

Status of electron acceleration and perspectives for VHEE with laser-plasma acceleration at ELI-Beamlines

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Collaborators:

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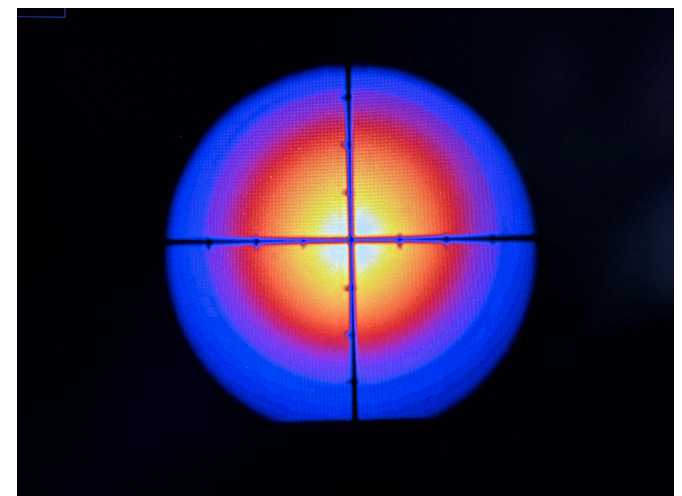
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³Department of Medicine and Surgery, LUM University, Casamassima, Italy

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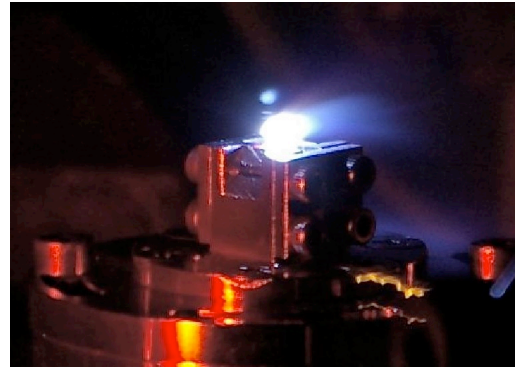
⁵ELI ALPS, ELI-HU Non-Profit Ltd., Szeged, Hungary





- ***High repetition rate LWFA of electrons at ELI-Beamlines: research and prototyping***
 - ❑ 1 kHz Electron beams at ALFA Beamline
 - ❑ Characterization and application for on-demand in-air irradiations
 - ❑ Conclusions

Why Plasma ?

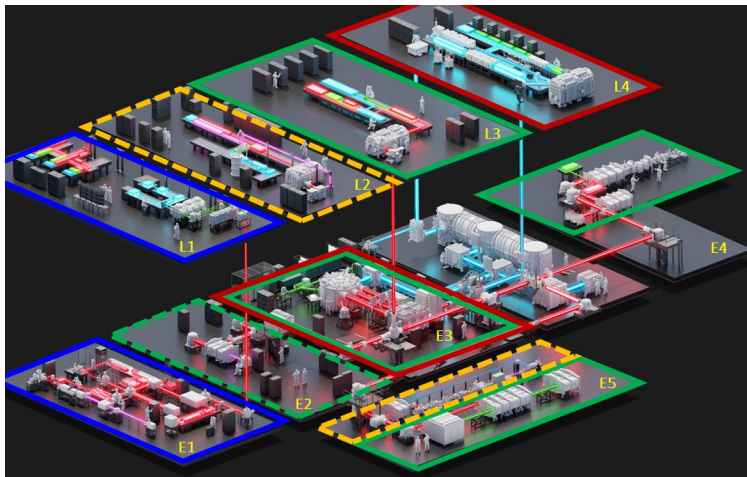


- Plasma is already ionized medium → **High electric field** $E_z \left[\frac{V}{m} \right] = \frac{cm_e \omega_p}{e} \sim 96 \sqrt{n_e [cm^{-3}]} \quad [1]$
 with $\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$ the plasma frequency, n_e the electron plasma density, c the vacuum speed of light, e and m_e the electron charge and rest mass.
- For plasma density $\sim 10^{18} \text{ cm}^{-3} \rightarrow \mathbf{100 \text{ GV/m}} \gg 100 \text{ MV/m}$ (demonstrated in [2-4])
- How to generate such plasma from gas targets? → high intensity laser pulses!

- [1] Dawson, J. M., Phys. Rev. 113, 383 (1959)
- [2] Gordon, D., et al., Phys. Rev. Lett. 80, 2133 (1998)
- [3] Malka, V., et al., Science 298, 1596 (2002)
- [4] W. P. Leemans et al., Nat. Phys., 2:696 (2006)

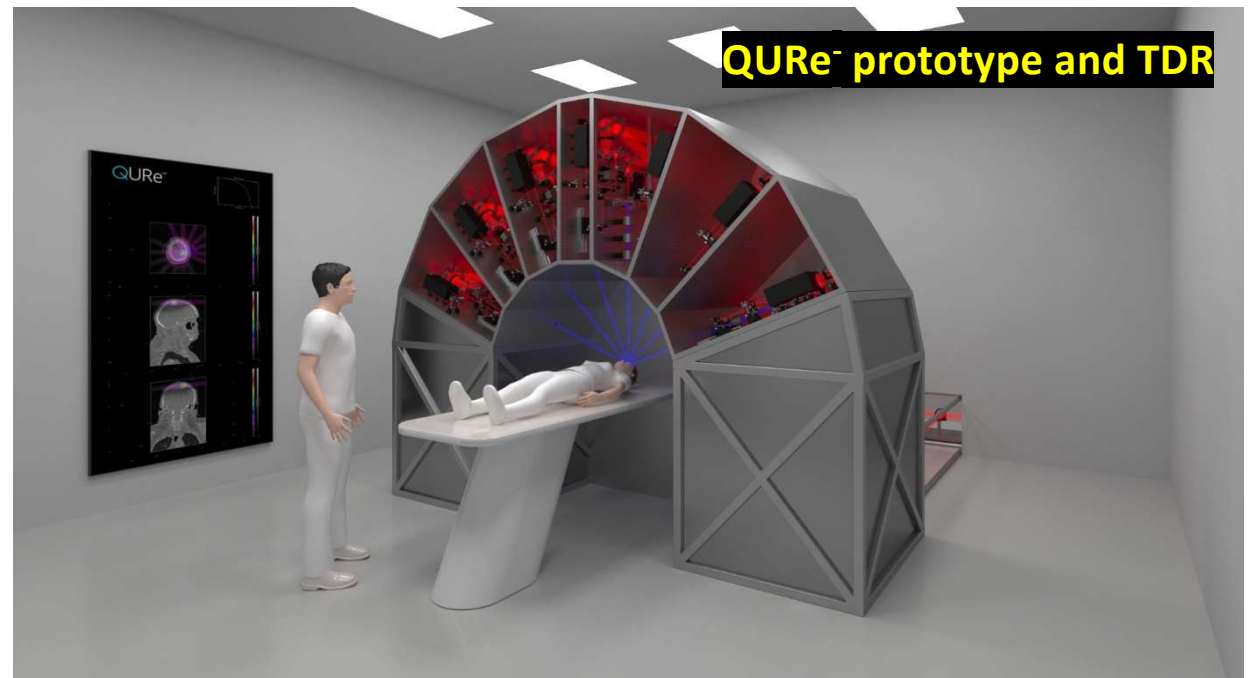
ELI Beamlines offers experimental platforms and ultrafast ionizing radiation sources for:

- ✓ **Very high energy electrons (VHEE) from 10 MeV to several GeV**
- ✓ **Compact accelerators: gradient $\rightarrow$ GeV/cm**
- ✓ **Biological effects study with highly adjustable laser-driven electron beams**
- ✓ **Treatment plan prototyping**
- ✓ **Therapeutic irradiation simulations**



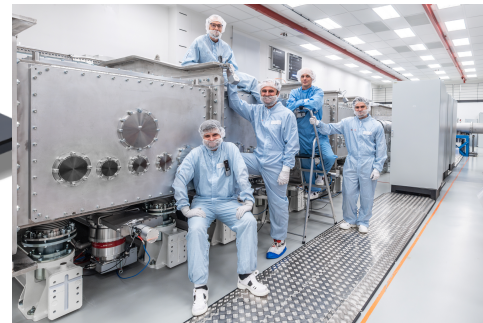
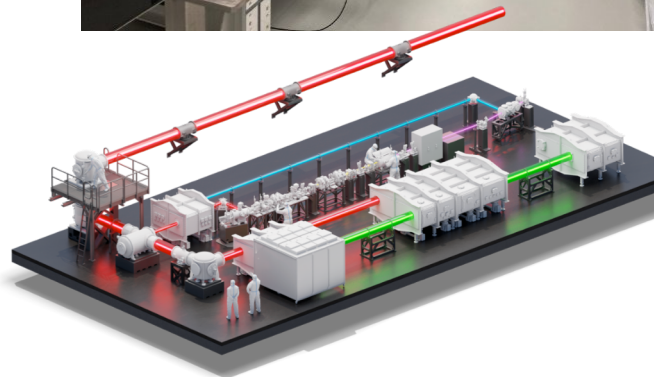
Patented ELI Beamlines technology

LU93102B1, US10603514B2, WO2017211331A1,
CZ2021247A3, CZ2023461A3



ELBA Beamline:

- 100 MeV → **10 GeV** electron beams
- 1 – > 3.3 Hz repetition rate
- High instantaneous dose rates (**up to 10^{12} Gy/s**)
- 0.1 Gy/pulse
- Based on L3 laser: 1 PW, 30 fs



Only kHz accelerator
based on power-
scalable laser!

