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The Rapiscan® Linac Test Beamline

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IOP Particle and Beams Conference

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S&T INNOVATION HUB

DISCOVER INCUBATE ACCELERATE

Contents

Introduction | Rapiscan Cargo & Vehicle Inspection

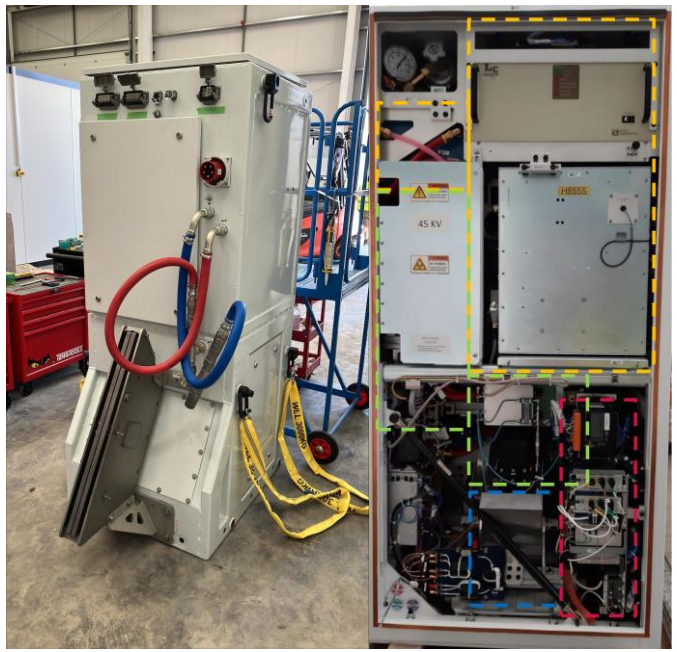
Rapiscan provide a series of security solutions

- **Vehicle screening technologies (CVI)**
- Aviation (baggage & people) screening technologies (ASI)
- Services, integration & training (S2 GLOBAL)

Stoke-on-Trent site primarily for production of X-ray Cargo & vehicle inspection (CVI) systems

- X-ray inspection of trains to HGV's, cars and their cargo via a variety of products and modalities (portal, gantry, mobile etc.)
  - For example, the P60 – 6/4 MeV dual energy fixed portal system
  - Deployed at borders, ports or anywhere in **challenging conditions** with **high up-time**
- Multi-energy accelerator-based Bremsstrahlung sources with **compact footprint**

P60 currently in use by S&T team.

