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PetaVolts per meter Plasmonics*

**conductive materials - semiconductors, semi-metals, metals*

quantum electron gas

Nanomaterials Based Nanoplasmonic Accelerators and Light-Sources IEEE Access
doi: 10.1109/ACCESS.2021.3070798

PAPER • OPEN ACCESS
PetaVolts per meter Plasmonics: introducing extreme nanoscience as a route towards scientific frontiers
Aakash A. Sahai[1], Mark Golkowski[1], Stephen Gedney[1], Thomas Katsouleas[2], Gerard Andonian[3],
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Journal of Instrumentation, Volume 18, July 2023
Citation Aakash A. Sahai *et al* 2023 *JINST* **18** P07019
DOI 10.1088/1748-0221/18/07/P07019

Plasmonic experiment timeline

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IEEE Access
doi: 10.1109/ACCESS.2021.3070798

timeline of expt. efforts - I

PAC 2020

Extreme plasmons - ***first expt. proposal***
large-amplitude oscillations of Quantum electron gas
trends towards smaller bunch dimn.s – match with FACET

- **proposed** - metallic nanostructures (nonporous Au) to control the quantum electron gas properties
- relativistic, large-amplitude dynamics of Fermi electron gas 3D simulations of plasmons - 10TV/m fields
- 300 kA beam G. White's work *[Science meeting 2019]*

PAC feedback – develop near-term, realistic expt. plan to utilize KPP beam *[report - "few micron"]*

- need "ionization" vs. ~~quantum electron gas (NOT understood)~~
- discussion of measurable expt. signature
- destruction of tubes

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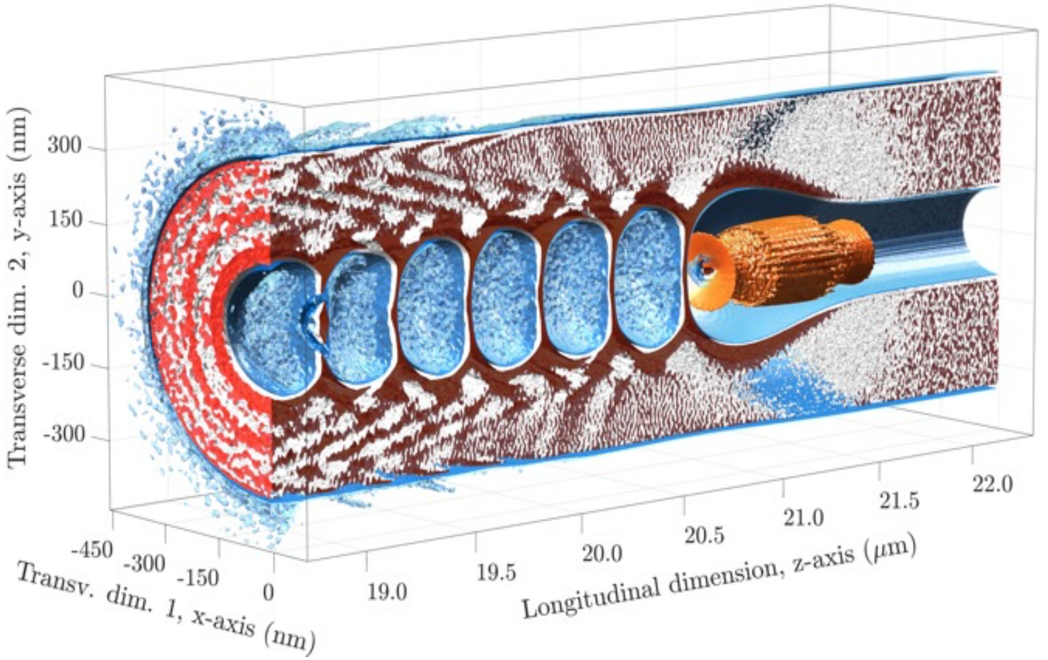


sub-μm bunch: $\sigma_{\|}$ ~ 400nm, σ_r ~ 250nm
plasmonic tube: r_t ~ 100nm, n_t ~ 2 x10^{22} cm^{-3}
nearly matched: $\lambda_{\mathrm{plasmon}} \simeq 250\mathrm{nm}$

timeline of expt. efforts - II

Tunable plasmon – match with “few micron” FACET-II beam

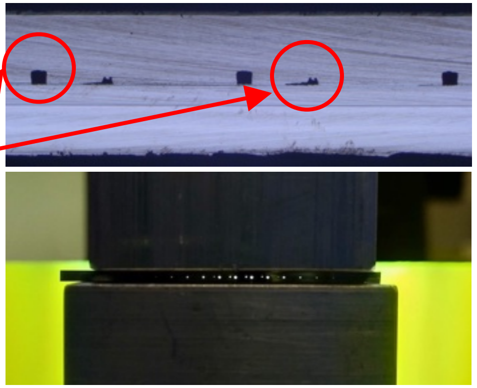
- doped Semiconductor tubes:
  tune quantum electron gas properties
  n-type **P-doped** Silicon
  Quantum e⁻ gas density ~ 10^{18}cm^{-3} **(~ n_b:KPP)**

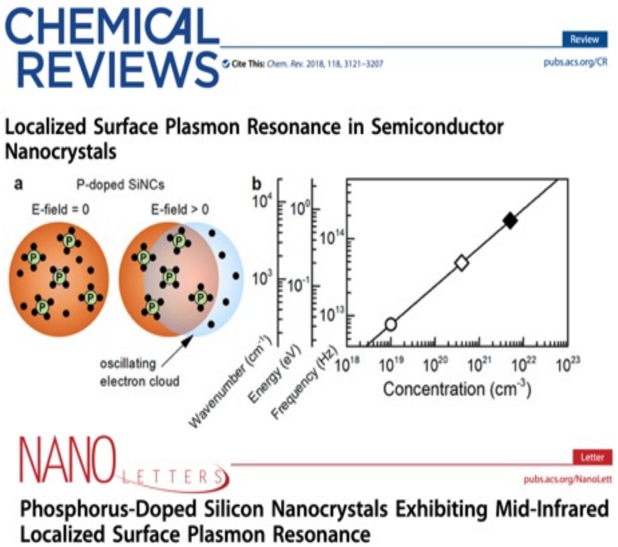
- tube radius: 100μm, 30μm
  $\lambda_{plasmon}$ ~ **tube dim. ~ 10s of μm**
  large-fraction of beam particles – inside the tube

- 100 GV/m acceleration and focusing fields computationally demonstrated

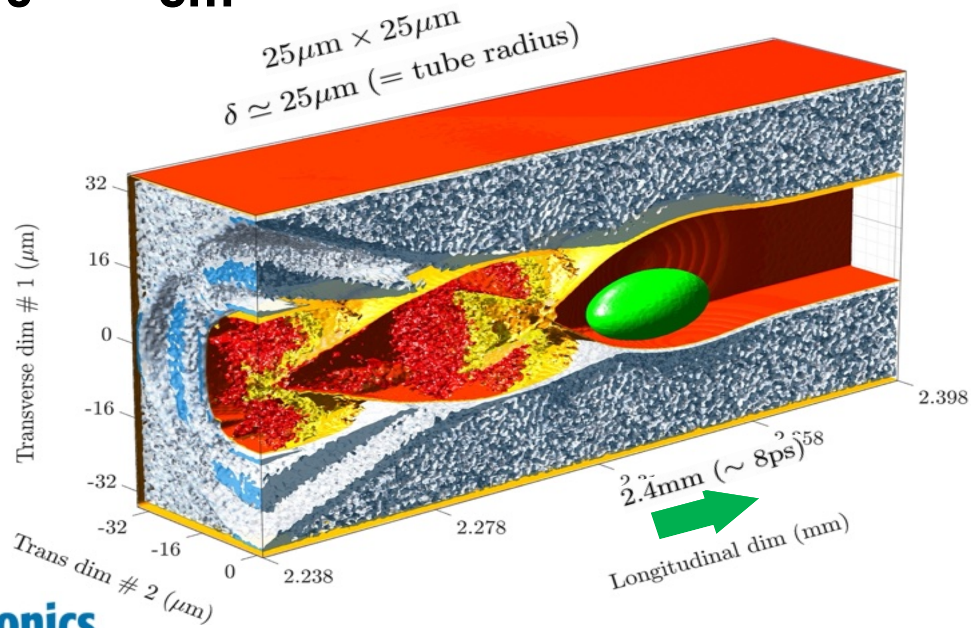
- expt. ready Si tubes – designed and fabricated

100 & 30 μm rect. tubes fabricated in Si





semiconductors:
n_t ~ $10^{12\text{-}21}$ cm^{-3}



PAC feedback – develop extensive expt. plan

- ionization of media

- dielectric properties

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Approaching PetaVolts per Meter Plasmonics Using Structured Semiconductors 10.1109/ACCESS.2022.3231481

Tunable plasmons - measurements

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Accelerators and Light-Sources
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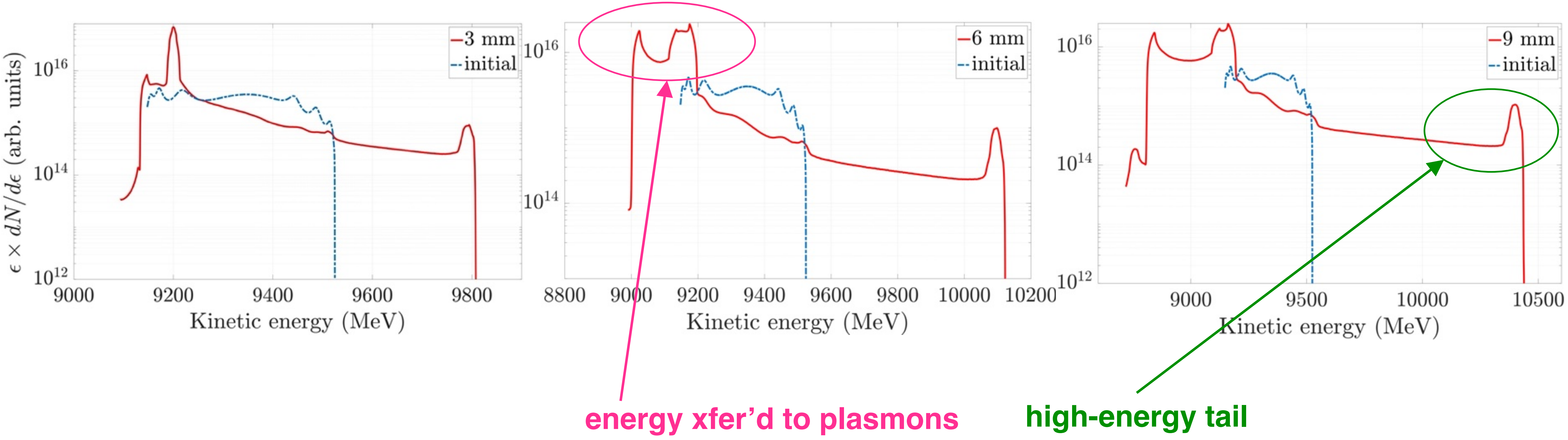
doi: 10.1109/ACCESS.2021.3070798

target-time: 0.5 to 3 yrs.

measurement # 1

plasmonic energy exchange with electron beam

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



MEASUREMENT: first-ever signature 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

