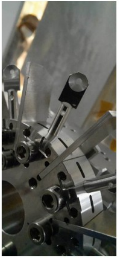
Laser beam alignment and focal spot check



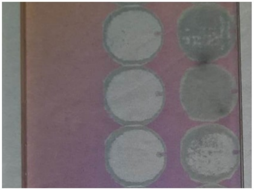
ELI-NP, Impressions of 10 PW HPLS commissioning. We did it! 13/04/2023



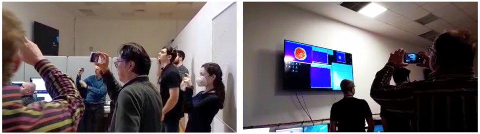
Interior of the interaction chamber. The picture shows clearly the several diagnostics and optics used to perform the experiment.



Target holder after the shot.



Damages left on plasma mirror by the interaction with the high-power laser beam.



Control room of the 10 PW experimental area: scientists are recording during the countdown of the first 10 PW shot coming soon on screen.

ELI-NP, raw spectra from the 10 PW HPLS commissioning

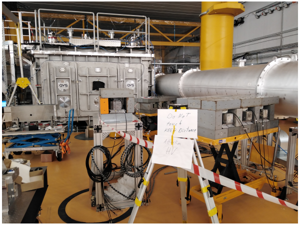


Fig. – Frontview of 10 PW setup at E1 with plastic detectors 13/04/2023

Fig. – Backview of 10 PW setup at E1 with plastic detectors 13/04/2023

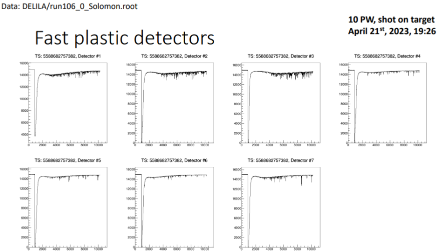


Fig. – Spectra of E232 plastic scintillators, $\gamma-$flash & neutron-bump? (analysis ongoing)

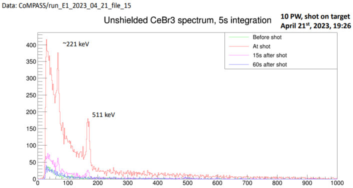


Fig. – Spectrum of $CeBr_3$, 511 keV very likely from $^{27}Al(\gamma, n)^{26,25}Al$

Planned experiments after commissioning in fundamental nuclear physics research

Fission fusion & neutron production experiments

Fission fusion & neutron production experiments

- An early concept, as seen in the ELI-Whitebook 2010
- Understanding the r-process by measuring the properties of heavynuclear around the $N = 126$ waiting point created by fission-fusion reactions and neutron capture reactions on heavy targets
- Merger of neutron star binaries is the main source for the heavier r-process branch
- Quenching of shells to explain abundance
- Currently, only very limited knowledge supporting campaigns at SPIRAL II and FAIR
- Needs additional mass separator & ion trap installed at huge costs

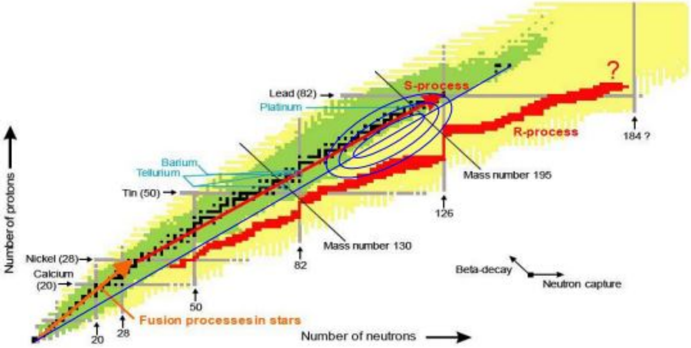


Fig. – Astrophysical nucleosynthesis: thermonuclear fusion (orange), s-process path (red vector) and the r-process generating heavy nuclei (red pathway)

Fission fusion & neutron production experiments

Negoita F. *et al.* Rom. Rep. Phys. **86**, S37-S144 (2016)

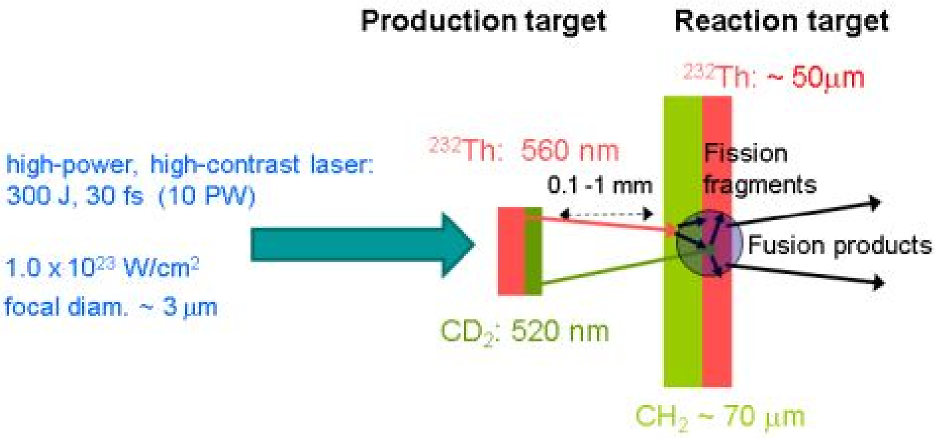


Fig. – Target arrangement for fission-fusion with ELI-NP using fissile ^{232}Th

Isomer depopulation of the 2.4 MeV isomer in ^{93}Mo

Nuclear Reaction in Plasma: Nuclear Excitation by Electron Capture in ^{93}Mo?

- Isomers such as $^{93}\mathrm{Mo}$ can store MeV energy per atom $\rightarrow$ highest human-made energy densities of GJ kg^{-1}
- Stored energy could be released by keV photon radiation (E_{trig}) in a controllable manner!, provided by plasma or directly by photons (small σ_{p}), so far ONLY few experiments in literature Belic *et al.* PRL 83 (**25**) 5242 (1999) on $^{180\mathrm{m}_2}\mathrm{Ta}$ and Chiara on $^{93\mathrm{m}}\mathrm{Mo}$ (Chiara *et al.*, Nature 554 216 (2018))
- Nuclear Excitation by Electron Capture (NEEC): A free electron is captured into an atomic vacancy and excites the nucleus to a higher-energy state:
  $E_{\mathrm{T}} = E_{\mathrm{I}} + E_{\mathrm{kin}}(e^{-}) + E_{\mathrm{b}}$
- Ideal candidate for *prima faci* studies of NEEC in laser-induced plasma: $^{93}\mathrm{Mo}$
  - $^{93\mathrm{m}}\mathrm{Mo}$ production: $^{93}\mathrm{Nb(p,n)}^{93\mathrm{m}}\mathrm{Mo}$ with $E_{\mathrm{p}} \sim 5 - 10\,\mathrm{MeV}$ ($E_{\mathrm{tr}} \sim 3.3$ MeV) and subsequent exposure to keV-plasma.
    - Only possible at a High Power Laser System (HPLS) such as ELI-NP
    - Trigger: $E_{\mathrm{trig}} \sim 5$ keV $\rightarrow$ 500 fold energy amplification!
  - High energy of 2.425 MeV, $\gamma-$decay sequence allows unambiguous identification
  - NEEC process with high probability claimed to be observed! Argonne National Lab (ANL) tandem accelerator with

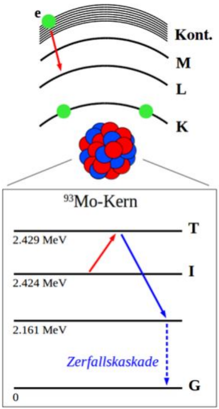


Fig. – NEEC-schematics for $^{93\mathrm{m}}\mathrm{Mo}$

ANL experiment: Depopulation of the 2.4 MeV isomer in ^{93}Mo

- Chiara and experienced team of the Argonne National Laboratory, using GAMMASPHERE with 92 Compton-suppressed high-purity germanium detectors, highest efficient $\gamma-$Spectrometer worldwide
- Using standard fusion evaporation experiment Chiara *et al.* (ibid), reaction $^{7}\mathrm{Li}(^{90}\mathrm{Zr},\,\mathrm{p},3\mathrm{n})^{93\mathrm{m}}\mathrm{Mo}$ @ $E(^{90}\mathrm{Zr}) = 840\,\mathrm{MeV}$ using the Argonne Tandem Linac Accelerator System
  - $^{93\mathrm{m}}\mathrm{Mo}$ is highly ionized and moves with $v/c \sim 5\%$
- $I(^{90}\mathrm{Zr}) \sim 6 \times 10^{8}$ ions s^{-1}, few weeks experiment
- Lithium target: complicated fabrication and careful handling

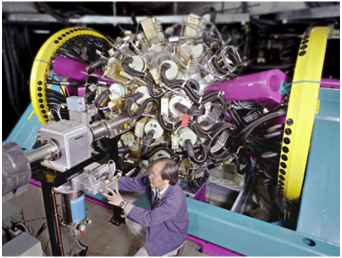


Fig. – GAMMASPHERE at ANL

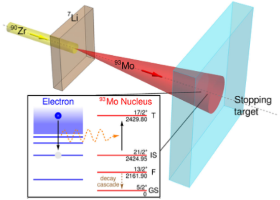


Fig. – Target Schematics in Chiara *et al.* (ibid) taken from Wu *et al.* PRL 122 **21** 212501 (2019)

