E305nano

Feasibility studies of the FACET-II beam interaction with nanotube materials

Q&A session

Q1: Can the experiment be combined with the one from A. Sahai?
Q2: What is the physics in the low intensity limit (without ionization)?
Q3: What are the objectives of a near term experiment?
Q4: What are the measurable signatures, e.g. betatron radiation?
Q5: What's the (damage) effect on the material?

Question 5:

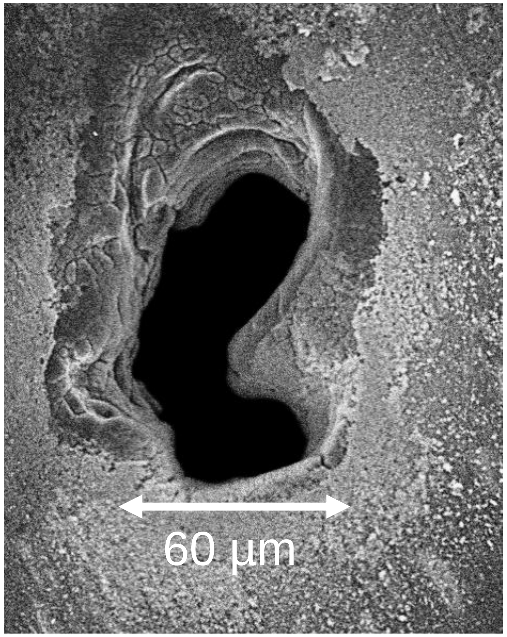
Q: What’s the (damage) effect on the material?

Answer:

The physics of damage in profoundly different in the femtosecond regime (compared to ps or higher time scales): energy deposition on electrons, neither thermal nor hydrodynamic during the interaction time (no ion motion).

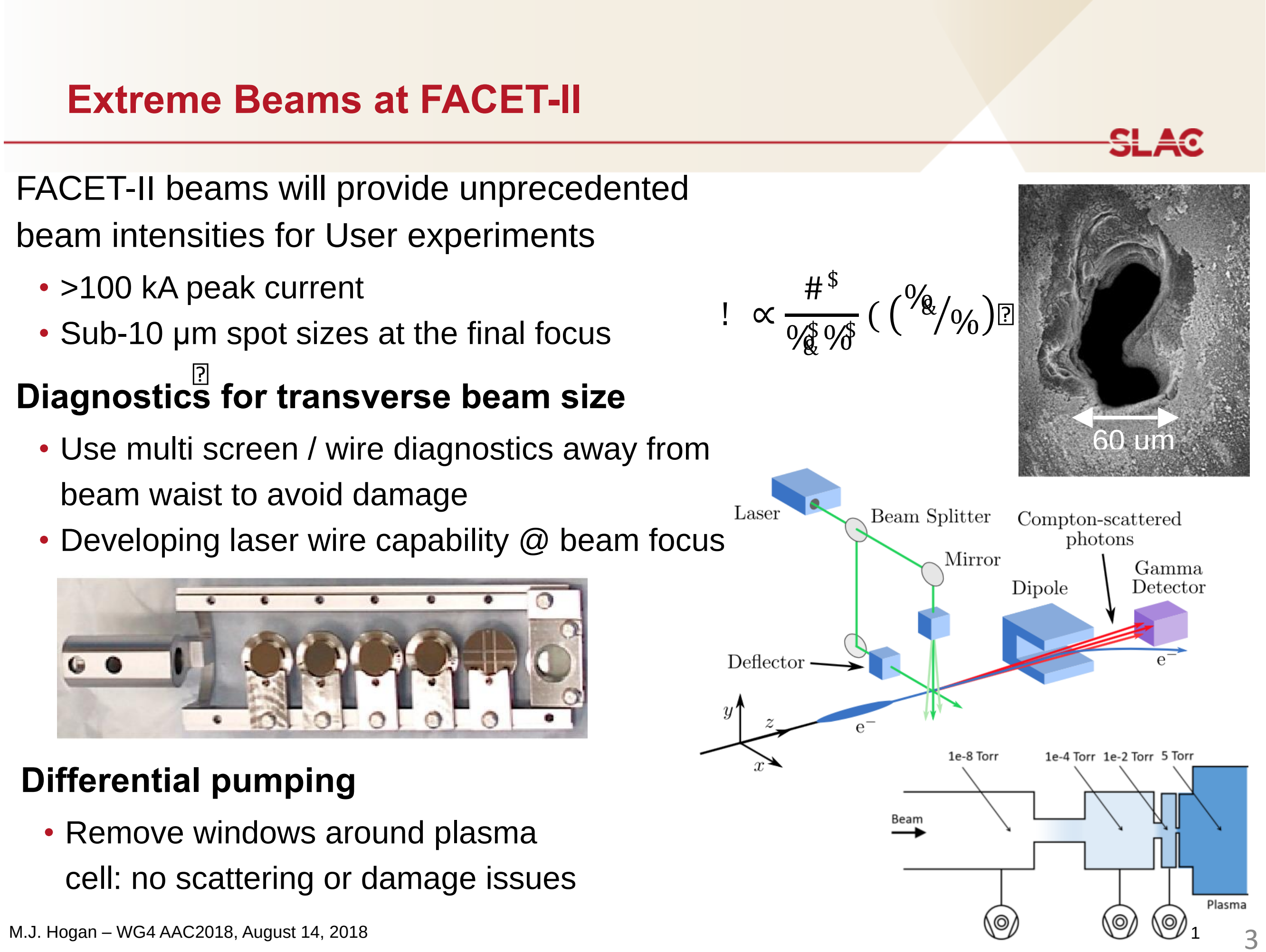
Yet, damage is to be expected when a high-current focused beam is sent through a solid. Two important processes: resistive current in the bulk, and along the surface (CTR).
The damage (hole in the foil) was observed during FACET I (bunch length of $\sim 30\ \mu\mathrm{m}$), with a size of $50-100\ \mu m$ typically).

E305nano plans to raster the sample, that is to translate it to a fresh area after every shot. The rastering step size will be determined after doing damage studies.



Question 5:

Q: What’s the (damage) effect on the material?



Extreme Beams at FACET-II

FACET-II beams will provide unprecedented beam intensities for User experiments

- >100 kA peak current
- Sub-10 μm spot sizes at the final focus

$! \propto \frac{\#^{\$}}{\%_{\&}^{\$}\,\%^{\$}}\left(\left({}^{\%}\&/\%\right)\right)$

Diagnostics for transverse beam size

- Use multi screen / wire diagnostics away from beam waist to avoid damage
- Developing laser wire capability @ beam focus

Differential pumping

- Remove windows around plasma cell: no scattering or damage issues

M.J. Hogan – WG4 AAC2018, August 14, 2018

1

Courtesy of M. Hogan

$50 - 100\ \mu m$ size hole
at FACET I

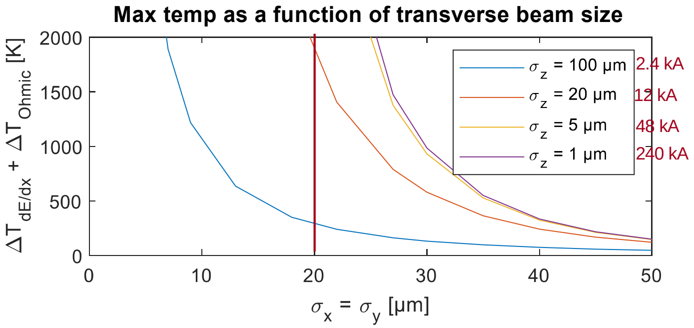
Question 5:

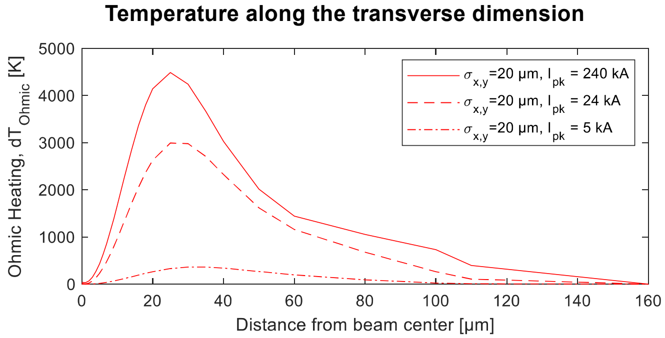
Q: What’s the (damage) effect on the material?

Ohmic heating

SLAC

- Surface heating effect from electric currents induced in metal foil by the magnetic field of the passing bunch
  - Stupakov, SLAC-PUB-15729 (2013):
    - Heating from image currents in metal foil impinged by a relativistic beam at a right angle
  - Lin & Whittum, PRSTAB 3, 101001 (2000)
    - Heating of metal pipe surface from image currents
- Magnetic field penetrates within the skin depth, ~200nm, so this is only a surface effect, but repeated shots may “drill” a hole
- Notes:
  - The bunches pass within a few fs, so what is the physical response to this impulse? Is it really enough to heat or just “shake” the surface electrons?
  - What does the beam do to an insulator?
    - Need to re-derive the formulas to account for dielectric!





Courtesy of D. Storey

Question 1:

Can the experiment be combined with the one from A. Sahai?

Answer:

We are very open to collaborative efforts, and our interest was already communicated. It is however important to have a concerted effort with everyone on board agreeing on how to proceed.

Question 2:

What is the physics in the low intensity limit (without ionization)?

Answer:

- With insulator/dielectric nanotubes in the “low intensity limit”, it is dielectric wakefield physics at the nanoscale and under very high fields, thus inducing conductivity. See B. O’Shea et al., PRL 123, 134801 (2019).
- For FACET-II parameters: we are not in the “low intensity limit”, we expect to ionize a region of $\gtrsim 100\ \mu\text{m}$ diameter around the beam, see ionization calculation results shown in Fig. 1 and 2. There might be a central region on-axis not ionized though.
- With conductive nanotubes (or alumina nanotube coated with carbon or metal), free electrons of the conduction band allow for a plasma-like behavior including resistive effects, which is more similar to the “high intensity limit” (with ionization).
- For intermediate “intensity”, some parts of the sample may be ionized and exhibit plasma-like behavior, and some other parts of the sample may not be ionized and exhibit dielectric-like behavior with some level of induced conductivity.