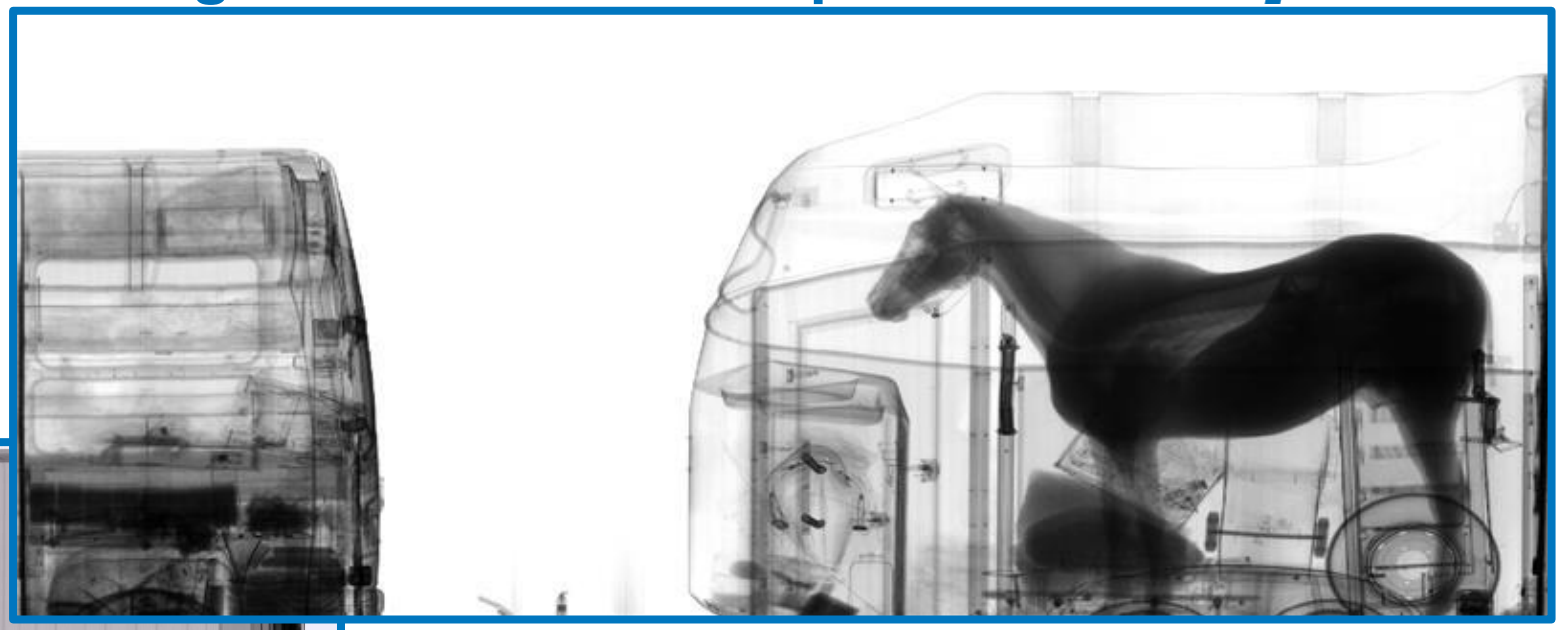


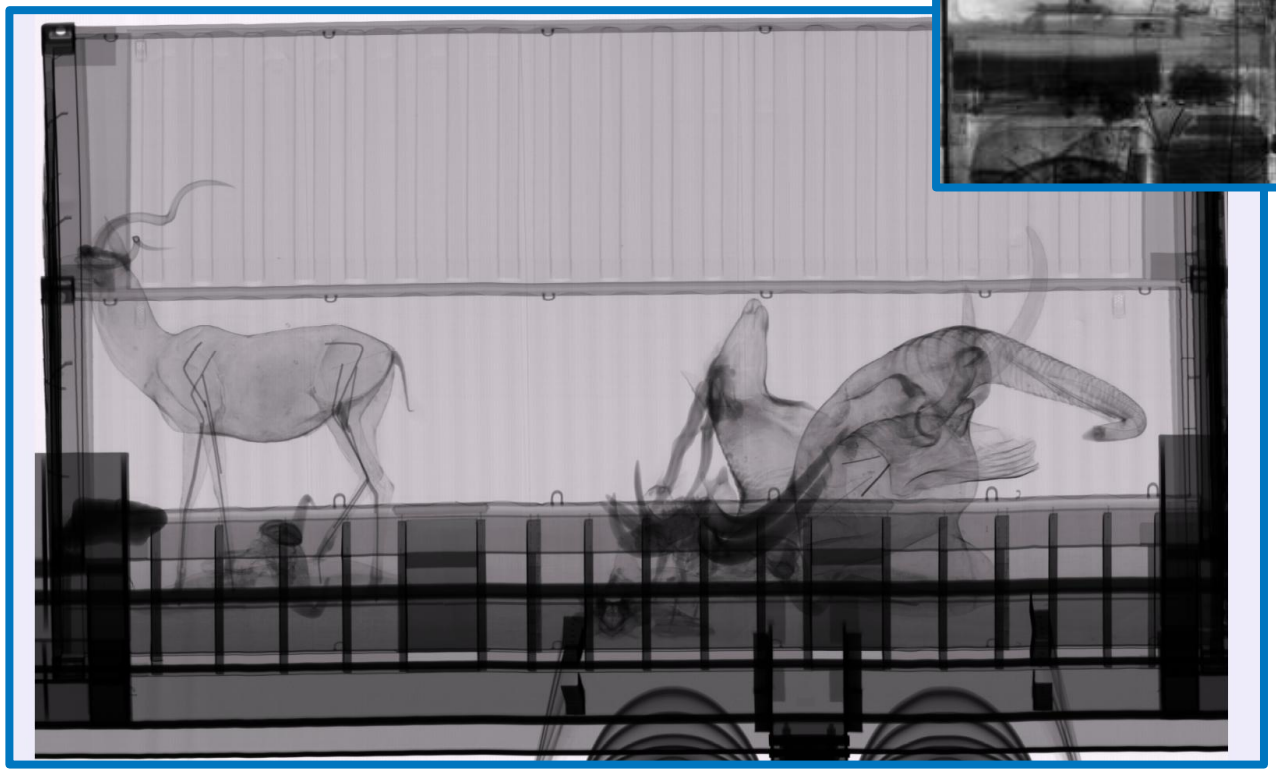
Left: linear accelerator prototype. Right: internals of an ETM cargo-scanning linac.

Linear accelerators used for transmission CVI typically

- Deliver Mev-scale X-rays via Bremsstrahlung
- Use **normal conducting** (S-, C-, X-band) accelerating cavities with **magnetron** RF power delivery
- Use a thermionic electron gun
  - Creates a long electron bunch(**-ish**) - duration of a few RF buckets
- Are collimation dominated
  - Apertures define the e^- beam at the converter target
- Have space charge impacted beam dynamics
  - Reasonably high ~sub-nC charge
- **Contain no electron beam diagnostics**