Depopulation of the 2.4 MeV isomer in ^{93}Mo

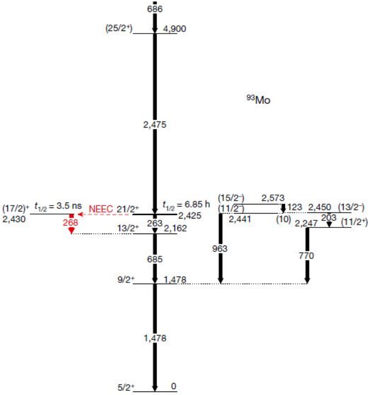
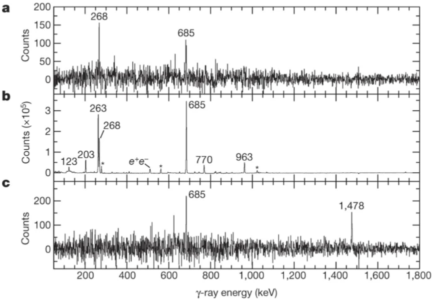


Fig. – ^{93}Mo Relevant lower level scheme



No correction for the Doppler effect has been applied. **a**, Spectrum obtained with a double gate on the Doppler-shifted 2,475-keV and unshifted 1,478-keV γ-rays. **b**, Spectrum obtained with a single gate on the unshifted 1,478-keV line. **c**, Spectrum obtained with a double gate on the Doppler-shifted 2,475-keV and unshifted 268-keV γ-rays. Peaks of ^{93}Mo shown in Fig. 1 are labelled with their energies in kiloelectronvolts. Additional known ^{93}Mo transitions, not shown in Fig. 1, are marked with asterisks in **b**. The label 'e^+e^-' indicates the 511-keV electron–positron annihilation peak. We note that transitions located above the isomer are too spread out in energy by the Doppler effect to be visible in these spectra.

Fig. – Coincidence Spectra

Depopulation of the 2.4 MeV isomer in ^{93}Mo

- Experimental evidence suggest 268 keV in 'decay path' **instead** of normal $^{93m}\mathrm{Mo}$ decay route including 263 keV attributed to NEEC.
- High NEEC probability claimed: $P_{\mathrm{NEEC}} = 0.010(3)$
- NEEC condition is attributed to the high rel. velocity $v/c \sim 5\%$ of the recoils fulfilling the NEEC requirement for the **bound** e^- in the $^{7}\mathrm{Li}$-target

but a controversy starts!

- NEEC explanation strongly disputed by Max Planck Institut für Kernphysik, (MPIK) Heidelberg, $P^{\mathrm{theo}}_{\mathrm{NEEC}} \sim 10^{-11}$. Wu *et al.* PRL 122 (**21**) 212501, (2019).
- (Even) Letter to Nature: Guo *et al.* *'Possible overestimation of isomer depletion due to contamination'* Nature (Matters Arising) 594 7861, E1-E2 (2021), citing Misinterpretation of prompt-Compton background
- Rzadkiewicz, J. *et al.* PRL **127** (4) 042501 (2021) & Gargiulo, S. *et al.* PRL **128** (21) 212502 (2022)

... and then the experimental tsunami

- Gou *et al.*, 'Isomer Depletion with an Isomer Beam', PRL 128 (**24**), 242502 (2022) (cited as Gou *et al.*)
  - $^{12}\mathrm{C}(^{86}\mathrm{Kr}, 5\mathrm{n})^{93m}\mathrm{Mo}$ with $E = 559$ MeV and transport isomer by secondary beamline to minimize background and associated artifacts.
  - NO isomer depletion consistent with $P_{\mathrm{NEEC}} = 0.010(3)$ detected, but consistent with very low $P^{theo}_{\mathrm{NEEC}}(\mathrm{MPIK})$

The NEEC controversy, NO confirmation of Chiara *et al.* by Gou *et al.*

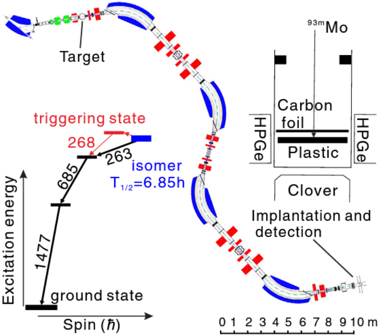


FIG. 1. Experimental setup in the present Letter. The secondary beam line RIBLL is shown with the corresponding distance scale. ^{93m}Mo residues were produced at the primary target position and transported to the end of RIBLL to study the isomer depletion. In the lower left area, the isomer depletion of ^{93}Mo is sketched together with the spontaneous decay of the long-lived isomer. The setup for implantation and detection is shown in the upper right area.

Fig. – Setup of ^{93}Mo investigation at Lanzhou, China

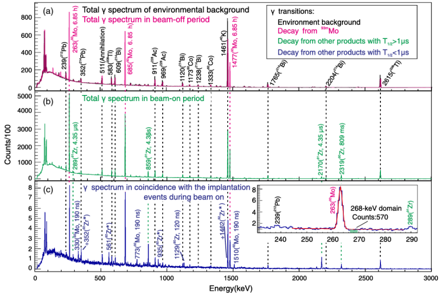


FIG. 2. Spectra acquired by germanium detectors in this measurement. (a) The γ spectra of decay events (in purple) and environmental background (in black). (b) The total γ spectrum recorded by the germanium detectors during the collection of products. (c) The γ spectrum in coincidence with implantation events. The detailed spectrum for the 263- and 268-keV transitions is shown in the inset and fitted by a combination of Gaussian and linear functions. The half-lives of the known isomers are marked for corresponding γ peaks, and the lines assigned to an unidentified isomer of ^{92}Zr are marked with asterisks. Two γ rays with nearly the same energy of 352 keV were identified to originate from ^{214}Pb and ^{92}Zr, respectively. The 352-keV line in (a) and (b) is attributed to ^{214}Pb, and in (c) this line has two components corresponding to ^{214}Pb and ^{92}Zr.

Fig. – γ-Spectra by Gou *et al.* (2022)

ELI-NP campaign, solving the ^{93}Mo conundrum

ELI-NP has provides the possibility to create $^{93m}\mathrm{Mo}$ *via* MeV proton beam bursts $^{93}\mathrm{Nb}(p,n)^{93m}\mathrm{Mo}$ and subsequent exposure to ns-long keV-plasma. A campaign has already started and will proceed with a beamtime at the 1 PW system at the CLPU in Salamanca Spain (Autumn 2023). As HPLS systems can provide keV-plasma in coincidence with the isotope production, there grant the unique opportunity to solve the current NEEC conundrum

- Three Tier systems (A,B,C) adopted for the investigation of ^{93m}Mo representing different experimental configurations
- Use of $^{45}\mathrm{Sc}(p,n)^{45}\mathrm{Ti}$as an isomeric reference ('spy') reaction to allow a deduction of the yield changes, indicating a potential depopulation in $^{93m}\mathrm{Mo}$, Yield ratio $R = Y(^{93m}\mathrm{Mo})/Y(\{^{45}\mathrm{Ti})$ measured for Tiers B & C
  - Tier-A
    - 6 hr of proton burst to produce $^{93m}\mathrm{Mo}$ (and $^{45}\mathrm{Ti}$), thin plastic target to maximize proton production.
  - Tier-B
    - 2 hr to 8 hr with laser-induced hard X-rays rays to test the depopulation of $^{93m}\mathrm{Mo}$ *via* the intermediate 4.85 keV state.
    - Bremsstrahlungs target: 4 mm thick Ta, long-term: X-ray production by multiple Compton-scattering and ReMPI Tomassini, P. (ibid)
  - Tier-C
    - 6 hr exposure to direct laser radiation to induce hot keVl plasma for NEEC.
    - Theoretical benchmark, Gunst, L. *et al.* PRL **112** 082501 (2014)

Schematics of the Three Tier systems adopted for ^{93m}Mo campaign

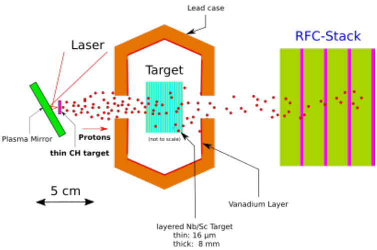


Fig. – Tier-A configuration for isomer production.

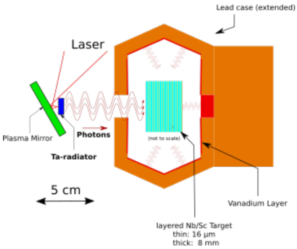


Fig. – Tier-B configuration for depopulation by X-rays. Hohlraum canvas in orange

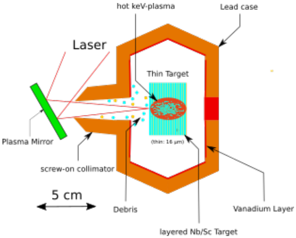
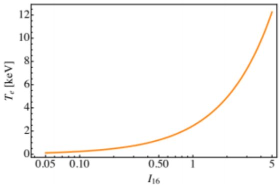


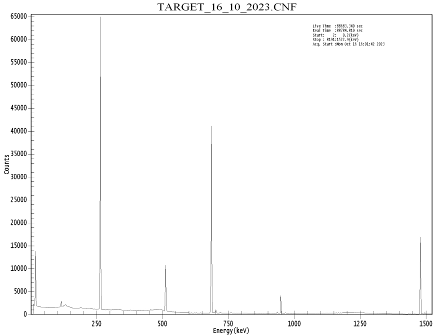
Fig. – Tier-C configuration, NEEC investigation by direct laser irradiation with $I \sim 1 \times 10^{16}\,\mathrm{Wcm}^{-2}$.

