Plasma Control of EM Waves/High Energy Density Plasma Jets

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Michigan Institute for Plasma Science and Engineering (MIPSE)
Seminar Series: March 28, 2018

Acknowledgements

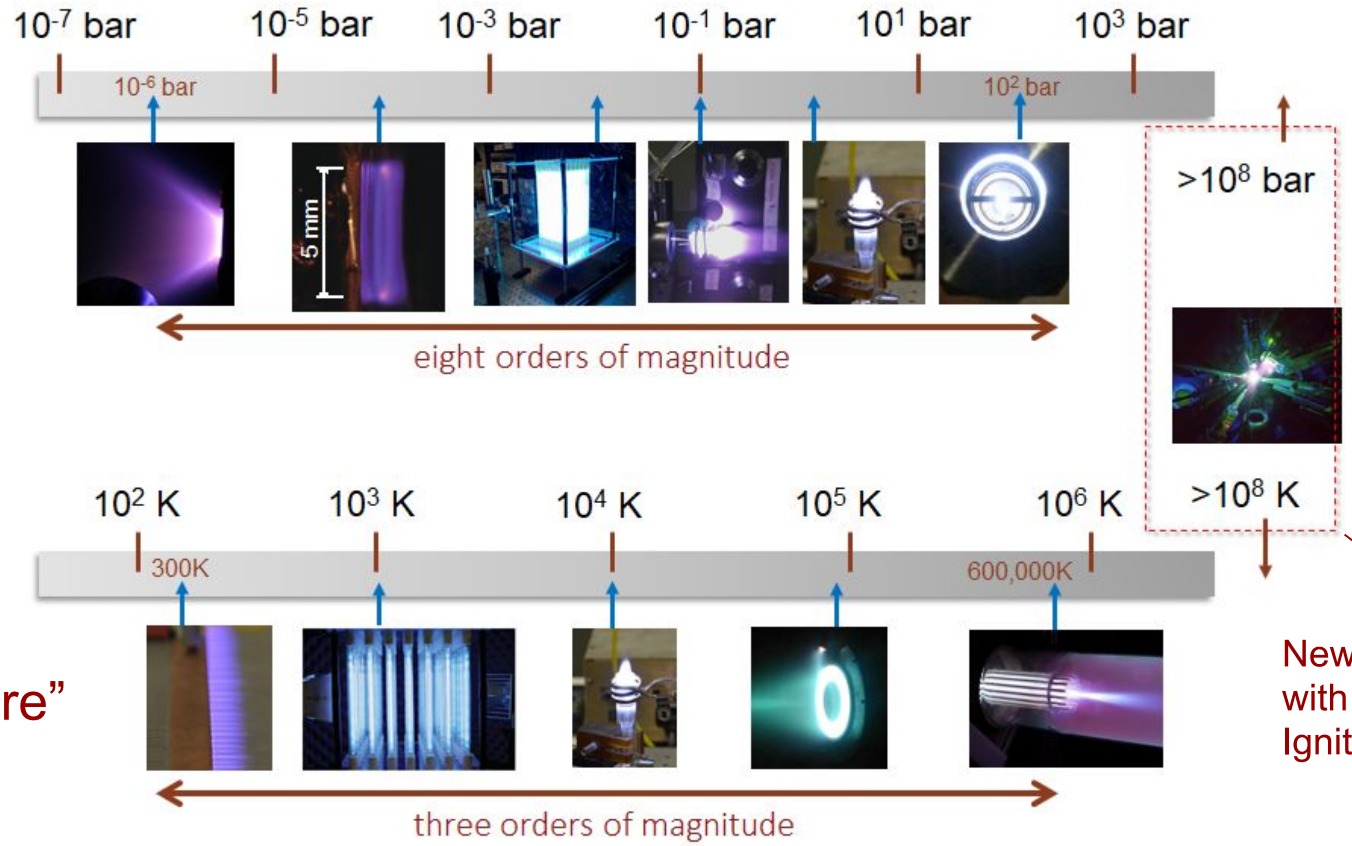
- AFOSR - MURI
- DOE (NNSA-SSAP)
- Collaborators: L. Raja, T. Ito
- Graduate students

Go Blue!

Expose Students to a Wide Range of Conditions

Pressure

Ion "Temperature"



New Collaboration with the National Ignition Facility

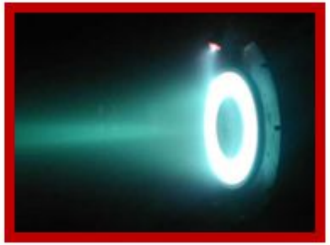
Research Interests

Plasma Aerophysics

Space Plasma Propulsion

Plasma-Assisted Combustion

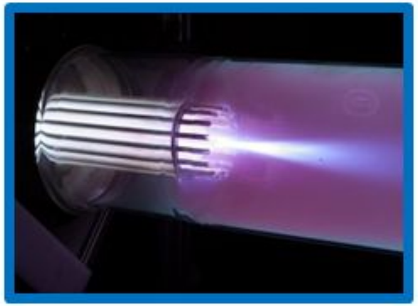
Plasma Aerodynamics



Plasmas in Extreme Conditions

High Pressure Discharge Physics and Chemistry — T. Yong

High Energy Density Plasma Physics — W. Riedel, T. Underwood

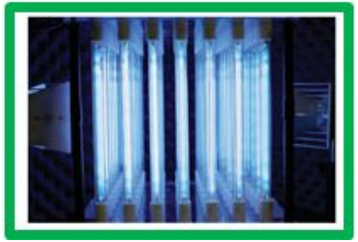


EM Wave-Plasma Interactions

Plasma Metamaterials — R. Colon, R. Lee

Plasma Photonic Crystals — B. Wang, F. Righetti

Plasma Control of Guided Microwaves — A.Marcovati, D. Biggs



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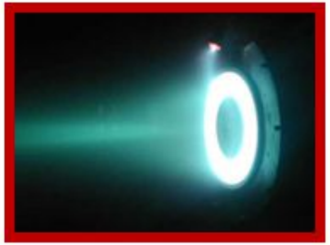
MIPSE 2012



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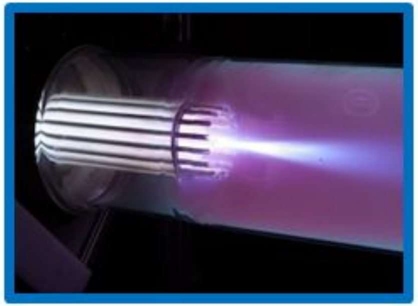

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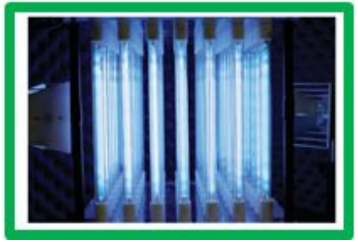

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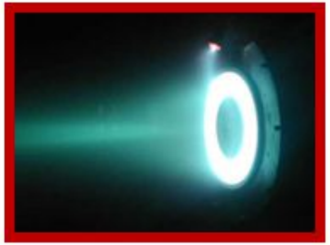

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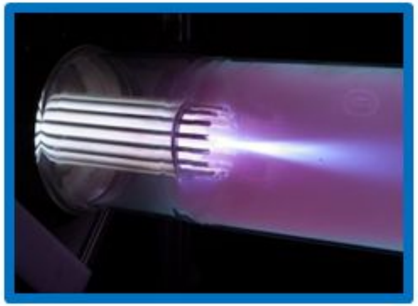

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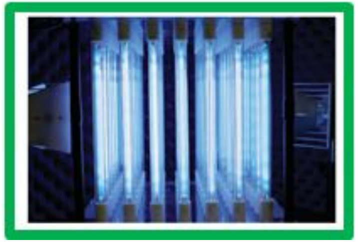
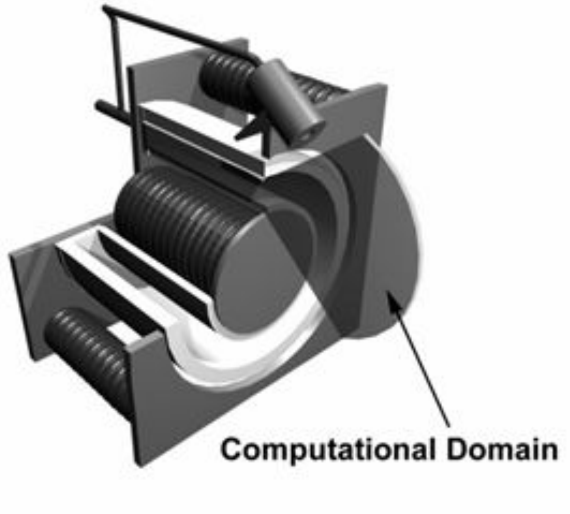
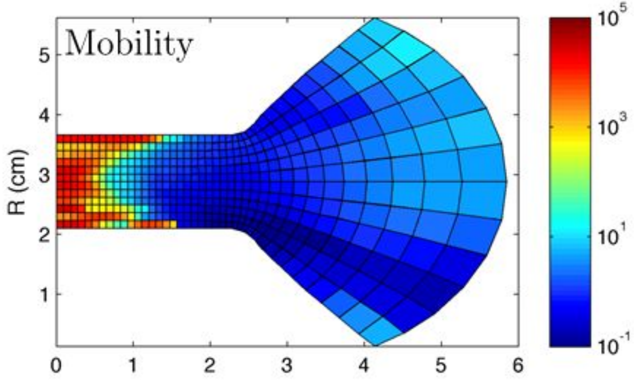


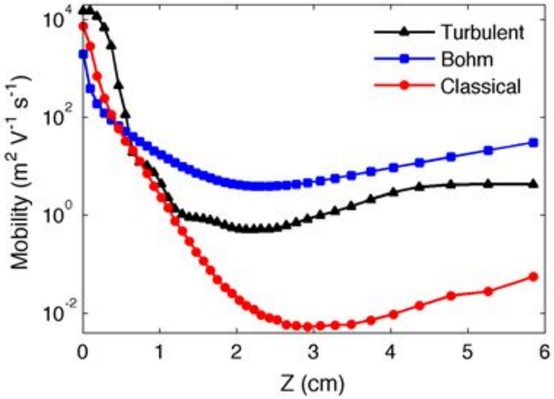
Hall Thrusters

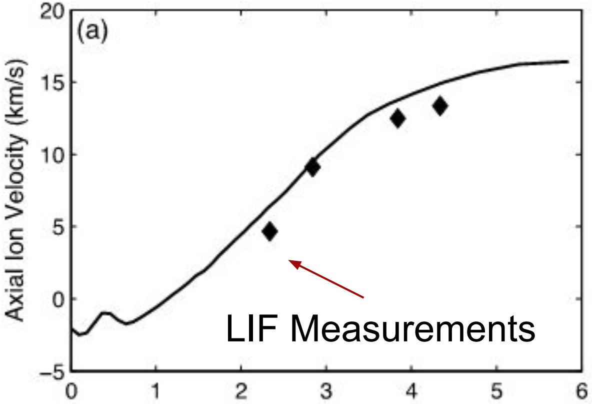
Electron Transport Models for Hall Thruster Simulations



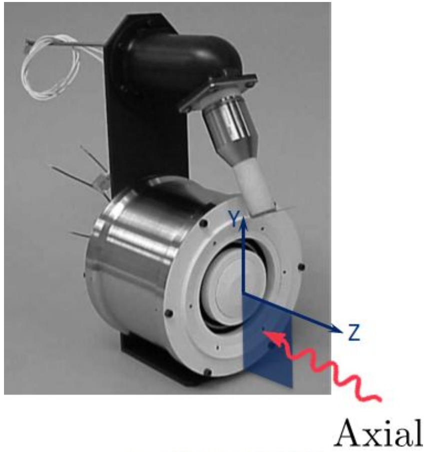


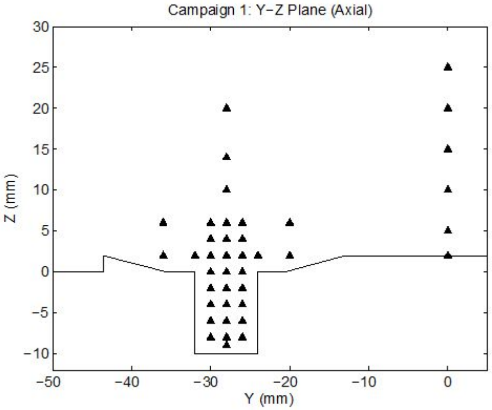
$$\mu_{\text{eff}} = \left(\frac{|J_{e\perp} E_{\perp}|}{K n_e e c_e^2 B^3} \right)^{1/2}$$





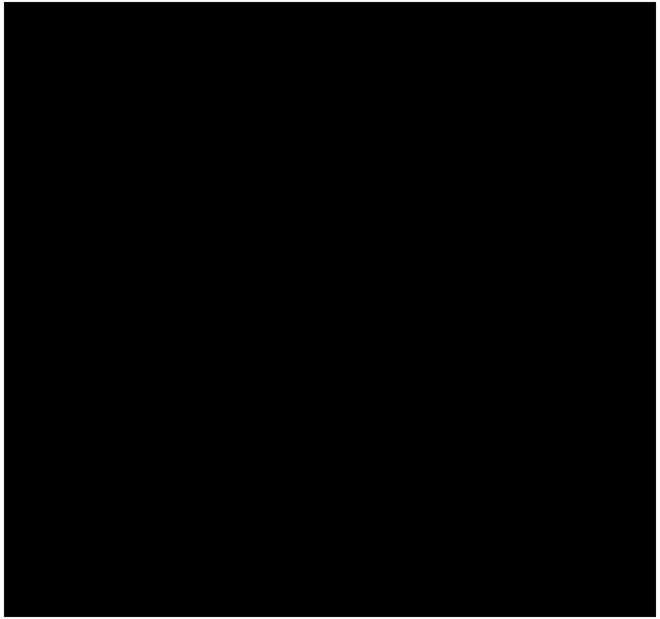
Hall Thruster Diagnostics



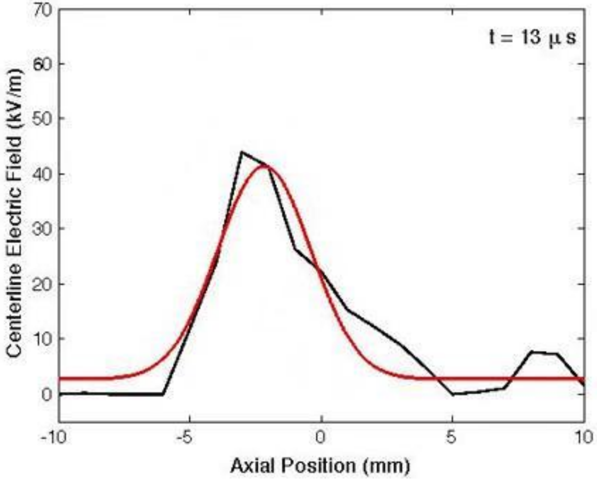


Time-Current Synchronized LIF Velocimetry

Axial Velocities within Channel



Inferred Electric Field



$$E_z = \frac{m_i}{e}\left(\frac{\partial v_z}{\partial t} + v_z \cdot \frac{\partial v_z}{\partial z}\right)$$

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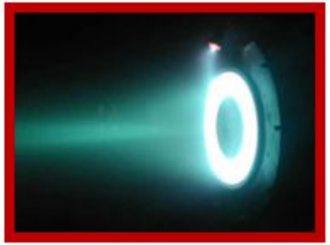

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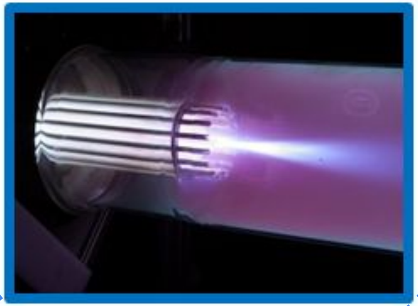

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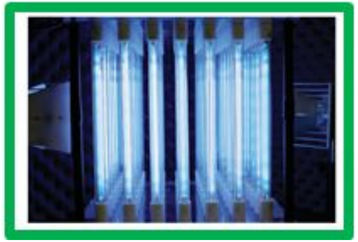
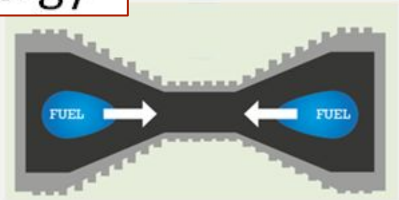
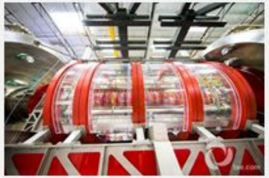


Fusion Quo Vadis? High Energy Density Plasma Jets?

