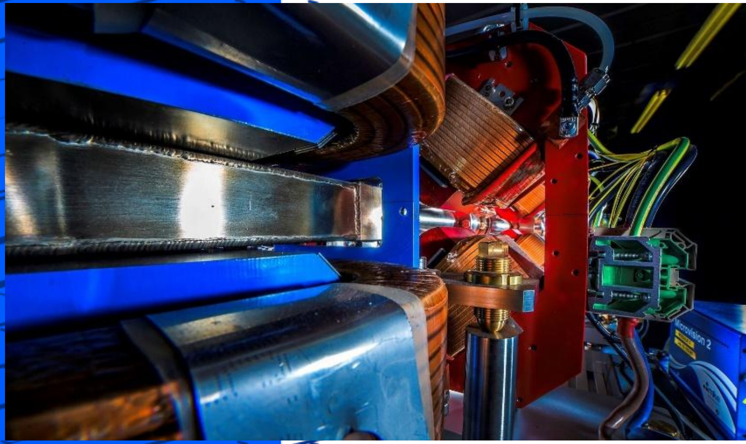
Science and Technology Facilities Council

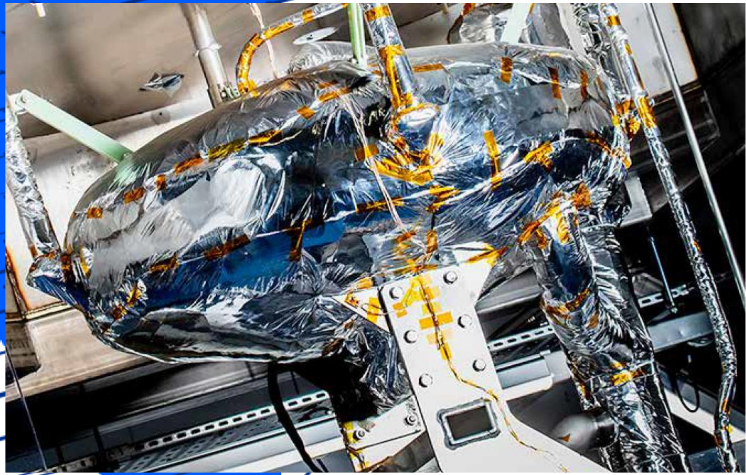
ASTeC

Making a brighter future through advanced accelerators

High Impact Beamlines for R&D Hubs

Dr. Thomas Pacey
ASTeC, STFC Daresbury Laboratory
and The Cockcroft Institute





EuPRAXIA-DN Camp III: Innovation
University of Pecs, 7/10/25

EuPRAXIA Doctoral Network

The Cockcroft Institute of Accelerator Science and Technology

What can beamlines do to help deliver plasma accelerators for applications?

Outline

- Beamline design principles
- Beamline tools
- Challenges of laser plasma accelerators
- Case Studies, CLARA & EPAC
- Examples of other designs & builds

My background

- PhD in novel acceleration:
  Dielectric Wakefield Accelerations
  - THz generation and bunch dechirping

- Leading the commissioning at CLARA accelerator and preparing for novel acceleration R&D

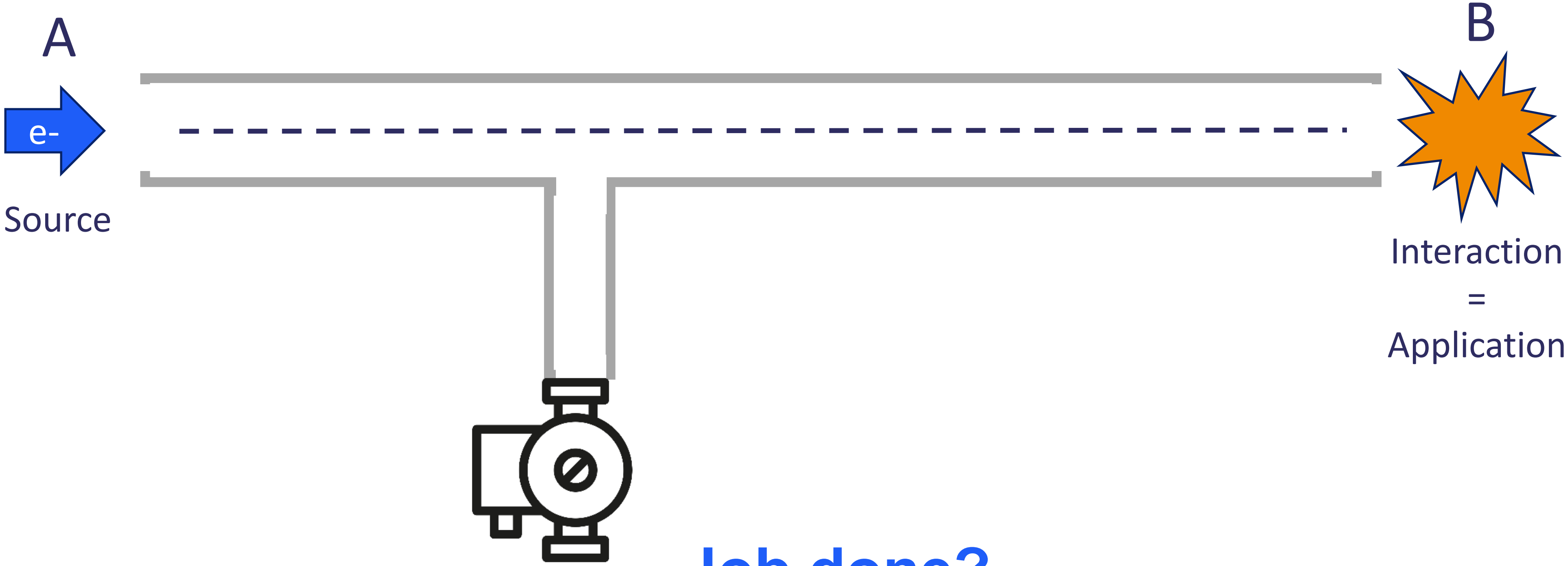
- Worked on electron beamline design for EPAC (LWFA) & RUEDI (ultrafast diffraction)

- Novel + conventional accelerators
- Design + Application & Exploitation

Beamline design

Beamline Design

- What is 'a beamline'?



Job done?

Beamline design

What does the beamline need to do?

1. Prepare beam for interaction

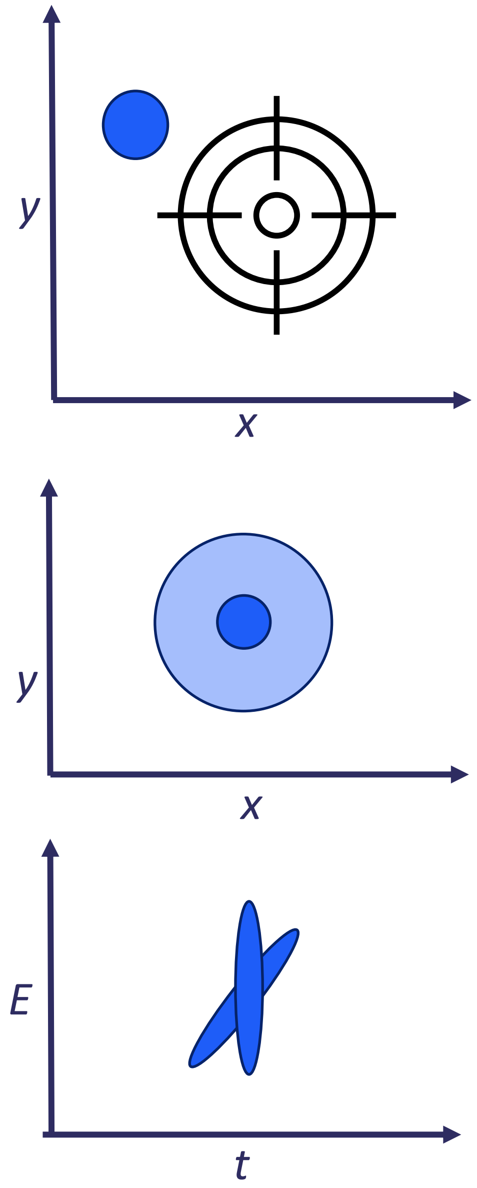
2. Preserve source beam properties we like

3. Correct the properties of the source beam we don’t like

Beamline design

Prepare the beam for interaction:

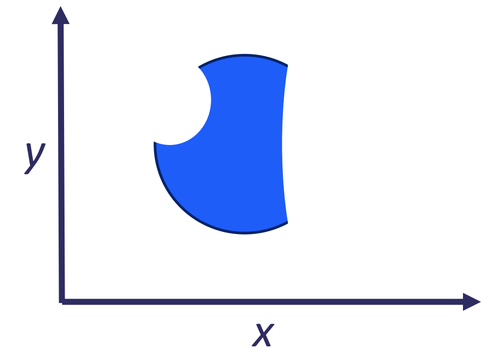
- Align beam to target
  - May need to set a defined axis
- Transverse focusing or defocusing
  - Set specific transverse optics
- Longitudinal compression
  - or decompression



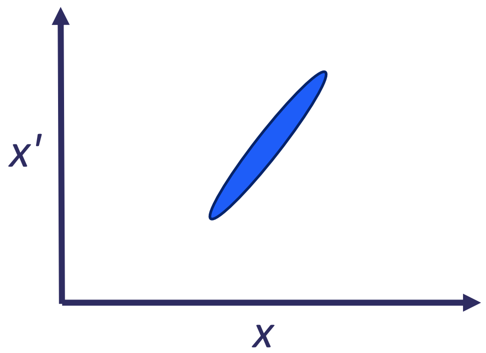
Beamline design

Preserve source beam properties we like

- Limit beam losses
  - Avoid transverse clipping
  - Have sufficient energy acceptance



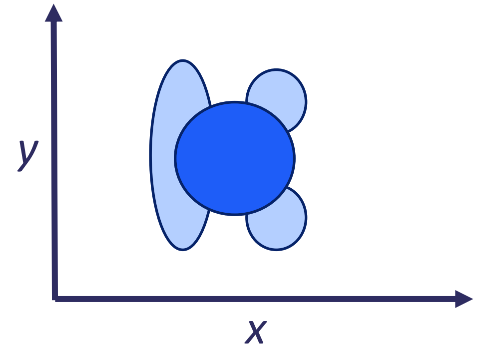
- Prevent excessive emittance dilution
  - Sufficient beam pipe vacuum
  - Mitigation of higher order effects
  - Limit interfaces (windows, ‘plasma mirrors’)
  - Reduce impact of collective effects



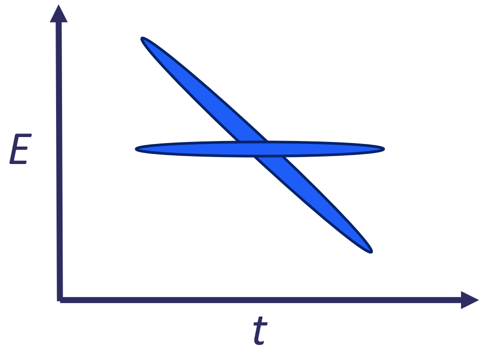
Beamline design

Correct the properties of the source beam we don't like

- Condition the beam, i.e. clean it up
  - Collimate, remove transverse halos and energy tails
  - Remove co-propagating radiation sources, e.g. lasers



- Set particular energy or energy spread/chirp
  - Reduce energy spread, control energy-time correlations

