Overview of Tutorial – Low Temperature Plasmas

Jose L. Lopez

- Fundamentals of Low Temperature Plasmas
- Plasma Generation & Chemistry
- Low-Pressure vs. High-Pressure Plasmas

Igor Kaganovich

- Computational, Modelling, and Simulations of Low Temperature Plasmas

Yevgeny Raitses

- Diagnostics
- Low Temperature Plasma applications & technologies

SETON HALL UNIVERSITY

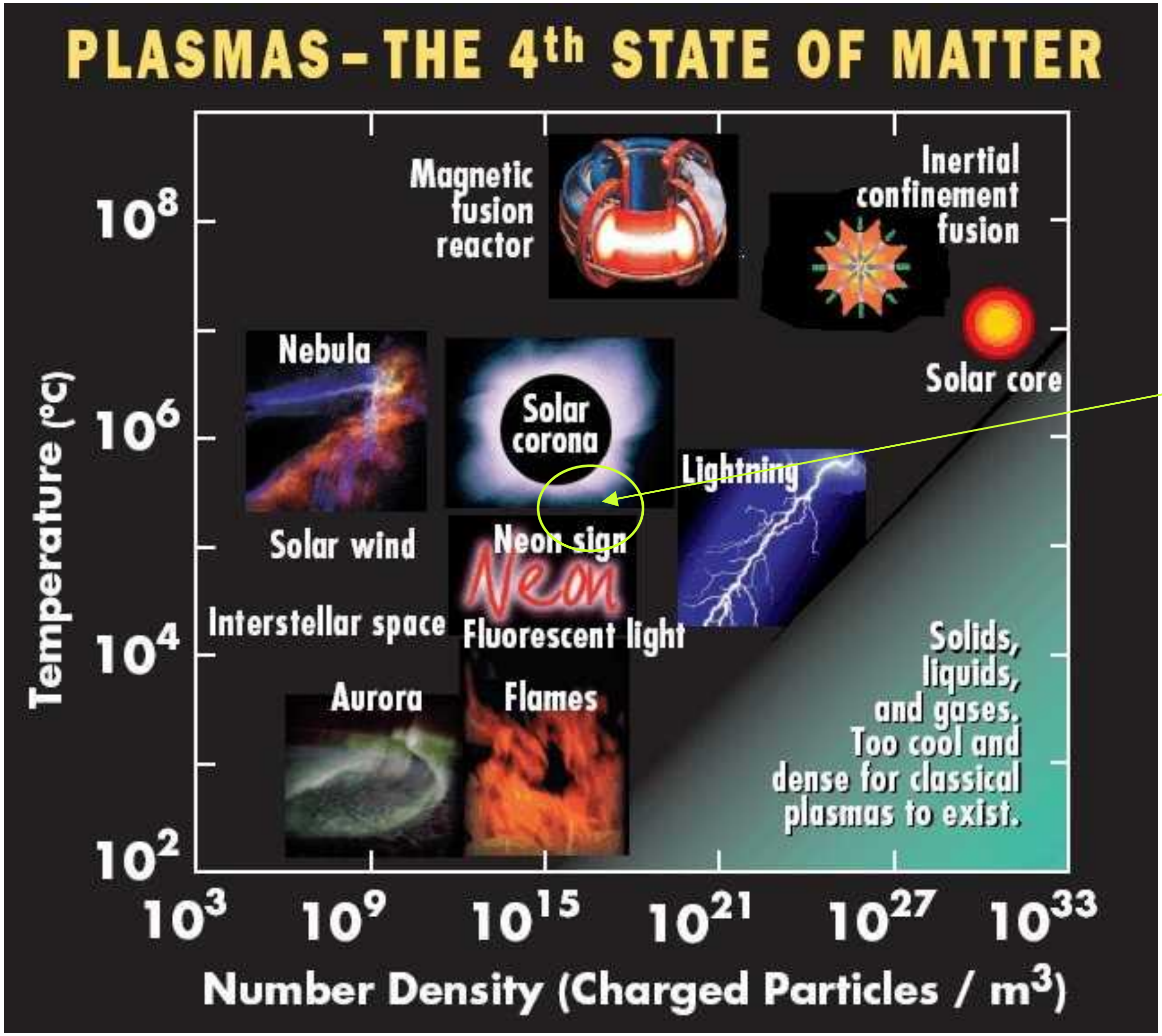
Low temperature plasma science for emerging applications in aerospace, materials synthesis, bio/med/agro, catalysis, and energy

Yevgeny Raitses

Princeton Plasma Physics Laboratory
Princeton, New Jersey

PPPL, Princeton, NJ, August 16, 2019

Low Temperature Plasmas

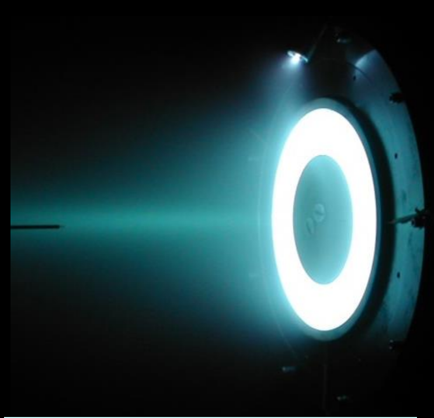


- Non-equilibrium: $T_e >> T_{ion} >> T_{atom}$
- Only partially ionized
- Less dense and colder than in tokamak, but hotter than in neon and fluorescent lights

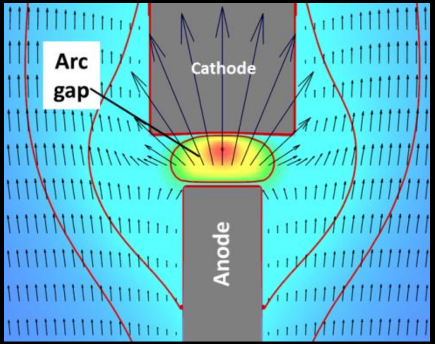
Low Temperature Plasma (LTP) Projects

Large thruster facility

Hall thrusters

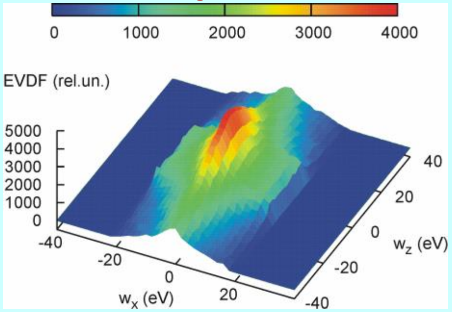


CFD simulations of atmospheric plasmas

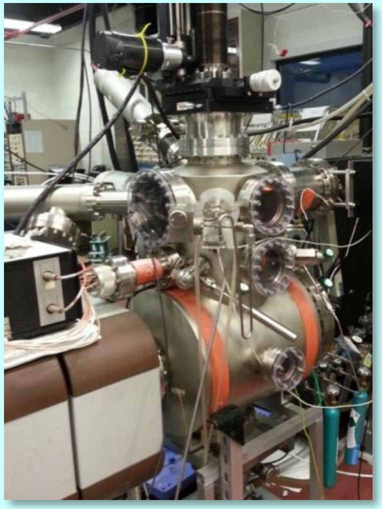


Plasma-based nanosynthesis

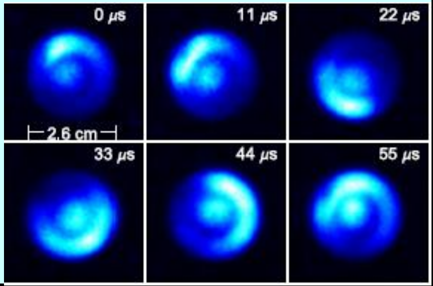
PIC simulations of LTP plasma



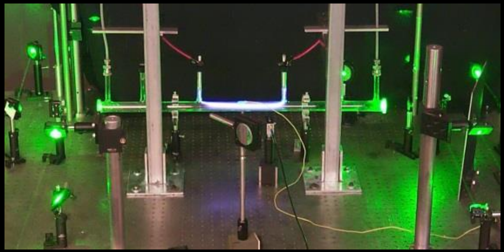
Secondary electron emission from plasma-facing wall materials



Coherent ExB plasma structures

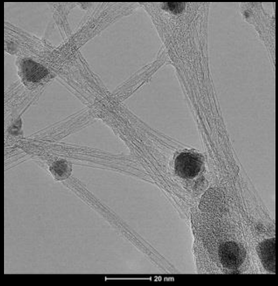


In-situ laser diagnostics of nanoparticles

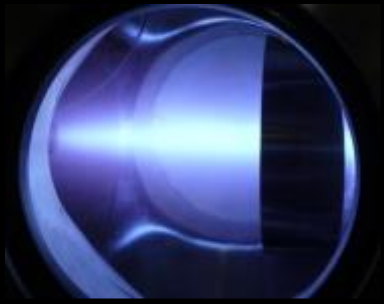


Reactive microplasmas for plasma catalysis

Plasma-produced nanomaterials



Plasma-based functionalization of nanomaterials



PPPL Research on LTP Science and Applications

Objectives:

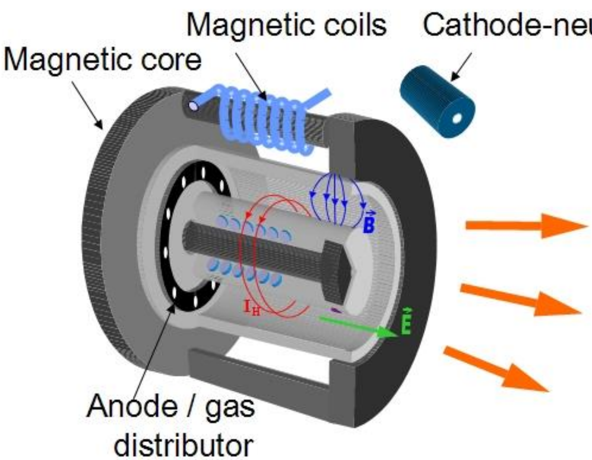
- **Developing methods of control of ion, electron and photon energy distribution functions in low temperature plasmas**
- **Advancing diagnostics, algorithms and computer models, fundamental data to facilitate the development of these methods, and their transfer to broader plasma community and industry**

Focus:

- **Plasma-wall interactions, waves and instabilities in partially ionized magnetized plasmas with application to practical ExB plasma devices**
- **Plasma-wall interactions, dusty plasmas, plasma chemistry in processing and synthesis of materials and other applications**

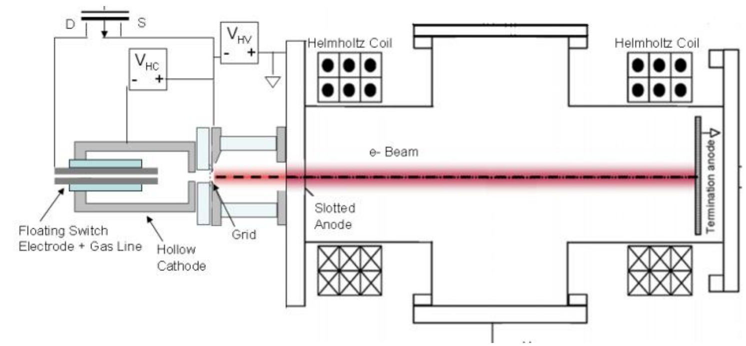
ExB Plasmas in Modern Applications

- **A number of emerging technologies use E ×B discharge and/or E ×B plasma flow for propulsion and processing applications:**

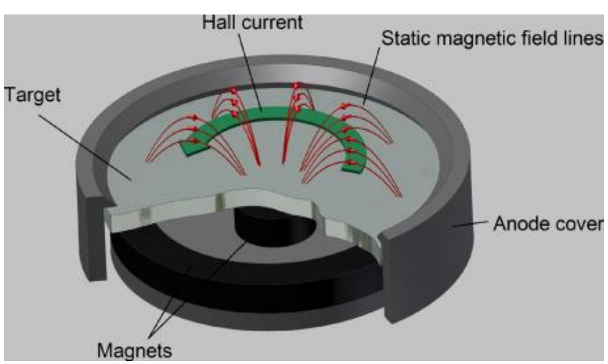


Neutral density ~ 10^{12}-10^{13} cm^3
Plasma density ~ 10^{11}-10^{12} cm^{-3}
Highly ionized flow: Γ_{ion}/Γ_n >100%
Ionization degree: from 10% to << 1%
Electron temperature ~ 20-60 eV
Ion temperature ~ 1 eV
Ion kinetic energy ~ 10^2-10^3 eV

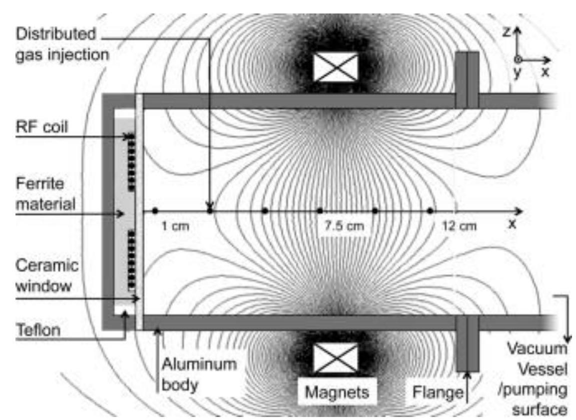
- **Hall thruster, A. I. Morozov**



- **Plasma-beam Penning system, US Patent by S. Walton et al., 2009**



- **Planar magnetron and hi-PIMS, J. Winter et al., J. D 2013**



- **Magnetic filter for ion-ion source/thruster** ***Aanesland et al., Appl. Phys. Lett. 2012***

Outline

- Plasma thruster physics research
- Synthesis of nanomaterials by plasmas
- Bio/med/agro/food applications

Plasma thruster and ExB physics research

http://htx.pppl.gov

Main Objectives:

- **Addressing emerging plasma science challenges for Hall thruster technology**
- **Understanding of fundamental limits of plasma acceleration and thrust in magnetized plasma thrusters**
- **Developing new physics concepts for plasma propulsion**

Team: Jacob Simmonds, Tasman Powis, Yevgeny Raitses, Igor Kaganovich, Andrei Smolyakov, Ahmed Diallo

1st year graduate student: Matthew Bledsoe

Just graduated from the 1st year: Eduardo Rodriguez and Valentin Skoutnev

The other student contributors (still in Princeton): Brian Kraus and Andy Alt

PRINCETON PLASMA PHYSICS LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Plasma thruster research at PPPL

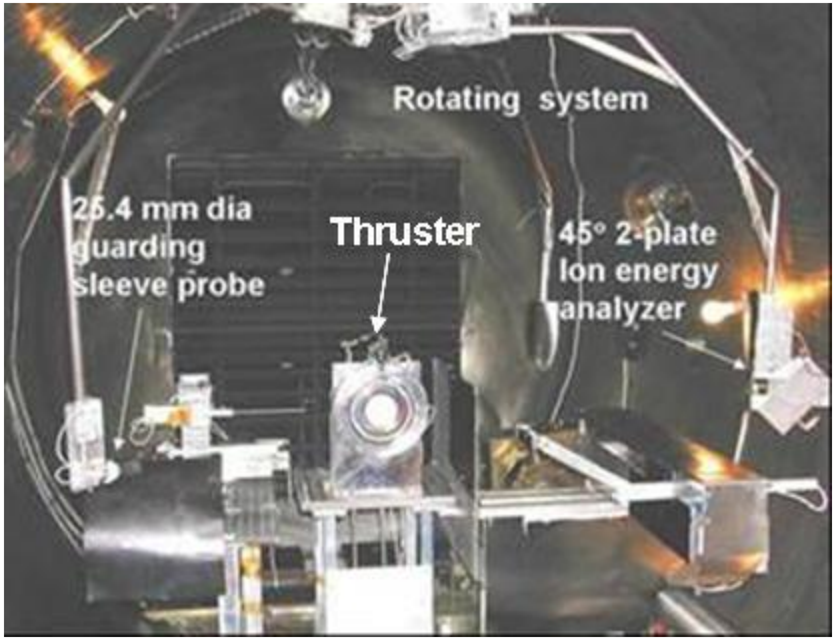
• In 1952, Lyman Spitzer discussed ion thruster concept in *"Interplanetary travel between satellite orbits"*

American Rocket Soc.

• Hall Thruster Experiment (HTX) in 1998

Goal: to develop scientific understanding of plasma thruster physics.

