Progress towards measuring emittance with the AWAKE spectrometer

AWAKE Collaboration Meeting

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Talk overview

- Requirements of the spectrometer
- Run 1 design and results
- Upgrade for Run 2
- November 2022
- Current status: Emittance measurements
- Current status: Resolution measurements

Requirements of the spectrometer

Run 1:

Separate electrons from proton driving beam

Introduce a transverse, energy-dependent spatial distribution to accelerated electrons

Measure intensity of spatially distributed electrons

Prevent significant beam loss of accelerated electrons prior to measurement

Provide a sufficient dynamic range of measurable electron energies

Measure, with sufficient resolution, the energy profile of electron bunch

Goals for run 2

Run 2a

Offer sufficient resolution such that the size and shape of the beam can be analysed

Run 2b:

Verify predictions from simulation

Serves as a ‘test bed’ for prospective run 2c technology

- Aim to achieve the resolution needed for smaller beams

Run 2c:

Verify predictions from simulation

Opportunity for magnet upgrades

- Clearing CNGS requires magnet removal
- Increase focusing power of quadrupoles
- Substantially increased upper limit on measurable energy range on the screen

Run 1 spectrometer design

Quadruple doublet followed by C-shaped dipole.

Vacuum chamber with scintillator screen mounted to the chamber window.

One camera, imaging entire scintillator screen.

Camera positioned in a dark room ~17m from the screen, after a series of 3 mirrors

Information available to us: electron beam energy, spread and bunch charge.

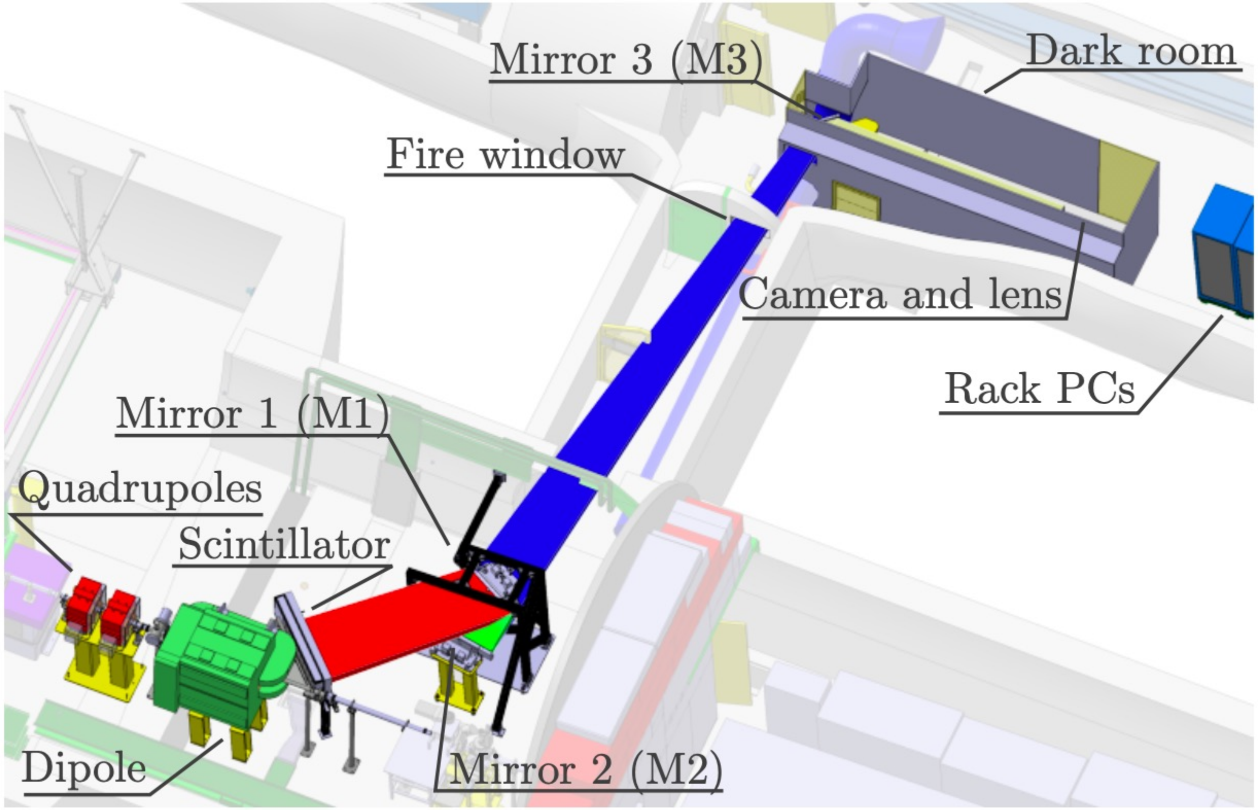


Image source: F. Keeble Doctoral thesis

Run 1 spectrometer design

Magnets

Quadrupoles

- Focus beam horizontally then vertically
- 6% shunt between them → same focal point

Dipole

- Separate accelerated electrons from SPS proton beam
- $\mathbf{B}_{\mathrm{max}}$ = 1.5T

