Wakefield Acceleration in Nanostructures: The E336 Experiment at FACET-II

Advanced Accelerator Concepts Workshop

November 7-11, 2022

Robert Ariniello on behalf of the E336 collaboration

SLAC NATIONAL ACCELERATOR LABORATORY

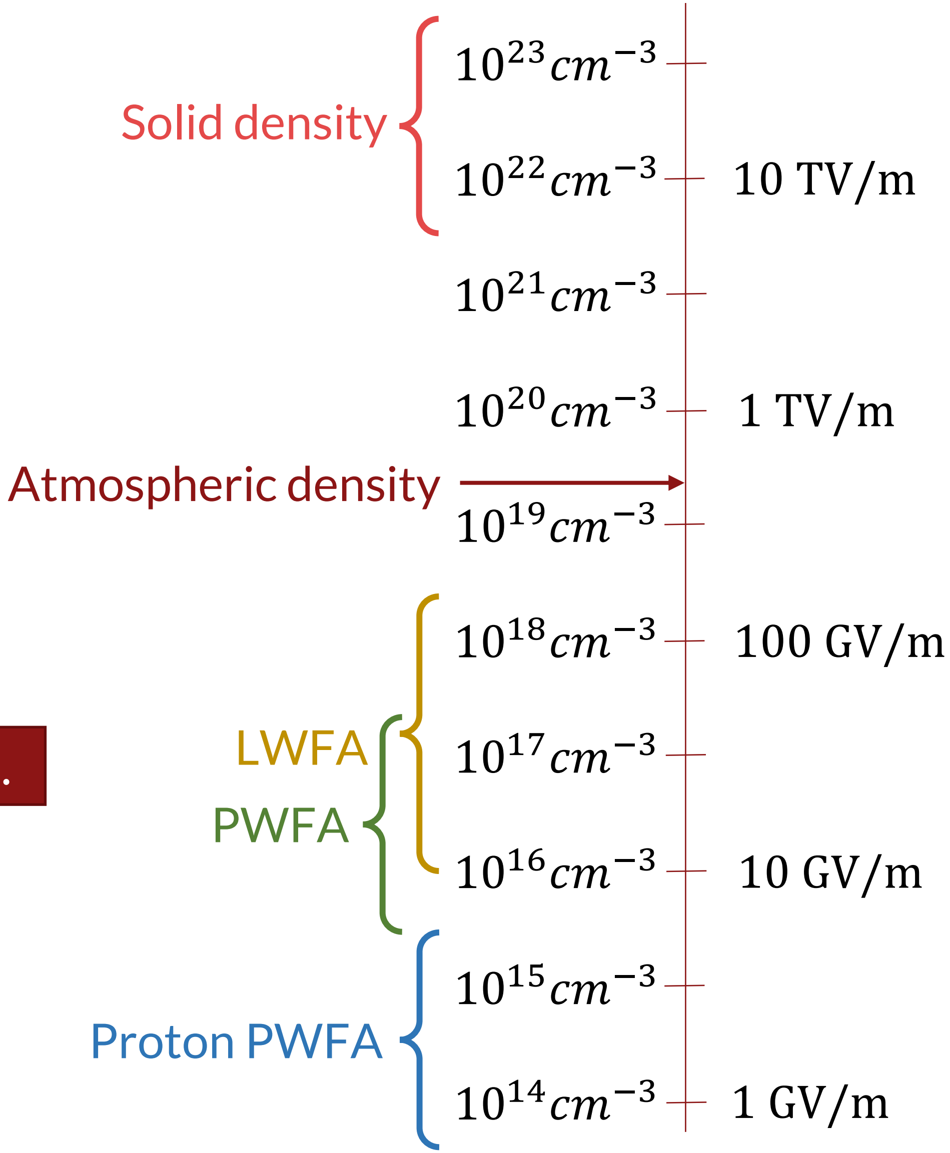
Stanford University | U.S. DEPARTMENT OF ENERGY

Why go to solid materials? Scaling of the wakefields

- The accelerating field in a wakefield accelerator scales as

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}.$$

- Most PWFA/LWFA is done in ionized gas plasma sources at densities much less than atmospheric
- Solids are 4-5 orders of magnitude more dense
- Drive a wake in a solid density plasma, get 2 orders of magnitude stronger fields than an LWFA

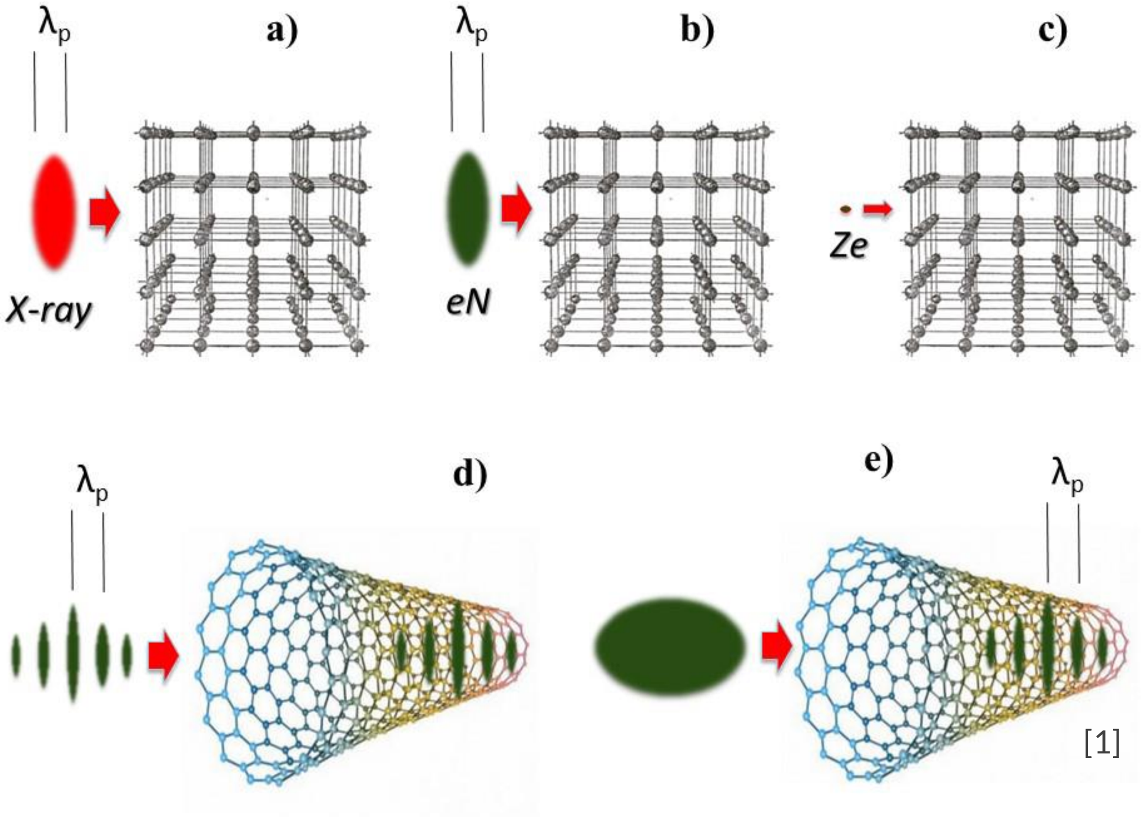


Solid density wakefield accelerators could produce fields of 10 TV/m.

The requirement for a nanostructure

- At solid densities, scattering from plasma ions becomes significant
- Leads to rapid pitch angle diffusion and particles escaping the wake

Acceleration in in a nanostructure (crystal or carbon nanotube) limits scattering off the solid's ions.