Introduction | Rapiscan Cargo & Vehicle Inspection

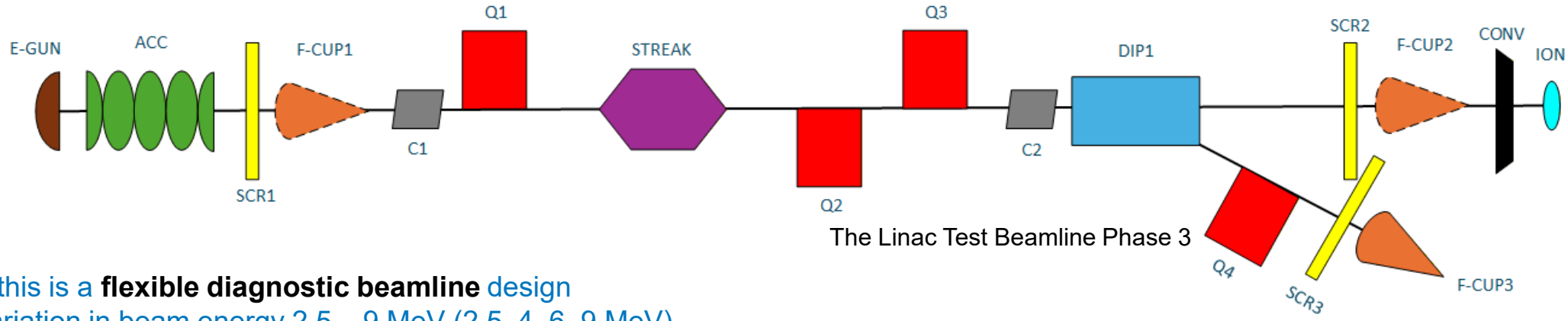




Introduction |The Linac Test Beamline

The linac test beamline (LTB) is being developed to

- Perform a **full 6D e⁻ beam characterisation** of the suite of linear accelerators deployed on Rapiscan CVI systems
- Act as a **development platform** for linear accelerator & CVI system-level research activities
- Support **external accelerator R&D** such as **university collaborations & potential external users** (component suppliers, NDT etc.)
- Train industrial accelerator scientists



The Linac Test Beamline Phase 3

In essence this is a **flexible diagnostic beamline** design

- Variation in beam energy 2.5 – 9 MeV (2.5, 4, 6, 9 MeV)
  - Variety of cavities, magnetron/klystron RF power sources under investigation
- Both e⁻ beam and high-energy X-ray diagnostics
  - Experiments in improvements to accelerator system for Bremsstrahlung X-ray generation
- Adaptable to varying use case i.e. e⁻ beam irradiation

The beamline is 3.8 m long. Located within a 5 x 10 m bunker at the Stoke-on-Trent S&T Innovation Hub.

Design process begun **late 2025** and expect construction of the beamline (first phases) to begin **late 2027** with first commissioning & experimental characterisation run in **2028**

- Proof-of-concept work in bunker beforehand → transition to LTB development

Beamline Design | Design Overview

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Both physics and engineering design stages ongoing in parallel

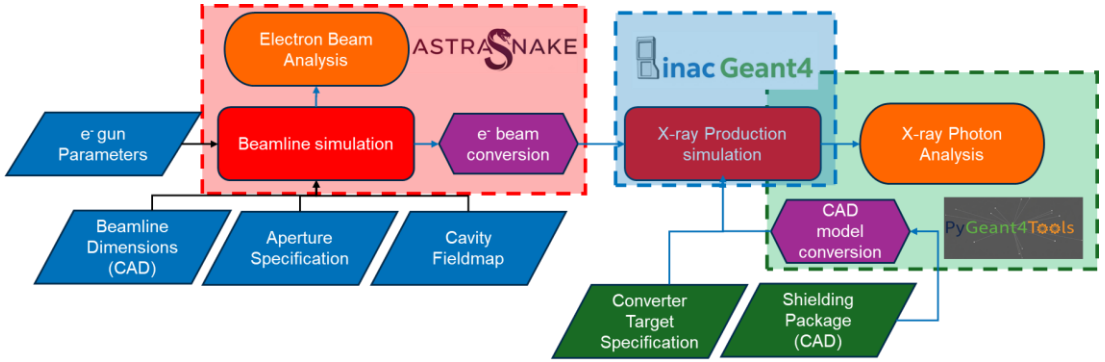
- **Physics design** involves optimising the beamline for the required modes and replicating measurements in simulation
- **Engineering design** focused on component specification, suppliers and infrastructure

Physics design uses of start-to-end (S2E) simulations & **developed toolkit**

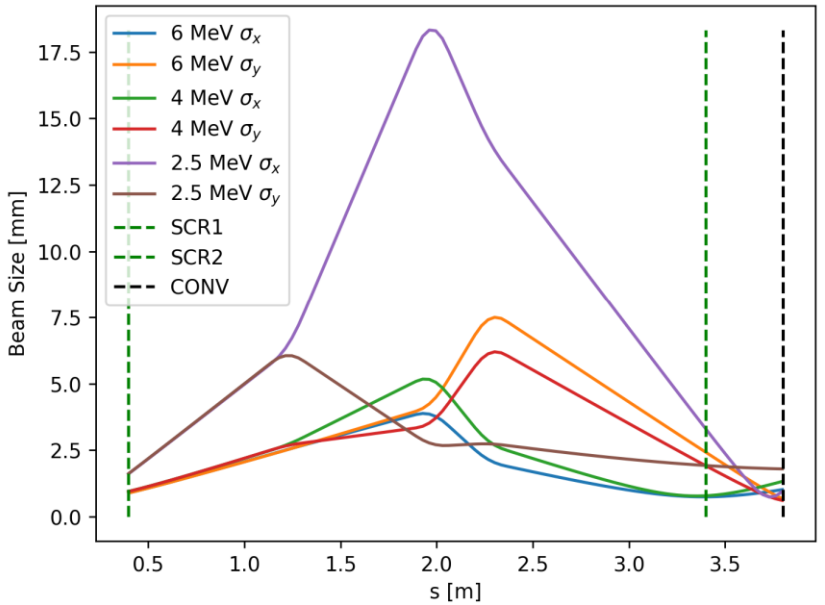
- Electron beam (ASTRA) + X-ray production (Geant4) simulations with CAD input
- Python-based wrapper for the whole S2E simulation

Developed **several modes** for operating the beamline

- Converter beam size matching ($\sigma_{SCR1} = \sigma_{CONV}$) – replicating X-ray production
- Minimum beam size on converter target
- Characterization measurements (Emittance, Momentum & Spread, Bunch Duration)



Schematic of the workflow for the S2E simulations using the Astrasnake, Linac Geant4 & PyGeant4Tools toolkits.