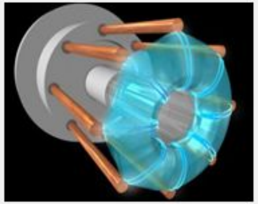
Helion Energy



Tri-Alpha Energy



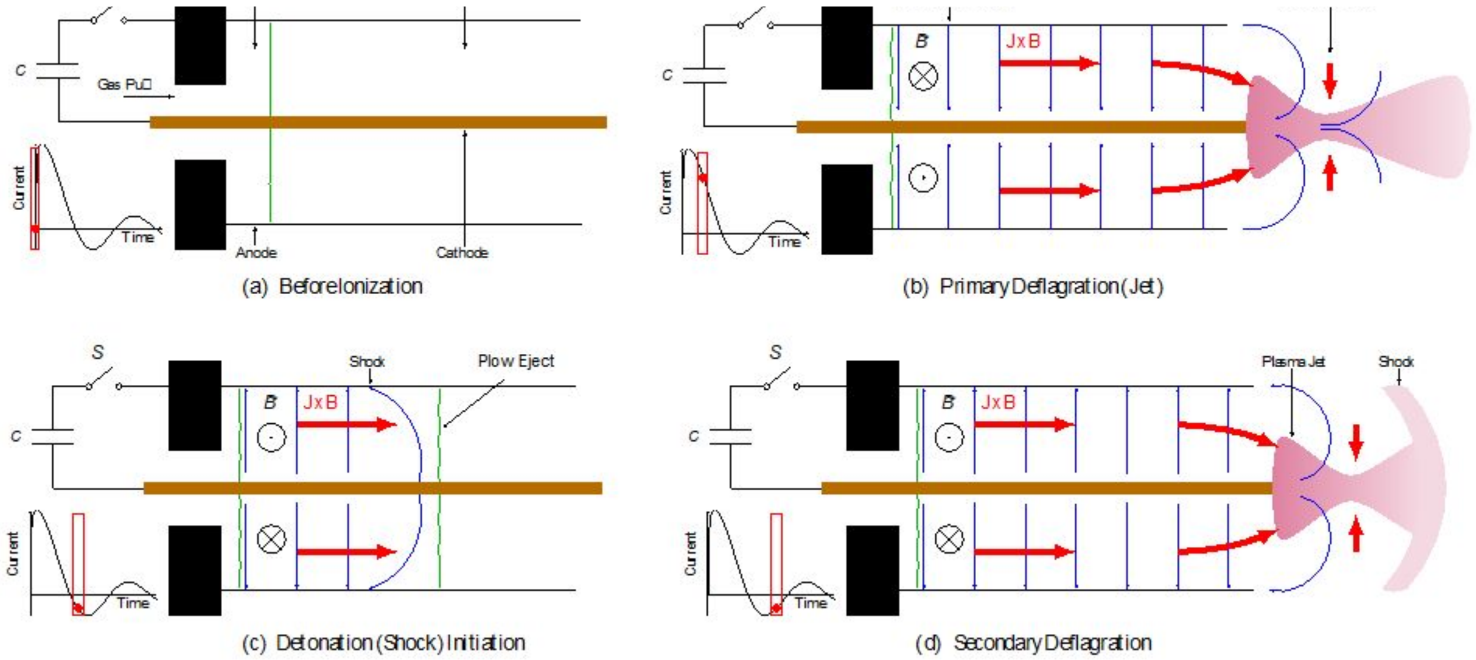
LPP Fusion

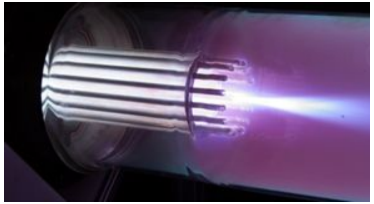


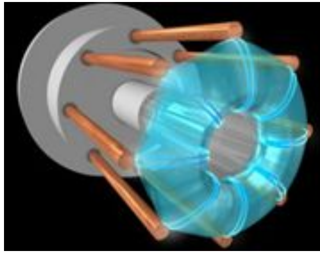
- Colliding/converging and magnetically-compressed plasma jets
- conditions intermediate to MCF and ICF
  - $n_e = 10^{17}$-10^{18} cm^{-3} (10^{23}-10^{24} m^{-3})
  - T = 10^6-10^7 K
  - T ~ 0.1 - 5 ms

Deflagration Plasma Accelerator (Mathers-type)

- two branches of operation (Loebner et al, PRL 2015)
  - smooth expansion into vacuum or shock
- distinguished by prefill or vacuum fill initial conditions





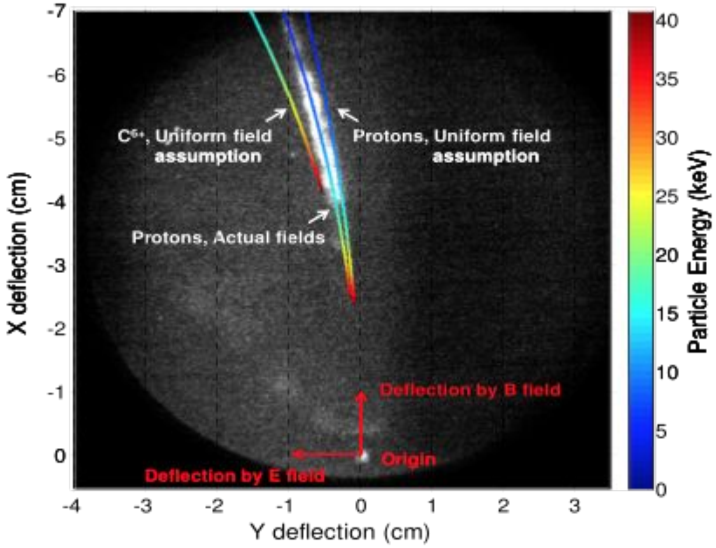


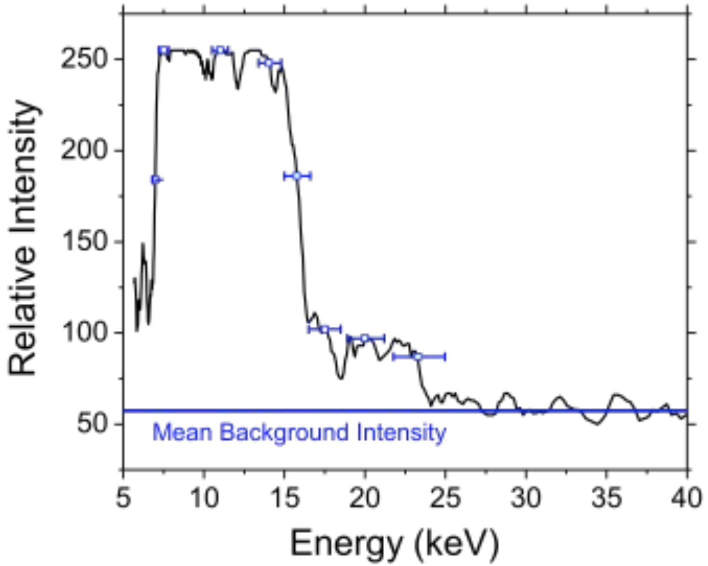
An Interesting (and Unresolved) Characteristic

In the deflagration mode the plasma is a source of high energy protons

- small fraction of the total hydrogen flux
- evidence of this also reported by Mather in 1969

Poehlmann et al, PoP 2013

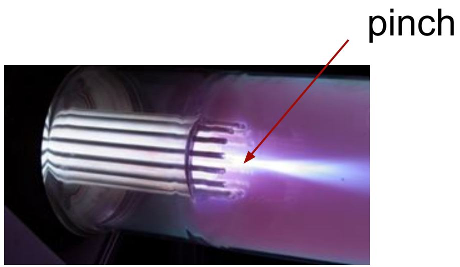


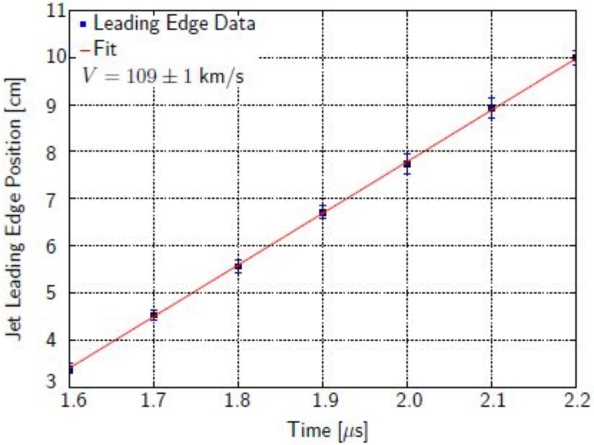


Interesting Properties at Exit of the Gun

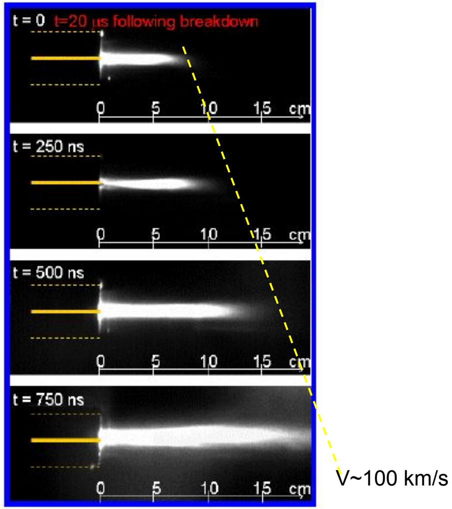
Measured:

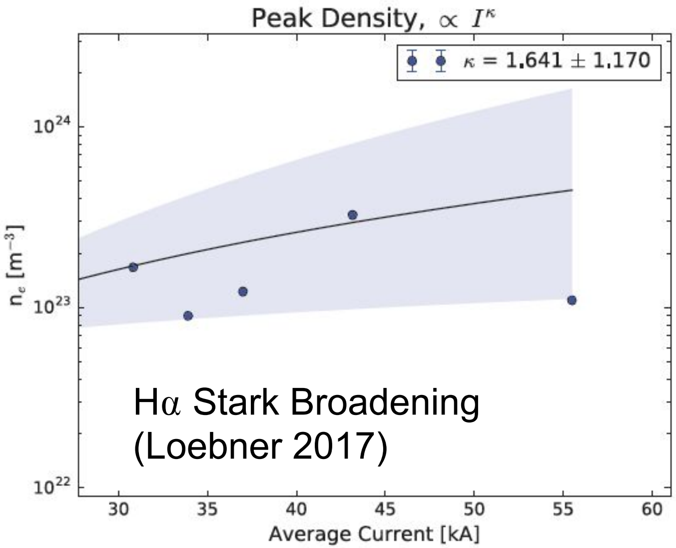
- jet velocity, pinch current, n_e
- infer self-generated B (~1T), T (20 – 50 eV)
- flow is supermagnetosonic: $M = \frac{V}{V_A} \approx 1 - 1.5$





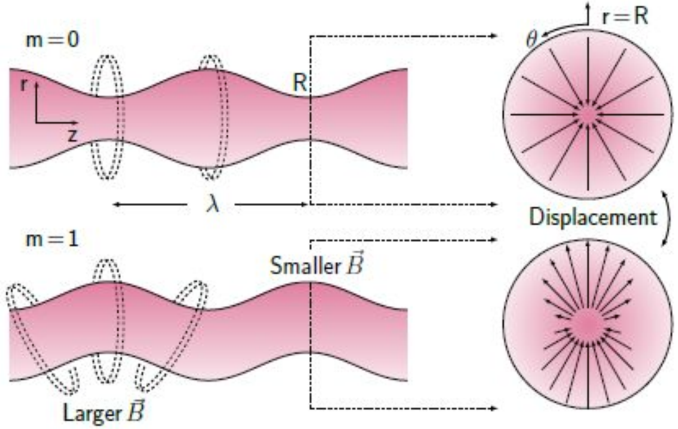
Underwood et al, HEDP 2017

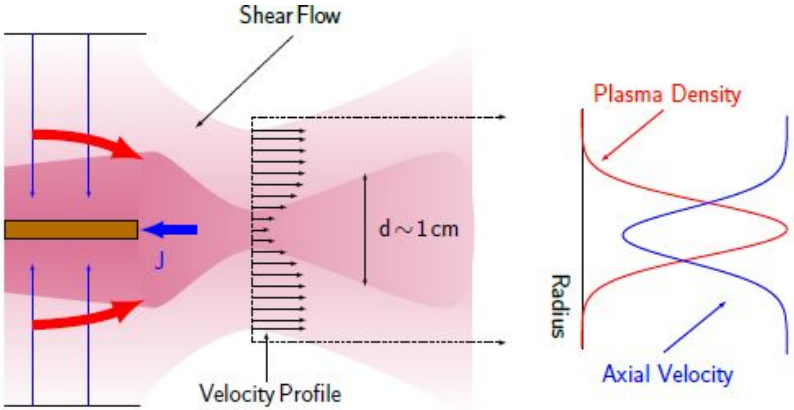


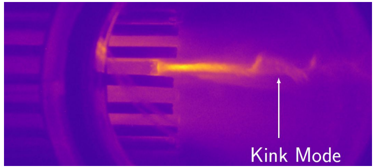


Expect Classic Pinch Instabilities

- plasma at exit is swept into the cathode wake where pinch assembles
- surrounding flow of higher velocity
- velocity shear serves to stabilize the pinch (Shumlak, PRL 1995)