Conclusion: under these large fields, the response of the most outer electrons is close to what the plasma model calculates, and there is no model problem.

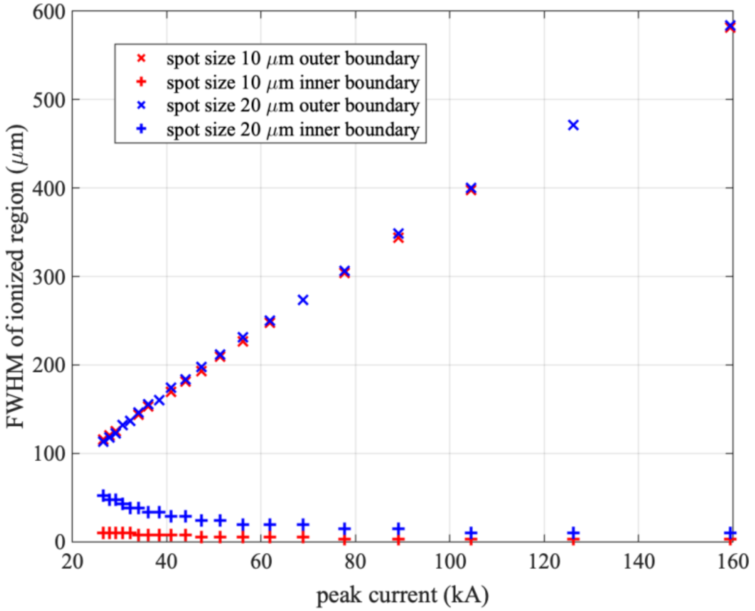


Figure 1. ADK calculation of beam-induced ionization for alumina, as a function of peak current and for 10/20 μm beam size. Credit: Alexander Knetsch.

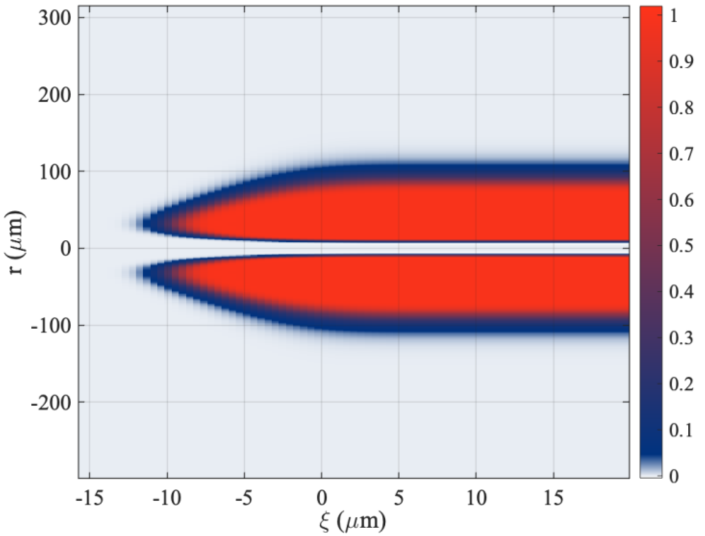


Figure 2. ADK ionization map for 50 kA beam and 10 μm beam size. Credit: Alexander Knetsch.

Question 3:

What are the objectives of a near term experiment?

Answer:

Near-term: evidence for clearly distinguishable interaction of FACET-II beam with structured solid targets in comparison to amorphous targets.

Proof-of-principle of nanotube wakefields as observed by increase of angular spread.

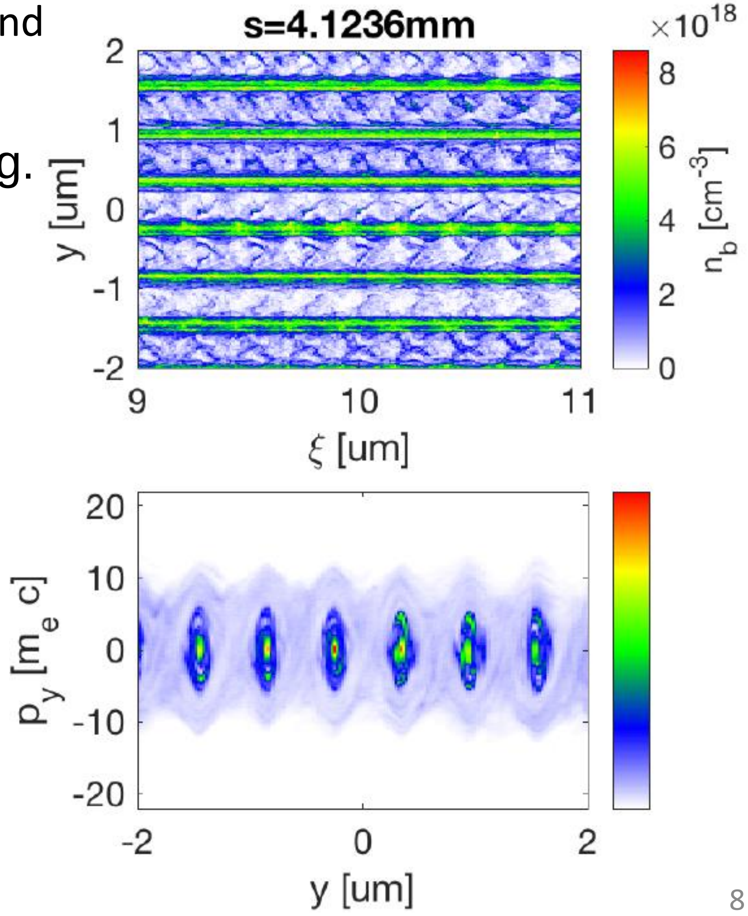
Mid-term (2nd year): Systematic parametric study of beam-nanotarget interaction for various sample thickness, pore diameter, material type, and beam parameters, and comparison/validation against theory, to support signature and evidence of beam nano-modulation.

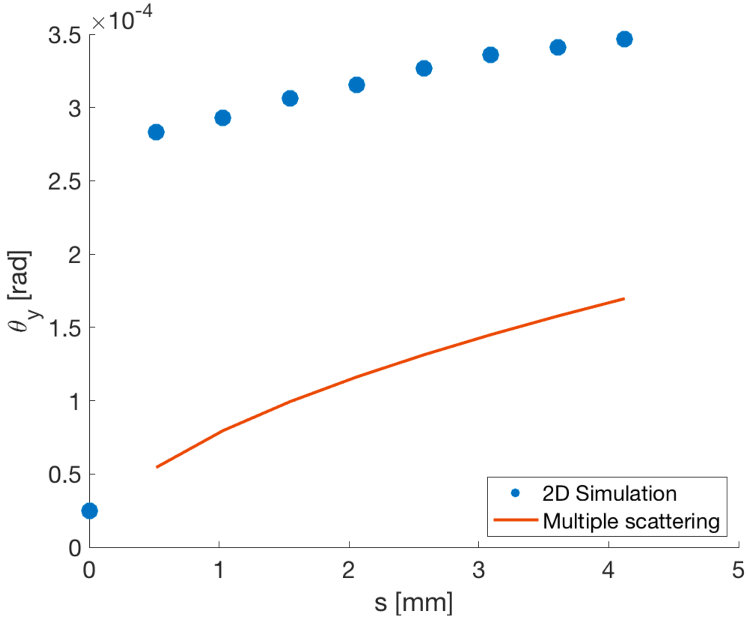
Question 4:

Q: What are the measurable signatures, e.g. betatron radiation?

Answer:

- Angular distribution, electron beam Twiss parameters and emittance. Possibly energy sprectrum.
- Radiation generation (betatron X rays and gamma rays). Needs to be distinguishable from bremsstrahlung.