ALFA Beamline:

- 10 – 50 MeV electron beams
- **1 kHz continuous**
- On-demand irradiations
- **High dose rates (up to Gy/sec)**
- Based on L1 laser: 3 TW, 15 fs



WR energy LWFA
electrons at kHz!

Physics of Plasmas

LETTER

pubs.aip.org/aip

Ultrarelativistic electron beams accelerated by terawatt scalable kHz laser

Cite as: Phys. Plasmas **31**, 030703 (2024); doi: 10.1063/5.0189051
Submitted: 26 November 2023 · Accepted: 28 February 2024 ·
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C. M. Lazzarini,^{1,2,a)} G. M. Grittani,¹ P. Valenta,¹ I. Zymak,¹ R. Antipenkov,¹ U. Chaulagain,¹ L. V. N. Gonçalves,¹ A. Grenfell,¹ M. Lamac,^{1,2} S. Lorenz,^{1,2} M. Nevrla,^{1,2} A. Spaček,^{1,2} V. Sobr,¹ W. Szuba,¹ P. Bakule,¹ G. Korn,¹ and S. V. Bulanov^{1,2}



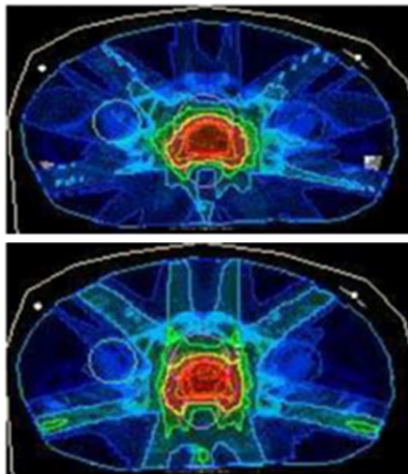
- ☐ High repetition rate LWFA of electrons at ELI-Beamlines: research and prototyping
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- ☐ Characterization and application for on-demand in-air irradiations
- ☐ Conclusions

A compact and reliable source of multi-10s MeV 1 kHz electron beams

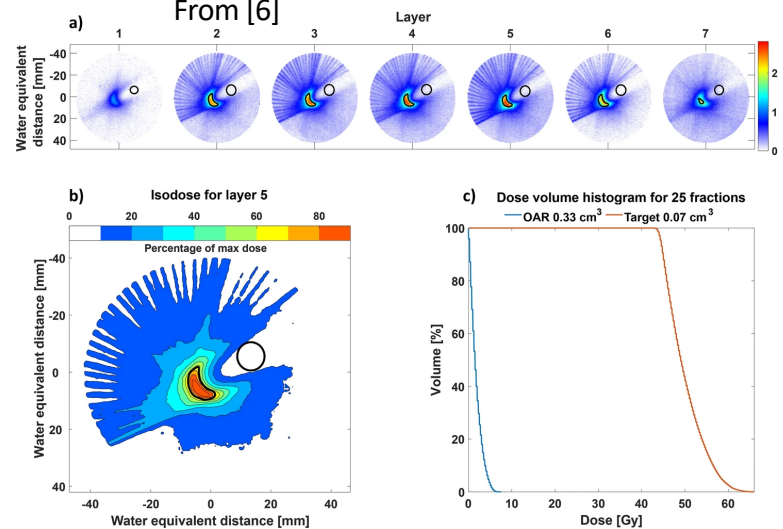
Applications

- Irradiation of biological sample to develop an innovative tool for radiotherapy (e.g. brain cancer) [5,6]
- Irradiation of electronic components for space exploration to study survival to radiation [7]
- Source of secondary beams (x-rays) for ultrafast imaging applications [8]

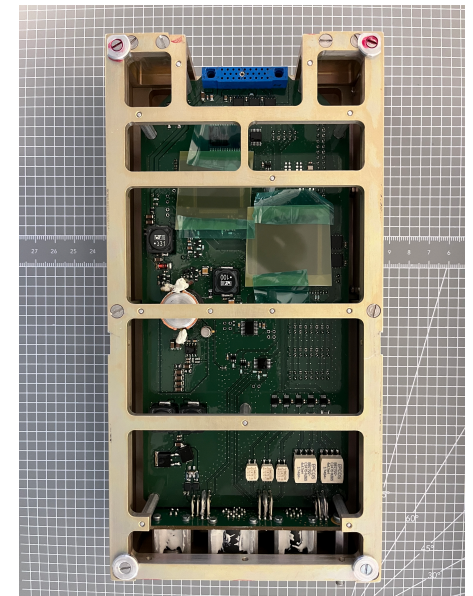
From [5]



From [6]



in-house R2E test (few 10² Gy)



[5] Fuchs et al., Phys. Med. Biol. 54:3315 (2009)

[7] E.G. Stassinopoulos, IEEE NSPEC Short Course, July, 1990

[6] Svendsen, K. et al. Sci. Rep. 11, 5844 (2021)

[8] Brummer, T. et al. PRAB 23, 031601 (2020)

A compact and reliable source of multi-10s MeV 1 kHz electron beams

Why 1 kHz?

- ✓ Solid laser technology delivering multi-TW, such as L1[9] and SYLOS [10] at ELI facilities
- ✓ Smaller area footprint → *radiotherapy devices could fit in existing hospital room!*
- ✓ Higher average current and dose rate → *for irradiation experiments*
- ✓ Higher statistics → *Machine Learning driven optimization*

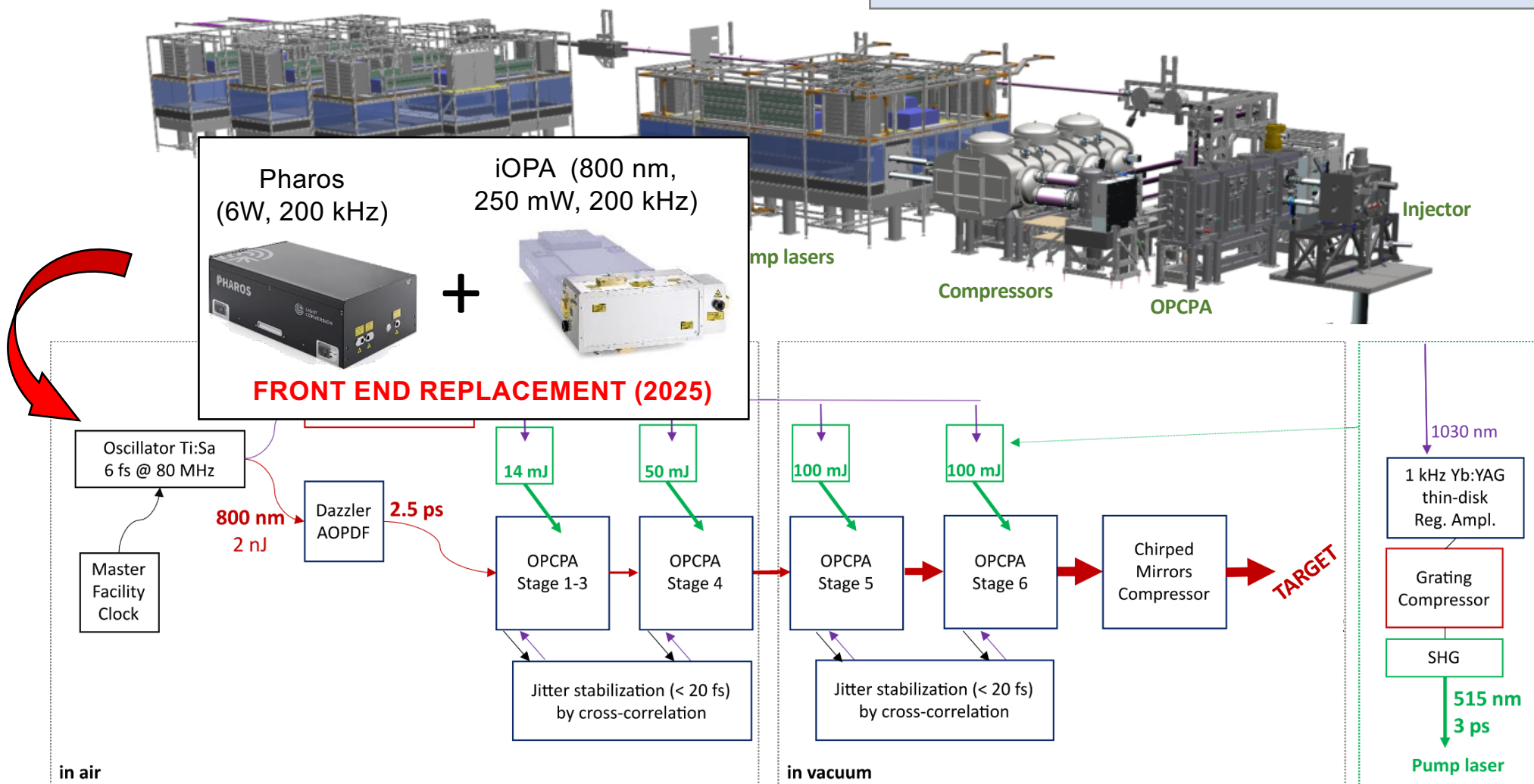
[9] Antipenkov, R. et al., doi.org/10.1117/12.2592432 (2021)

