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Development of 6D electron beam diagnostics for novel acceleration experiments at FEBE on CLARA

Thomas Pacey,

S Mathisen, T Overton, J Wolfenden, C Swain, D Walsh, J Henderson, N Joshi, C Tollervey, A Bainbridge, J Jones, A Pollard, E Snedden, Y Saveliev, D Angal-Kalinin

ASTeC, STFC, Daresbury Laboratory

MANCHESTER 1824 The University of Manchester

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

2022 IBIC

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CLARA & FEBE Overview

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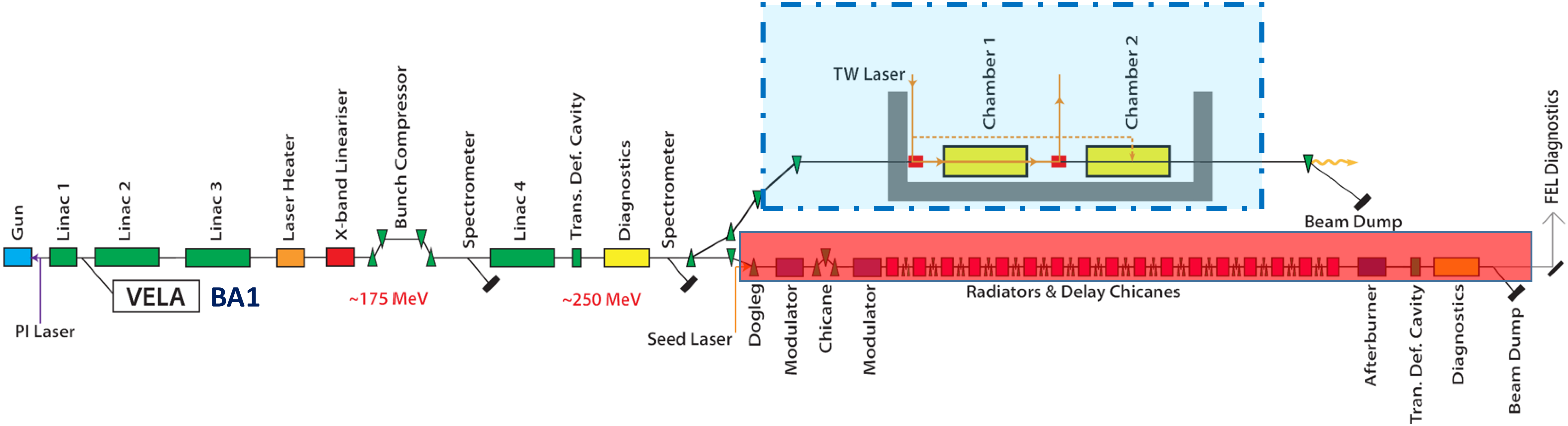


