Compact Beamline for Laser-Plasma-Based Radiotherapy

Dr. Jonas Björklund Svensson
Postdoctoral Researcher | Accelerator Physics and FELs
Division of Synchrotron Radiation Research
Department of Physics, Lund University
Lund, Sweden
jonas.bjorklund_svensson@fysik.lu.se

Lund University

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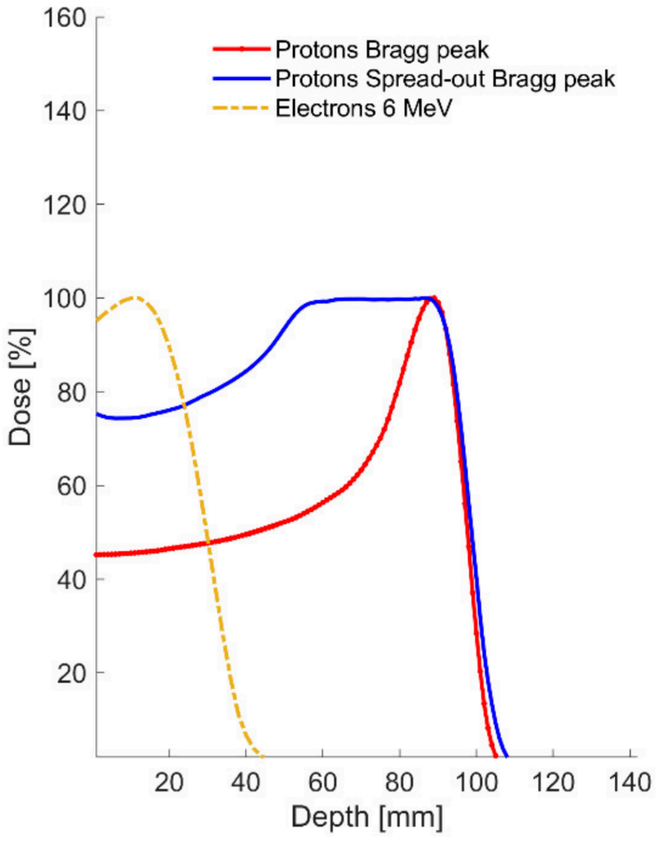
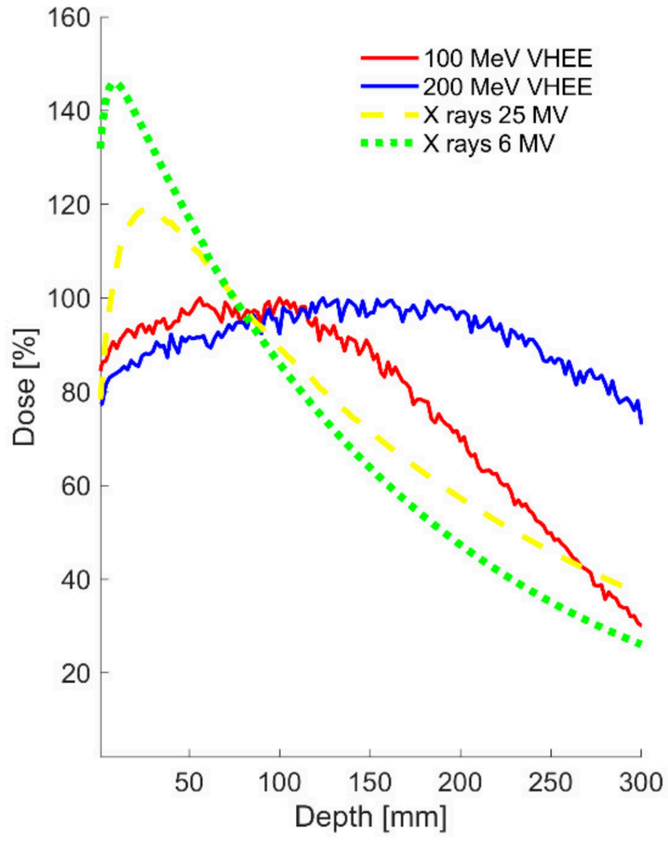
BACKGROUND

- Laser-plasma-generated particle beams interesting for radiotherapy
  - High instantaneous dose rate gives access to FLASH effect [1]
  - Potentially compact treatment facilities





M. G. Ronga, et al., Cancers **13**, 4942 (2021)

- Very-high-energy electron (VHEE) bunches gaining interest
  - Not as specific as ions, but better than X-rays [2]
- Promising application for LPA beams
  - Not emittance sensitive
  - Modest energies (100-300 MeV e^-)
- Needs dose stability, monitoring, low background radiation

[1] M.C. Vozenin, J. Bourhis, M. Durante, Nat. Rev. Clin. Oncol. Clin. Oncol. **19**, 791 (2022)
[2] M. G. Ronga, et al., Cancers **13**, 4942 (2021)