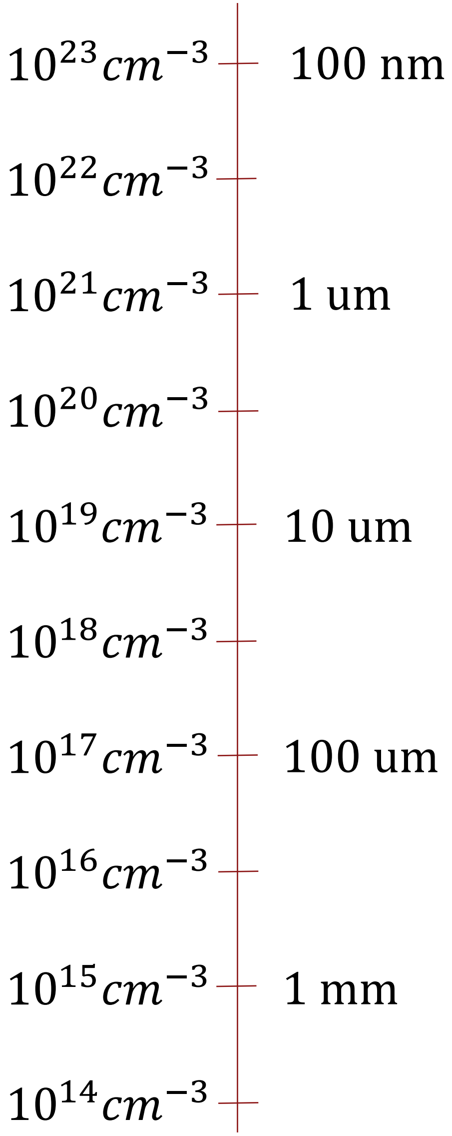


Self modulation of the electron beam

- Size of the wake scales as

$$\lambda_p = 2\pi \frac{c}{\omega_p}$$

- Driver needs to have spatial scale on the order of the wake scale
- For solid densities, this is difficult to achieve with current facilities

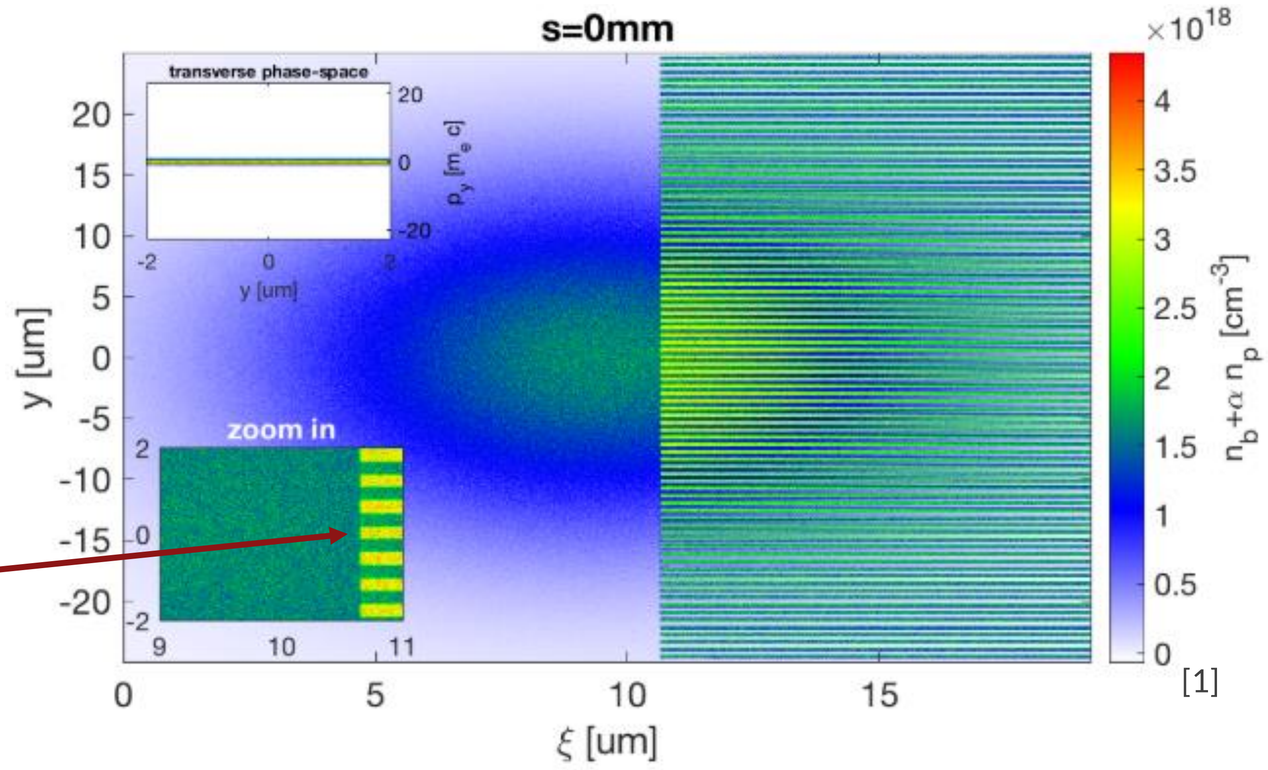


Self modulation of the electron beam

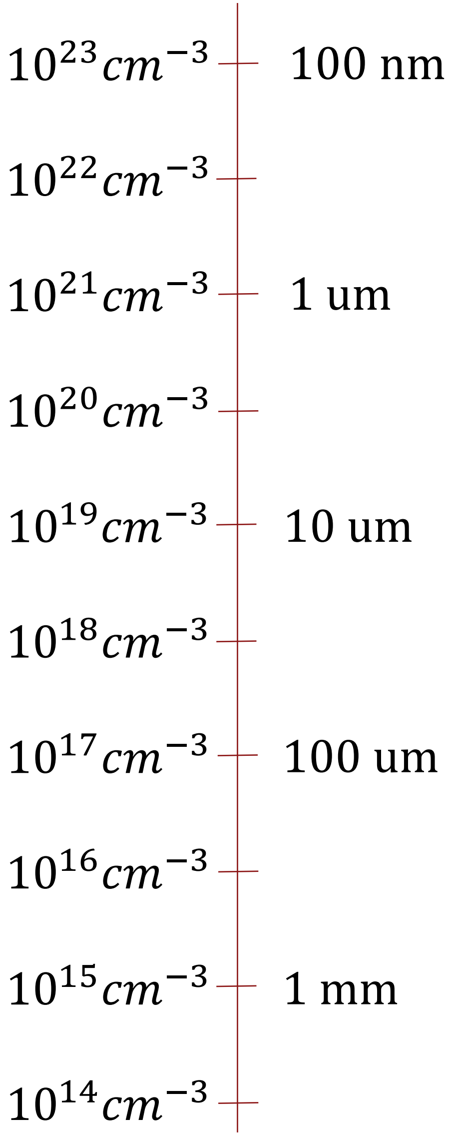
- Size of the wake scales as

$$\lambda_p = 2\pi \frac{c}{\omega_p}$$

- Driver needs to have spatial scale on the order of the wake scale
- For solid densities, this is difficult to achieve with current facilities



Plasma density has the same structure as the nanotarget!