PHASE 1:
50 MeV,
250 pC, 10 Hz

- User area Beam Area 1 (BA1)
- Beam exploitation, inc. novel acceleration

PHASE 2:
250 MeV ASSEMBLED & INSTALLED OFFLINE

- 2022/23: Installation
- 2023/24: Commissioning

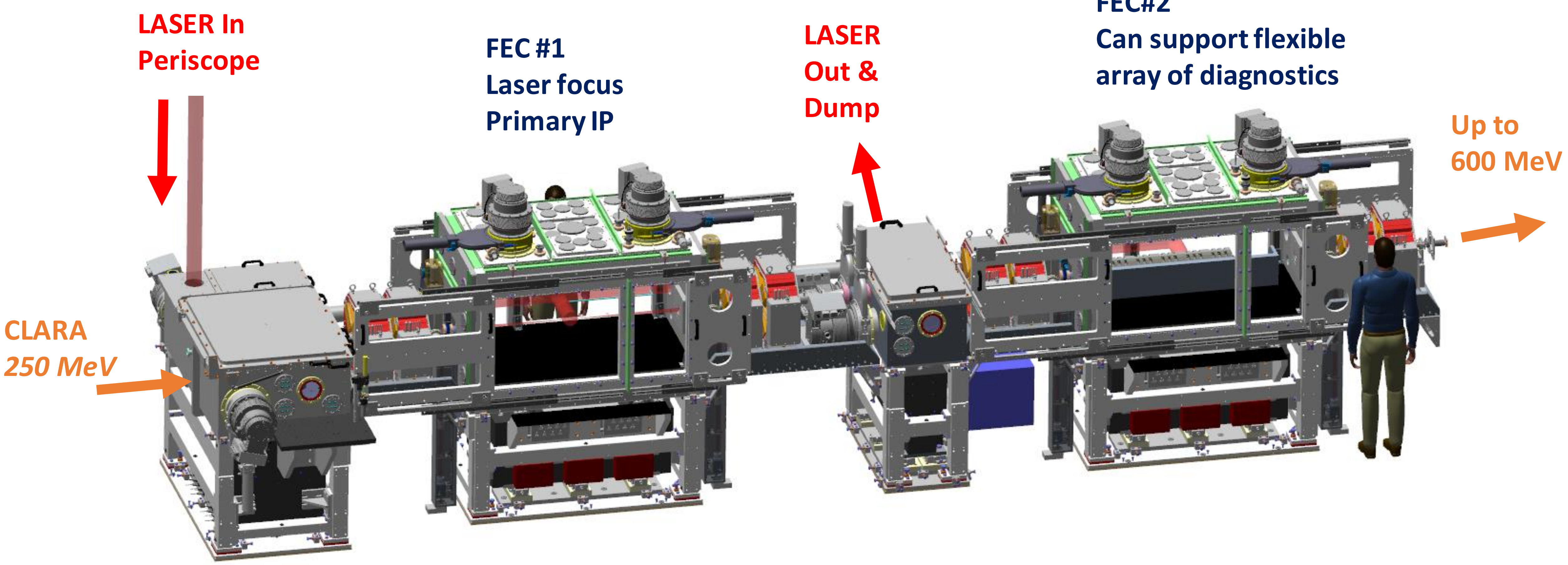
FEBE:
SHIELDED USER FACILITY

- Branch line to shielded hutch
- Flexible user exploitation space
- 100 TW class laser

PHASE 3:
100 nm FEL
NOT YET FUNDED

- Tied to decision on next stages of UK XFEL

FEBE Hutch


LASER In
Periscope
FEC #1
Laser focus
Primary IP
LASER
Out &
Dump
FEC#2
Can support flexible
array of diagnostics
Up to
600 MeV
CLARA
250 MeV

Beam parameters – "Day 1"

Parameter	High charge	Low charge
Energy [MeV]	250	250
Charge [pC]	250	5
RMS t [fs]	100	50
σ_E/E [%]	<5	<1
RMS x [μm]	100	20
RMS y [μm]	100	20
ε_N x [μm]	5	2
ε_N y [μm]	5	2

Important: all parameters to be confirmed through measurement using appropriate diagnostics.

Beam parameters – Future potential

Parameter	High charge	Low charge
Energy [MeV]	250	250
Charge [pC]	250	5 → <5
RMS t [fs]	100 → 50	50 → <50
σ_E/E [%]	<5 → 1	<1
RMS x [μm]	100 → 50	20 → 1
RMS y [μm]	100 → 50	20 → 1
ε_N x [μm]	5 → <5	2 → 1
ε_N y [μm]	5 → <1	2 → <1

R&D: Meeting these parameters will require upgraded and/or new diagnostics

Additional challenges for novel acceleration

'novel' -> plasma, laser, dielectric, THz -> high gradients, high transverse forces

- Single shot diagnostics required :
  - Beams with instability & providing feedback systems
- Meeting exacting IP parameters requires:
  - Precise measurements
  - Monitoring of shot-shot variation & longer term drifts
- Variety of experiments -> broad range of beam parameters = fundamentally challenging
- **High impact experiments need good diagnostics!**

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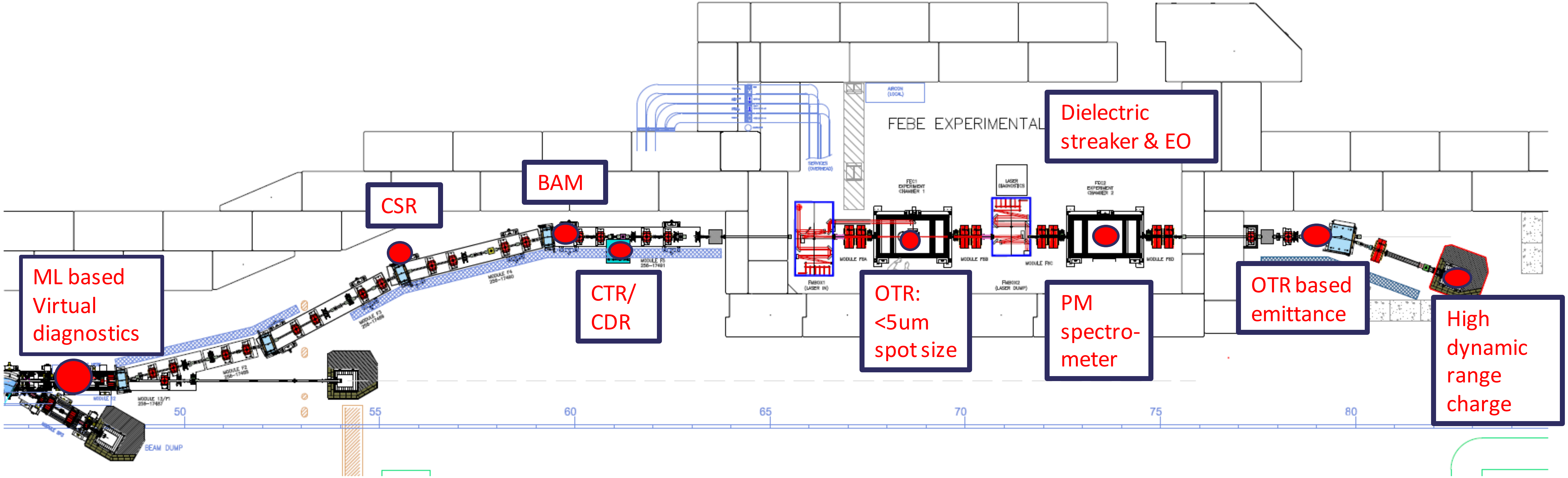
6D Diagnostics R&D