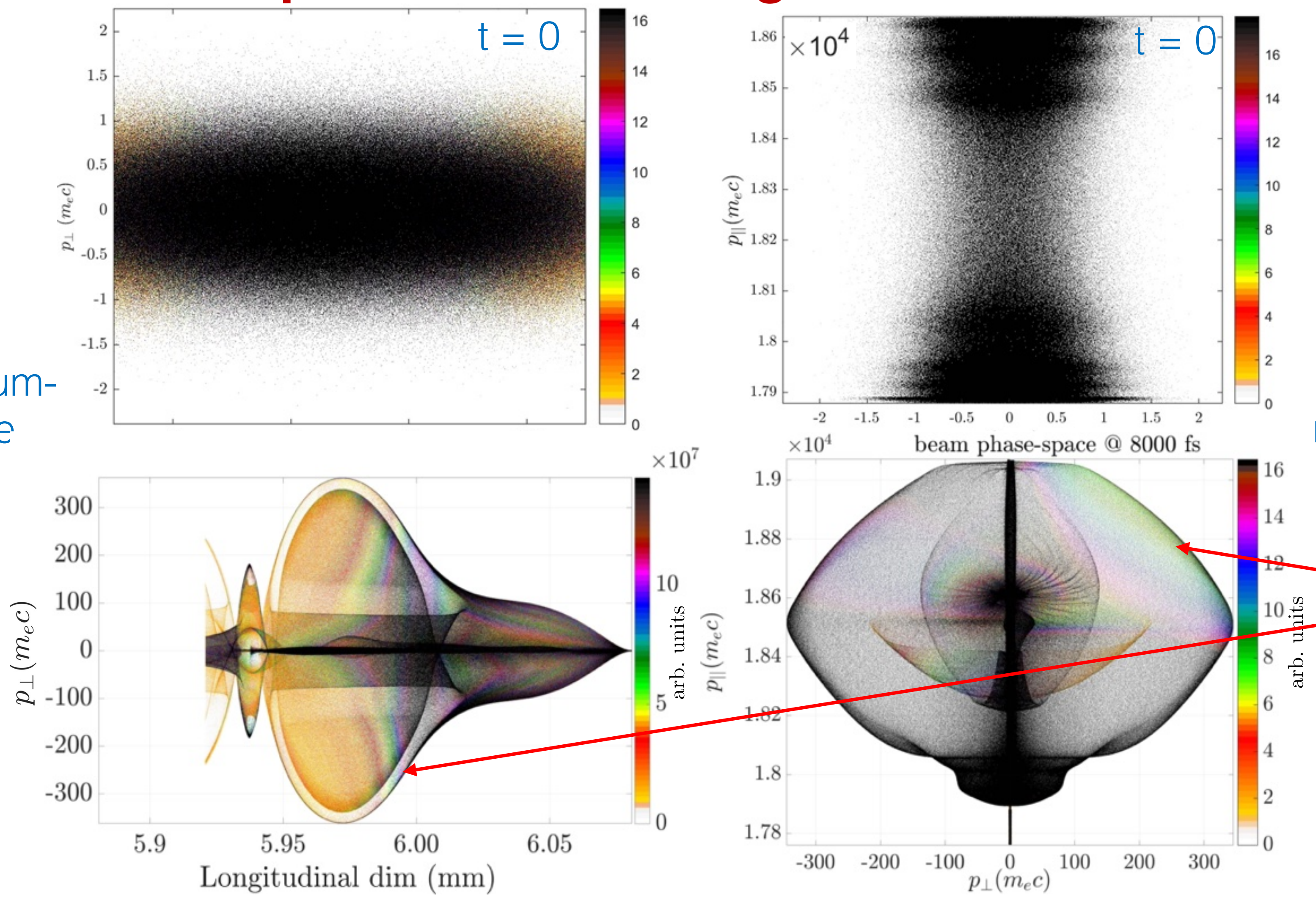
Cerenkov air spectrometer
Energy – dispersed (y) plane

target-time: 0.5 to 3 yrs.

measurement # 2

plasmonic focusing of electron beam

transverse momentum-longitudinal space



transverse-longitudinal momentum phase-space

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

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

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

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measurement # 3

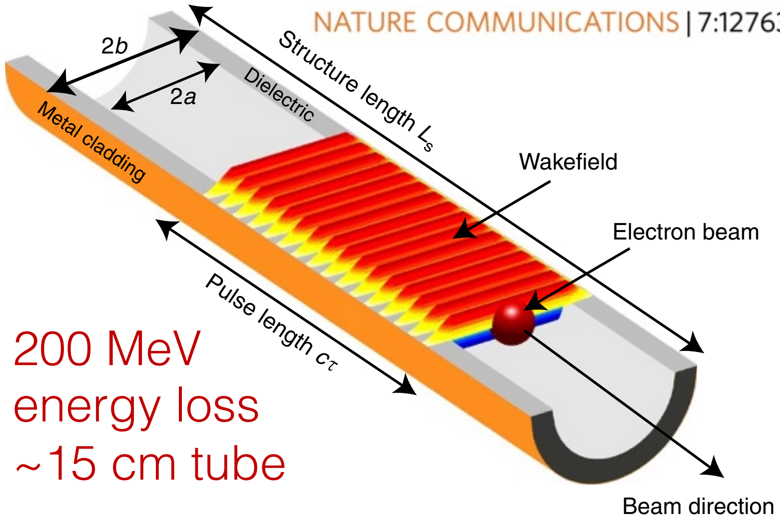
target-time: 0.5 to 3 yrs.

DIFF Cherenkov mechanism

INSULATOR

Cherenkov radiation & guided mode

NATURE COMMUNICATIONS | 7:12763



200 MeV energy loss ~15 cm tube

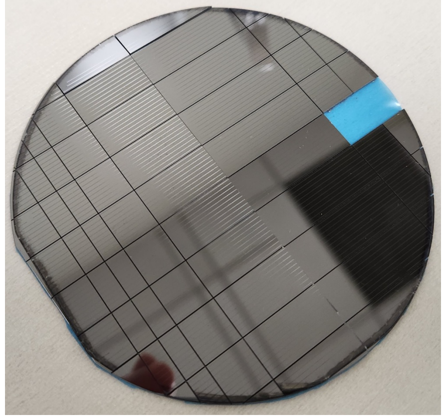
TM_{01} wavelength ~ 250 μm

~ 1cm tube length

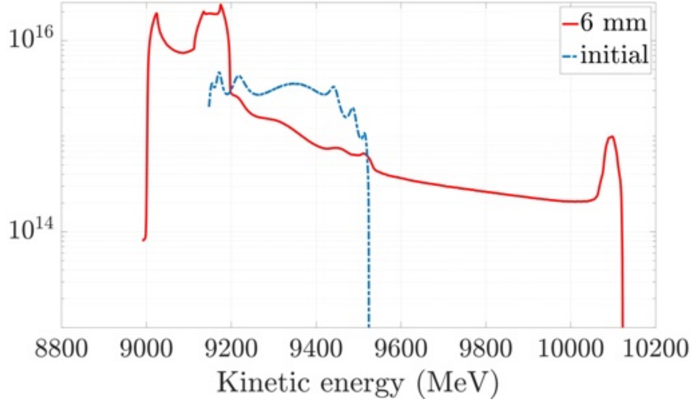
ONLY a **ten MeV energy loss** exp. couples to ***Cherenkov rad.*** (unguided)

MATCHED PLASMON

matched dimension & density



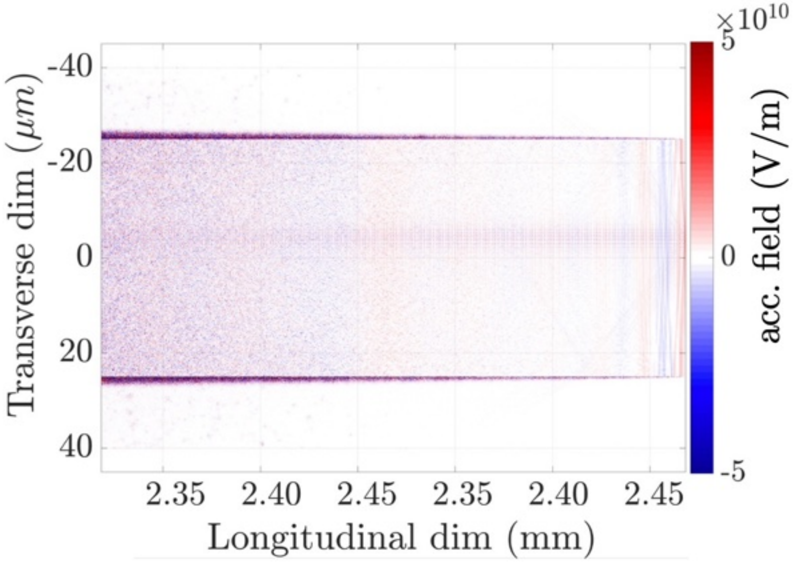
P-doped Si wafer with fabricated tubes



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.

MEASUREMENT: differentiate plasmonic vs. dielectric vs. metallic modes

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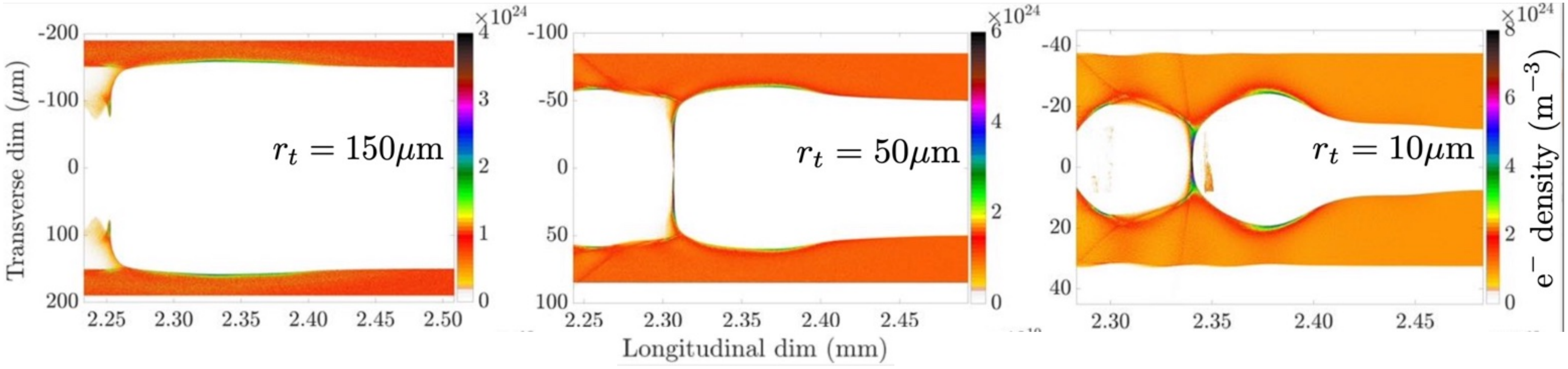
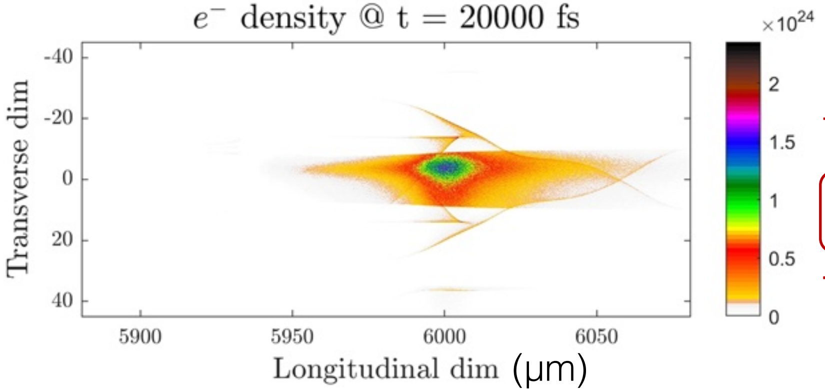
target-time: 0.5 to 3 yrs.

measurement # 4

Beam bunching and coherent photon production





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

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

Tens of MeV photons

diff. bremsstrahlung vs. coherent photons – detect and tune photon spectral features

Plasmonics fundamentals

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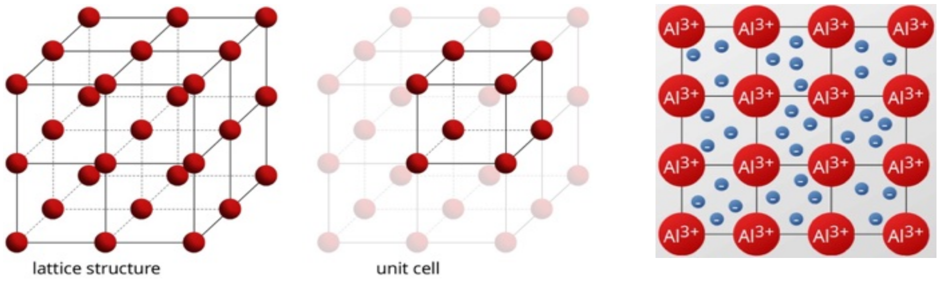
Accelerators and Light-Sources
IEEE Access
doi: 10.1109/ACCESS.2021.3070798

