Extreme focusing of high-energy beams using near-field coherent transition radiation

FACET-II

Facility for Advanced Accelerator Experimental Tests

AAC24 Advanced Accelerator Workshop

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On behalf of the E332 Collaboration

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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

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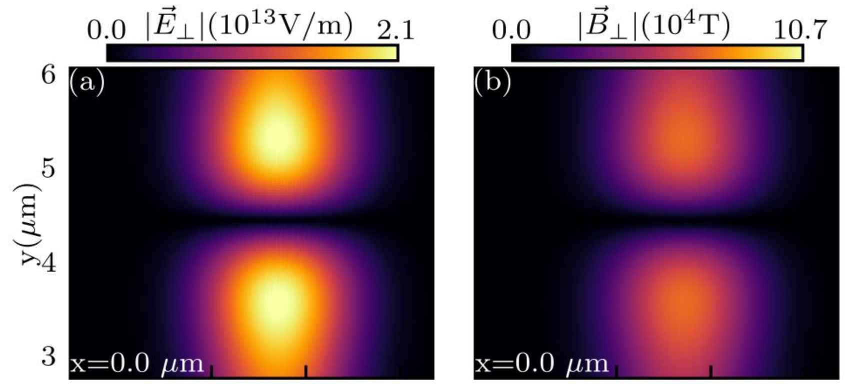
NF-CTR focusing effect

- A dense beam colliding with a conducting surface generates strong coherent transition radiation (CTR) at the surface
  - E field at surface → 0
  - B field at surface → ~ x2

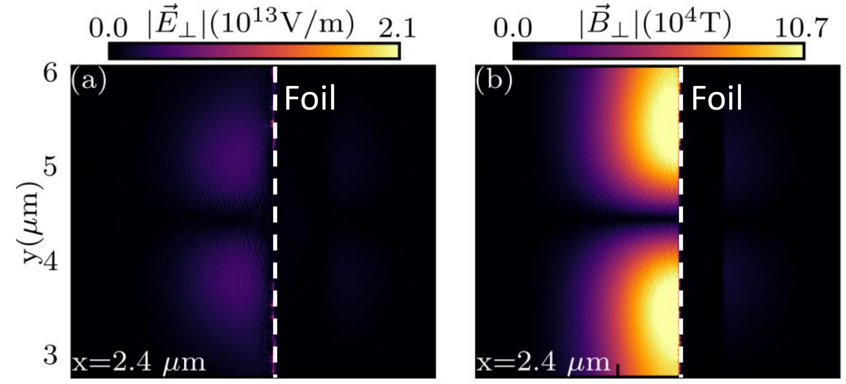
- Near-field CTR fields act on the beam, providing a focusing effect
  - Focal length of $f = \frac{8\pi\epsilon_0\sigma_\perp^2 * \epsilon_n}{q^2 N}$

- NF-CTR focusing strength increases with smaller spot sizes!

Initial beam fields – electric and magnetic:



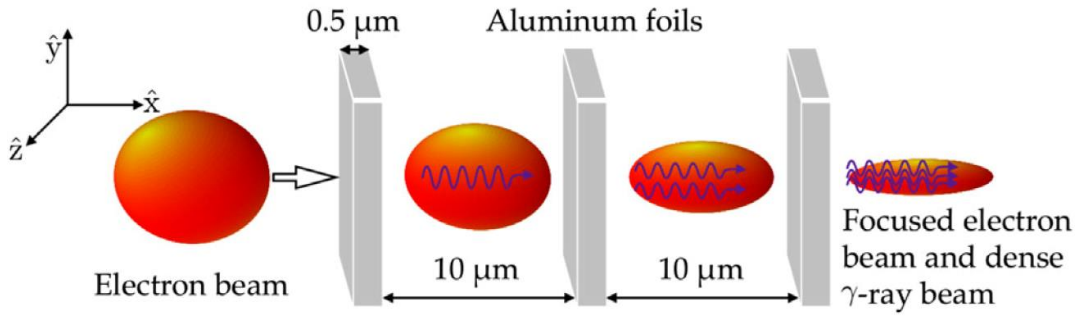
Fields at a foil surface:

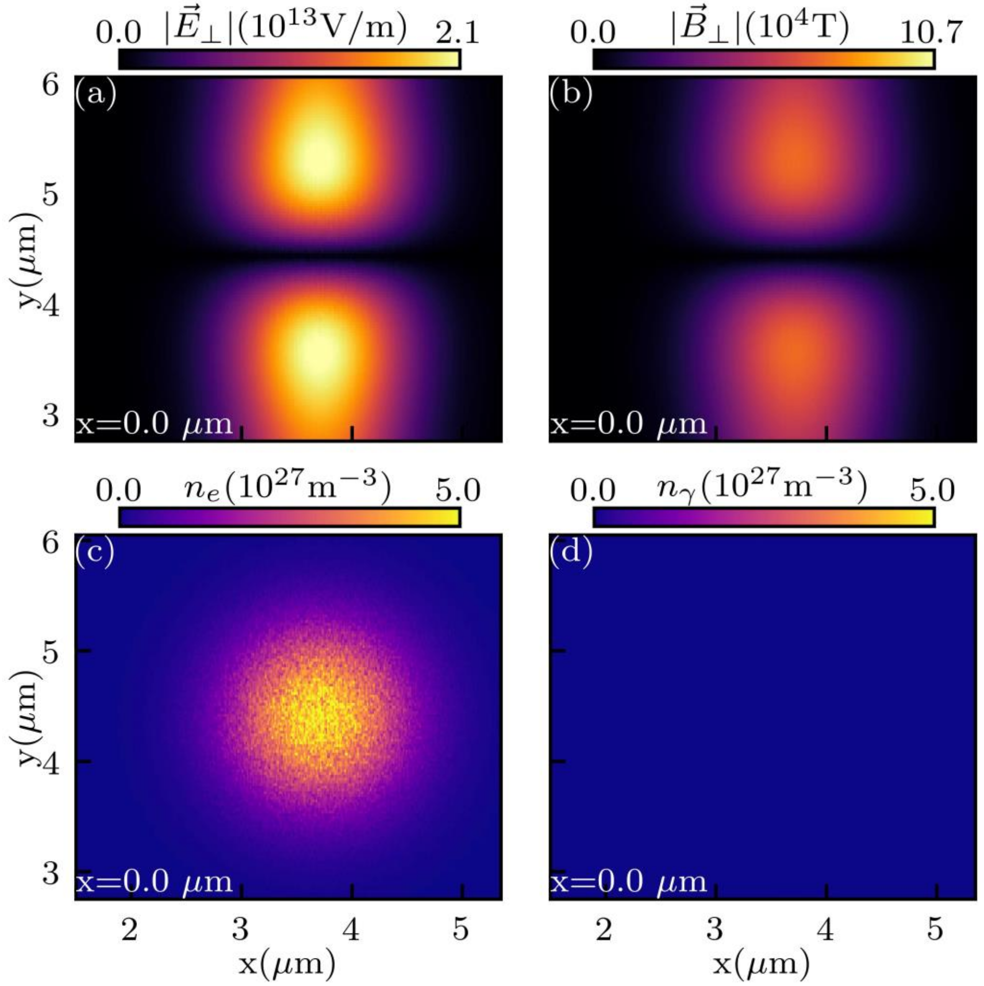


Sampath, A. *et al.* Extremely Dense Gamma-Ray Pulses in Electron Beam-Multifoil Collisions. *Phys. Rev. Lett.* **126**, 064801 (2021).