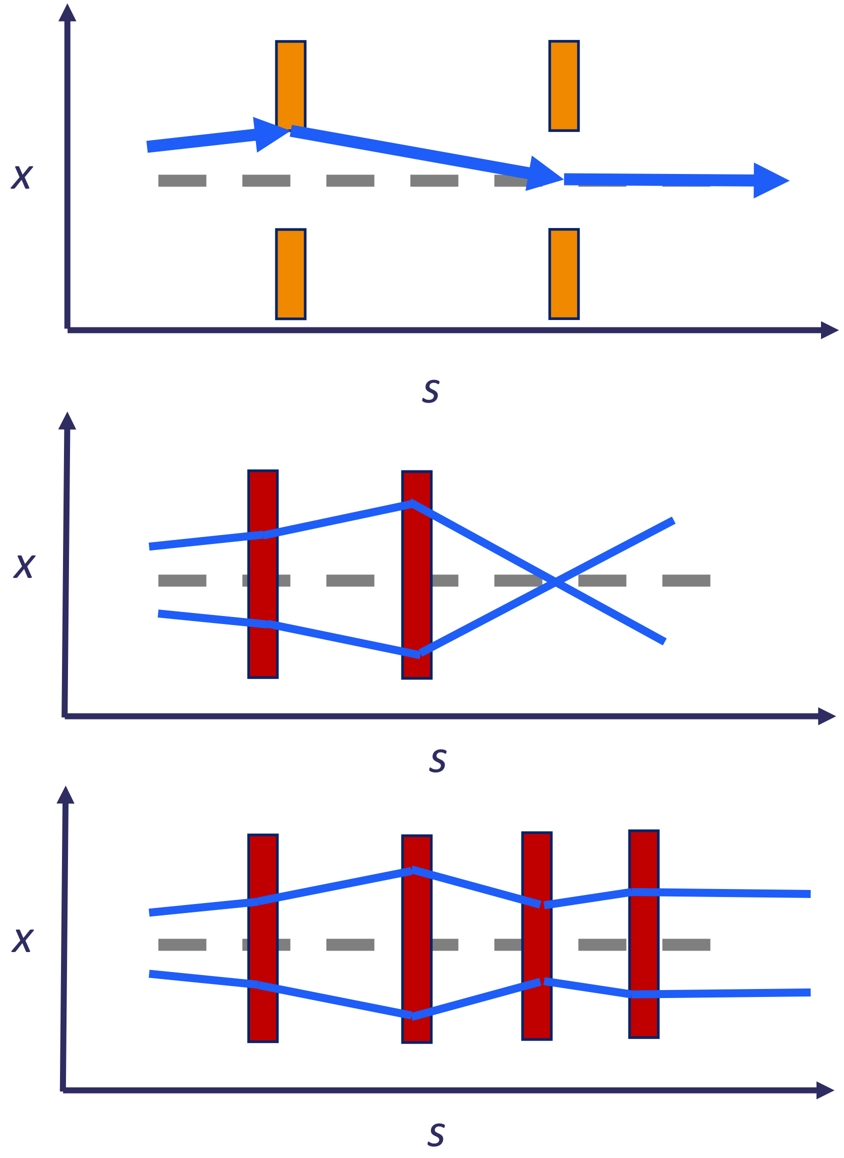


Beamline tools

Tools: Spatial properties

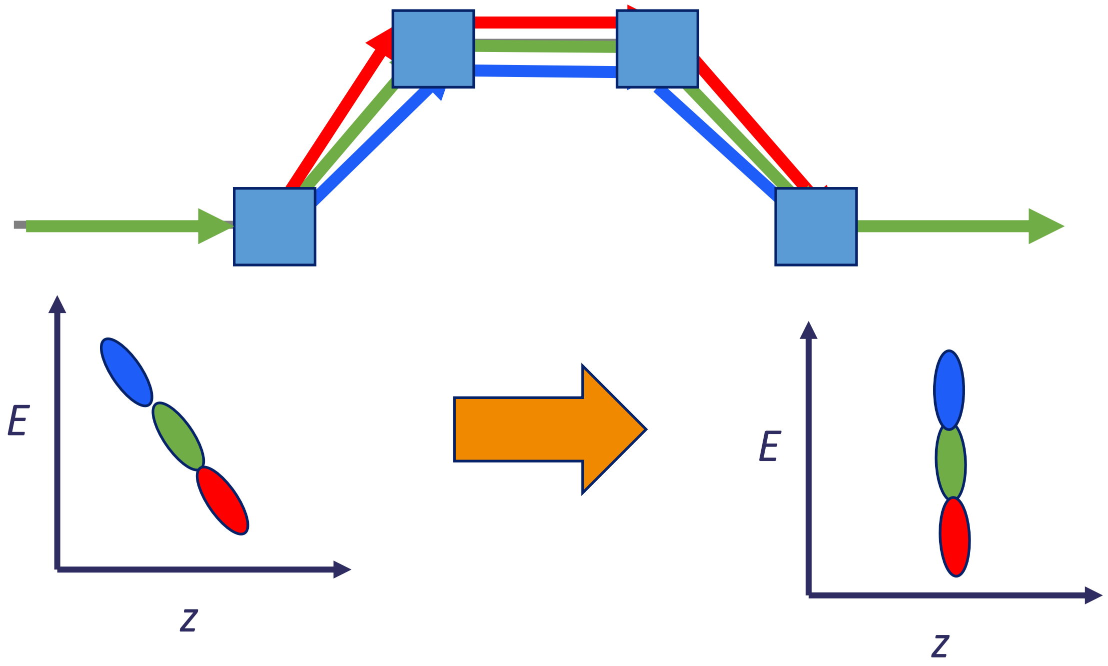
- Aligning beam to target:
  - ‘Humble’ corrector magnet
  - 'Weak' EM dipole
  - Only ever want to make small corrections!
  - Want a well-aligned beamline!

- Focusing of beam:
  - Quadrupoles
  - >=2 Needed for focus in both planes
  - Usually many more in beamline
  - Required for setting optics through other elements



Tools: Longitudinal compression

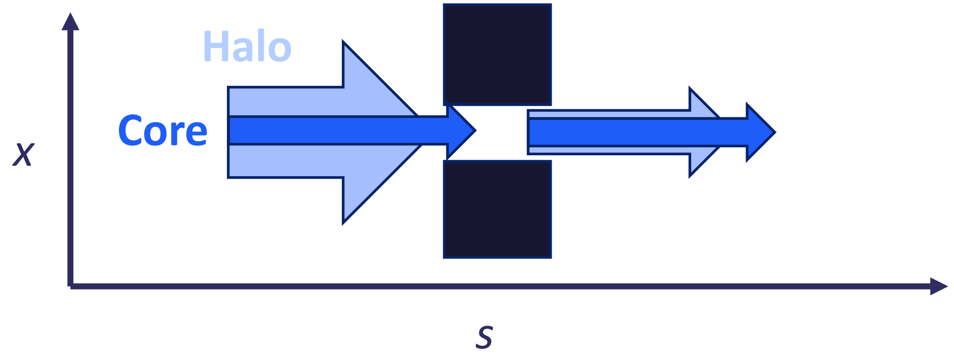
- Compress (or decompress)
  - Magnetic chicane or arc
  - Rect. dipoles introduce vertical focusing
    - Add quadrupoles…
  - Higher order effects
    especially when energy spread is large
    - Add sextupoles...



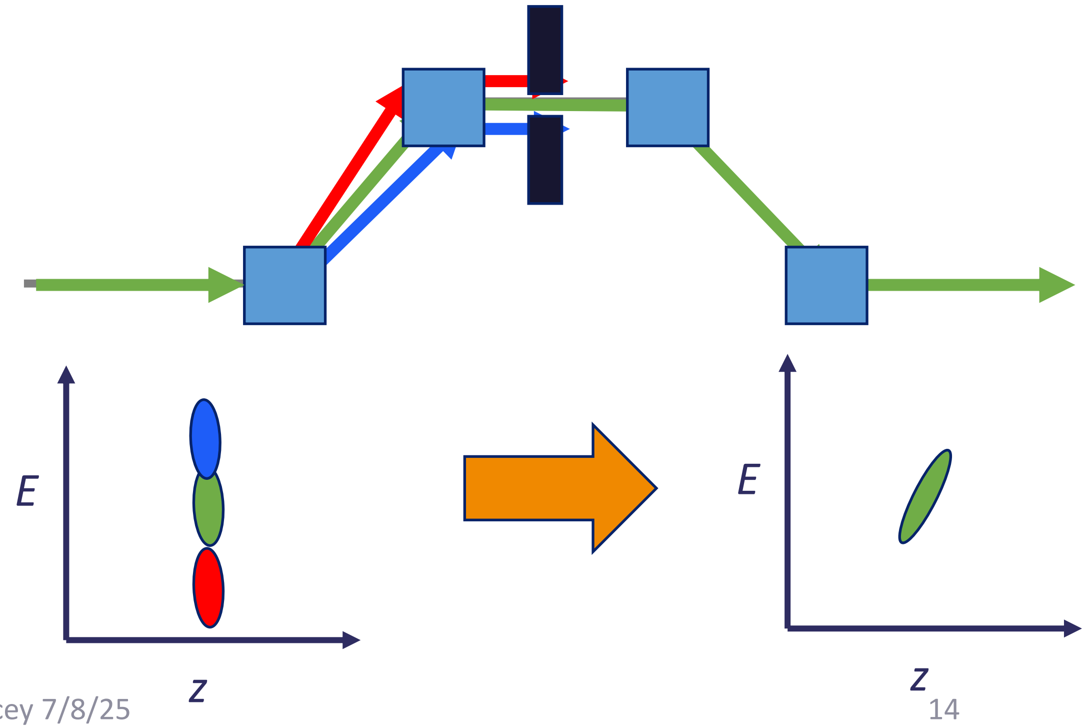
- Velocity bunching
  - Drift bunch at “low energy”
  - Then accelerate again to 'freeze' in place
    - Requires chirp control + space + further acceleration
  - *Velocity de-bunching can also occur*

Tools: Collimation

- Transverse collimation
  - Can add transverse focusing for more control



- Dispersive collimation
  - Will define energy spread & central energy exactly
  - But its lossy; not in energy acceptance = gone!
  - Can turn energy instability into charge instability
  - Can be designed to alter longitudinal compression or not
(isochronous, R56 = 0, need some quads!)



Tools: Collimation

- The higher the energy the more material is needed
  - 2mm Tungsten -> 1 GeV electrons scatter 17mrad
  - 5 Gev <1 mrad

$$\frac{d\langle\theta^2\rangle}{dz} \cong \left[\frac{16\pi NZ(Z+1)r_e^2}{\gamma^2\beta^4}\right]\ln\left(\frac{204}{Z^{0.33}}\right)$$

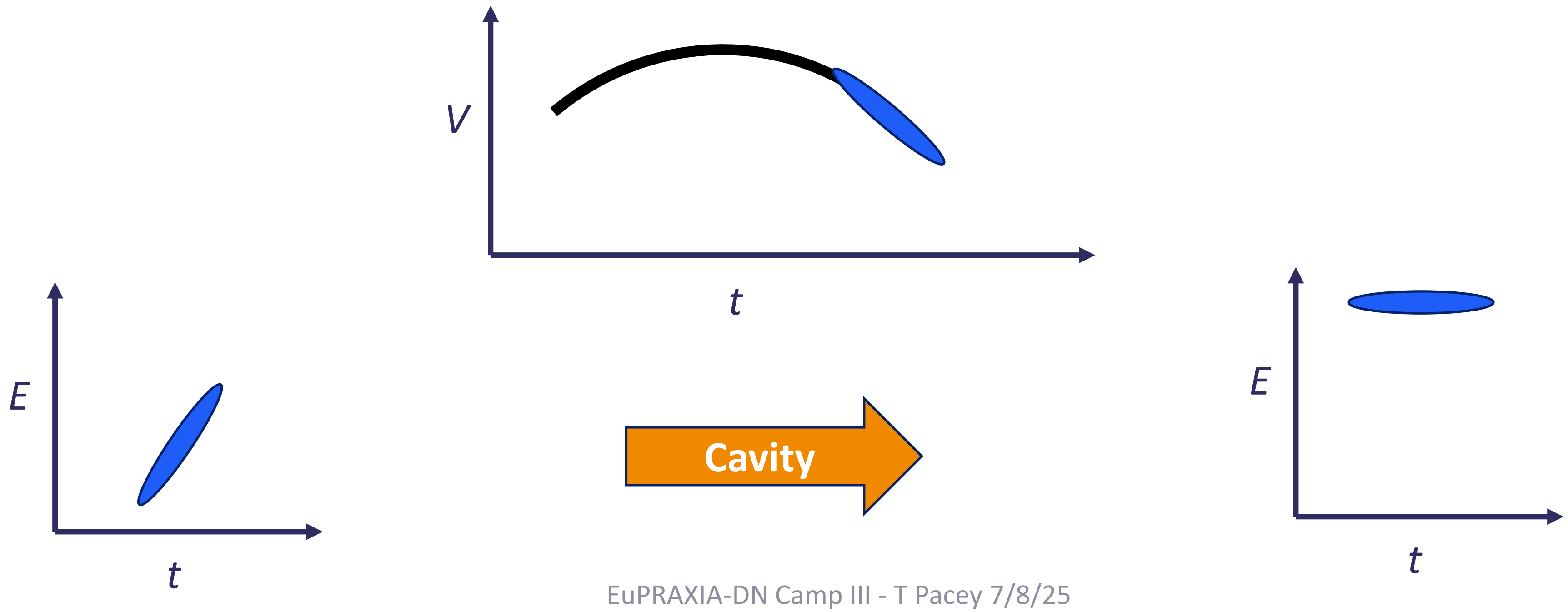
Jackson, Classical Electrodynamics,1975

- Beyond just 'scattering' out of beam, may want to "absorb"
  - 250 MeV electrons: >10cm of lead
  - Generates additional radiation

- Higher average power (energy x charge x rep rate) = more problems with activation
  - Implications for building 'compact lab sources'