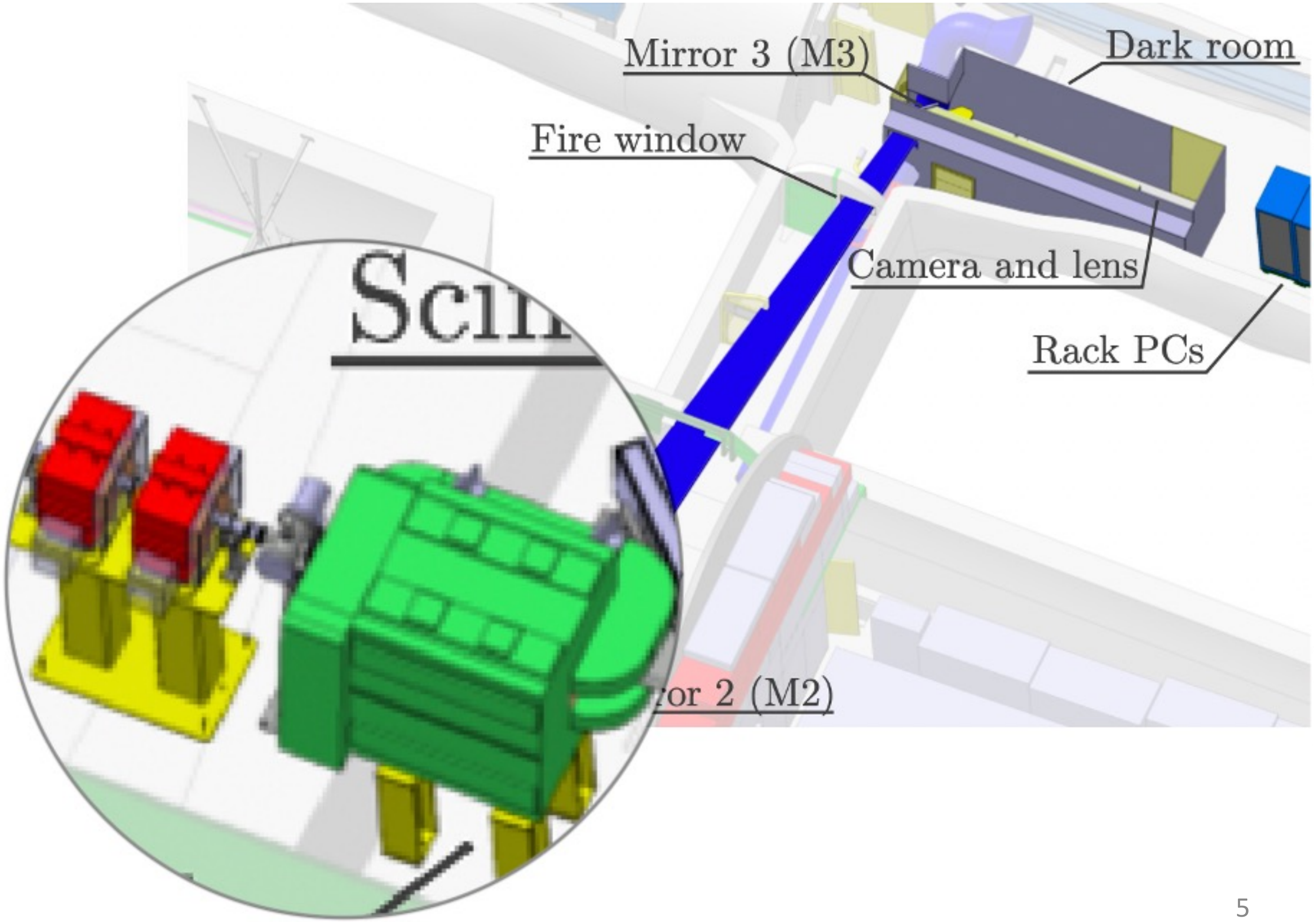


Image source: F. Keeble Doctoral thesis

Run 1 spectrometer design

Screen

Vacuum chamber

- Within dipole → reduce losses during deflection
- Chamber terminates with 2mm thick Al window

Scintillator

- Terbium doped Gadox
- 507um thick
- DRZ-High → prioritises brightness over resolution

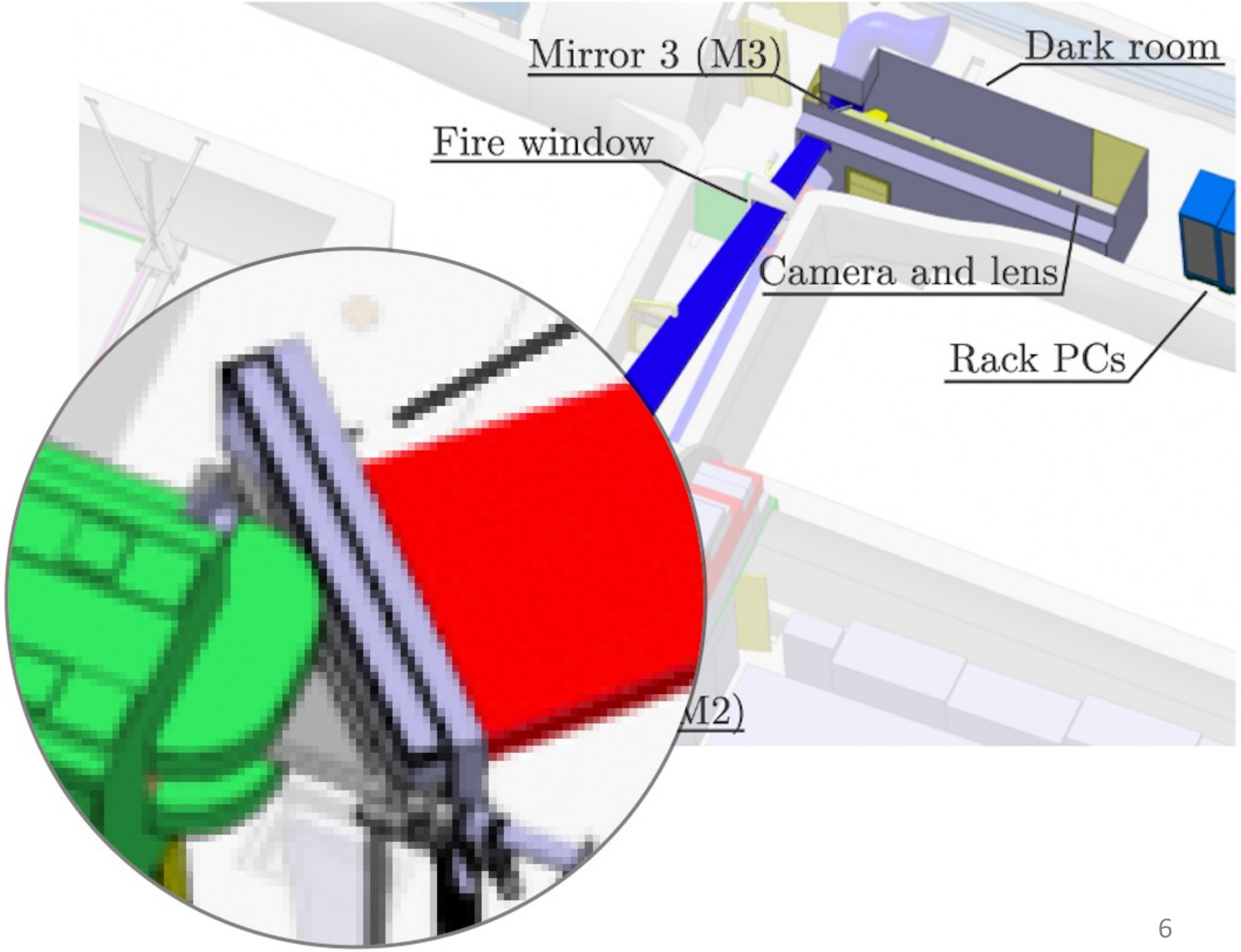


Image source: F. Keeble Doctoral thesis

Run 1 spectrometer design

Camera

- Andor iStar 340T
- Intensified, 16-bit, 2048 × 512 pixel CCD
- Cooled -30 Celsius
- Long focal length lens: 400mm
- Large field of view → images entire screen
- Filter to reduce ambient light
- Located in TSG4 tunnel for radiation shielding