Plasma evaluation and first results of the CLPU ^{93m}Mo campaign



Wu, Y. private communication (2019)

- We can achieve keV plasma with the 1 PW and 10 PW system
- Plasma duration extends into ns



- ^{93}Mo successfully produced
- together with ^{45}Ti from 'spy' reaction (511 keV)

Cosmos in the laboratory, ^{26}Al in the Universe

Cosmos in the laboratory, $^{26}\mathrm{Al}$ in the Universe

- Cosmogenic $^{26}\mathrm{Al}$, $t_{1/2}(^{26}\mathrm{Al}_{\mathrm{g.s.}}) = 7.17 \times 10^5$ a, **most important isotope** in nuclear astrophysics (star formation, astrophysical clock).
- Production of $^{26}_{13}\mathrm{Al}_{\mathrm{g.s.}}$ $^{26\mathrm{m}}\mathrm{Al}$ isomer, $t_{1/2} = 6.35$ s with ~ 100 A-kA currents of laser accelerated protons with $E_{\mathrm{Thresh.}} \geq 4.97$ MeV:

$$^{26}_{12}\mathrm{Mg}\,(\mathrm{p},\mathrm{n}) \begin{cases} ^{26}_{13}\mathrm{Al}_{\mathrm{g.s.}} \xrightarrow{t_{1/2}=7.17\times 10^5\ \mathrm{a}} {}^{26}_{12}\mathrm{Mg} + \gamma_{(1809\ \mathrm{keV})} \\ ^{26\mathrm{m}}_{13}\mathrm{Al} \xrightarrow{t_{1/2}=6.35\ \mathrm{s}} {}^{26}_{12}\mathrm{Mg}_{\mathrm{g.s.}} \end{cases}$$

2^{nd} order forbidden β^+

superallowed β^+.

Mahoney, W. *et al.*, Astrophys. J., **286**, 578 (1984)

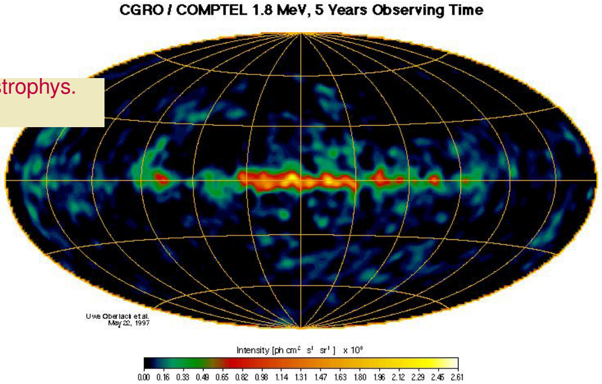
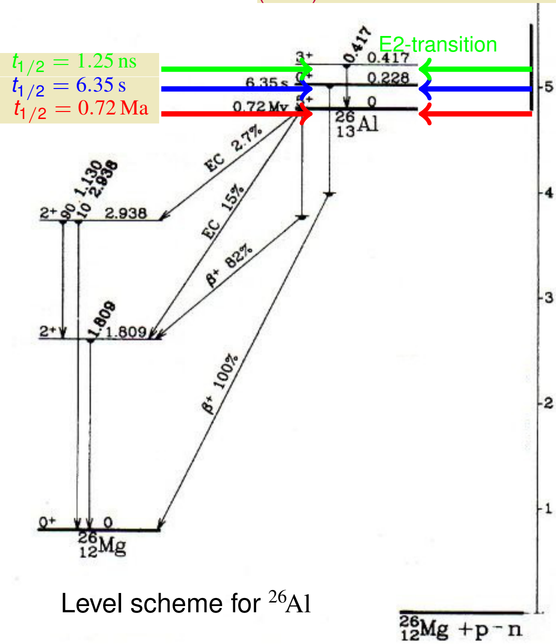


Fig. – $^{26}\mathrm{Al}$ in the Universe

Cosmos in the laboratory, production and decay of ^{26m}Al

Skelton, R. *et al.*, Phys. Rev. C**35** (1), 45 (1987)
Norman, E. *et al.*, Nucl. Phys. A**357**, 228 (1981)

$t_{1/2} = 1.25$ ns
$t_{1/2} = 6.35$ s
$t_{1/2} = 0.72$ Ma



Level scheme for ^{26}Al

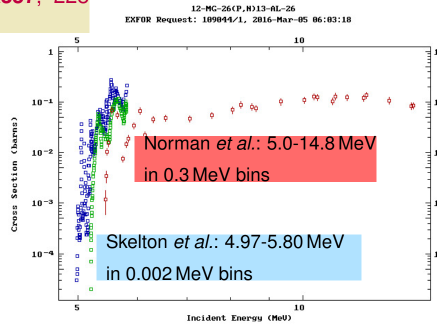


Fig. – cross-sections for ^{26}Al

σ^{int} for $4.97 \le E_{\text{p}} \le 5.80$ MeV

Cosmos in the laboratory, theory of ^{26}Al-decay in plasma

Gupta, S. & Meyer B., Phys. Rev. C**64** (2), 025805 (2001)
Coc, A. *et al.*, Phys. Rev. C**61**(1), 015801 (1999)

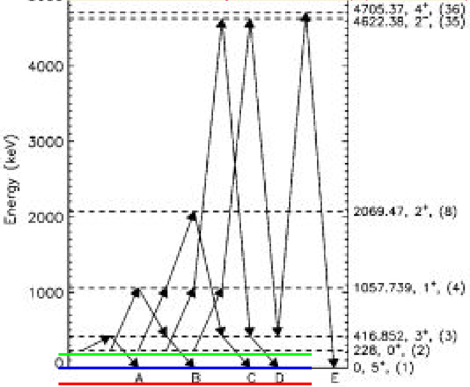


FIG. 2. The dominant pathways at (A) $T_9=0.2$, (B) $T_9=0.6$, (($T_9=1.3$, (D) $T_9=3.0$, and (E) $T_9=5.0$ in the internal equilibratic of ^{26}Al. At low temperatures, the dominant pathways must take sp jumps larger than unity. At higher temperatures, large energy trai sitions are possible. This allows strongly favored spin jumps (unity in the dominant pathway, thereby dramatically increasing tl effective equilibration rates. Levels are denoted by the format, e ergy in keV, spin parity, and (level number) on the right-hand side of the energy-level diagram.

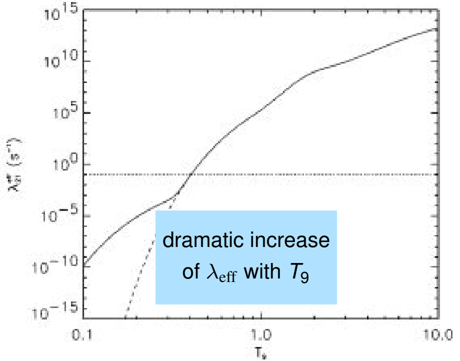


FIG. 1. The effective transition rate λ^{eff}_{21} for ^{26}Al as a function of temperature. The solid line gives the result of the full calculation. The dashed line gives the rate when the direct transitions between levels 2 and 3 are disabled. For reference, the dotted line gives the β^+-decay rate of the 0^+ metastable state. For $T_9 \lesssim 0.4$, the metastable state has no chance of equilibrating with the ground state before β decaying.

Fig. – Enhancement of $\lambda_{\rm eff}(^{26}{\rm Al}) = f(T_9)$

Fig. – Dominant pathways for ^{26}Al

Cosmos in the Laboratory, the isotope $^{26}\mathrm{Al}$

- VULCAN Petawatt system (PW), Rutherford Appleton Laboratory (Oxfordshire), $E_{\mathrm{pulse}^{max}} \sim 2.5\,\mathrm{kJ}$, $I \sim 10^{21}\,\mathrm{Wcm}^{-2}$,$\lambda = 1054\,\mathrm{nm}$, ≤ 15 pulses/day.
- Two beams available: Proton production & X-ray pulse, adjustable time delay between beams -1 ns to 4 ns.

Advantages

- Protons not mono-energetic, Maxwellian distribution, with $\mathrm{k}T \sim 1 - 3\,\mathrm{MeV}$.
- Fluctuation between pulses, reproducibility!
- Electromagnetic Pulse (EMP) saturates standard detectors. Difficulty to measure any prompt particle or gamma radiation.
- Stability of targets which are more complex as those in low intensity experiments.
- Multi-A to kA of protons, in ~ 100 ps-time scales $\rightarrow$ highest man-made intensities & plasma generation!
- Short duration of reaction driving pulse leads to a manifold of new fundamental and applied possibilities.
- Coinciding X-ray pulse, $E \sim 100\,\mathrm{J}$, ~ 10 ps duration with $\mathrm{k}T \sim 3 - 6\,\mathrm{MeV}$, resulting in hotter & denser plasma.

