Recent Progress on Laser-Driven Very High Energy Electron Radiotherapy

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Global radiotherapy market

- **Cancer is one of the biggest threats to human life**
- **Radiotherapy (RT), relies on ionizing radiation (e.g., photons, electrons, ions) to locally deposit energy to break DNA strands of cancer cells.**

High incidence rate of cancer

New cancer cases:

~ 20 million (annually)

Death rate:

~ 50%

Big demand of radiotherapy

Requirements:

> 50% of cancer patients

Cure rate:

> 60%

Large market size

Current scale:

~ $8 billion

Expected:

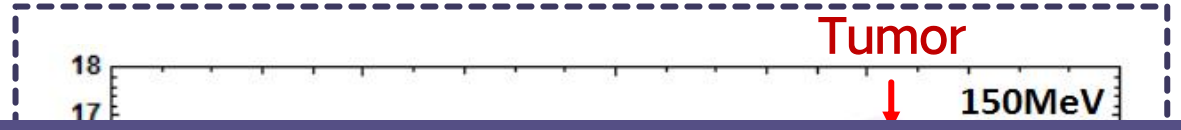
> $13 billion (2030)

Limitations of current RT modalities

Mainstream RT modalities: X-ray, proton/ions

Dose distribution of X-rays of few MeVs

Dose distribution of protons



Is it possible to develop a new radiotherapy device with high compactness/cost-effectiveness/treatment precision?

√ Relative low costs ($5-6 M)

√ **Compact device** (~10s m²)

× **Undesired dose distribution**

× **potential damage to normal tissues**

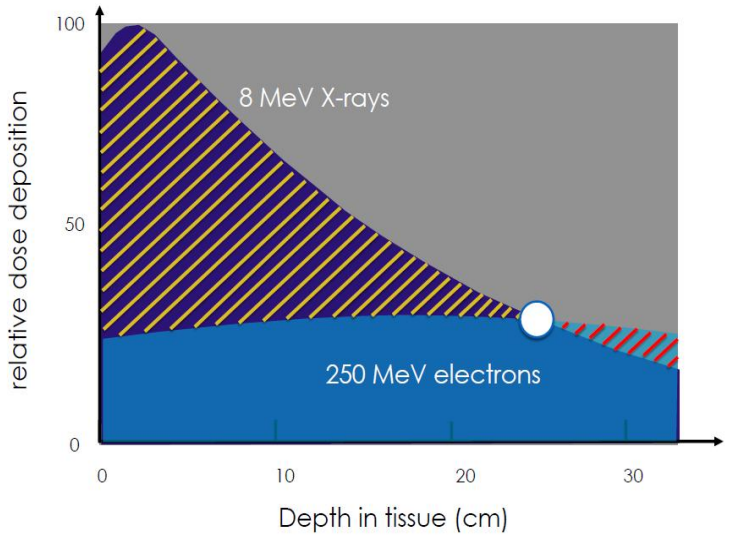
√ **"Bragg peak" effect** (can accurately strike tumors with minimal damage to normal tissues)

× **High costs** ($50+M)

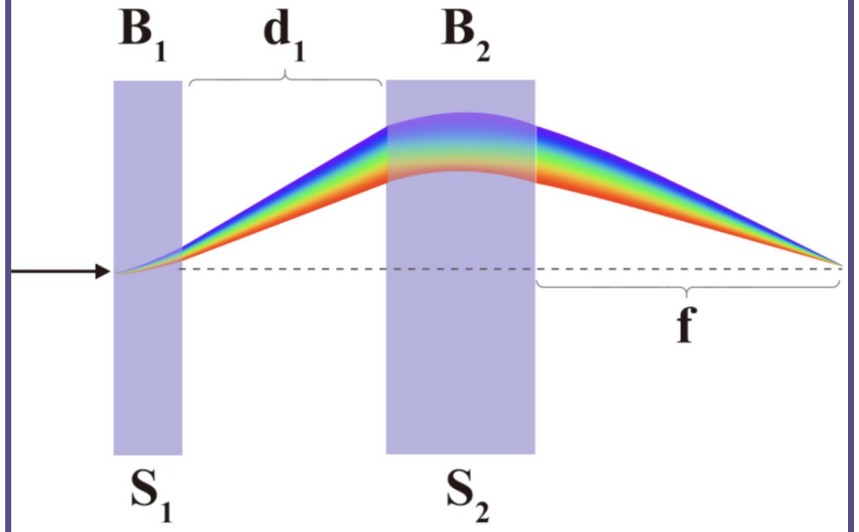
× **Large machine** (~100s m², including shieding and power supplies)

Very high energy electron radiotherapy (VHEE-RT)

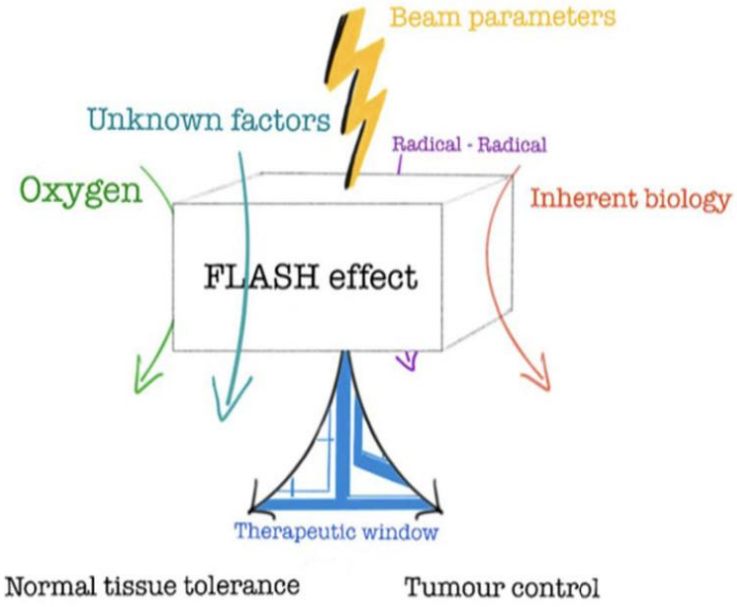
- **Using high energy electrons (50-300MeV) to irradiate deep-seated (10-20cm) tumors**



√ **Better dose deposition characteristics** (compared to X-rays)



√ **Easier to be manipulated by magnetic components** (Compared to ions and X-rays)

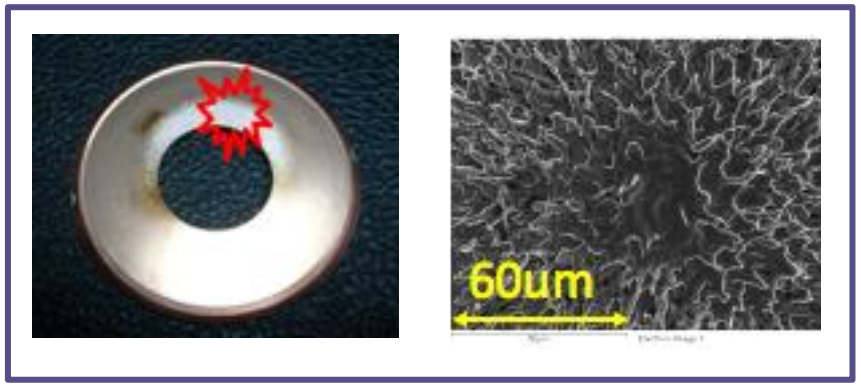


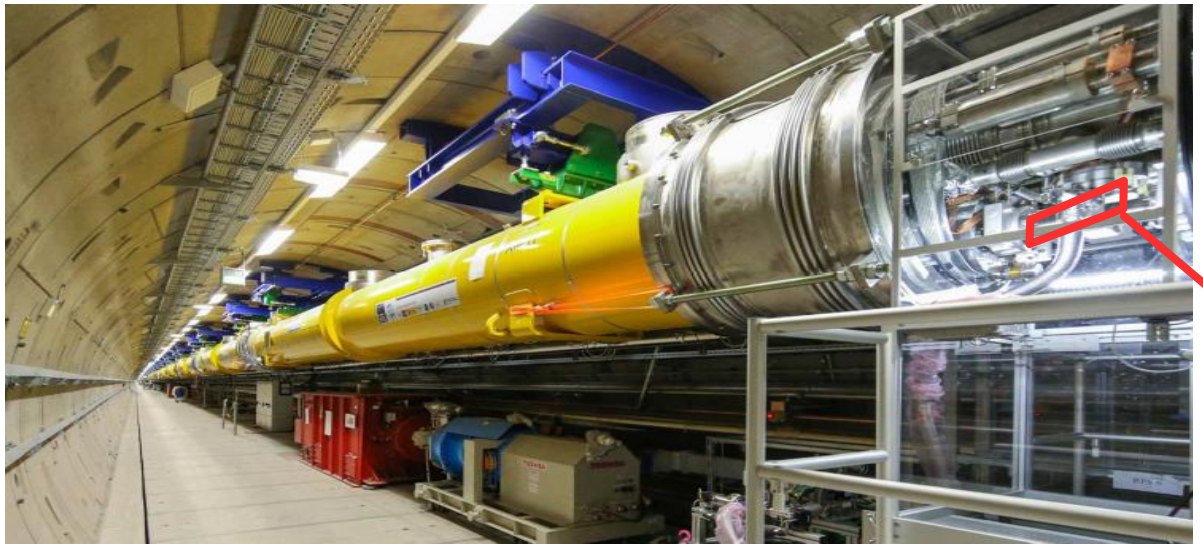
√ **Easier to reach ultra-high dose rate for FLASH effect**

Phys. Med. Biol. 45, 1781 (2000); Technol. Cancer Res. Treat. 1, 105–110 (2002)

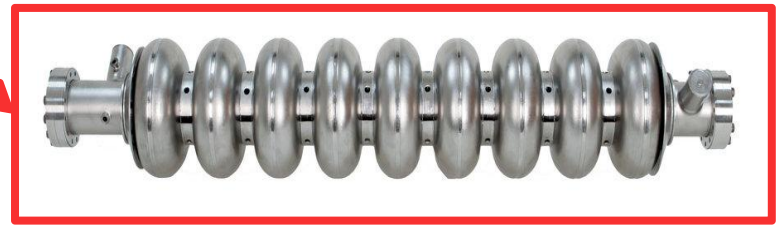
Why VHEE-RT has not yet come to market?

- **Since 2000, VHEE-RT has been actively studied, with numerous international conferences (e.g., VHEE/FRPT workshop)**
  - **Radio-frequency accelerators with accelerating gradient << 100MeV/m, are too large and too expensive**

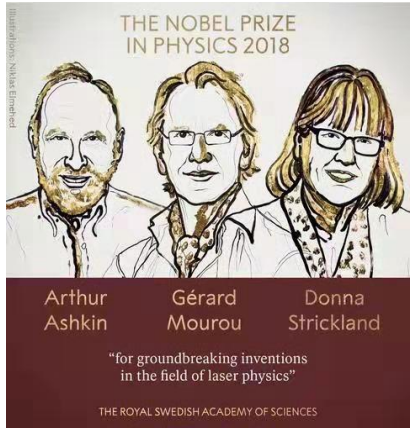




RF Cavity



New route to VHEE-RT: Laser wakefield accelerator

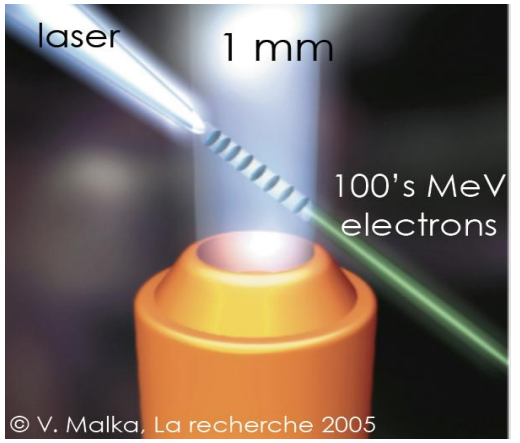


Ultra-short
Ultra-intense
laser pulse

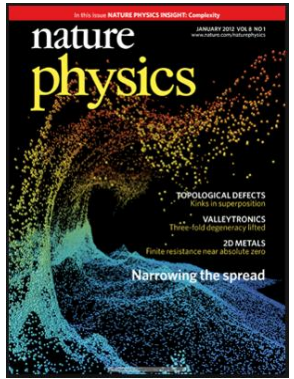
（2018 Nobel prize）

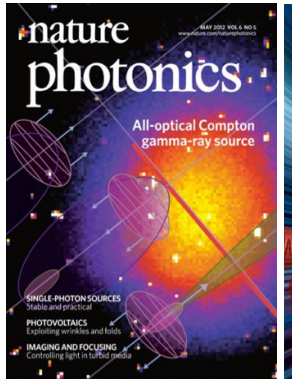
Plasma

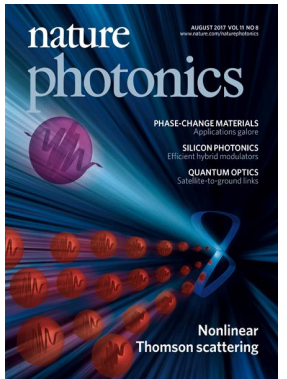
Laser wakefield accelerator

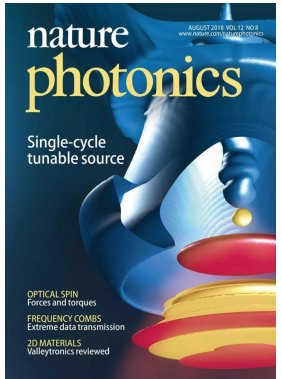


- ✓ **High gradient（>100GV/m，>1000 times higher than RF linac）**
- ✓ **Small structure（<100 μm）**
- ✓ **Unique electron beam properties（fs duration、kA current、 ultrahigh pulse dose rate）**