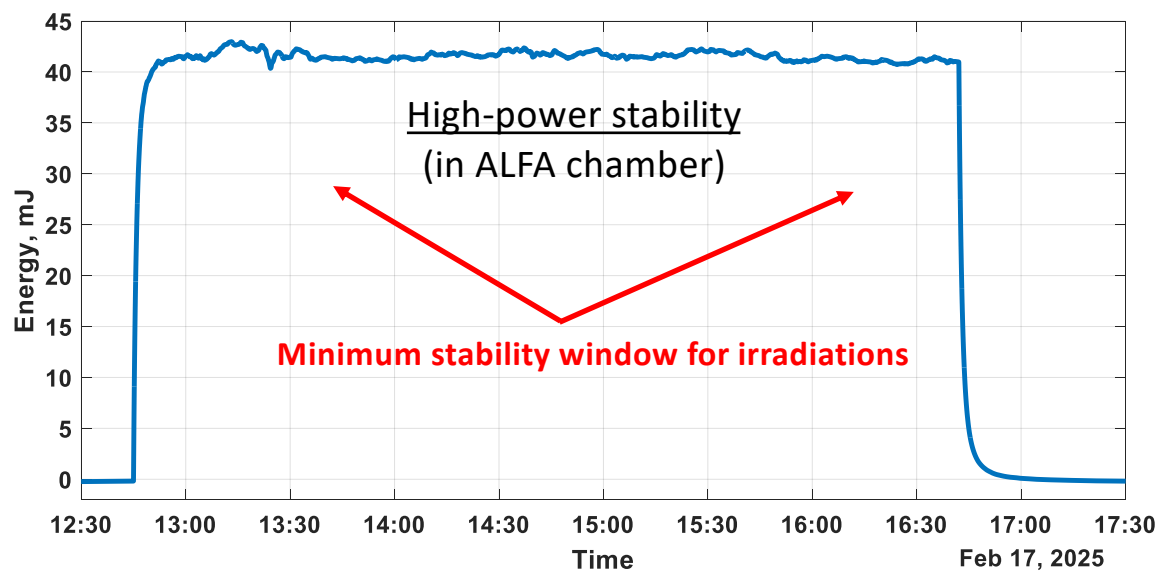
[10] J. Csontos et al. in *Laser Congress 2023 (ASSL, LAC)*, paper AW5A.2.

1 kHz / 15 fs OPCPA system now operating @ 40-45 mJ.

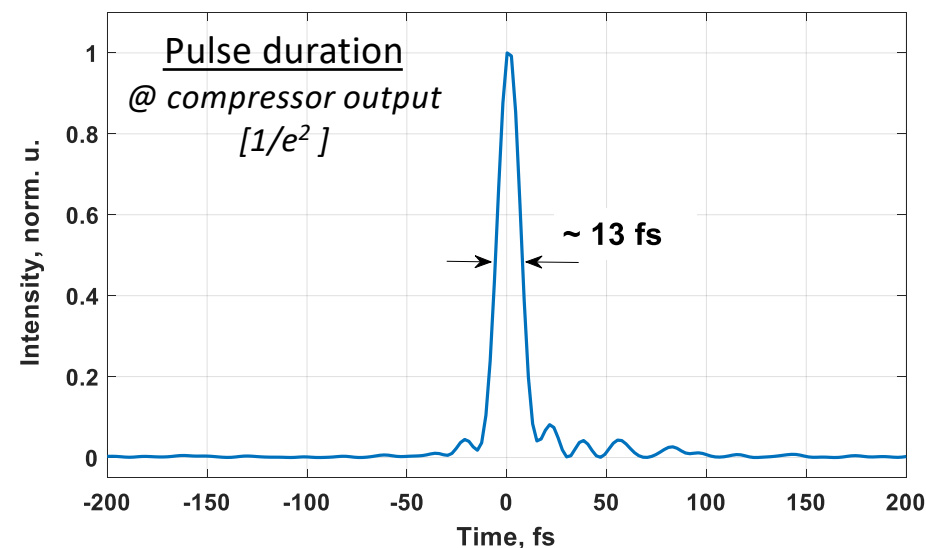
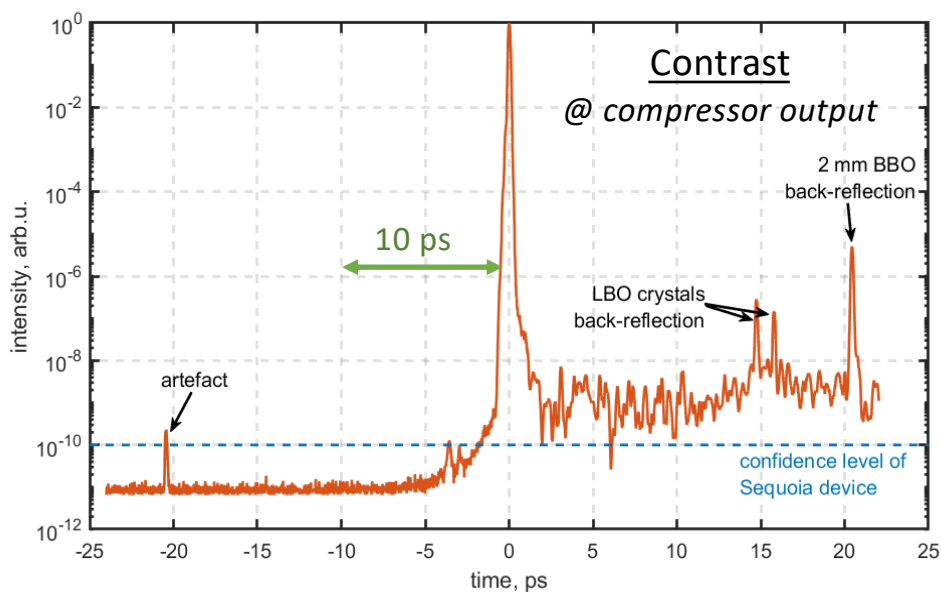
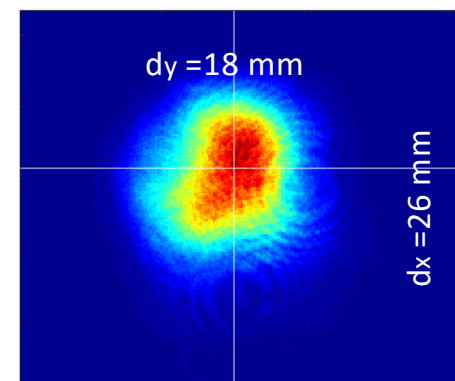
[5] Antipenkov, R. et al., doi.org/10.1117/12.2592432 (2021).

