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Acceleration of a 100keV Electron Beam by Interaction with a Terahertz Pulse in a Tapered Dielectric-Lined Waveguide

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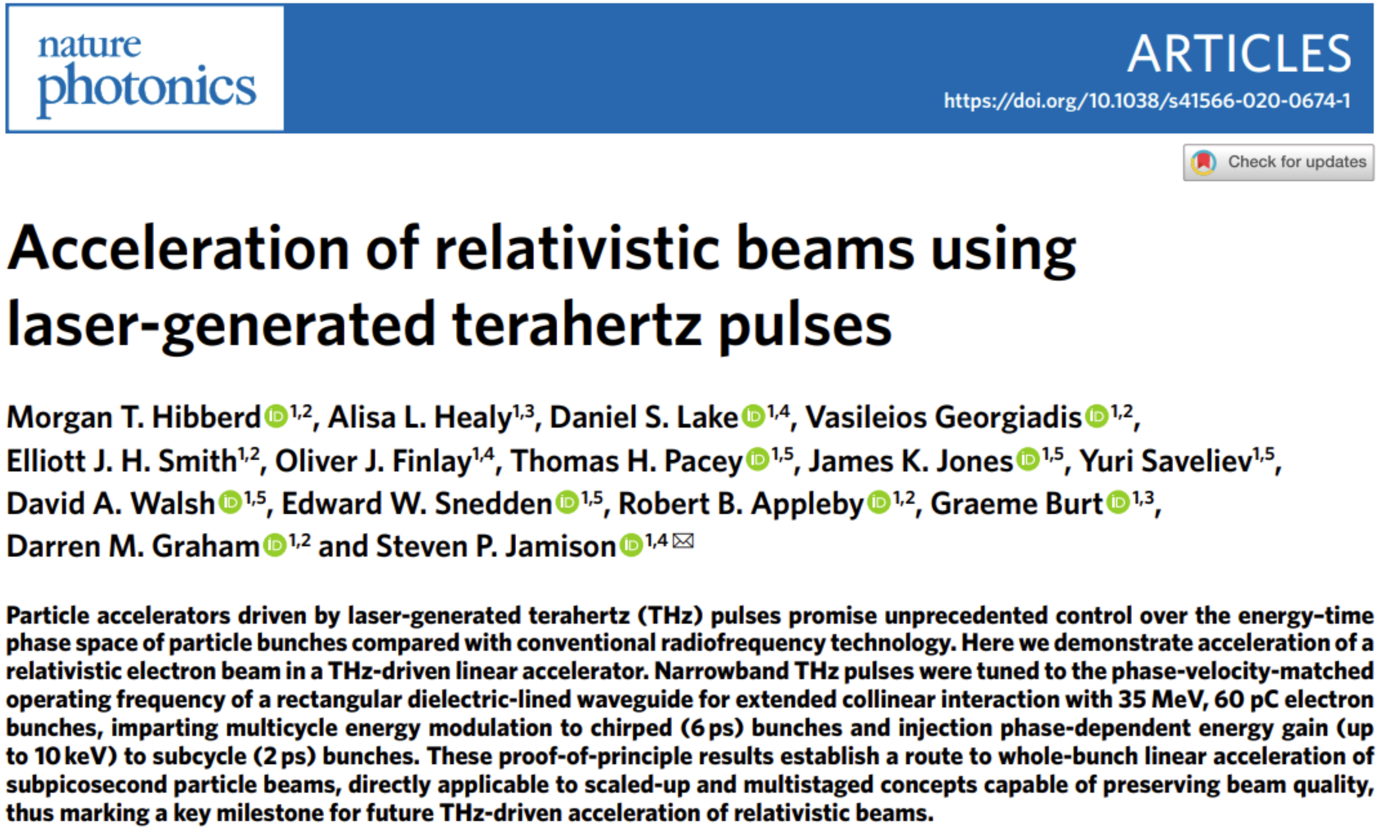
Introduction

Why? Terahertz-driven acceleration is a novel technique that offers good control over the phase-space of particle bunches in compact structures.

How? We match the phase velocity of a THz pulse with the electron beam velocity, keeping the bunch in an accelerating phase as they travel through the waveguide together.

Previous work in our group:

- proof-of-concept results with a relativistic beam at the CLARA facility, reported in Nature Photonics.
- DLWs designed for deflection



nature photonics

ARTICLES

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Acceleration of relativistic beams using laser-generated terahertz pulses

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Particle accelerators driven by laser-generated terahertz (THz) pulses promise unprecedented control over the energy-time phase space of particle bunches compared with conventional radiofrequency technology. Here we demonstrate acceleration of a relativistic electron beam in a THz-driven linear accelerator. Narrowband THz pulses were tuned to the phase-velocity-matched operating frequency of a rectangular dielectric-lined waveguide for extended collinear interaction with 35 MeV, 60 pC electron bunches, imparting multicycle energy modulation to chirped (6 ps) bunches and injection phase-dependent energy gain (up to 10 keV) to subcycle (2 ps) bunches. These proof-of-principle results establish a route to whole-bunch linear acceleration of subpicosecond particle beams, directly applicable to scaled-up and multistaged concepts capable of preserving beam quality, thus marking a key milestone for future THz-driven acceleration of relativistic beams.

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Previous Work – Acceleration of a relativistic beam at the CLARA facility

