PetaVolts per meter Plasmonics

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

quantum electron gas

Extreme plasmons

arXiv:2404.02087

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

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Quantum electron gas fundamentals

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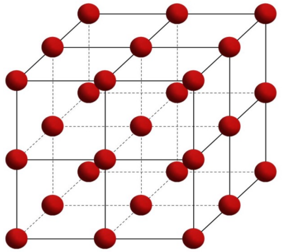
doi: 10.1109/ACCESS.2021.3070798

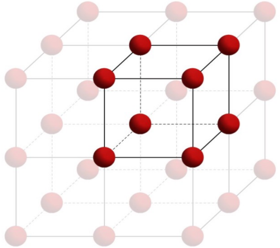
understanding Quantum electron gas

ionic lattice

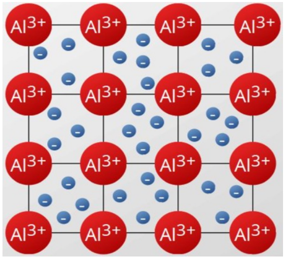
periodic potential is **PRESENT**
over plasmonic timescale *(strained under high fields)*



lattice structure



unit cell



energy band structure

lattice structure – Bloch's theorem : ***QUANTUM***
electrons - specific occupancy states, $\mathbf{k}_\ell$
near-continuum Energy levels, $\mathcal{E}_\mathbf{k}$– **energy BANDs**

$$\textbf{Quantum degeneracy parameter: } \chi = \frac{8}{3\sqrt{\pi}}\left(\frac{\mathcal{E}_F}{k_B T}\right)^{3/2}$$

$$\textbf{Quantum correlation parameter: } \Gamma = 8\frac{2^{1/3}}{3\pi^2} d_0 a_0^{-1}$$

non-interacting Fermions

Pauli's exclusion principle : ***QUANTUM***

Quantum electron gas: conduction band e⁻ - **delocalized, nearly free *(collisionless limit)***

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

$$\langle \omega_Q \rangle \simeq \left(1 + 3\alpha\left[1 + \frac{3}{10}\beta^2\right]\right)\omega_p \equiv \mathscr{F}_Q(\mathbf{k},\mathbf{p})\ \omega_p \qquad \lambda_Q \lesssim \frac{30}{\sqrt{n_0(10^{24}\mathrm{cm}^{-3})}}\ \mathrm{nm}$$

Extreme plasmons
arXiv:2404.02087

Extreme Plasmons

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

"θ" - angular disp. of collective e⁻ osc.

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

trajectory amplitude

$\Delta n_e \ll n_0$

$\Delta n_e \simeq n_0$

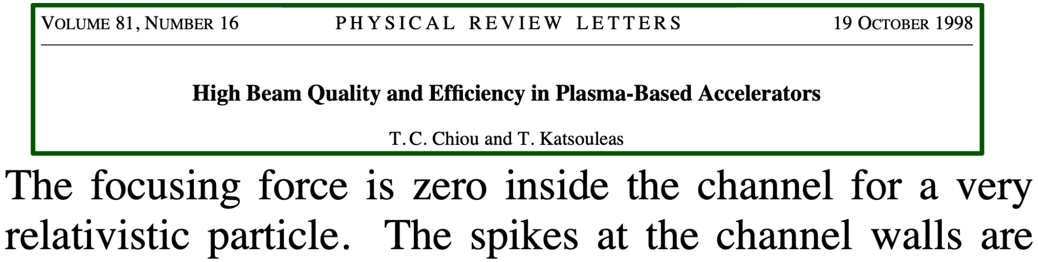
e⁻ density displacement

Quantum coherence limit

$$\mathrm{E}_Q = \mathscr{F}_Q(\mathbf{k},\mathbf{p})\left(\frac{m_e c^2}{e}\right)\frac{2\pi}{\lambda_Q} \simeq 0.1\mathscr{F}_Q\sqrt{n_0[10^{24}\mathrm{cm}^{-3}]}\ \mathrm{PVm}^{-1}$$

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"

Aakash A. Sahai
Phys. Rev. Accel. Beams **20**, 081004 – Published 23 August 2017

