EuPRAXIA Doctoral Network

Activities at CNR-INO (Pisa, Italy)

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Luca Labate

Consiglio Nazionale delle Ricerche (CNR)

Istituto Nazionale di Ottica

Pisa, Italy

UK Research and Innovation

CNR Campus in Pisa

The Intense Laser Irradiation Laboratory (ILIL)

EuPRAXIA Doctoral Network

A node of the Italian ELI Network
A founding member of the EuPRAXIA infrastructure project

People

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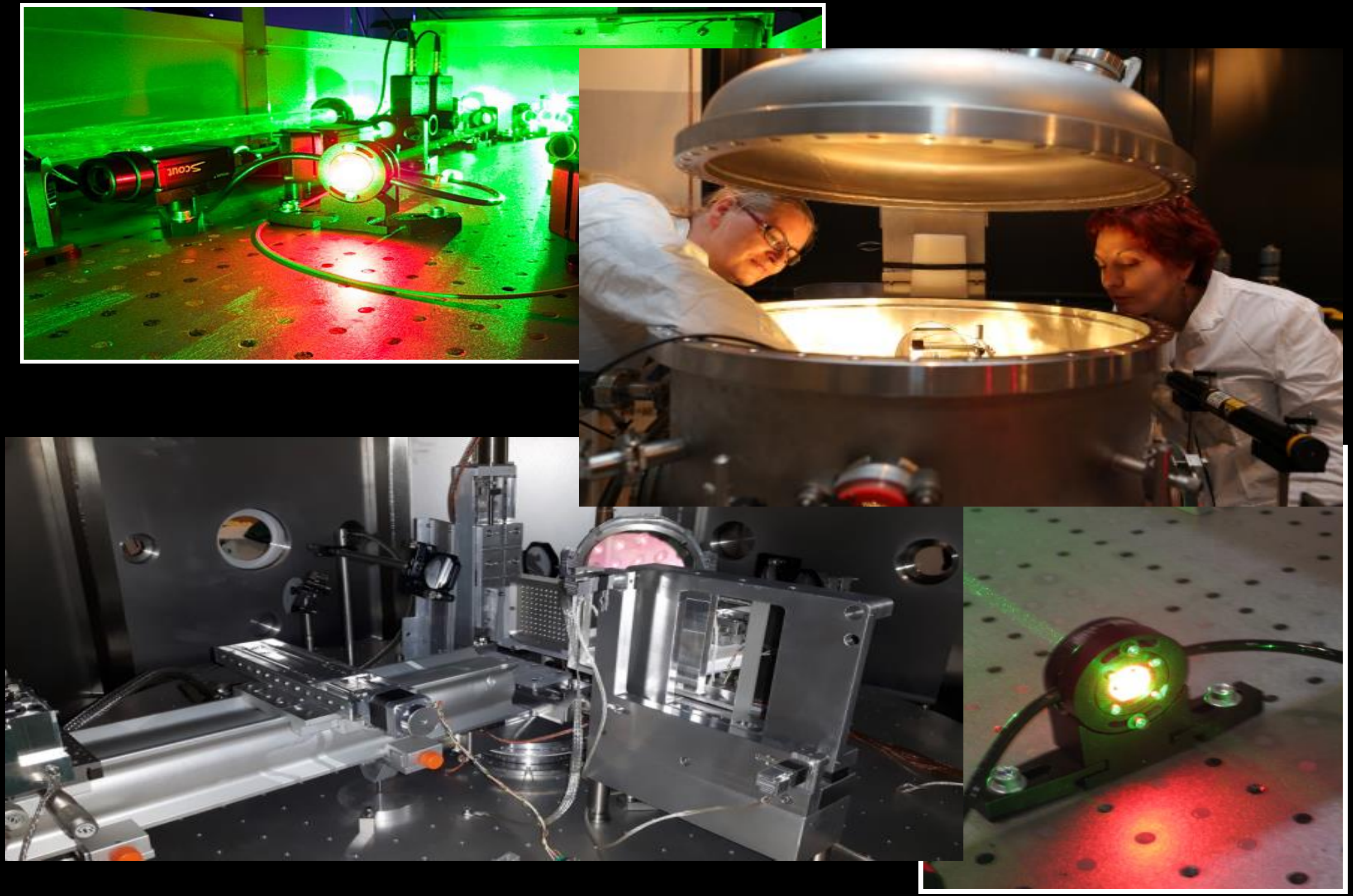

Research fields

Laser-driven particle acceleration
- High quality LWFA e- bunches
- LWFA VHEE for applications in radiotherapy
- TNSA proton beams for radiobiology

ICF experiments (energy coupling, instabilities,…)
R&D on high average power ultrashort lasers

http://www.ilil.ino.it

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The Intense Laser Irradiation Laboratory (ILIL): Lab layout (with ongoing upgrades)