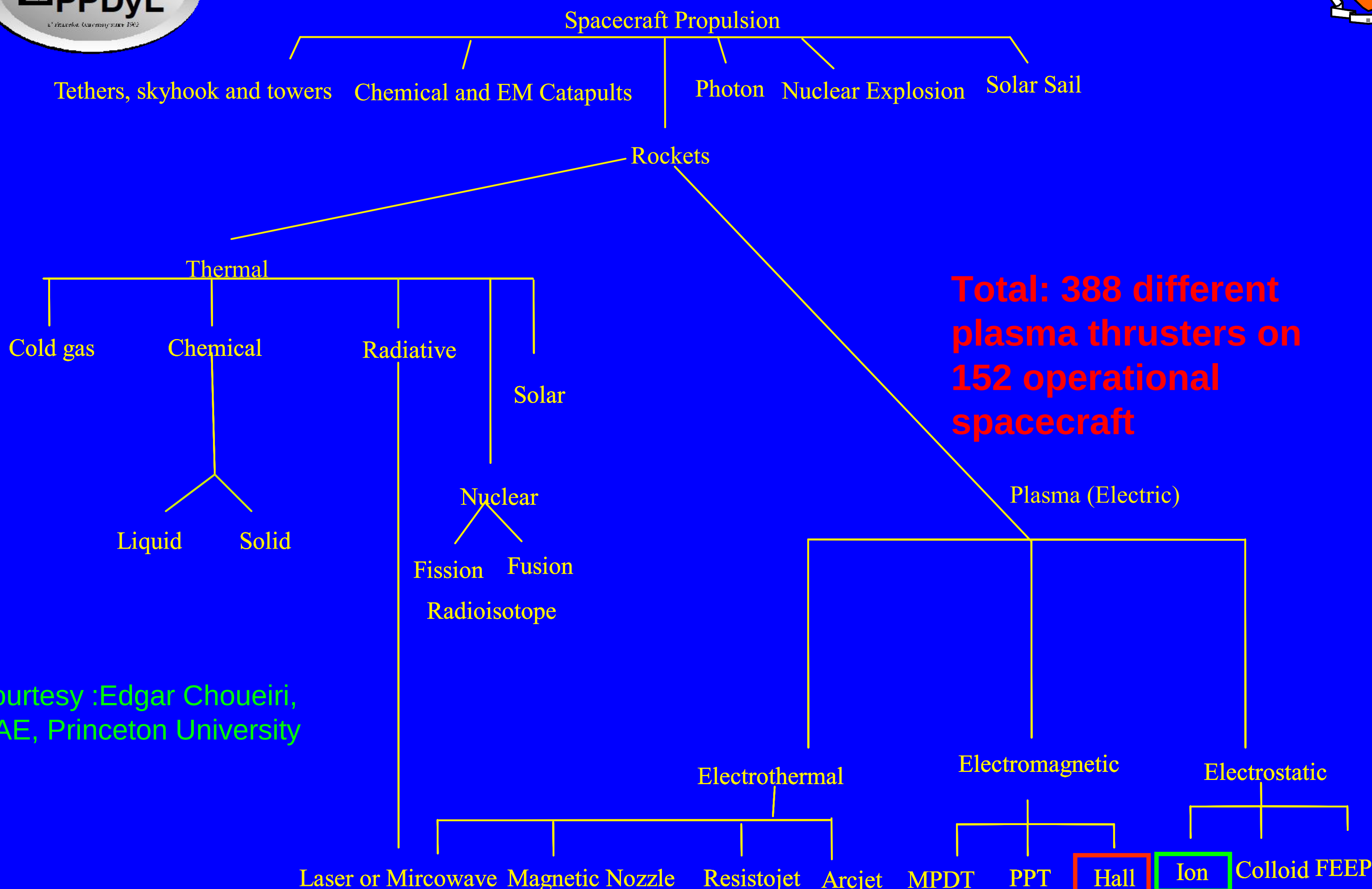
• Upgraded in 2003 →



- Support from DOE, Air Force (AFOSR), DARPA, NJ Science & Technology .

http://htx.pppl.gov

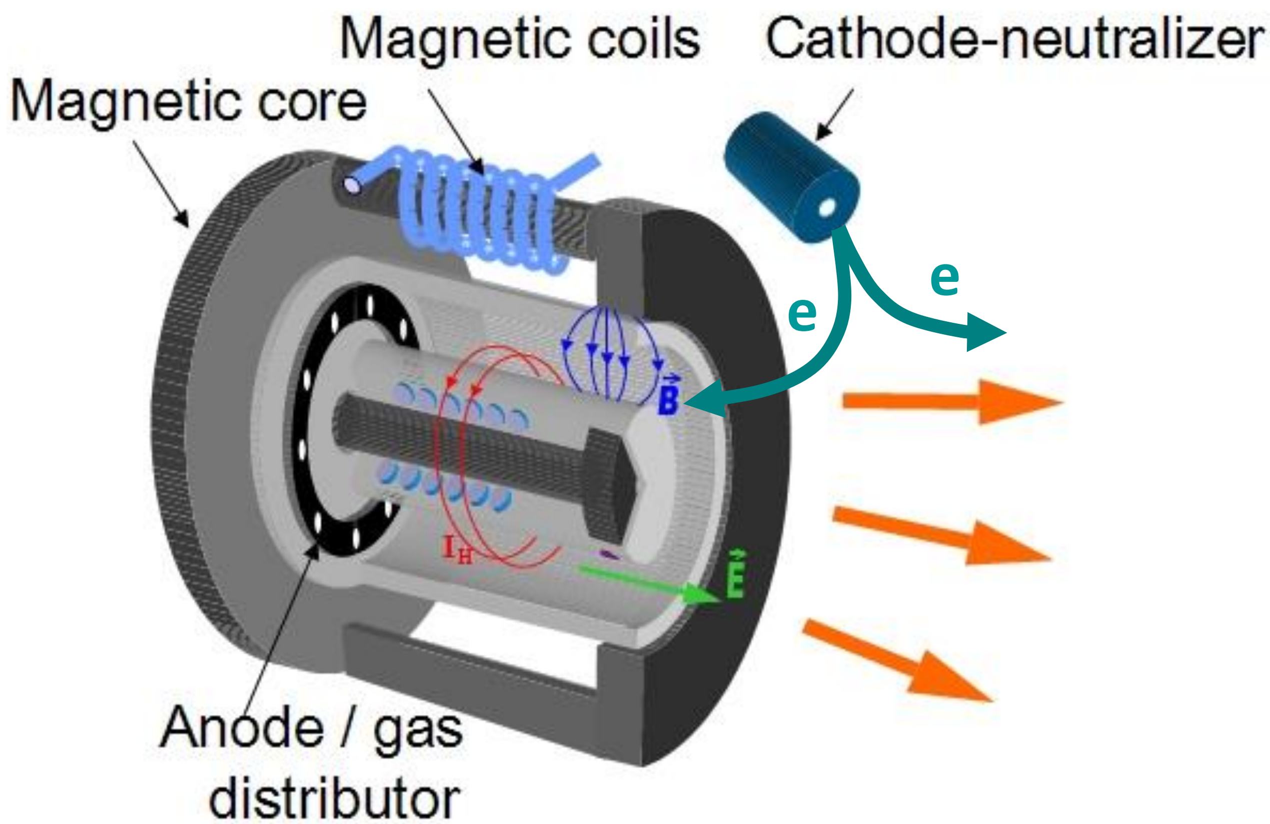
Hierarchy of Propulsion Concepts



Total: 388 different plasma thrusters on 152 operational spacecraft

Courtesy :Edgar Choueiri, MAE, Princeton University

Hall thruster (HT)



$$E \approx -v_e \times B$$

$$\rho_e << L << \rho_i$$

Electrons are magnetized
Ions are non-magnetized

- **Thrust force exerts on m......t**
- **Not space-charge limited**

Hall thruster plasma

Neutral density ~ 10^{12}-10^{13} cm^{3}

Plasma density ~ 10^{11}-10^{12} cm^{-3}

Highly ionized flow: Γ_{ion}/Γ_{n} >100%

Ionization degree: from 10% to << 1%

Electron temperature ~ 20-60 eV

Ion temperature ~ 1 eV

Ion kinetic energy ~ 10^{2}-10^{3} eV

Weakly collisional, partially ionized, partially magnetized (only electrons are magnetized), non-equilibrium plasma.

- Different from typical low temperature plasmas
  - Electron temperature increases with the power, plasma density increases with the pressure.

State-of-the art Hall thrusters

- **By now over 250+ kW-class flown on various space missions, mainly for station keeping and orbit transfer.**

From: http://www.nasa.gov/centers/glenn /news/pressrel/2002/02-050.html

Diameter **~ 10-50 cm,**

Power **~ 0.5- 50 kW**

B ~ 100-300 Gauss

Working gases: Xenon, Krypton

Discharge voltage **~ 200- 1000 V**

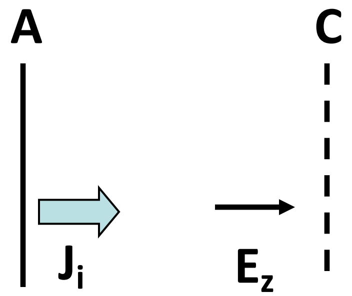
Thrust ~ 10^{-3} - 1N

Isp **~ 1000-3000 sec**

Efficiency ~ 40-70%

Fundamental limitations of HT

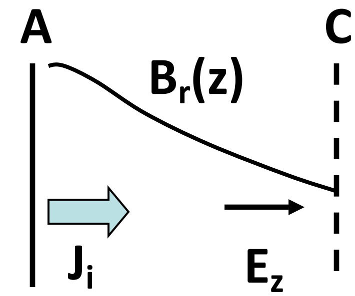
Ion thruster *by space charge*



$$J_{i\max} = J_i^{CL} = \frac{\sqrt{2q}\phi_0^{3/2}}{9\pi d^2\sqrt{M_i}}$$

$$\frac{J_{i\,max}^{HT}}{J_{i\,max}^{CL}} = \left(\frac{3}{4}\frac{B_{max}}{E^{CL}}\right)^2$$

Hall thruster *by maximum B field*



$$M_i J_{i\max} V_{if} = q\frac{B_0^2 - B_1^2}{8\pi}$$

B_{max} is limited by material properties

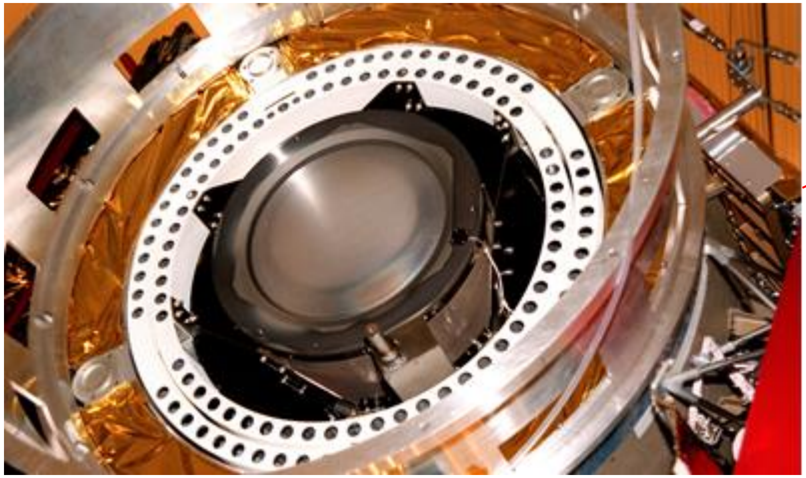
$E^{CL} = V^*/d$

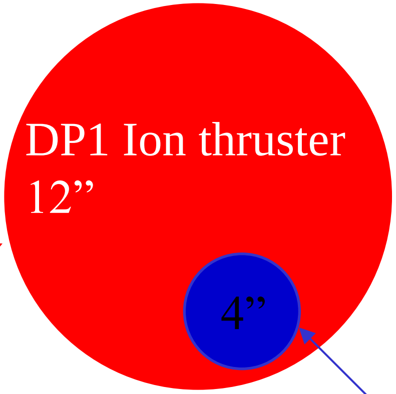
For B_{max} ~ 2 kG, d ~ 0.1cm ???

J^{HT}/J^{ch} =1 at V^*= 45 kV

Operating without space charge limitation, Hall thrusters can be more compact than ion thrusters

Deep Space Mission Ion thruster





SMART -1

Hall thruster:

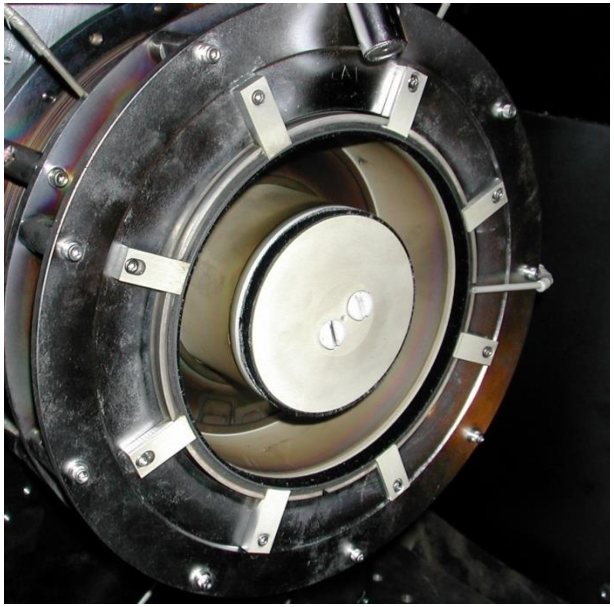
PPS-1350: 1200 W

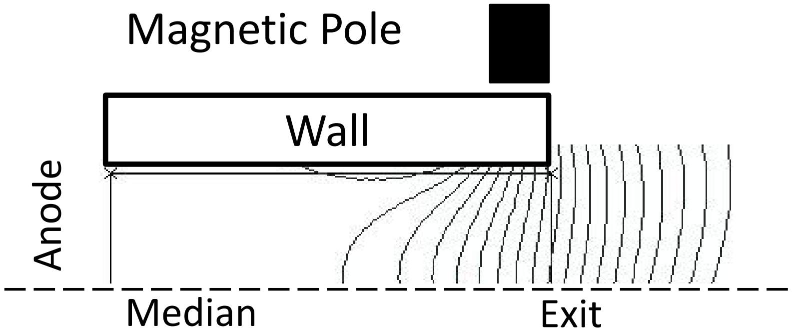
10 cm OD, 68 mN

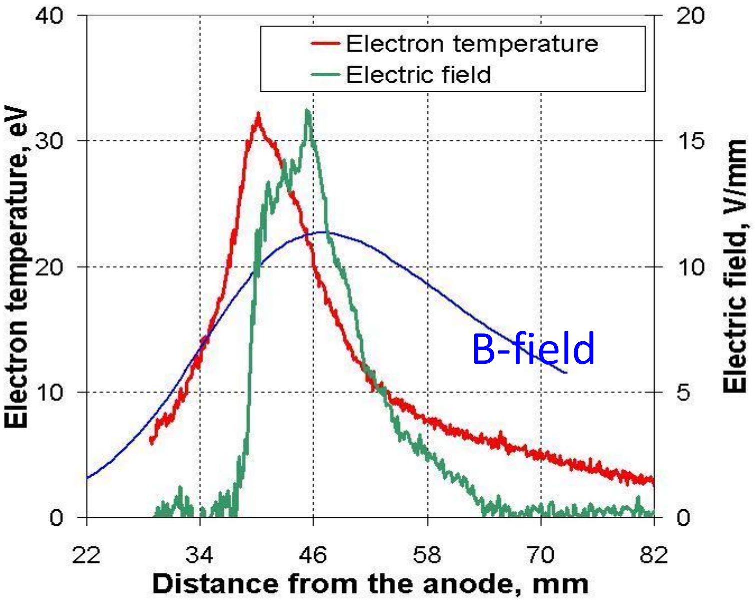
Hall thrusters are also advantageously more simple than ion thrusters (more reliable, less expensive, etc)

Details on Hall thruster plasma

- **Non-uniform E ×B fields, with plasma density/temperature gradients.**







- **Measurements in a 12 cm diam., 2 kW PPPL Hall thruster.**

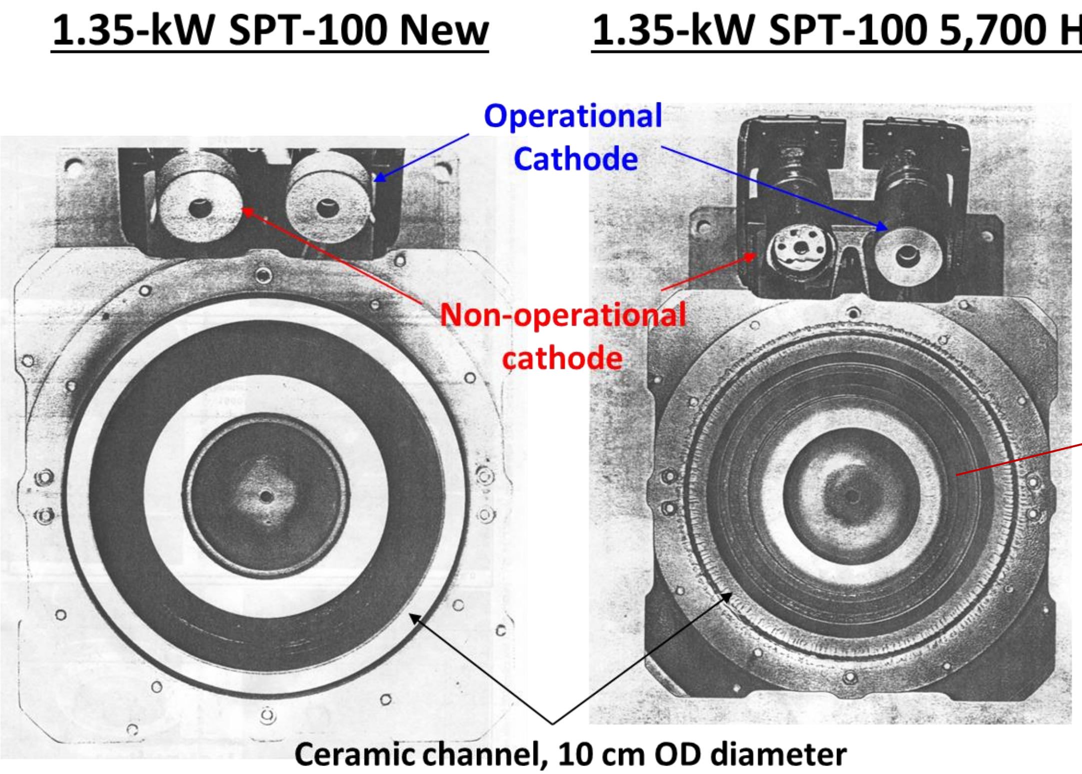
- **Achievable electric field is much higher than in linear devices.**

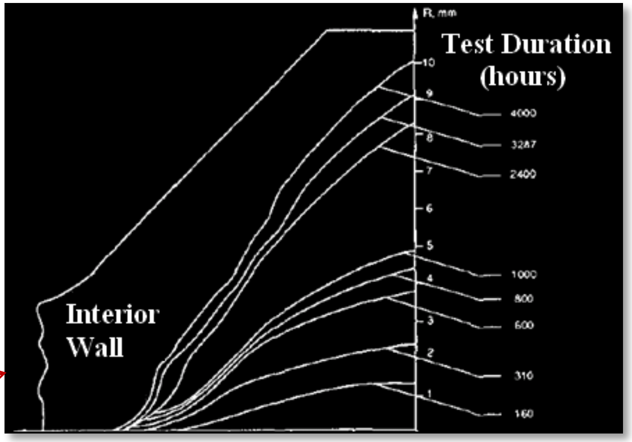
What stops us from designing the thruster capable to operate at the thrust density limit?

- Plasma-wall interactions in the presence of strong fluxes of particles from the wall leading to the thruster erosion.
- Enhanced (anomalous) electron cross-field transport limiting the thruster efficiency

- How plasma-wall interaction and electron transport will change at the thrust density limit?
- What will be the main instabilities and how to keep the thruster operation stable?
- How to design compact and high power density plasma thruster?

Why to care about plasma-wall interaction in Hall thrusters?





