Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

Facility development at CNR-INO

towards EuPRAXIA 2nd site

Leonida A. Gizzi, CNR-INO and INFN

28/02/2023, INFN, Roma

CNR, Area della Ricerca del CNR, Pisa

Intense Laser Irradiation Laboratory

Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

CNR INO CONSIGLIO NAZIONALE DELLE RICERCHE ISTITUTO NAZIONALE DI OTTICA

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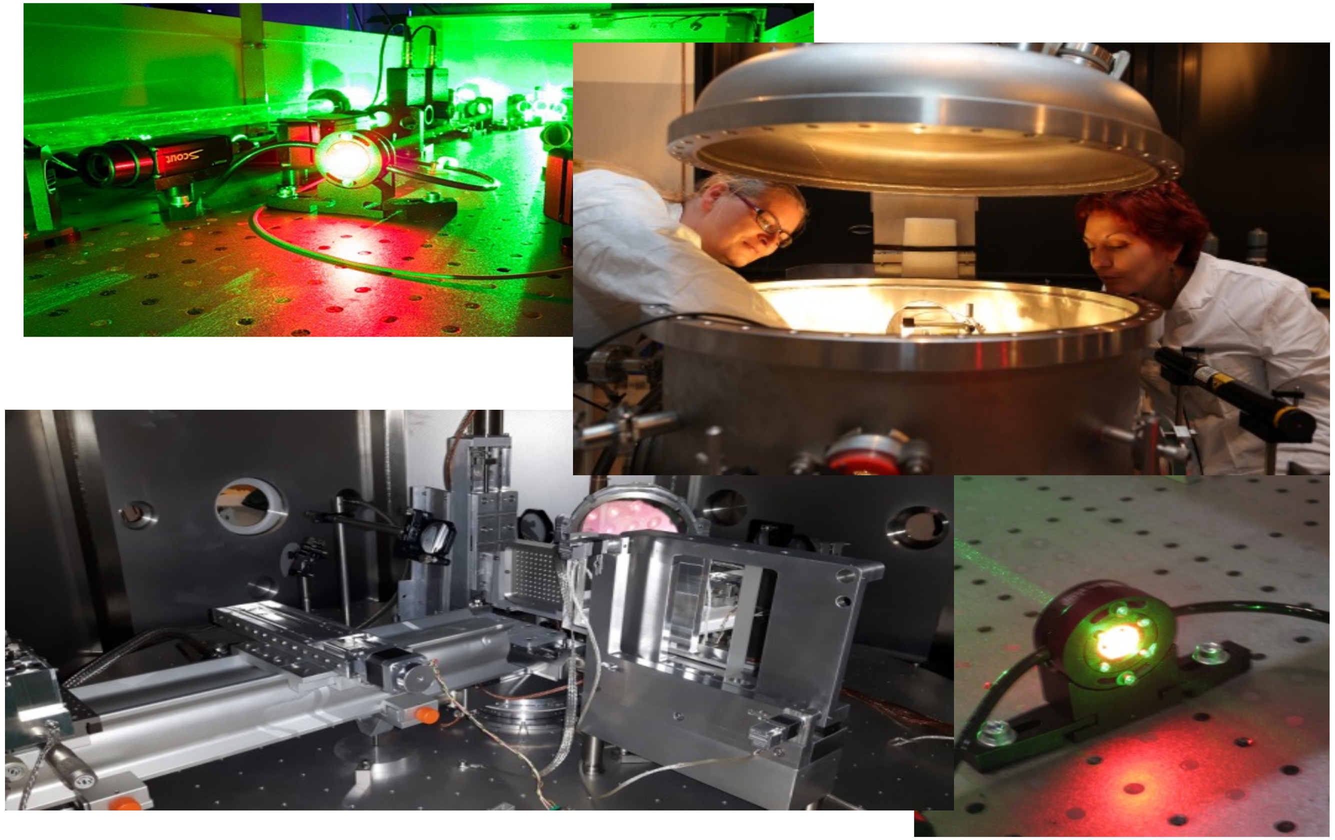
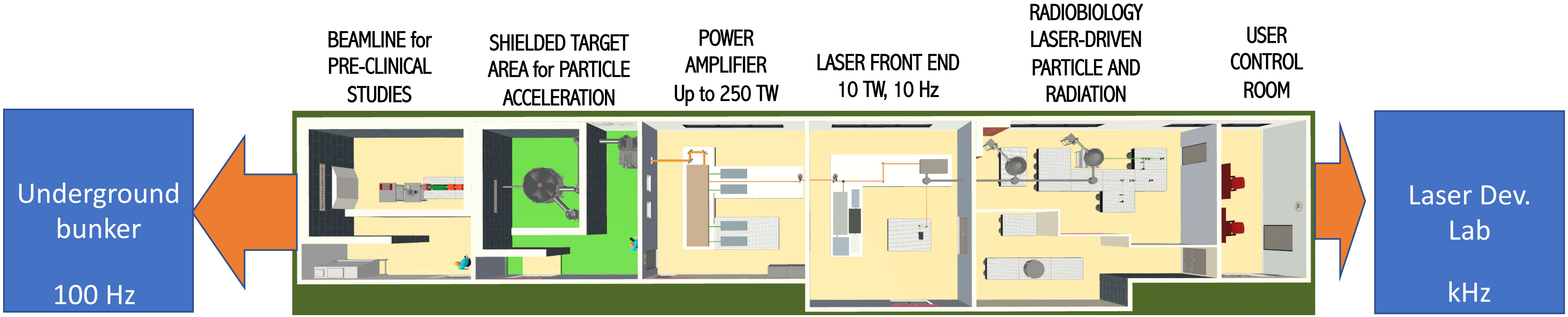


http://www.ilil.ino.it

SYNERGY WITH PNRR RESEARCH INFRASTRUCTURES *IPHOQS* AND *EUAPS*



UPGRADE OF ILIL FACILITY FOR:

1. Upgrade of existing laser system (240 TW) for enhanced stability and control
2. New laser systems for high repetition rate operation (100 Hz-1J, 1kHz-20 mJ)
3. New Infrastructure development for user access to beamlines