BACKGROUND

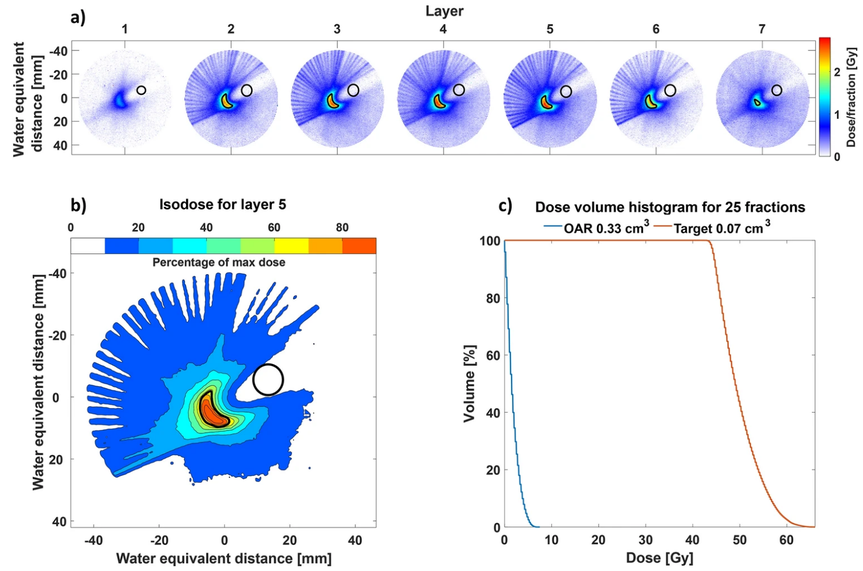
> Earlier work: we did an experiment using LPA electrons

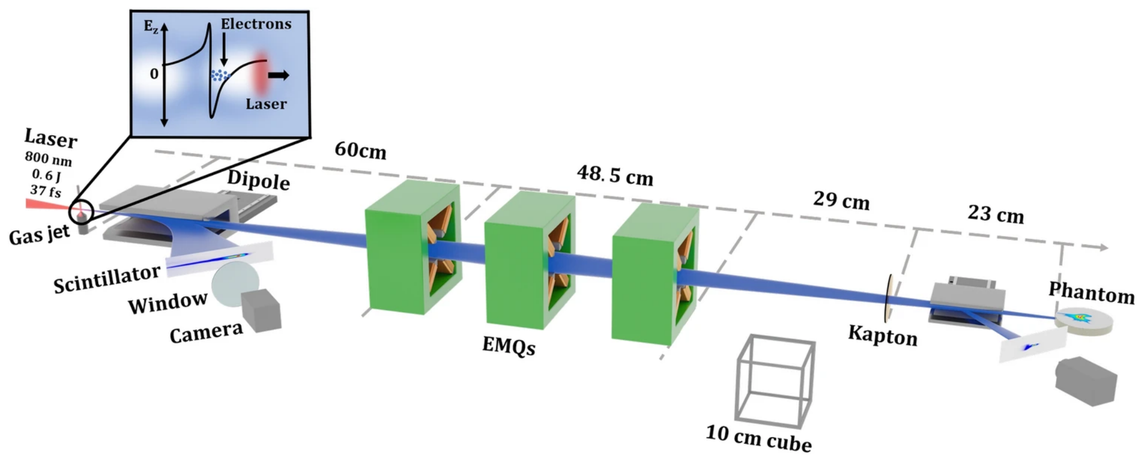
> Quadrupole imaging onto phantom yielded good dose distribution

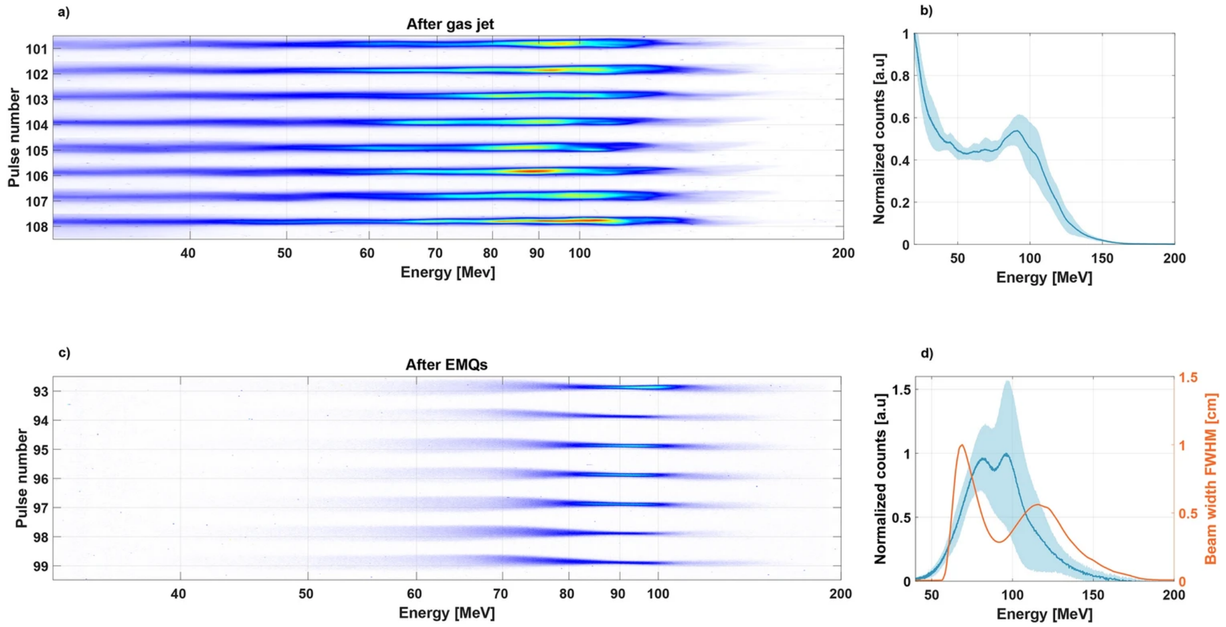
  > Point-to-point imaging ensured minimal impact from pointing jitter