Courtesy: Yiangos Mikellides, NASA JPL

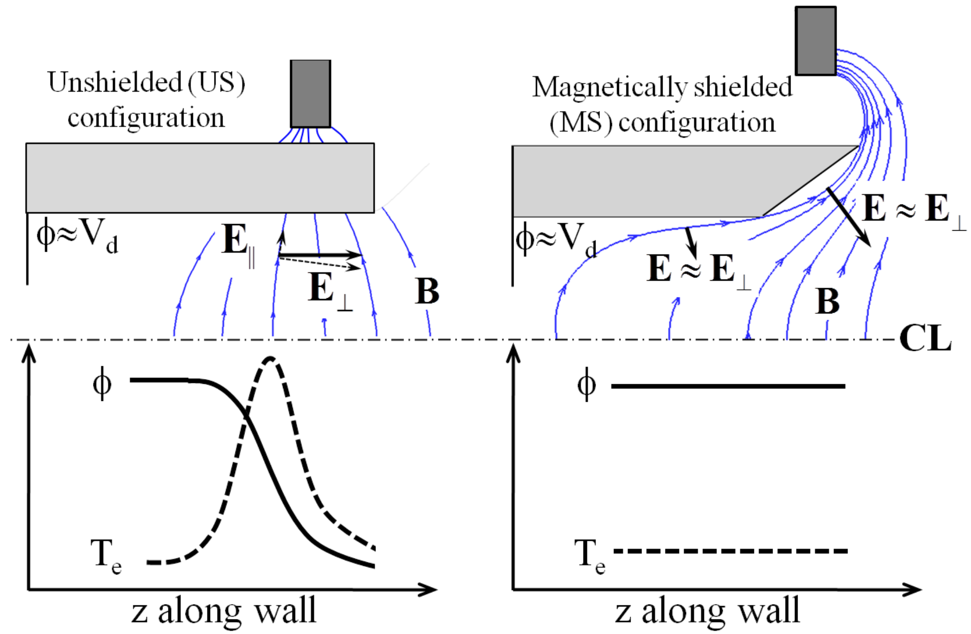
- **Life expectancy of typical Hall thrusters < 5000 h.**
- **Channel erosion is the main reason that no Hall thruster has ever propelled a deep space mission!**
- **New space missions require 25,000 hours!**

Towards a solution, learning from a magnetic fusion: a divertor configuration: magnetically-shielded HT

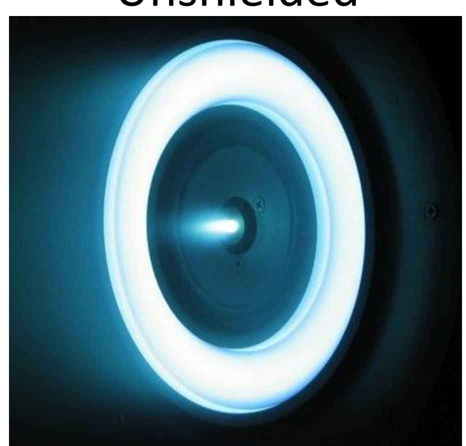
- **Low electron temperature near the wall → low sheath potential →**
- **Low energy of ions impinging the walls → low wall erosion → longer thruster lifetime.**
- **Oblique magnetic field may prevent SEE electrons from flowing to the plasma → → no near-wall conductivity.**

I. Mikellides, Phys. Plasmas (2011)
I. Mikellides et al, Appl. Phys. Lett. (2013)

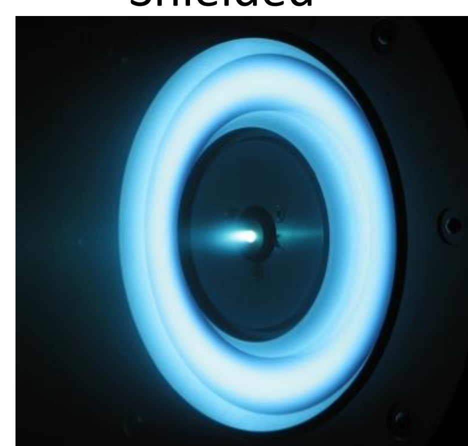
- **NASA JPL Hall Thruster with magnetic shield.**



Unshielded



Shielded



Why to care about electron cross-field transport?

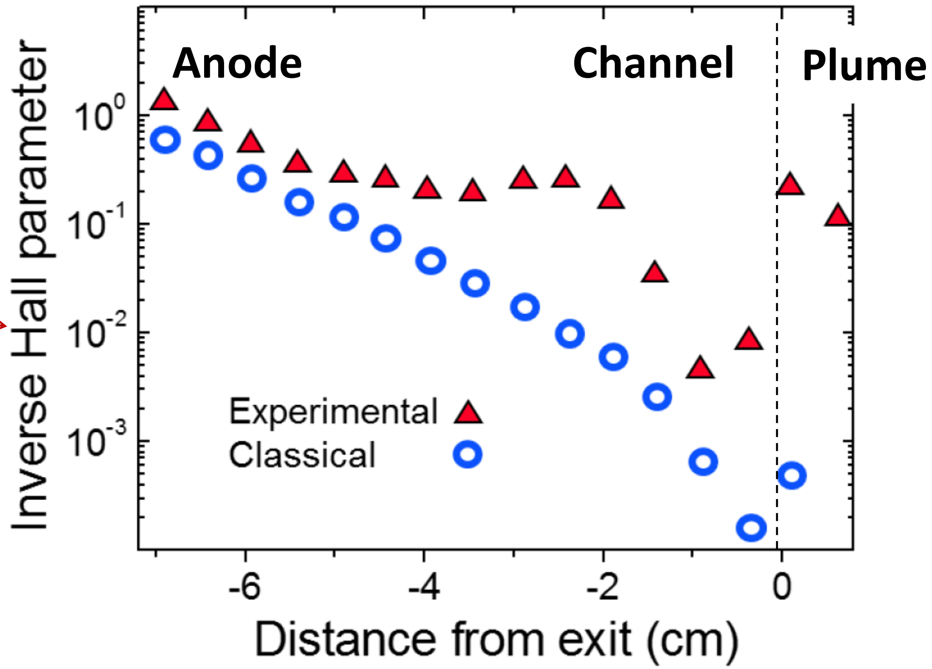
- **Efficiency reduces with the electron cross-field current!**

✓ **Thruster efficiency** $\eta \equiv \frac{TV_{jet}}{2P_e} \propto \frac{I_i}{I_i + I_{e\perp}}$

Recall today's talk by J. P. Boeuf

$$I_{e\perp} \approx e\mu_{e\perp} N_e E$$

$$\mu_{e\perp} \approx \frac{1}{B}\frac{\nu_{eff}}{\omega_{ce}}$$

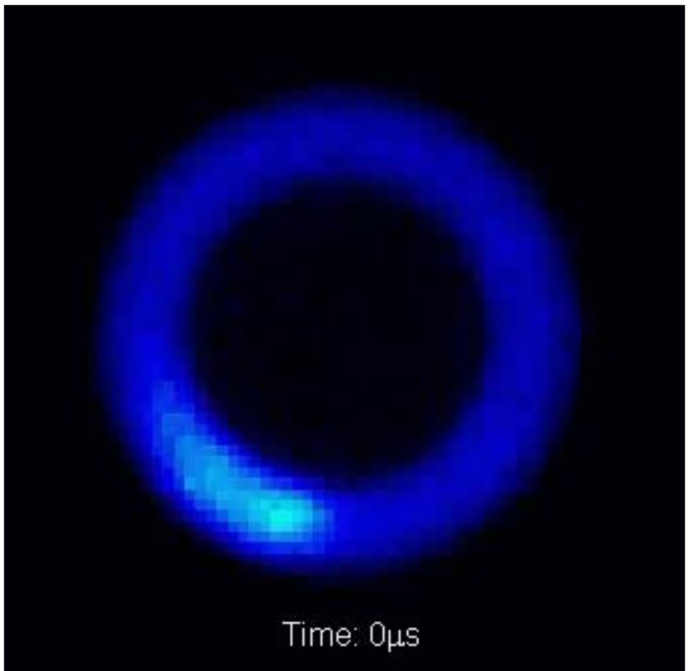


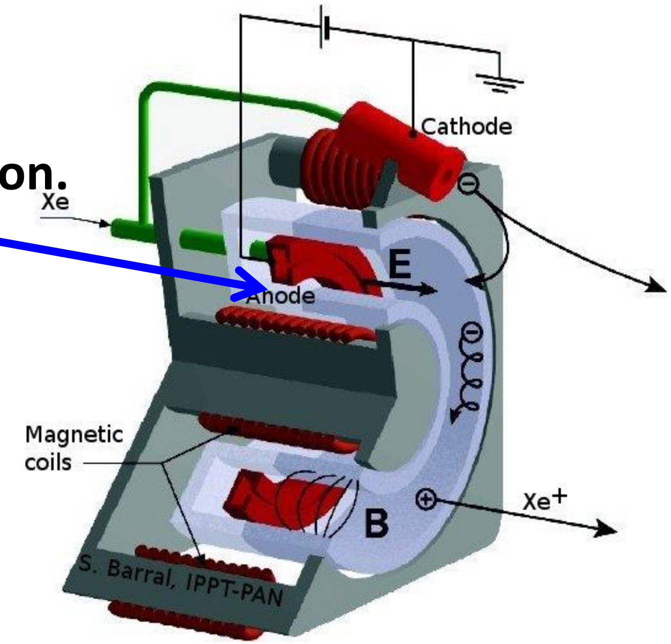
Meezan,Hargus, Cappelli., Phys. Rev. (2001)

Scenarios for anomalous cross-field current in HT

Inside the channel near the anode:

Large-scale low frequency coherent structures,
Moving ionization zones (e.g. magnetic striations)
due to anomalous (enhanced) heating and ionization.

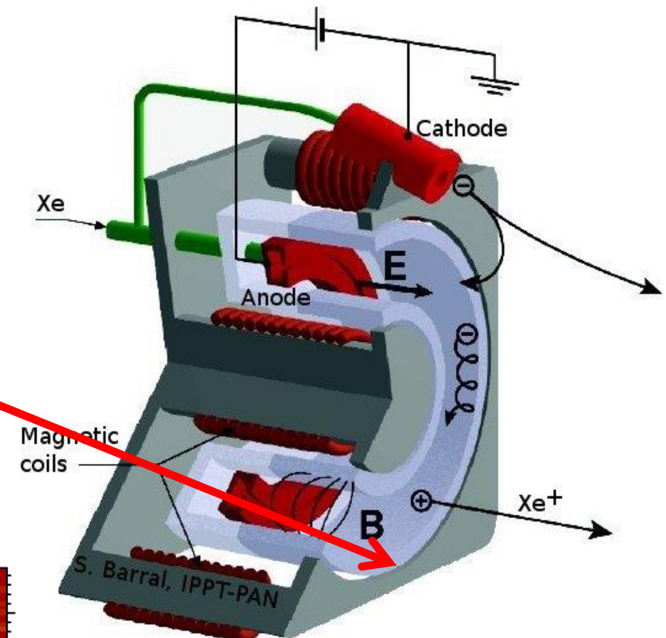




- **Spoke frequency ~ 10 kHz**
- **10's times slower than E/B**
- **Spoke frequency >> Ω_{ci}**

J. B. Parker, Y. Raitses, and N. J. Fisch, Appl. Phys. Lett. 97, 091501 (2010)
C. L. Ellison, Y. Raitses and N. J. Fisch, Phys. Plasmas ***19****, 013503 (2012)*

Scenarios for anomalous cross-field current in HT

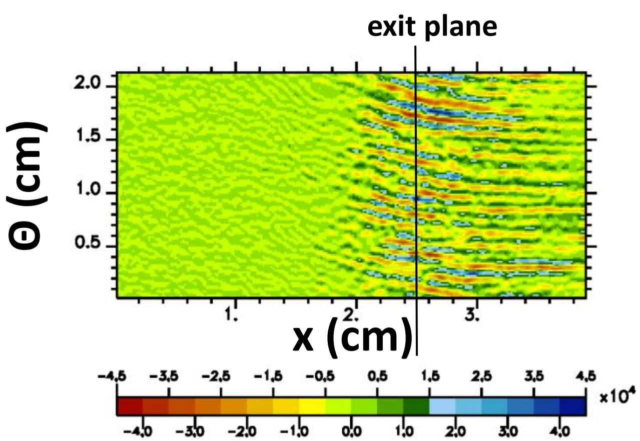


***Outside the channel and in the near-field plume*:**

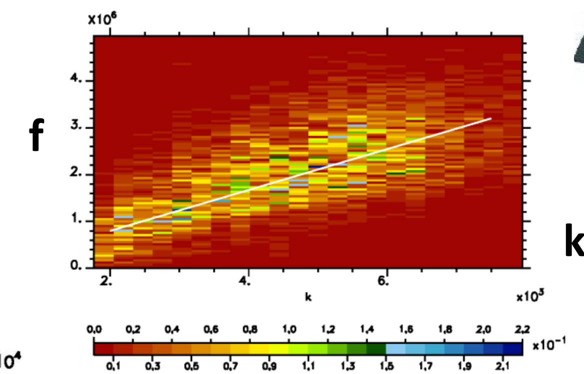
Small scale fluctuations ,~ 10 MHz, ion-sound and lower hybrid instabilities

*A. A. Litvak, Y. Raitses, and N. J. Fisch, Phys. Plasmas **11**, 1701 (2004)*

- **2-D self-consistent PIC simulations[2]**



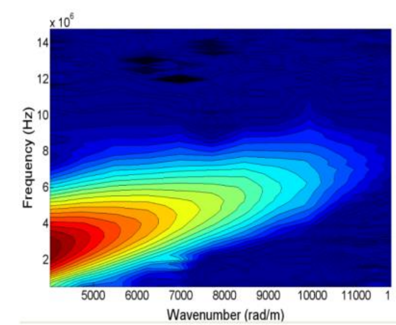
electric field



potential

Experiment:

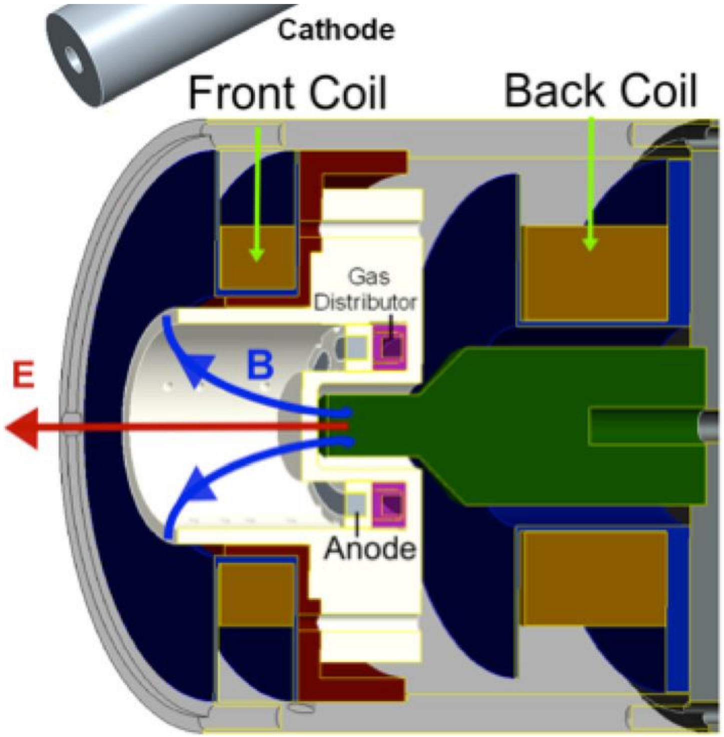
Density fluctuations



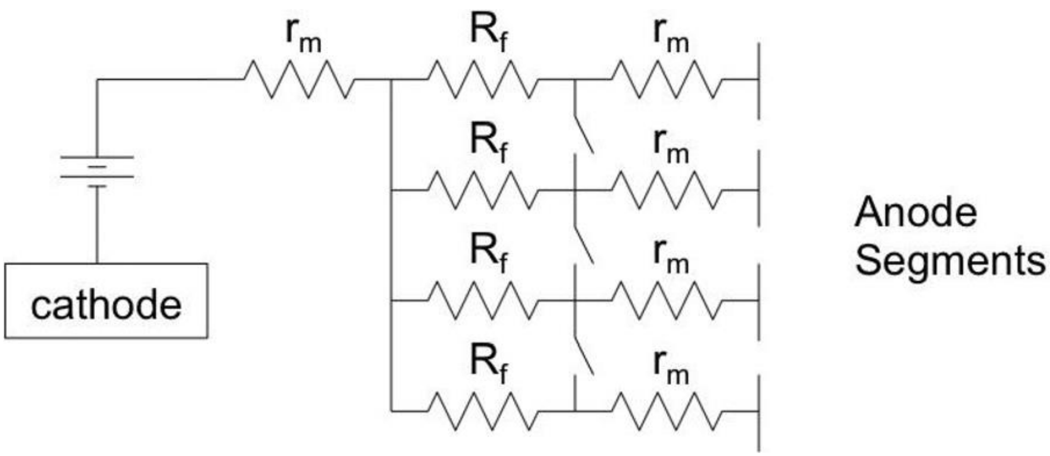
Adam, Héron and Laval, Phys. Plasmas (2004)

Tsikata, et al., Phys. Plasmas (2009)

Towards a solution: suppression of the spoke by a negative feedback control of the plasma



- Resistors attached between each anode segment and the thruster power supply
- The feedback resistors, Rf, are either 1Ω, 100 Ω, 200 Ω, or 300Ω