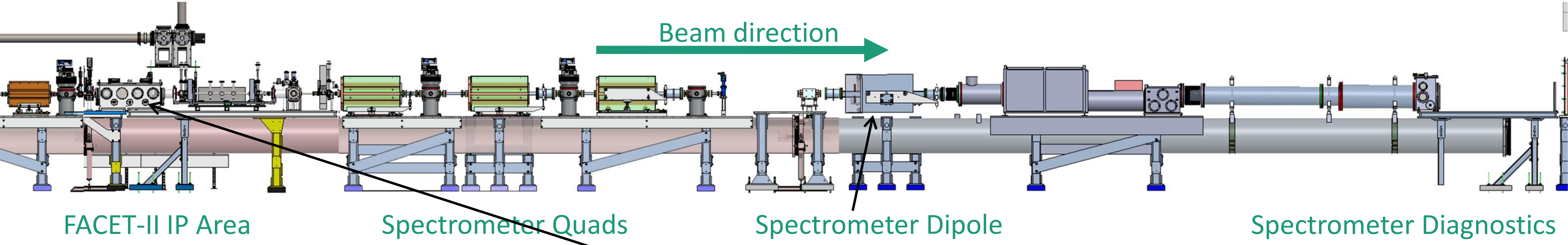
Enhance near-field CTR focusing through multiple foils

- Focusing can be enhanced by passing the beam through multiple foils
- Beams can be focused to radial density of order 10^{29} m^{-3}
- Simulation:
  - 20 consecutive Al foils
  - 0.5 µm thickness
  - 10 µm separation between foils



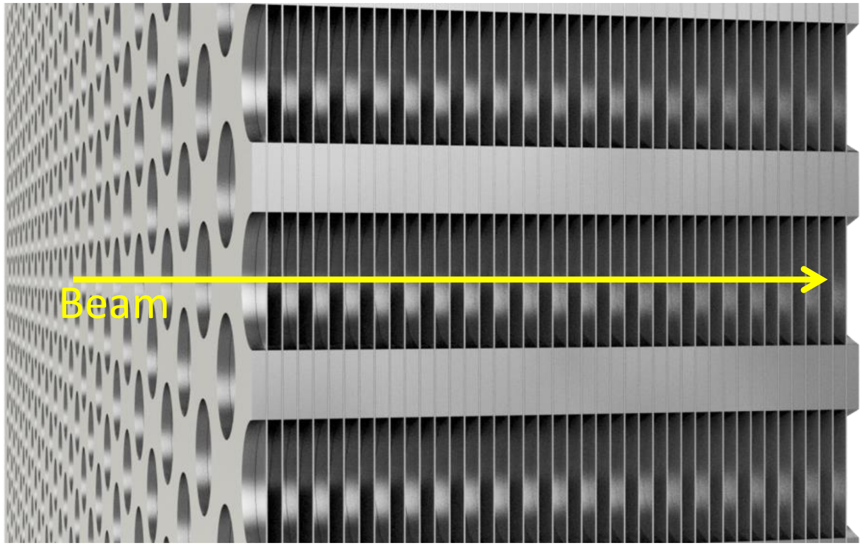


E332 experimental set-up



- E332 experiment at FACET-II will probe this effect
- Beam parameters available to date:
  - Electron energy: 10 GeV
  - Charge per bunch: 1.6 nC
  - Min. spot size: Order 10 μm
  - Min. bunch length: Order 10 μm
- Single and multi-foils inserted at FACET IP
  - 20 to 111 x 0.9 μm foils

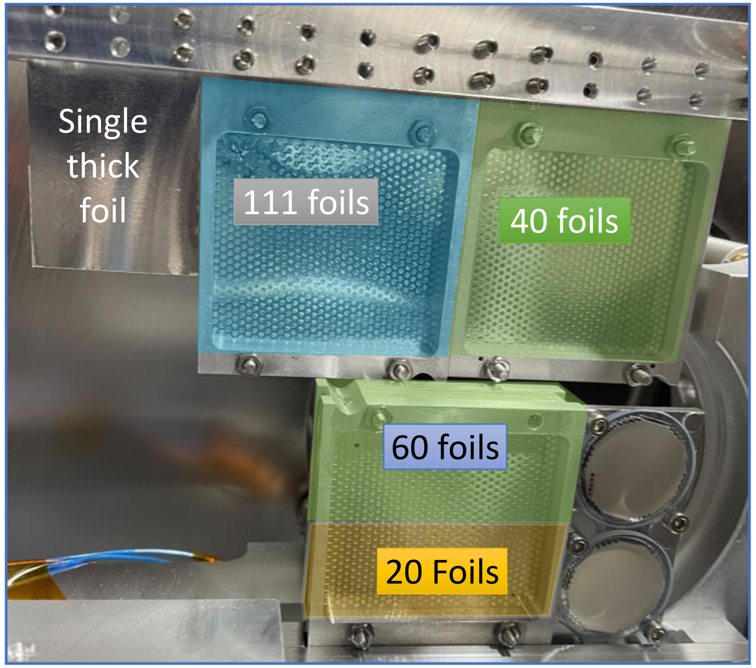
- ~1 μm thick Al foils
- 100 μm foil separation
- 1 mm holes