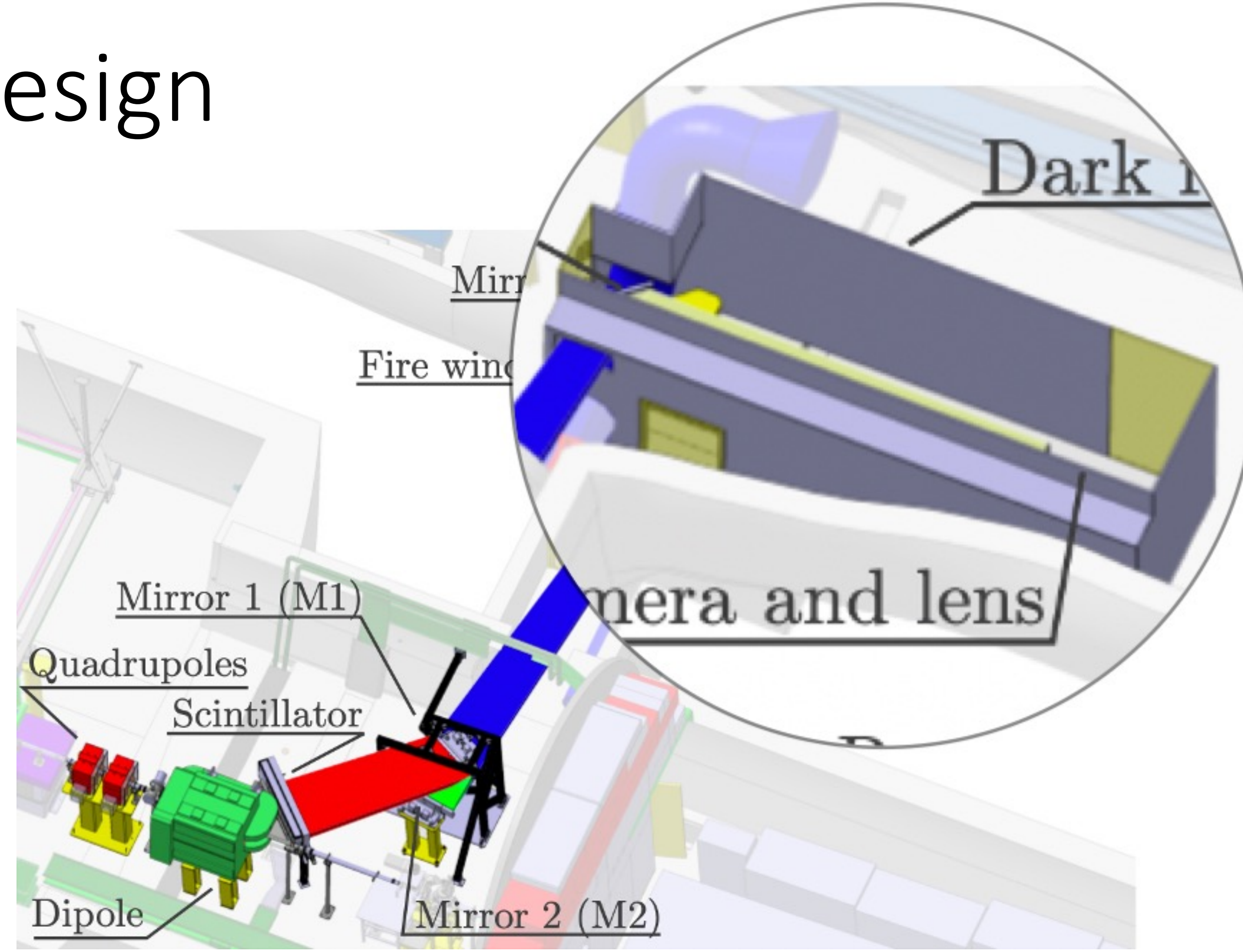


Image source: F. Keeble Doctoral thesis

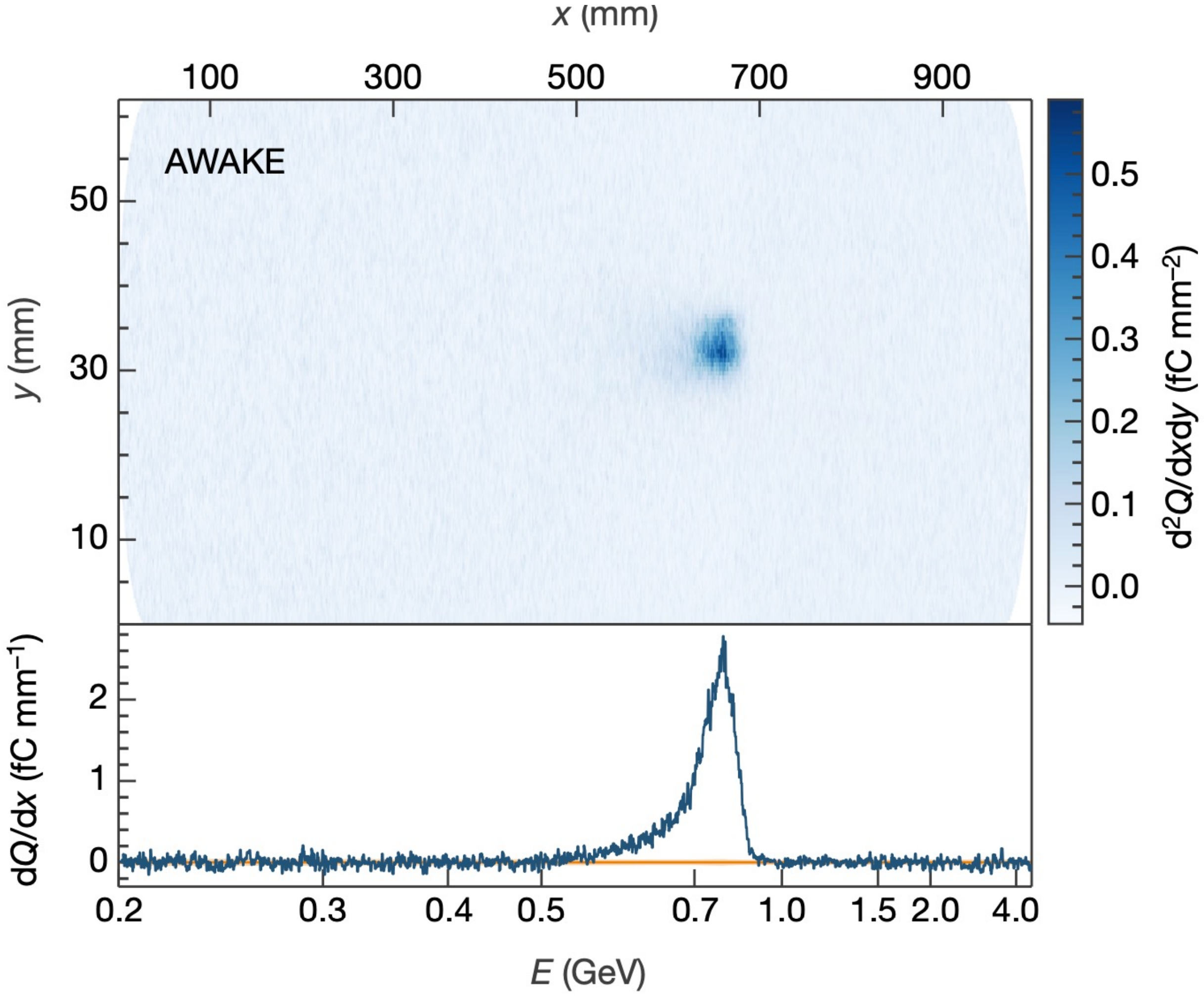
Results with run 1 spectrometer

Energy profile offers:

Energy gain determined from horizontal distance on the screen

Charge capture from area under curve

Spread from FWHM of peak



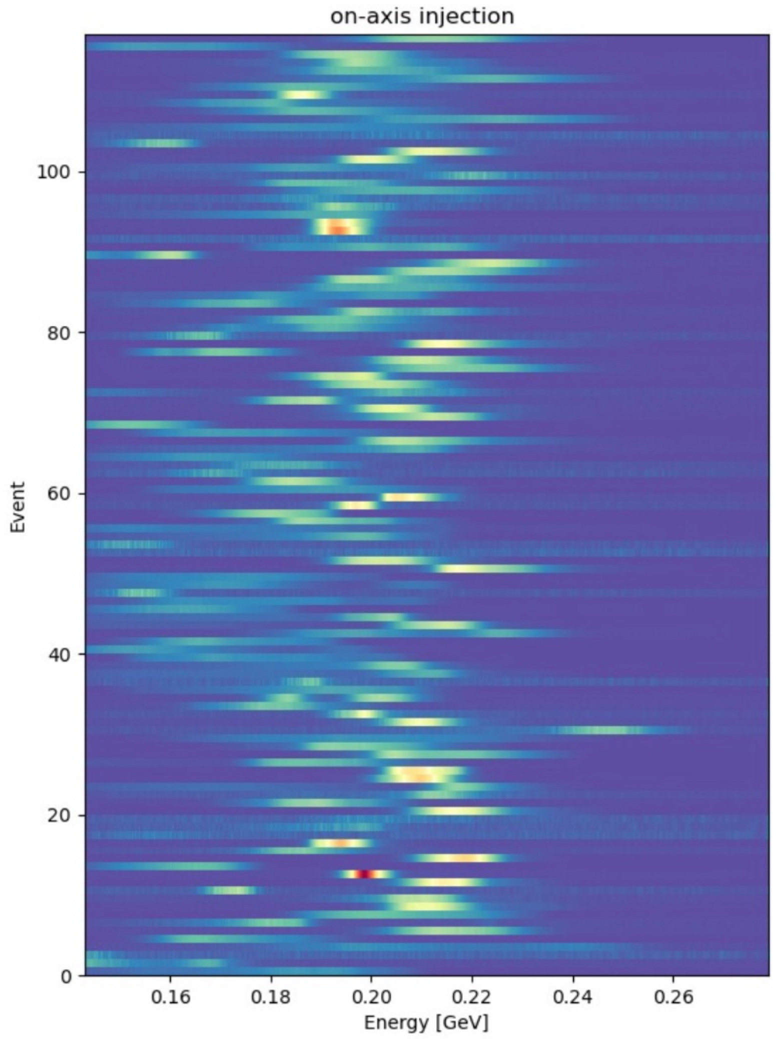
: AWAKE Collaboration 2018. Acceleration of electrons in the plasma wakefield of a proton bunch. Nature, 561(7723), pp.363-367.

Run 2a/b spectrometer upgrade

- Resolving shape of accelerated bunch requires increased resolution
- Four cameras (Basler acA1920-40gm) with reduced FoV → Each imaging a portion of the screen
- Simplified transport → direct imaging of the screen
- Cameras angled below the horizontal to reduce impact of radiation.