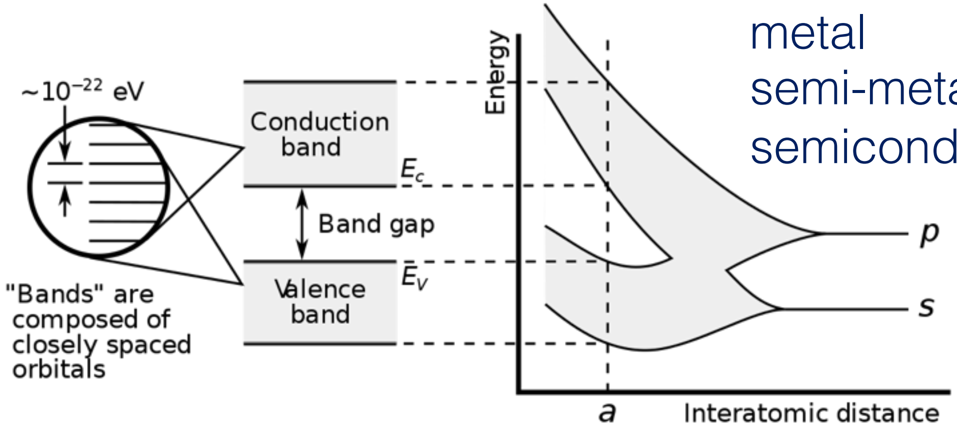
understanding Quantum electron gas

ionic lattice
periodic potential is **PRESENT**
over plasmonic timescale *(strained under high fields)*

energy band structure
lattice structure – Bloch's theorem : ***QUANTUM***
electrons - specific occupancy states (k-space)
near-continuum Energy levels – **energy BANDs**
energy band-gap – characterizes media

non-interacting Fermions
Pauli's exclusion principle : ***QUANTUM***





metal
semi-metal
semiconductor

Quantum electron gas: conduction band e⁻ - conductive media – highest terrestrial e⁻ density
delocalized, free to move around the entire lattice

PLASMON – Quantum e⁻ gas oscillations in response to EM excitation

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

NANO-ELECTROMAGNETICS

Large-amplitude Plasmons

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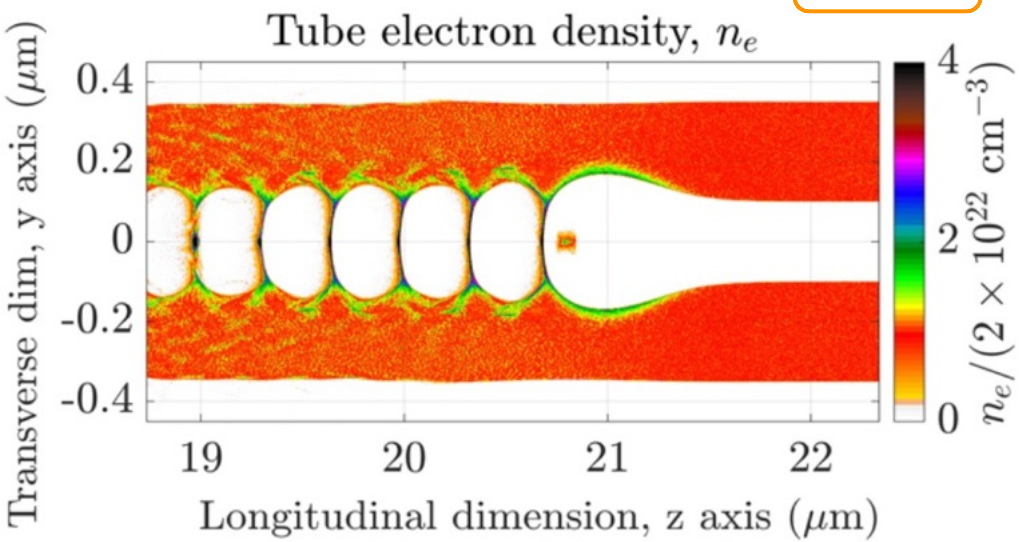
Perturbative *(conventional)*	$\delta = \theta(2\pi)^{-1}\lambda \ll \lambda$ *"θ" - angular disp. of collective e⁻ osc.*	trajectory	$\Delta n_e \ll n_0$	e⁻ density
Large-amplitude *(unexplored)*	$\delta \simeq \lambda$	amplitude	$\Delta n_e \simeq n_0$	displacement

Quantum coherence limit

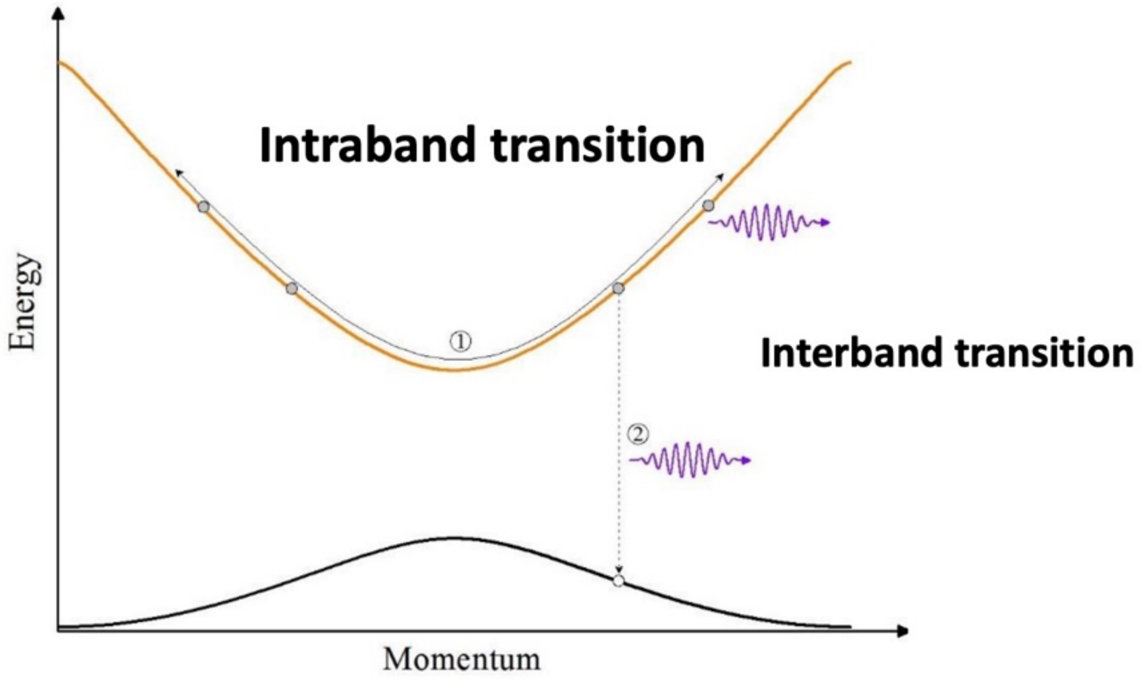
$$E_p = \frac{m_e c^2}{e}\frac{2\pi}{\lambda_{plasmon}} \simeq 0.1\sqrt{n_0[10^{24}\mathrm{cm}^{-3}]}\ \mathrm{PVm}^{-1}$$

- 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

$\delta \simeq \lambda$



Inter- and Intra-band transitions
~~Ionization~~ - Quantum electron gas



- while ion-lattice exists: electrons in specific energy states (quantum)
- high-field – result in intra- and inter-band transitions
- but, need empty states to accommodate transitioning VB electrons

"lasik"-like transition – target damage

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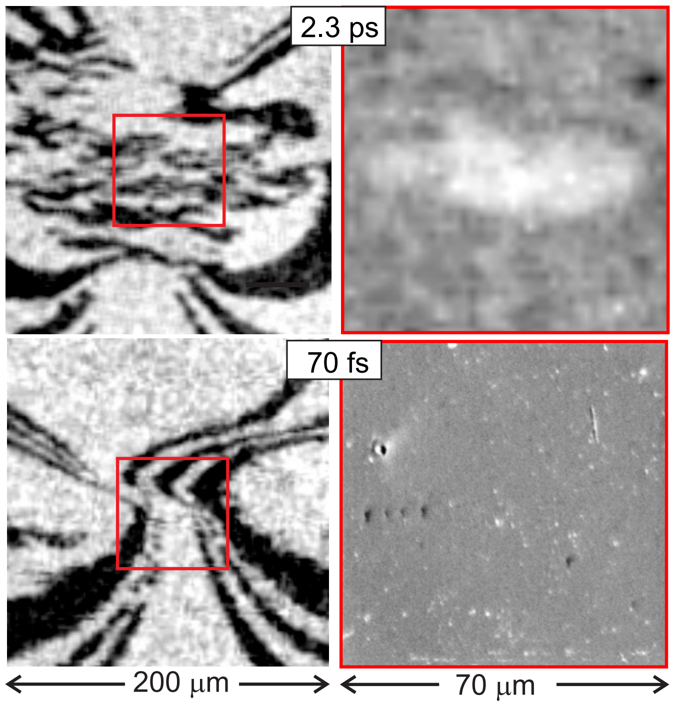
- OBSERVED: ***"lasik"-like effect***
  at FFTB (predecessor of FACET)

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]

- ultrafast magnetic switching expt. (Cobalt-Iron alloy)
  2.3ps, few micron e⁻ bunch ~ 2nC***: TOP***
  70fs, few micron e⁻ bunch ~ 2nC***: BOTTOM***



PRL **102,** 217201 (2009)

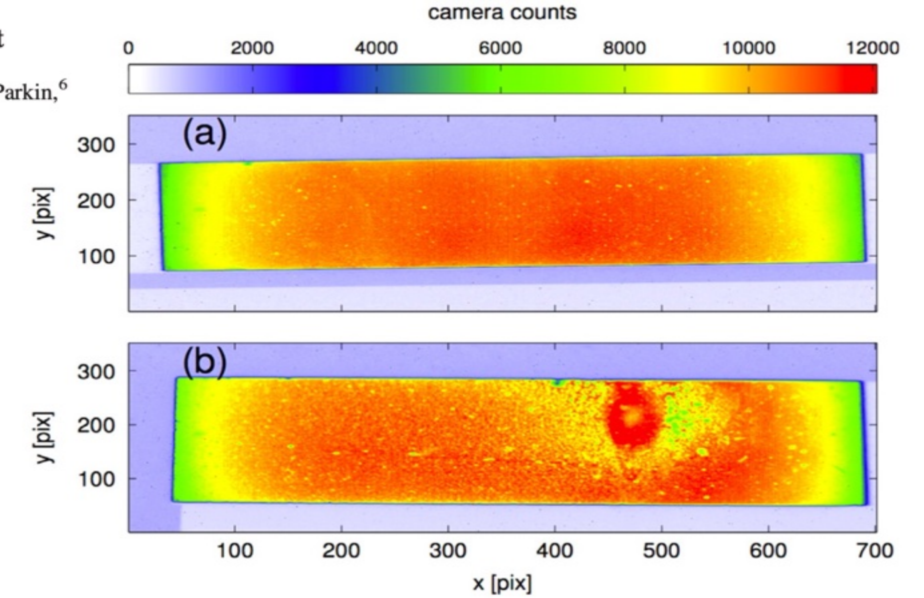


Fig. 10. (a) Reflection of diffuse light off silicon wafers used for the FACET experiments in 2013. These wafers were exposed to a few times 10^5 pulses of up to 2×10^{10} electrons, and show no visible sign of degradation. (b) Reflection of diffuse light off silicon wafers which have been in the beam 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.