E305nano

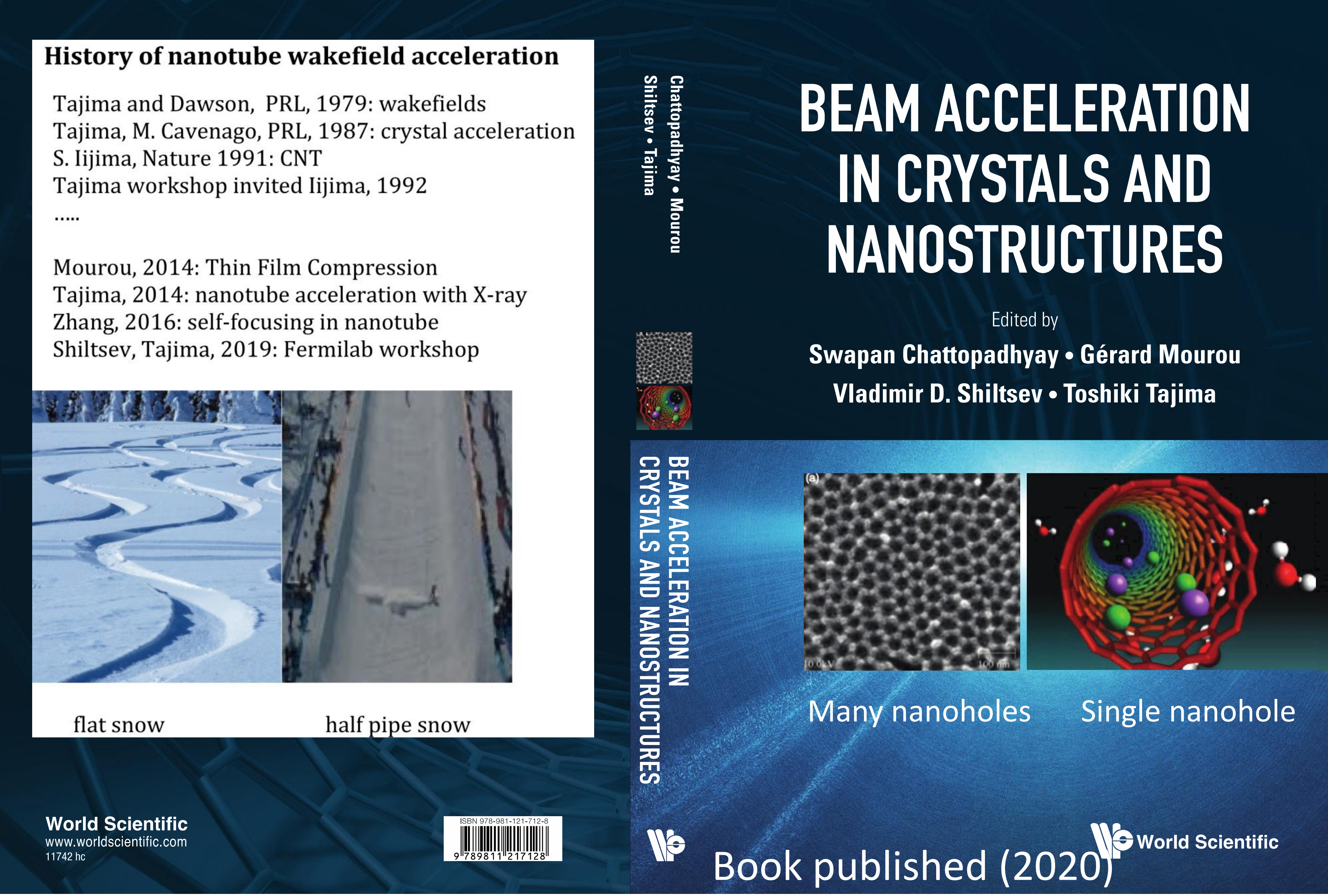
Feasibility studies of the FACET-II beam interaction with nanotube materials

Principal Investigators: S. Corde and T. Tajima

New Proposal

FACET-II PAC

October 26-29, 2020



History of nanotube wakefield acceleration

Tajima and Dawson, PRL, 1979: wakefields
Tajima, M. Cavenago, PRL, 1987: crystal acceleration
S. Iijima, Nature 1991: CNT
Tajima workshop invited Iijima, 1992
.....

Mourou, 2014: Thin Film Compression
Tajima, 2014: nanotube acceleration with X-ray
Zhang, 2016: self-focusing in nanotube
Shiltsev, Tajima, 2019: Fermilab workshop

flat snow half pipe snow

World Scientific
www.worldscientific.com
11742 hc

ISBN 978-981-121-712-8

Chattopadhyay • Mourou
Shiltsev • Tajima

BEAM ACCELERATION IN
CRYSTALS AND NANOSTRUCTURES

BEAM ACCELERATION IN CRYSTALS AND NANOSTRUCTURES

Edited by

Swapan Chattopadhyay • Gérard Mourou
Vladimir D. Shiltsev • Toshiki Tajima

Many nanoholes Single nanohole

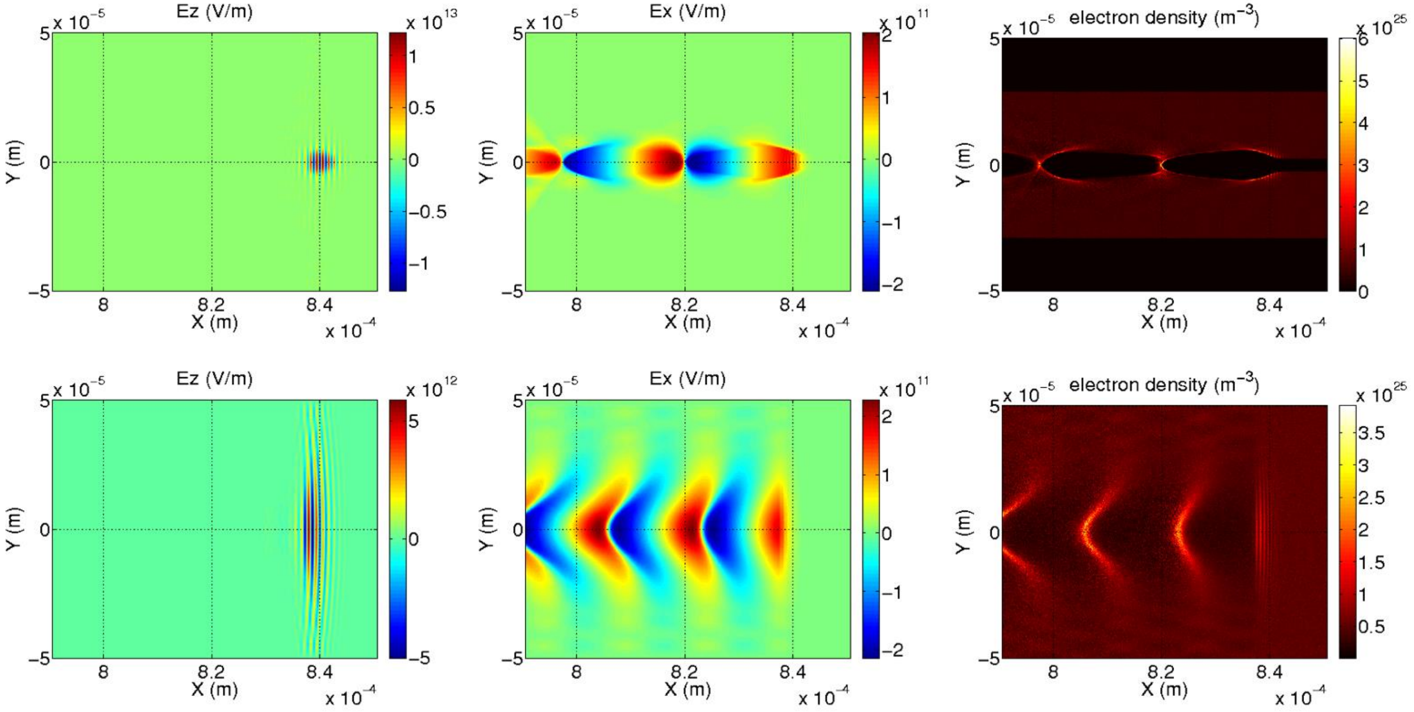
World Scientific

Book published (2020)

Gathered for nanotube wakefield acceleration (Fermilab, 2019)

Nanotube effects on wakefields

X. Zhang (PRAB 19, 101004 , 2016)



in nanotube

in uniform solid

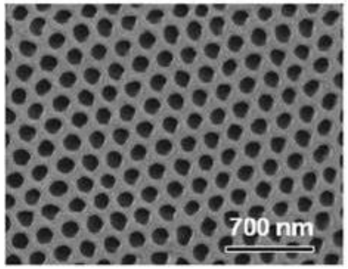
Set up 10TeV/m wakefield in the tube (in this example by 1keV X-ray in 100 nm tube)

more strongly confined and focused in the tube cf: uniform solid

Project: **proof-of-principle experiments, augmented with theory, modeling and diagnostics development**

CNT diameter: 10s-1000 nm, singular or bundle of nanotubes

driver: ultra-dense *e*- bunch



Goals: Electron nano-modulation, X-rays (betatron), modeling confirmation

Collaborators: Corde, Tajima, Shiltsev, Taborek, Davoine, Gremillet, Zhang, Chen, Sydora;

[open armed in the future: Dollar, Bulanov (ELI-ALPS), Kawachi (QST), Sone (JST), Iijima, Sahai, …]

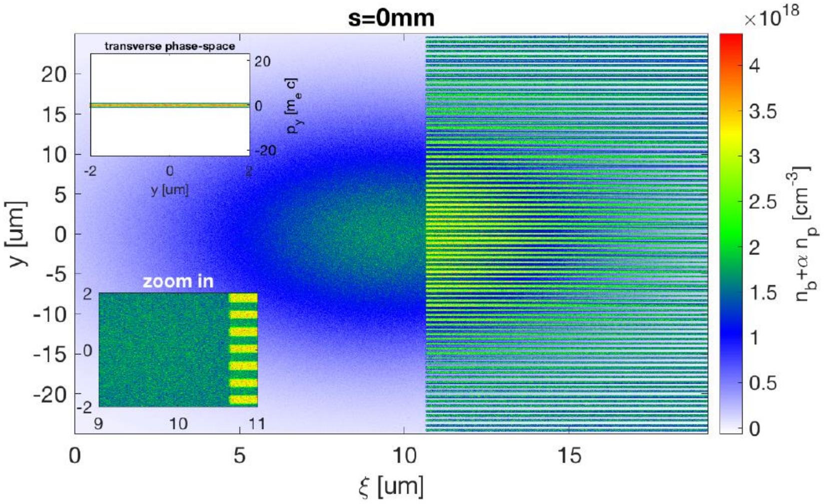
Definition of success:

- Evidence for clearly distinguishable interaction of FACET-II beam with structured solid targets in comparison to amorphous targets. Year 1.
- Systematic parametric study of beam-nanotarget interaction for various sample thickness, pore diameter, material type, and beam parameters, and comparison/validation against theory, to support signature and evidence of beam nano-modulation. Year 2.