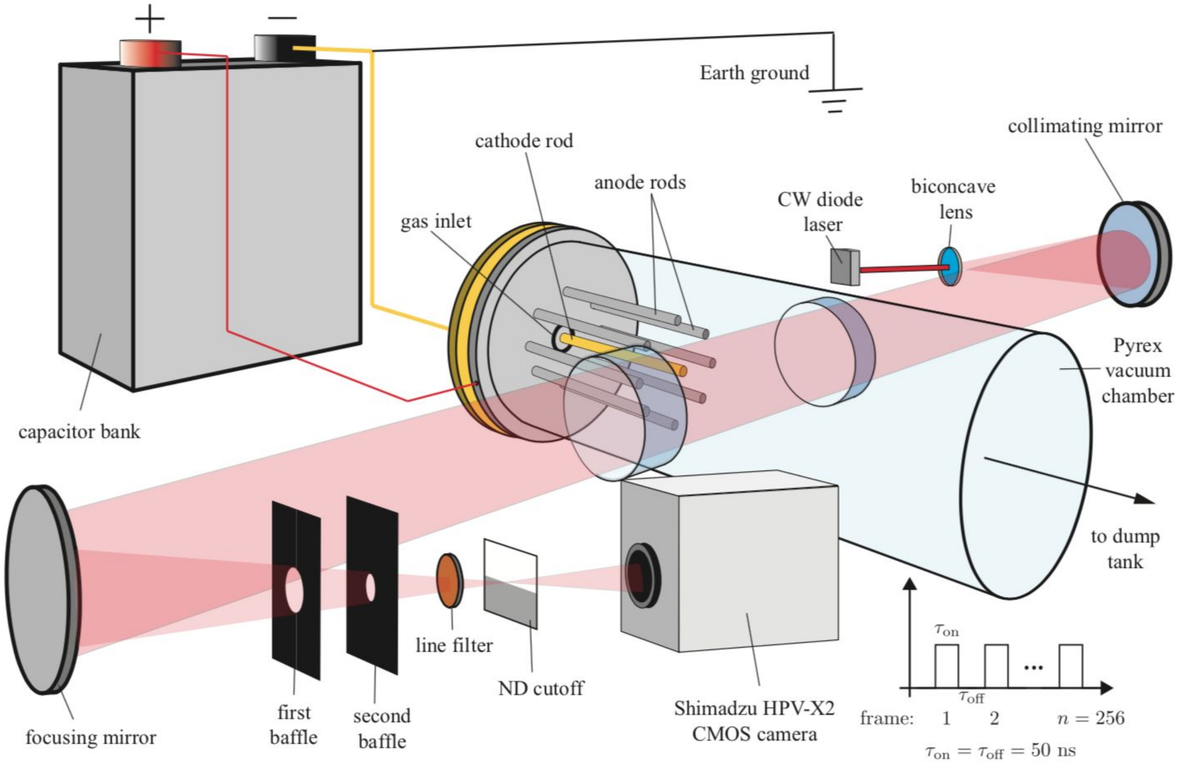






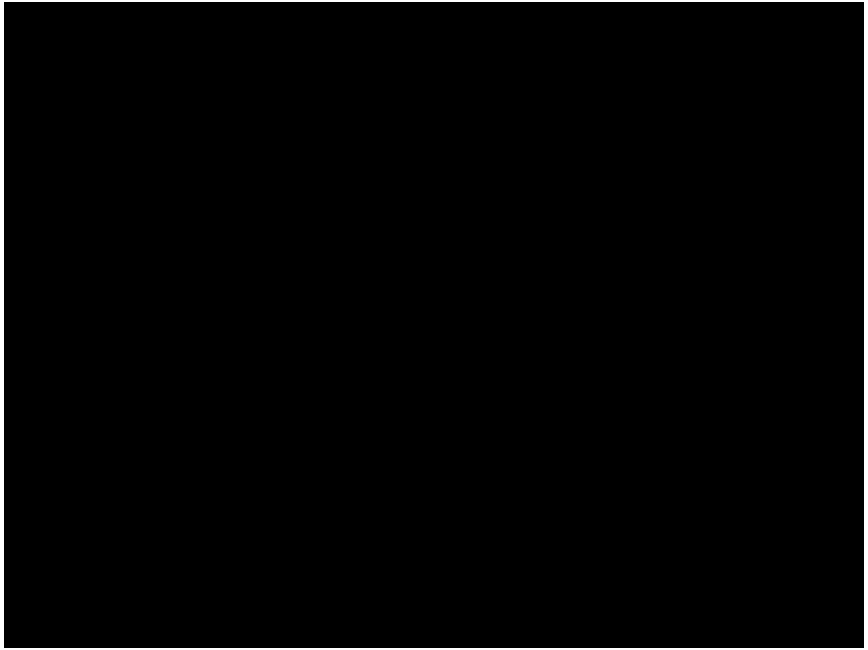
evidence of kink (m = 1) instability

Schlieren Videography of Jet and Pinch Region

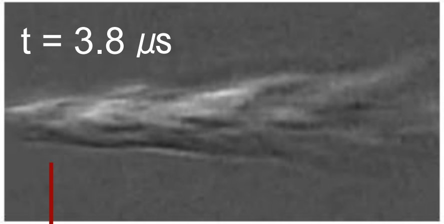


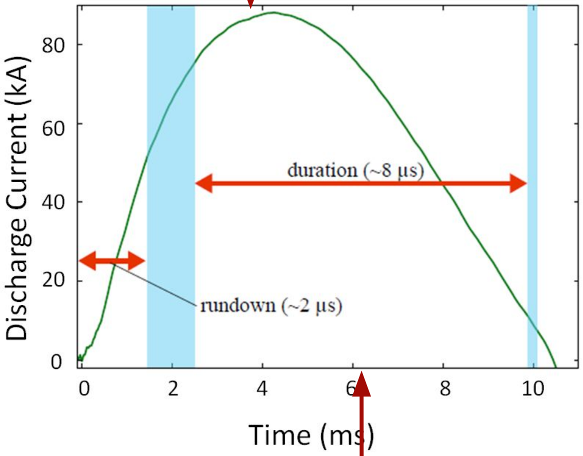
Schlieren Videography of Jet and Pinch Region

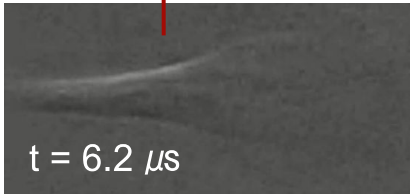
Full 10 MHz Video



low current/low shear

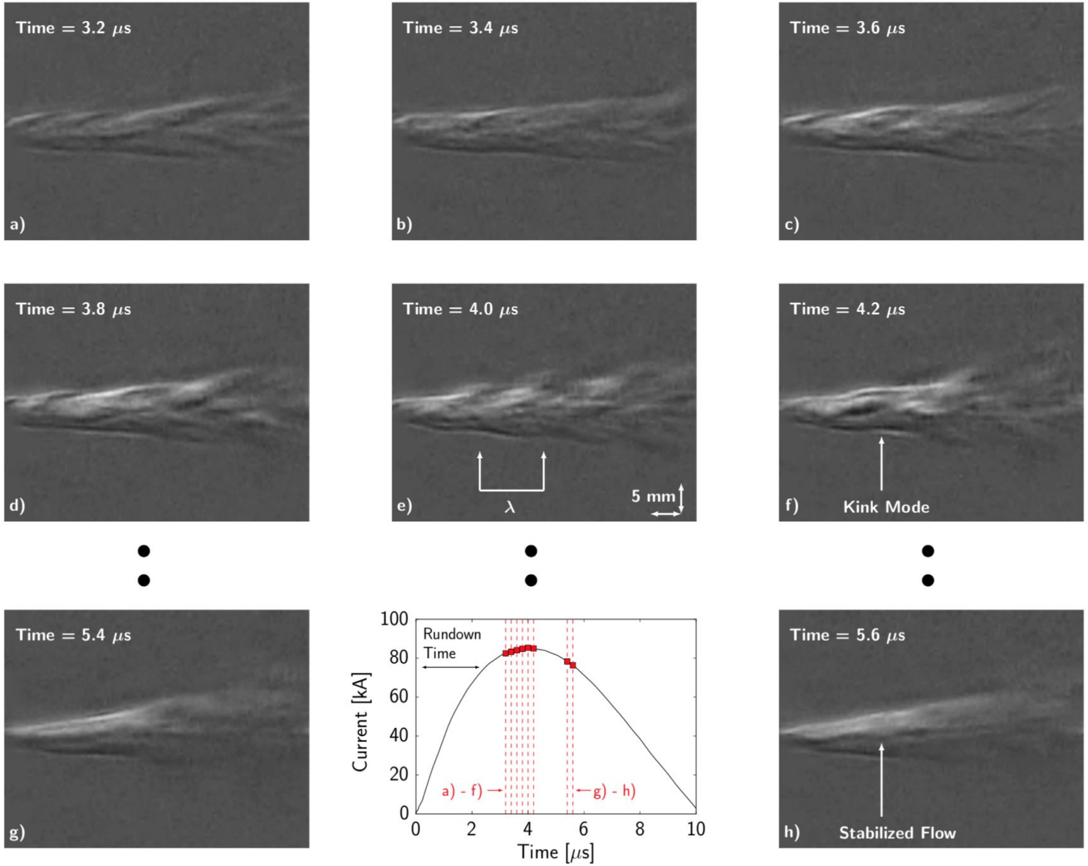




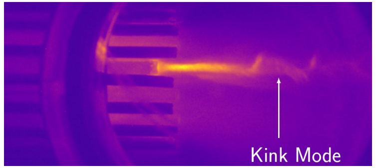


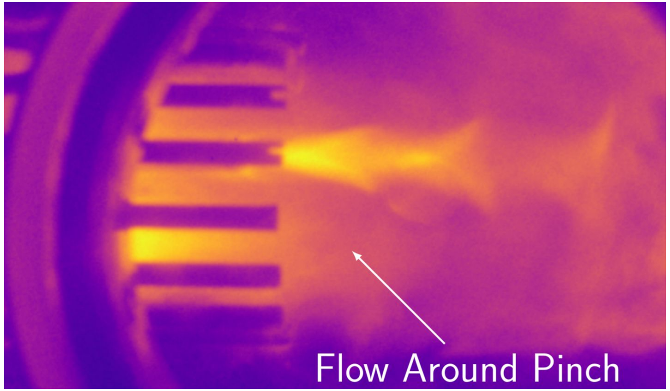
high current/high shear

9 kV (Hydrogen)



Lower voltages (4 kV): lower external flow velocity and current:

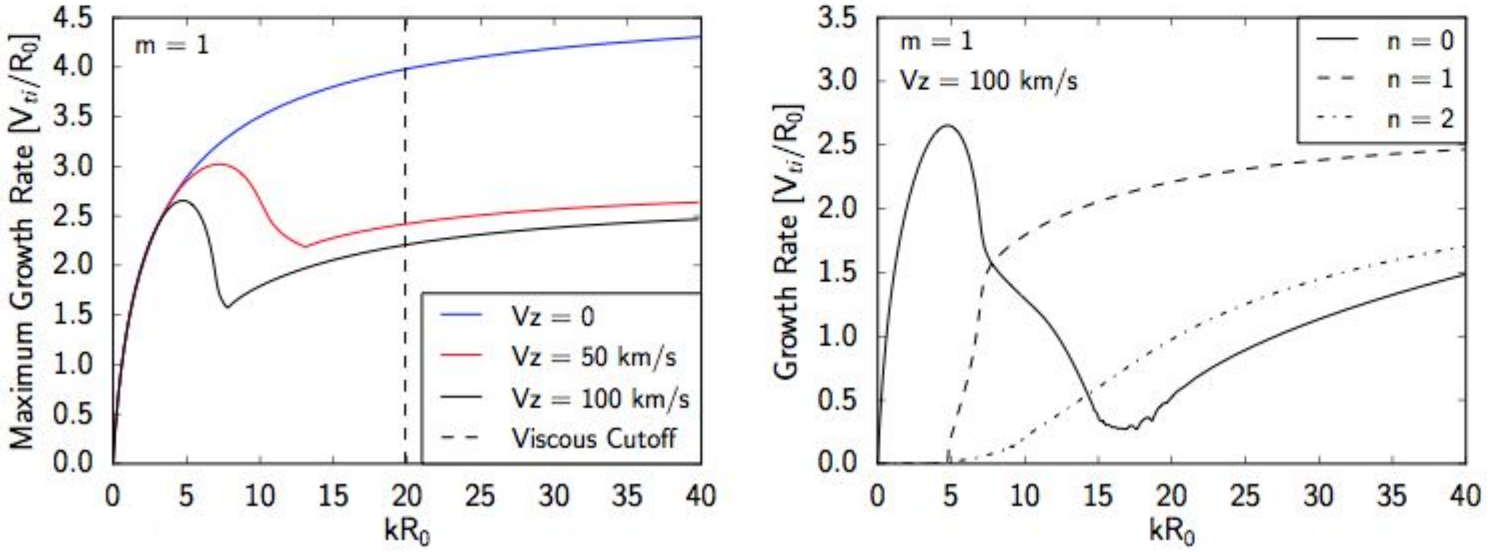




5 ns frames from ICCS camera

Linear Analysis of Jet Stability

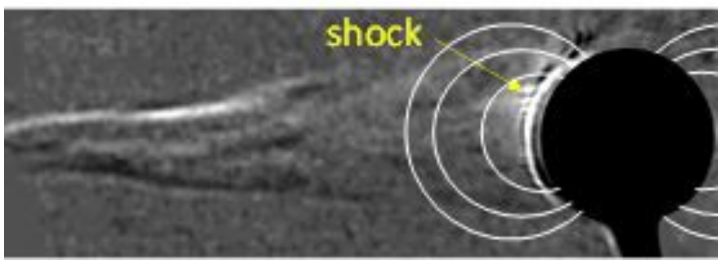
- Fourier analyzed the linearized ideal MHD equations
- Identified the fastest-growing axial mode (m = 1, kink)
- Surrounding flow found to damp higher k contributions (shorter wavelength)



Future Work

- What is the source of these fast ions?
- Can we extend the stable period by extending current pulse duration and total energy?
- shocks (for astrophysical relevance)

Interstellar shock around young star L.L. Ori



Schlieren image of shock around magnetized (B = 1T) sphere (terrella)

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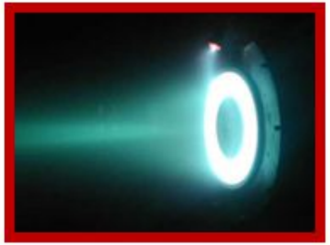
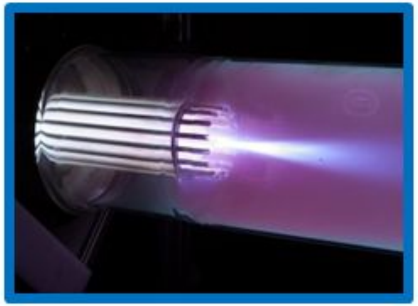
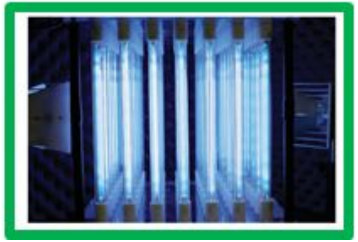






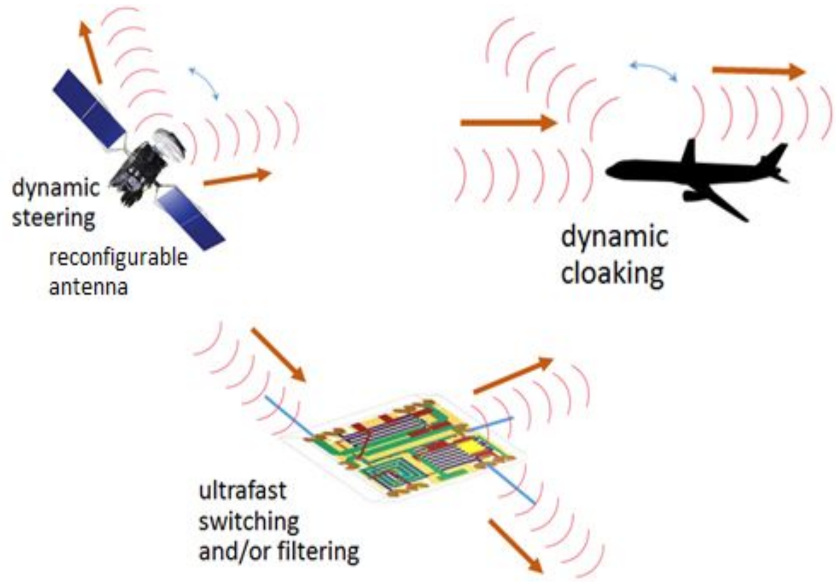
Manipulation and Control of mm-Waves with Plasmas

Currently a field of much commercial and military interest

- reflect/steer/tune
- switch or filter
- amplify or mix
- modulate...