6D Diagnostics R&D across FEBE beam line

- Diagnostics undergoing active R&D
- All supplemented by well developed diagnostics, e.g. BPMs, YAGs, ICTs



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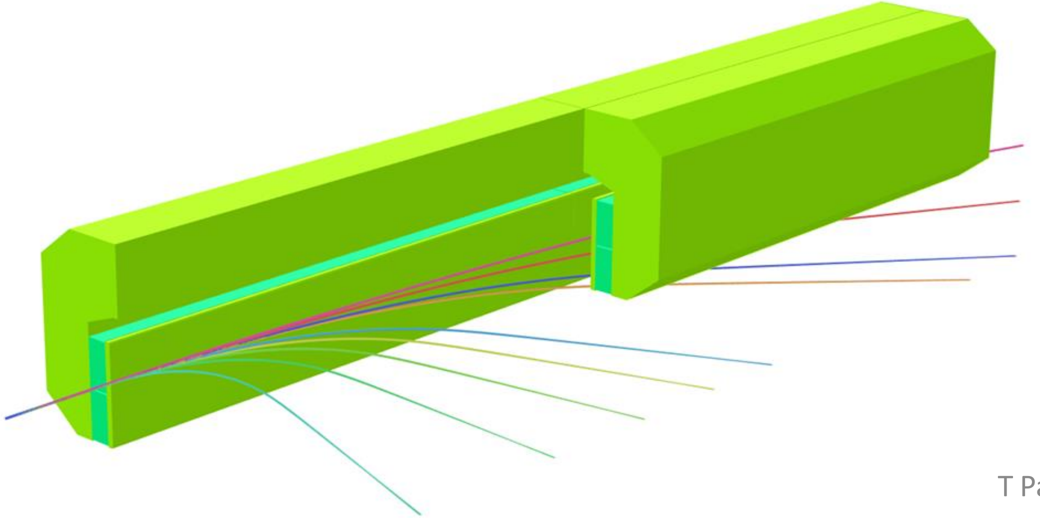
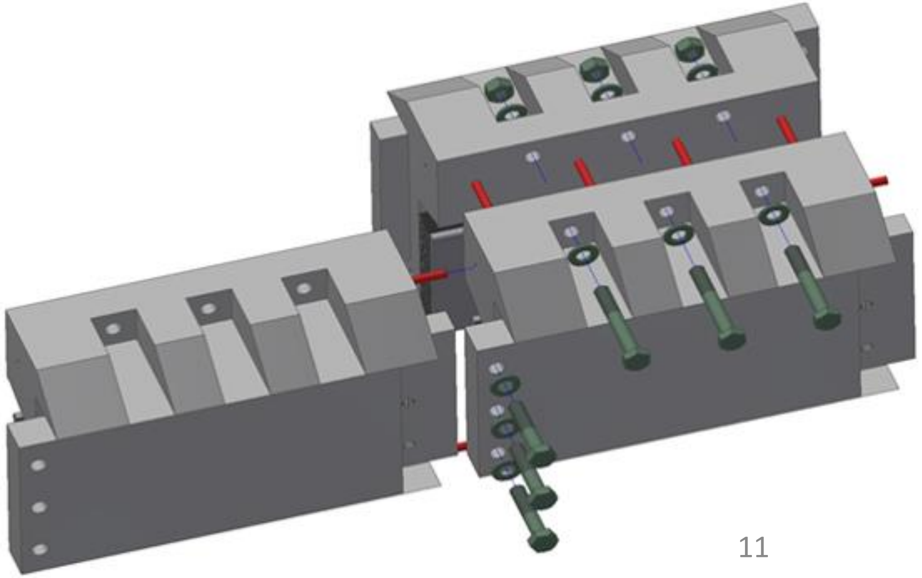
Longitudinal Diagnostics

Broadband PM spectrometer

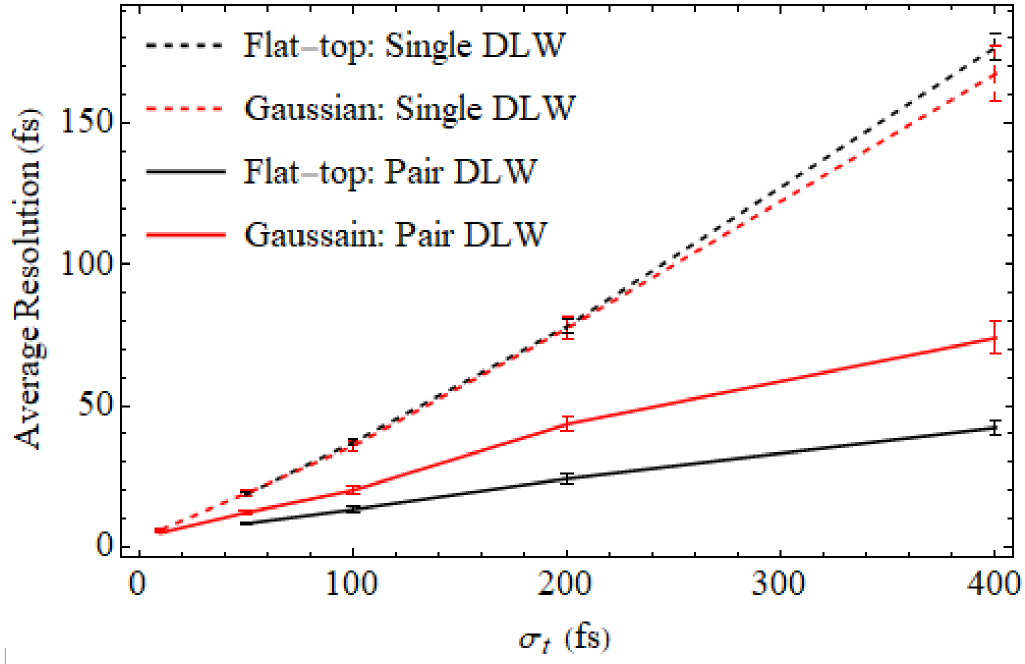
- Can be deployed in second chamber for commissioning beams with energy > 600 MeV
- Energy range 50 MeV - 2 GeV
- Upstream quad. doublet + correctors for matching into dipole
- Modular design, 200mm blocks, 5 modules for 2 GeV
- Full range requires ~1m scintillator screen