Tools – Active energy spread control

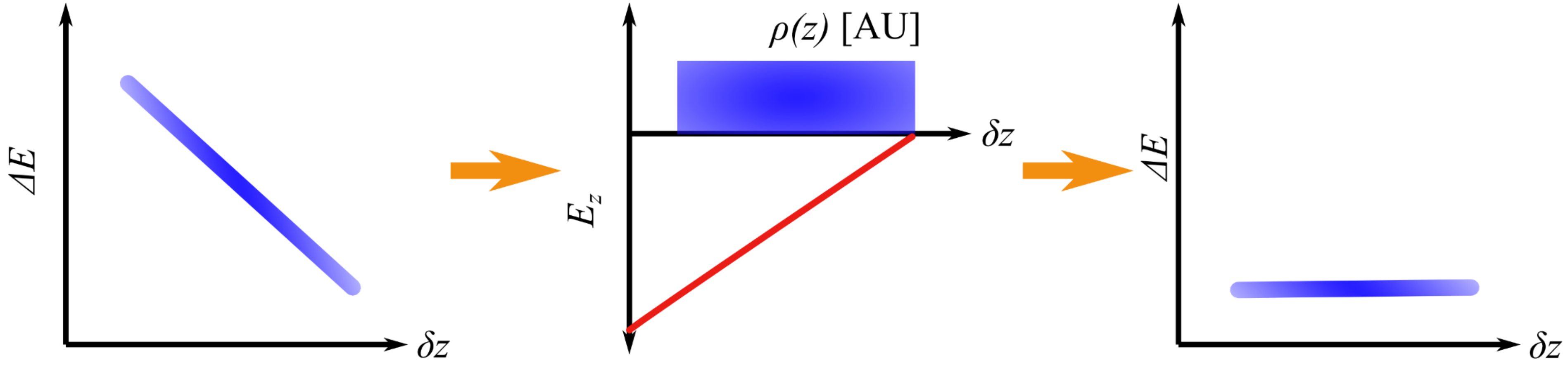
- Can be RF Cavities or a driven plasma
    - Can be done with net acceleration
    - Timing jitters will map to energy jitters



Tools – Passive Energy spread control

Passive dechirpers

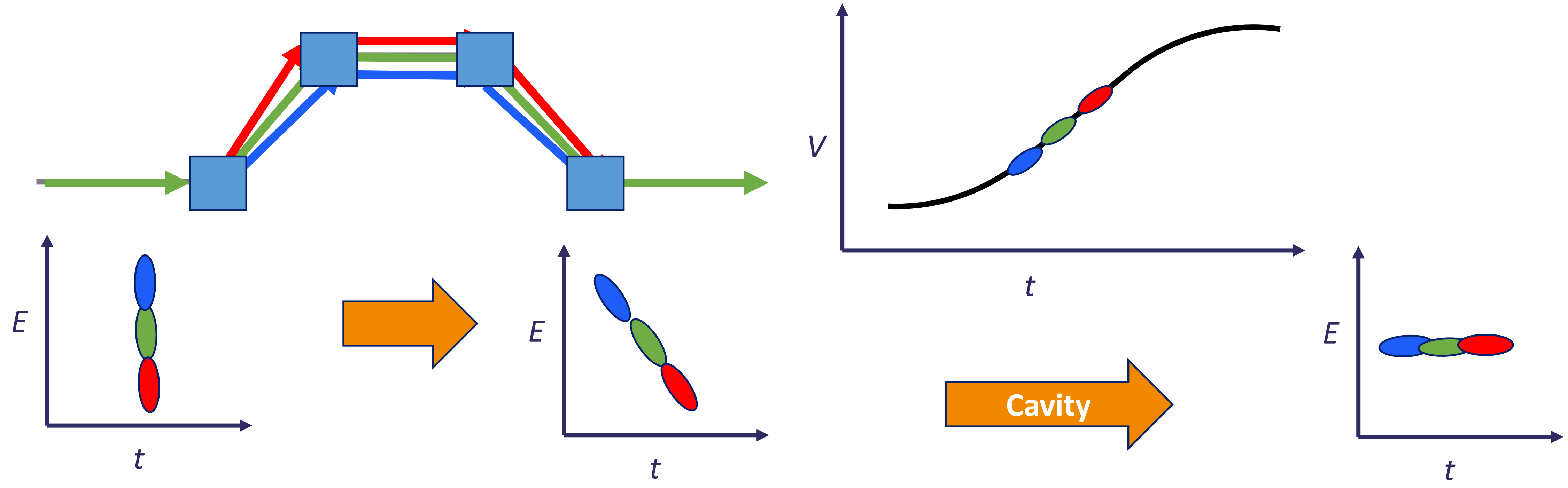
- Use beam wakefield: self synchronised !
- *Head slows down the tail*
- Field depends on bunch longitudinal profile and charge
- Can have transverse effects: spoil beam in other dimensions!



- B.H, Gonzalez,, et al. "Detailed simulation study of wakefield induced beam dynamics in the dielectric dechirper at CLARA." IPAC24 . JACoW, 2024.
- R. D'Arcy et. Al Tunable Plasma-Based Energy Dechirper | Phys. Rev. Lett.

Tools – Energy jitter compensation

- Map energy jitter onto time jitter
- Active: RF cavities (or even plasma)



Experimentally applied to LPA

P. Winkler et. Al., Active energy compression of a laser-plasma electron beam | Nature 2025

Note that 1deg of S-Band RF = ~1ps time delay

Interjection

Using the tools

How do we use the tools operationally?

- Diagnostics!
- Need to measure the output of our beamline ‘tools’ and tune appropriately
- Ensure we have “set our beam” for the application
- Lots of established systems…do they all work for plasma accelerators?

Tools – Diagnostics

- Typical diagnostic tools for MeV – GeV electron beams

"Basic":

- Screens + cameras (scintillators, transition radiation)
- Current transformers, Faraday Cups
- Dipole + Screen (measure energy and energy spread)

i.e. straightforward to implement in laser lab context, Limited total number of components

"Advanced":

- Beam Position Monitors
- Compression monitors (Coherent radiation generation)
- Spectrometer beamline w/ dipole + quads (measure energy + energy spectrum precisely)
- Transverse deflecting structures (RF cavities or passive wakefield)

Diagnostics

- R&D systems can also be applied
- ***Does an 'application' want an experiment on an experiment?***

- More on diagnostics:
- See Dr Joe Wolfenden's talk:
  - EuPRAXIA-DN School on Plasma Accelerators (22-26 April 2024): Beam Diagnostics for Plasma Accelerators · Agenda (Indico)

- See Prof Alessandro Cianchi talk:
  - EuPRAXIA-DN Camp I: Technologies (7-8 April 2025): Diagnostics for beam and plasma · Agenda (Indico)

Beamline design - Tools

- Transverse Collimators
- Dispersive Collimators
- Transverse focusing
- Emittance preserving transport
- Magnetic compressors
- Energy spread compensation
- "Basic" Diagnostics
- "Advanced" Diagnostics

Challenges of plasma accelerators

(Break)

Challenges of plasma accelerators

Fundamental

- Non-linearities & sensitivity to jitters
  - From high gradient & high frequency fields
- Energy jitter
- Small, divergent sources

Characteristic

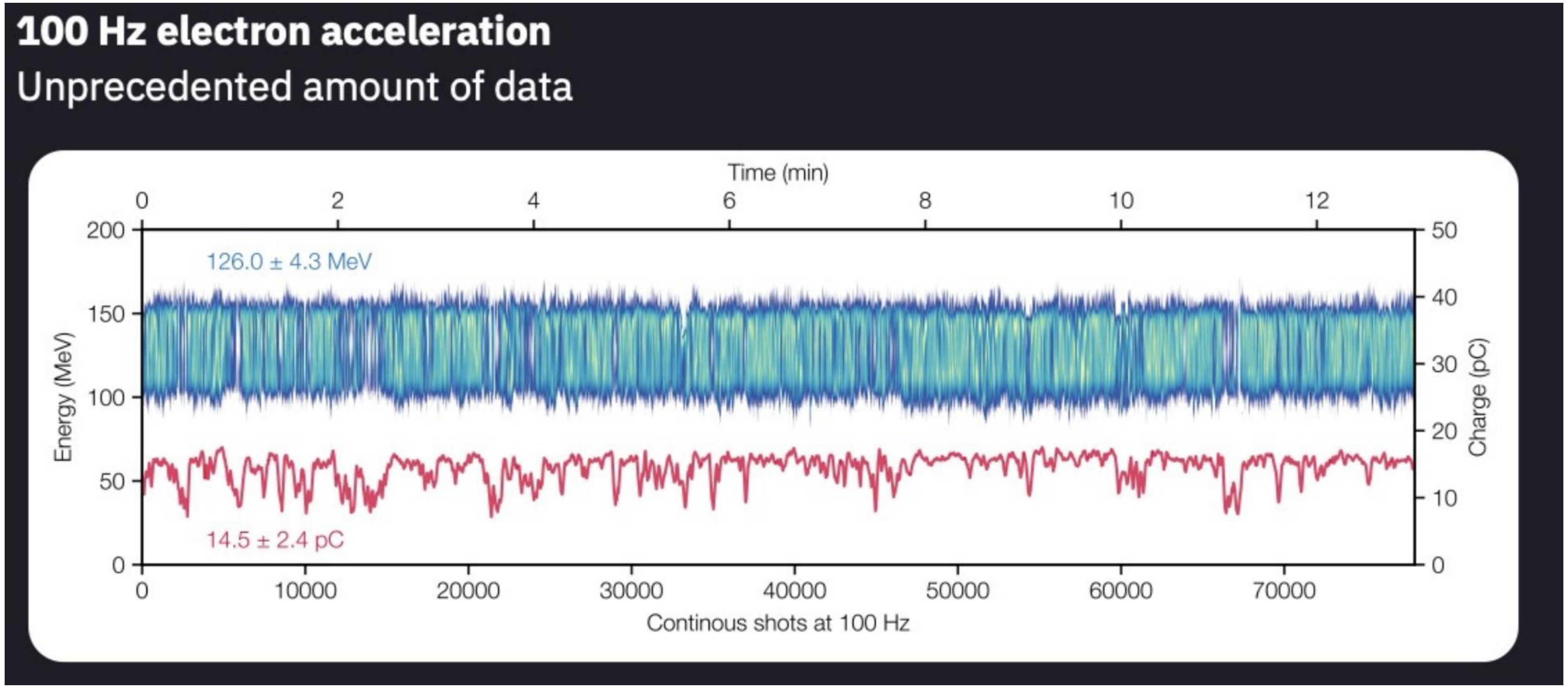
- High energy spread
- Pointing & Charge jitter
- Ultrashort bunches driving collective effects
- Beam halos, energy tails, undesired backgrounds
- Desire for compactness
- Source parameter uncertainty

Challenges - Fundamental

- High gradients; >0.5Gv/m
  - Non-linear wakes have highest gradients
- Non-linear -> more sensitivity to jitters
- High frequency wakes; more sensitive to timing jitters
  - Operating at ~10THz
- Dealing with energy jitter is a key challenge
  - Maybe best not approached as a job of the beamline but as a job of the source
  - Likely x10 bigger on plasma than RF beamline (RF run at <= 10^-4 stability)

Progress in source energy & charge energy jitter

- **EAAC25: DESY, KALDERA laser, MAGMA source**



- [7th European Advanced Accelerator Conference (21-27 September 2025): First Electron Beams from the High-Average-Power Laser-Plasma Accelerator KALDERA · Agenda (Indico)]

Challenges – Fundamental

Emittance growth in transport

- Source is small, emittance is <= 1um, divergence is high ~5mrad
  - growth comes in transport; divergence dominates early in beamline

$$\epsilon_{n,f}^2 = \epsilon_{n,i}^2 + \gamma^2 \frac{\sigma_E^2}{E^2} \sigma_{x'}^4 s^2$$

Start: $\varepsilon_{n,i}$ = 0.1um, 500 MeV, 5% energy spread, 2.5 mrad divergence

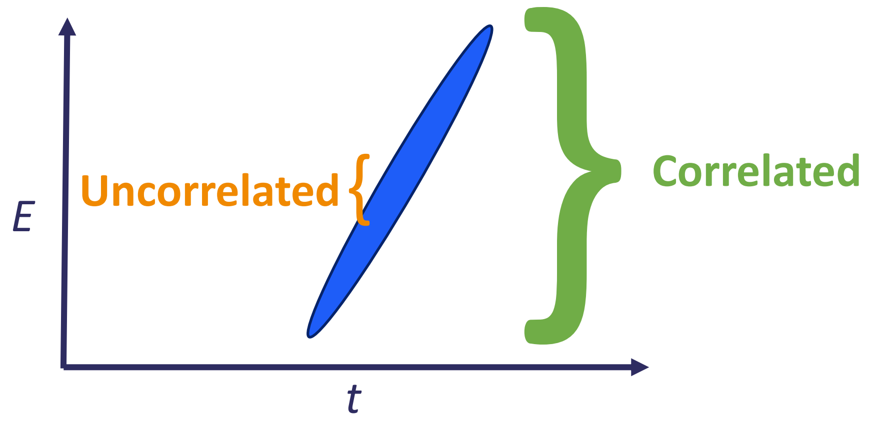
After 1m: $\varepsilon_{n,f}$ = 300 um (!)