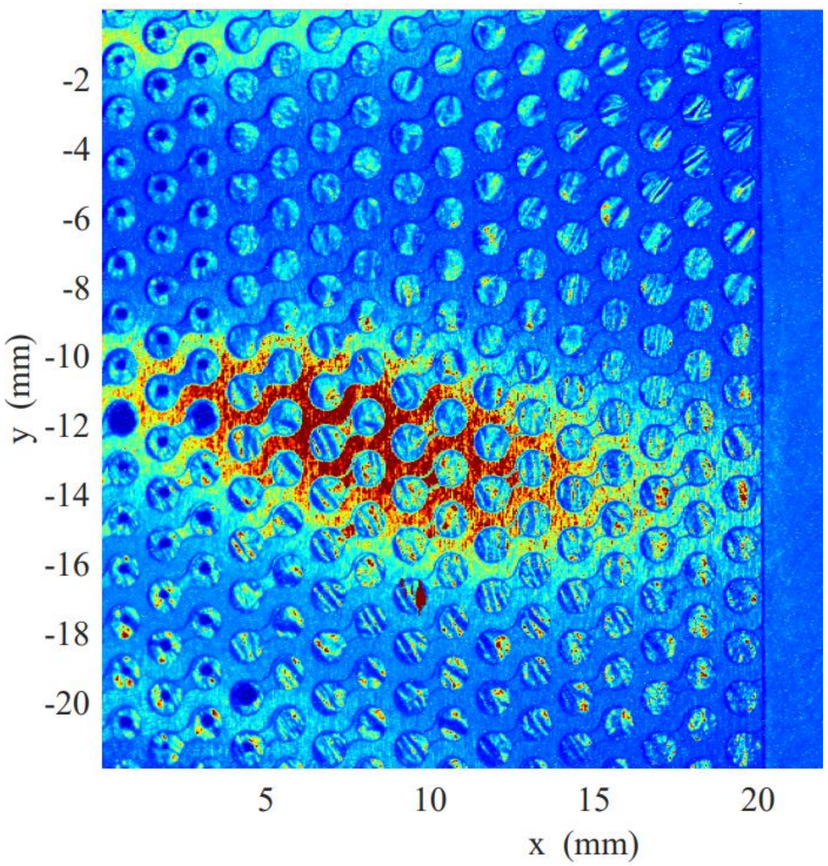
Experimental challenges – Single shot damage of foils

- This same process that drives the self focusing also drives image currents within the foil surface
- Ohmic losses from this current results in surface heating
  - 111 foils (100 µm of material) can be destroyed within only a few shots

- The multifoil stacks are installed on a target mover
- Assembly moves to a new “hole” for each series of shots