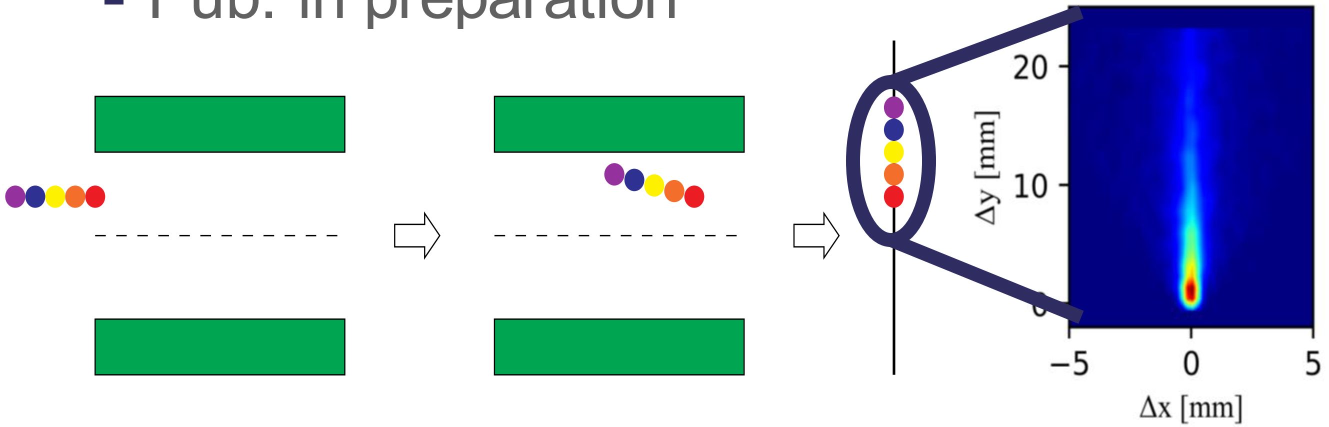




Dielectric wakefield streaker

- Passive, robust, single shot bunch length measurement
- RMS estimate or full profile reconstruction
- Broadband, ~50 fs > 1 ps
- Resolution improved using pairs orthogonally orientated plates
  - Pub. in preparation





- Resolution is given by:

$$r(s) = \frac{\sigma_Y(s)}{R_{12}\frac{dK_0(s)}{ds}}$$

Transverse beam size at s

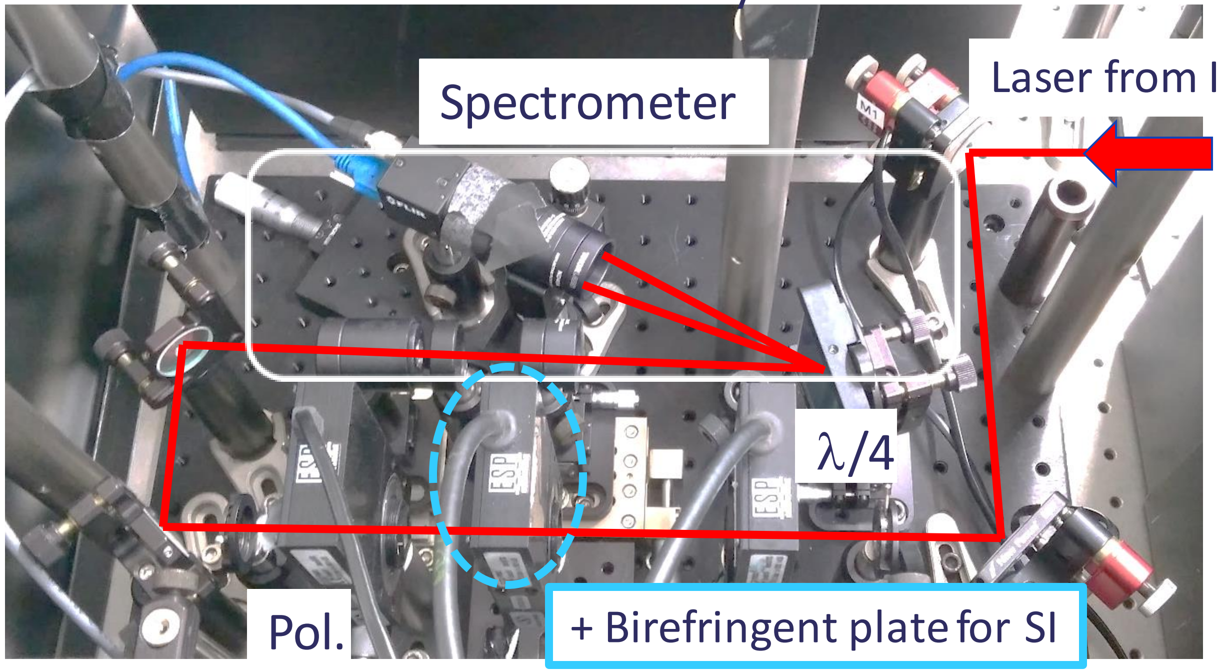
Longitudinal variation in streak

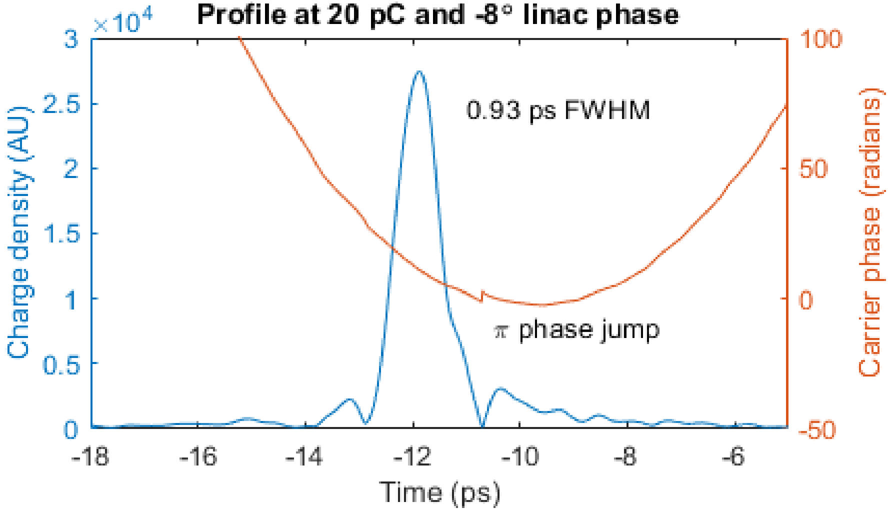
See also, Y. Saveliev, PRAB 2022

Electro-optic temporal bunch profile reconstruction

- EO spectral interferometry (EOSI) system developed
  - Improved resolution over spectral decoding system (EOSD)
- Proof of concept experiments complete in CLARA BA1
  - Working across 2 – 150 pC, down to ~300fs RMS length
  - 100 pC reconstruction with crystal 1cm from beam
  - Pub. in preparation
- Future – robust fibre coupled design for FEBE experimental chamber