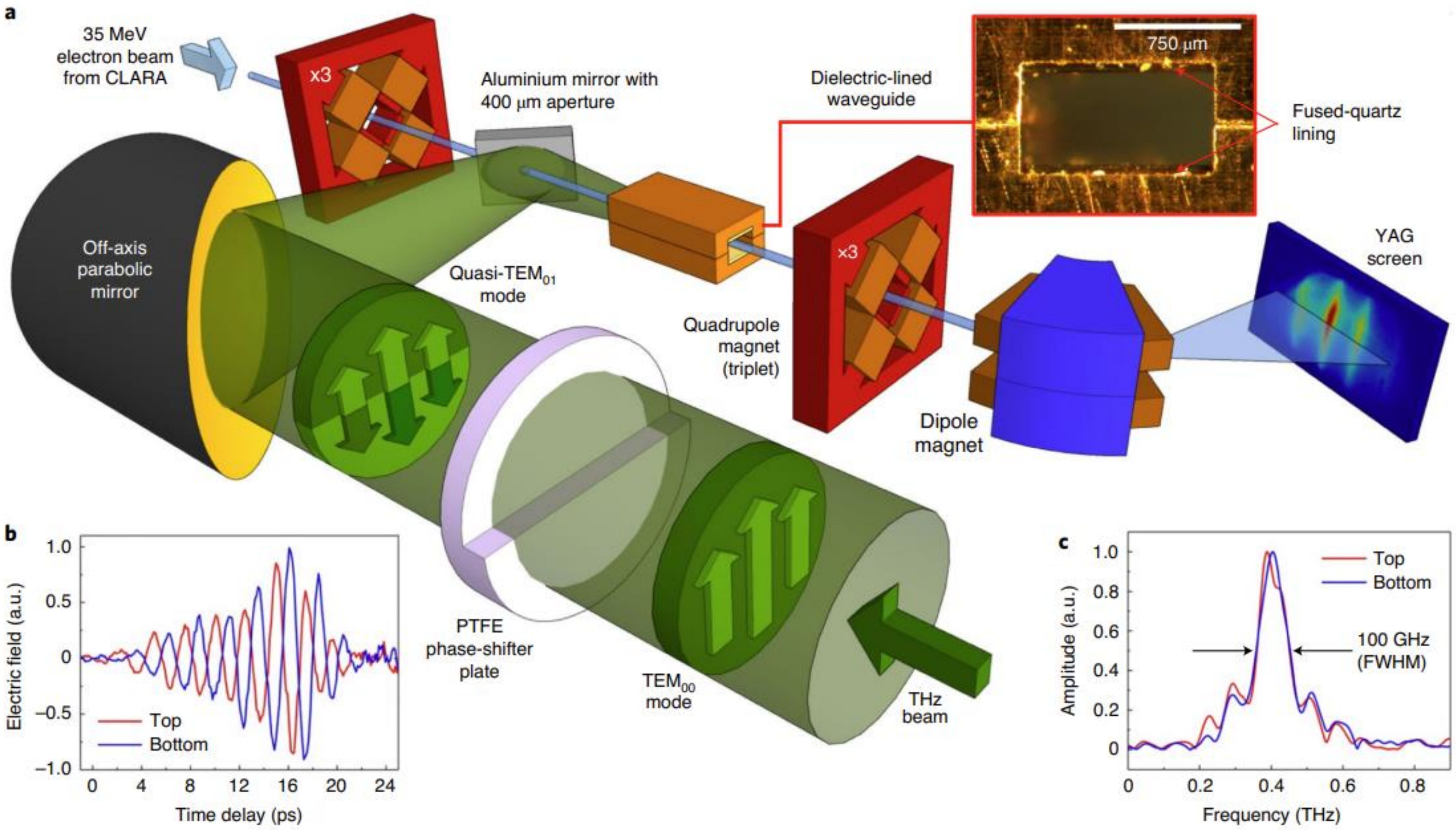


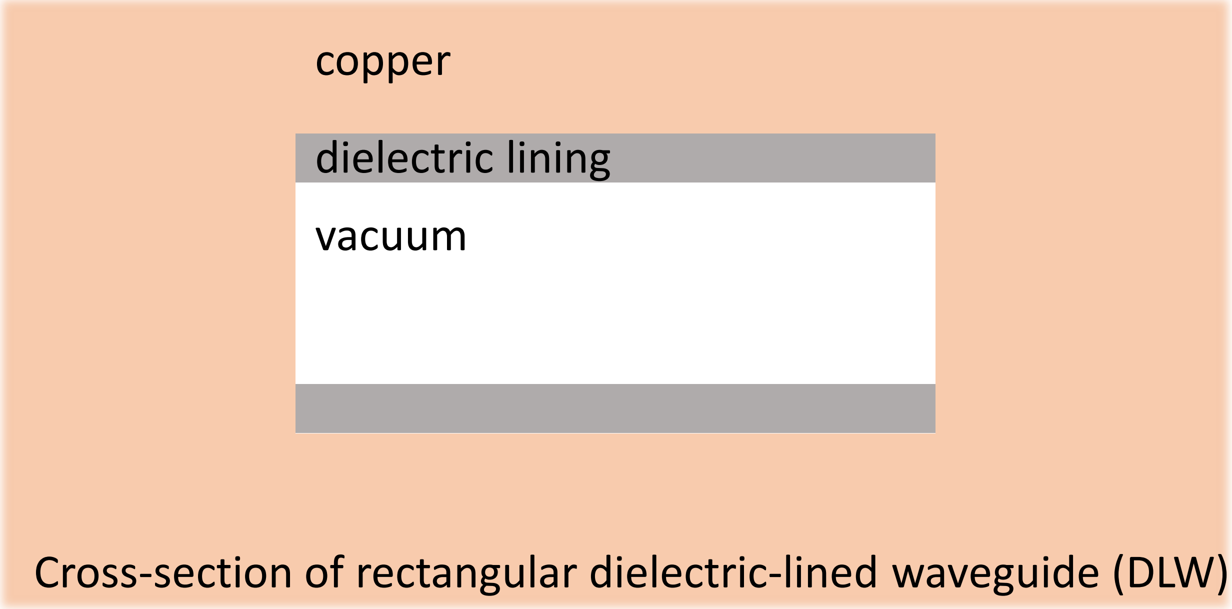
Fig. 1 | Experimental set-up. a, Schematic showing the THz beam converted into a quasi-TEM$_{01}$ mode by a polytetrafluoroethylene (PTFE) phase-shifter plate and focused into the DLW for collinear interaction with the 35 MeV electron beam. A microscope image of the DLW exit is shown, revealing the dielectric lining along the top and bottom surfaces. **b**,**c**, Electro-optic sampling measurements of the temporal (**b**) and spectral (**c**) profiles of the THz pulse transmitted through the top and bottom half of the phase-shifter plate, recorded at the entrance to the DLW coupling horn.

This shows the experimental set-up used for the Nature paper.

There will be some differences when we test the new design, but the general concept will be similar.