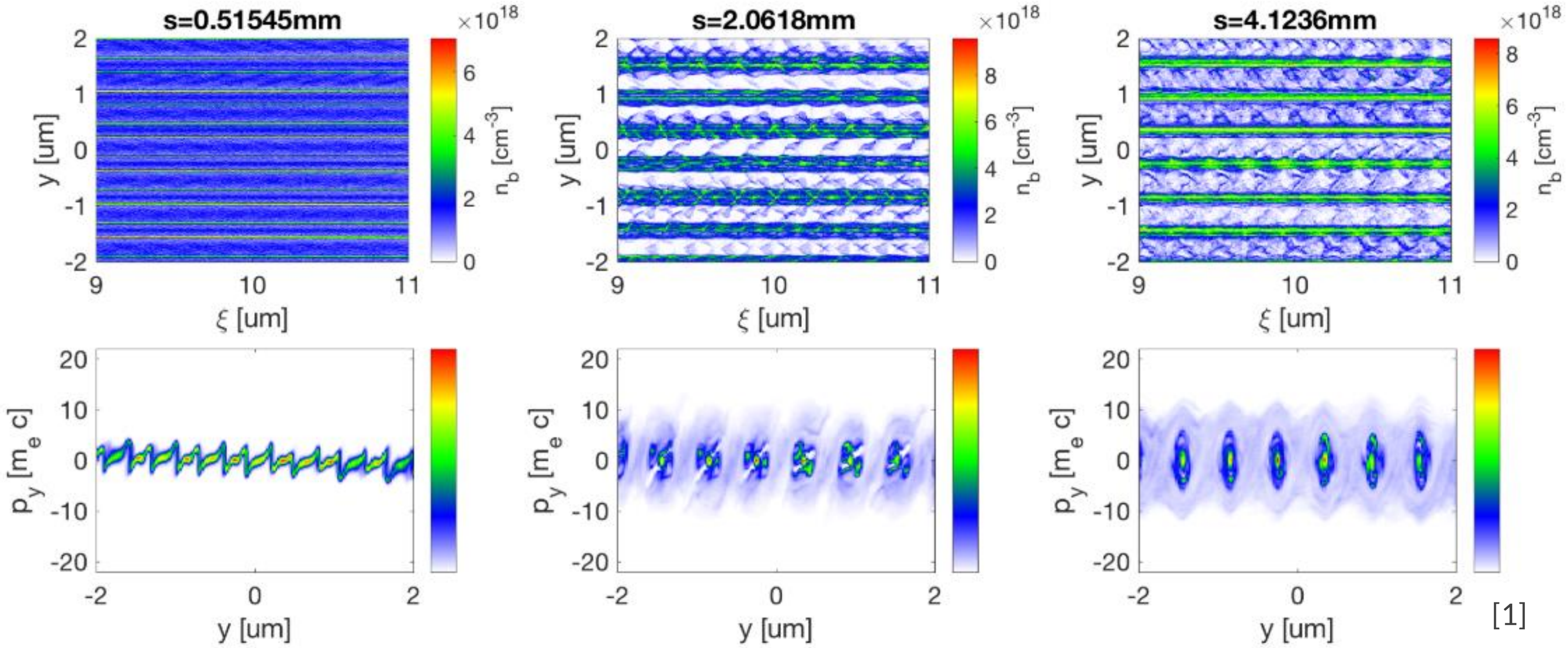


Self modulation of the electron beam

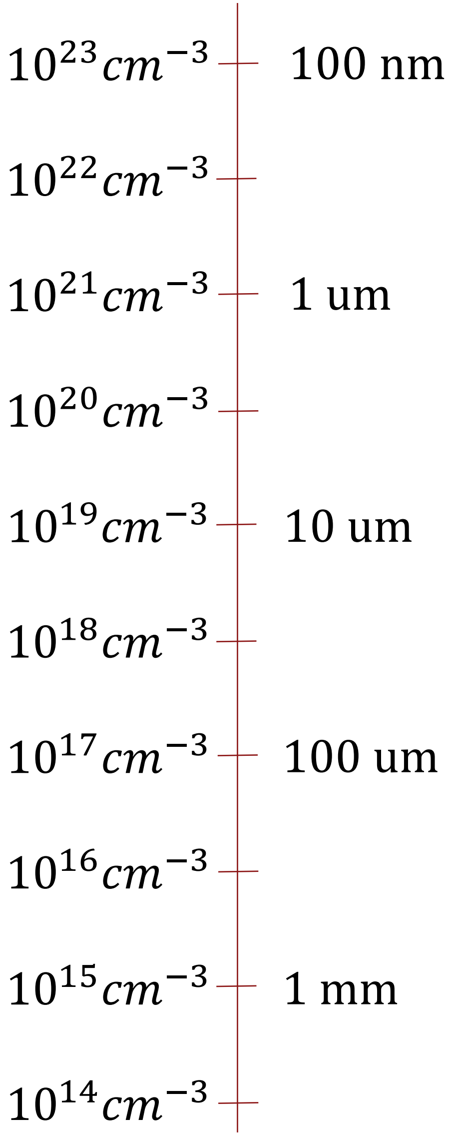
- Size of the wake scales as

$$\lambda_p = 2\pi \frac{c}{\omega_p}$$

- Driver needs to have spatial scale on the order of the wake scale
- For solid densities, this is difficult to achieve with current facilities



[1]



Don't need a small driver! Imprint the target structure on the drive beam.

The E336 experiment at FACET-II

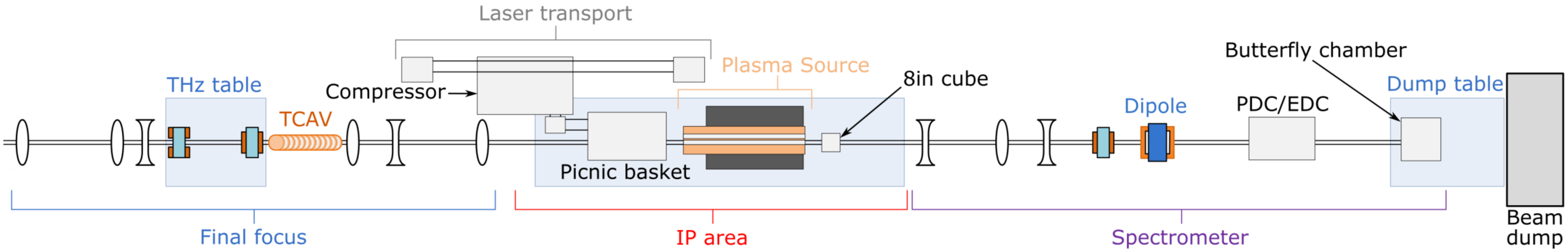
- Need a proof-of-principle experiment to demonstrate the phenomenon
- FACET-II has sufficiently high beam current to excite wakes in nanostructures
  - To efficiently excite wakefields, the beam density needs to approach the plasma density

Scientific goals:

- Proof-of-principle experiment - demonstrate the feasibility of the study of beam-nanotarget interaction and of beam-induced wakefields in nanotargets
- Observation of electron beam nano-modulation
- Observation of betatron X-ray radiation
- Confirmation of simulation models

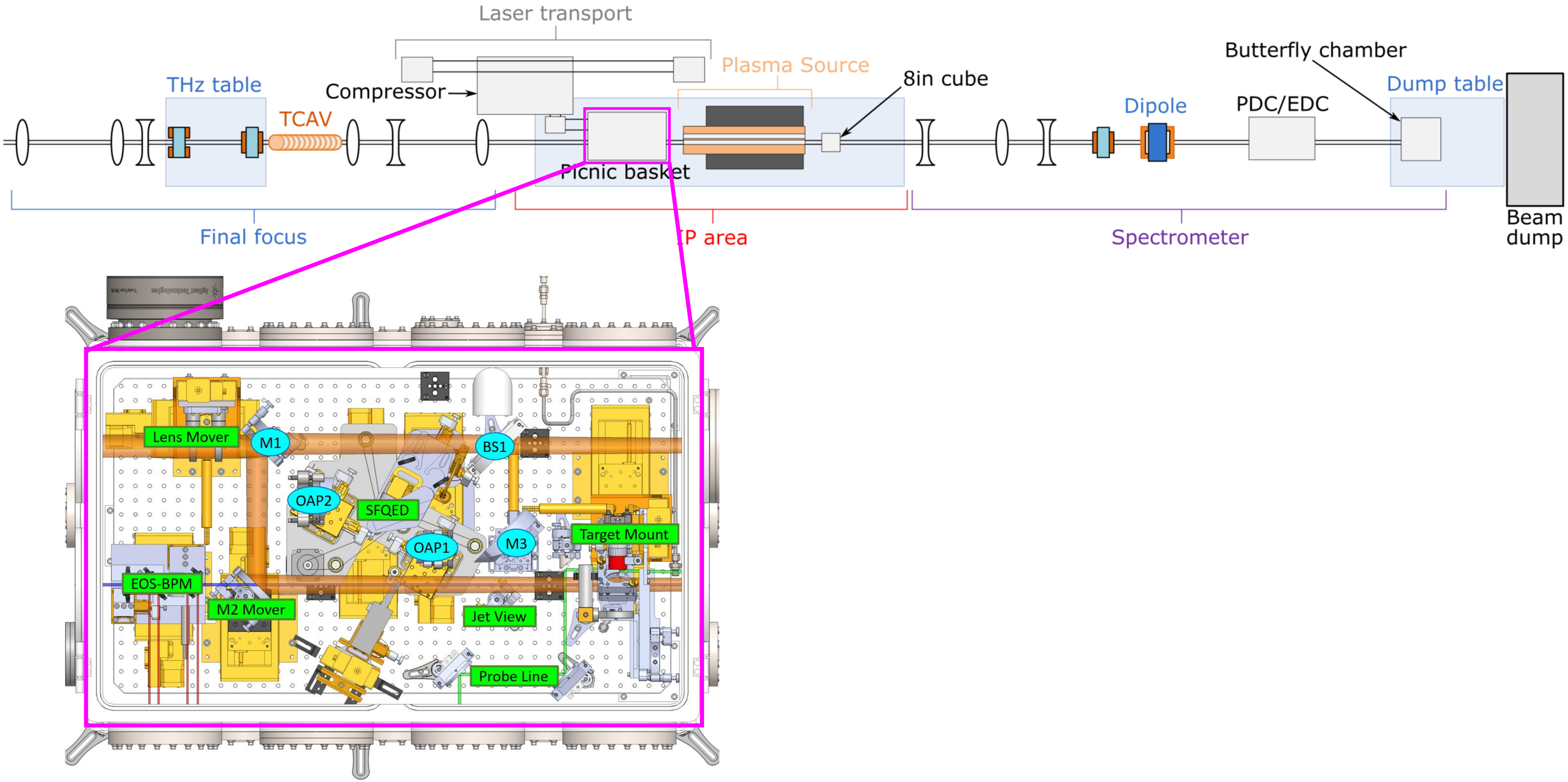
E336 is a proof-of-principle experiment. Demonstrate that the interaction can be observed and benchmark simulations.

