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Generating VHEE Beams from a Laser-Plasma Accelerator and Characterizing their Stability for Medical Applications

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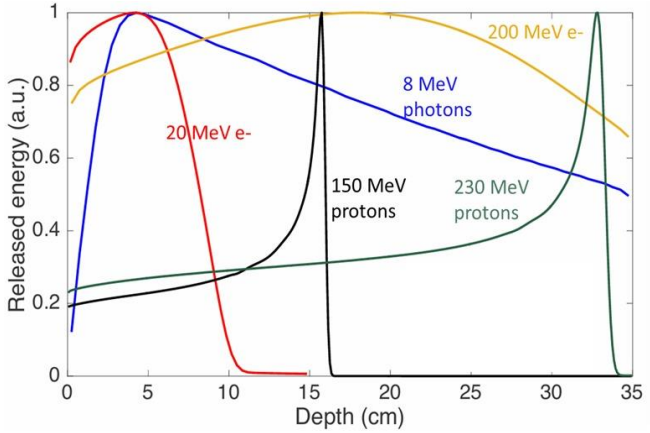
LOA

Particle Beams for Medical Physics

- Very High Energy Electron (VHEE) Beams (E_k > 50 MeV)
  - Effective for treating deep seated tumors



- Dose deposition in short bursts → Ultra-high Dose-rate (UHDR)

- Beam Requirements
  - Flat-top (transversally) beams
  - High charge bunches (~100s pC/shot)
  - Tunable repetition rate
  - Minimal pointing fluctuations (sub-mm at target)

[M. Cavallone, Application of laser-plasma accelerated beams to high dose-rate radiation biology, 2020]
[Courtesy Dr A. Flacco]

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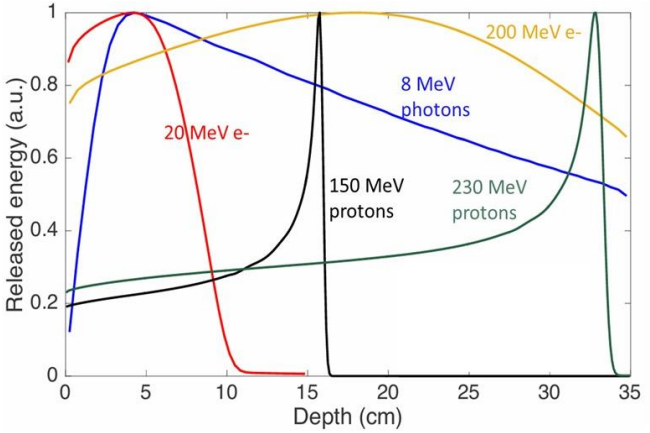

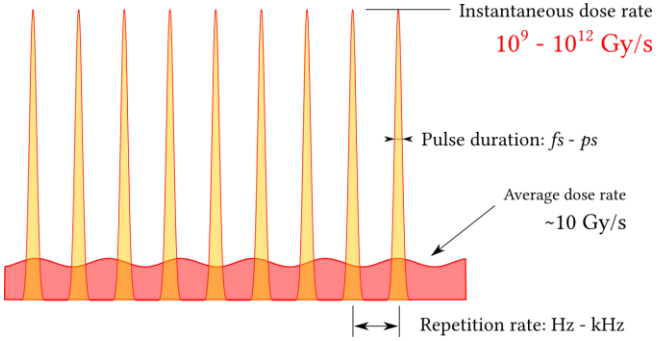

[M. Cavallone, Application of laser-plasma accelerated beams to high dose-rate radiation biology, 2020]
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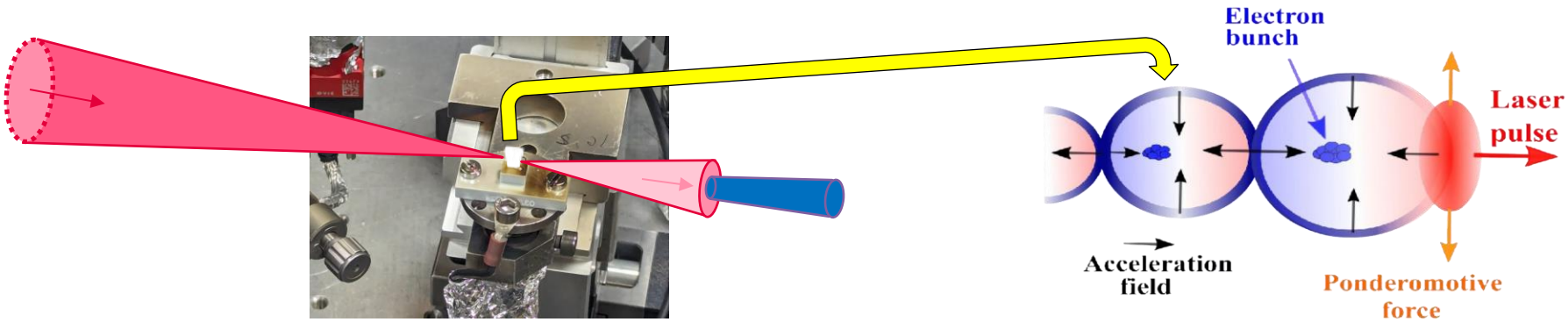
Laser-driven Plasma Accelerators (LPAs)