Part of : PNRR I-PHOQS INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES

Strong link with eli ESFRI

Part of : PNRR EuPRAXIA Advanced Photon Source

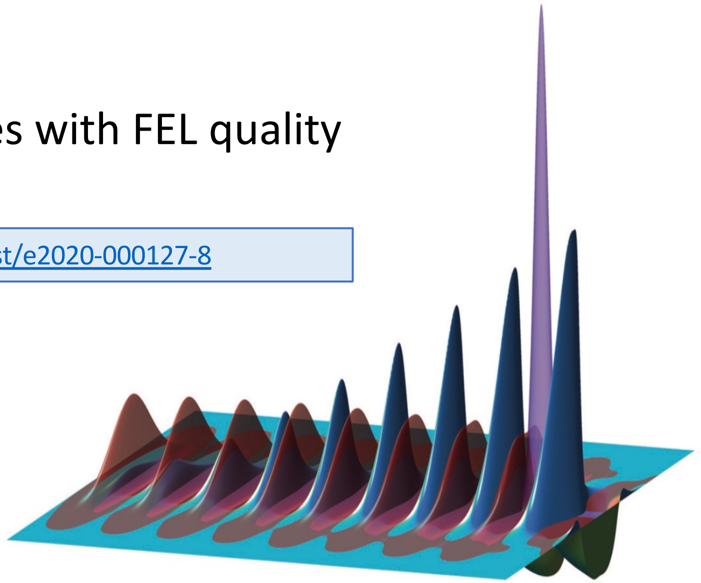
MAIN SCIENTIFIC ENGAGEMENT

High intensity laser-plasma interaction physics and applications

- VHEE beamline for medical applications (PNRR Tuscan Health Ecosystem)
- High quality GeV electron beamline design (Eupraxia design study)
- Advanced laser-target interaction for TNSA proton beamline and applications
- 100 Hz beamline (EuAPS WP4 and EuPRAXIA front end development case)
- kHz laser technology development for high efficiency operation
- kJ, laser concept development and LPI studies for Inertial Fusion (HiPER+)
- Laser-grade ceramics development, characterization and optimization (LACE)
- Materials studies for fusion reactor studies (ENI)
- Integration of user facility operation (LASERLAB)

HIGH QUALITY GEV SCALE LWFA

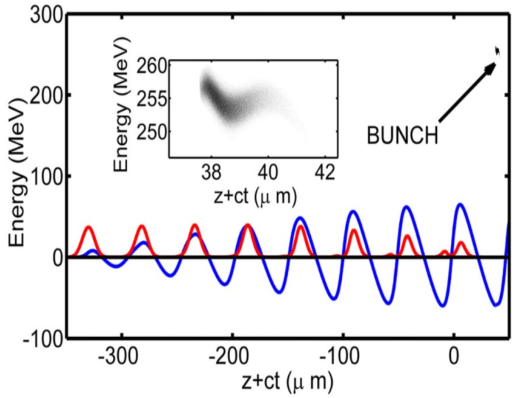
Motivation: Within the EuPRAXIA project we aim at generating 4.5/5GeV bunches with FEL quality



R. Assmann et al., "EuPRAXIA Conceptual Design Report" The European Physical Journal Special Topics **229**, 3675–4284 (2020); https://doi.org/10.1140/epjst/e2020-000127-8

Bunch specifications - GOAL:	dE/E SLICE	ε_n SLICE	Q	I_{peak}
	<0.1%	**<0.1 mm mrad**	>30 pC	>2kA

- This is a very challenging working point for a plasma-based accelerator.
- We developed a laser-driven scheme, the *Resonance Multi-Pulse Ionization Injection scheme (REMPI [1])*
- The REMPI scheme combines the most advanced concepts conceived to date in LWFA to deliver high quality electron beam to drive an X-ray FEL.



Test platform: P. Tomassini et al., "The resonant multi-pulse ionization injection," Physics Of Plasmas 24, 103120, 2017.

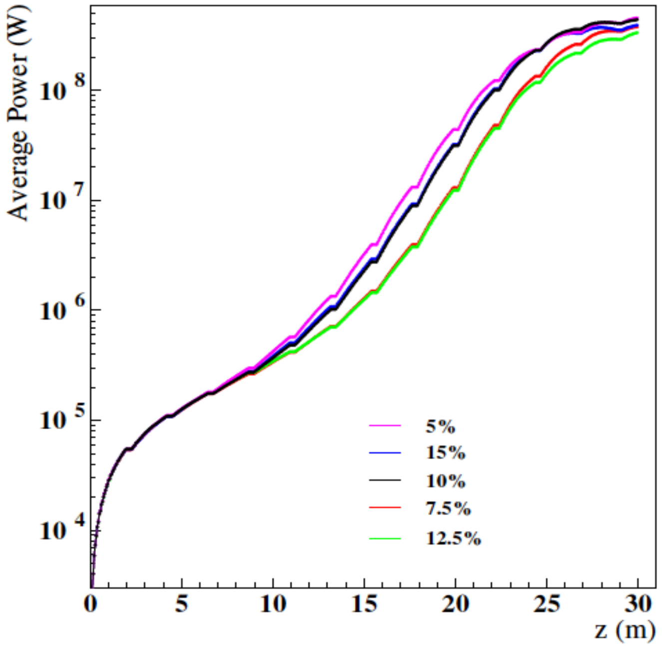
[1] P. Tomassini et al., *Physics of Plasmas 24, 103120 (2017)*

FEL EMISSION MODELLING

Laser-plasma REMPI SCHEME → TRANSPORT to undulator → FEL emission

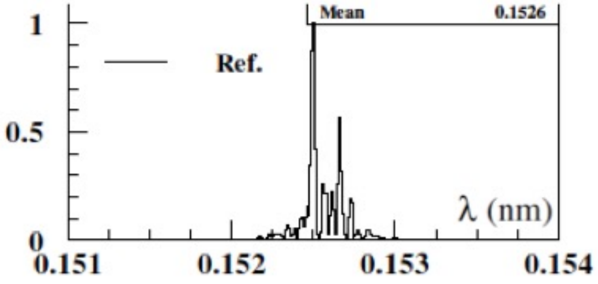
Up to 39 m planar undulator line with period λ_u = 14 mm, with $E_{beam} \approx 4.5$ GeV, the resonant wavelength of 1.5 Å.

The Self-Amplified Stimulated Emission (SASE) vs. pulse energy, gain length and resonant wavelength



e-beam	L_G [m]	$E_p(z_{exit})$ [μJ]	λ_{exit} [nm]
7.5%	1.753	9.28	0.152619
15%	1.781	9.60	0.152533
5%	1.912	11.15	0.152546
12.5%	1.756	8.22	0.152574
10%	1.791	10.78	0.152568
RMS	0.065	1.6	0.000033

Emission stable against plasma density variations (10%)



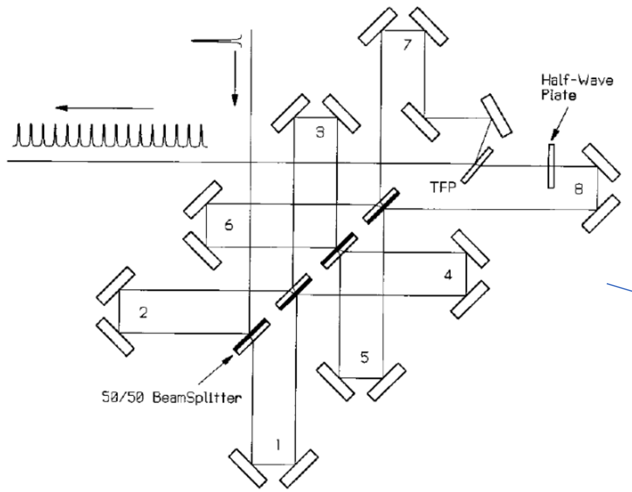
SIS 1.3 simulations by **Federico NGUYEN** (ENEA, Frascati)

Now working on the proof of principle implementation

P. Tomassini, L. Giannessi, A. Giribono, F. Nguyen, and L. A. Gizzi, “Brilliant X-Ray Free Electron Laser Driven by Resonant Multi-Pulse Ionization Injection Accelerator”, presented at the FEL2022, Triest, Italy, Aug. 2022, paper TUP17.