… EM waves with high dynamic fidelity

- not prone to disruption by natural or other EM interferences



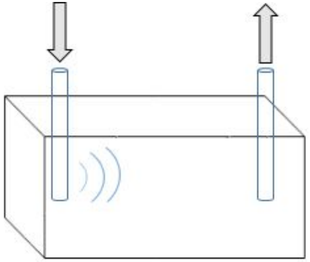
*next generation 5G operates in the 28-40 GHz range of carrier frequencies

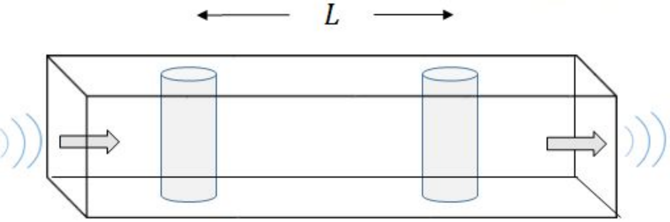
Example EM Platforms

“Artificial” Materials

Cavity Resonators

closed



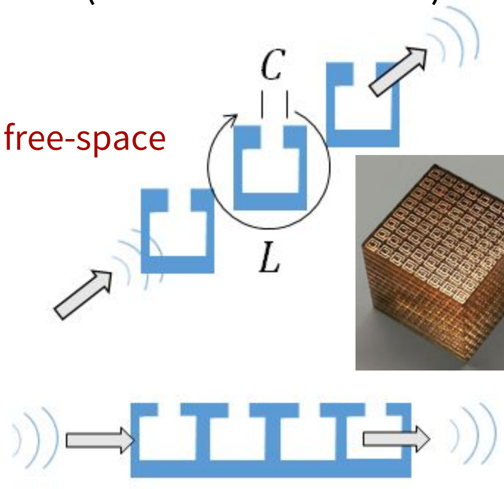


guided

$$\omega_o = \frac{c_o}{L}\frac{1}{n}$$

Structural Resonators (“metamaterials”)

free-space



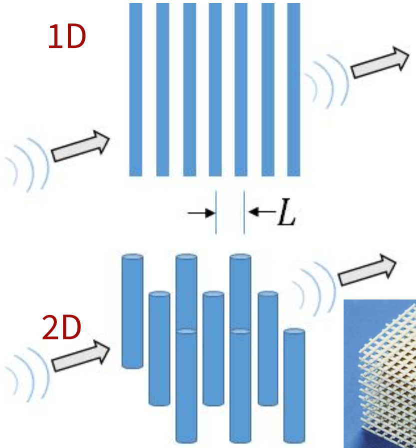
guided

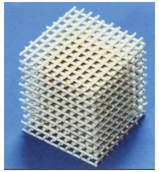
$$\omega_o = \frac{1}{\sqrt{LC}}$$

Bragg Resonators Bandgap Materials (“photonic crystals”)

1D

2D



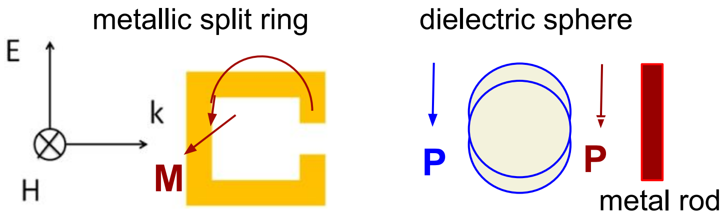


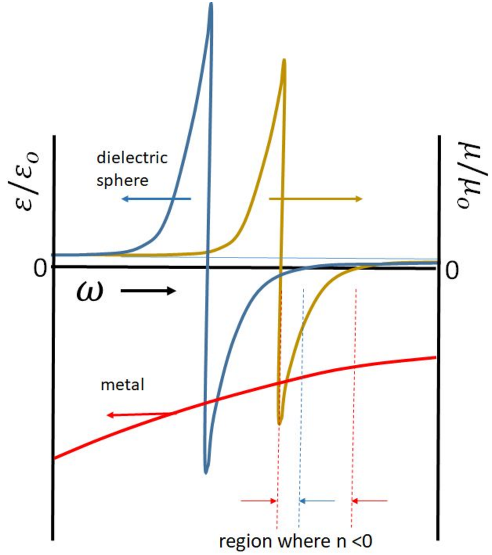
$$\omega_o = \frac{n_1 + n_2}{n_1 n_2}\frac{c_o}{L}$$

(mid-gap frequency for maximum gap width)

“Artificial” Materials: Structural Resonators

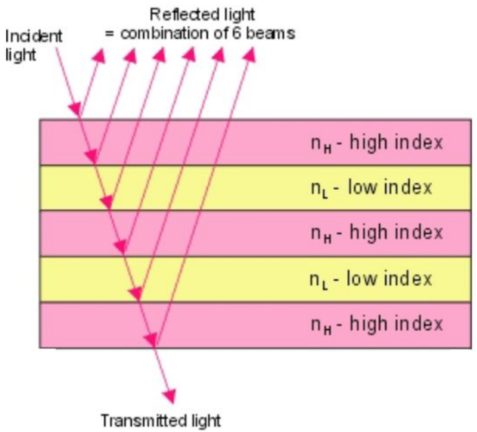
- “elements” (“atoms”) have a geometry that elicits EM response
- array or results in macroscopic transmission properties defining an ϵ, μ
- some configurations can combine elements to engineer unique properties (e.g. negative refraction)
- response is often limited to narrow ranges of ω and not tunable

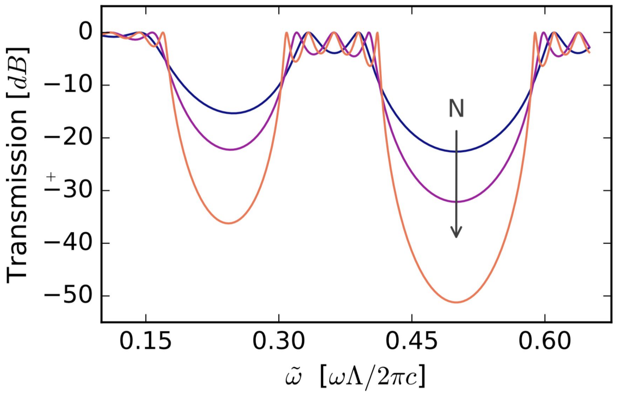




"Artificial" Materials: Bragg Resonators

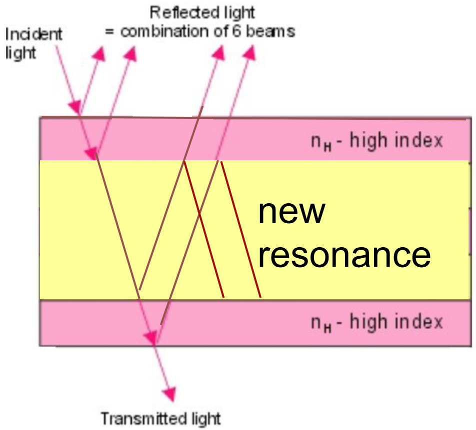
- "Bragg scattering" - used in understanding atomic structure in materials
- "elements" ("atoms") have an ordered structure resulting in interface reflection
- constructive/destructive interference produces bandgaps/transmission windows

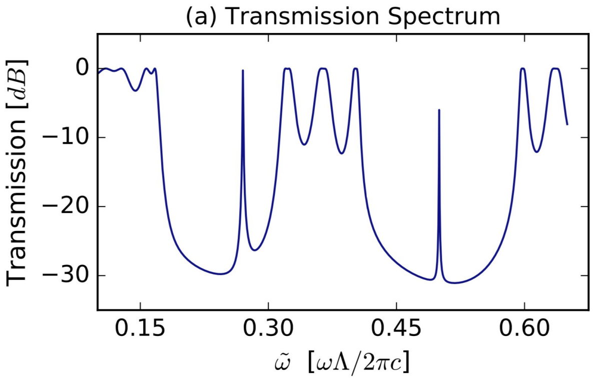




“Artificial” Materials: Bragg Resonators

- “Bragg scattering” - used in understanding atomic structure in materials
- “elements” (“atoms”) have an ordered structure resulting in interface reflection
- constructive/destructive interference produces bandgaps/transmission windows
- configurations can be engineered to have “defects”
- generally not tunable/reconfigurable





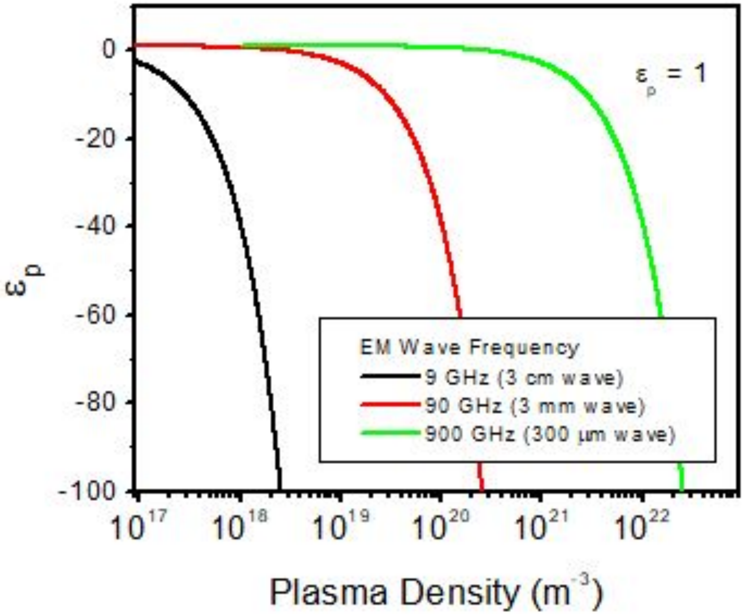
Can a plasma be used to dynamically reconfigure metamaterials or photonic crystals?

Can a plasma be used to dynamically reconfigure metamaterials or photonic crystals?

$$\epsilon_p = 1 - \frac{\omega_p^2}{\omega^2}$$

Refractive index:

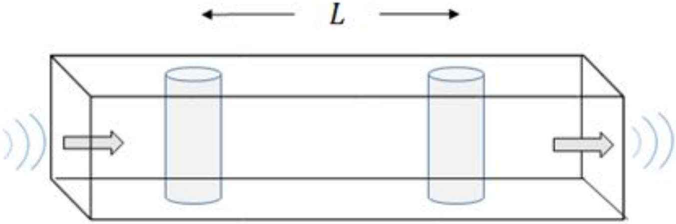
$$n = \sqrt{\epsilon_p}$$



Example EM Platforms

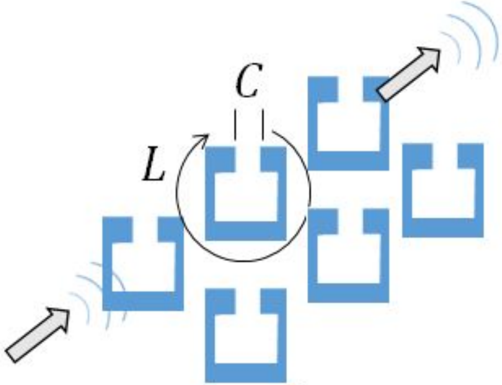
“Artificial” Materials

Cavity Resonators



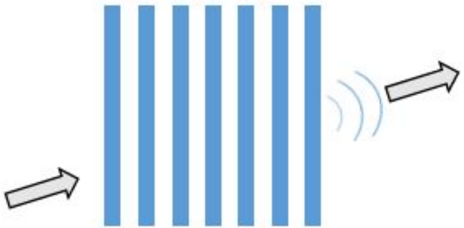
$$\omega_o = \frac{c_o}{L}\frac{1}{n}$$

Structural Resonators (“metamaterials”)



$$\omega_o = \frac{1}{\sqrt{LC}}$$

Bragg Resonators (“photonic crystals”)

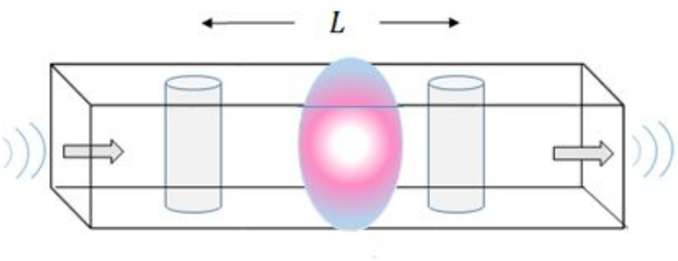


$$\omega_o = \frac{n_1 + n_2}{n_1 n_2}\frac{c_o}{L}$$

Plasma Functionalization

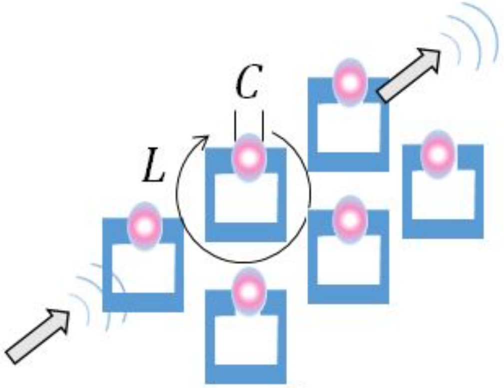
"Artificial" Materials

Cavity Resonators



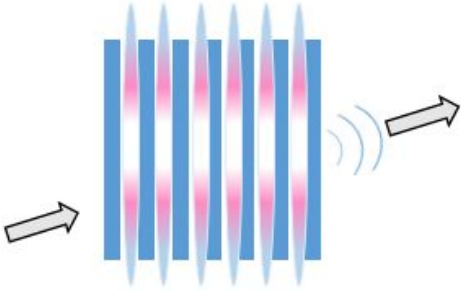
$$\omega_o = \frac{c_o}{L}\frac{1}{n}$$

Structural Resonators ("metamaterials")



$$\omega_o = \frac{1}{\sqrt{LC}}$$

Bragg Resonators ("photonic crystals")