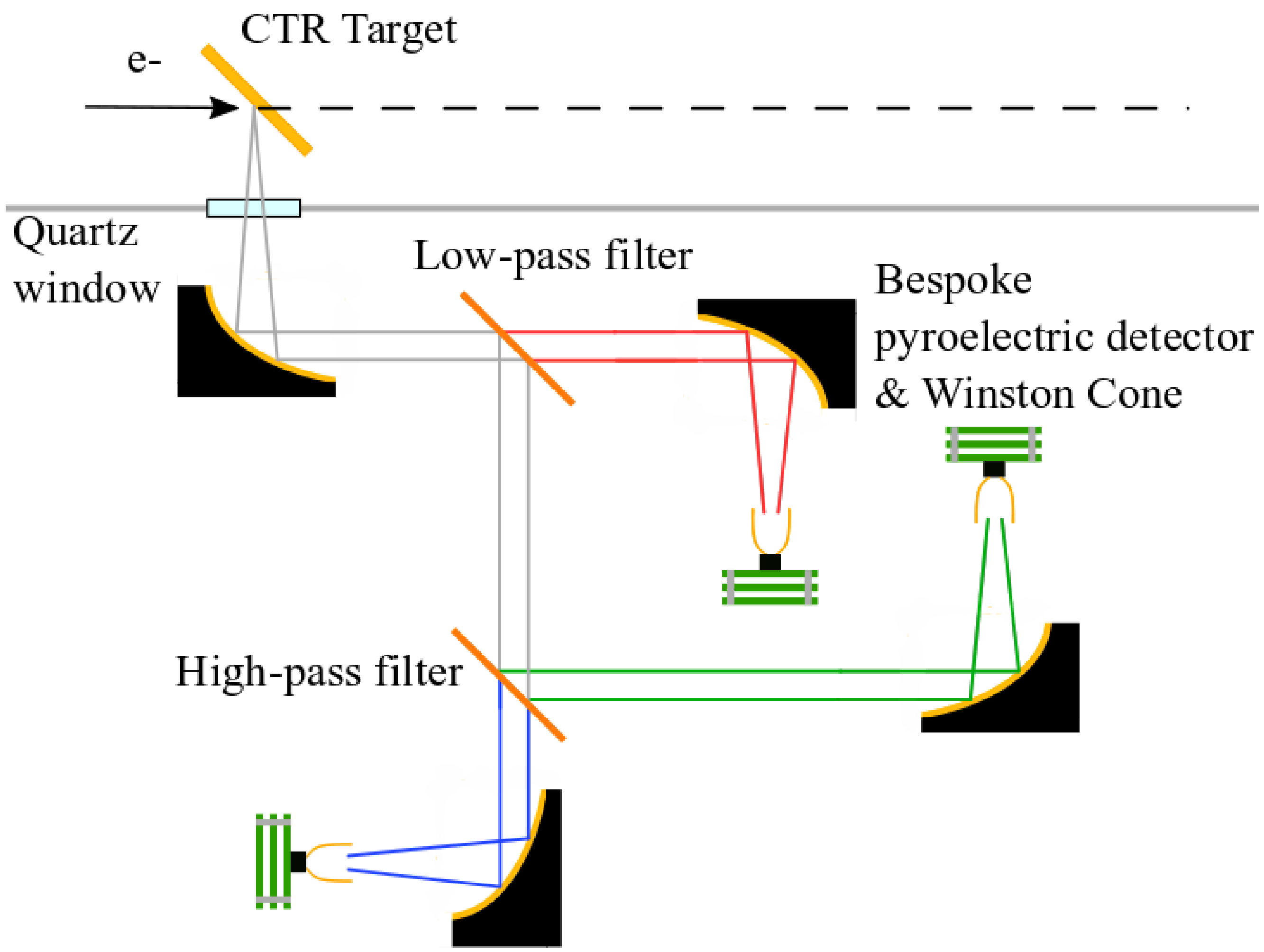
Standard EOSD system





Coherent radiation Bunch Compression Monitors

- CTR based BCM used for BA1 for machine tuning
- Upgrade for FEBE: compact "spectrometer"
- Custom pyroelectric sensors with variable gain & active noise cancellation
- Can be replicated on arc dipoles for CSR detection
- Optional CDR target non invasive, ML driven virtual diagnostics (e.g. LPS)



Laser synchronization & TOA jitter measurement

FEBE laser oscillator will be optically synchronized to the CLARA optical clock:

- Ultralow noise optical clock (complete)
- Stabilized (<10 fs over 24 hr (design and testing complete)
- Two-colour laser-laser locking (testing underway, all-fibre upgrade design in progress)

- **On track to provide <10fs locking of FEBE laser to optical reference**

Beam arrival monitor (BAM) R&D:

- Developing new design for BAM with removable pick-ups
- Targeting 10fs arrival time measurement @20 pC,
- Push 10 fs @<5pC beam charge with upgraded pickups.

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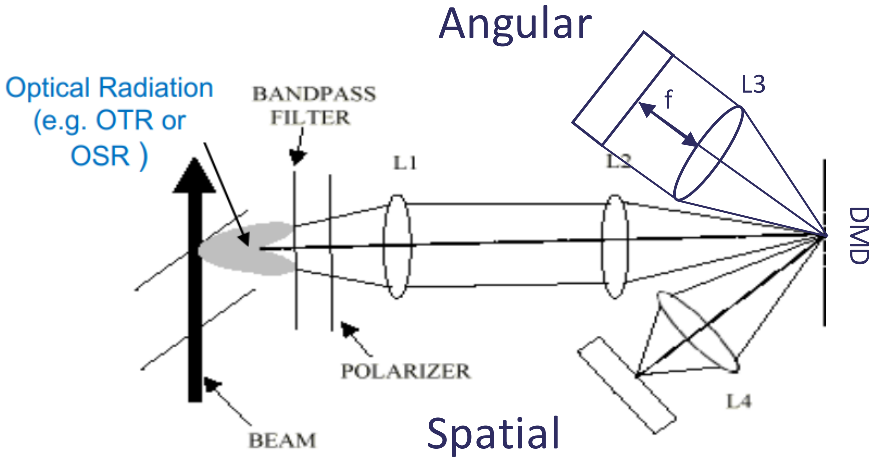
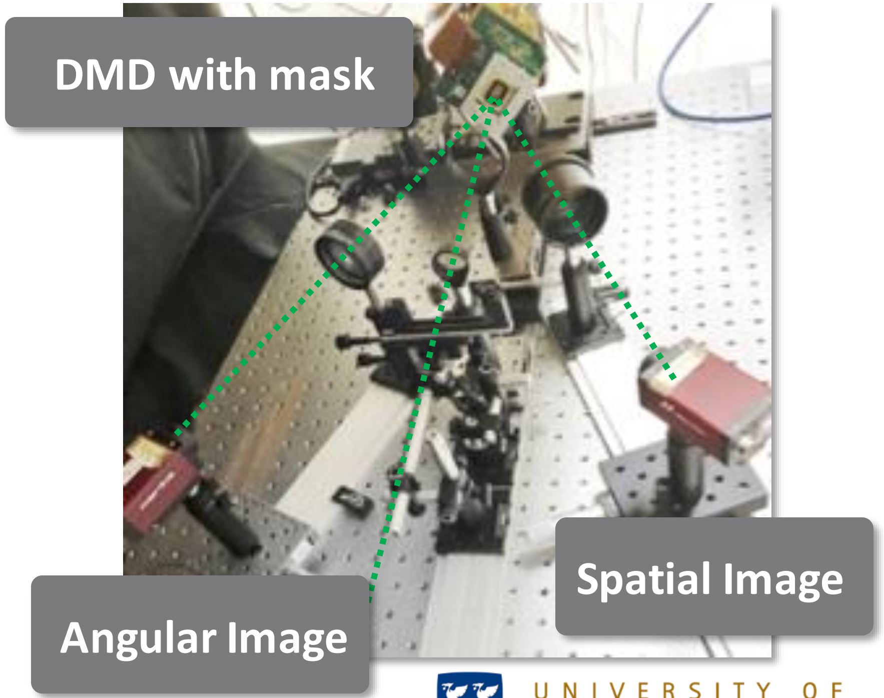
Transverse Diagnostics