- Ultra-high-intensity laser pulses drive through plasma creating wakefields that can accelerate injected electron bunches

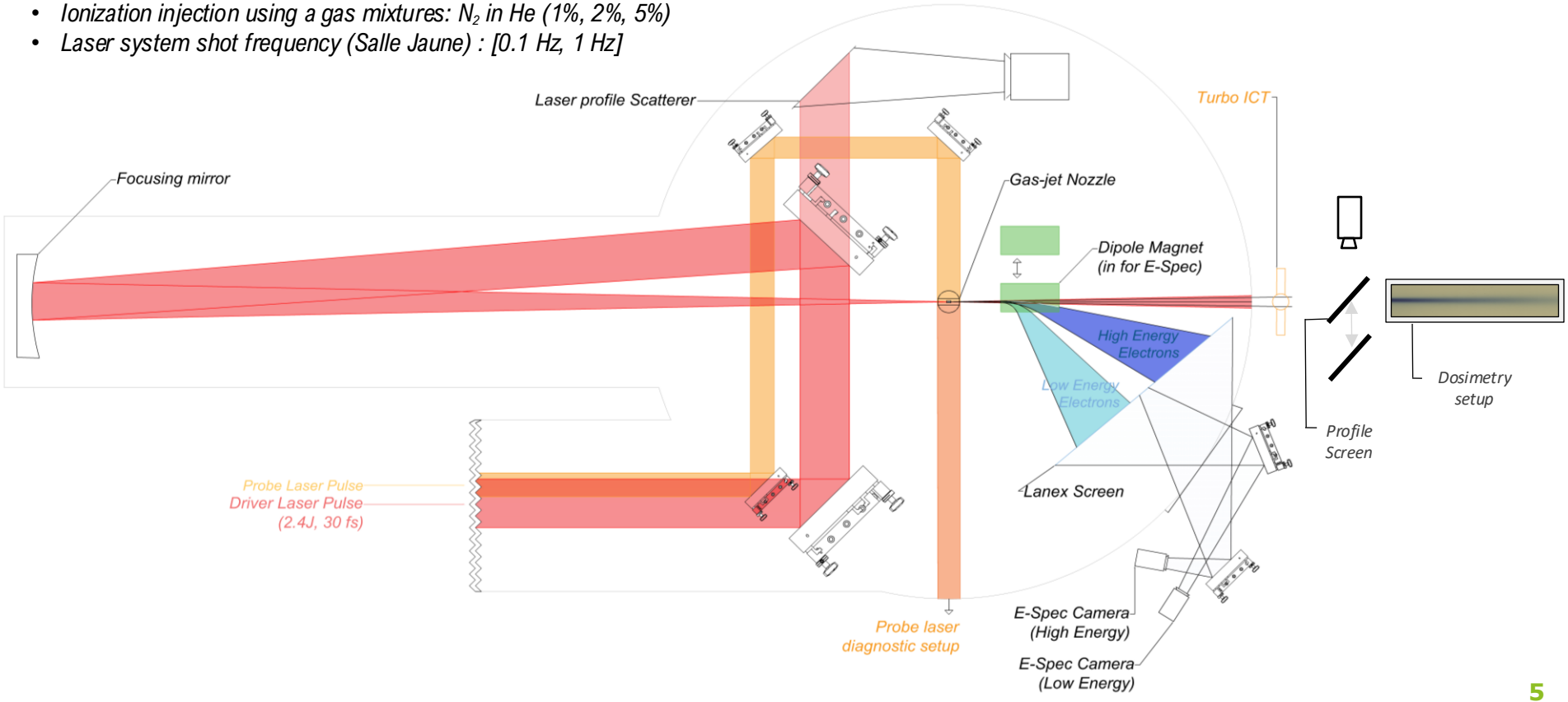


- Allows for mm–scale acceleration in VHEE regime
- Can generate (sub-)picosecond-duration electron bunches
- Experimentally demonstrated improvements in stability

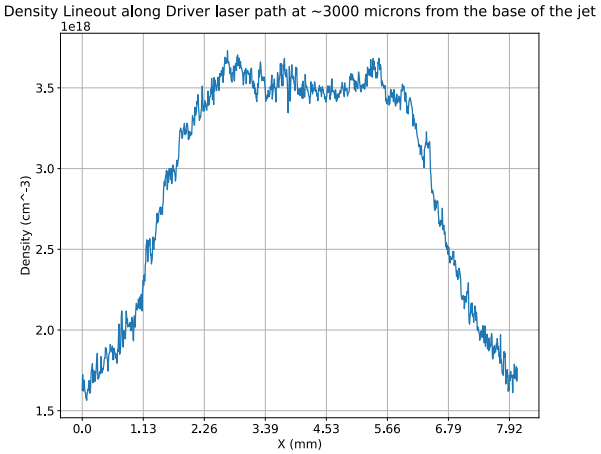
[T. Tajima & J.M. Dawson. Laser Electron Accelerator. Phys.Rev. Lett., 43(4), July 1979]
[H.T. Kim et al. Multi-GeV Laser Wakefield Electron Acceleration with PW Lasers]
[L. Rovige et al.. Demonstration of stable long-term operation of a kilohertz laser-plasma accelerator]