Principles of THz Acceleration in Dielectric-Lined Waveguides (DLW)

A rectangular DLW supports a type of hybrid mode which has a strong longitudinal field component and, if the dielectric is thick enough, a phase velocity below *c.*

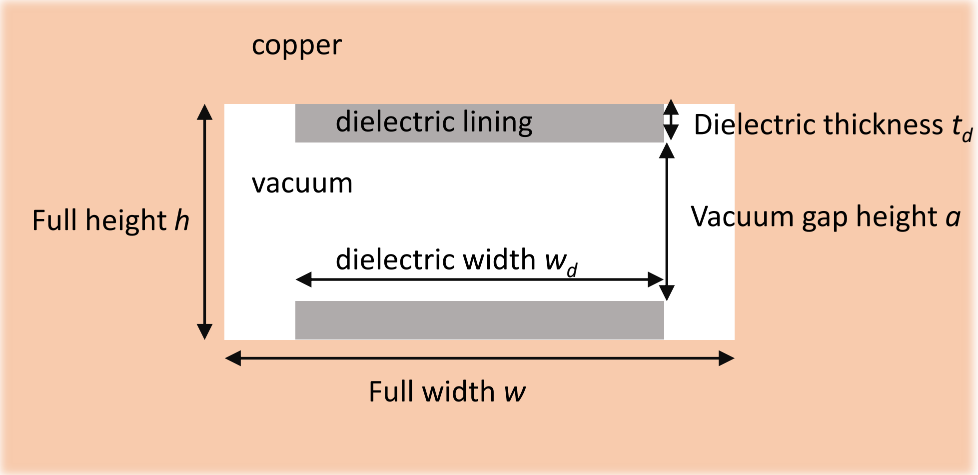


Cross-section of rectangular dielectric-lined waveguide (DLW)

Highly relativistic beam: $v_e \approx c$, and this doesn't change much as particles gain energy, so we can find a cross-section where $v_p = v_e$ and expect fairly low phase-slippage.

100keV beam: The velocity of particles increases by a large amount as they gain energy – so we need to make the phase velocity increase too.

Velocity Matching in DLWs



Geometric variables of DLW cross-section

The phase velocity in a DLW of a fixed height and dielectric thickness can be controlled by choosing its full width w and dielectric width w_d

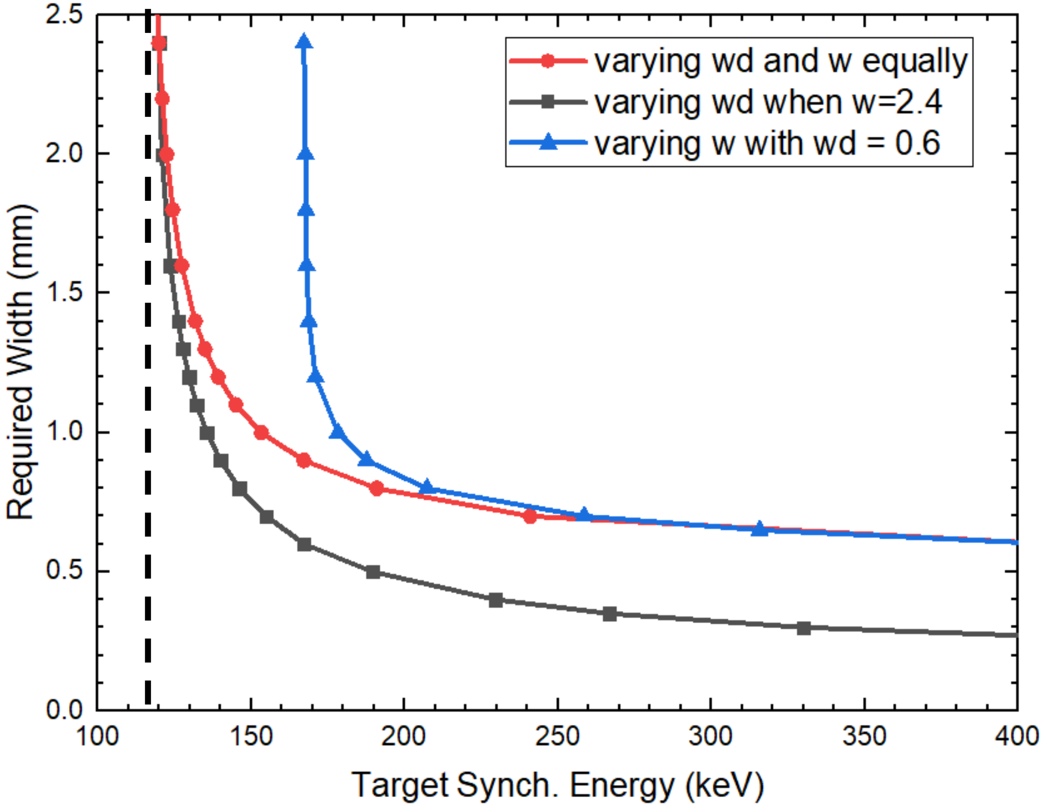
In this case we have a 380µm layer of fused silica in a 1240µm high waveguide (thus leaving a 480µm vacuum gap)*

*these parameters were chosen based on the phase velocity, group velocity, and characteristic impedance of the required mode at 200GHz, with additional limits set by expected electron beam size and availability of dielectric materials

Velocity Matching in DLWs

For a set dielectric thickness, there is a minimum synchronous energy when the required width approaches infinity

In this case, it is around 119keV



Using a different dielectric thickness or dielectric constant shifts the position of the graph, but the general shape remains consistent.

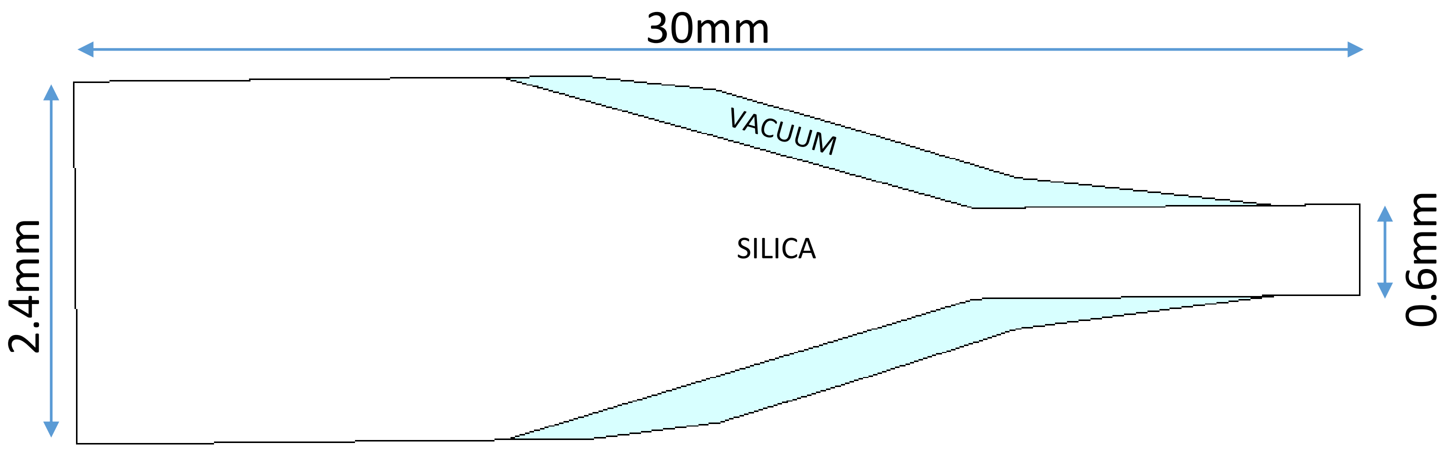
We have 100keV electrons, but the minimum phase velocity would synchronise with 119keV – why choose this mismatch?