Optimised for Δσ~0.5 mm tolerance converter beam size matching for the on-momentum core (6/4 ±0.5 MeV, 2.5 ±0.1 MeV) of the bunch with space charge.

Challenges

Aperture/Collimation dominated beam dynamics

- On-target beam size set by collimation

Thermionic electron gun producing long pulses

- No bunching so we see a few buckets of beam

Space charge

- High dose requires high charge, which means space charge affects out beam dynamics

Complexity does not necessarily scale with accelerator size

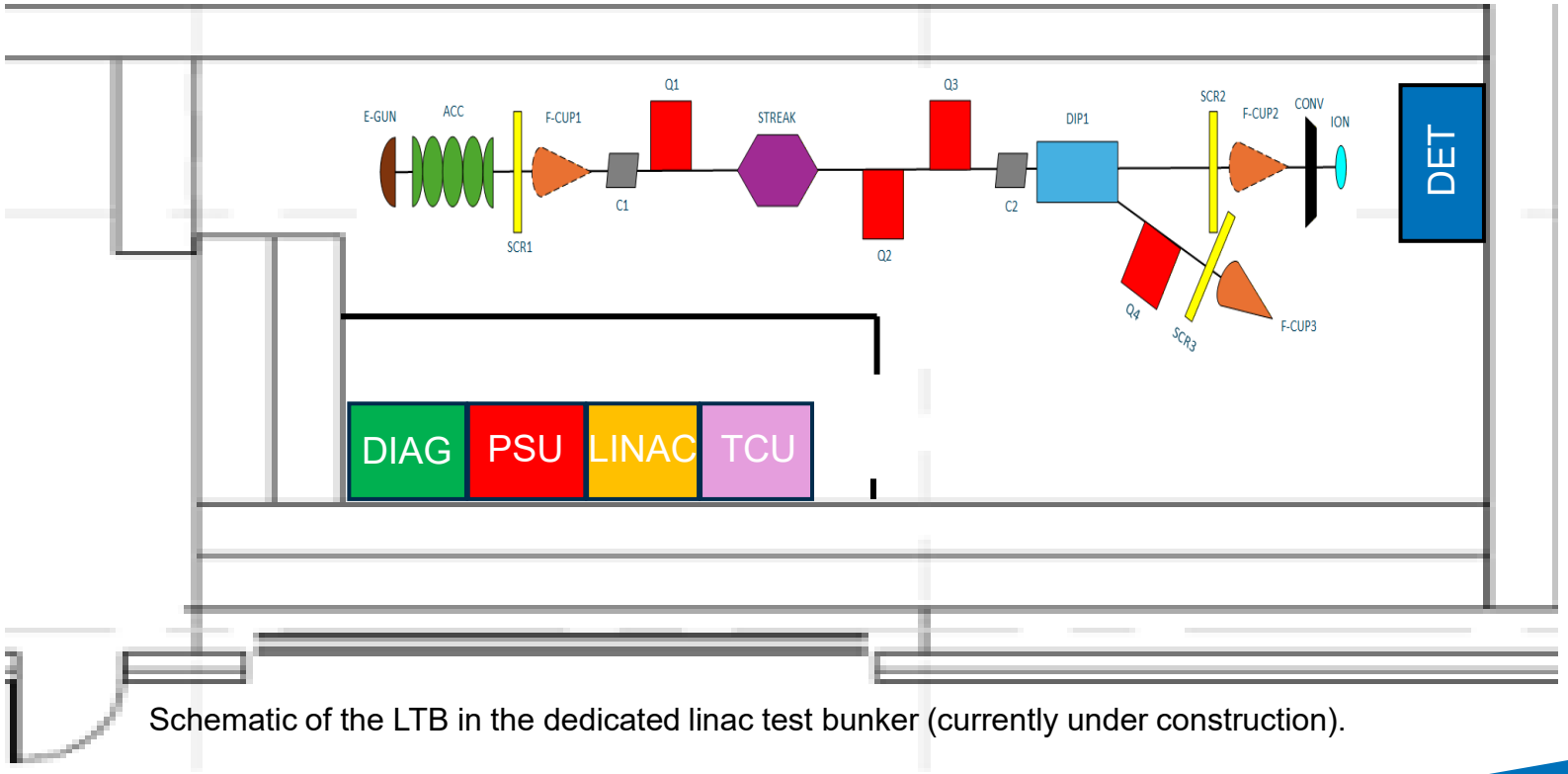
Beamline Design | Design Overview

Engineering design considers as holistic view of the beamline

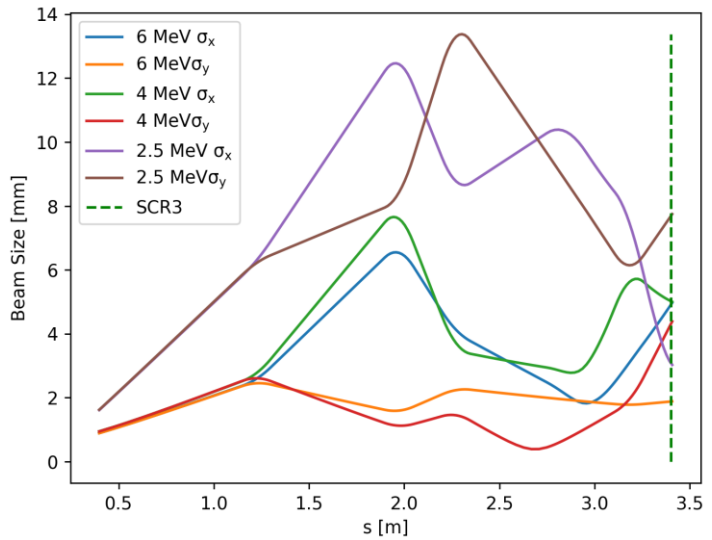
- Putting together magnet, diagnostic, vacuum, controls & infrastructure specifications
- Considering a staged development of the beamline