Image supplied by Eugenio Senes

November 2022 run

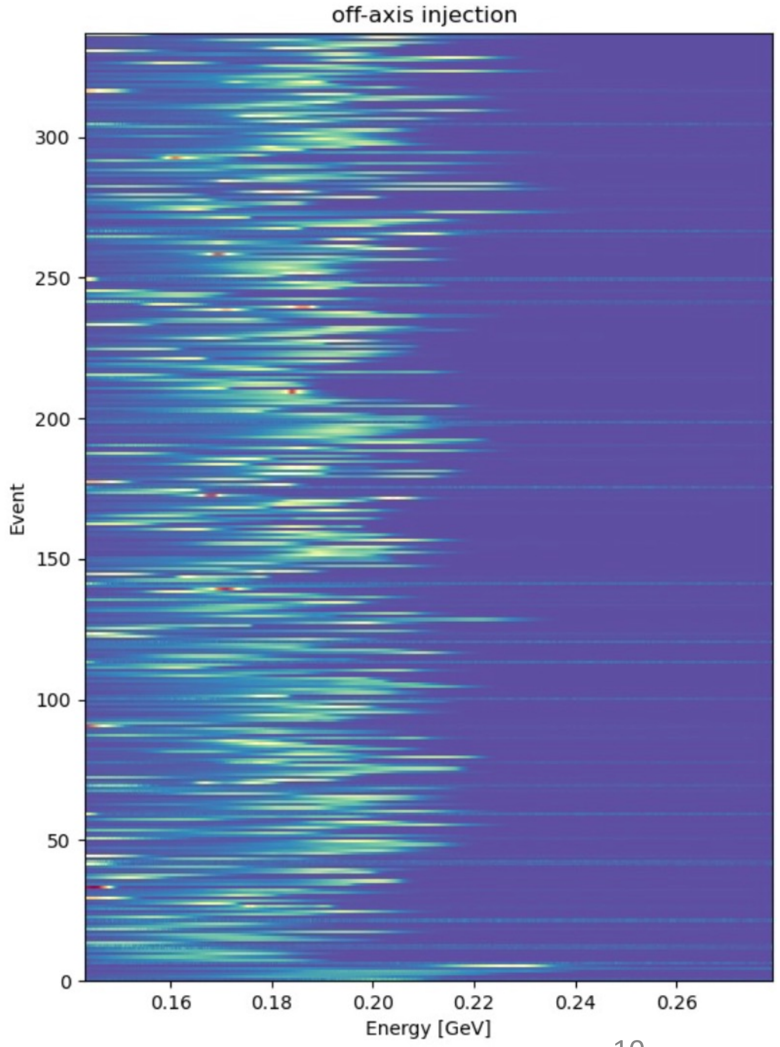


140 on-axis events

106 with charge capture

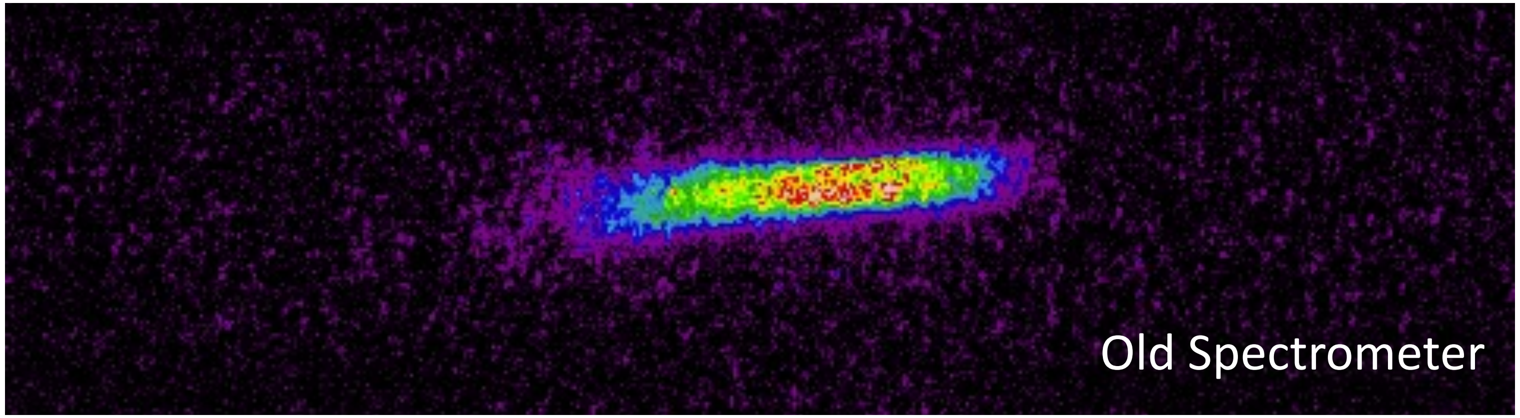
457 off-axis events

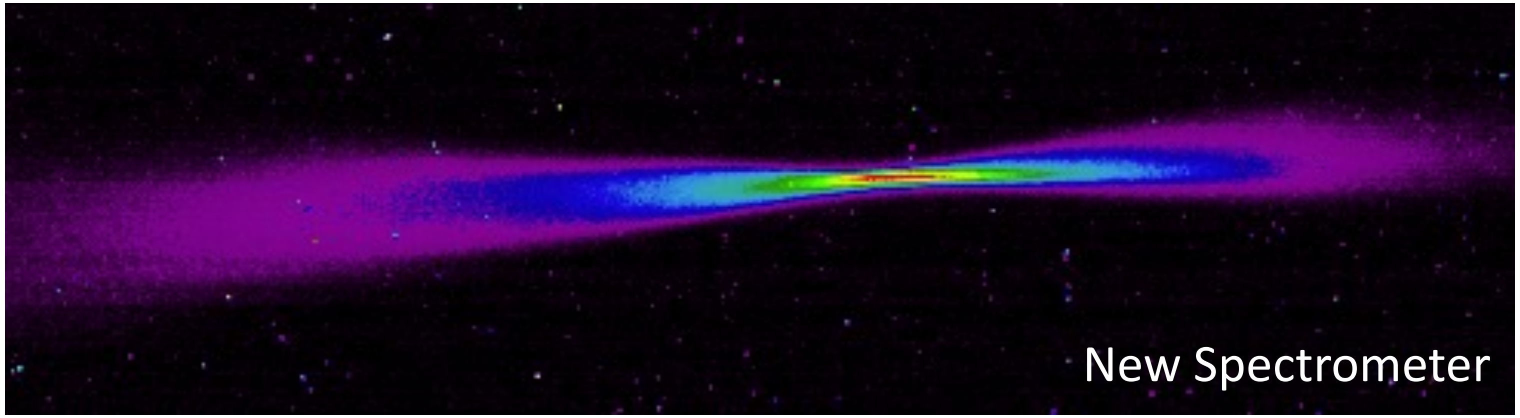
349 with charge capture



November 2022 run

- Cameras moved closer together and nearer the screen to maximize resolution
- Able to identify previously hidden features of the beam spot
- Step towards resolving the waist of the accelerated beam
- Waist size essential indicator in emittance analysis



