EUROPEAN UNION

Structural Instruments 2014-2020

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

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

Nuclear physics in plasma at EuPRAXIA
(a view of what’s happening at ELI Nuclear Physics that might be on interest for EuPRAXIA)

Paolo Tomassini, Domenico Doria, Vojtech Horny, Paul Constantin, Andi Cocuanes, Dan Stutman

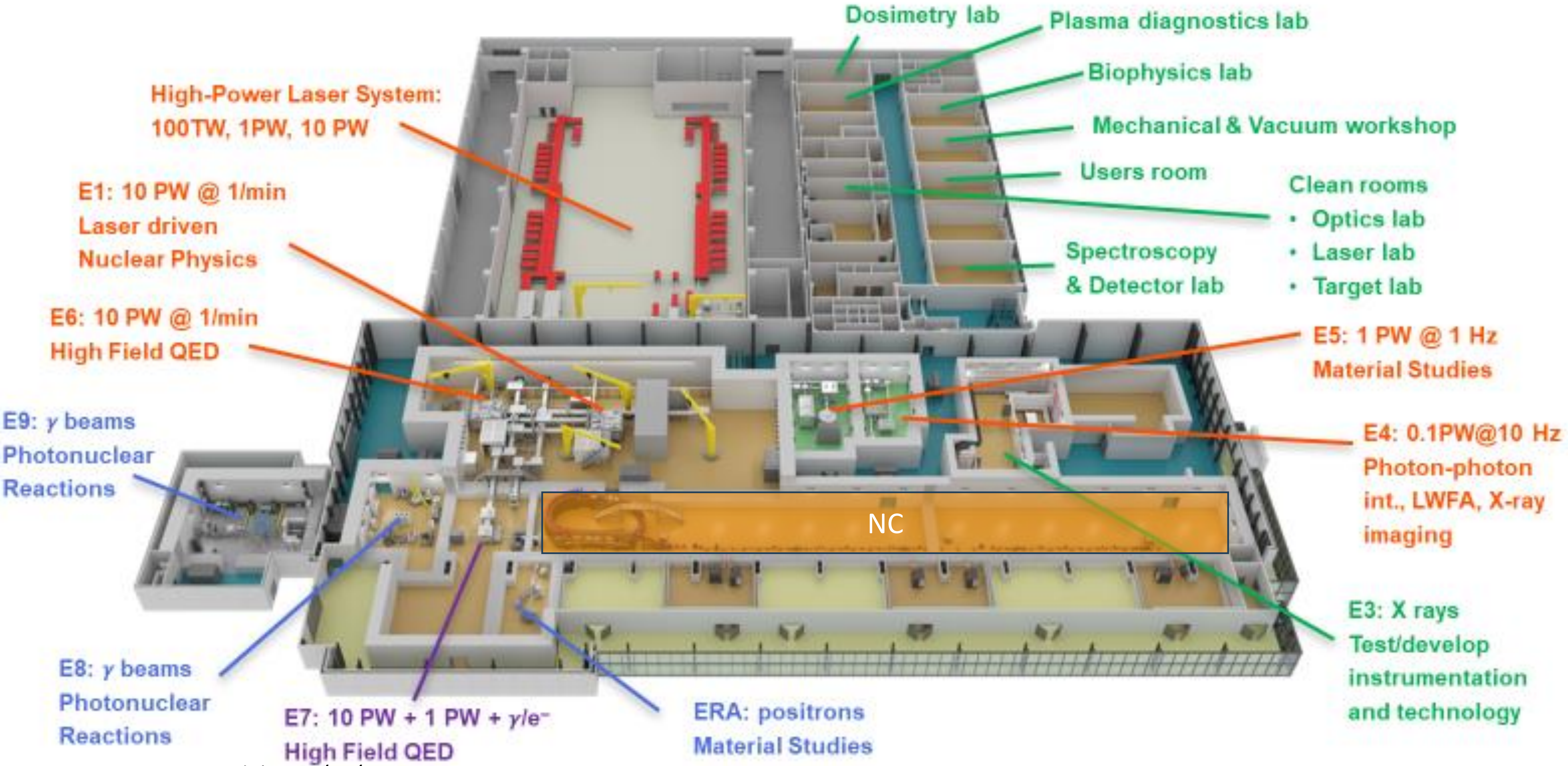
Extreme Light Infrastructure (ELI-NP), Str. Reactorului no.30, P.O. box MG-6, Bucharest - Magurele, Romania

Cautionary note 1:
PT is not a nuclear physicist

Cautionary note 2:
PT was one of the proponents of the EUROGAMMAS consortium

EuPRAXIA meeting, La Biodola , 27/09/2024

Experimental building layout



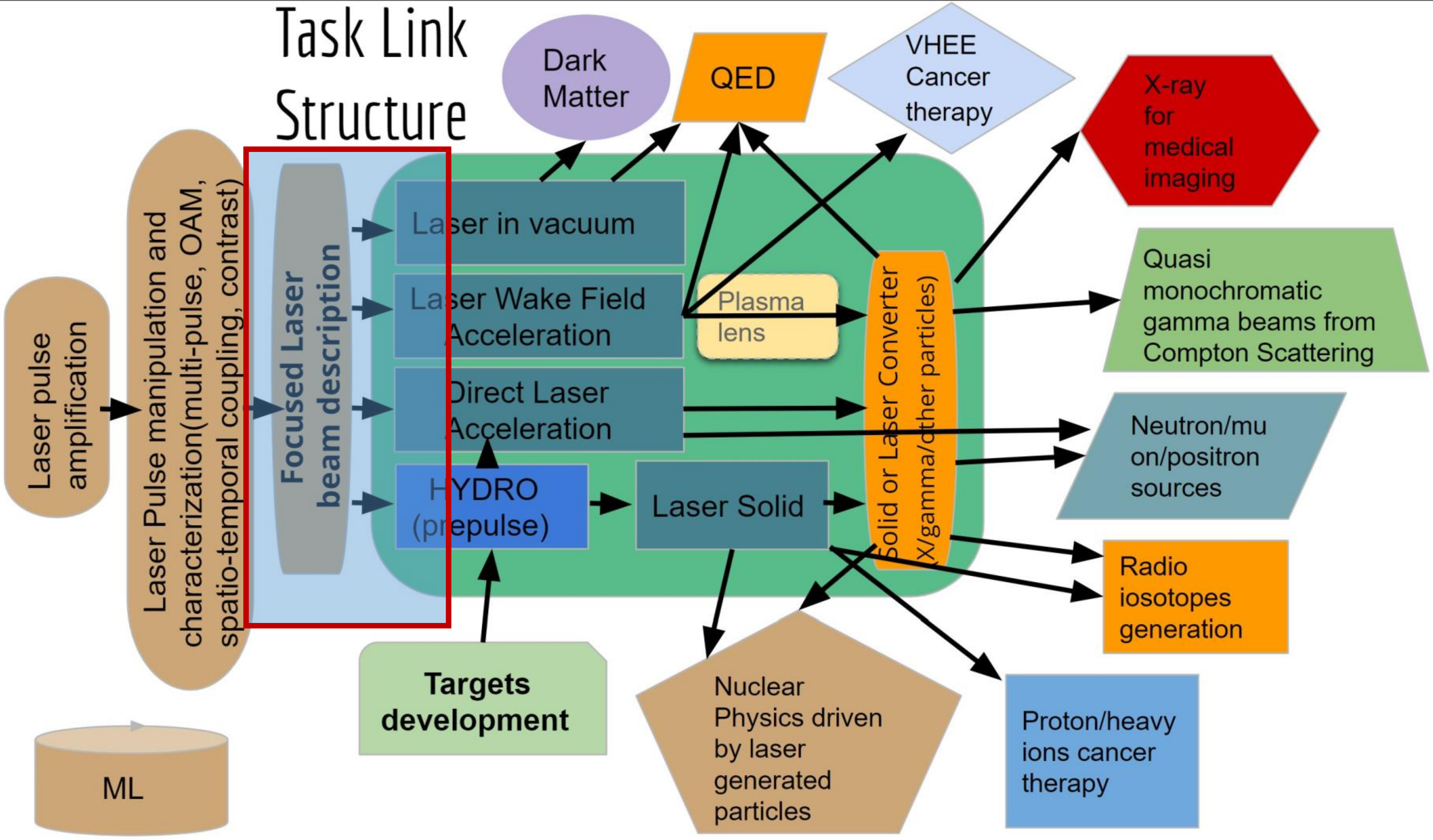
The Simulation Group of ELI-NP

The SG@ELI-NP Simulation Group of the ELI-NP pillar was created (along with the other transversal groups) in March 2023 under initiative of the **Scientific Director, V. Malka**

Group Coordinator
P. Tomassini

Performs simulation researches and drives research for the whole ELI-NP pillar

SG @ ELI-NP
Simulation Group



Theory@LDED

The group is part of the **LDED** (Department Head: **Domenico Doria**)

Group Coordinator
P. Tomassini

Performs theory and simulation researches (mostly) for LDED

- Nuclar Physics
- Laser Solid
- LWFA/DLA
- Radiation and secondary sources

Paolo Tomassini
Head of Research

Nuclear Physicist

Chieh-Jen Yang
Young Researcher

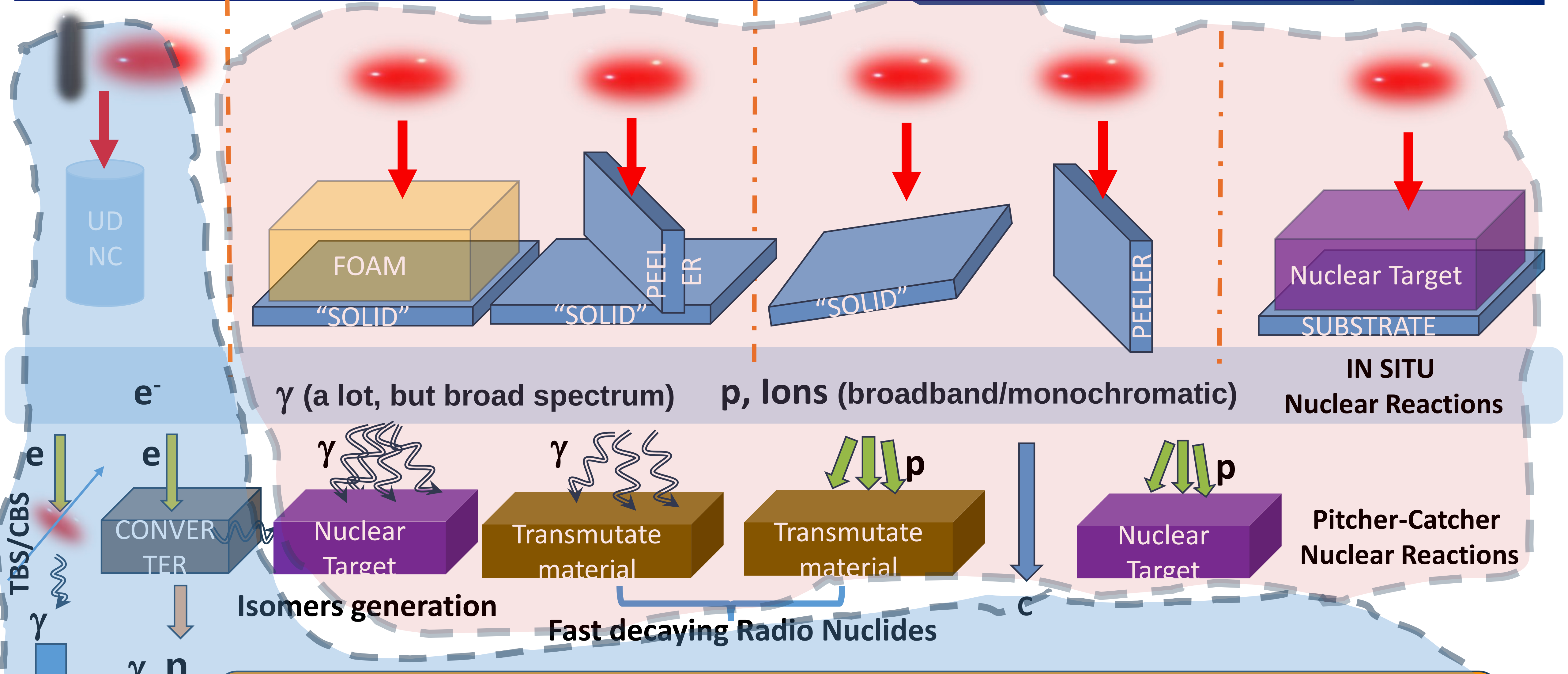
Vojtech Horny
Young Researcher

Dragana Dreghici
Ph. D. student

Bogdan Corobean
Ph. D. student

Federico Avella
Ph. D. student@CNR-INO
(co tutoring)

Interaction zoology (useful for NP studies) at ELI-NP



TBS/CBS from structured pulses with OAM will generate γ carrying OAM, thus opening channels for nuclear studies (say on isomers) which were forbidden by selection rules

High-fidelity PIC simulations with aberrated/structured pulses

Virtual Lab Infrastructure **VLI-LPIC package (VLI-Laser to PIC interface)**

(P. Tomassini, F. Avella)

SG @ ELI-NP
Simulation Group

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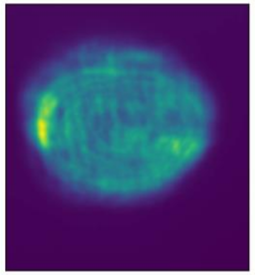
TO PIC (OUTPUT)

Federico Avella
Ph. D. student@INO
(co tutoring)

Solve the Helmoltz equation for the propagation

$$2ik_0\partial_z\hat{E}(x,y,z) = \nabla_\perp^2\hat{E}(x,y,z)$$

INPUT



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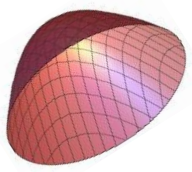
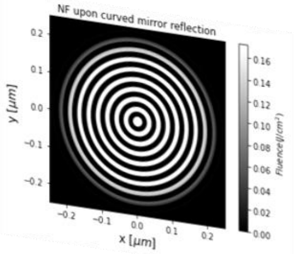