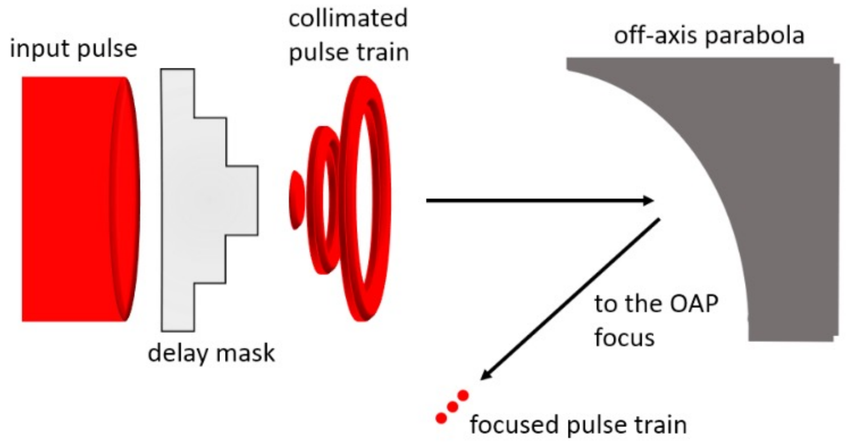
MULTI-PULSE LASER GENERATION

N-Michelson interferometers



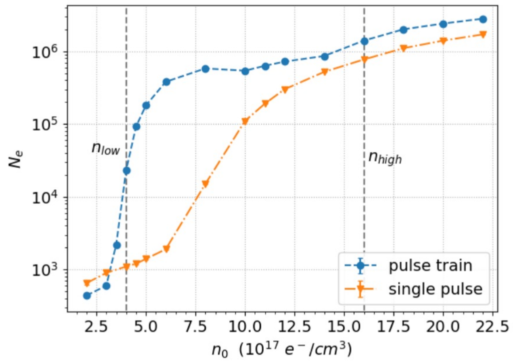
C. W. Siders et al., "Efficient high-energy pulse-train generation using a 2n-pulse Michelson interferometer," Applied Optics Vol. 37, Issue 22, 1998.

Large beams: Delay mask

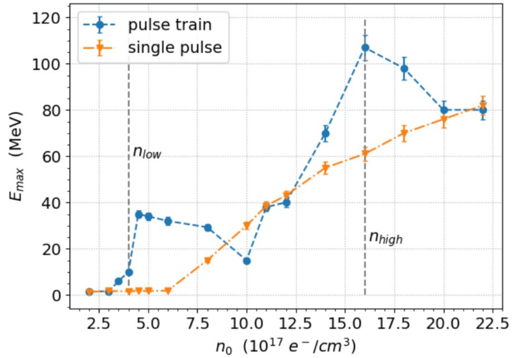


A. Marasciulli, PhD thesis, 2023

Proof of principle validation using a two pulse "train", in progress



(a) Number of accelerated electrons versus target density



(b) Maximum electron energy versus target density

TOWARDS EuPRAXIA LASER DEVELOPMENT FOR 2nd SITE

- Three main modules: LASER1, LASER2, LASER3
- LASER1: stand-alone for LPI 150 MeV
- LASER2: output stage for LPI 1 GeV, second stage for LPA 5GeV
- LASER3: high energy stage for LPA 5GeV
- Two levels of performance : P0 and P1

EUAPS

LASER FRONT-END
100 HZ
J-SCALE

LASER1
E_{out} 8.8 J (P0) / 12.5 J (P1)
E_{pump}: 19.2J (P0)/ 25.7 J (P1)
To the compressor

LPI 1GeV

LASER1
E_{out} 8.8 J (P0) / 12.5 J (P1

LASER2
E_{out} 18.8 J (P0) / 37.5 J (P1)
E_{pump}: 37.2J (P0)/ 65.2 J (P1)
To the compressor

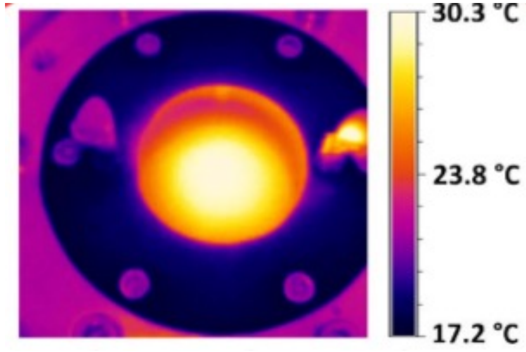
LPA 5GeV

LASER1
E_{out} 8.8 J (P0) / 12.5 J (P1)

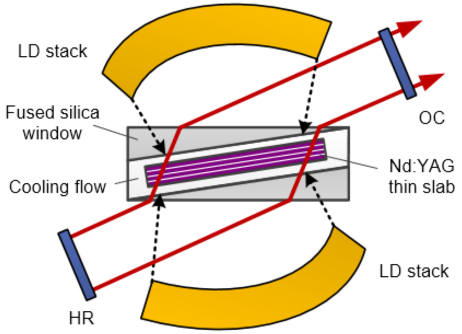
LASER2
E_{out} 18.8 J (P0) / 37.5 J (P1)

LASER3
E_{out} 62.5 J (P0) / 125 J (P1)
E_{pump}: 105J (P0)/ 197 J (P1)
To the compressor

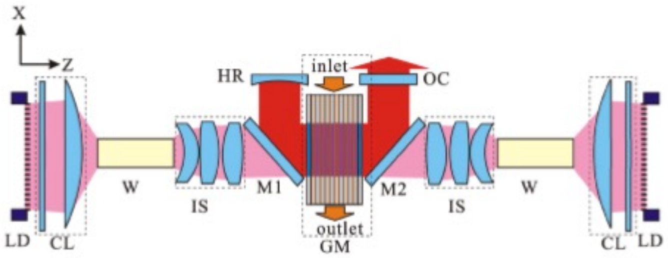
HIGH ENERGY AMPLIFIER DEVELOPMENT: THERMAL MANAGEMENT



Water cooled Ti:Sa amplifier ("Active Mirror" configuration) under development at ELI-HU (After V. Cvhykov *et al.* , Opt. Lett, **41,** 3017, 2016)