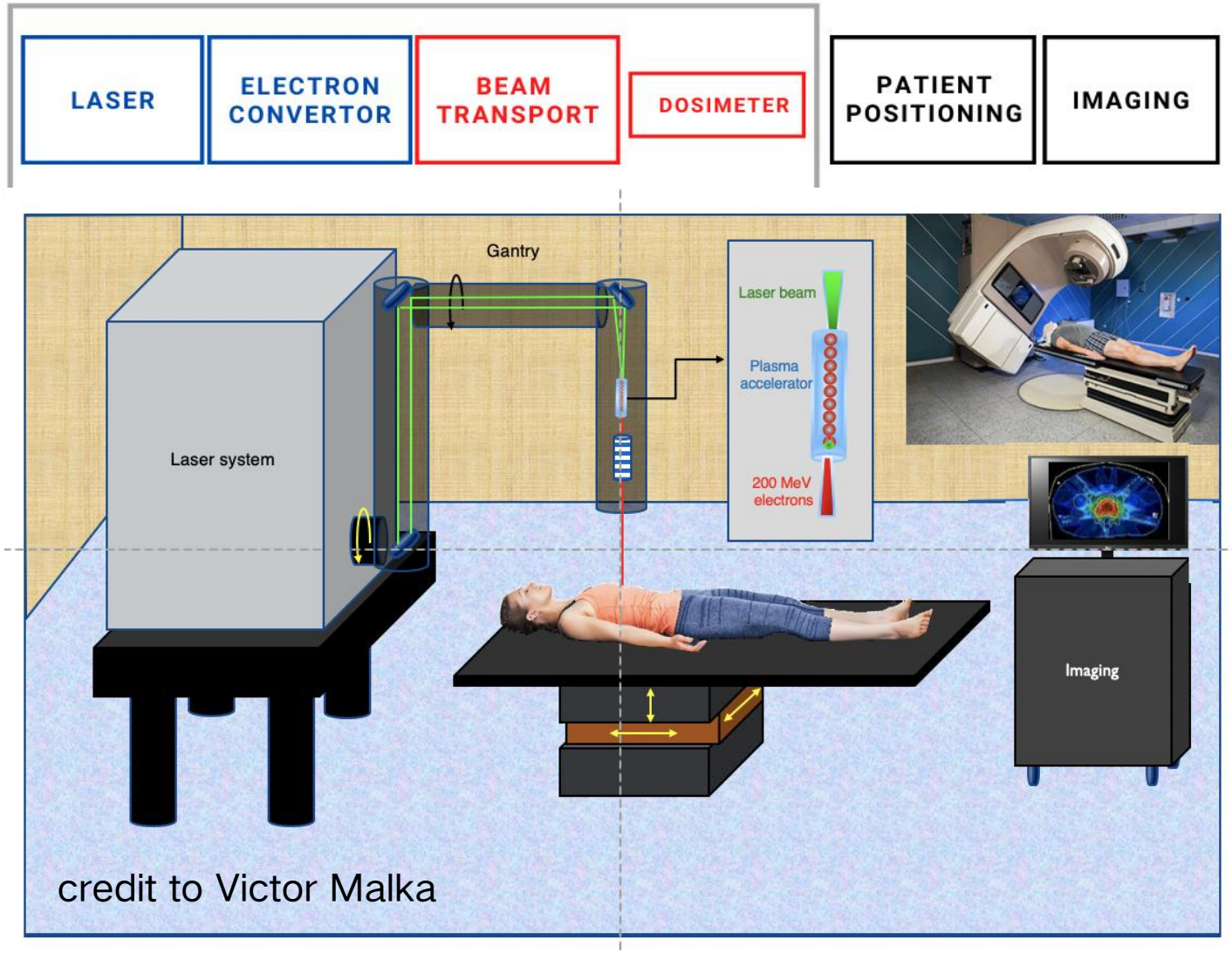








Possible layout of LWFA-based VHEE-RT



Advantages of LWFA-VHEEs

- Compact and cost-effective

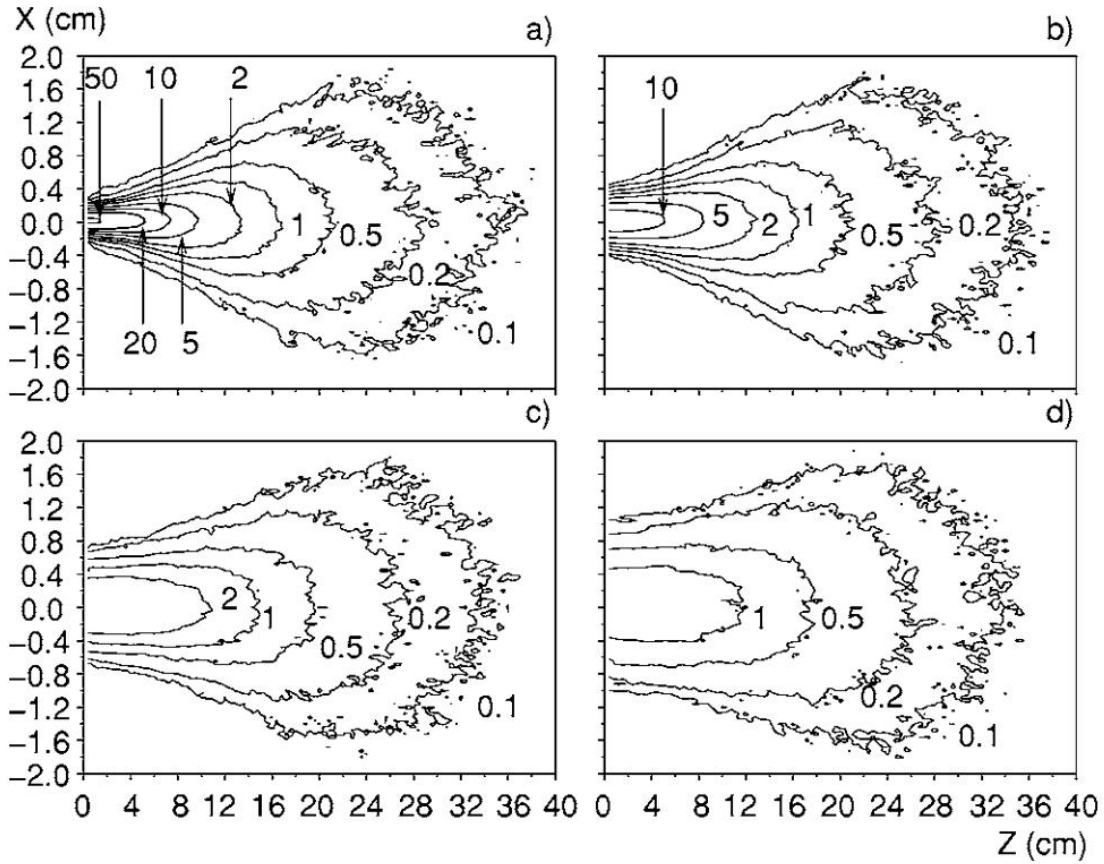
  ($3-6 M, <20m²)

- Similar treatment precision as protons, significantly better than X-rays

(Using focused VHEEs)

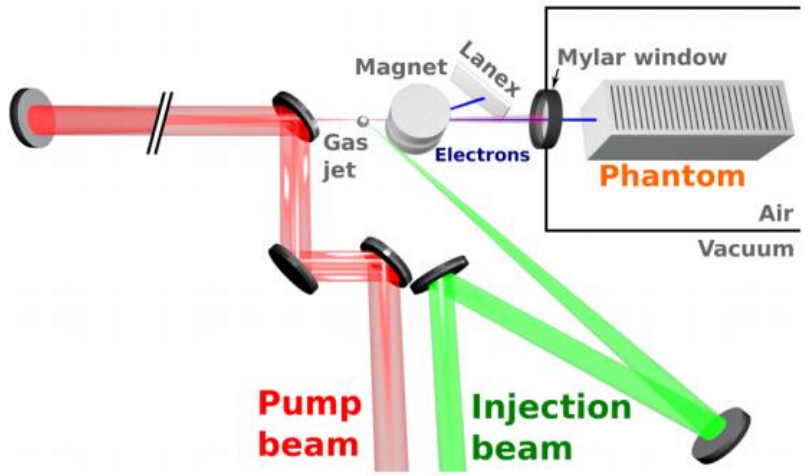
Overview of recent LWFA-VHEE studies

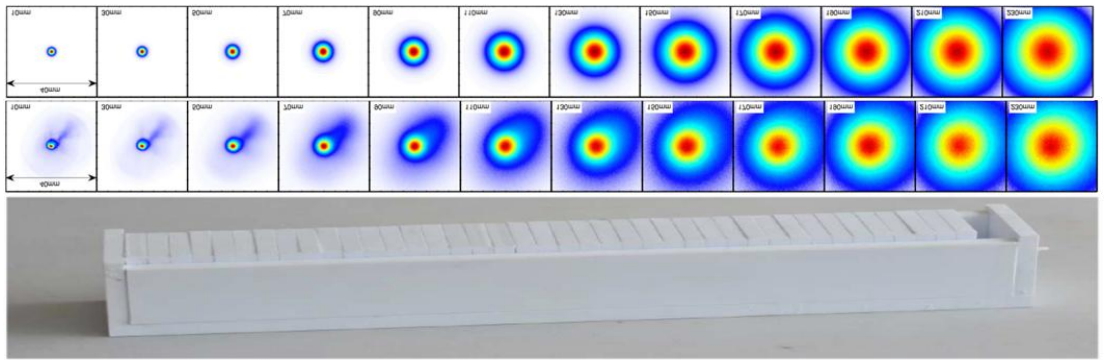
- **2006, first propose to use LWFA-based VHEE for radiotherapy (LOA)**



Y. Glinec et al, Med Phys, 33, 155-162 (2006)

- **2012, measurement of the 3D dose distribution of LWFA-based VHEE (LOA)**

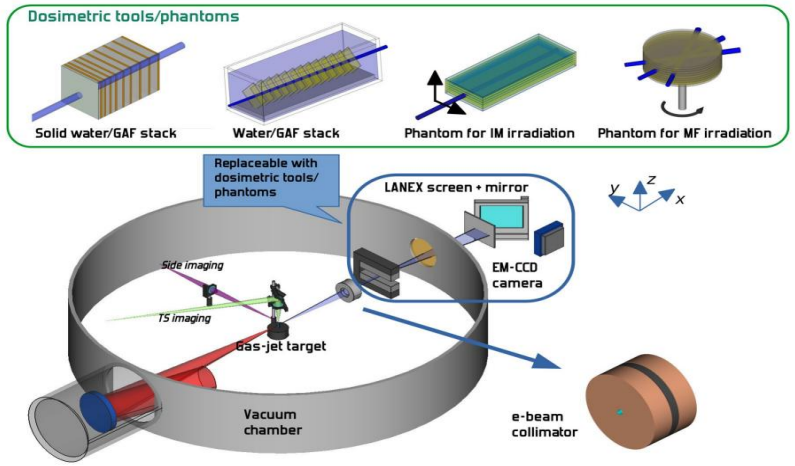


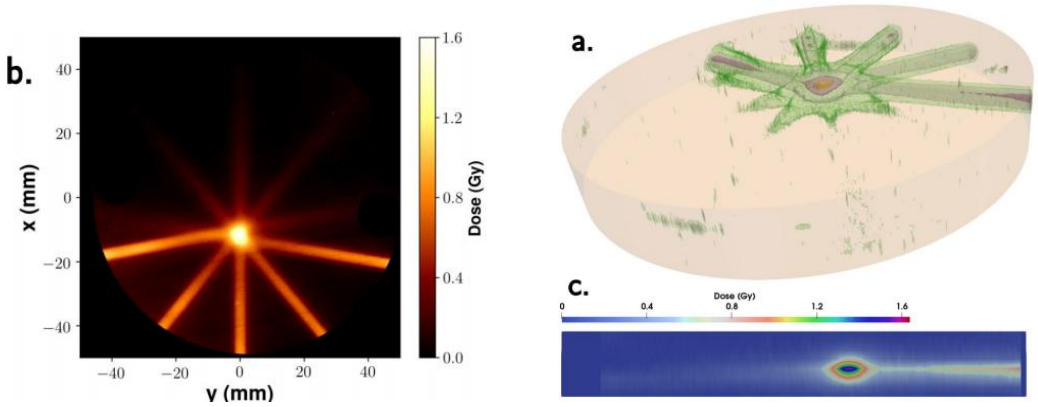


O. Lundh et al, Med Phys, 39, 3501-3508 (2012)

Overview of recent LWFA-VHEE studies

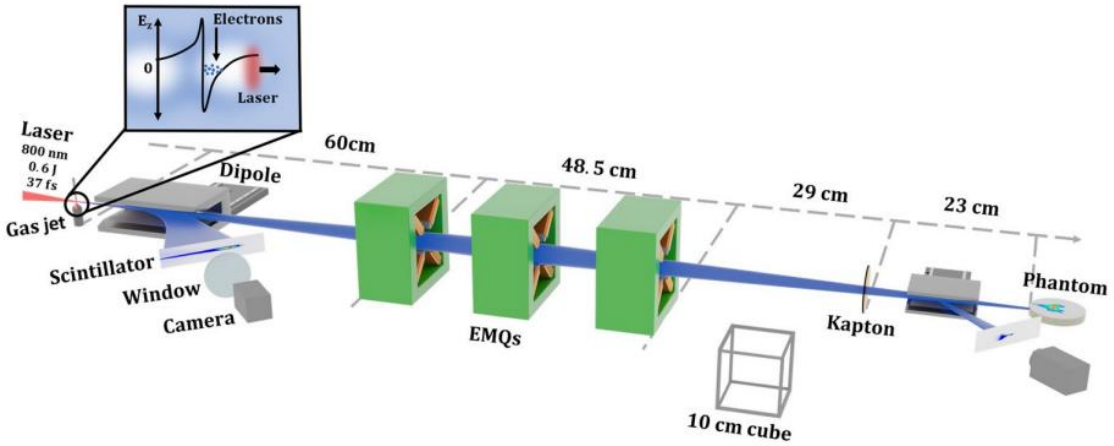
- **2020**, using LWFA-based VHEE (unfocused) for multi-angle irradiation (CNR - INO)