Measurement and diagnostic methodology for the beamline still to be decided

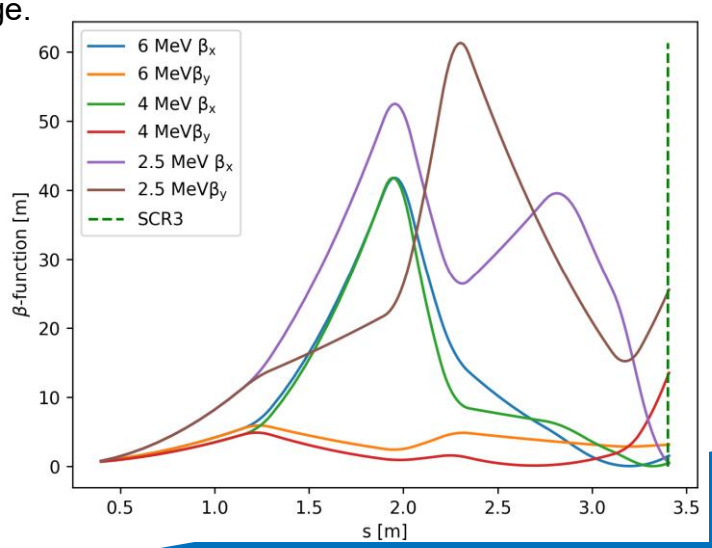
- Bunch duration measurement method
- Current measurement via Faraday-cup or ICT(Charges of ~100's pC)
- Necessity of BPM & setup of screens
- EPICS based control system & measurement scripts



Schematic of the LTB in the dedicated linac test bunker (currently under construction).

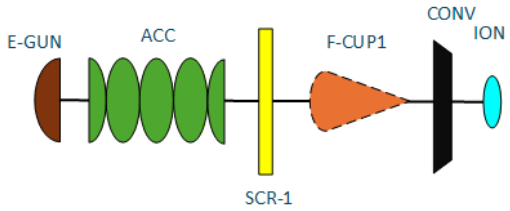


Optimised for spectrometer for min β_x on screen, small beam size at SCR3 and overall, for the on-momentum core (6/4 ±0.5 MeV, 2.5 ±0.1 MeV) of the bunch without space charge.



Beamline Design | Phased Development

PHASE 1



Enable measurements of

- Transverse beam profile at the converter
- Charge present on the converter
- Expected dose via the ion chamber

→ correlate charge & beam size with dose

→ converter experiments

Demonstrate basic control & diagnostic system for charge diagnostic and scintillator screen

Beamline Design | Phased Development

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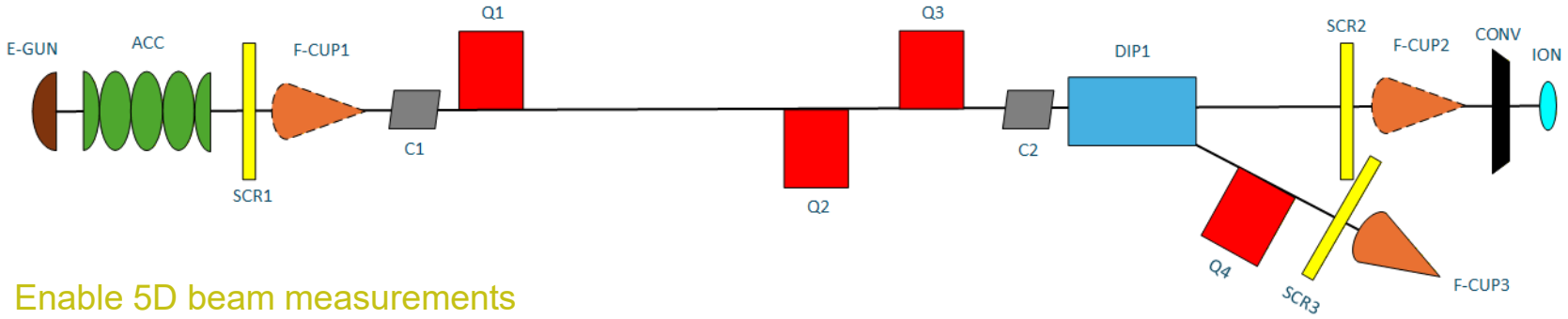
PHASE 2



Enable 5D beam measurements

- Transverse profile and emittance (4D)
- Momentum and Momentum spread measurements
- Trajectory correction

→ 5D characterisation

→ comparison of linacs

→ beginning of internal & external R&D experiments – not limited to accelerator group

Demonstrate full beamline control system, diagnostics, magnets, vacuum & ancillary systems– linac separate or included