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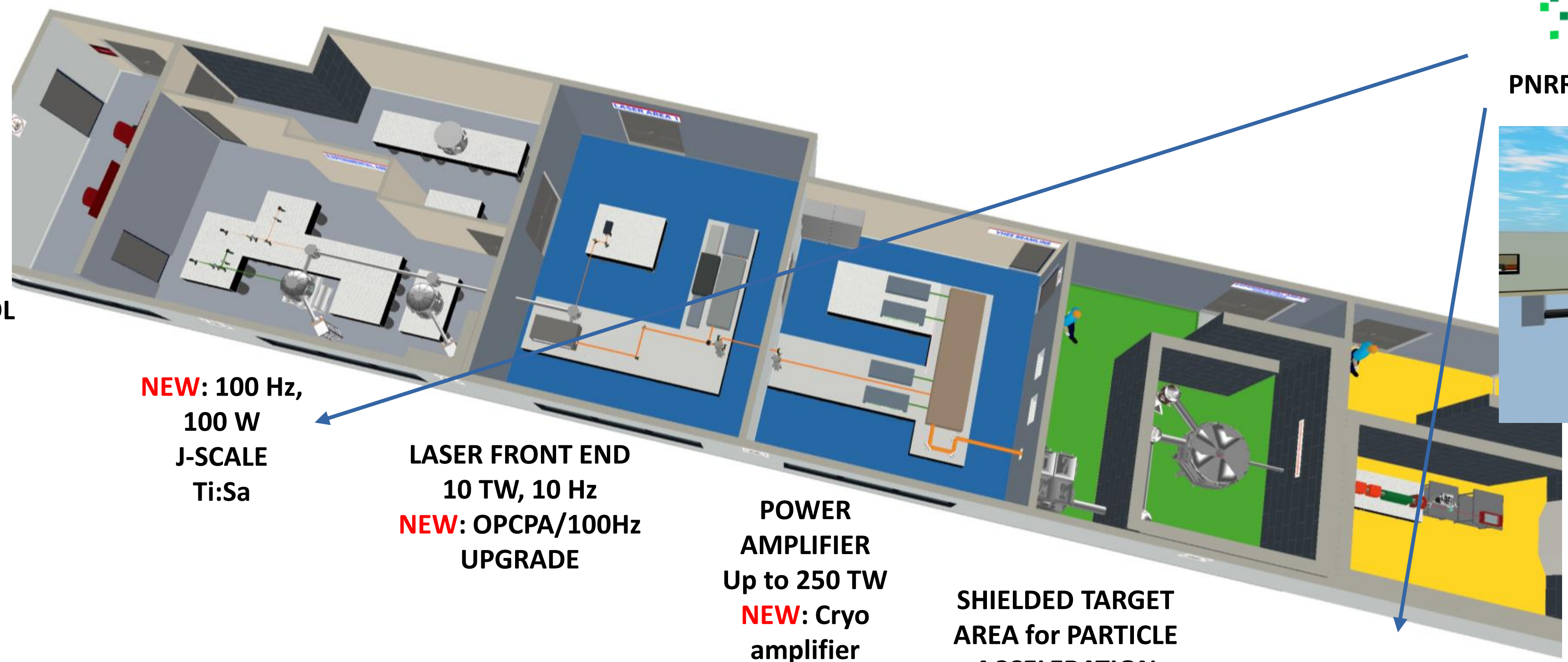
NEW: HAP kHz LASER DEV. LAB

USER CONTROL ROOM



NEW: 100 Hz, 100 W J-SCALE Ti:Sa

LASER FRONT END 10 TW, 10 Hz
NEW: OPCPA/100Hz UPGRADE

POWER AMPLIFIER Up to 250 TW
NEW: Cryo amplifier upgrade

SHIELDED TARGET AREA for PARTICLE ACCELERATION

NEW: BEAMLINE for *FLASH* PRE-CLINICAL STUDIES

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

PNRR (“Piano Nazionale di Ripresa e Resilienza”)

NEW: UNDER-GROUND BUNKER

The Intense Laser Irradiation Laboratory (ILIL): User infrastructure upgrades

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Major lab upgrade expected to be carried out over the next 24 months, funded within 3 NG-EU projects

- EuPRAXIA Advanced Photon Sources (EUAPS) project (INFN, CNR, UTV)
- Photonics and Quantum Science (IPHOQS) project (CNR, POLIMI, LENS)

