University of Colorado
Denver

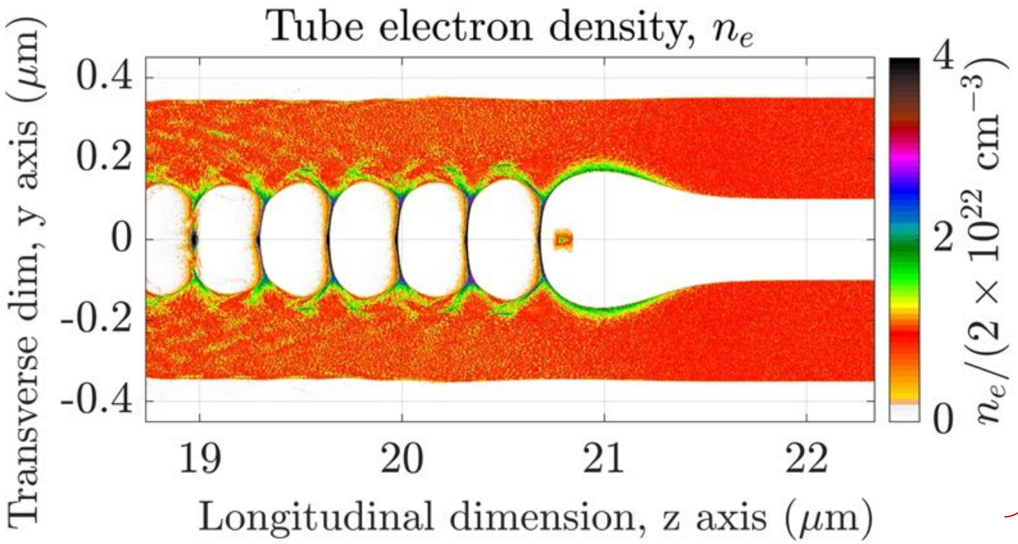
PetaVolts per meter Plasmonics*

using

structured semiconductors

**semiconductors, semi-metals, metals*

fundamentally new research – large-amplitude, relativistic plasmons



NOT ANOTHER plasma sim.

PIC - generalized ***Maxwell solver***

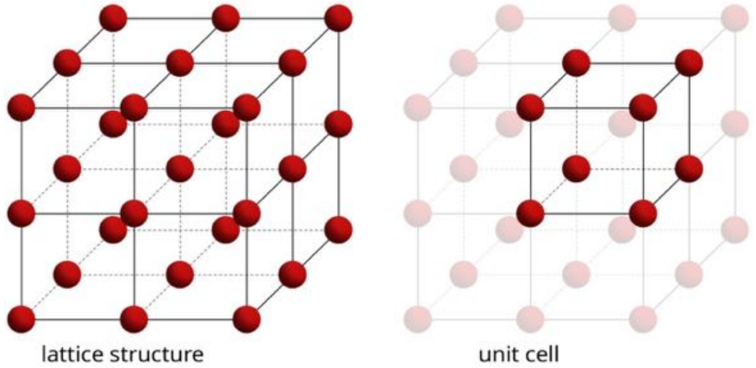
where $\boldsymbol{\rho}_e$ and $\boldsymbol{J}_e$ NOT SET to 0

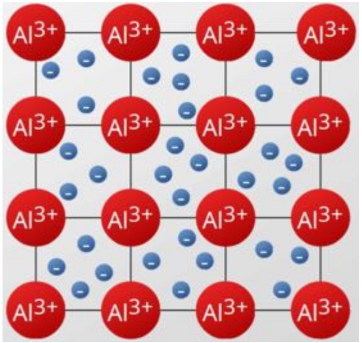
Nanomaterials Based Nanoplasmonic Accelerators and Light-Sources IEEE Access

doi: 10.1109/ACCESS.2021.3070798

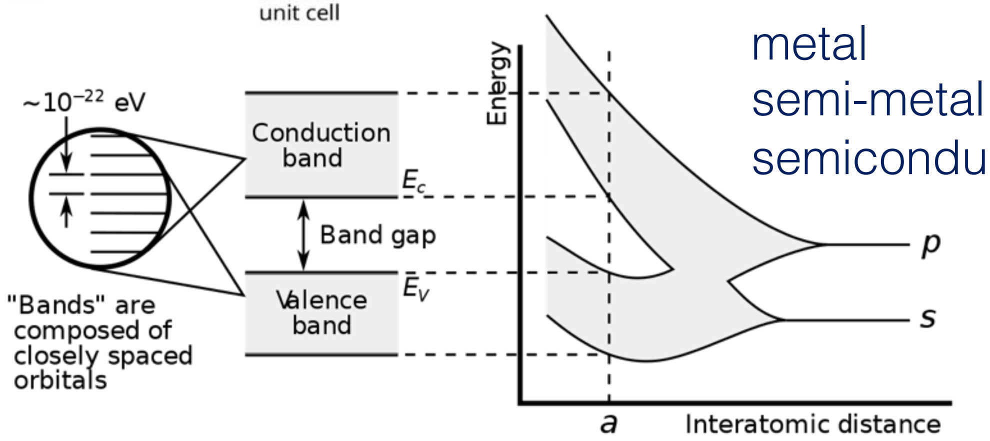
Plasmonics fundamentals

ionic lattice
is **PRESENT** over
plasmonic timescale
(may be modified under high fields)


lattice structure
unit cell



energy band structure
lattice structure – Bloch's theorem
electrons have specific occupancy states
near-continuum Energy levels – **energy BANDs**
energy band-gap – characterizes media



metal
semi-metal
semiconductor

free electron Fermi gas

conduction band e^- – Quantum mechanical entity – highest e^- density - conductive media

delocalized, free *(in the collisionless limit)* to move around the entire lattice

PLASMON – Fermi e^- gas oscillations in response to EM excitation

$$\boxed{\lambda_{\rm plasmon} = 33\ (n_0[10^{24}{\rm cm}^{-3}])^{-1/2}\ {\rm nm}}$$

NANO-ELECTROMAGNETICS

Large-amplitude Plasmons – new research area

Perturbative *(conventional)* $\delta = \theta(2\pi)^{-1}\lambda \ll \lambda$

θ is angular disp. of collective e^- osc.

trajectory amplitude

$\Delta n_e \ll n_0$

e- density displacement

Large-amplitude plasmonics *(unexplored)* $\delta \simeq \lambda$

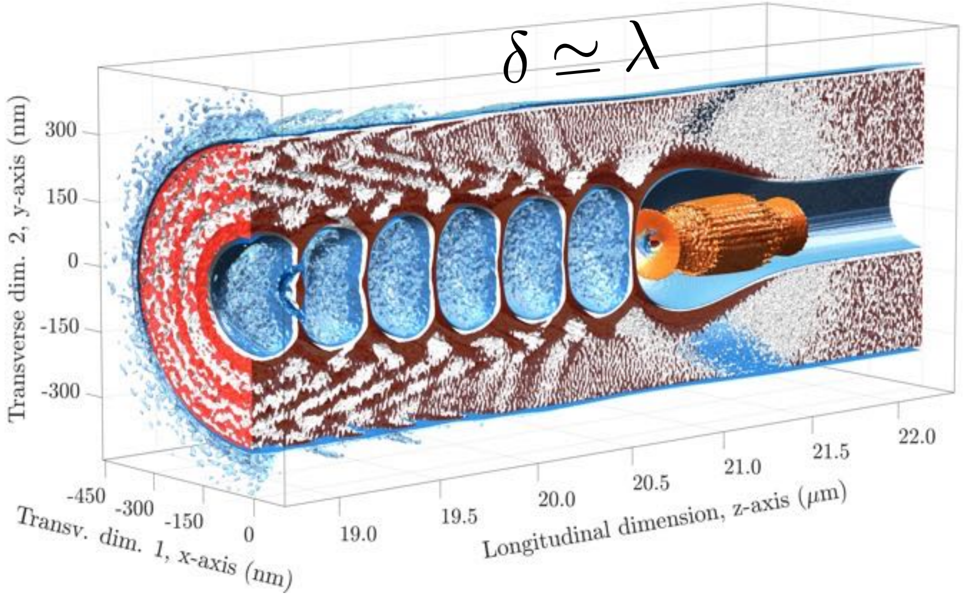
$\Delta n_e \simeq n_0$

PV/m plasmonics

plasmonic coherence limit

$$\mathrm{E_p} = \frac{m_e c^2}{e}\frac{2\pi}{\lambda_{\mathrm{plasmon}}} \simeq 0.1\sqrt{n_0[10^{24}\mathrm{cm}^{-3}]}\,\mathrm{PVm}^{-1}$$