Experimental Setup

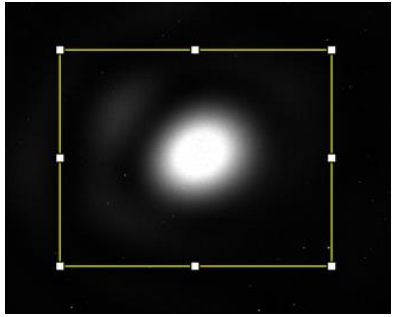
- *Ionization injection using a gas mixtures: N_2 in He (1%, 2%, 5%)*
- *Laser system shot frequency (Salle Jaune) : [0.1 Hz, 1 Hz]*



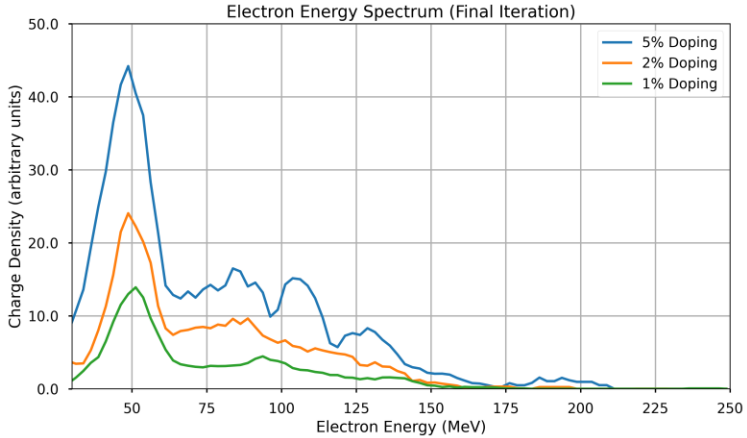
PIC Simulations



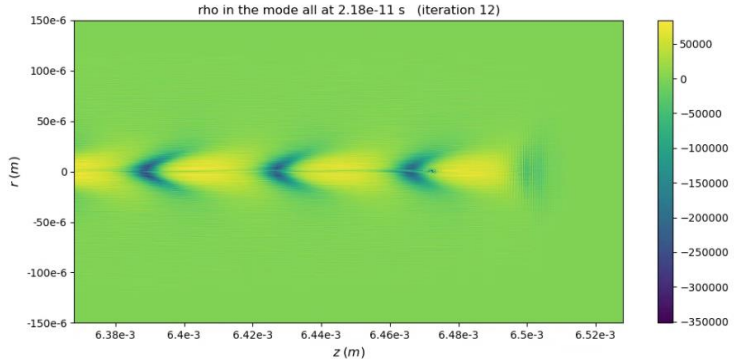
35 µm focal spot



FBPIC

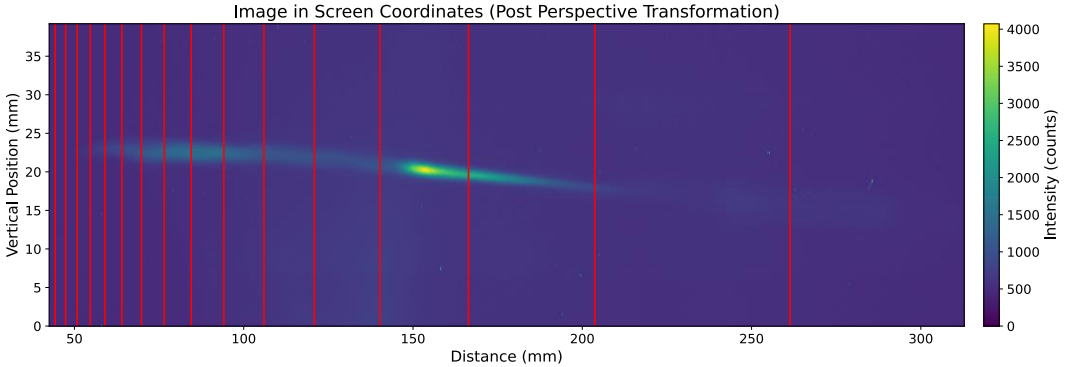


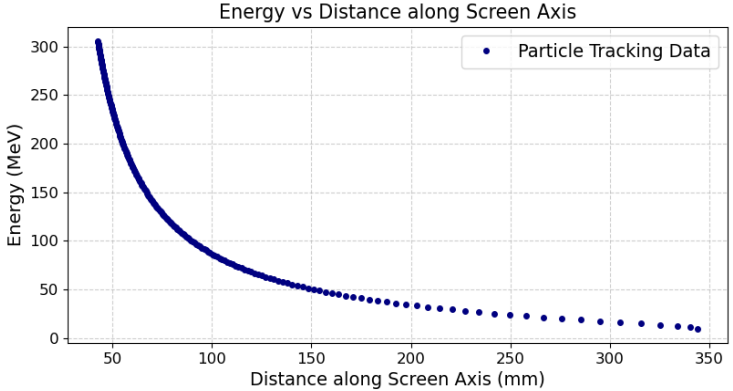
Injected charge: ~235 pC for 5% N_2 doping