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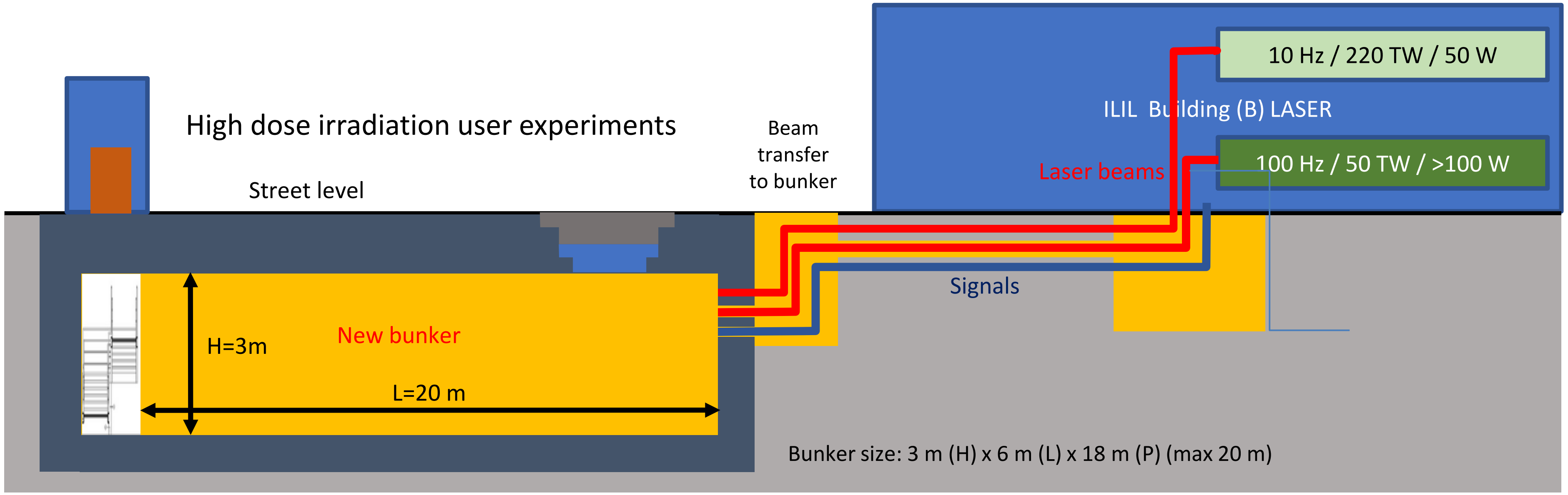
- Tuscany Health Ecosystem (THE) project (UniFirenze, CNR): radiobiology, dosimetry, RT planning for FLASH treatment with laser-driven VHEE beams



EUAPS WP2: High average power, high repetition rate laser beamline: 4.8 M€
IPHOQS A3.6 Ultrafast, high repetition rate radiation beamlines: 1.4 M€
IPHOQS A3.5: High Intensity, extreme laser beamlines*: 1.5 M€*

EUAPS

IPHOQS

R&D on ultrashort lasers at ILIL-INO-CNR: Laser development for future LPA

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Required specs of the EuPRAXIA laser very challenging

Eupraxia laser development is aimed at delivering more efficient, kW class PW laser driver for plasma acceleration at >100 Hz rate

Ultrashort pulses (large bandwidth <50 fs)
High repetition rate (100 Hz – 10 kHz)
High average power (~kW -10 kW)
High wall-plug efficiency (>30%)

- **CURRENT**
- **PW class,**
- **Hz repetition rate,**
- **≈10 W average power**
- **flashlamp pumped**
- **No thermal load transport**

EuAPS

- **EuAPS@CNR-Pisa**
- 30 TW peak power
- 100 Hz repetition rate
- 100 W average power
- Diode pumped
- Thermal load effects

- **EuPRAXIA**
- PW class,
- 100 Hz repetition rate,
- multi kW average power,
- diode pumped

"EuAPS" system at CNR: expected to match the final EuPRAXIA front-end laser specs

Research platform for studies in the field of high average power (high rep rate) laser optics, amplification and control

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R&D on ultrashort lasers at ILIL-INO-CNR: Toward 100Hz, kW power ultrashort systems