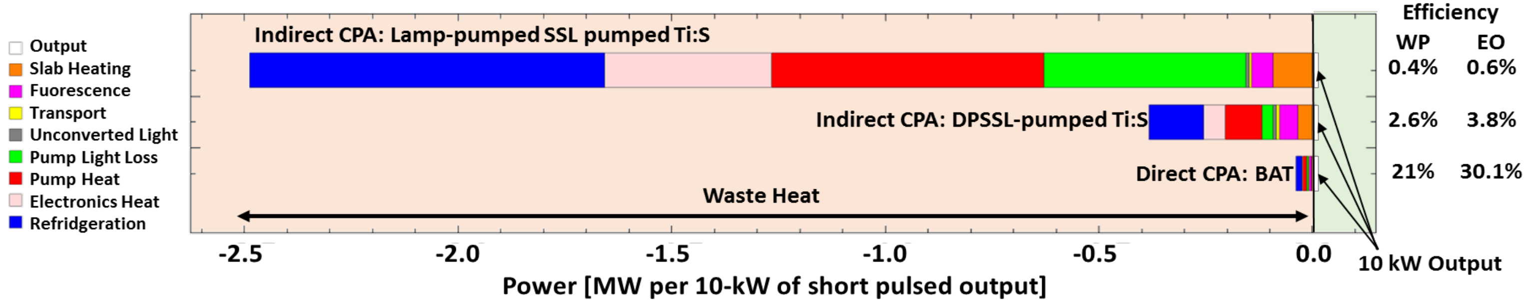
Fluid (D_2O) cooled 3 kW Nd:YAG laser, 20 kW CW pump power, D_2O (After X. Fu *et al.* , Opt. Express, **22**, 18421 (2014)



Fluid (Siloxane) cooled Nd:YLF laser, 5 kW CW pump power (After Z. Ye *et al.* , Opt. Express, **24**, 1758 (2016)

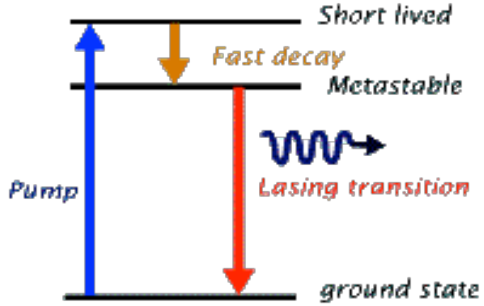
LASER DRIVER EFFICIENCY PATH

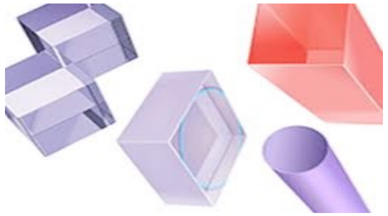
From flashlamp to indirect to direct diode pumping



C. Siders et al., EAAC 2017

Quantum defect



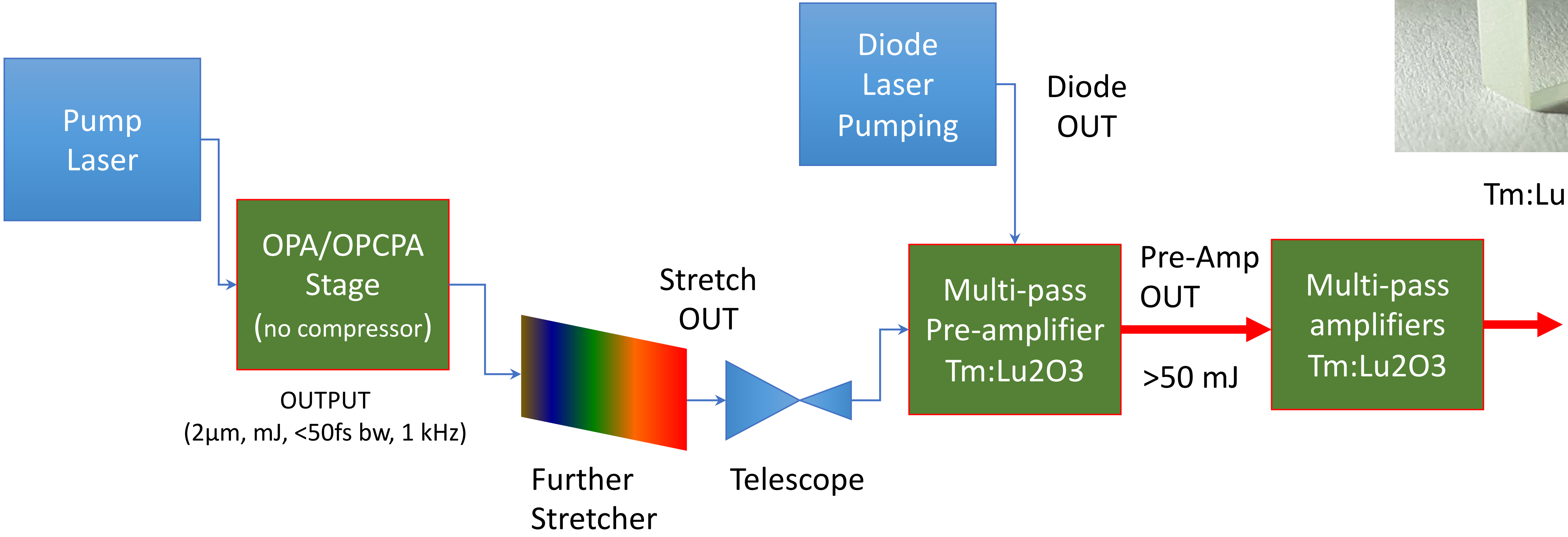


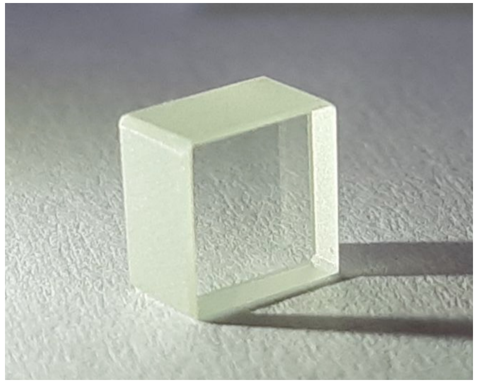
WP Efficiency > 50% possible:
e.g. Yb-doped medium

We need a **gain medium** that can support amplification on a large bandwidth, has a **low quantum defect** and can be pumped **directly** with diode lasers:
under study Tm:Lu2O3

A kW-kHz CPA LASER DEVELOPMENT WITH DIRECT DIODE PUMPING

Development of a new laser platform «APOLLO»