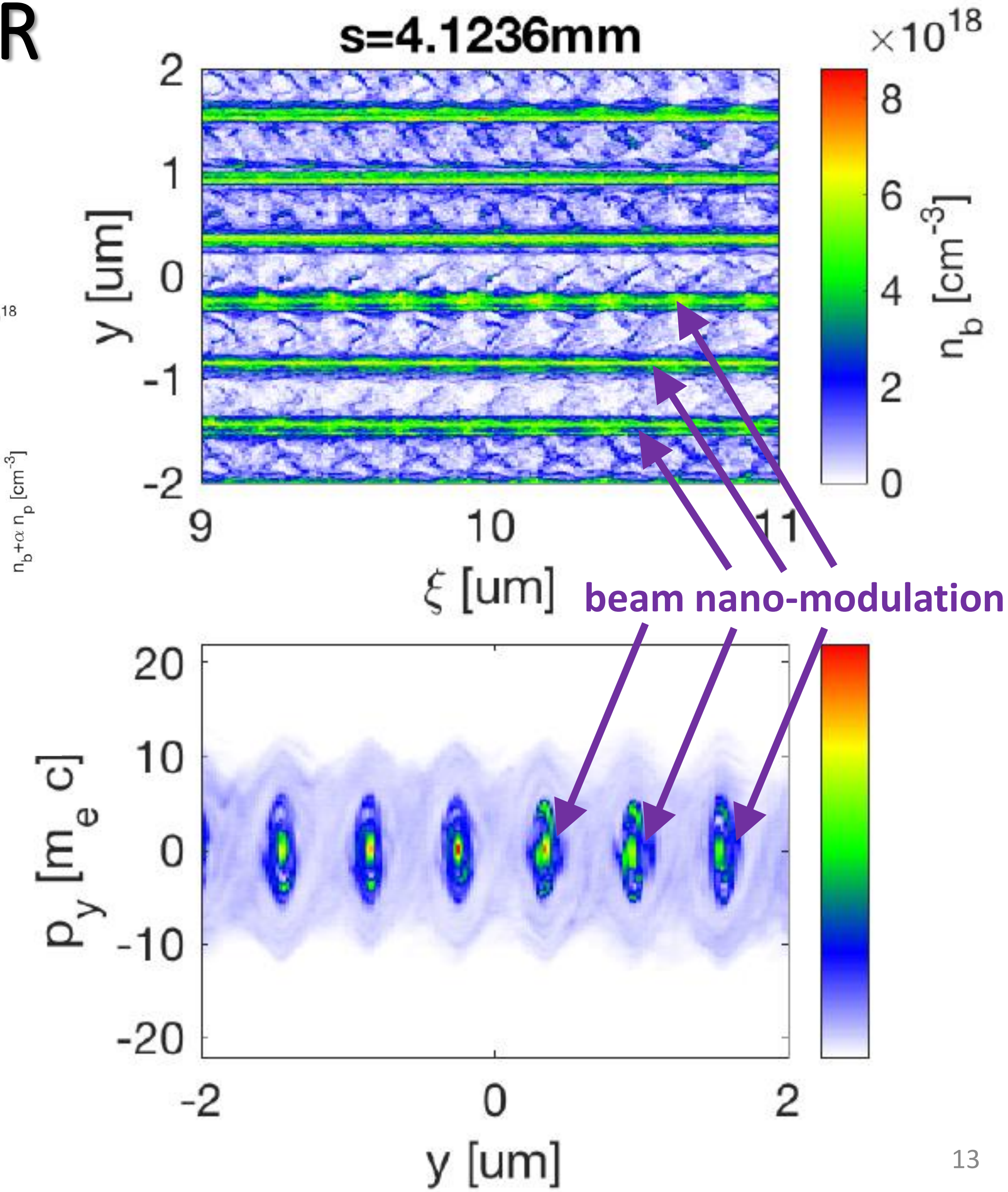
Timeline:

- From PAC 2020 to T_0 + 0.5 year (T_0 = start of FACET-II experimental beam time): preparation, design, planning supported by simulation campaign to define specs and choice of samples, get a final design for the experimental hardware, iterate and converge on desired beam parameters
- From T_0 + 0.5 year to T_0 + 1.5 year: first tests of beam-nanotarget interaction with initial FACET-II beam parameters, iterate to improve/upgrade experimental hardware
- From T_0 + 1.5 year to T_0 + 2.5 year: advanced characterization with full set of sample, upgraded hardware and improved FACET-II beam parameters

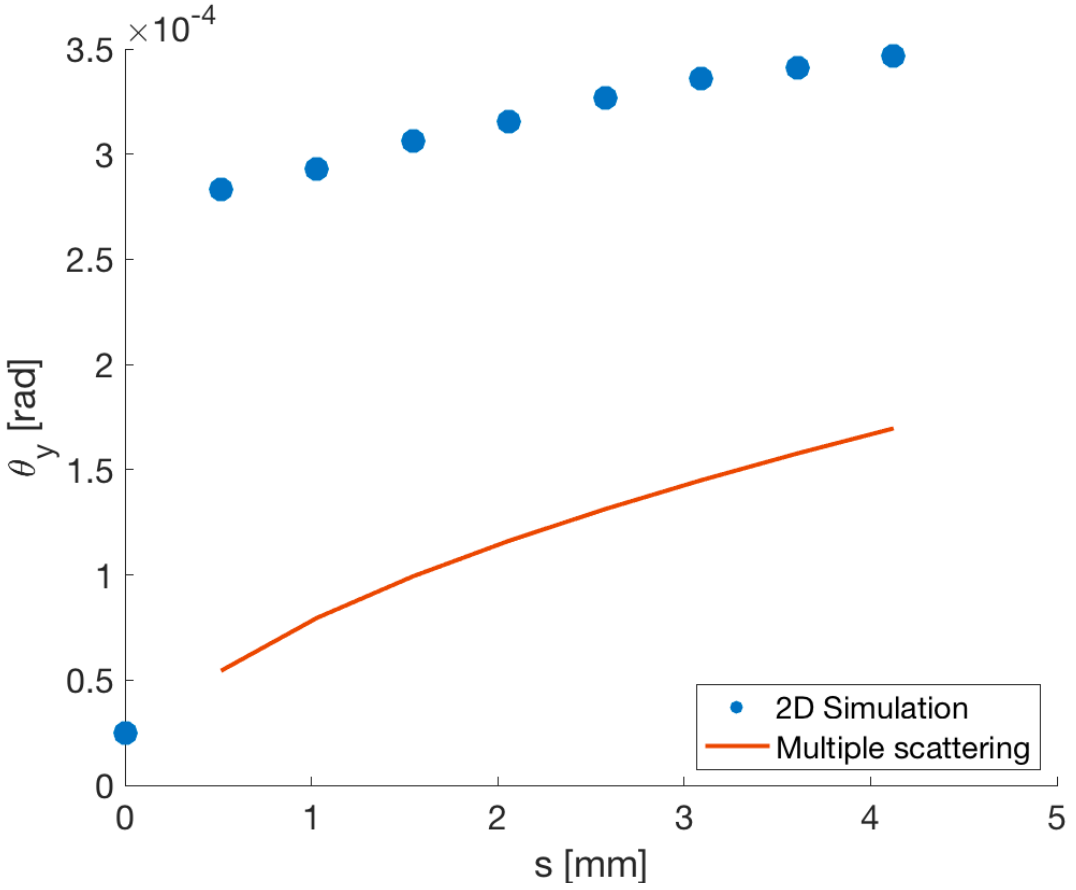
Results from CALDER 2D PIC simulations



FACET-II electron beam, with 10 GeV energy, 2 nC charge, 50 kA peak current, 5 mm.mrad emittance and 10 µm rms size, enters a 2D-nanostructured carbon target, with 300-nm-wide vacuum sections separated by plasma sections of electron density 2×10^{22} cm^{-3}.



Growth of angular spread



The blue data points show the outcoming beam divergence as a function of target thickness from the CALDER 2D PIC simulation of a 2D-nanostructured carbon target. The red solid line is from multiple scattering in an amorphous carbon target.

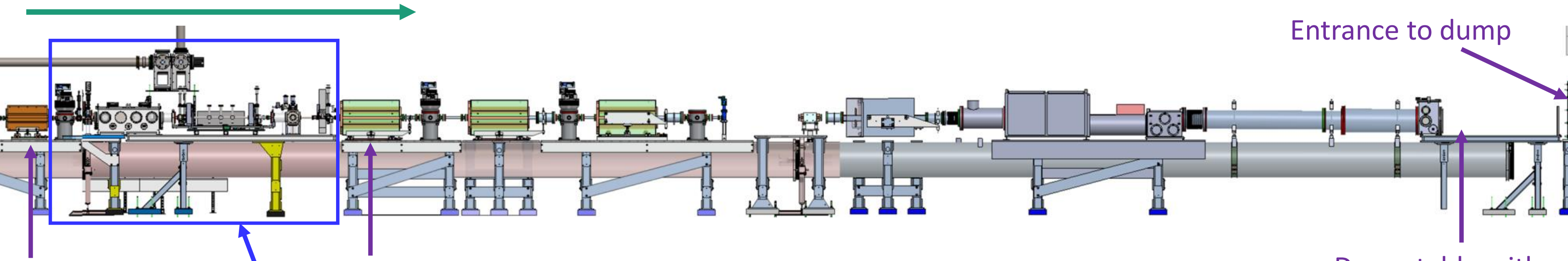
Match E305nano to FACET-II

- Beam parameters are paramount for the effect to be observable.

- If considering 20 kA, 20 mm.mrad and 10 µm size beam (instead of 50 kA, 5 mm.mrad), the angular beam spread only increases from its initial value of 100 µrad to 110-120 µrad after the interaction with the nanostructure. Indeed, the wakefields are reduced in this case due to the smaller peak current, and the emittance opposes, and somewhat prevents, focusing in the vacuum sections.