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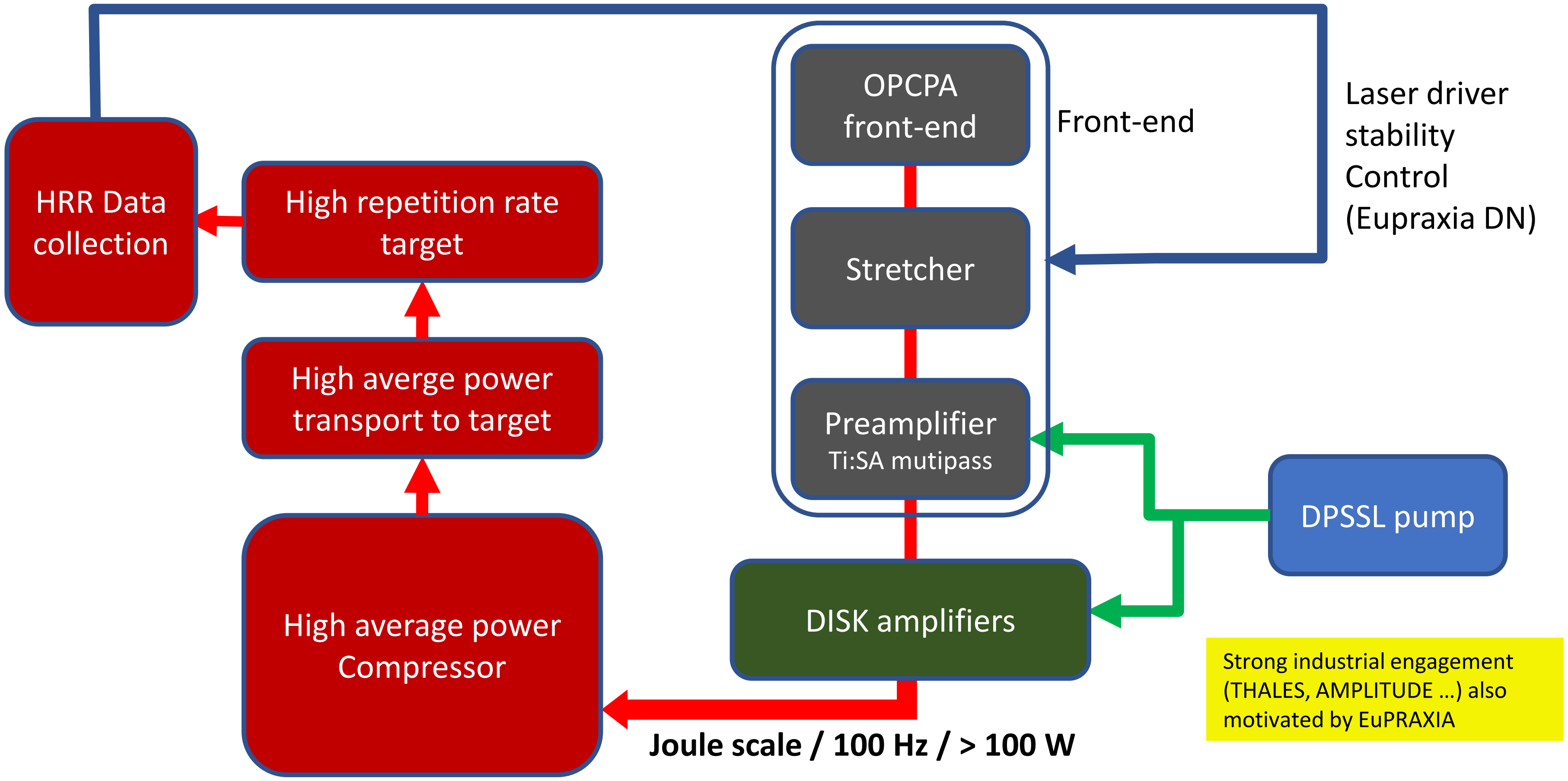

100 Hz, >100 W average power – Eupraxia front end and HAP R&D
High repetition rate target and data collection with ML stability loop (established collaboration with LASERIX and ISTI-CNR Pisa)

Toward kHz rep rate, kW power ultrashort systems based on the Multi-Pulse Extraction scheme

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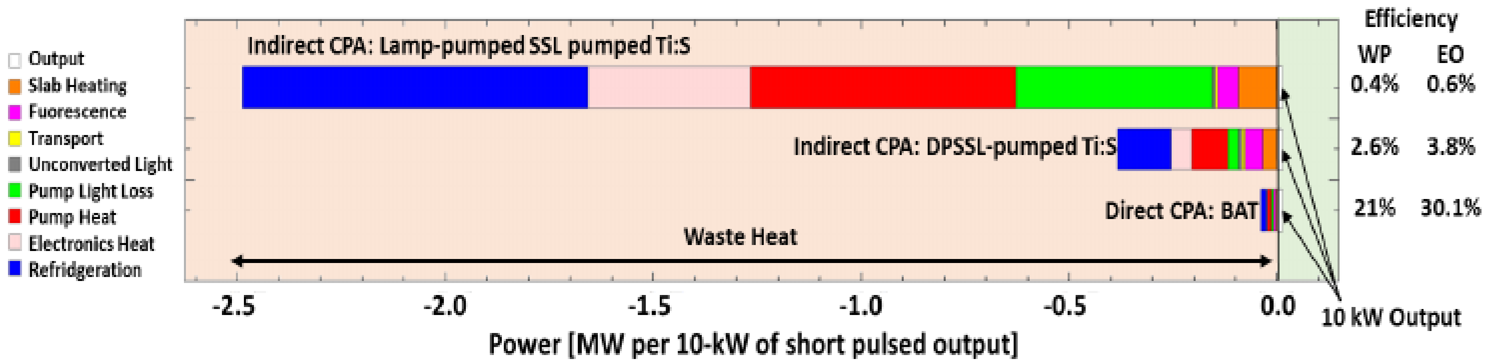
Report on Laser Technologies for kBELLA and beyond (2017)

2.C. Laser technology for a long-term 10 GeV, 100 kHz LPA collider module

- TiSa with incoherently combined pump lasers
- TiSa with diode pumped pump lasers (thick or thin disk)
- Tm:YLF with direct pumping CPA
- Fiber-based lasers with coherent combining

Due to efficiency limitations, TiSa-based technologies unlikely to go beyond the ~kW average power (could be used for injector stage or as single stage LPA for future light sources)

Tm based materials with Multi-Pulse Extraction



C. Siders et al., EAAC 2017

Multi-Pulse Extraction
- energy is stored over long (life)times (comparable to the inverse of the rep rate)
- possibility of (quasi)CW pumping, possibly with commercial diodes
- extraction fluence can be much lower than in SPE schemes (possibly affecting the B-integral, …)
- allows the usage of high saturation fluence materials → direct pumping, lower QD, ...