  > Uncontrolled charge loss, large *E*-spread at target

  > Must be improved for potential clinical use!







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

IMPROVED ELECTRON TRANSPORT

> Ionization injection typically yields broad, reproducible spectra

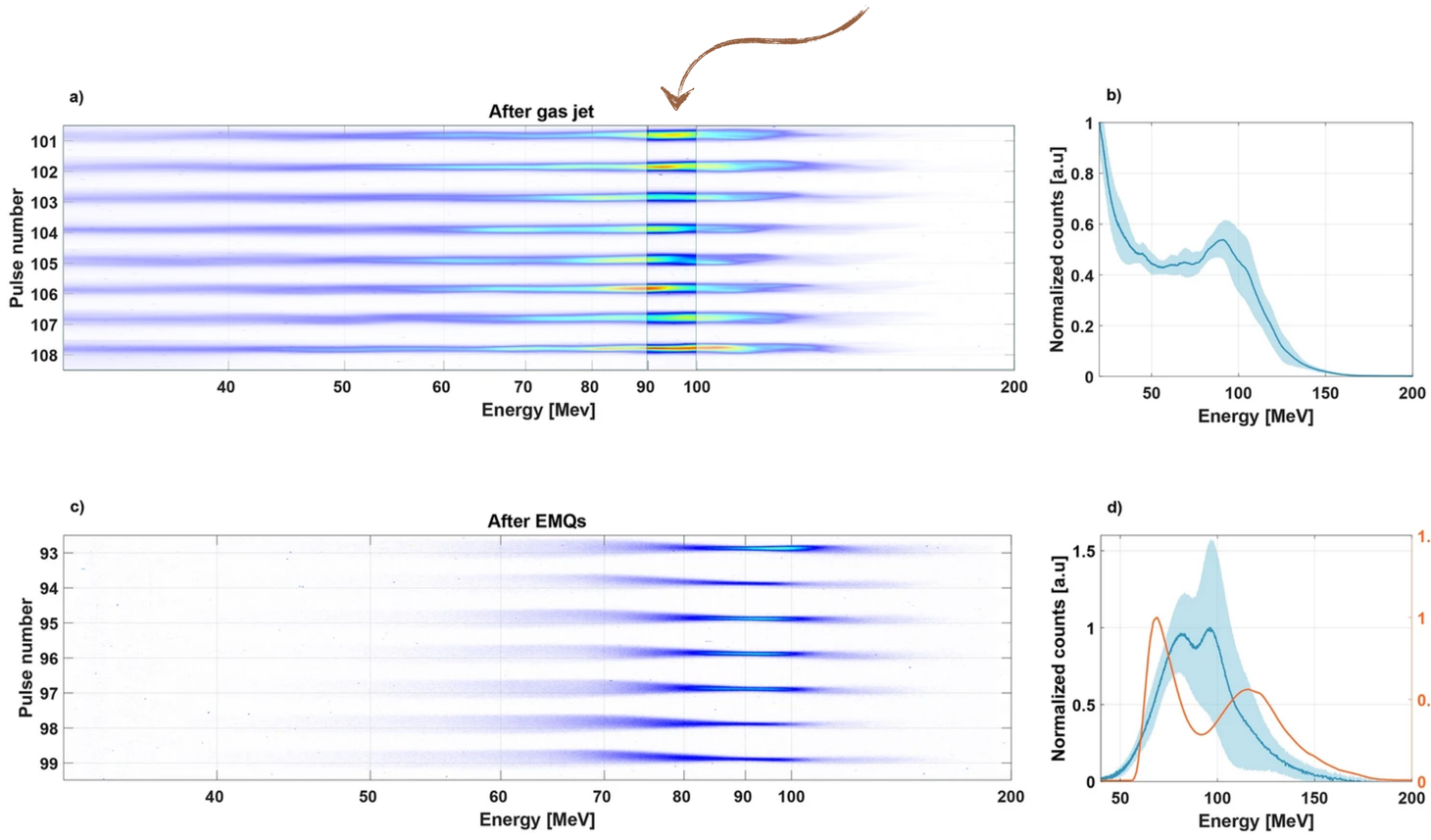
> Part of the spectrum could be extracted in a controlled way