NF Image

+

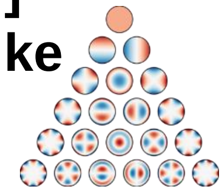
Add Masks



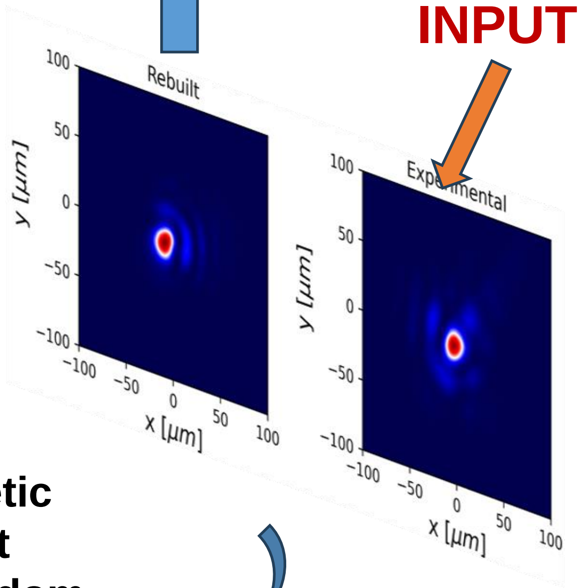
+

Add aberrations

$Z=[z_1,\dots, z_{28}]$
List of Zernike Polinomial coefficients



INPUT



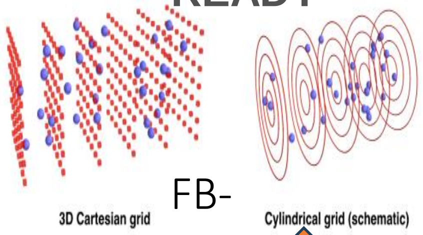
P. Tomassini, F. Avella et al., "Automatic reconstruction of the laser transverse intensity and phase structures near the focal plane for advanced Particle In Cell modelling", to be submitted **on J. Comp. Physics**

Optimization

Currently a genetic algorithm + pivot preceded by random sampling of the 28th dimensional space

Virtual Lab Infrastructure VLI-LPIC package (VLI-Laser to PIC interface)

READY



FB-PIC

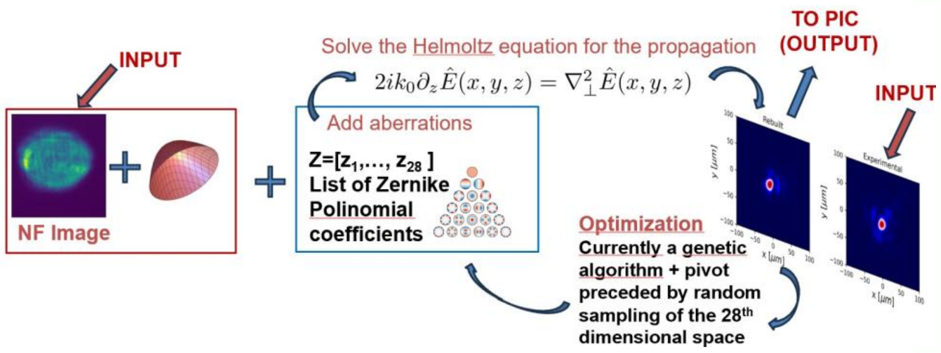
READY

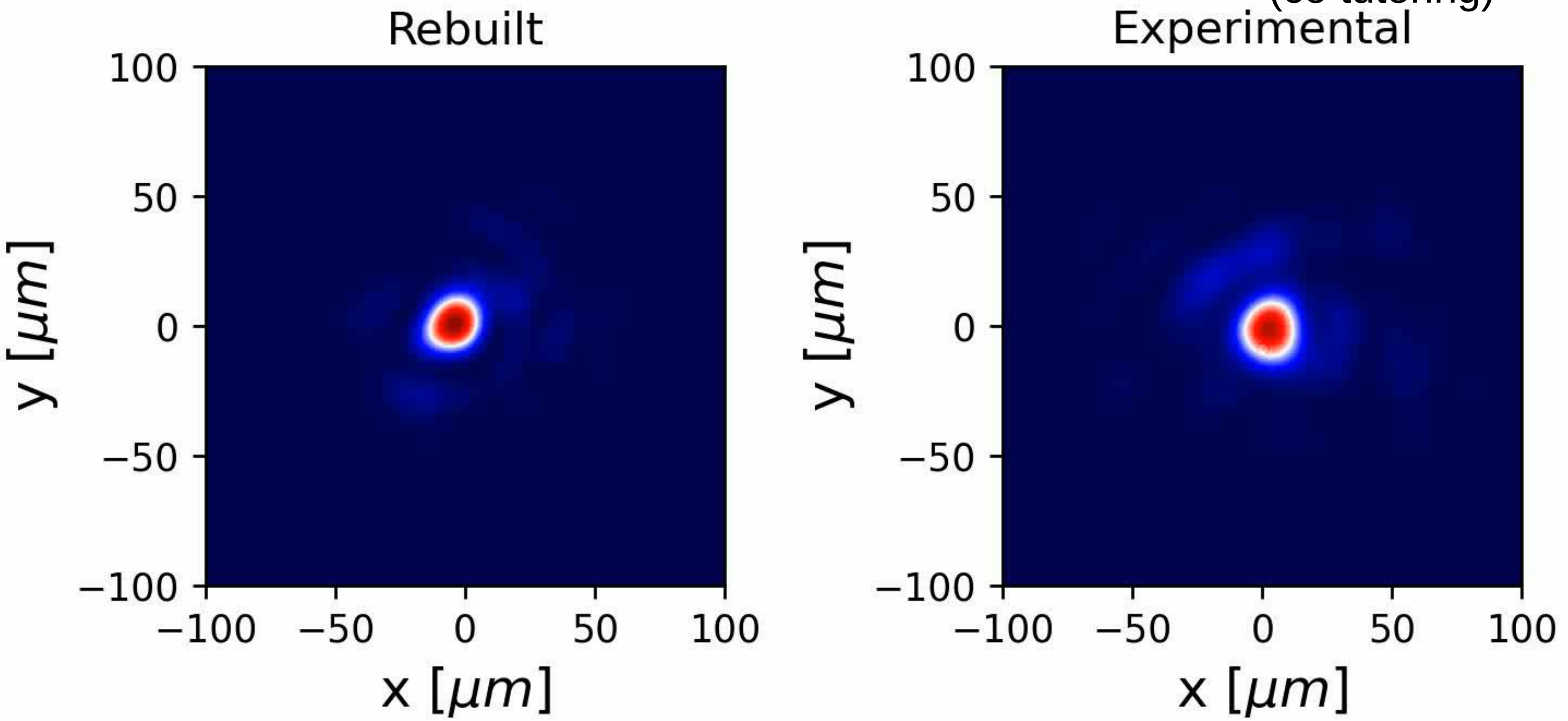
+ SMILEI + EPOCH +….

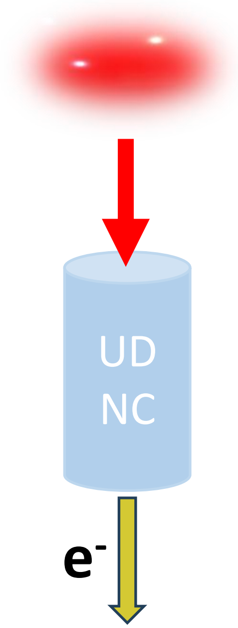
CONSIGLIO NAZIONALE DELLE RICERCHE ISTITUTO NAZIONALE DI OTTICA

Federico Avella
Ph. D. student@INO
(co tutoring)

3D rebuilt pulse directly sent to PIC codes

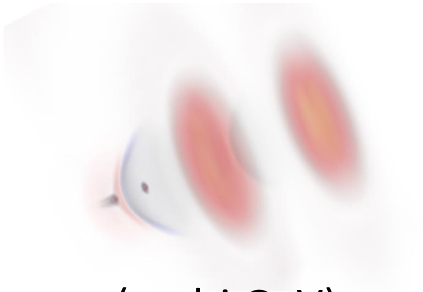






- <1PW **High-brightness** 1-2GeV **w/wo ultrashort** (sub fs) option with a two-subpulses **ReMPI** scheme (P. Tomassini, L.A.Gizzi+CNR-INO, D. Doria)

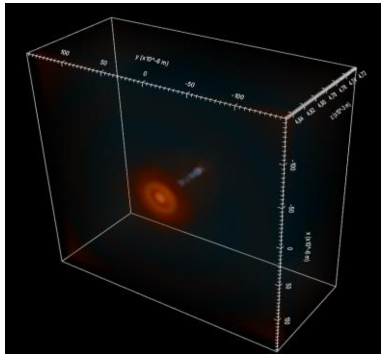
FEL X and TBS quasi monochromatic γ beams



- 1PW/10PW standard acceleration for **high charge** (nC class)/**high energy** (multi GeV) beams [***guiding needed for E>5GeV, working on that***] (P. Ghenuche, D. Doria, V. Malka+Weitzmann, , P. Tomassini)

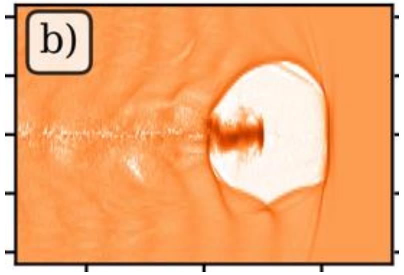
NOT SHOWN HERE

Broad Band γ and μ generation [see G. Sarri]



- 100TW scale**/10/100Hz multi nC low energy beams** with the **high-efficiency** LWFA regime **<u>(efficiency of 50%)</u>** employing post-compressed pulses (V. Horny, G. Bleotu, D. Ursescu, V. Malka, P. Tomassini)

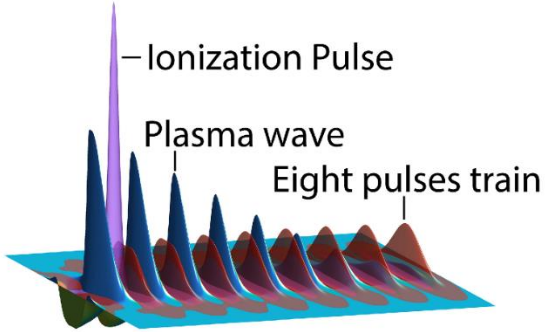
Broad band X/γ, VHEE, n, RadioIsotopes



The first FEL compliant version of ReMPI for 5GeV suffered from "gigantism".

8 pulses

(1PW, EuPRAXIA)



30 pC

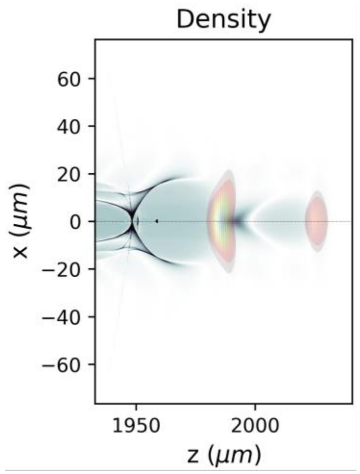
$$\epsilon_n \simeq 80nmrad$$

P. Tomassini et al., High-quality 5GeV electron bunches with the resonant multi-pulse ionization injection, PPCF P 62 (2020) 014010

P. Tomassini et al., BRILLIANT X-RAY FREE ELECTRON LASER DRIVEN BY RESONANT MULTI-PULSE IONIZATION INJECTION ACCELERATOR, proc. FEL 2022 conference, Trieste.

(200TW)

2 pulses

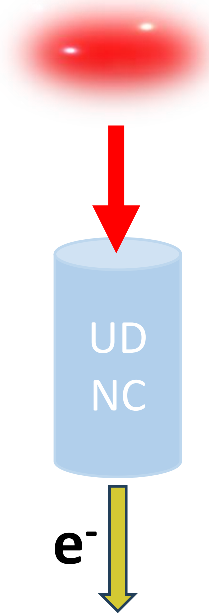


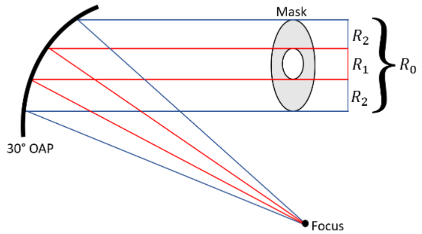
5-30 pC

$$\epsilon_{n,x} \simeq 120nmrad$$
$$\epsilon_{n,y} \simeq 60nmrad$$

P. Tomassini et al., High-Brightness e-beams with the ReMPI scheme employing two driver pulses, in preparation

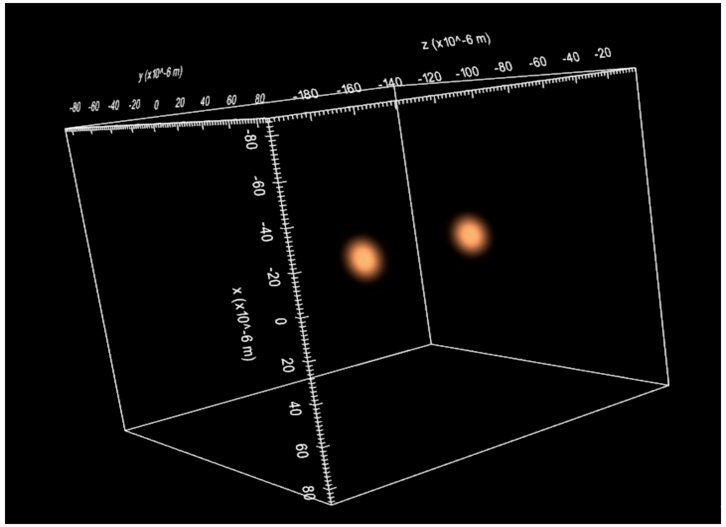
Interaction zoology at ELI-NP: LWFA + High Brightness beams



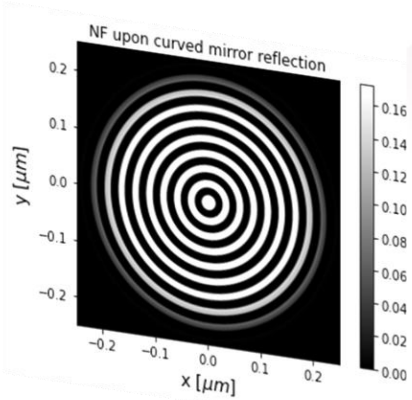


N=1 ring (efficiency 70%)

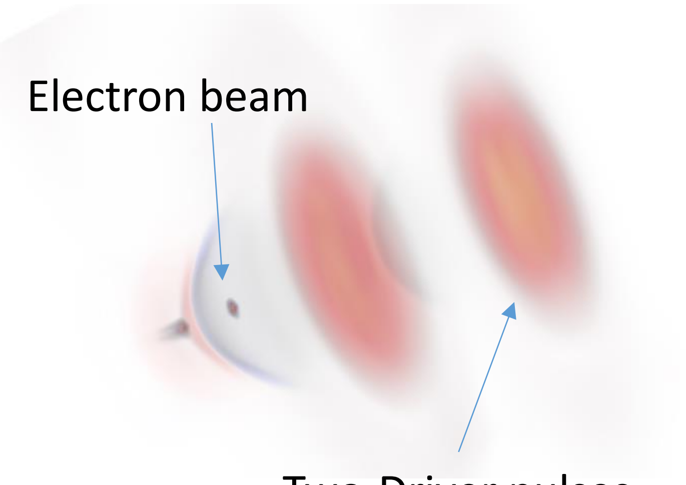
VLI-LPIC to FB-PIC
Full pulse description including aberrations
(with **F. Avella** CNR-INO)