OTR based emittance

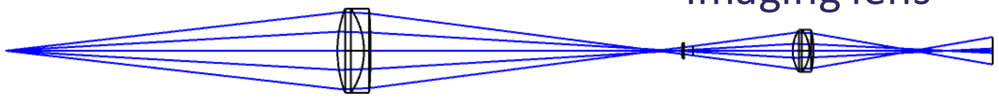
- Aiming for single shot emittance measurements
- Developing techniques for imaging with micro-lens array and masking with digital micromirror (DMD)
- Building up test optical systems & improving simulation tools in zemax
- Resolution limits TBC
- Collaborating with UoL and SPARC lab @ INFN

DMD method

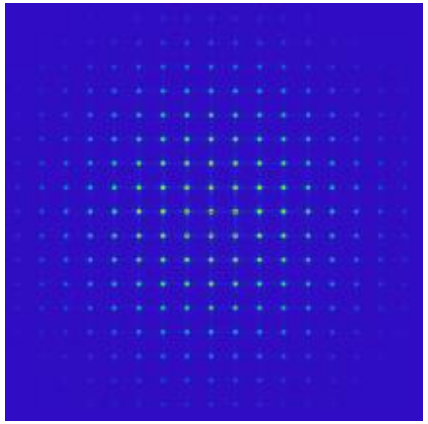




MLA method



Beamlet image



R. Fiorito et al., AIP Conf. Proc. 648, (2002)
F.G. Bisesto et al, NIMA 909 (2018)

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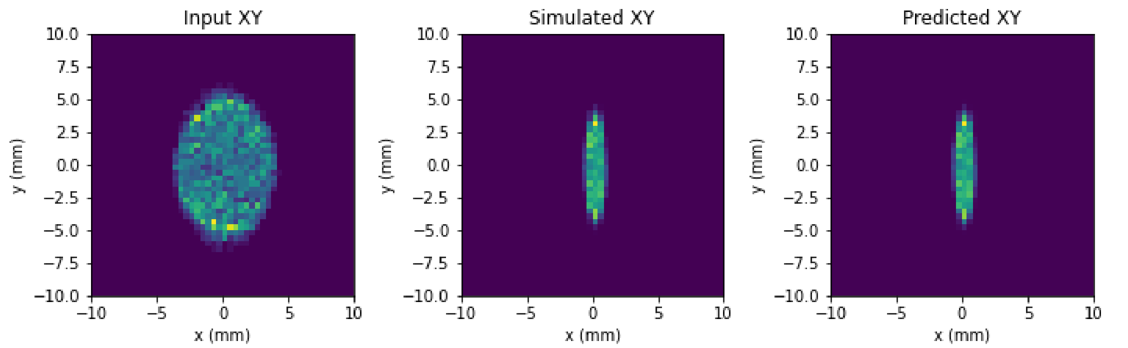
Machine Learning & Virtual Diagnostics

- Demonstrated in simulation ML prediction of IP spatial profiles as function of machine settings
- Operates in “forward” and “backward” mode
  - Arc -> IP or Dump -> IP
- Could allow for shot-shot IP prediction when IP diagnostics not available
- Future: extend to LPS prediction utilising CDR/CSR information

Forward prediction

Example optics #1

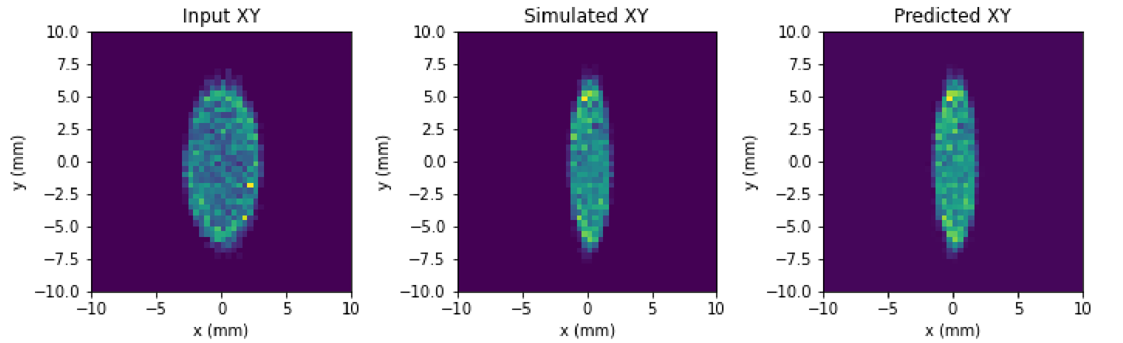
Input: arc | IP from elegant | IP from ML model