- large-amplitude, relativistic plasmons **radial motion driven** by collective beam fields
- large-scale e^- ionic-lattice displacement ***strongly electrostatic plasmon***
- RELATIVISTIC e^- - kinetic energy > surface potential surface e^- – ***go across the surface***
- **particle-tracking sim.** – highly localized e^- density **PIC codes** – instead of FDTD - large-amp. plasmons



Tunable Plasmons – matched excitation

metals: $n_t \sim 10^{22\text{-}24}$ cm^{-3}
semi-metals: $n_t \sim 10^{20\text{-}22}$ cm^{-3}
semiconductors: **$n_t \sim 10^{15\text{-}21}$ cm^{-3}**

arxiv:2208.00966

$$\lambda_{\rm plasmon} = 3.3\ (n_0[10^{20}{\rm cm}^{-3}])^{-1/2}\ \mu{\rm m}.$$

TUNABLE PLASMONs – *tune the properties* of free e⁻ gas – **doped semiconductor**

2020 proposal based on **FACET-II TDR**

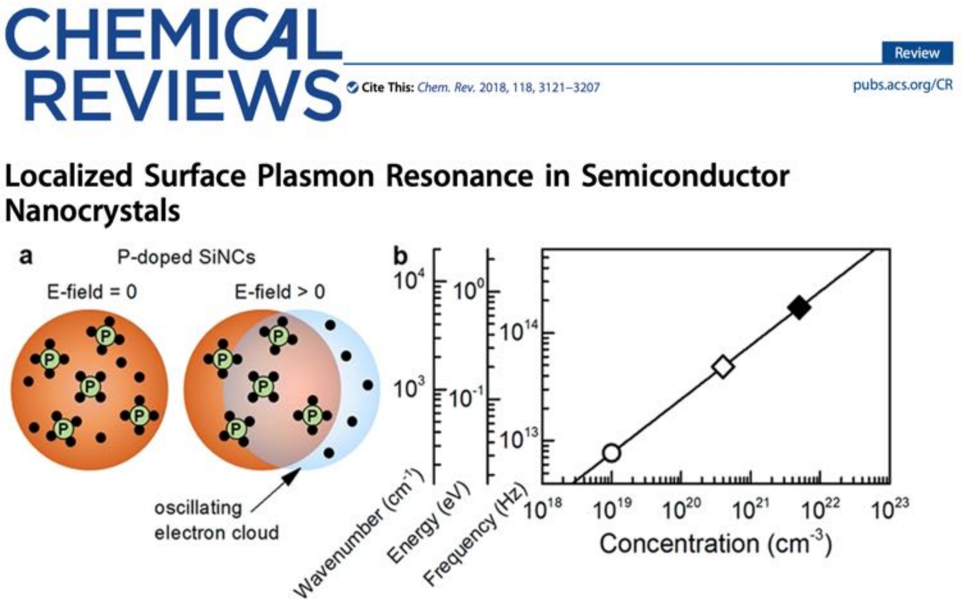
sub-μm bunch: $\sigma_{\parallel} \sim$ 400nm, $\sigma_r \sim$ 250nm
plasmonic tube: $r_t \sim$ 100nm, $n_t \sim 2 \times 10^{22}$ cm^{-3}
nearly matched: $\lambda_{\rm plasmon} \simeq 250{\rm nm}$

metallic plasmons – <μm bunch NOT accessible YET

TUNE Fermi electron gas properties to

MATCH

CURRENTLY available beam



CHEMICAL REVIEWS

Review

Cite This: *Chem. Rev.* 2018, 118, 3121−3207

pubs.acs.org/CR

Localized Surface Plasmon Resonance in Semiconductor Nanocrystals

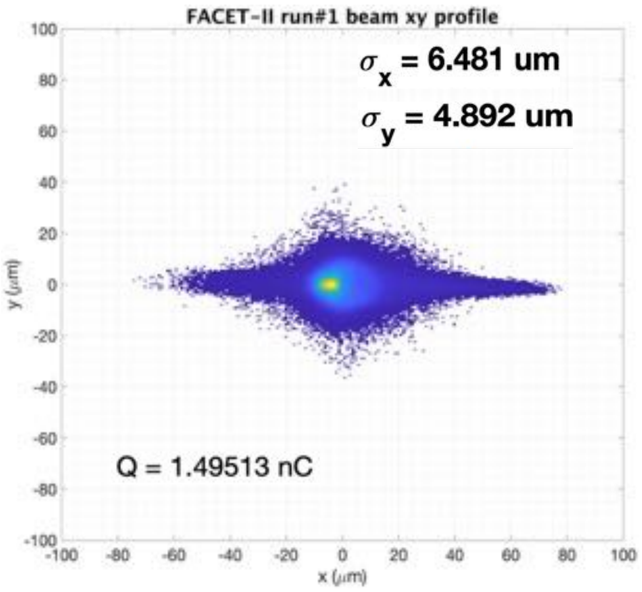
NANO LETTERS

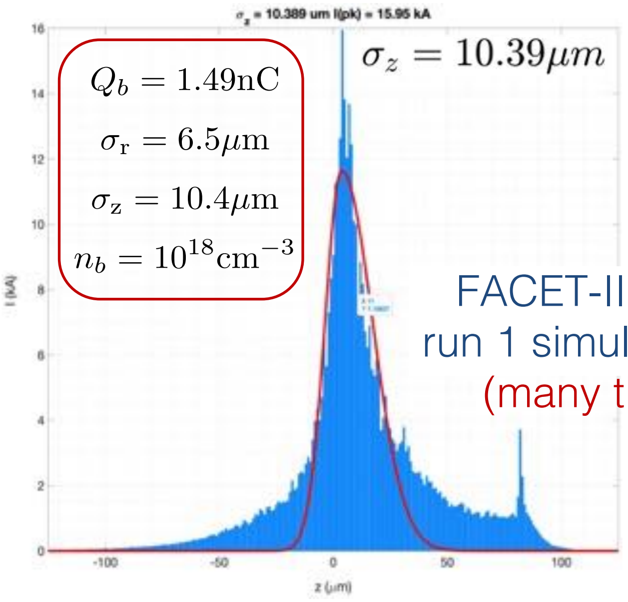
Letter

pubs.acs.org/NanoLett

Phosphorus-Doped Silicon Nanocrystals Exhibiting Mid-Infrared Localized Surface Plasmon Resonance

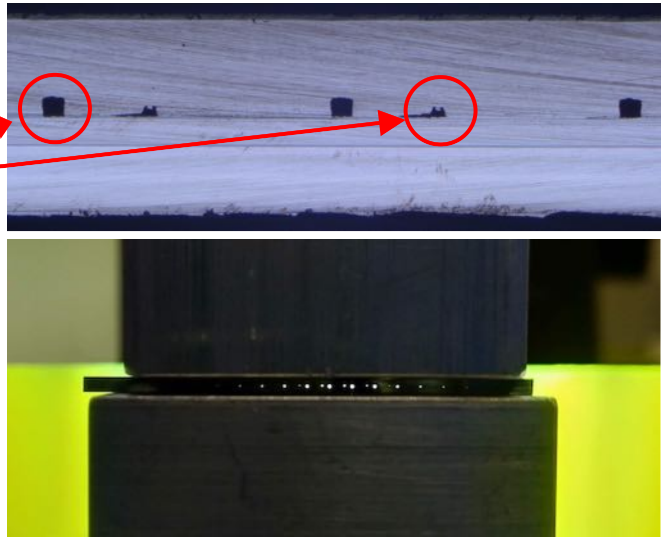
Match with FACET-II





$$Q_b = 1.49\text{nC}$$
$$\sigma_r = 6.5\mu\text{m}$$
$$\sigma_z = 10.4\mu\text{m}$$
$$n_b = 10^{18}\text{cm}^{-3}$$