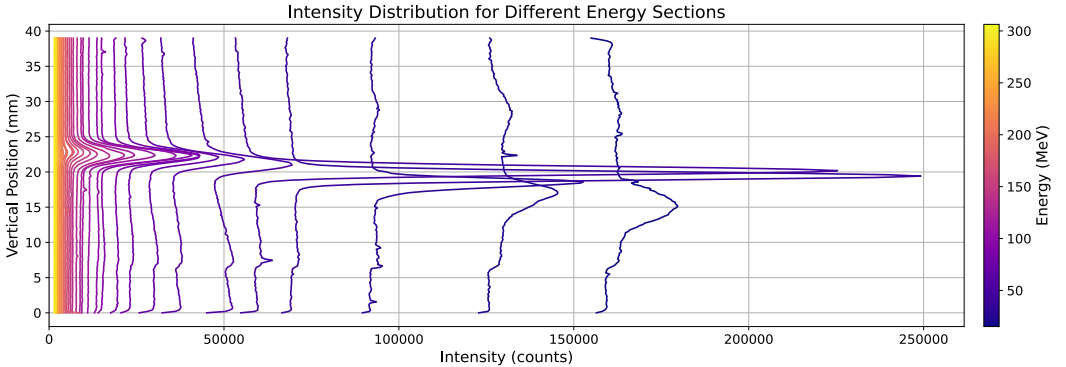


Electron Energy-Spectrometer

- Performs perspective transformation
- Deconvolution from space to energy coordinates
- Energy-section wise background subtraction
- Divergence estimation







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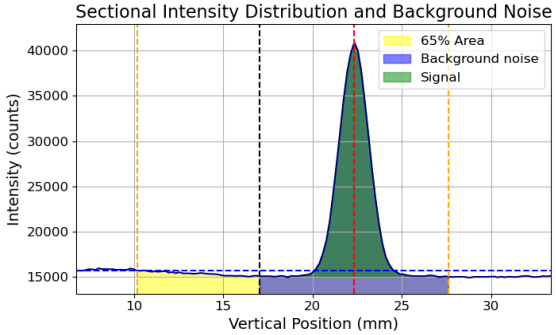
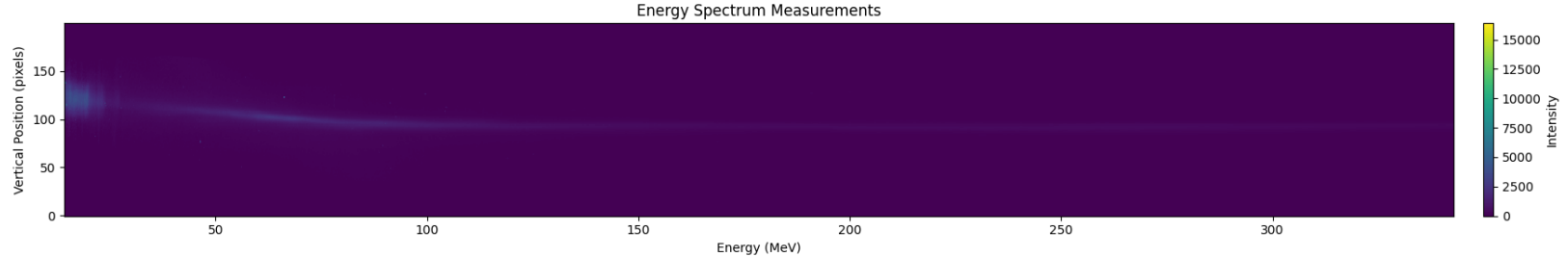
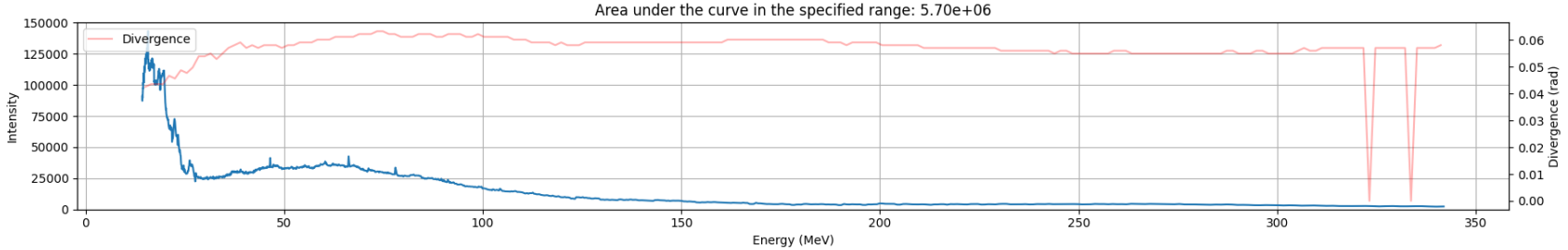
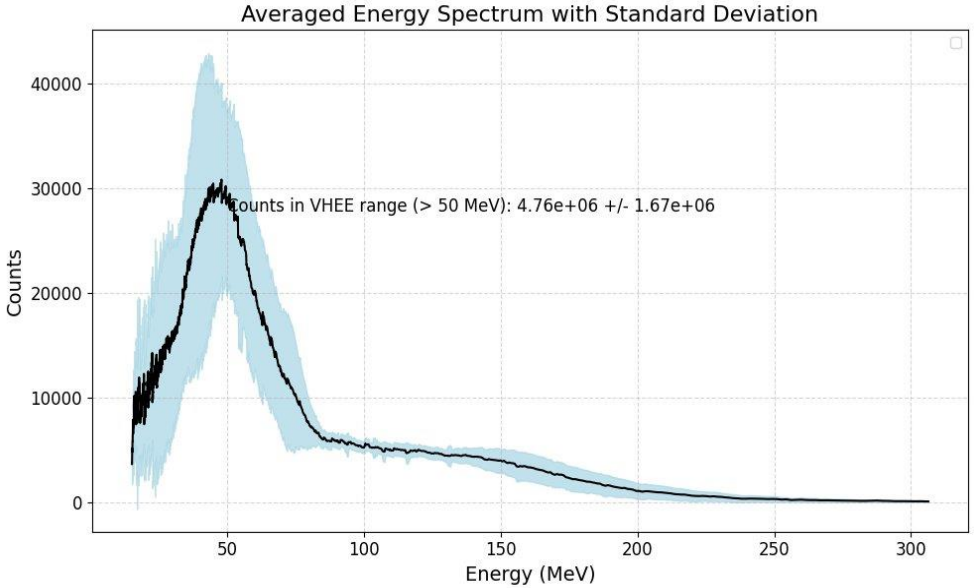