R&D on ultrashort lasers at ILIL-INO-CNR:
The APOLLO laser (kHz rep rate, ~1kW average power)

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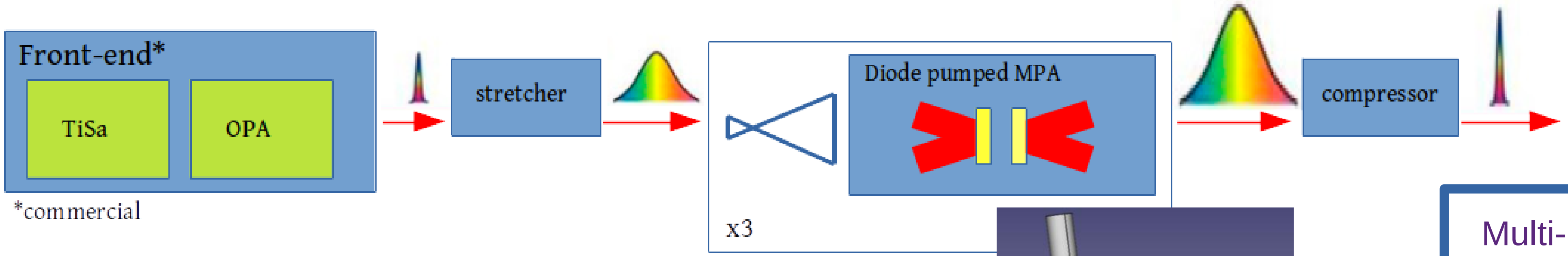
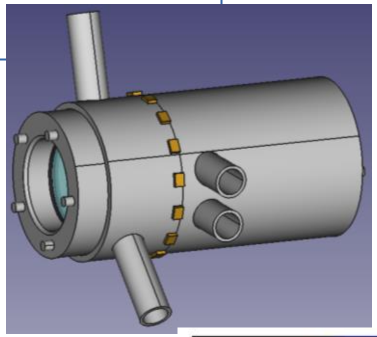
Development of a direct diode pumped, high average power system based on multipulse extraction and ceramic active materials (APOLLO project)

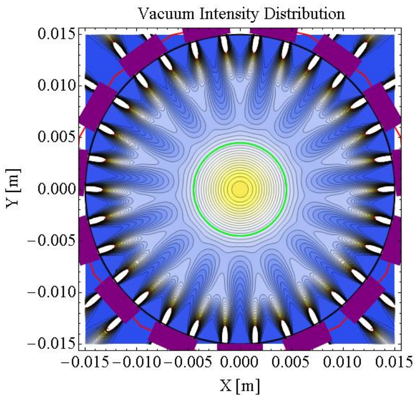




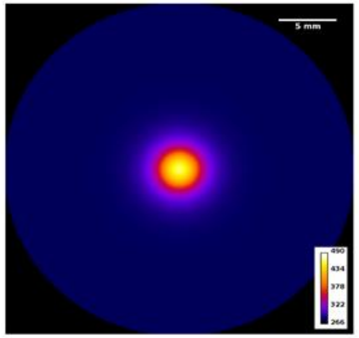
APOLLO system design specs: pulse duration ~50-100fs (potential), pulse energy > 500mJ, repetition rate 1kHz

Selected material: *Tm:Lu2O3*
- Emission at 2 µm (eye-safe)
- Large amplification bandwidth
- Direct pumping at 800 nm, using diodes operating in (quasi) CW mode (available and scalable)
- Multi-pulse extraction at high repetition rate > 1 kHz; Ideal for accelerator technology
- Mature ceramic production technology

Edge diode pumping



Thermal load



Multi-Pulse Extraction: time dependent level dynamics

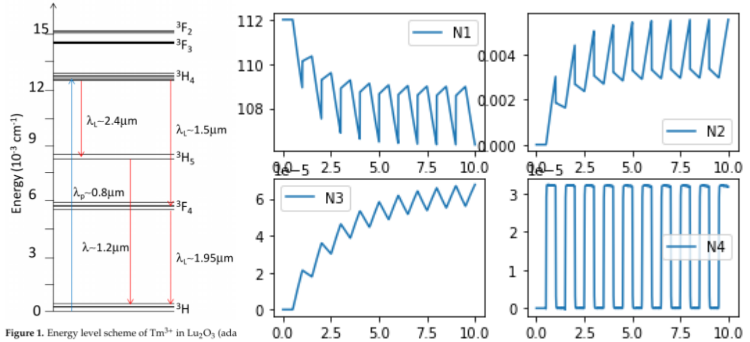


Figure 1. Energy level scheme of Tm^{3+} in Lu_2O_3 (ada

D. Palla, L. Labate*, F. Baffigi, G. Cellamare, L.A. Gizzi, Optics & Laser Technology, **156**, 108524 (2022)

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R&D on laser-driven VHEE sources for advanced radiotherapy protocols (FLASH radiotherapy)