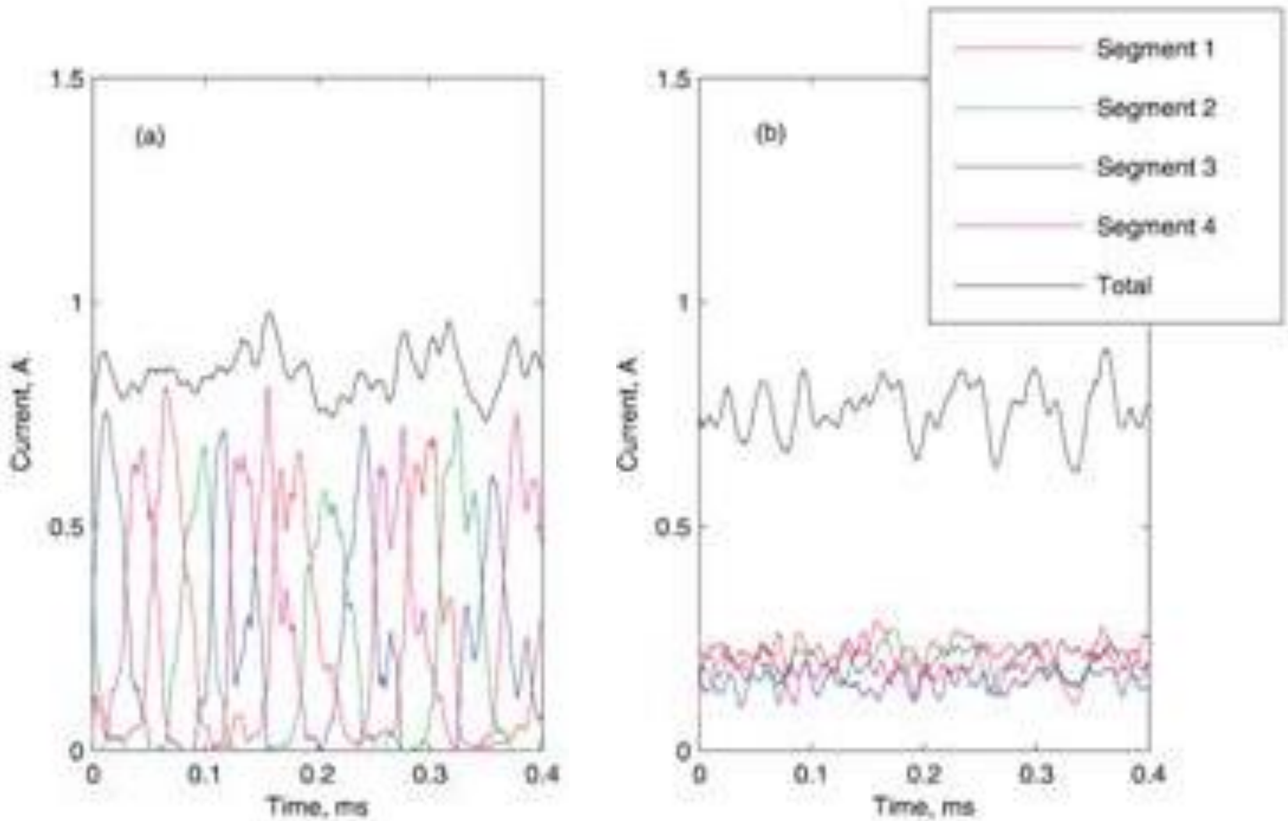


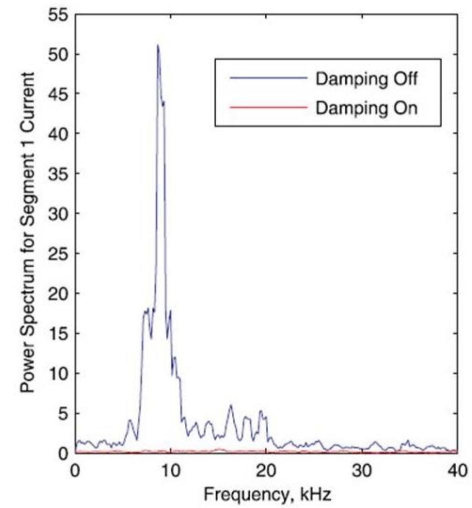
- Spoke increases the current through the segment leading to the increase the voltage drop across the resistor attached the segment.
- This results in the reduction of the voltage between the segment voltage and the cathode.

M. Griswold, C. L. Ellison, Y. Raitses, and N. J. Fisch, Phys. Plasmas ***19****, 053506 (2012)*

Spoke suppression with the feedback control

- **Feedback off**
- **Feedback on**



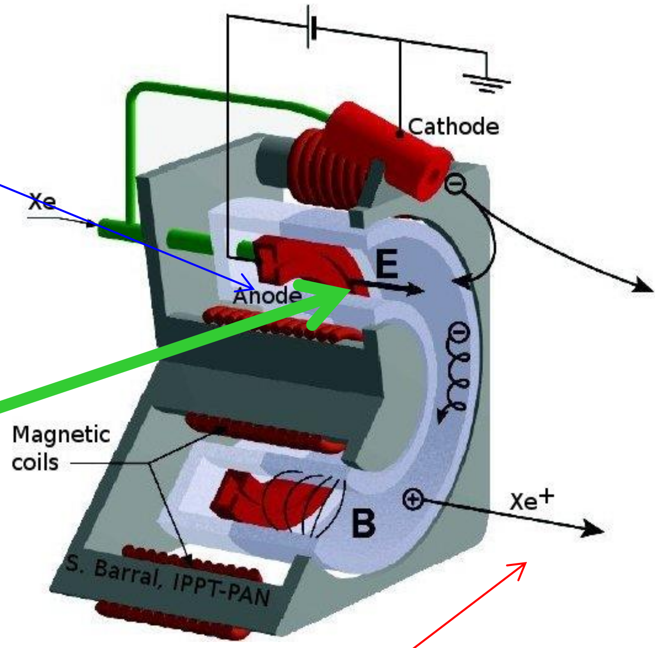


- **The suppression of the spoke leads to a reduction in the total discharge current due to the anomalous current that is carried by the spoke.**

M. Griswold, C. L. Ellison, Y. Raitses, and N. J. Fisch, Phys. Plasmas ***19****, 053506 (2012)*

Scenarios for anomalous cross-field current in HT

Inside the channel near anode region:
Large-scale low frequency coherent structures.

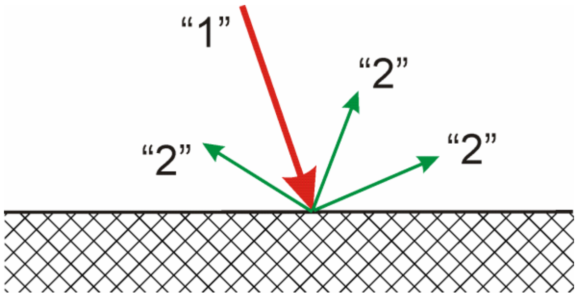


***Inside the channel near the exit*:**
SEE-induced near wall conductivity
(focus of this talk)
and
high frequency fluctuations.

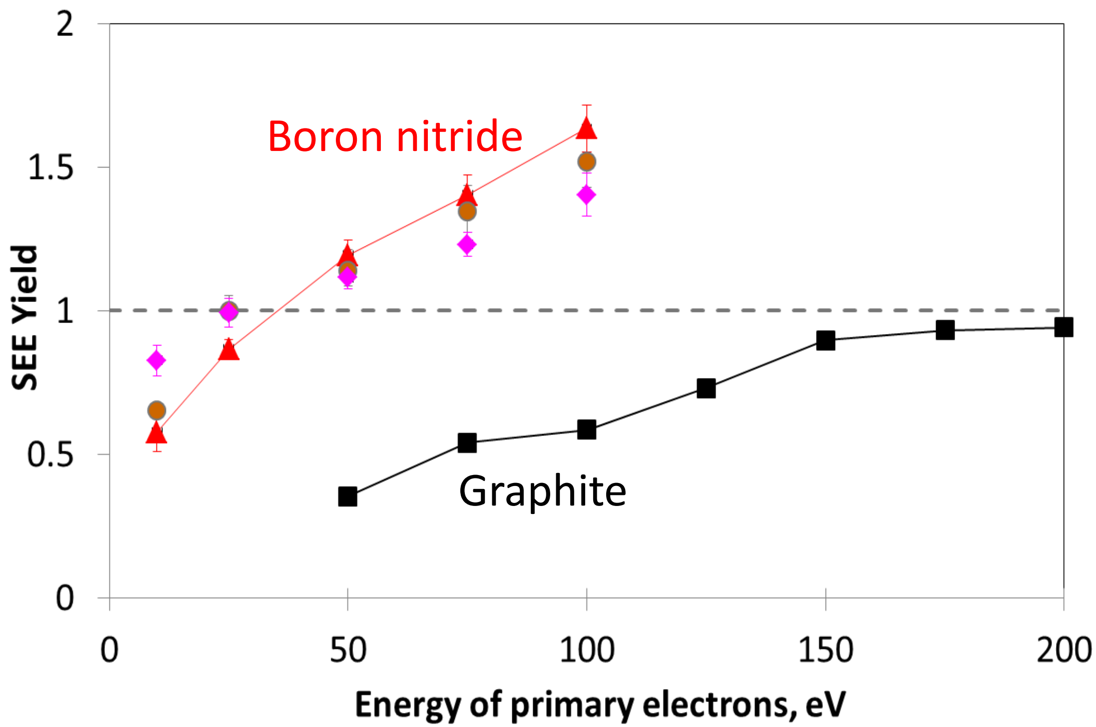
Outside the channel: small scale fluctuations

*Y. Raitses, I. D. Kaganovich, A. Khrabrov, D. Sydorenko, N. J. Fisch, A. Smolyakov, IEEE Trans. Plasma Sci. **39**, 995 (2011).*

Electron-induced secondary electron emission (SEE) plays a very important role in Hall thruster operation



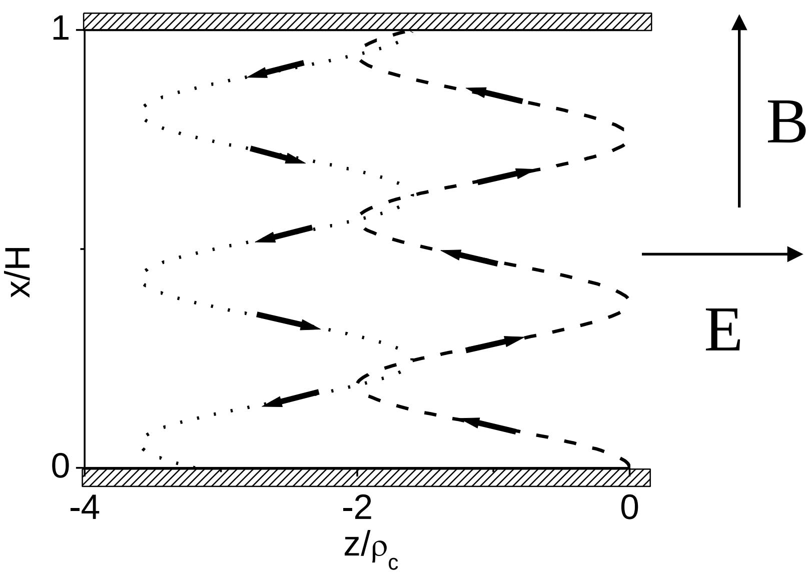
$$\gamma = \frac{\text{SEE}}{\text{Primaries}}$$



- **For ceramic materials, SEE yield is higher and approaches 100% at lower energies than for graphite and metals.**
- **Use of conductive channel walls can lead to short-circuit current (across magnetic field) increasing power losses.**

Enhanced electron cross-field current by SEE-induced near-wall conductivity

- **Exchange of primary magnetized electrons by non-magnetized SEE electrons induces so-called near-wall conductivity across magnetic field.**
- **The displacement ,** $\rho_c = v_\perp / \omega_c$ **,** $v_\perp = u_d = \frac{E_z}{B_x}$ **during the flight time** H/u_{bx} **gives SEE-induced cross-field current:**



$$J_{bz} \approx \frac{m}{H}\frac{\gamma_p}{1-\gamma_b} n_e \sqrt{\frac{T_{ex}}{M}}\frac{E_z}{B_x^2}$$

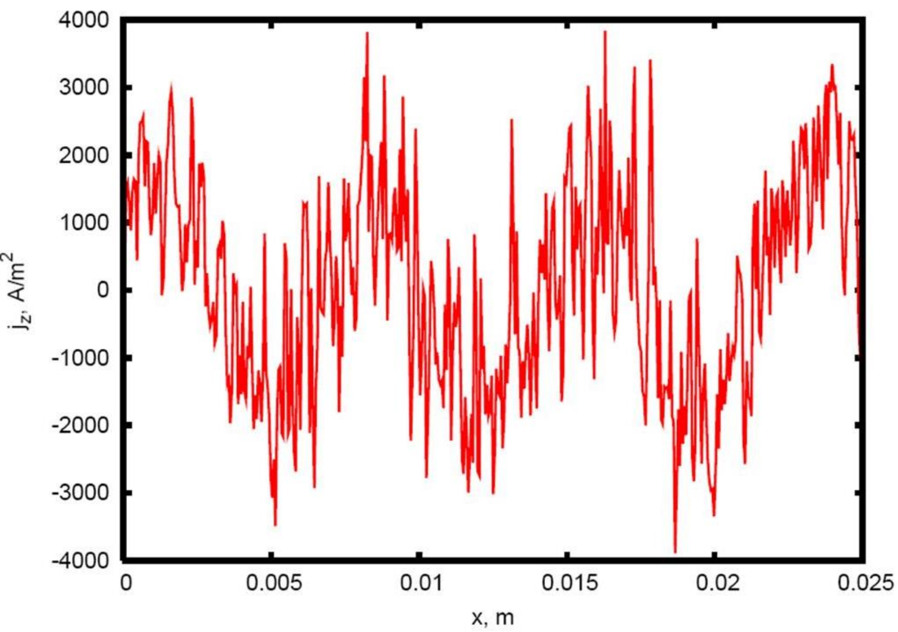
γ_p – SEE plasma electrons,
γ_p – SEE beam electrons.

Kaganovich, Raitses, Sydorenko. Smolyakov, Phys. Plasmas (2007)

Two predicted profiles of the cross-field current for two discharge voltage regimes and high SEE

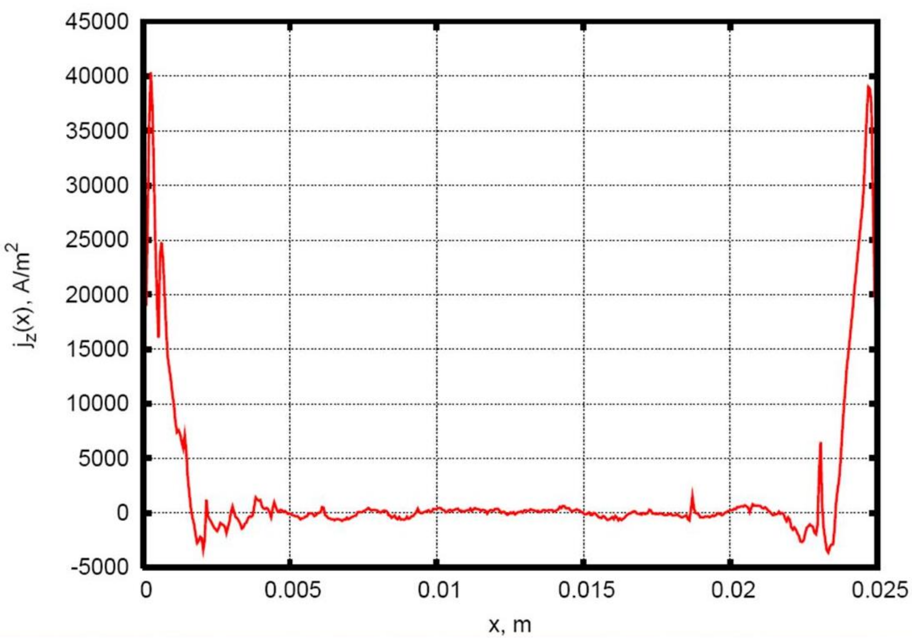
Strong SEE

$\gamma \leq 1$, E = 200 V/cm



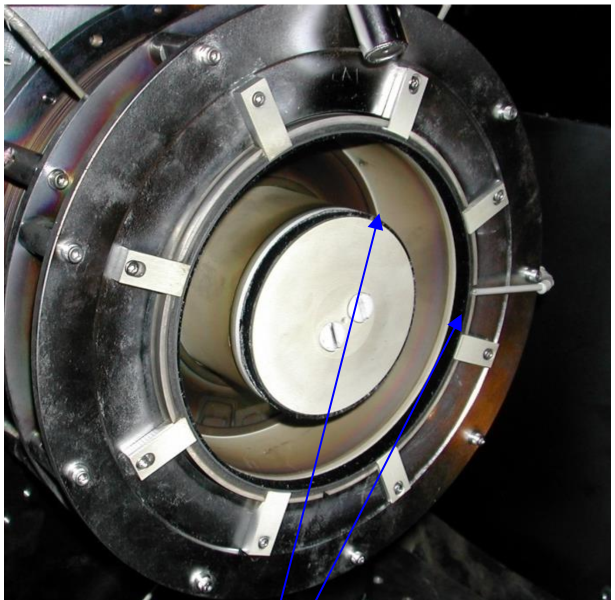
Very strong SEE

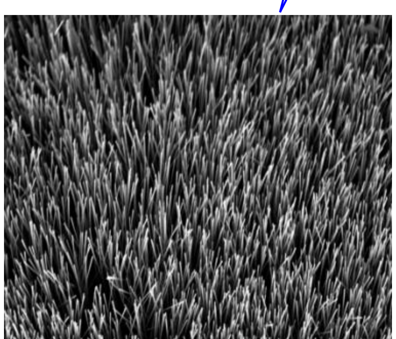
$\gamma > 1$, E = 250 V/cm



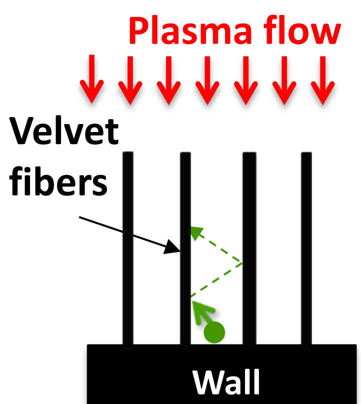
- **Non-zero averaged current over the channel width.**