Backward prediction

Example optics #2

Input: dump | IP from elegant | IP from ML model

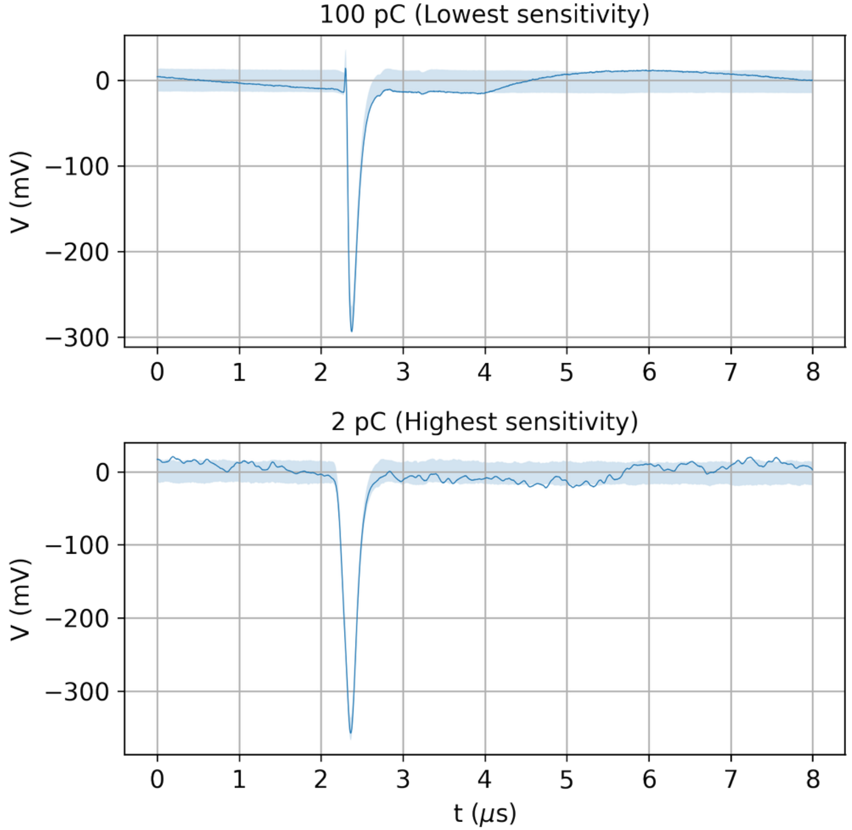


J. Wolfenden, MOPORI05, LINAC 22
M. Maheshwari, WEPAB318, IPAC 2021

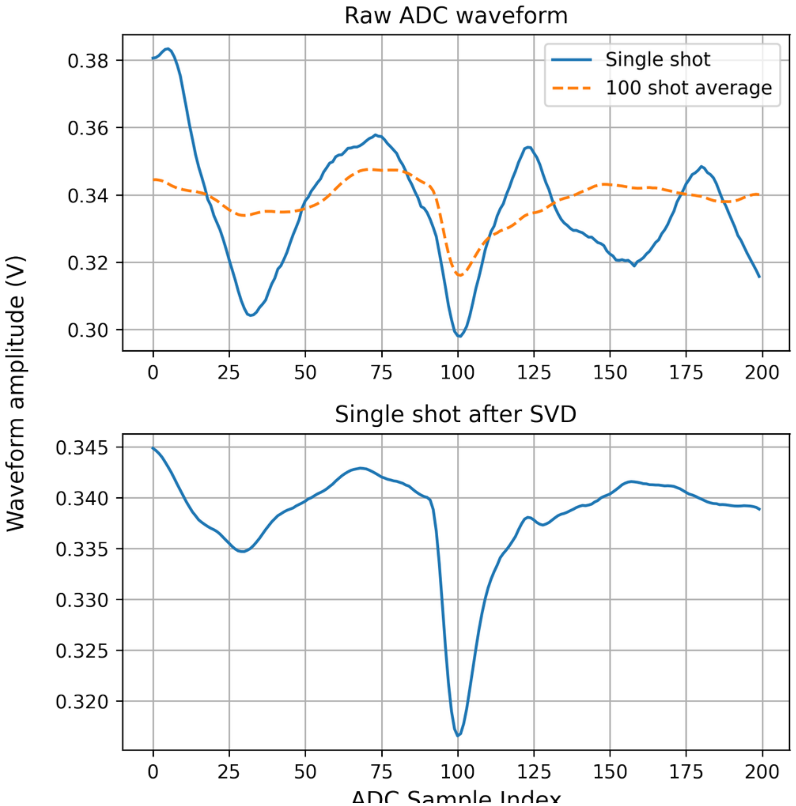
High dynamic range charge diagnostics

- Low charge important for some novel experiments
  - Delivers high peak current whilst maintaining transverse quality

High dynamic range



Single shot <0.5pC measurement



See poster contribution by S. Mathisen, Monday Session MOP32

Conclusions

- Diagnostic challenges for novel acceleration experiments
- Users will benefit from a sum of diagnostics greater than the parts
- FEBE provides strong platform to test systems for future accelerators
- We are open to collaborative opportunities for R&D

- We welcome experiments at CLARA on instrumentation
- More information on FEBE proposal call provided by 2024
- Contact directly for more information

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thomas.pacey@stfc.ac.uk

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Thank you