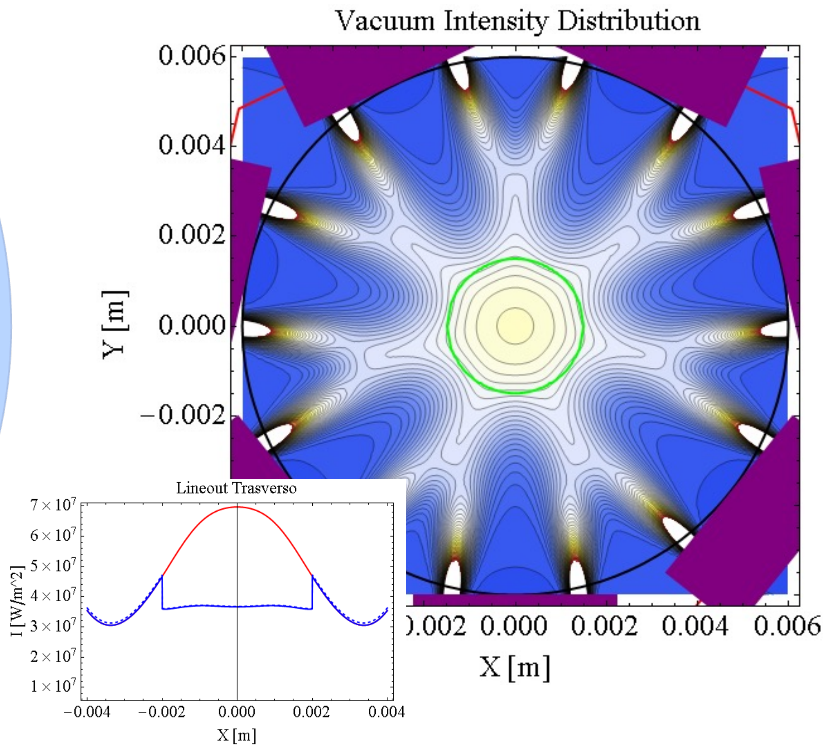
$Tm:Lu_2O_3$

Main development effort in amplifier modules

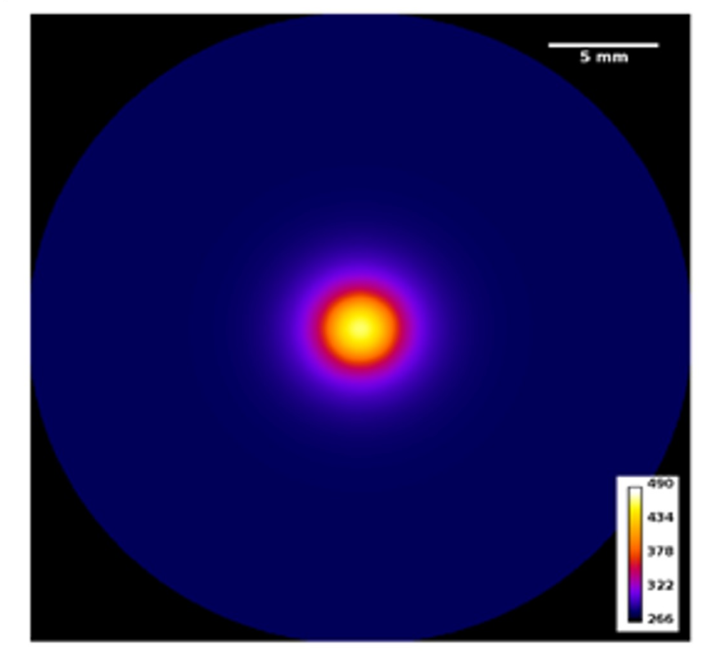
ACTIVE MIRROR AMPLIFIER DEVELOPMENT

Geometry

Edge Pumping



Thermal load



Diodes total power: **1950 W,** Diodes energy (1ms): **1.95 J,** Linear bar power: **19.4 W/mm => 1 J output**

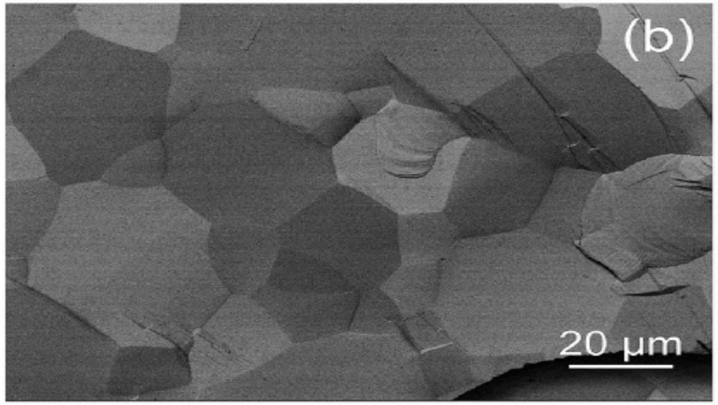
[1] J. Vetrovec, et al., "Wide-Bandwidth Ceramic Tm:Lu2O3 Amplifier", Proc. SPIE 9834, 983407 (2016); doi:10.1117/ 12.2224411
[2] J. Vetrovec, et al., "2-micron lasing in Tm:Lu2O3 ceramic:initial operation", Proc. SPIE 10511, 1051103 (2018); doi:10.1117/ 12.2291380

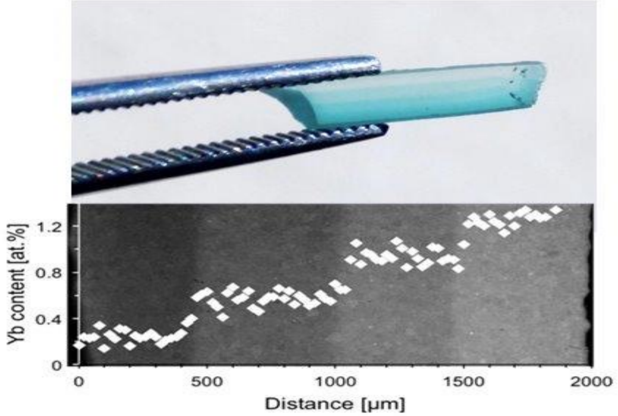
LASER GRADE CERAMICS

- Faster and cheaper vs. single crystal growth process.
- Large components, -shaping, -graded doping also optimized for thermal management – **features not available for single crystals.**
- Several compositions (e.g. **YAG, LuAG , Sc_2O_3, Lu_2O_3**) and dopants (**Nd, Yb, Er, Tm**…) already available
- Spectroscopic and thermomechanical properties similar to those of the corresponding single crystals
- Better uniformity of dopant distribution on large gain elements

Industrial and R&D effort: KONOSHIMA (Japan); Research in China, Japan, Russia, USA, France and Italy (ISTEC-CNR) (ZENITH Smart Polycrystals)