We may jump straight to PHASE 2

Beamline Design | Phased Development

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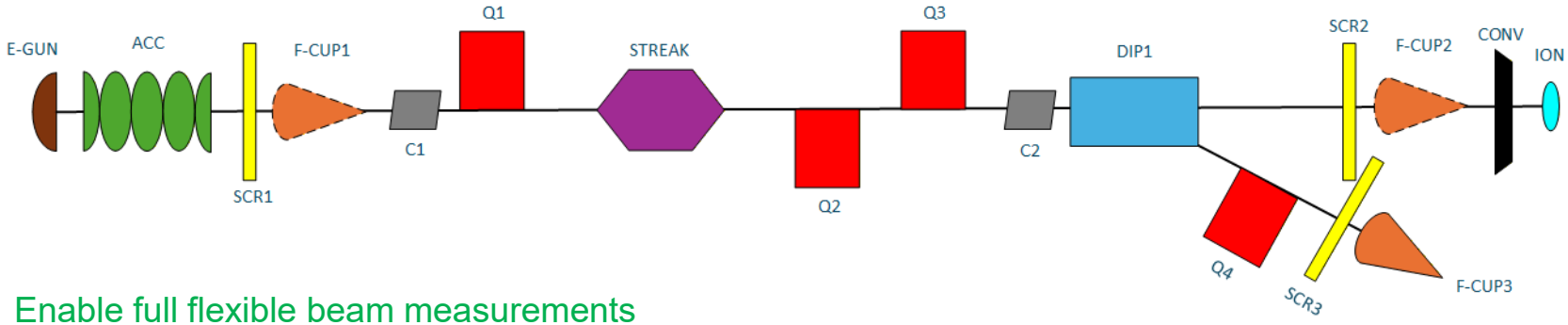
STAGE 3



Enable full flexible beam measurements

- Temporal diagnostic for bunch duration measurements

→ Full 6D characterisation

→ Ful range of internal R&D experiments

Integrated linac & beamline controls with detector array

Fully complete for all Linac R&D needs. Available for internal & external R&D

Beamline Design | Phased Development

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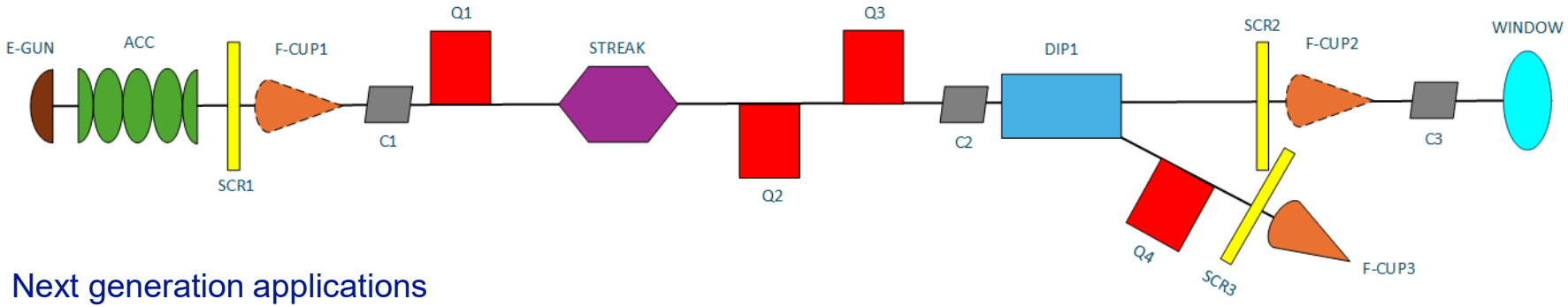
STAGE 4



Next generation applications

- Example of electron beam irradiation capability
- Wider support of more accelerator technologies (klystrons etc.) and improved infrastructure

→ Full 6D characterisation

→ Upgrades to satisfy demands of future internal R&D

Upgrades to linac R&D abilities and support for future developments

Measurement Replication | Emittance Measurement

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Replicating measurements to demonstrate lattice design is robust enough to perform characterisation and validate which measurement approach will perform best

Replicated emittance measurement in simulation using the quadrupole scan method

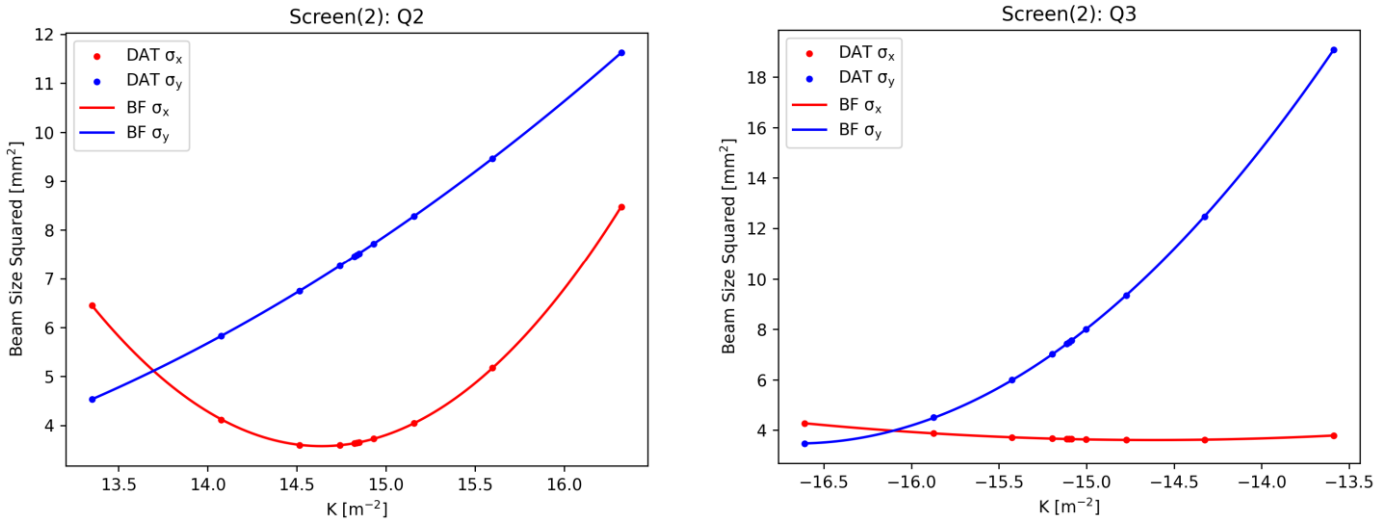
- A series of simulations with varying quadrupole K1 parameters
  - Swing K1 ± 20% of nominal K1 value
    - Fails with small nominal K1 – better to swing around 10% of max value
  - 100K macroparticle simulations with space charge
  - Currently using the converter beam size matching mode