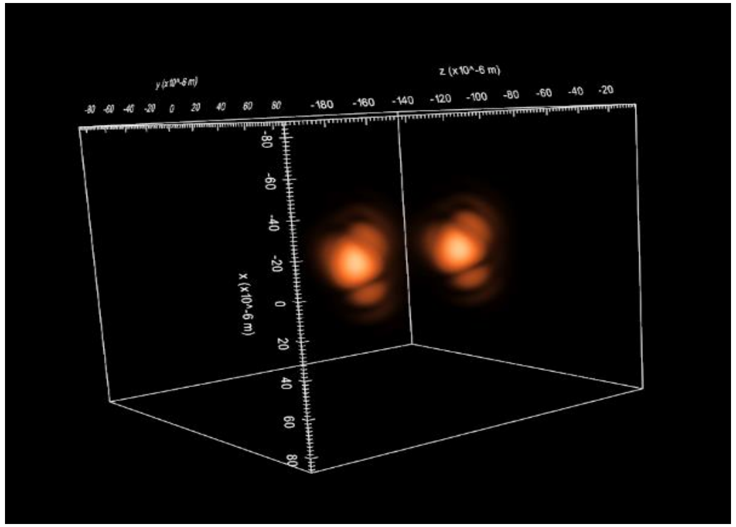


(Nθ=5 modes: no aberrations, with a lot of aberrations)



N=20 rings (efficiency 50%

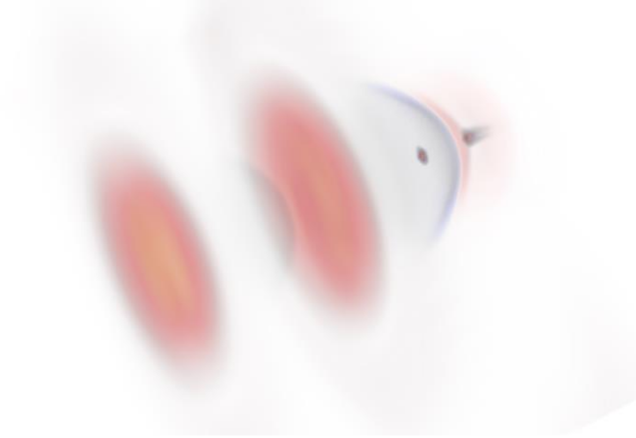




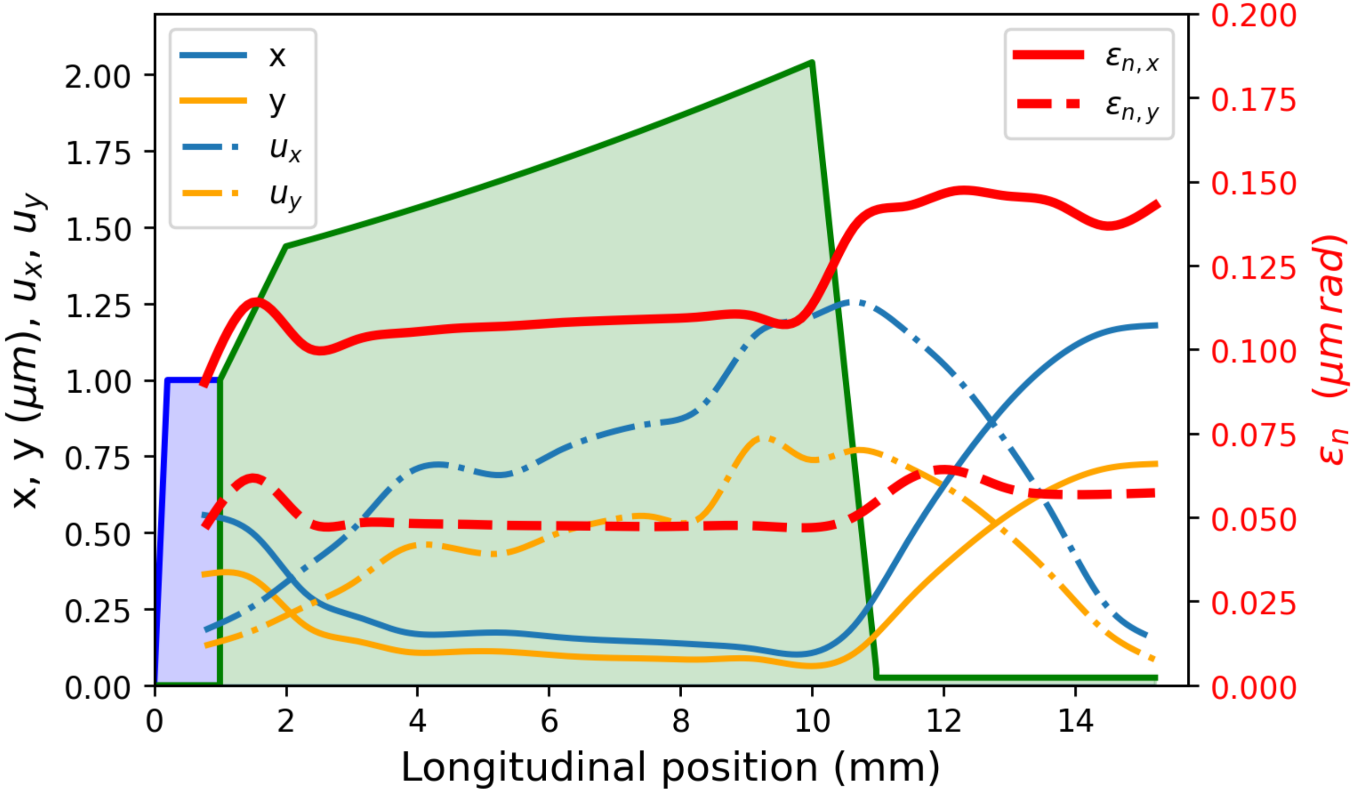
CNRINO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

SINGLE Ti:Sa 200TW/300TW laser system, Circularly Polarised pulses

- 2x 23fs FWHM pulses, w0=30 μm , total 4.2J on TEM00,
- 1x 30fs FWHM ionization pulse **in III** harmonics, w0=3.5 μm, on TEM00, 20mJ



- **100%Ar (8+) plasma, n0=0.75e18 1/cm^3,**
- **1mm plateau + 100He 10mm accelerating structure, guided pulse with radially parabolic density profile**



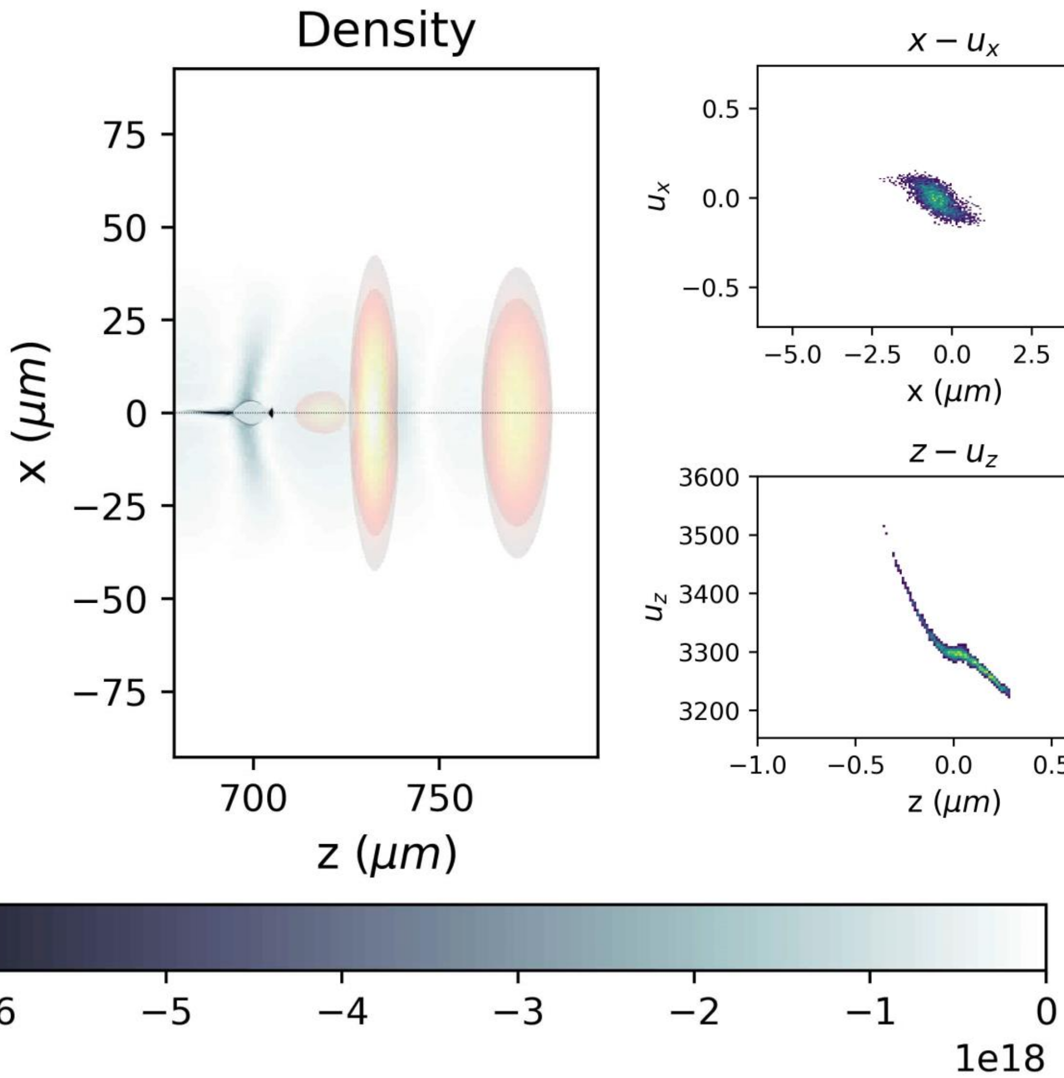
Plasma lens after the downramp to reduce beam divergence

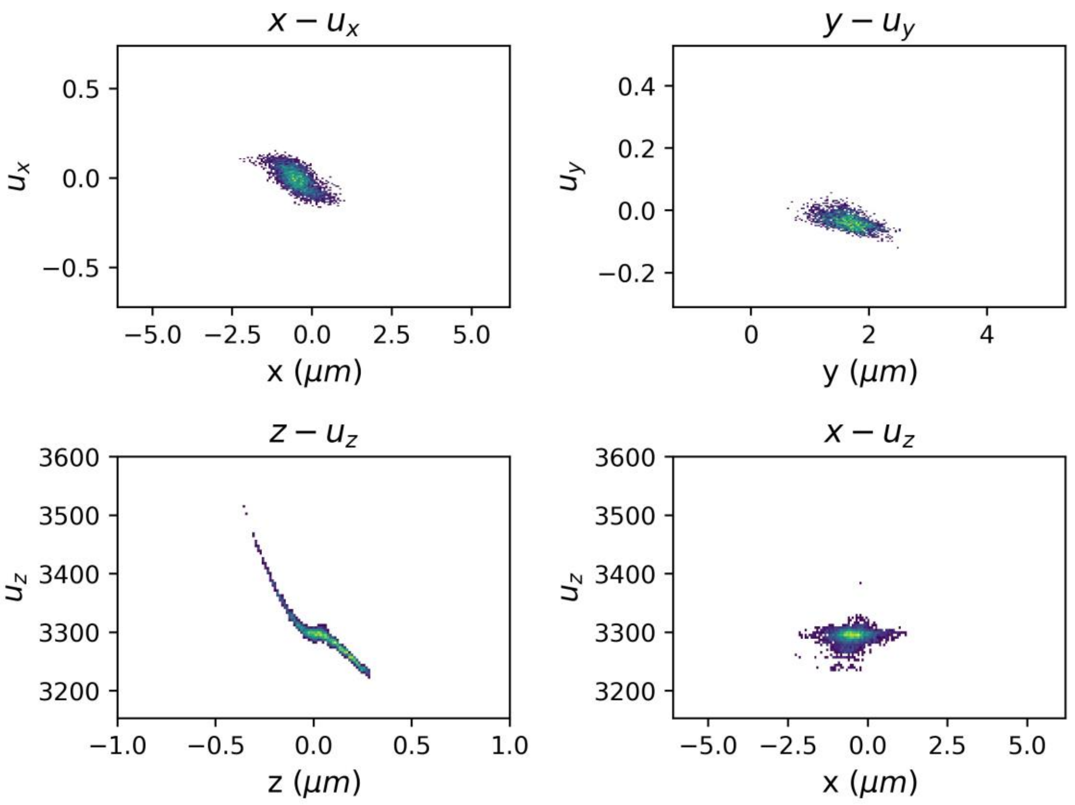
Interaction zoology at ELI-NP: LWFA + High Brightness beams

FB-PIC q3D simulation Nθ=3

Projected, Q=20pC

Projected Quality
δE/E (rms) 0.7%
ε_n = 0.09 μmrad (geom. mean)
L = 0.2 μm
B6D = $5 \cdot 10^{17} A/m^2/0.1\%$