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

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]

- NO DAMAGE:
  monocrystalline media →
  relativistically induced ballistic transport

Technical design

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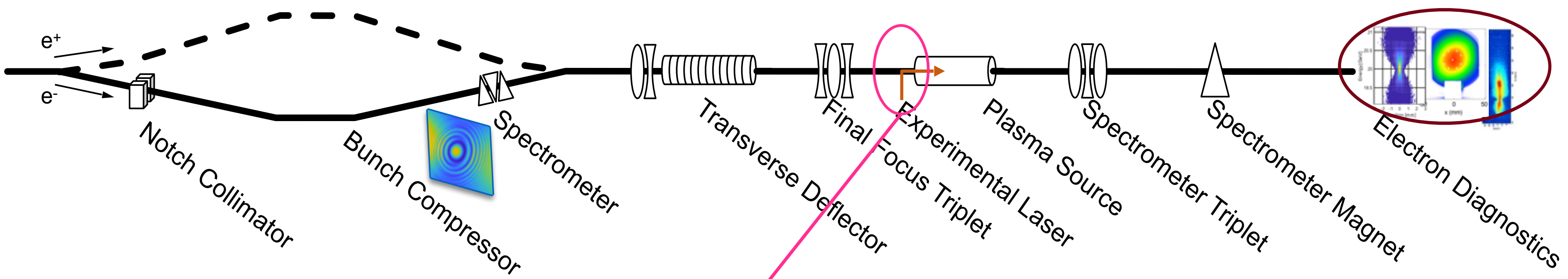
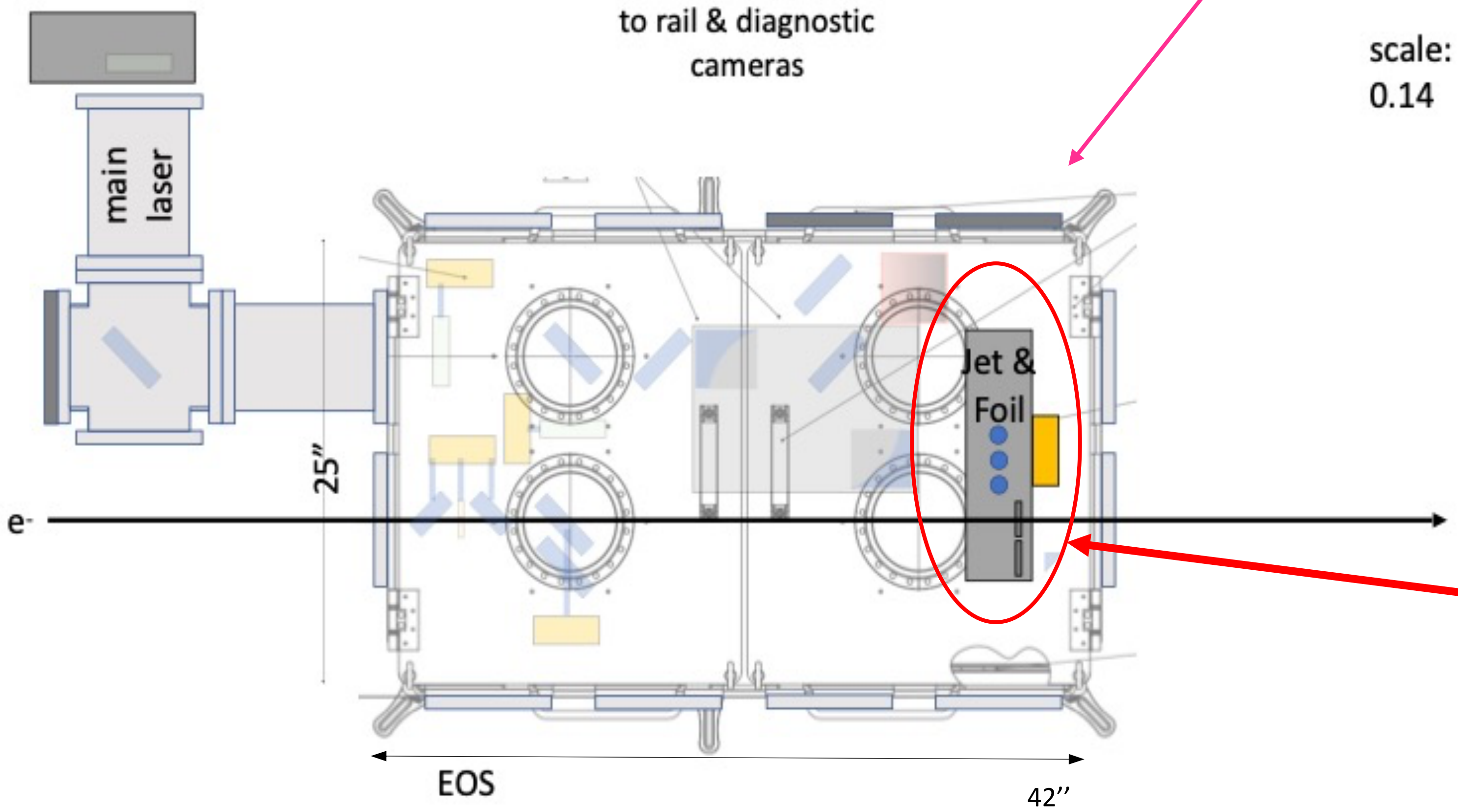
expt area schematic & picnic-basket chamber



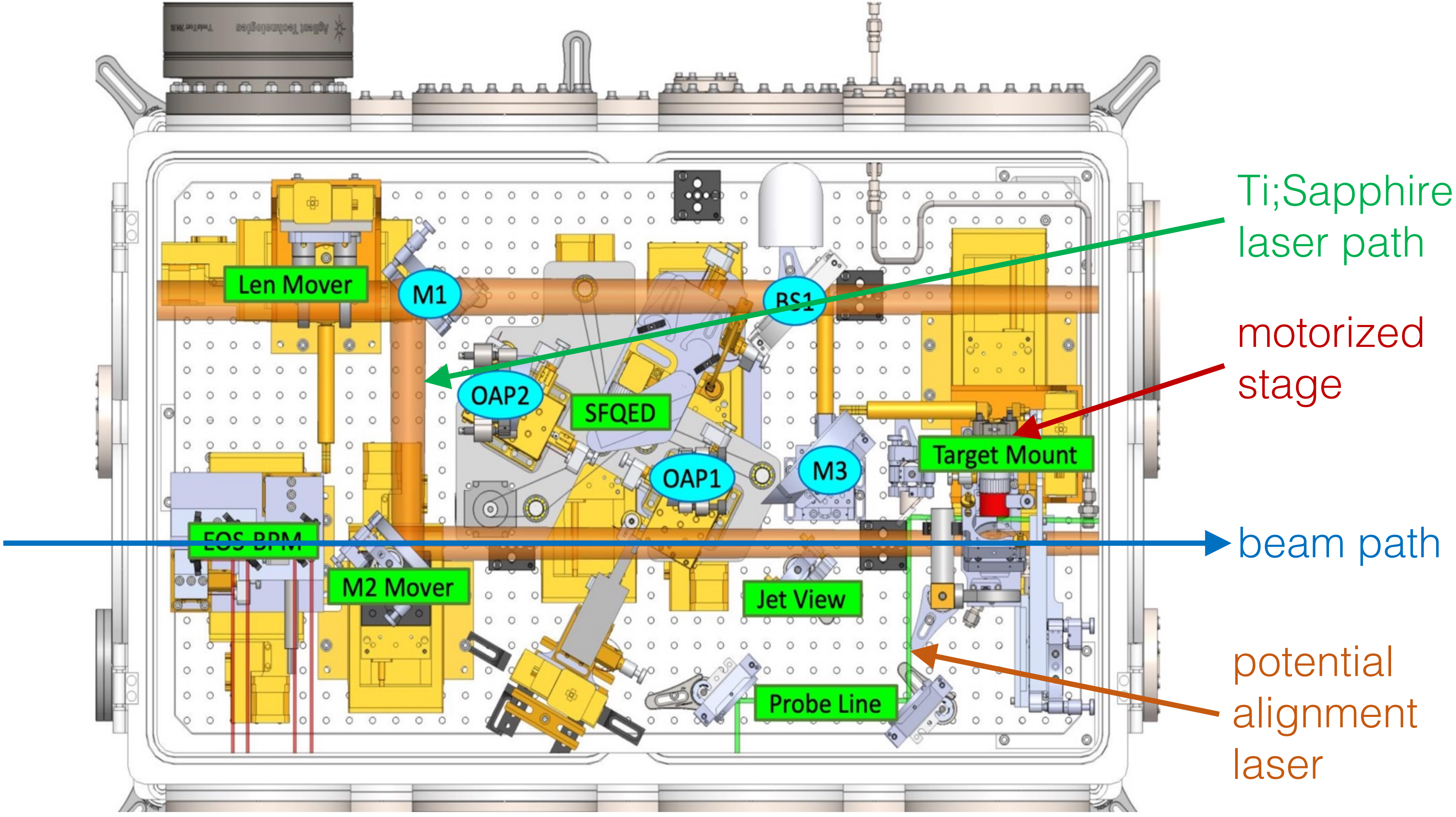


scale: 0.14

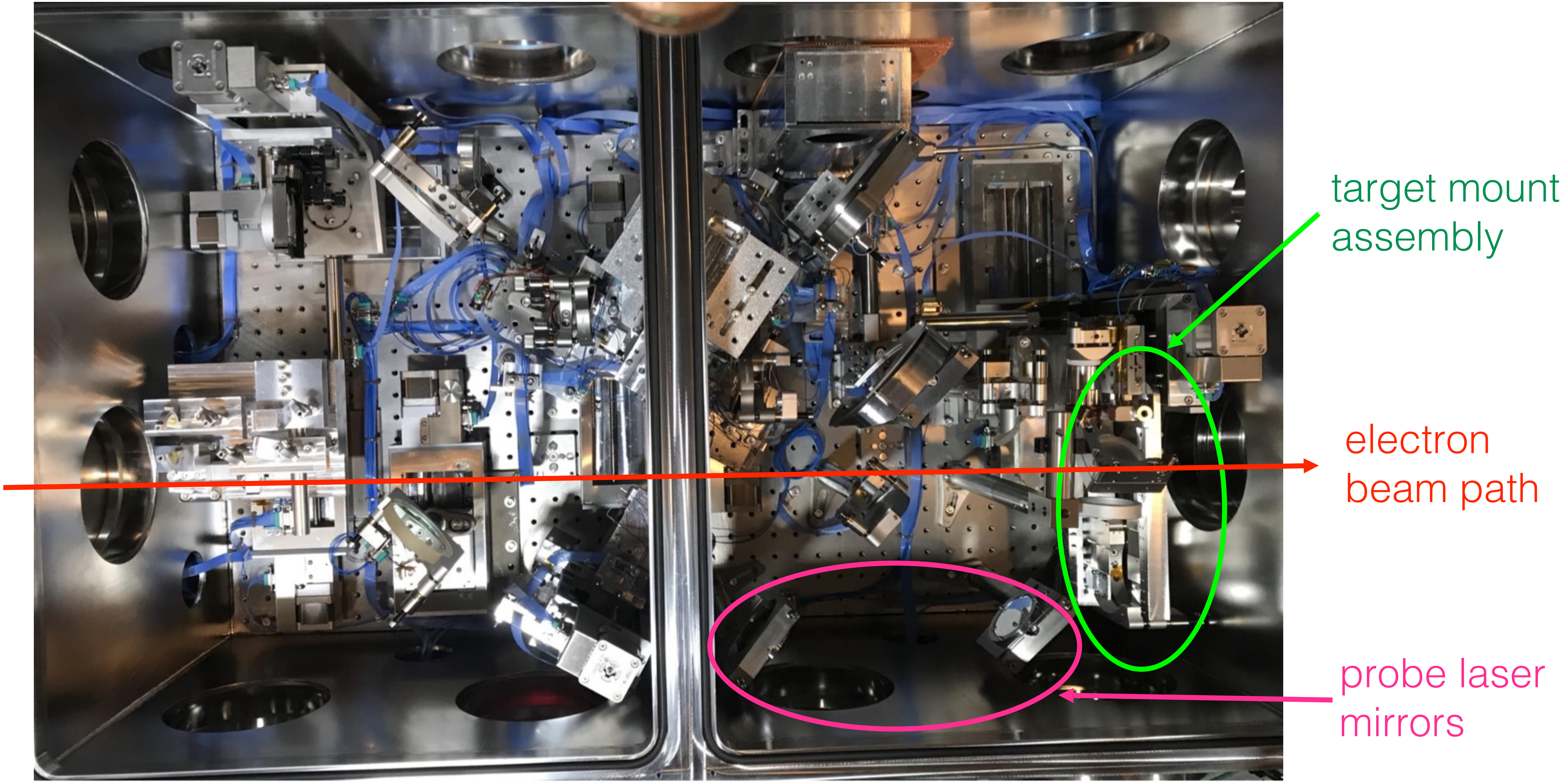
Picnic basket
plasmonic sample placement