Trialled multiple different analysis methodologies

- Parabola fit method
- Matrix method
  - Pseudoinverse using Tikhonov regularisation

Method	ε_x [nm-rad]	ε_y [nm-rad]
Parabola	5291 ± 2908	6667 ± 5548
Matrix	3847 ± 223	8741 ± 643
Tracked	3361	9621

Comparison of simulated measured emittances (various analysis methods) with the tracked bunch emittance.



Parabola beam size squared against K1 for Q2 and Q3 quadrupoles in the straight-ahead branch.

Work in progress…

- Develop an improved, dedicated emittance measurement mode
- Further investigate emittance measurement analysis
- Introduce proper apertures into the replication
- Demonstrate emittance measurement with errors applied

Measurement Replication | Spectrometer

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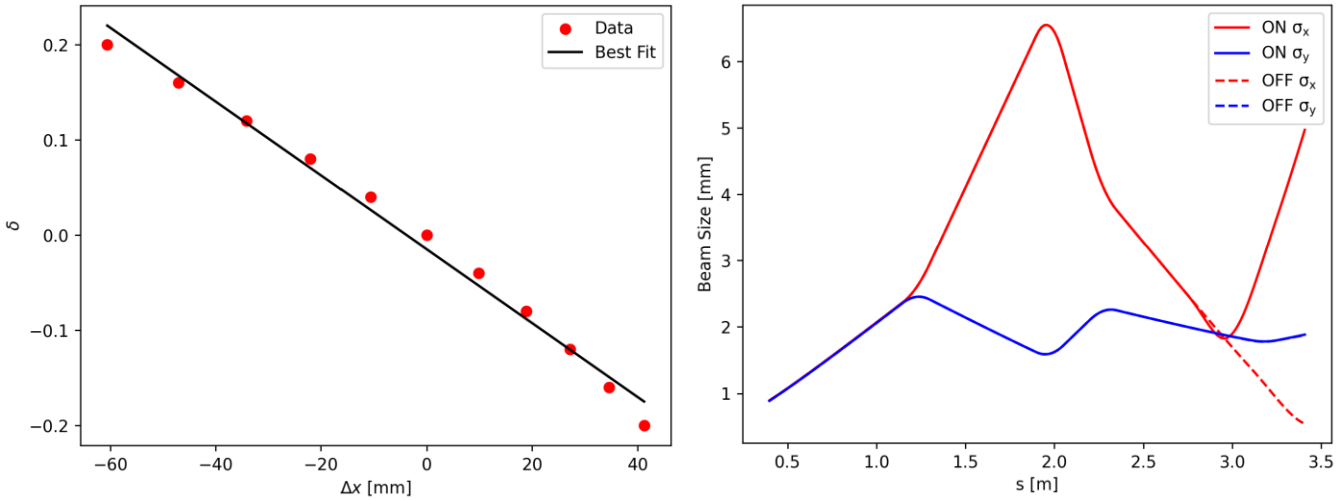
Replicated a momentum spread measurement
- Simulated 6 ± 0.5 MeV on-momentum core bunch with ±20% momentum variation in 10 trials
- No space charge simulation, 100K macroparticles

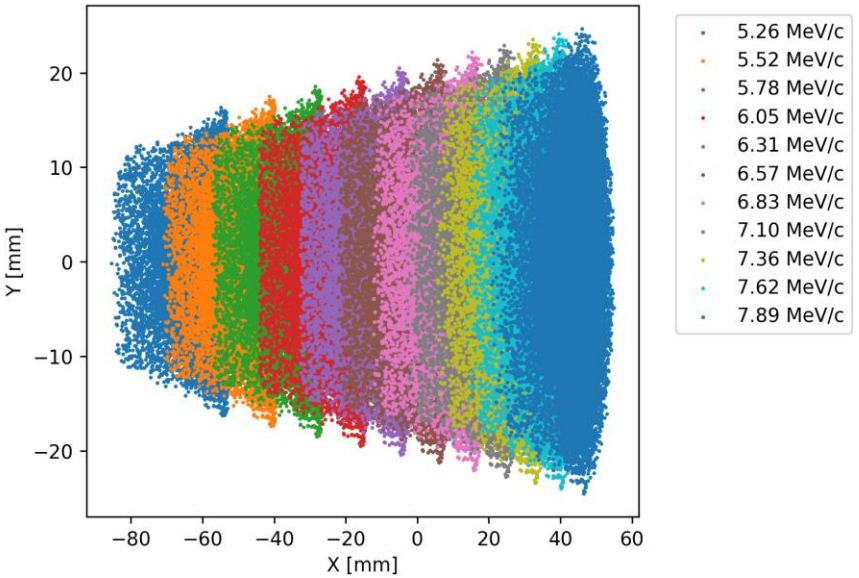
Momentum variation currently only from interface to the linac test beamline, not simulated from the bunch generation point
- Required to properly calibrate momentum measurement