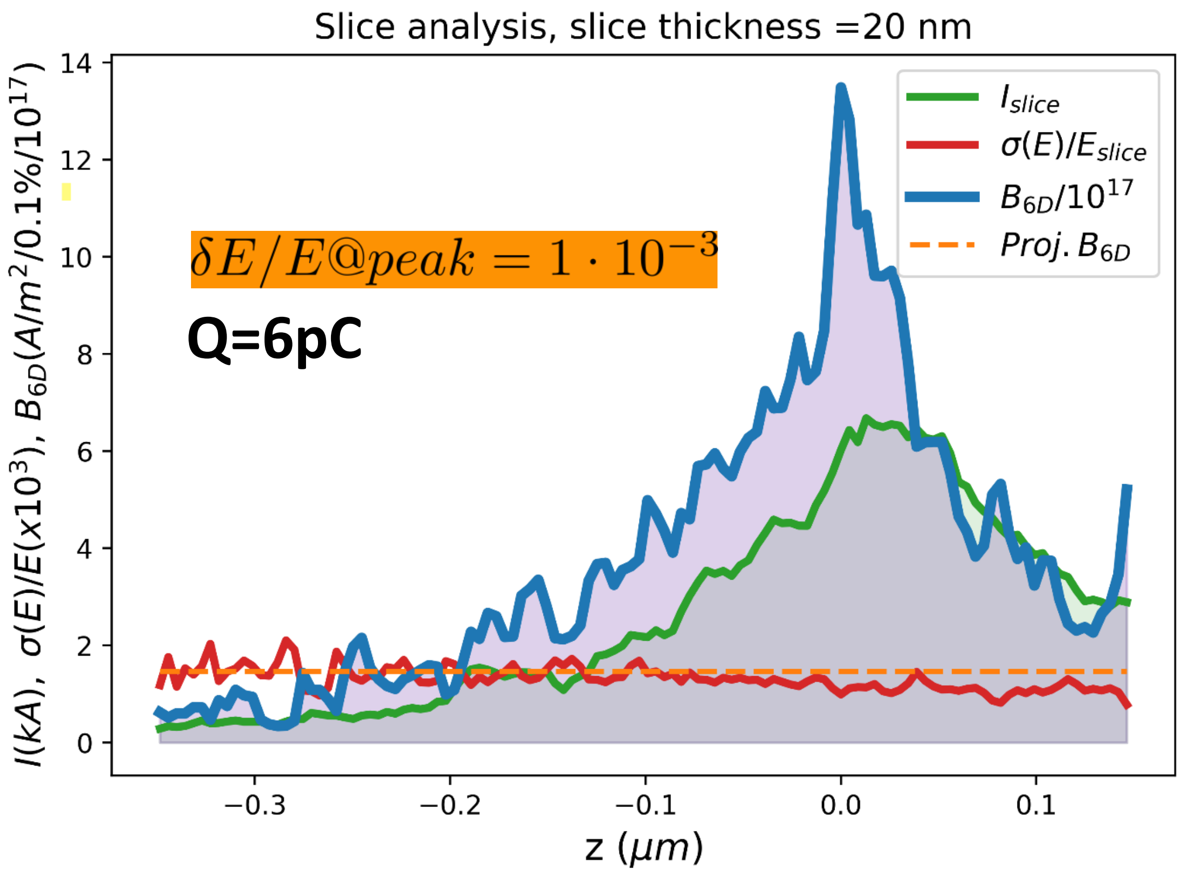


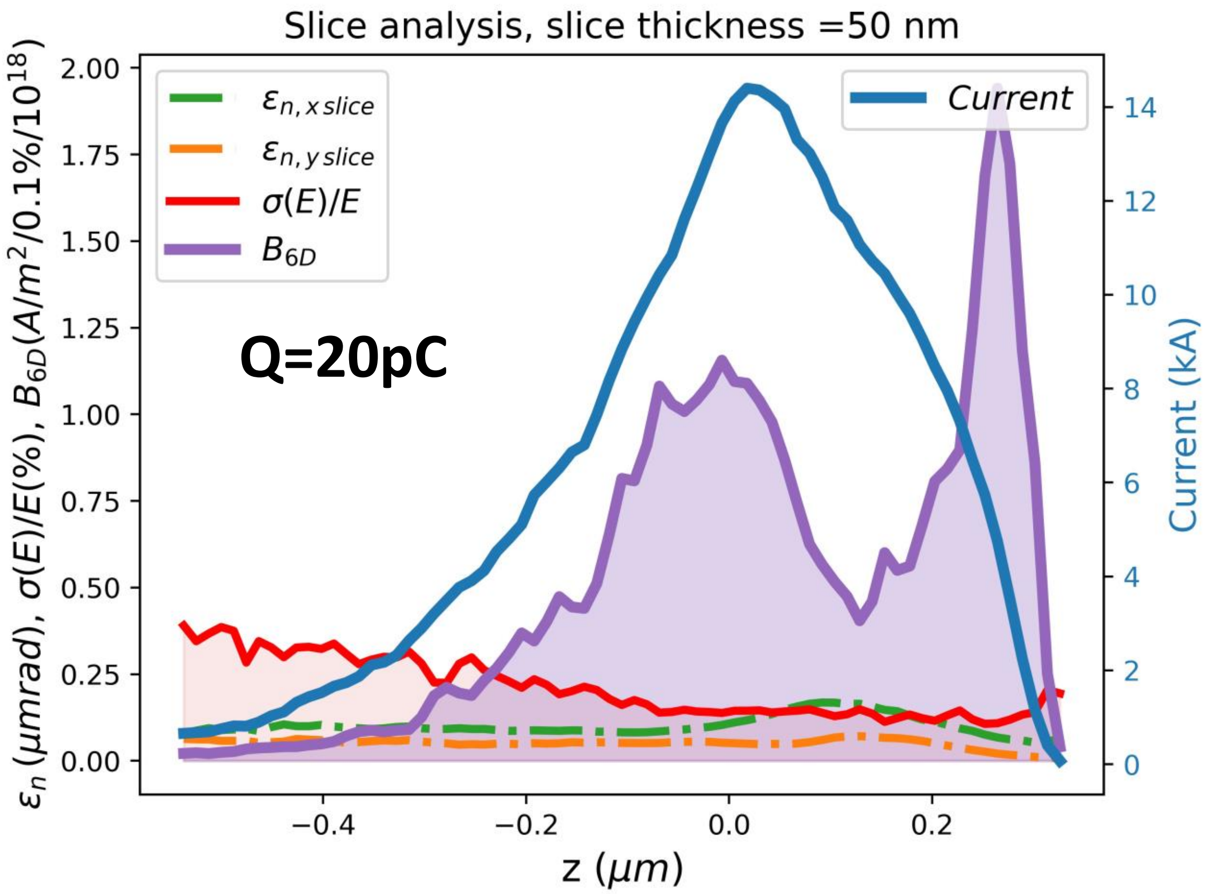


Interaction zoology at ELI-NP: LWFA + High Brightness beams

Duration (rms)	Projected Brighthess 6D	δE/E (rms)
250 as	$1.5 \cdot 10^{17} A/m^2/0.1\%$	0.6%

Duration (rms)	Projected Brighthess 6D	δE/E (rms)
600 as	$5 \cdot 10^{17} A/m^2/0.1\%$	0.7%

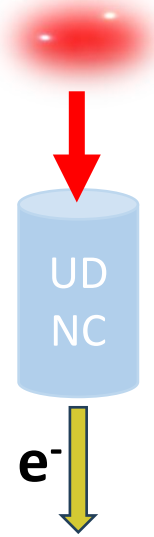




FEL-oriented

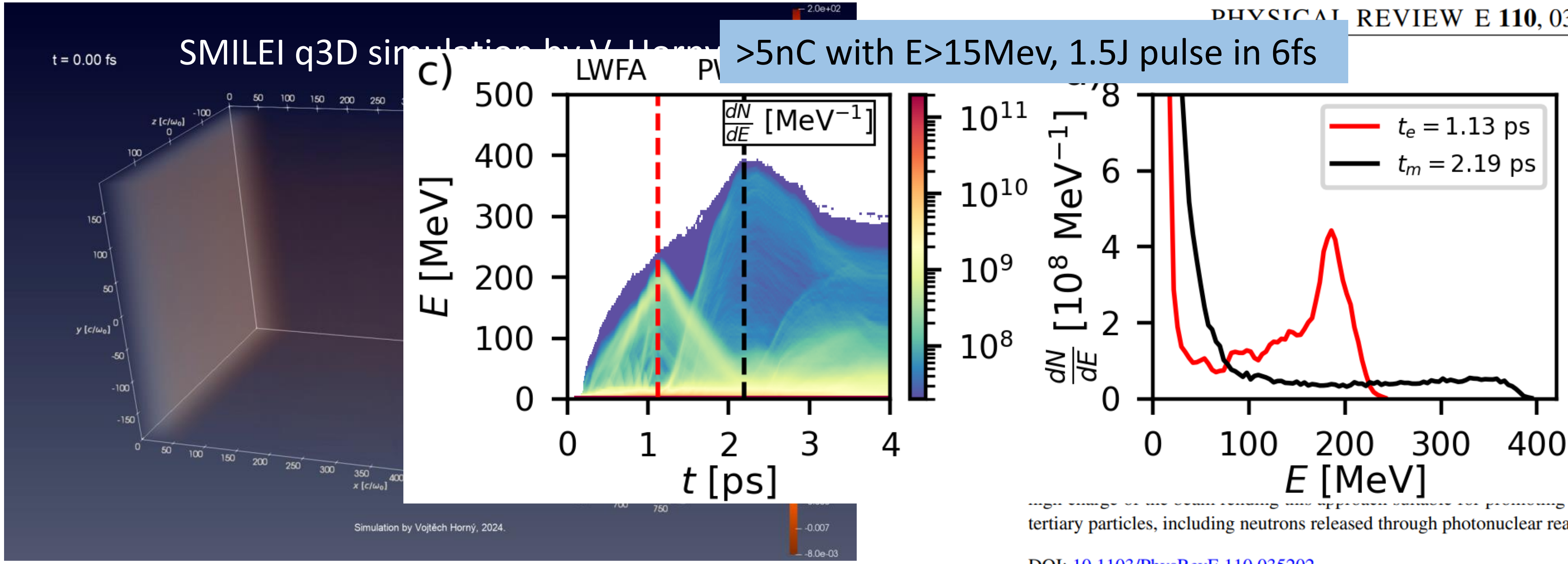
Thomson BS oriented

Interaction zoology at ELI-NP: LWFA



1. <1PW **High-brightness** 1-2GeV **w/wo ultrashort** (sub fs) option with a two-subpulses **ReMPI** sc
2. 1PW/10PW standard acceleration for **high charge** (nC class)/**high energy** (multi GeV), beams [*q...*
   needed for E>5GeV, working on that]
3. **100TW scale/10/100Hz multi nC low energy beams** with the **high-efficiency** LWFA regime **<u>(efficiency of 50%)</u>** employing post-compressed pulses

Vojtech Horny
Young Researcher



PHYSICAL REVIEW E **110**, 035202 (2024)

...ion dominated bubble regime

...,[1,2] and P. Tomassini[1]
...30, RO-077125 Magurele, Romania
...f Science, Rehovot 7610001, Israel

...blished 6 September 2024)

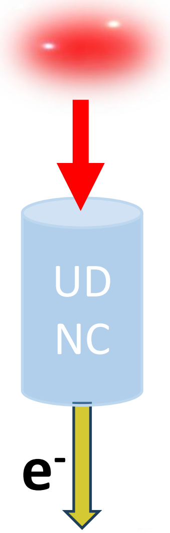
...ass laser pulses are nowadays available ...z repetition. In this Letter, we explore ... The numerical modeling predicts that ...nergy above 15 MeV, and with charge ...nergy. In such a regime, the laser pulse ...ld. The self-steepening effect induces a ...elf-injection that explains the extremely ...Bremsstrahlung emitter and generator of tertiary particles, including neutrons released through photonuclear reactions.

DOI: 10.1103/PhysRevE.110.035202

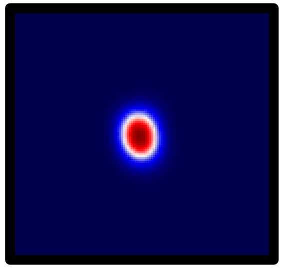
Interaction zoology at ELI-NP: LWFA

100TW scale**/10/100Hz multi nC low energy beams** with the **high-efficiency** LWFA regime employing post-compressed pulses

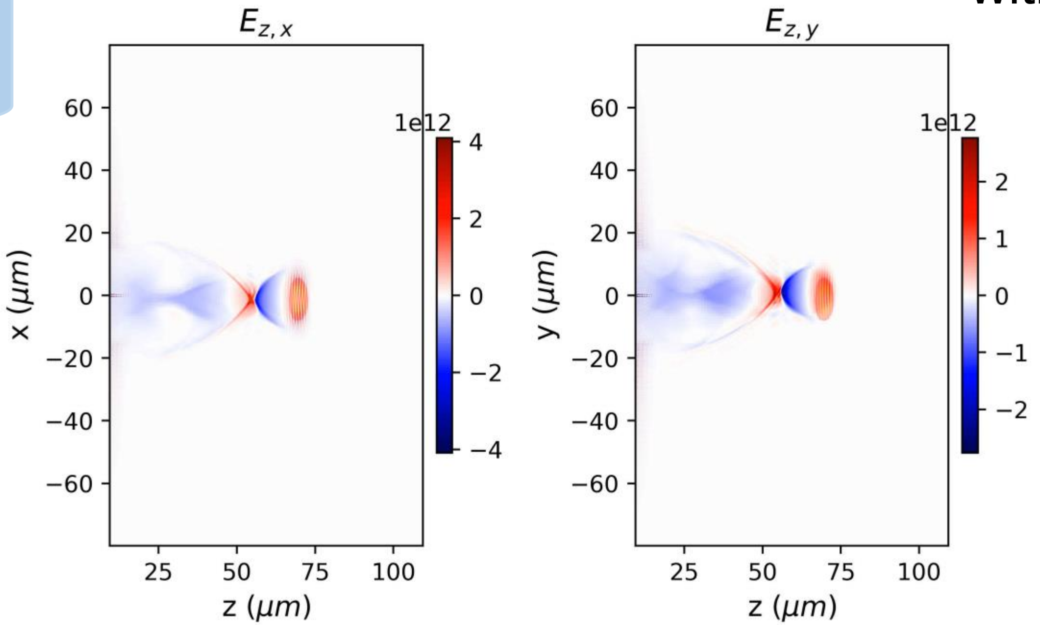
Examples: towards start-to-end simulations with post compressed Joulse-scale pulses (<u>11fs FWHM, 1J</u>)

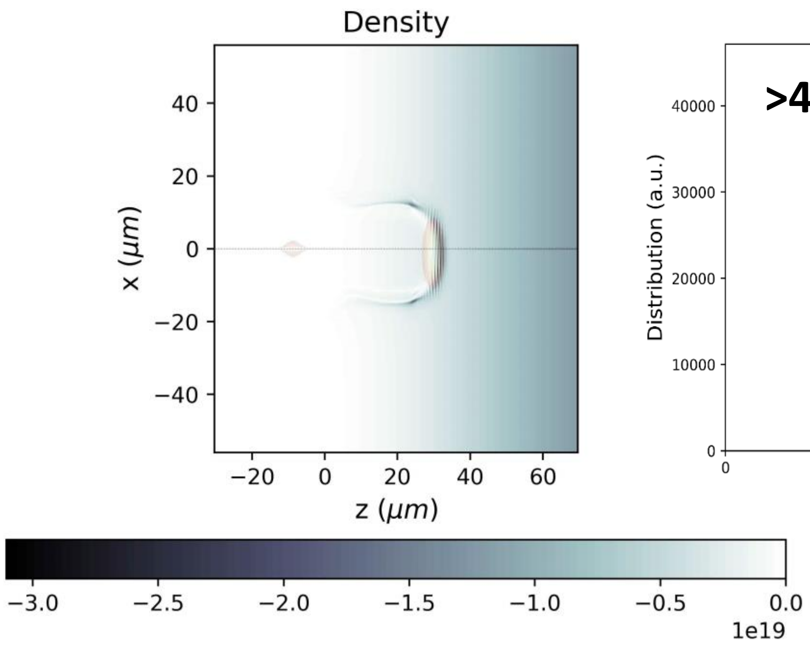


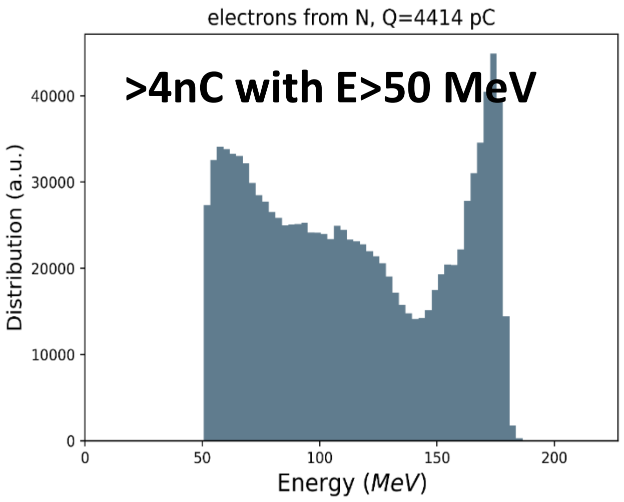
Virtual Lab Infrastructure **VLI-LPIC package (VLI-Laser to PIC interface)**



q3D simulations
with FBPIC



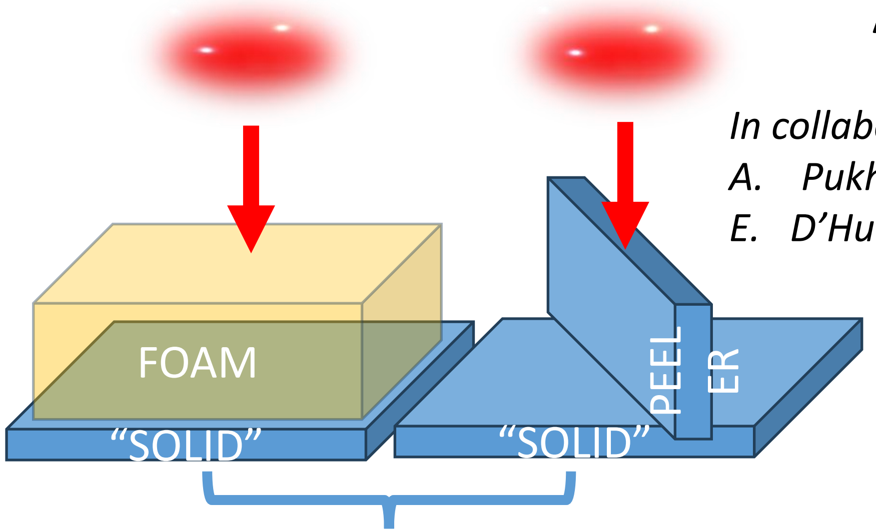




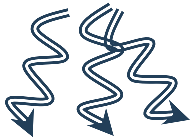
Electron bunches useful for broadband γ conversion and VHEE