Fig. – Compressor & Target-Chamber

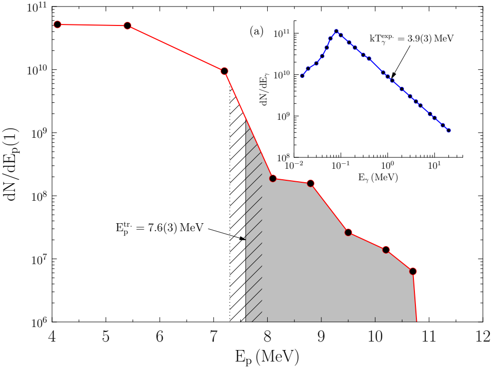
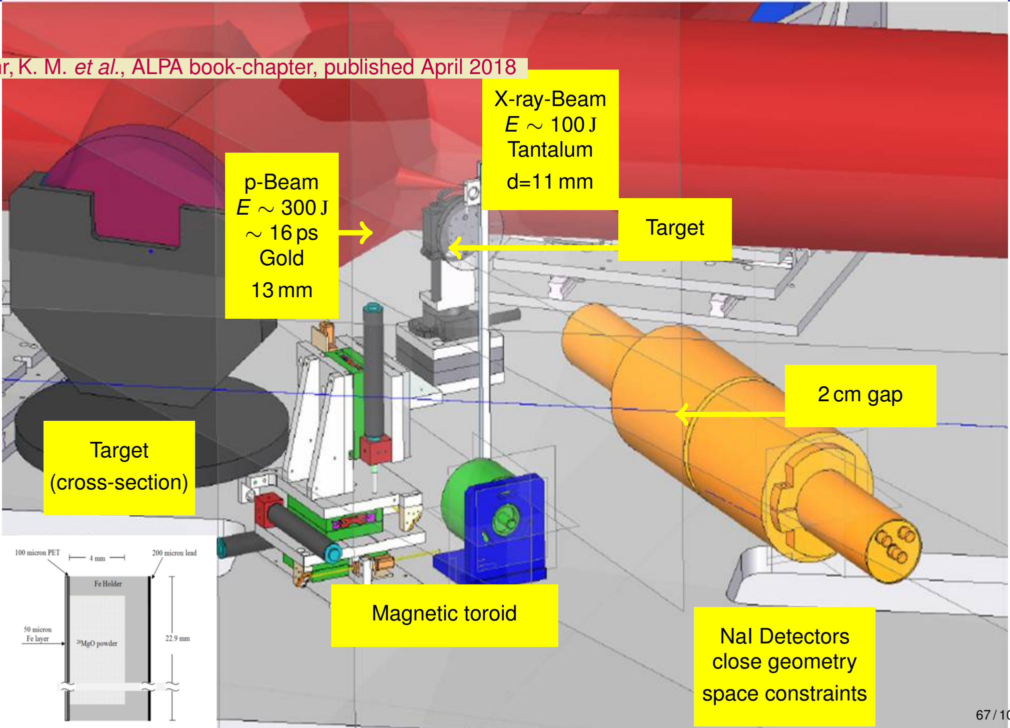


Fig. – VULCAN proton and X-ray (inlet) spectra

Cosmos in the laboratory, RAL-experimental set-up

ohr, K. M. *et al.*, ALPA book-chapter, published April 2018



Cosmos in the laboratory, identification $^{26m}\mathrm{Al}$

- Per 300 J proton pulse on Au primary production target, $A \sim 300 - 500\,\mathrm{kBq}$ of $^{26m}\mathrm{Al}$, thick target $d_{\mathrm{thick}} = 1\,\mathrm{mg}\cdot\mathrm{cm}^{-2}$, $N_{\mathrm{p}} \sim 10^{10-11}$.
  - Full confirmation of VULCAN results & identification of the prompt 417 keV transition with a dedicated Tandem-ALTO experiment at the IPN-Orsay.
- With coinciding X-ray pulse ($E \sim 100$ J) $\longrightarrow$ substantial enhancement of $^{26m}\mathrm{Al}$ yield Y_{228}.
  - Labaune C. *et al.*, Nat. Commun. **4**, 2506 (2013) $^{11}\mathrm{B}(\mathrm{p},\alpha)^{8}\mathrm{Be} + 8.59\,\mathrm{MeV}$.

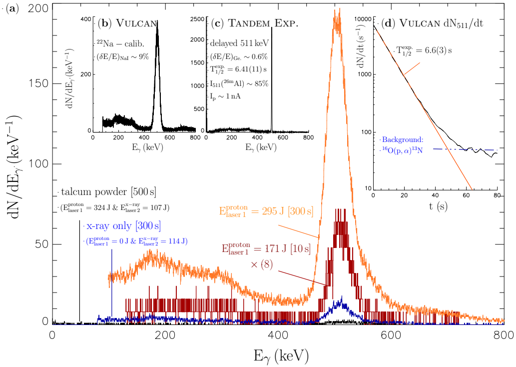


Fig. – Delayed activity at VULCAN

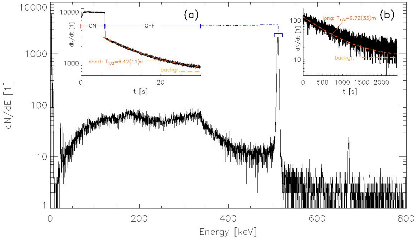


Fig. – Delayed activity at ALTO

Cosmos in the laboratory, HPLS mimics GK conditions

- Snapshot of yield distributions of the excited states as they emerge from the nuclear compound reaction in a hot, internal state.
- These high internal temperatures reflected in the yield distributions states mimic astrophysical conditions
  - The nuclei are HOT (for fs-ps time span, defined by $t_{1/2}$ of the nuclear state which define the cooling down period. Normally $t_{1/2 \sim \mathrm{fs-ps}}$, only a few isomers with $t_{1/2} > \mathrm{ns}$.
  - The surrounding is NOT, so no real plasma as such! BUT:
  - The temperature of the nuclear states is relevant, as *e.g.* the influence of electron temperature in the surrounding is of minor influence for the nuclear temperature
- Due to the shortness of the driving laser pulse, shortness of ion bunch
- High yield for reaction products driven by a very short pulse, defining sharply t_0 of the reaction onset $\delta t_0 \sim \mathrm{few}$ ps
  - RF technology, μs as best
- Subsequent exposure of the isotopes to hard X-ray radiation possible by second beam

Cosmos in the laboratory, HPLS, mimics GK conditions

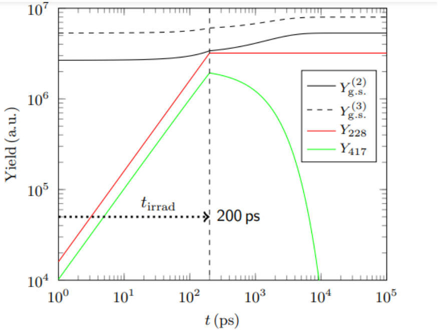


Figure 2. Calculated yields Y_{228} (red) and Y_{417} (green) as function of time t per proton pulse with $t_{irrad} = 200$ ps (vertical dashed line) and $4.988\,\text{MeV} \leq E_p \leq 5.820\,\text{MeV}$. The accumulated yields $Y_{g.s.}$ for the ground state are superimposed for the 2nd (solid black) and 3rd (dashed black) consecutive proton pulses. We assume those pulses to impact on the same target volume in the secondary production target. Note the influence of the direct feeding from the 417 keV level to the ground state from the non-linear enhancement of $Y_{g.s.}$ during t_{irrad}. A time interval of 100 s between the 2nd and 3rd pulse was assumed.

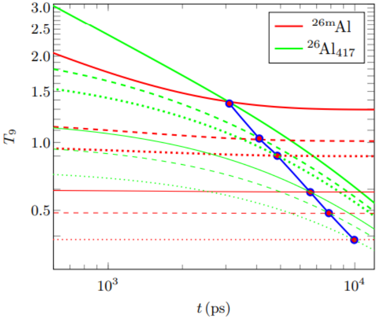


Figure 3. Calculated T equivalents for $Y_{228}/Y_{g.s.}$ (red lines) and $Y_{417}/Y_{g.s.}$ (green) from yield distributions according to Maxwell-Boltzmann distribution, for consecutive pulse numbers 1 (solid thick), 2 (dashed thick), 3 (dotted thick), 5 (solid thin), 25 (dashed thin) and 100 (dotted thin). The protons are considered to irradiate the same volume in the secondary target. The times t_{equi} for each pulse at which the two yield ratios converge to resemble one temperature value T, are indicated by the blue & red circles which are connected with a blue line to guide the eye.