- To lower the minimum v_{sync} we could use a thicker dielectric – but the thicker the dielectric, the lower the on-axis value of accelerating field. Some mismatch is necessary to have decent gradient.
- Particles injected ahead of crest will slip back to crest due to the mismatch.
- If they gain 19keV from off-crest acceleration by the time they slip back, then they can be synchronised the rest of the way with width tapering.

The Tapered Structure - overview

- The taper profile is optimised for a specific gradient - the higher gradient, the steeper the taper
- Two designs were developed
  - One to demonstrate the concept with a higher energy THz pulse (i.e. a pulse energy that is feasible, but not currently available in our lab)
  - One to be assembled for experimental testing.
  - The physics and design process are largely the same in each case, but with different taper geometries – the former will only be mentioned as a point of comparison to some results highlighted.

Top-down view of the optimised waveguide



Pulse Details

High Energy Theoretical Design - 200GHz, 20μJ delivered over 10 cycles.

Modest Energy Experimental Design – 200GHz, 12μJ over 8 cycles.

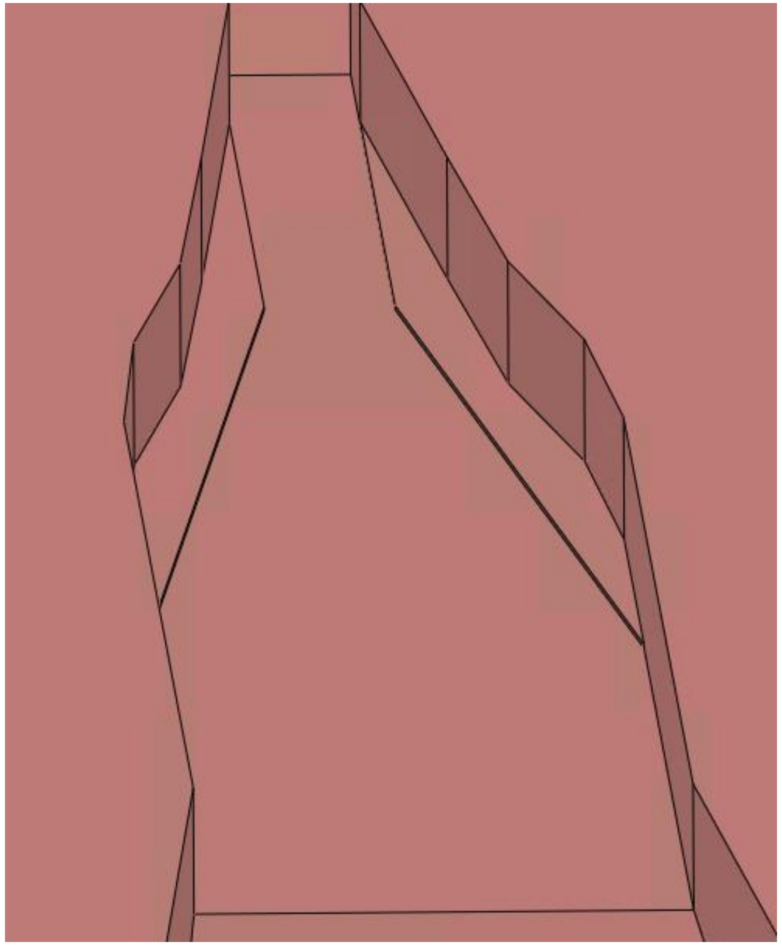
Energies here refer to energy in the waveguide (see slides on coupler design for context)

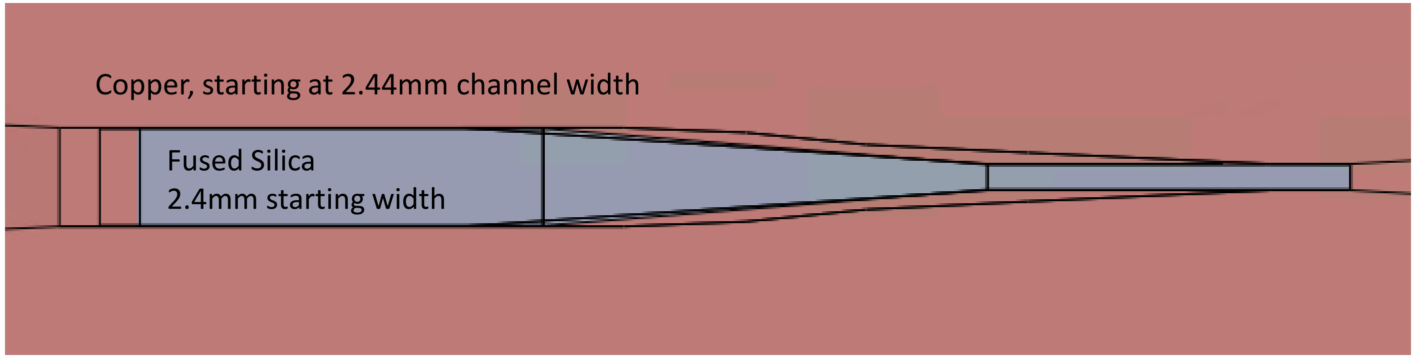
The Tapered Structure - manufacturing

- We keep the dielectric to a single linear taper as it is challenging to cut extremely complex shapes
- The metal geometry can be much more complicated
- We add a small amount of space and a ridge to aid alignment when fitting the dielectric lining

There is no significant impact on PIC results when these features and modifications are included.