Surface-architectured materials to suppress SEE and the near-wall conductivity

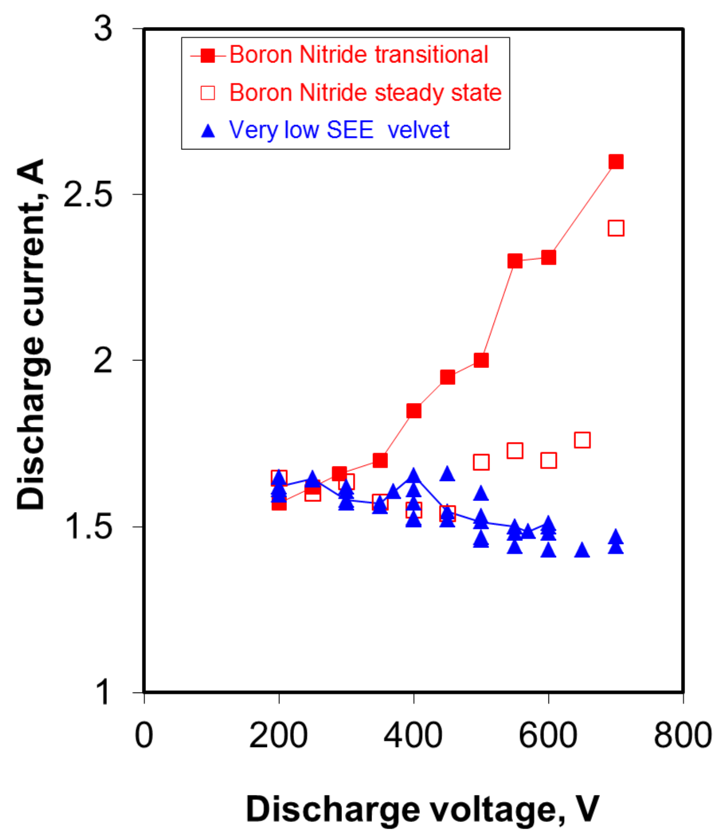




Carbon velvet



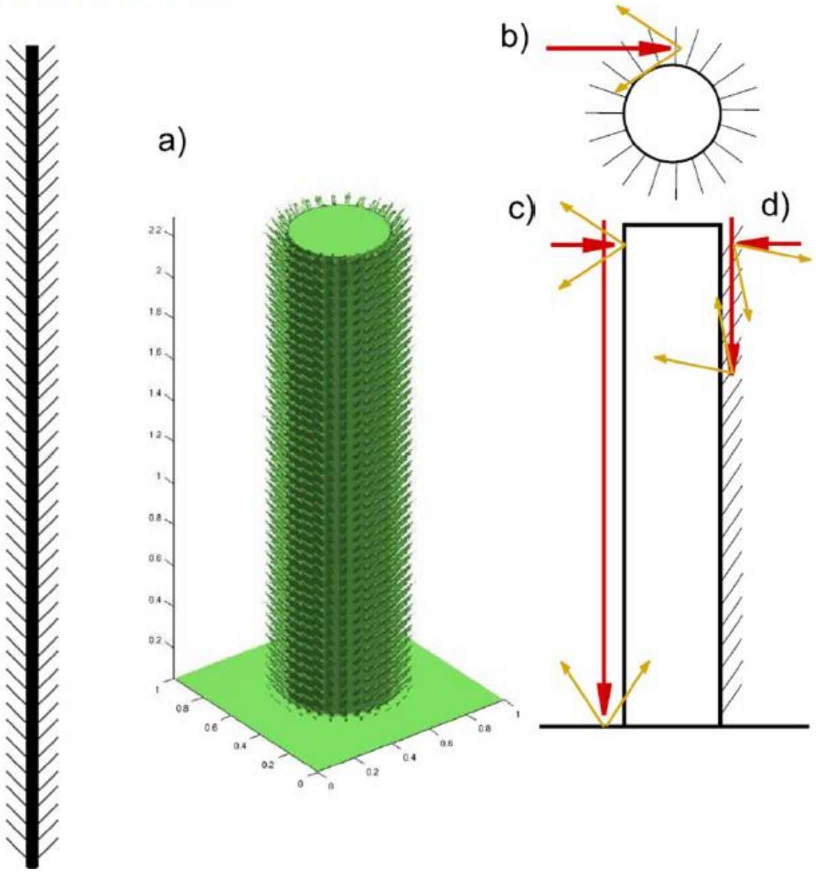
- High SEE material
- Very low SEE material



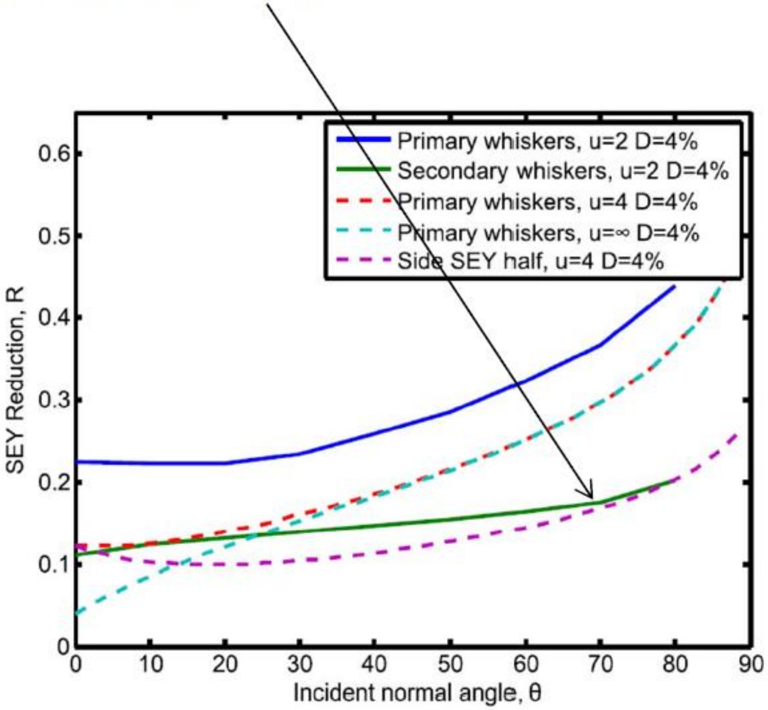
Raitses, et al., Phys. Plasmas (2011)

New materials with feathered surfaces

Feather: lattice of normally-oriented fibers with smaller, secondary fibers on the sides of that fiber.



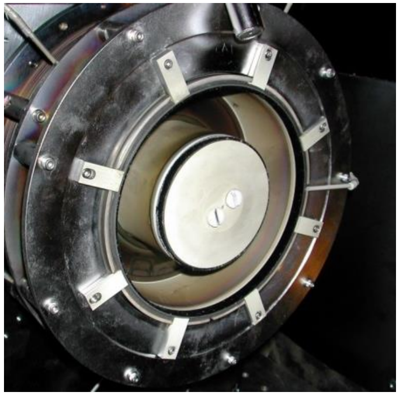
SEY as a function of incident angle for different packing density of foam. Feathers are able to suppress SEE for all electrons ~1/4.

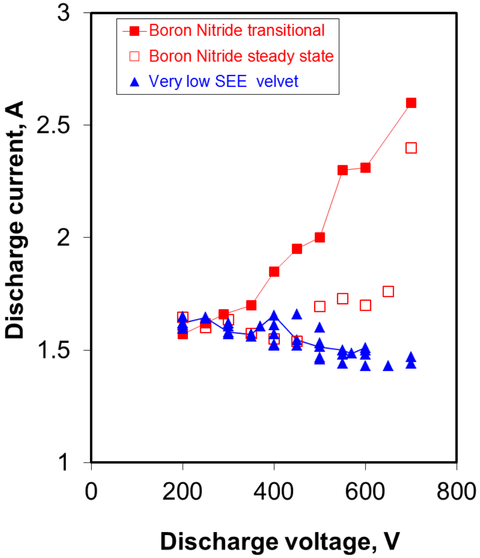


Swanson, Kaganovich, J. Appl. Phys. ***122,****043301 (2017)*

Applications with adverse effects of SEE

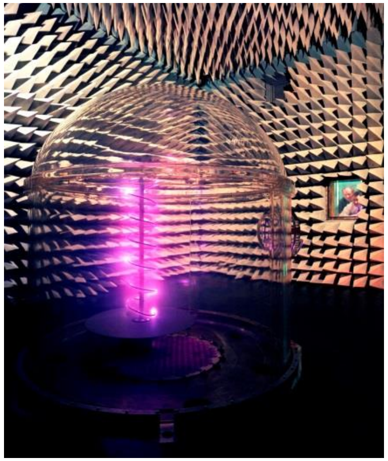
- **Enhanced transport and power losses in plasma thrusters (Hall, FRC etc).**





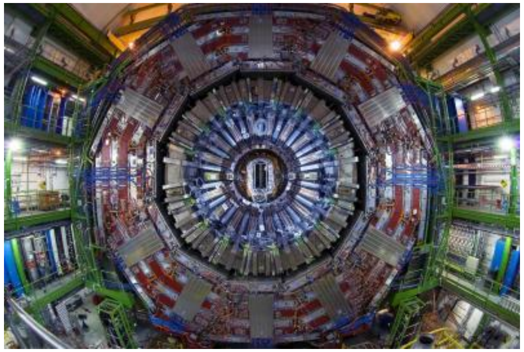
- **Damaging and destroying high power RF device through multipactor discharge.**

NASA JPL Mesa Antenna Measurement Facility

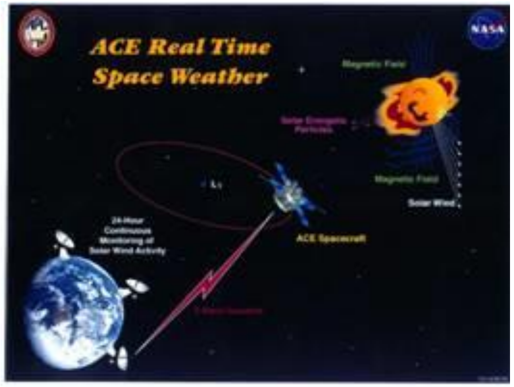


- **SEE-induced electron cloud effect a possible limitation for particle accelerators.**

Large Hadron Collider at CERN

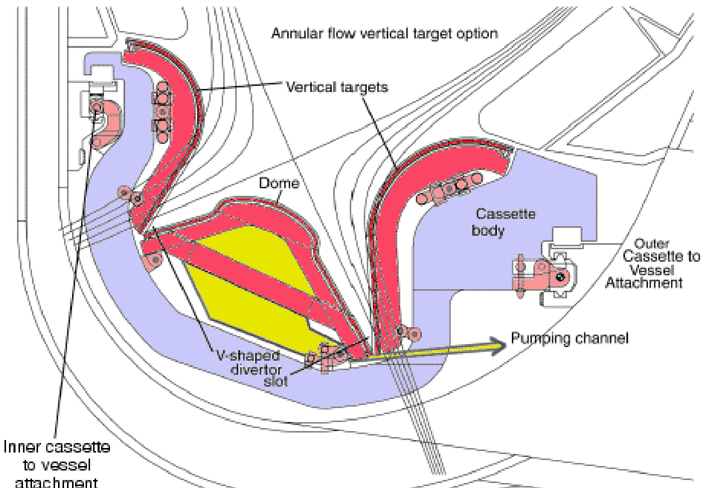


- **Spacecraft charging**



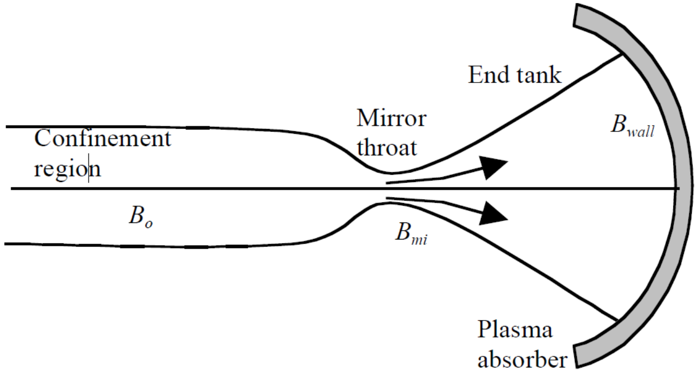
Magnetic fusion applications with *potentially* adverse effects of SEE

- **Tokamaks**

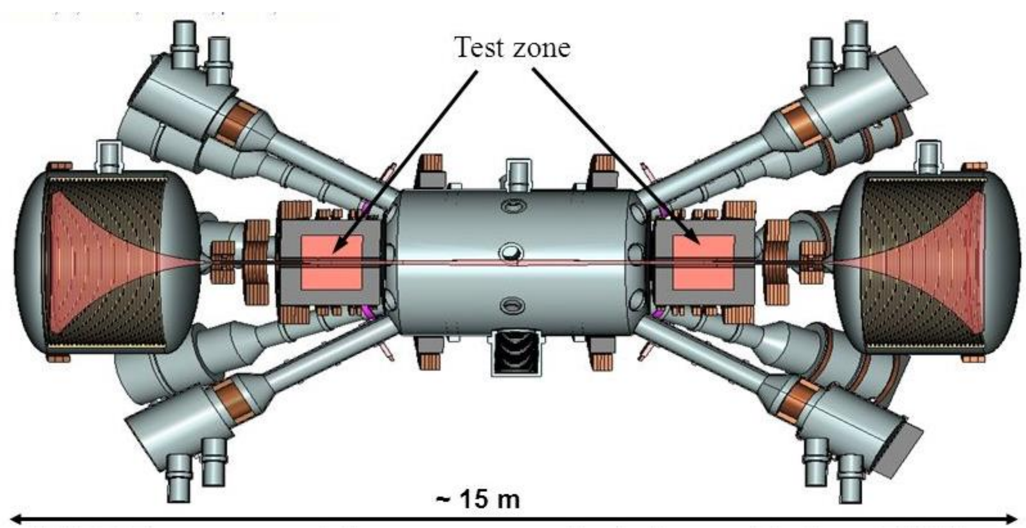


ITER divertor components

- **Magnetic mirror machines, FRC**



Gas-Dynamic Trap



Plasma-based processing and synthesis of nanomaterials

http://nano.pppl.gov

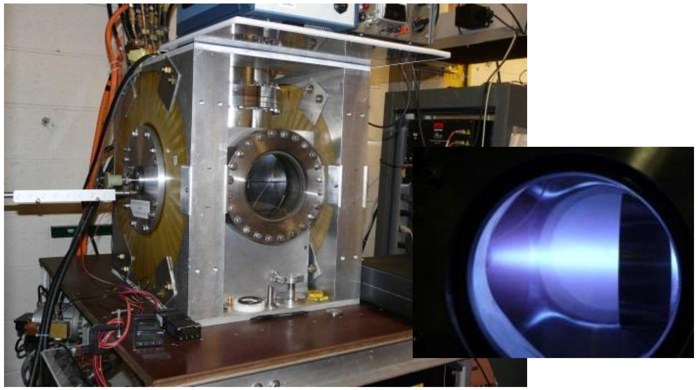
Main Objectives:

- **Understanding of synergy of plasma and materials processes involved in nucleation and growth of nanoparticles in plasma**
- **Developing methods of control of synthesis selectivity in plasma (e.g. use electric and magnetic field, leverage from charging of nanoparticles)**
- **Building materials at atomic scale with the help of plasma**

Application of ExB Plasma for Hydrogenation of Graphene

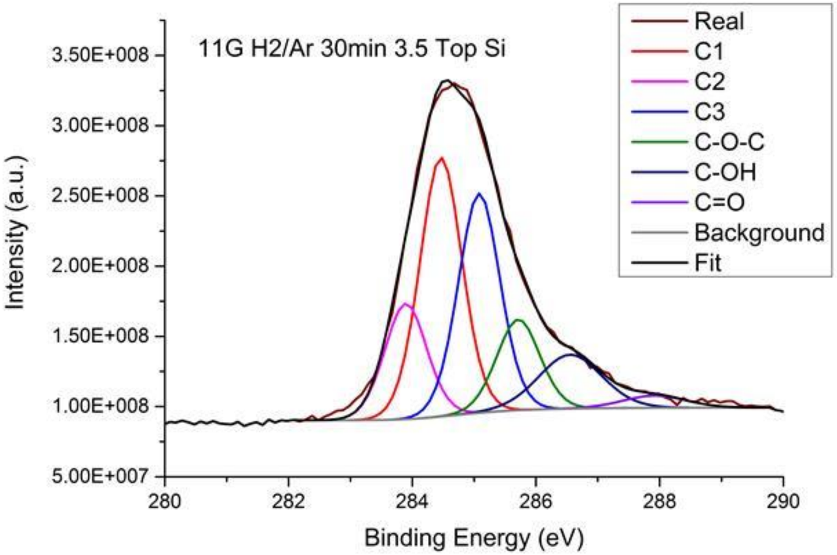
Team: Yevgeny Raitses, Fang Zhao and Chris Tully (Princeton University)

Fig.1 Low-temperature magnetized plasma source, http://htx.pppl.gov/penning.html



Use a cold magnetized plasma (H_2, N_2, Ar, Xe) produced by electron beam (10-100 eV) to minimize a damage to thin film (e.g. graphene) and increase a hydrogen coverage of the film (0.1-10's mtorr)

Fig.2 X-ray photoelectron spectroscopy (XPS)



H coverage=C3/(C1+C2+C3)

C1 is C-C sp^2

C2 is neighbor of C-H

C3 is from sp^3

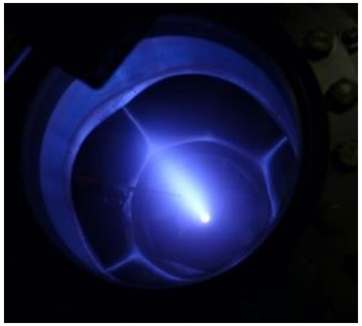
Achieved a record high 38% hydrogen coverage of graphene

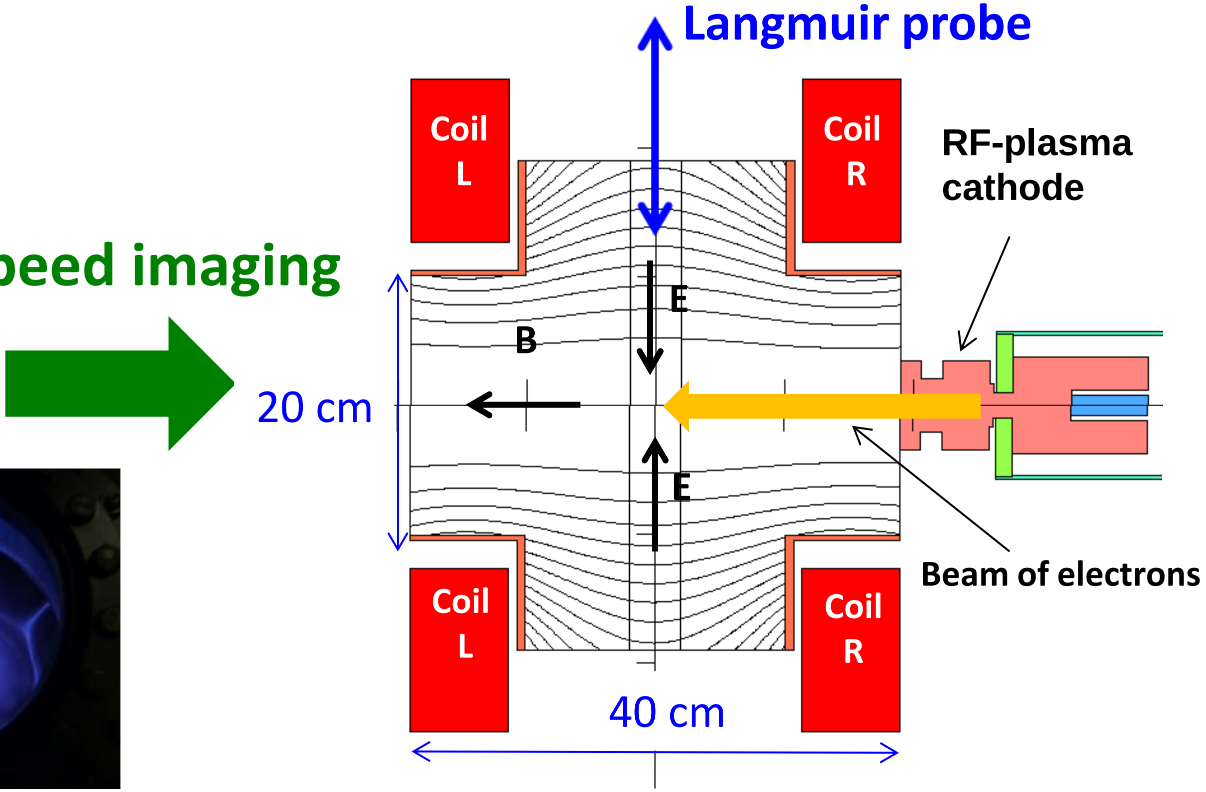
Understanding and Control of Instabilities in ExB plasmas

Team: Yevgeny Raitses, Igor Kaganovich, Andrei Smolyakov (Saskatchewan), Tasman Powis, Eduardo Rodriguez, Valentin Skoutnev, Jacob Simmonds

- E_r and B_z with input parameters, Pressure, B-field , discharge V-I similar to Hall thrusters, but larger plasma size.