  > Safely dump unusable charge, facilitate further transport

  > Minimizes charge fluctuation at target

  > Enables raster scanning

Example selected charge for transport



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

IMPROVED ELECTRON TRANSPORT: CONCEPT

> Utilize imaging with combined plasma- and magnetic-optic transport

> Image electron source onto collimator using active plasma lens (APL)

> Magnification >1

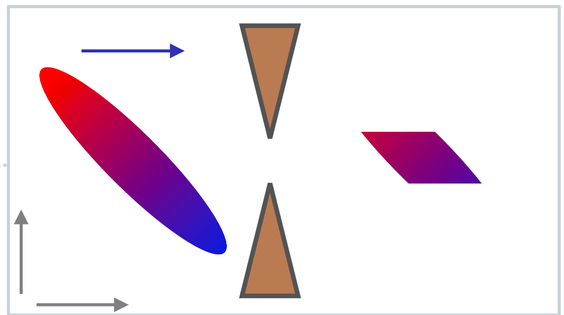
> Minimize position jitter on collimator

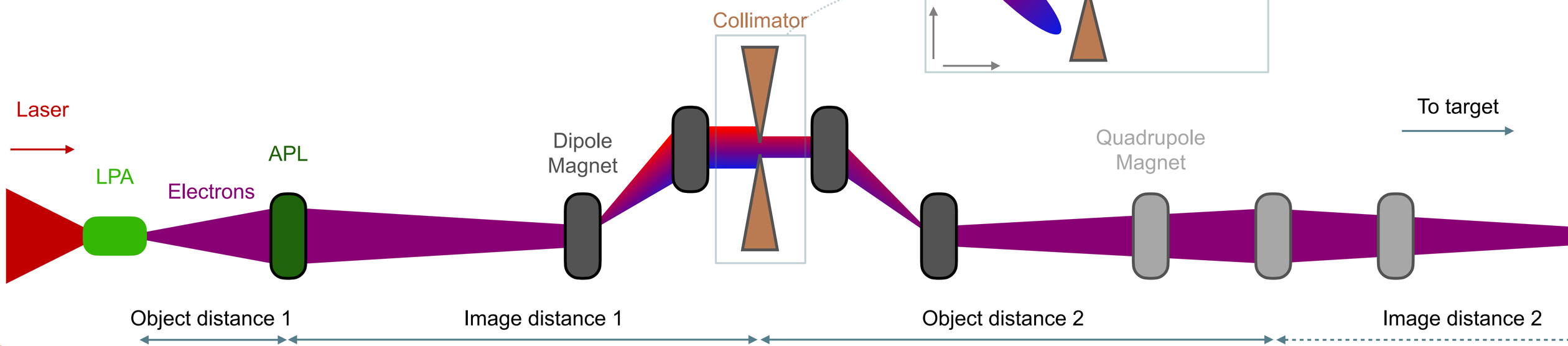
> Place collimator inside dispersive section, select same energy as APL imaging

> Desired BW (collimator width)

> Image collimator onto target using magnetic quadrupoles (QPs)