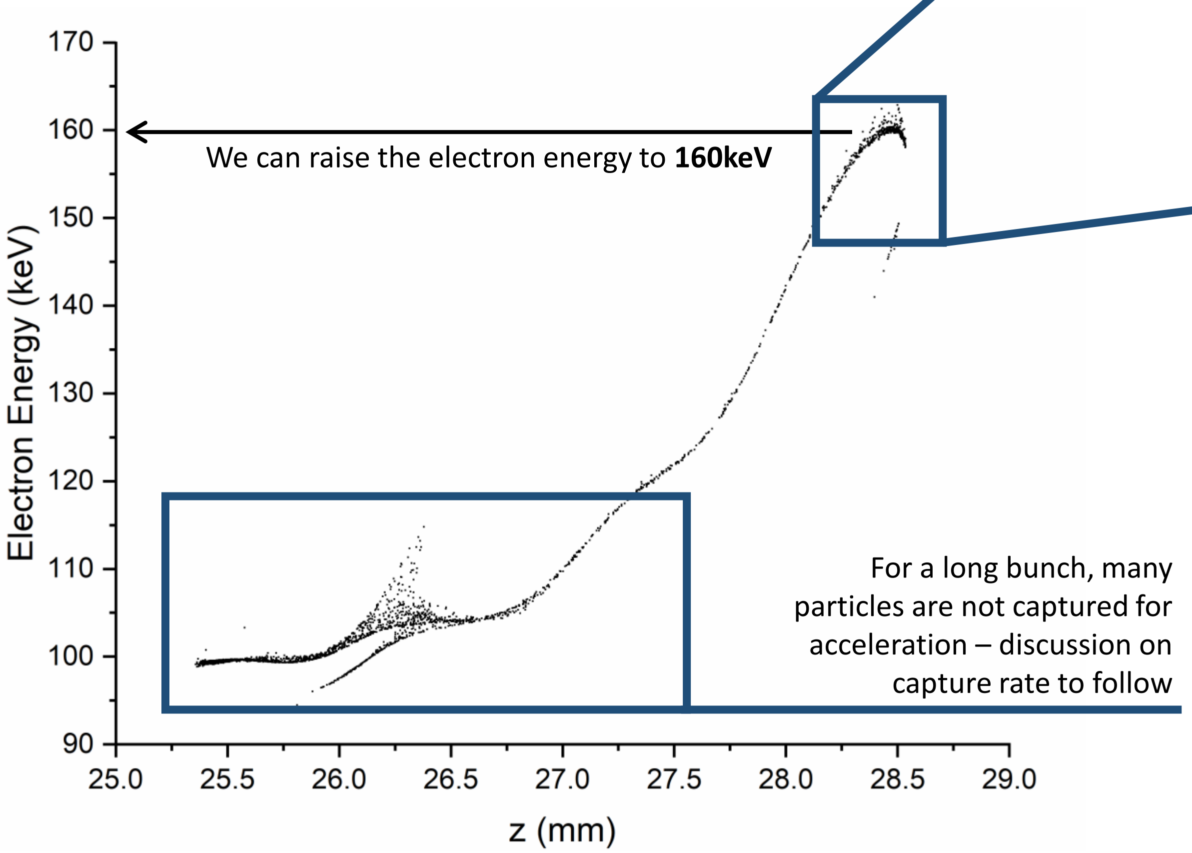
The two halves of the waveguide are to be machined separately.





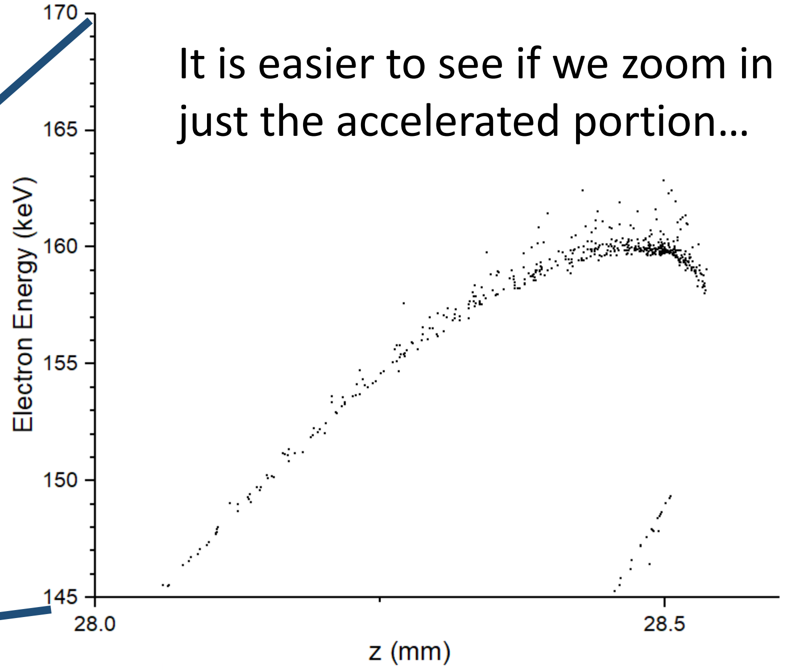
PIC Simulation Results

This figure shows the energy and axial position of each macroparticle at a timestep just before the bunch leaves the waveguide.



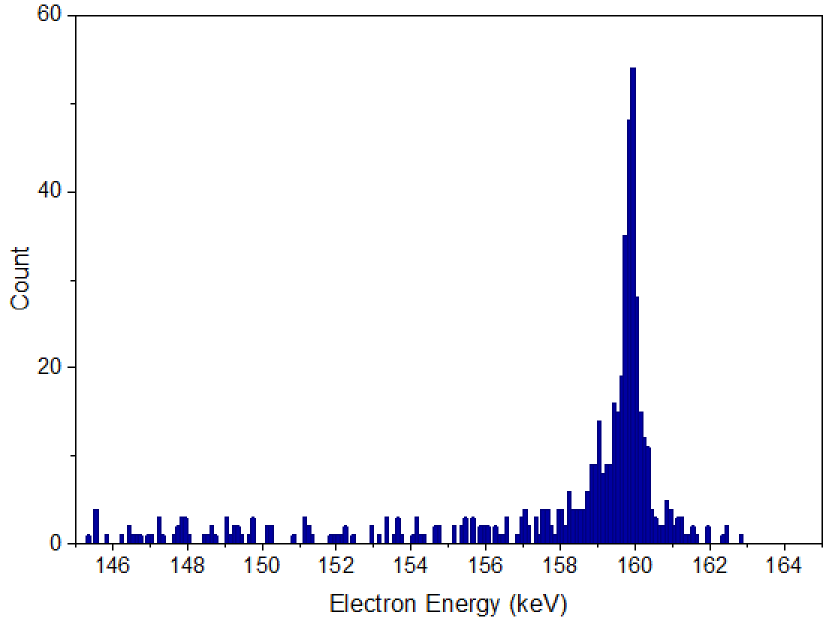
We can raise the electron energy to **160keV**