Spohr, K M. *et al.*, Galaxies **7**, 4 (2019)

Neutron skin of ^{208}Pb with the $\gamma-$Beam at ELI-NP

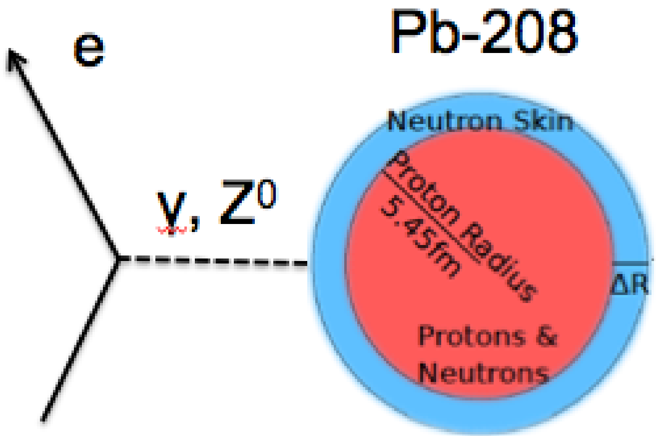


Fig. – ^{208}Pb, a nuclear 'orange', mini neutron star

Neutron skin of ^{208}Pb with the $\gamma-$Beam at ELI-NP

- Initiated by discussions with W. Nazarewicz, MSU & Chief Scientist at FRIB, formerly Scientific Director of the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory & Visiting Professor at UWS & Glasgow Uni.
- Neutron-rich ^{208}Pb has the highest N/Z ratio of any known stable isotope at 1.537. Neutrons hence form a skin around its core. Its thickness r_{skin} is of uppermost importance for theory,

$$r_{\text{skin}} = r_{\text{n}}^{\text{rms}} - r_{\text{p}}^{\text{rms}} ,$$

  with $r_{\text{p}}^{\text{rms}} = 5.45\,\text{fm}$ being rather well known.
- Neutron skin of ^{208}Pb is purest form of neutron “only” matter in Earth-bound laboratories.
  - Dedicated “Lead Radius Experiment” (PREX) at Jefferson Lab, USA.
- Precision measurement of neutron skin thickness allows to deduct the neutron Equation of State (EOS) and to benchmark most modern theories in the framework of the UNEDF theory.
  - UNEDF (Universal Nuclear Energy Density Functional), collaborative theoretical effort to use state-of-the-art energy density functionals to establish, with error estimates(!), the combinations of protons and neutrons which can form nuclei.

VEGA system at ELI-NP, operational 2026

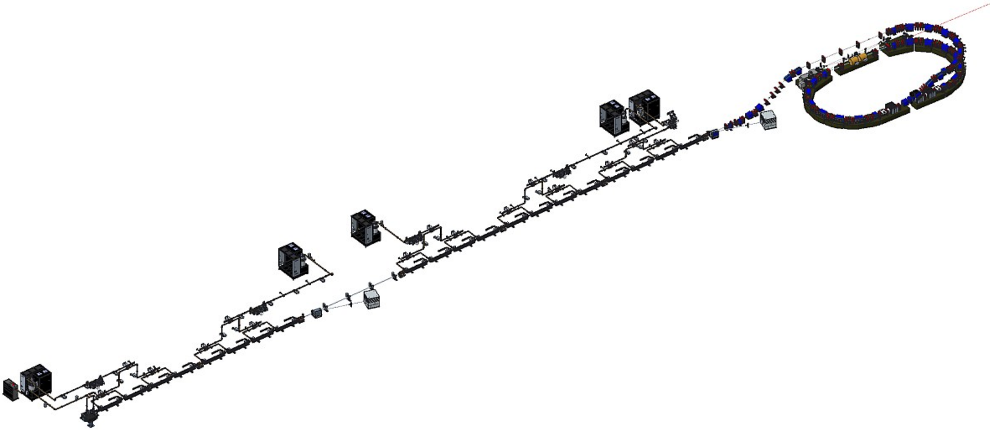


Fig. – VEGA $\gamma-$beam facility at ELI-NP

Neutron skin of ^{208}Pb & neutron EOS

Reinhard, P. & Nazarewicz W., Phys. Rev. C**81**, 051303(R) (2010)

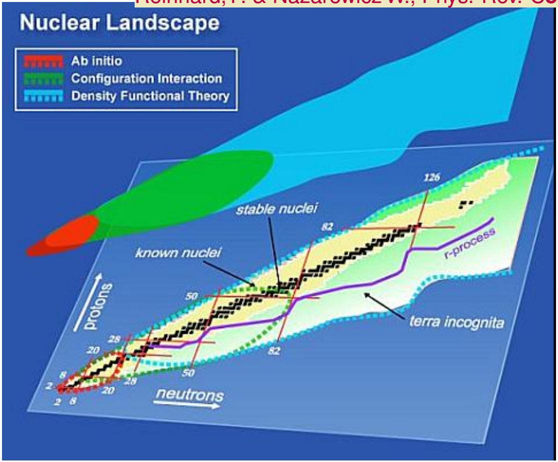


Fig. – UNEDF & Nuclear Landscape

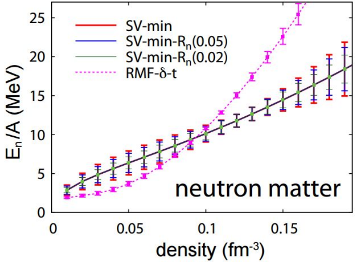


FIG. 3: (Color online) Extrapolation errors for the neutron matter EOS predicted by EDF SV-min (obtained by a fit to the standard pool of data) and SV-min-R_n (obtained by adding to the data set the neutron radius in ^{208}Pb with an adopted error of 0.02 fm and 0.05 fm. The neutron EOS predicted by RMF-δ-t is also shown for comparison).

Fig. – Neutron EOS

from: http://www.unedf.org

Neutron skin of ^{208}Pb & dipole polarizability

Reinhard, P. & Nazarewicz W., Phys. Rev. C**81**, 051303(R) (2010)

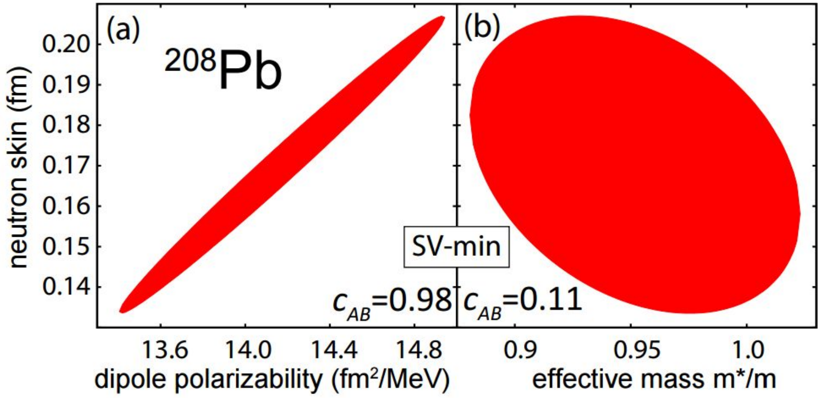


Fig. – Correlation α_D & r_{skin}

Measurement of $r_{\rm skin}(^{208}\rm Pb)$ with the $\gamma-$beam at ELI-NP

- With the $\gamma-$beam at ELI-NP $\alpha_{\rm D}$ could be precisely measured with photoabsorption. $E_\gamma^{\max} \leq 19.5\,\rm MeV$ is just about right.
- UNEDF will improve substantially if $\Delta r_{\rm skin}/r_{\rm skin} \leq 0.5\% \to \Delta r_{\rm skin} \sim 0.001\,\rm fm$!

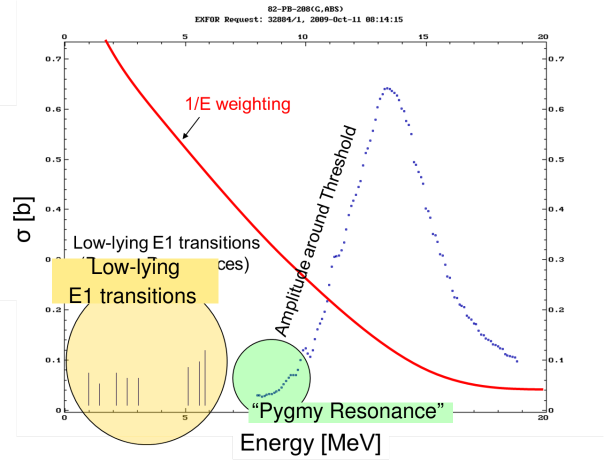


Fig. – Photoabsorption cross-section for $^{208}\rm Pb$

The neutron skin of ^{208}Pb with the $\gamma-$beam at ELI-NP

- Measurement of $\alpha_{\rm D}$ with ELI-NP could supplement and potentially even succumb *e.g.* PREX measurements.
  - With the projected γ-beam features at ELI-NP $\longrightarrow$ smallest value for $\Delta r_{\rm skin}$.
  - Minimisation of $\Delta r_{\rm skin}$ is as essential as value for $r_{\rm skin}$ itself.
- Currently value via Coloumb excitation measurements induced by proton scattering:

$$\alpha_{\rm D} = 20.1(6)\,{\rm fm}^3$$

  from which the authors derived a value of,

$$r_{\rm skin} = 0.165 \pm (0.009)_{\rm exp} \pm (0.013)_{\rm the} \pm (0.021)_{\rm est}\,{\rm fm}\,.$$

  This equates to a high uncertainty of $\sim 26\%$ in the worst case scenario. Moreover, the biggest contribution to the uncertainty comes from a model dependent estimation of the symmetry energy at saturation density, Tamii, A. *et al.*, Eur. Phys. J. A**50**, 28 (2014).
- In addition: Measurement will allow to address newest theoretical work by Reinhard, P. & Nazarewicz W., Phys. Rev. C**87**, 014324 (2013) which questions the interpretation of low-energy dipole excitations to be interpreted as collective "Pygmy" resonances, but should be understood in the frame of rapidly varying particle-hole excitations.
- BUT PREX: $R_mathrmn - R_mathrmp = R = 0.283(71)$ Adhikari, D. et al. PRL, 126, 17, 172502 2021

Planned programmes in applied nuclear physics research

Gerard Mourou's Vision for HPLS research

On the (far) future of research with HPLS systems:

https://international.andra.fr/transmutation-radioactive-waste-high-power-laser-challenge-gerard-mourou

"By further increasing the pulse power of the laser via the CPA technique, Gérard Mourou sees other applications such as the cleaning of space debris, but especially the ***transmutation of radioactive elements*** *contained in some of the most radioactive and long-lived waste. Already studied in France since the 1991 law (Bataille law) and in international projects such as Myrrha (see box), transmutation aims at transforming long-lived radioactive elements into radioactive elements with shorter lives. "The method remains almost identical, what changes with the laser is the starting point: the impulse that will generate a stream of protons and then trigger the chain reaction with sufficient energy"*

https://news.engin.umich.edu/2019/03/nobel-laureate-and-laser-pioneer-discusses-the-past-and-future-of-extreme-light

"Lasers of tomorrow might neutralize nuclear waste, clean up space junk and ***advance proton therapy*** *to treat cancer, says Gerard Mourou."*

Nuclear Transmutation

Nuclear Transmutation, general comments: Nuclear Power & Waste: World/EU/Rom.