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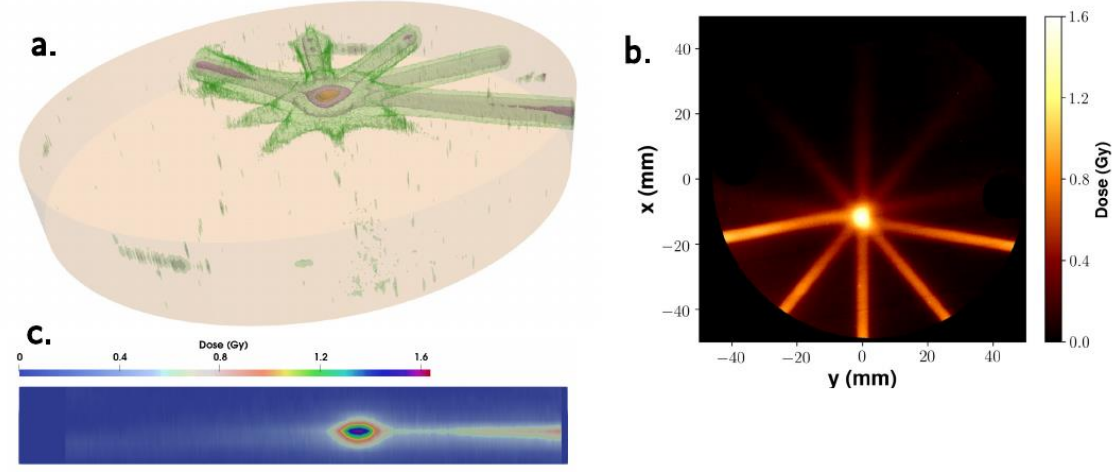
RT modalities/protocols exploiting the FLASH effect (>~40Gy/s, ~200ms irradiation time) require high charge/(average)current particle beams, with the required penetration depth to allow deep seated tumors to be treated

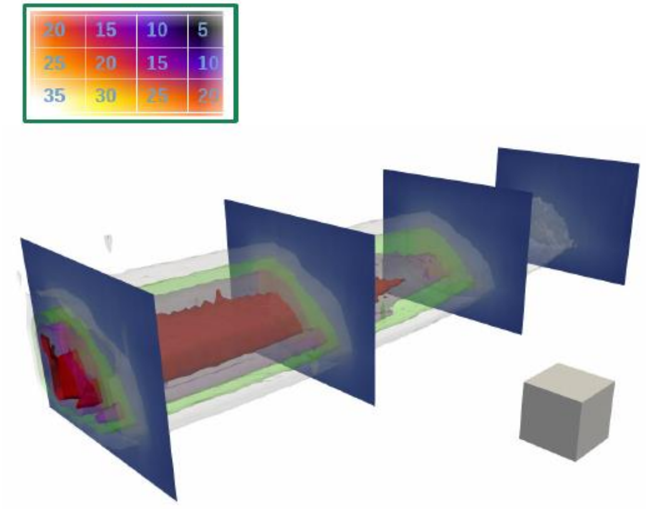
Laser-driven VHEE beams among the most promising candidates for FLASH RT

RT approaches with LWFA VHEE pencil beams

Multi-field irradiation of a mm-sized target volume



IMRT-like dose painting



Maximum dose on the “target” volume 2.5x the dose at the entrance and 4x the dose a few mm apart

- Dose up to 2 Gy (using 200 laser shots) delivered in a 2 mm diameter pencil beam at 50mm water depth.
- Dose “painting” with sub-mm resolution demonstrated.
- In perspective, FLASH-RT needs therapeutic doses **(tens of Gy)** in a short time (**200 ms)**
- This is challenging for all accelerators (including RF)
- LPA can address with compact footprint, with highest charge per bunch and high repetition rate (>100 Hz).