- Connection to other experiments:
  - E305: strong overlap in hardware and expertise, mutual benefits: nanotargets can be used to seed filamentation in amorphous solid, oblique filamentation can help to pre-modulate (longitudinally) the beam to induce much stronger wakefields in the nanotubes
  - E308: plasma lens can help to reach smaller beam size, higher bunch density, thus considerably increasing the nanotube wakefields

E305nano Conceptual Layout



Beam direction

Entrance to dump

Last final focus quadrupole

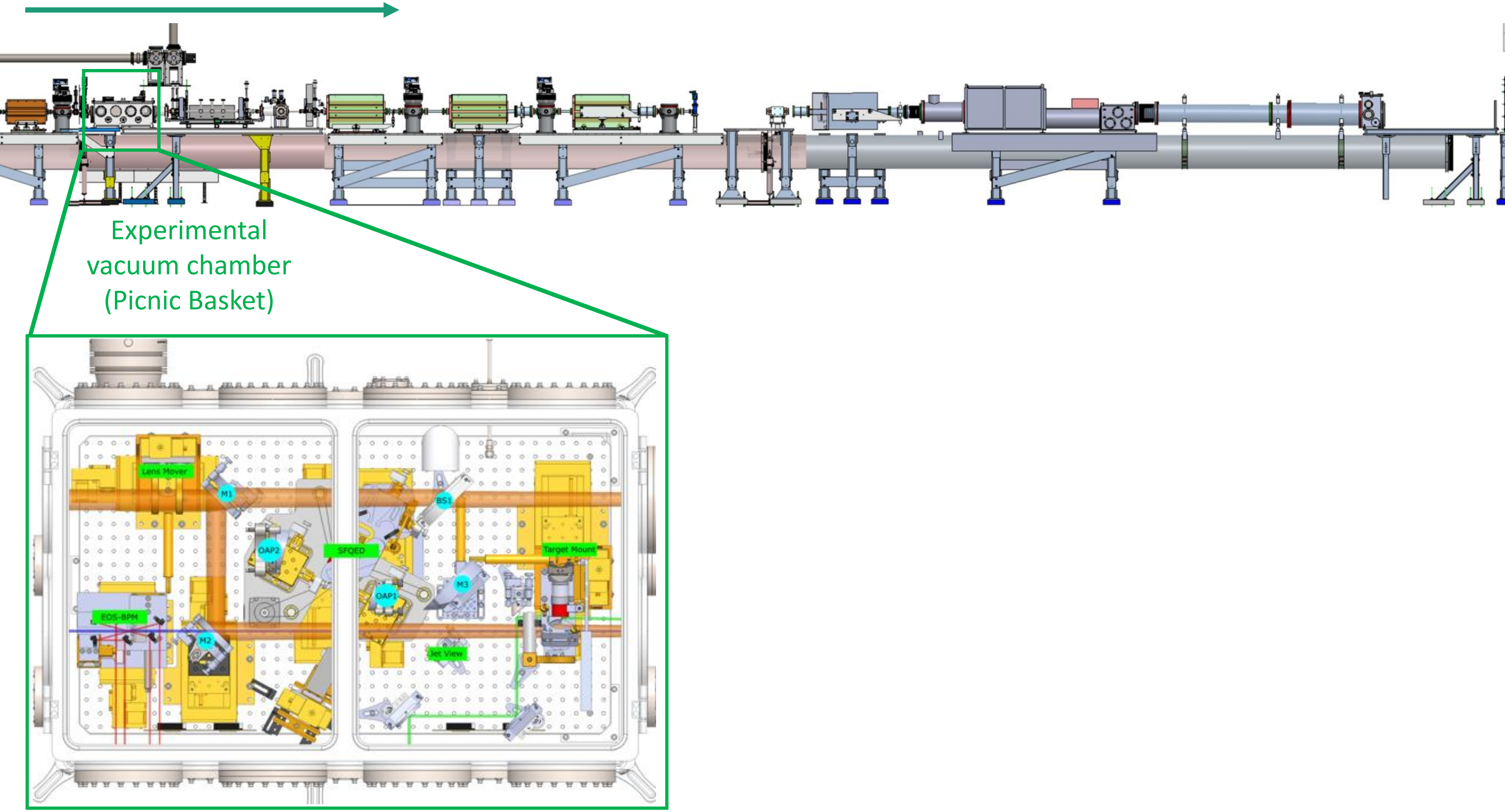
First dump line quadrupole

Dump table with electron and gamma diagnostics

IP area

E305nano Conceptual Layout

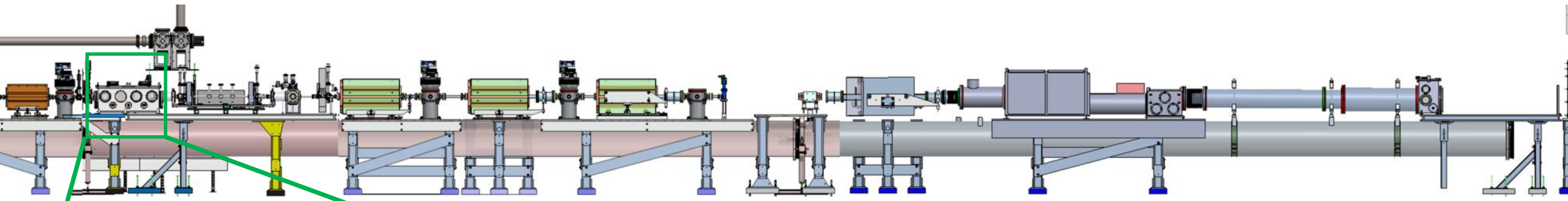
Beam direction



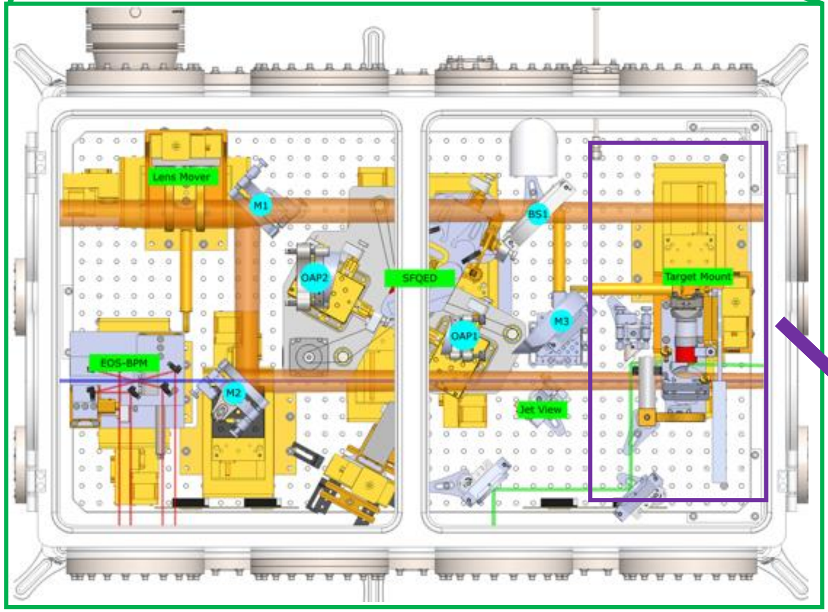
Experimental vacuum chamber (Picnic Basket)

E305nano Conceptual Layout

Beam direction



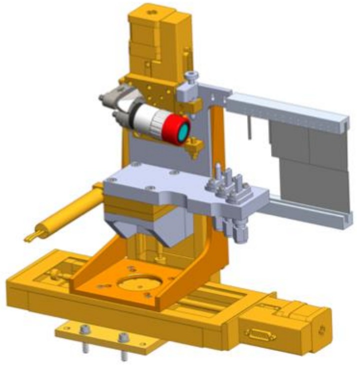
Experimental vacuum chamber (Picnic Basket)



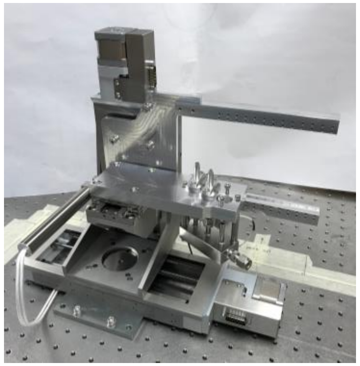
Possible options for the installation of nano samples

- Angular requirements: 10-20 μrad precision, 2-3 degrees range
- Positioning requirements: 10-100 μm precision, 5 cm range

1) Modification to the E305 Target Mount



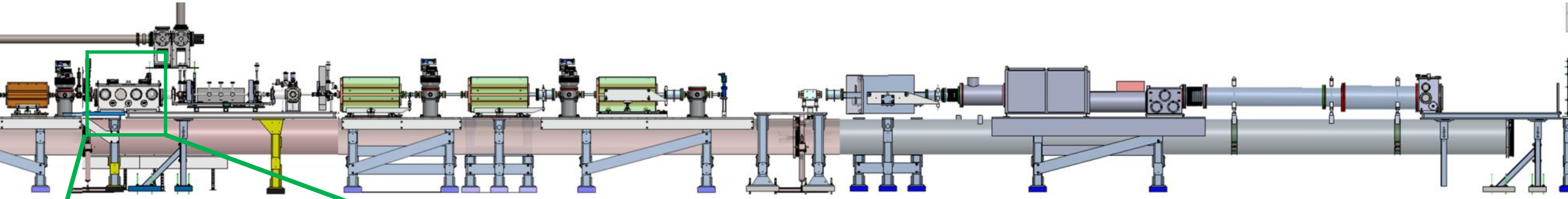
Current design



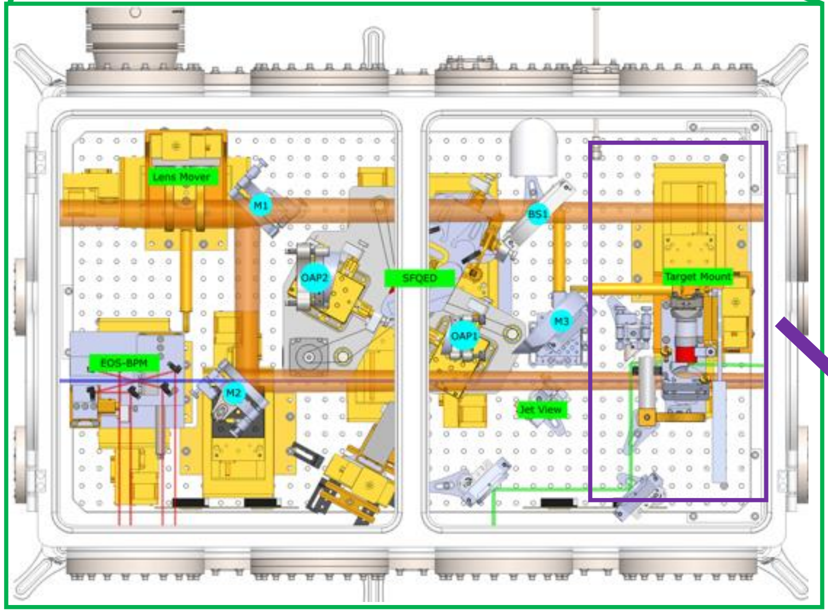
As built (as of Oct 16, 2020)

