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?
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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 ~30 μm), with a size of 50 – 100 μm 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

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

Courtesy of M. Hogan

50 – 100 μm size hole at FACET I

M.J. Hogan – WG4 AAC2018, August 14, 2018
Question 5:

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

**Ohmic heating**

- 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
    - 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!

![Max temp as a function of transverse beam size](image1)

![Temperature along the transverse dimension](image2)

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 ≥ 100 μm 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.
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 (2\textsuperscript{nd} 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 spectrum.
- Radiation generation (betatron X rays and gamma rays). Needs to be distinguishable from bremsstrahlung.
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
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

Gathered for nanotube wakefield acceleration (Fermilab, 2019)
Nanotube effects on wakefields

X. Zhang (PRAB 19, 101004, 2016)

in nanotube

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

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
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 $2 \times 10^{22}$ cm$^{-3}$.

Results from CALDER 2D PIC simulations
The blue data points show the outgoing 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

Last final focus quadrupole

First dump line quadrupole

IP area

Entrance to dump

Dump table with electron and gamma diagnostics
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
Possible options for the installation of nano samples

1) Modification to the E305 Target Mount

- Angular requirements: 10-20 \( \mu \)rad precision, 2-3 degrees range – can add piezo actuators for tip/tilt control
- Positioning requirements: 10-100 \( \mu \)m precision, 5 cm range – already available with UTS150 and UTS100 stages
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.
Possible choices for the samples:

- Start conservative with $\mu$m-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 $\mu$m down to 20 nm), using alumina nanotubes.
- Consider 2D-structured targets, to allow easier distinction with multiple scattering.

Key point for the success of this feasibility study:

Have experts in nanofabrication in the collaboration: Prof. Taborek and collaborators, UC Irvine.
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 ±1 mrad acceptance if DS holed mirror aperture present).
Diagnostics and Observables

Other diagnostics at the dump table:

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:


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)].


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)

A. Halavanau, et al
Commissioning and First Results From Channeling Radiation At FAST

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