- **Implication: Deal with source divergence early in beamline**
- Need strong focussing near the source
  - Can't have just a vacuum pipe

First emittance measurement of the beam-driven plasma wakefield accelerated electron beam

Intrinsic normalized emittance growth in laser-driven electron accelerators | Phys. Rev. ST Accel. Beams

Challenges - Characteristic



High energy spread

- Correlated can be adjusted
- Uncorrelated is harder to solve

Jitters

- Cannot be corrected for with feedbacks within beamline
- Pointing (want it to go down beamline)
- Energy jitter
- **Charge jitter**

Charge jitters

Laser stabilisation and feedback can improve jitters and drifts

- Still presence of large charge jitter

K. JENSEN *et al.* PHYS. REV. ACCEL. BEAMS **28,** 092802 (2025)

TABLE I. Quantitative effects of stabilization on LPA performance.

Quantity	Stabilization off: All shots	Stabilization off: Shots ≥ 5 pC	Stabilization on: All shots	Stabilization on: Shots ≥ 5 pC
Missed shots (< 5 pC)	145 (29%)		32 (6%)	
Charge (pC)	19.4 ± 17.9	26.8 ± 16.2	40.4 ± 20.4	43.1 ± 18.3
Average energy (MeV)	120.3 ± 18.9	111.8 ± 4.3	111.1 ± 9.1	109.7 ± 3.8
Energy spread (%, rms)	5.3 ± 3.0	4.1 ± 0.7	4.3 ± 1.9	3.9 ± 0.4

BERKELEY LAB

- Improved laser-plasma accelerator stability via high-bandwidth longitudinal focal position stabilization of a 100 TW-class laser system | Phys. Rev. Accel. Beams

Challenges - Characteristic

Ultra short bunches

with high peak current straight from source

- <50fs bunches, >5kA peak currents

Need to be mindful of:

- Coherent Synchrotron Radiation from bends
  - Will spoil projected emittance, can be mitigated with beamline design
- Coherent Optical Transition Radiation
  - Can complicate beam imaging
  - Can also be used for advanced diagnostics!

Challenges - Characteristic

Desire for Compactness

- Use high gradient focusing systems
  - Permanent Magnet Quads: Be aware of field quality, narrow aperture etc.
  - Plasma lenses
  - EMQ 50 T/m, PMQ 500 T/m, Plasma lens 5 kT/m

- If we want to preserve emittance, transport a large range of energies and have limits on our magnet strengths…
- *We will need many quads*

Challenges - Characteristic

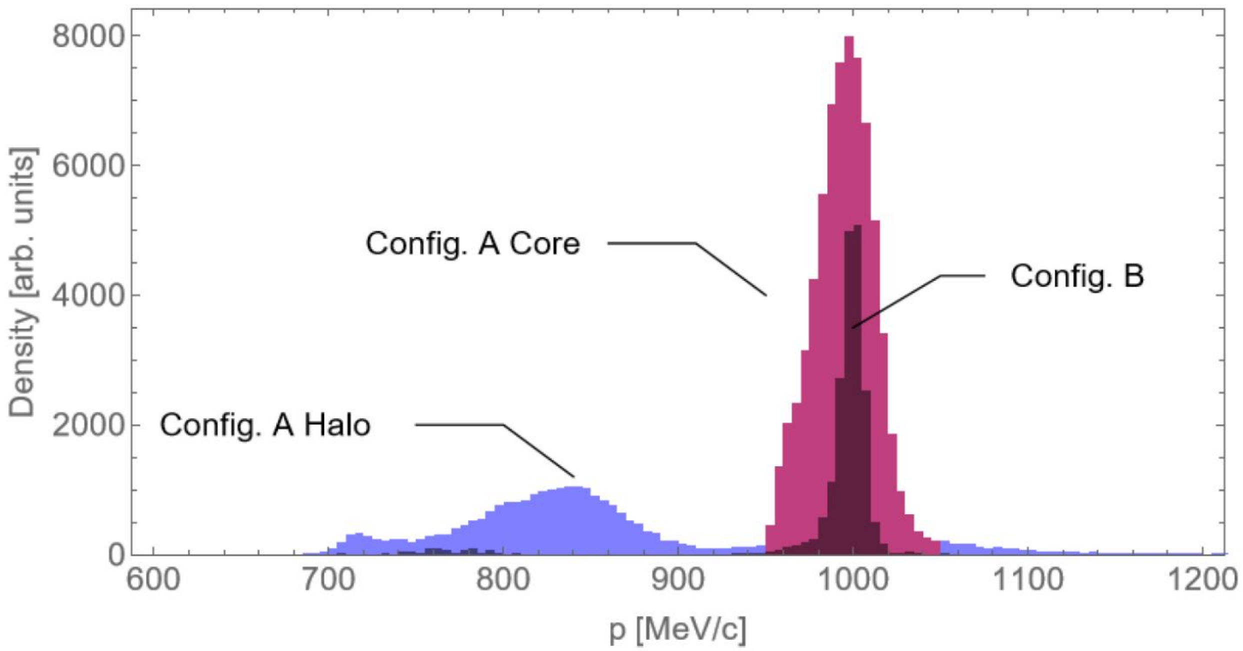
Desire for compactness

- Laser based = RF free (in most cases)
- RF systems put demand on lab infrastructure,
  - Hard to add post-hoc in small settings
- Removes some of the ‘beamline tools’

Challenges - Characteristic

Halos and energy tails

- E.g EPAC FBPIC simulated beams:
- Config core 'A' is *bright*
  - But it comes with a large trailing halo
- Config 'B' is *less bright*
  - But no halo!



Sims. courtesy O. Finlay, pub. in review

- E.g. Low energy particles from solid targets
  - TNSA has many off energy particles +additional species
  - "Plasma detritus"

Challenges – Characteristic

Source simulations and uncertainty of beam parameters:

- How well is the high power laser drive behaviour known?
  - Even mature commercial technology will produce differences between spec. and delivery

- Complex interplay between parameters :
  energy, charge, source exit size, and divergence

- Much **potential** from just a gas jet and a ~ PW laser
  - E.g pC to nC of charge, <1um emittance, 0.5 GeV to 5 GeV
  - Can't do all parameters at once!

- **More uncertainty and/or wider parameter space makes beamline design harder**

Challenges – Measuring and tuning

- Diagnostics are needed for
  - Feedbacks: stabilise interactions and account for drifts
    - These need to be non-invasive
  - Optimisation:
    - These need to single shot measurements; deal with jitters
- **Non-invasive and/or single shot diagnostic are the most challenging!**
- High energy systems >0.5 GeV
  - Diagnostic beamlines for rigid beams are not short

Challenges

- Charge jitter
- Energy Jitter
- Energy Spread
- Transverse halos
- Off-energy halos or tails
- Pointing jitter
- Emittance growth
- Source parameter uncertainties

Applications

Electron Beam Applications

Photon generation:

- FEL
- ICS
- Bremsstrahlung
- Betatron radiation

Direct use of beam:

- Direct irradiation
  - Medical radiotherapy/radiobiology
- Medical or industrial imaging, nuclear physics
- Storage ring injector, further plasma acceleration
  - (e.g. staging for collider)
- Generation of secondaries (positrons)

Applications – Betatron Radiation

- Charge jitter
- Energy Jitter
- Energy Spread
- Transverse halos
- Off-energy halos or tails
- Pointing jitter
- Emittance growth
- Source parameter uncertainties

- Transverse Collimators
- Dispersive Collimators
- Transverse focusing
- Emittance preserving transport
- Magnetic compressors
- Energy spread compensation
- "Basic" Diagnostics
- "Advanced" Diagnostics

Applications – Bremmstrahlung

- Charge jitter
- **Energy Jitter**
- Energy Spread
- Transverse halos
- Off-energy halos or tails
- Pointing jitter
- Emittance growth
- Source parameter uncertainties

If you want a focus,
energy jitter will be an issue
But, potentially not significant

- Transverse Collimators
- Dispersive Collimators
- **Transverse focusing**
- Emittance preserving transport
- Magnetic compressors
- Energy spread compensation
- "Basic" Diagnostics
- "Advanced" Diagnostics

Applications – Industrial Imaging

- Charge jitter
- Energy Jitter
- Energy Spread
- Transverse halos
- Off-energy halos or tails
- Pointing jitter
- Emittance growth
- Source parameter uncertainties

If one wants to illuminate a large area, focussing and jitters need to be addressed

- Transverse Collimators
- Dispersive Collimators
- Transverse focusing
- Emittance preserving transport
- Magnetic compressors
- Energy spread compensation
- "Basic" Diagnostics
- "Advanced" Diagnostics

Applications – Radiobiology/-therapy

- Charge jitter
- Energy Jitter
- Energy Spread
- Transverse halos
- Off-energy halos or tails
- Pointing jitter
- Emittance growth
- Source parameter uncertainties

Collimating to solve these problems could cause *more* charge jitter

- Transverse Collimators
- Dispersive Collimators
- Transverse focusing
- Emittance preserving transport
- Magnetic compressors
- Energy spread compensation
- "Basic" Diagnostics
- "Advanced" Diagnostics

Applications – FEL

- Charge jitter
- Energy Jitter
- Energy Spread
- Transverse halos
- Off-energy halos or tails
- Pointing jitter
- Emittance growth
- Source parameter uncertainties

All the challenges need to be addressed
All the tools are needed

- Transverse Collimators
- Dispersive Collimators
- Transverse focusing
- Emittance preserving transport
- Magnetic compressors
- Energy spread compensation
- "Basic" Diagnostics
- "Advanced" Diagnostics

Applications - FEL

- More certainty on source parameters = more efficient design
- Deploying all the tools from the toolbox results in not a “compact system”
- Must also consider the length of the undulators

The better *you look after the beam*, the shorter the undulators will be

Case Study:
CLARA

CLARA

- Daresbury Laboratory's Flagship accelerator
- Medium energy user facility for accelerator R&D
- 250 MeV, 250pC, 100Hz

- FEBE Experiment hutch and dedicated beamline
  - 120 TW Laser: Amplitude Ti:Saph, 2.8J, 23fs, 5Hz

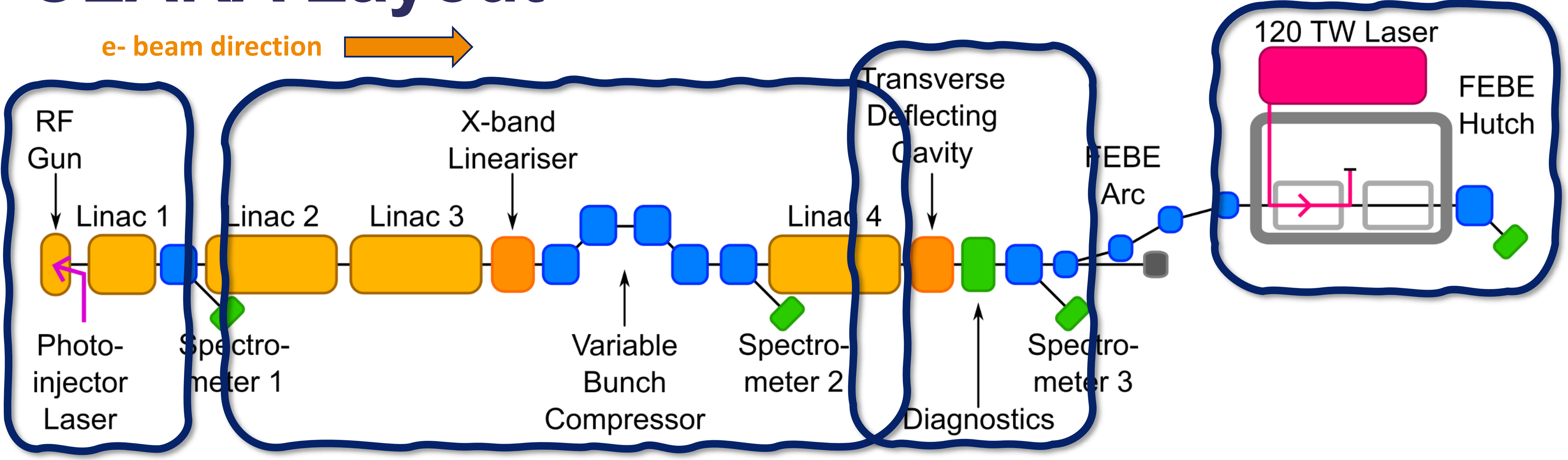
- **Key Science Themes:**

  Electron radiotherapy/radiobiology, Novel Accelerators, Laser-electron interactions, Advanced diagnostics, AI for accelerators

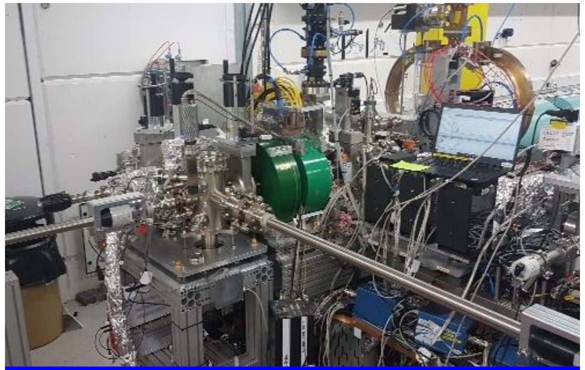
Not a "plasma beamline"
a beamline for plasma accelerator R&D!