Experimentally obtained beams – Energy Spectra



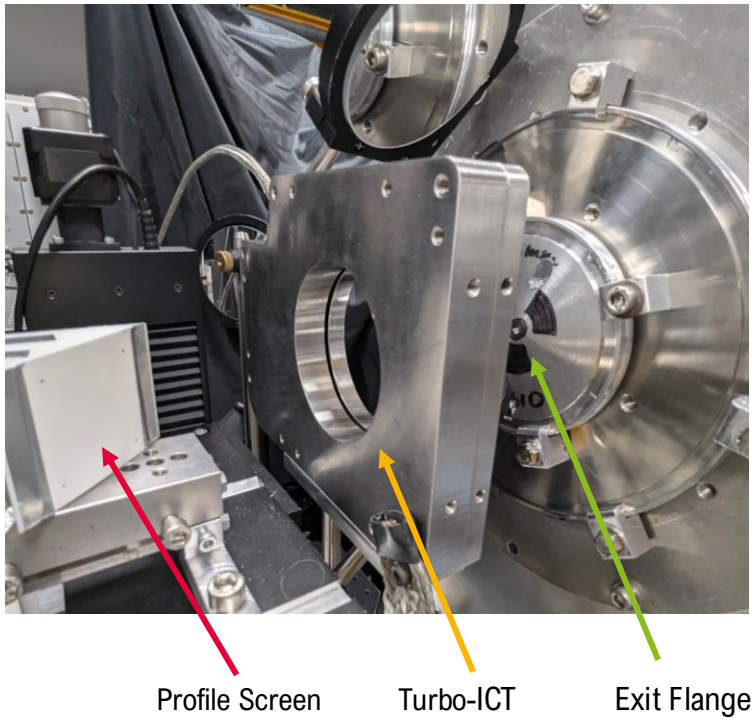
[5% N_2 in He, 9.5 bar, 4 mm nozzle]

Energy spectra peaked around 50 MeV, and stable high-energy tails were obtained and used to irradiate targets.

Experimentally obtained beams - Charge

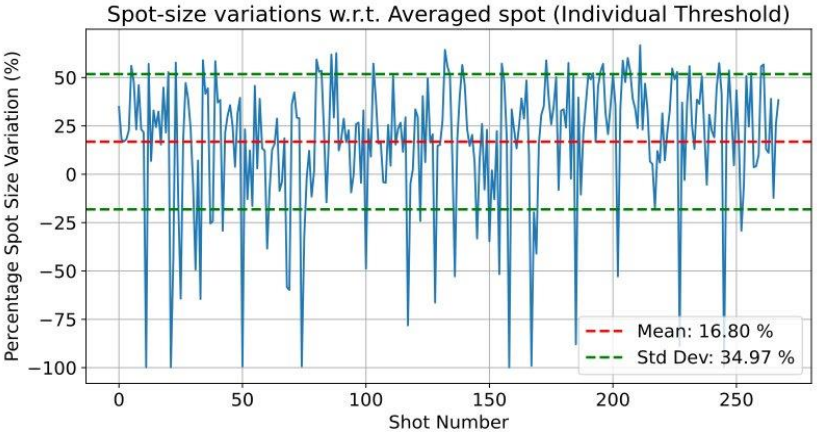
Noteworthy Cases	Average Charge/shot (pC)	Normalized Relative Instability (%)
Highest Charge	559.58	1.83
Best Stability	385.11	1.07
Balanced Performance	426.06	1.24