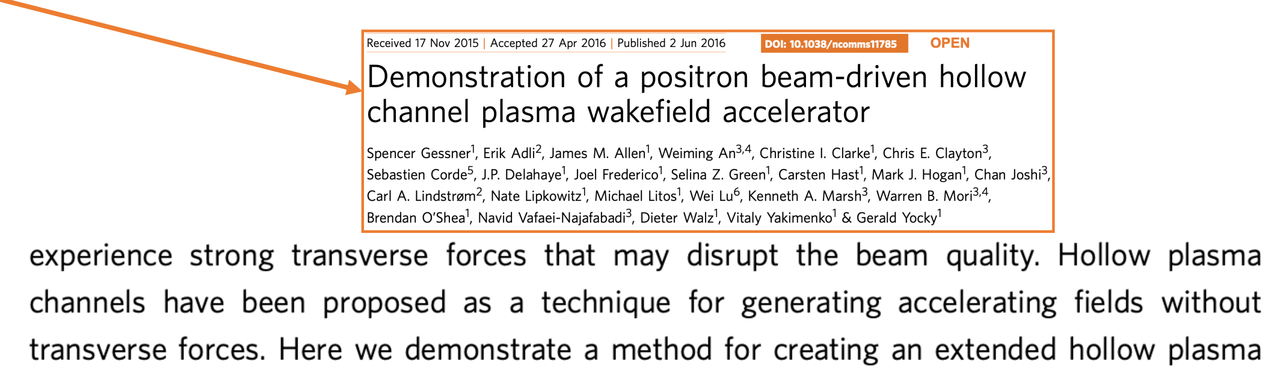


VOLUME 81, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1998

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]

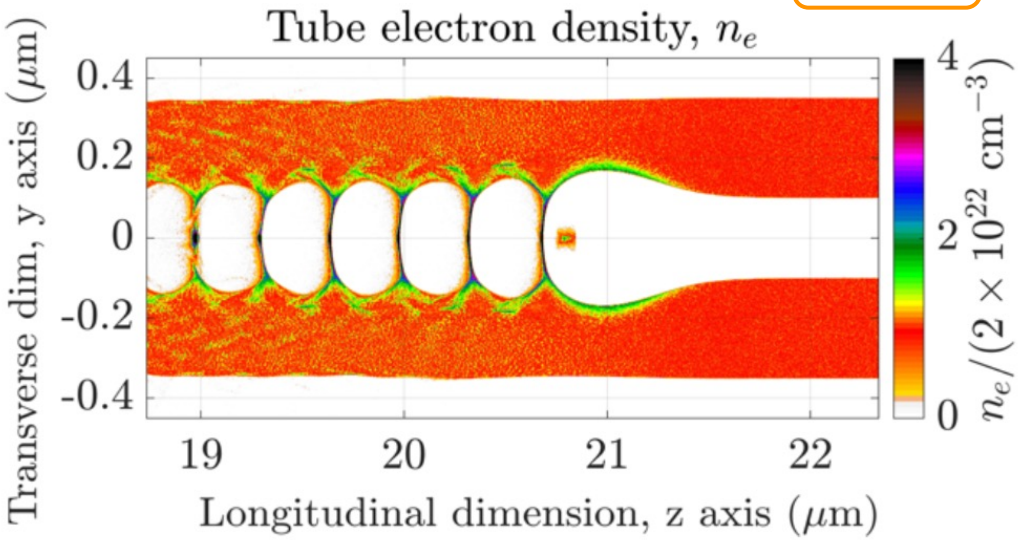
experience strong transverse forces that may disrupt the beam quality. Hollow plasma channels have been proposed as a technique for generating accelerating fields without transverse forces. Here we demonstrate a method for creating an extended hollow plasma

University of Colorado
Denver

Crunch-in Plasmon

- 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

$\delta \simeq \lambda$



2018-19 put forth ***extreme plasmonics*** – using Quantum electron gas to prototype the crunch-in mode and make use of its advantageous char. Quantum e⁻ 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-ARIES workshop

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

SLAC expt. program – FACET-II beam

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doi: 10.1109/ACCESS.2021.3070798

expt. efforts - I

SLAC FACET-II 2020

Extreme plasmons - ***first expt. proposal***

large-amplitude oscillations of Quantum electron gas
trends towards smaller bunch dim.s – match with FACET

- **proposed** - metallic nanostructures (nano-porous Au walls) 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:

- need “ionization” ? ~~quantum electron gas (NOT understood)~~
- discussion of measurable expt. signature ?
- destruction of tubes ?