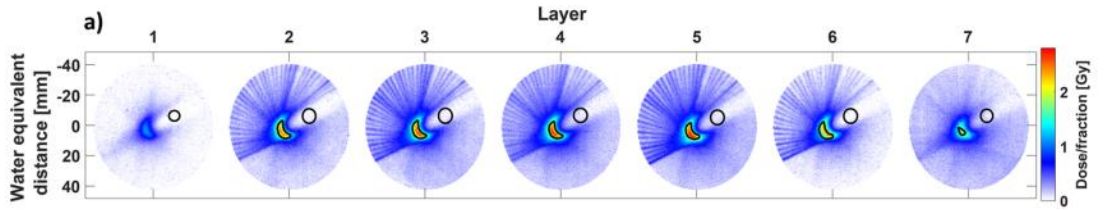




L. Labate et al, Sci Rep, 10, 17307 (2020)

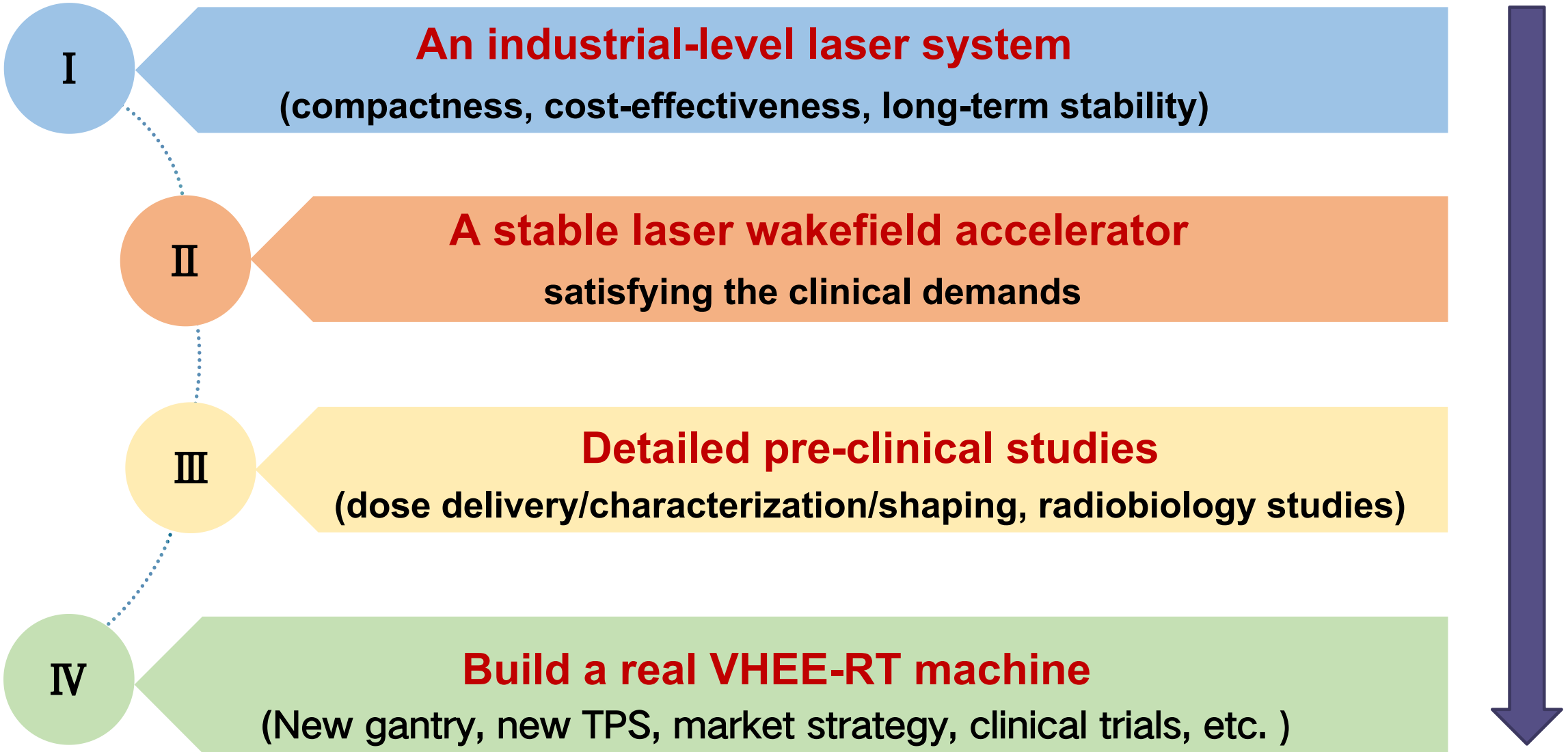
- **2021**, using focused LWFA-based VHEE for multi-angle irradiation (Lund Unix)





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

Key steps for LWFA-based VHEE-RT to be reliable



Joint team for LWFA-based VHEE-RT

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

郑州大学
ZHENGZHOU UNIVERSITY

清華大學
Tsinghua University


Wei Lu


Yang Wan


Xiangbo Wan


Jianfei Hua


Bo Peng


Shuang Liu


Bo Guo


Zhiyuan Guo


Bing Zhou


Qiyu Yang


Junqi Liu


Haiyang Wang


Yifei Pi


Xiaoyan Wang

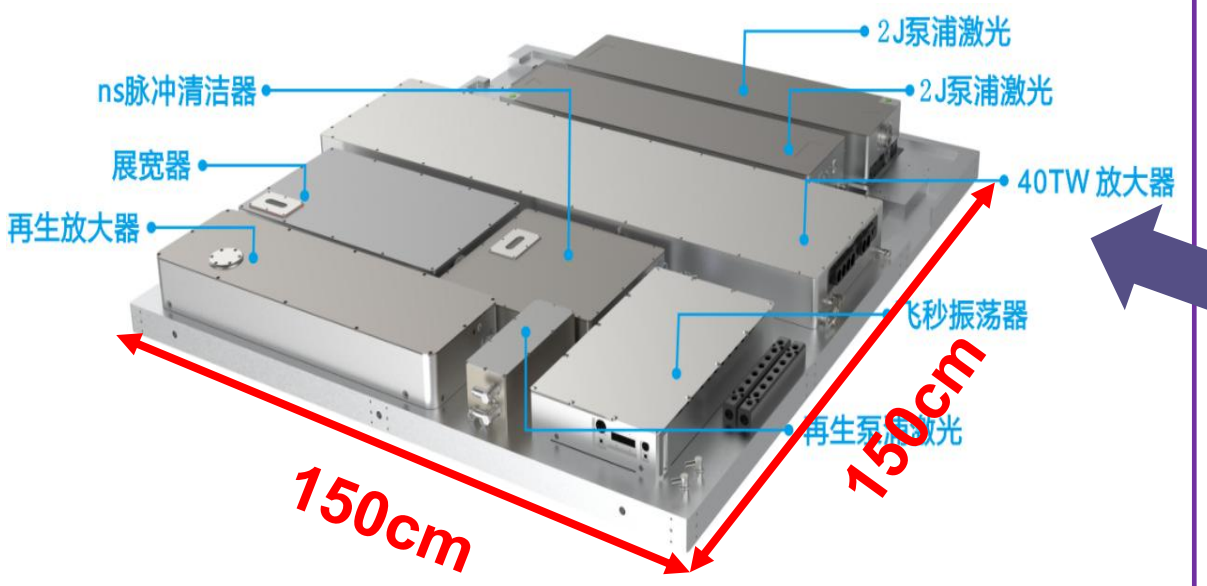

Yiying Mo

BAQIS
北京量子信息科学研究院

郑州大学第一附属医院
THE FIRST AFFILIATED HOSPITAL OF ZHENGZHOU UNIVERSITY

北京智源
BAAI

1. Compact intense laser development (40TW/30fs/10Hz)

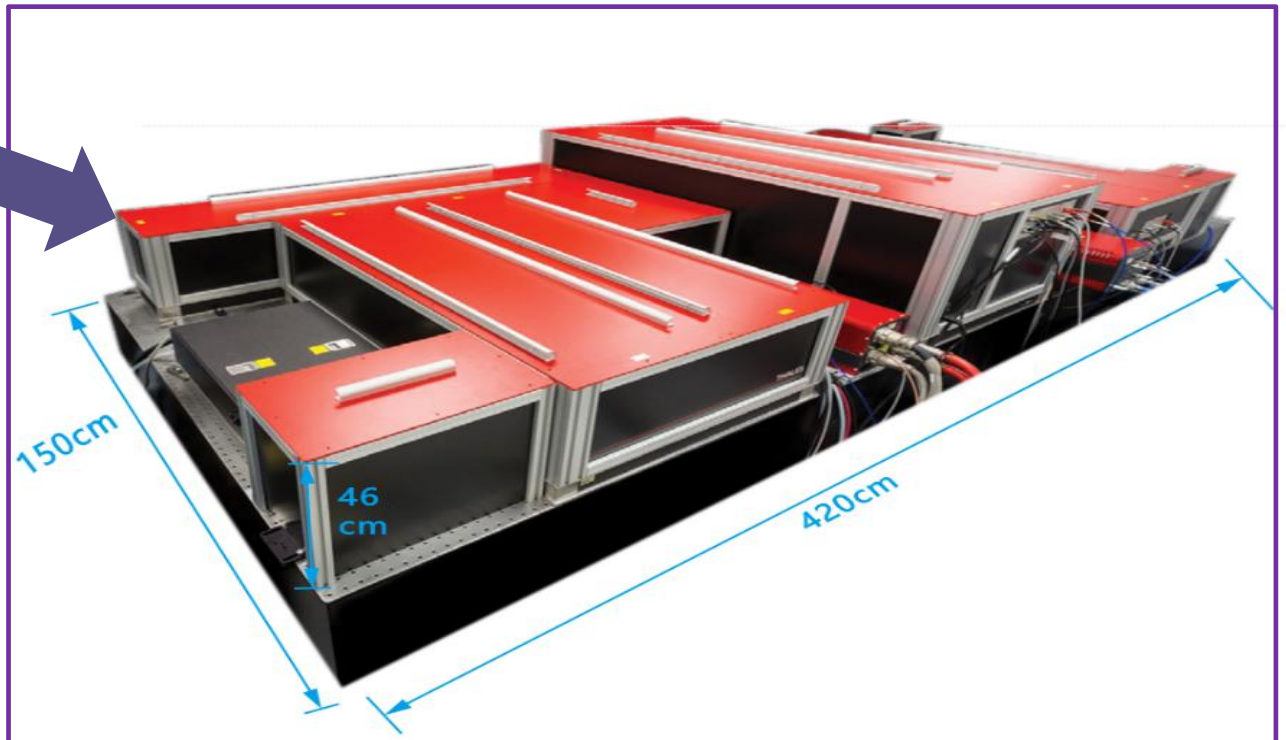


Our 40TW laser

The cost is largely reduced !

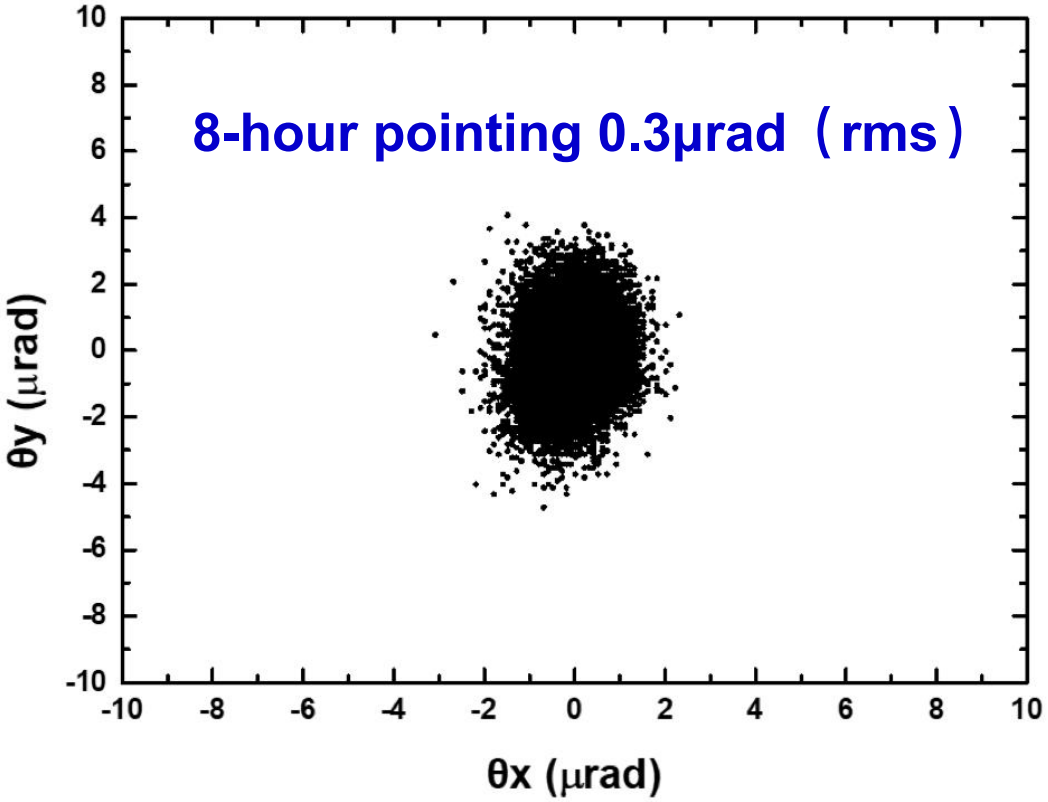
(Oscillators/Pumps/Amplifiers/Pocket Cells are all made by our team)