- World: $\sim$ 450 power stations in 31 countries, 2.6 PW
  - 300 000 tons of spent fuels (1960-2010)
  - 70 000 tons of spent fuel est. (2010-2030)
  - $<$ 100.000 tons is being reprocessed at 5000 tons per year
- Europe: 'Green Deal', EU, climate-neutral by 2050, €100 m
  - Europe (excl. Russia), $\sim 2.5 \times 10^6\,m^3$, ~20% awaiting disposal
  - 25 tons plutonium and high-level wastes (HLW)
  - $\sim$ 3.5 tons of minor actinides (Am, Cu, Np) & $\sim$ 3 tons of long-lived fission products (*e.g* ^{119}I)
- Romania: 2007 2 plants at Cernavoda, 20.6% of the total electricity
  - Plans for 2 CANDU-type reactors, Soc. Nat. Nuclearelectrica SNN & Chinese Group
  - Production of necessary nuclear fuel within its own borders

Strategy for Waste Management

Partitioning and transmutation to reduce of the minor actinides and other long-lived fission products.

Transmutation

- Effective reactor and fuel cycle strategies, Fast Reactors (FRs) & Accelerator-Driven Systems (ADS)

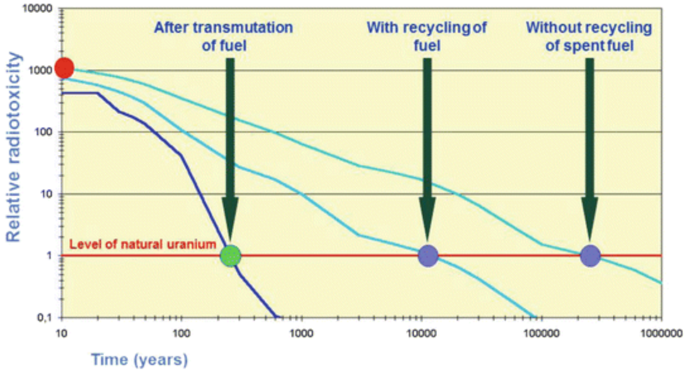


Fig. – Relativie radiotoxicity over time normalized to natural uranium ore

Accelerator-Driven System (ADS) as Transmutator

- MYRRHA (Multi-purpose Hybrid Research Reactor for High-tech Applications) by 2036, €1.6 b, efficient for actinide burning
  - Sub-critical $k = 0.95$ fast reactor, eutectic Pb/Bi coolant ($T_{\mathrm{m}} = 130\,^\circ\mathrm{C}$), feasible & economical
  - LINAC DC-accelerator, $\ell \sim 100\,\mathrm{m}$, $E_{\mathrm{p}} = 600\,\mathrm{MeV}$, $I_{\mathrm{p}} = 4\,\mathrm{MA}$

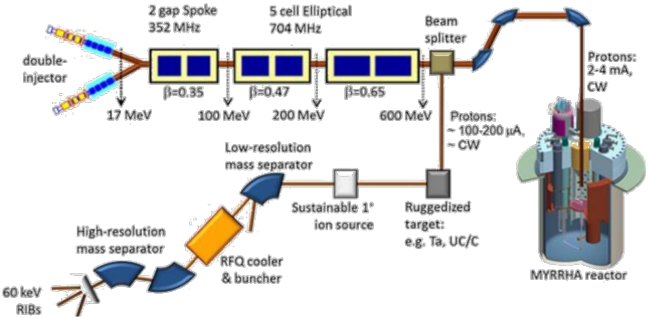


Fig. – MYRRHA with Accelerator

A pathway for a laser-driven transmutator in the far far future

The core strategy for laser-driven transmutation research at ELI-NP

With the ADS concept most advanced, transmutation research at HPLS-sites only become in reach if high rep rate syustems with $E_{\mathrm{p}} \sim 1\,\mathrm{GeV}$ and even higher, eventually deliverable with high average currents, $I_{\mathrm{p}} = \mathrm{mA}$ *via* a dedicated novel laser system based on Radiation Pressure Dominant Acceleration (RPDA), and Single Cycle Laser Acceleration (SCLA).

- Fast protons induce fast MeV neutrons via spallation on a heavy target, *e.g.* Pb/Bi
- Fast neutrons induce further transmutation of actinides (MYRRHA (Belgium) *modus operandi*
- 'Replace' LINAC at ADS (MYRRHA)

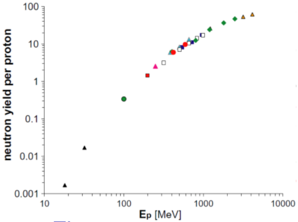


Fig. – $n_{/} n_{\mathrm{p}} = f(E_{\mathrm{p}})$

- **Macroscopic bulk acceleration** with $E_p \sim 1$ GeV
- **'Burning' of Long-Lived Fission Products LLFP with γ radiation** $E_0 \approx E_i + E_\gamma$, with $E_\gamma \sim 30\%$ hence parasitic, *e.g* $^{129}\mathrm{I}$
- **Slow neutron induced fission** a few radiotoxic actinides such as $^{239}\mathrm{Pu}$ have $\sigma(n_t, F) \sim$ few 100's of barn
- BUT: Laser not even: $I_p \sim 1$ nA 1×10^{-6} less than LINAC I_p

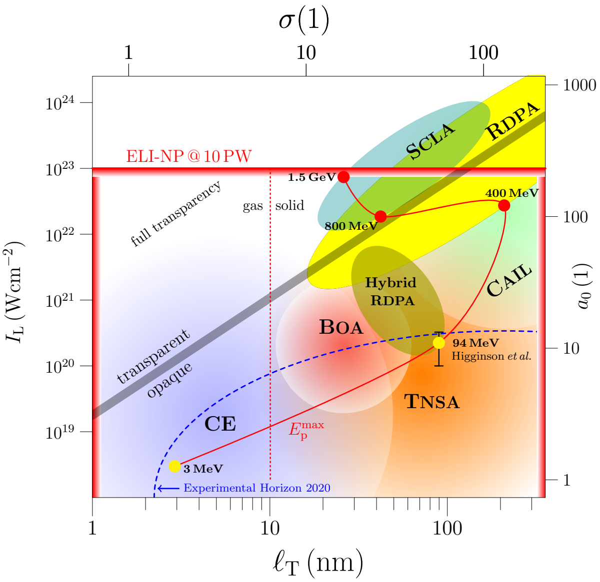


Fig. – Acceleration Regimes in ℓ_T and I_0 plane.

Laser-driven neutron source: E_p; neutron yield, n_N and fission yield

- **Laser proton acceleration** at E5 & E1 at 10 PW $E_\mathrm{p} \sim 200\,\mathrm{MeV}$ (2021)
- **First Demonstrator (FD):** Thin plastic production target, Pb/Bi for neutron production, U-target for fission yield, activation measurements of fission products offline, use of n-moderator $\sigma(\mathrm{n_t}, \mathrm{F})$
- **Online NRF measurements** at E7 by 2023 (unique at ELI-NP)
- **Transmutation by γ flash radiation** hence parasitic, *e.g* $^{129}\mathrm{I}$.