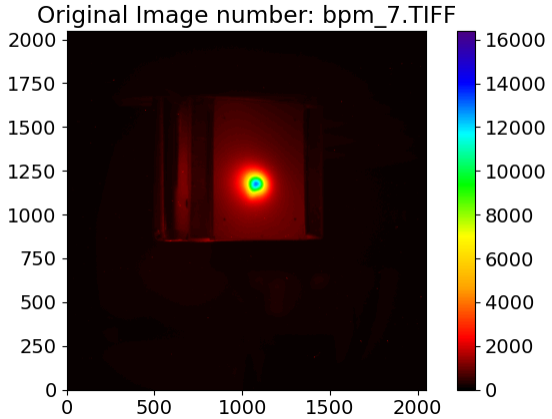
$$\text{Normalized Relative Instability (\%)} = \frac{(\text{Standard Deviation / Mean Charge}) \times 100}{\sqrt{(\text{Number of shots})}}$$

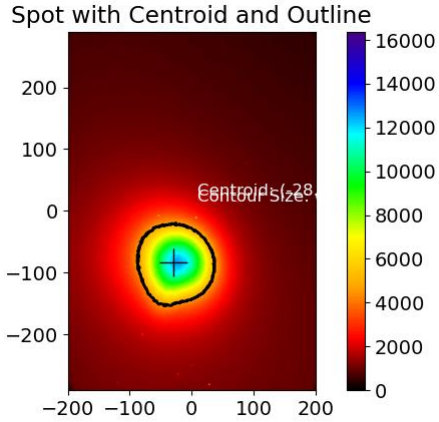


Beam Profile Monitor

- Measurement of spot size based on 1/e thresholding
- Pointing stability and size variation of electron beam-profile
- Integral charge variation using common thresholding
- Average profile readout at every n shots







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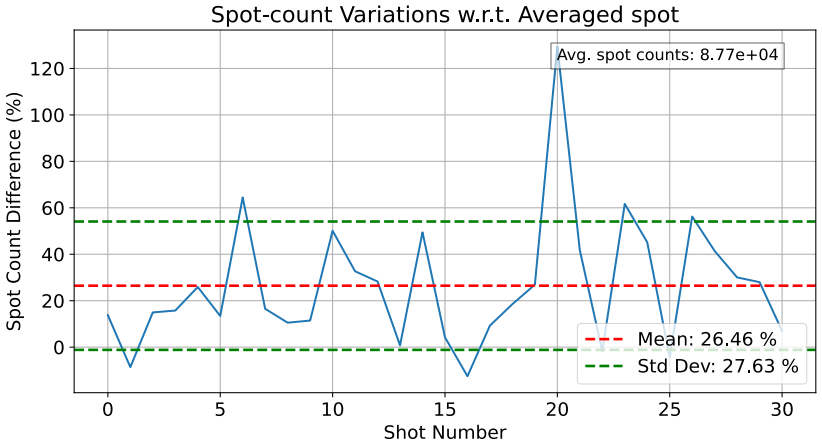
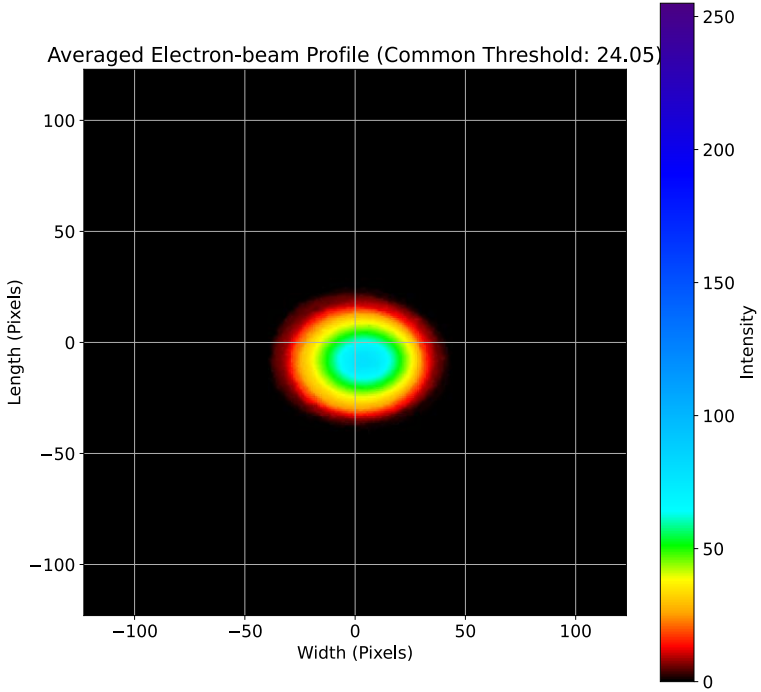
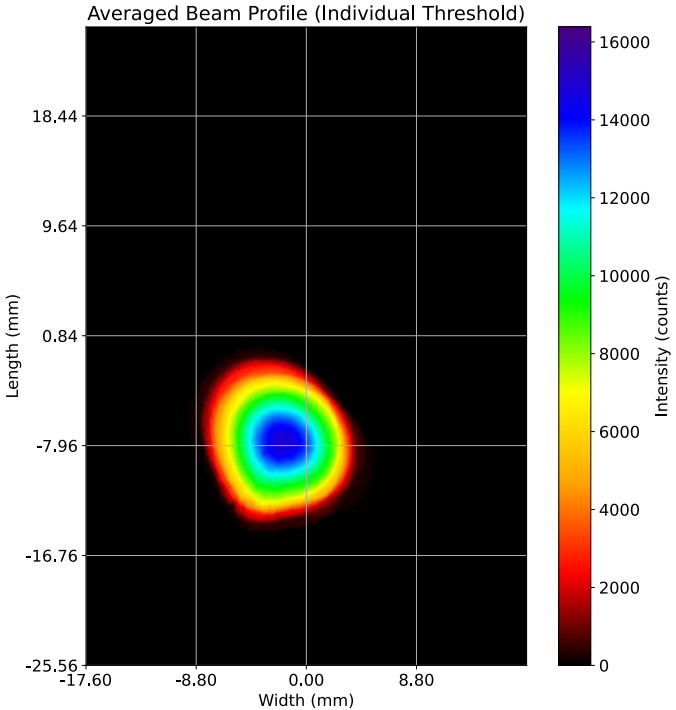
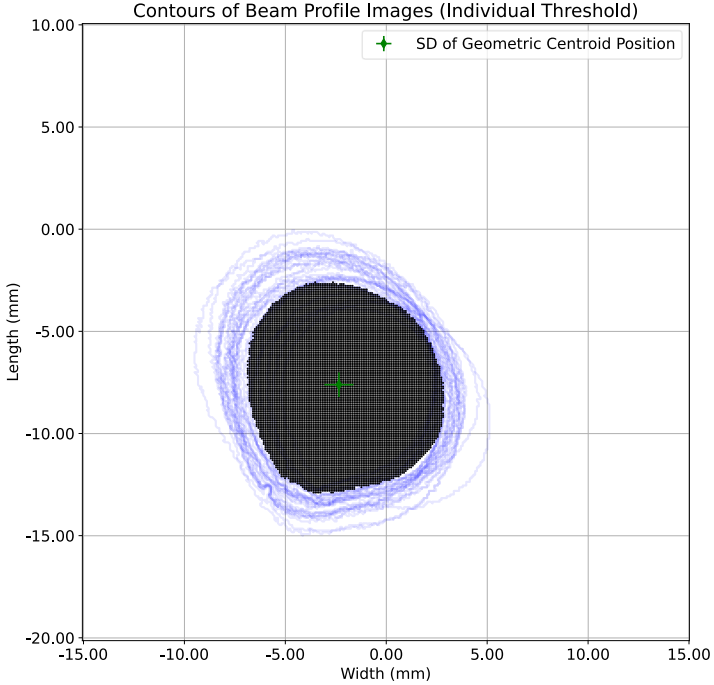