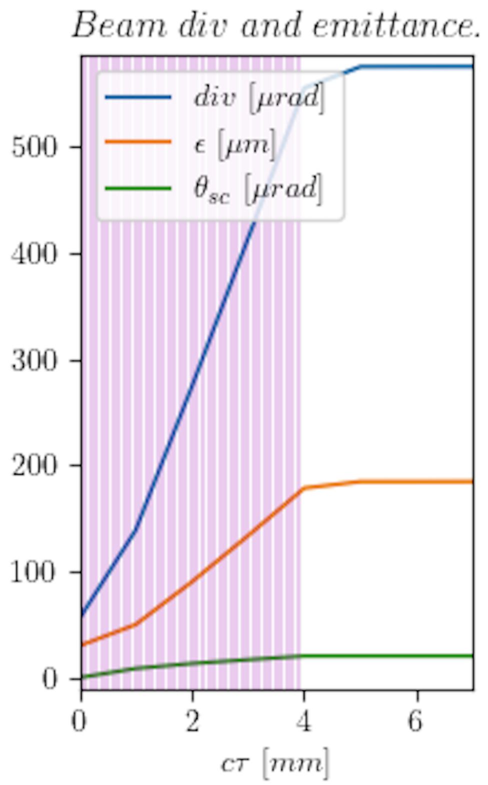


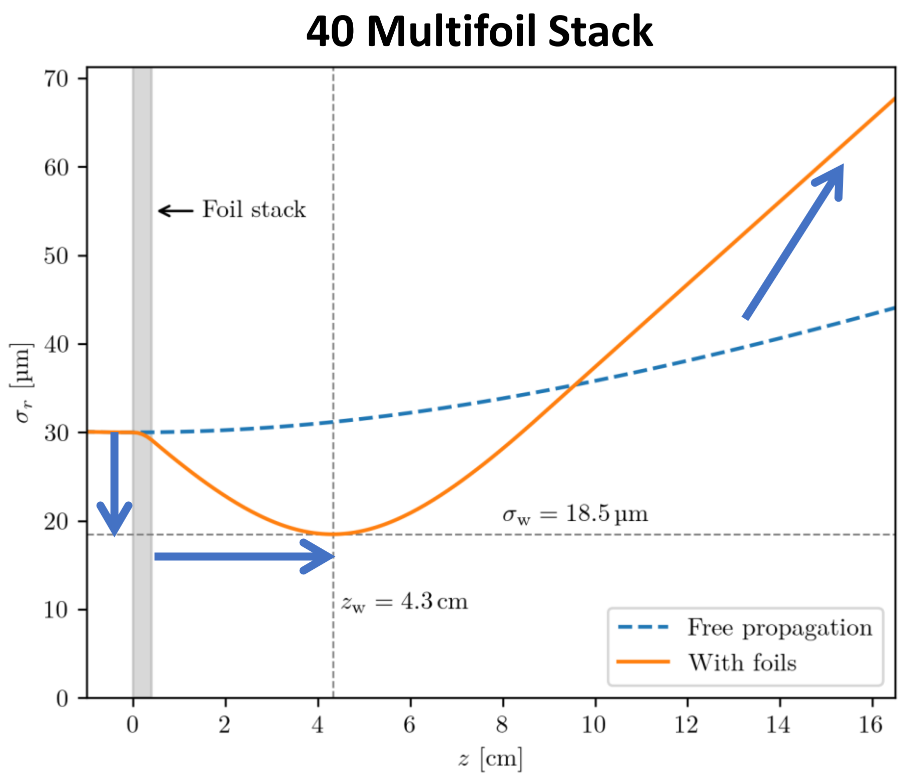
Multifoil Surface



Experimental observables

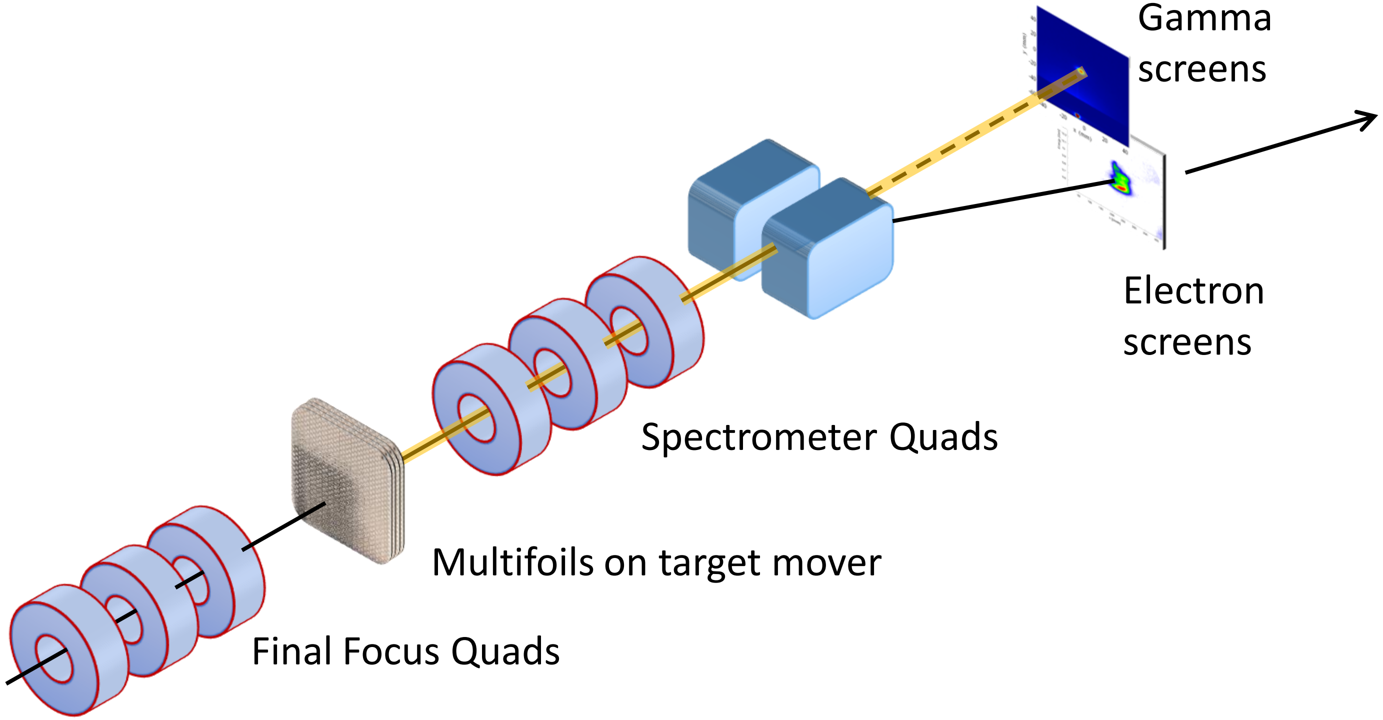
- Simulation of 40 foil stack
  - 1 µm Al foils
  - 100 µm spacing
  - Beam with:
    - $\sigma_r = \sigma_z = 30$ µm
    - $Q = 1.6$ nC at 10 GeV
- Foil focus the beam from $\sigma_r = 30$ µm to <20 µm
  - Focal length of ~4 cm
- Divergence increases from 60 µrad to 600 µrad

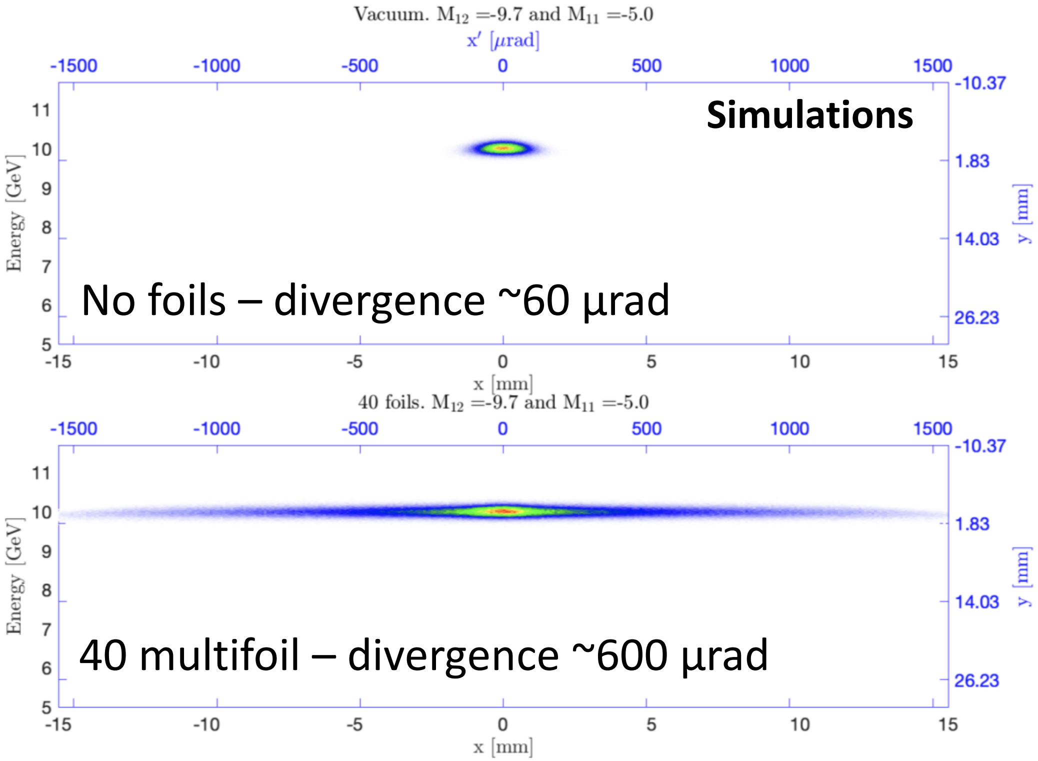




Spectrometer imaging

- Beam divergence and spot size at the IP can be measured by the FACET-II spectrometer beamline
- Can image either:
  - $M_{12} = 0$ to measure the spot size after the foils
  - $M_{12} > 0$ to measure the divergence