- High speed imaging





- Diagnostics: emissive and biased probes, high speed imaging, OES, LIF, RGA

Laboratory for Plasma Nanosynthesis

Princeton Plasma Physics Laboratory

LPN-PPPL Team

The LPN-PPPL collaborative team is assembled of high-level professional experts in the areas of theoretical and experimental plasma and materials sciences as well as advanced plasma and materials diagnostics.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON DC

CASE WESTERN RESERVE UNIVERSITY EST 1826 think beyond the possible

Stony Brook University

U.S. DEPARTMENT OF ENERGY | Office of Science


Yevgeny Raitses (PPPL)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Michael Keidar (George Washington Univ.)


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Bruce Koel (Princeton Univ.)


Predrag Krstic (Stony Brook Univ.)


Longtao Han (Stony Brook Univ.)


James Mitrani (PPPL)


Valerian Nemchinsky (Keisa Univ.)


Angie Capece


Biswajit Santra (Princeton Univ.)

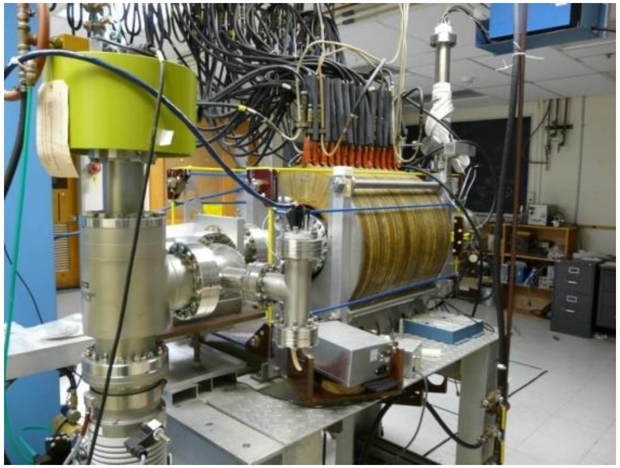

Mohan Sankaran (Case Western Reserve Univ.)

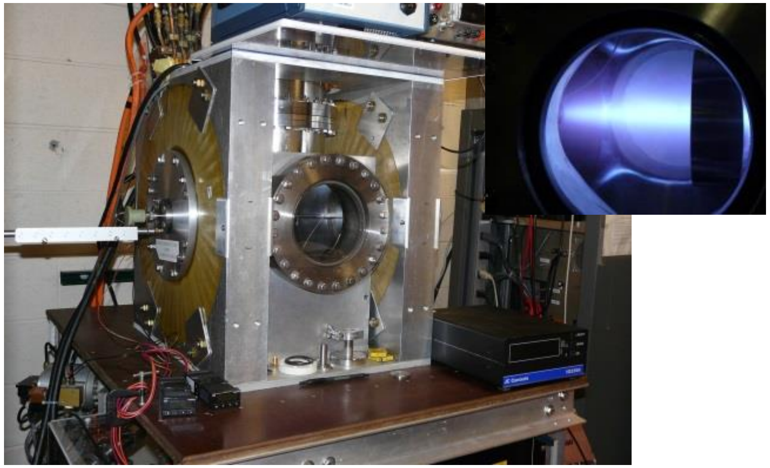

Vladislav Vekselman (PPPL)


Yao-Wen Yeh (PPPL)

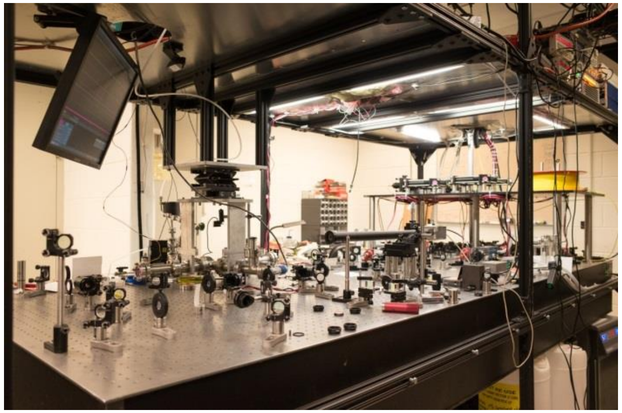

Shurik Yatom (PPPL)

PPPL Laboratory for Plasma Nanosynthesis





- **Atmospheric plasma for synthesis of nanomaterials.**
- **Magnetized plasma for synthesis and functionalization of nanomaterials and material processing at nanoscale.**

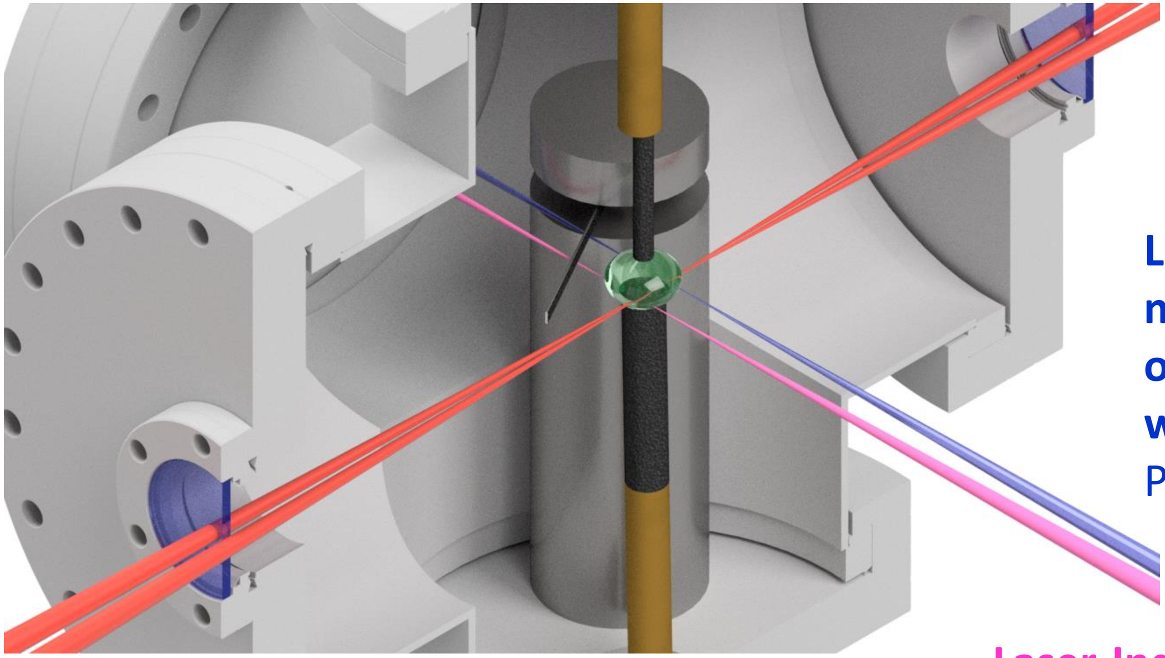


- **In situ laser diagnostic of nanoparticles**
- **New state-of-the-art nanolaboratory for safe work with nanomaterials**

Advanced In-situ Diagnostics for Characterization of Plasmas and Nanoparticles

Fast movable probe to collect & extract nanoparticles from plasma, < 0.5 s, 500 µm (GWU). Collected samples characterized ex-situ by SEM, EDS, TEM, Raman, XRD, etc.

Optical emission spectroscopy (OES), FTIR, Filtered Fast Imaging (FFI) for time-resolved (1 µs) characterization of plasma species.

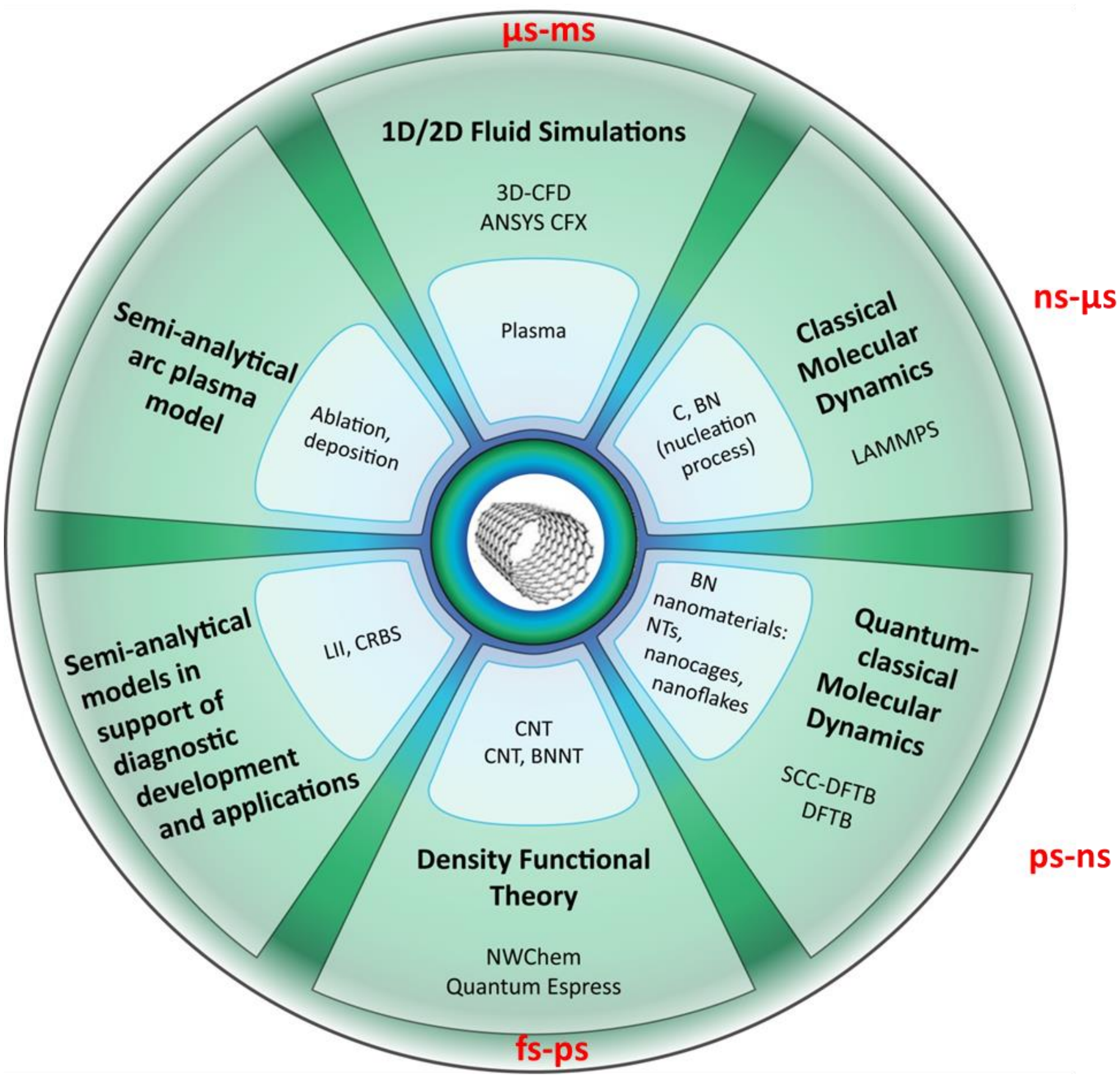


Laser-Induced Fluorescence (LIF) to measure density and temperature of atomic and molecular species with resolution: 10 ns, 100 µm
Pump & Dye lasers, 10 ns, 40 mJ

Laser-Induced Incandescence (LII) to detect nanoparticles > 10 nm with resolution: 10 ns, 2mm x 5mm
Laser: 1064 nm, 100 mJ, 10 ns

Coherent Rayleigh-Brillouin Scattering (CRBS), to detect nanoparticles 1-100 nm with resolution: 10 ns, 100 µm
Lasers: 1064 nm, 200 mJ, 10-1000 ns

Computational tools used for simulations of breakdown, plasmas and nucleation and growth of nanostructures

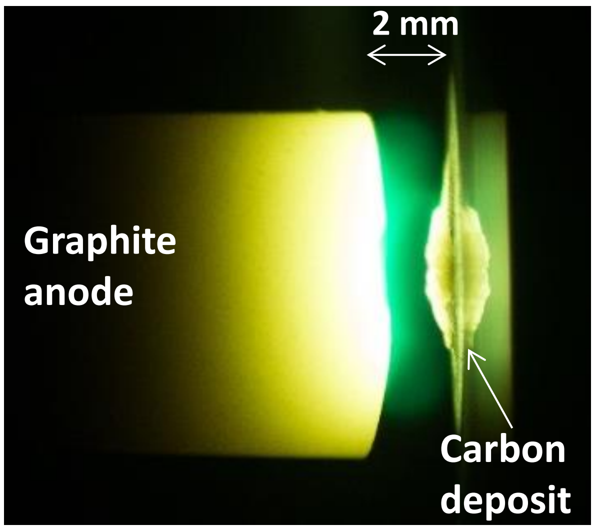


Particle-in-Cell Codes:

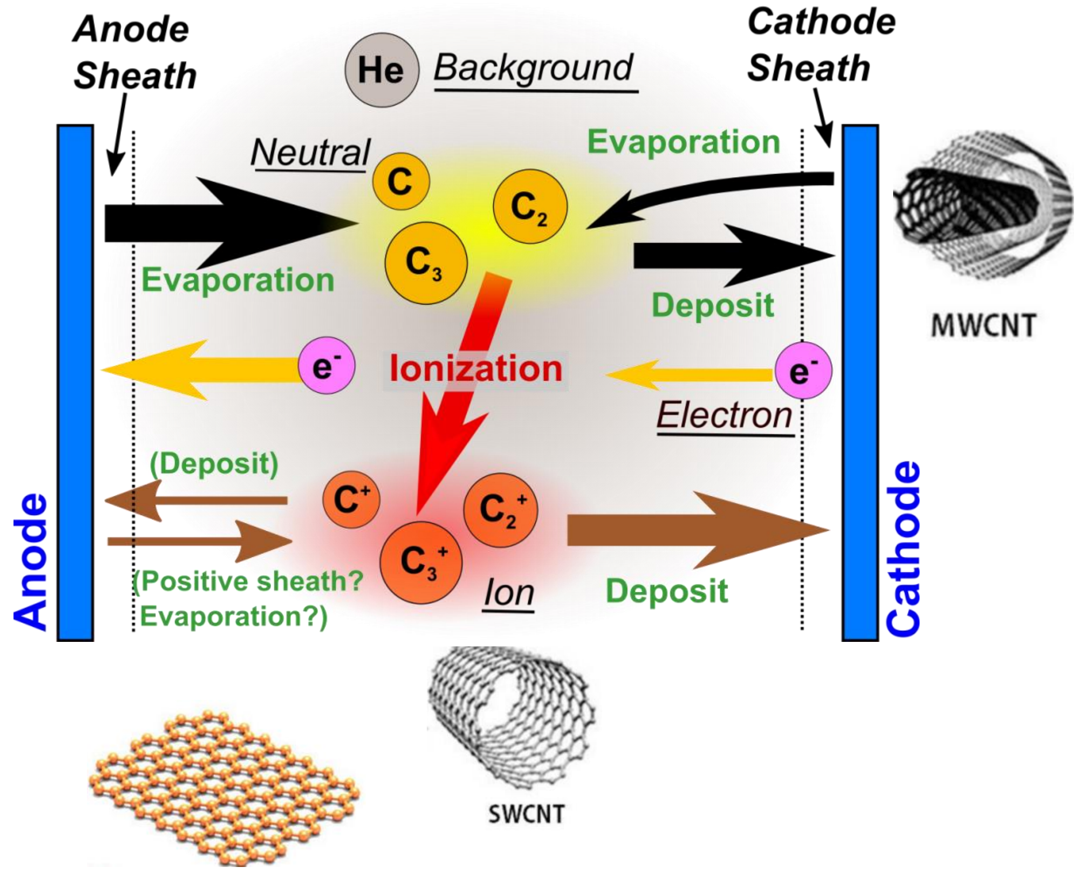
- **EDIPIC code 1-2D, 3V with electron, ion and fast-atom collisions**
- **LSP code 3D, 3V: Modified commercial particle-in-cell Monte-Carlo-collisions (PIC-MCC) code LSP to develop self-consistent kinetic codes which are scalable to simulation sizes for modeling real devices in two and three-dimensions**
- **Both PIC codes are benchmarked and experimentally validated**

Basic plasma and synthesis processes in the arc

- A versatile and extensively studied method of vaporization nanosynthesis
- Good for fundamental synthesis studies– different nanostructures synthesized at different arc conditions: C60, MWCNT, SWNT, graphene flakes, nanofibers
- Evaporation of the graphite electrode (usually anode) heated by the electric arc provides carbon feedstock to produce plasma and nanomaterials