100 and 30 µm rectangular tubes fabricated in Si



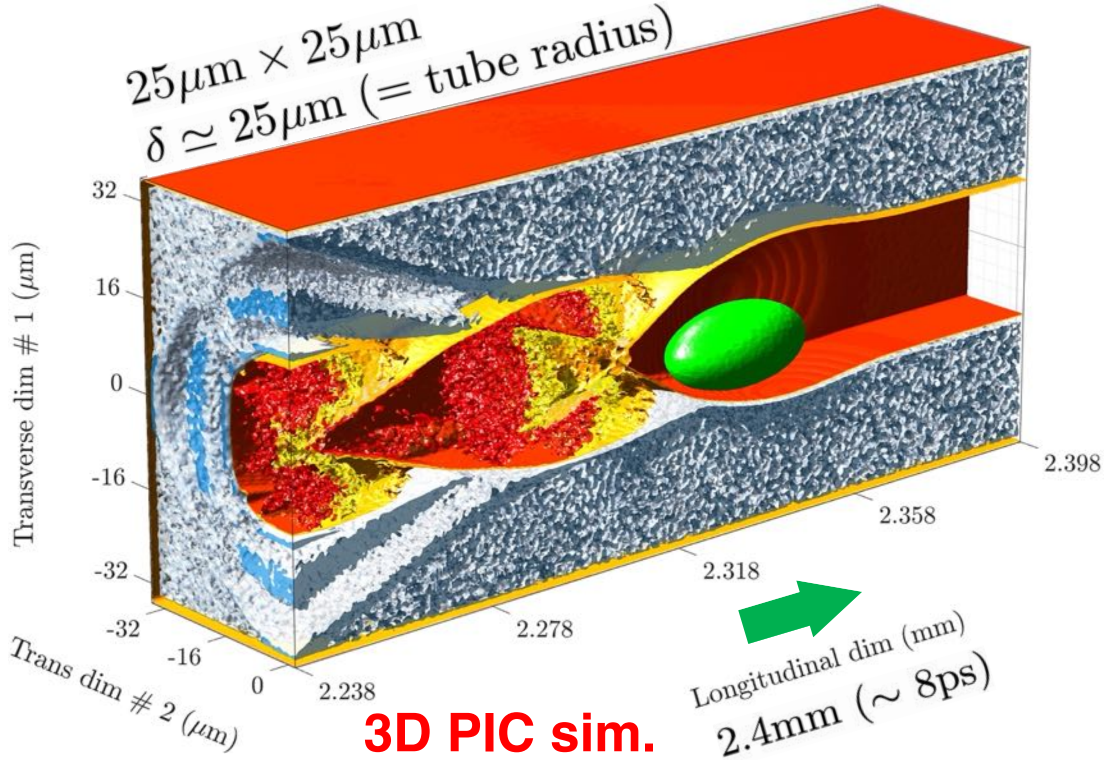
FACET-II beam phase-space for run 1 simulated using Lucretia code (many thanks to Dr. G. White)

MATCH: Plasmon ≈ Beam properties

n-type **P-doped** Silicon
free e⁻ Fermi gas density ~ 10^{18}cm^{-3} **($\sim n_b$)**

Plasmon wavelength: $\lambda_{\text{plasmon}}[10^{18}\text{cm}^{-3}] = 33\mu\text{m}$
λ_{plasmon} ~ **tube dim.** **~ 10s of µm**

maximize: beam-plasmon energy exchange



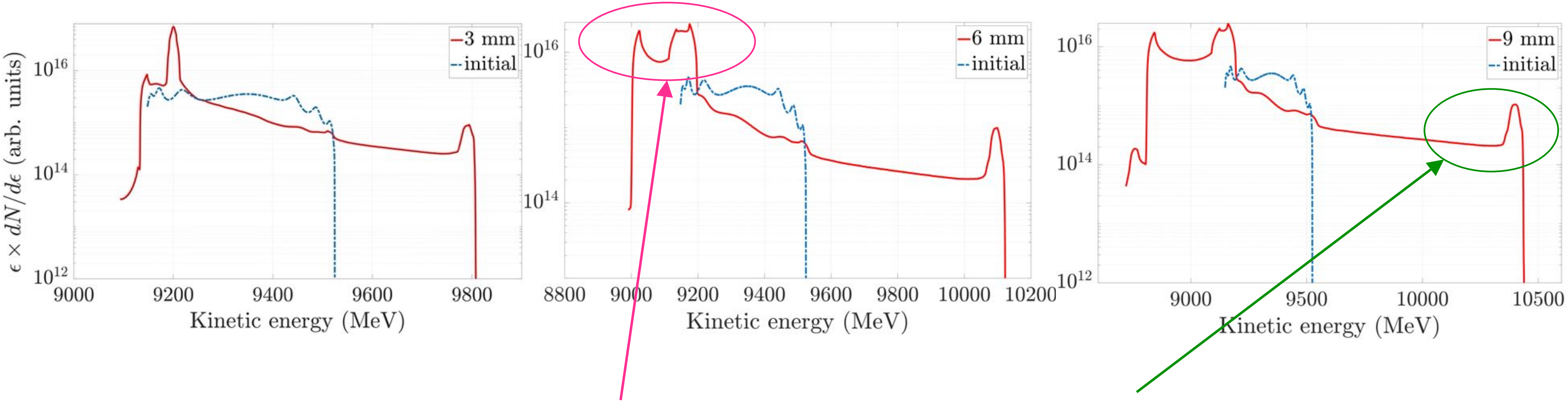
3D PIC sim.

target-time: 0.5 to 3 yrs.

Science goal # 1

Plasmonic Acceleration of electron beam

$r_t = 20\mu\text{m}$, $n_b = n_t \sim 10^{18}\text{cm}^{-3}$



energy xfer'd to plasmons

high-energy tail

SUCCESS: first-ever measurement of tens of GV/m acc. plasmonic fields

- 100s of MeV **energy loss** – large fraction of beam particles
- 100s of MeV **acceleration** – significant frac. of beam particles

Cerenkov air spectrometer
Energy – dispersed (y) plane

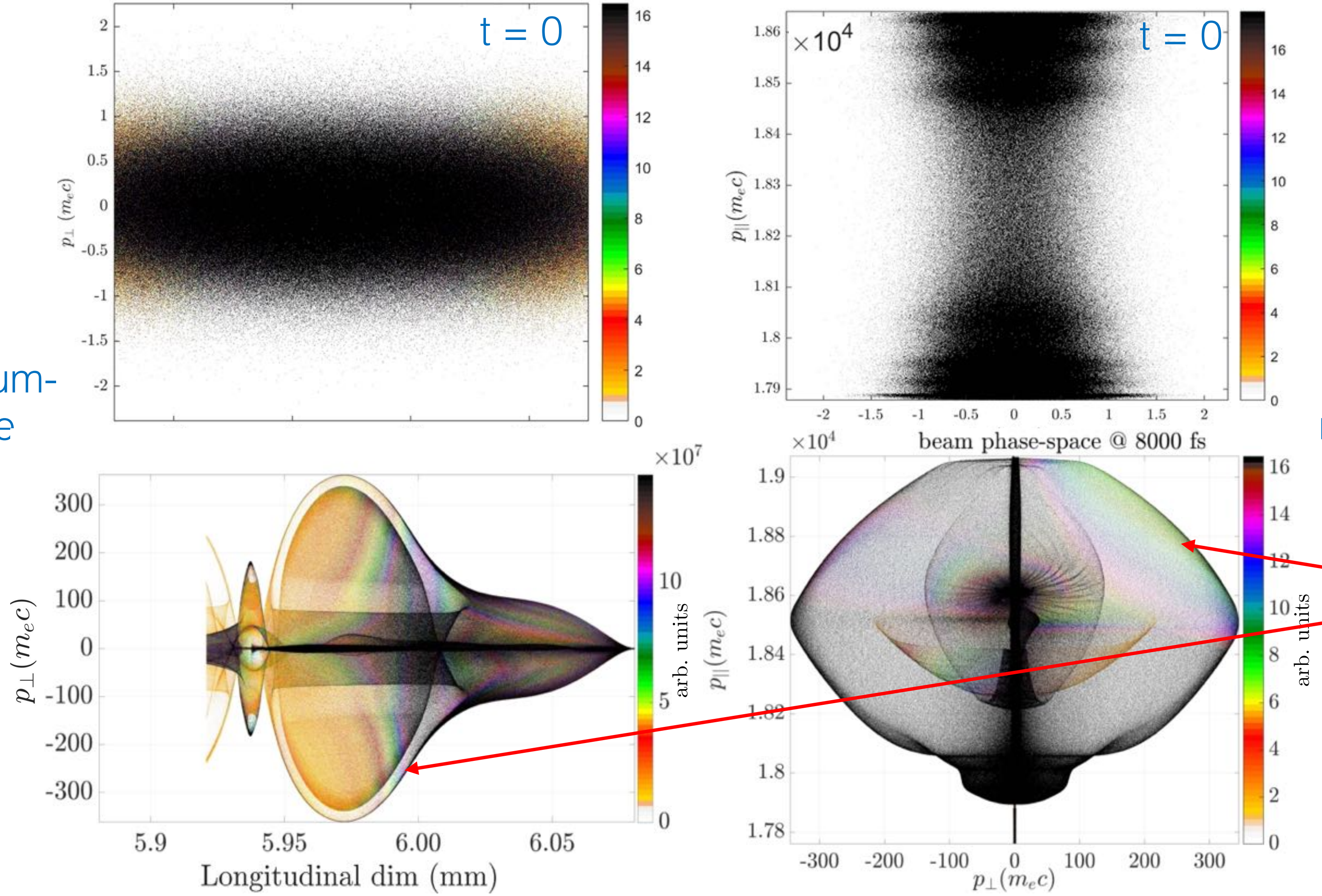
target-time: 0.5 to 3 yrs.