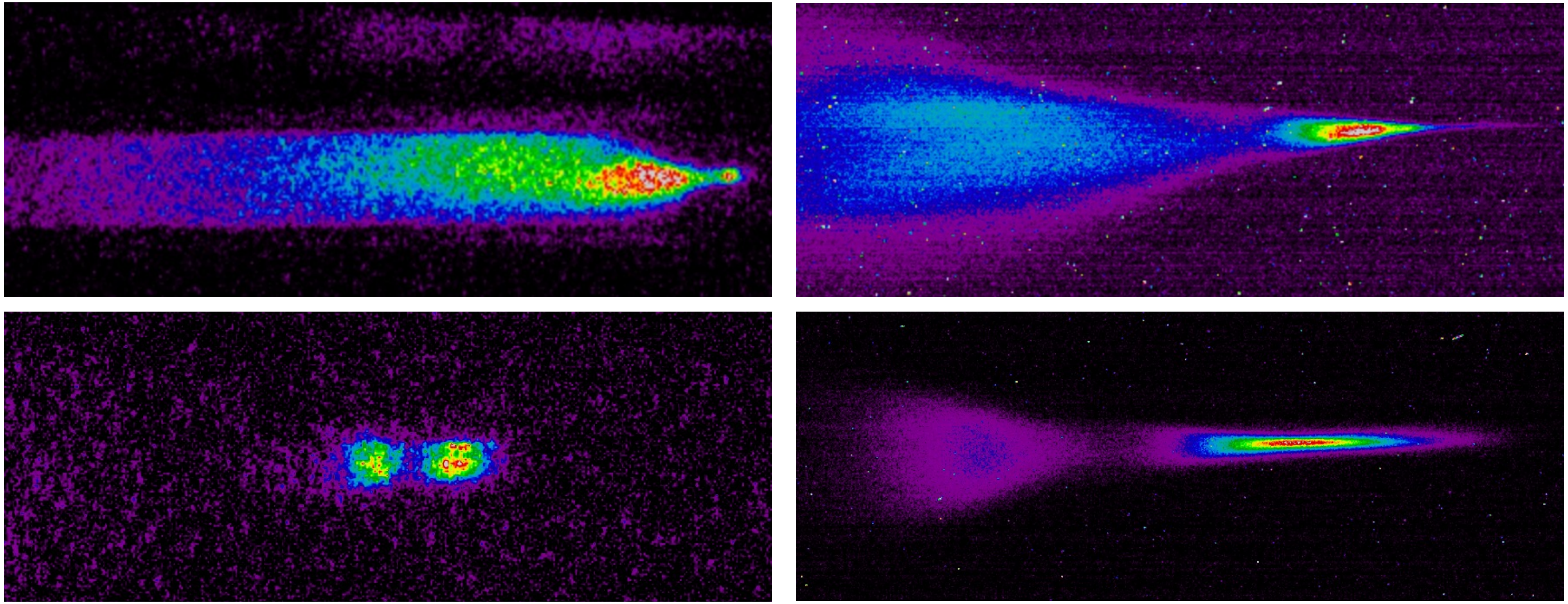


Energy gain →

November 2022 run

Not every event is suitable for emittance analysis → important to identify these and discard

Old Spectrometer | New Spectrometer



Energy gain →

Progress towards emittance

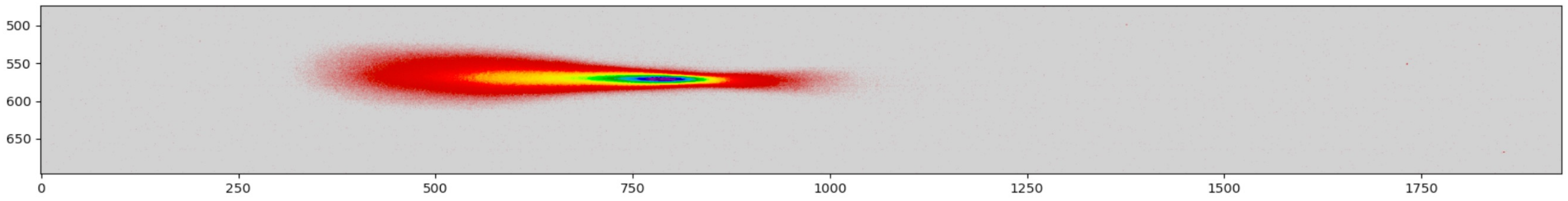
Emittance methods currently being investigated

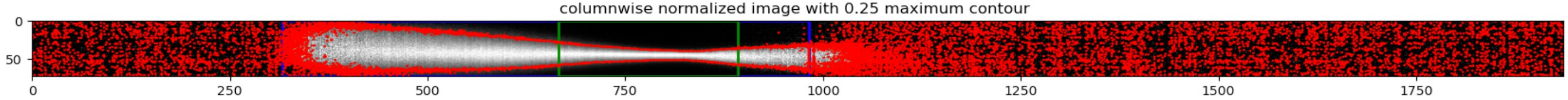
- Quad scan (multi-shot method)
- Butterfly (single-shot method)
- Phase space tomography reconstruction (single-shot method)

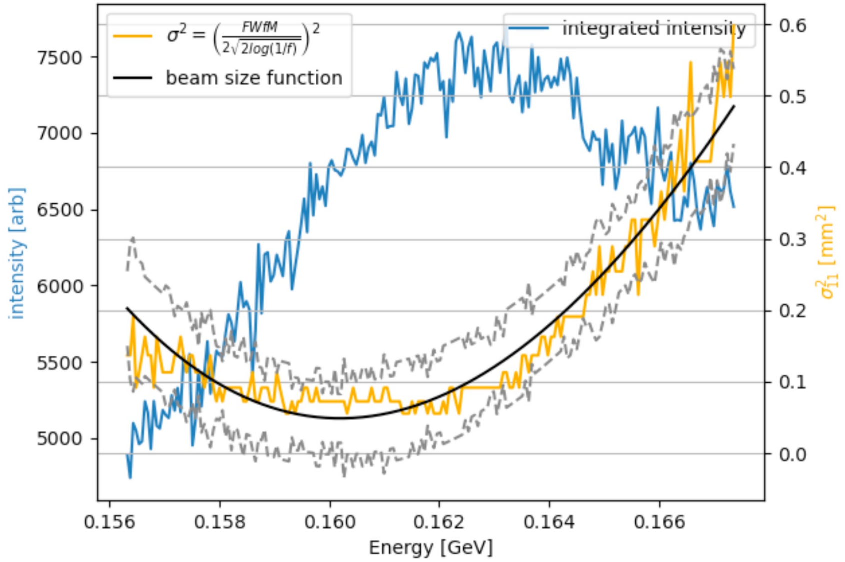
Resolution directly impacts emittance

- What is the minimum emittance we can measure with this setup?
- What could be limiting our resolution?