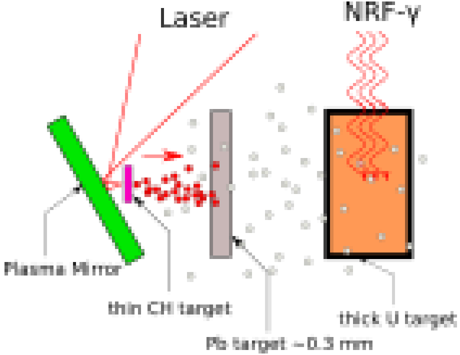


Fig. – Sketch of First Demonstrator

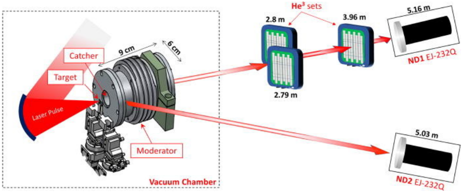


Fig. – Sketch of compact n-moderator, Mirfayzi *et al.* Appl. Phys. Let. *116* (17). 174102 (2020)

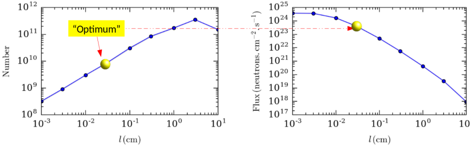


Fig. – Optimum Pb-thickness for n-yield

Optimizing Laser-Driven neutron production based on Thin Film Compression (TFC)

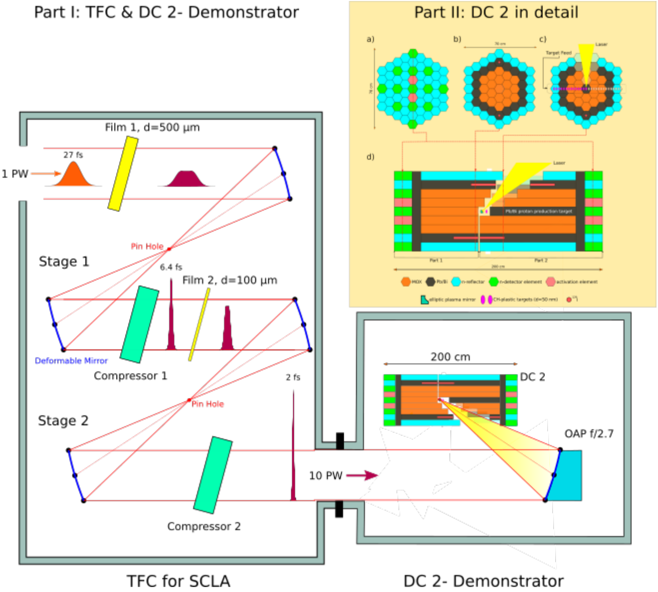


Fig. – TFC principle (Part I) & Front and side cut of DC 2 (Part II), Big success: Gabriel Bleoutu, 3 fold compression down to 8at ELI-NP, PhD-thesis 2024!!!!!

A dedicated LDT laser system, employing TFC

- TFC technique allows 10-fold power (1 PW to 10 PW to 100 PW)
- Spatial and temporal very confined beam, produced within the spent fuel core (only 10% of Ω_{tot} needed)
- No beam-steering by large magnets of a LINAC
- RDPA and SCLA can be reached, $E_{\mathrm{p}} = 1.5\,\mathrm{GeV}$, effective target thickness 60 cm in Pb/Bi.
- Critical volumes $k > 1$ around laser proton impact (to be investigated, TRIGA-like)
- Phase space confinement & $E_{\mathrm{p}} = 1.5\,\mathrm{GeV}$ allow to 'catch up' by a factor of 10 $\Rightarrow$ Laser $I_{\mathrm{p}}^{\mathrm{Las}} / I_{\mathrm{p}}^{\mathrm{Lin}} \sim 10^{-5}$
- Advances in glass-fiber technology, high-rep rate EW-class lasers

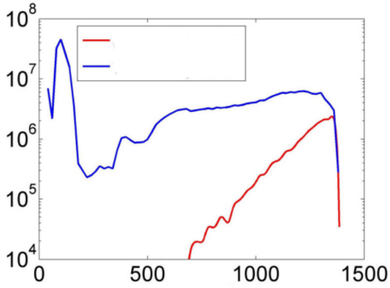


Fig. – Energy distribution of SCLA with 50 μm Ch-target

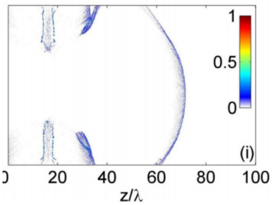
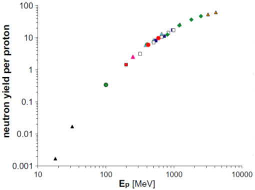
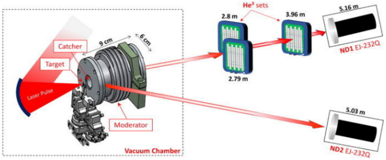


Fig. – Spatial distribution of protons, after 160 fs, Zhou *et al.* 2016

ELI-NP: Laser-driven neutron source (LDNS)

- Development of a high-intensity short-pulsed laser-driven neutron source
- Low-energy nuclear reaction on $^{7}\mathrm{Li}$, pitcher-catcher or proton-induced fission of heavy metal target (*e.g.* Pb)
- Photonuclear (γ,n) reaction, (QED-effects based
- Fast neutrons, but also cold feasible using ultra-compact, moderator in the few cm-length, pulse duration $\sim$ µs
- Programs using LDNS at ELI-NP
- Spatially and temporal confined neutron-source with $t_{\mathrm{pulse}}^{\mathrm{fast}} \sim$ 1 ns, $t_{\mathrm{pulse}}^{\mathrm{slow}} \sim$ 10 µs, and $\varnothing \sim$ 100 µm
- Radiography by a bright source of laser-driven thermal neutrons and X-rays Yogo A. *et al.* 2021 Appl. Phys. Express **14** 106001 (2021)
- Epithermal and thermal neutrons *via* compact moderators for *e.g.* immunotherapy supported BNCT (3 patents (K. Spohr)





R. Mirfayzi *et al.*, APL,**111**, 4, 044101 (2017)

Laser-driven hadrontherapy

Laser-driven hadrontherapy

Although in its infancy there are projects have been envisaged to evaluate the use a HPLS system as driver of oncology treatments in the next decade. In the very moment conceptual studies for particle radiation based methods are envisaged. The research aligns perfectly with the quest to achieve proton acceleration to $E_p \sim 200\,\text{MeV}$

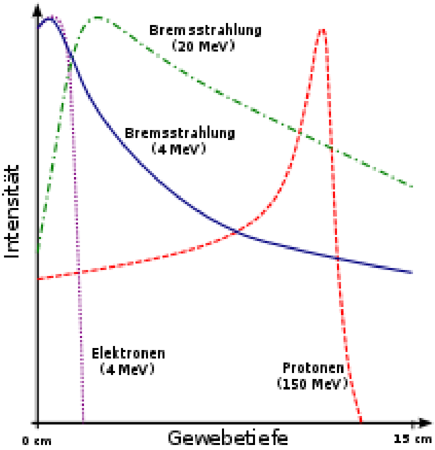


Fig. – Ionization-range for radiation types

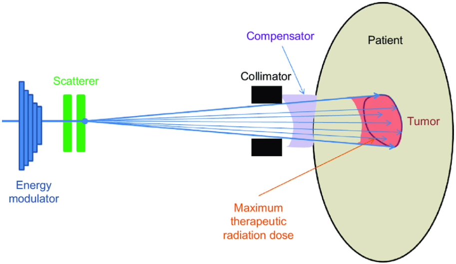


Fig. – Schematics of tumor scanning

Laser-driven radiology with hadrons

- Bragg peak allows focused delivery of radioactive dose inside a body
- Impact on surrounding healthy tissue minimized
- To reach inside the full depth of a human body to combat deep-sited tumors one needs $E_{\mathrm{p}} \sim 200\,\mathrm{MeV}$ (Eye-cancer: 70 MeV)
- Currently turn-key solutions available: Mini-cyclotrons, delivering protons
- Hadrontherapy with heavier ions such as *e.g.* $^{12}\mathrm{C}$ has more defined Bragg-Peak, hence better scanning of cancer possible

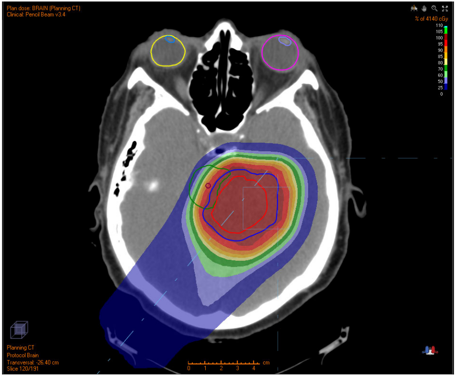


Fig. – Ion-beam treatment

Fig. – Turn-key proton cyclotron (€20m)

Laser-driven hadrontherapy: Cons & Pros

– Laser-driven proton therapy so far limited to $E_{\mathrm{p}} < 100\,\mathrm{MeV}$
– Currently, HPLS systems deliver bad quality, non-mono-energetic particle beams with a low integrated intensity
– Beam pulses fluctuate from shot-to-shot in intensity and energy profile
– In-beam laser-driven patient treatment is probably decades away
– Critical perception in the established oncology community
+ Laser-driven systems have potential to be extremely minimized, esp. the need for shielding
+ Ion-source potentially very small in dimension, hence delivery of ion-pulse will not need a massive gantry which is especially necessary for heavier ions such as $^{12}\mathrm{C}$ that have better treatment characteristics.
+ Ultra-high radiation dose per shot, which is likely to enhance cancer cell mortality
+ Possibility of delivering a cocktail of different ions in one treatment which may enhance cancer cell mortality

Radiology with hadrons, RF-technology at its finest and heaviest

- The Heidelberg Ion Therapy Center 750 m
- Treats 1000 patients per year
- EU-27: 1.2 m cancer casualties per year!