M. Hogan, Expt. area, Sci. meeting 2019

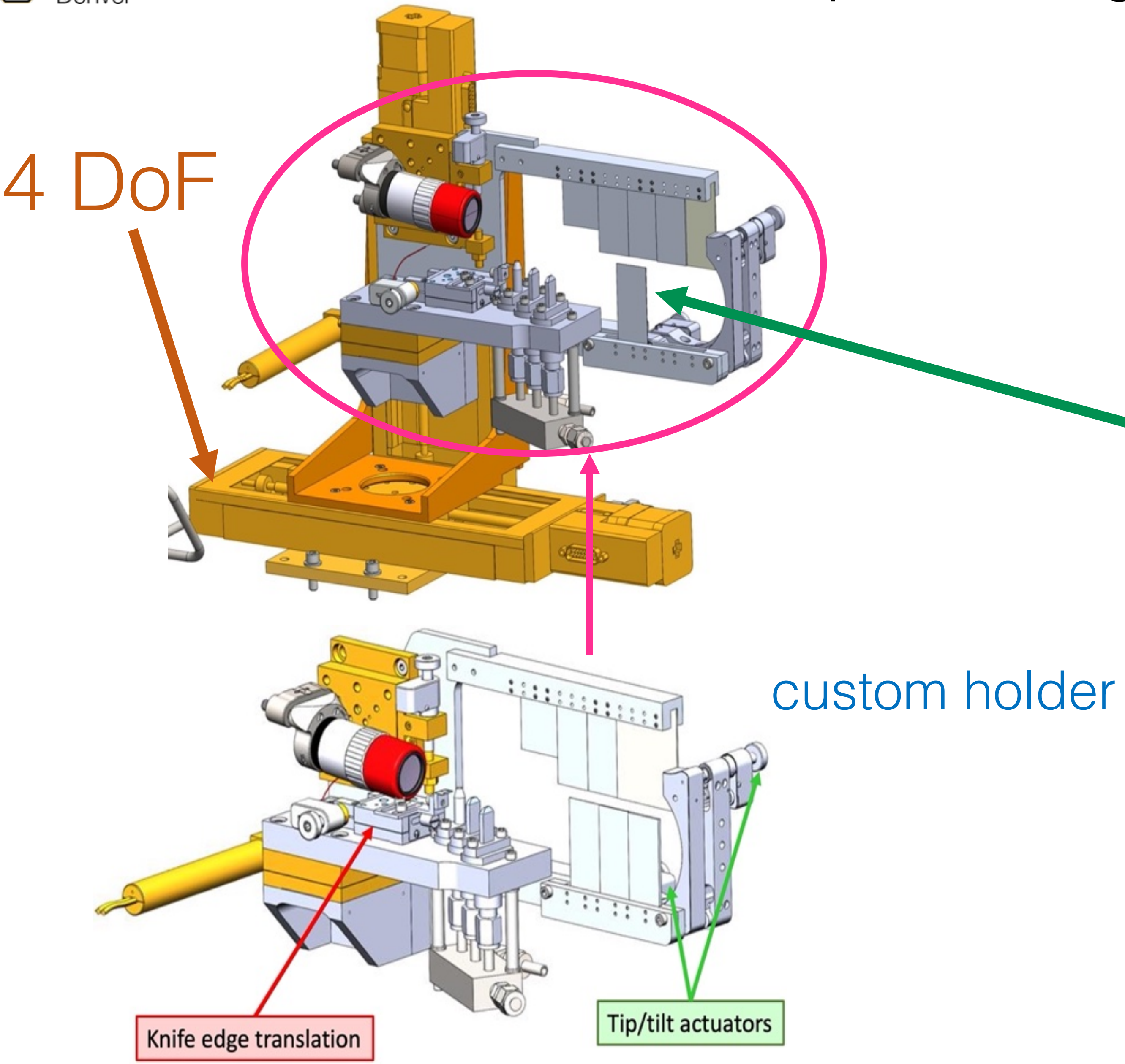
picnic-basket chamber schematic

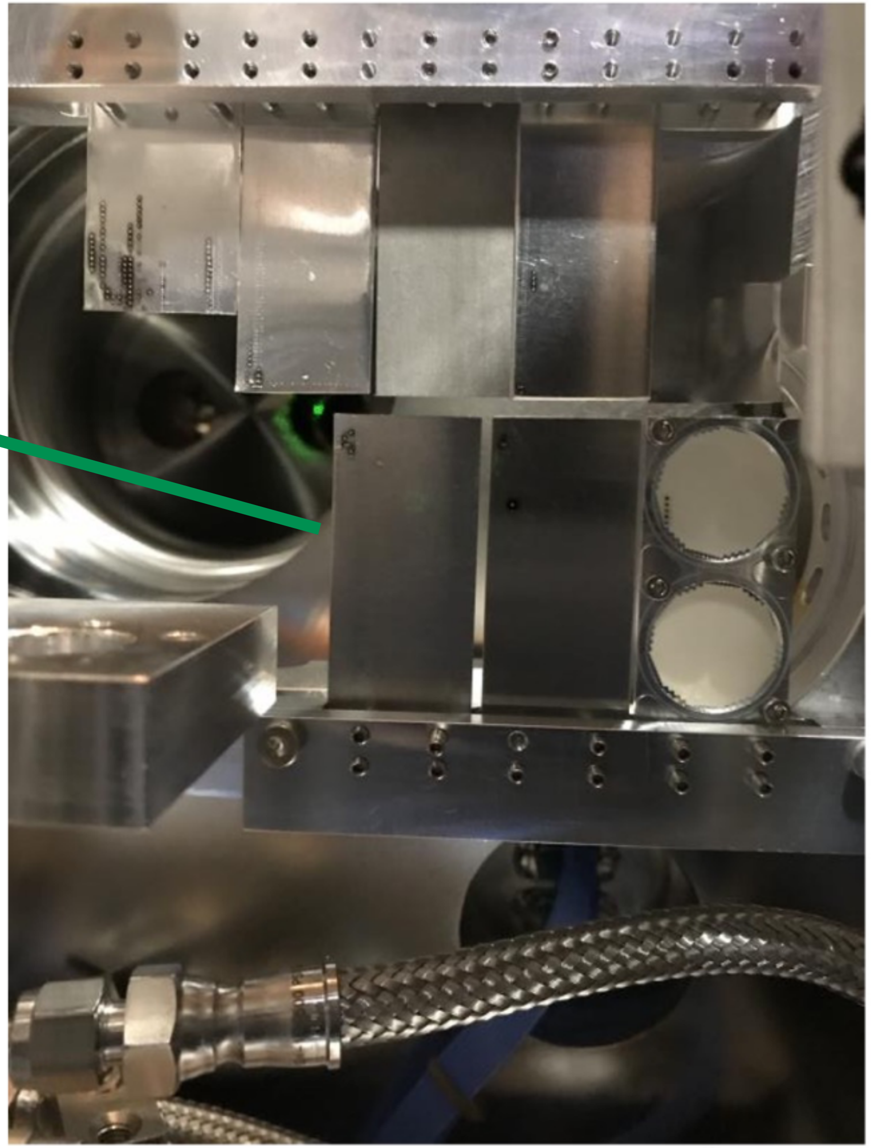


picnic-basket chamber – top-view



motorized optical stage & custom holder





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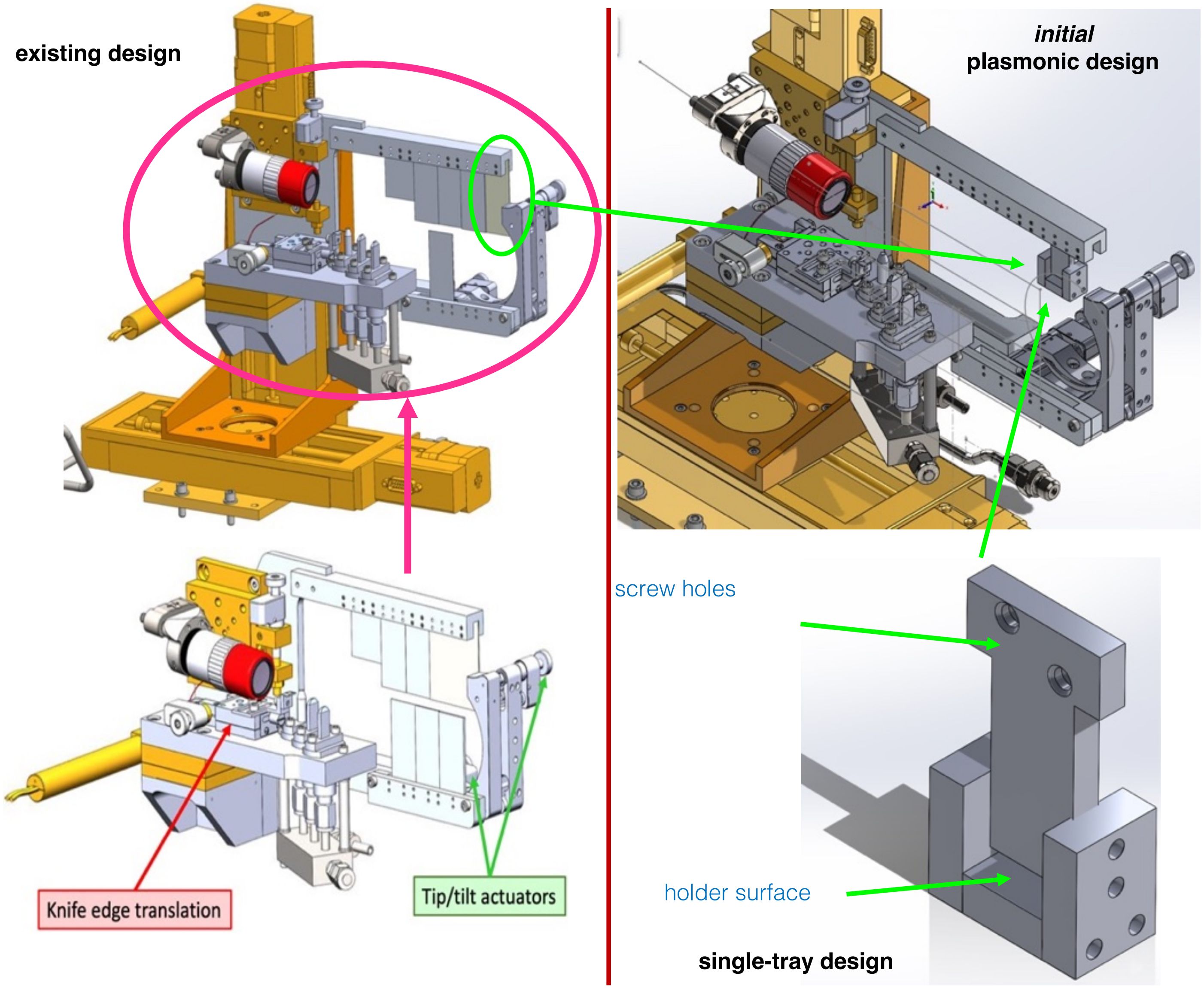
plasmonic sample holder assembly