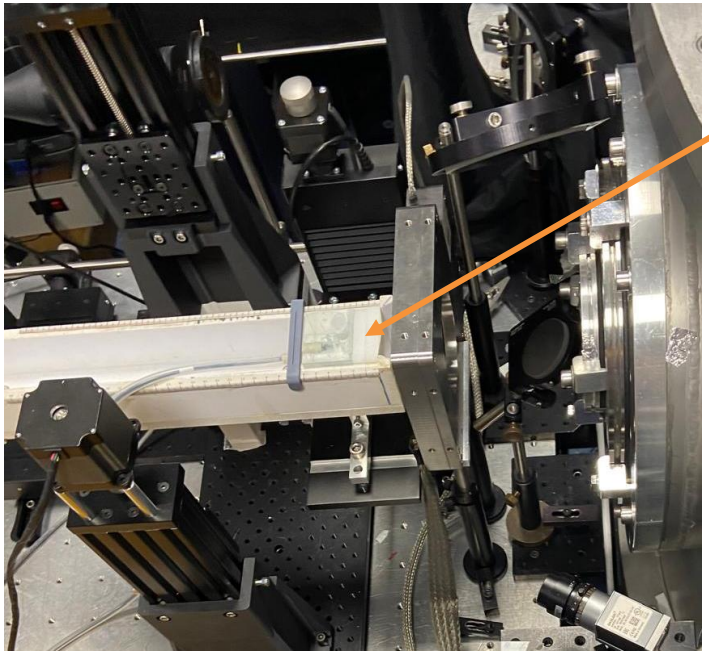
Experimentally obtained beams – Beam Profile

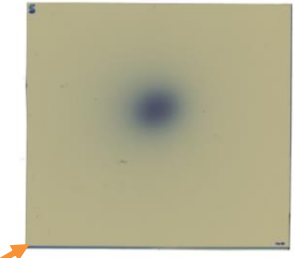




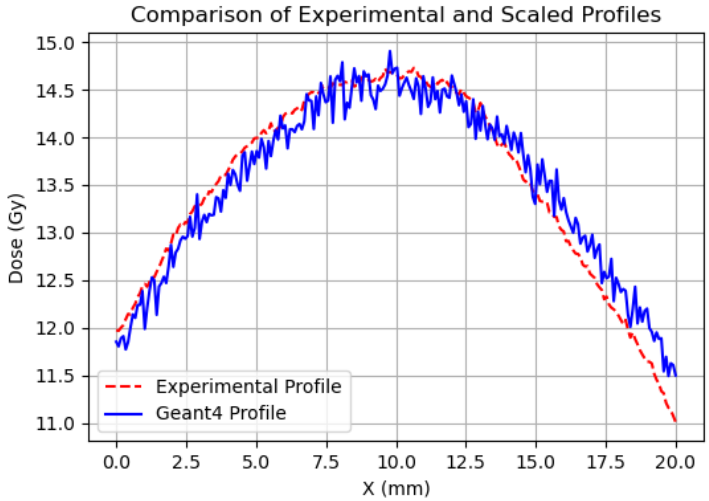
24.6% spot size variations, centroid motion ~1.25 mm

