Diagnostics for the Front End Test Stand

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Dedicated to the memory of Dr. Christoph Gabor.

Proton Accelerators for Science and Innovation Workshop
11-13th November 2015
Fermi National Accelerator Laboratory

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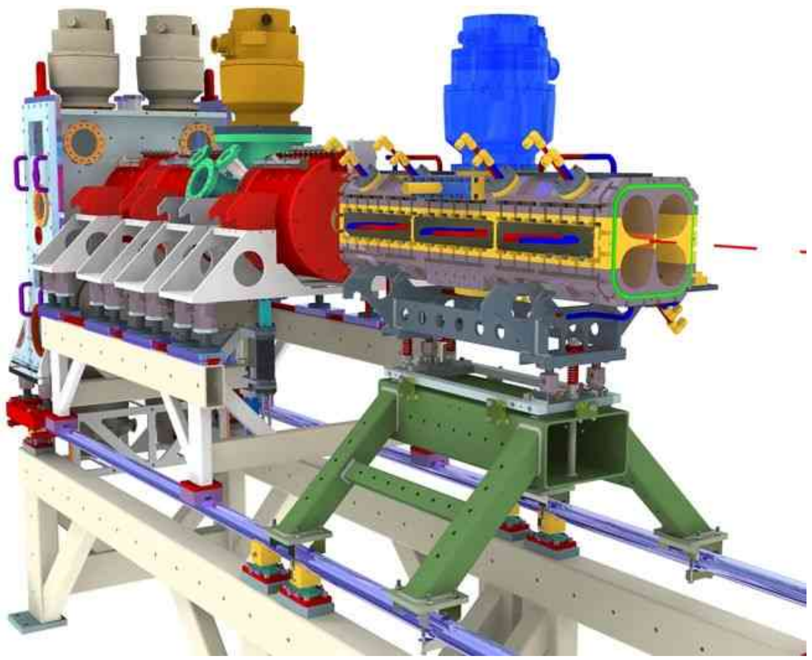
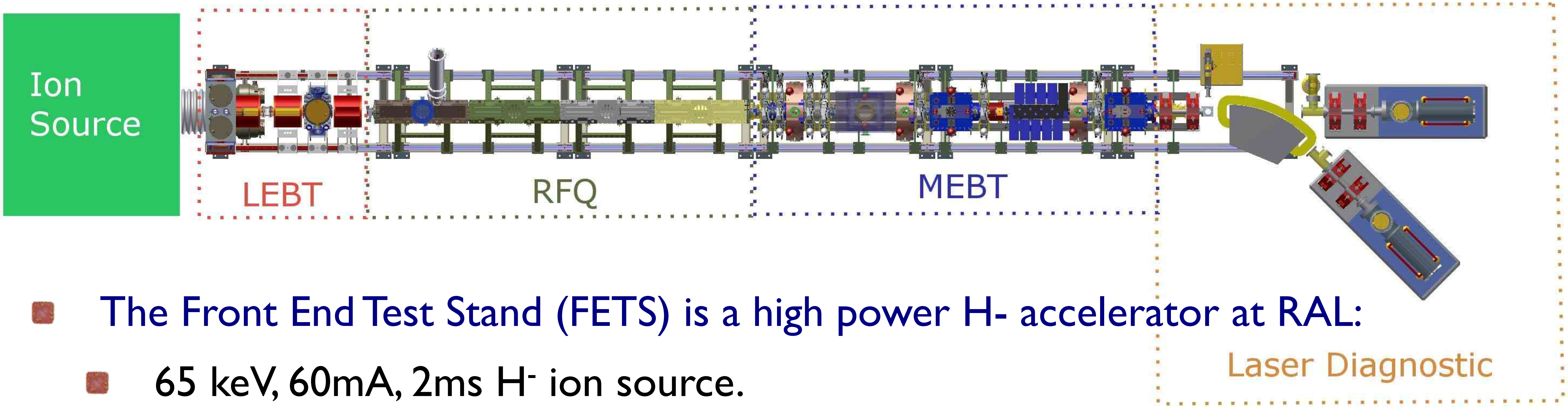
Outline



- Overview of FETS Diagnostics
  - Beam current monitors
  - Beam position monitors
  - H^- laserwire emittance scanner.
- Results of tests of the FETS laserwire at CERN's Linac4
  - FETS - Linac4 collaborative laserwire development.
  - Emittance measurements at 3 and 12 MeV.
  - Current activities: 50 MeV profile measurements.
- Future FETS laserwire:
  - Updated laserwire design.
  - Particle tracking simulations.
  - SLED: *Sliding Laser Emittance Diagnostic*.
- Conclusions and outlook

Overview of FETS Diagnostics

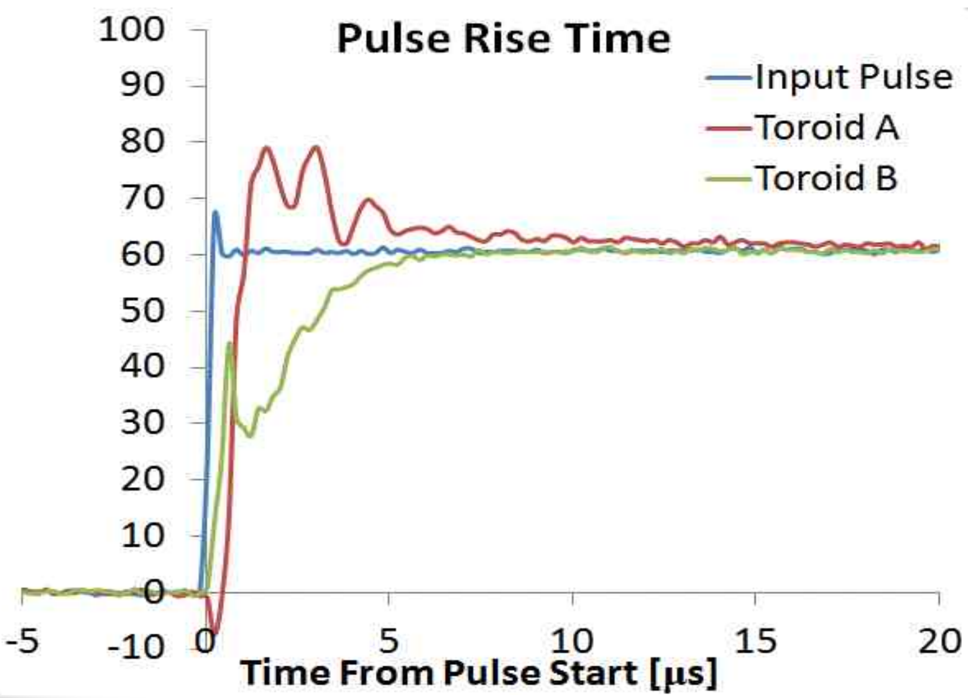


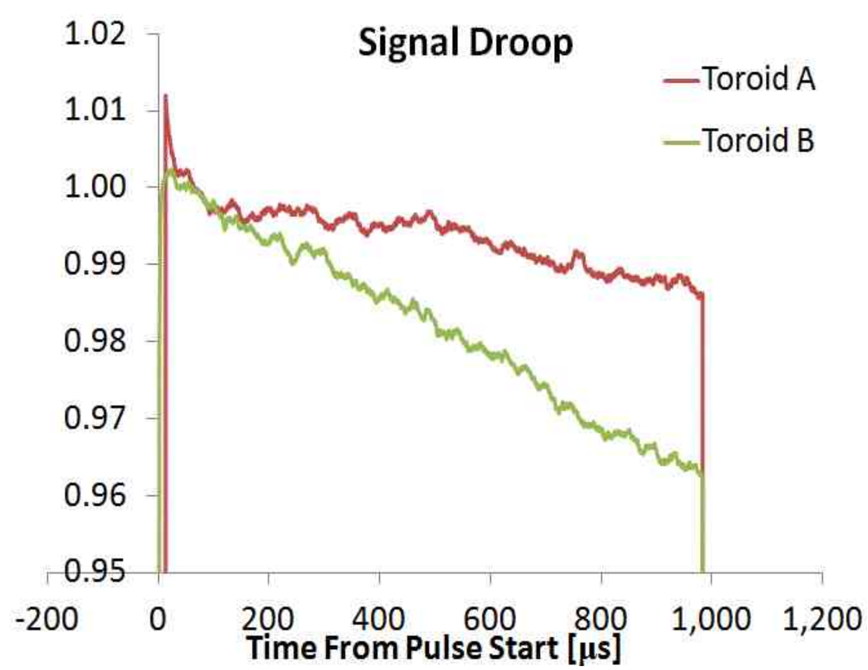
- The Front End Test Stand (FETS) is a high power H- accelerator at RAL:
  - 65 keV, 60mA, 2ms H^- ion source.
  - 3 solenoid magnet Low Energy Beam Transport.
  - 324 MHz 4-vane bolted RFQ: 3 MeV beam
  - Slow and fast chopping within the MEBT
  - Laserwire emittance scanner diagnostic
- ***Status:*** Ion source and LEBT operational prior to shielding installation in 2015. RFQ sections now machined, verified by bead-pull, and soon to be installed.
- Beam diagnostics are essential for alignment and to measure the critical parameters to demonstrate the system performance.

For a FETS overview please see Alan Letchford's talk in WG1 session 2

Beam Current Monitors

- Nine conventional AC current transformer toroids monitor the beam current at various locations along the beam-line.
- Toroids have been already operated successfully for over a year in the LEBT.
- Ultimately aim to determine the transmission performance of the RFQ and fast and slow beam choppers.
  - Eight toroids have been designed, constructed and tested in-house, while the toroid immediately after the ion source is a Bergoz ACCT with a fast response.
  - Bench tests of these devices have met the required rise-time specification.
  - One had a measured droop of 3%/ms due to low core permeability.

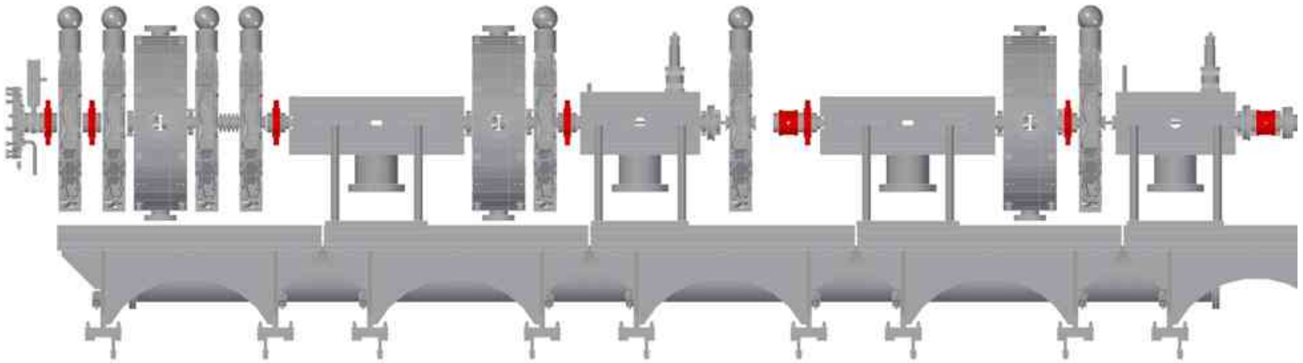




Scott Lawrie

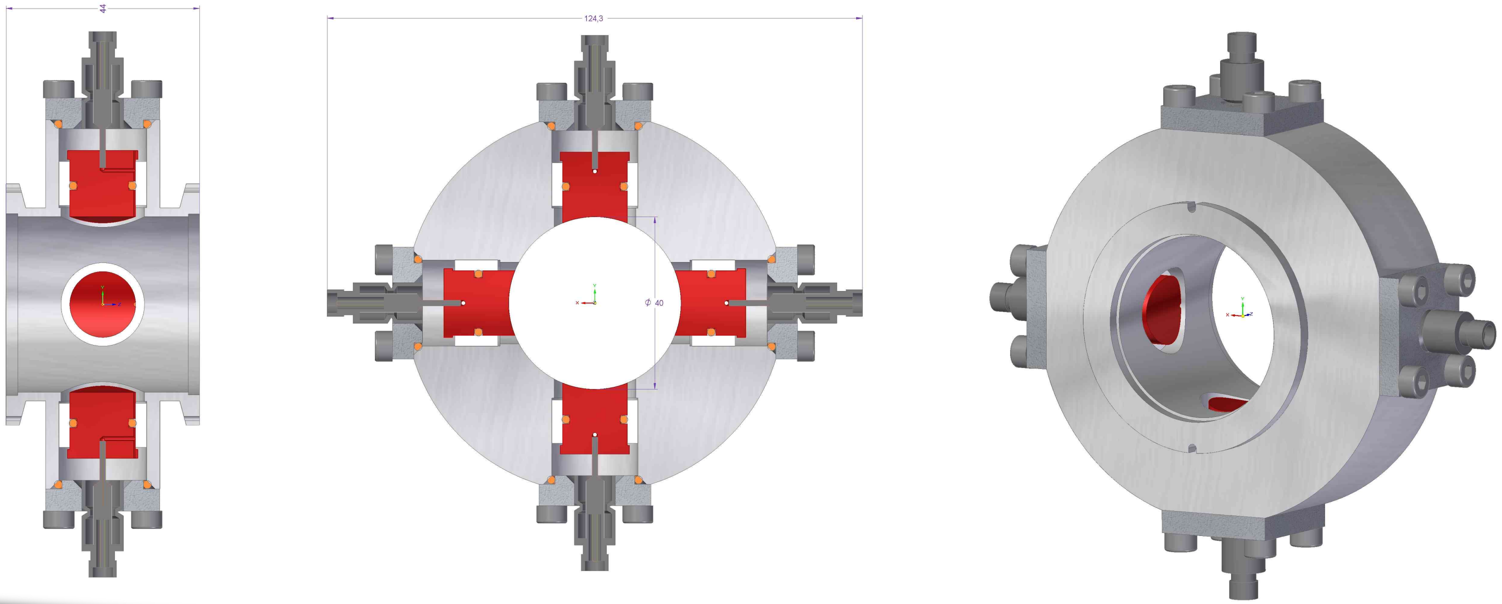
Beam Position Monitors

- Multiple BPM locations within MEBT



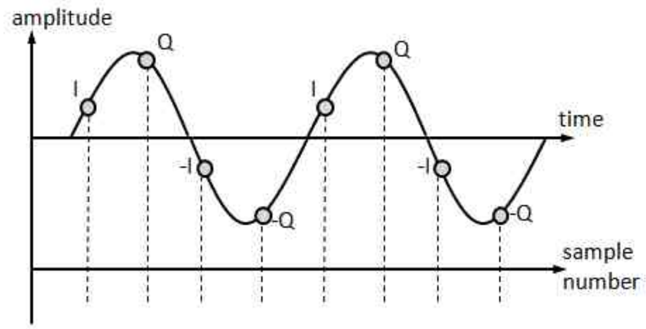
- Two designs
  - CERN Linac4 shortened stripline
  - RAL custom button, designed by A. Letchford, with modified dielectric for fast RF pickup.

Linac4 shortened stripline design



Beam Position Monitors

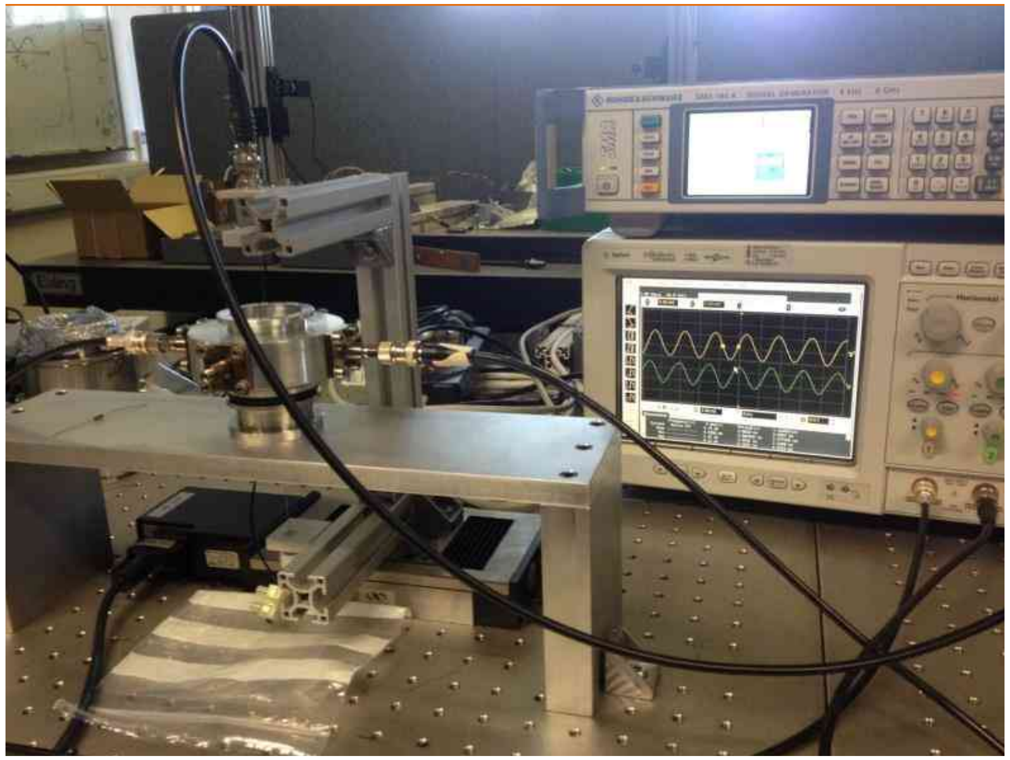
- IQ sampling at 40.5 MS/s
  - 324 MHz down- mixed to IF=10.125 MHz using LO 313.875 MHz.
- Digitizer & FPGA
  - NI PXI-based FPGA card and digitizer to acquire the IF signals.
  - 32 channel, 12-bit parallel processing within a microsecond.
- Wire-rig BPM tests:
  - Position resolution is <1%, <20μm, 5x better than required.