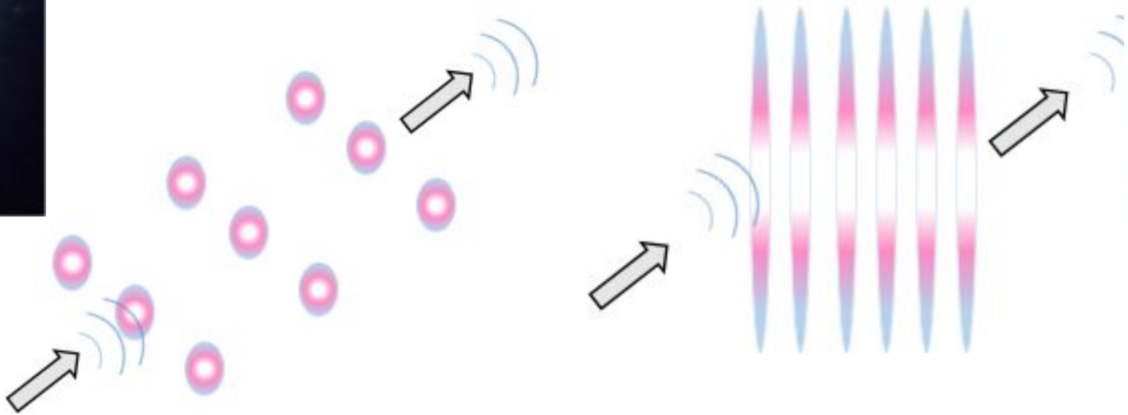
$$\omega_o = \frac{n_1 + n_2}{n_1 n_2}\frac{c_o}{L}$$

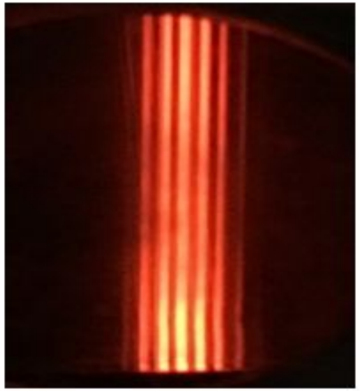
Plasmas Themselves can Serve as the Structures and Scatterers

"Artificial" Materials

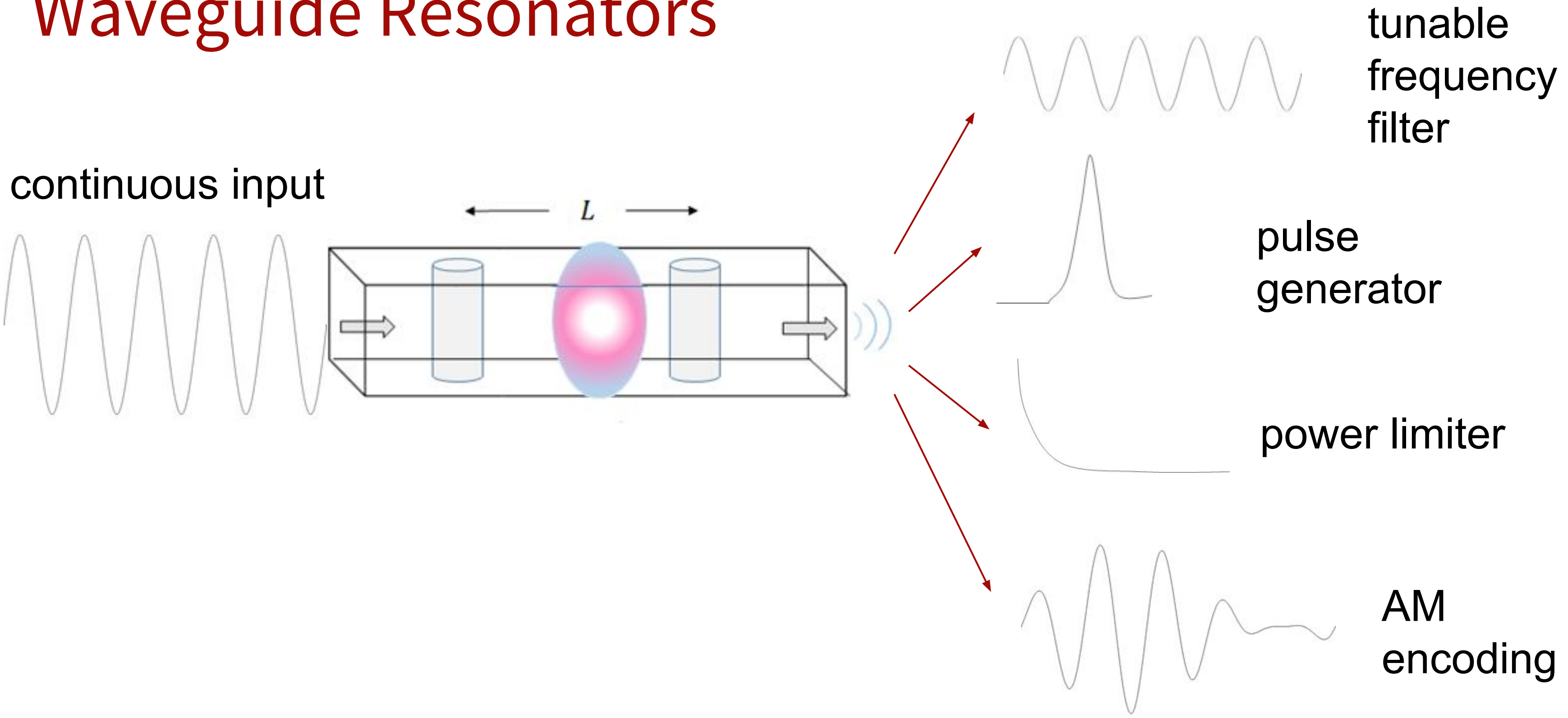
Structural Resonators ("metamaterials")

Bragg Resonators ("photonic crystals")





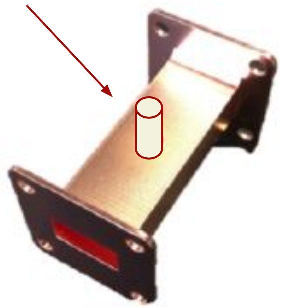
Waveguide Resonators



Plasma-Tuned Waveguide Filter

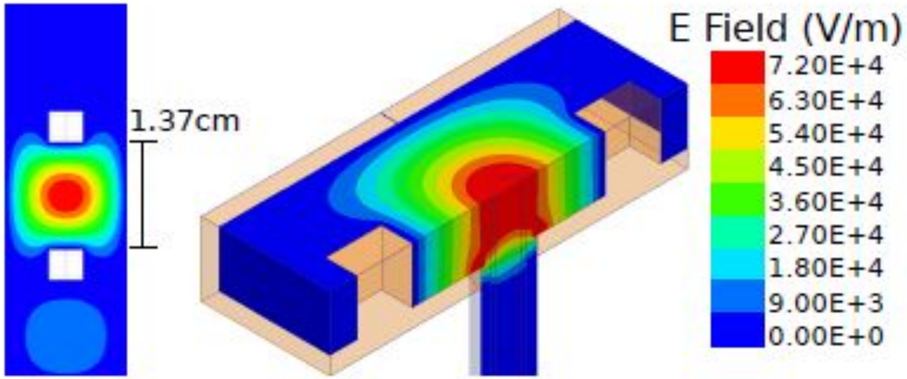
Enables tunable transmission in the range of the empty cavity resonance

5 mm diameter discharge tube



- Cavity dimensions: 15 x 13.7 x 7.5 mm
- Frequency: 14 GHz
- Quality: 1800

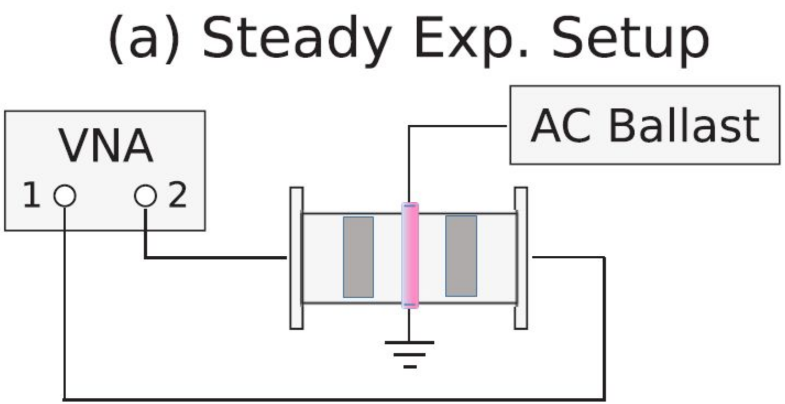
TE_{01} Resonant Mode
ω_o = 13.73 GHz



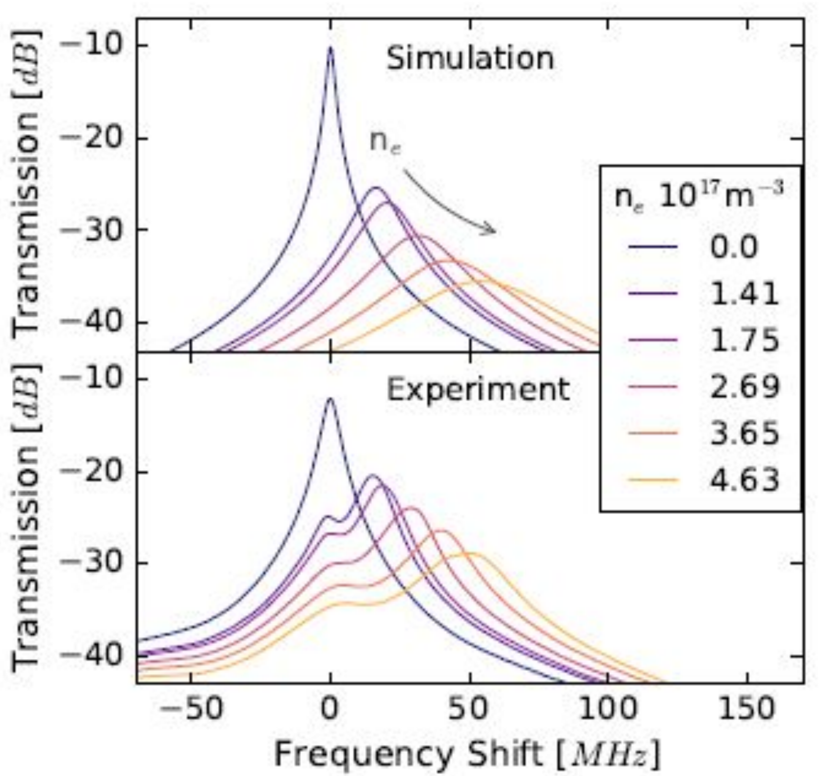
ANSYS (HFSS) simulations of cavity fields

Biggs and Cappelli, APL (2016)

Tunable Filter



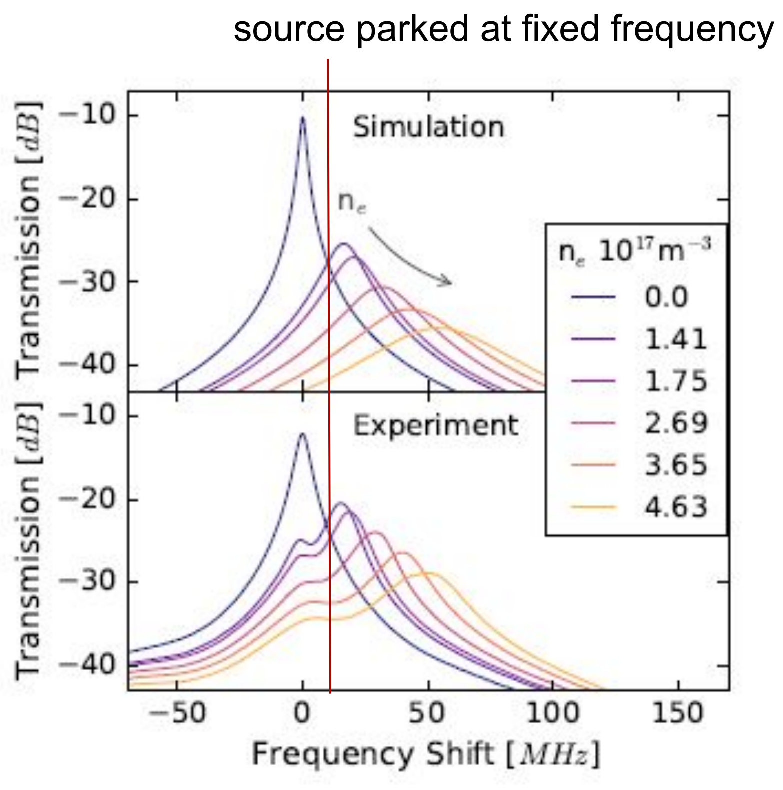
Discharge: 70 kHz, 125 V_{rms}, 2 mA
Ar-Hg (~5 Torr)

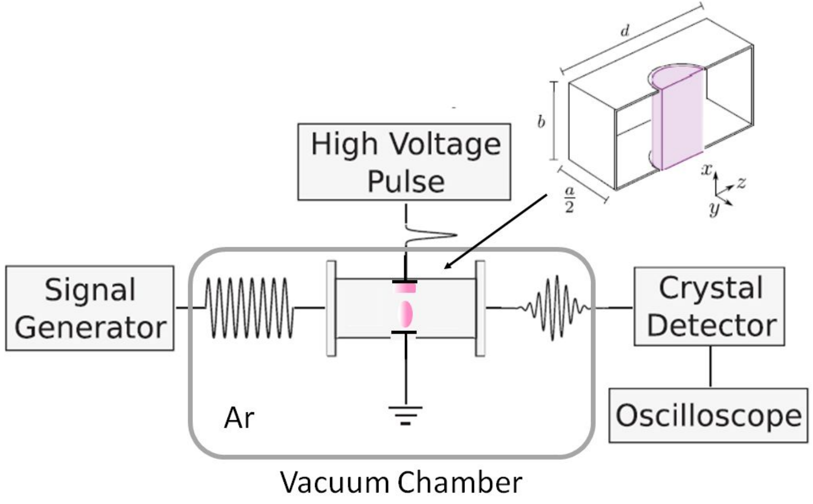


- simulated shifts for plasma column of uniform density
- measure shifts for various discharge currents
  - average plasma density estimated from current and voltage
- good agreement between measured and simulated shiftsc

Biggs and Cappelli, APL (2016)