For a long bunch, many particles are not captured for acceleration – discussion on capture rate to follow



It is easier to see if we zoom in on just the accelerated portion…

…or plot the energies as a histogram



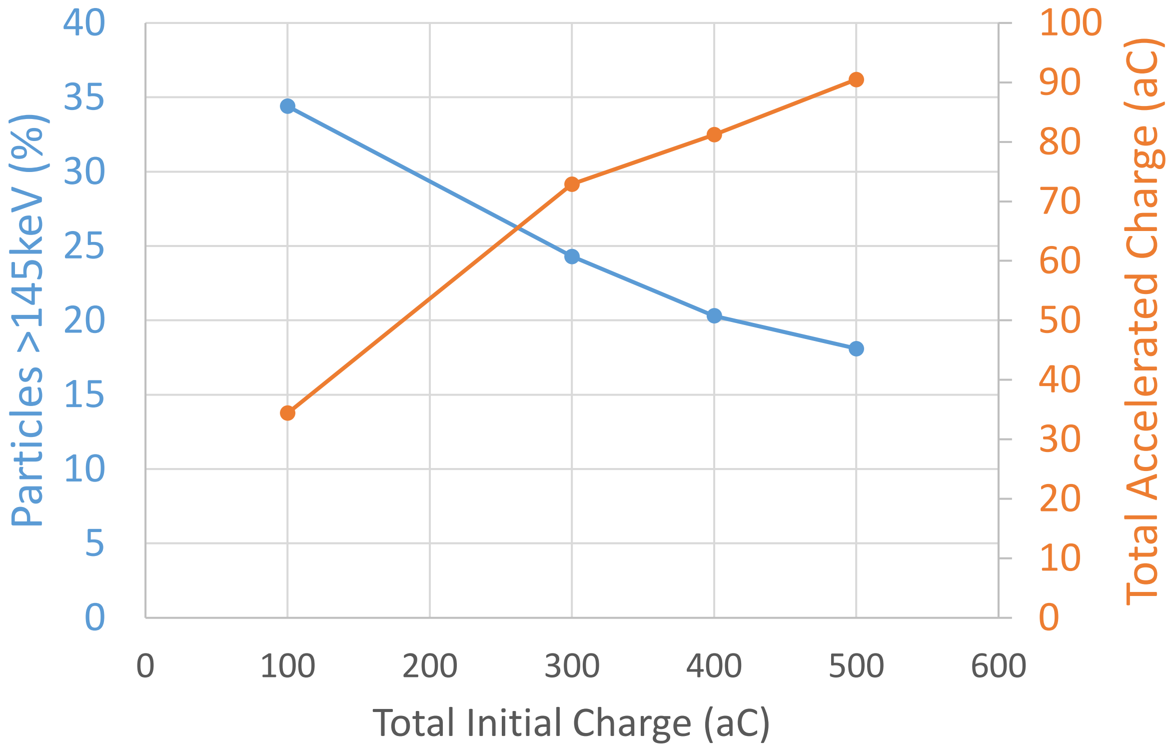
PIC Simulation Results

Parameter	High Energy Theoretical Design	Modest Energy Experimental Design
Freq. (THz)	0.2	0.2
Pulse Energy in waveguide (μJ)	20	12
Number of cycles	10	8
Apprx. Accel. Bunch Energy (keV)	200+	160
Capture of 0.5fC bunch*	15% over 170keV**	18% over 145keV**
Capture of 0.1fC bunch	25% over 170keV	35% over 145keV

*capture % increases the shorter the bunch is – see following slide

**these thresholds are slightly arbitrary, as there is no clear line between bunch and tail.

PIC Simulation Results



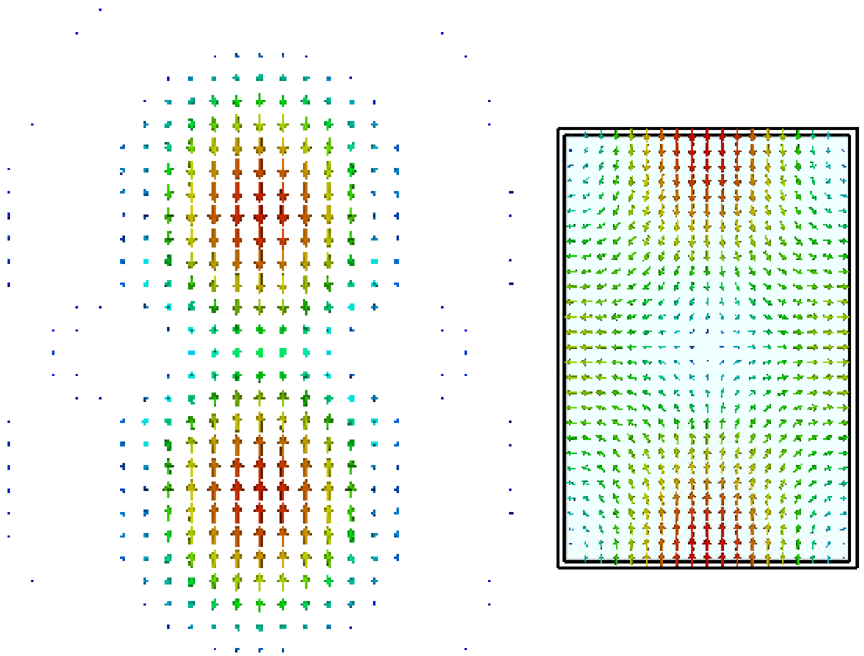
The capture rate increases as initial bunch length decreases.

We see 35% capture rate of our 0.1fC bunch and only 18% for our 0.5fC bunch – but 18% of 0.5fC is still a lot more absolute charge than 35% of 0.1fC