Science goal # 1

Plasmonic focusing of electron beam

transverse momentum-longitudinal space

transverse-longitudinal momentum phase-space



$p_\perp / p_\parallel$ = 320 / 19800 ≃ 16 × 10^{-3} rad

SUCCESS: first-ever measurement of tens of GV/m focusing fields

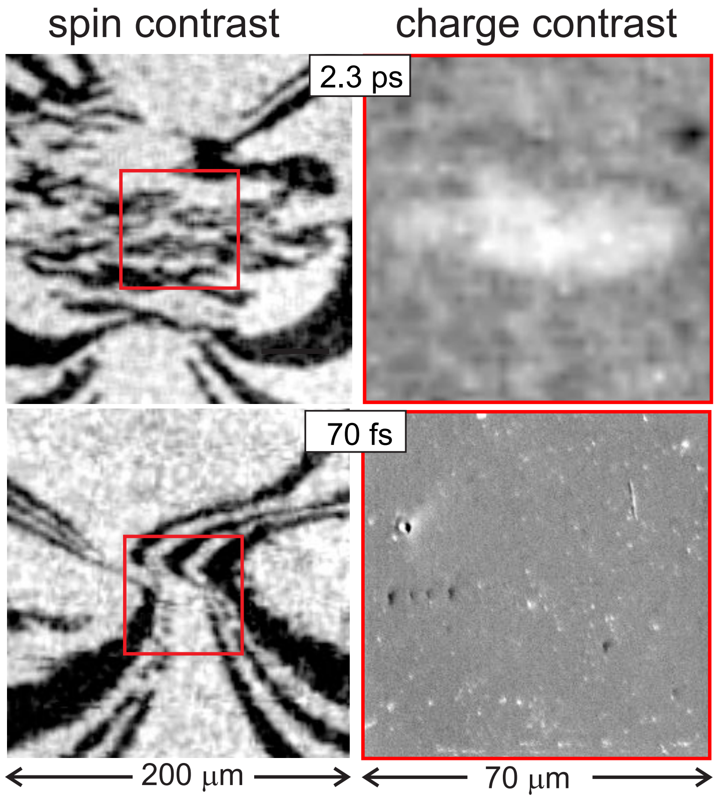
Spectrometer - non-dispersed (x) plane - tens of mrad – opening angle

University of Colorado Denver

target-time: 0.5 to 3 yrs.

Science goal # 2 –
Relativistically Induced ballistic e^- transport

NOT ANOTHER beam damage study



PRL **102,** 217201 (2009)

Electric Field Induced Magnetic Anisotropy in a Ferromagnet

S. J. Gamble,[1,2] Mark H. Burkhardt,[2,3] A. Kashuba,[4] Rolf Allenspach,[5] Stuart S. P. Parkin,[6] H. C. Siegmann,[1] and J. Stöhr[1,3]

- OBSERVED:
  2.3ps vs. 70fs e^- bunch ~ 2nC
  NO DAMAGE - Cobalt-Iron alloy
- 33-fold bunch compression
  E-field increased by this factor
- PLASMONIC MODEL:
  Fermi e^- gas collision w/ ion-lattice
  cross sec. $\propto (1/\gamma_e)^2$
- 33^2 or about 1000 times longer
  mean-free-path
  for 70fs compared to 2.3 ps pulses

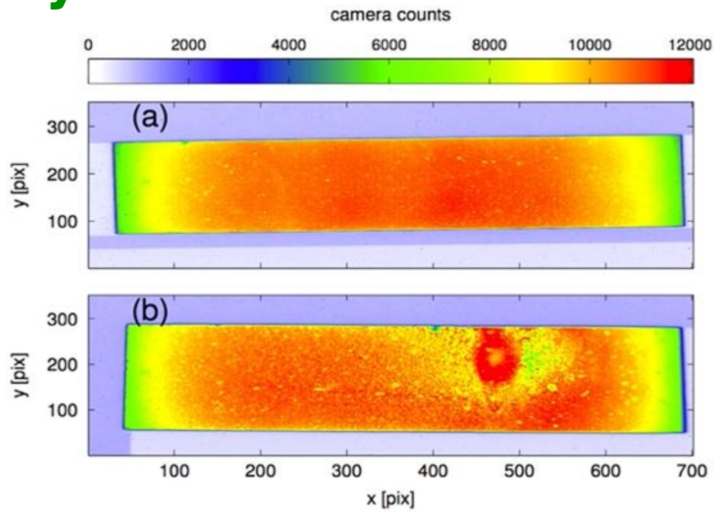


Fig. 10. (a) Reflection of diffuse light off silicon wafers used for the FACET experiments in 2013. These wafers were exposed to a few times 10^5 pulses of up to 2×10^{10} electrons, and show no visible sign of degradation. (b) Reflection of diffuse light off silicon wafers which have been in the beam line during all of the FACET commissioning in 2013. These wafers were exposed to a few times 10^7 pulses of up to 2×10^{10} electrons, and shows significant degradation, which translates to reduced light yield in the affected areas.

Cherenkov light-based beam profiling for ultrarelativistic electron beams

E. Adli[a,b,*], S.J. Gessner[b], S. Corde[b], M.J. Hogan[b], H.H. Bjerke[b,c]

Nuclear Instruments and Methods in Physics Research A 783 (2015) 35–42

SUCCESS: characterize novel Relativistically induced ballistic transport effect

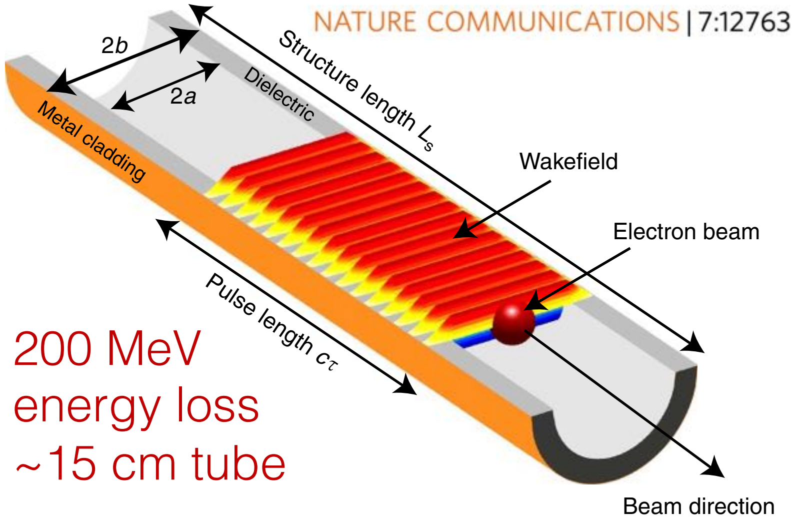
- confirm NO DAMAGE of samples: < tens of femtosecond bunches
- scan sample type (diff. Fermi gas densities, insulators), thickness, bunch lengths etc.

target-time: 0.5 to 3 yrs.

Science goal # 2 –
NOT ANOTHER Cherenkov experiment

INSULATOR

Cherenkov radiation & guided mode


NATURE COMMUNICATIONS | 7:12763

200 MeV
energy loss
~15 cm tube

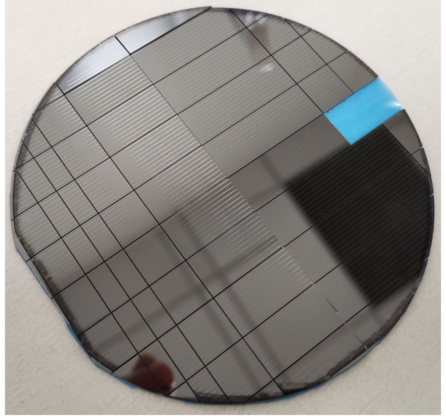
TM_{01} wavelength ~ 250 μm

~ 1cm tube length

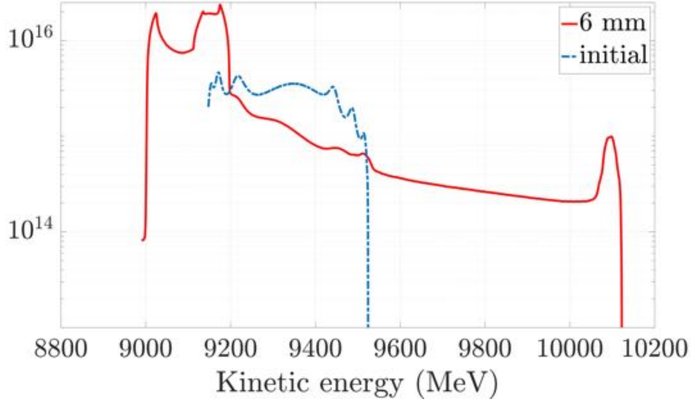
ONLY a **ten MeV energy loss** exp.
couples to ***Cherenkov rad.***
(unguided)