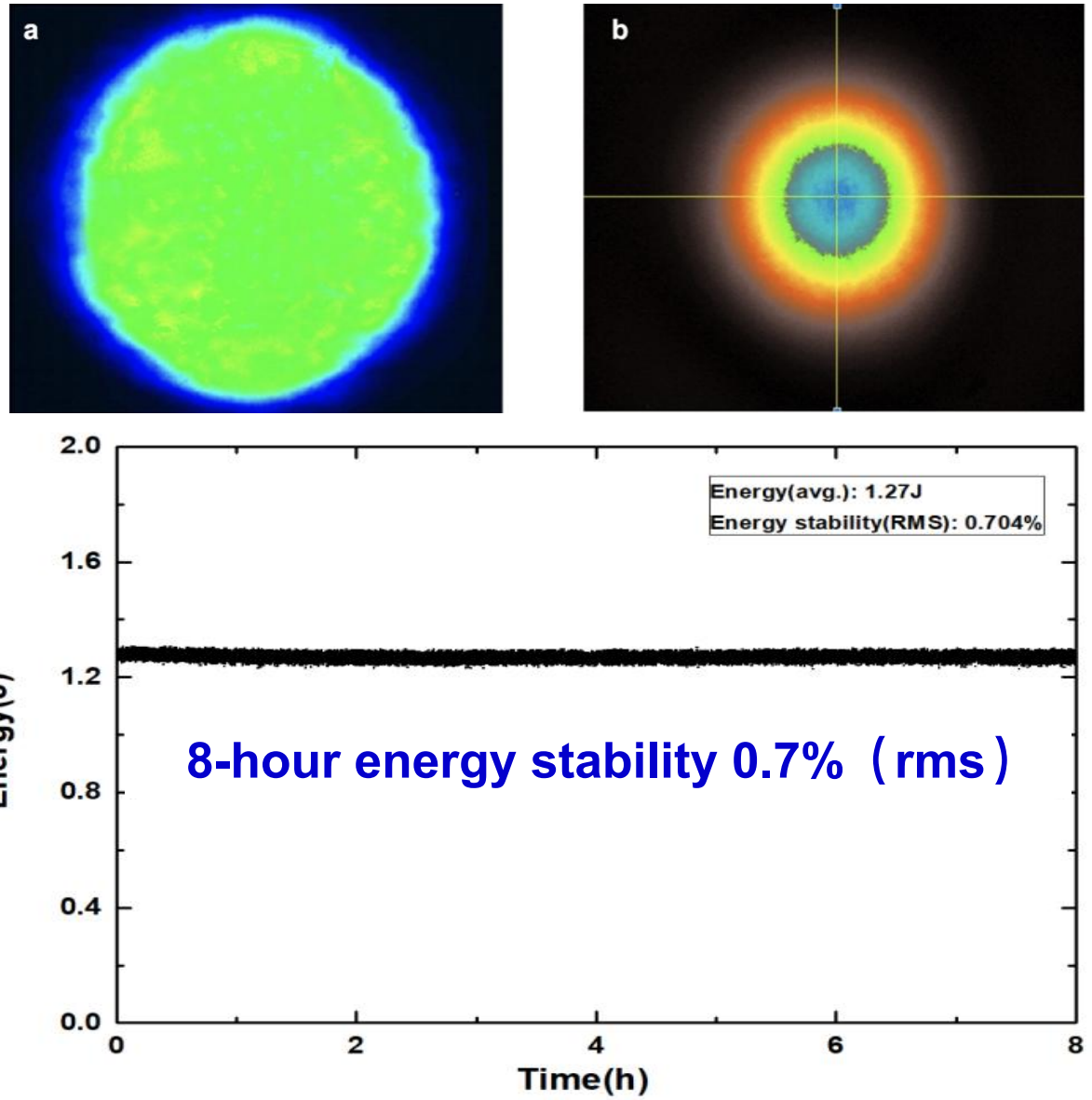
Very compact !



Thales Quark 45 laser

40TW/30fs/10Hz laser system

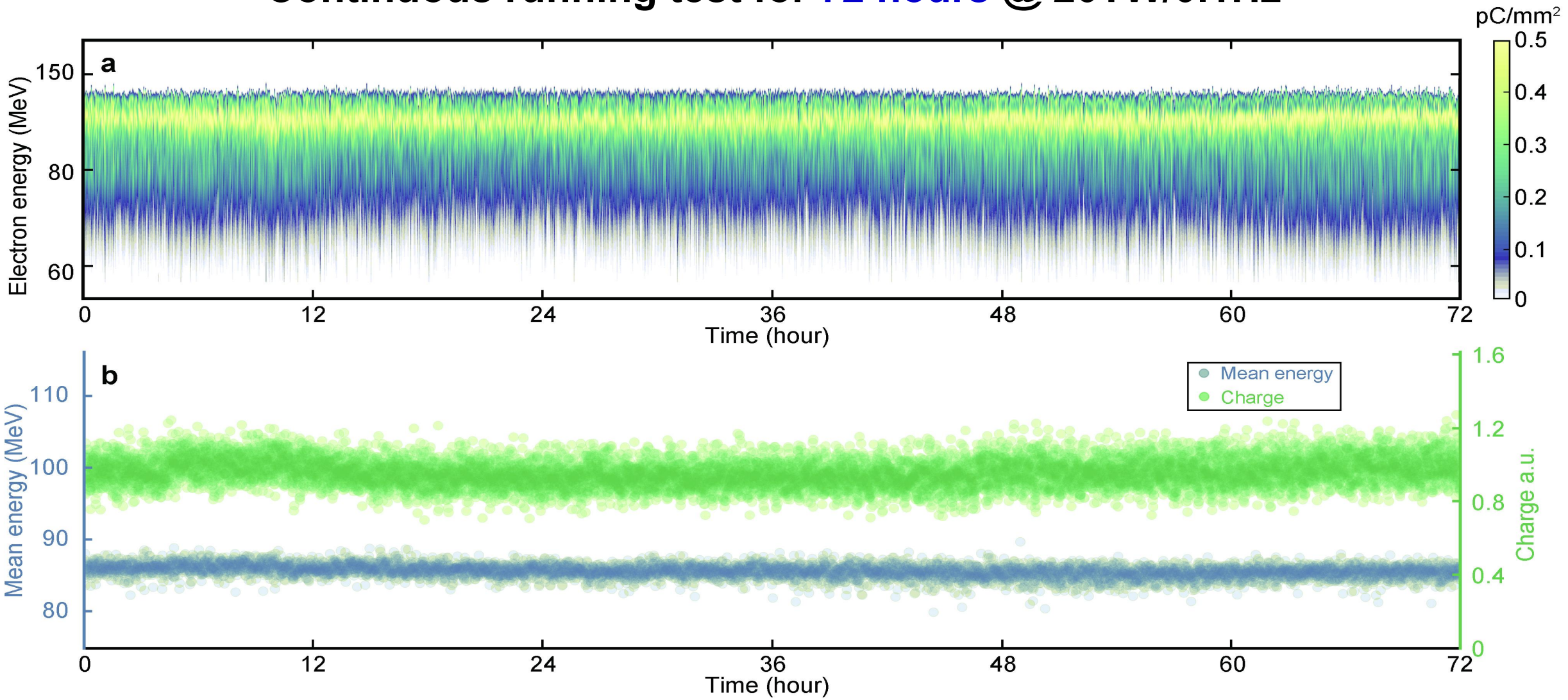




High operation stability

2. Stable LWFA development

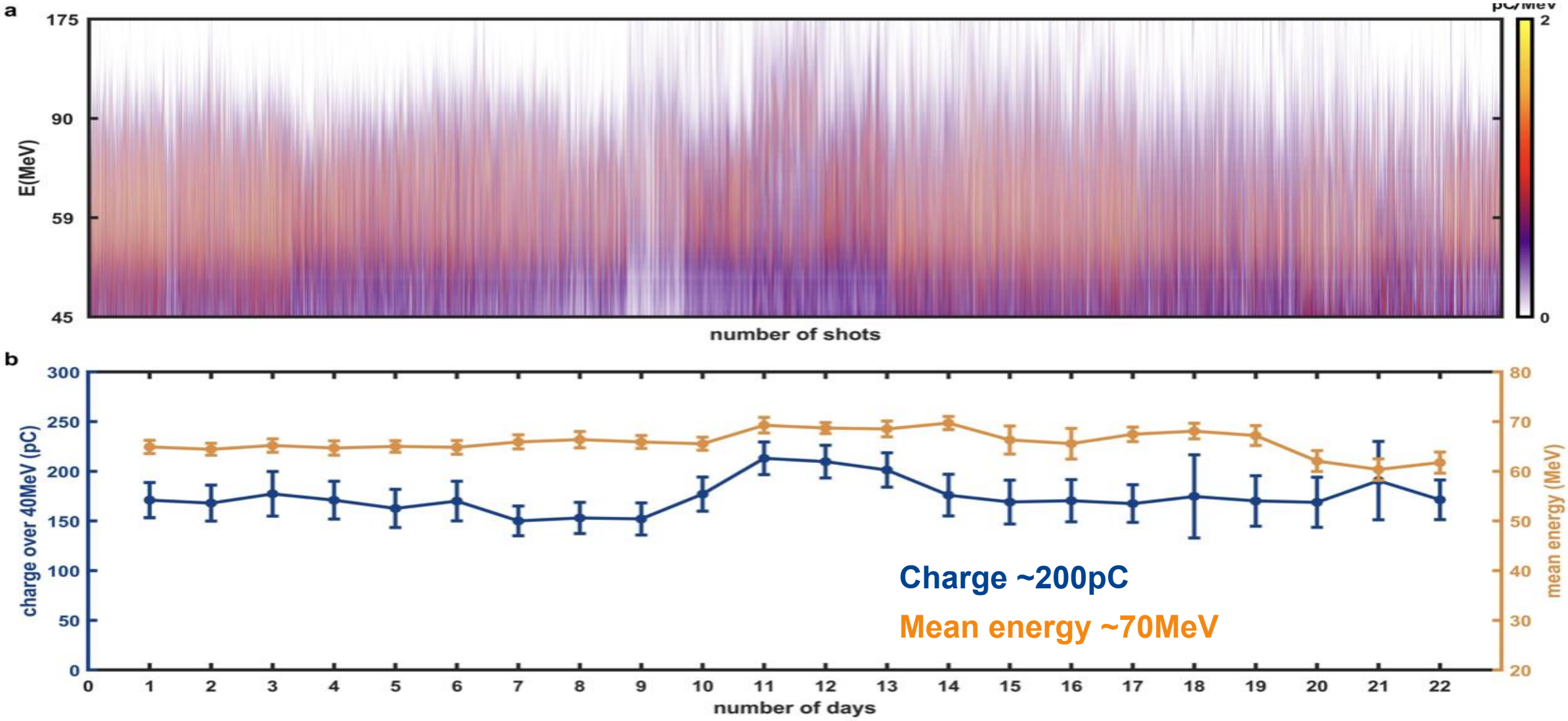
Continuous running test for 72 hours @ 20TW/0.1Hz



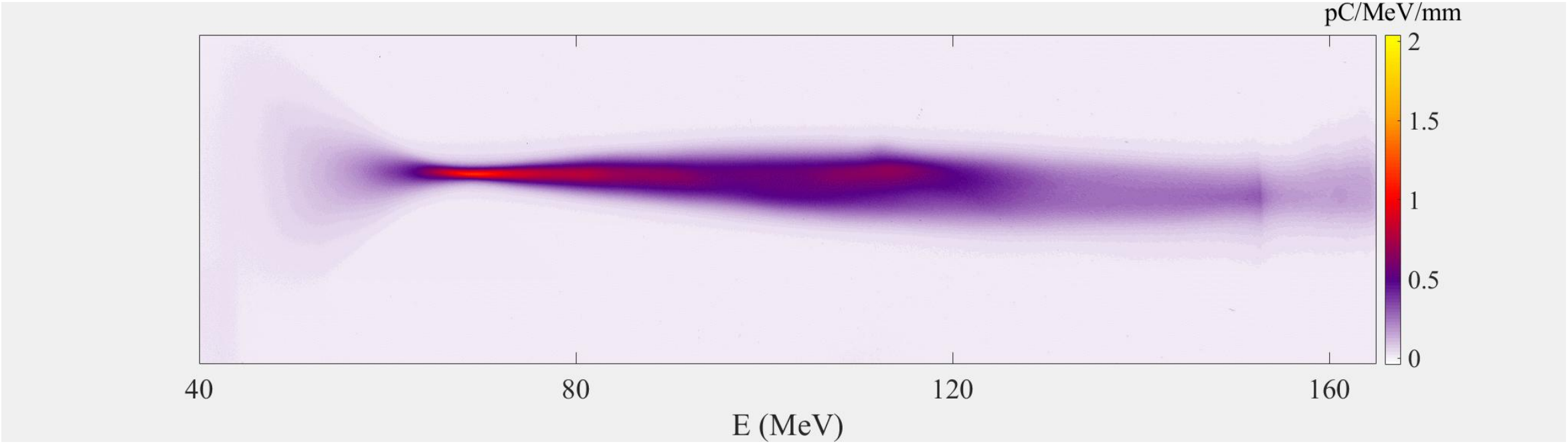
B. Guo et al., in preparation

LWFA stability test for one month

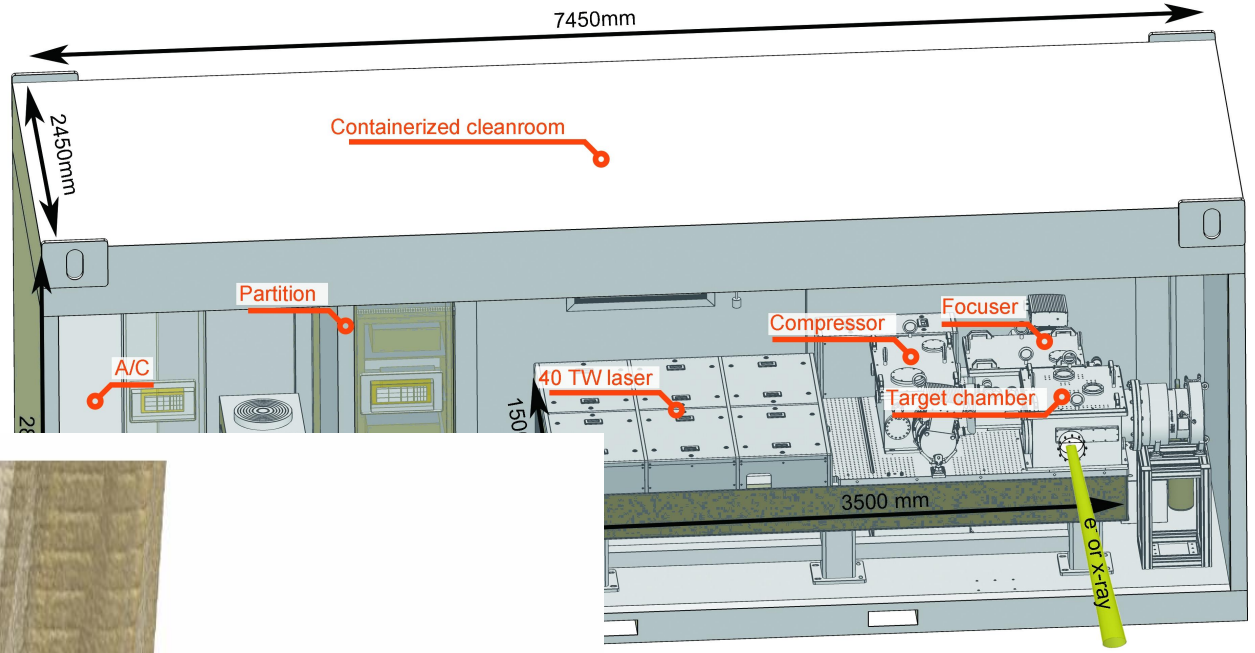
Running for one month (~3000 shots/day @ 20TW/1Hz）