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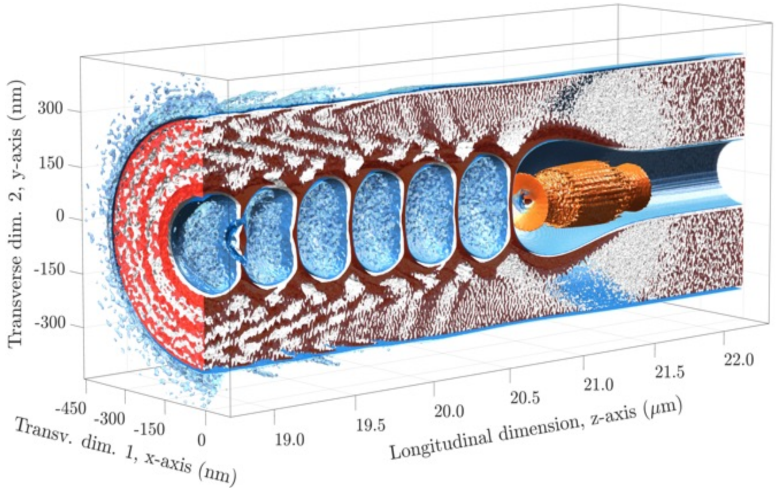
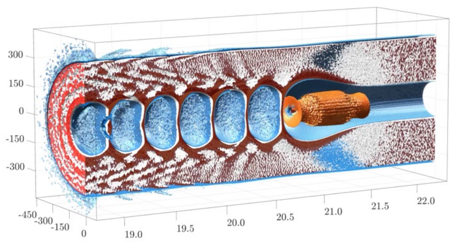




sub-μm bunch: $\sigma_{\parallel}$ ~ 400nm, σ_r ~ 250nm
plasmonic tube: r_t ~ 100nm, n_t ~ 2 x10^{22} cm^{-3}
nearly matched: $\lambda_{\text{plasmon}} \simeq 250\text{nm}$

expt. efforts - II

SLAC FACET-II 2022

Tunable plasmon – match with FACET-II beam

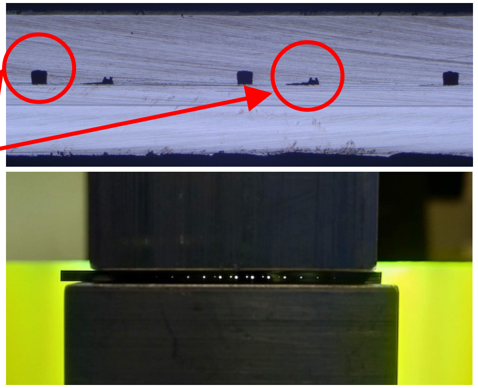
- doped Semiconductor tubes:
  tune quantum electron gas properties
  n-type **P-doped** Silicon
  Quantum e⁻ gas density ~ 10^{18}cm^{-3} **(~ n_b:KPP)**

- 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

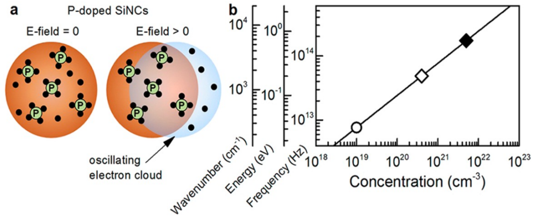
PAC feedback – develop extensive expt. plan



100 & 30 μm
rect. tubes
fabricated in Si

CHEMICAL REVIEWS
Review
Cite This: *Chem. Rev.* 2018, 118, 3121–3207
pubs.acs.org/CR