Progress towards emittance: Single shot







Assumes emittance for each energy slice is equivalent

Beam is dispersed horizontally by energy, so quad strength is different at each horizontal position

Fit beam parameters before quads to this curve (just like a regular quad scan, but with more points)

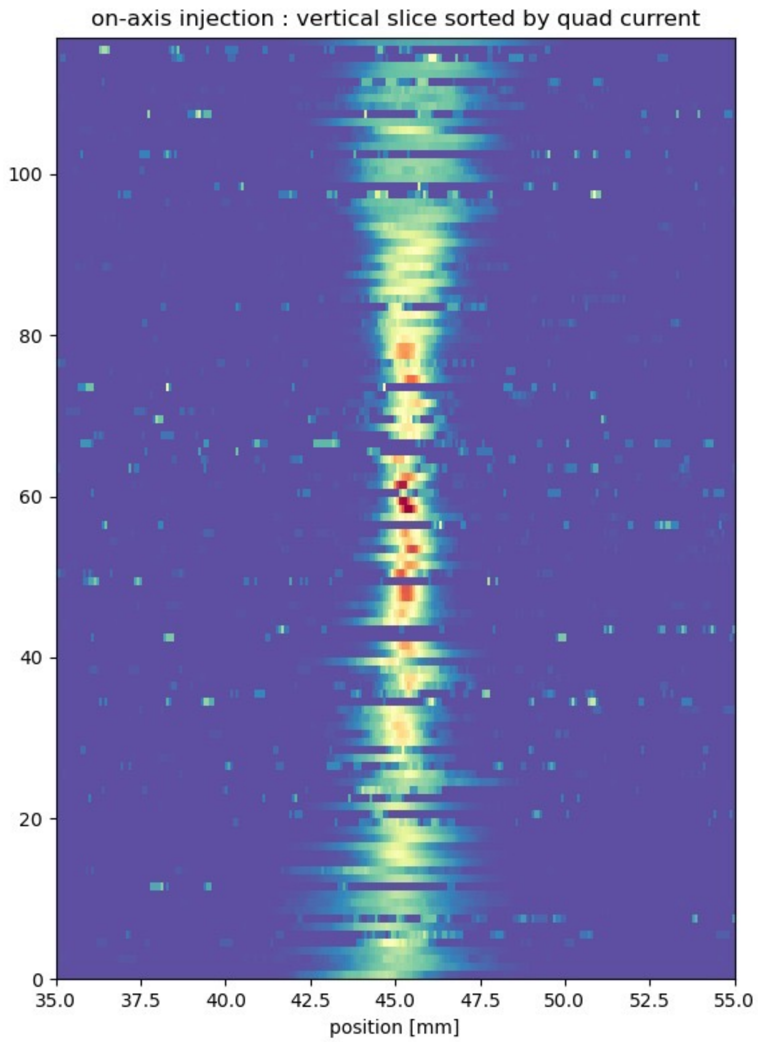
Progress towards emittance: Quad scans

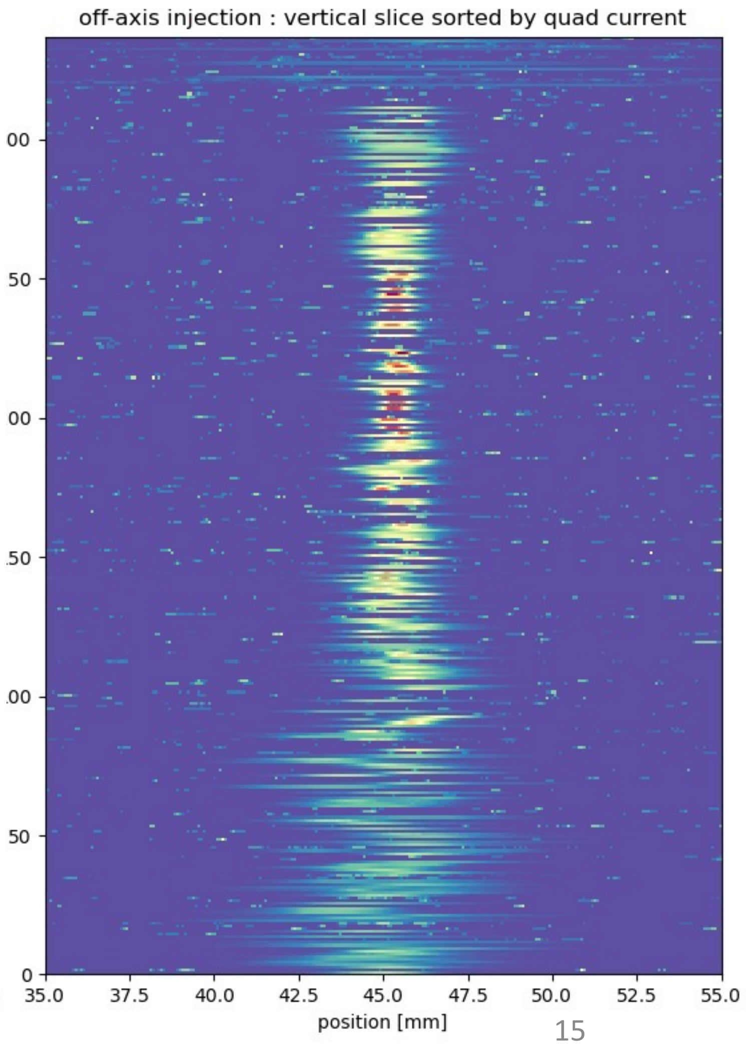
Assumes emittance is constant between shots

Choose a vertical slice through the image and sort by quadrupole current reveals the quad scan

Slice chosen so the minimum beam size is near the middle of the scan

Despite charge variations, shot consistency suggests beam parameters may not be varying much between shots





Investigating the resolution

Preliminary emittance values should be quoted once the resolution has been established

Resolution comes from both the lens and the screen

We need to assess the contribution of both components of the spectrometer, to see if we can optimise further (for best 2023 setup, and then beyond)