MATCHED PLASMON

matched dimension & density



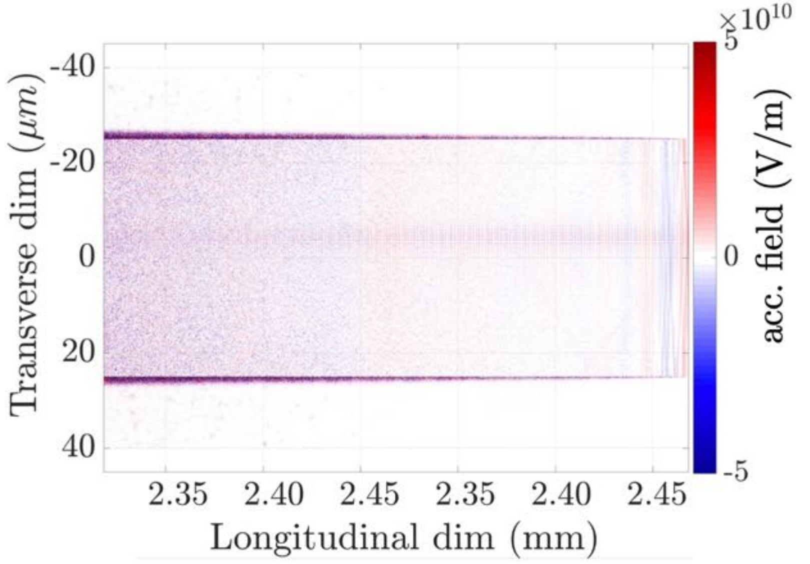
P-doped Si wafer with fabricated tubes



100s of **MeV energy loss**
as well as **energy gain**

UNMATCHED METAL PLASMON

FACET-II run#1 beam - n_t=2 x10^{22}cm^{-3}



$\lambda_{plasmon}$ (2 x10^{22}cm^{-3}) = 250nm

run#1 beam: σ_r ~ 5μm, σ_z ~ 10μm

ONLY a **few MeV energy loss** exp.

SUCCESS: differentiate plasmonic vs. dielectric vs. metallic

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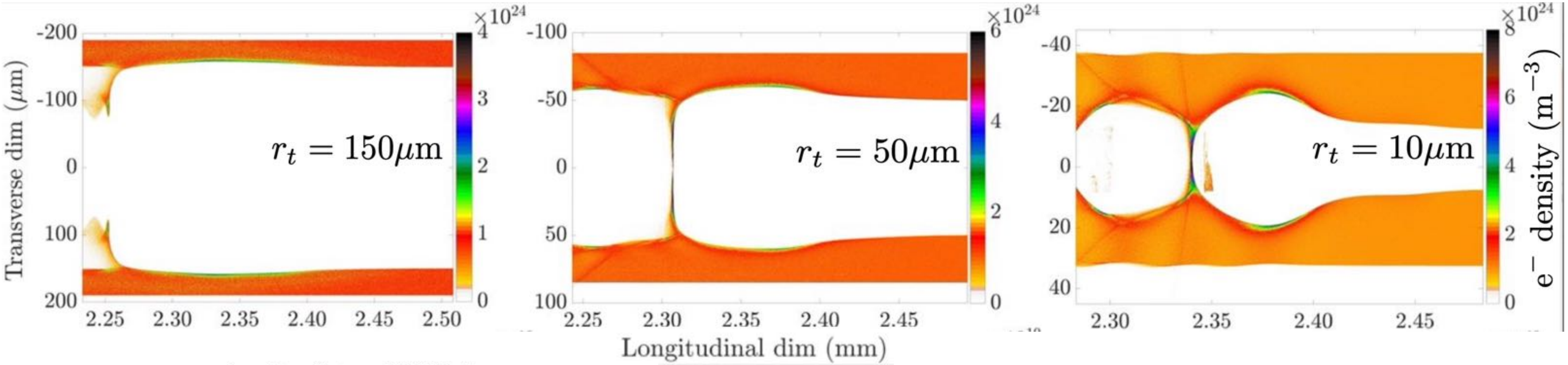
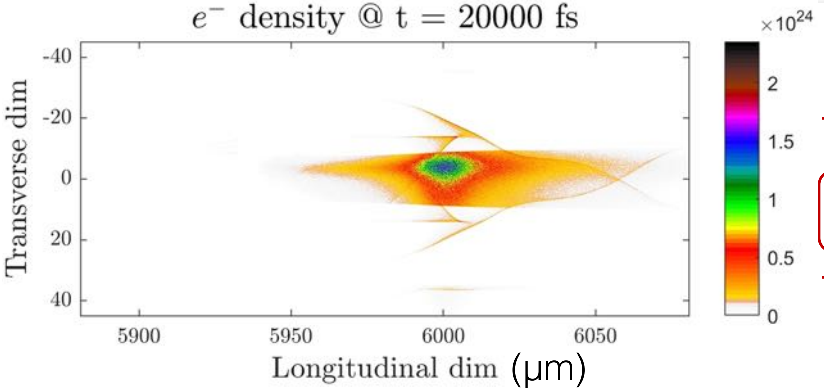
Denver

target-time: 0.5 to 3 yrs.

Science goal # 3 –
Beam bunching and coherent photon production





10s of microns – spatial features due to beam particle trajectories in the focusing fields

$$\boxed{hc\ 2\gamma_b^2/\lambda_{\rm osc}}$$

Tens of MeV photons

SUCCESS: characterize plasmonics-based high-power coherent photon production

- diff. bremsstrahlung vs. coherent photons – detect and tune photon spectral features
- scan tube properties, beam properties, offset from channel axis etc.
- match focusing fields of non-linear surface plasmon ~ exp. photon spectra

Connection with other expts.

- E300: plasma wakefield acceleration experiment: TCAV longitudinal profile, energy Cerenkov spectrometer, bunch profile, profile of acc. & foc. fields etc.

- E-321: Dielectric wakefield – tube alignment, diagnostics etc.

- E317: TV per meter plasma wakefield: kT/m Perm. Magnet Quad. triplet and COTR diagnostics

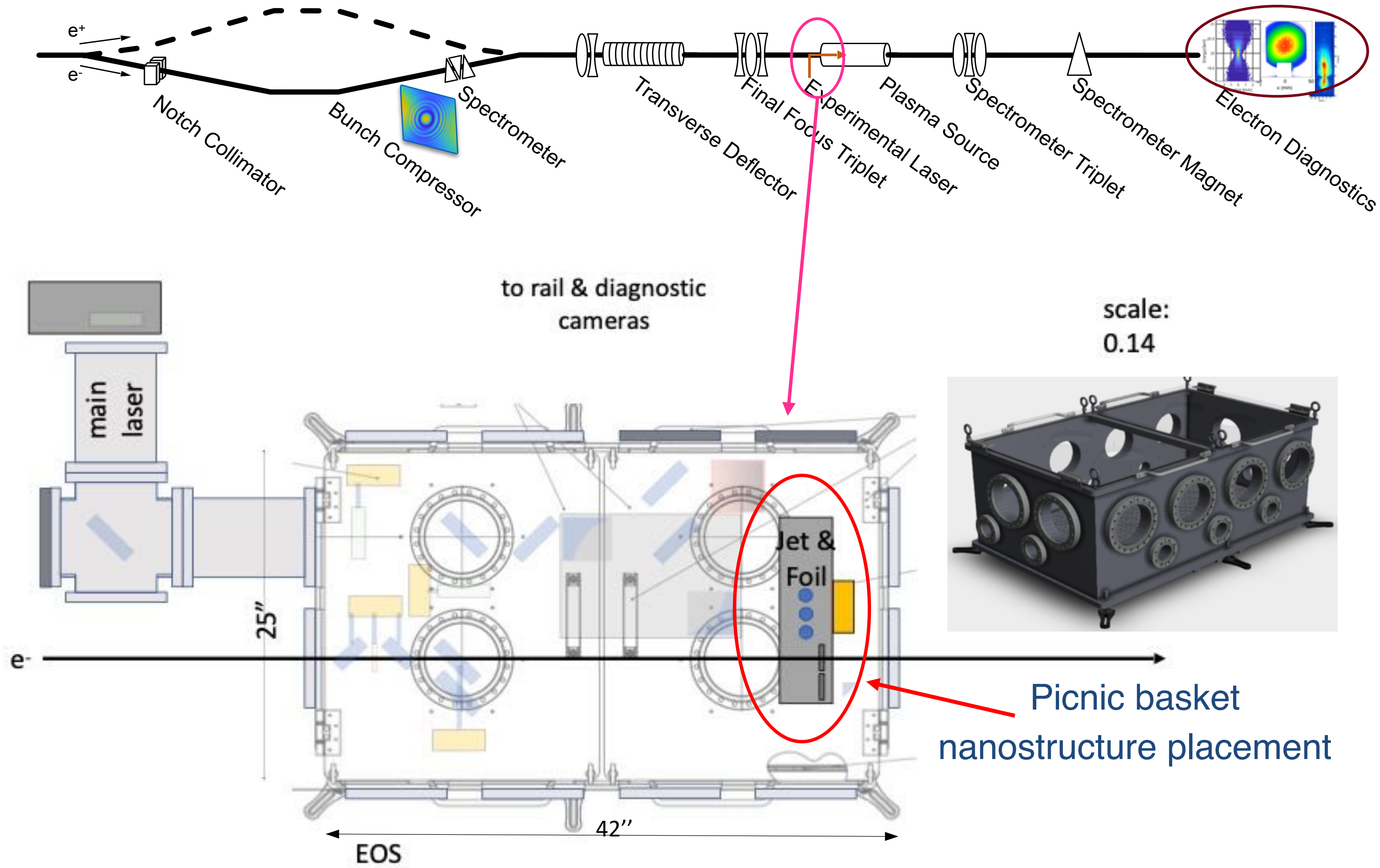
- E-308 & EOS: diagnostics and Plasma ion-channel focusing