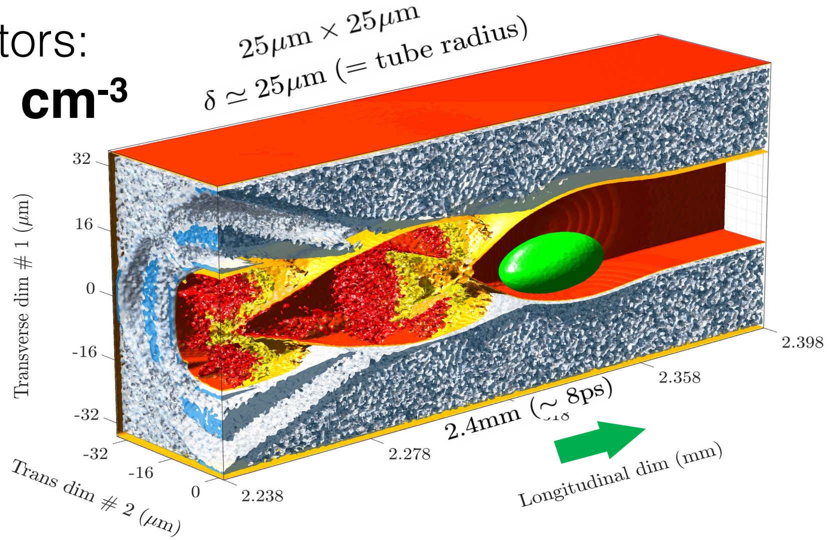
Localized Surface Plasmon Resonance in Semiconductor Nanocrystals



NANO LETTERS
Letter
pubs.acs.org/NanoLett

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

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



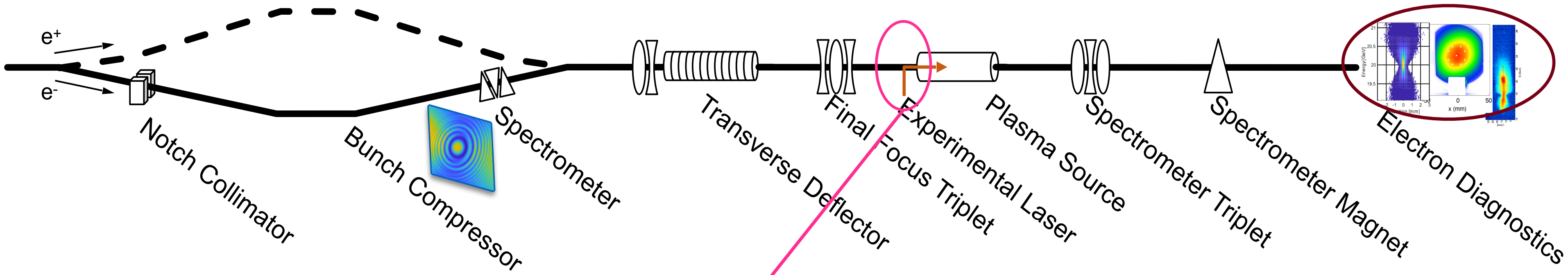
IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