ZENIT Smart Polycrystals

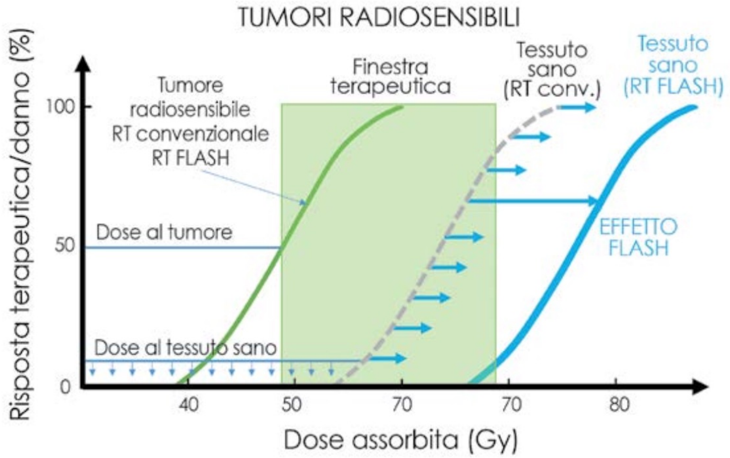




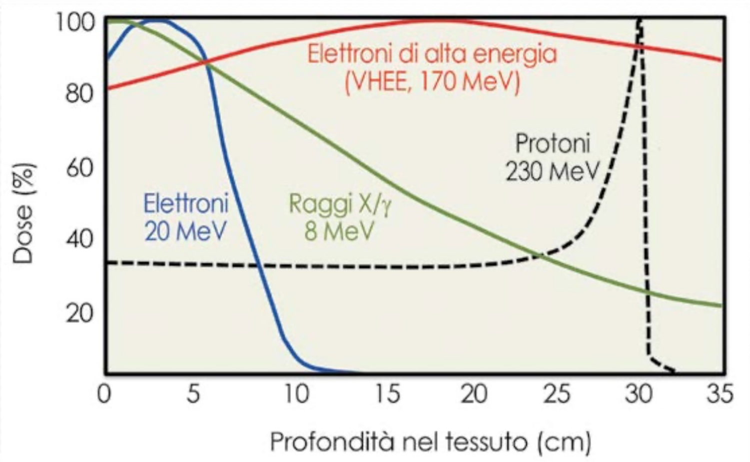
"LACE" EDF Proposal Submitted (Large European consortium)

NOVEL BEAMS FOR RADIOTHERAPY

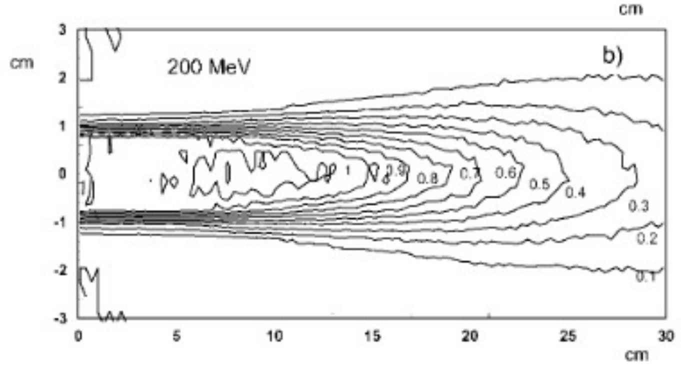
High dose-rate radiobiology and the “FLASH effect”



V. Favaudon et al., *Science Translational Medicine* **6**, 245ra93 (2014)



VHEE beams



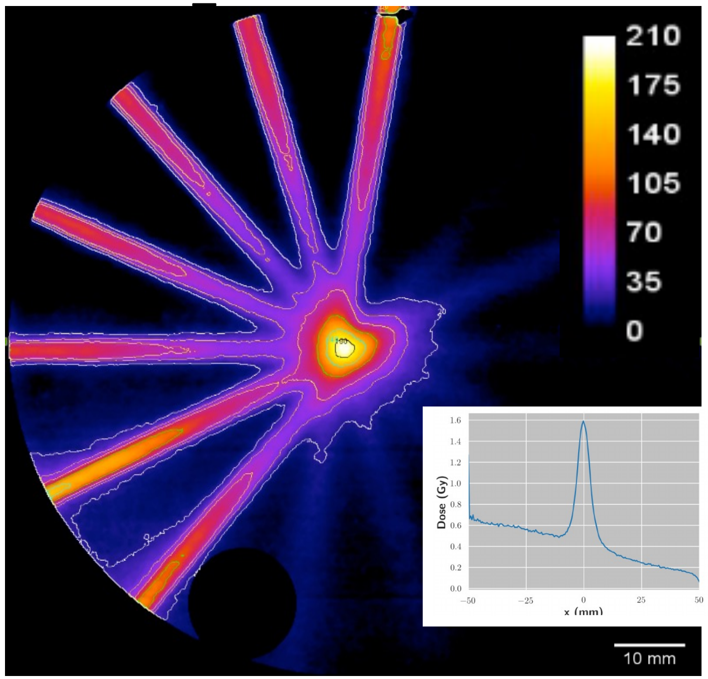
- Same therapeutic effect on tumor tissue
- Sparing of healthy tisssue

[1] C DesRosiers *et al* 2000 *Phys. Med. Biol.* **45** 1781,

Flash: dose to be delivered in a very short time <200 ms (to date)

FLASH compliant VHEE beam

MULTI_FIELD - 7-Fields irradiation

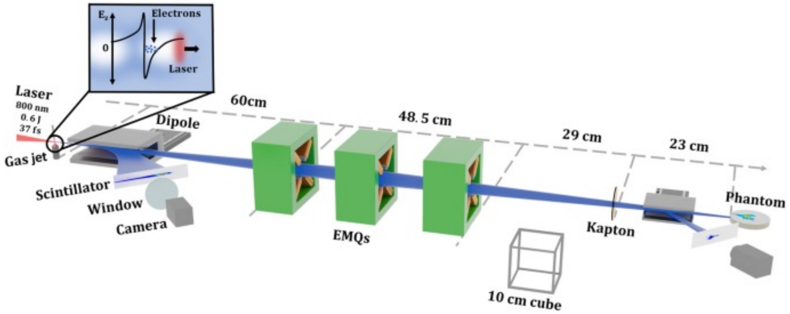


L. Labate et al., Scientific Reports **10**, 17307 (2020)

- **Increasing charge** and **focusing** can enable single pulse dose in the pencil beam at a few Gy per shot, very valuable for fundamental studies on the FLASH effect

Magnetic focusing

(challenging for broadband beams)



Svendsen et al., *Sci Rep* **11,** 5844 (2021).
https://doi.org/10.1038/s41598-021-85451-8

- In perspective, FLASH-RT needs therapeutic doses **(tens of Gy)** in a short time (**in 200 ms)**
- This is challenging for all accelerators (including RF): LPA needs high repetition rate (kHz)