Left *top*: existing solid target holder assembly,

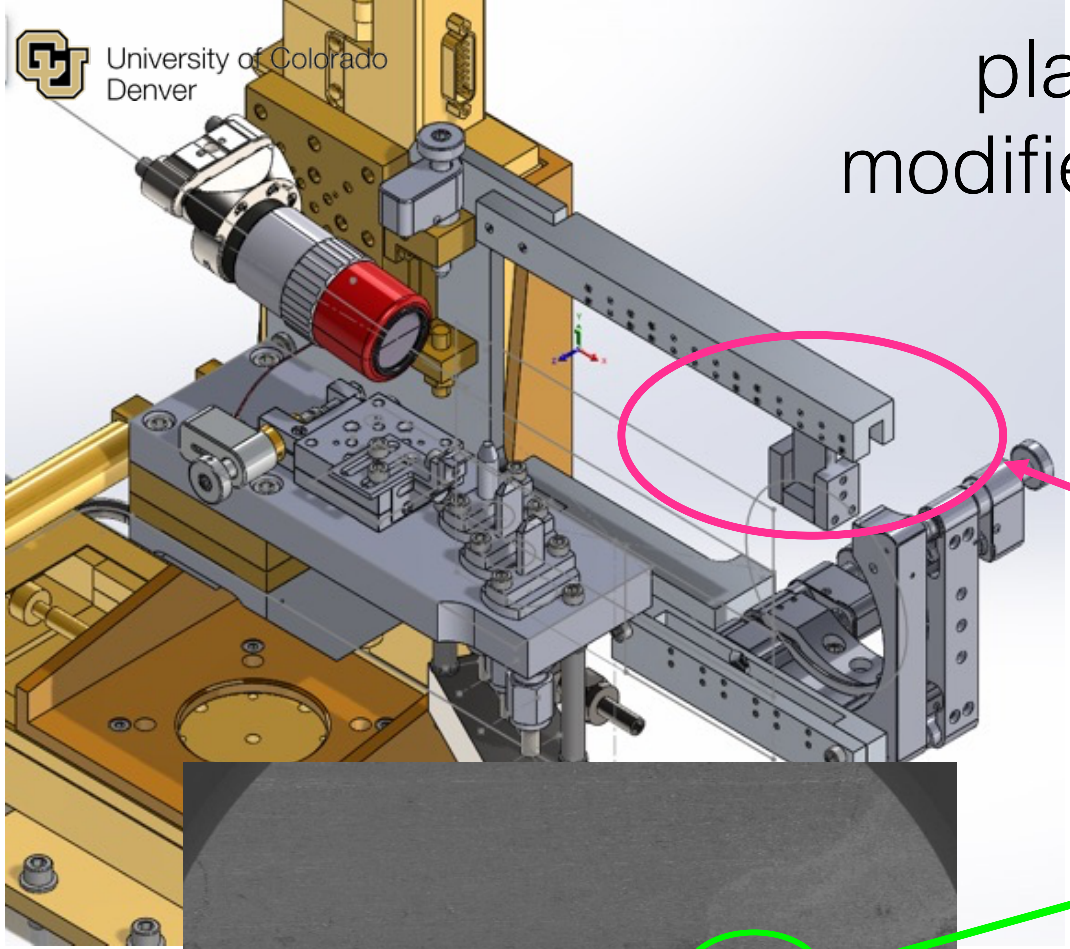
Right *top*:

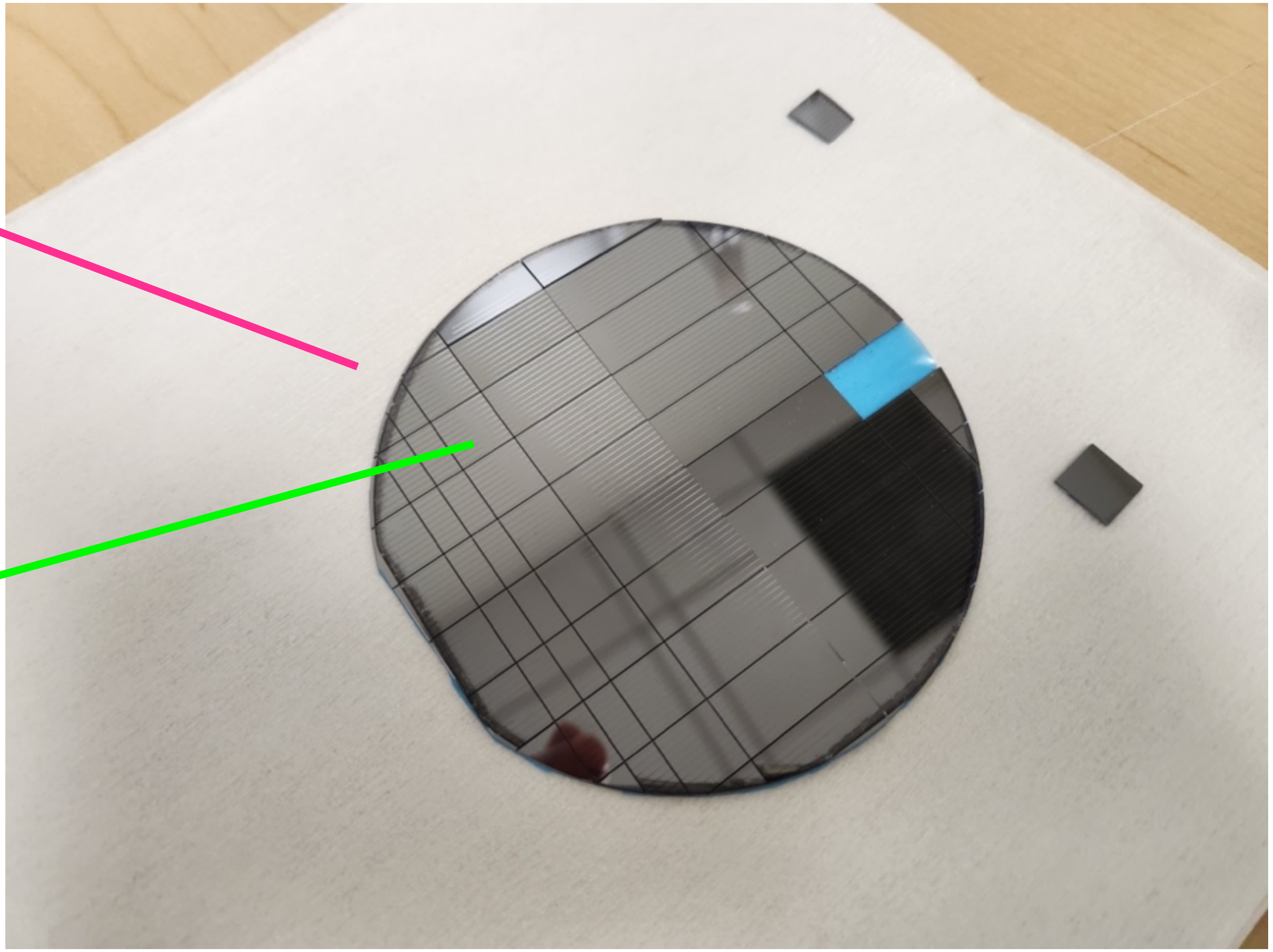
modified target assembly with plasmonic sample holder design compatible with existing solid sample holder,

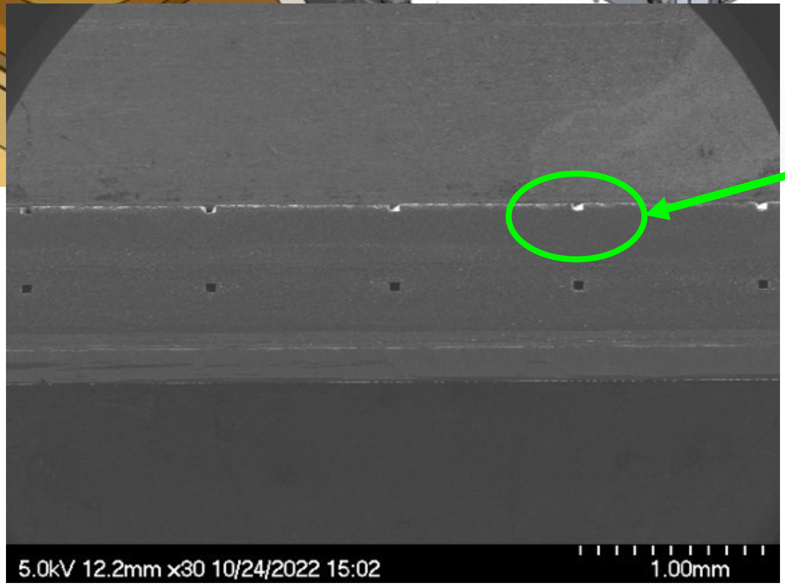
Left *bottom*:
custom screw rail

Right *bottom*:
zoomed-in drawing of the tray-based plasmonic target holder

plasmonic sample holder modified for flat plasmonic tubes







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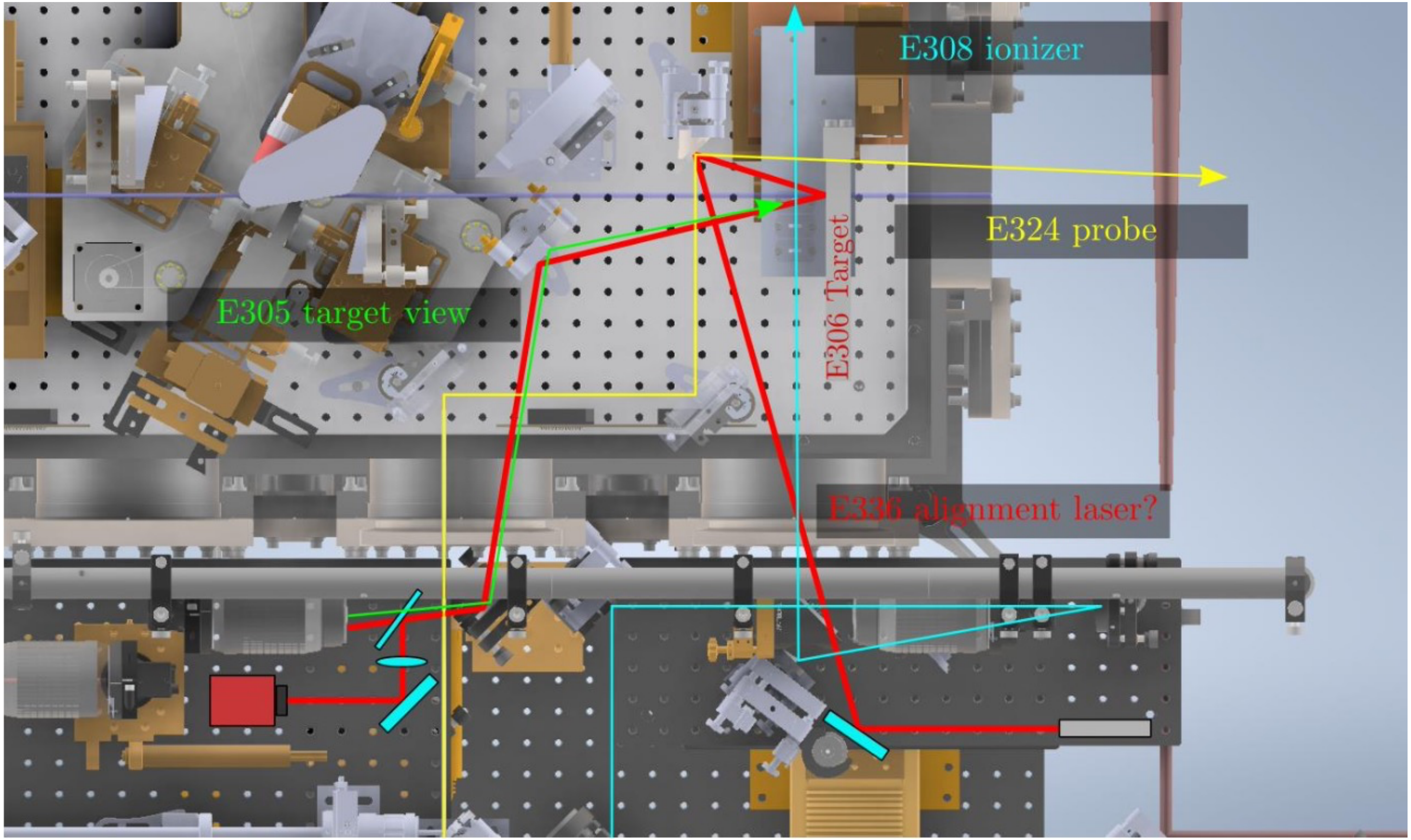
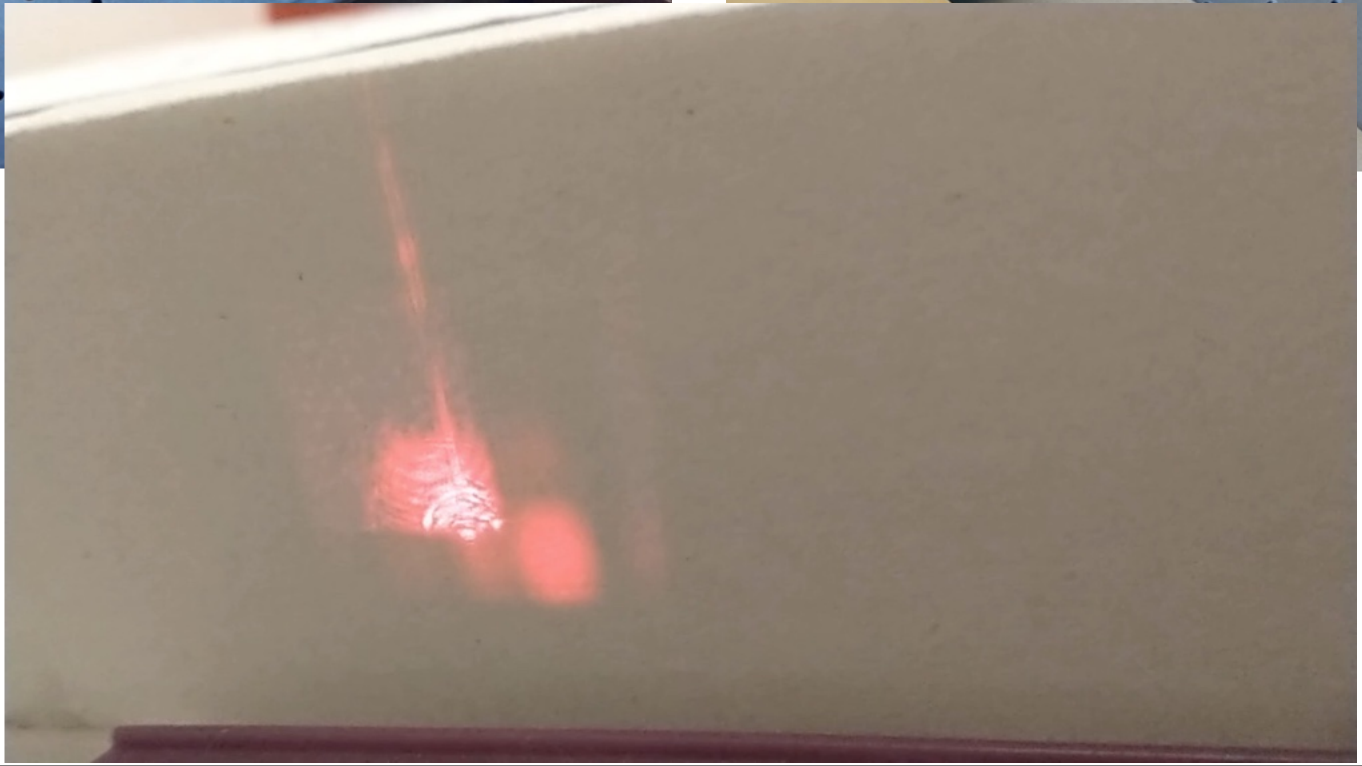
Picnic-basket – possible alignment laser paths