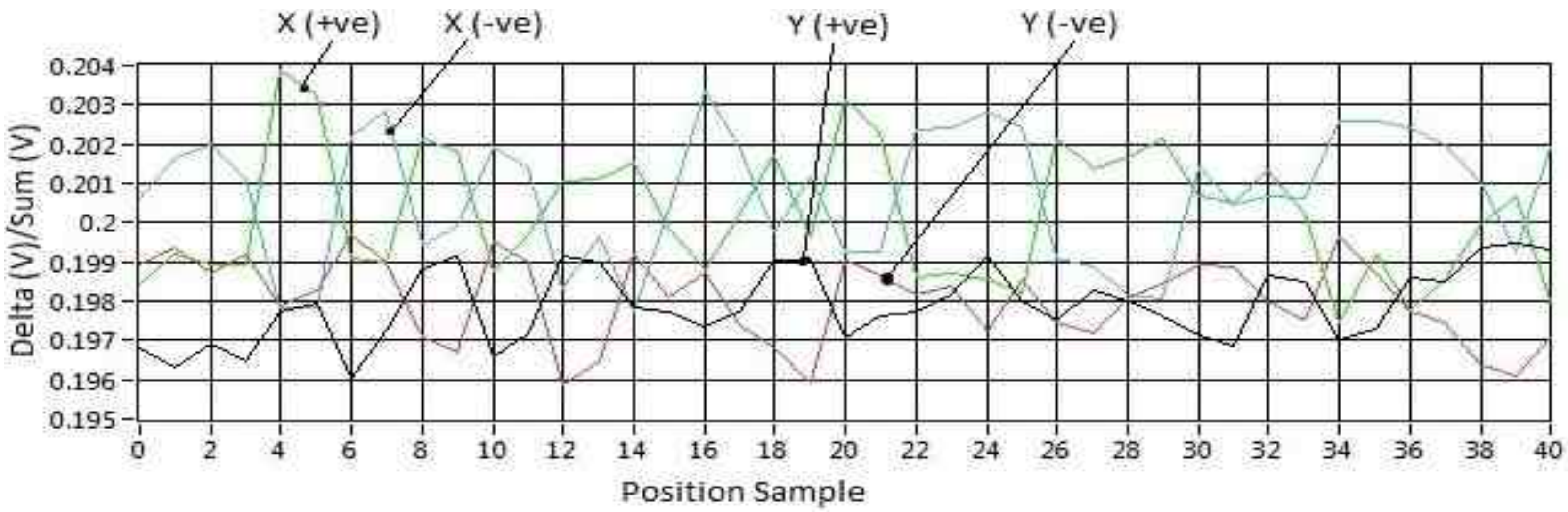


$$V_{peak} = \sqrt{I^2 + Q^2}$$

$$Position_x = k_x * \frac{V_{right} - V_{left}}{V_{right} + V_{left}}$$

$$Position_y = k_y * \frac{V_{top} - V_{bottom}}{V_{top} + V_{bottom}}$$

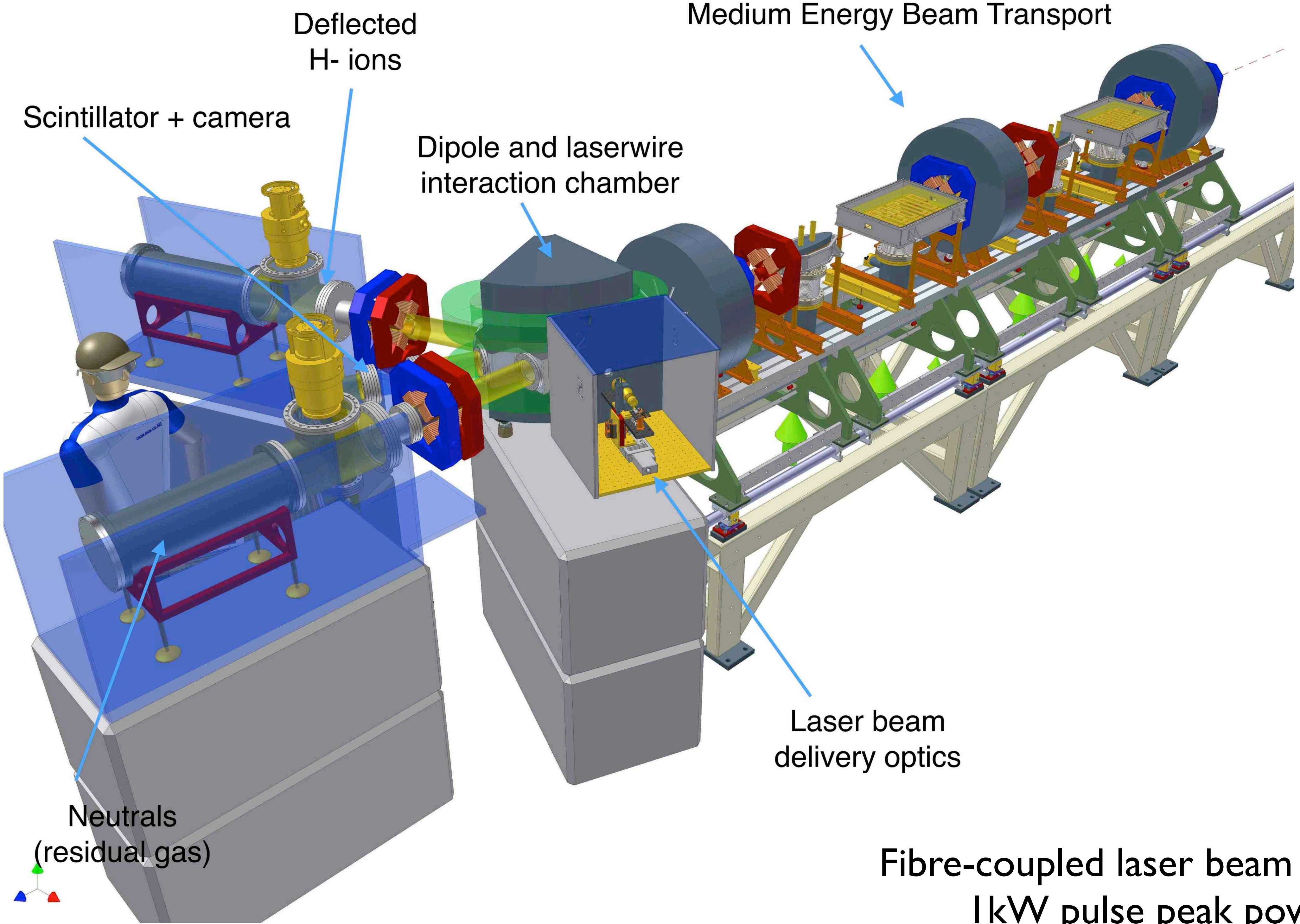




G. Boorman et al, *"Beam-Line Diagnostics at the Front End Test Stand (FETS), Rutherford Appleton Laboratory, Oxfordshire, UK"*, TUPC26, IBIC2013, Oxford, UK.
G. Boorman et al, *"Development of a BPM System using a Commercial FPGA Card and Digitizer Adaptor Module for FETS"*, THPME186, IPAC2014, Dresden, DE..
G. Boorman et al. *"Characterising the Signal Processing System for Beam Position Monitors at the Front End Test Stand"*, TUPB073, IBIC2015, Melbourne, Australia.

FETS Laserwire Emittance Scanner

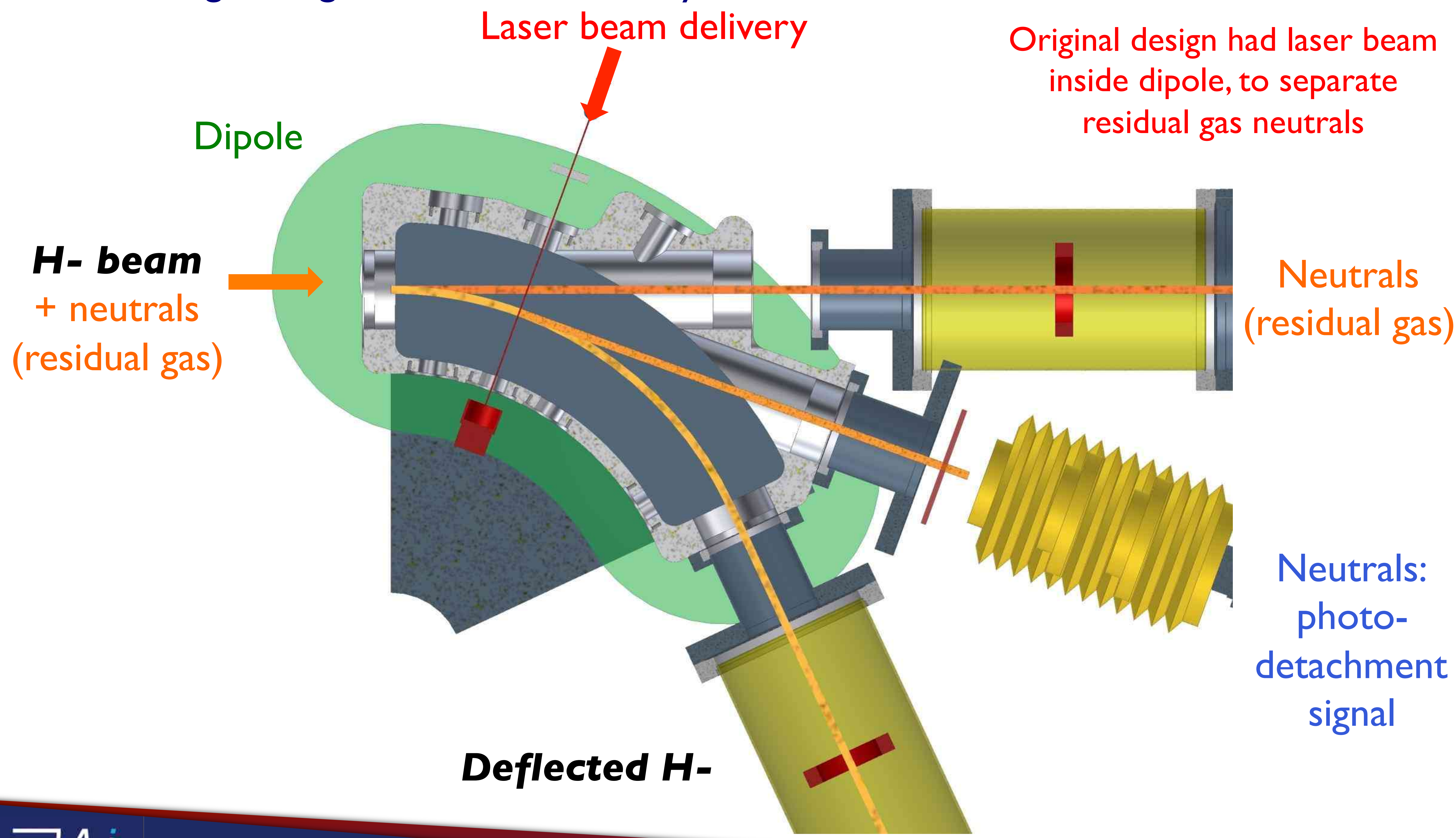
- Photo-neutralization of H- ions for profile and emittance measurements @ 3MeV



Fibre-coupled laser beam delivery:
1kW pulse peak power.

Emittance via photo-detachment

- Basic principle: laser interacts with H- in chamber to photo-detach electrons, leaving H0 signal to be measured by scintillator + camera.