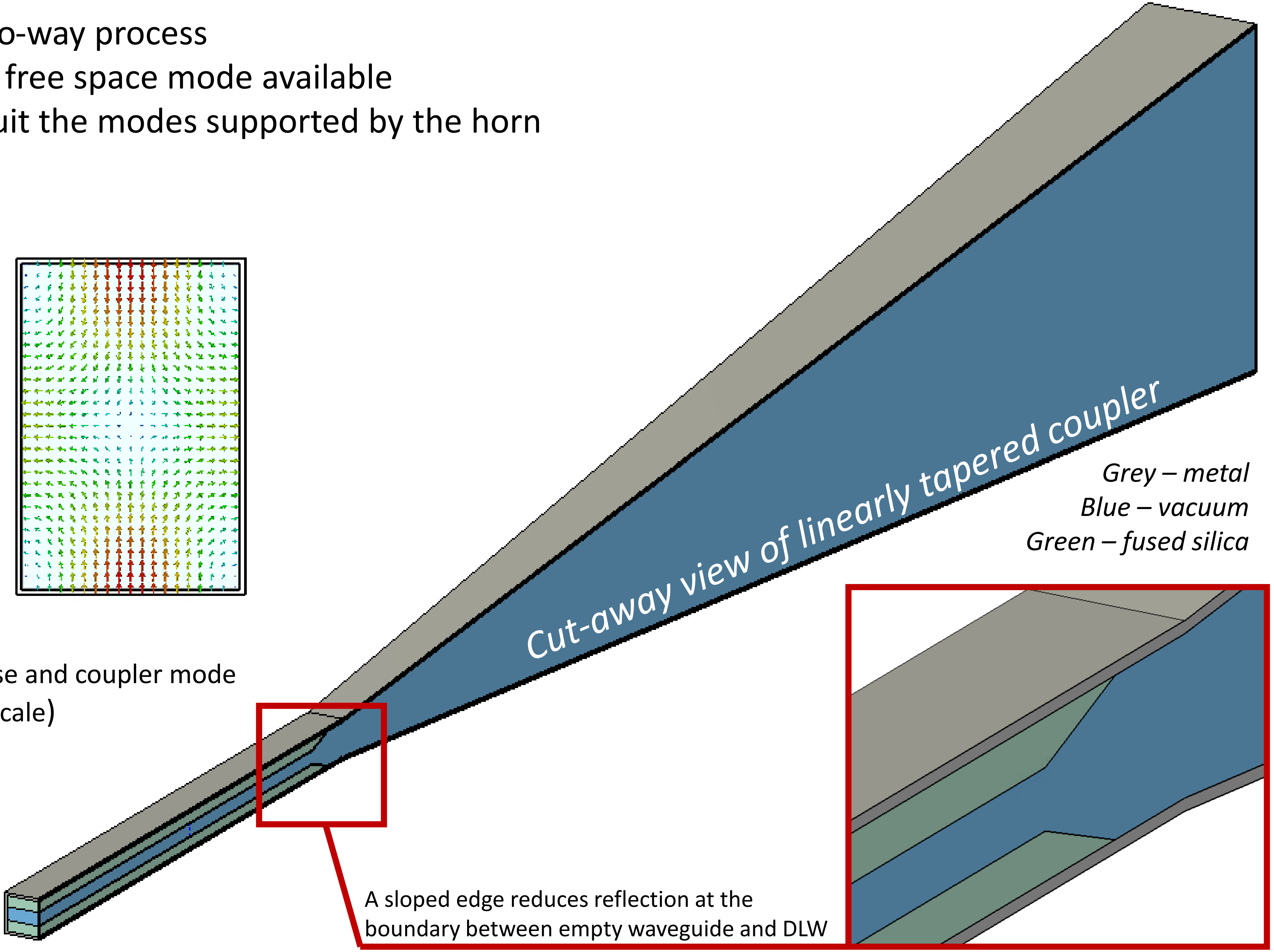
Coupling into the Accelerating Mode

Getting the coupling right takes a two-way process

- We can tailor the horn to suit the free space mode available
- We can tailor the THz source to suit the modes supported by the horn



Comparison of free space pulse and coupler mode (not to exact scale)



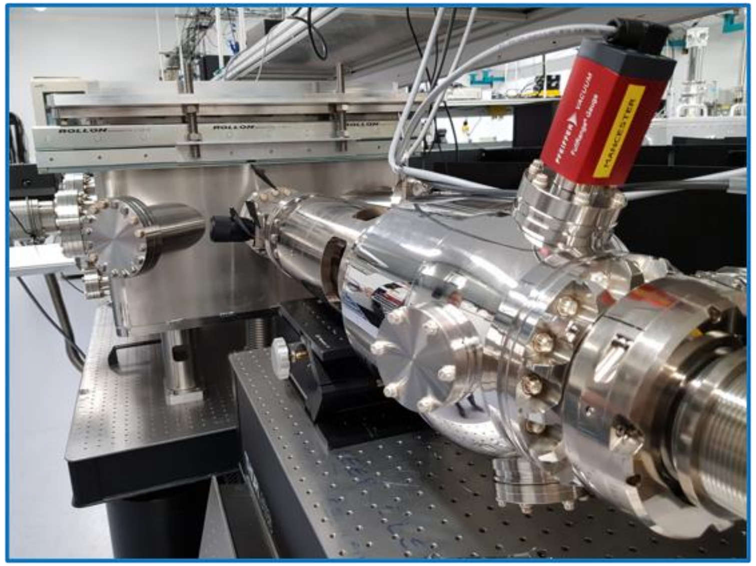
Grey – metal
Blue – vacuum
Green – fused silica

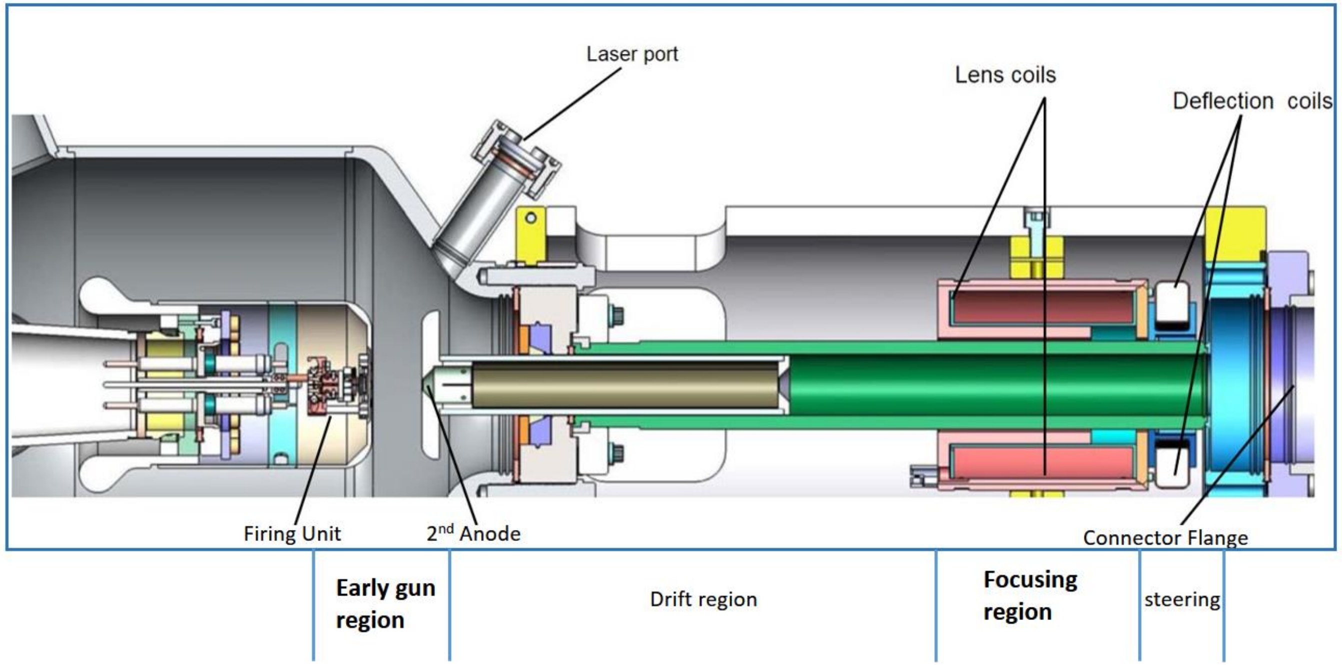
A sloped edge reduces reflection at the boundary between empty waveguide and DLW