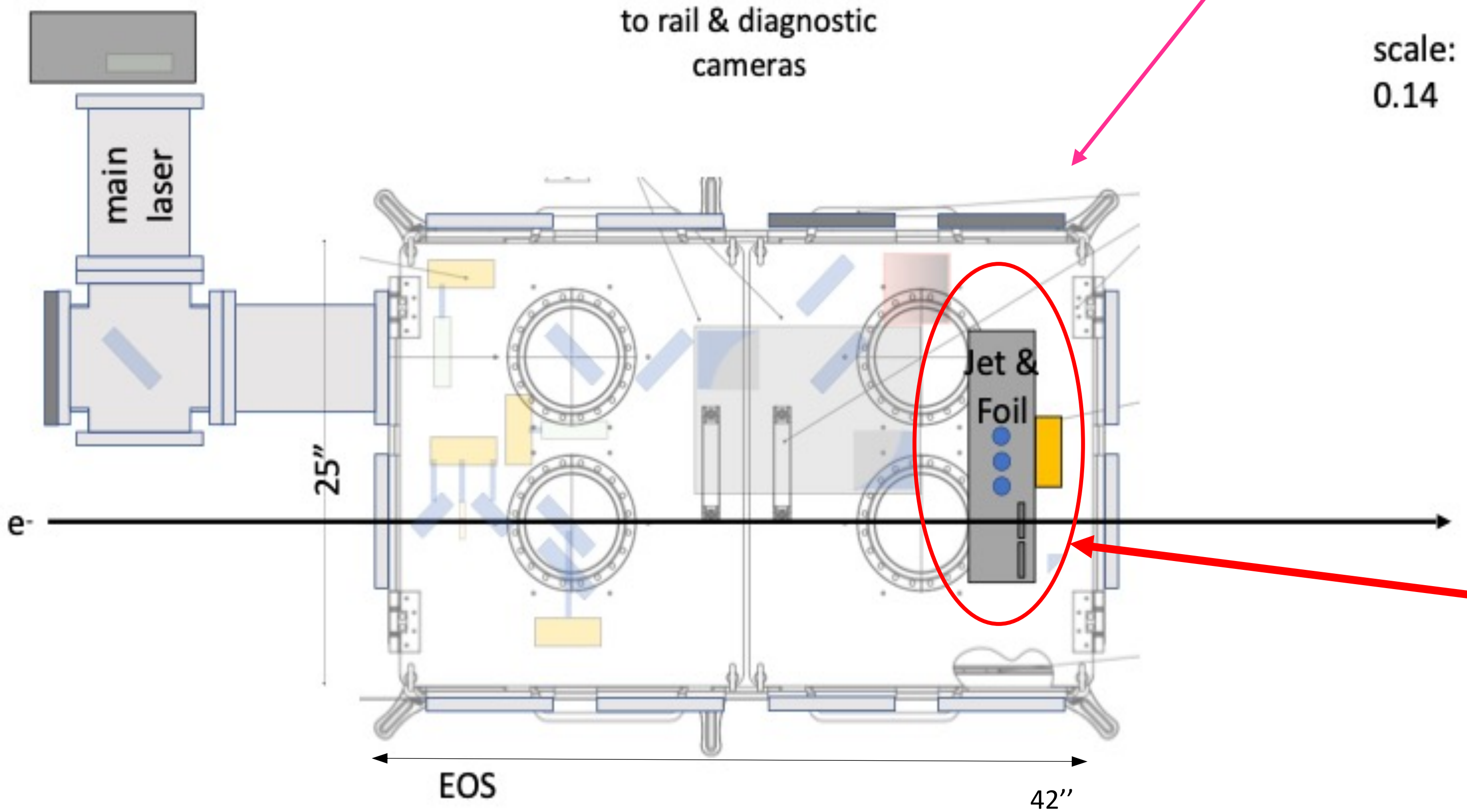
Approaching PetaVolts per Meter Plasmonics Using Structured Semiconductors