Fibre Laserwire beam delivery

Fibre

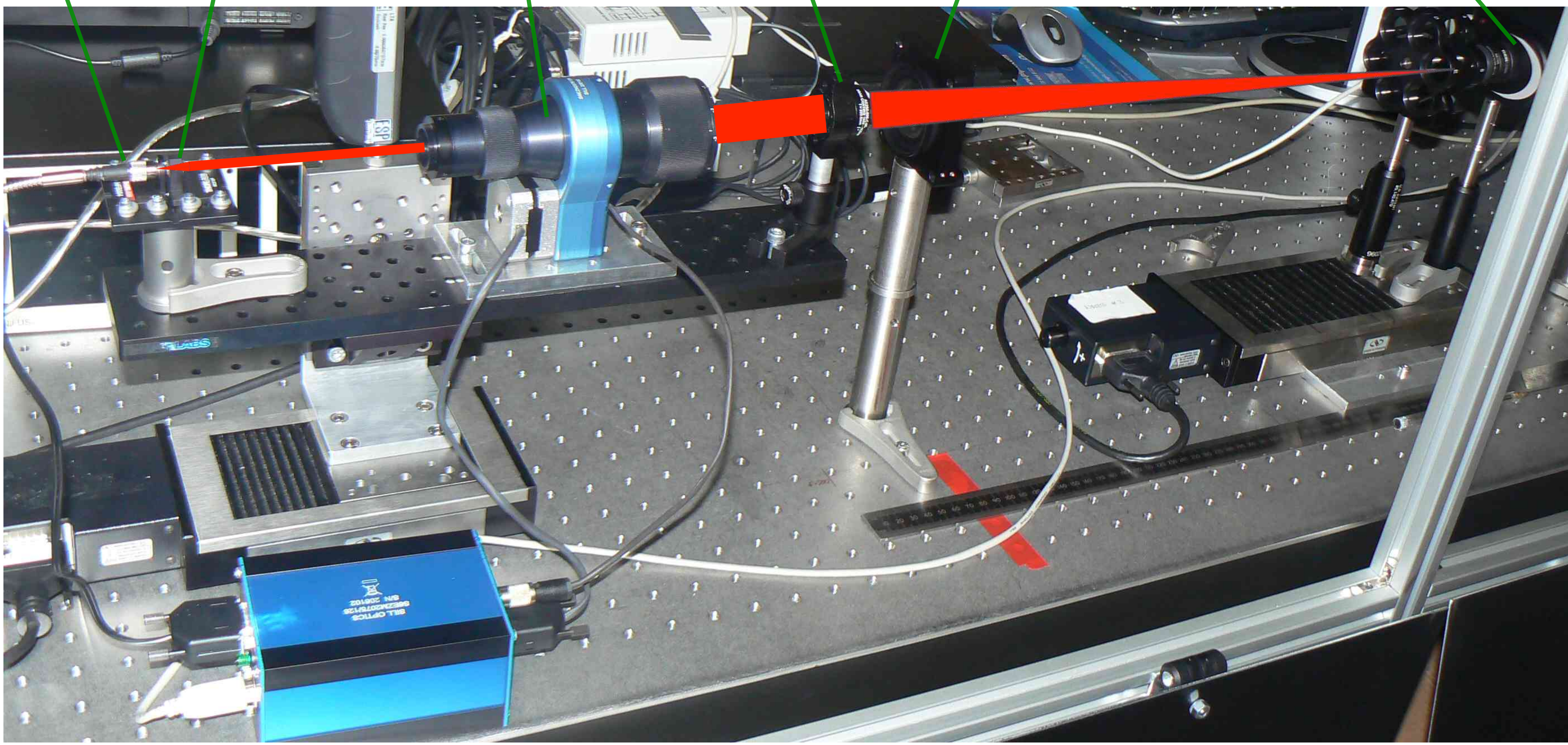
collimating Lens f=6.4mm

motorized beam expander

focusing lens f=500mm

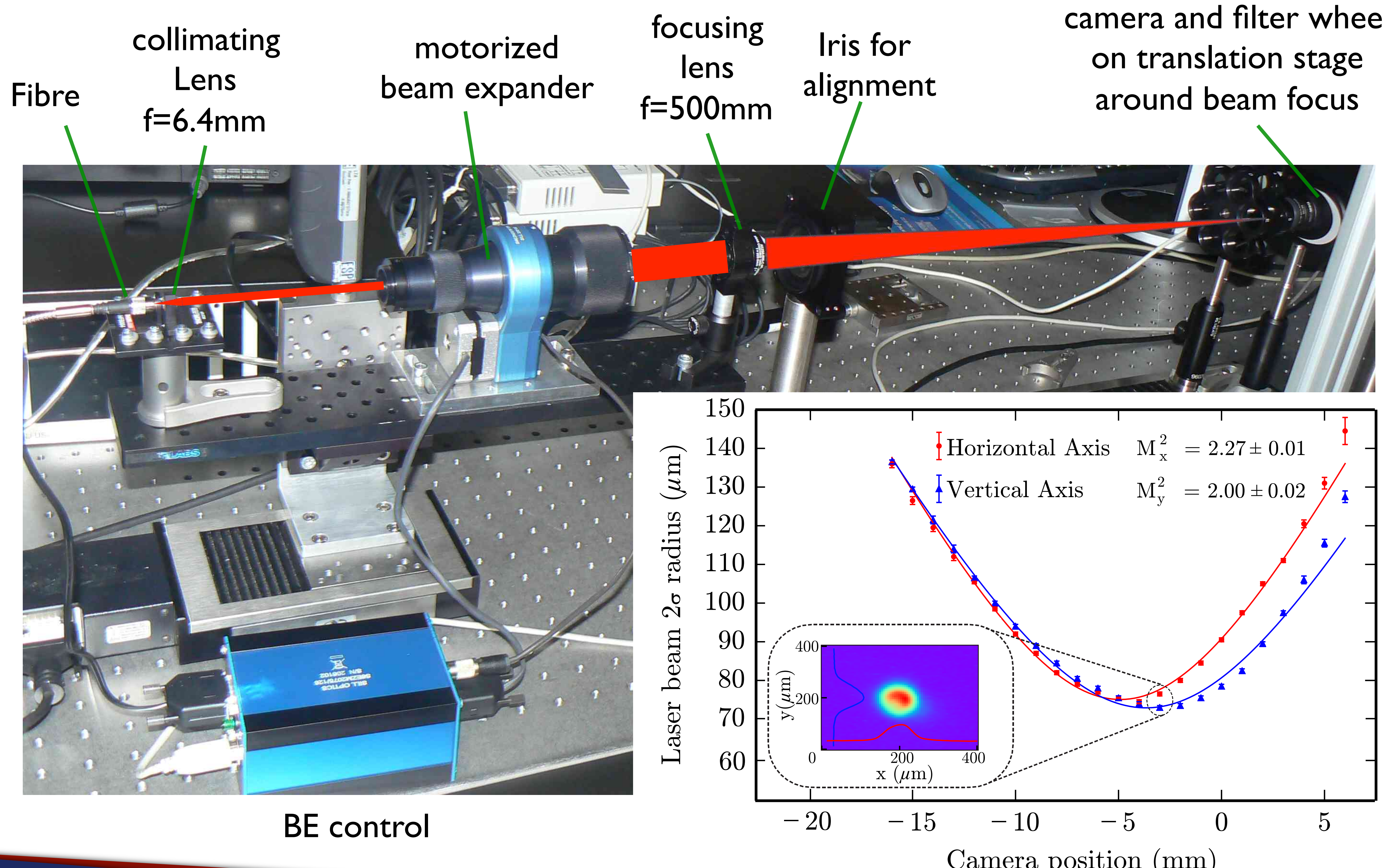
Iris for alignment

camera and filter wheel on translation stage around beam focus



BE control

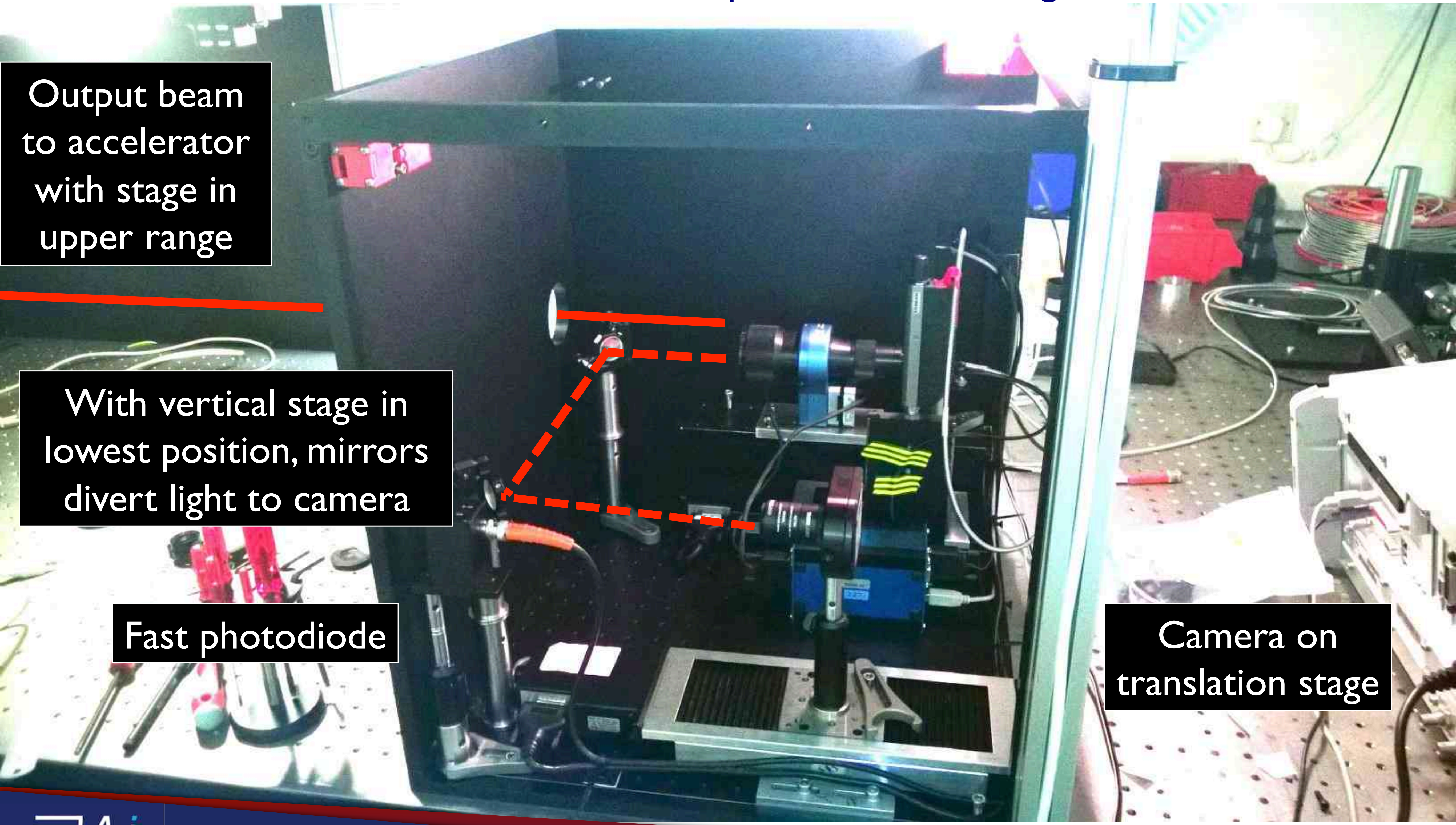
Fibre Laserwire beam delivery



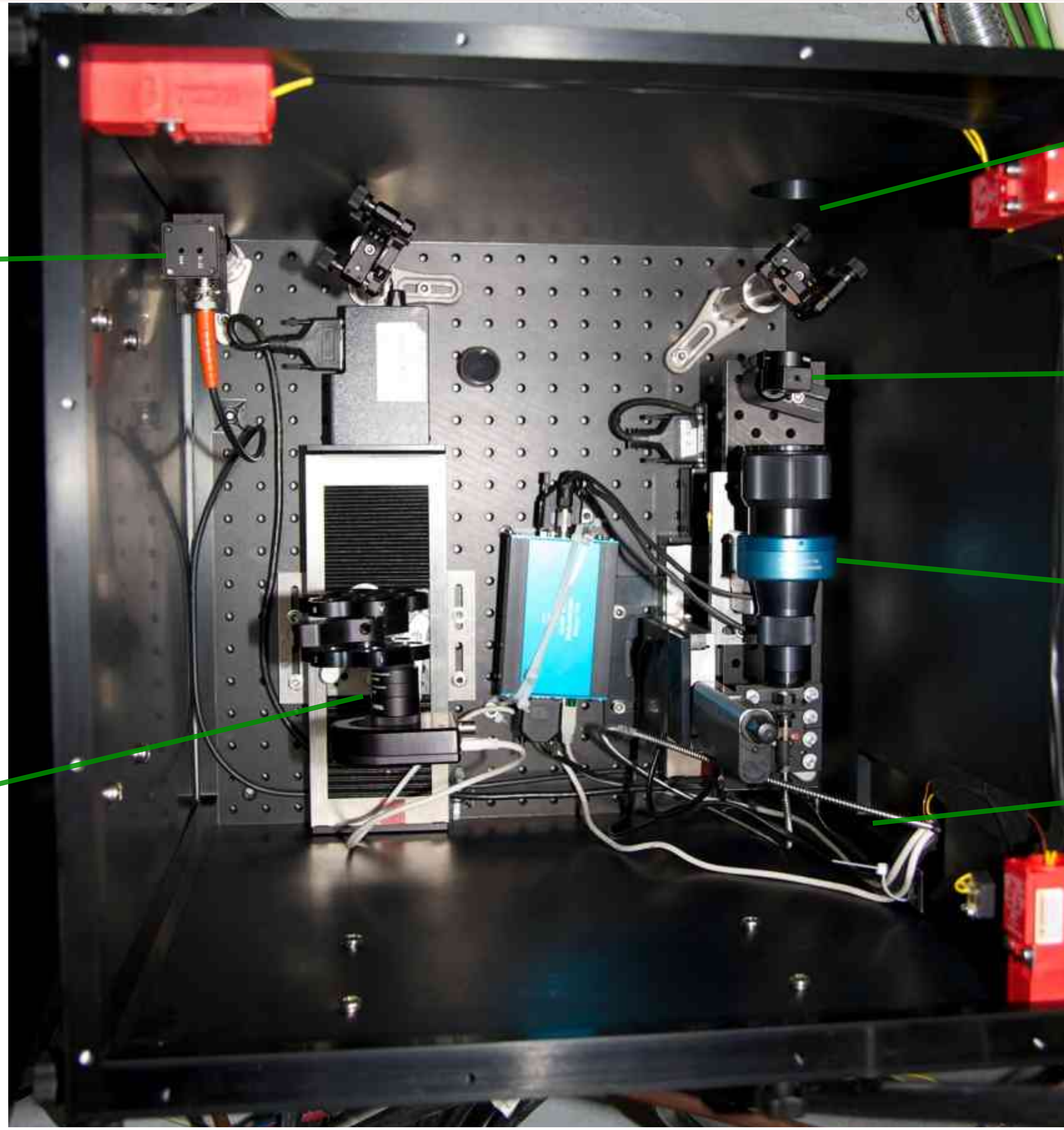
BE control

Motorized laser delivery system

- Remotely controlled scanning of laserwire focal position delivered to the accelerator, with in-situ feedback via photodiode and diagnostic camera.



Laserwire beam delivery



Port to accelerator vacuum chamber

Fast photodiode

Focusing lens

Beam expander on motion stages, X and Y

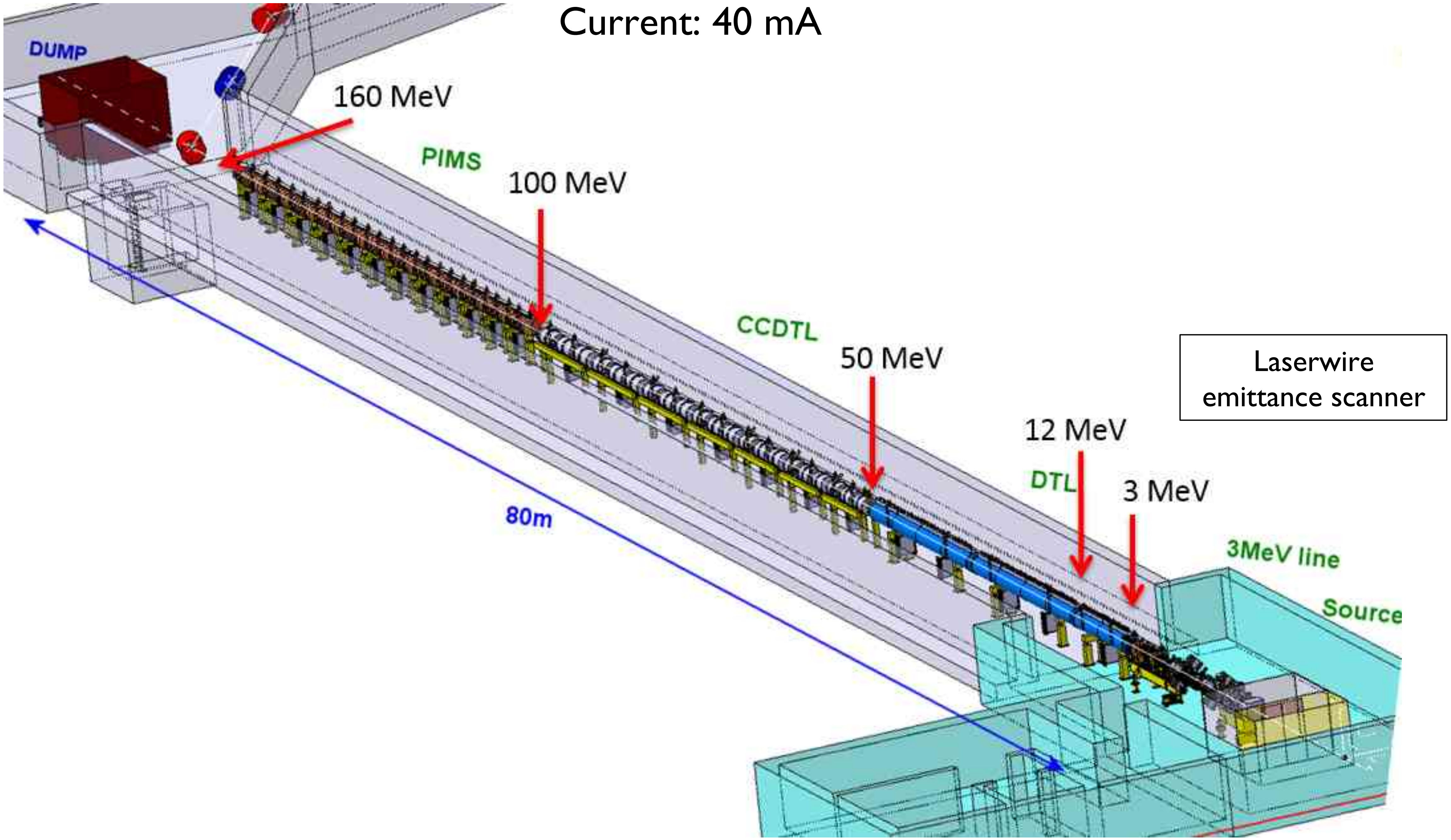
Filter wheel and camera on Z translation stage

Fibre input / services

Linac4 commissioning at CERN

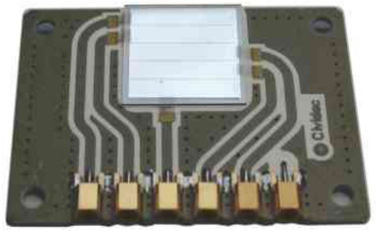
- Linac2 will be replaced in 2018 by Linac4 as the main injector for the LHC and HL-LHC.

H^- ions to 160 MeV
Current: 40 mA

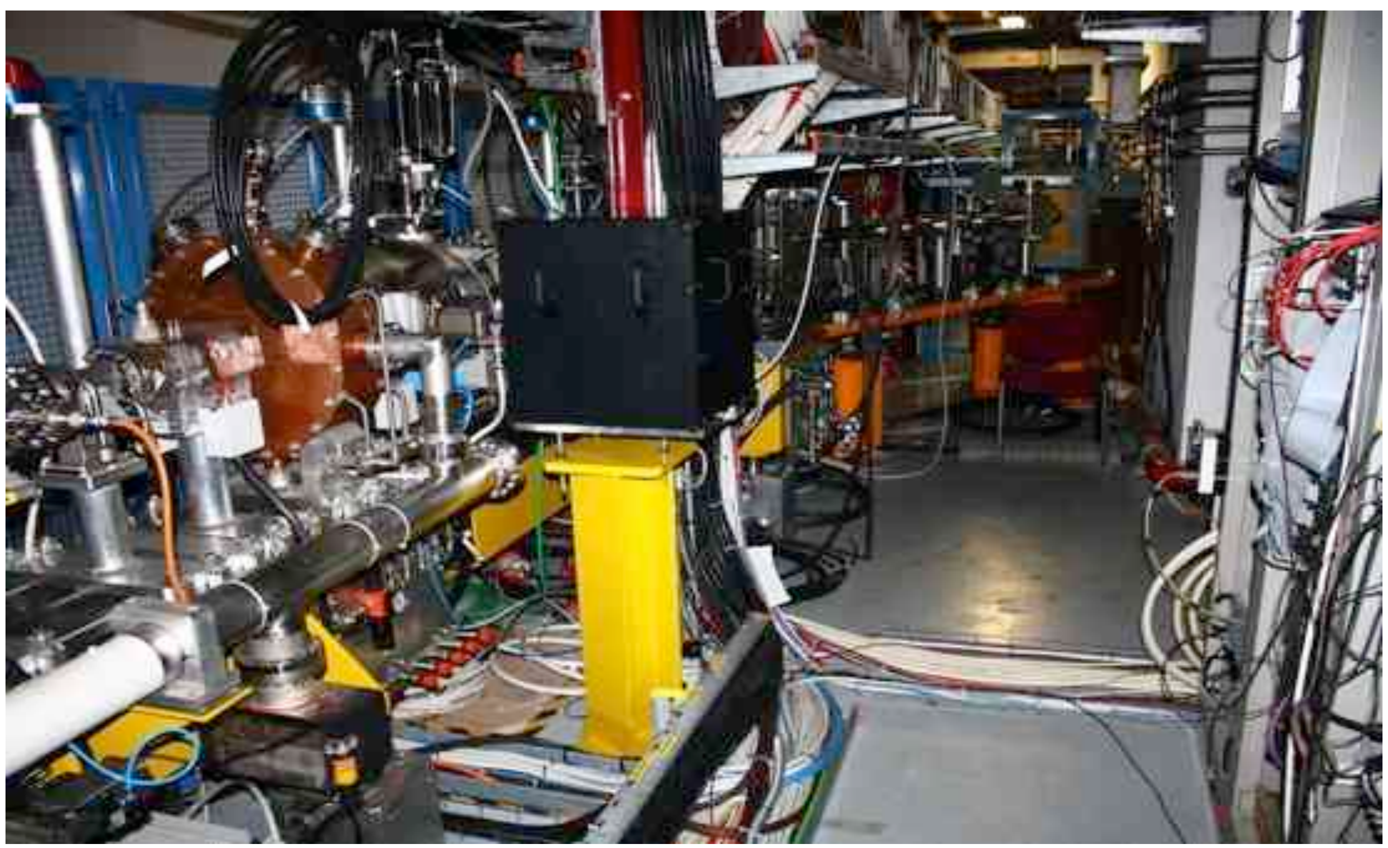


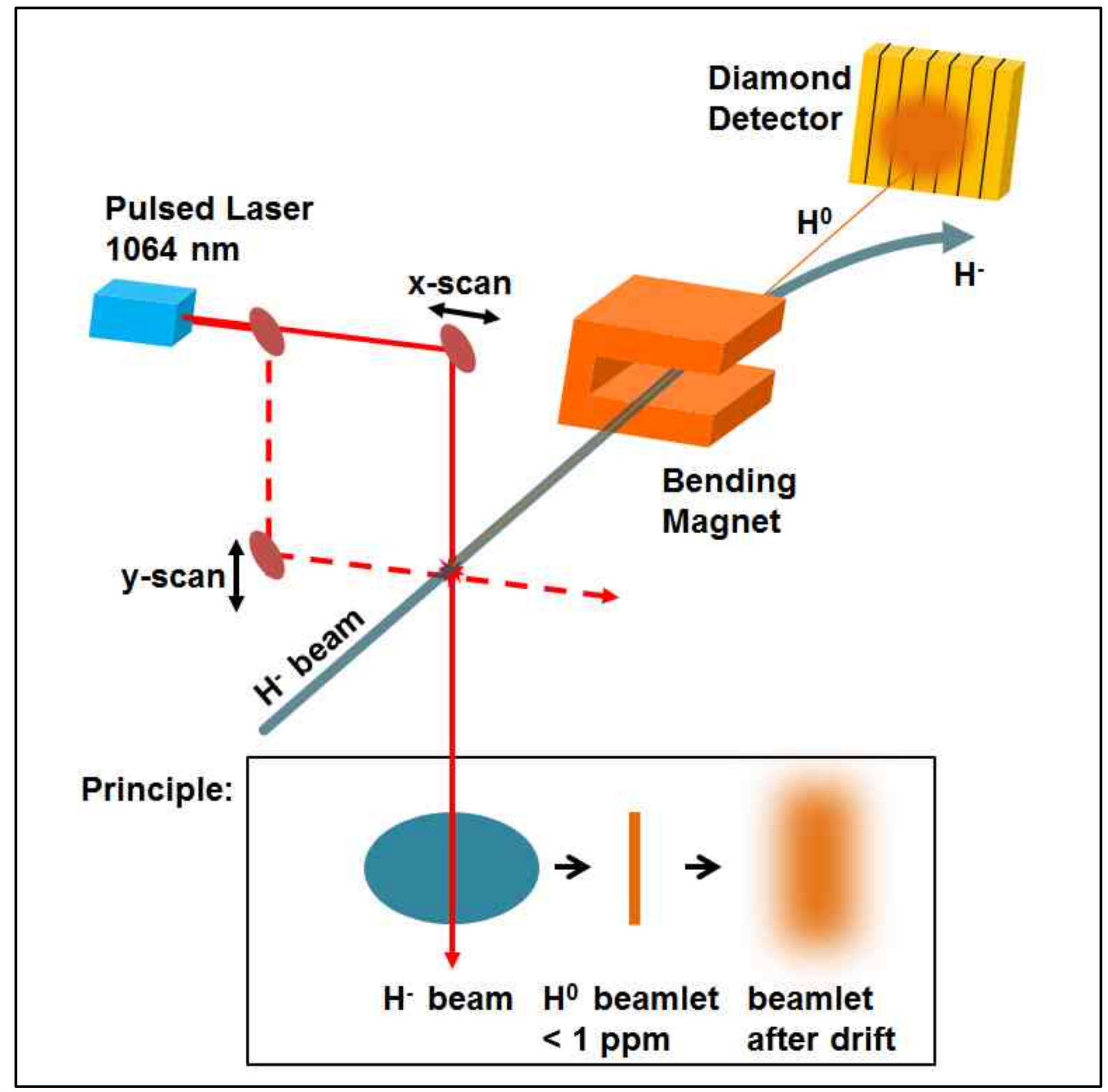
FETS-Linac4 Laserwire Collaboration

- CERN Linac4 is the new 160 MeV H^- linear accelerator under construction to replace Linac2 as the main injector to the PS for the LHC (~2018). and ultimately HL-LHC.
- Due to synergies with UK FETS diagnostics, a collaboration was formed with CERN BE to install a laserwire emittance scanner in the Linac4, 3 MeV beam tests.
- Emittance measurement via photo-detachment
- Beamlet of H0 neutrals are recorded by a downstream diamond detector
- Laser delivery optics installed in Linac4 tunnel:



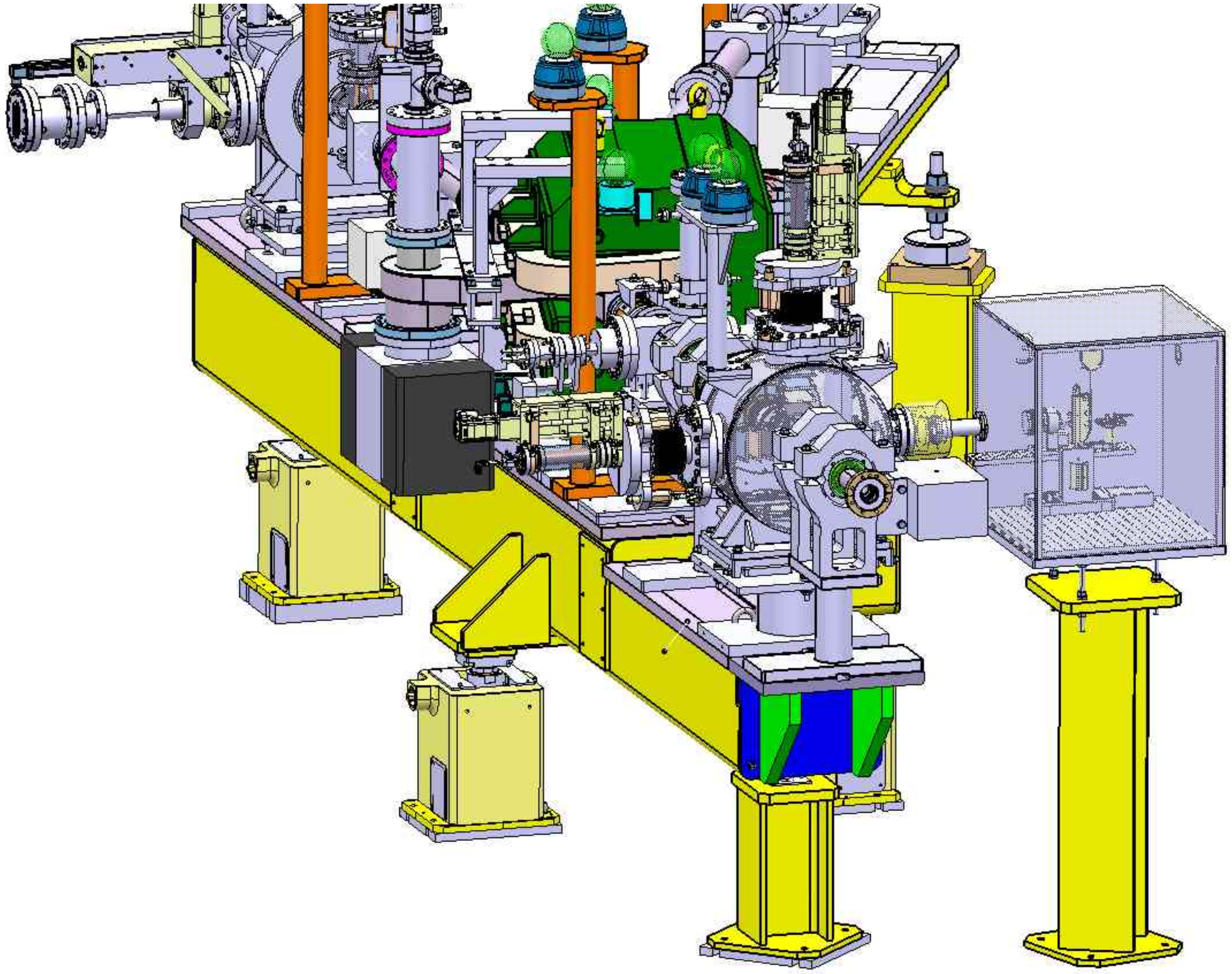
CIVIDEC Instrumentation, Austria

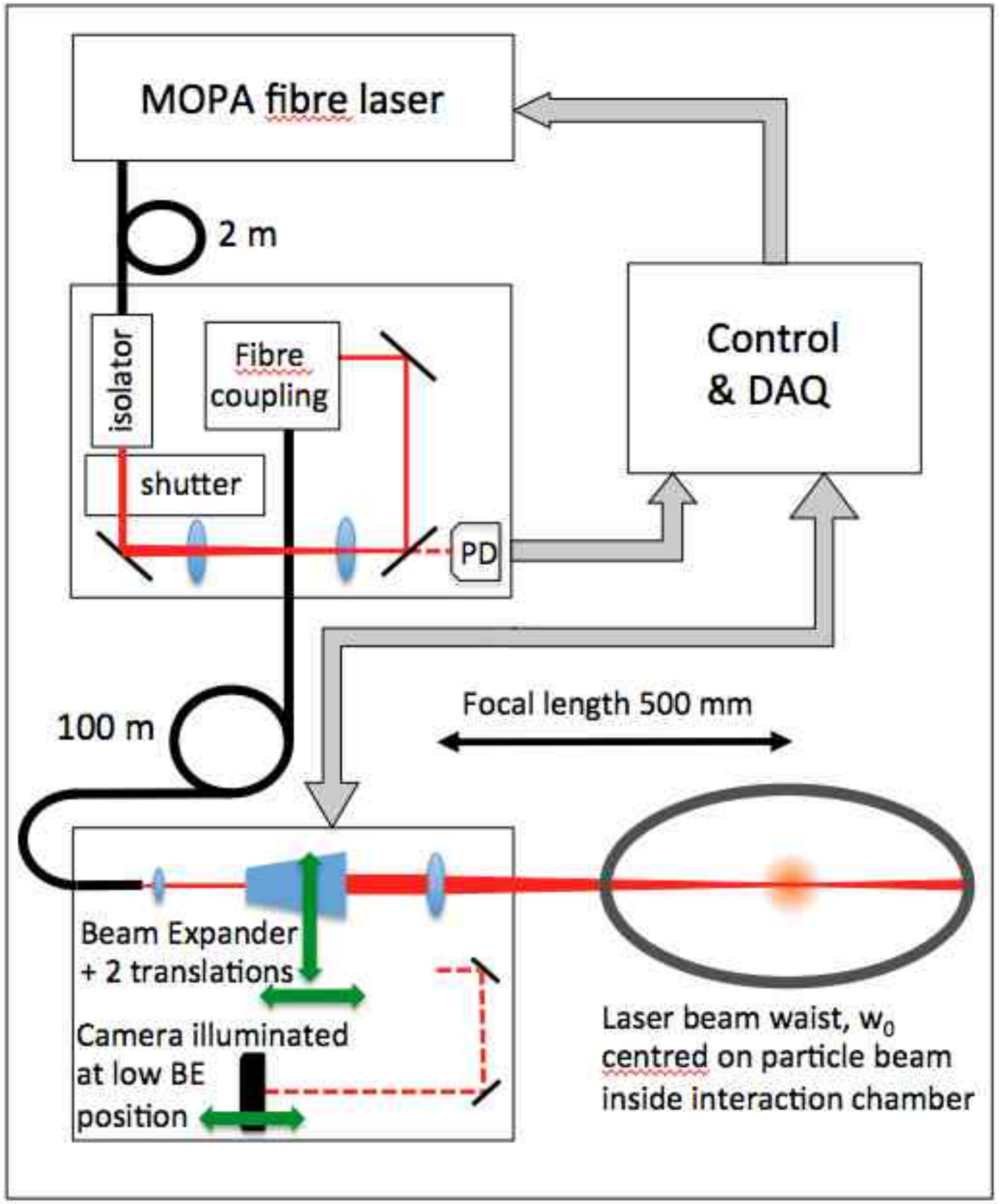




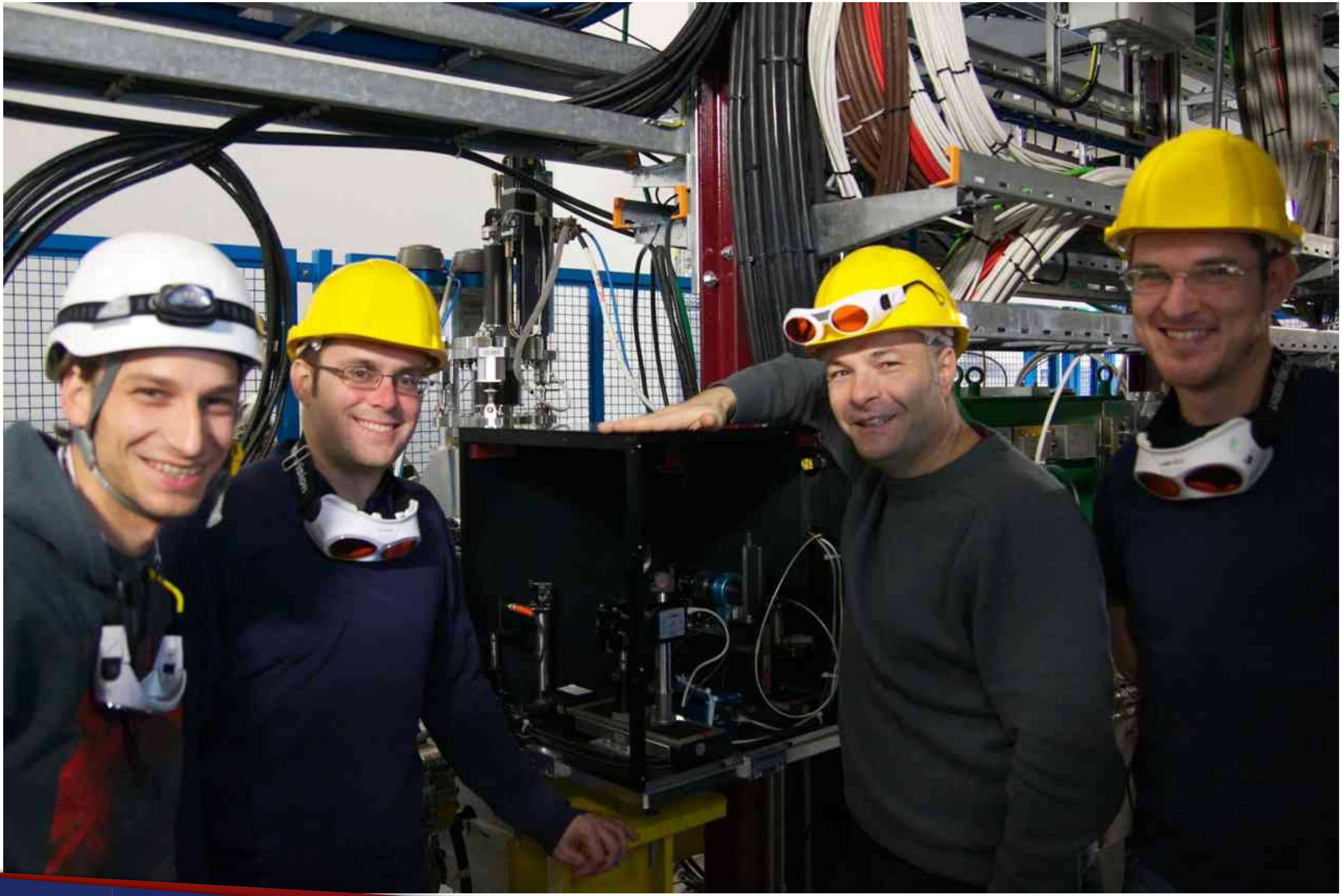
Integration with Linac4

- Portable enclosure to deliver laser beam to vacuum chamber, integrated with Linac4 layout.



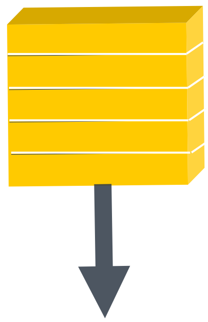


Linac4 laserwire installation team

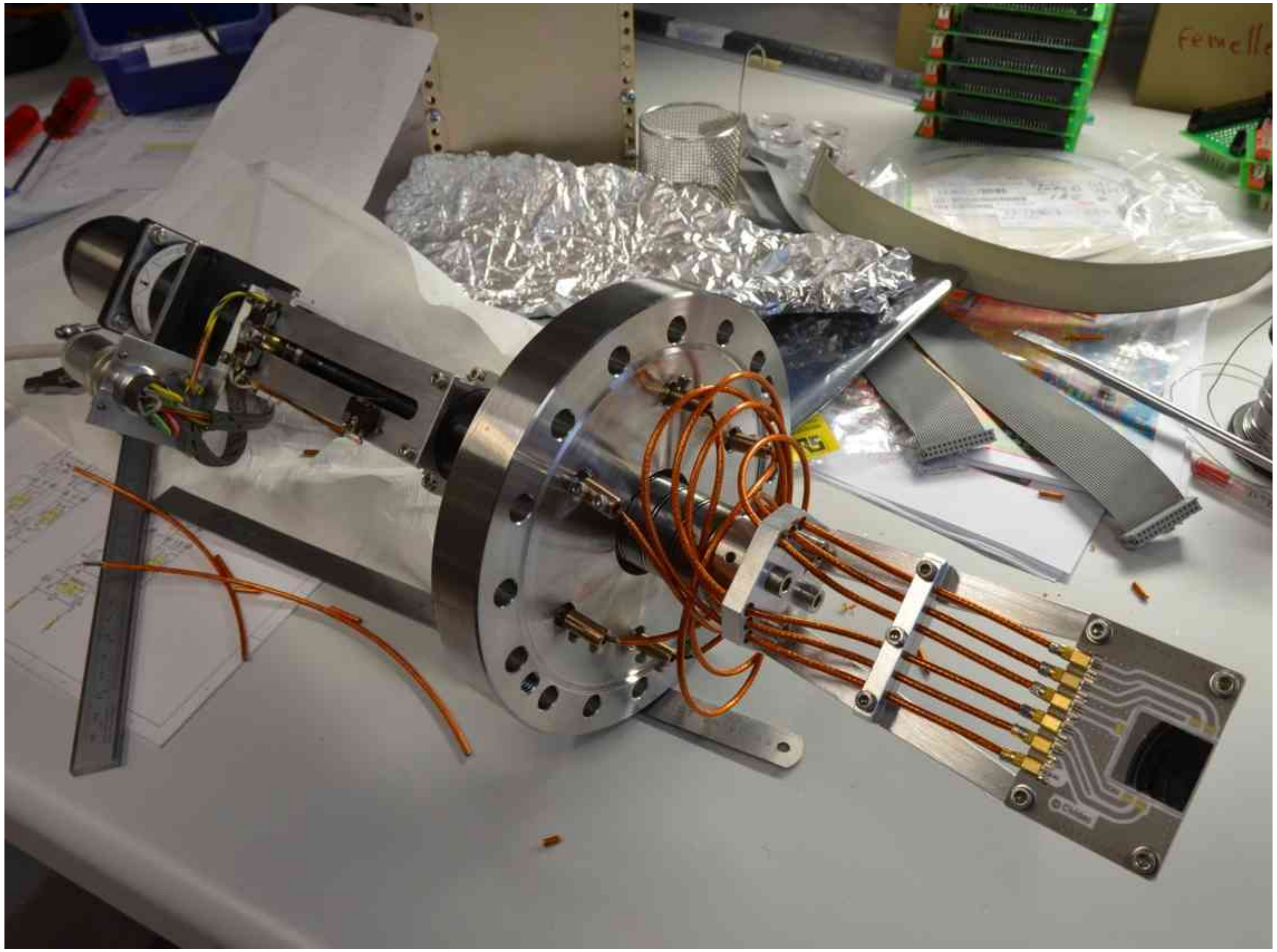


Linac4 diamond detector

- Main H^- beam deflected by spectrometer magnet.
- Neutral H^0 are undeflected and arrive at a downstream 5 strip diamond detector, which can be moved into the beamline via translation stage:



- Each horizontal strip has a vertical width of ~3.5mm.
- Small gap of 300um between strips
- 600V nominal bias (adjustable).
- Strips was instrumented with charge sensitive and linear amplifiers.



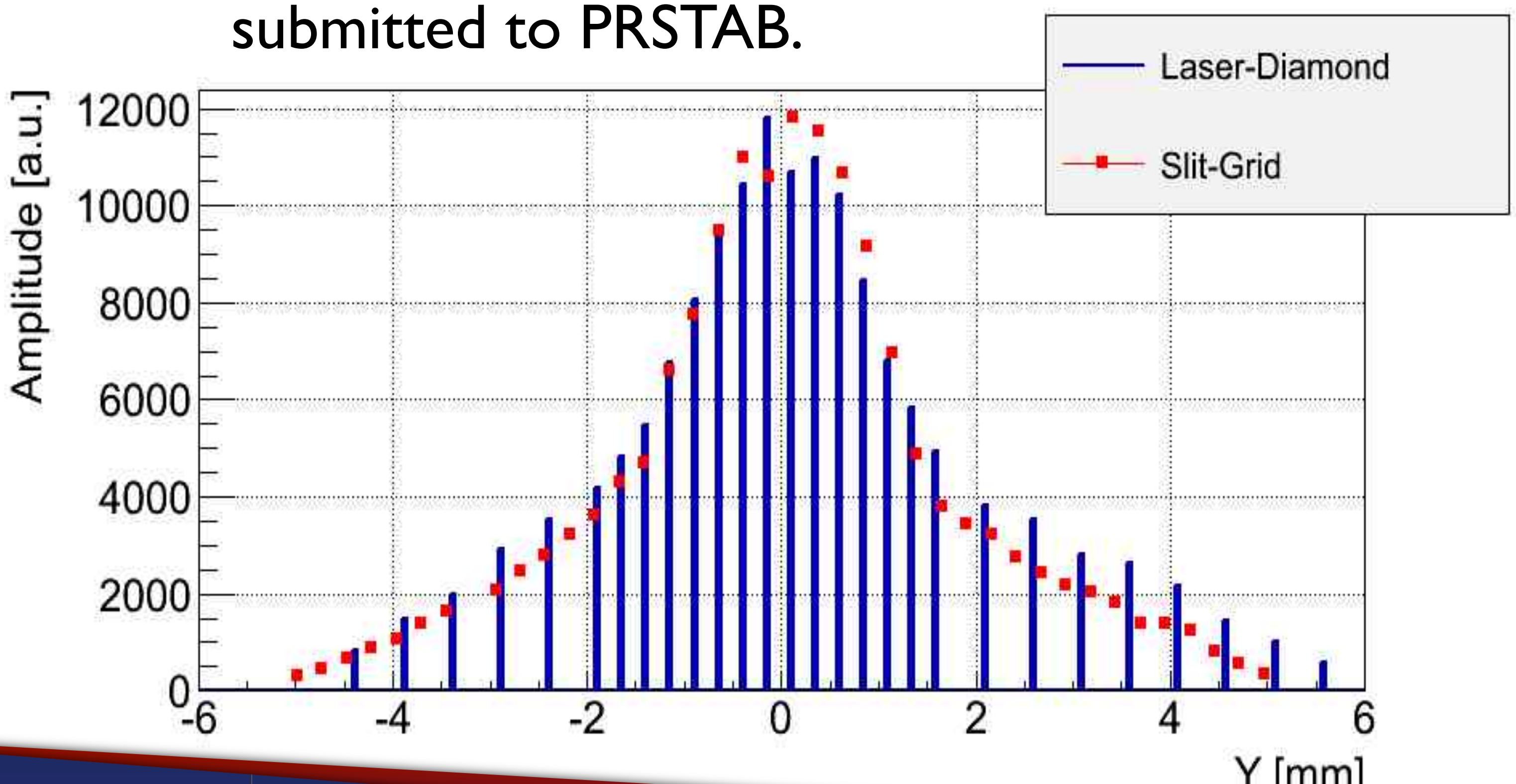
FETS-Linac4 3 MeV results

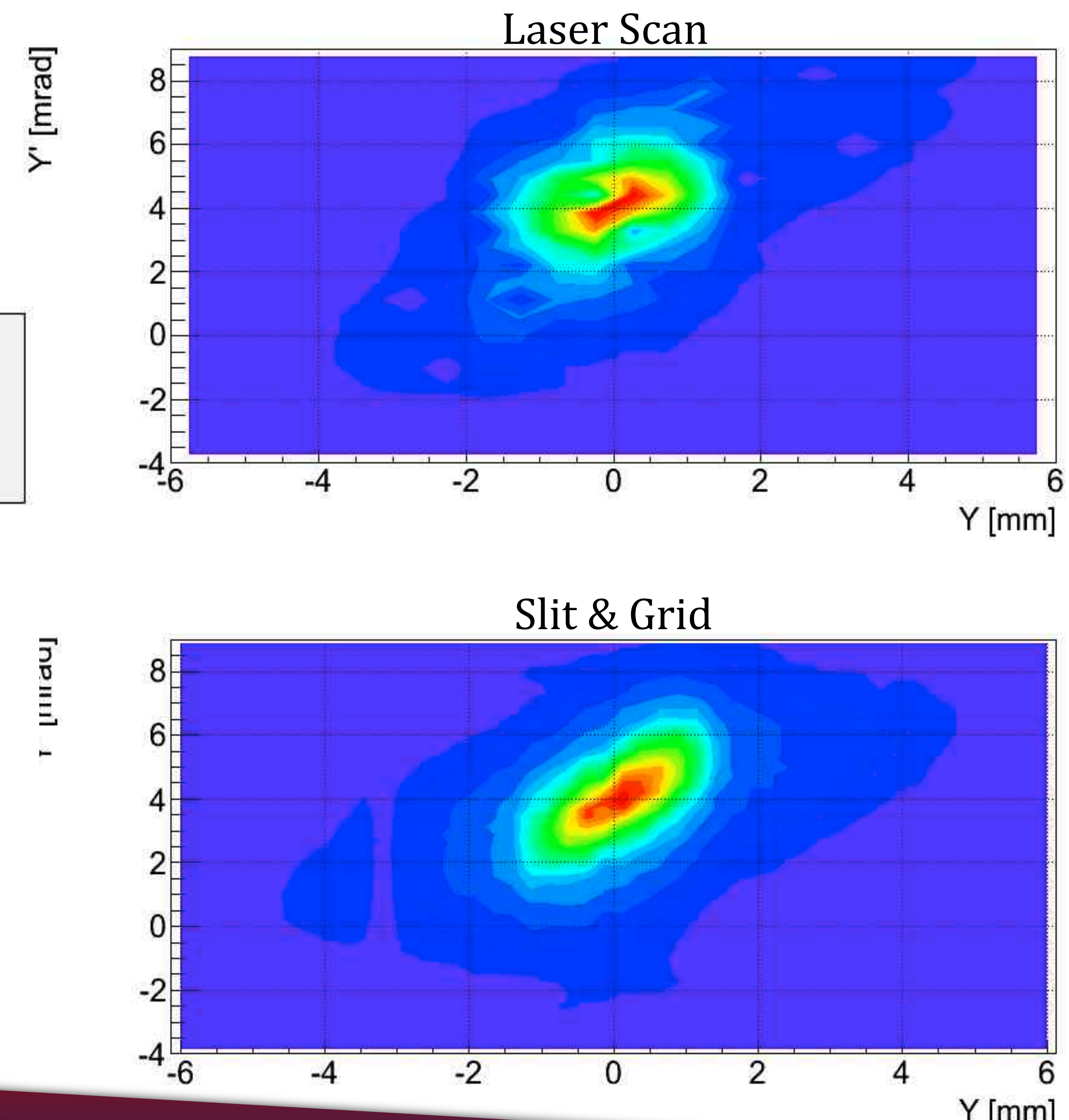
- Laser based profile scan and emittance measurement are compared with a traditional slit & grid scan for 3 MeV set-up. First results were very promising:

FETS + CERN Team

  - Profile shows very good agreement in beam-core.
  - Emittance measurement show good agreement, even with low resolution laser scan.