Experimental setup

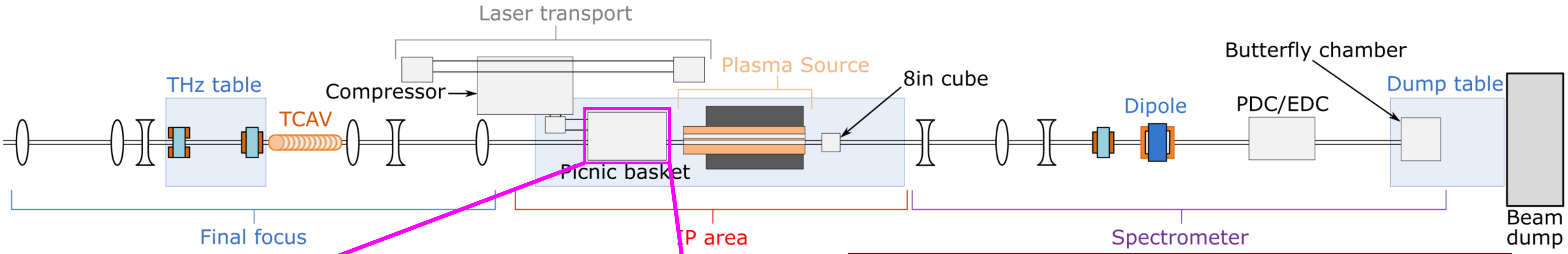


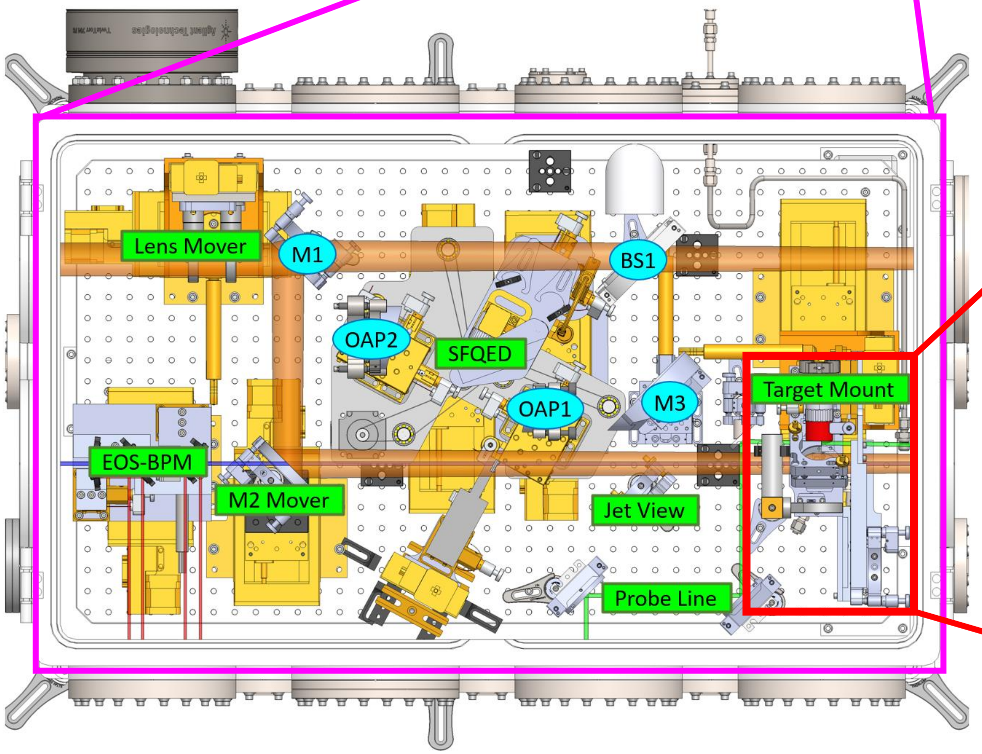
- FACET-II can deliver electrons:
  - 2 nC bunches
  - 10 GeV
  - >50 kA peak current