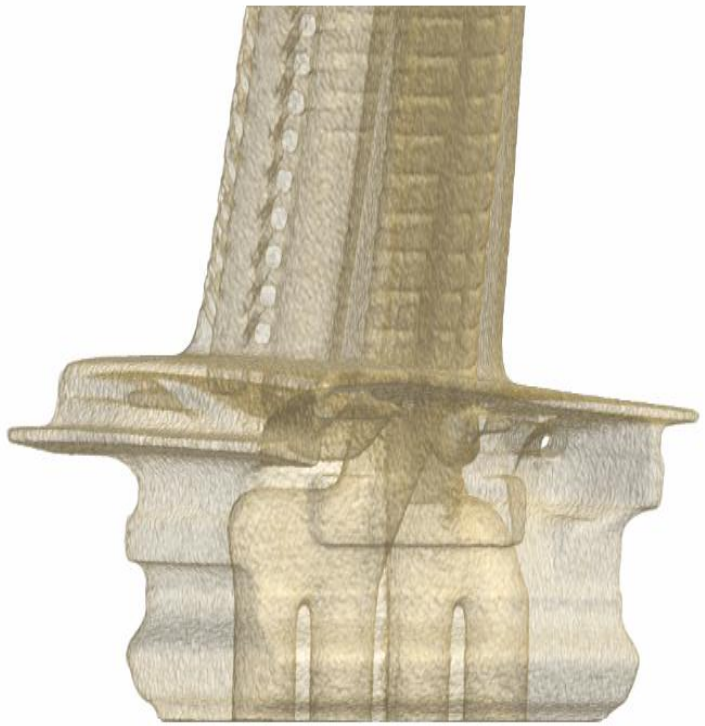


1000 consecutive shots/3.3Hz



The first transportable LWFA for high-resolution industrial CT





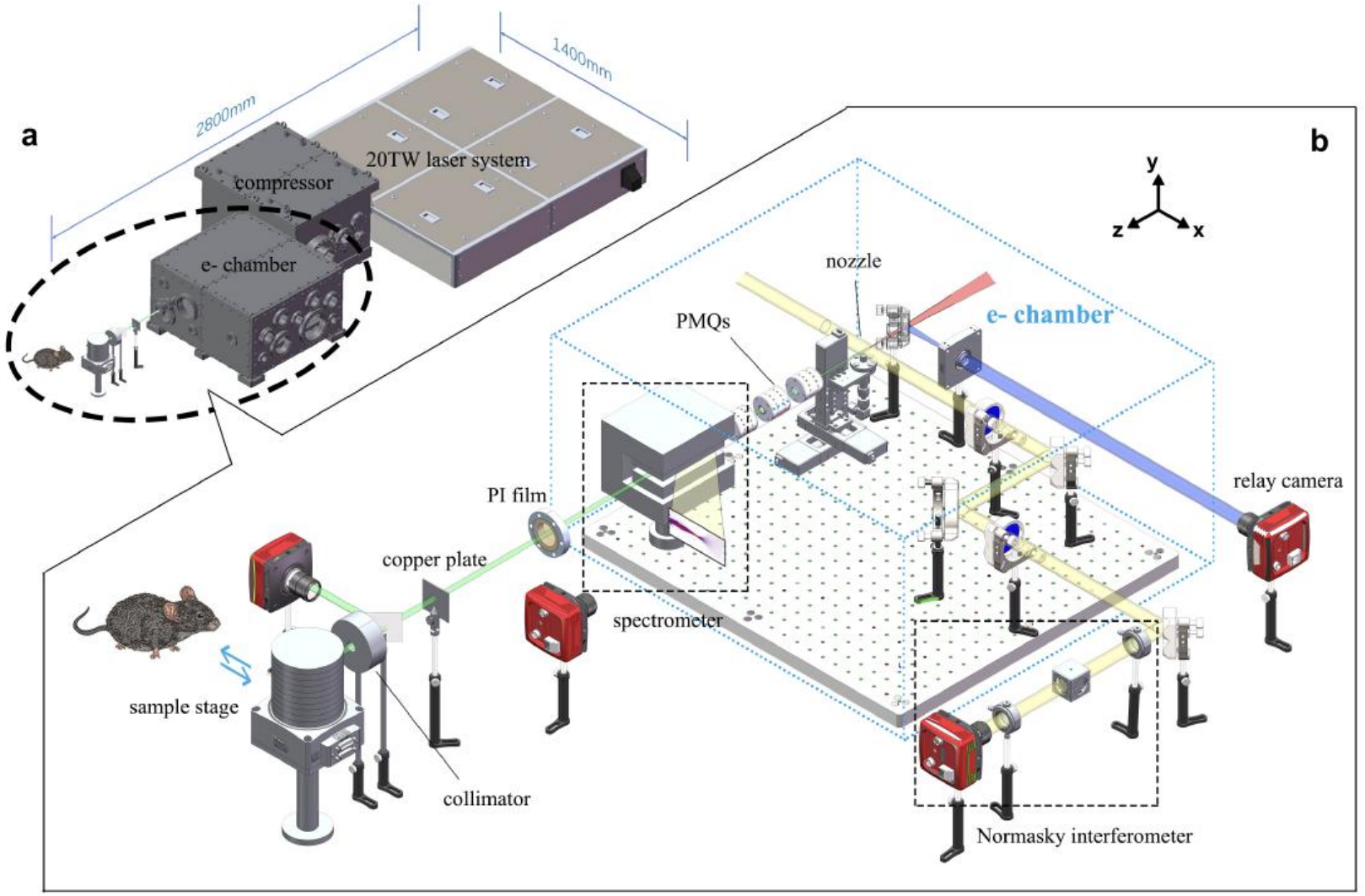
CT of turbine blade

- ✓ 60,000 shots @ 3.3Hz
- ✓ resolution: 43μm

B. Guo et al., in preparation

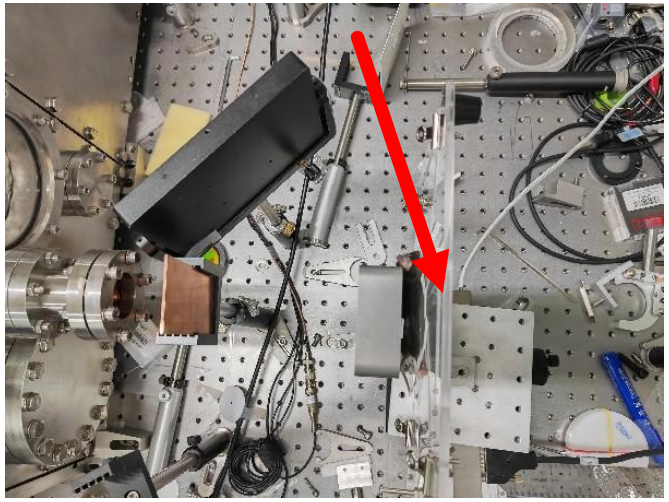
3. Mice tumor irradiation using LWFA-based VHEE

Physical layout (2.8m*1.4m)

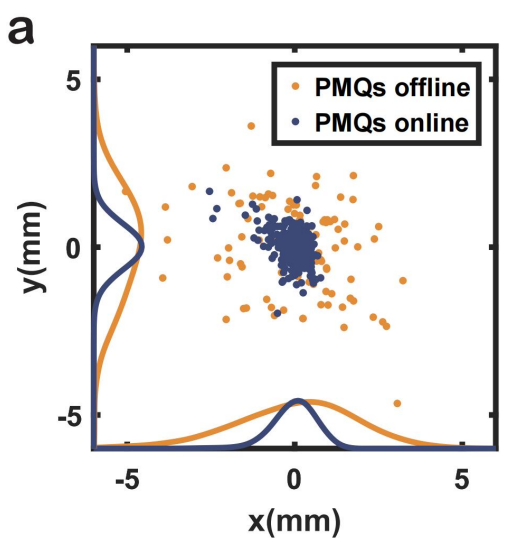


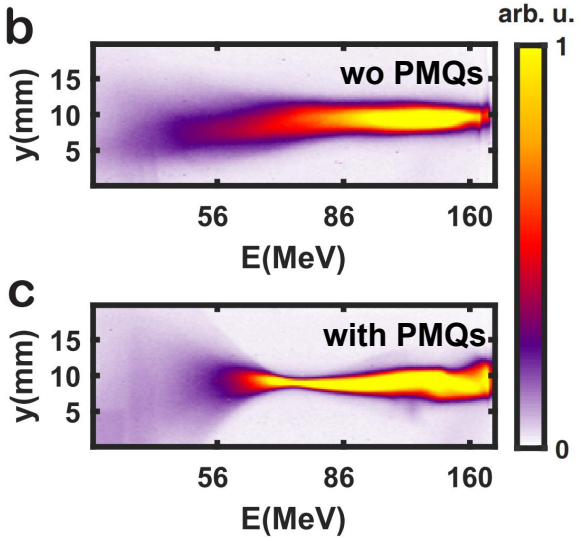
Solid water+EBT3

Mounts for positioning mice



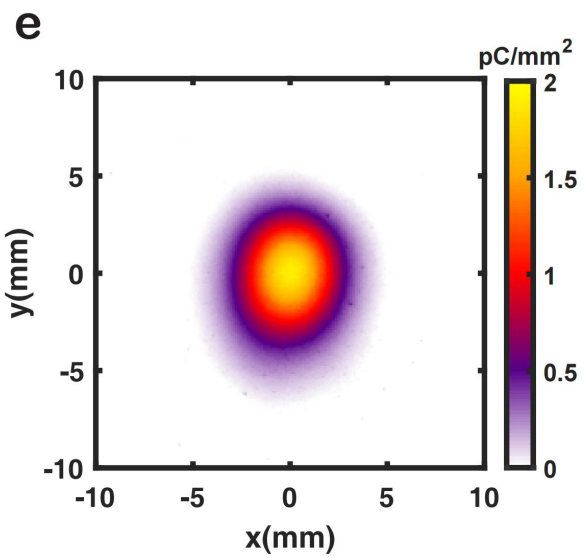
Optimizing the VHEE dose delivery



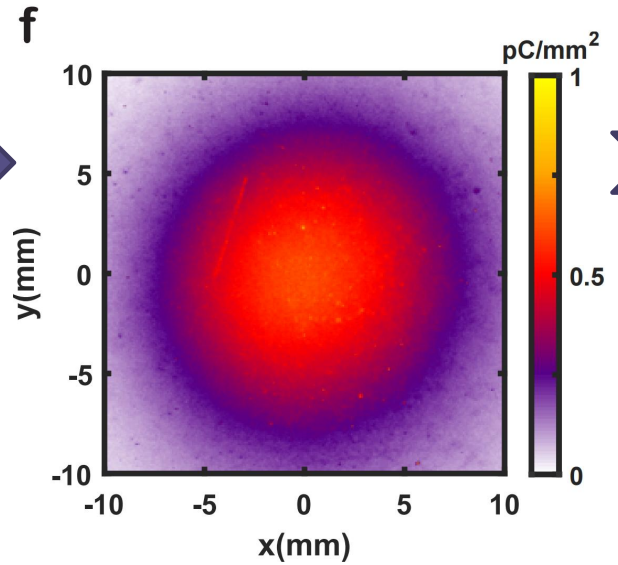


Transport with a small PMQ triplet

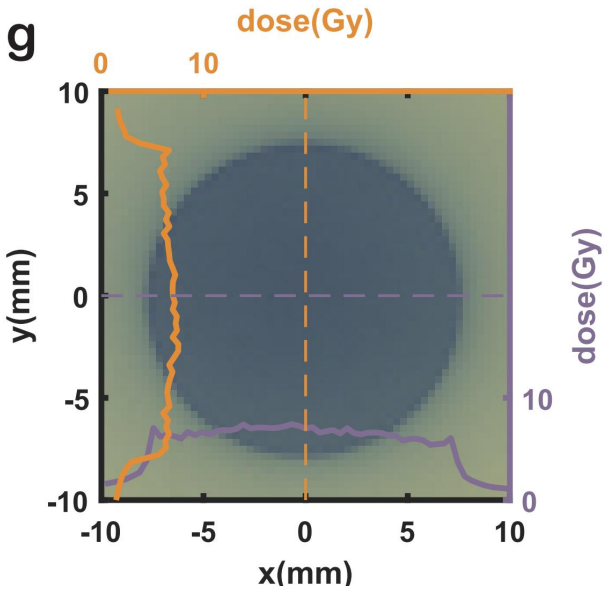
- improve the beam pointing jitter by almost one order (from~2.4 mm to ~0.3 mm)
- filter out low-energy electrons (below 50 MeV)