plasmonic tube alignment – prototyping effort



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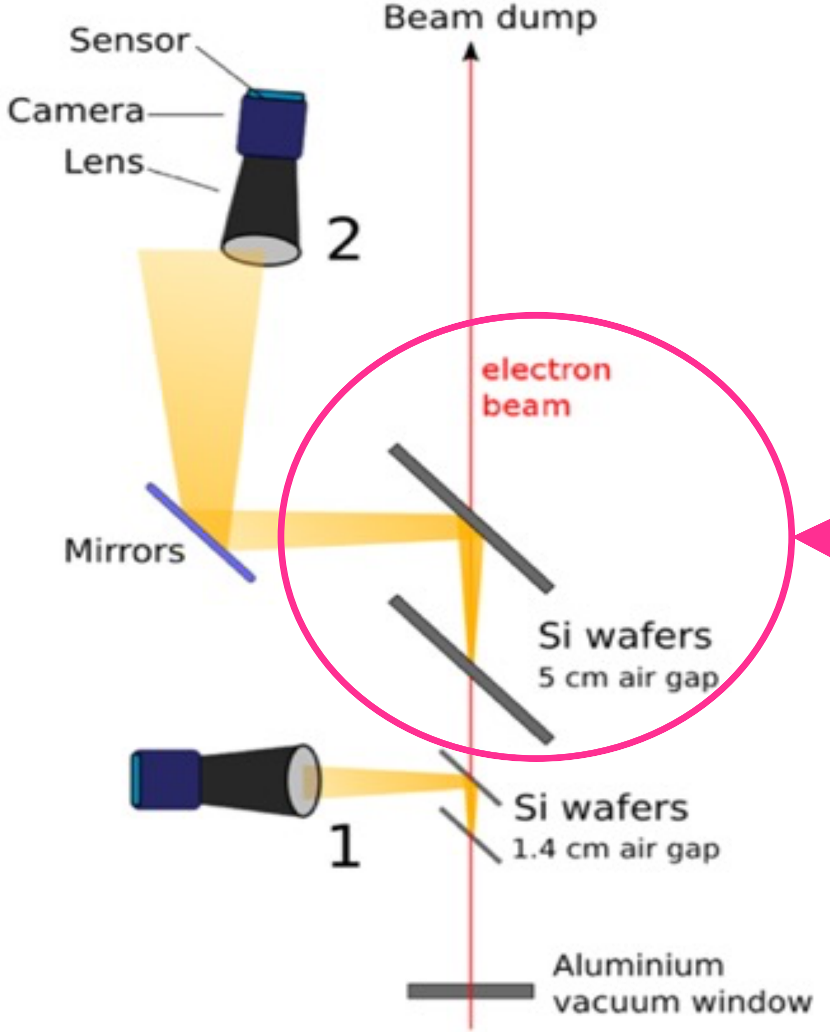
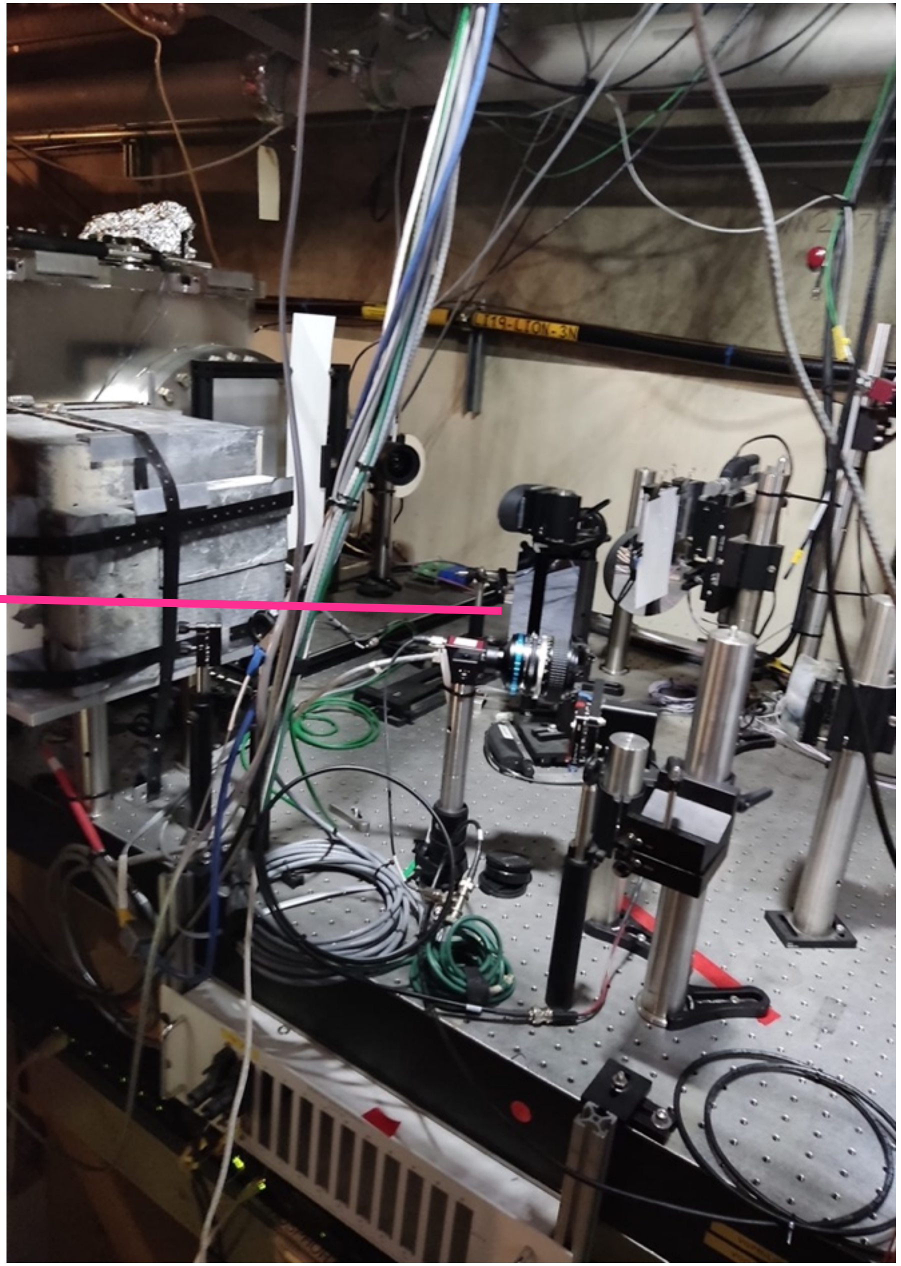
diagnostics - I



Cherenkov light-based beam transverse profile monitor and energy spectrometer, reproduced from published work.