Experimental setup

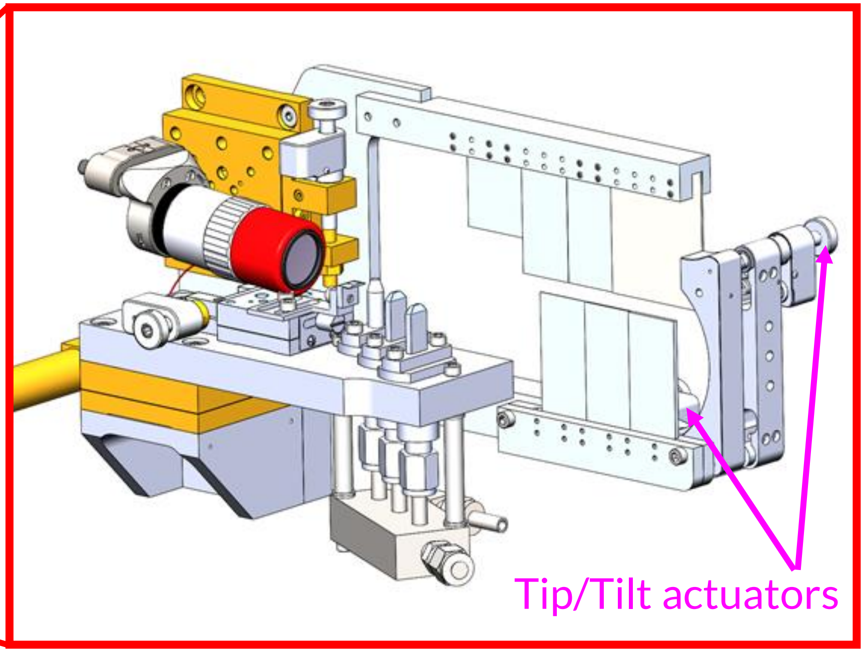


Experimental setup

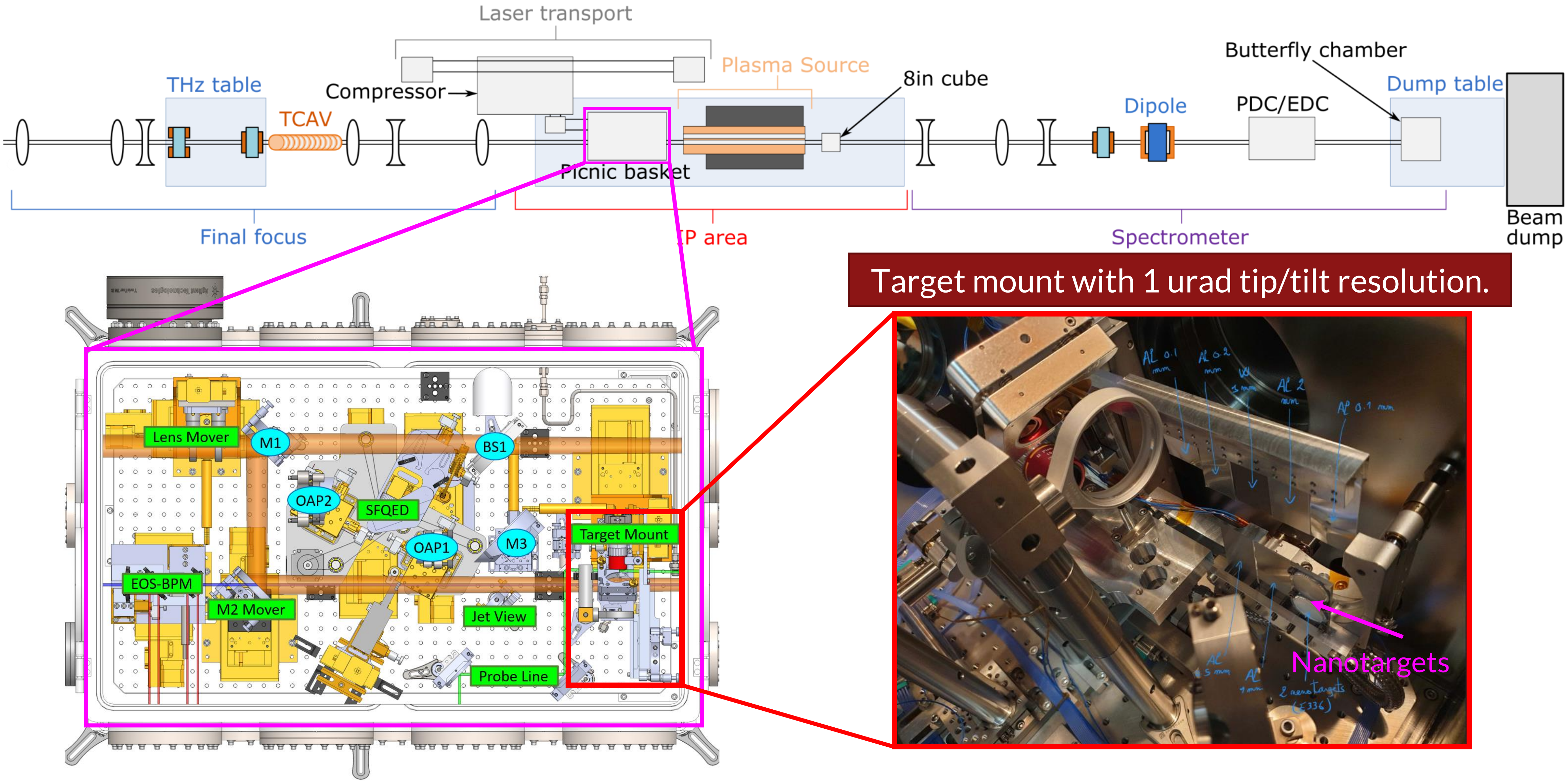




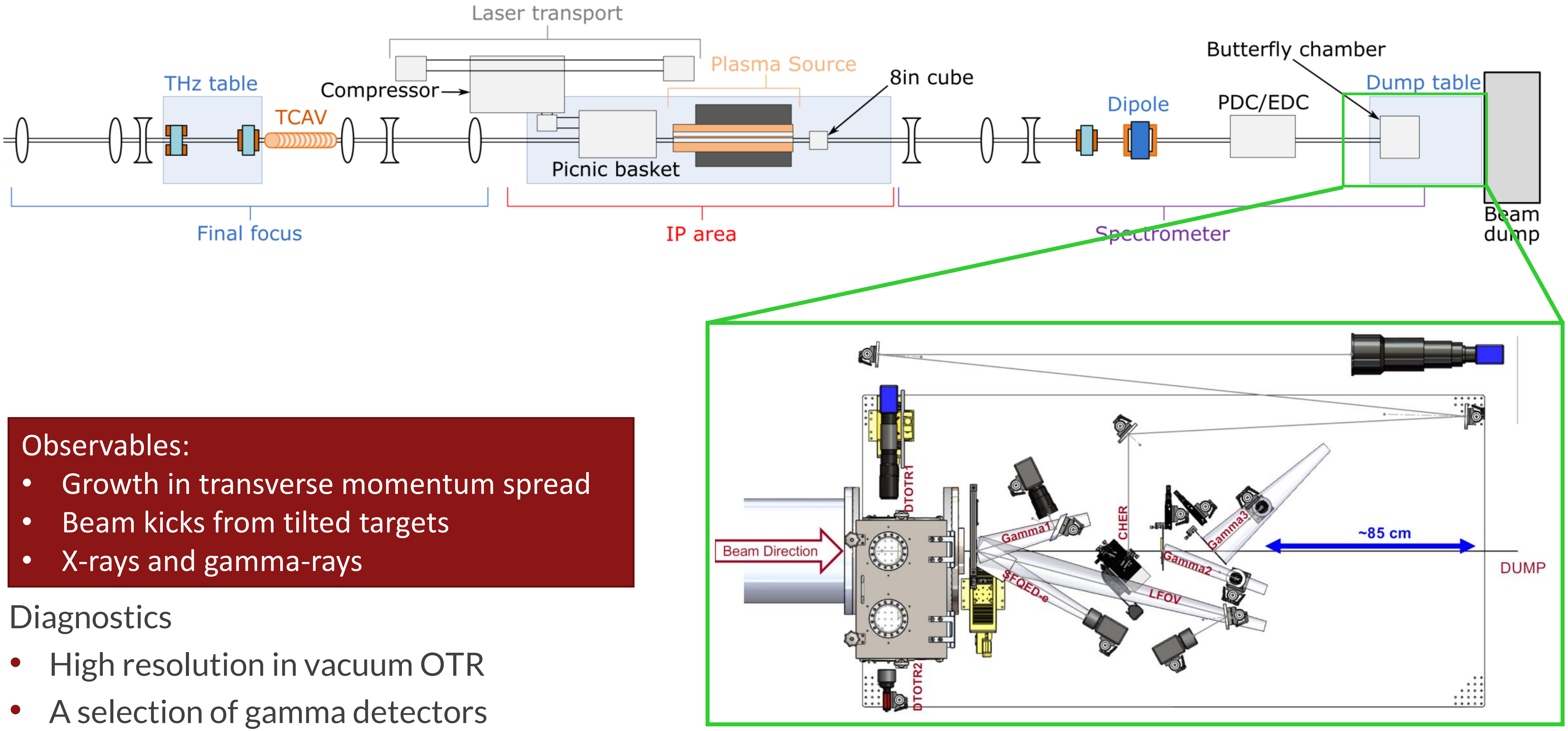
Target mount with 1 urad tip/tilt resolution.



Experimental setup



Diagnostics and observables



Observables:

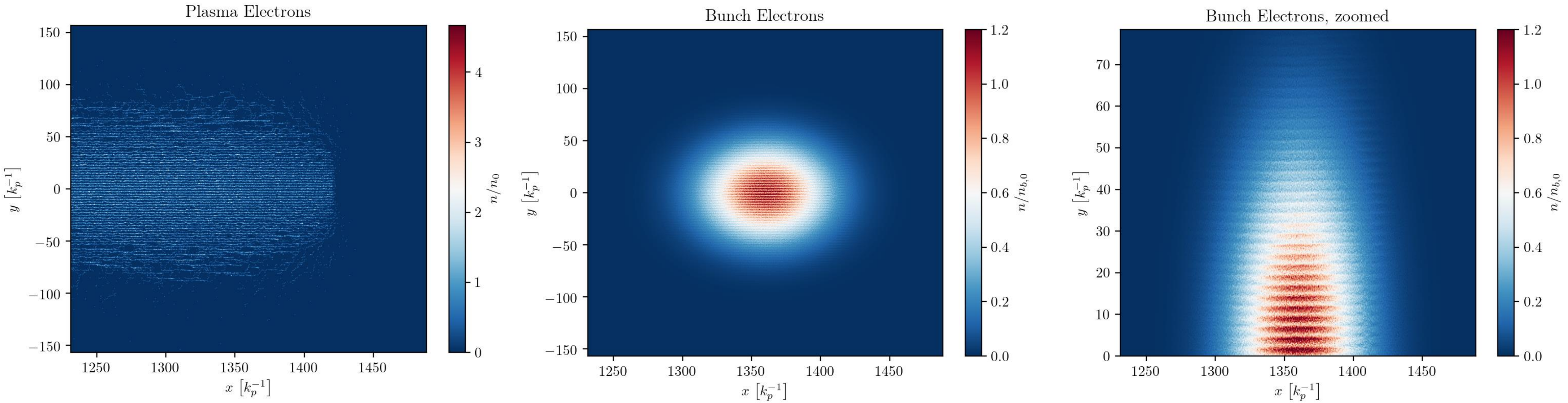
- Growth in transverse momentum spread
- Beam kicks from tilted targets
- X-rays and gamma-rays

Diagnostics

- High resolution in vacuum OTR
- A selection of gamma detectors

Simulation campaign

- 2D PIC simulations of a 5x5x5um beam (2 nC, 10 GeV)
- 200nm tubes in silica
- Plasma ionized by beam self fields