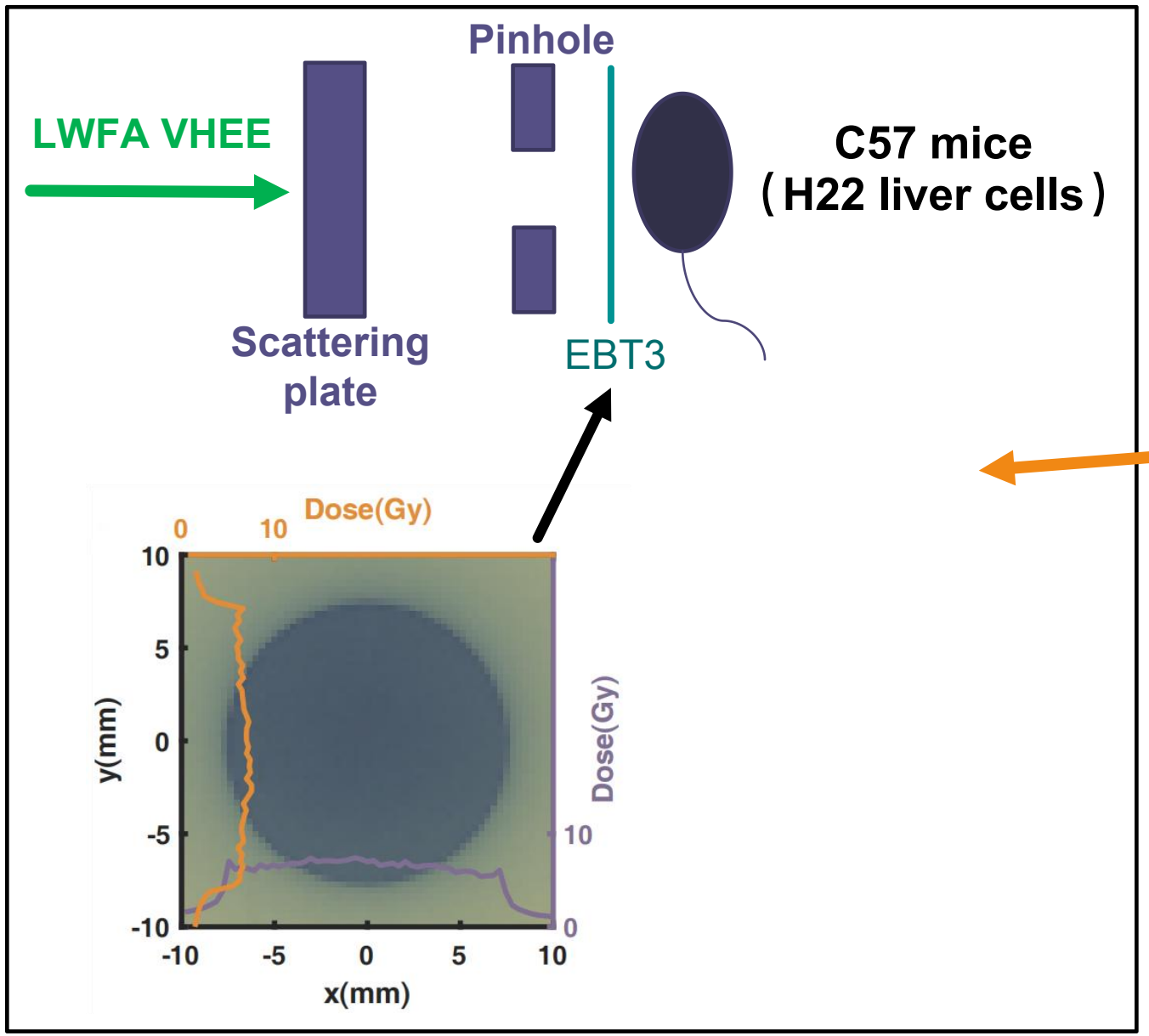
Scattered by a 1.5mm-thick copper



Confined by a 15 mm-diameter apeture



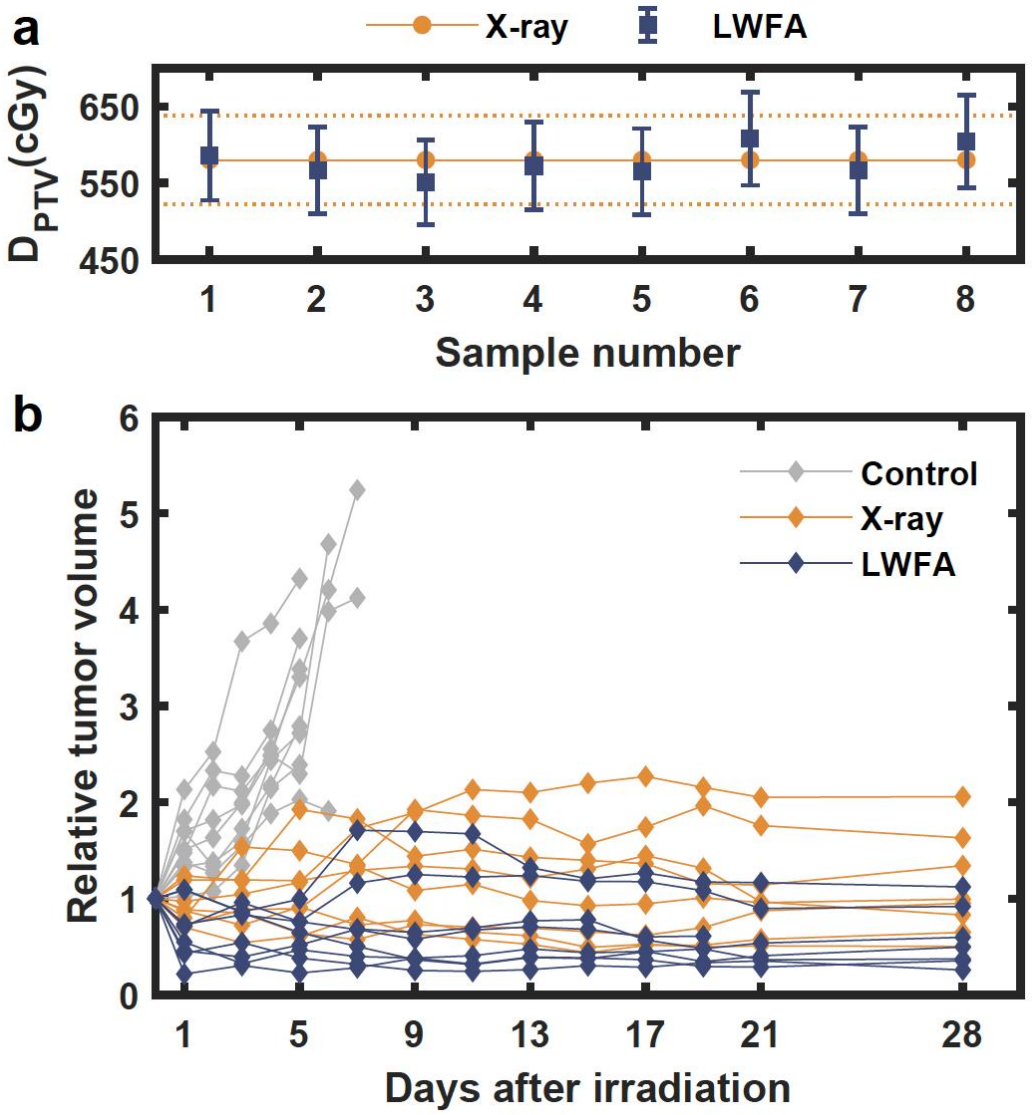
Irradiating mice tumors with LWFA-based VHEE



24 mice (5-6 weeks old, male) with tumor size of ~7mm (1 week growing) are divided equally into 3 groups:

- **Control group**
- **LWFA VHEE group**
- **X-ray radiotherapy group**

Irradiation results



- Commerccial X-ray device: 5.8 Gy
- LWFA VHEE: 5.8± 0.2 Gy

In both groups, tumors are effectively controlled by a one-month monitoring

nature communications

Article

https://doi.org/10.1038/s41467-025-57122-z

Preclinical tumor control with a laser-accelerated high-energy electron radiotherapy prototype

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Check for updates

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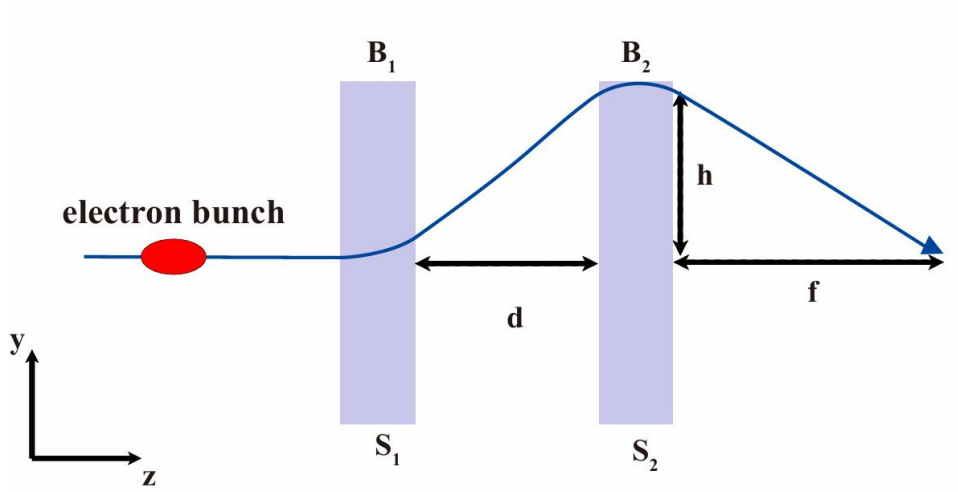
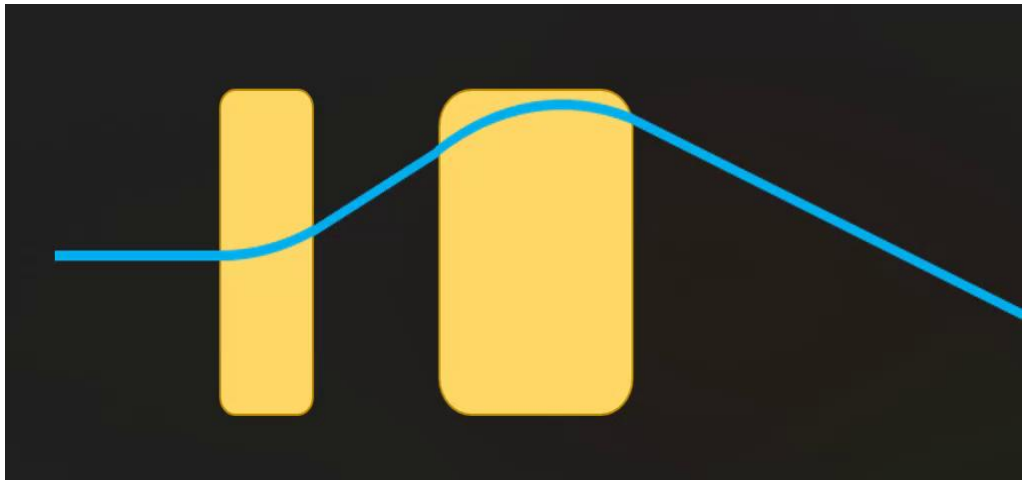
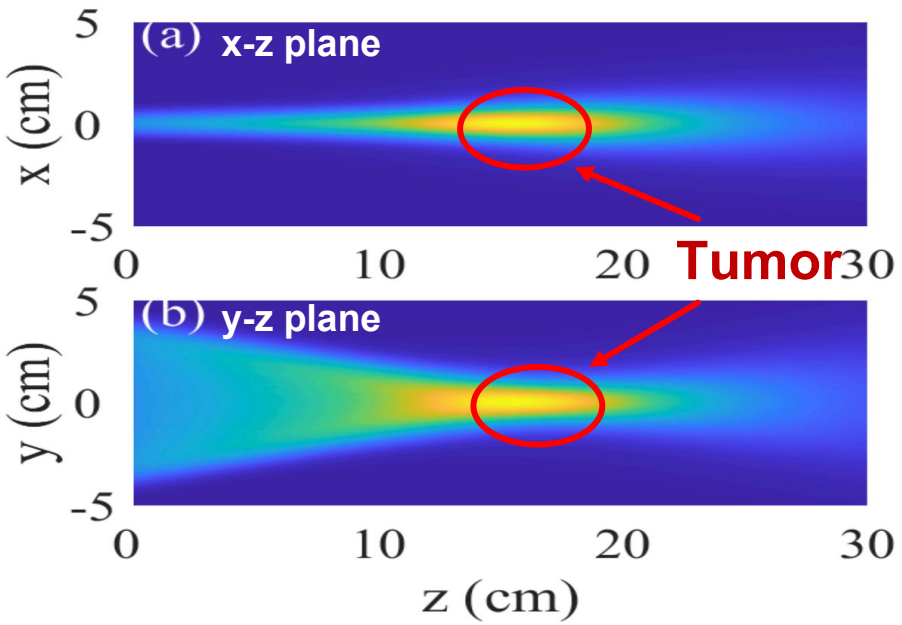
Radiotherapy using very-high-energy electron (VHEE) beams (50-300 MeV) has attracted considerable attention due to its advantageous dose deposition