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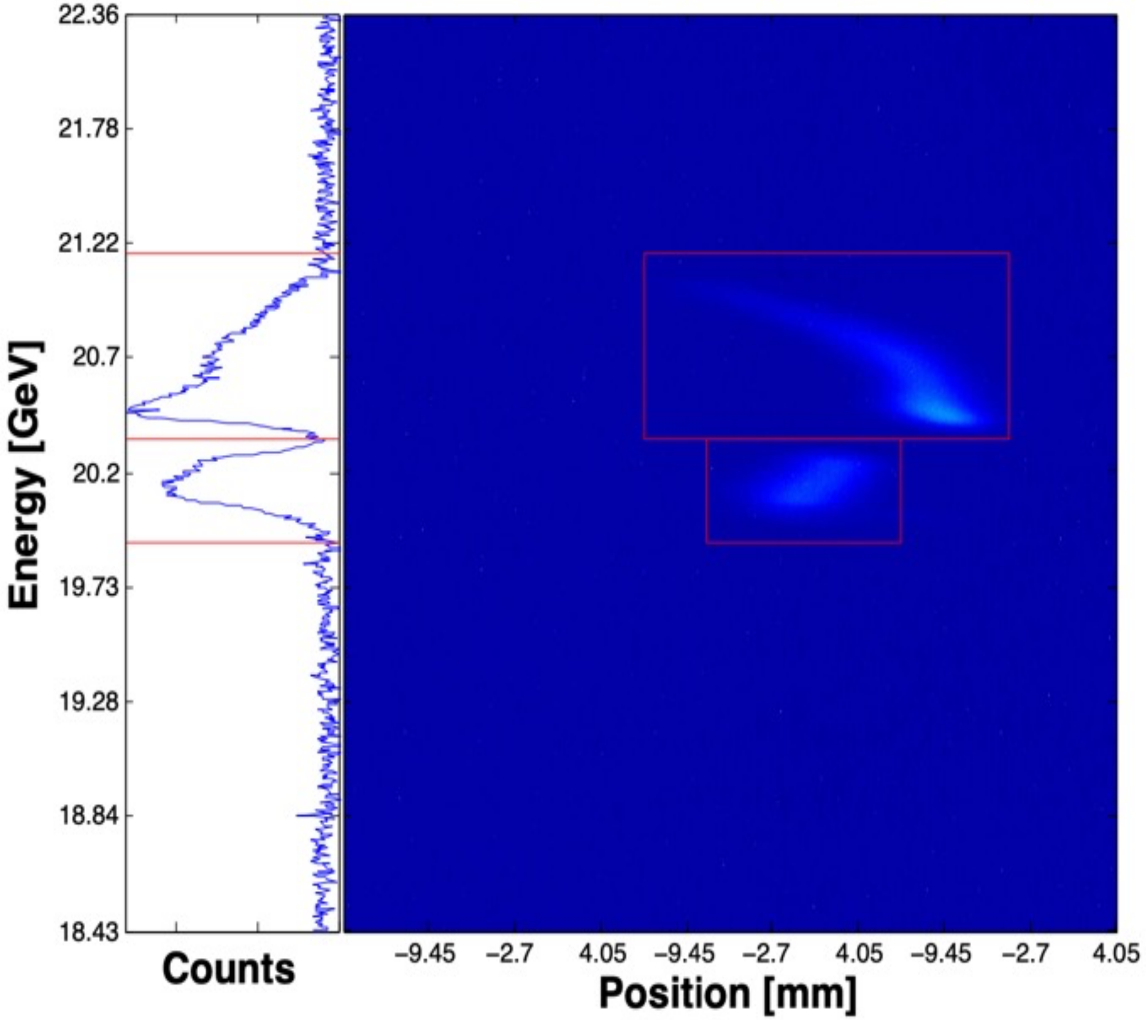
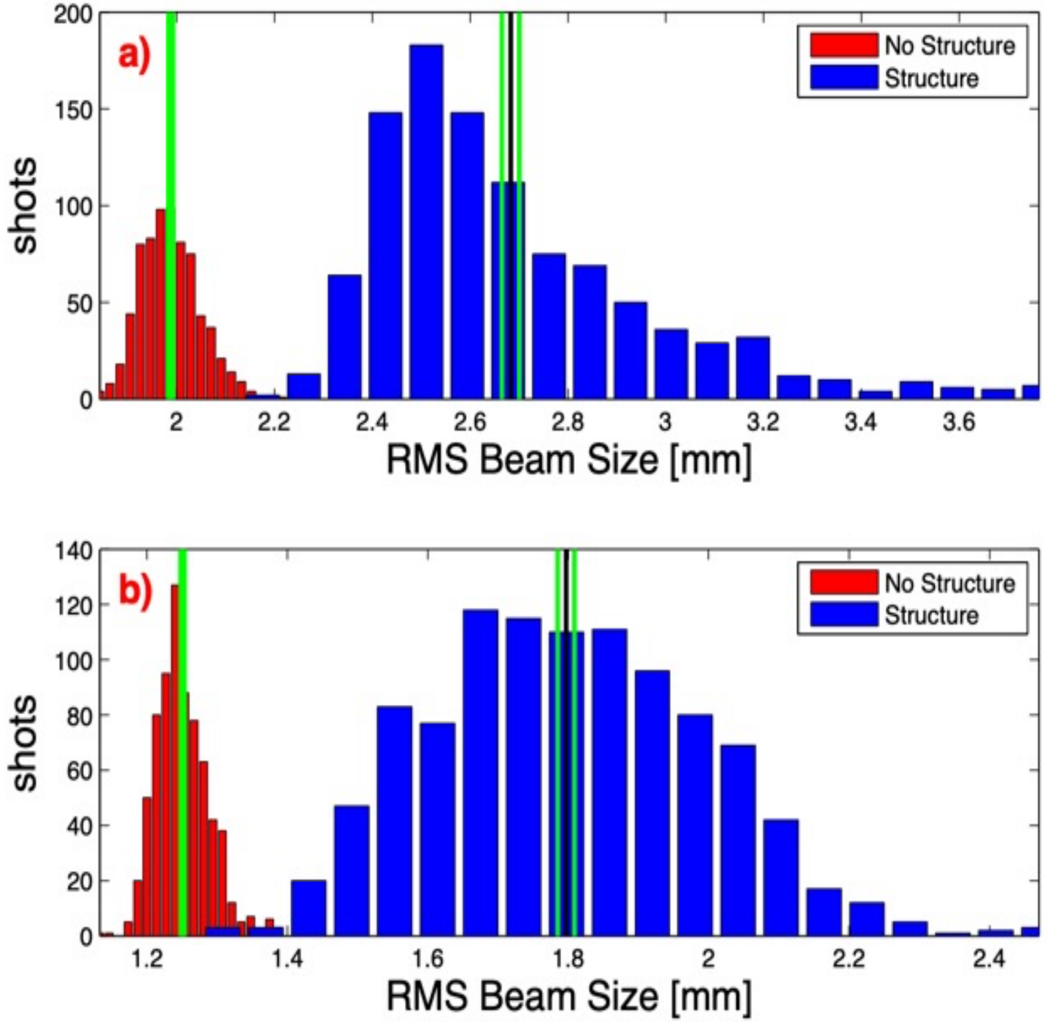
diagnostics - II





Left, raw spectrometer image obtained using Cherenkov radiation with vertical footprint representing the energy profile and horizontal footprint the transverse profile. **Right**, estimated RMS beam-size.

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nano^{2}WA collaboration

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

Powerbeam Inc. – opto-mechanical, electronics, embedded systems experts, located in Mountain View

Univ of California Irvine – P. Taborek

Univ of California Los Angeles – G. Andonian

Univ of California Los Angeles – C. Joshi (*advisory only*)

Univ of Connecticut – T. Katsouleas (*advisory only*)

Acknowledgements:
EPOCH PIC code
NSF XSEDE CU Summit Supercomputer

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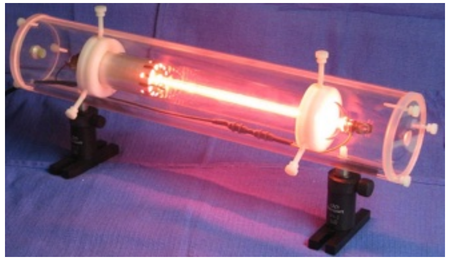
Extreme field frontier - gas vs solid excitations

excitations in gases

excitations in solids

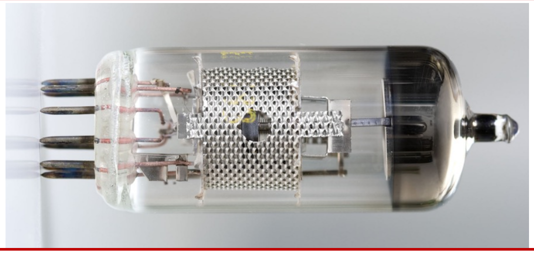
paradigm shift

discharge arc
active media
Gaseous lasers

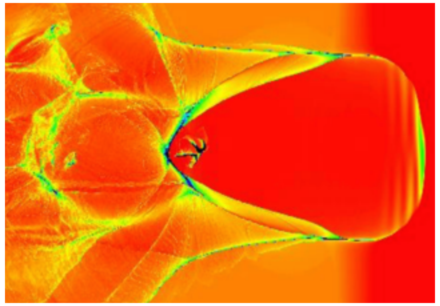


ionized gas
discharge arc
fluorescence
CFL lamps

control e⁻
flow in gas
vacuum tubes



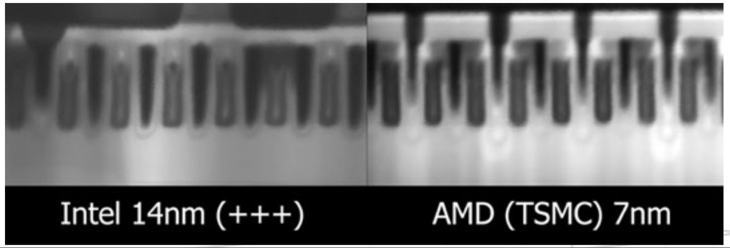
gaseous plasma
collective mode
Plasma Acc.



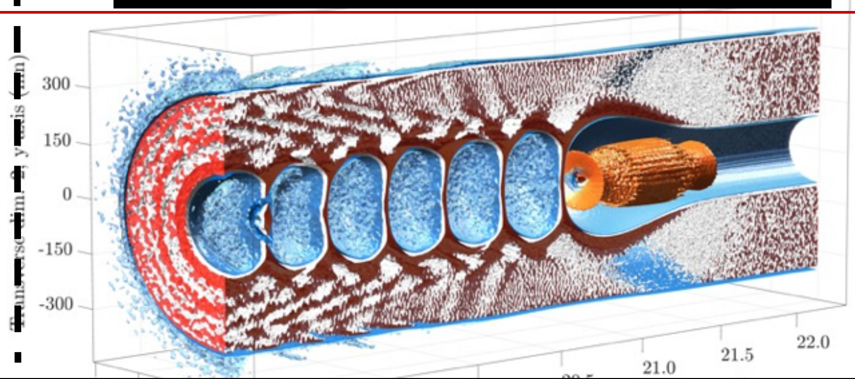
solid-state
active media
solid-state lasers

solid-state
active media
LED lamps

SILICON VALLEY



conduction e⁻ control
transistor
VLSI chip



conduction electron
collective mode
Nanostructure
Nanoplasmonic Acc.

backup slides

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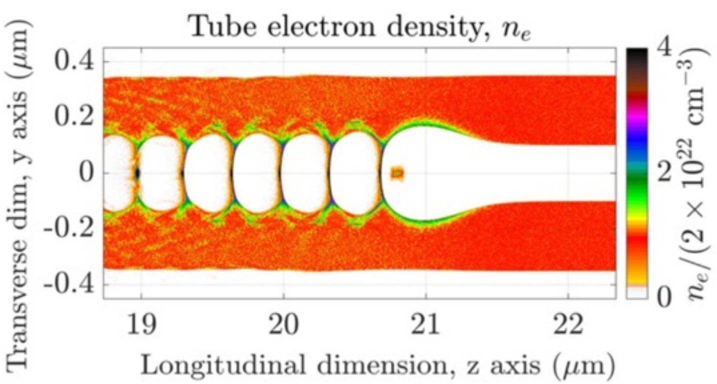
Theoretical efforts

crunch-in mode



2014-15 proposed new mode in a tube – ***"crunch-in mode"***
published in 2015 (IPAC) and 2017 (PRAB)
violates the well known and expt. characterized "hollow-channel mode"

VOLUME 81, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1998

High Beam Quality and Efficiency in Plasma-Based Accelerators

T. C. Chiou and T. Katsouleas

The focusing force is zero inside the channel for a very relativistic particle. The spikes at the channel walls are

Received 17 Nov 2015 | Accepted 27 Apr 2016 | Published 2 Jun 2016 DOI: 10.1038/ncomms11785 OPEN

Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator

Spencer Gessner[1], Erik Adli[2], James M. Allen[1], Weiming An[3,4], Christine I. Clarke[1], Chris E. Clayton[3], Sebastien Corde[5], J.P. Delahaye[1], Joel Frederico[1], Selina Z. Green[1], Carsten Hast[1], Mark J. Hogan[1], Chan Joshi[3], Carl A. Lindstrøm[2], Nate Lipkowitz[1], Michael Litos[1], Wei Lu[6], Kenneth A. Marsh[3], Warren B. Mori[3,4], Brendan O'Shea[1], Navid Vafaei-Najafabadi[3], Dieter Walz[1], Vitaly Yakimenko[1] & Gerald Yocky[1]

experience strong transverse forces that may disrupt the beam quality. Hollow plasma channels have been proposed as a technique for generating accelerating fields without transverse forces. Here we demonstrate a method for creating an extended hollow plasma

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2018-19 put forth ***extreme plasmonics*** – using Quantum electron gas to prototype the crunch-in mode and make use of its advantageous char. consequence – Fermi gas densities – 10^{24} cm^{-3}

$$0.1\sqrt{n_0[10^{24}\mathrm{cm}^{-3}]}\ \ \mathrm{PVm}^{-1}$$

PV/m EM field frontier

2019 invited talk at Fermilab XTALs workshop
Mar 2020 invited talk at CERN workshop

preliminary publication

Intl. Jour. Modern Phys. A, **34**, 1943009 (2019)
DOI: 10.1142/S0217751X19430097