CLARA Layout

Total Length ~80m



Generate **Accelerate & Manipulate** **Measure** **Experiment**


CLARA Gun

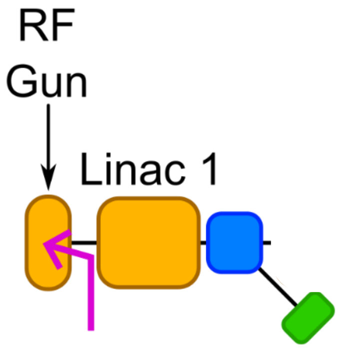

RF Linac


Transfer arc to FEBE hutch


FEBE hutch

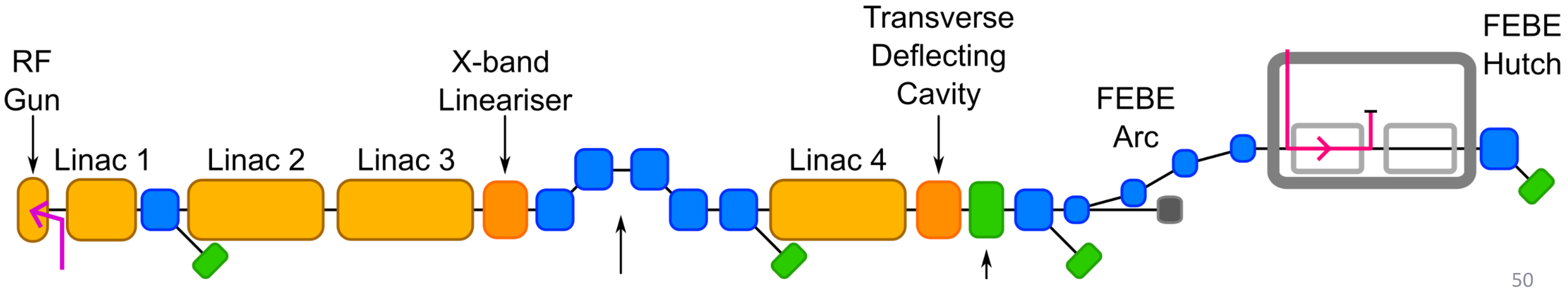
CLARA in numbers

Example technical system	CLARA Front End
RF Structures	2
Magnets	22
Diagnostic Systems	13
Vac. Gauges + Pumps	57

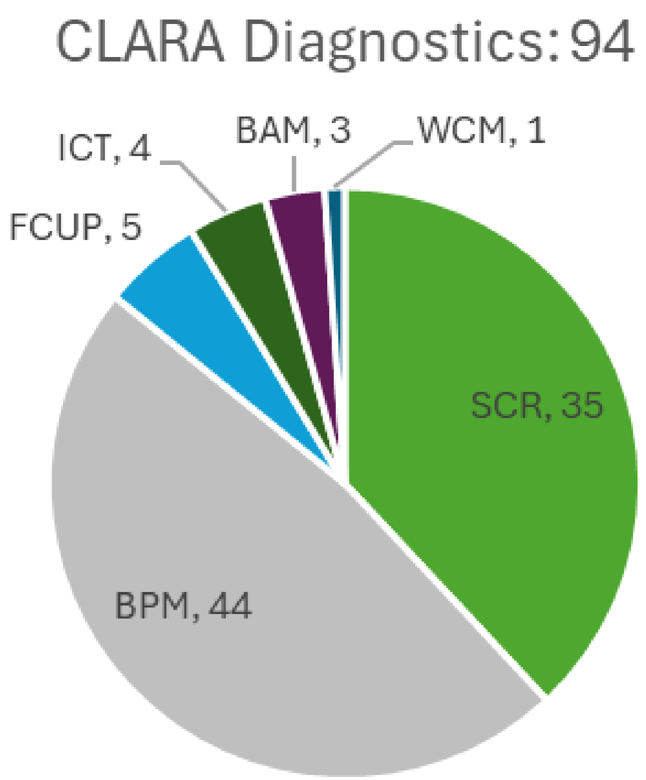


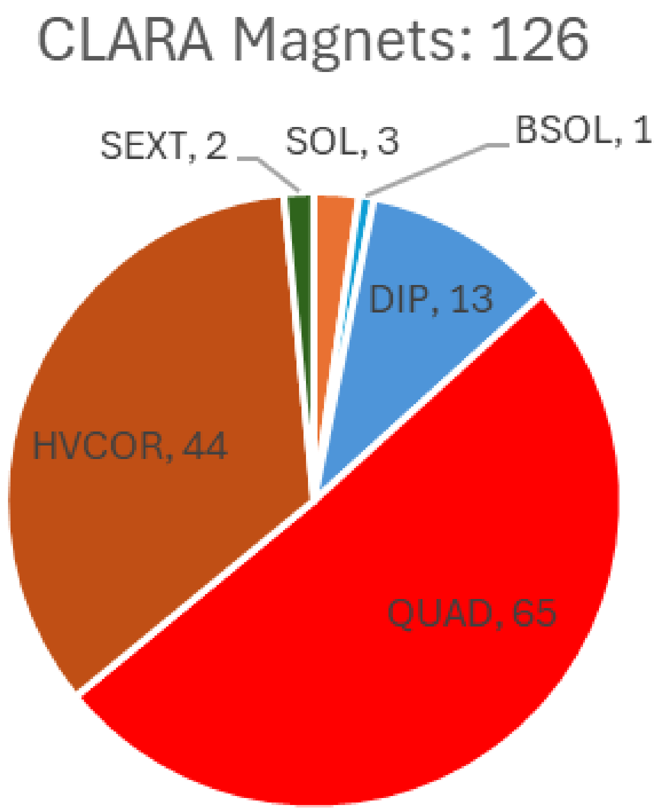
CLARA in numbers

Example technical system	CLARA Front End	CLARA 250 MeV	CLARA + FEBE
RF Structures	2	7	7
Magnets	22	77	126
Diagnostic Systems	13	65	94
Vac. Gauges + Pumps	57	109	155



CLARA systems breakdown



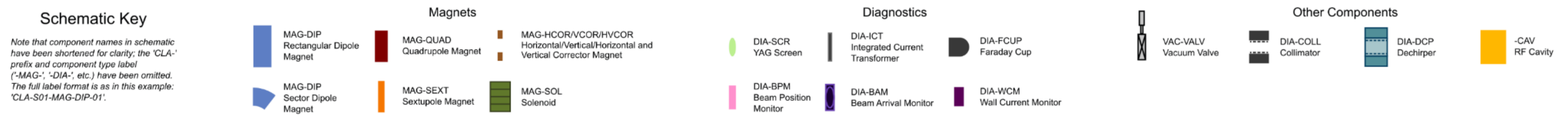


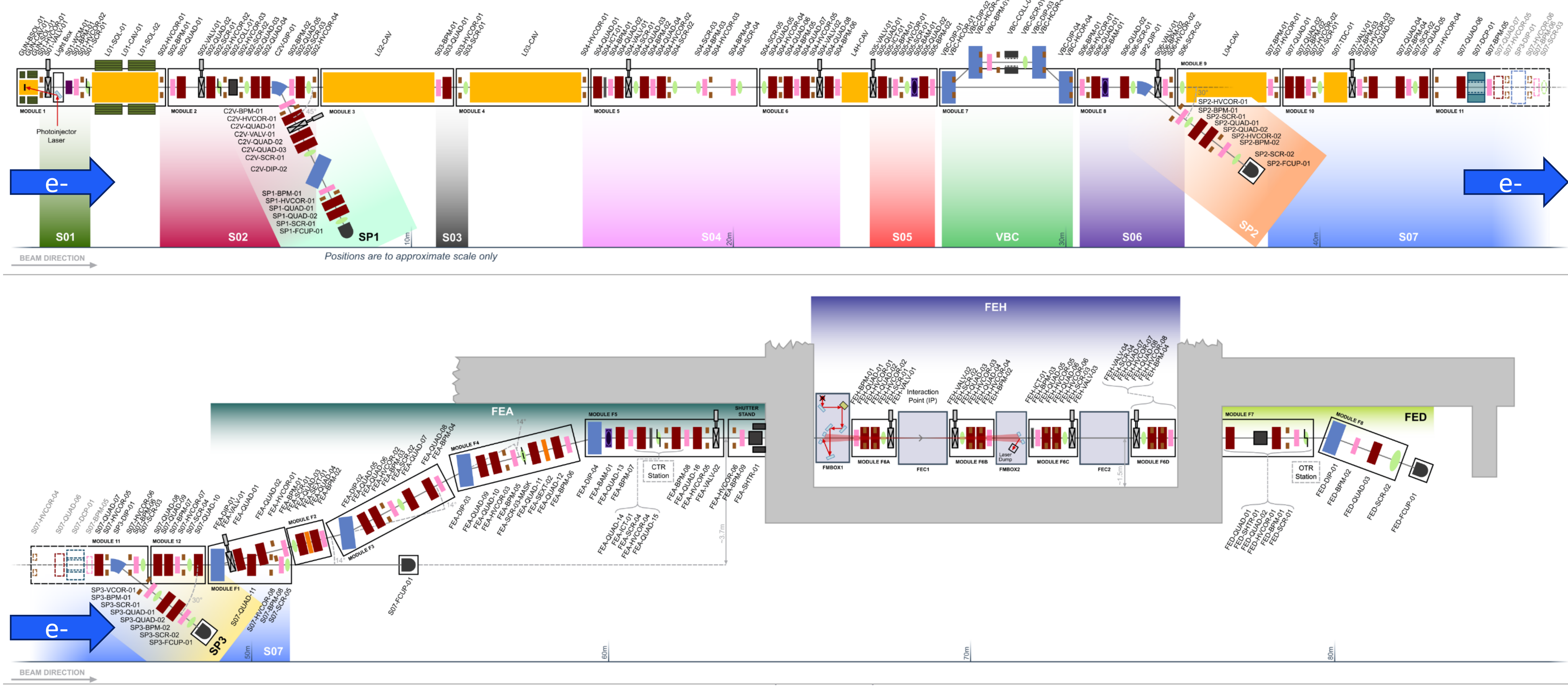
CLARA Schematic

v1.0 06/01/2025

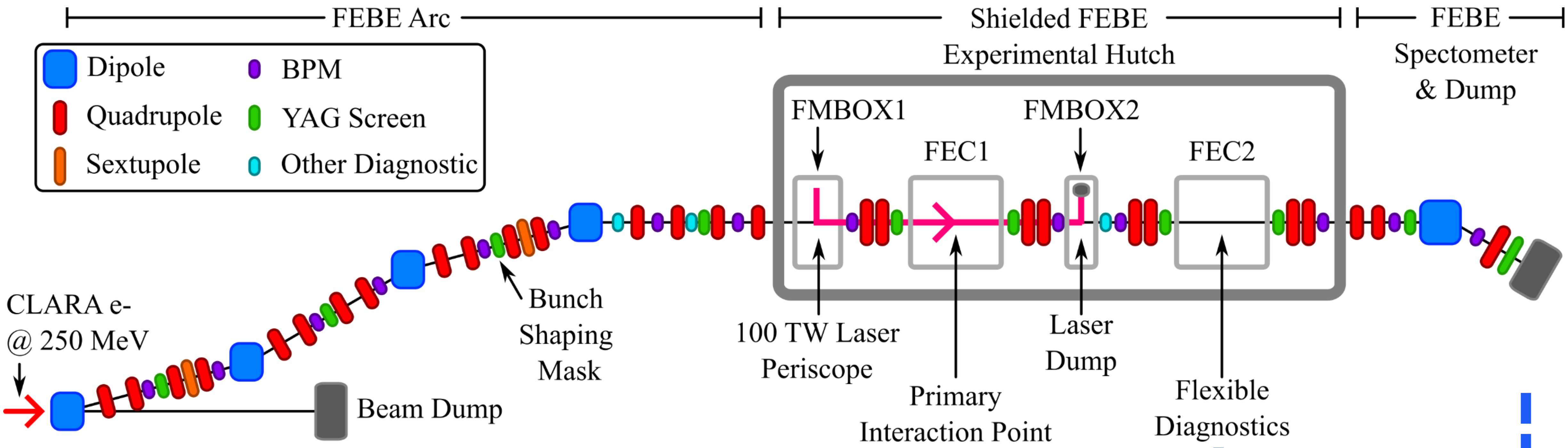
Associated technical drawing: 256-21097-A