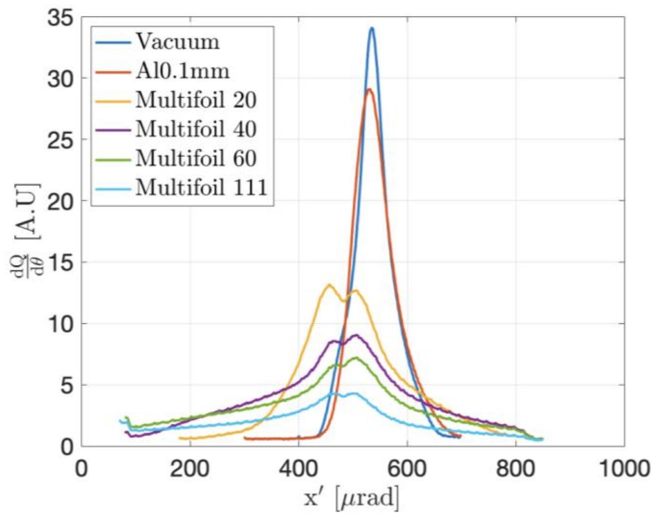


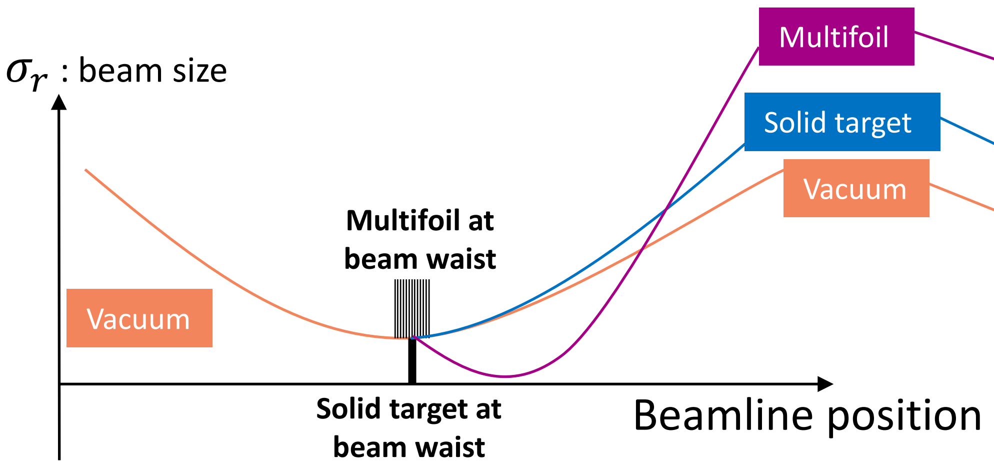


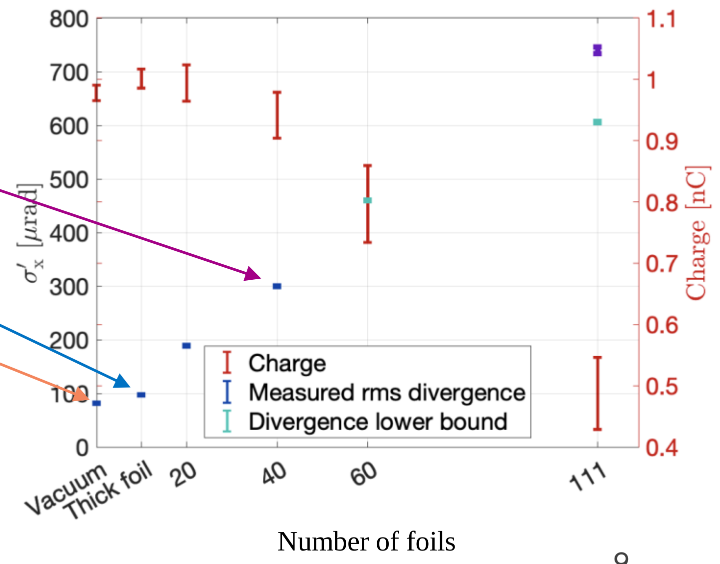
Simulations by A. Matheron

Experimental observation of increase in divergence by multifoil

- Increase in divergence provides evidence of near-field CTR focusing in multifoils
- Divergence measurement results:
  - Incoming divergence: 83 µrad
  - 100 µm single foil: 98 µrad
  - 20 to 111 multifoils: 190 to 740 µrad
- Increase in divergence is well above the component from multiple scattering