- Demonstrates non-destructive method using fibre-based laserwire.
  - S.M. Gibson et al., `*A fibre coupled, low power emittance scanner at CERN Linac4*' THPME190, IPAC 2014.
  - T. Hofmann et al. `*Demonstration of a laserwire emittance scanner for the CERN LINAC4 H⁻ Beam*', submitted to PRSTAB.





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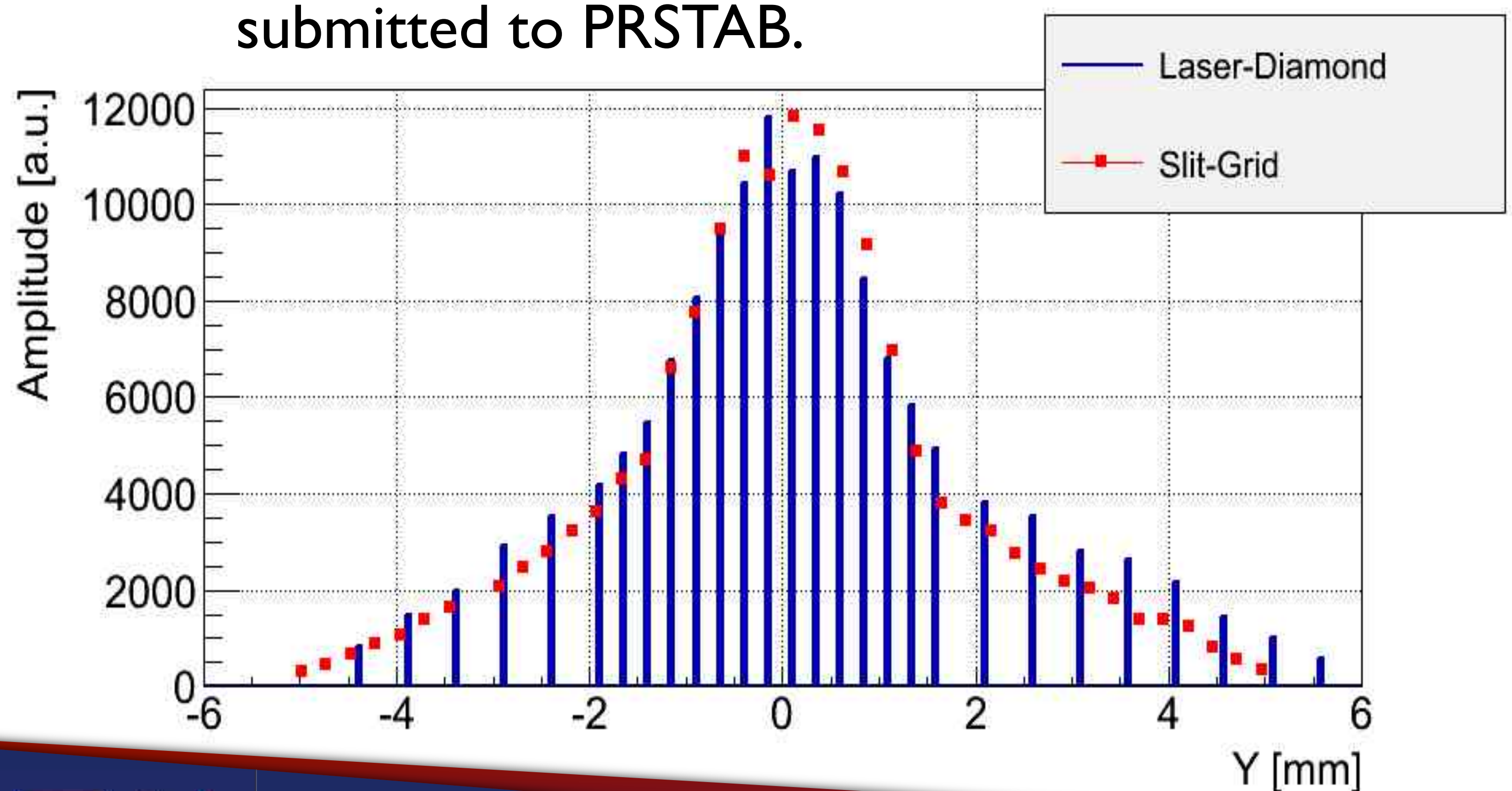
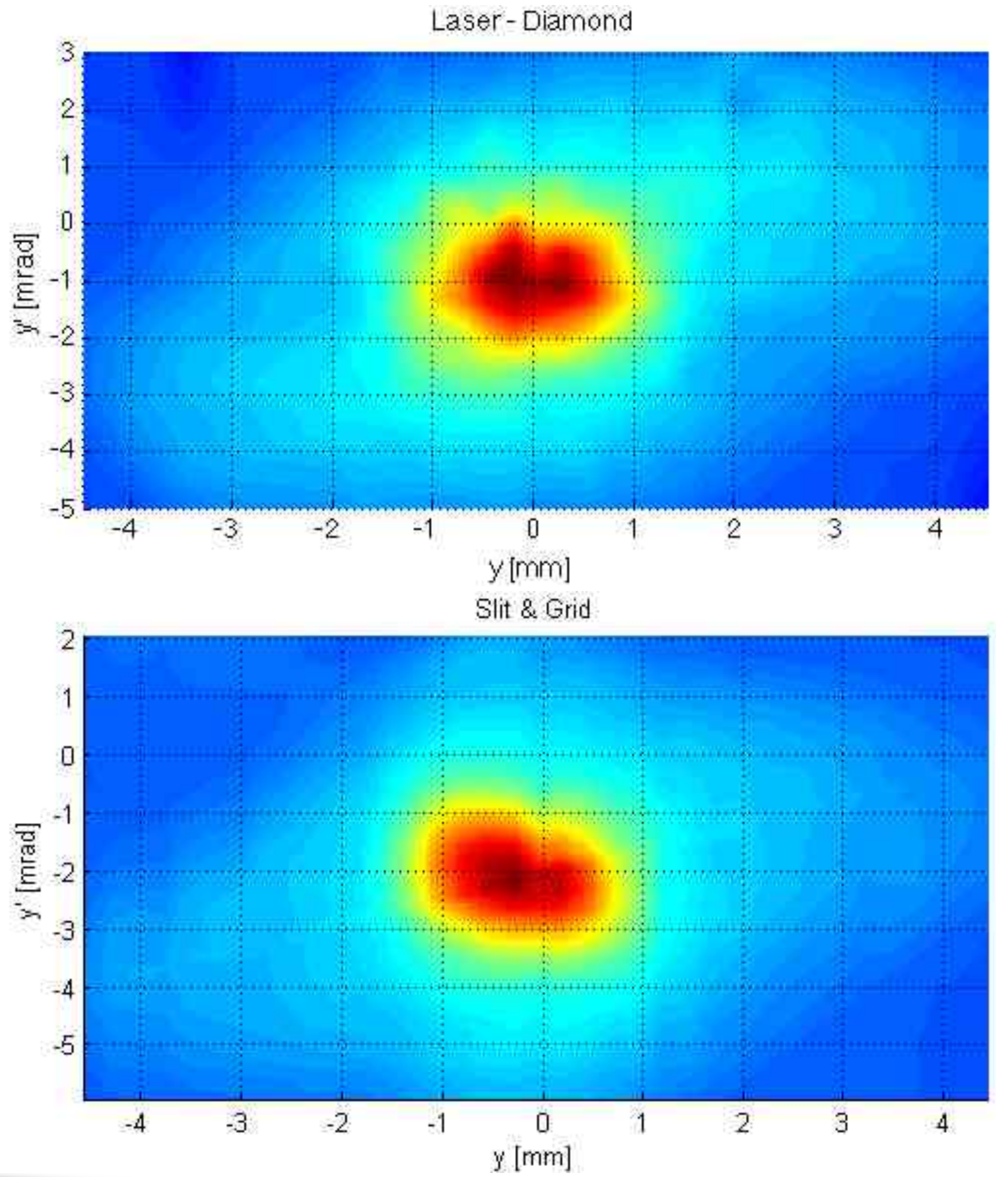
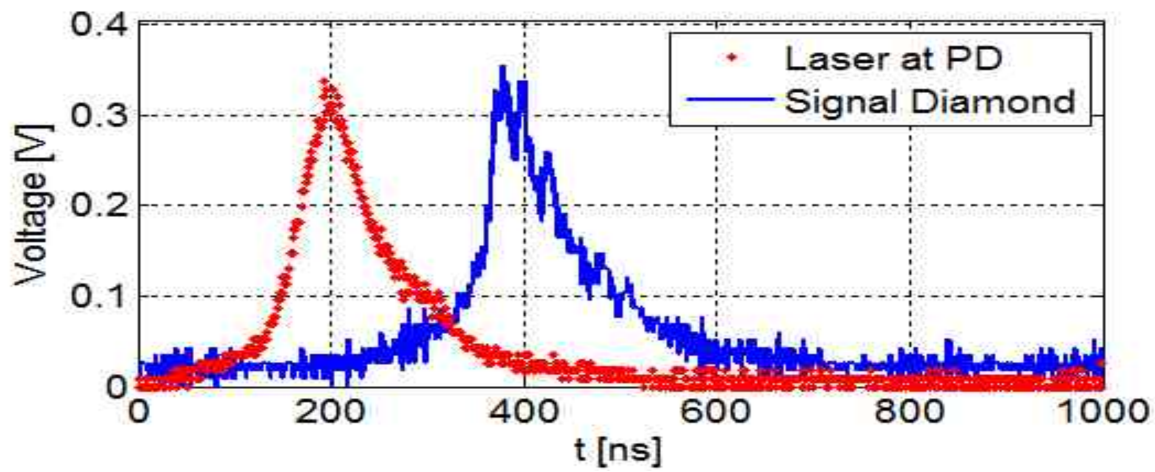


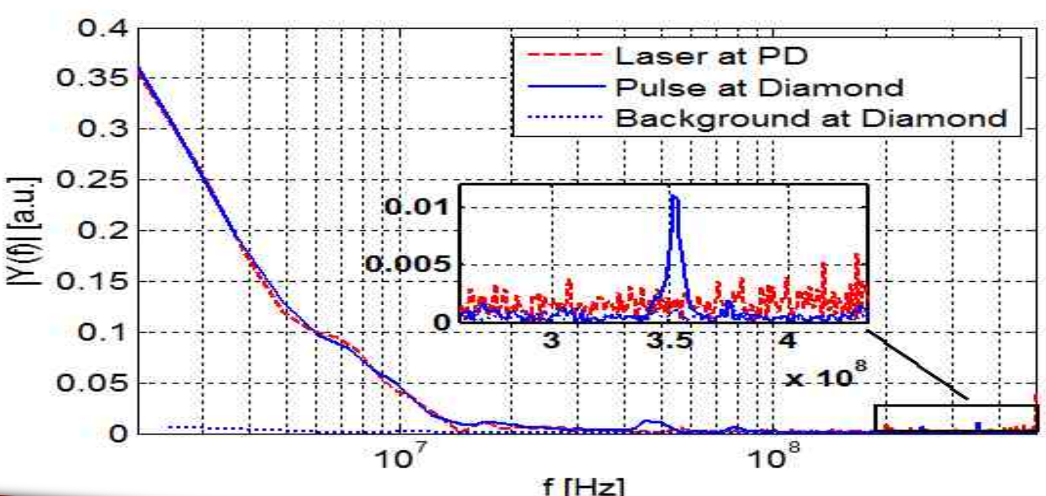


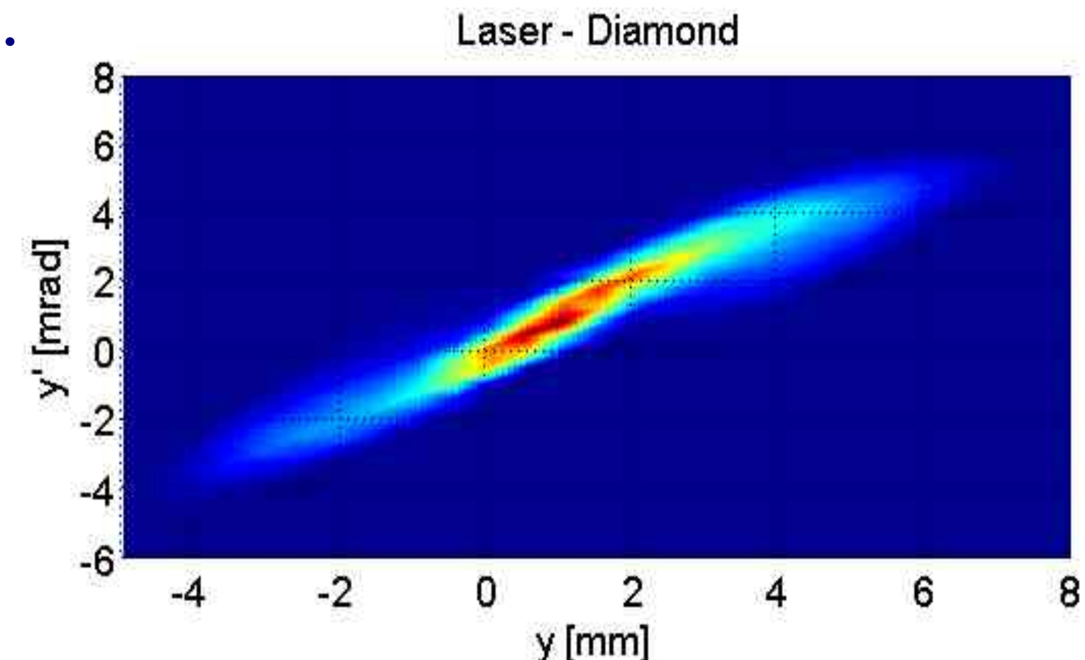
12 MeV results at Linac4

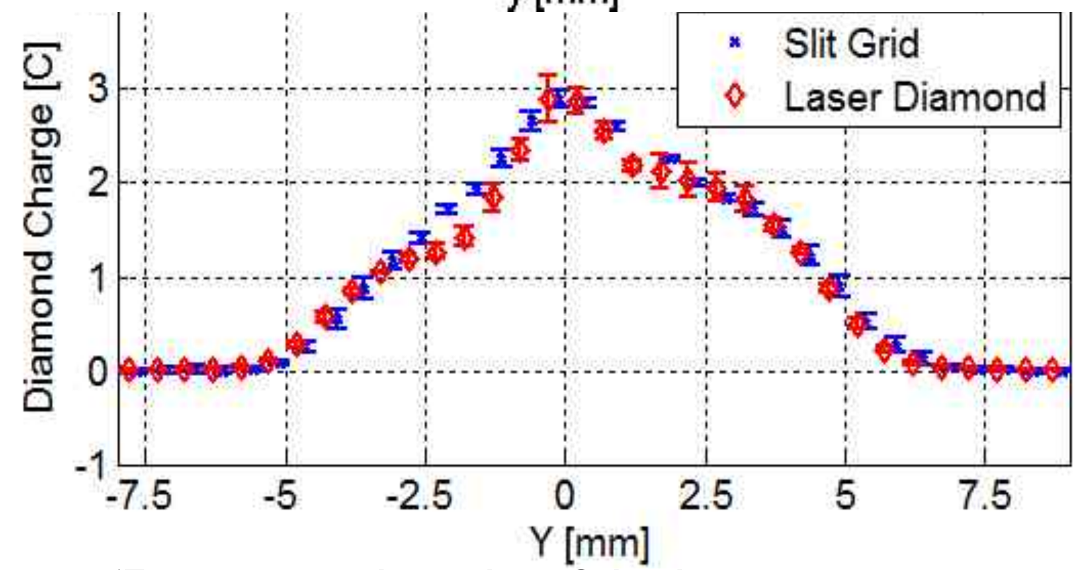
- The laserwire scanner was moved downstream for the second stage of Linac4 commissioning at 12 MeV: setup similar to 3 MeV.
- Profile measurement again shows good agreement with slit-grid measurements, at the new location with different beam optics.
- Diamond detector signal shape matches laser pulse recorded with fast photodiode.



- Even observe peak at 352 MHz RF frequency in a Fourier Transform of the diamond signal.



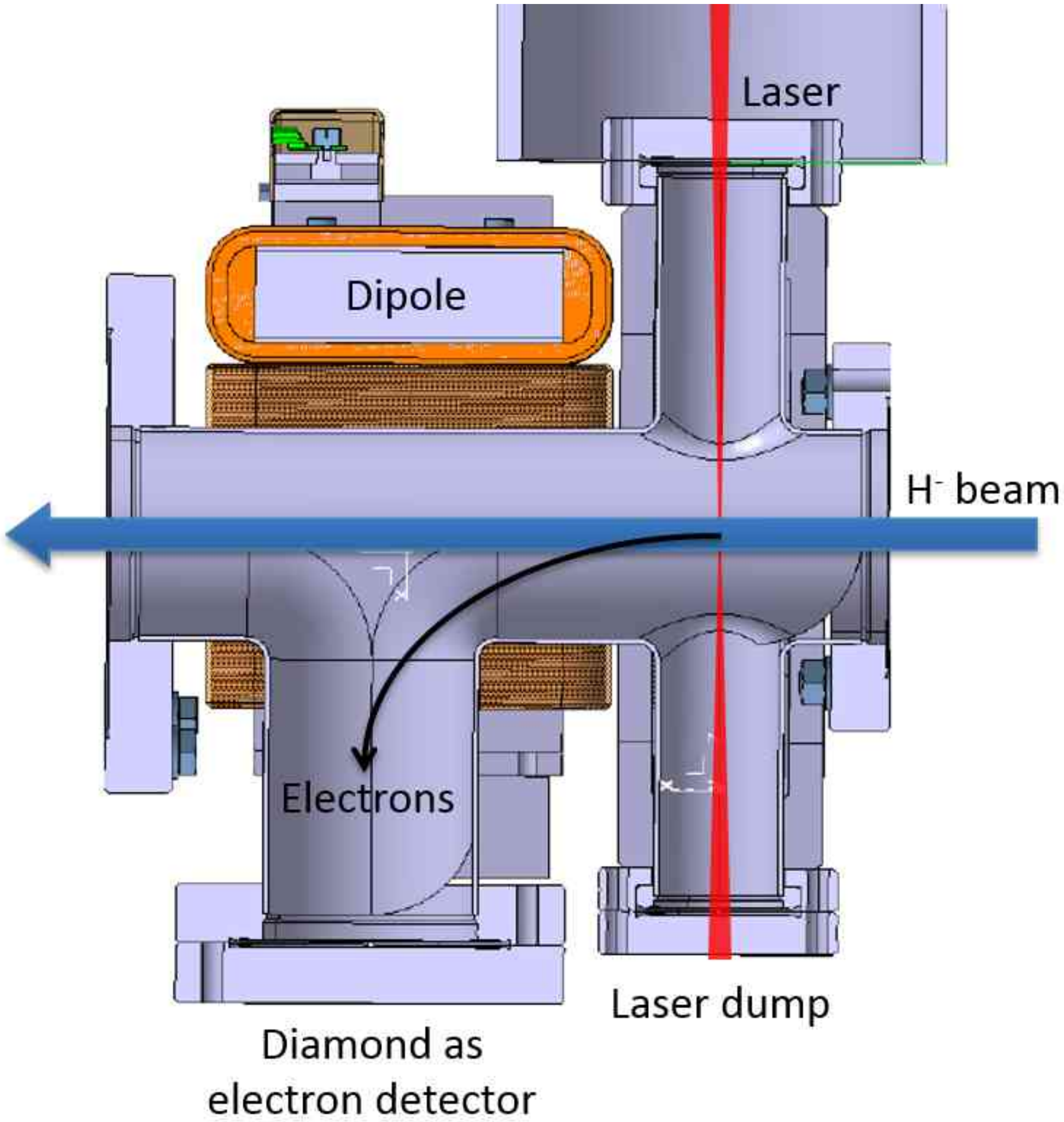




T. Hofmann et al., *'Experimental results of the laserwire emittance scanner for LINAC4 at CERN'*, International Conference on Laser Applications at Accelerators, LA3NET 2015 + submitted to NIMA.