This design is projected to achieve around 65% coupling from source to accelerating mode.

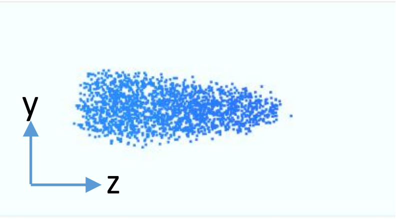
Electron Beam

Input bunches used in PIC simulation come from GPT model matching the 100keV electron gun at Daresbury.

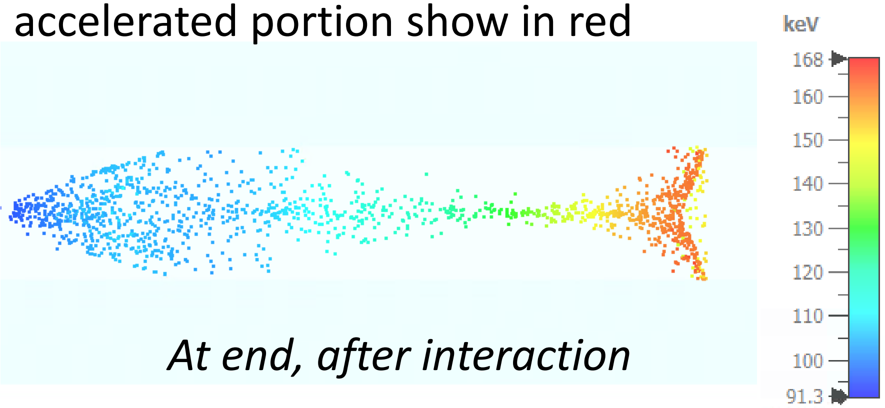




During acceleration, it takes on a fish-like shape with the accelerated portion show in red

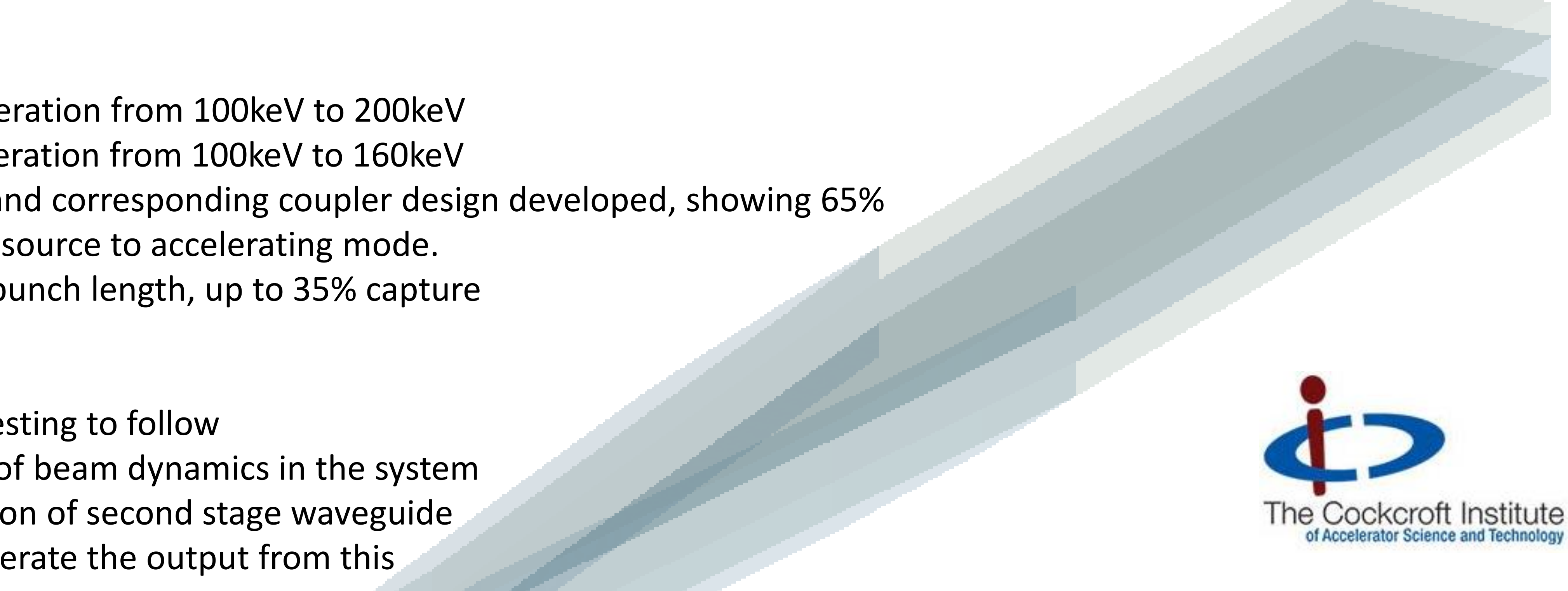


Just inside waveguide



At end, after interaction

Summary and Next Steps



Main Results:

- Design A: acceleration from 100keV to 200keV
- Design B: acceleration from 100keV to 160keV
- Twin THz spot and corresponding coupler design developed, showing 65% efficiency from source to accelerating mode.
- Depending on bunch length, up to 35% capture

Next Steps:

- Experimental testing to follow
- In depth study of beam dynamics in the system
- Investigate option of second stage waveguide to further accelerate the output from this waveguide

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