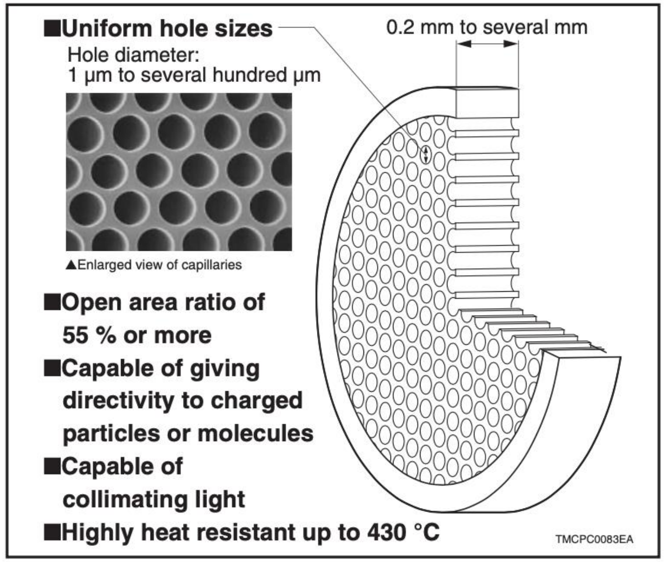


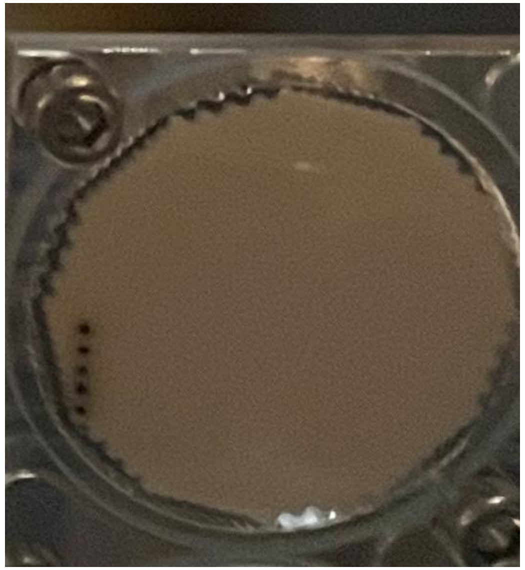
PIC simulation campaign to explore how tube/beam parameters effect interaction.
For details see Alexander Knetsch simulation talk in WG3, 16:30 Nov. 8

Initial progress

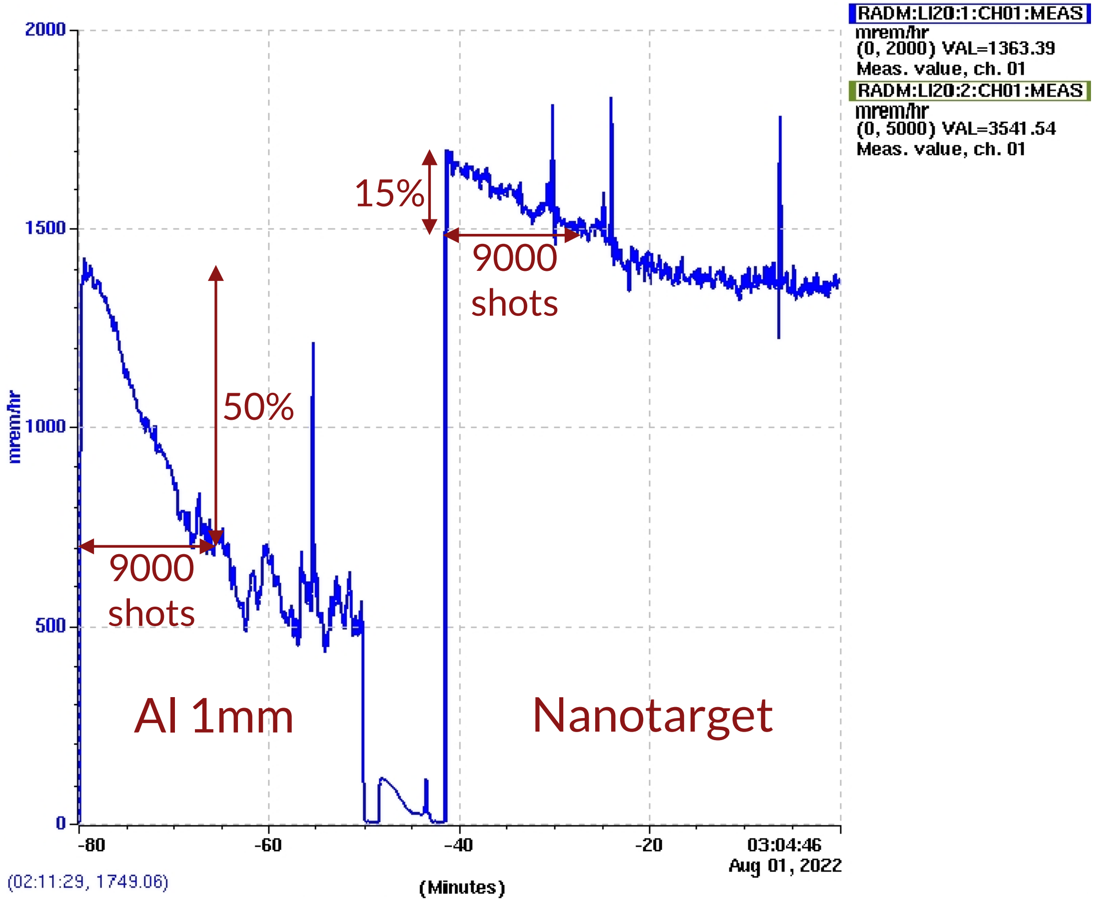
- 1 mm thick, 6 micron-diameter nanotubes in lead glass
- Radiaton monitor downstream – drop tells how quickly the target is being damaged/drilled
- Initial damage tests carried on nanotargets

Damage observed, but targets relatively robust:
15% decrease in radiation in 9000 shots