Dosimetry Affirmation





RadioChromic Film



[Courtesy C. Giaccaglia]
[Courtesy J. B. Amakkattu]

Perspectives

- Laser fluctuations (pulse energy and focus) and high-repetition operation challenge consistent beam delivery
- Plasma source variability at ~3k shots a day

- LAPLACE-HC aims to provide 1J @ 100 Hz
- Alternative plasma sources/injection mechanisms being explored
- Bayesian Optimization based control for LPA

Future Work

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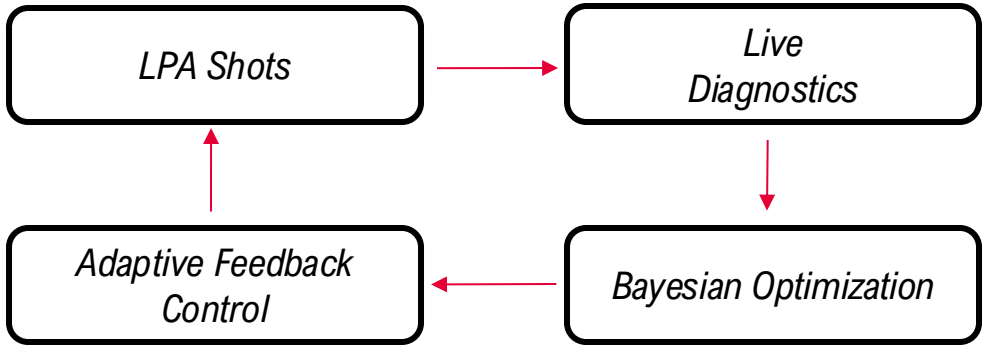

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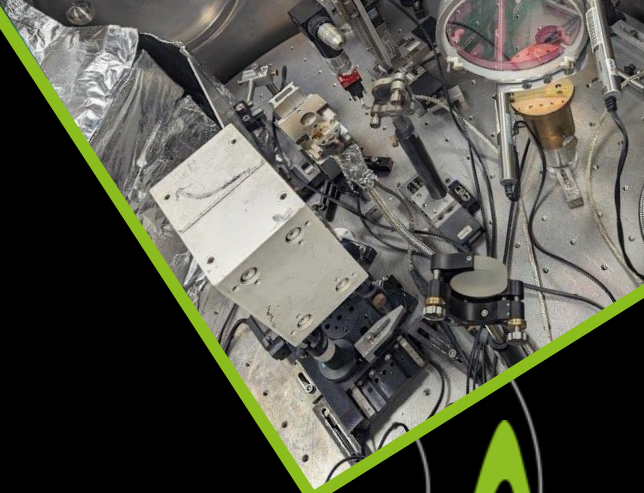


LOA

Thank you for your attention!

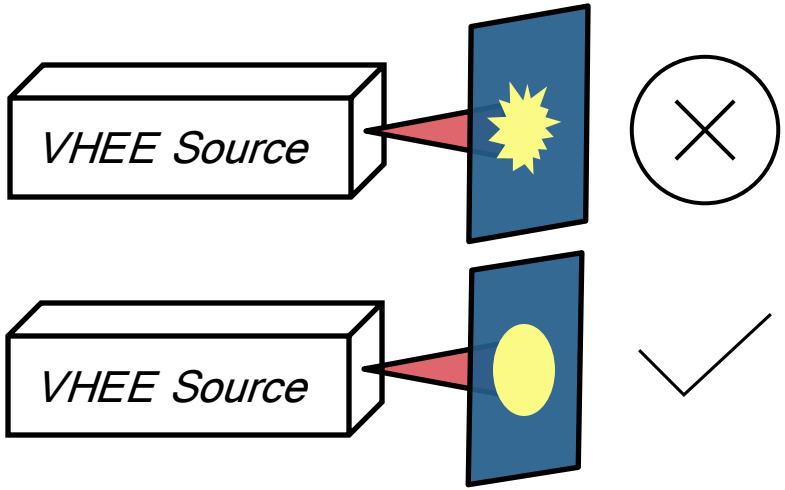
Credits to the team:

Camilla Giaccaglia, Alessandro Flacco, Julien Gautier,
Jean-Philippe Goddet, Amar Tafzi, Pascal Rosseau

Backup Slides

Beam Requirements

- Flat-top VHEE beams
- High charge bunches (~100s pC/shot)
- Tunable repetition rate (~10 - 100Hz)
- Minimal pointing fluctuations (sub-mm at target)



Beam Profile Monitor

- Positional stability of electron beam-profile
- Measurement of spot size variation
- Average profile readout at every n shots
- 1/e thresholding for spot identification