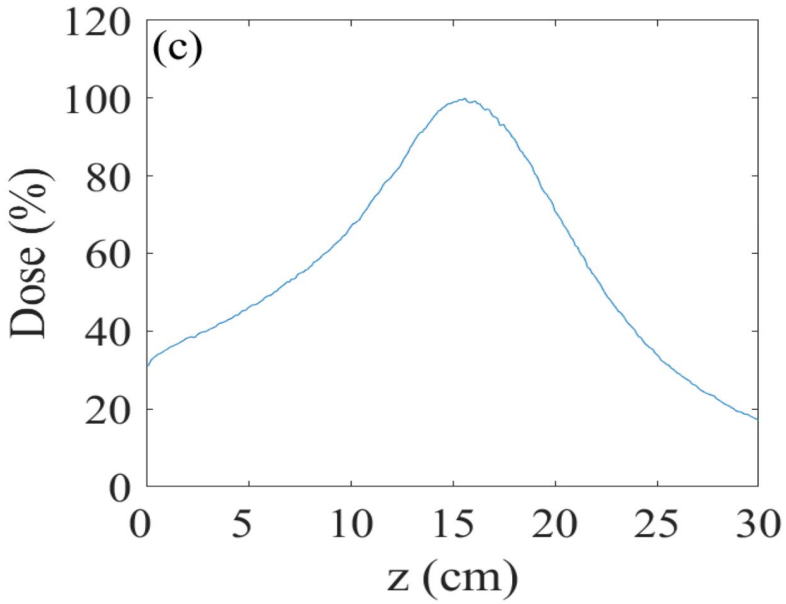
4. A new beam delivery system for LWFA-based VHEE

- **Consist of only two dioples (B_1, B_2)**







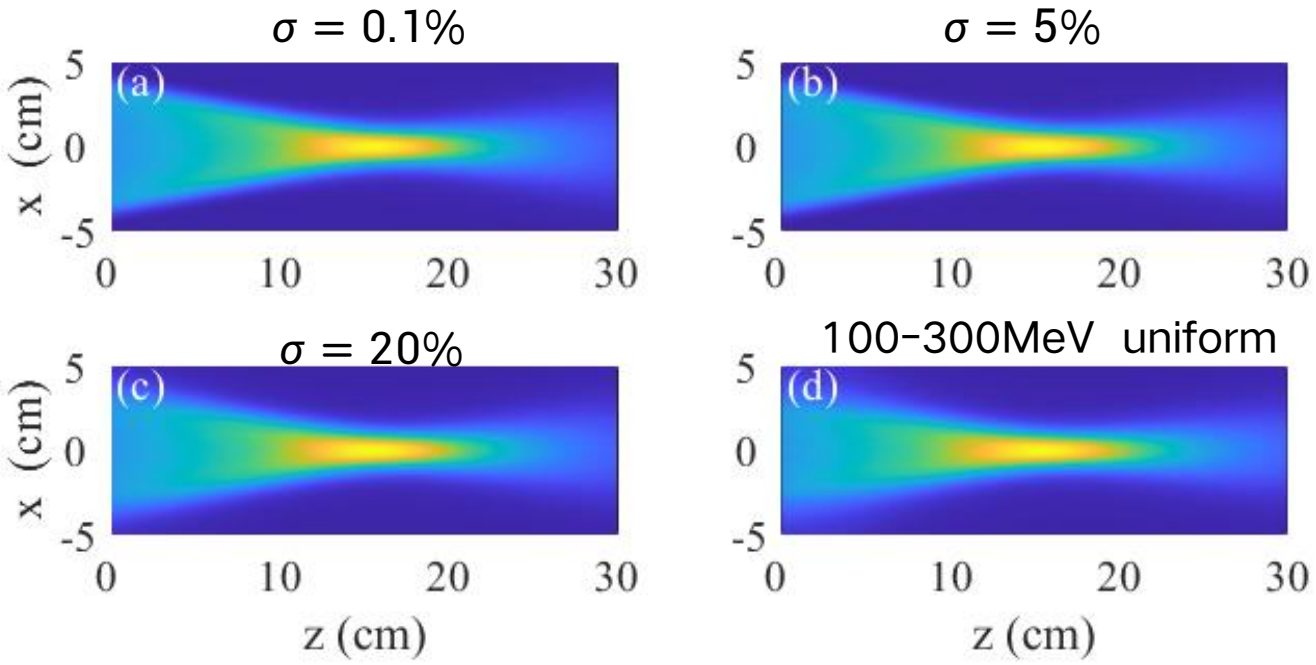


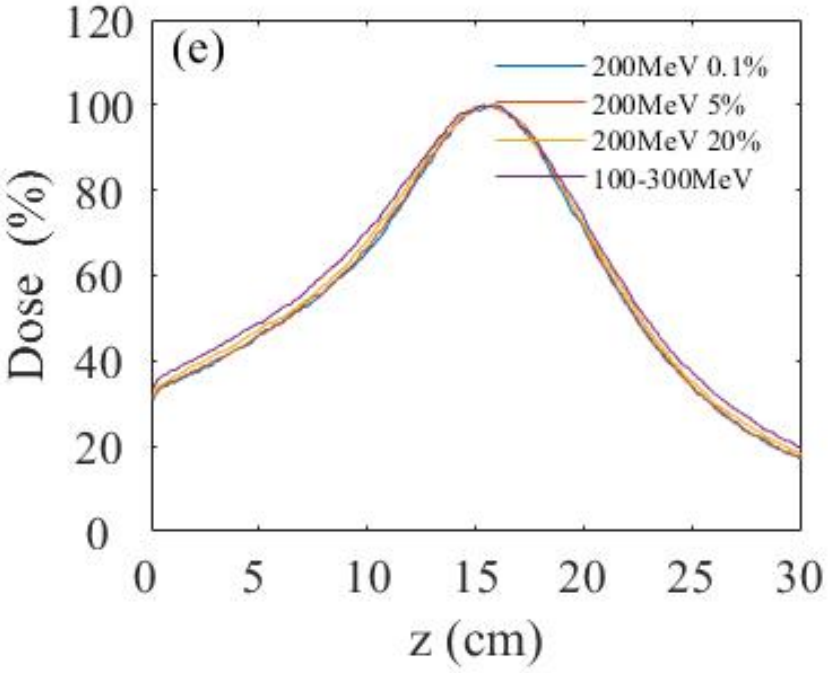
Create a maximum dose deeply inside the body (10-20cm)

Transporting beams with large enegy spread

$$f \approx \frac{h}{\theta_2 - \theta_1} = \frac{d_1}{\frac{R_1}{R_2}\frac{S_2}{S_1} - 1} = \frac{d_1}{\frac{B_2}{B_1}\frac{S_2}{S_1} - 1}$$

The converging position is irrelevant to VHEE energy

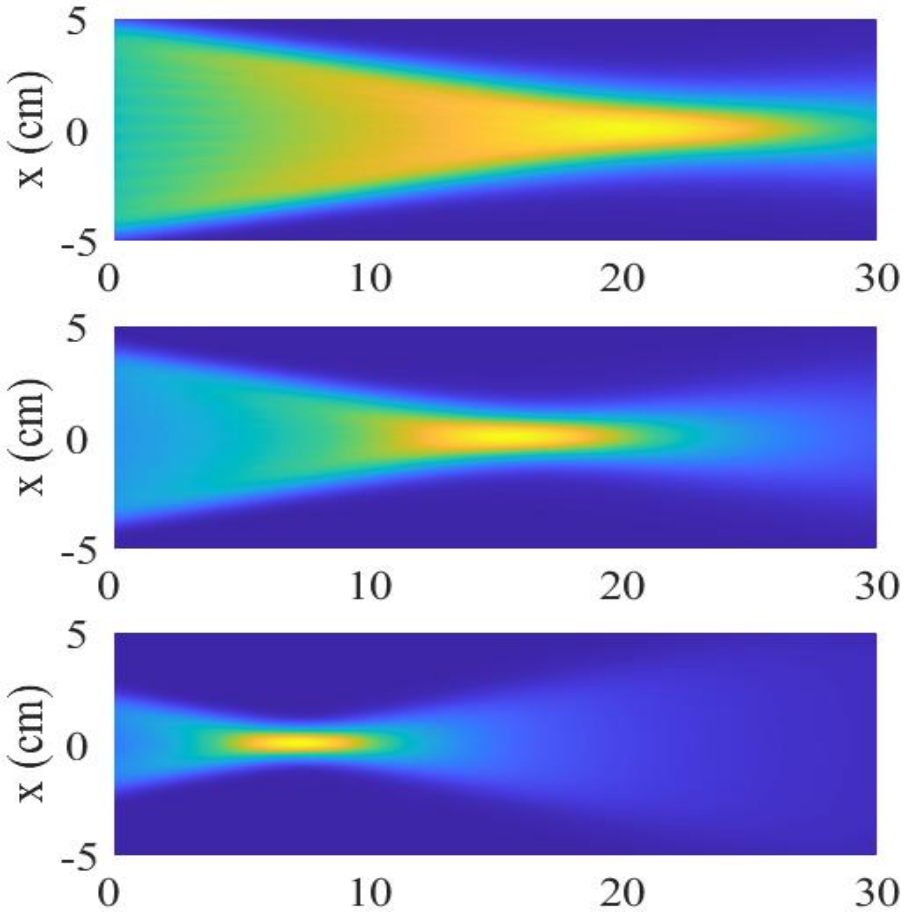




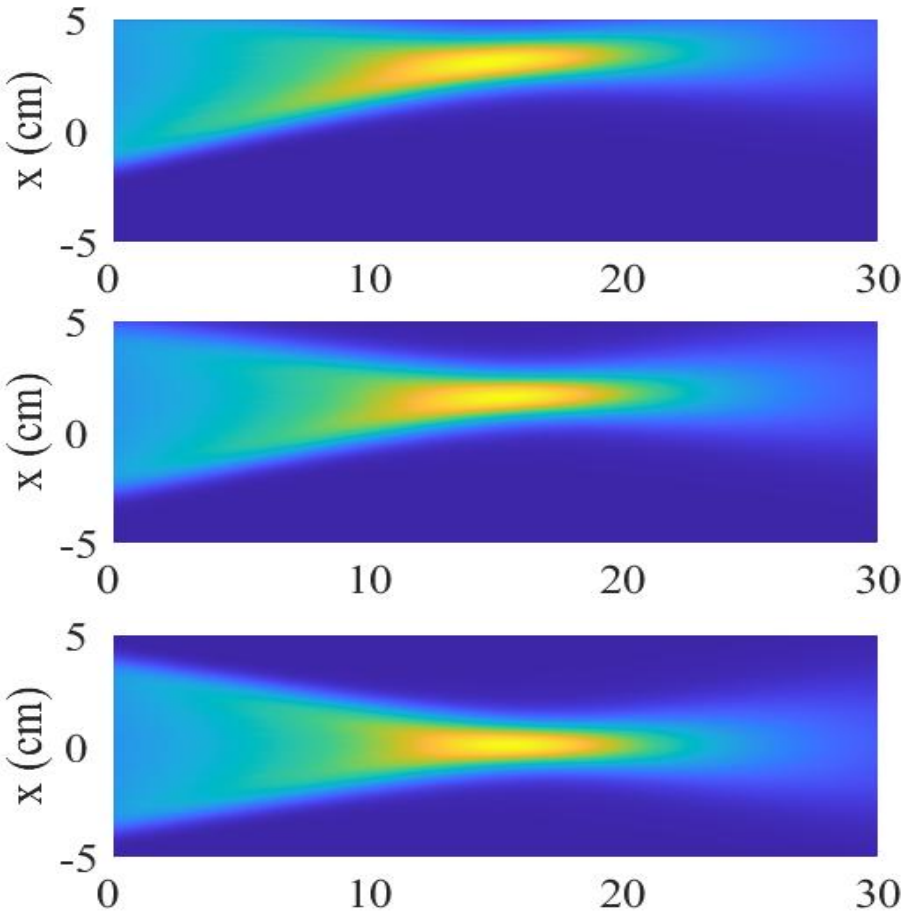
Tuning the dose peak position

By adjusting B1, B2 strengths, we can move the dose peak position

longitudinally in a range of 10 cm



transversely in a radius of 3 cm



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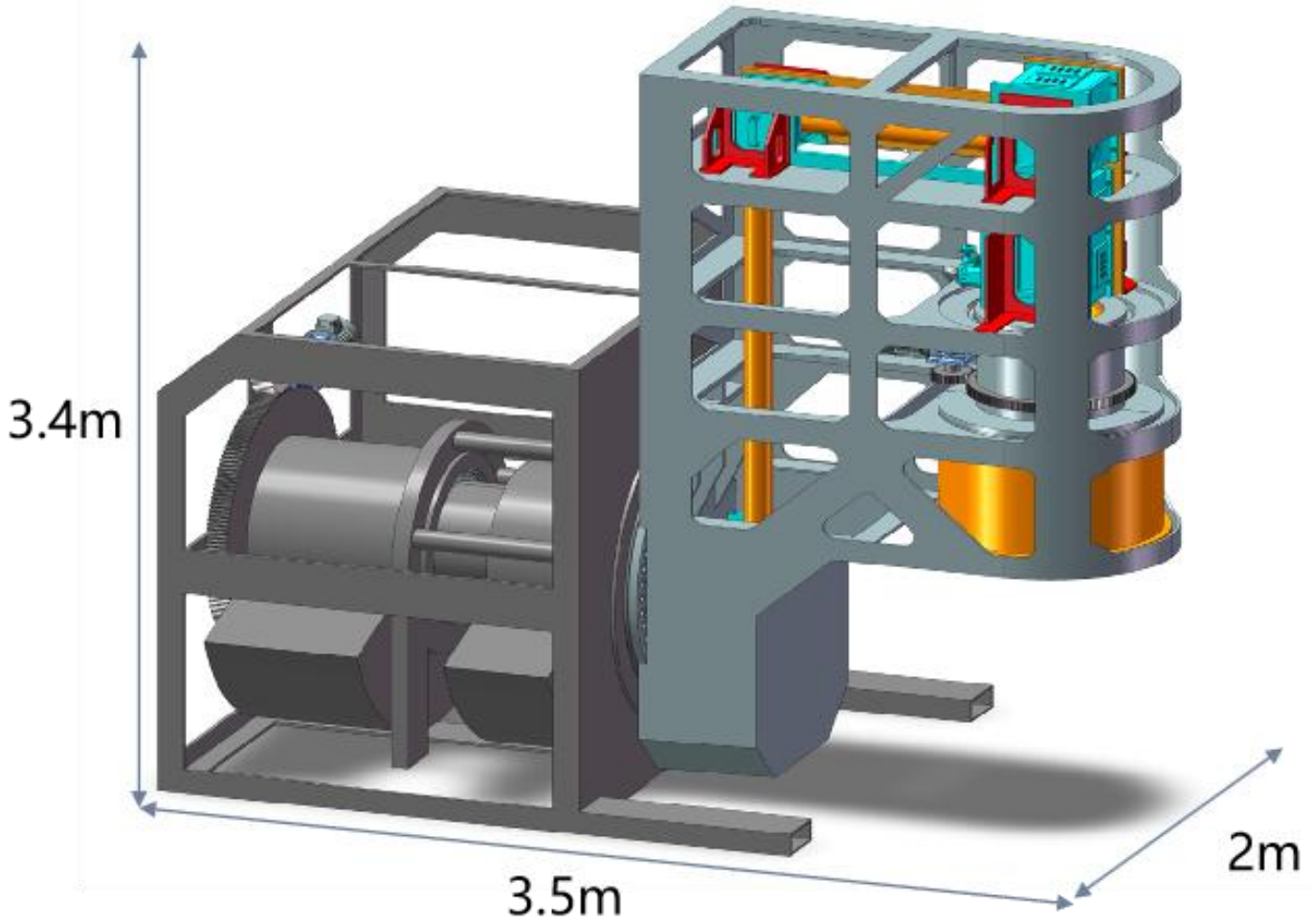
5. LWFA-based VHEE-RT machine development (ongoing)



- Rotational gantry (180', with **IMRT**)
- **Laser optics**, **LWFA module**, and **beam transport system** all integrated
- Gantry weight **<2t**, with size **<15m²**
- Plan to target **deep-seated tumors** in large animals.