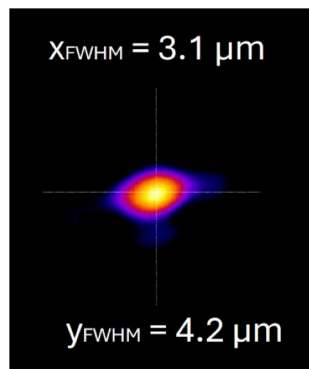
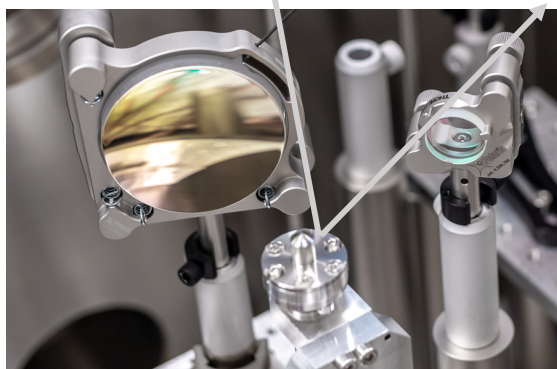
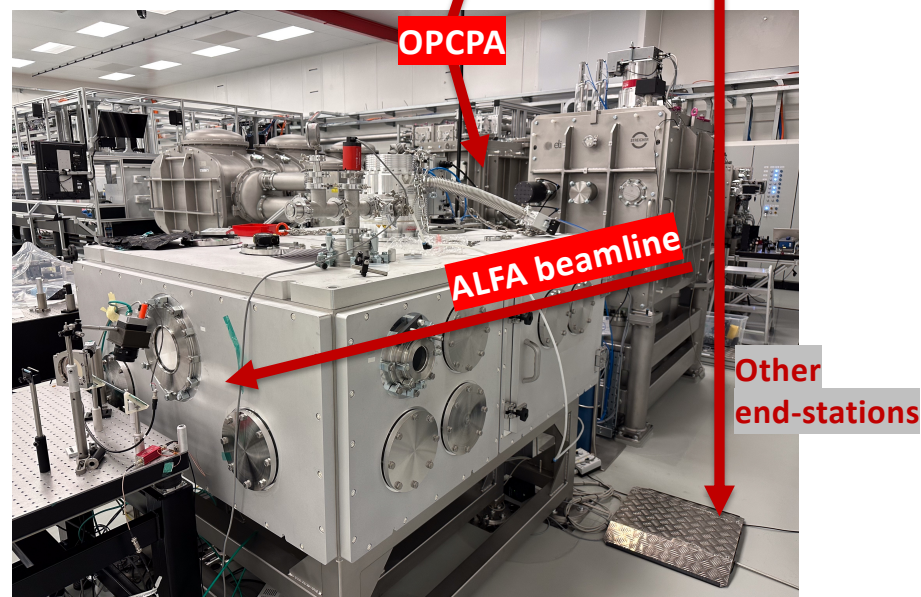
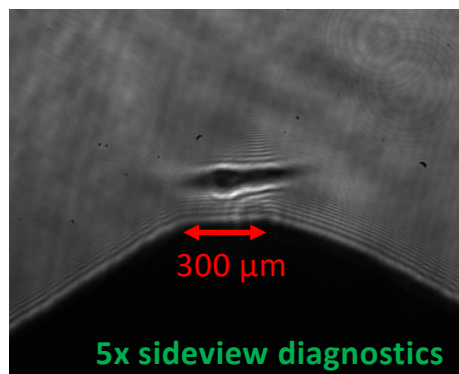
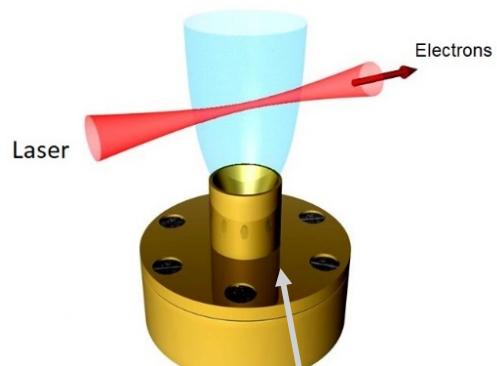
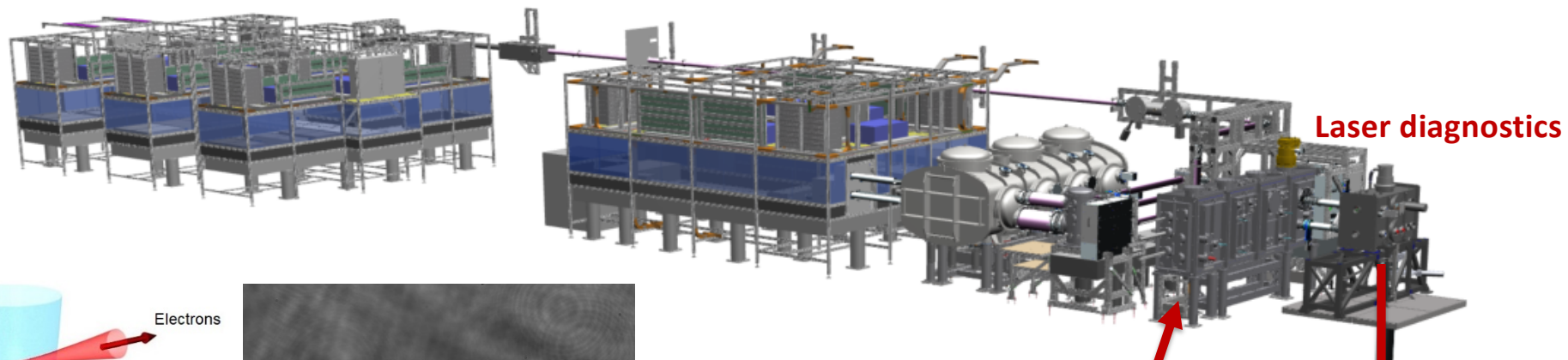
[7] Batysta, F. et al., Optics Express vol. 22, issue 24,30281 (2014).

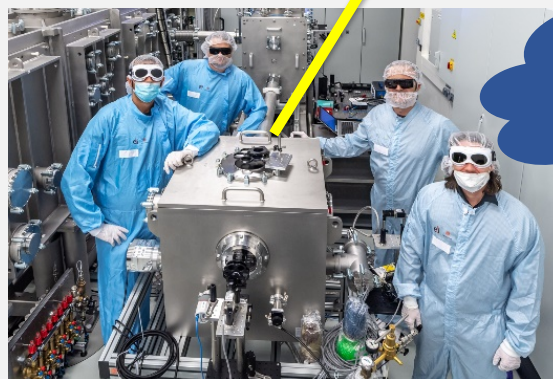
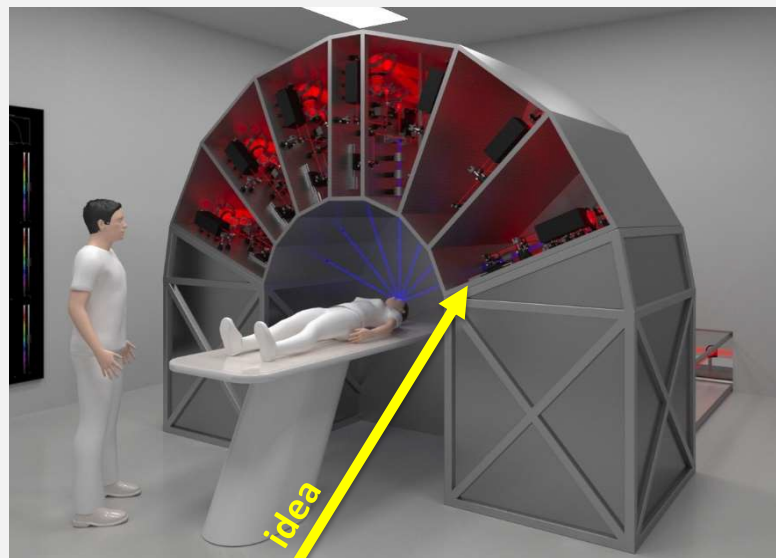




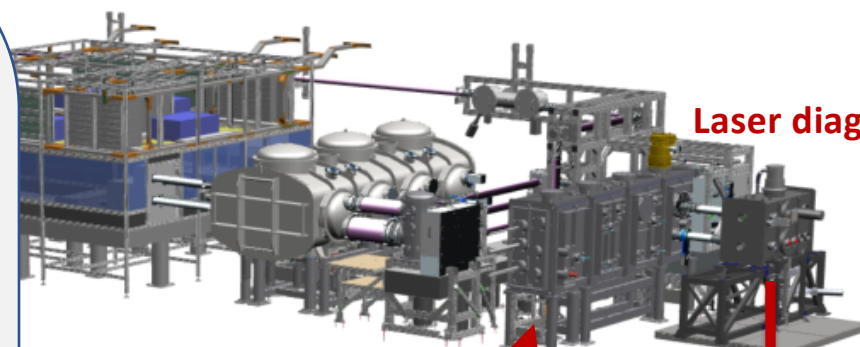
Near field beam profile
@ compressor output [$1/e^2$]



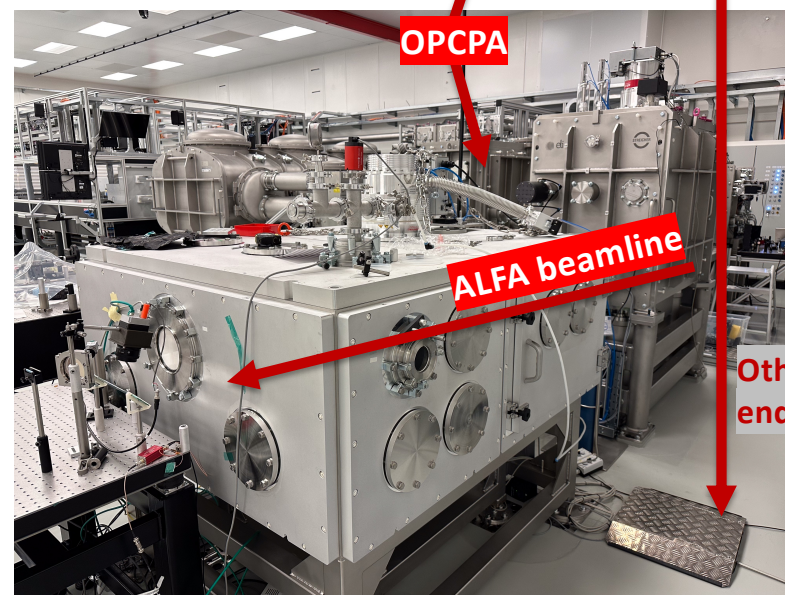




Most compact 50 MeV
@ kHz $\sim 0.3 \text{ m}^3$



Laser diagnostics



OPCPA

ALFA beamline

Other
end-stations

Physics of Plasmas
LETTER
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Ultrarelativistic electron beams accelerated by terawatt scalable kHz laser

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Scilight

12 April 2024

High-energy electron beam with fast repetition rate offers potential for new medical applications

Avery Thompson

Using a terawatt laser with a kHz pulse rate, electrons can be accelerated to high energy over a millimeter distance.