Interaction zoology at ELI-NP: Gamma ray bursts at NP 1/1

A lot of MeV scale photons can be generated, but at **very low rep rate**

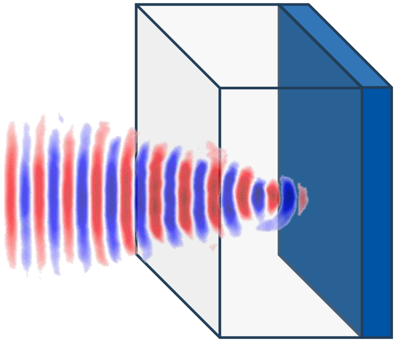


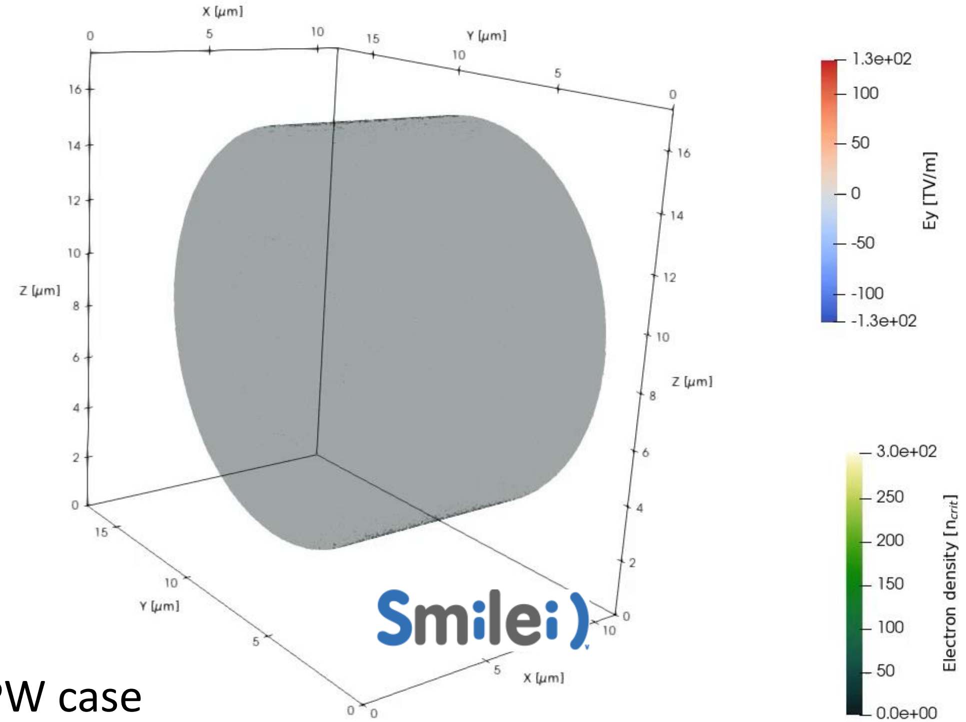
γ (a lot, but broad spectrum)



In collaboration with
A. Pukhov and
E. D'Humieres

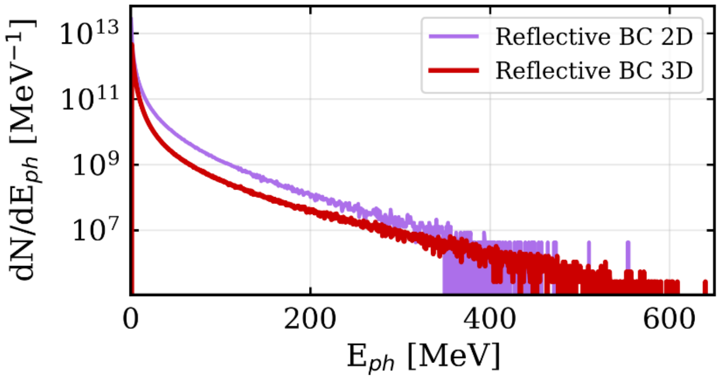
Dragana Dreghici
Ph. D. student





10PW case

3D sim. By D. Dreghici, V. Horny/ELI-NP



Conversion efficiency:

laser to photons:

12%

nature COMMUNICATIONS

ARTICLE

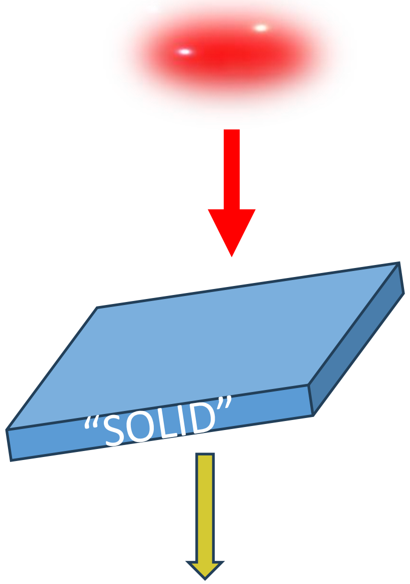
Check for updates

https://doi.org/10.1038/s41467-021-27694-7 OPEN

Forward-looking insights in laser-generated ultra-intense γ-ray and neutron sources for nuclear application and science

M. M. Günther[1✉], O. N. Rosmej[1,2,3], P. Tavana[2], M. Gyrdymov[2], A. Skobliakov[4], A. Kantsyrev[4], S. Zähter[1,2], N. G. Borisenko[5], A. Pukhov[6] & N. E. Andreev[7,8]

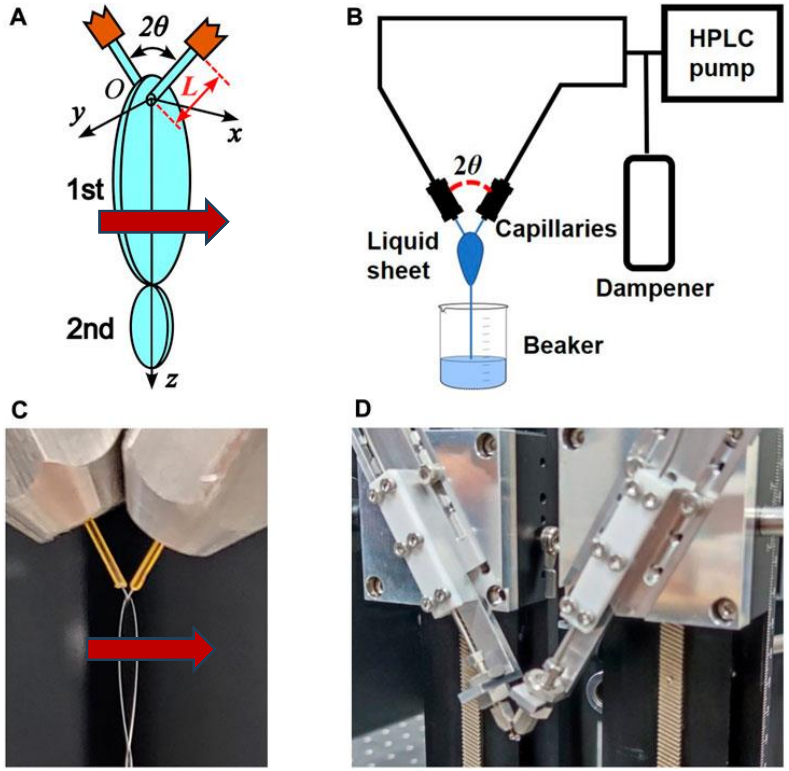
Interaction zoology at ELI-NP: Liquid targets for TNSA proton generation



p (broadband)

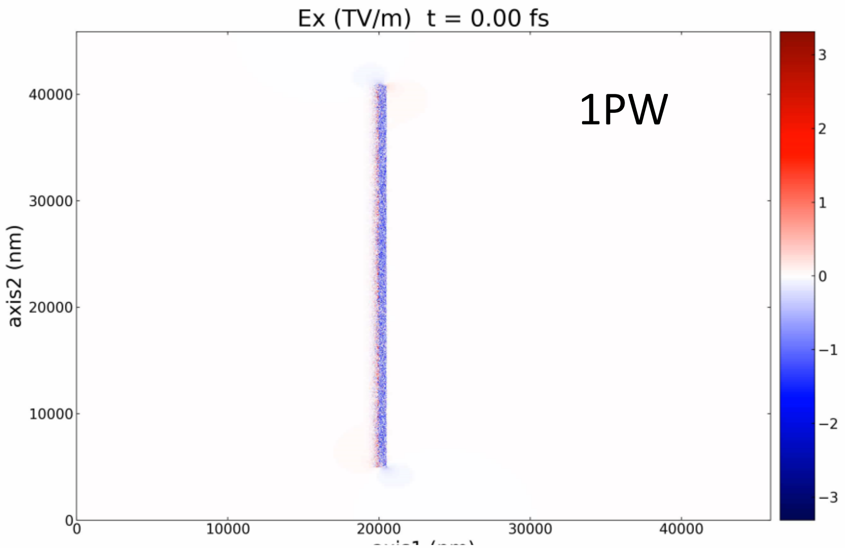
Protons can be used for neutron or fast decaying radionuclides generation

Here the key is a "high" rep-rate. We are optimizing the usage of water target leaf. **Thickness of a few microns.**

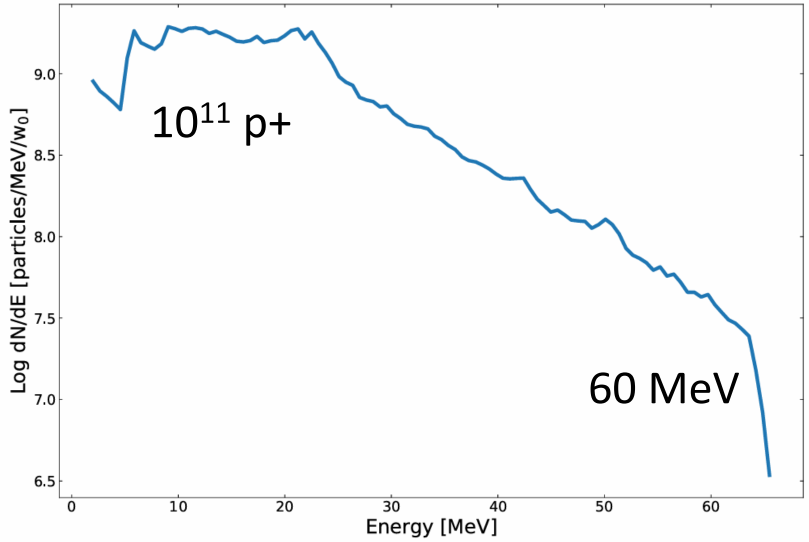


Z. Cao et al., Front. Phys., 2023 Nuclear Physics
Volume 11 - 2023 | https://doi.org/10.3389/fphy.2023.1172075

2D PIC simulation by B. Corobean/ELI-NP



Bogdan Corobean
Ph. D. student

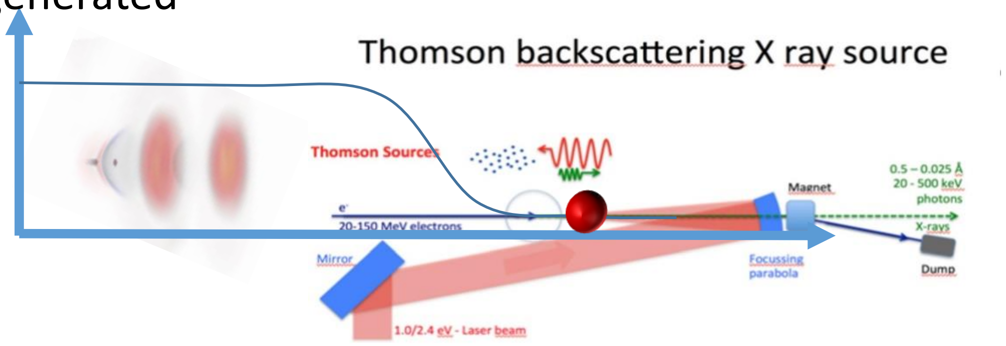


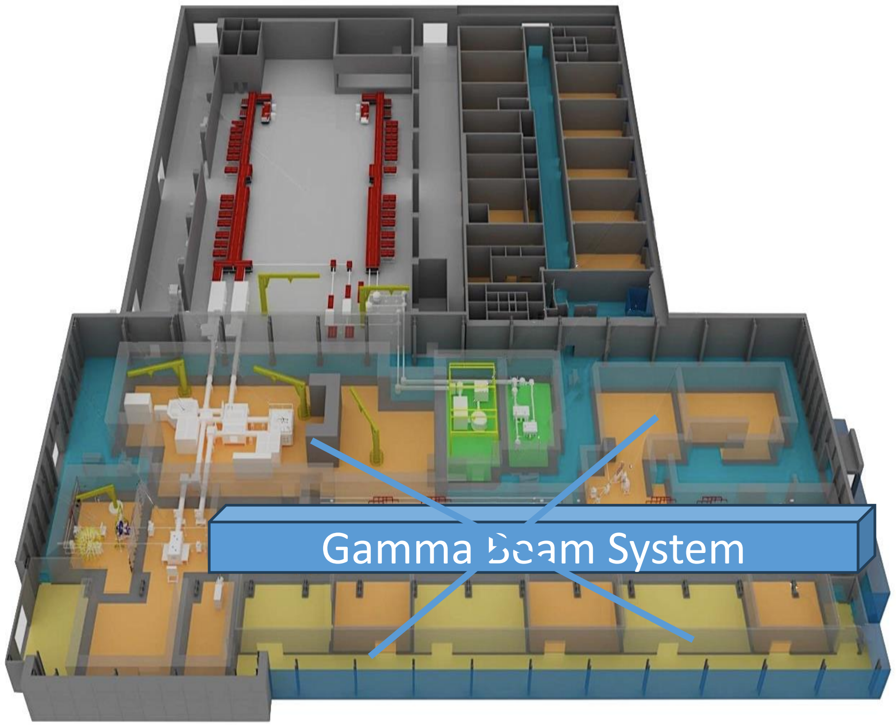
Nuclear Physics with Compton/Thomson BS gamma beams