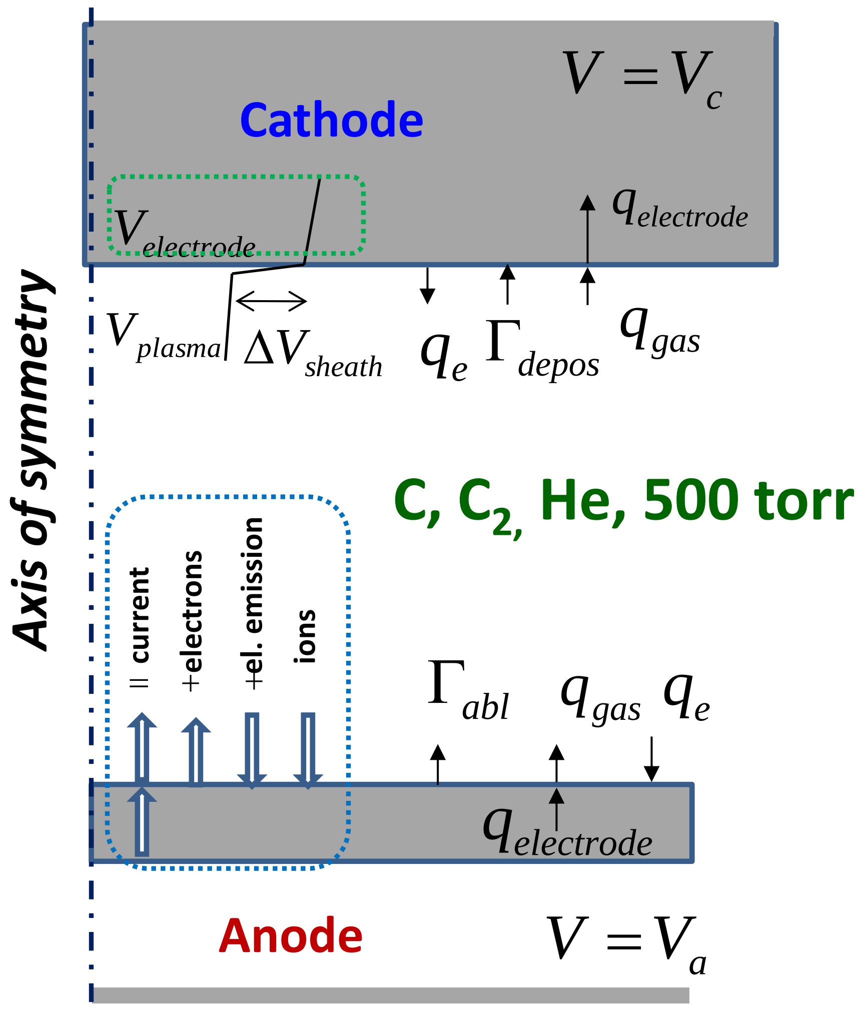


- 1-2 kW input power
- Helium buffer gas
- Atmospheric pressure
- 10 A/cm^2, 10's of Volts



Self-consistent 2-D simulations of the carbon arc

- **The arc model was implemented into a general-purpose code ANSYS-CFX which was highly customized.**



- **Fluid model of plasma**

  -Non-equilibrium plasma ($T_e \neq T_g$, $n_e \neq n_{Saha}$)

  -Drift and diffusion of electrons

- **Self-consistent arc model:**

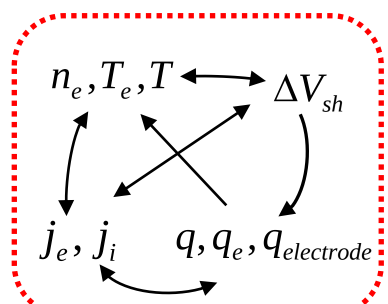
  -Conjugate heat transfer and current flow

  -Plasma-electrodes boundary conditions

  -Heat transfer:

  - ablation/deposition
  - electron emission
  - radiation
  - sheath contribution
  - work function
  - ionization energy

- **Parameters coupling at the electrodes:**

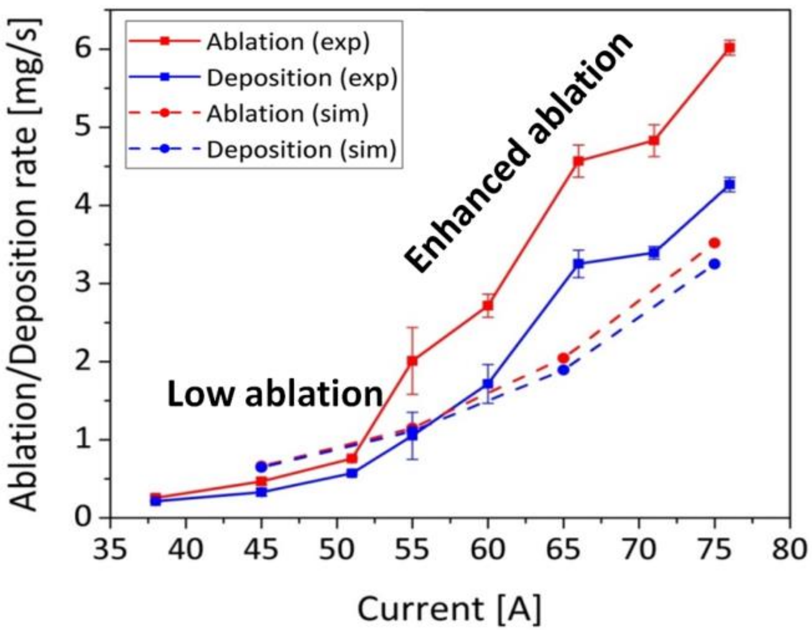


!!! Non-uniform parameters at the electrode surfaces

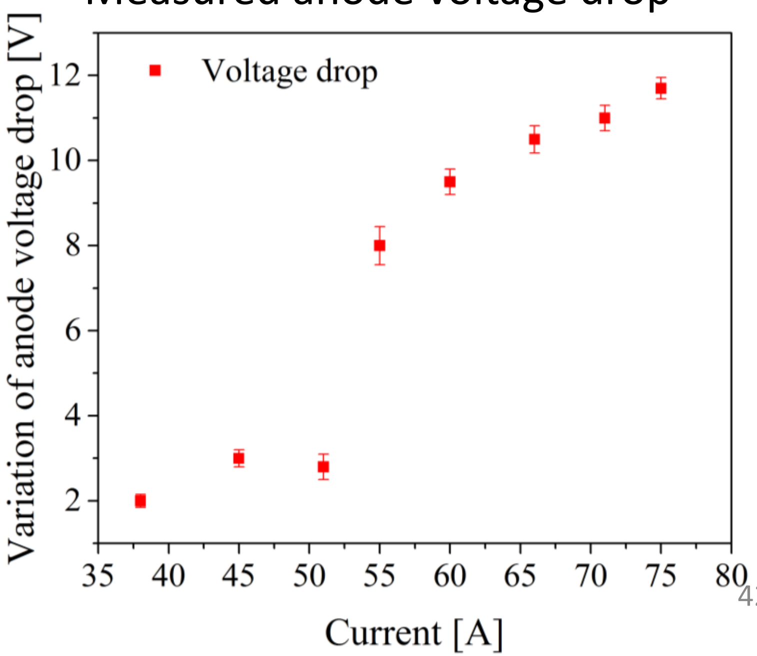
Carbon feedstock by ablation of the graphite anode

- **Two ablation modes of the graphite anode: low ablation and enhanced ablation are typical for carbon and non-carbon arcs.**
- **Simulations show lower ablation rates at large currents than experiments**
- **Theory predicts the increase of the heat conduction to the anode with the flux of ablated carbon products that further increases the anode heating, ablation and the anode voltage drop to conduct the current to the anode.**
  - **We are now incorporating these predicted effects in simulations.**

Measured and simulated ablation/deposition

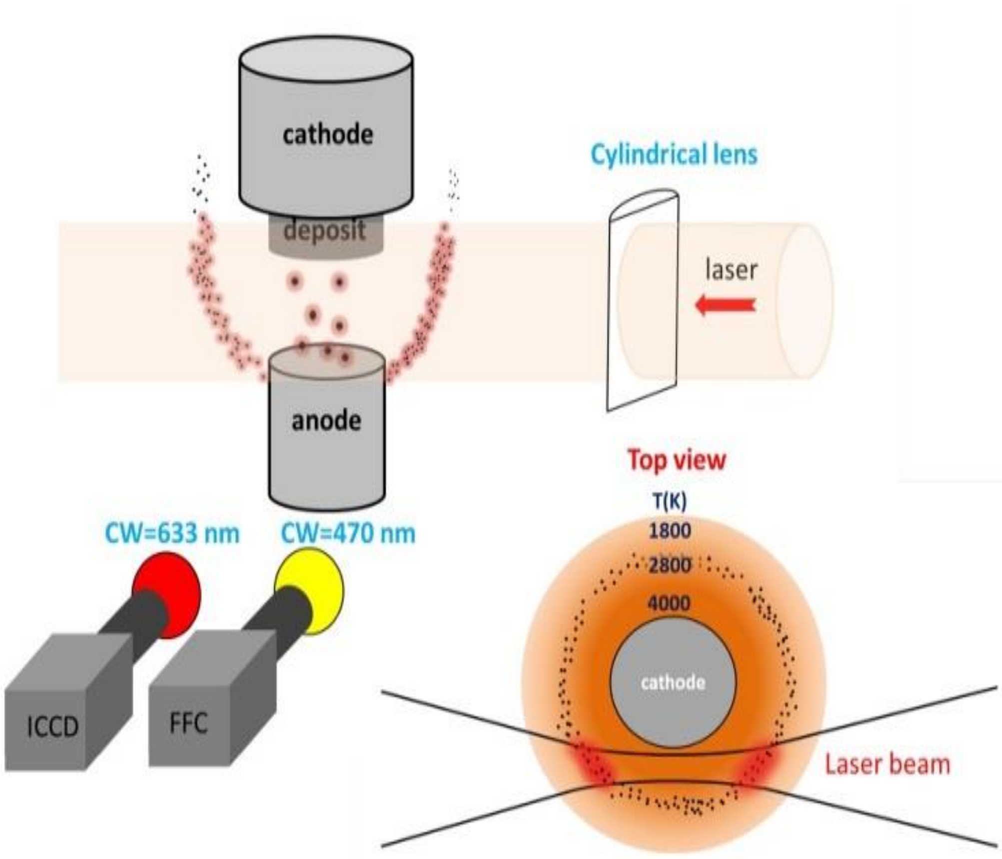


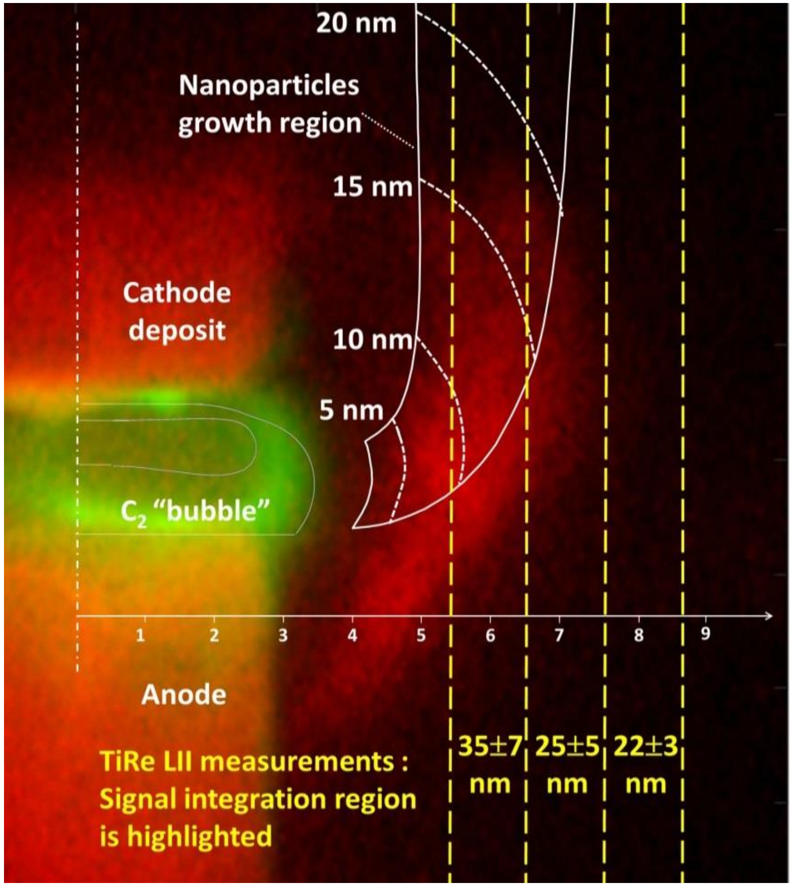
Measured anode voltage drop



Measurements and simulations of nanoparticles

- Experimental set up for laser-induced incandesce (LII), spectral imaging, laser-induced fluorescence (LIF) and the laser beam intersection with the region of nanoparticle growth.
- Areas from which a LII signal was collected are highlighted and the mean particle diameter for each area is shown from LII (yellow) and simulations (white).

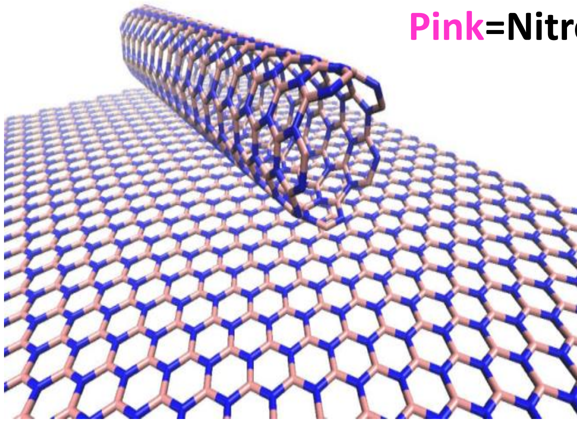




New frontier: *Boron Nitride and B-C-N nanotubes*

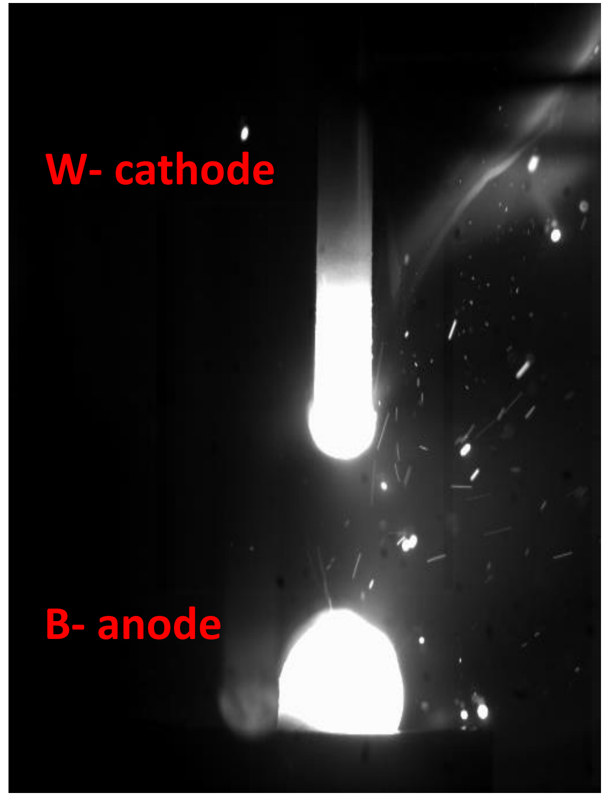
BN nanotubes (BNNTs)

Blue=Boron
Pink=Nitrogen



- Unlike CNT, BNNTs- electrically insulating
- Thermally and chemically stable
- Strong UV and neutron absorption

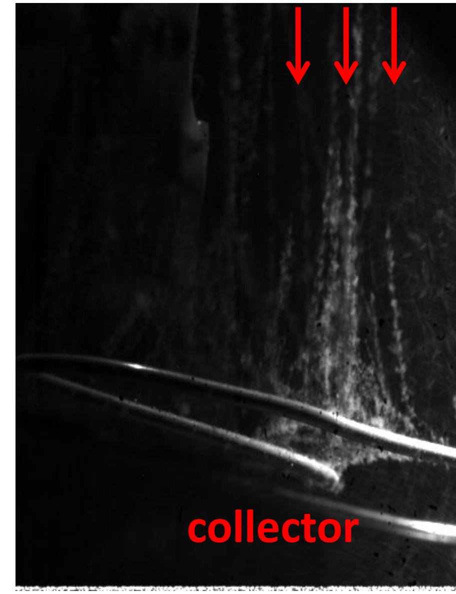
Fast frame (3kfps) video



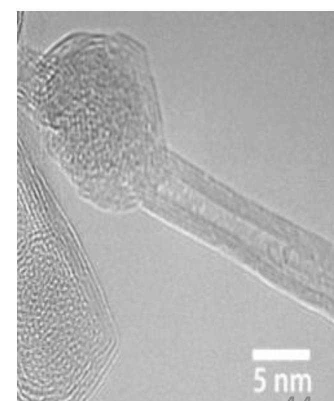
A DC 1 kW arc between 3 mm diameter tungsten cathode and boron anode at 400 torr N_2

Current: 40 A, Voltage~ 30-40 V

BNNT web

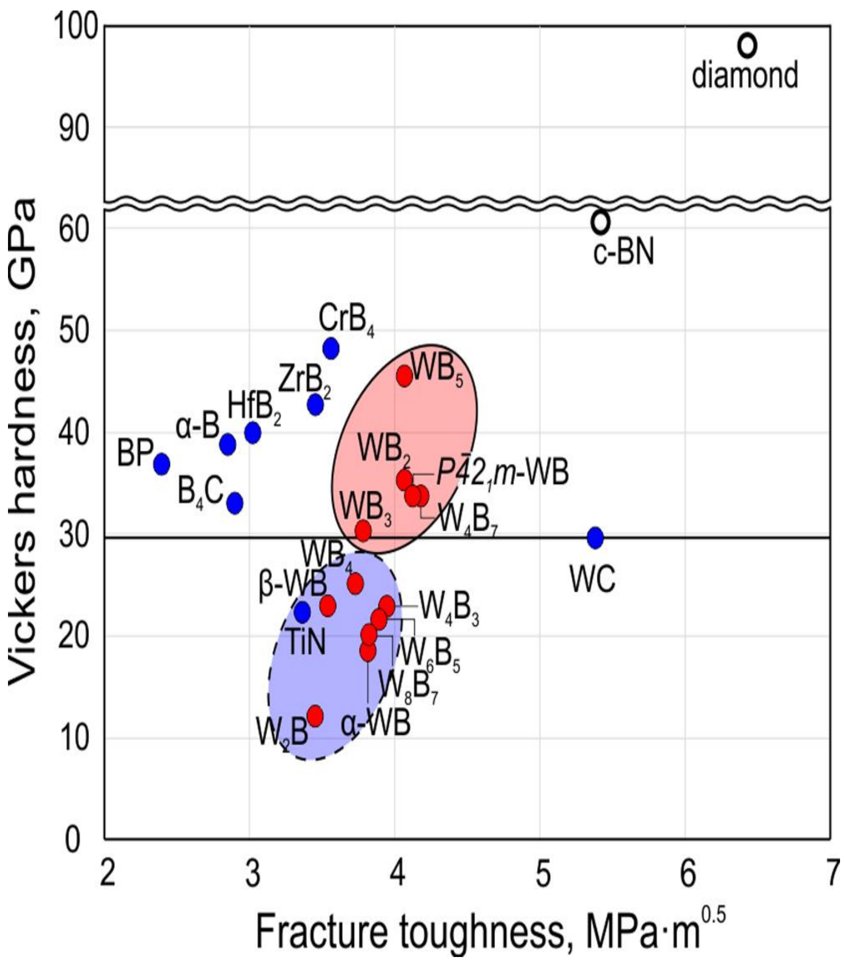


BNNT on boron droplet



New frontier: *New superhard materials*

- **Boron atoms build strong covalent metal-boron and boron-boron bods responsible for hardness of WB materials**