50 MeV in 50 μm

(a) Quasi-monoenergetic

$n_{\text{el}}/n_{\text{critical}} = 0.034$
 $(5.7 \times 10^{19} \text{ cm}^{-3})$
 $E_{\text{max}} \sim 50 \text{ MeV}$
Div. (FWHM) = 2.1 mrad
 $\Delta E/E$ (FWHM) $\approx 25 \%$
 Pointing 6.9 mrad

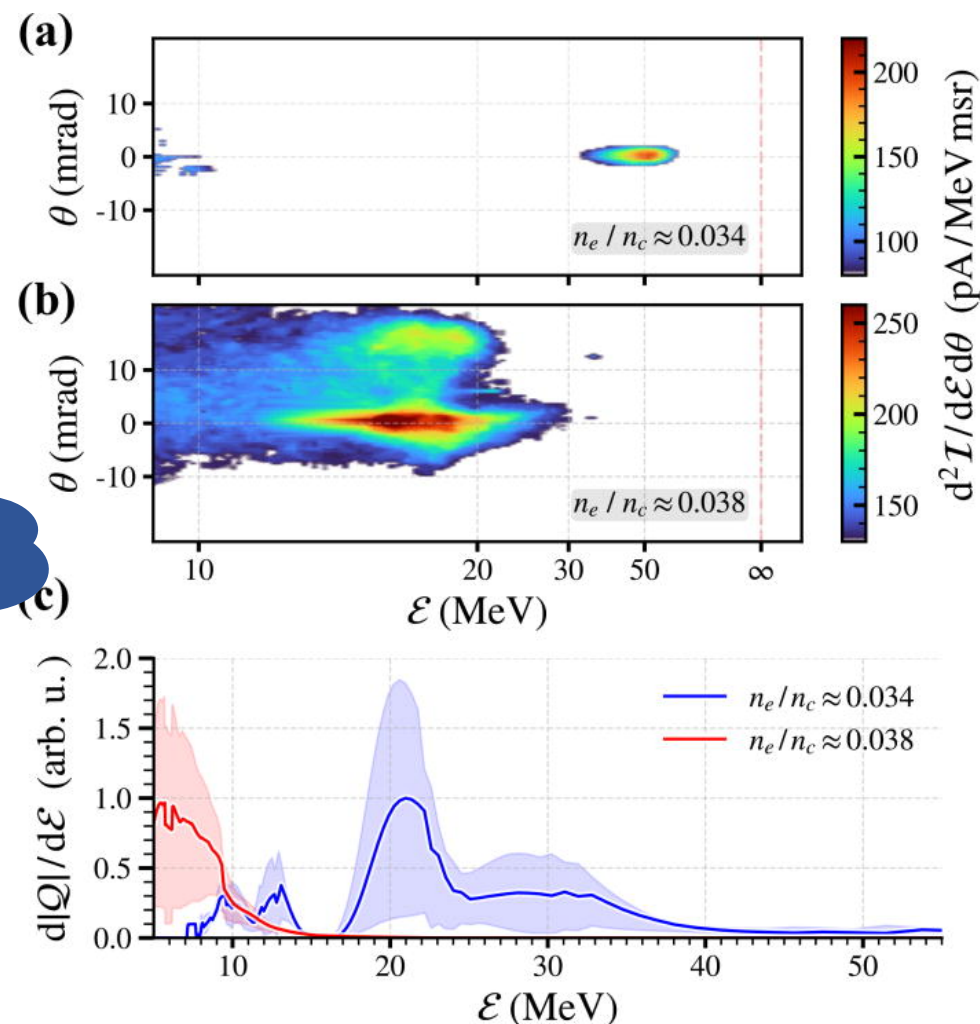
(b)

$n_{\text{el}}/n_{\text{critical}} = 0.038$
 (+13%)
 $E_{\text{max}} < 30 \text{ MeV}$
 Div $> 10 \text{ mrad}$
 Not stable

Achieved $\sim 26 \text{ mJ}$ ($a_0 \sim 1.7$)

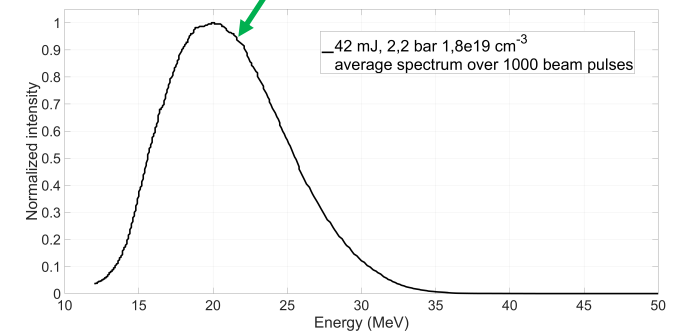
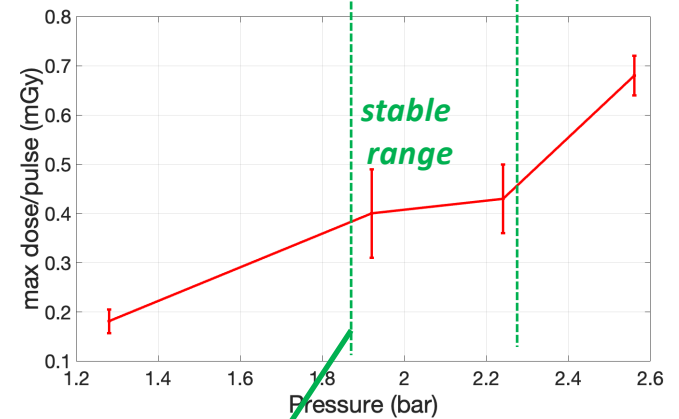
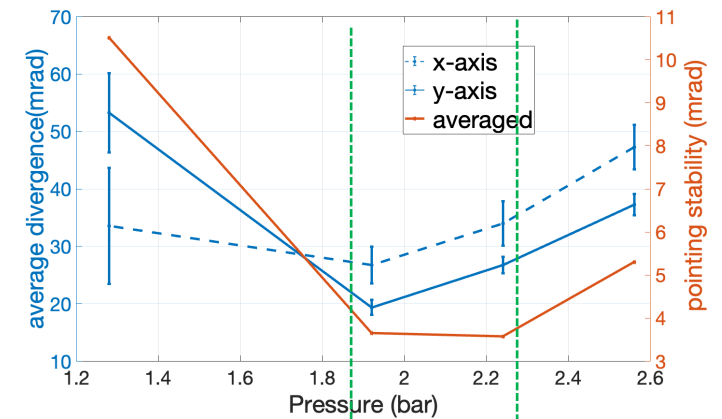
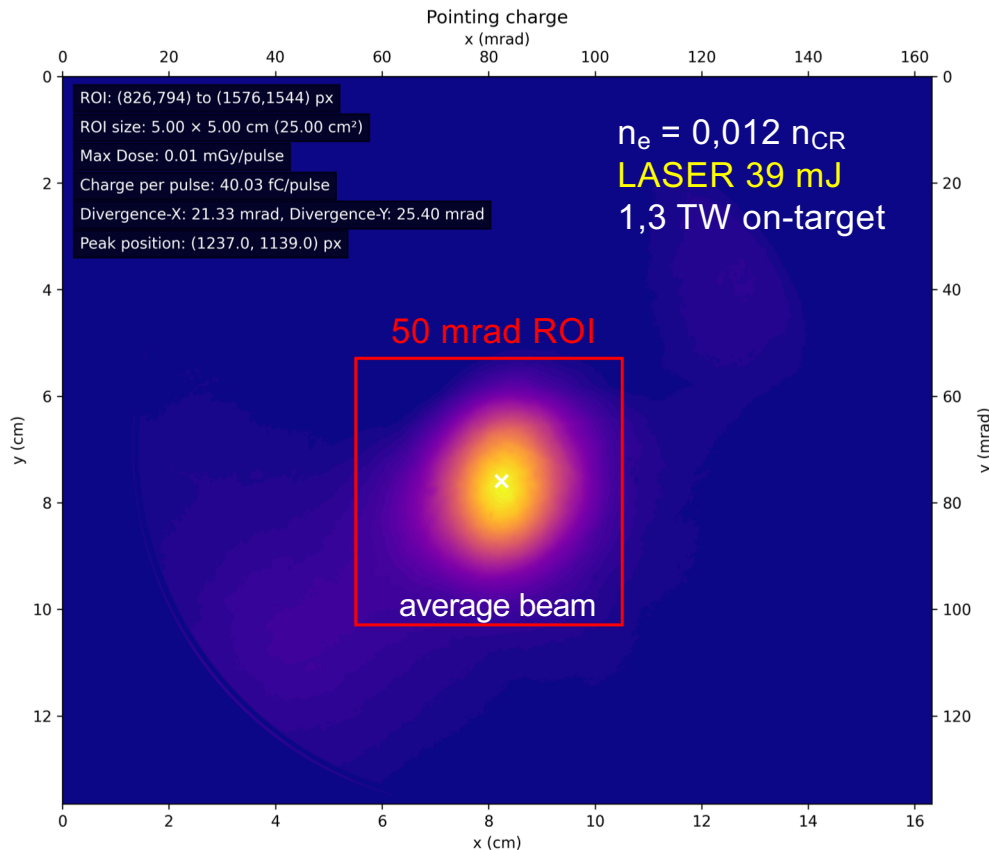
&