- gamma-ray diag: E330/Laserwire experiment, the E320/SFQED experiment, the E300/plasma wakefield acceleration experiment and the E306/Beam-Driven Ion Channel Laser experiment

- E320 and E305: e^+-e^- pair spectrometer

- E330/Laserwire experiment: possibility of laserwire after the picnic basket chamber

Conceptual experimental layout



Picnic basket nanostructure placement

Beamline location and layout of nanostructure sample setup in the picnic basket chamber [M. Hogan, Expt. area, Sci. meeting 2019]

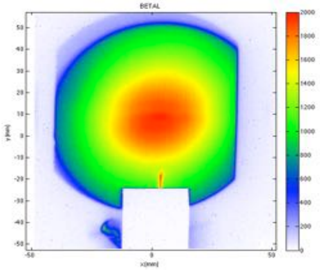
- Picnic basket chamber
- 6-axis motorized stage and goniometer
- integrate sample stage with the EPICS control system
- initially use dump table diagnostics
- build post picnic basket chamber diags. (beam profile, gamma, energy etc.)

Diagnostics and observables

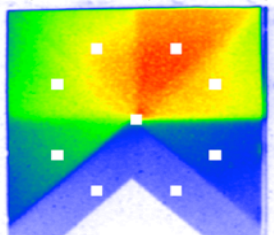
- Cerenkov air spectrometer
  - energy spectra – loss and acceleration
  - mapping the beam transverse momentum phase-space
- edge radiation or OTR beam diag. after the sample
- photon / gamma-ray diagnostics (dump table)
- e^+-e^- pair spectrometer (30 to 50 cm from the sample)

Gamma-rays

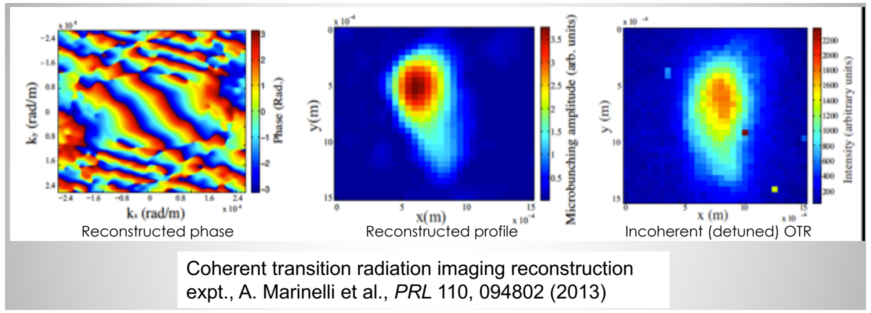
Angular distribution:
convertor + scintillator, and pixelized CsI array for higher sensitivity



Spectrum:
transverse array of filters/convertors
Ross filters (<100keV)
Step filters (up to 250keV)



gamma-ray diagnostic setup dump table
M. Hogan, Expt. area, Sci. meeting 2019



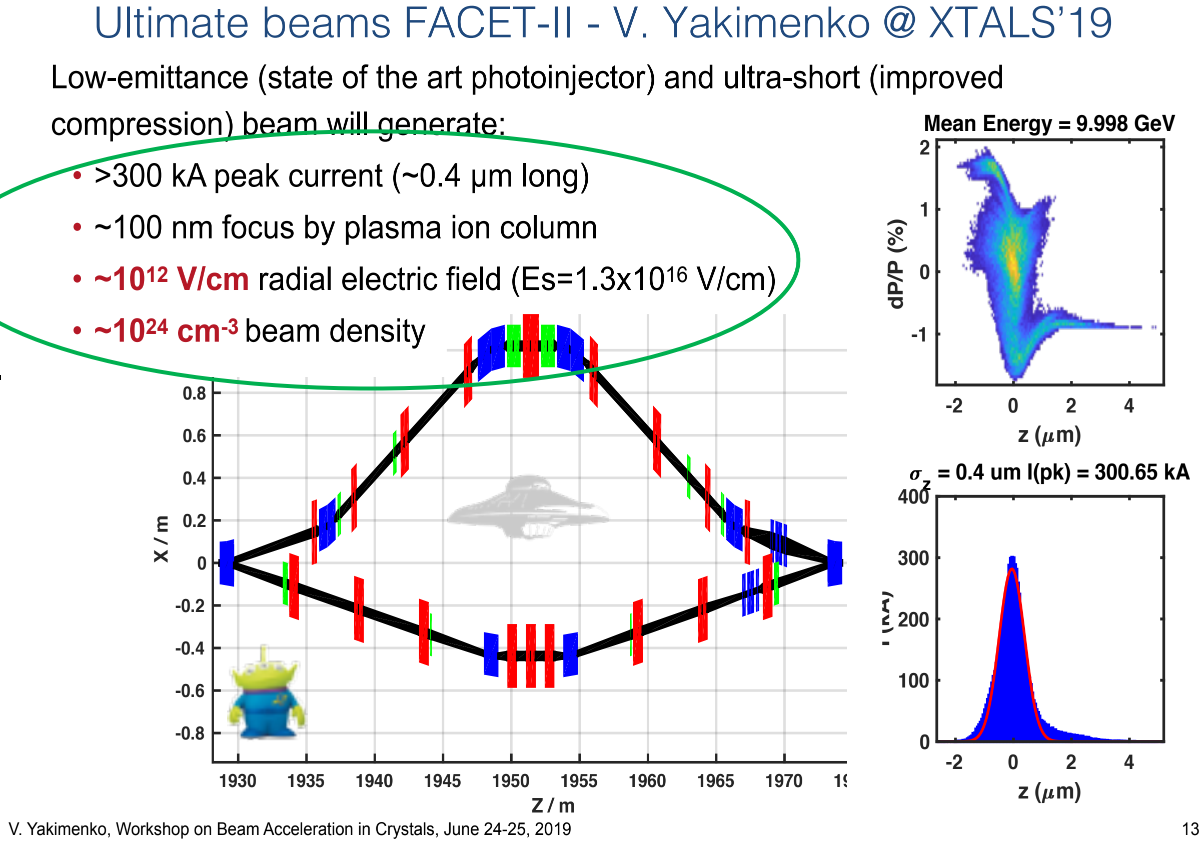
Coherent transition radiation imaging reconstruction expt., A. Marinelli et al., *PRL* 110, 094802 (2013)

COTR sub-micron bunch trans. profile diag (E317)
Rosenzweig, Science meeting 2017

University of Colorado Denver

Desired facility upgrades

- **sub-micron** bunch length, $\sigma_\parallel \sim \mathcal{O}(100\text{nm})$
  $\mathcal{O}(100\text{nm})$ long. and tran. beam diag.
- plans for PMQ triplet or plasma ion-column focus.
  $\sigma_r \sim \mathcal{O}(100\text{nm})$ scale
- 2-bunch $\mathcal{O}(100\text{nm})$ 100pC config. – drive & witness
- high-energy photon diag.
- AI-based automated alignment
- $\mathcal{O}(100\text{nm})$ positron bunches