The point spread function (PSF) can be measured for both of these components

Camera resolution progress

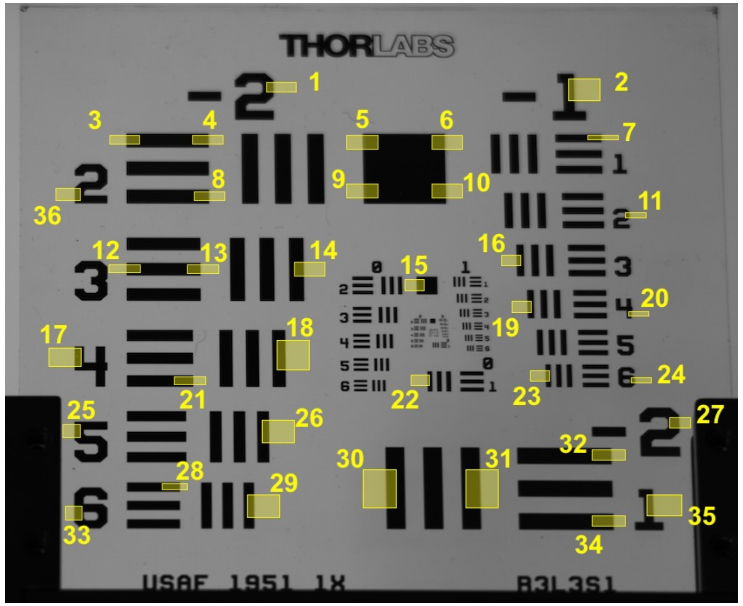
- March 2023 lab tests replicating Nov 2022 tunnel setup
- Images are not spatially invariant → analyse <u>suitable</u> edges across entire target
- PSF sigma LAB: 56 – 126 um
- PSF sigma TUNNEL: 84 – 115 um

Investigating additional image processing methods to improve lower limits further

- Lab serving as ‘ideal’ setting – tunnel conditions much noisier
  - Tunnel conditions can be improved upon
- Work still on-going → want to fully assess resolution across a variety of settings (lenses, FoV etc.)

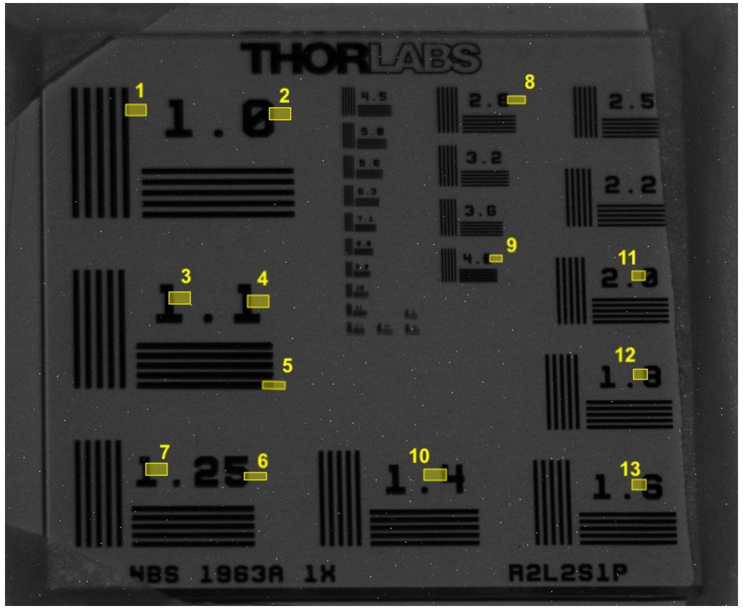
Lab Image

USAF 1951 Target



Tunnel Image

NBS 1963 Target



Scintillator resolution

GEANT4 simulations show the screen substantially contributes to the resolution of the system *O*(100 um)

Difficult to verify light transport in simulations → should measure PSF directly

6 samples of Gadox scintillator from Mitsubishi, varying priorities (light yield versus resolution)

LAB TESTS

Pinholes allow for the creation of a point source

Light sources: green (replication of scintillation light), UV (generation of scintillation light)

Observe point spread through a microscope

Scintillator resolution

GEANT4 simulations show the screen substantially contributes to the resolution of the system *O*(100 um)

Difficult to verify light transport in simulations → should measure PSF directly

6 samples of Gadox scintillator from Mitsubishi, varying priorities (light yield versus resolution)

POSSIBLE FURTHER TESTS

Scope for testing scintillators at CLEAR → application for beam time in progress

Convergent, point-like electron beam *O*(10 um)

Waist size should be small, but constant over scintillator thickness

Measure spread of scintillation light with microscope → mirror setup required to remove lens from beam path

Program of work

May 2023 — Camera resolution

Developing a lens/FoV/DoF ‘menu’ for a broad range of settings

May 2023 — Scintillator resolution

Lab tests with green and UV light through pinholes for initial values

Scope for CLEAR tests at a later date (depending on availability)

June 2023 — Preliminary emittance results

Preliminary measurements of emittance based only on Nov 2022 data

Inform future measurements and assess emittance analysis approaches

Spectrometer improvements

Continual development informed via resolution tests and (preliminary) measurements

Conclusion

- The AWAKE spectrometer is a key diagnostic for acceleration experiments
- Run 1 design fulfilled the initial criteria; Run 2 design requires an enhanced setup to meet the physics goals up to Run 2c
- Emittance measurements are essential for assessing quality of accelerated beam → multi-shot and single-shot approaches are under development
- Emittance values are directly impacted by the resolution of the optical setup
- In progress: Resolution of possible camera/lens configuration → a resolution/FoV "menu"
- Coming soon: Resolution of various scintillator screens
- Continually striving to enhance the spectrometer for physics requirements of Run 2c and beyond

Thank you for listening!

Backup

November 2022 run

- Proton intensity: $1{\times}10^{11}$
- Plasma density: $1{\times}10^{14}\mathrm{cm}^{-3}$
- Electron delay: 360ps behind RIF
- RIF position: on-axis set: -30ps relative to proton bunch centre
- RIF position: off-axis set: +20ps relative to proton bunch centre
- Off-axis: focus at +1m, 1mrad offset in y
- On-axis: focus at 0m
- Electron bunch
  - Charge: 600pC
  - Focused size at plasma entrance: (0.25, 0.35)mm
  - Emittance at beginning of line: 3mm mrad

- Basler acA1920-40gm
- 12-bit, 1920 × 1200 pixel CMOS
- Focal length lens: 75mm
- Small field of view → each imaged 15cm of screen
- Filter to reduce ambient light
- Cameras 110cm from screen
- 30 degrees below horizontal

Edge Spread Function (ESF)

Resolution is limited to the pixel size

Fit: $a + b \ * errfunc\ (\frac{x-c}{d})$

Error func argument from normal dist. of width σ is $\frac{x-\mu}{\sigma\sqrt{2}}$

$d = \sigma\sqrt{2}$ → obtain d from fit

σ = in pixels (pixel size 77um in object plane)

σ of PSF via ESF method: (pixels x pixel size)um

Example on the right: σ ~ 0.75 pixels = 55.6um