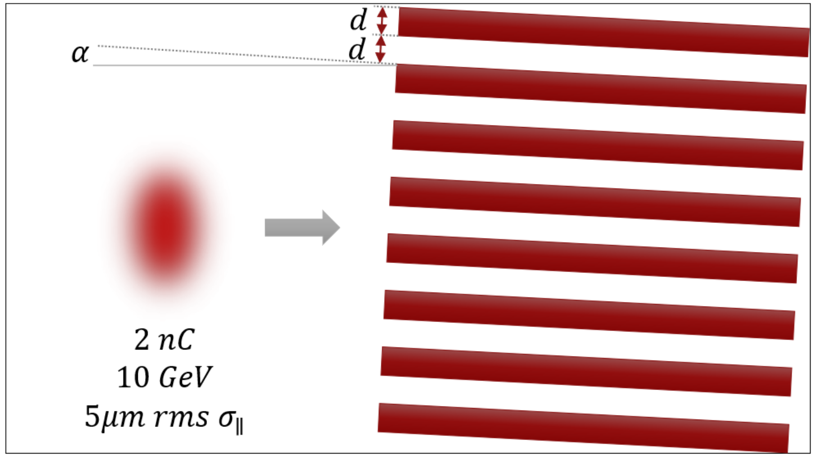
Radiation monitor

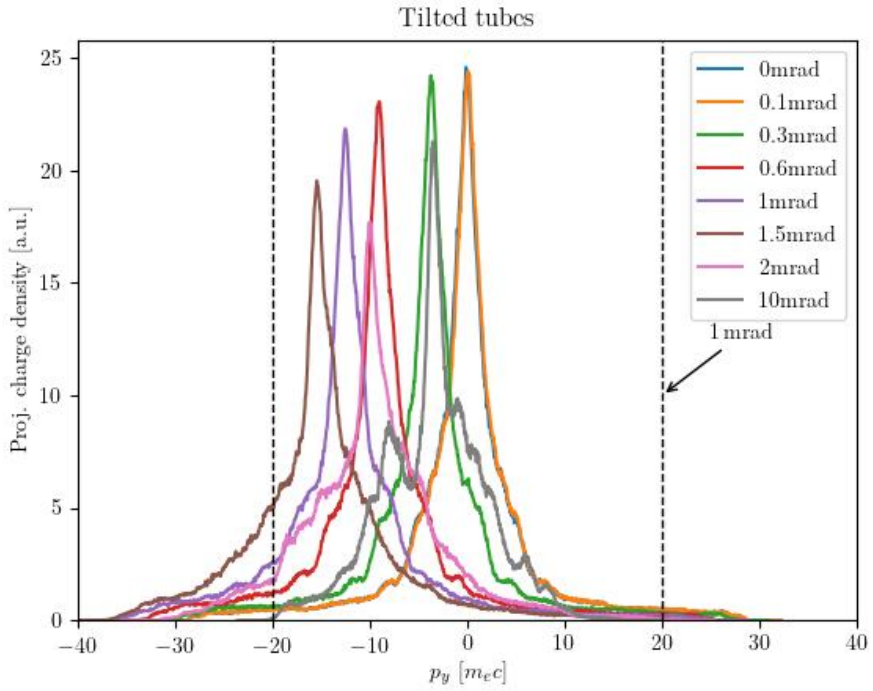


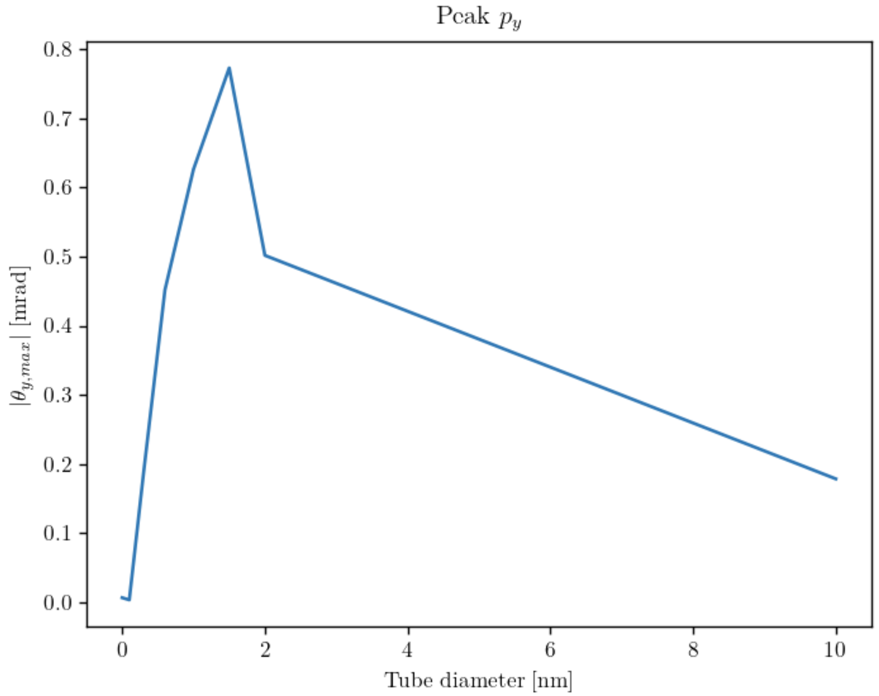
Future plans – aligning the beam to the structure

- 2D simulations in Alumina with 2um tubes, 5x5x5um beam
- The beam is kicked when the target is tilted
- A way to do beam based fine angular alignment

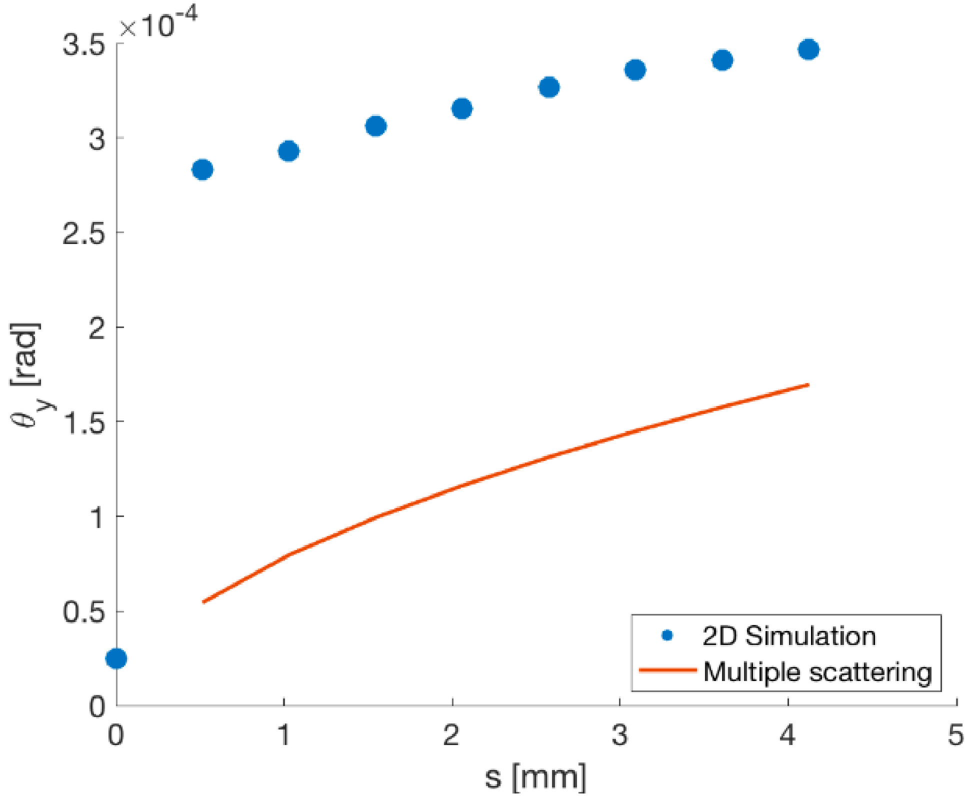
The beam gets a transverse kick when misaligned to the structure. Signature of beam-nanotarget interaction.







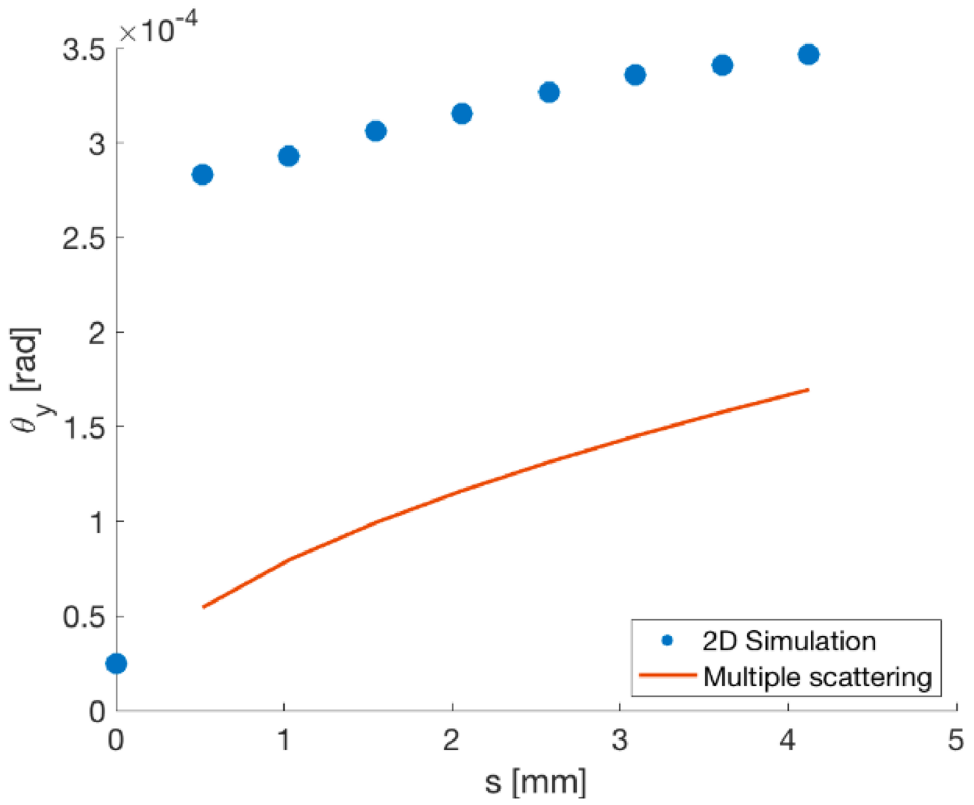
Future plans – more divergence than amorphous