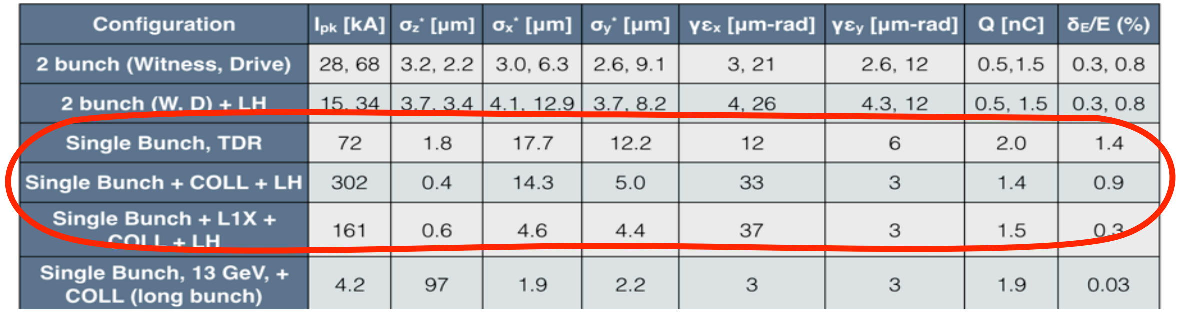


Ultimate beams FACET-II - V. Yakimenko @ XTALS'19

Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam will generate:

- >300 kA peak current (~0.4 μm long)
- ~100 nm focus by plasma ion column
- **~10^{12} V/cm** radial electric field (Es=1.3x10^{16} V/cm)
- **~10^{24} cm^{-3}** beam density

V. Yakimenko, Workshop on Beam Acceleration in Crystals, June 24-25, 2019 13



Configuration	I_{pk} [kA]	σ_z^* [μm]	σ_x^* [μm]	σ_y^* [μm]	$\gamma\varepsilon_x$ [μm-rad]	$\gamma\varepsilon_y$ [μm-rad]	Q [nC]	δ_E/E (%)
2 bunch (Witness, Drive)	28, 68	3.2, 2.2	3.0, 6.3	2.6, 9.1	3, 21	2.6, 12	0.5,1.5	0.3, 0.8
2 bunch (W. D) + LH	15, 34	3.7, 3.4	4.1, 12.9	3.7, 8.2	4, 26	4.3, 12	0.5, 1.5	0.3, 0.8
Single Bunch, TDR	72	1.8	17.7	12.2	12	6	2.0	1.4
Single Bunch + COLL + LH	302	0.4	14.3	5.0	33	3	1.4	0.9
Single Bunch + L1X + COLL + LH	161	0.6	4.6	4.4	37	3	1.5	0.3
Single Bunch, 13 GeV, + COLL (long bunch)	4.2	97	1.9	2.2	3	3	1.9	0.03

G. White, Science Workshop, October 29, 2019

Potential future evolution

futuristic science reach – recently summarized in Snowmass'22 white paper **arXiv:2203.11623**

- Nonlinear QED – plasmonic nanofocusing of particle beams
- Access Teravolts to Petavolts per meter acceleration gradient – futuristic colliders
- intense (coherent) gamma-ray beams (gamma-ray lasers) – light-sources
- ultrashort e^+ bunches → positron focusing and acceleration in plasmonic materials
- $\mathcal{O}(GeV)$ gamma-ray for muon yield
- Non-collider tests of high-energy physics, QCD etc.

Nano^{2}WA Collaboration

Univ of Colorado Denver – Sahai, Golkowski, Harid (*2 stud.*)

Univ of Connecticut – Prof. Katsouleas (*advisory, 1 stud.*)

Univ of California Los Angeles – Dr. Gerard Andonian (*0.5 stud.*)
Dr. Chris Clayton
Prof. Chan Joshi (*advisory*)

Univ of California Irvine – Prof. P. Taborek

SLAC – Dr. G. White

Lawrence Berkeley National Lab – Dr. Daniele Filippetto

CERN – Dr. A. Latina

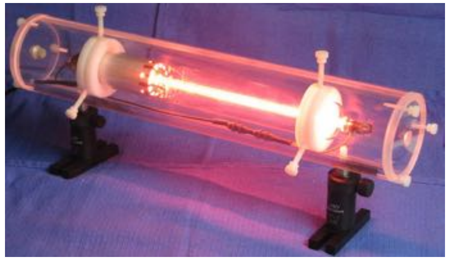
Acknowledgements:
EPOCH PIC code
NSF XSEDE CU Summit Supercomputer

University of Colorado
Denver

Extreme field frontier - gas vs solid excitations

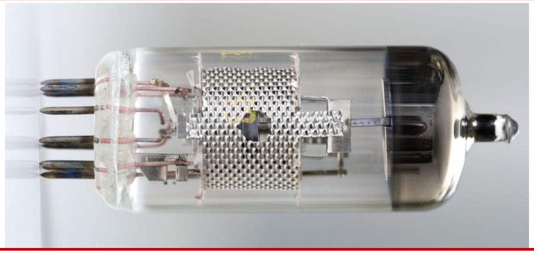
excitations in gases

discharge arc
active media
Gaseous lasers

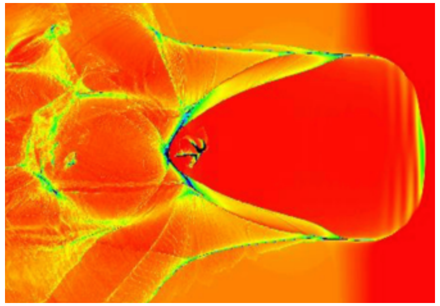


ionized gas
discharge arc
fluorescence
CFL lamps

control e⁻
flow in gas
vacuum tubes



gaseous plasma
collective mode
Plasma Acc.



paradigm

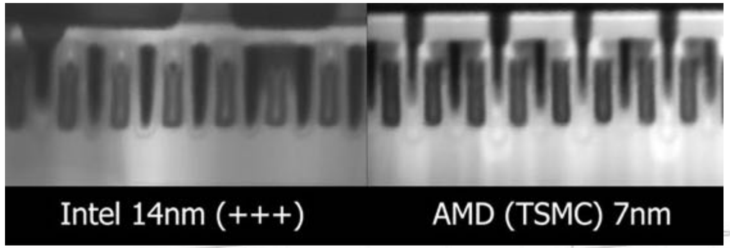
shift

excitations in solids

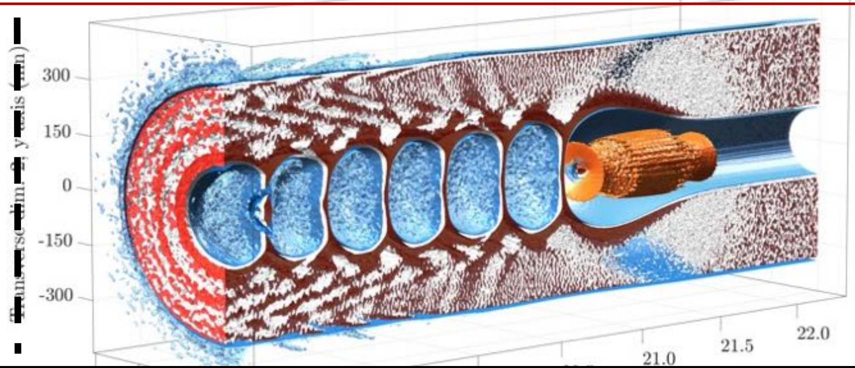
solid-state
active media
solid-state lasers