50 MeV laserwire design

- New configuration designed for 50 MeV required as main diagnostics dipole is unavailable. Instead count liberated electrons deflected using small steerer magnet.
  - T. Hofmann et al, *'Design of a laser based profile monitor for Linac4 commissioning at 50 MeV and 100 MeV'*, TUPB005, IBIC 2015. http://ibic.synchrotron.org.au/papers/tupb055.pdf



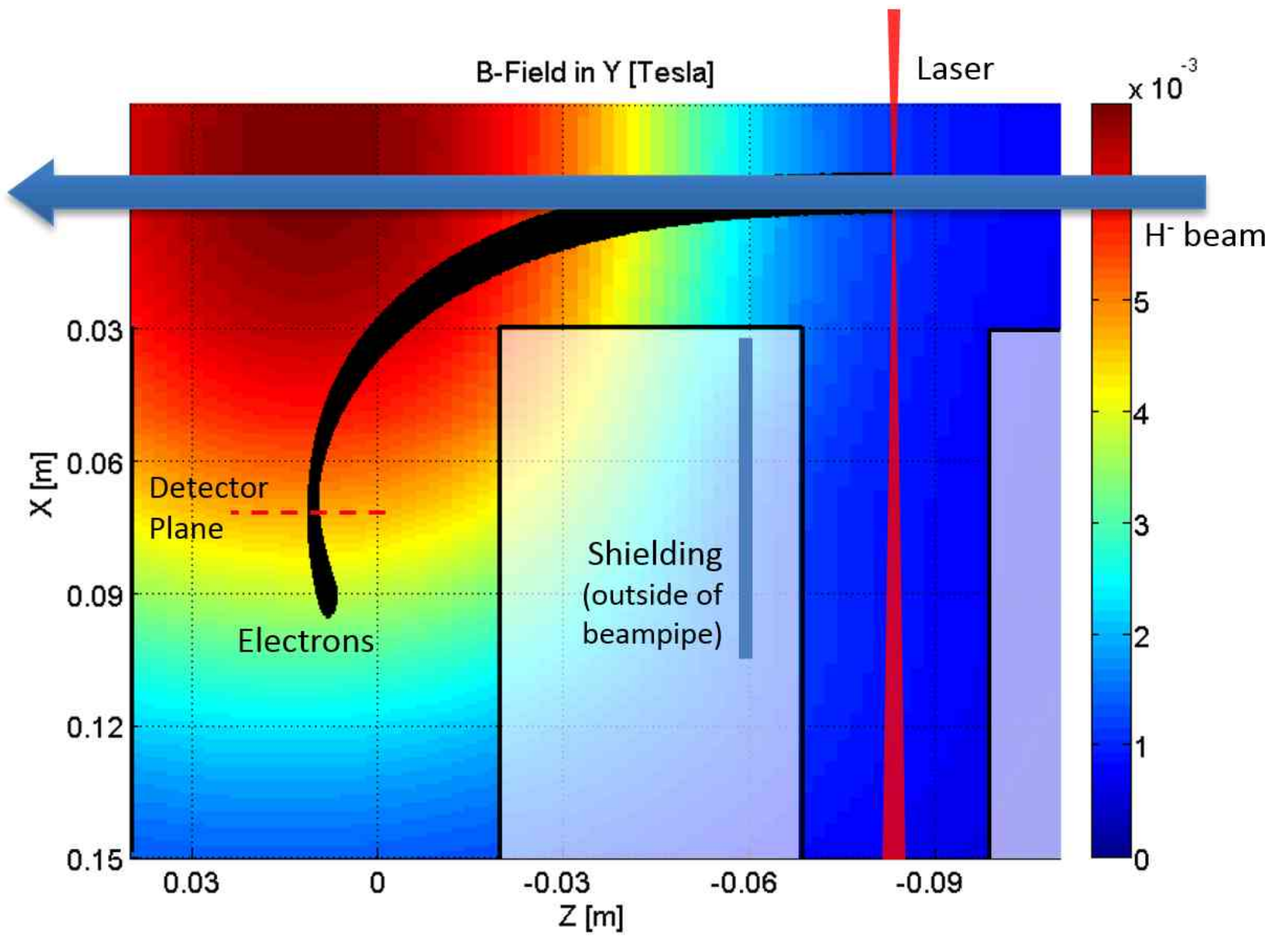


Figure 6: Magnetic field map (in Tesla) and electron trajectories (black) from the laser interaction point to the diamond detector. White areas are outside of beam-pipe.

50 MeV laserwire design

- Small sCVD diamond detector to register electrons. Diamond moves with laser to ensure beam is captured.
    - T. Hofmann et al, *'Design of a laser based profile monitor for Linac4 commissioning at 50 MeV and 100 MeV'*, TUPB005, IBIC 2015. http://ibic.synchrotron.org.au/papers/tupb055.pdf

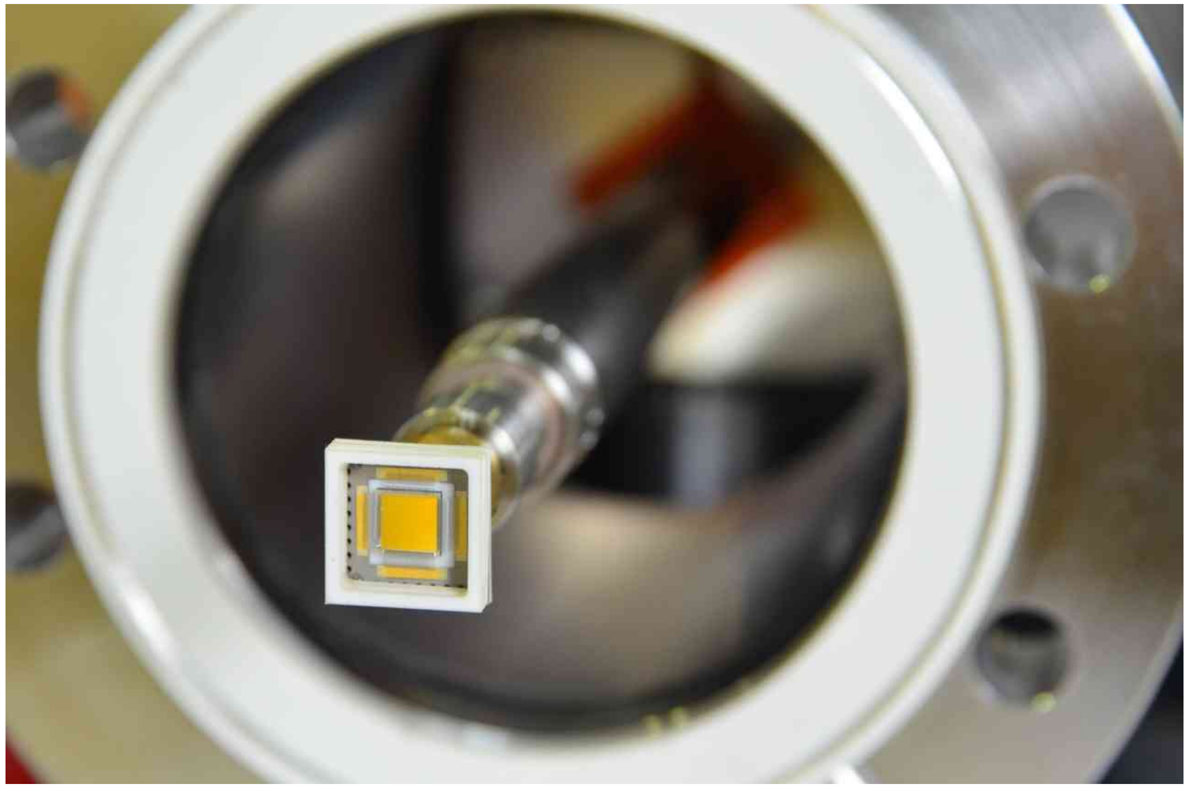


Figure 8: sCVD diamond detector [12] mounted on the actuator that is part of the laser monitor assembly for the 50 MeV experiment.

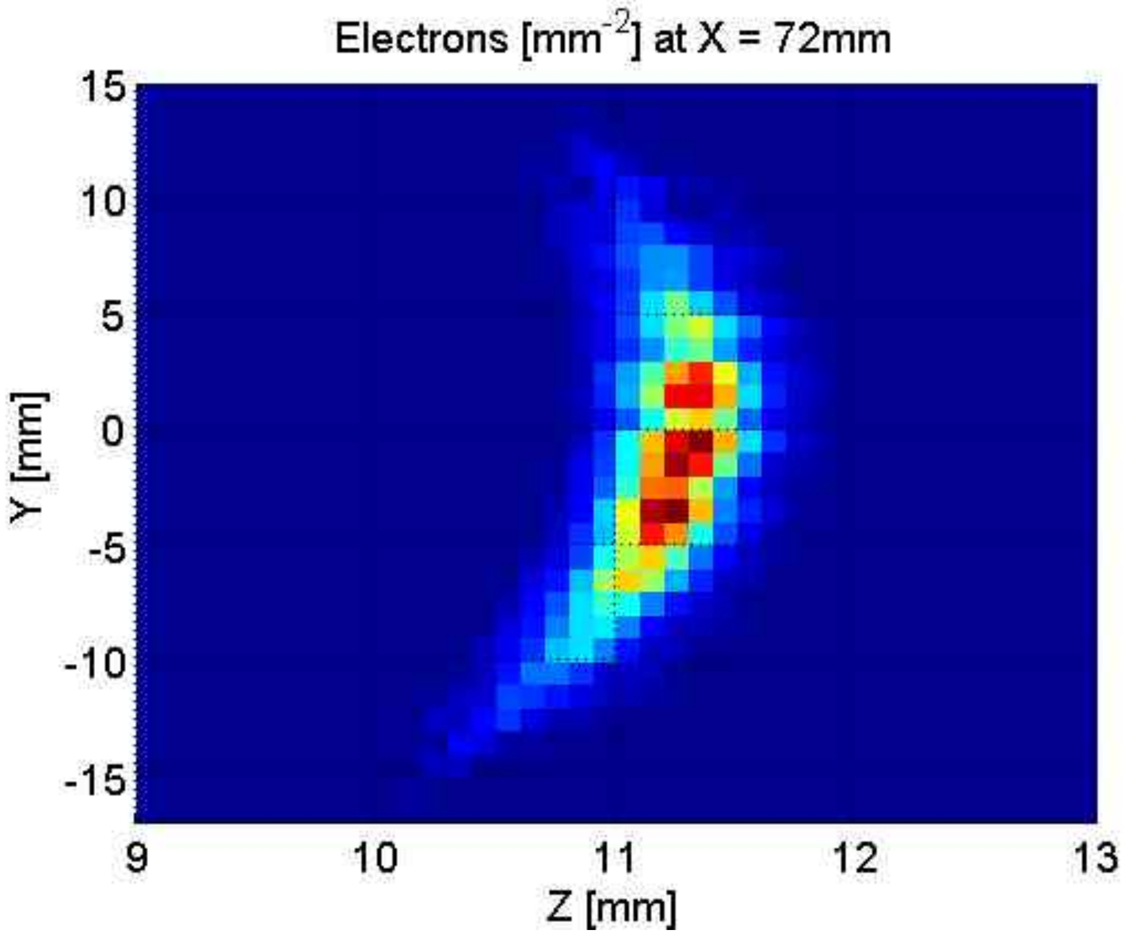
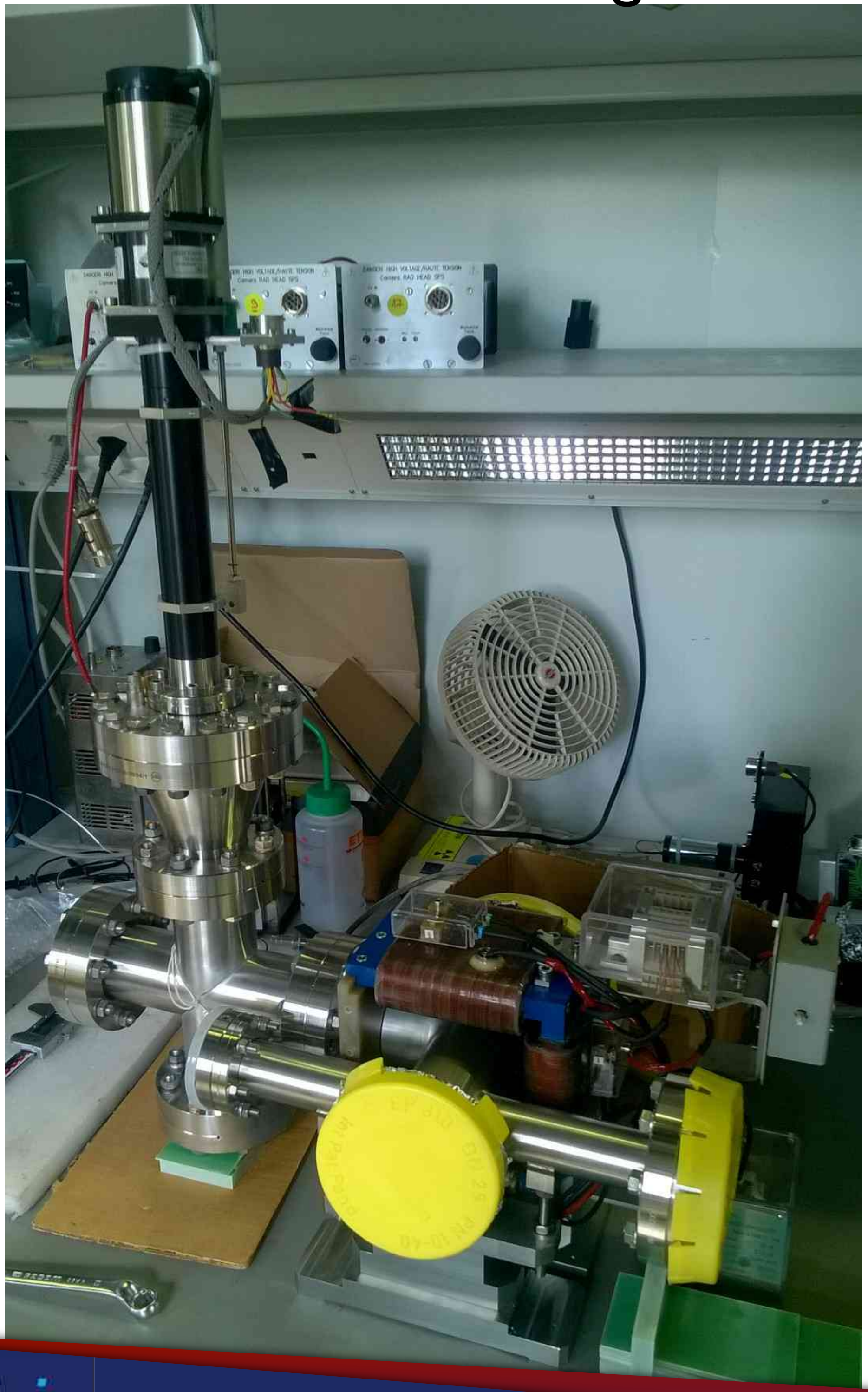


Figure 7: Expected electrons distribution at the detector plane, accounting for all laser positions during a scan.

50 MeV laserwire installed

Diamond mover, and chamber with steerer magnet



Vacuum chamber installation in Linac4

50 MeV laserwire installed

- T. Hofmann et al, *'Design of a laser based profile monitor for Linac4 commissioning at 50 MeV and 100 MeV'*, TUPB005, IBIC 2015. http://ibic.synchrotron.org.au/papers/tupb055.pdf

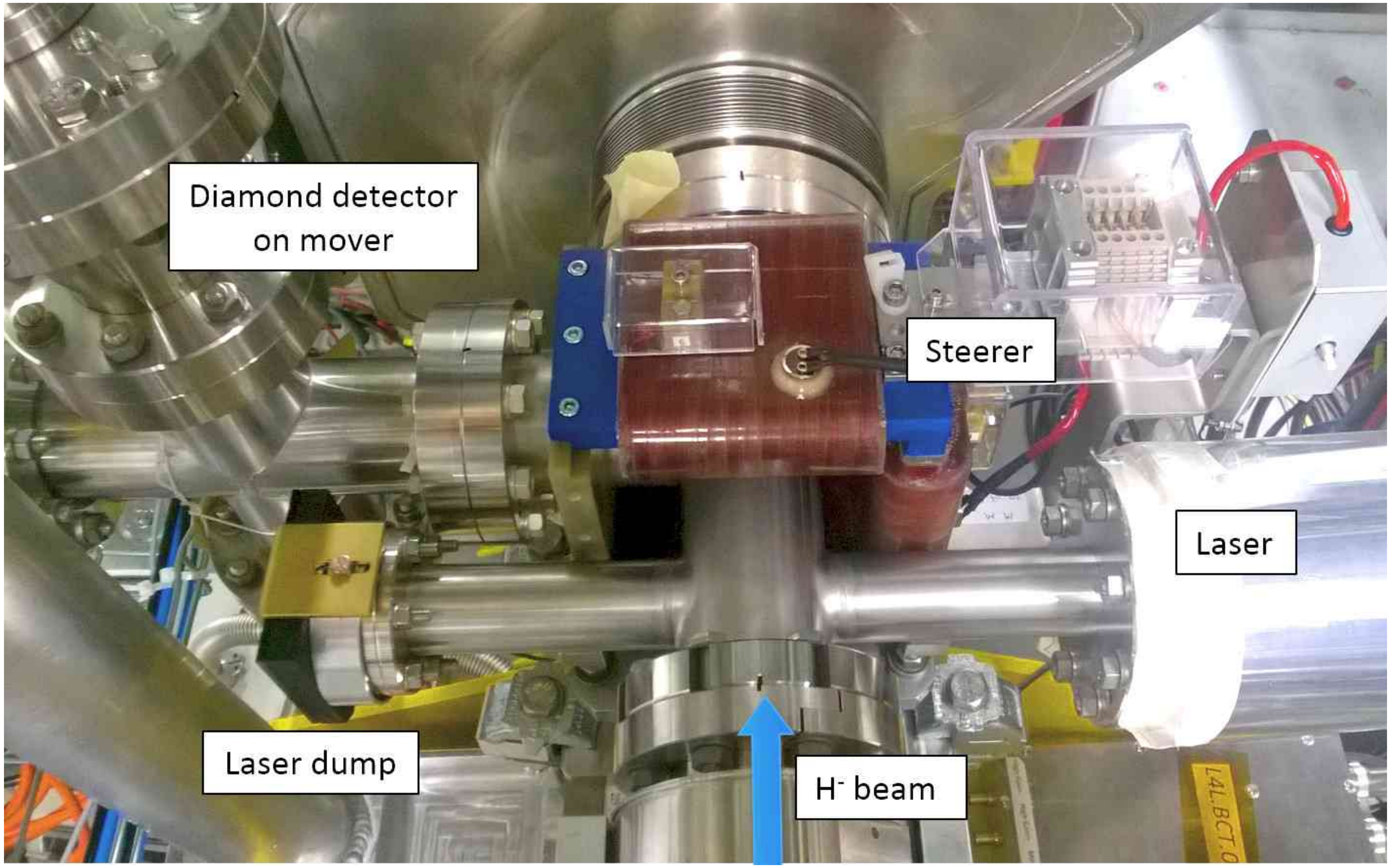
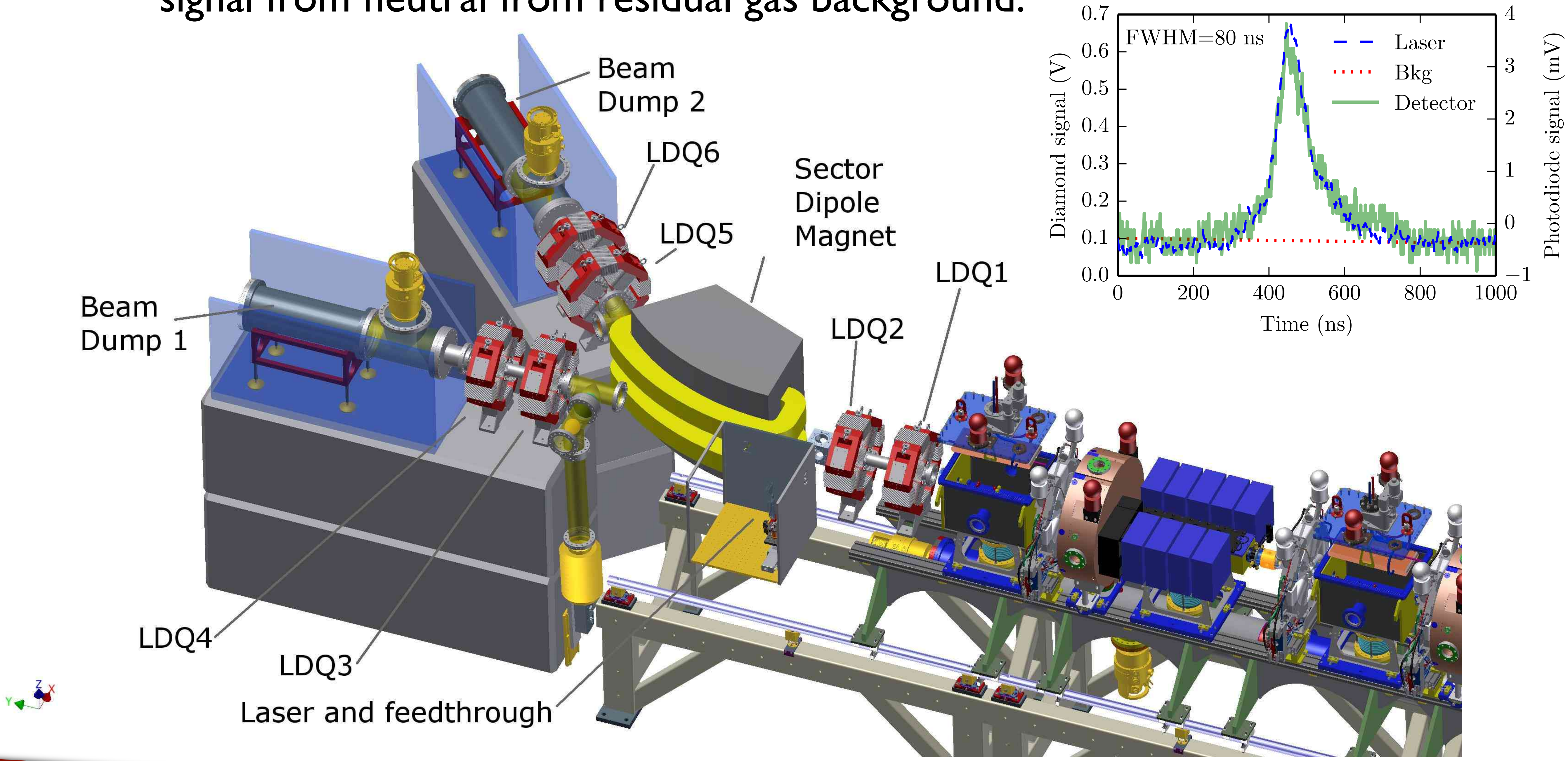