> Larger APL magnification facilitates QP transport



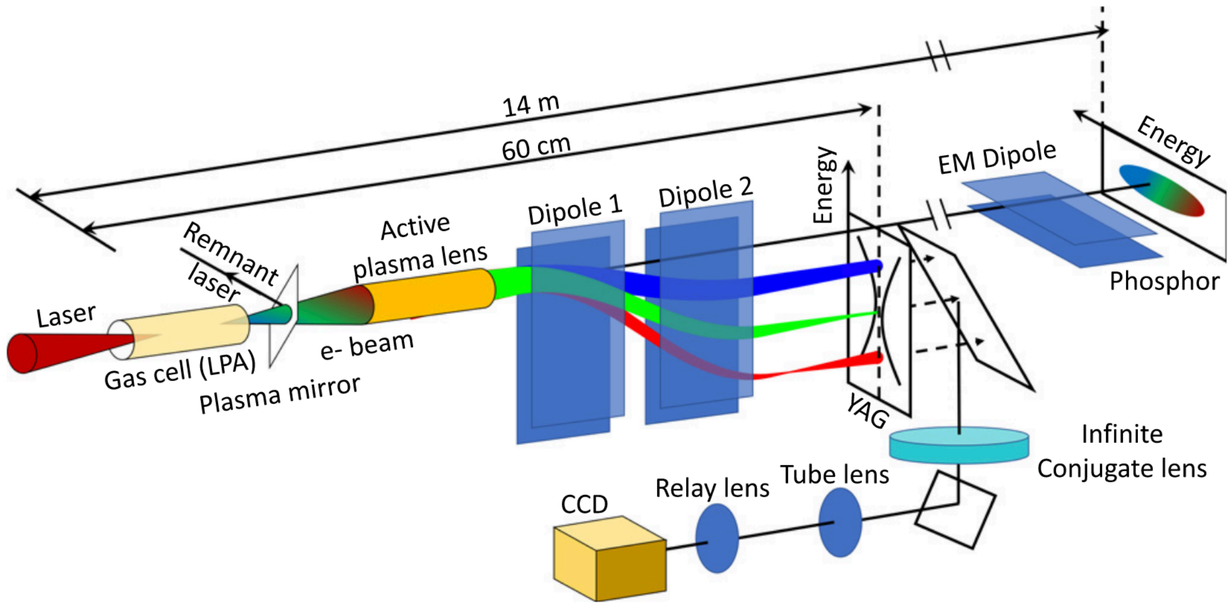


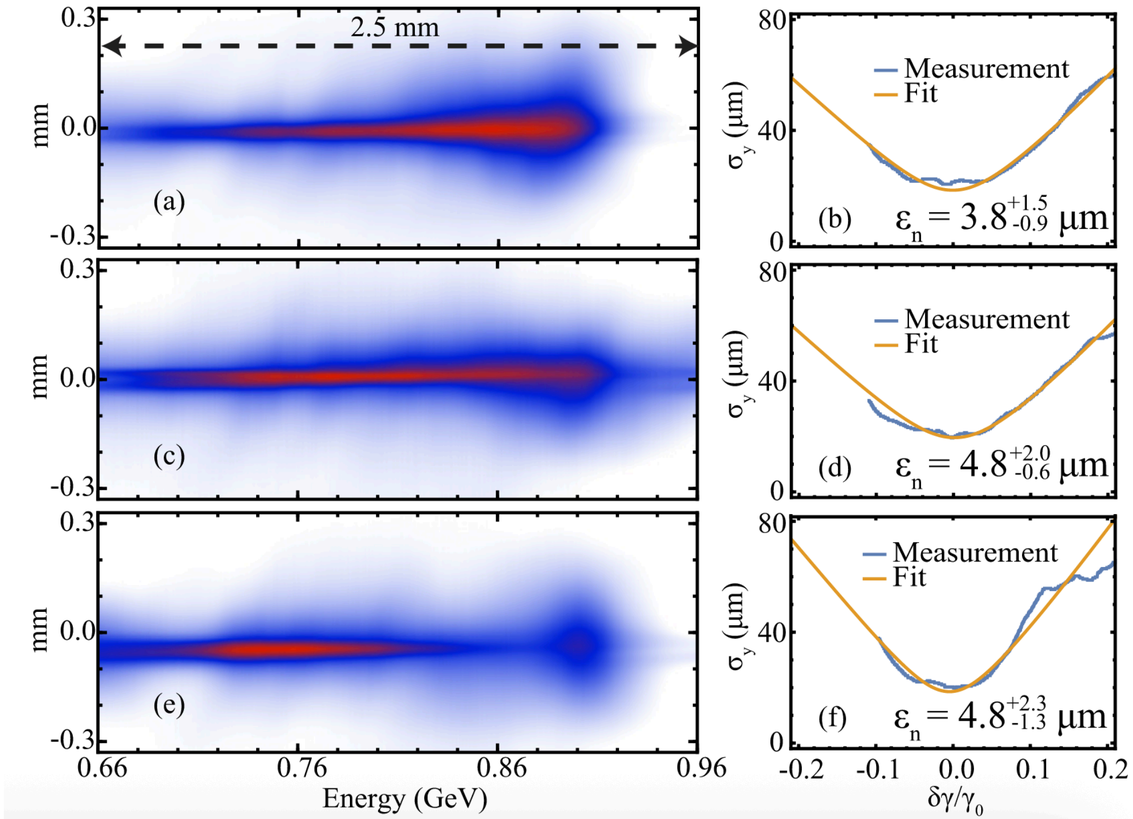
IMPROVED ELECTRON TRANSPORT: CONCEPT

> Effectively two mirrored imaging spectrometers

> Collimator instead of screen

> Part of the concept experimentally demonstrated

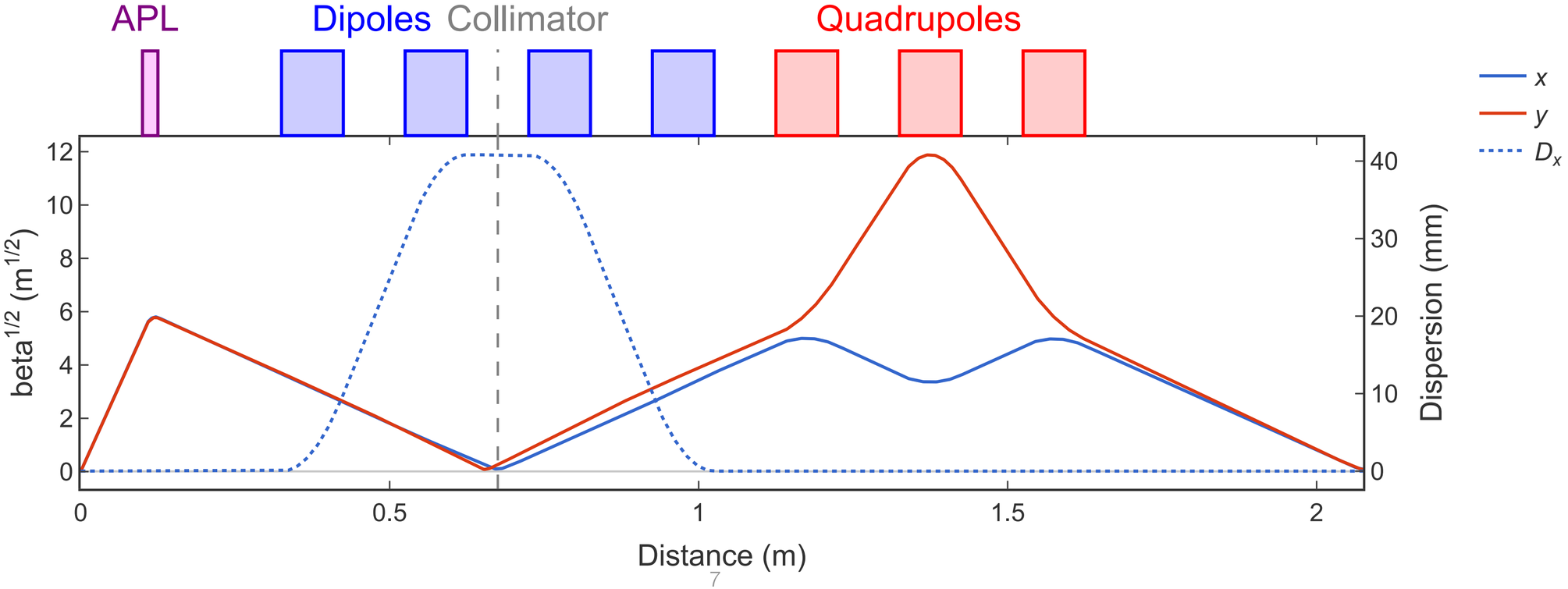




S. K. Barber *et al*., Appl. Phys. Lett. **116**, (2020)