The missing EUROGAMMAS gamma beam (now being substituted) TBS with high-brightness beams

While waiting for a gamma beam system, studies with Compton/Thomson backscattered radiation can be done

We cannot expect the same spectral density/flux/energy spread of the gamma beam system, but at least quasi-monochromatic beams must be generated





The **minimum attainable** energy spread of the gamma beam is [P. Tomassini et al., Appl. Phys. B 80 (2005)]

$$(\delta\omega/\omega)_{min} \simeq \sigma(u_\perp)^2 + 2\frac{\delta\gamma}{\gamma} + a_0^2/2$$

(Ψ=0, negligible pulse BW)

Very useful definition of the normalized acceptance

$$\Psi \equiv \gamma \cdot \theta_c$$

$$\text{if } \Psi \ll 1 \Rightarrow N_{Acc}(\Psi) \simeq \delta\omega/\omega \simeq \Psi^2$$

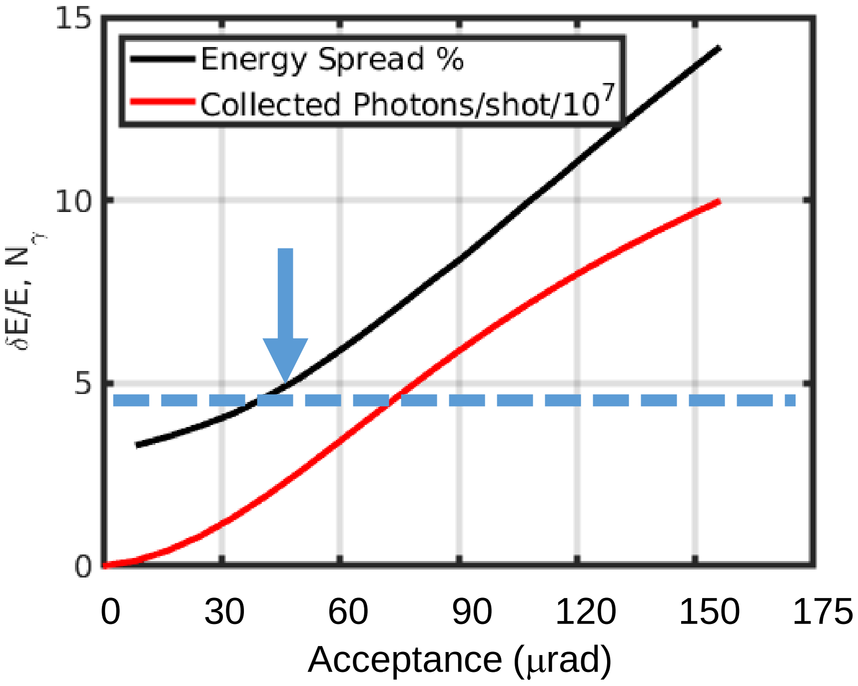
Therefore, a **high brightness** LWFA 100's MeV/GeV **must be employed** so as to get monochromatic and low transverse momentum electron beam.

Projected beam quality (ReMPI/2pulses)

σ(E)/E	Q	σ(u perp.)	σ(x perp.)	σ(z long.)
0.7%	20pC	0.12	1 μm	0.2μm

Counterpropagating pulse Yb:YAG (1.053 μm)

Energy	Duration	w0	a0
1J	2ps	12.5 μm	0.2



Expected minimum energy spread

$$(\delta\omega/\omega)_{min} \approx 3\%$$

The **peak** brilliance is very large

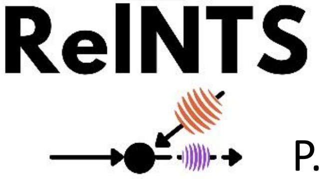
$$B = \frac{N_{ph}\text{‰}bw}{\delta t_\gamma(s) S(mm^2)\theta^2_{max}(mrad^2)} =$$

$$\mathbf{2 \cdot 10^{28}}\, ph/(s \cdot mm^2 \cdot mrad^2 \cdot \text{‰}bw)$$

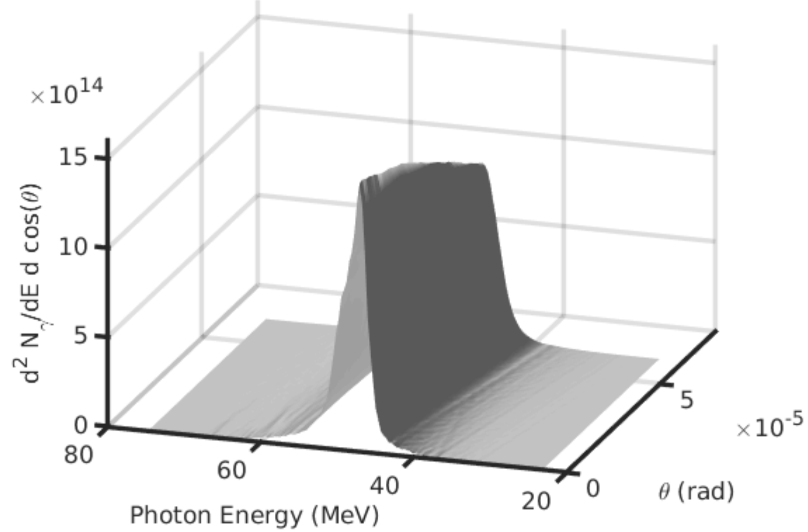
But the (average) spectral density and photon number are low (we don't have any recirculation)

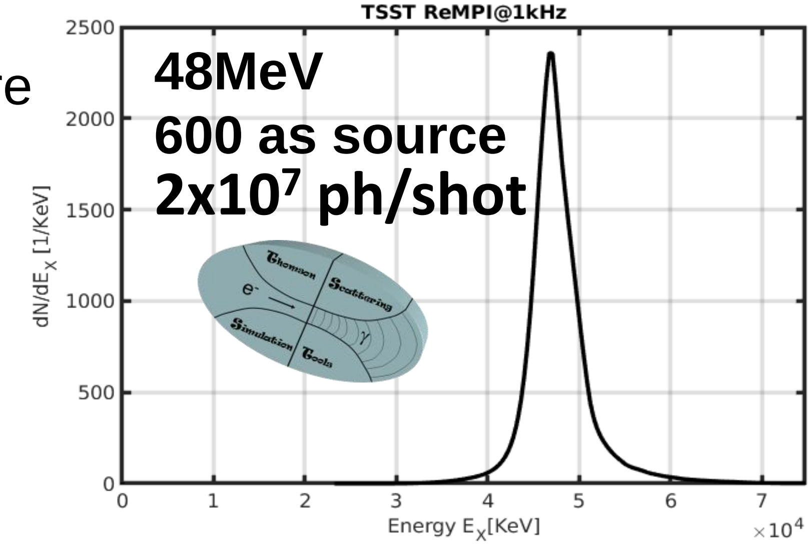
S = 50 γ/eV/s (10 Hz)

Vortex (LG with OAM) gamma beams can also be generated



P. Tomassini,2022





Quasi monochromatic and brilliant OAM gamma beam with TBS

Beside the standard gamma beams with flat/quasi-flat phase fronts and quasi TEM00 spatial distribution, **backscattering with structured beams carrying Orbital Angular Momentum (OAM) can be made**, thus generating γ **beams with OAM**

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Generation of High-Energy Photons with Large Orbital Angular Momentum by Compton Backscattering

U. D. Jentschura and V. G. Serbo
Phys. Rev. Lett. **106**, 013001 – Published 5 January 2011

More

Phys. Lett. B 852 (2024) 138622

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Letter

Vortex photon induced nuclear reaction: Mechanism, model, and application to the studies of giant resonance and astrophysical reaction rate

Yi Xu [a,*], Dimiter L. Balabanski [a,*], Virgil Baran [b,c], Cristian Iorga [b,d], Catalin Matei [a]

[a] Extreme Light Infrastructure - Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Strada Reactorului 30, Bucharest-Magurele, 077125, Ilfov, Romania
[b] Faculty of Physics, University of Bucharest, Strada Atomistilor 405, Bucharest-Magurele, 077125, Ilfov, Romania
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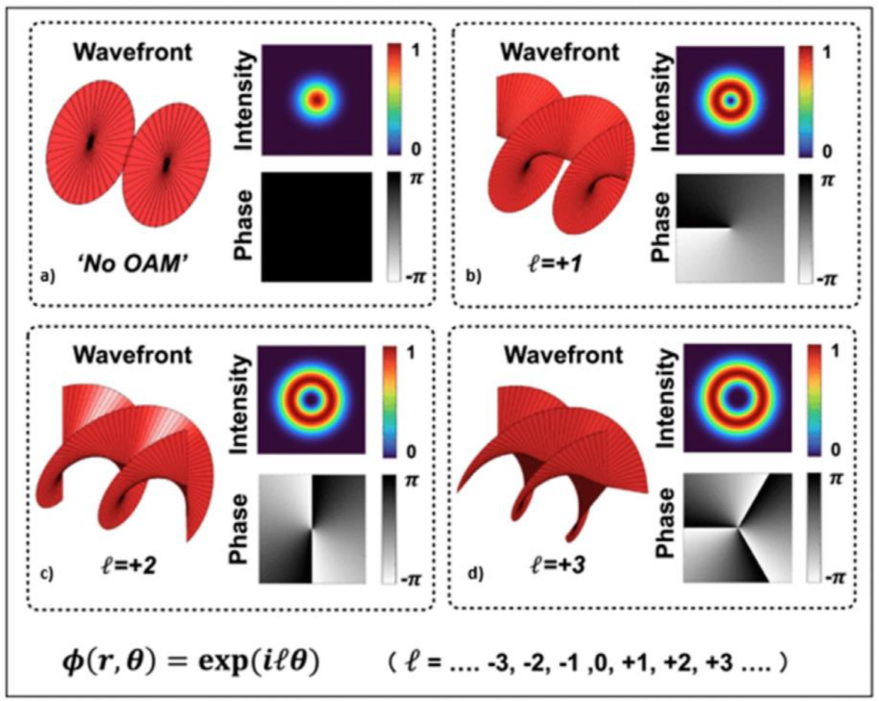
[d] National Institute for Laser, Plasma and Radiation Physics, Strada Atomistilor 409, Bucharest-Magurele, 077125, Ilfov, Romania



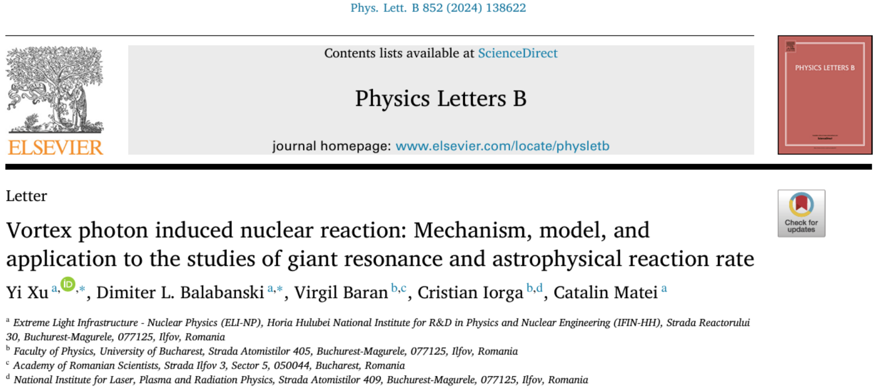
T. M Olaye et al., 10.3390/photonics10060664

Vortex (LG with OAM) gamma beams can also be simulated

ReINTS

P. Tomassini,2022

Quasi monochromatic and brilliant OAM gamma beam with TBS: Application to NP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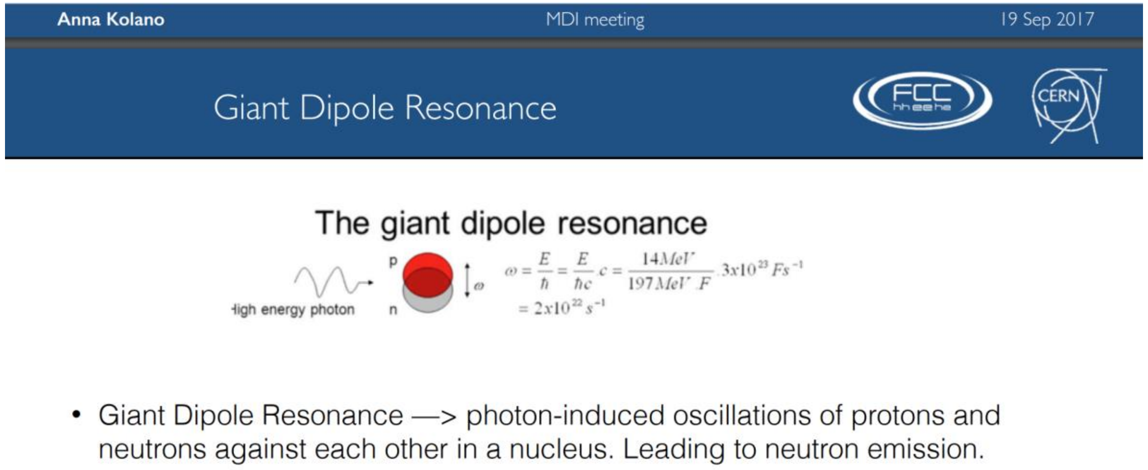
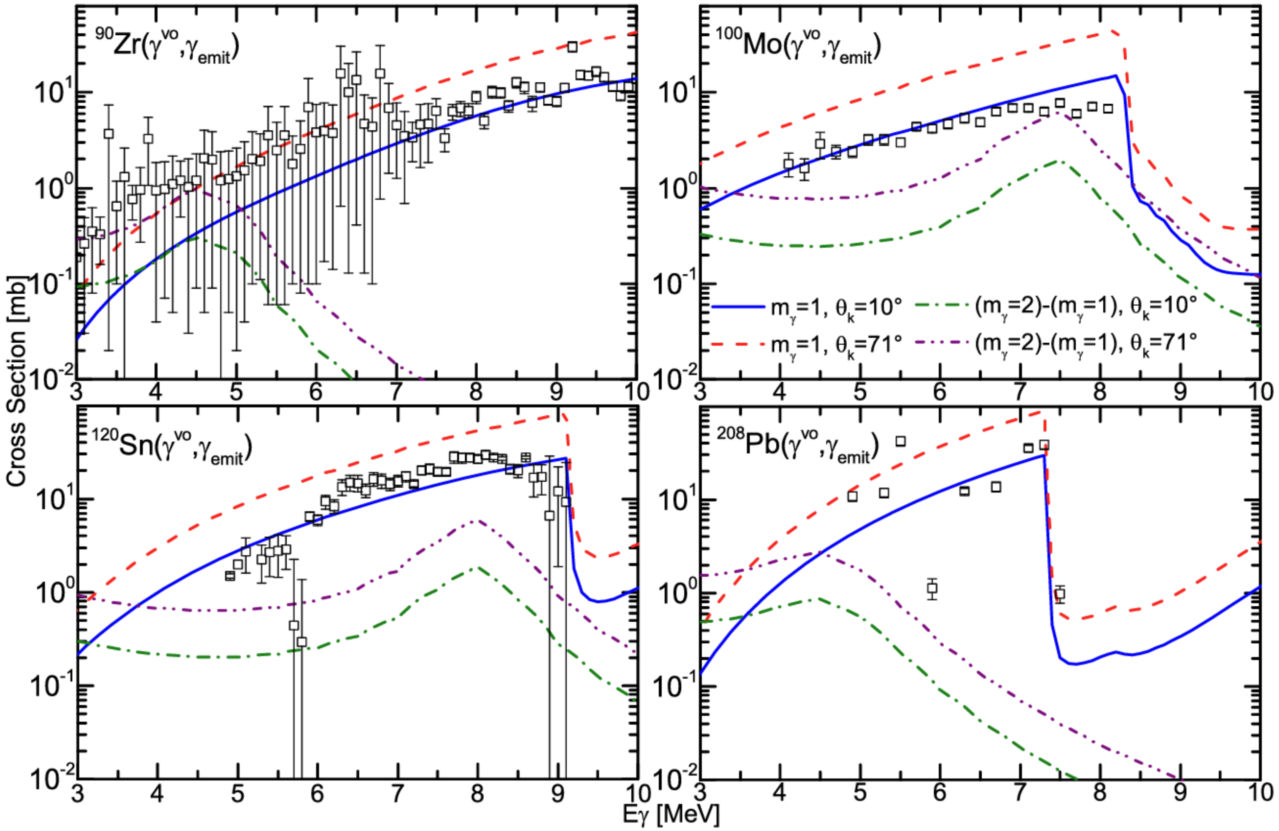
Y. Xu, D.L. Balabanski, V. Baran et al.