“THE” Tuscany Health Ecosystem PNRR

Also in: FRIDA (CSN5) INFN

VHEE beam: enhancing charge and spectral control

Ionization injection with bubble shaping and extraction with plasma downramp

	ε_{nx} ($\times 10^{-3}$ mm)	σ_x (μm)	$\sigma_{p_x}/m_e c$
ramped	3.51	1.33	2.65
plateau	3.55	1.14	3.12

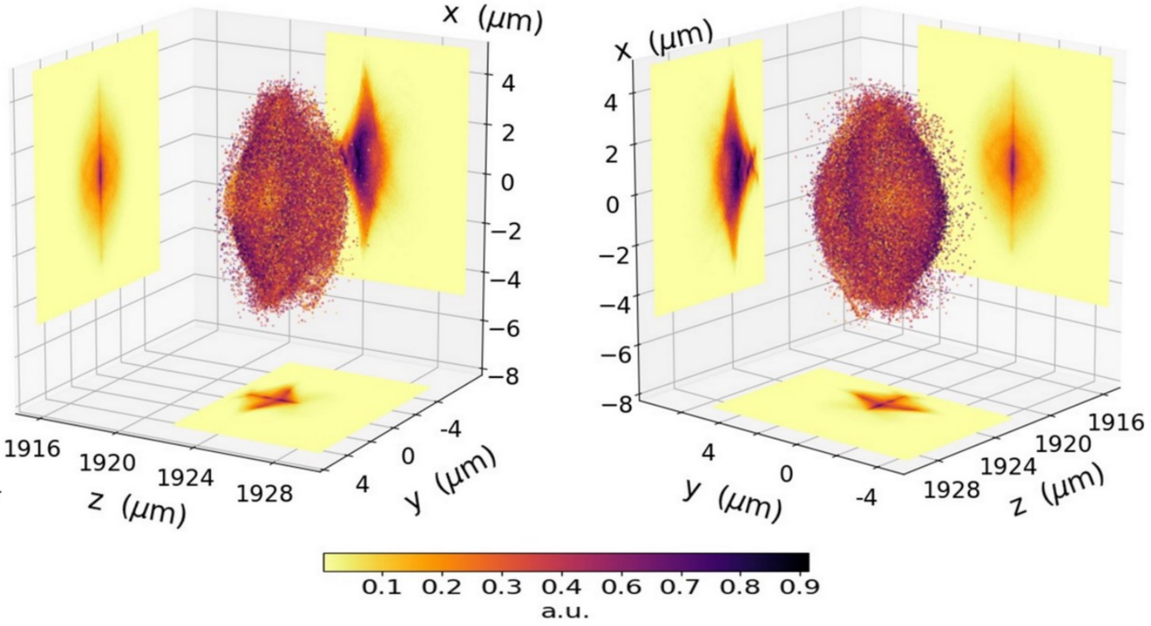
	ε_{ny} ($\times 10^{-3}$ mm)	σ_y (μm)	$\sigma_{p_y}/m_e c$
ramped	1.49	0.84	1.82
plateau	1.53	0.74	2.10

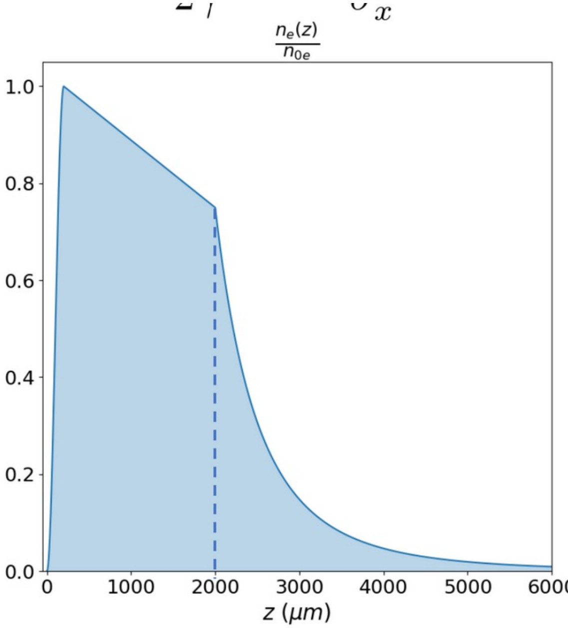
$2\sigma_x = 2.66\ \mu\text{m}$

$2\sigma_y = 1.68\ \mu\text{m}$

$2\sigma_z = 1.42\ \mu\text{m}$

- $\mathcal{E}_m = 195$ MeV
- $\sigma_{\mathcal{E}} = 6\%$
- $Q = 115$ pC





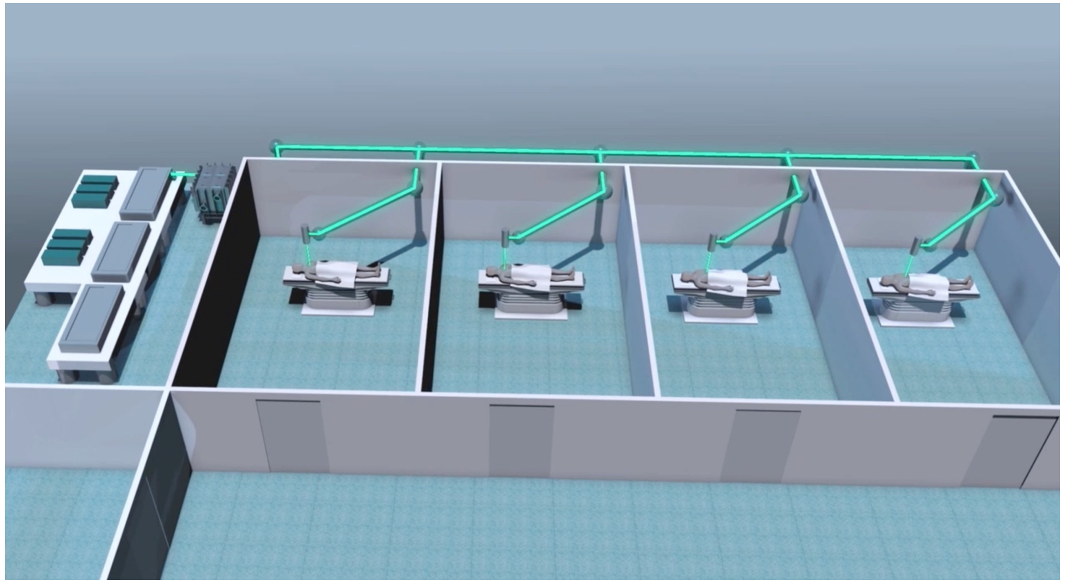
Federico Avella, 1st Degree Thesis, 2023