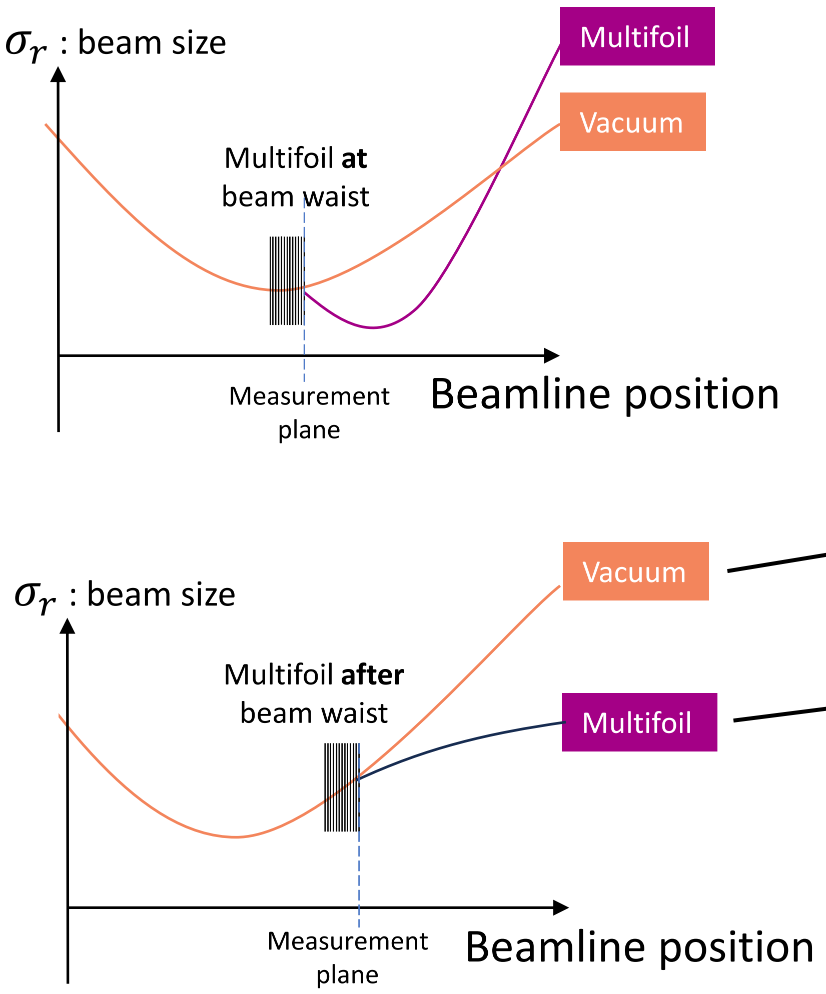




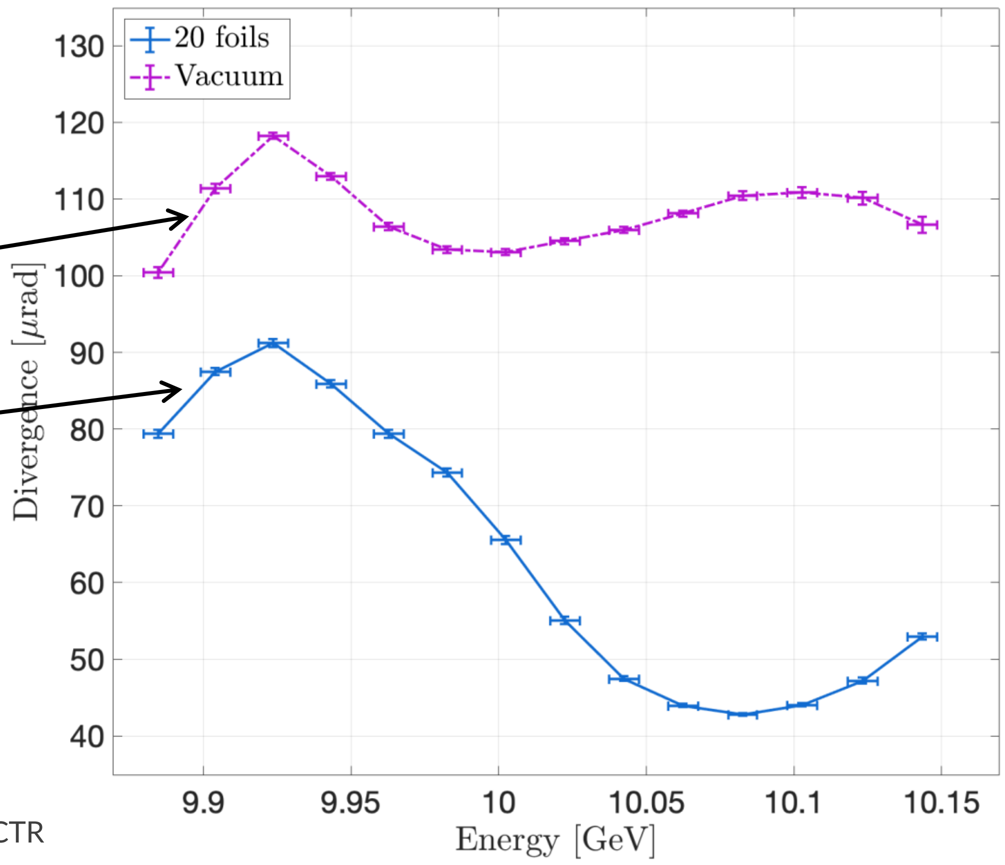


Analysis performed by A. Matheron

Observation of decrease in divergence

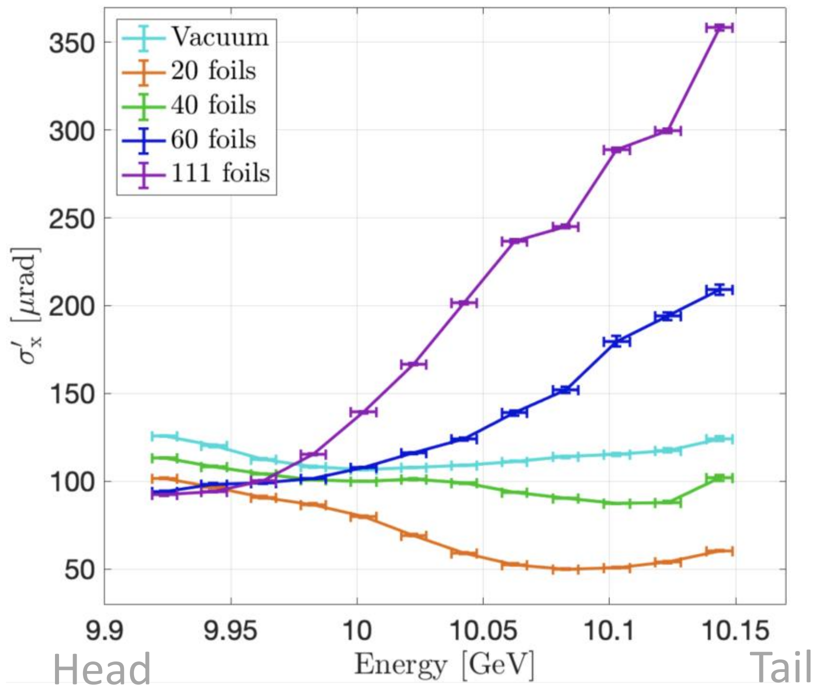


- What happens if the beam is diverging when it passes through the foils?
  - We observe a **reduction in divergence** due to NF-CTR focusing



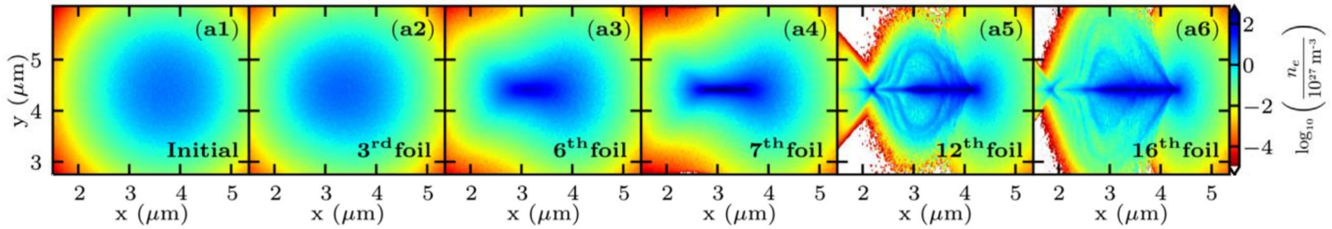
Head-to-tail focusing effect

- Chirped beam passing through the multifoil stacks:
  - Low energy is at the head of the bunch
  - Incoming beam was focused slightly ahead of the foils
- Stronger focusing observed towards back of the bunch
  - For 20 and 40 multifoil – we see a reduction of divergence
  - For 60 and 111 multifoil – the focusing effect strong enough that we see a steady increase in divergence
- Behavior matches expectation from simulations:
  - *Note – simulation shown here is with more extreme beam parameters*