L. Labate *et al.,* Sci. Rep. 10, 17307 (2020)

Tuscan Health Ecosystem “THE” (NG-EU) project funded: High Rep rate VHEE beamline development: 1.7 M€

R&D on high quality laser-driven electron beams: The REMPI scheme

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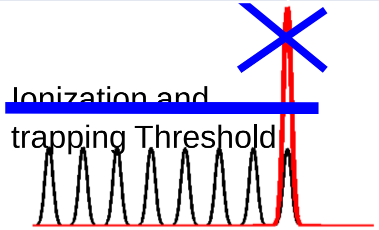
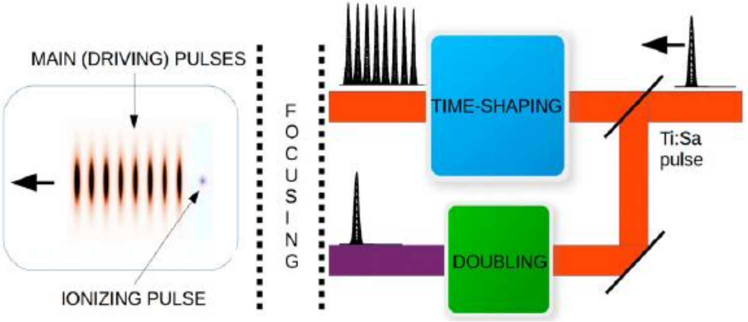
Motivation: Within the EuPRAXIA project we aim at generating 4.5/5GeV bunches with FEL quality

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

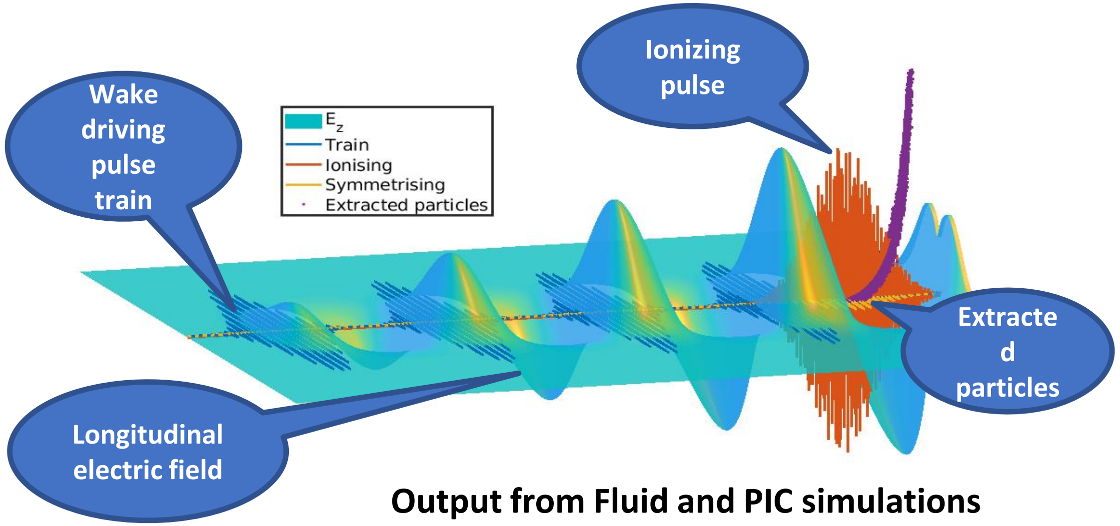
Bunch specifications - GOAL:	dE/E SLICE	ε_n SLICE	Q	I_{peak}
	<0.1%	**<0.1 mm mrad**	>30 pC	>2kA

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





dE/E (rms)	ε_n	Q	I_{peak}
0.9% (**92% of the charge**) 1.8 % (tail included)	**0.085** mm mrad	32 pC	**3.5 kA**



Output from Fluid and PIC simulations

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

R&D on high quality laser-driven electron beams:
Generation of ultrashort pulse trains for the REMPI scheme

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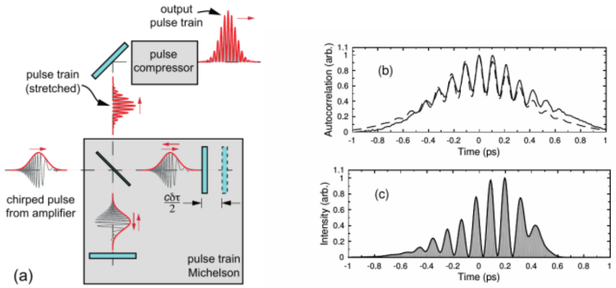
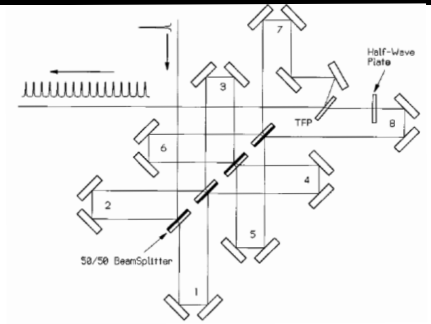
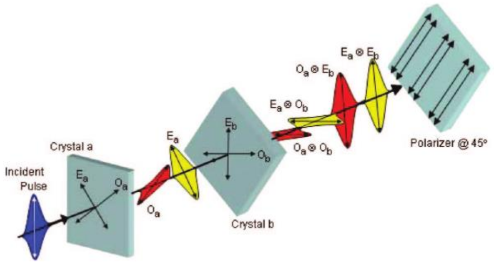