SIMULATION RESULTS

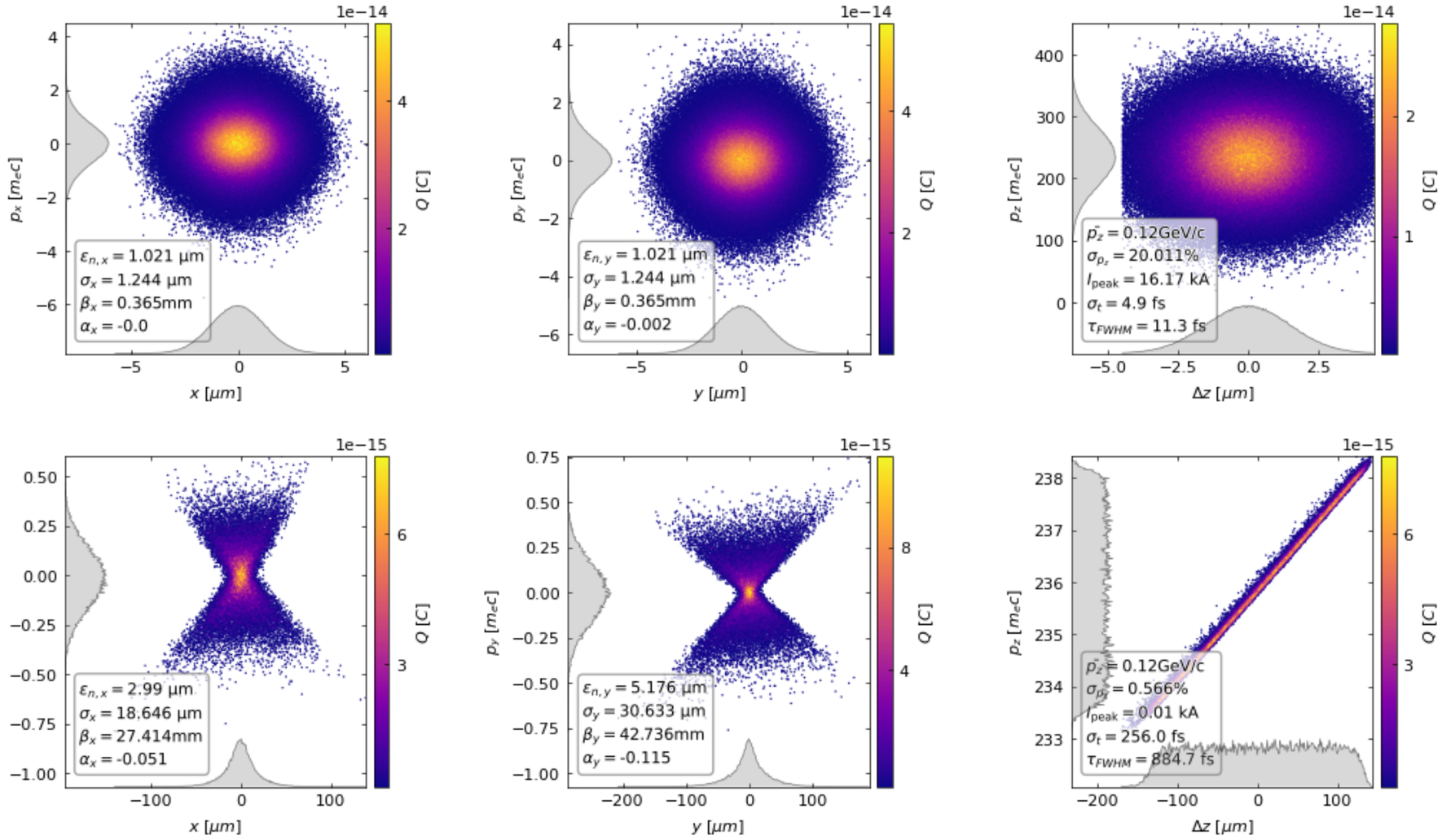
- Simplest extension of setup from K. Svendsen *et al*. (2021)
- M_1 = 5, M_2 = 1; D = 41 mm
- Dipole focusing introduces slight astigmatism
  - Mostly compensated by quadrupole imaging
  - APL *could* replace quadrupole triplet, would lose astigmatism control
- Magnifies beam size ($M = M_1 \times M_2$), demagnifies divergence ($\times 1/M$)