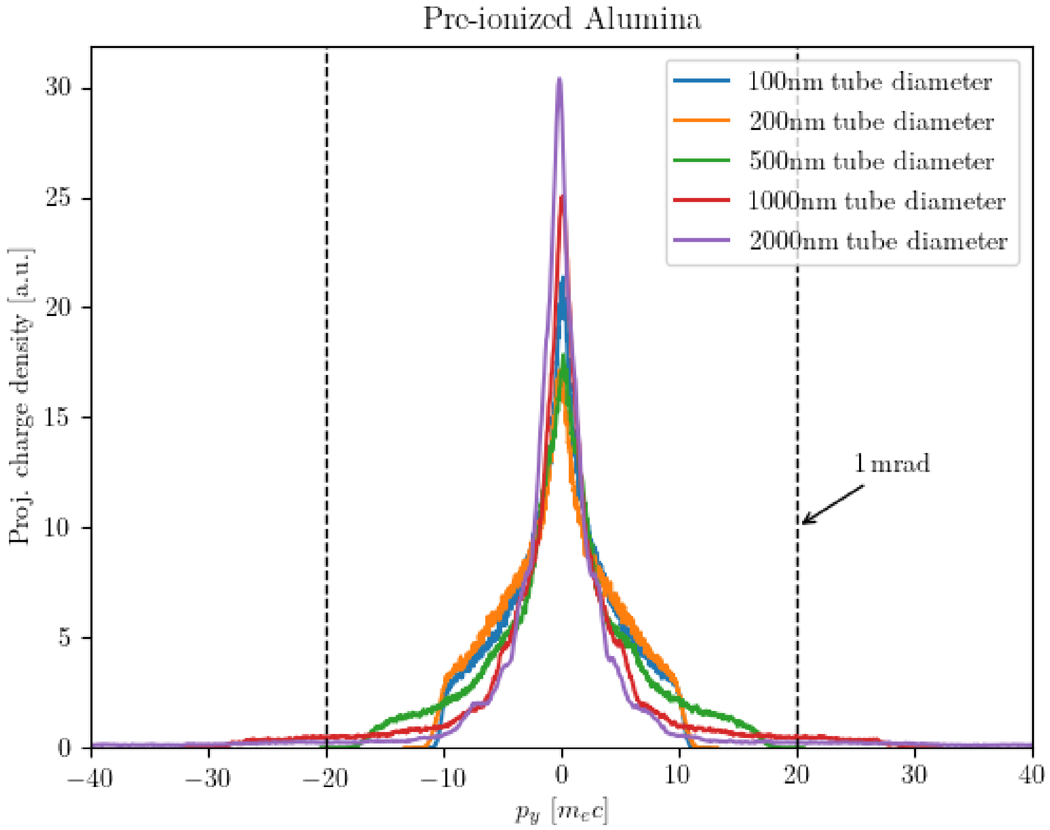


- Expect larger divergence than amorphous due to microbunching.

Future plans – more divergence than amorphous

Goal is systematic study of how nanotube and beam parameters impact observables.





- Expect larger divergence than amorphous due to micorbunching.

- Larger transverse kicks in larger tubes
- More particles interact in smaller tubes

Summary and future extensions

- Plasma wakefield acceleration at solid densities has the potential to produce TV/m fields
- Nanostructures are required to limit the beam ion scattering
  - Also naturally channel the beam leading to small natural emittances

- Driving the wake requires a beam with spatial scales on the order of λ_p
- Can experimentally explore the physics with current facilities by taking advantage of self modulation
- E336 experiment aims to detect evidence of nanostructure induced in the beam
  - Study dependence of the interaction and beam and target parameters

Possible future research directions:

- Use transversely sub-micron electron beams to drive the acceleration
  - Use a thin plasma lens to focus the FACET-II beam
  - Use an ultrahigh brightness beam produced by on of the proposed injection schemes

The E336 collaboration

Collaboration and institutions

- IP Paris/LOA: Sébastien Corde, Max Gilljohann, Yuliia Mankovska, Pablo San Miguel Claveria, and Alexander Knetsch
- UC Irvine: Peter Taborek and Toshiki Tajima
- Fermilab: Henryk Piekarz and Vladimir Shiltsev
- SLAC: Robert Ariniello, Henrik Ekerfelt, Mark Hogan, and Doug Storey
- CEA: Xavier Davoine and Laurent Gremillet
- IST: Bertrand Martinez
- INFN: Alexei Sytov and Laura Bandiera

Publications

- White paper for Snowmass
  in AF6 Advanced Accelerator Concepts
  [1] arXiv:2203.07459

Channeling Acceleration in Crystals and Nanostructures and Studies of Solid Plasmas: New Opportunities

Robert Ariniello[1], Sebastien Corde[2], Xavier Davoine[3], Henrik Ekerfelt[4], Frederico Fiuza[4], Max Gilljohann[2], Laurent Gremillet[3], Yuliia Mankovska[2], Henryk Piekarz[5], Pablo San Miguel Claveria[2], Vladimir Shiltsev[5], Peter Taborek[6], and Toshiki Tajima[6]

See Alexander Knetsch simulation talk in WG3, 16:30 Nov. 8

FACET-II | Facility for Advanced Accelerator Experimental Tests

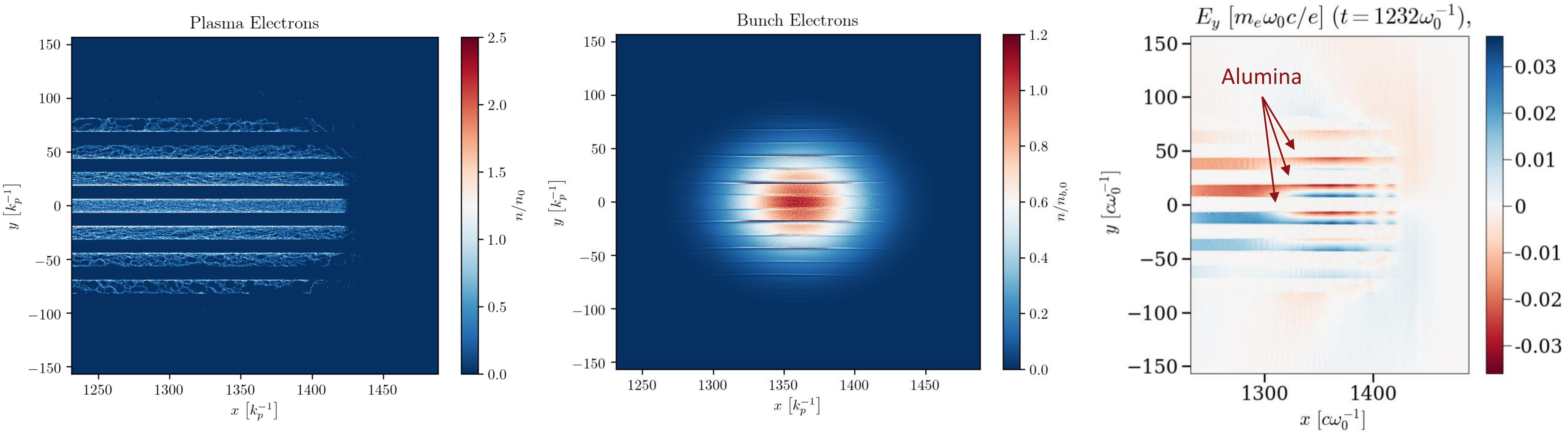
Questions?

Advanced Accelerator Concepts Workshop

November 7-11, 2022

Beam self fields: ionization and screening

- 2D PIC simulations of a 5x5x5um beam
- 2000nm tubes in alumina
- Plasma ionized by beam self fields



- Beam self fields are intense enough to ionize bulk material
- As material starts to ionize, plasma electrons screen self fields
- Overall effect is several percent level ionization

Beam requirements

- E336 benefits from the high bunch densities and small emittances.

  - The charge per tube scales as $Q/{\sigma_r}^2$ (area charge density) and the scale of the transverse force on the beam particles scales as $n_b d$ (with d as the nanotube diameter).

  - The emittance acts against beam transverse modulation, with an effective force in the envelope equation going as ${\epsilon_n}^2/d^3$, which must be small compared to the force from the nanotube plasma.

  Example: for d=0.3μm and 10μm transverse beam size, 50 kA and 5 mm.mrad the modulation is strong, 20 kA and 20 mm.mrad it will not be detectable.

Max gradient for the transverse force for long bunch in plasma:

$$g_{\max}^{\text{long}} = -\frac{eNc\mu_0}{2\sqrt{2\pi}^3 \sigma_r^2 \sigma_z} \chi(k_p \sigma_r).$$

(arXiv:1802.02750)

Transverse wakefield:

$$W_\perp \propto \frac{Q(d^2/\sigma_r^2)}{d^3} \frac{d}{\sigma_z} \propto n_b$$

Applications of such acceleration techniques

- High gradient has the potential to reach multiple TeV energies in a single stage
  - Drive with intense x-rays pulses coupled in from the side
  - A km long fiber as the acceleration medium
  - High energy physics applications of the technique
- High gradient and continuous focusing produce small emittances
  - In a crystal, channel sizes on the order of angstroms could produce extreme emittances

X-rays guided in a channel

X-rays in amorphous material