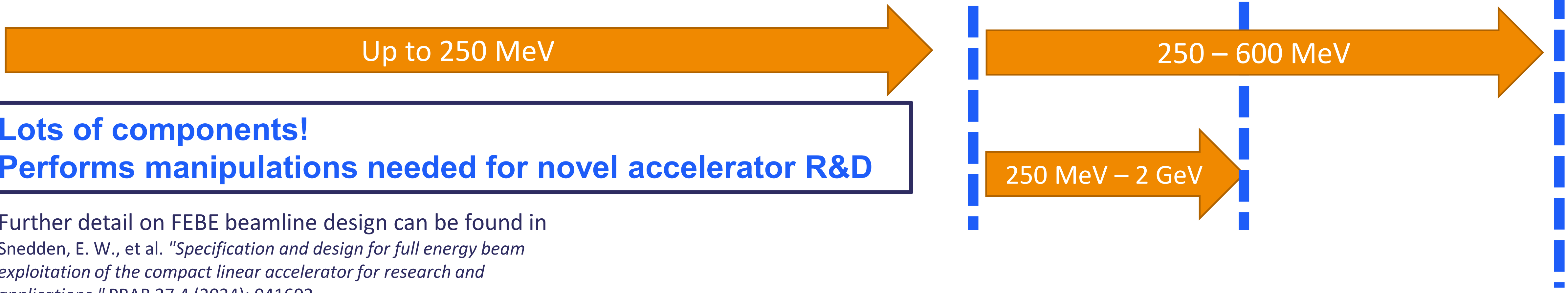
Associated lattice version tag: 240715





FEBE Beamline & Energy Sectors

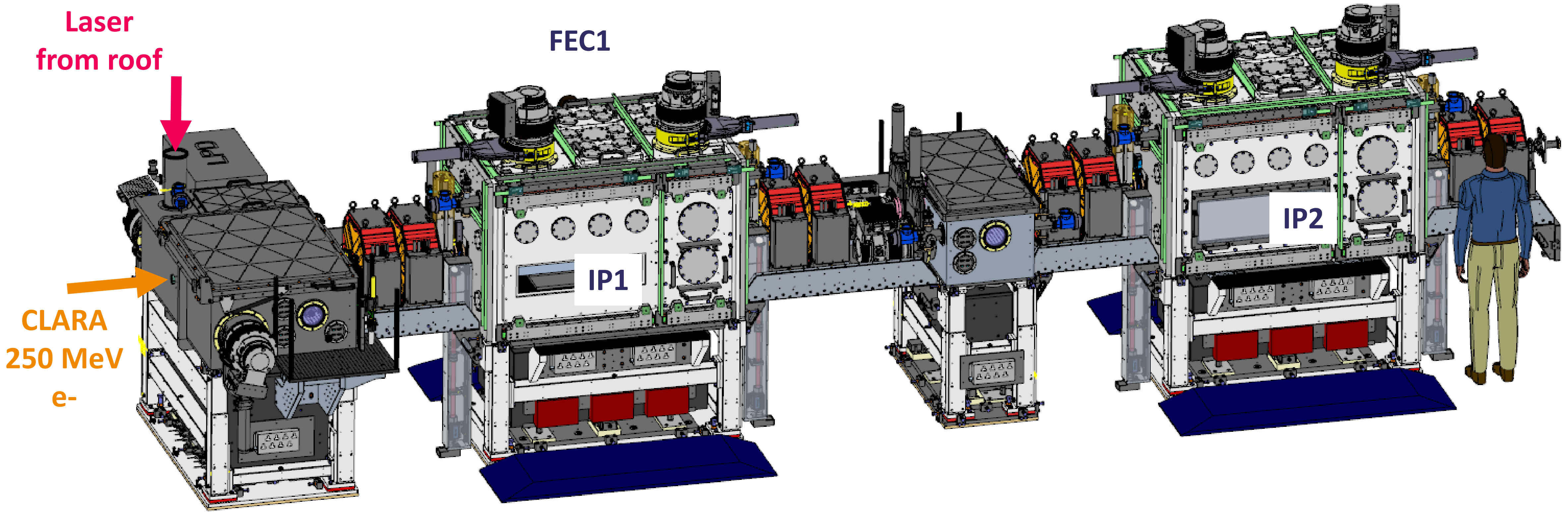




Lots of components!
Performs manipulations needed for novel accelerator R&D

Further detail on FEBE beamline design can be found in
Snedden, E. W., et al. *"Specification and design for full energy beam exploitation of the compact linear accelerator for research and applications."* PRAB 27.4 (2024): 041602.
https://doi.org/10.1103/PhysRevAccelBeams.27.041602

FEBE Hutch



Gas Management

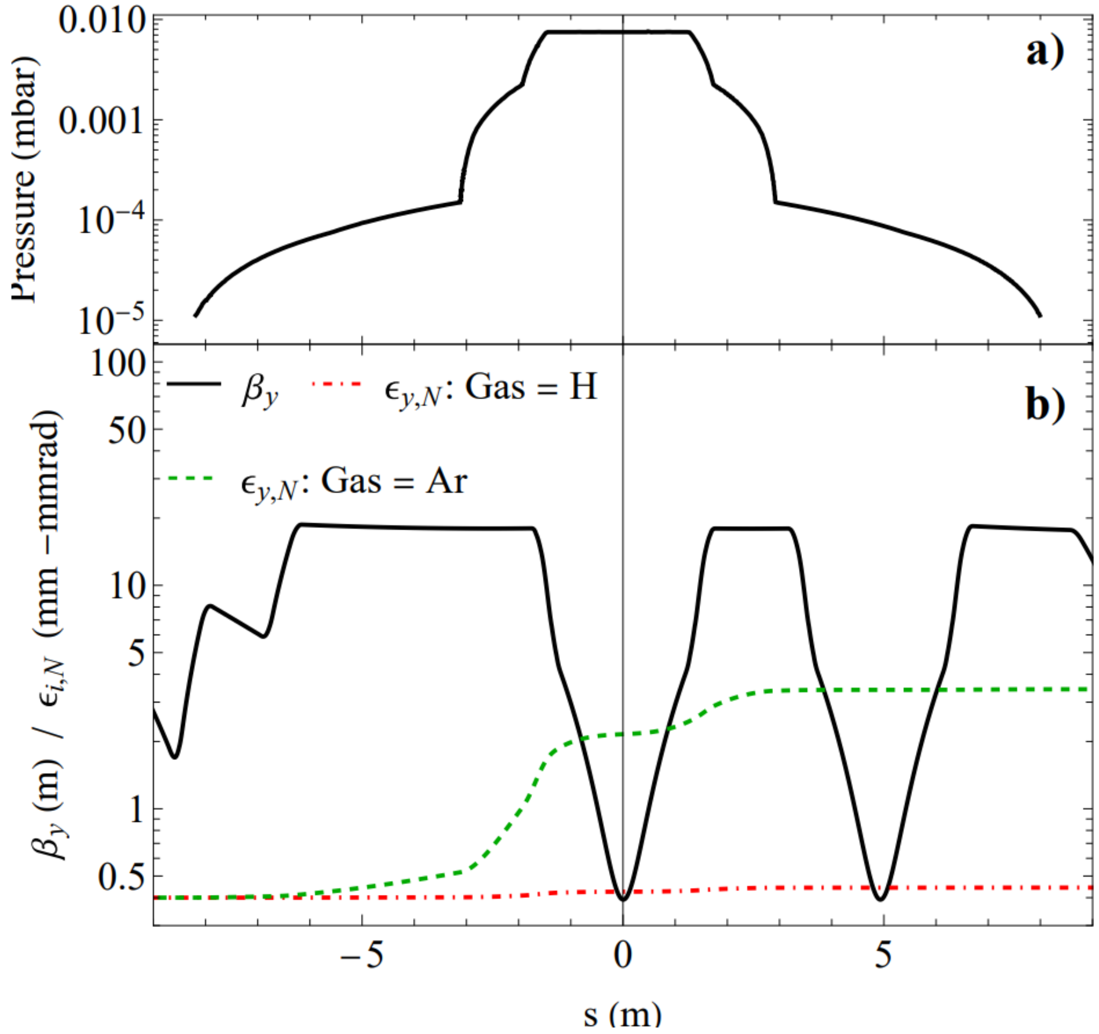
- High power laser -> **Large** apertures
- Gas load -> **Small** apertures

  - Invested in large volume turbos on experimental chambers & mirror boxes 6 at ~ 2000l/s

  - Upstream irises and apertures to reduce gas propagation in electron beamline

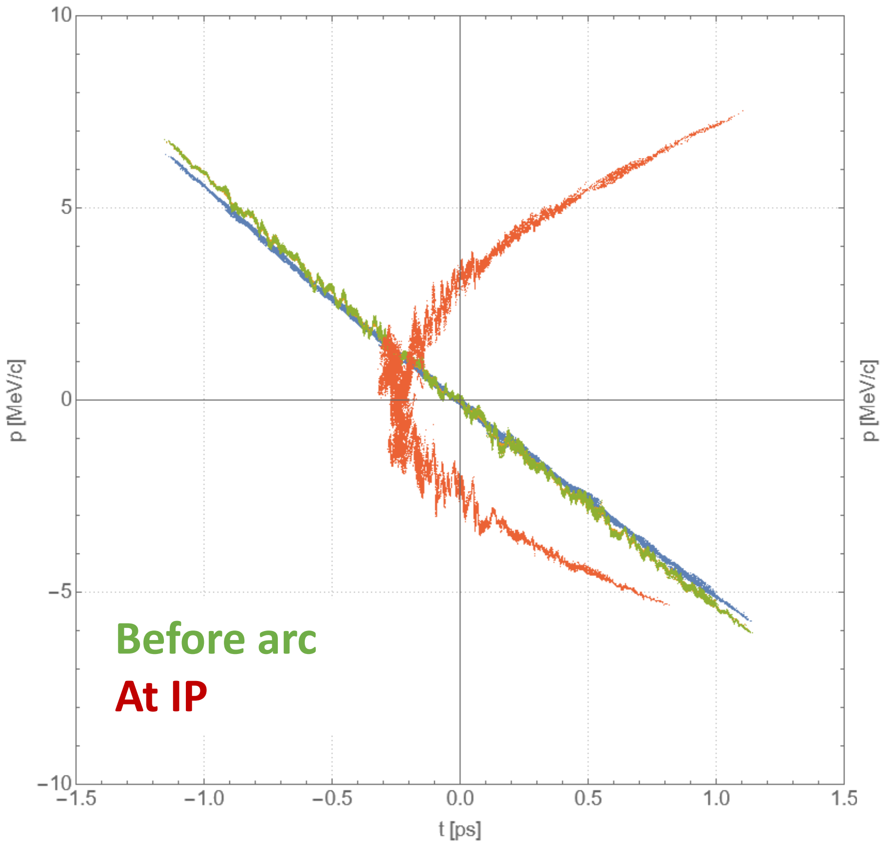
Don't what large beta & high pressure at same places

- Negligible modelled emittance growth for Hydrogen,
  - Limited growth for heavier species, e.g. Argon

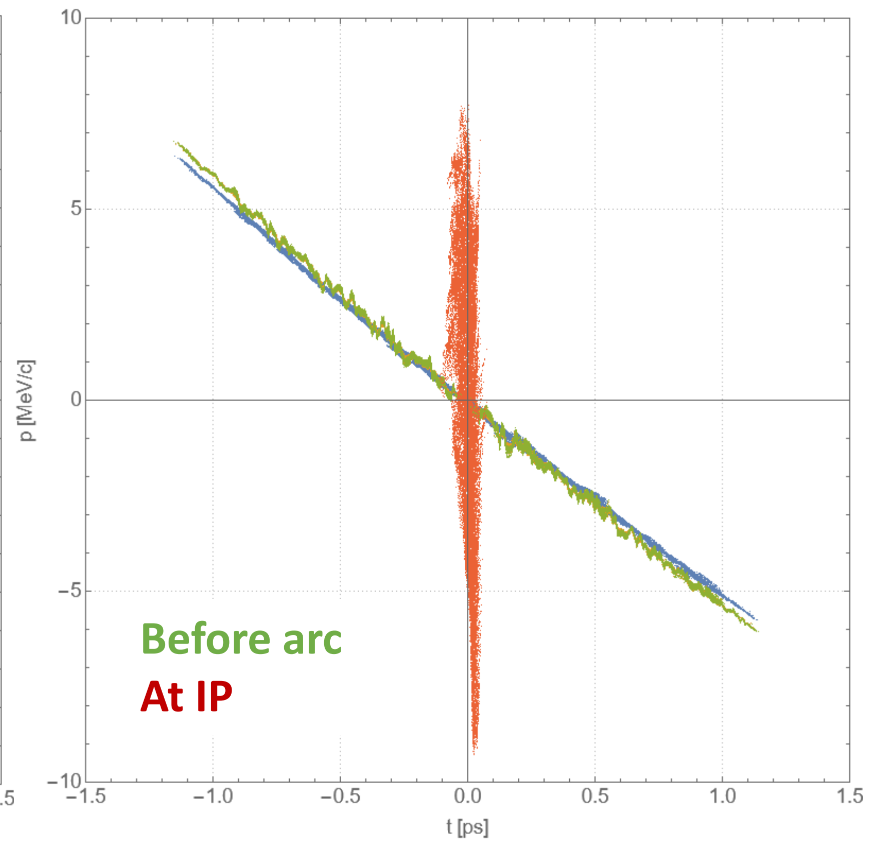


Mitigation of higher order terms

- Needed an arc
- Fixed displacement and length
  - Bunker size is fixed
- High order aberations when energy spread is large ***(RMS ~1%!)***
- Energy spread is large when we want to compress
- Need sextupoles to correct!