10.1109/ACCESS.2022.32314

Technical design – FACET-II

expt area schematic & picnic-basket chamber



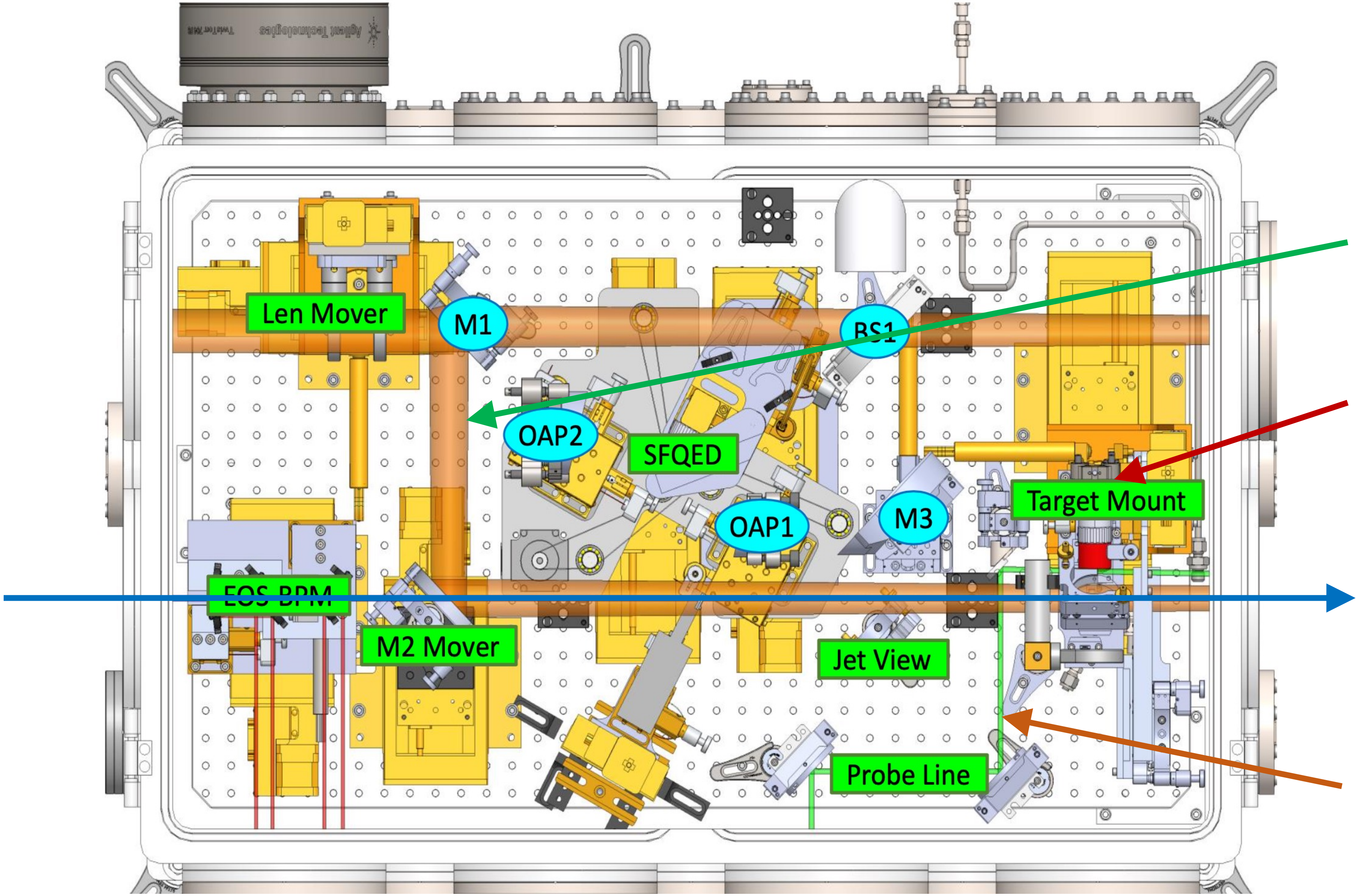


Picnic basket
plasmonic sample placement

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

University of Colorado
Denver

picnic-basket chamber schematic



Ti;Sapphire laser path

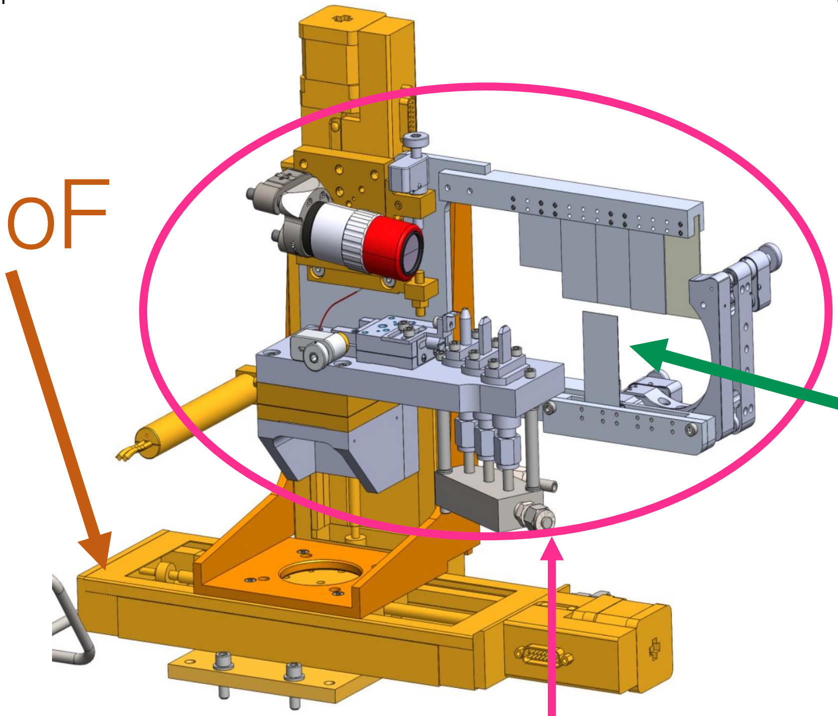
motorized stage