- **WB_X composites, even with X>3, are less expensive than diamond**
- **Can be produced in "standard" environments (already produced or predicted e.g. WB_5)**

A. G. Kvashin et al., J. Phys. Chem. Lett. 9 (2018)

Plasma applications in bio/med/food/agro

Shurik Yatom, Sophia Gershman, Sierra Jubin, Daoman Han, Yevgeny Raitses, Philip Efthimion

Main Objectives:

- **Understanding of scaling of the DBD plasma devices**
- **Uncovering the role of ion-induced and electron-induced SEE processes**
- **Control of stability and interactions (cross-talking) in the multi-plasma array**

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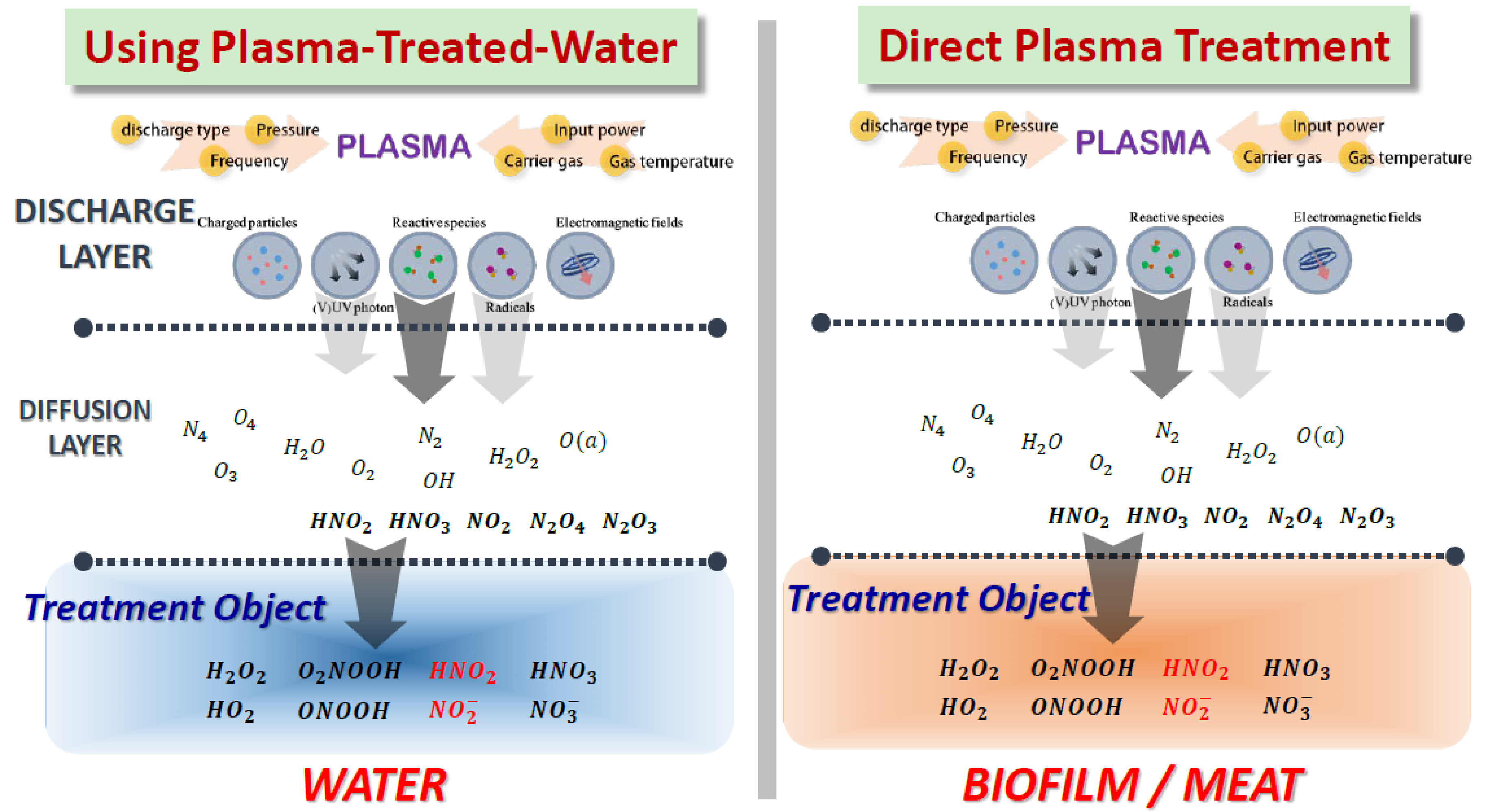
Two viable ways of plasma application for food/agriculture



KAIST

GDPL KAIST Gas Discharge Physics Lab.

Courtesy of Prof. Wonho Cho, KAIST

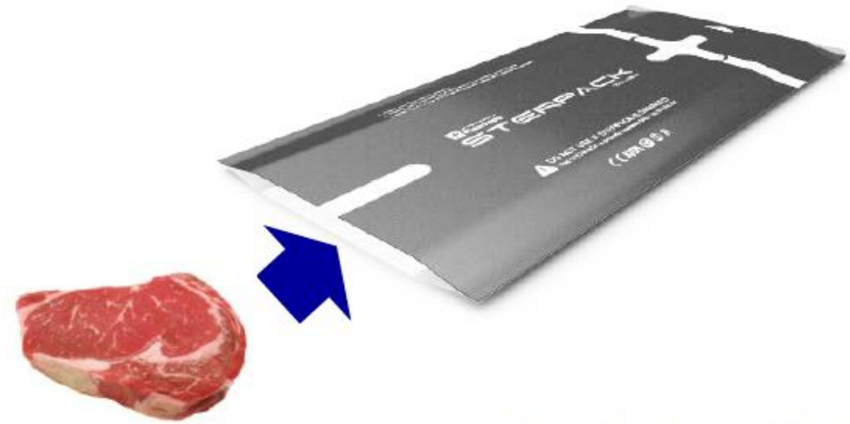
Smart packaging for food products

"Plasma in a Box"

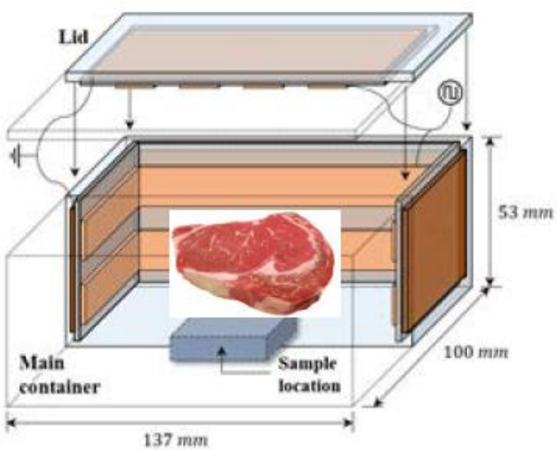
(Lock&Lock^{TM} type plasma packaging)

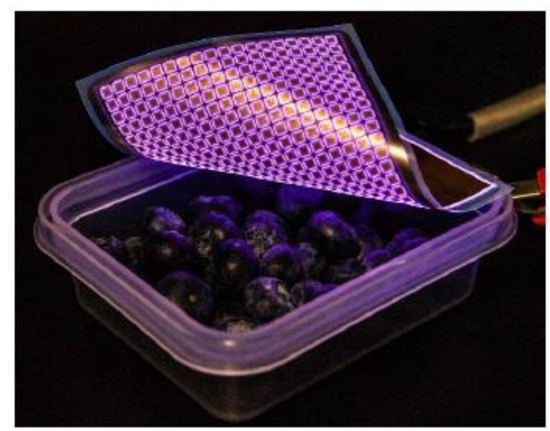
"Plasma in a Pouch"

(Plastic bag type plasma packaging)



Plastic bag / lid



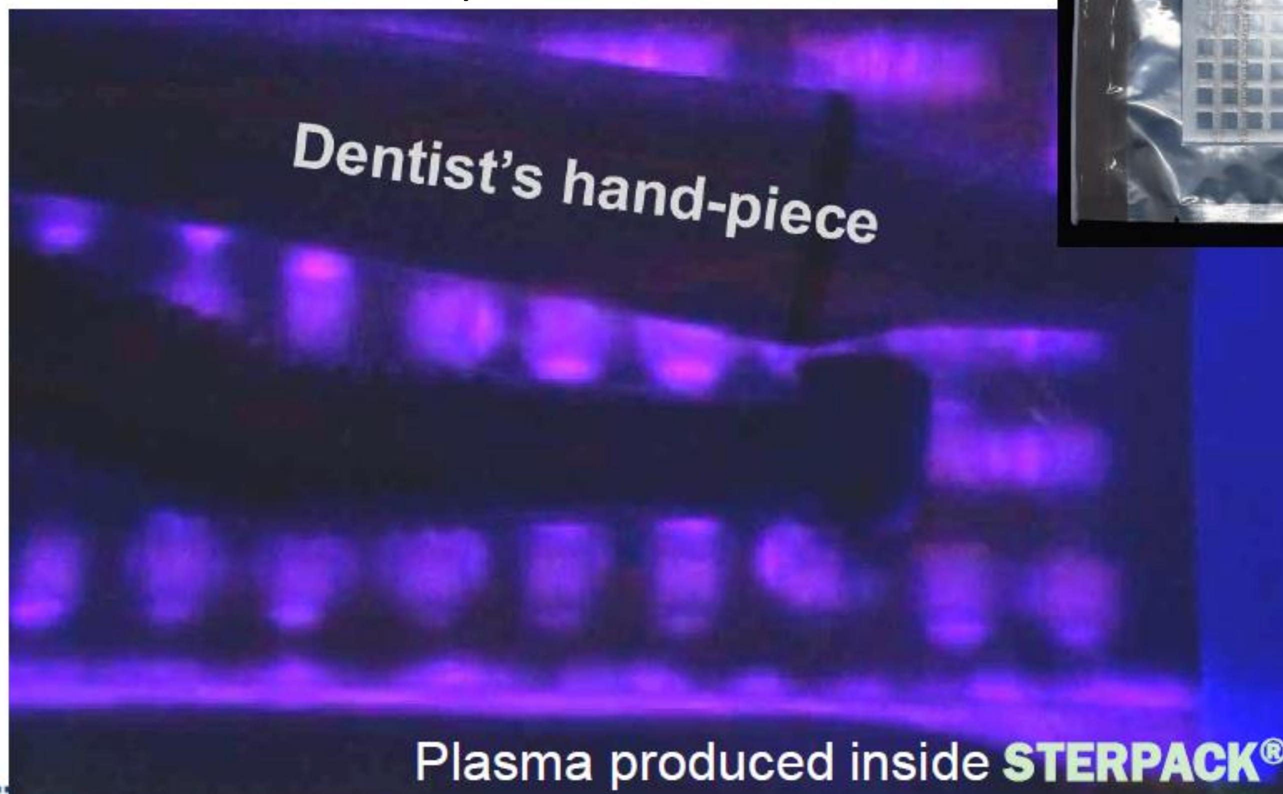


Courtesy of Prof. Wonho Cho, KAIST

Smart packaging for medical devices

- Medical devices are sterilized by the plasma discharged inside **STERPACK®**.
- Tests with chemical and biological indicators demonstrate that **5 minutes** is sufficient for successful **sterilization (10x shorter** than conventional commercial product).

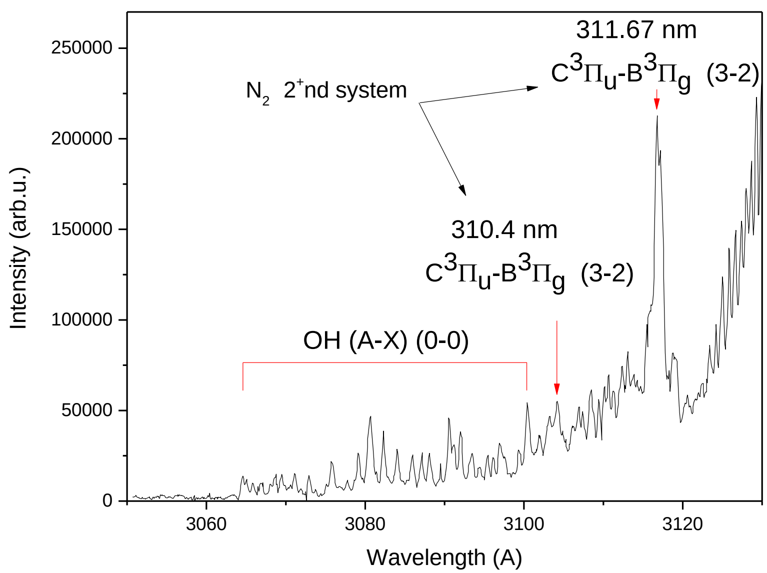
Courtesy of Prof. Wonho Cho, KAIST



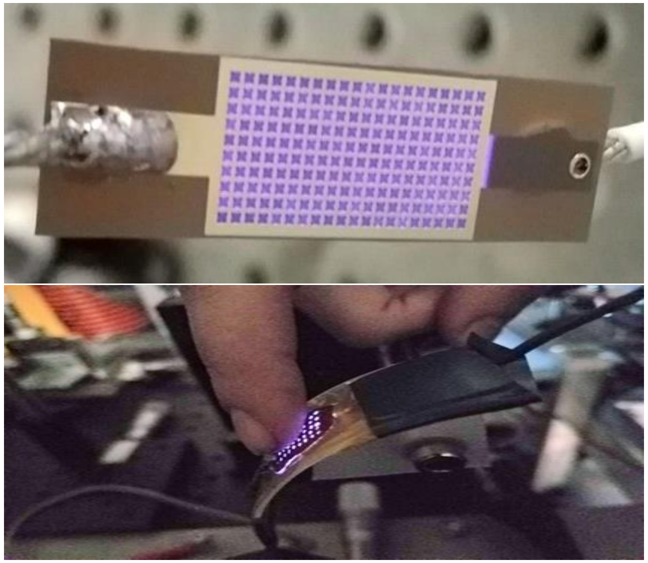
Find plasma solutions at
Plasmapp

PPPL Flexible source of cold plasma for applications on sensitive tissues

- Flexible dielectric barrier discharge (DBD) device was developed as a source of cold and electrically safe plasma, produced across a large area (~ cm^2)
- The generated plasma is chemically active: dissociation of water in the ambient atmosphere is detected via emission from excited OH molecules.
- The device is operated by AC power supply, at frequencies 20-50 kHz, Power<1 W
- Research focus: scaling of the active plasma area with applied power



- Emission of hydroxyl radical



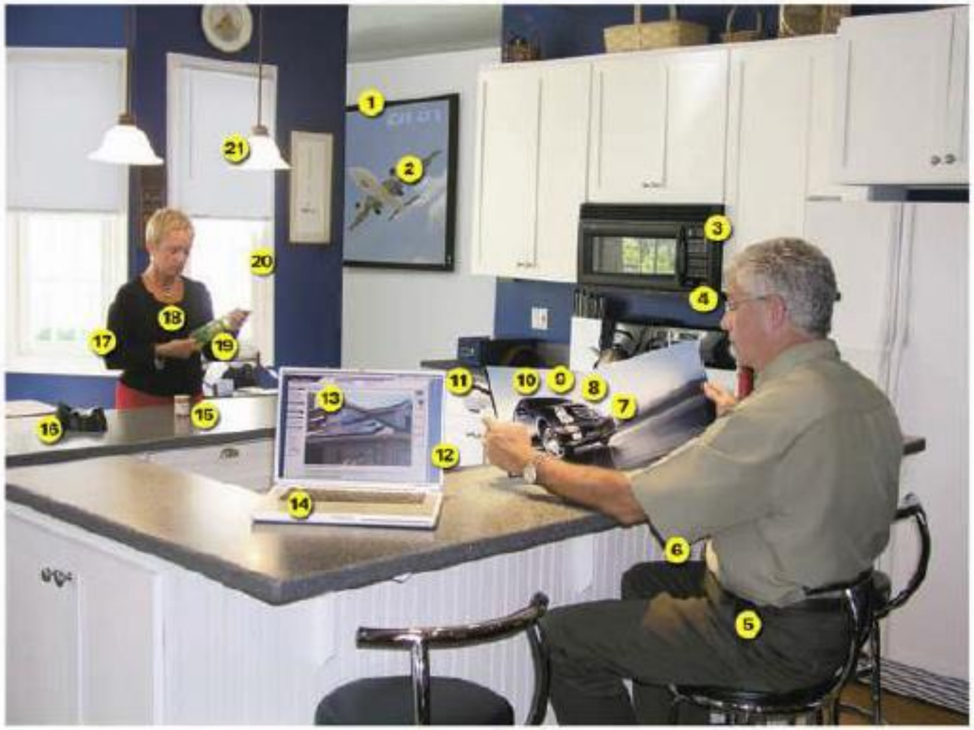
- Flexible DBD device in action

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

psc Department of Energy Plasma Science Center

DOE Plasma Science Center
Control of Plasma Kinetics

Low Temperature Plasma is Everywhere



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

Plasmas in the kitchen. Plasmas and the technologies they enable are pervasive in our everyday life. Each one of us touches or is touched by plasma-enabled technologies every day.

Plasma Science: Advancing Knowledge in the National Interest. Plasma 2010 Committee, Plasma Science Committee, National Research Council. ISBN: 0-309-10944-2, 280 pages, (2007)

Acknowledgment

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Jose Lopez