Analysis performed by A. Matheron

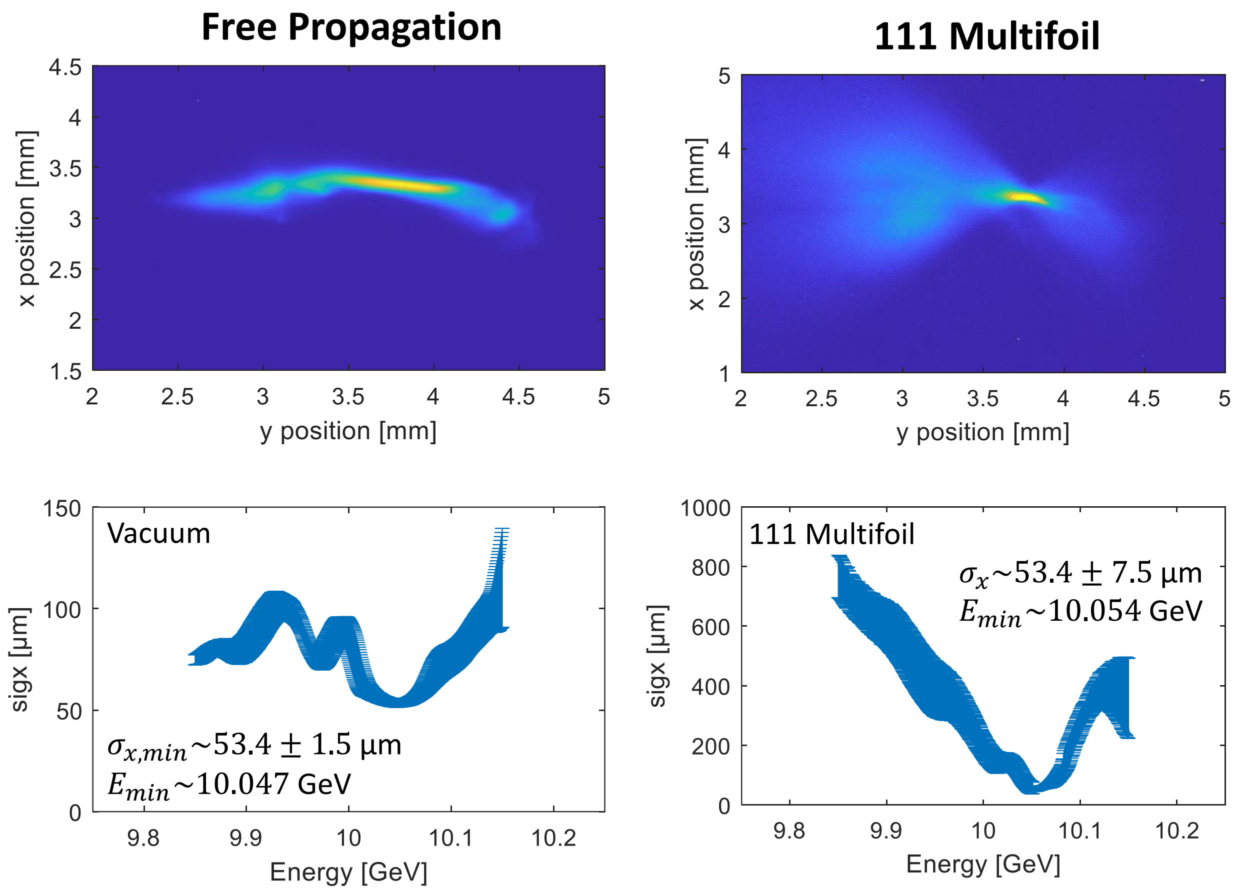
Bunch density:



Sampath, A. *et al.* Extremely Dense Gamma-Ray Pulses in Electron Beam-Multifoil Collisions. *Phys. Rev. Lett.* **126**, 064801 (2021).

Direct measurement of focused spot size (attempted)

- Direct measurements of the minimum spot size and focal position are complicated by:
  - Existing correlations in the beam
  - Resolution limits of the diagnostics
- Plots show the initial attempts at this direct measurement
  - Minimum spot size is roughly at the resolution limit in both cases
- A higher resolution profile monitor has been implemented to reduce this measurement resolution