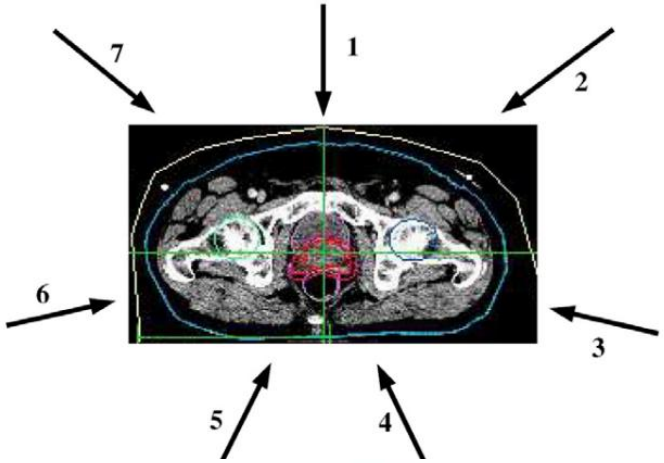
Design is almost finished. Construction will be completed in 7-8 months.
In 12 months, beam will be ready to shoot

Summary and perspective

- Laser wakefield accelerator is a promising approach for compact VHEE RT
- We are trying our best to push LWFA based VHEE towards clinical applications
  - ✓ Develop compact industry-level high-power laser system
  - ✓ Develop stable laser-wakefield accelerator
  - ✓ Preclinical studies (dose characterization and mice irradiation, more needed)
  - ○ Build LWFA-based VHEE-RT prototype machine (ongoing)
    - ➢ New Gantry for LWFA based VHEE (ongoing)
    - ➢ New algorithms for VHEE-RT TPS (ongoing)
    - ➢ Incorporate intelligent image-guiding system (under investigation)
    - ➢ Start the registration procedure for going to the market


Thank you !

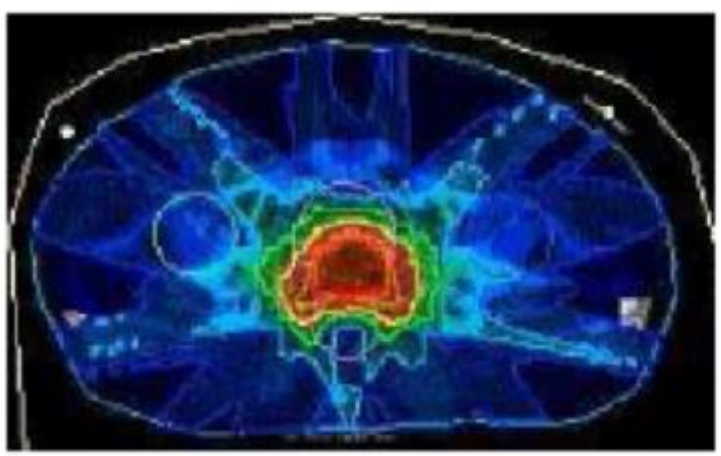
VHEE-RT is more effective than X-rays



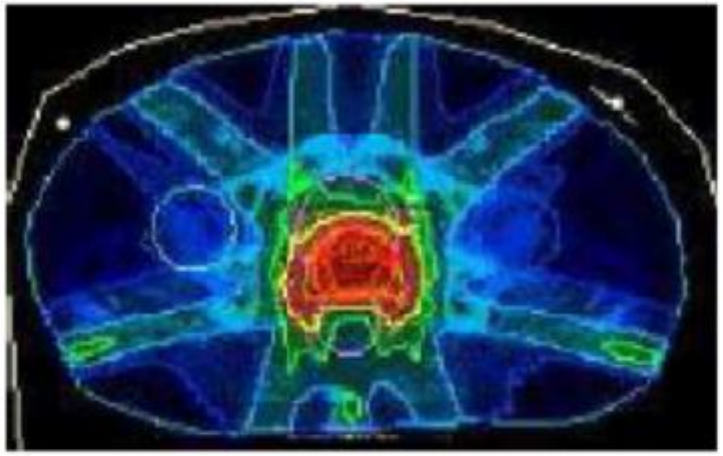
- **Using Monte Carlo simulation for multi angle irradiation targeting prostate tumors, pediatric brain tumors, etc**

T. Fuchs *et al.* Phys. Med. Biol. 54, 3315-3328, 2009

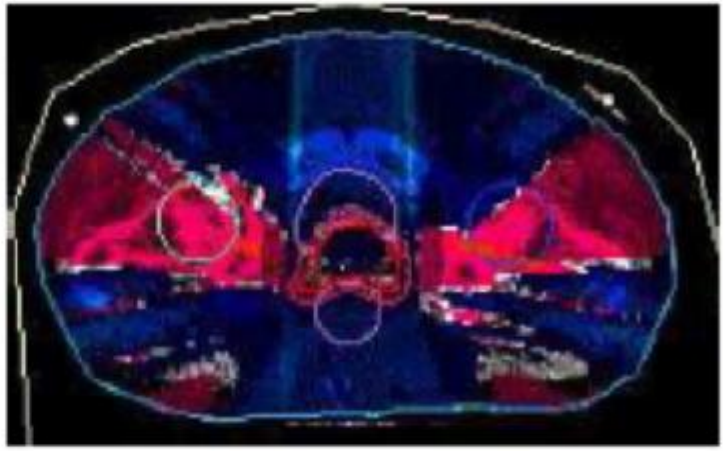
M. Bazalova-Carter *et al*, Medical Physics, 42(5), 2015



250 MeV electrons



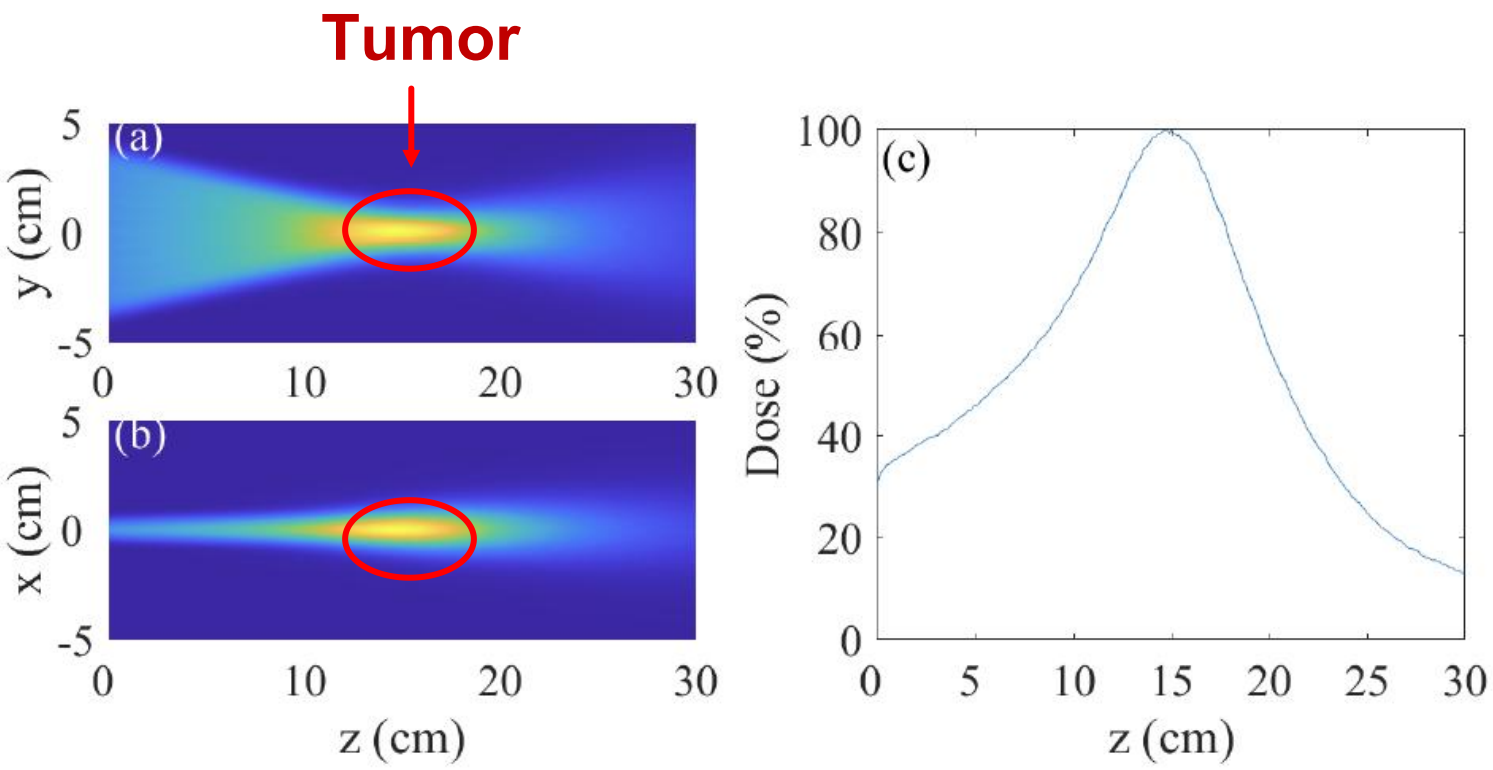
X rays IMRT

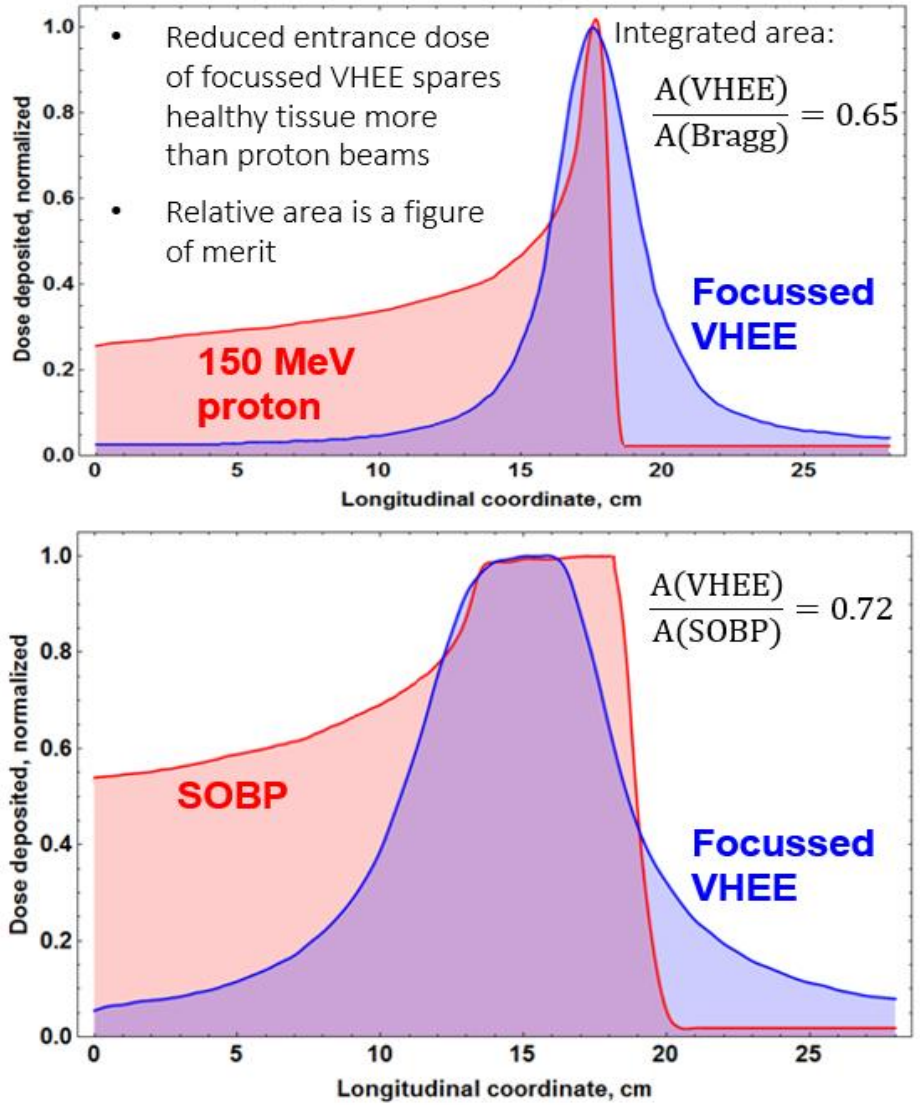


Difference

Compared to X-rays, VHEE can reduce damage to normal tissues by 20% -70%

Focused VHEE can target tumors precisely





L. Whitmore et al., Sci Rep 11, 14013 (2021)

B. Zhou et al., accepted in PRAB