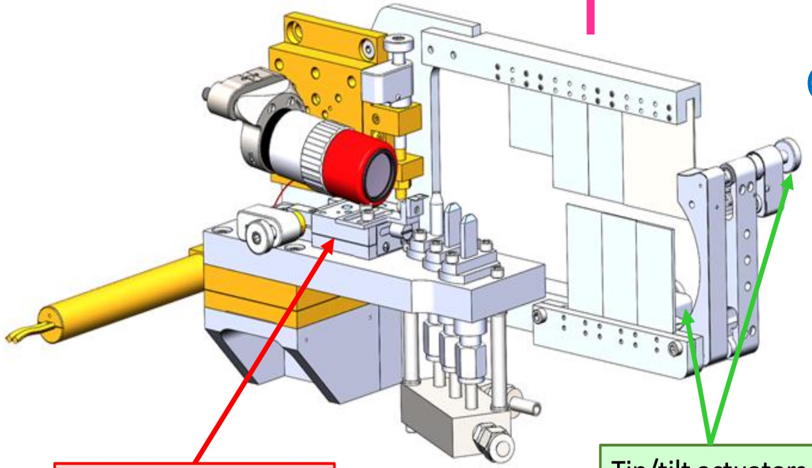
beam path

potential alignment laser

motorized optical stage & custom holder

4 DoF

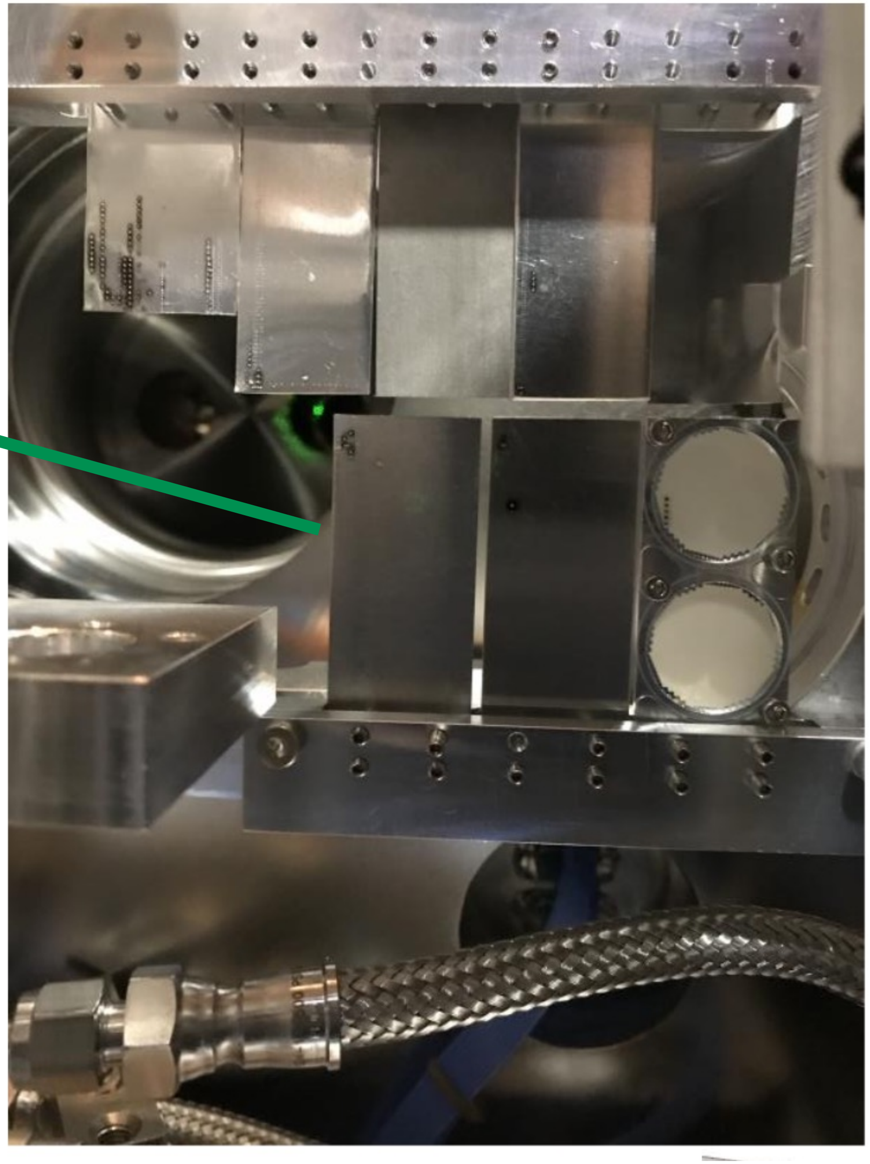




custom holder

Knife edge translation

Tip/tilt actuators



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*)

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Thanks! → Any questions ?

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