solid-state
active media
LED lamps

SILICON VALLEY



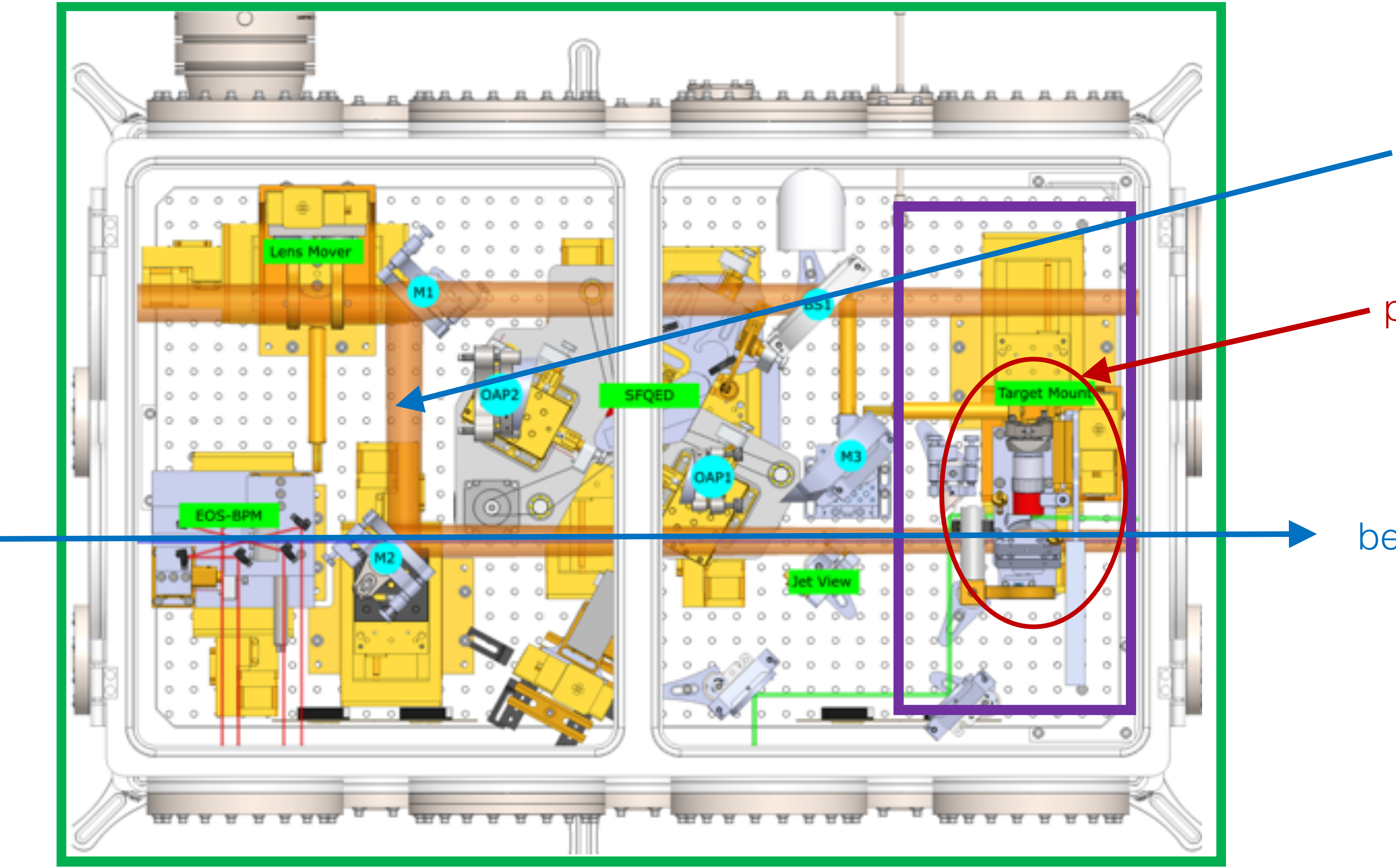
conduction e⁻ control
transistor
VLSI chip



conduction electron
collective mode
Nanostructure
Nanoplasmonic Acc.

backup slide

Picnic basket chamber - **plasmonic** setup

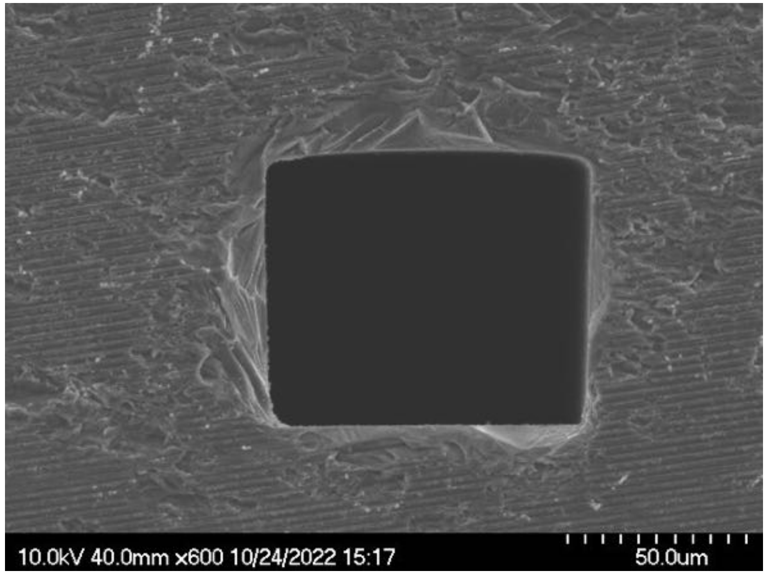


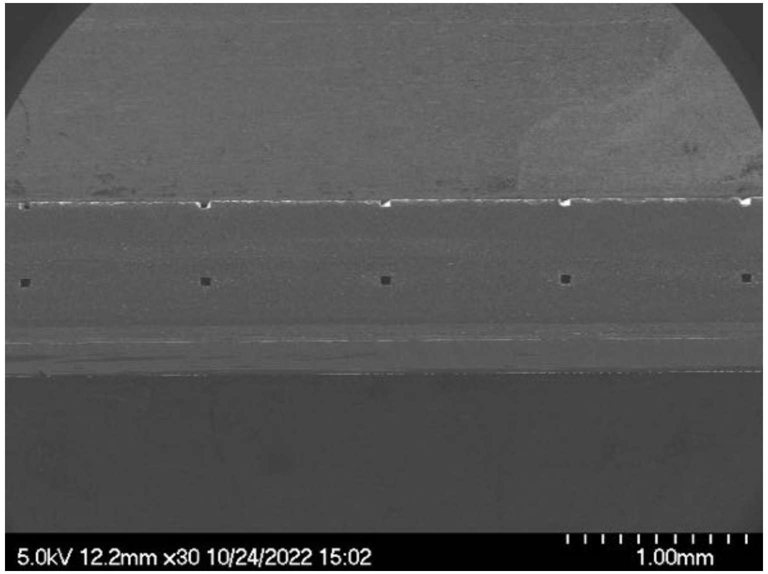
possible path for alignment laser

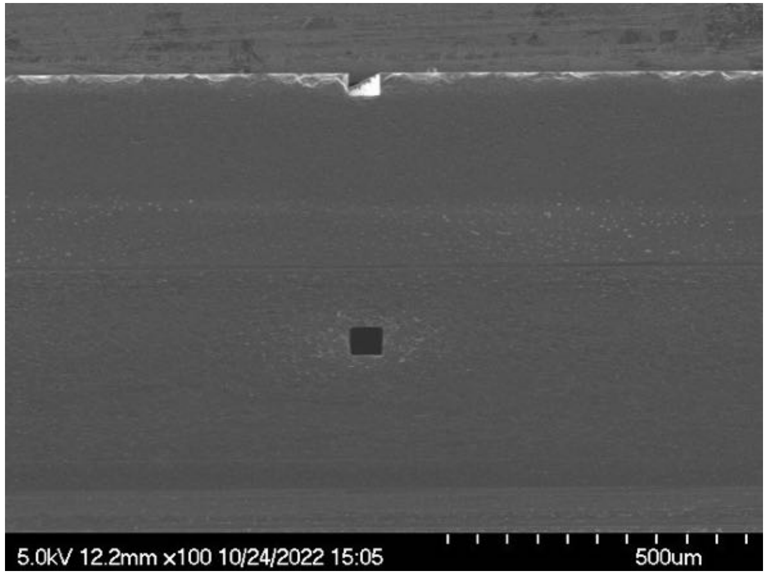
possible 6-axis stage

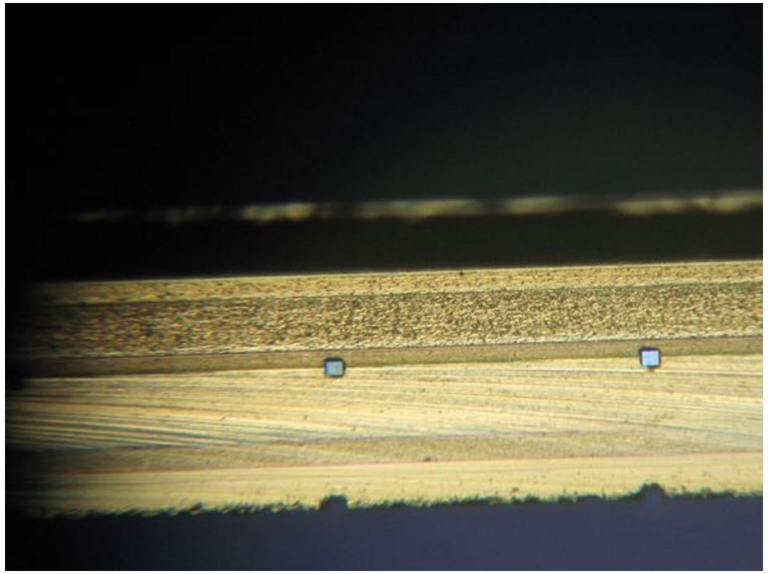
beam path

Doped Silicon **plasmonic** tube - fabrication









backup slide

- Simulation campaign effort/date – details of the “tunable plasmon” model are accessible in arxiv:2208.00966, including estimated ***readily measurable signature*** of energy loss and transverse momentum phase-space

- Conceptual design (30% confidence) done

- experimental design (90%): will work towards beam-time, have the 90% design ready 30 days before beam-time

- ready for installation: plasmonic samples have been fabricated and are ready to install upon integrating positioning + alignment stage with EPICS

- first science: beam requirements - FACET-II run # 1 beam – sim. using Lucretia (many thanks to Dr. White)

- 2 phases of the program: *next phase to be proposed at next PAC*