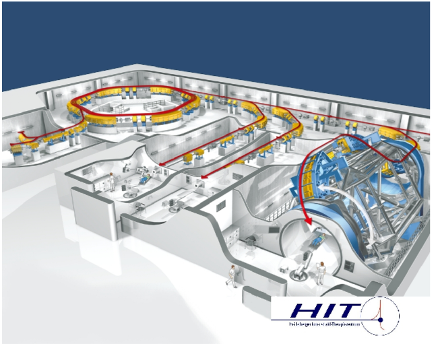


Fig. – The Heidelberg Ion Therapy Center

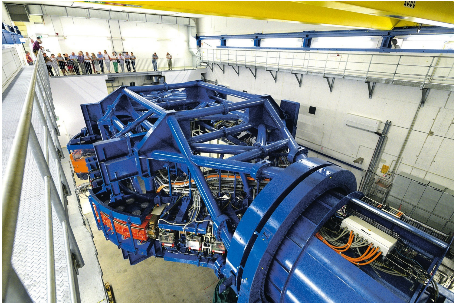


Fig. – 600 t gantry $\delta x < 0.3$ mm

Laser-driven hadrontherapy, novel techniques developed at ELI

- At the ELI consortium scientist are aware of the challenges for laser-driven systems with regard to medical applications and look for smart alternatives for nuclear physics based therapy
- ELI-Beamlines in Prague, exploited the $\mathrm{p} + ^{11}\mathrm{B} \rightarrow 3\alpha$ reaction to generate a decay into three alpha particles with a clinical proton beam. In this method the reaction is triggered by low-energy protons with $E_\mathrm{P} \gtrsim 400\,\mathrm{keV}$. HPLS can provide (Cirrione *et al.* Scientific Reports **8** 1141 (2018) DOI:10.1038/s41598-018-19258-5)
- If protons in the GeV regime are achievable a new approach afar from harvesting the LET energy transfer in the Bragg-Preak can be envisaged with the straight ion trajectories of several beams overlapping (analogue to a $\gamma-$knive concept).
- At ELI-NP: Funding accrued for a new approach regarding the combination of immuno-technology with radiology in which a precision delivery of isotopes relevant for oncology is foreseen. In combination with exposure to epithermal neutrons at a later stage, cancer treatment is envisaged which is free from the restrictions of ion beam delivery and reliance on the Bragg-Peak.

Our latest work: Using high-intensity lasers to pump nuclear isomers via non-linear effects

- Uploaded yesterday to arXiv (submitted to PRL, revision stage)

arXiv:2404.07909v1 [nucl-th] 11 Apr 2024

A new scheme for isomer pumping and depletion with high-power lasers

C.-J. Yang,[1] K. M. Spohr,[1,2] M. Cernaianu,[1] D. Doria,[1] P. Ghenuche,[1] and V. Horný[1]

[1] *ELI-NP, "Horia Hulubei" National Institute for Physics and Nuclear Engineering, 30 Reactorului Street, RO-077125, Bucharest-Magurele, Romania*[*]

[2] *School of Computing, Engineering and Physical Sciences, University of the West of Scotland, High Street, PA1 2BE, Paisley, Scotland*[†]

(Dated: April 12, 2024)

We propose a novel scheme for the population and depletion of nuclear isomers. The scheme combines the γ-photons with energies $\gtrsim 10\,\mathrm{keV}$ emitted during the interaction of a contemporary high-intensity laser pulse with a plasma and one or multiple photon beams supplied by intense lasers. Due to nonlinear effects, two- or multi-photon absorption dominates over the conventional multi-step one-photon process for an optimized gamma flash. Moreover, this nonlinear effect can be greatly enhanced with the help of externally supplied photons. These photons act such that the effective cross-section experienced by the γ-photons becomes tunable, growing with the intensity I_0 of the beam. Assuming $I_0 \sim 10^{18}\,\mathrm{Wcm}^{-2}$ for the photon beam, an effective cross-section as large as $10^{-21}\,\mathrm{cm}^2$ to $10^{-28}\,\mathrm{cm}^2$ for the $\gamma-$photon can be achieved. Thus, within state-of-the-art 10 PW laser facilities, the yields from two-photon absorption can reach 10^6 to 10^9 isomers per shot for selected states that are separated from their ground state by E2 transitions. Similar yields for transitions with higher multipolarities can be accommodated by multi-photon absorption with additional photons provided.

PACS numbers: 25.30.Bf, 21.60.Cs,01.30.-y, 01.30.Ww, 01.30.Xx

Nuclear isomers are excited states of nuclei that have a longer half-life ($t_{1/2} \gtrsim 1\,\mathrm{ns}$) than the states in the prompt decay paths of a nucleus following an induced excitation. Isomers with $t_{1/2} > 10$ years (e.g., ^{93m}Nb, ^{113m}Cd, ^{178m}Hf, etc.) are ideal candadids for nuclear batteries that outperform conventional ones by $\times 10^6$ in energy density [1]. Many isomers with $t_{1/2} \gtrsim$ hours have proven medical potentials [2–4]. Furthermore, isomers generally serve as pathways to enable nuclear lasing [5, 6]. Since their discovery [7], the efficient creation and induced depopulation of isomers has been one of the outstanding problems in physics. Any breakthrough on this topic will enable exciting applications in nuclear photonics.

The production of isomers by brute force via photon absorption toward the desired state is inefficient and riddled with technological challenges. In general, it requires pumping through intermediate states with shorter lifetimes, except for a few cases where favorable transitions of ground-state to a higher excited state followed by its decay into the isomer state exist. Herein, the dilemma is that generating a large number of γ-photons to be absorbed resonantly by the nuclear level within a short time is difficult. Moreover, the direct pumping of a state exhibiting a longer half-life is challenged by the relatively narrow absorption bandwidth (e.g., 10 ps correspond to a natural width of only $6.6 \cdot 10^{-5}\,\mathrm{eV}$), which leads to the so-called graser dilemma, i.e., the half-life/width combinations given in nature requires elusive laser pumping powers or the very unrealistic scenario of an induced nuclear explosion [5, 6]. As the energy gap between nuclear transitions often leads to isomers $\gtrsim 100\,\mathrm{keV}$, no existing laser can be used in direct pumping.

Other than γ-excitation, alternative ways to generate isomers discussed in the past involve various nuclear reactions or Coulomb excitation provided that suitable seed nuclei are available [8, 9]. However, the triggered depletion of isomers, i.e., how to harvest the energy with high efficiency, seems still an unsolvable problem [10–32]. Nevertheless, proposals that utilizing intensive ($\gtrsim 10^{10}\,\mathrm{Wcm}^{-2}$) optical photons toward a virtual state followed by spontaneous emissions to the desired state provide an interesting alternative [33–38].

High-power laser systems (HPLS) can become core entities to spearhead associated developments [39–51] as they are able now to deliver intensities up to $\mathcal{P} \sim 10^{21-23}\mathrm{Wcm}^{-2}$ [52–57] [1]. When interacting with an over-dense target, HPLS accelerate electrons in the materials to highly relativistic energies and drive strong currents in the plasma enviroment. The extreme, quasistatic magnetic fields then interact with energetic electrons, generate dense γ-photons [58–69] and rejuvenates the hope of a mass production of isomers. However, existing schemes of manipulating isomers incorporate either a single- or multi-step excitation via very dense γ-photons to some "stepping" intermediate states in the decay chain toward the desired state [27, 28, 70, 71], which, even with an optimal HPLS-based γ-production, give yield estimations that are far from even suggesting a technical realization [68, 72–80]. Reaching a sufficient population yield for the isomer population remains an insurmountable challenge.

Fig. – A fresh approach to a long-standing problem

Summary & Outlook

Summary & Outlook

- Laser-driven nuclear physics heralds a new era in nuclear experimentation, allowing insights into nuclear (astro-)physics and applied technologies which were hitherto unthinkable
- Laser-driven nuclear physics has matured in the last decade and informs state-of-the-art nuclear physics research. It is a truly multidisciplinary field.
- Challenge to theory at the interface of atomic and nuclear physics, informing *e.g.* UNEDF.
- There is a huge potential for nuclear physics due to high intensity I and the related shortness of particle pulses.
- Interaction of electrons with the nuclear core may show new unexpected new regimes in plasma and the emergence of new reaction channels such as NEEC. The possibility of a controlled release of energy from an isomer can be studied.
- Mimicking of population distributions in nuclei at high MK-GK temperatures. Unexpected scenarios may arise which can be technologically exploited (population inversion).
- ELI-NP systems can help to evaluate the EoS of neutrons, thus informing nuclear astrophysics.
- ELI-NP on the pathway of becoming a laboratory for earth-bound nuclear astrophysics studies.
- Fundamental studies on the influence of high dose rates with respect to oncology.
- : Challenges:
- Huge challenge in making subsequent laser pulse more reproducible.
- Challenge to develop new detector systems and materials.
- Electro-magnetic pulse (EMP) problematic, saturating electronics, handicapping prompt measurements.
- Target assemblies are totally different from low-intensity experiments.

Summary: Future Vision

Final Remark

The future of HPLS-systems as ELI-NP is as bright and intense as its pulses. ☺
ELI-NP will become a world-leading center for *e.g.* astrophysical & applied research, initiating a paradigm shift in the way we conduct nuclear physics experiments. World-leading research will be undertaken, and new phenomena at the interface of atomic and nuclear physics will be discovered. You can take part in these developments with sound experimental campaigns based on your knowledge & vision, to promote physics with laser-driven high-intensity accelerators.

Thank you for your attention!