Pulse Generation

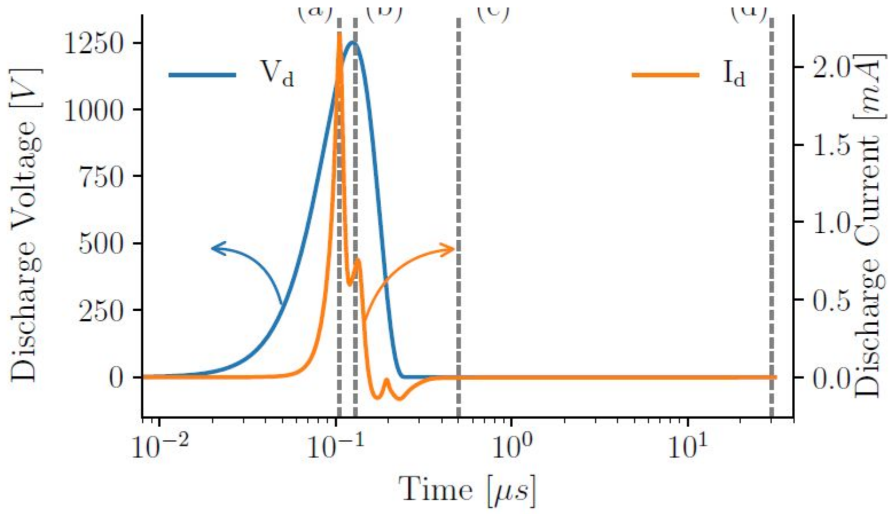


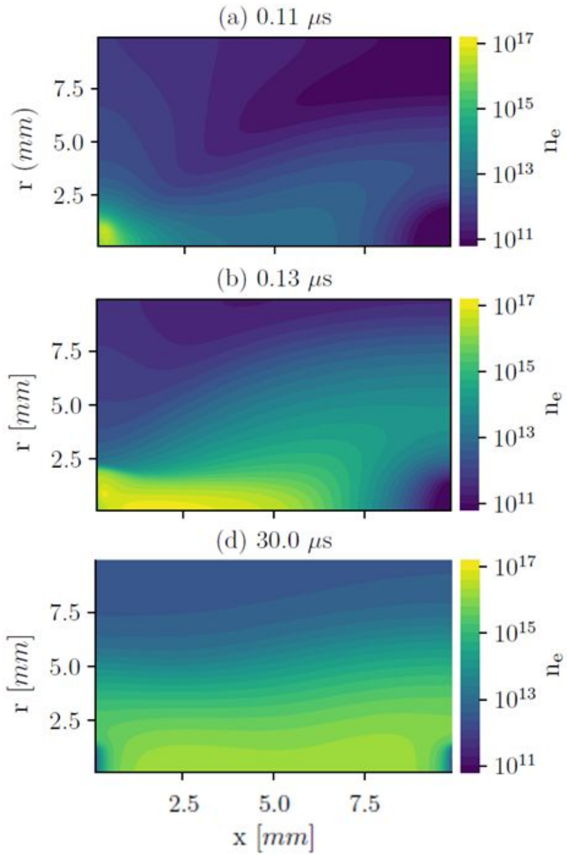


- plasma rise time ~ 0.01 μs < cavity response time
- plasma decay time ~ 1-10 μs

Pulse Generation (simulations)

- 2D 2nd order space 4th order time
- SG scheme for fluxes
- transport lookup table from EEDF solver
- finite rate kinetics (including metastable)





Pulse Generation (simulations)

Model the conductor-filled resonator response (Slater, 1946)

Shift:

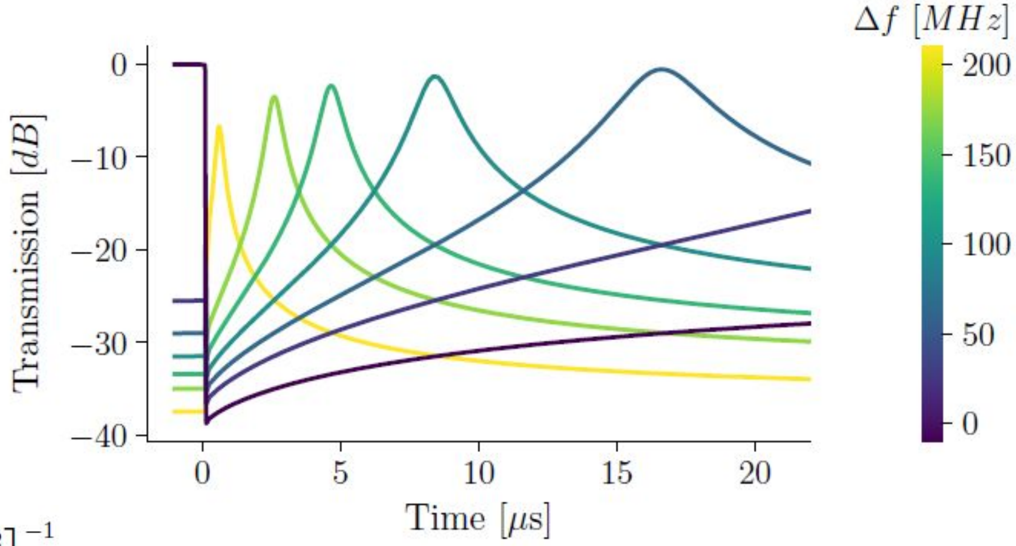
$$\Delta\tilde{\omega}_{\text{res}} = \left(1 - \frac{i+1}{Q_0} - \int_V \frac{\omega_{\text{P}}^2}{\omega_0^2 + i\nu_{\text{e}}\omega_0} E_0^2\, dV\right)^{\frac{1}{2}} - 1$$

Quality:

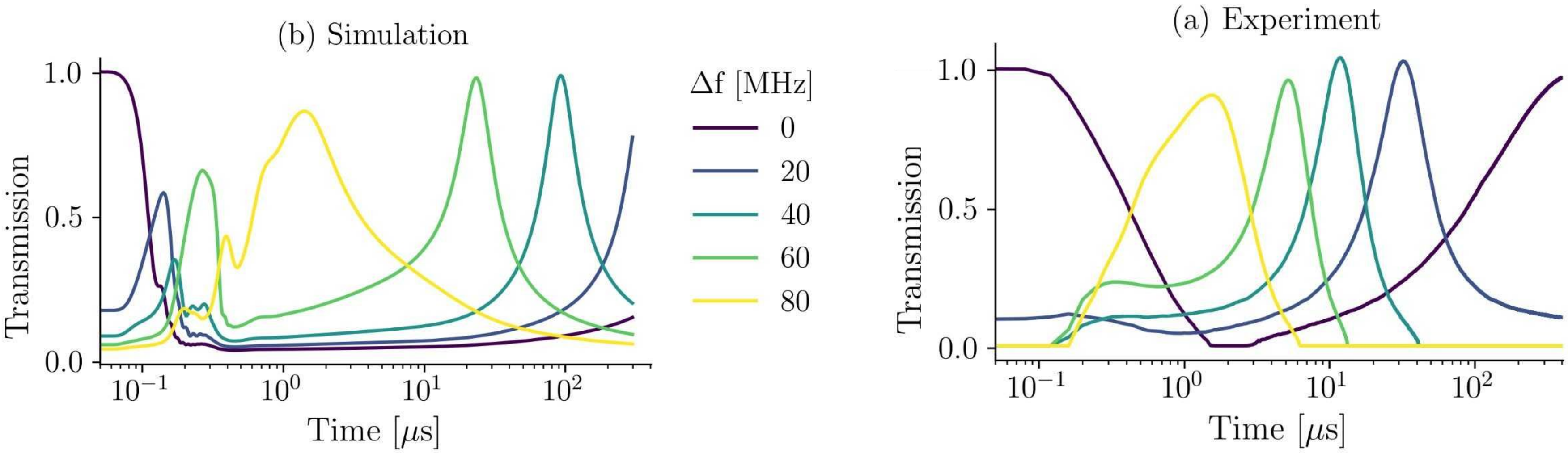
$$Q = -\tfrac{1}{2}\left[1 + \text{Re}(\Delta\tilde{\omega}_{\text{res}})\right] \text{Im}(\Delta\tilde{\omega}_{\text{res}})^{-1}.$$

Transmission:

$$T(\omega) = \left(\frac{1}{Q_0}\right)^2 \left[\left(\frac{\omega\,\omega_0^{-1}}{1+\Delta\tilde{\omega}_{\text{res}}} - \frac{1+\Delta\tilde{\omega}_{\text{res}}}{\omega\,\omega_0^{-1}}\right)^2 + \left(\frac{1}{Q}\right)^2\right]^{-1}$$



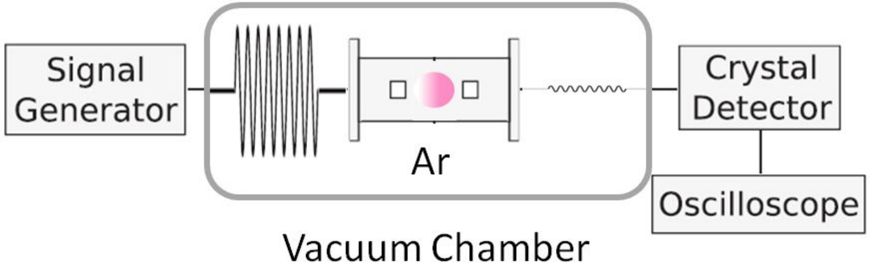
Comparison to Experiments



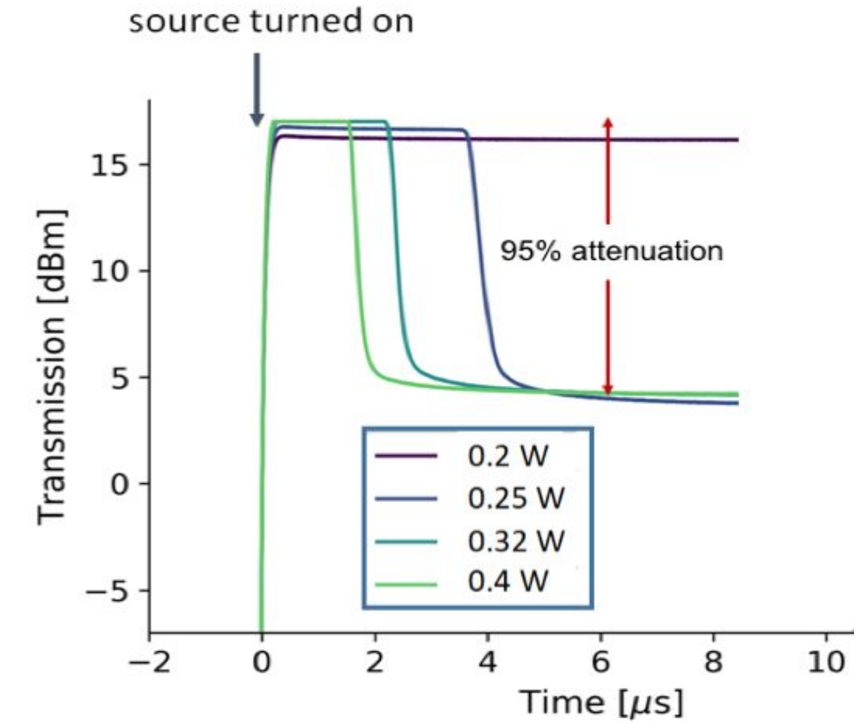
- resolve ionization and recombination signature
- model is <u>underpredicting</u> Ar recombination rates
  - means of measuring recombination rates?

Power Limiter

image: Popular Mechanics 2009

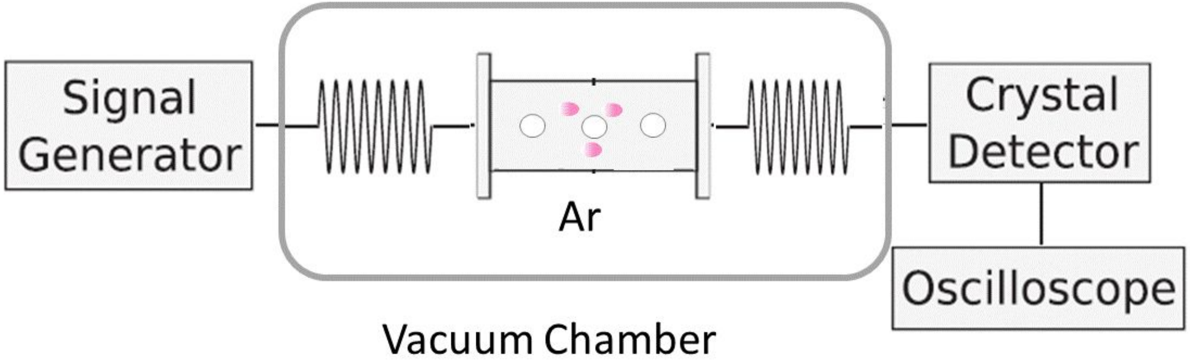


Experimental Results



Amplitude Modulator

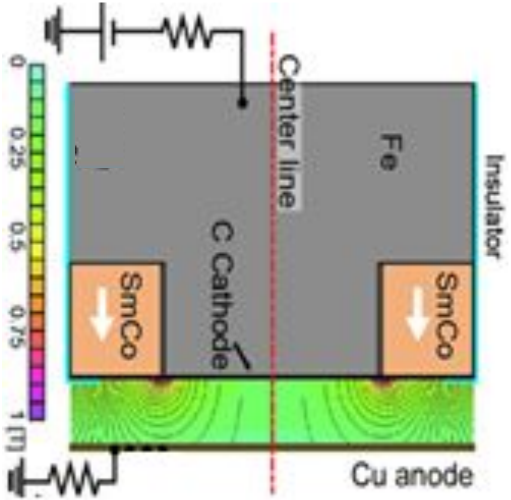
Location of plasma within resonator posts strongly affects transmission

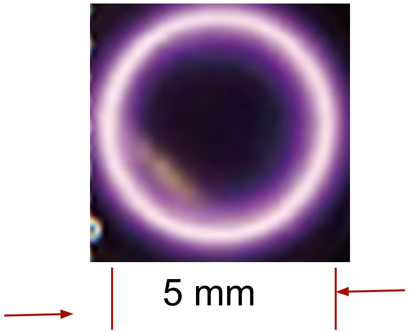


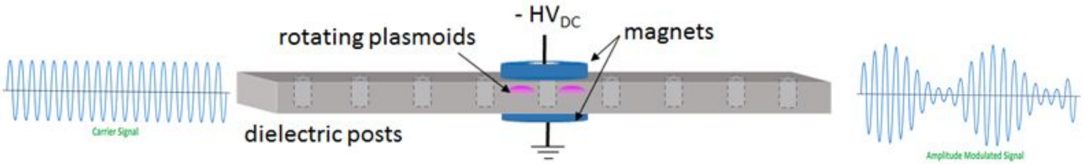
Can we generate coherent structures that rotate at high frequencies (MHz)?