INDUSTRIAL DEVELOPMENT OF LASER DRIVEN VHEE BEAMS

Laser control and stability

LWFA at high repetition rate (100 Hz)

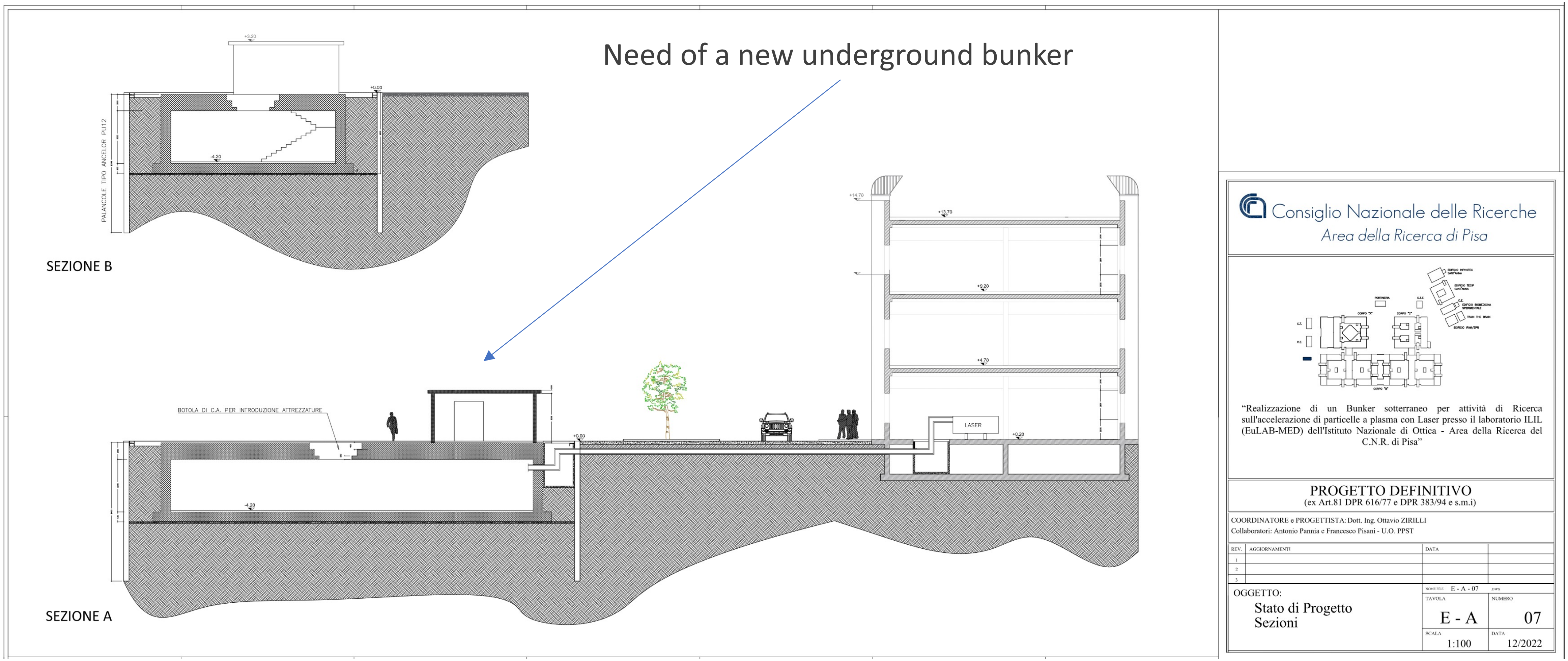
AI and ML accelerator management



EuPRAXIA is boosting these developments

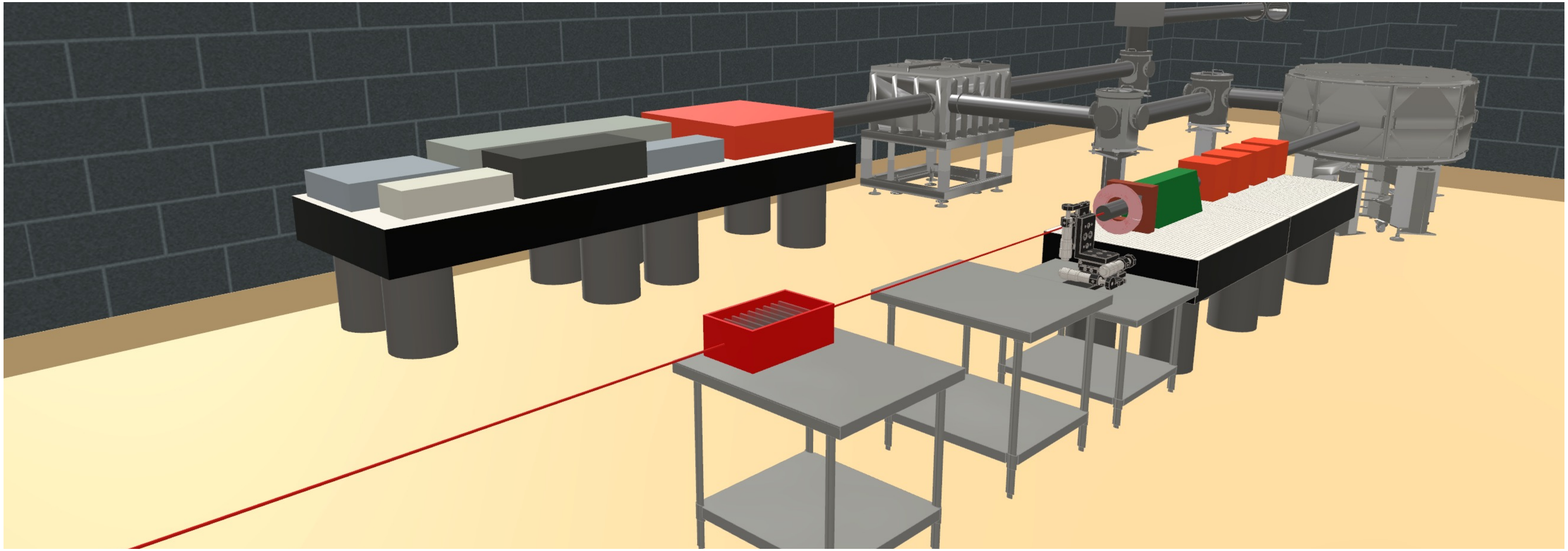
EXPANDING HIGH AVERAGE POWER (HIGH DOSE) OPERATION

100 Hz and kHz operation will generate significant more dose that current Hz or 10 Hz systems



UNDERGROUND BUNKER DESIGN

High dose-rate VHEE beamline and GeV Beamline development (240 TW)



Thank you

EuPRAXIA
Advanced Photon Source

I-PHOQS
INTEGRATED INFRASTRUCTURE INITIATIVE IN PHOTONIC AND QUANTUM SCIENCES