(Spectral) interference of chirped, time delayed pulses (PRL 119,044802 (2017))



2n-pulse Michelson interferometer (Appl. Opt. 37, 5302 (1998))

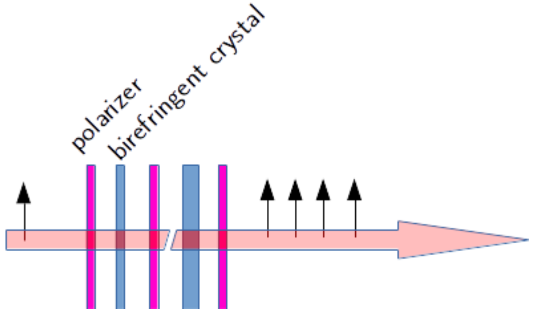


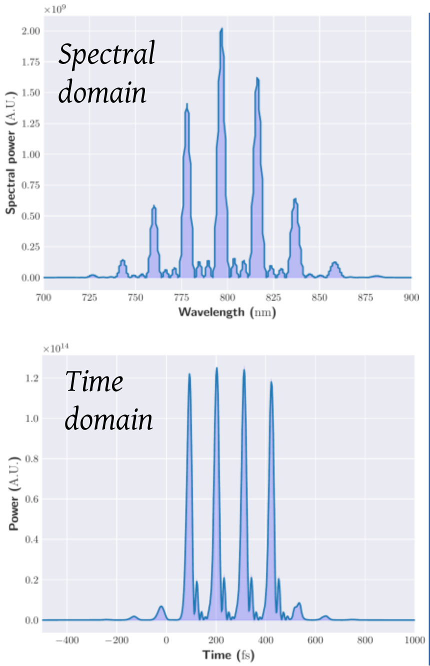
Array of birefringent plates (Appl. Opt. 46, 5142 (2007))

- 50% energy loss
- Pulse-to-pulse intensity difference unacceptable
- ...

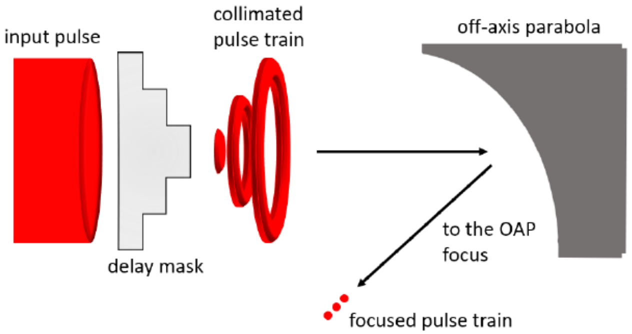
Stack of polarizers/birefringent plates used early in the amplification chain

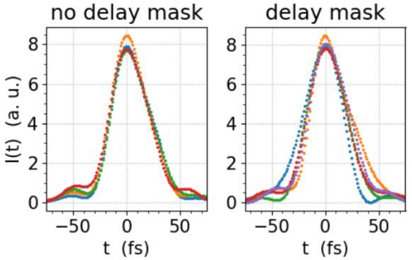
Spectral interference: manageable
Self-phase modulations: not trivial





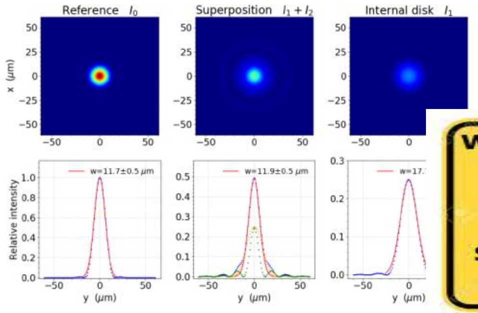
Annular shaped delay mask





Time profiles (exp)

Intensity map (numerical)



G. Vantaggiato *et al.*, NIM A 909, 114 (2018)

PhD fellowship at CNR-INO: The research project

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Title: Characterization and manipulation of ultrashort laser pulses for high quality electron bunch acceleration

Study of ultrashort pulse train generation for advanced LWFA schemes (REMPI)
Ultrashort lasers characterization and stabilization for applications (e.g., long term operation of FEL, FLASH RT with LWFA VHEEs)

Milestones
M1 (m18). Theoretical studies of ultrashort pulse train generation.
M2 (m30). Study of laser parameters control/optimization for high quality bunch acceleration.
M3 (m38). Experimental demonstration of pulse train generation at a 100TW power level

Deliverables
D2 (m18). Report on activity related to M1
M2 (m24). Paper on proof-of-concept method for pulse train generation
M3 (m42). Paper on laser control and manipulation for high quality bunches acceleration

Secondments: IP-ASCR (laser R&D), ELI-NP (REMPI scheme), D-BEAM (advanced instrumentation)

Further infos on the activities foreseen in the framework of the PhD will be provided tomorrow

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