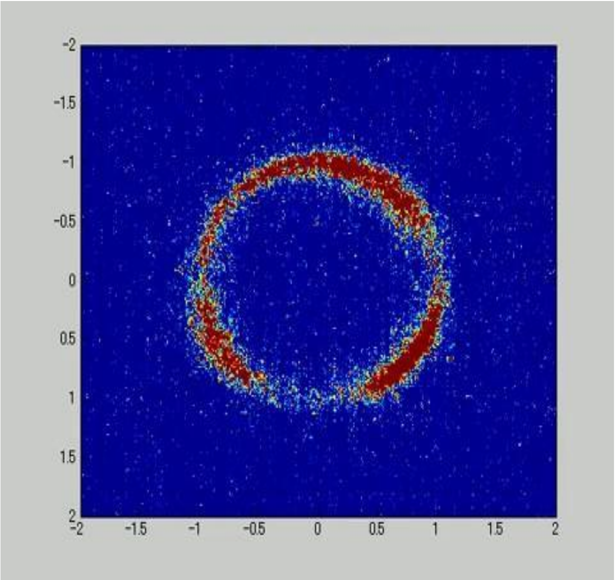
(and fit within a Ku-Band waveguide - 12-18 GHz)

Amplitude Modulator - Micro Magnetron Discharge



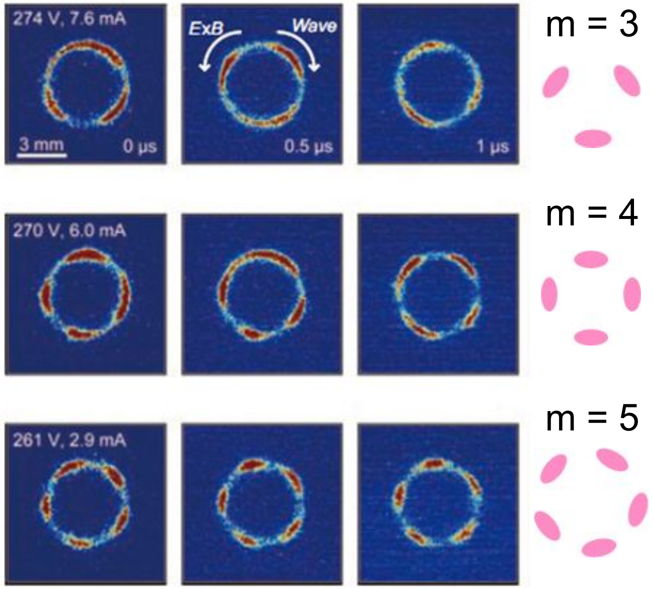


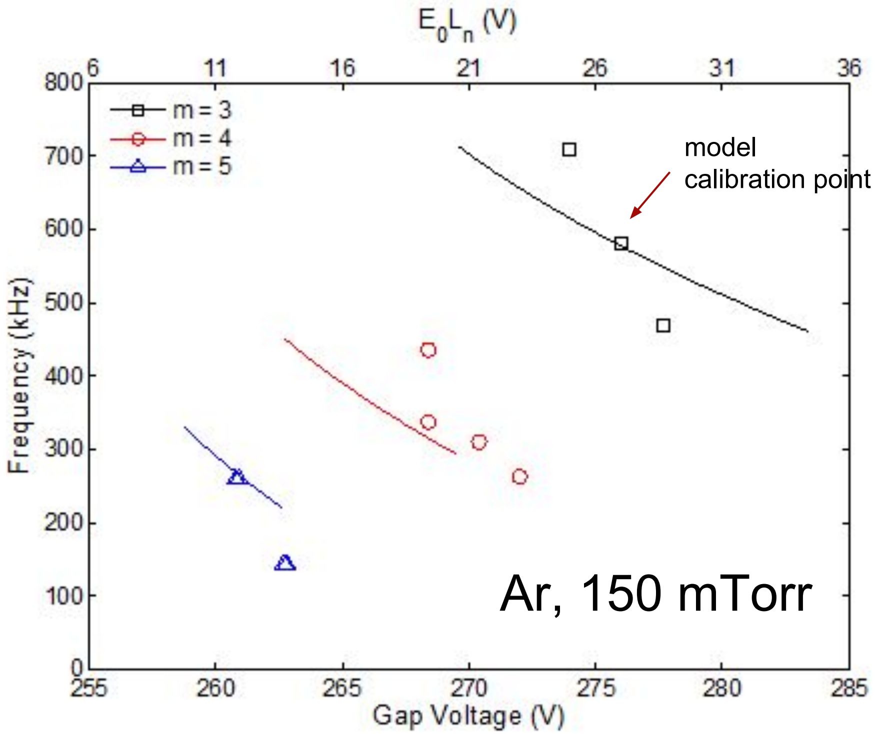




Frequency and Mode Controlled by Voltage

frames from high speed video camera

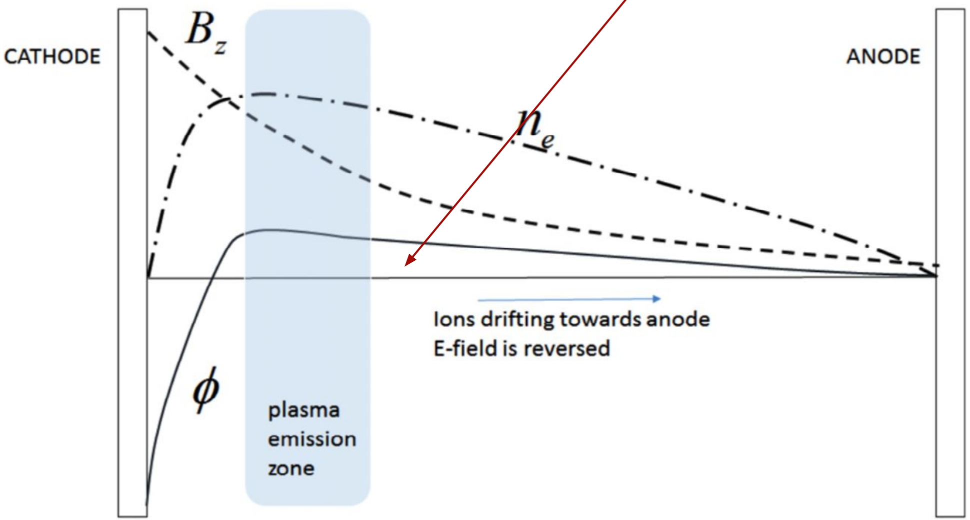




Model: Gradient-driven drift instability driven by the local E x B electron rotation (Ito et al, 2016)

Local Field Reversal

gradients drive more electrons
than anode demands

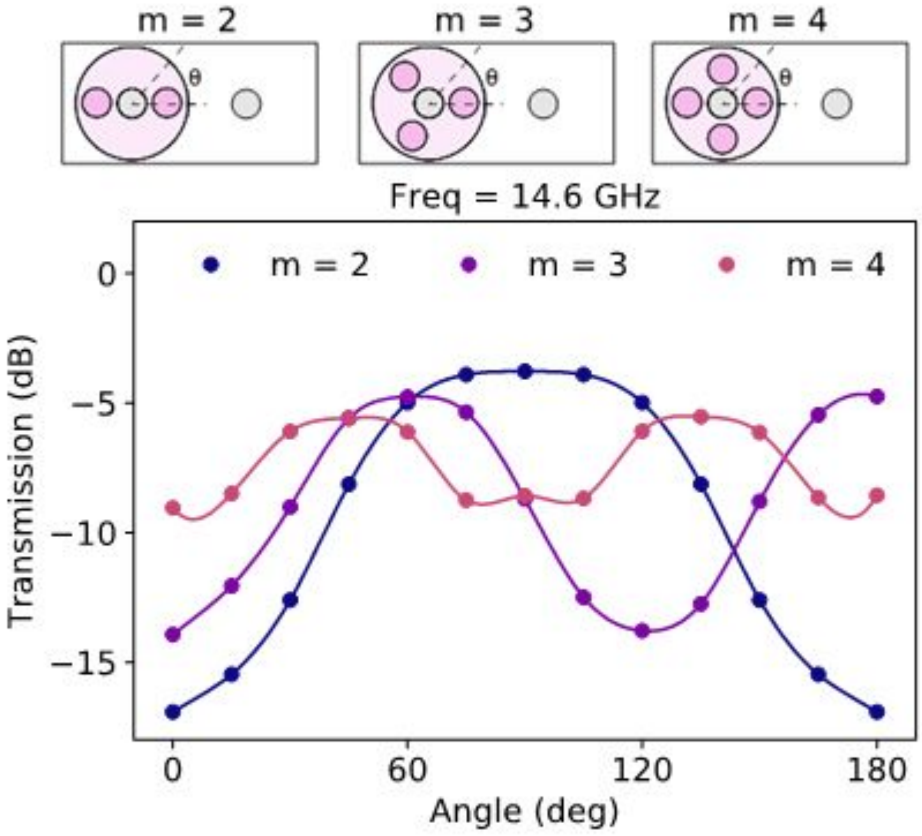


$$\omega^2 - \left(2k_x v_{i0} + \frac{k_\perp^2 c_s^2}{\omega^* - \omega_D}\right)\omega + k_x^2 v_{i0}^2 + \frac{k_\perp^2 c_s^2(\omega_0 + \omega_D)}{\omega^* - \omega_D} - i\frac{k_\perp^2 c_s^2 \nu_c}{\omega^* - \omega_D} = 0$$

Gradient-drift wave dispersion

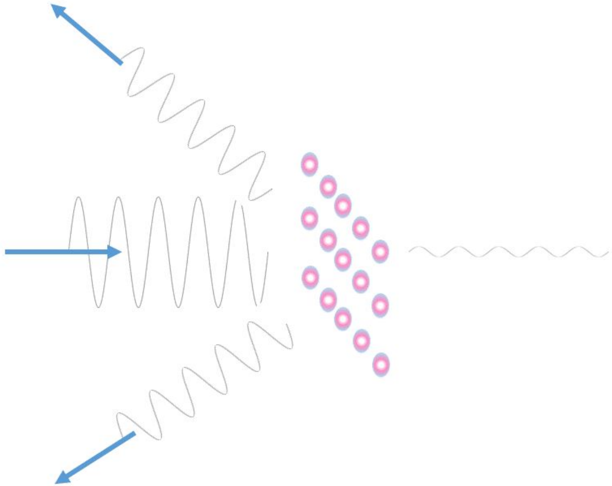
HFSS Simulations

- assumes uniform plasma blobs of circular cross-sections
- indicates a favoring of the m = 2 mode (higher modulation amplitudes)

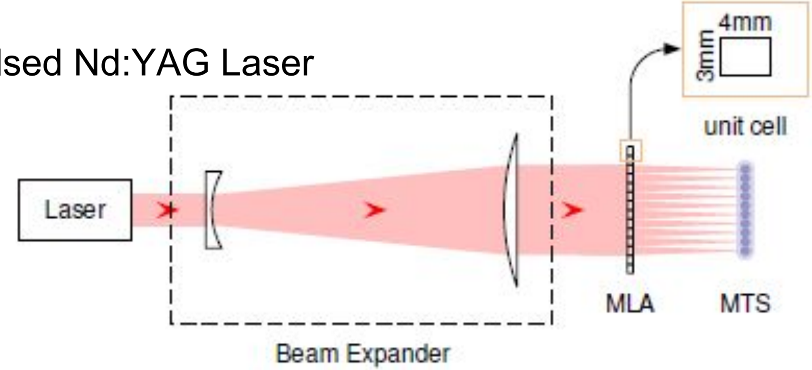


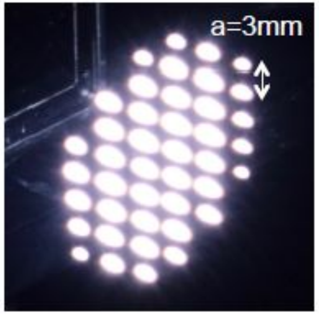
Can we generate a mm-wave mirror in air on demand ?

Laser Plasma Metamaterial Reflectors

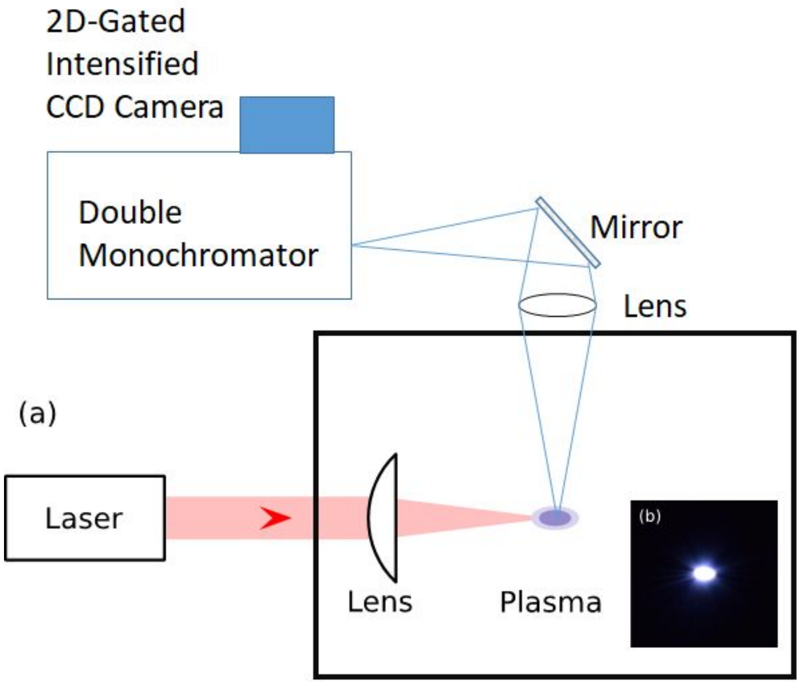


Pulsed Nd:YAG Laser

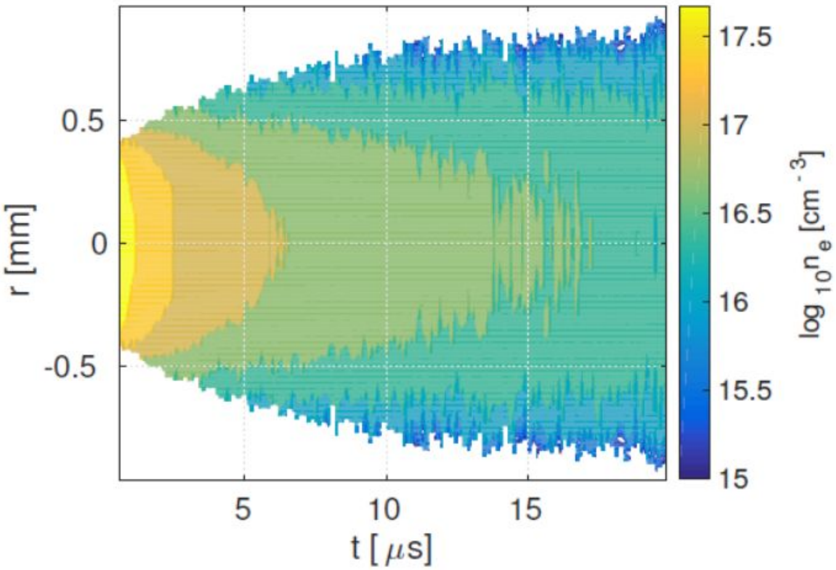




Characterizing Single Laser Plasma Kernel



Vacuum Chamber (Ar, H_2, 1-760 Torr)



20 Torr Ar (H2 Seed)
Ne from Hα Stark Broadening

Modeling the Mie Resonance of a Plasma Kernel

Following Mie Theory:
Electric polarization

$$\boldsymbol{P} = \alpha \boldsymbol{E}$$

Polarizability:

$$\alpha = v \frac{\epsilon_p - 1}{1 + L_e(\epsilon_p - 1)}$$

Eccentricity-dependent parameter:

$L_e = 1/3$ Sphere

$L_e = 1/2$ Cylinder

Absorption and scattering cross sections:

$$\sigma_{abs} = k \, \mathrm{Im}\{\alpha\}$$

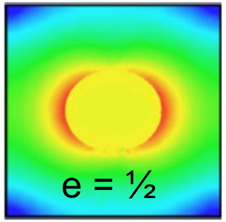
$$\sigma_{scatt} = \frac{k^4}{6\pi} |\alpha|^2$$

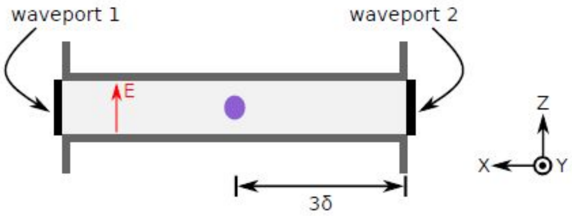
collisionless resonance →

$$\omega_o = \sqrt{L_e} \; \omega_p$$

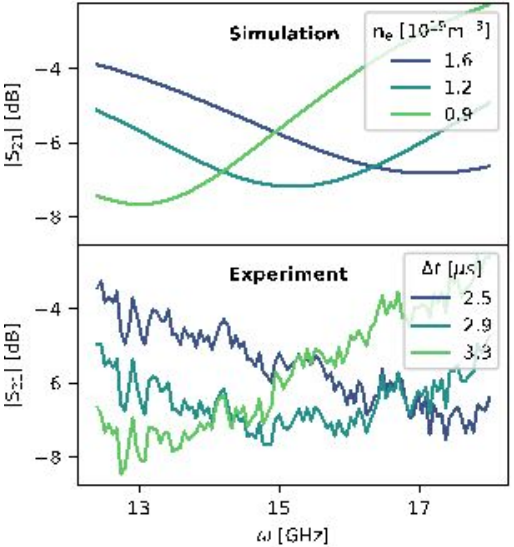
localized surface plasmon mode

Fields in plasma ellipsoid





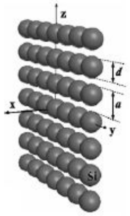
Validating Experiments for Single Plasma Particle in Waveguide