Simple linear fit of fractional momentum spread – centroid variation to determine the dispersion η_x = -0.26 m

Momentum spread determined as Δp/p = 1.63% (on-momentum core of the beam)
- Tracked value is 1.83%



Left: Plot of the fractional momentum variation against centroid position. Right: Beam size with (solid) and without (dashed) the spectrometer.



Transverse profiles of all the tracked variable energy bunches at SCR3

Work in progress…
- Simulate momentum & momentum spread measurements from bunch generation onward – changing cavity parameters to modify energy
- Investigate effect of space charge
- Introduce proper apertures into the replication
- Demonstrate spectrometer measurements with errors applied

Engagement Opportunities

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The Stoke-on-Trent S&T team comprises of 13 people with 2 accelerator scientists + 2 technicians delivering **~15 active & 17 pipeline accelerator research projects**

- The linac test beamline is **just one** of these but is required by **10+** accelerator R&D projects
- LTB can support a range of other projects in image quality, detection etc.
- **Support required from academic & national laboratory partners to deliver this project**

The Linac Test Beamline would benefit from **external input** into the following areas

- Diagnostics, Magnet design, Vacuum & Control Systems

Possible research project topics for the Linac Test Beamline could include

- Beamline testing & development (E-guns, cavities, targetry)
- Low energy diagnostics
- NDT & Bremsstrahlung-based X-ray studies

Some external R&D projects linked to the Linac Test Beamline are already planned

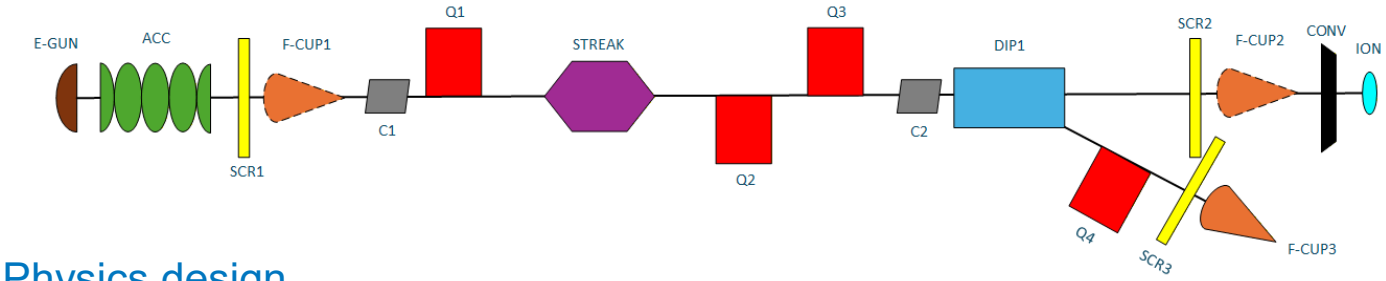
- Lower energy Beamline (University of Lancaster) - Possible KTP
- e^- beam irradiation (Texas A&M)
- PhD project (University of Manchester)
- Possibilities for MPhys & summer student projects

See David Sharp's presentation for more details on this & wider academic engagement

Summary

The Linac Test beamline is being developed to give insight on existing linac-based X-ray CVI systems and support a range of internal & external R&D projects

- Full characterisation of suite of CVI linacs
- Development platform for R&D



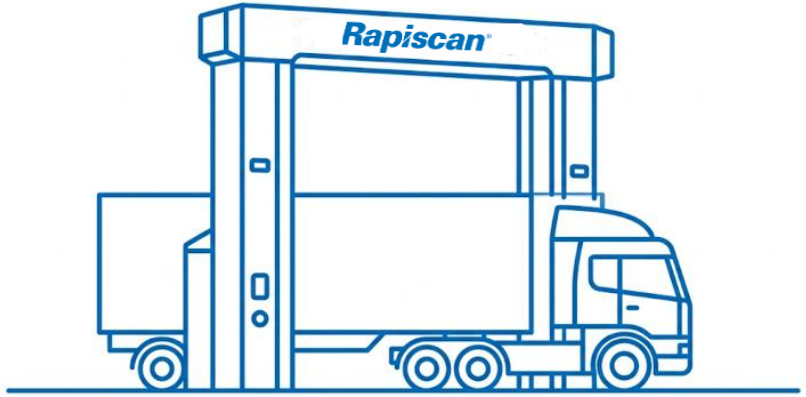
Physics design

- Finalizing the first-pass beamline design
- Demonstrated beamline design is feasible
- Error analysis, measurement & experiment simulations outstanding

Engineering design

- Specifying requirements placed upon beamline
- Engaging with component suppliers
- Identifying external partners for support in development of the LTB

Welcoming external engagement on the Linac Test Beamline to assist in development activities or conduct R&D projects.



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