Study of the influence of OAM on the Giant Dipole Resonance of some nuclei



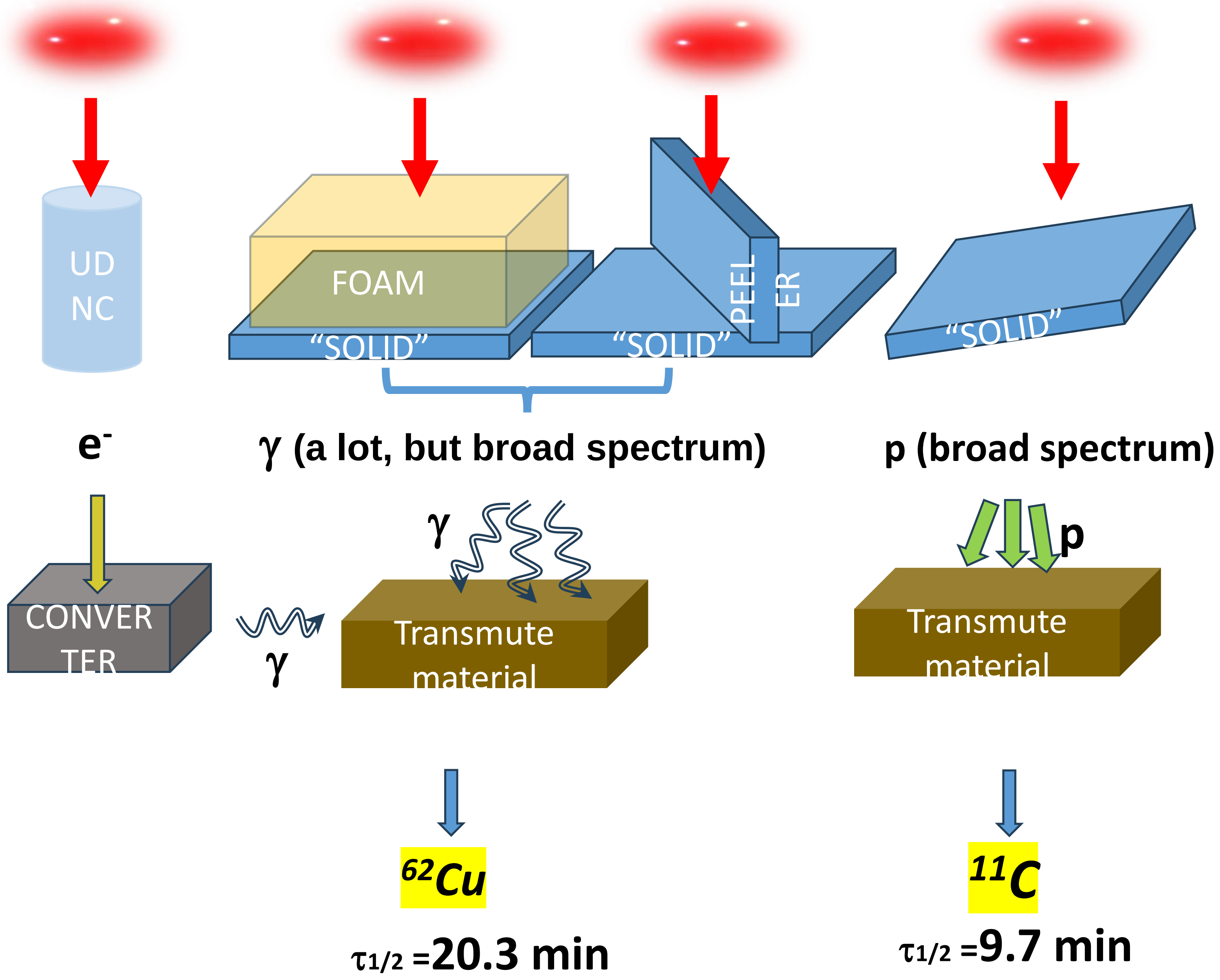


https://indico.cern.ch/event/666960/contributions/2726609/
attachments/1526494/2387021/19SEP17MDI.pdf

Change by orders of magnitude of the cross sections for the cases w/wo OAM are expected

Fast Radio Isotopes generation

Paths to use HPLS for fast decaying Medical Radioisotope Production



PROS	CONS
➢ *Type of beam flexibility with different targets* ➢ *Potential for minimization, possibility of "table-top" systems*	➢ *Presently low repetition rate, Hz level with ≤ PW lasers* ➢ *Radiochemistry needs to be optimised*

Towards Societal Applications: Laser-driven radioisotope production

- ***The full chain of radioisotope production with lasers has never been demonstrated****. Small laser (hundreds of TW) systems have the greatest potential.*

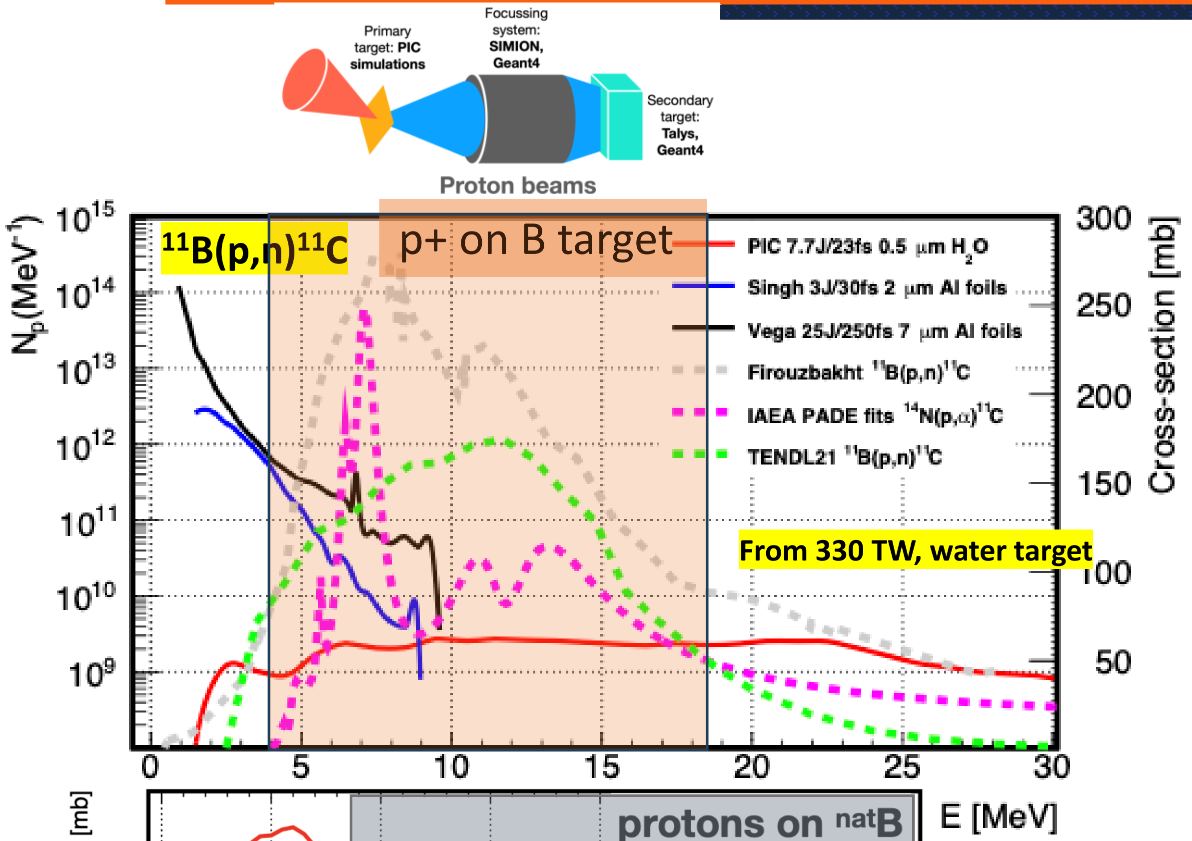
- *Several studies (review: Z.Sun AIP Adv. 2021) shown isotope production based on single/few shots events, and then extrapolated to hours beamtime.*

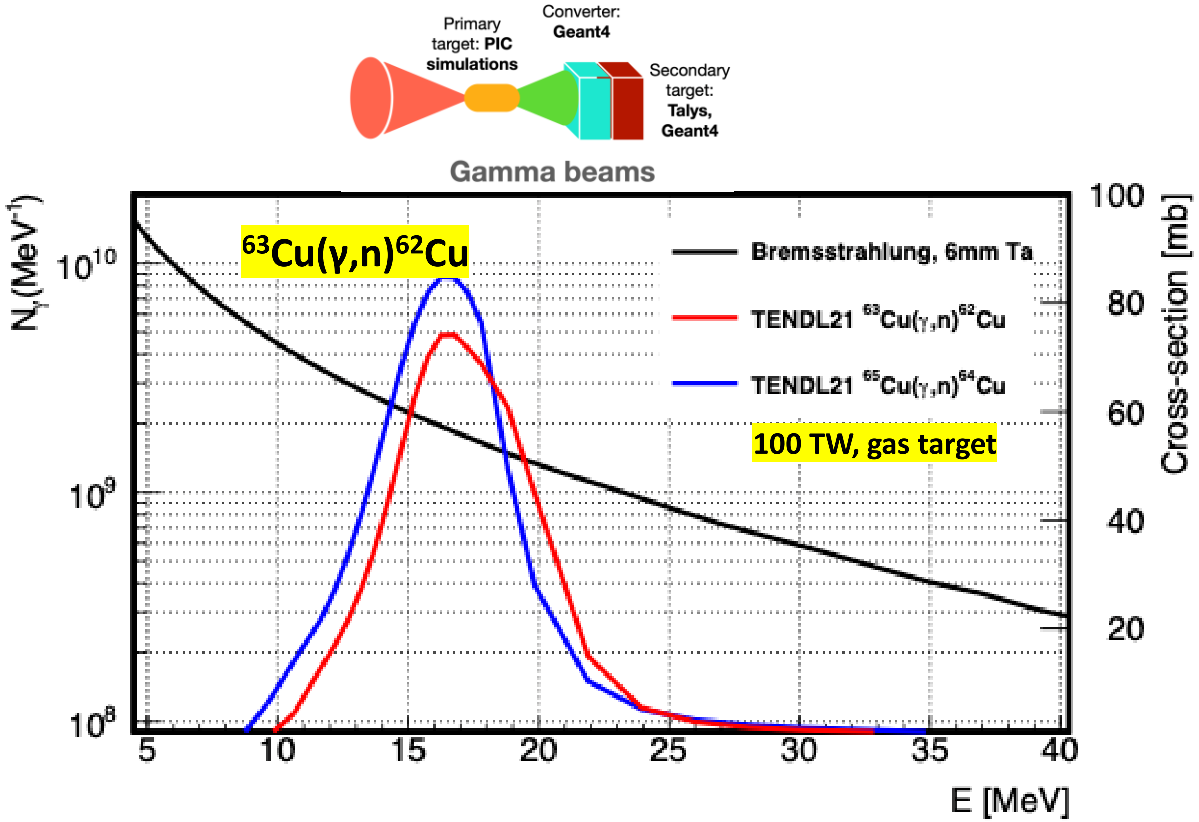
- *2 examples: ^{11}C with **proton** beams via **$^{11}B(p,n)^{11}C$** and ^{62}Cu with **gamma** beams via **$^{63}Cu(\gamma,n)^{62}Cu$** :*

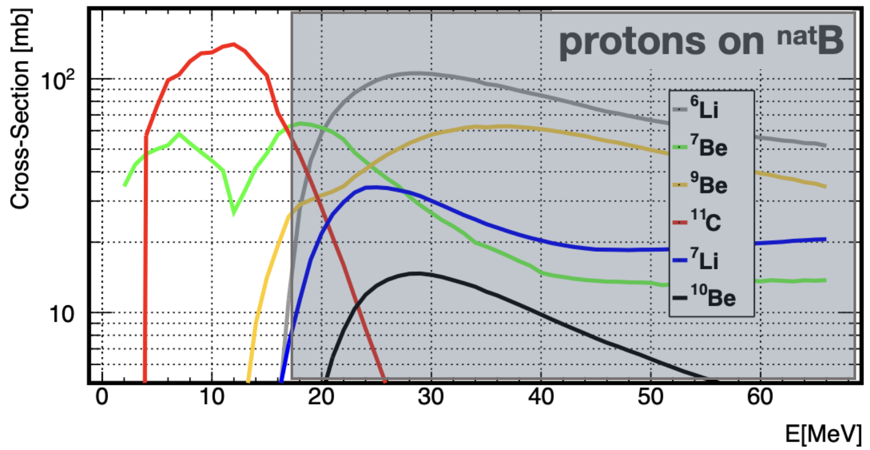
Ref. ^{11}C prod.	E [J]	Pulse T [fs]	Rep. [Hz]	Activ [MBq]	Obs.
Tayyab et al. 2019	2.4	25	1	9	**7-10 shots (2-3 min) meas. Cu,Al, Ni foils**
Singth et al. 2018	3	30	1	7.6	**Spectrum meas. Al foils, analysys in** *Penas et al.*
Penas et al. 2024	25	250	1	21.7	**174 shots at 0.1 Hz meas., Al foils**
ELI-NP estim.	**8**	**23**	**1**	**30**	**PIC + TENDL21 CS, water-leaf tg.**