Without sextupoles



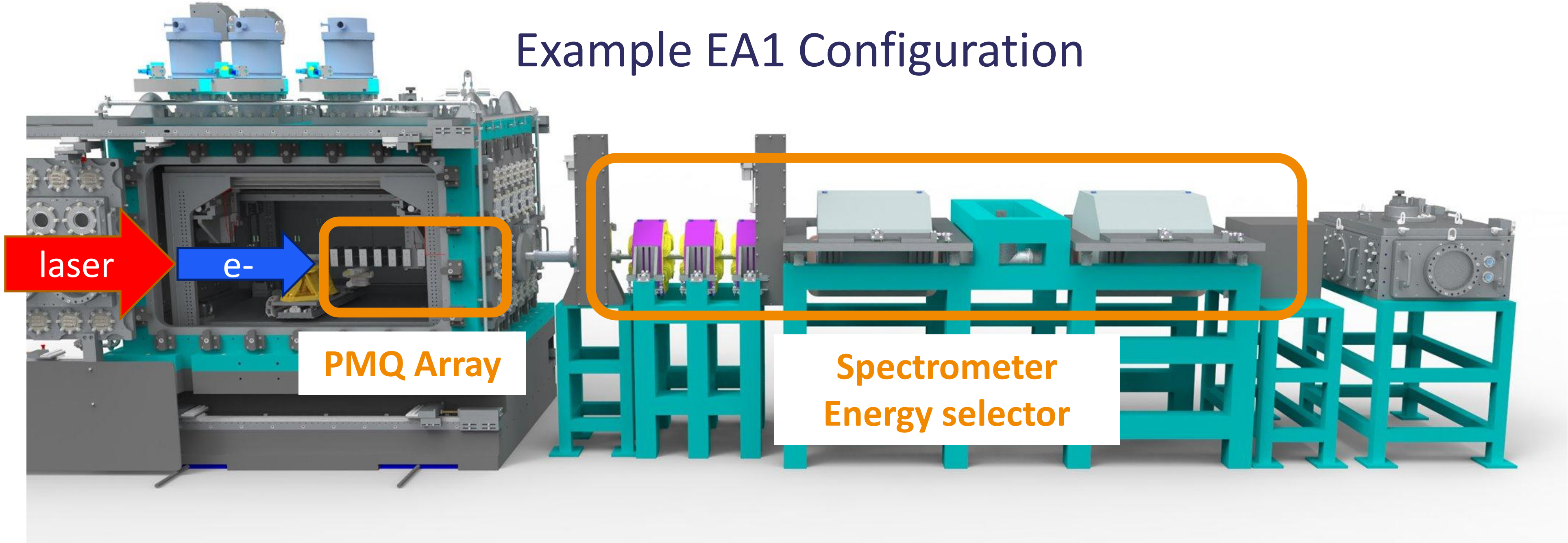
With sextupoles

Case Study:
EPAC EA1

EPAC EA1 Electron beamline

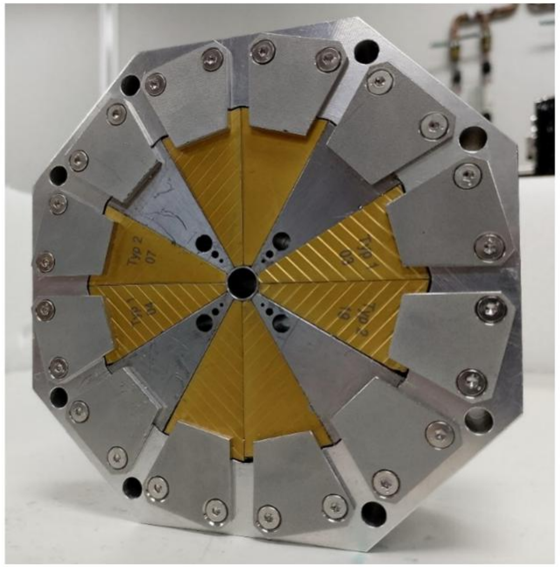
- EPAC is built, laser being commissioned, beamline components being installed
- Laser: 1 PW, 10 Hz, 30 J, <30 fs
- Electrons: 1-5 GeV, 0.1 – 1 nC, 1 – 25% energy spread

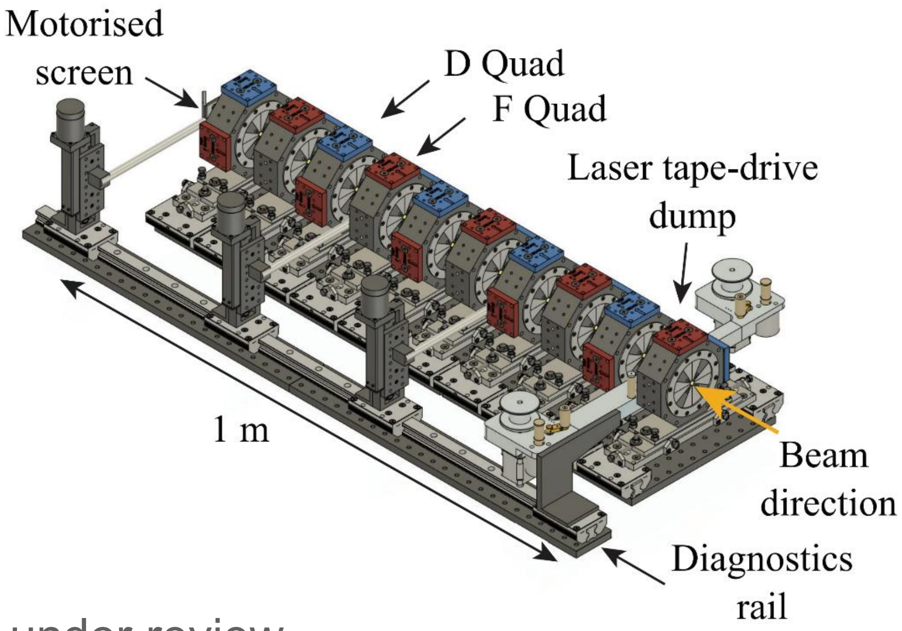
Example EA1 Configuration

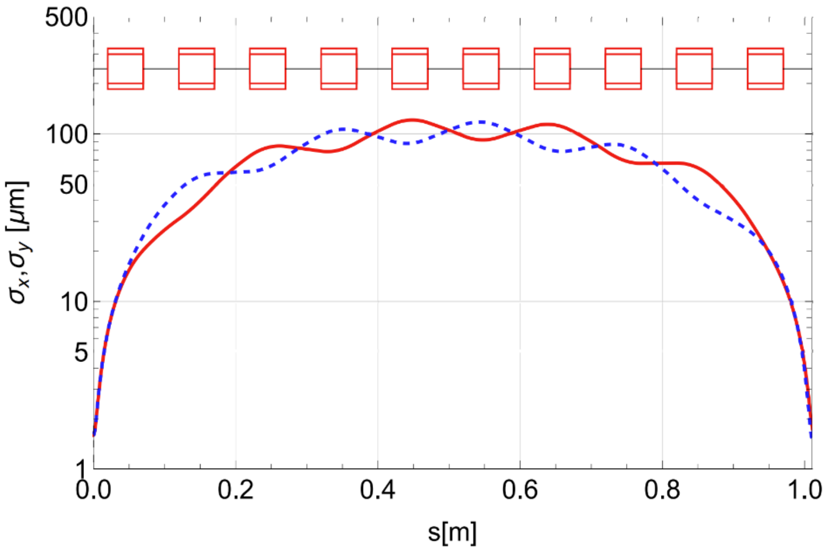


EPAC PMQ Array

- ~500 T/m Halbach quadrupoles, 5cm long, 5cm separation
- Relays electron beam focus from source to application
- Relatively robust to jitters in source terms







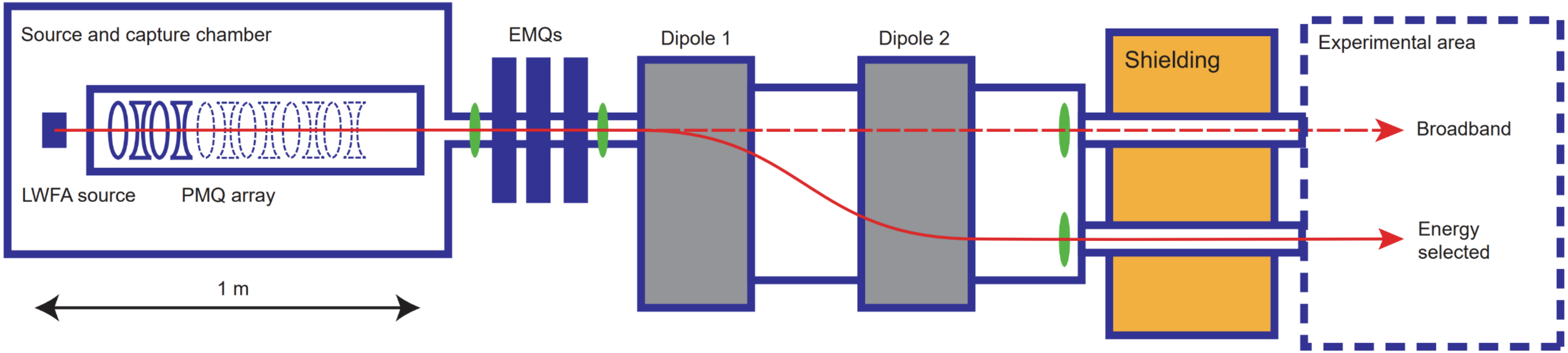
Paper on beamline design under review

Building these quadrupoles to specification has challenges:

- [Measurement and Simulation of Demagnetization in a Prototype Halbach Array Quadrupole]

EPAC Spectrometer line

- Energy spectrum measurement, up to 5 GeV
- Energy selection and collimating to deliver to application

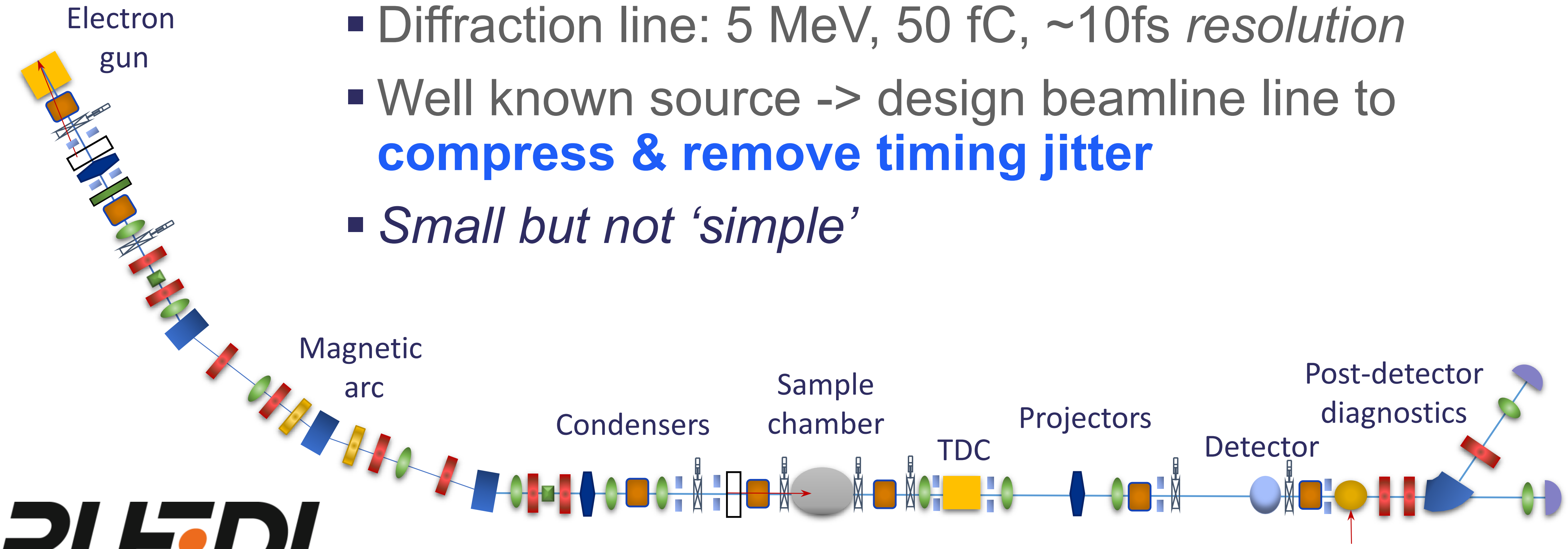


- Large EM Dipoles have been procured
- **Requires high current DC power supplies & water cooling -> Integration challenges!**