E305nano Conceptual Layout

Beam direction



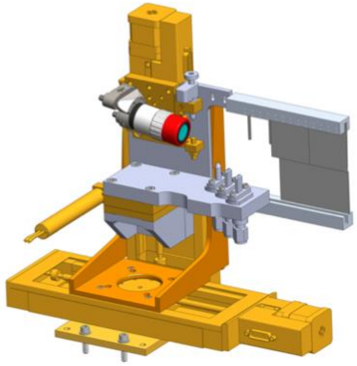
Experimental vacuum chamber (Picnic Basket)



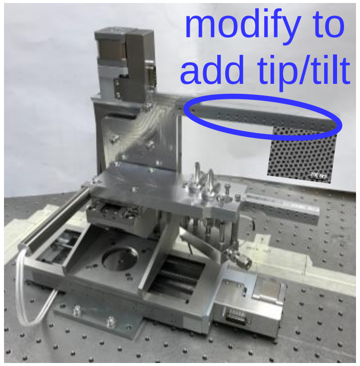
Possible options for the installation of nano samples

- Angular requirements: 10-20 μrad precision, 2-3 degrees range – can add piezo actuators for tip/tilt control
- Positioning requirements: 10-100 μm precision, 5 cm range – already available with UTS150 and UTS100 stages

1) Modification to the E305 Target Mount



Current design

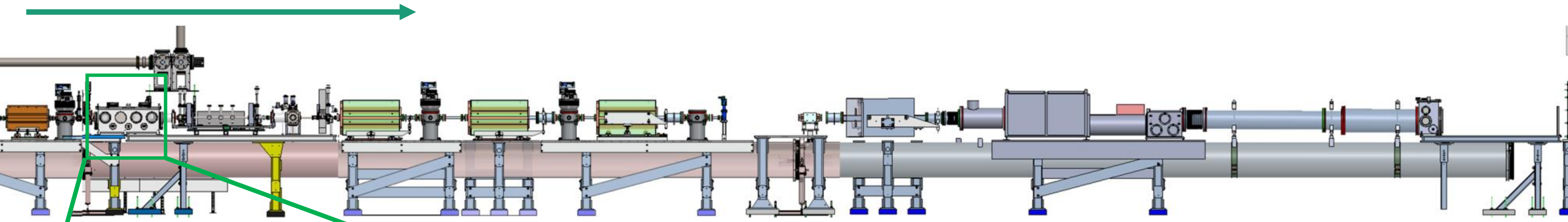


modify to add tip/tilt

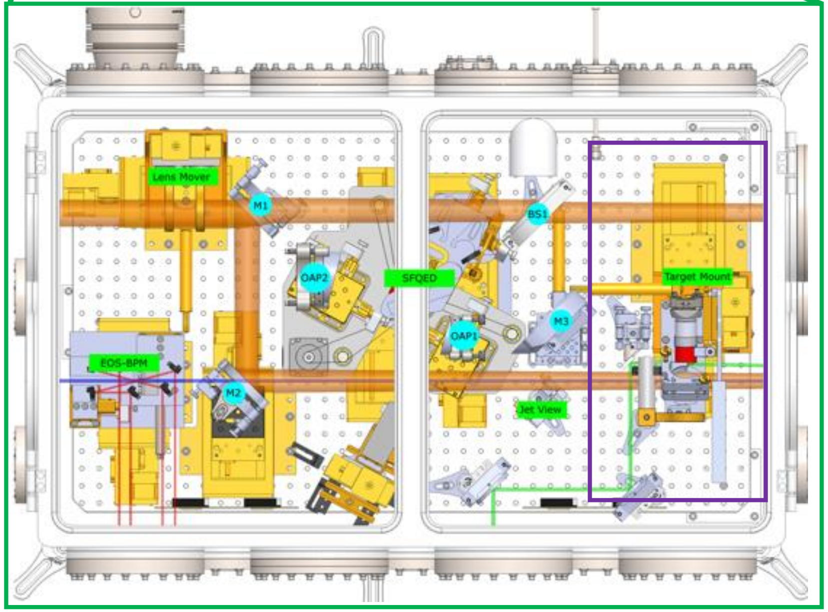
As built (as of Oct 16, 2020)

E305nano Conceptual Layout

Beam direction



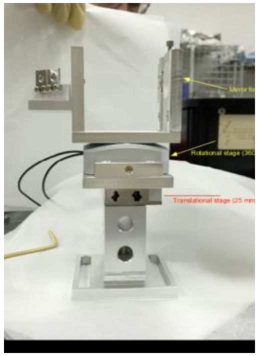
Experimental vacuum chamber (Picnic Basket)



Possible options for the installation of nano samples

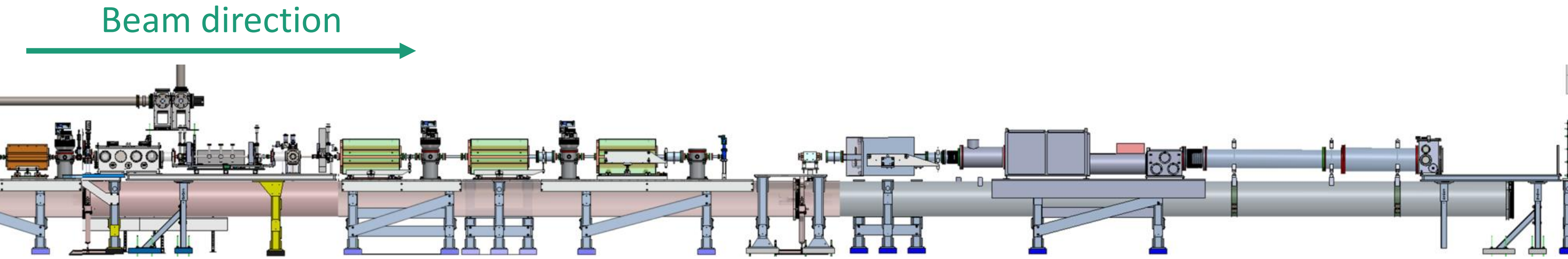
- Angular requirements: 10-20 μrad precision, 2-3 degrees range
- Positioning requirements: 10-100 μm precision, 5 cm range

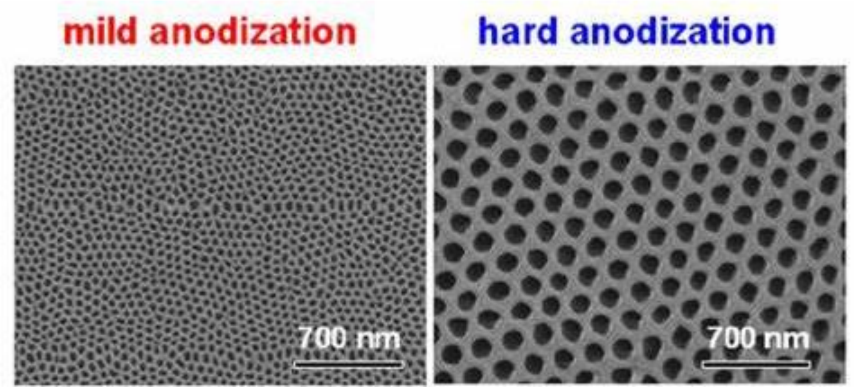
2) Re-use E212 hardware



3) Re-use Fermilab goniometer; requires large footprint (2 feet long), not compatible with Picnic Basket.