Figure 10: Installed system at the LINAC4 diagnostic test-bench.

First 50 MeV beam at CERN Linac4 this week…

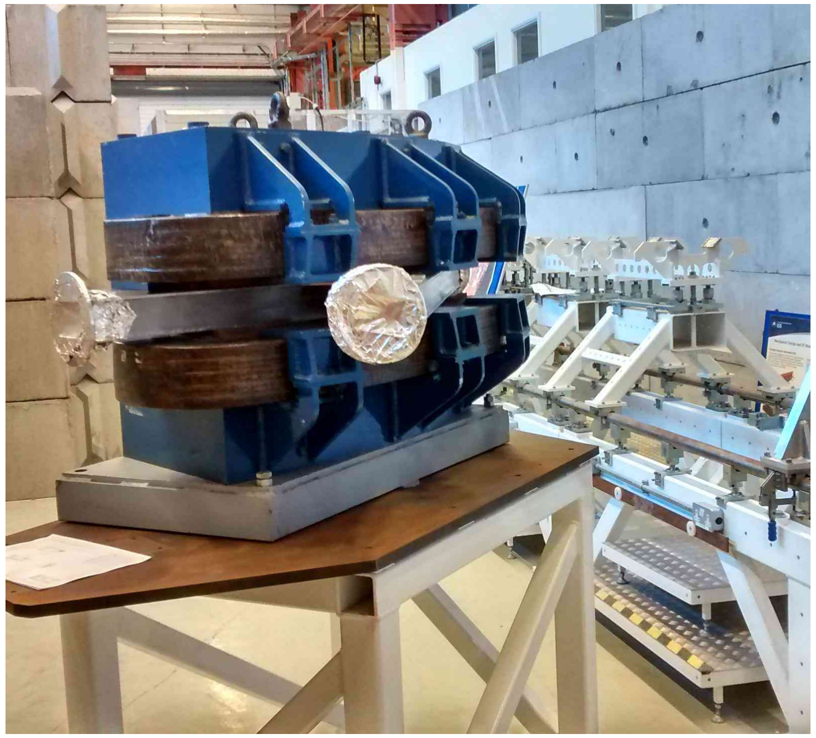
Future FETS diagnostics

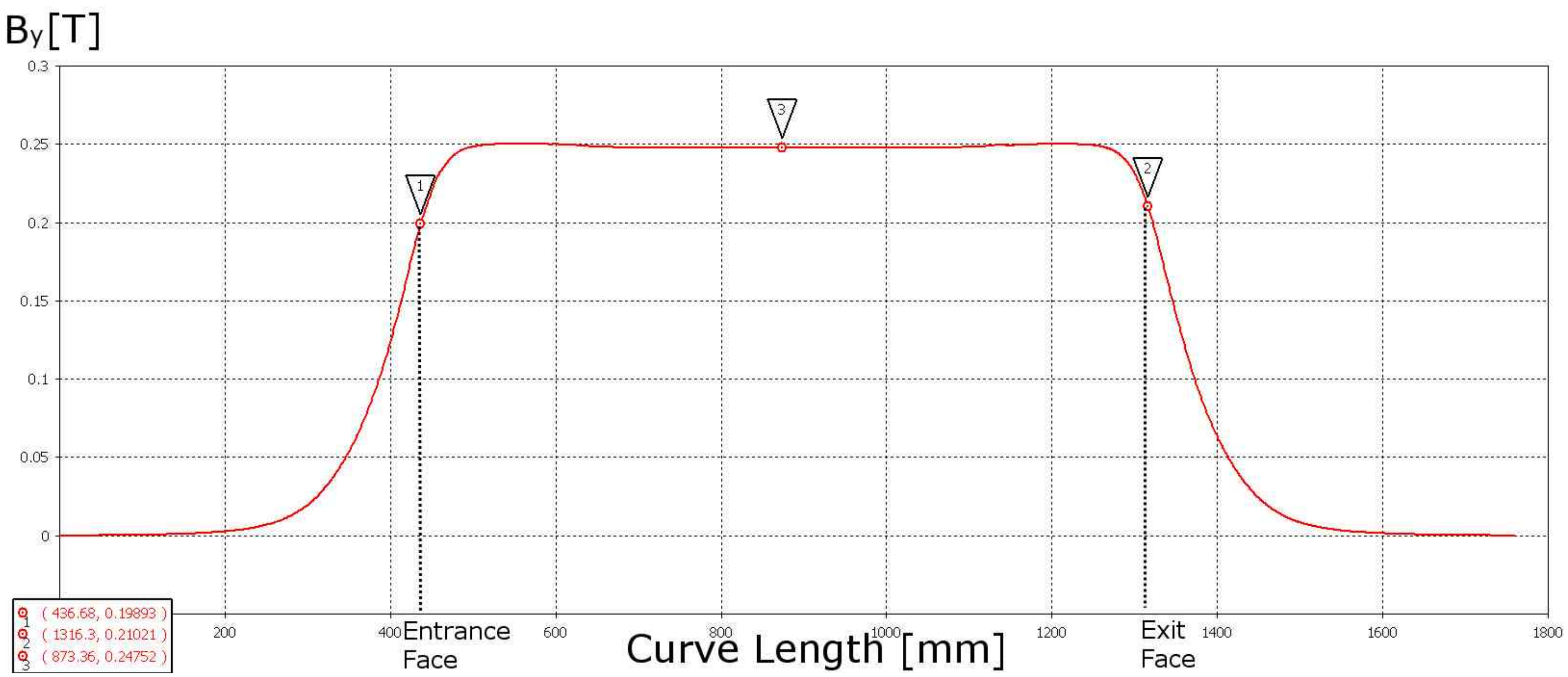
- Experience gained from the tests of the laserwire at CERN Linac4 has allowed us to simply the design at FETS:
  - Bring laser upstream of dipole and rely on fast detector to extract pulse signal from neutral from residual gas background.

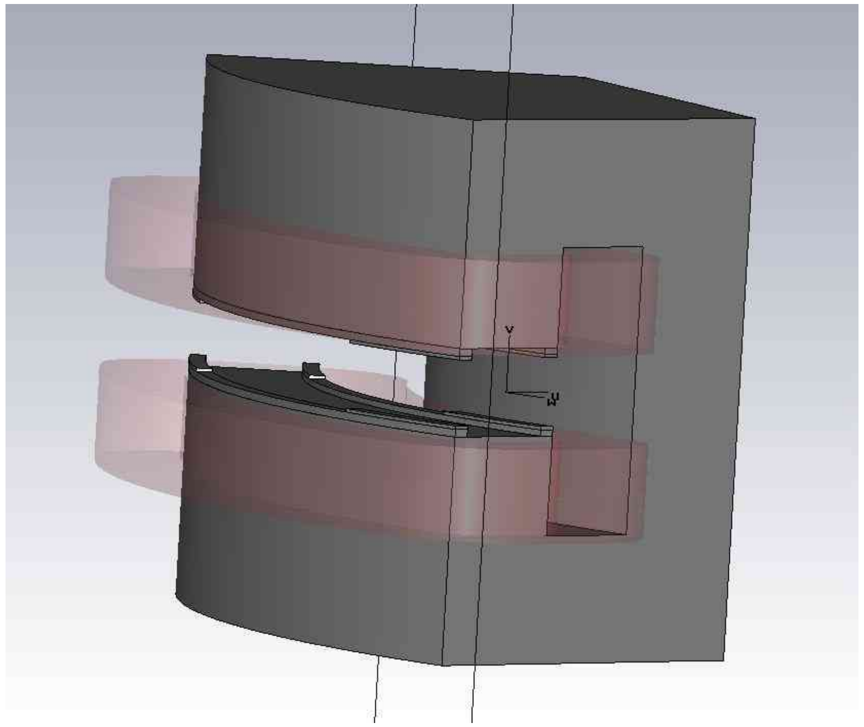


Dipole magnet and field simulation

- Existing dipole magnet checked for suitability:
- 3D field map model created
  - Geometry of yoke and coils.
  - 100A gives 0.2475T in the centre of the magnet.
  - Fringe fields extend to 300 mm beyond faces.



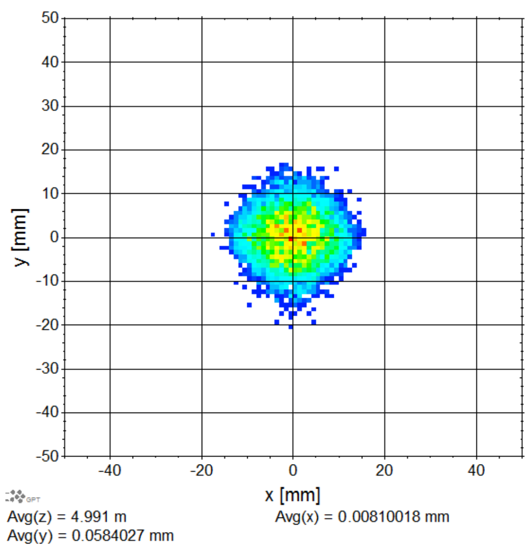




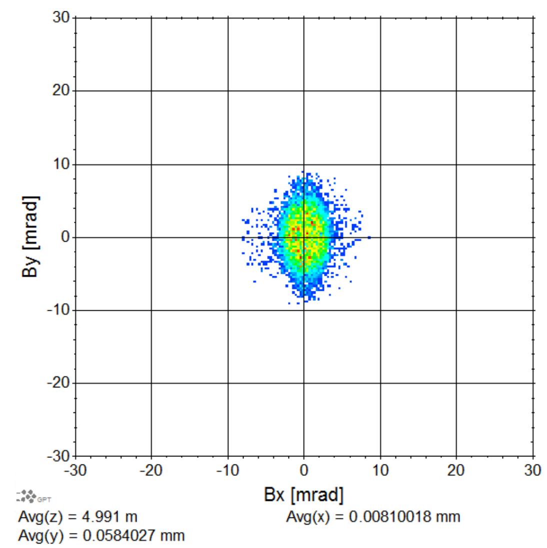
Particle tracking simulations

- GPT simulations of the lattice and laserwire interaction demonstrate the suitability of the dipole.
  - A. Kurup et al, `*Simulation of the FETS diagnostic*', TUPB071, IBIC2015

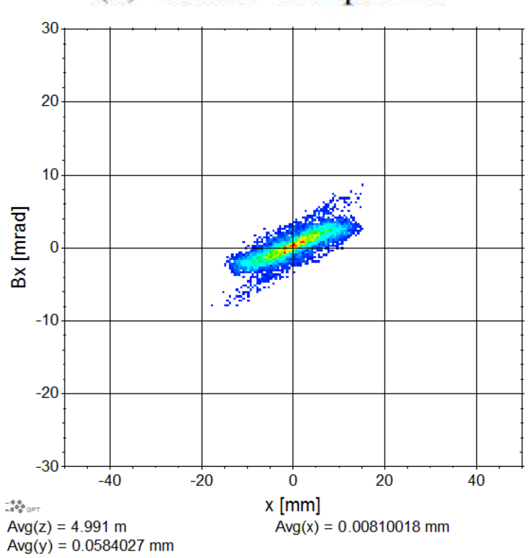
Beam at the laser interaction



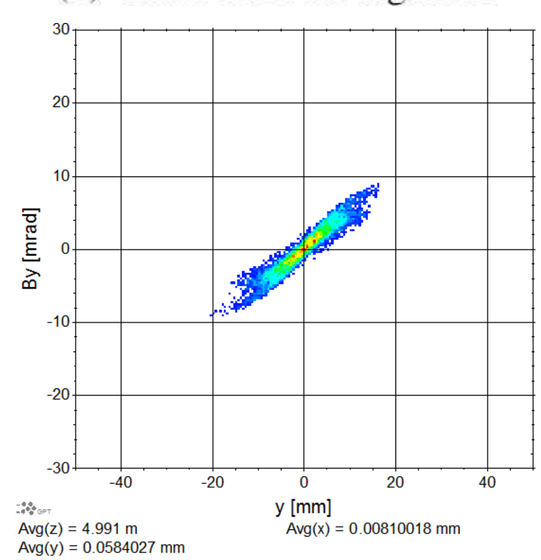
(a) Transverse profile



(b) Transverse divergences

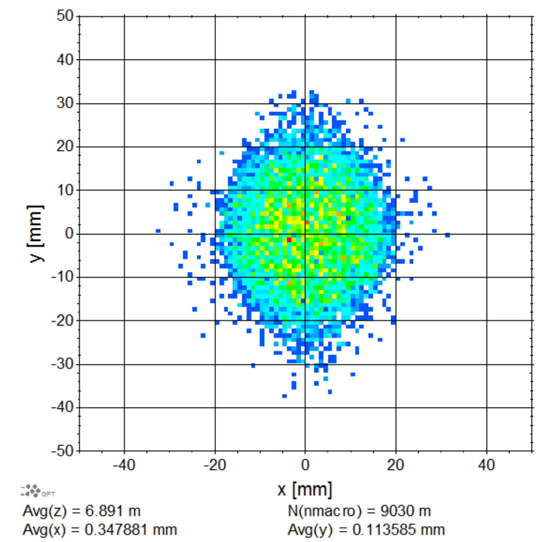


(c) x Emittance

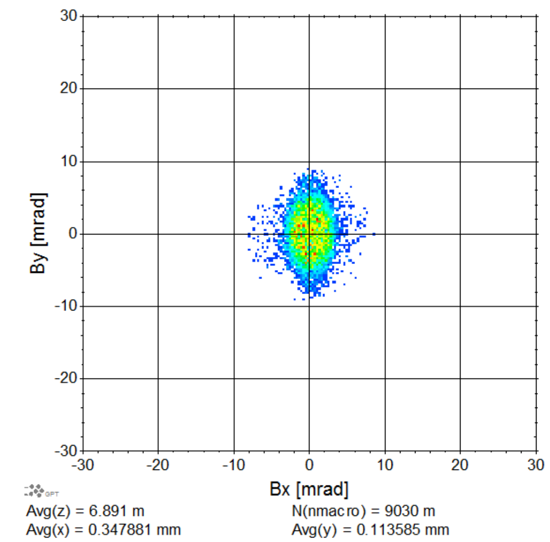


(d) y Emittance

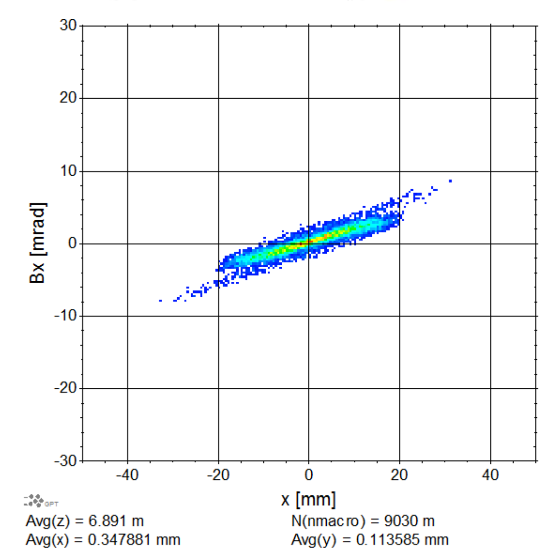
Beam at the detector



(a) Transverse profile



(b) Transverse divergences



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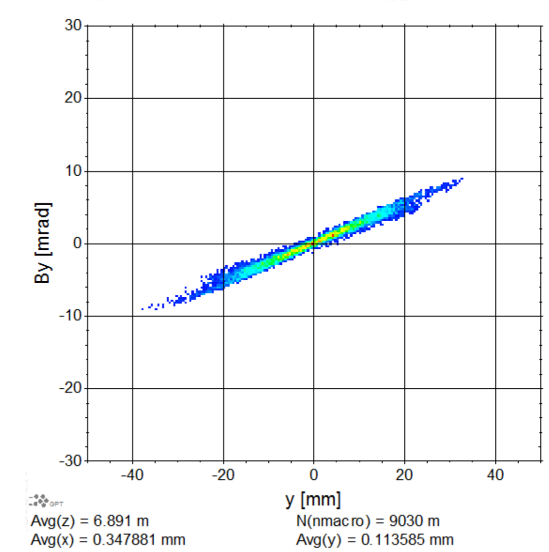