SIMULATION RESULTS

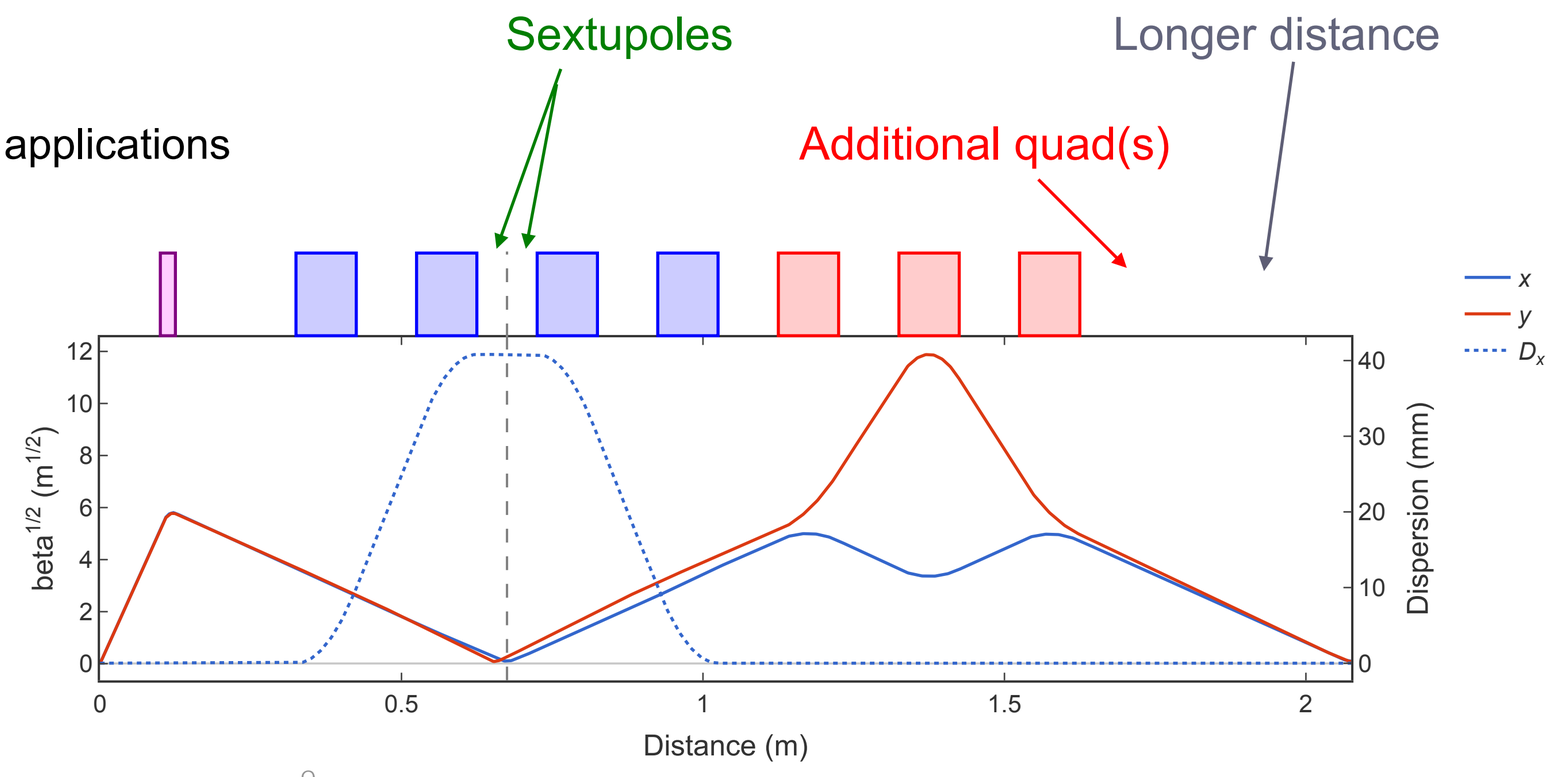
> Tracking 120-MeV, LPA-like beam

> Collimator width set to $w = dE/E / (2D) = 0.8$ mm - 1 % energy spread (2 mm vertical width)