E305nano Conceptual Layout





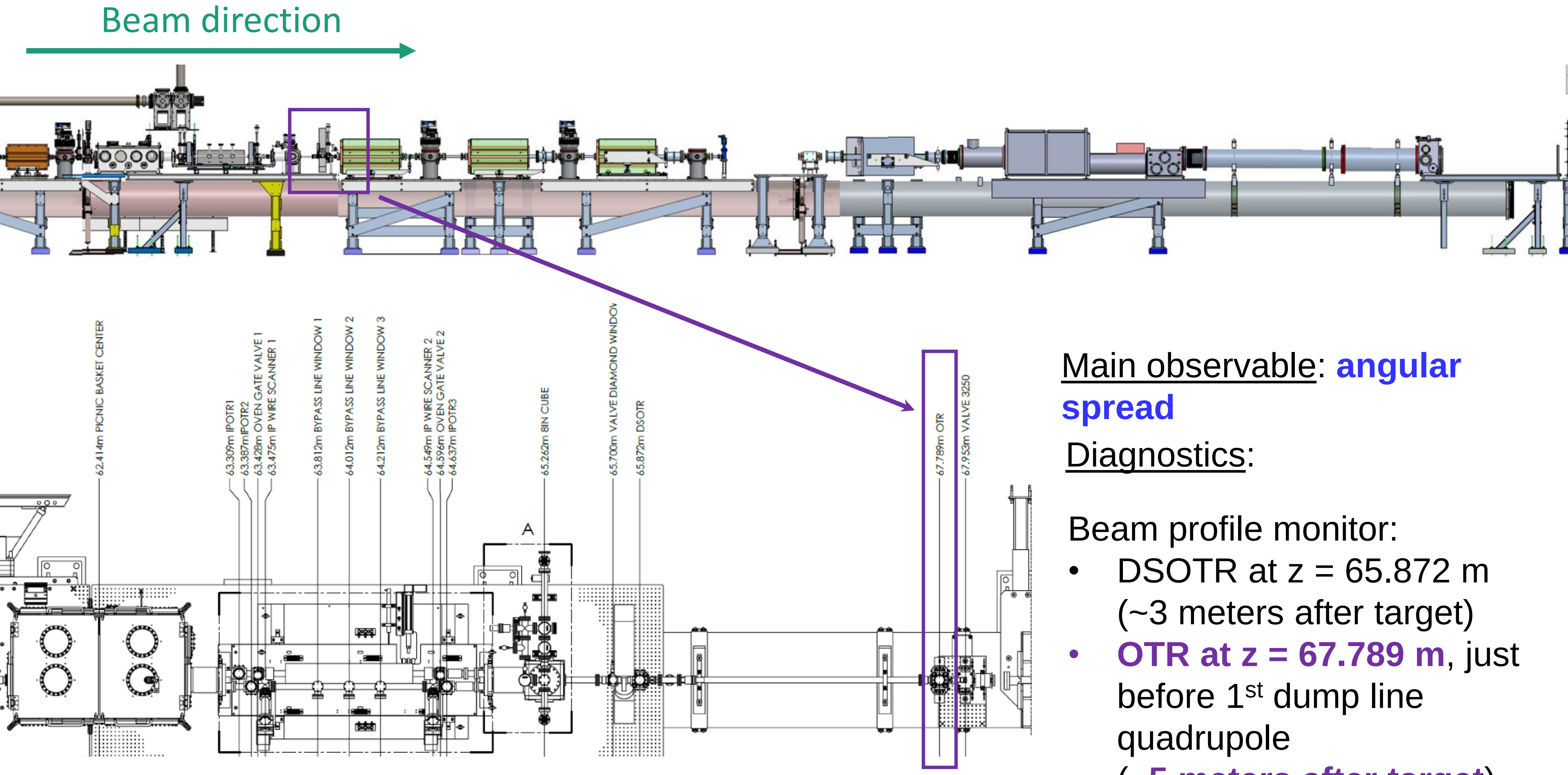
Key point for the success of this feasibility study:

Have experts in nanofabrication in the collaboration: Prof. Taborek and collaborators, UC Irvine.

Possible choices for the samples:

- Start conservative with μm-size pores: made in glass or alumina.
- Aim for mm-thickness and cm-size samples
- Study beam-nanosample interaction as a function of the pore diameter (from μm down to 20 nm), using alumina nanotubes.
- Consider 2D-structured targets, to allow easier distinction with multiple scattering.

Diagnostics and Observables



Main observable: **angular spread**

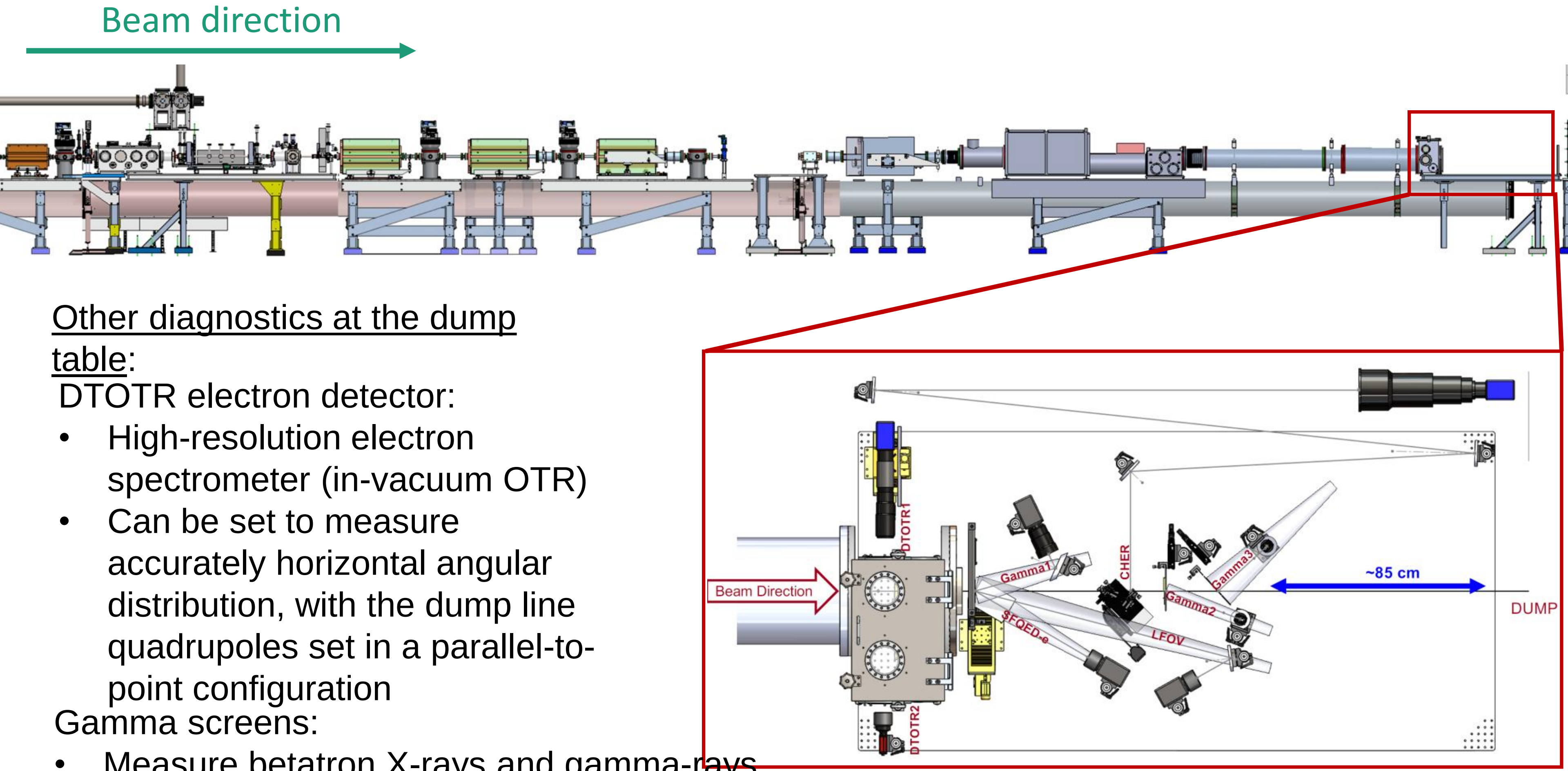
Diagnostics:

Beam profile monitor:

- DSOTR at z = 65.872 m (~3 meters after target)
- **OTR at z = 67.789 m**, just before 1st dump line quadrupole (**~5 meters after target**)

Expected beam size on OTR: from fraction of a mm (100 μrad angular spread) to few mm (maximum of $\pm$1 mrad acceptance if DS holed mirror aperture present).

Diagnostics and Observables



<u>Other diagnostics at the dump table</u>:

DTOTR electron detector:

- High-resolution electron spectrometer (in-vacuum OTR)
- Can be set to measure accurately horizontal angular distribution, with the dump line quadrupoles set in a parallel-to-point configuration

Gamma screens:

- Measure betatron X-rays and gamma-rays from nanotube wakefields
- Needs to be distinguishable from bremsstrahlung

Potential future evolution of E305nano

The E305nano experiment, if successful, will provide important input and pave the way for future experimental studies on:

i) the interaction of ultrahigh-density particle beams with crystals, CNTs and porous alumina nanostructures [S. Iijima, Nature **354**(6348),56-58 (1991); R. Lazarowich, P. Taborek, et al, J. Appl. Phys. **101**, 104909 (2007).];

ii) CNT/crystal incoherent channeling radiation [C. Brau, P. Piot, et al., Synchr. Rad. News **25**(1), 20-24 (2012)];

iii) controlled focusing and self-bunching/slicing of ultrahigh-density beams in CNTs/crystals [A.Sahai, T.Tajima, V.Shiltsev et al., IJMPA **34**(34), 1943009 (2019)];

iv) coherent X-ray and gamma radiation from the ultrahigh-density beam in CNTs/crystals [S. Hakimi, PhD Thesis, UCI, 2020; S. Corde, et al., Rev. Mod. Phys. **85**, 1 (2013)];

v) generation and detection of extreme-gradient (TeV/m) beam-induced wakefields in CNTs/crystals [V.Shiltsev, IJMPA **34**(34), 1943002 (2019); Y. Shin, A. Lumpkin, R. Thurman-Keup, NIM-B, **355**, 94-100 (2015)].