(d) y Emittance

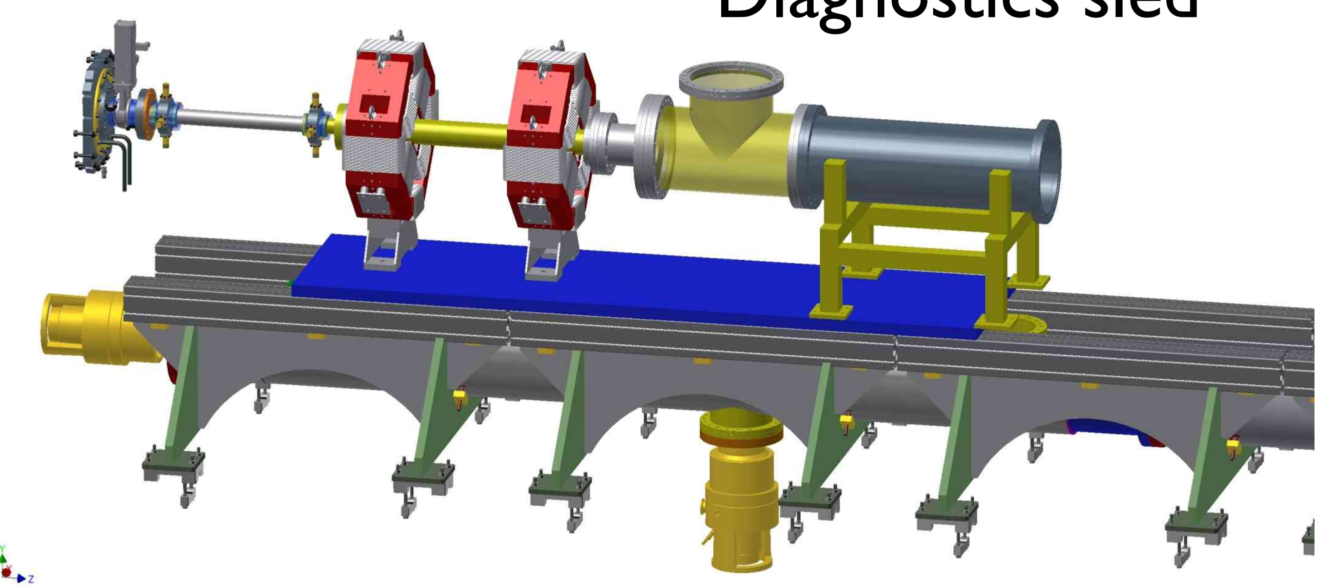
Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

RFQ via BPM to diagnostics sled

Stage I

Diagnostics sled

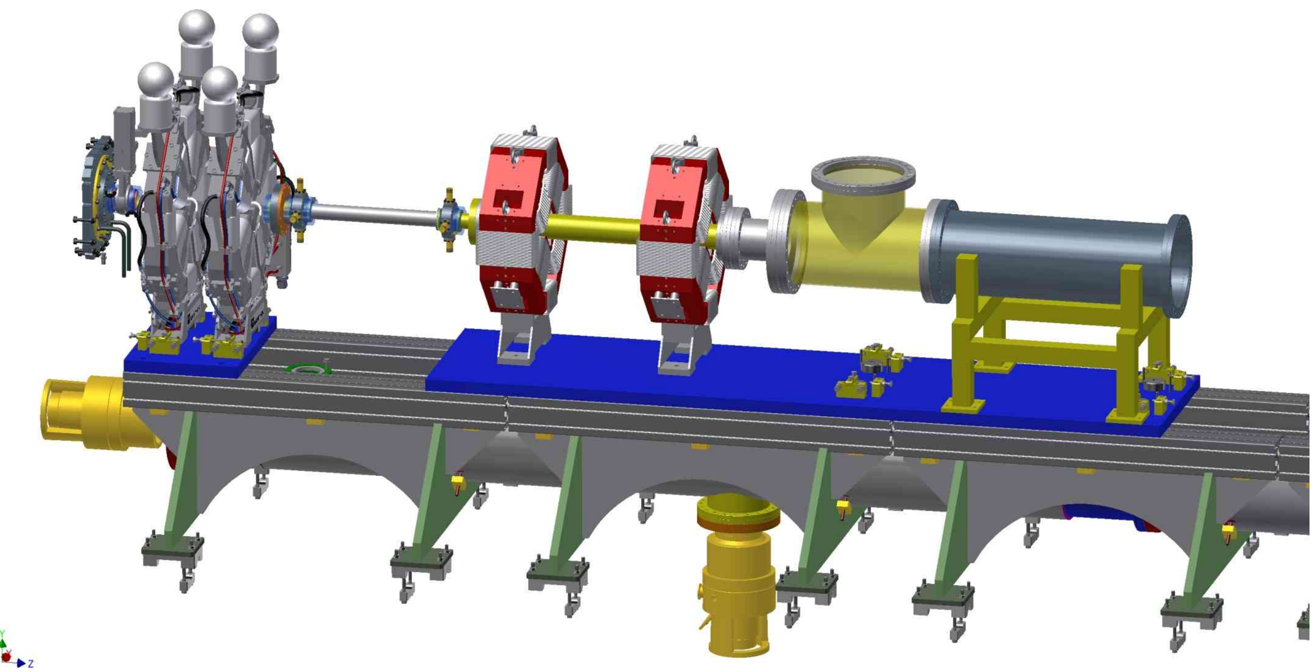


Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

First quadrupole pair and BPM

Stage **2**

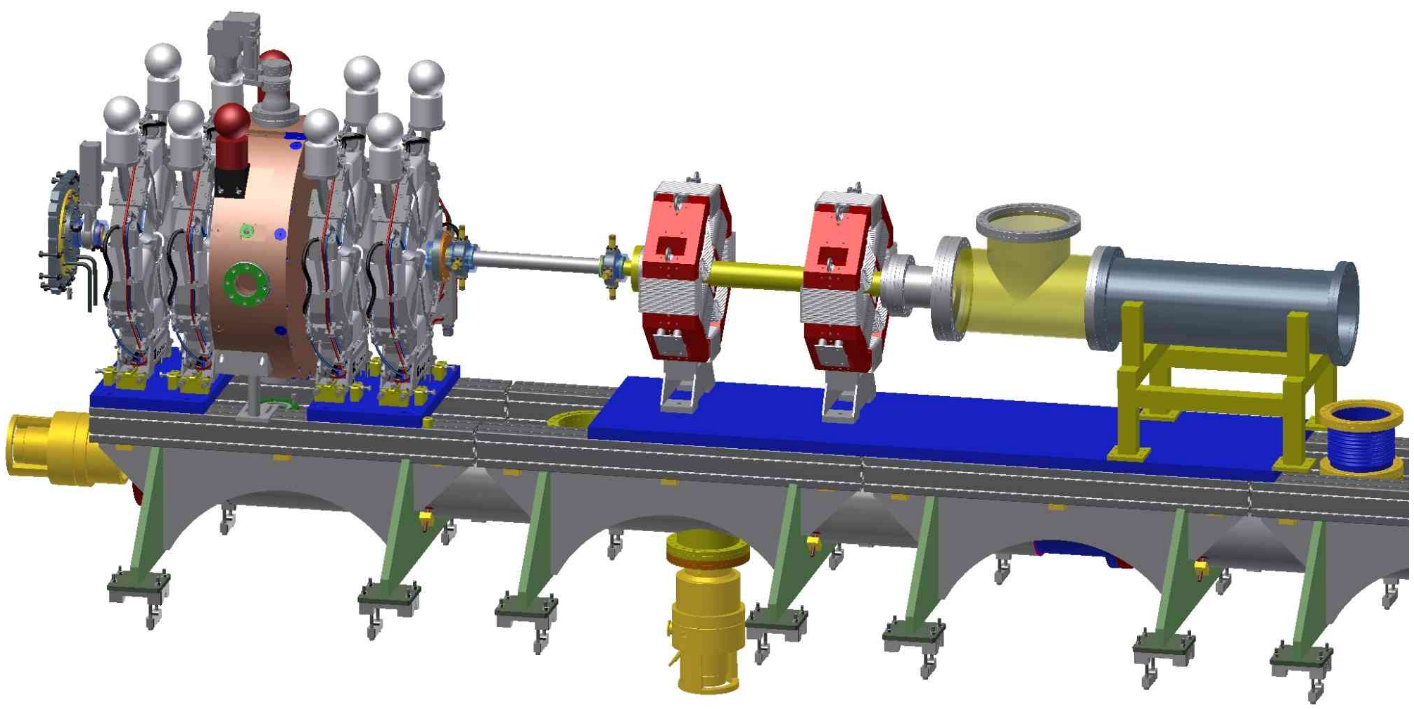


Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

First rebunching cavity, next quadrupole pair, BPM

Stage **3**

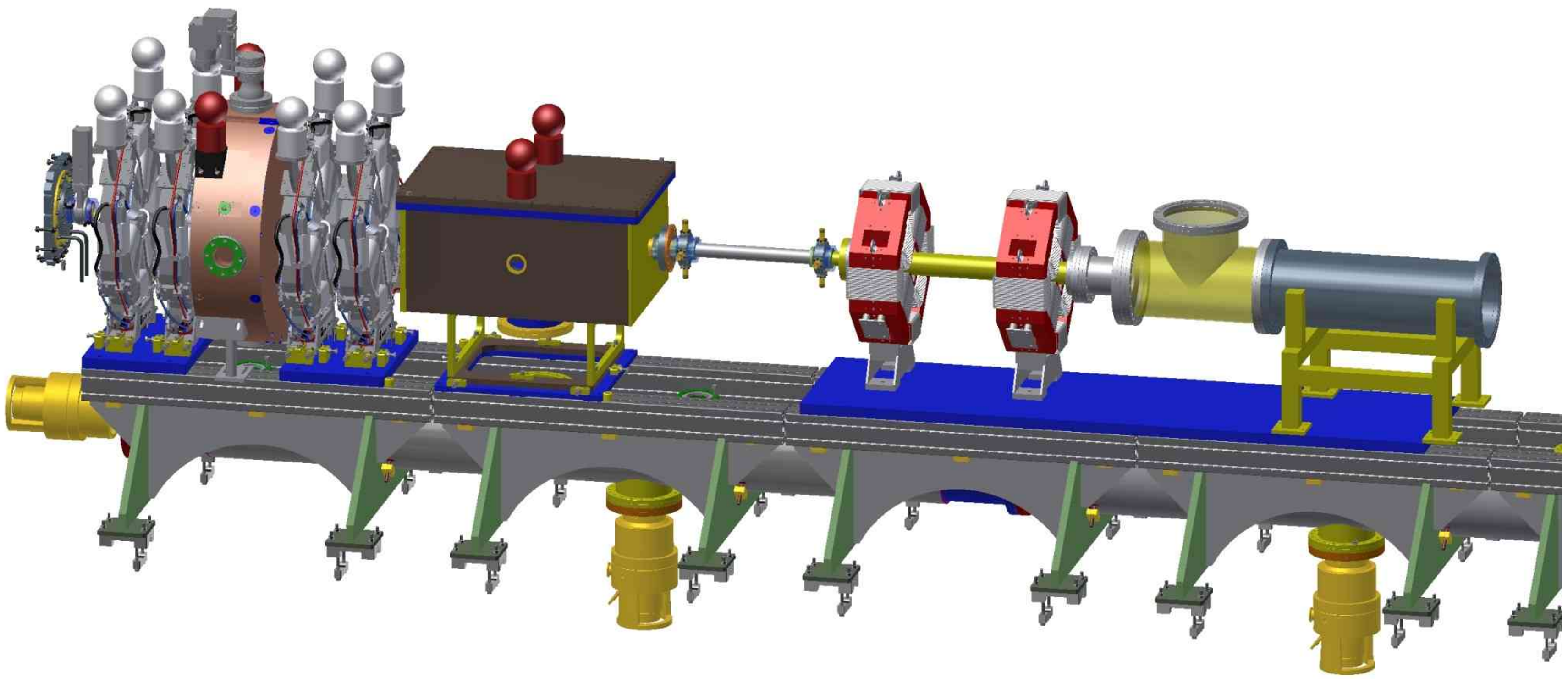


Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

Chopper 1 chamber

Stage **4**

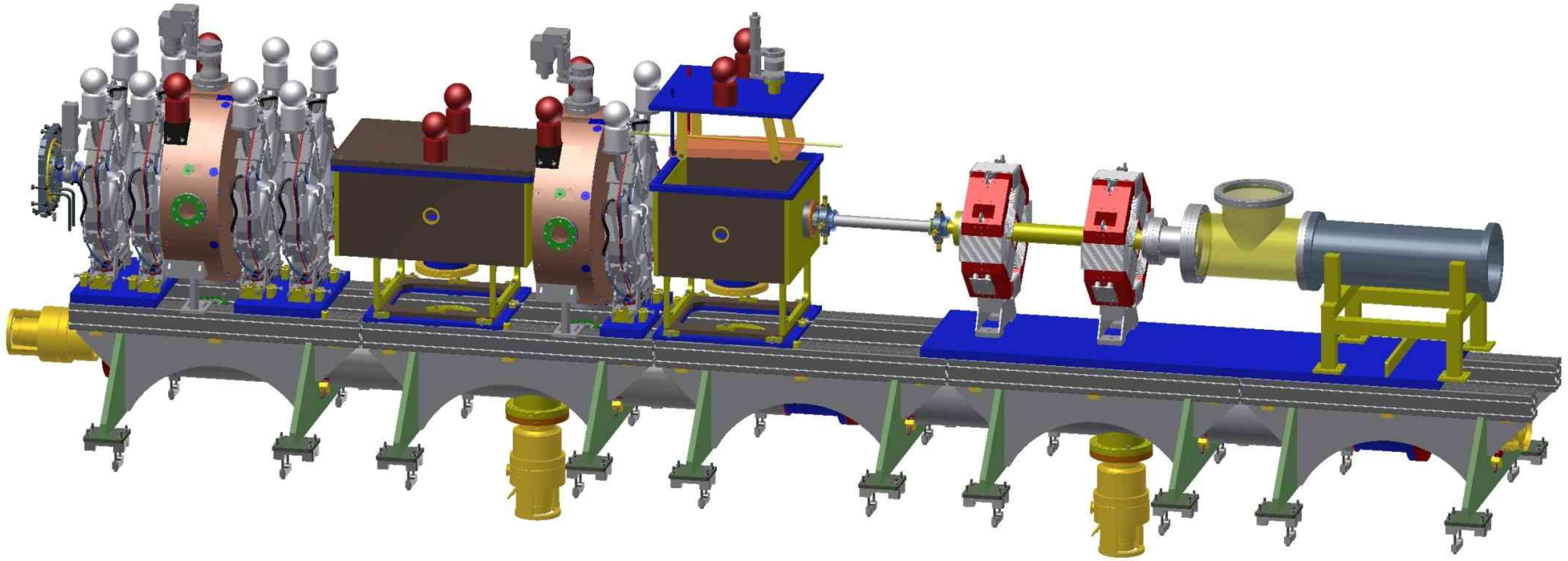


Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

Rebuncher 2, quad, BPM, chopper 1 beam dump and toroid

Stage **5**

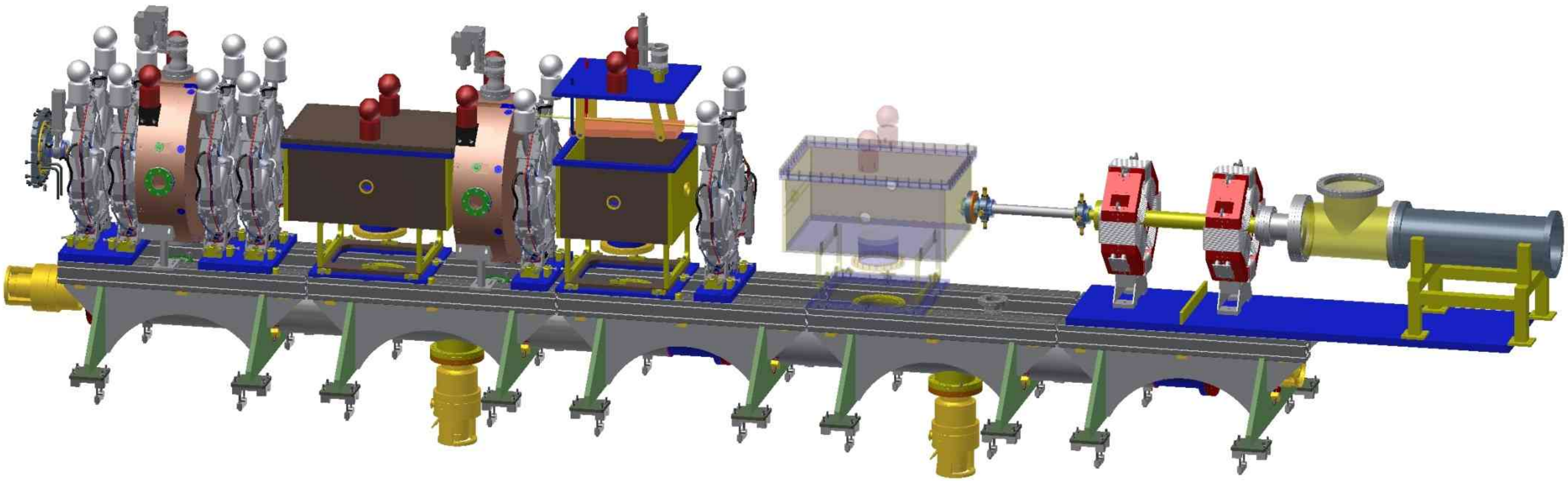


Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

Quadrupole, button+stripline BPMs and chopper 2 chamber

Stage **6**

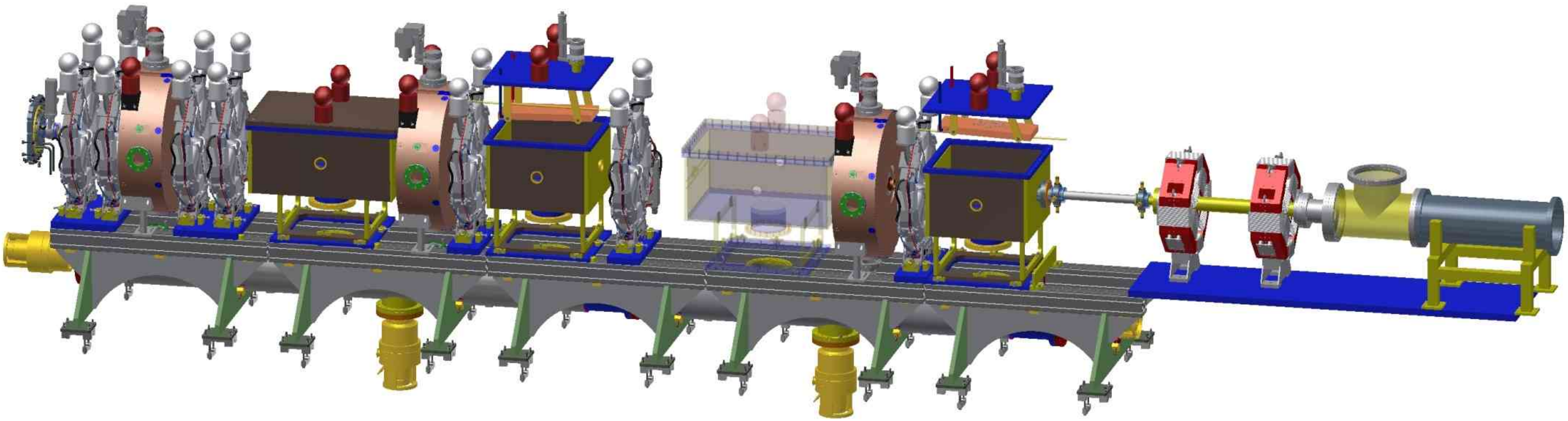


Sliding Laser Emittance Diagnostic

- Installation of the MEBT will proceed in steps.
- Plan to use sliding diagnostics to measure the beam profile, using laserwire and either a Faraday cup or diamond detector.

Rebuncher 3, BPM, quad, chopper 2 beam dump and toroid

Stage **7**



Summary

- FETS diagnostic developments are well advanced. Tests of the beam position monitors demonstrate excellent resolution in a wire-rig system.
- The H- fibre coupled laserwire for FETS has been successfully demonstrated in collaboration with CERN at Linac4:
  - Laser emittance scanner matches slid-grid measurements at 3 MeV and 12 MeV.
  - Profile laserwire system developed and installed for 50 MeV and 100 MeV.
- Revised plans of FETS laserwire diagnostics presented based on existing dipole magnet with suitable parameters, validated by particle tracking simulation.
- Sliding diagnostics planned for MEBT installation.

Thank you – questions?