DESIGN OUTLOOK

- Possible improvements
  - Chromaticity reduction with sextupoles
    - Somewhat longer chicane
    - Better beam optics control at few-percent level BW
  - More quadrupoles
    - Better optics control at target
  - Larger M_2
    - More appropriate beam size for typical applications
    - Longer beamline



But what about ions?

> All results so far valid for electrons

> Ions more favorable for radiotherapy, but laser-based beams not yet viable

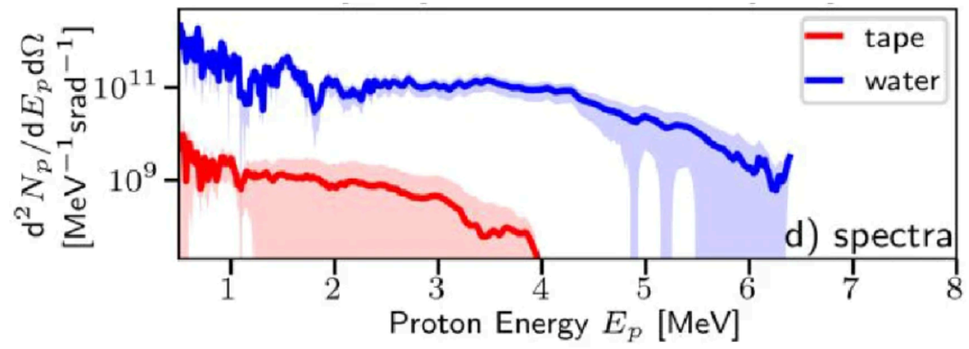
  > Recent advances reduce proton source divergence; increase stability; replenishable targets; …

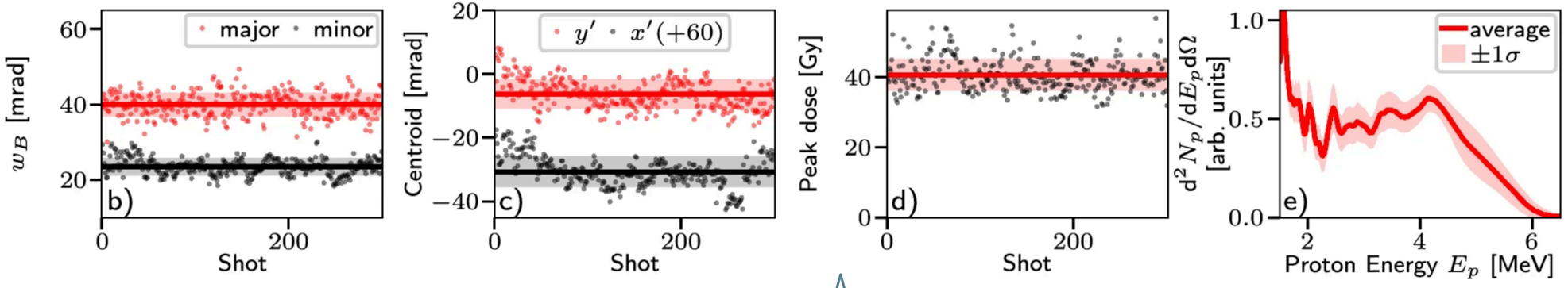
  > See C. Palmers plenary from Monday (https://agenda.infn.it/event/46259/contributions/271594/)

> Good news: imaging beamline works for positive particles too! [3]

  > APL and magnet polarity can be switched

  > APL magnification increased (smaller initial object distance)





M. J. V. Streeter *et al.*, Nat Commun **16**, 1004 (2025).

[3] Y. Yan et al., Phys. Rev. Accel. Beams **27**, 052802 (2024).

CONCLUSIONS

> Simple, compact transport system

  > Buildable in small lab

> Crucial parts already demonstrated

  > “Low risk”

> Works for both electrons and ions (small modifications)

> Important step towards better radiotherapy experiments and eventually (potential) clinical implementation

> Not adressed in this work: beam profile shaping

  > Top-hat / flat-top profiles best suited for radiotherapy

  > Good news: we have a method for this too!

Improved electron transport, possible alternative

- Utilize imaging with combined plasma- and magnetic-optic transport
  - Image electron source onto aperture using active plasma lens (APL)
    - Magnification >1
    - Minimize position jitter on slit
  - Possible simplification (less energy selectivity, but still some):
    - Replace chicane and slit by a pinhole
    - Chromaticity causes energy-dependent focal plane
    - Smaller selectivity than dispersion, less control