Desired facility upgrades

The E305nano experiment will strongly benefit from the following upgrades:

- Low emittance beams, down to 3 mm.mrad
- High peak currents, from 50 to 300 kA

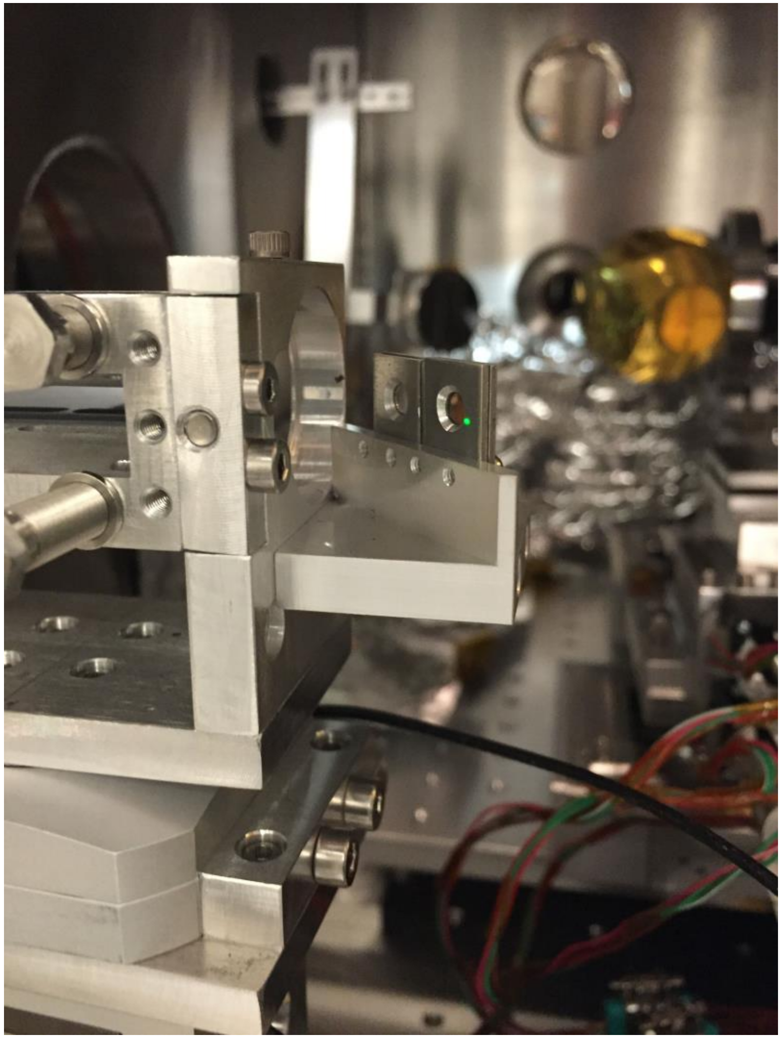
The E305nano collaboration

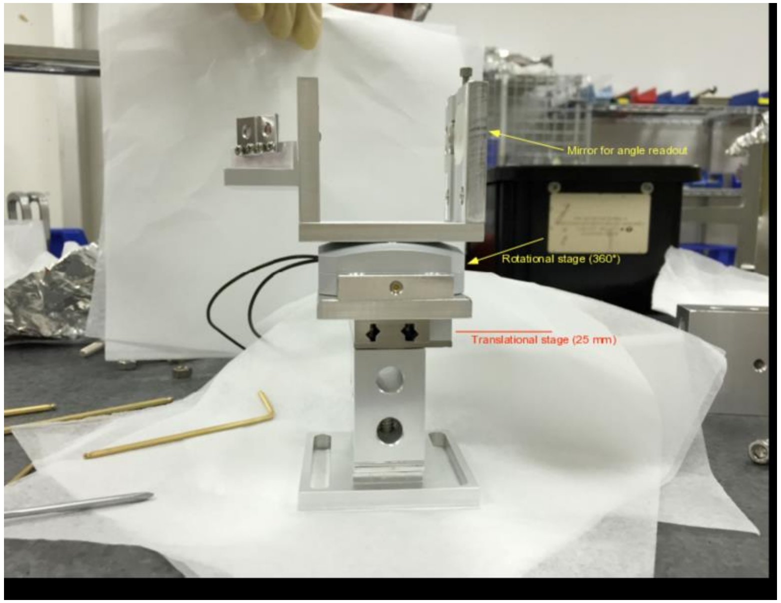
- IP Paris/LOA: Sébastien Corde, Yuliia Mankovska, Pablo San Miguel Claveria, and collaborators
- UC Irvine: Toshiki Tajima and collaborators
- Fermilab: Vladimir Shiltsev and collaborators
- UC Irvine: Peter Taborek and collaborators
- CEA: Xavier Davoine and Laurent Gremillet
- Argonne National Laboratory: Uli Wienands and collaborators
- Shanghai Normal University: Xiaomei Zhang and collaborators
- Shanghai Jiao Tong University: Liming Chen and collaborators
- U. Alberta: Rick Sydora and collaborators

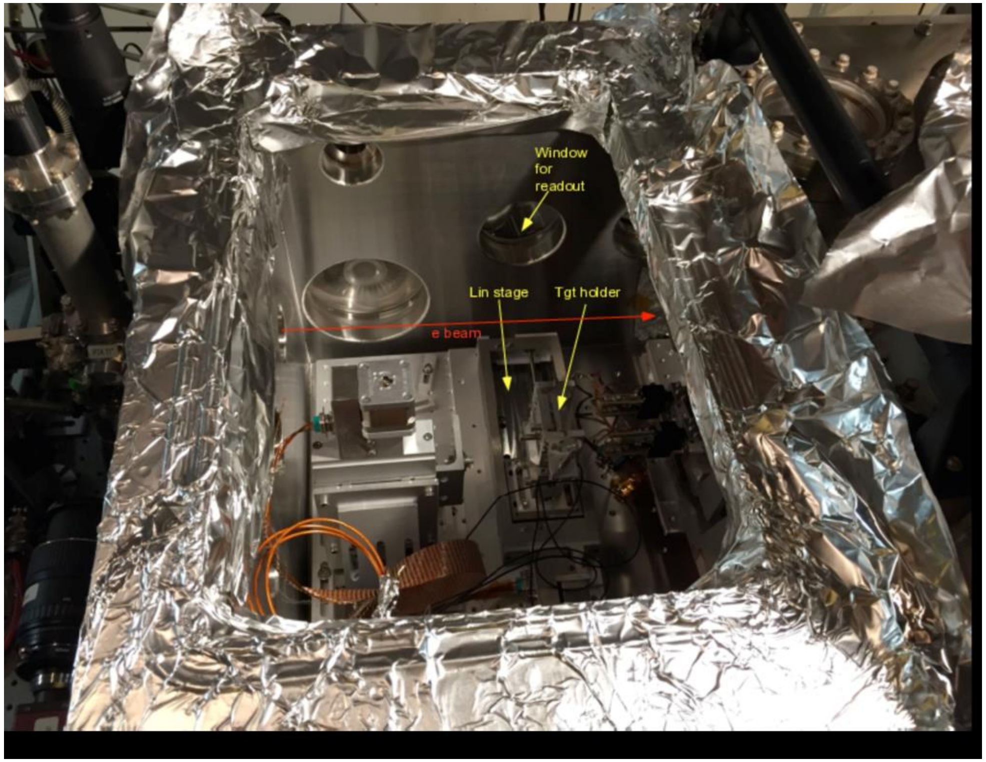
Thank you for your attention

Back-up

Re-use FACET-E212 experimental hardware

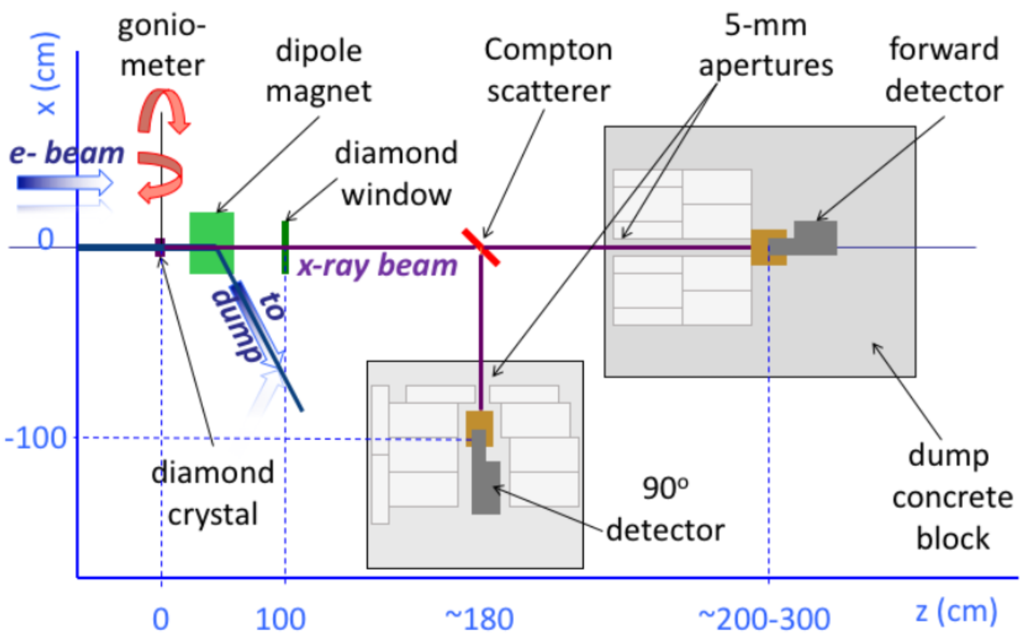






Hardware from the 2016 FAST Xtal channeling expt (P. Piot et al)

arXiv:1612.07358



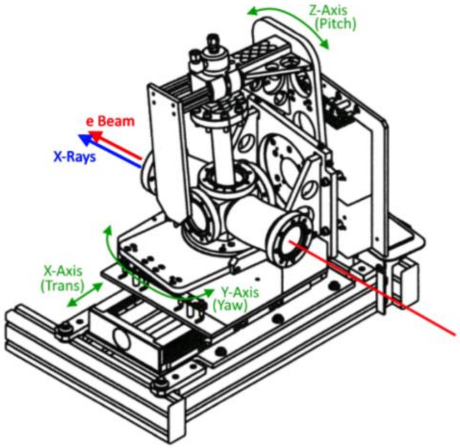


Figure 1: The goniometer from Helmholtz Zentrum Dresden Rossendorf (HZDR) used in the crystal channeling efforts during the 50-MeV run [10].

A. Halavanau, et al

Commissioning and First Results From Channeling Radiation At FAST