Target: mixture He(98%)-N(2%), 300 μm nozzle



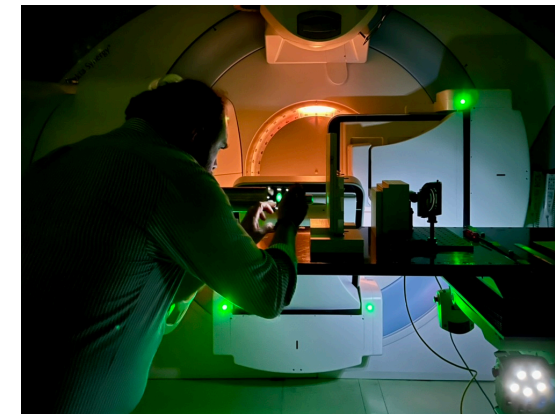
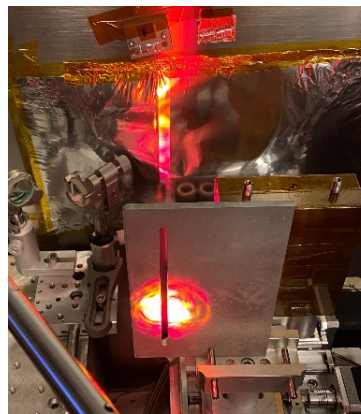
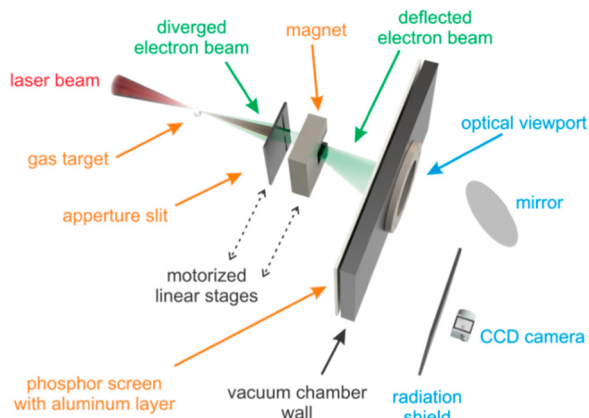
Important Laser Parameters (2024)

- **Laser energy = 39 mJ, optimized GDD**
- **f/5 OAP -> $a_0 \sim 1$ on target**
- **Pure Nitrogen**
- color scale is normalized
- each image is averaged with background subtraction
- error bars are 1 std





- ☐ High repetition rate LWFA of electrons at ELI-Beamlines: research and prototyping
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- ***Characterization and application for on-demand in-air irradiations***
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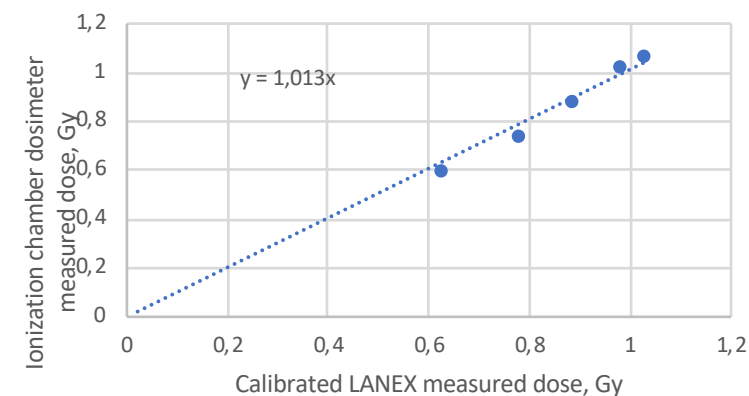


Electron spectrometer calibrated with a medical LINAC (@ Policlinico di Bari, Italy)

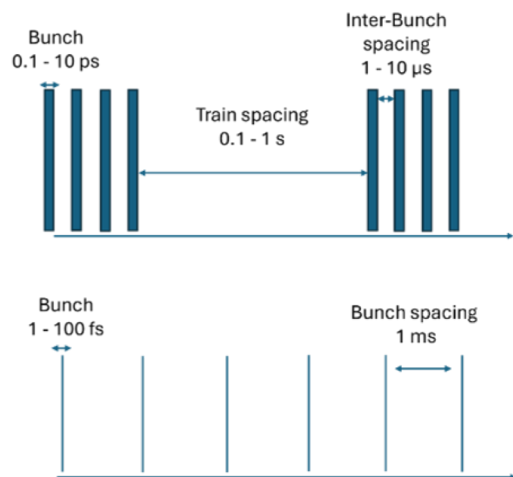
I. Zymak, M. Favetta, G.M. Grittani, C.M. Lazzarini et al., «Characterization of kHz Repetition Rate Laser-Driven Electron Beams by an Inhomogeneous Field Dipole Magnet Spectrometer» Photonics, 11(12), 1208 (2024). doi.org/10.3390/photonics11121208

Dose for saturation 34 ± 5 mGy

Charge for saturation 17 ± 3 pC/cm²



Time



Radio-Frequency linear accelerator

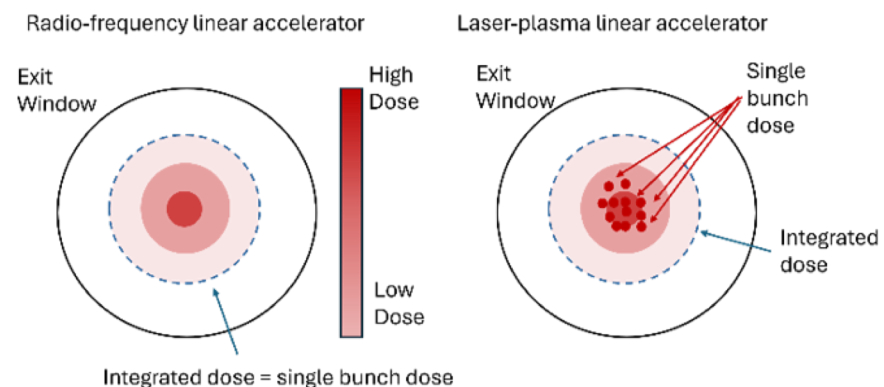
Bunch time duration	ps
Train time duration	ns
Train repetition rate	Hz
Charge per bunch	nC
Average current	μA

Laser-Plasma linear accelerator

Bunch time duration	fs
Bunch repetition rate	kHz
Charge per bunch	pC
Average current	nA

Space

Single bunch and integrated dose over multiple bunches



Scheme

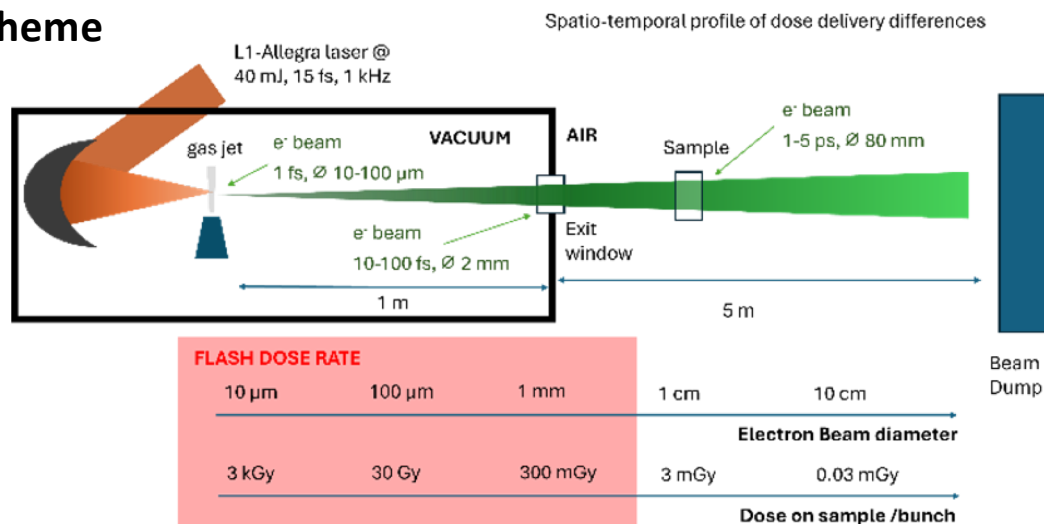


Table 2. Bunch lengths at different depths as calculated with FLUKA.