Other beamline designs and builds at Daresbury Lab & Cockcroft Institute

RUEDI

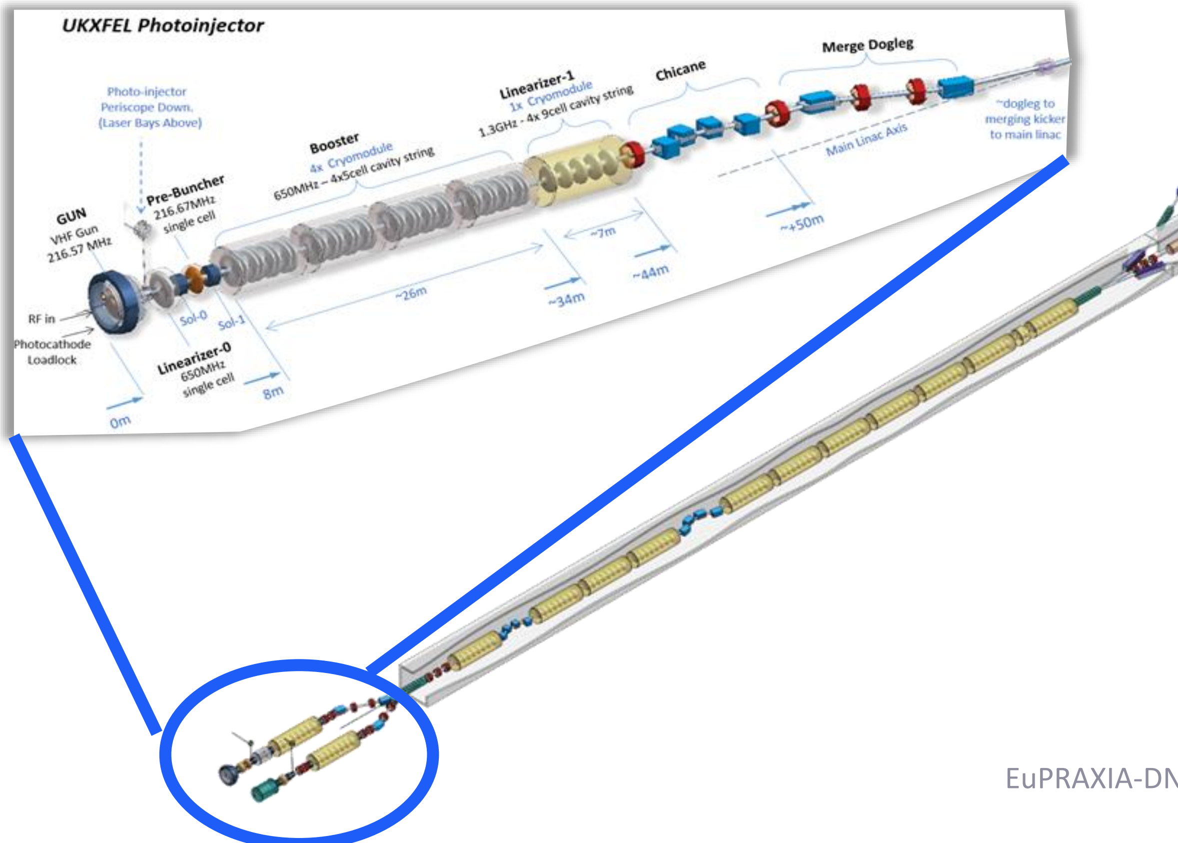
- CDR, TDR complete,
  now moving to final design & procurement
- Diffraction line: 5 MeV, 50 fC, ~10fs *resolution*
- Well known source -> design beamline line to **compress & remove timing jitter**
- *Small but not 'simple'*

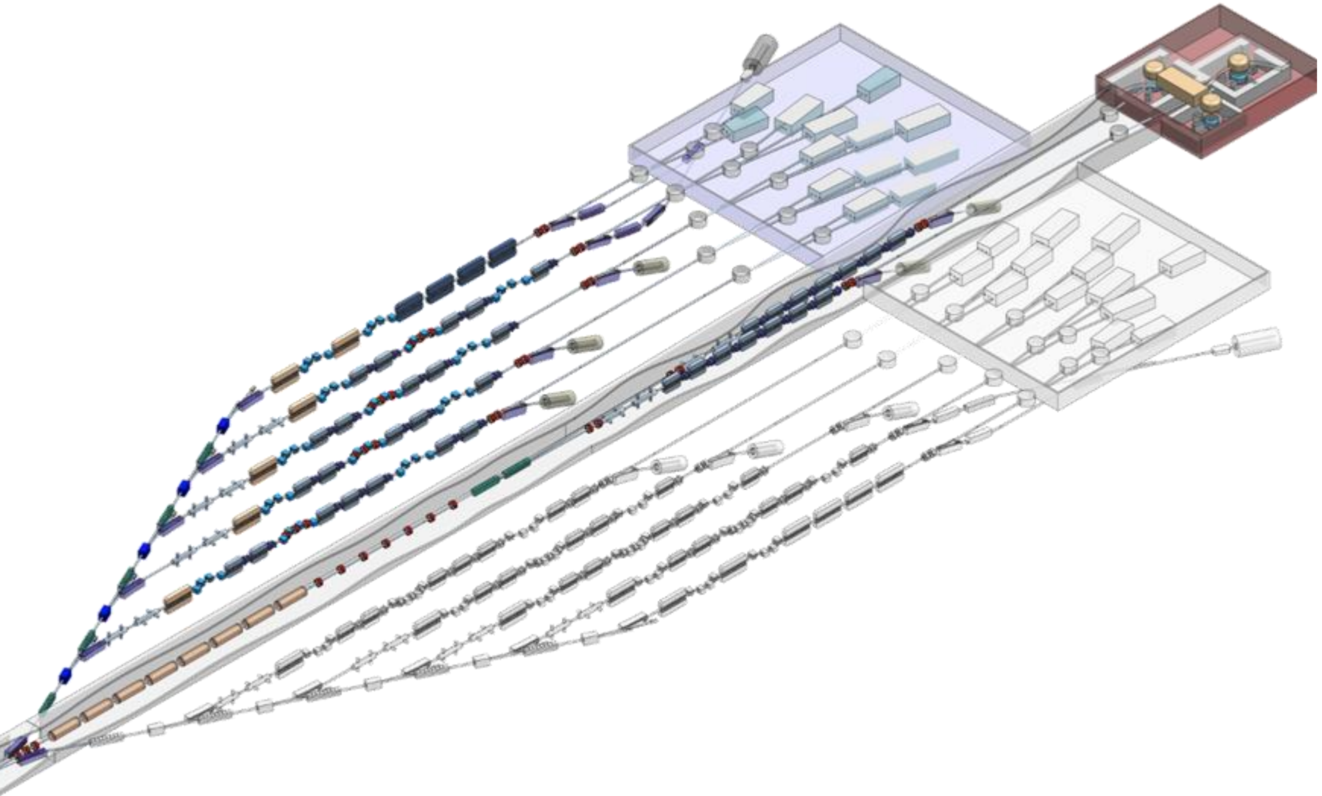


RUEDI

UKXFEL

- Design study: CDR and Options Analysis complete





- 8 GeV SC FEL facility
- Includes PWFA booster beamline
- Includes work on X-ray beamlines + additional sources

Christie Hospital Research Beamline

- Proton therapy research beamline (cyclotron source)
  - At a cancer therapy hospital
- Aiming at proton FLASH research
  - (cells now, in future small animals)

- Conventional beamline, functionally independent from treatment beamlines
  - Cockcroft Institute: design
  - ASTeC: proton beam shaping in 3D for treatment

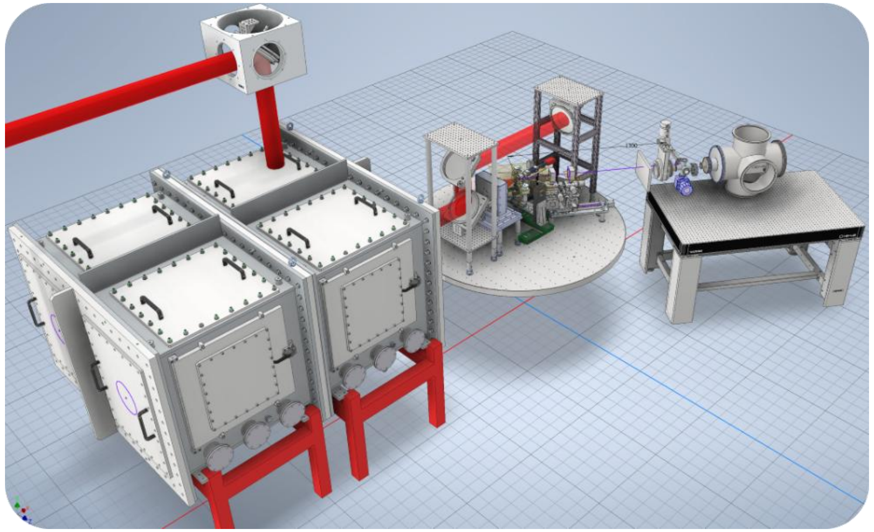
[*The proton therapy research beamline at the Christie NHS foundation trust - PubMed*]

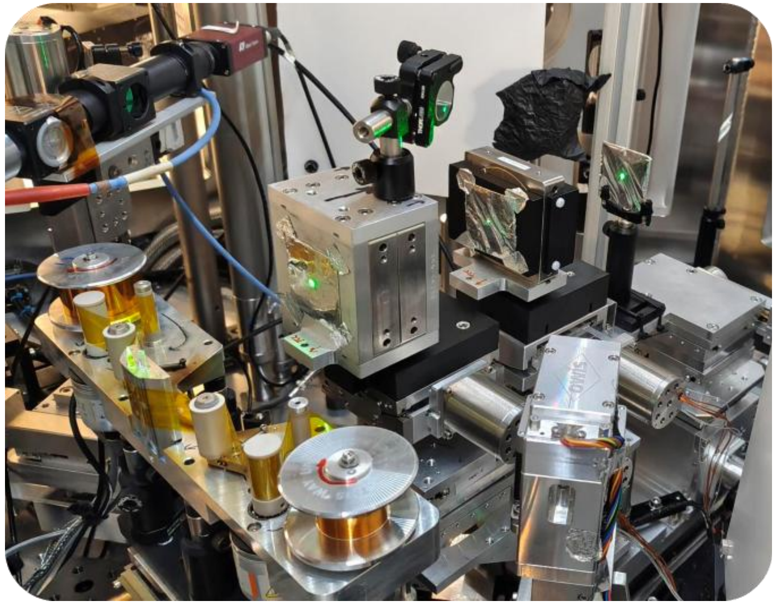
The Cockcroft Institute of Accelerator Science and Technology

MANCHESTER 1824 The University of Manchester

ITRF/LhARA & PoPLAR

- LhARA:
  - Large collaboration across many partners; Plasma sources for Radiobiology
- ITRF: Project to design dedicated facility for radiobiology
  - Beamline, infrastructure, + more
- PoPLAR:
  - Proof of principle beamline @ SCAPA University of Strathclyde
  - Commissioned; >10 MeV TNSA for FLASH





PoPLAR Beamline, credit Dr. R. Gray

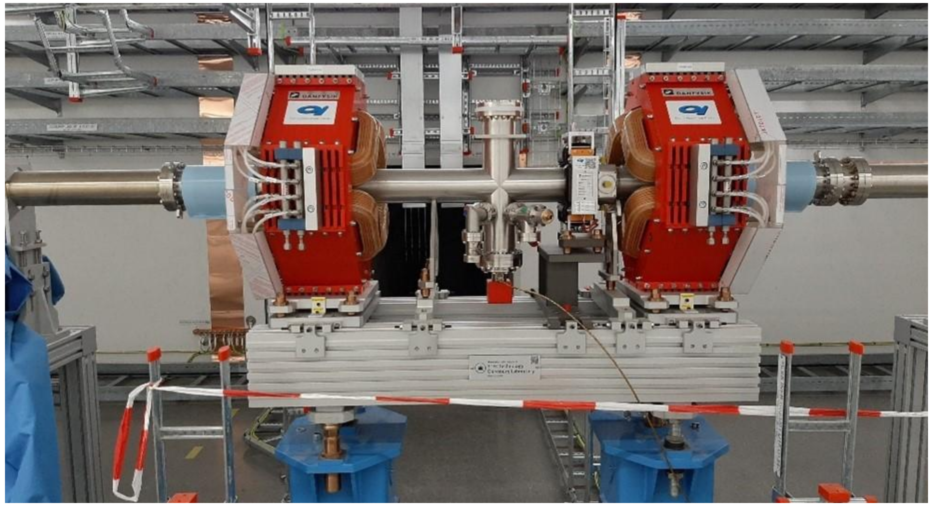
The Cockcroft Institute of Accelerator Science and Technology

University of Strathclyde Glasgow

Other beamline builds completed at Daresbury Laboratory

ESS beam transport modules

- 74 built for SC linac cleanliness



BTM installed at ESS

- Technology European Spallation Source: Beam Transport Modules (BTM)

ELI-NP electron beamline modules

- 35 modules, mechanical + controls

- Ready for despatch to ELI-NP - The ingredients to generate gamma beams of unprecedented brilliance

Conclusion

Summary

- Tools are availible to make LWFA beams suitable for applications
  - Invest effort now in diagnostics to support future advanced beamlines
- Source charge jitter should be prioritised
  - Unlock more radiobio-/therapy applications
- Complex applications will require complex beamlines
  - Means bigger facility footprints
- Large experience at Daresbury Laboratory designing and building beamlines and working with novel plasma schemes