Ref. ^{62}Cu prod.	E [J]	Pulse T [fs]	Rep. [Hz]	Activ [MBq]	Obs.
Ma et al. 2019	11.5	33	1	180	**PIC + Geant4, Varlamov CS**
Lobok et al. 2022	4	30	1	87	**PIC + Geant4**
ELI-NP estim.	**2.3**	**23**	**1**	**35**	**PIC + Geant4, TENDL21 CS.**

Towards Laser-driven radioisotope production: Challenges



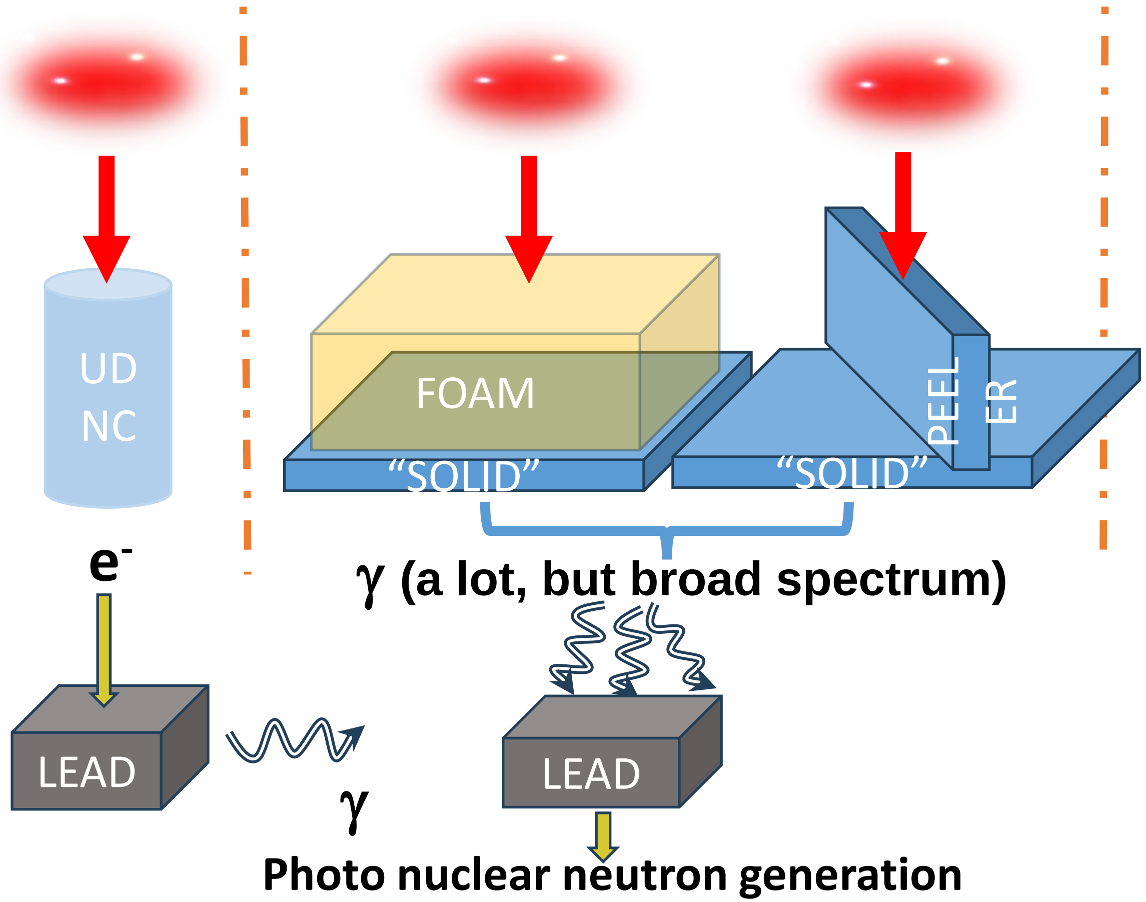


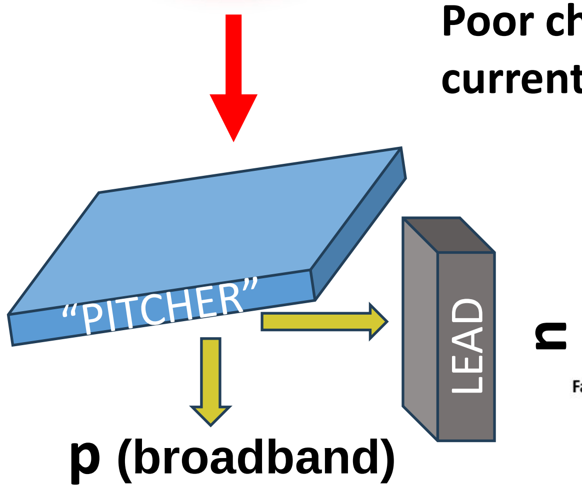


- ➢ *laser-based isotope production channels might be different wrt the cyclotron-based reactions due to the different beam characteristics → **need for fast radiochemistry of "non-traditional" channels.***
- ➢ *Need for isotope producing **targets optimized** for laser-based production and **efficient focusing** system (contaminants, specific activity, radiochemistry).*

Neutron sources

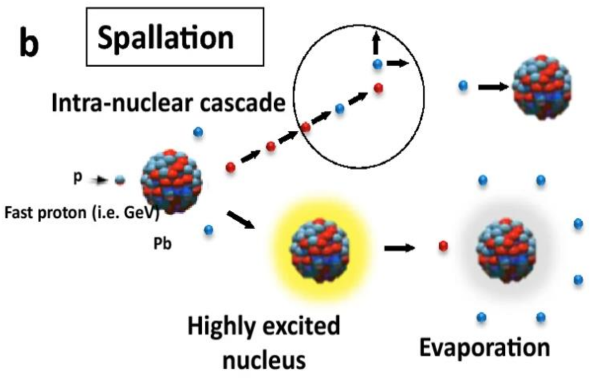
Paths for fast neutron generation at ELI-NP

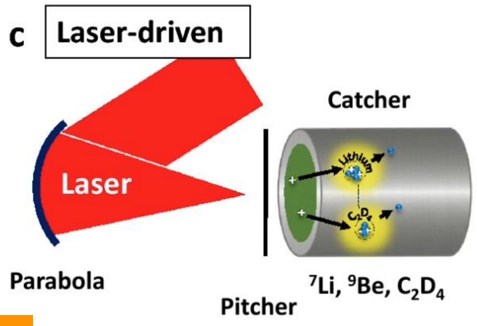




Spallation with Pb needs GeV scale proton beams

Poor chances to go there soon with current lasers/ideas





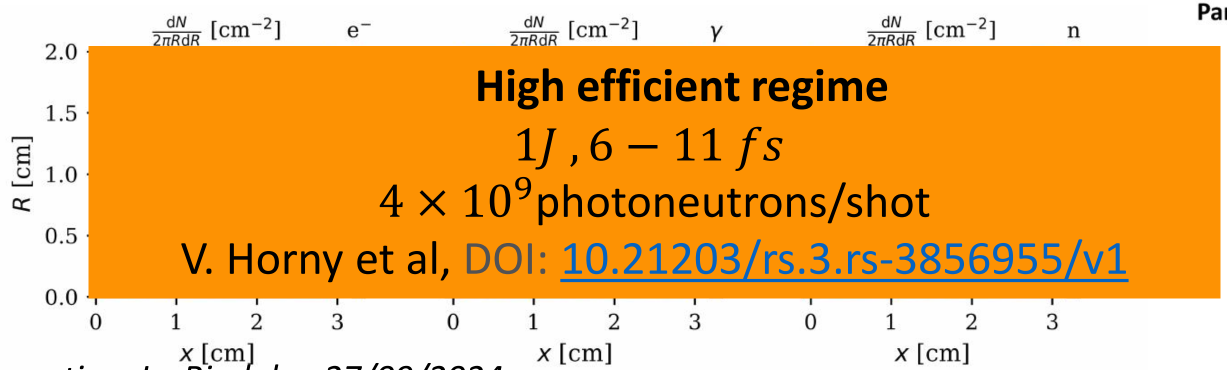
$^2_1d(\bar{d},n)^3_2He$ and $^7Li(p,n)^7\bar{Be}$

scientific reports

https://doi.org/10.1038/s41598-020-77086-y

OPEN **Proof-of-principle experiment for laser-driven cold neutron source**

S. R. Mirfayzi[1,2], A. Yogo[1], Z. Lan[1], T. Ishimoto[1], A. Iwamoto[3], M. Nagata[1], M. Nakai[1], Y. Arikawa[1], Y. Abe[1], D. Golovin[1], Y. Honoki[1], T. Mori[1], K. Okamoto[1], S. Shokita[1], D. Neely[4], S. Fujioka[1], K. Mima[5], H. Nishimura[1,6], S. Kar[4,7] & R. Kodama[1]



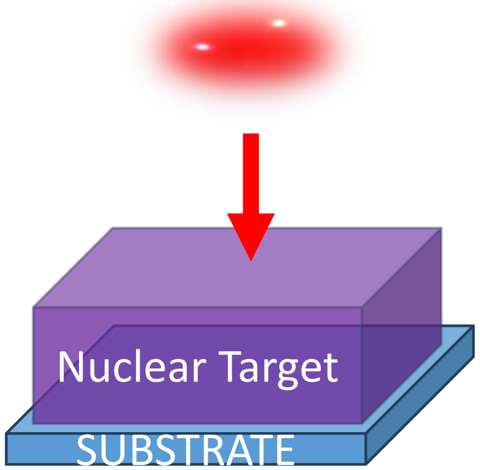
High efficient regime

$1J\,, 6-11\ fs$

4×10^9photoneutrons/shot

V. Horny et al, DOI: 10.21203/rs.3.rs-3856955/v1

Laser-Driven Nuclear Reactions



Laser Boron Fusion Reactor

H. Hora *et al.*, "Laser Boron Fusion Reactor With Picosecond Petawatt Block Ignition," in *IEEE Transactions on Plasma Science*, vol. 46, no. 5, pp. 1191-1197, May 2018, doi: 10.1109/TPS.2017.2787670.

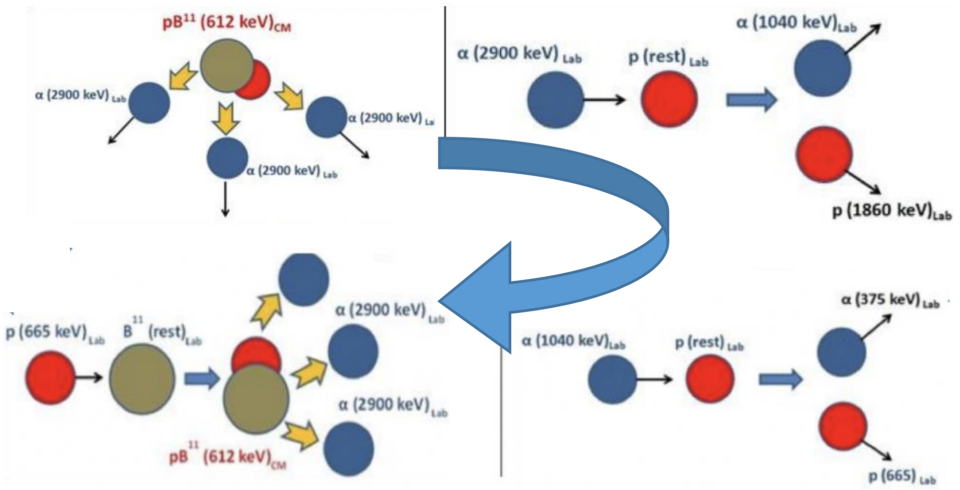
Aneutronic fusion of hydrogen with the boron isotope 11, **$H^{11}B$**.

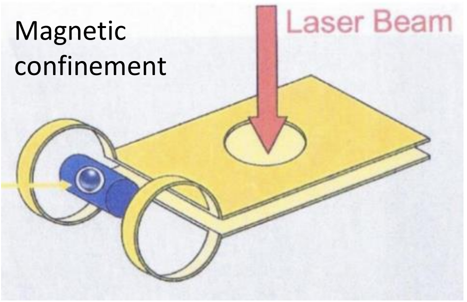
At local thermal equilibrium, is 10^{5} times more difficult than fusion of deuterium and tritium (DT)
But at extreme nonequilibrium plasma conditions the fusion of $H^{11}B$ is comparable to DT fusion

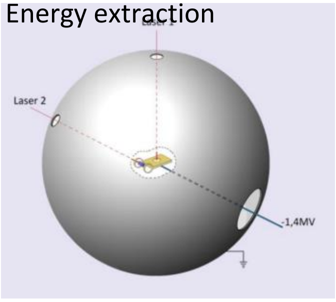
Method

- **H11B rod a cm size**
- **Main laser for driven-ignition:** 30PW laser energy and ps pulse duration
- **A second laser for magnetic field generation of ~10 kT:** 1kJ energy and ns pulse duration

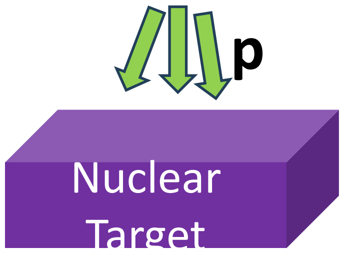
Nuclear reaction schema







Using a container electrostatically charged to -1.4 MV, it will be possible to generate about **277 kWh** of energy per laser **shot**.



Pitcher-Catcher Nuclear Reactions

Comments

Super short overview of similarities with EuPRAXIA and ELI-NP lines of research on NP:

NP with electron acceleration (LWFA, NCD) PWFA:

- ✓ Neutron generation with LWFA + bremsstrahlung **[Suitable for the 2nd site+Short parabola]**
- ✓ Fast radioisotopes generation with gamma induced reactions **[Suitable for 2nd site+Long parabola, Marginally suitable for the 1st site]**
- ✓ Gaussian and Laguerre Gaussian gamma beams through CBS and isomers generation/NP studies **[Suitable for both sites+Long parabola]**

NP with laser/"solid" ion acceleration:

- ✓ In Target fusion preparation studies **[Marginally suitable]**
- ✓ Neutron generation from protons **[Suitable for the 2nd site+Short parabola]**
- ✓ Fast radioisotopes generation with protons induced reactions **[Suitable for the 2nd site+Short parabola]**
- ✓ Isomers generation by "nuclear excitation by electron capture" (NEEC) " **[Not shown, Marginally suitable]**

Any collaboration between EuPRAXIA and ELI-NP is welcome, also for testing some acceleration modules.