Depth [cm]	Bunch length [ps]
5	0.075
10	0.39
15	1.056
20	2.295
25	4.08
30	7.0

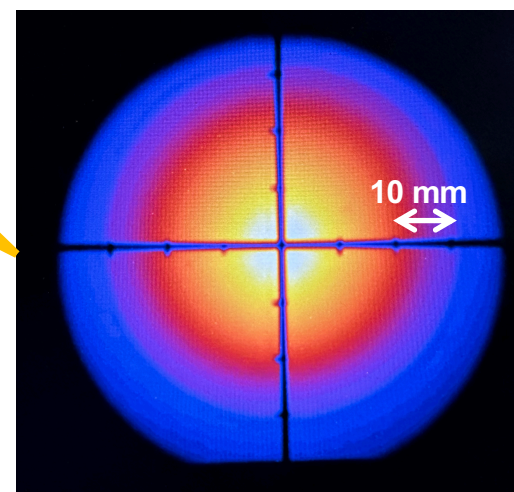
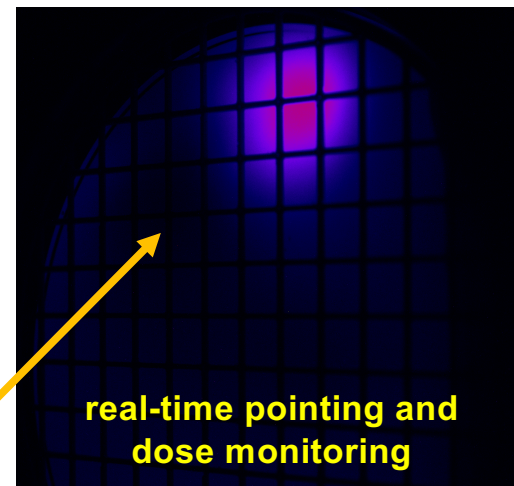
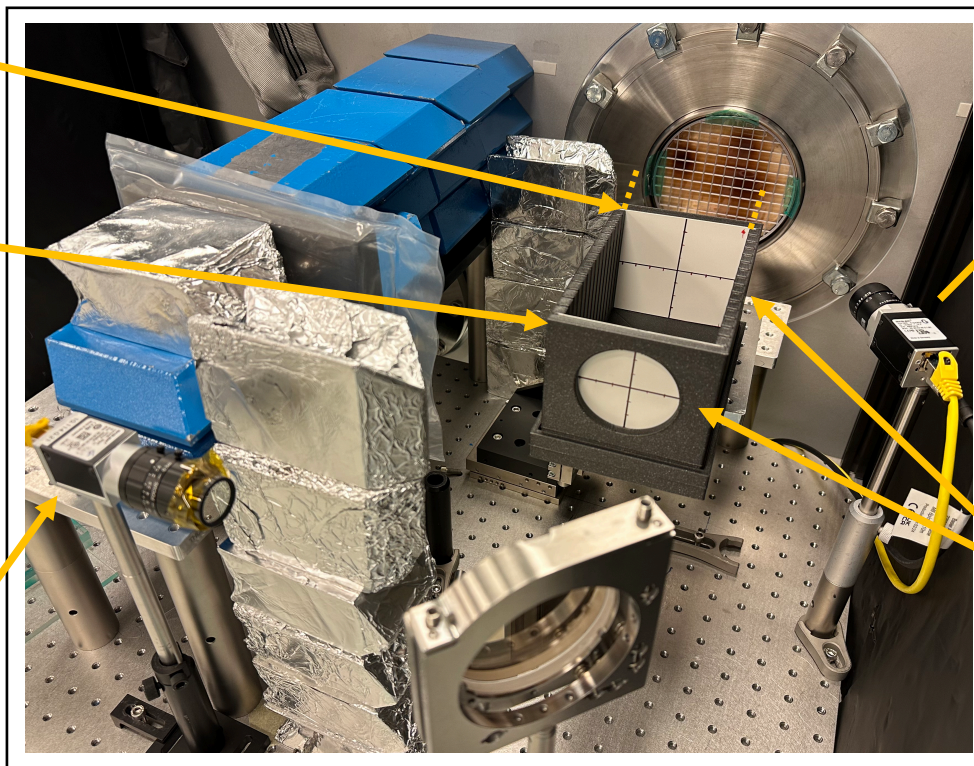
D. Horvath, et al., «Time dynamics of the dose deposited by relativistic ultra-short electron beams», Phys. Med. Biol. 68 22NT01 (2023)

e-beam target area for irradiations

Front distance tunable
10-30 cm from flange
(100-130 cm from source)

3D printed target support
for user experiments

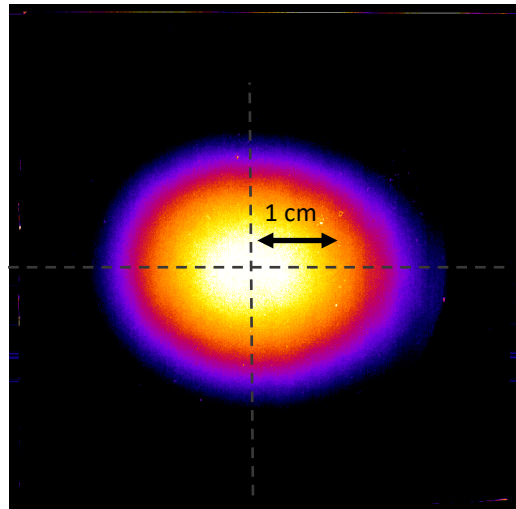
Main calibrated
spectrometer camera



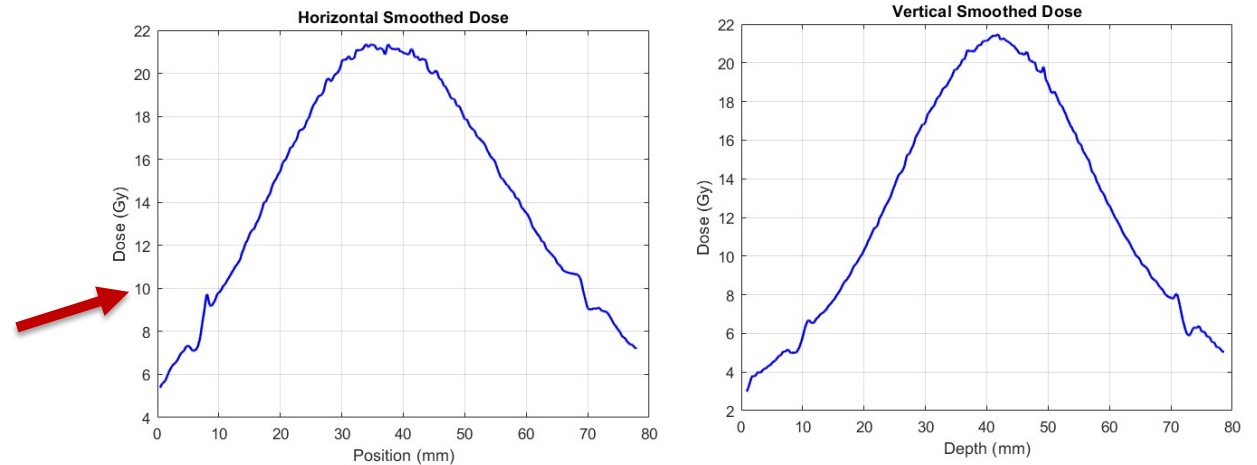
sub-mrad over 15 cm!

Thanks to Dr. Favetta user run

Radiochromic film at the entrance



Front film dose line plots



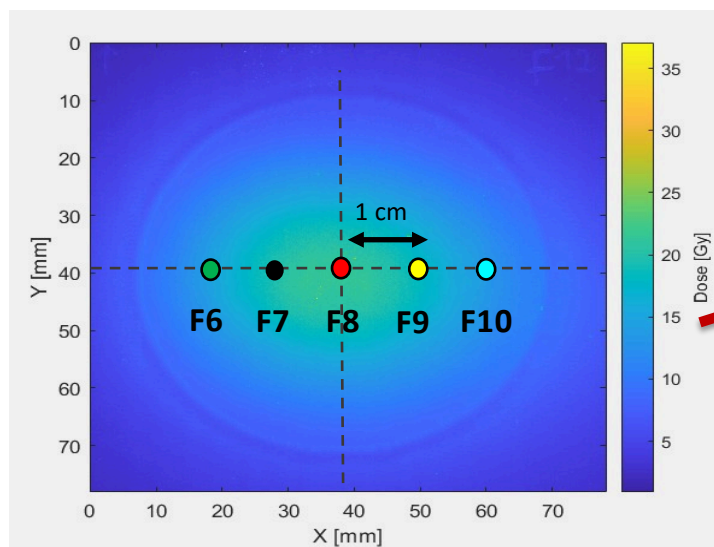
Achievements:

- ✓ Dose of ~ 30 Gy in 60 sec confirmed with Alanine
- ✓ Max dose rate 0.5 Gy/sec over cm²
- ✓ R50 at 5-6 cm

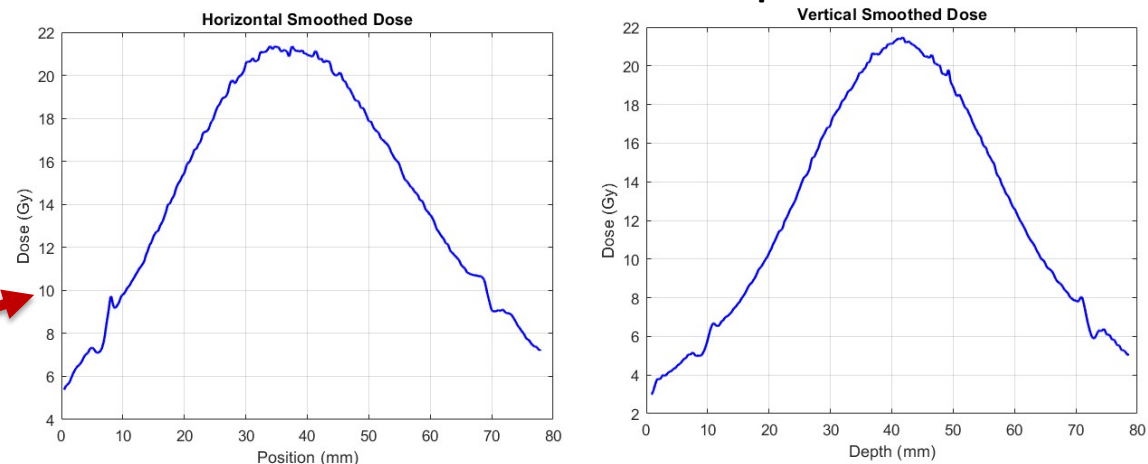
Next:

- Simulations to reconstruct electron spectrum from PDD
- New beamtime in 2026 for improvement measurements:
 - 3D gel
 - Graphite calorimeter
 - Silicon Carbide dosimeters -> *G. Milluzzo talk*

Radiochromic film at the entrance



Front film dose line plots



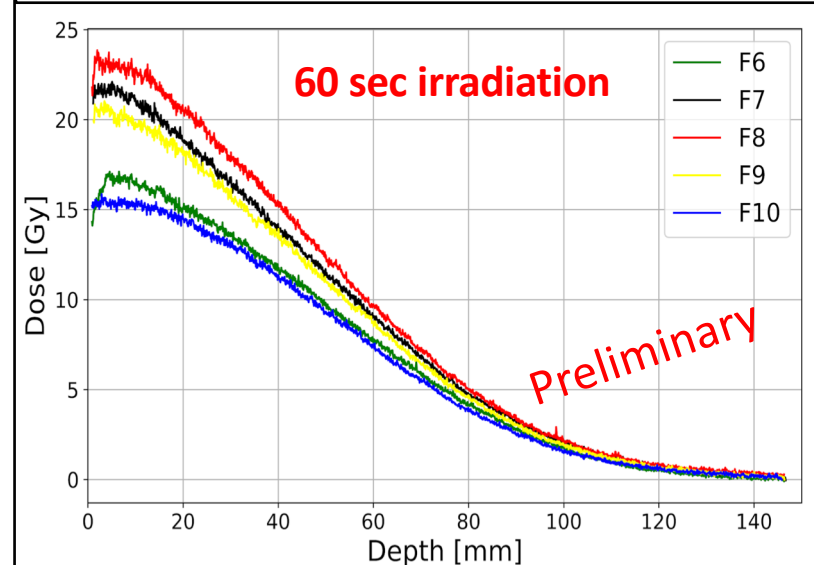
Achievements:

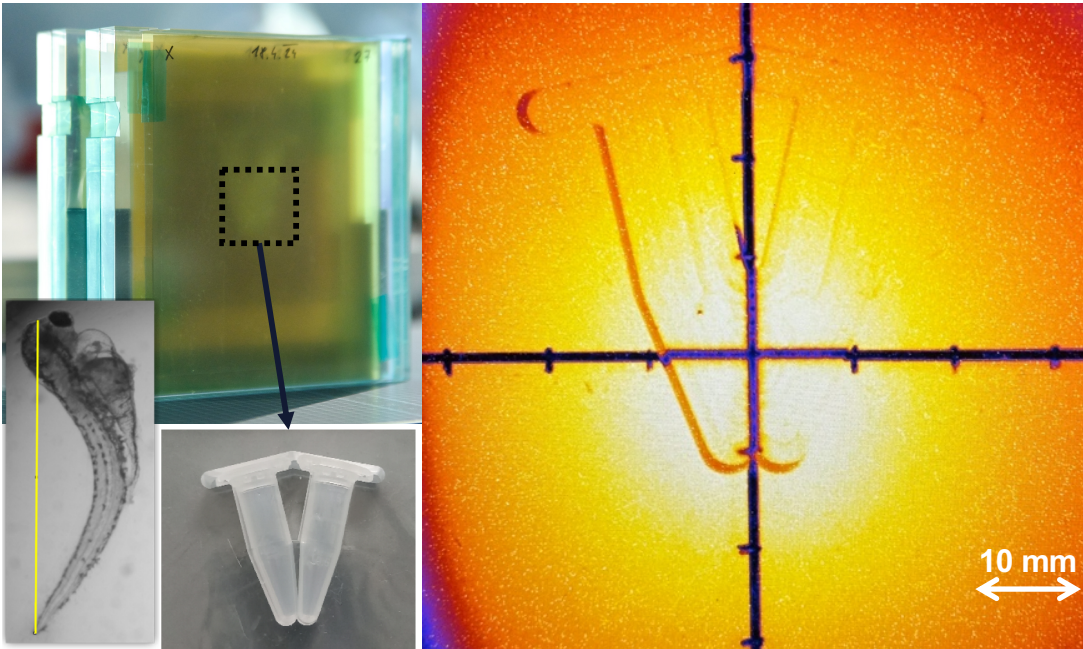
- ✓ Dose of ~ 30 Gy in 60 sec confirmed with Alanine
- ✓ Max dose rate **0.5 Gy/sec over cm²**
- ✓ **R50 at 5-6 cm**

Next:

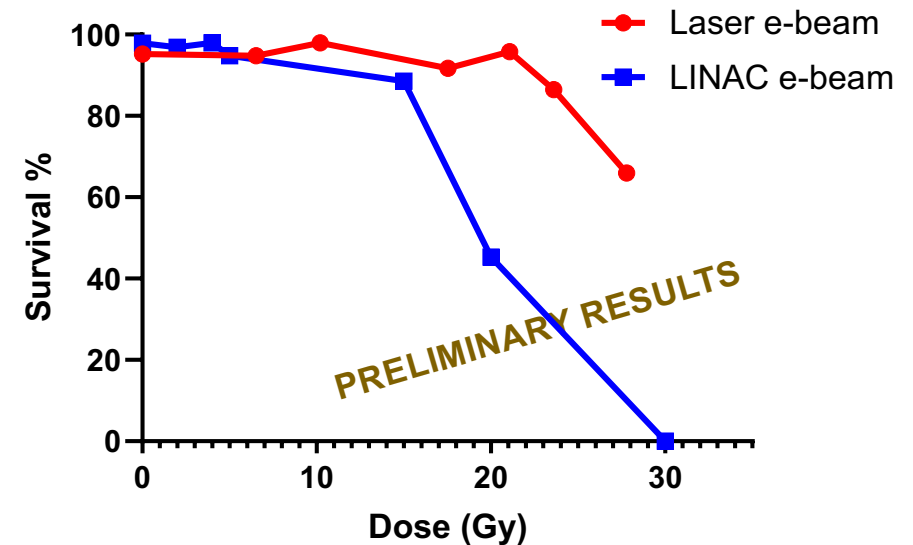
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Depth dose profile in different positions





Target: zebrafish embryos in 2x2 cm target area

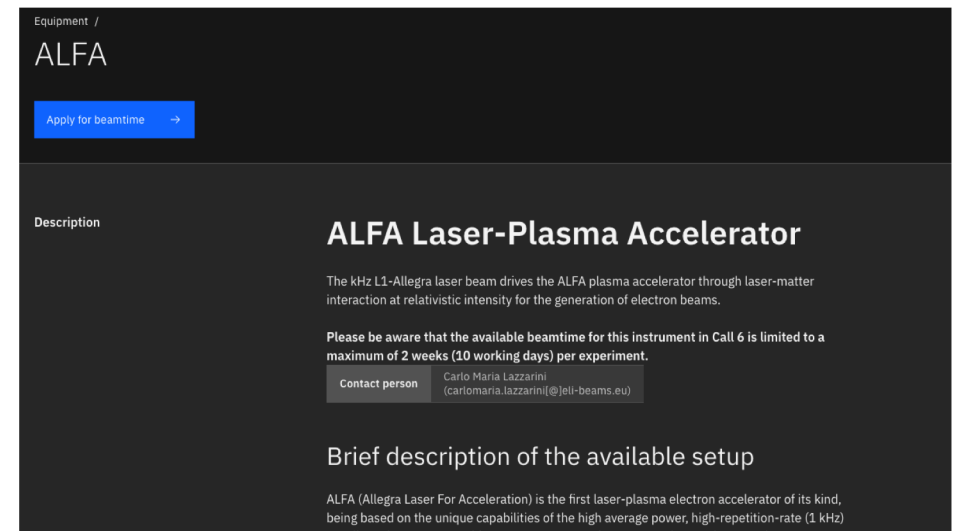


- **First ever on-demand in-vivo irradiation of biological sample with kHz electrons**
- **On-demand = target doses (within 5%) at specific hour agreed 48 hours in advance**
- **Surface dose uniformity < 5% at 1 cm depth, 4 cm²**

- ✓ Highest laser-driven energy electrons (10-50 MeV) at kHz available to Users
- ✓ High dose rate on-demand irradiations in air (in-house protocol)
- ✓ First in-vivo irradiation of biological sample with kHz laser-driven electrons
- ✓ New procedures for precise dosimetry in development (beamtime 2026, PI: Favetta)

<https://up.eli-laser.eu/equipment/alfa-1415577923>

CarloMaira.Lazzarini@eli-beams.eu



The screenshot shows a web interface for the ALFA equipment. At the top, it says 'Equipment / ALFA'. Below this is a blue button labeled 'Apply for beamtime' with a right-pointing arrow. The main section is titled 'Description' and 'ALFA Laser-Plasma Accelerator'. The text describes the kHz L1-Allegra laser beam driving the ALFA plasma accelerator. A note states that the available beamtime for this instrument in Call 6 is limited to a maximum of 2 weeks (10 working days) per experiment. A 'Contact person' box lists Carlo Maria Lazzarini with the email carlomaria.lazzarini@eli-beams.eu. At the bottom, there is a section for a 'Brief description of the available setup'.