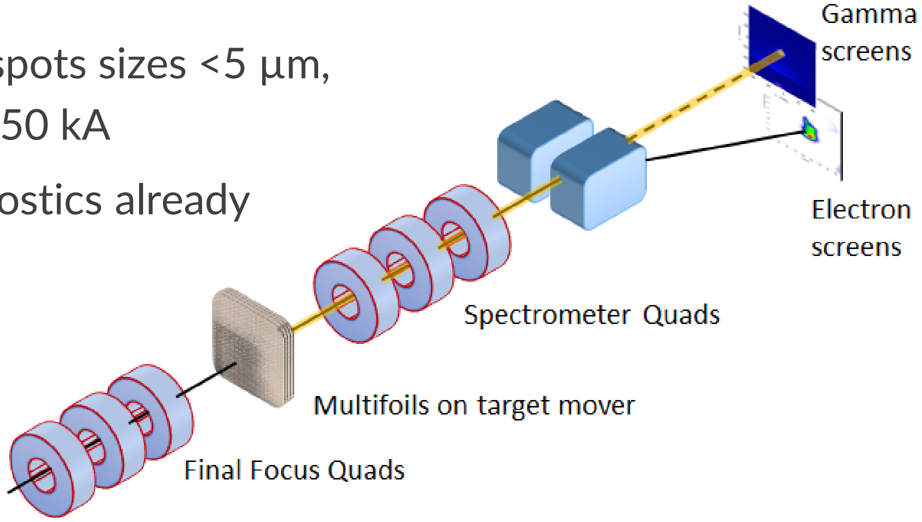


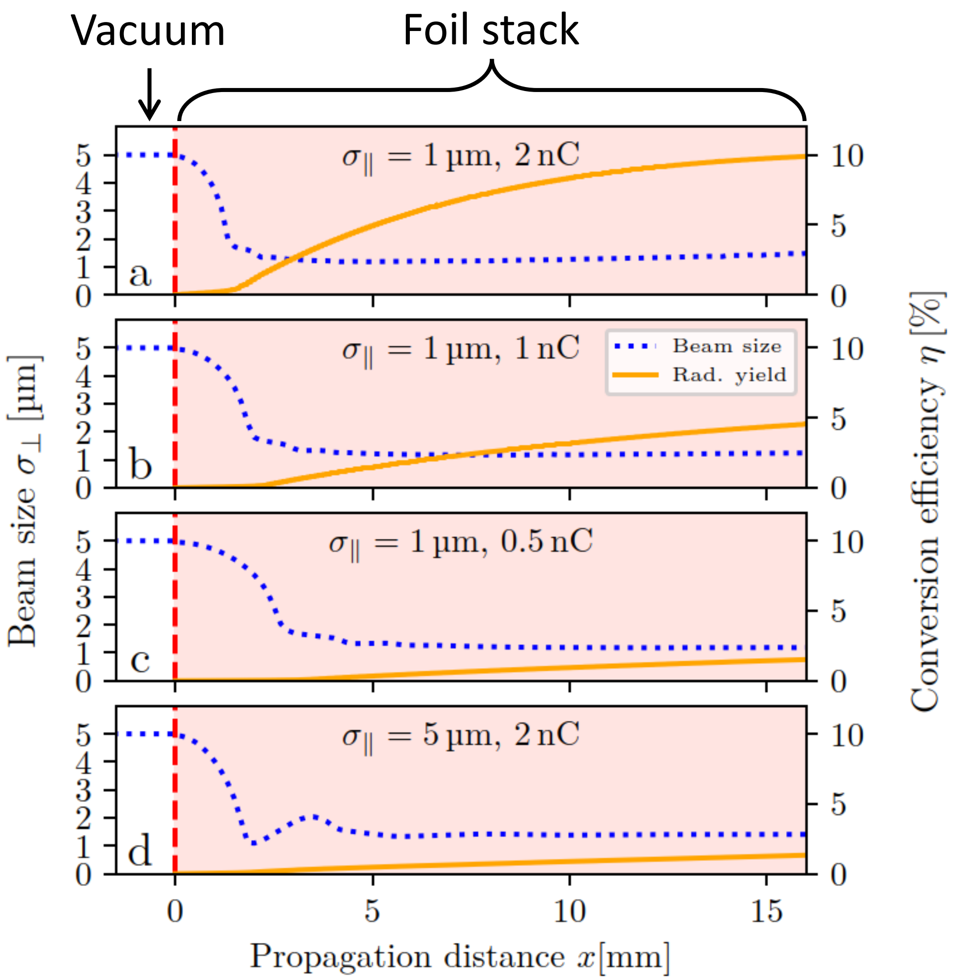
Note the different y-axis scales!

Future plans – Intense gamma-ray emission

- Extreme focusing is accompanied by the emission of intense gamma-ray photons
  - Can achieve order ~10% of beam energy converted to gamma-ray photons
  - Photon density matches beam density
    - Can reach solid density photons beams ~10^{29} m^{-3}

- Next steps:
  - Reach beam spots sizes <5 µm, and current >50 kA
  - Photon diagnostics already exist for this

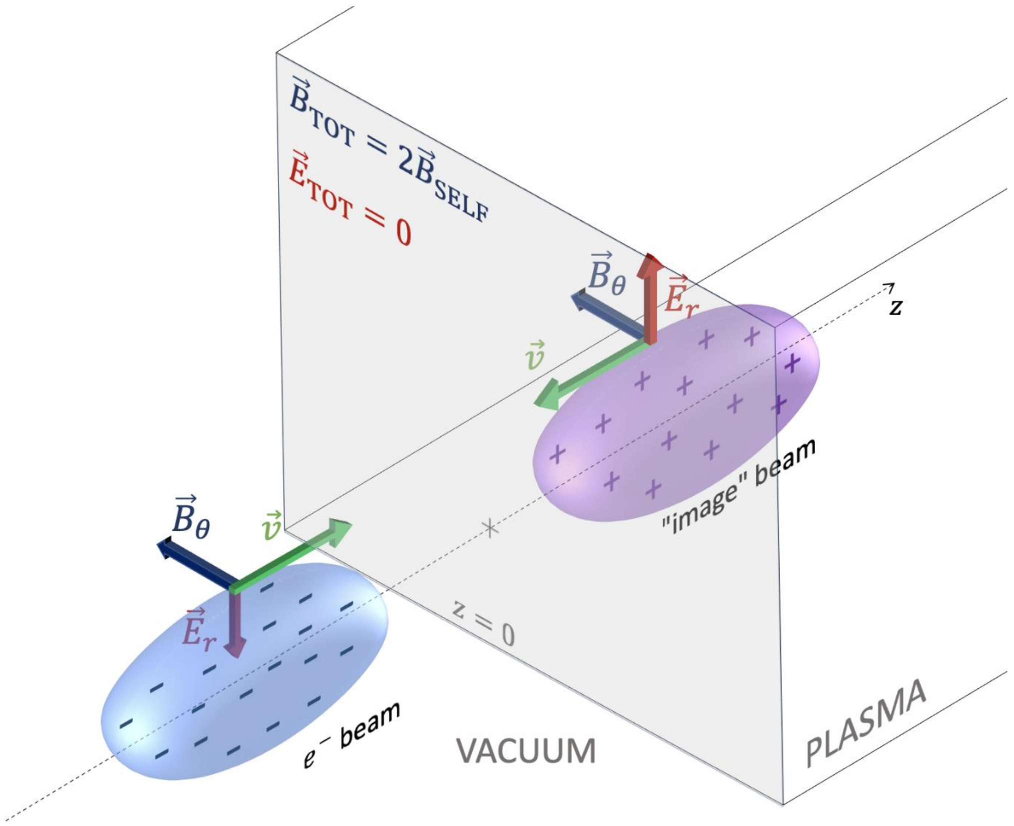




S. Corde et al., hal-02937777 (2020)

Future plans – Strong field QED studies

- Present experiments probe the nonperturbative regime of SF-QED using collisions between high power lasers and highly relativistic electron beams
  - *See the talk by* ***A. Knetsch in WG6*** *now!*
- Beam-beam collisions have been proposed:
  - Requires high energy (~100 GeV)
  - Compressed beams (~10’s of nm)
  - Very sensitive to alignment
- Non-perturbative regime accessible through beam-foil collision when the beam becomes dense enough
  - Beam “collides” with its image



Matheron, A. *et al*. Probing strong-field QED in beam-plasma collisions. Comm. Phys (2023)

- Nonperturbative QED effects start happening when $\chi = \frac{E^*}{E_{cr}}$ approaches 1

Summary

- Near Field CTR can result in strong transverse fields at a foil surface boundary that have a strong impact on the beam:
  - Strong self focusing can achieve electron beams with ~solid-density
  - Intense emission of gamma-ray photons

- First experimental demonstration shows a clear focusing effect under multiple configurations:
  - Different numbers of foils
  - Different waist positions and sizes
  - Chirped beams

- Future prospects of this include:
  - Generation of intense gamma-rays
  - As the beam approaches solid density we can start to probe the SF-QED regime