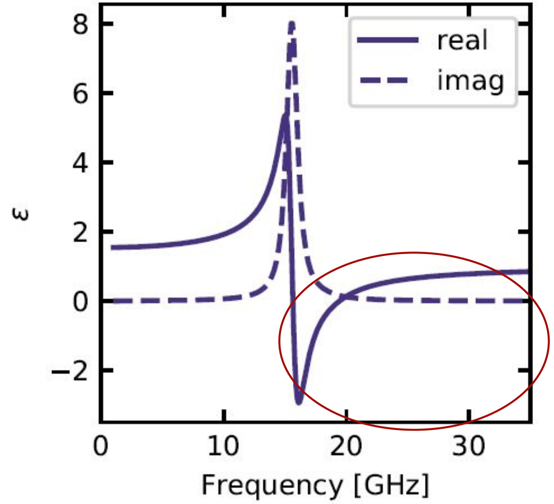


Response of the all-Plasma Metasurface

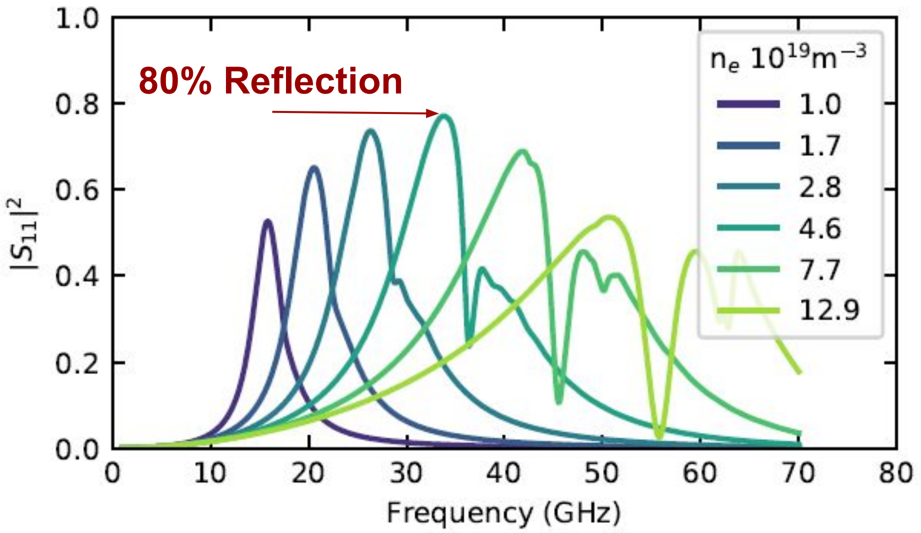
Model the array as volume-filling Lorentz Oscillators (fill fraction, *f*)

$$\epsilon = 1 + \frac{f\omega_p^2}{\omega_0^2 - \omega^2 - i\gamma\omega}$$



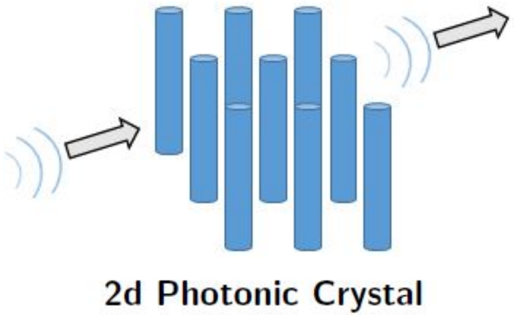


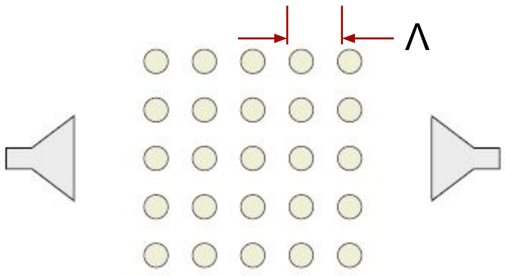
ANSYS simulations of reflection from an infinite array of a = 3 mm plasma ellipsoids



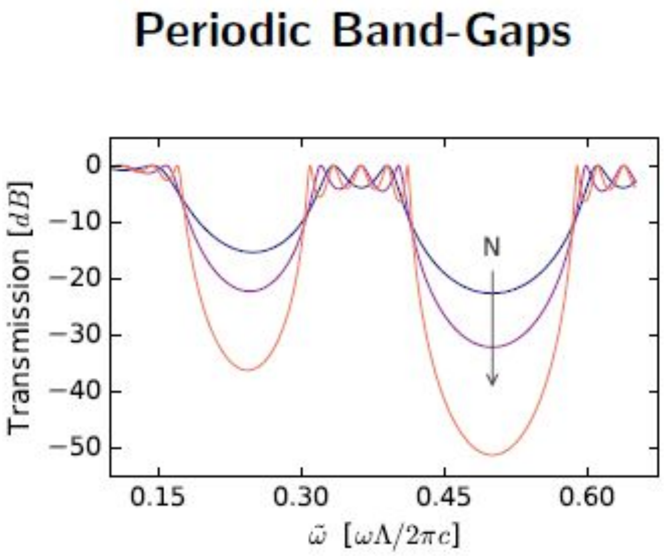
Scattering experiments from the arrays are currently underway

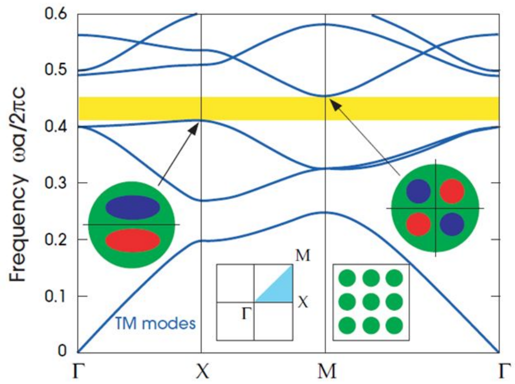
Bragg Resonators: 2D Photonic Crystals





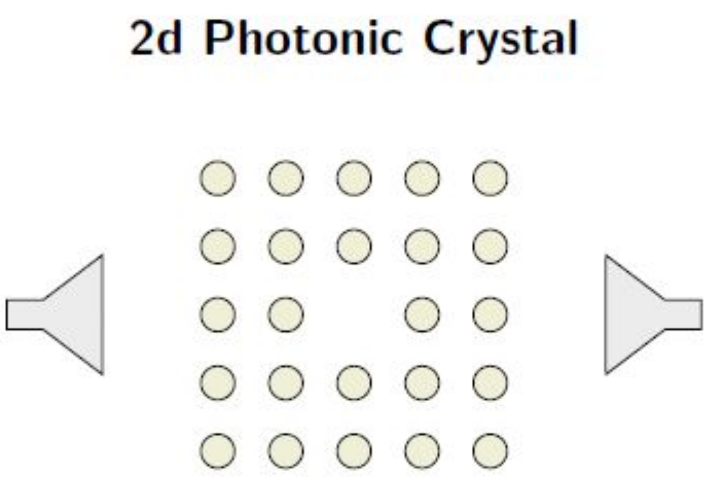
view from above





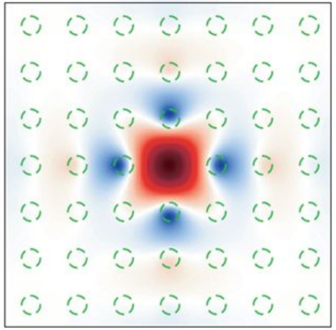
- band gaps are a result of an imaginary wavenumber (dispersion)
- strength of bandgap depends on ratio of dielectric constants (rod and matrix)

Vacancy Defects

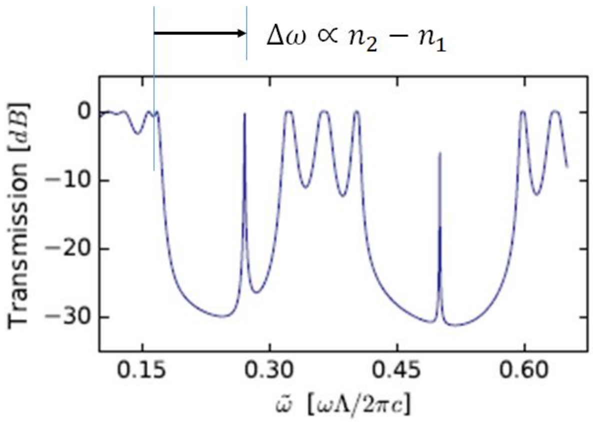


- vacancy defect acts as a resonant cavity
- incident waves at defect resonance “tunnel” in/out through evanescent coupling
- resonant frequency

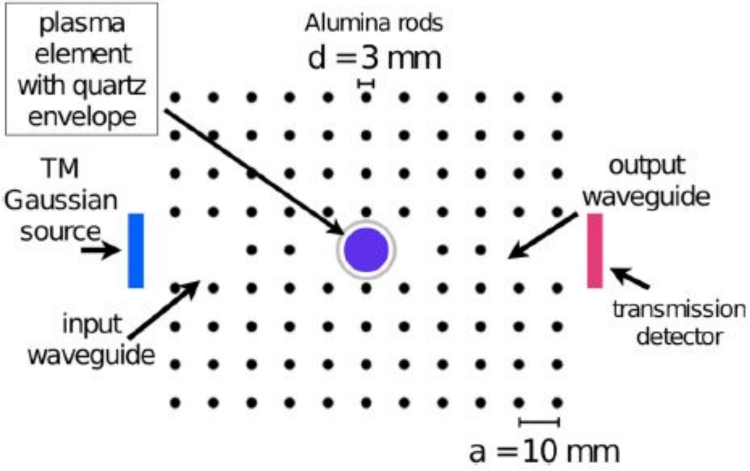
Vacancy Defect Fields

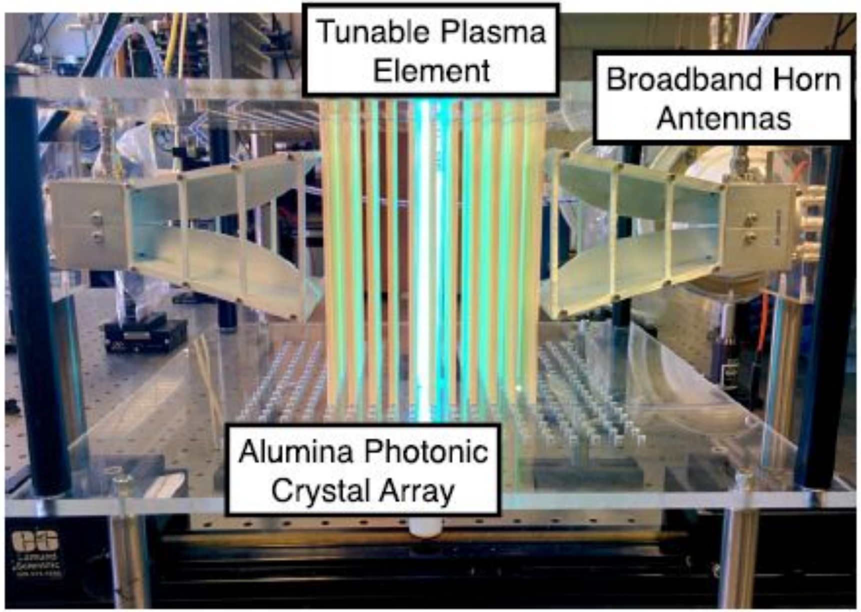


Defect State Resonance

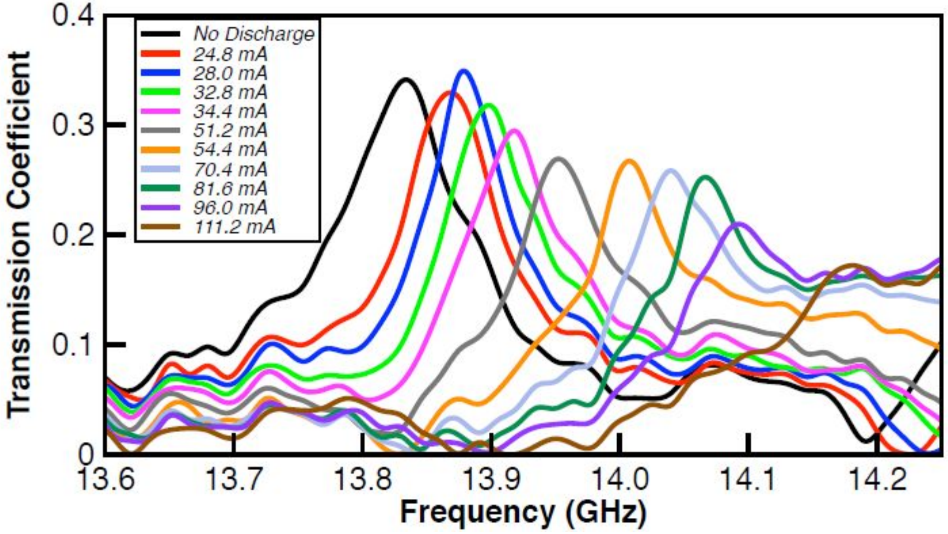


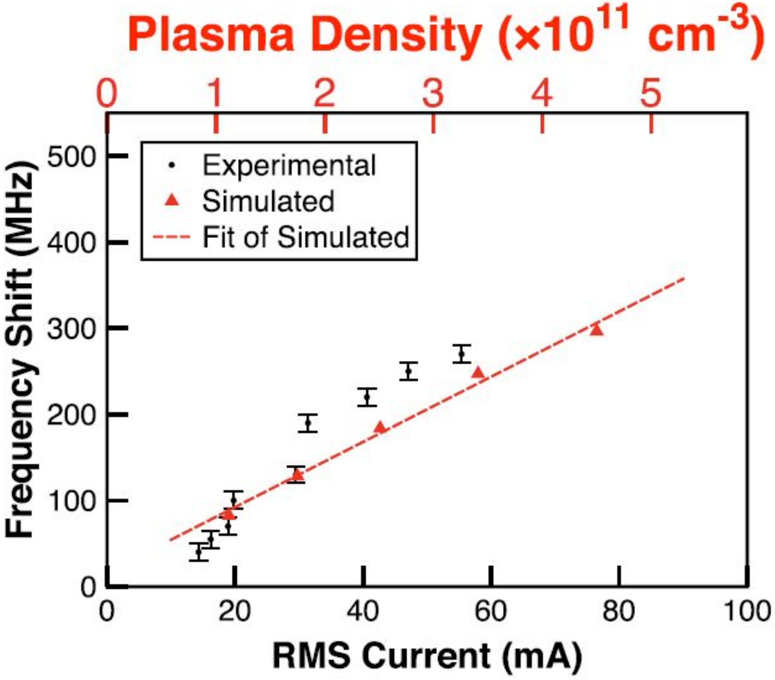
2D Photonic Crystal - Plasma Defect



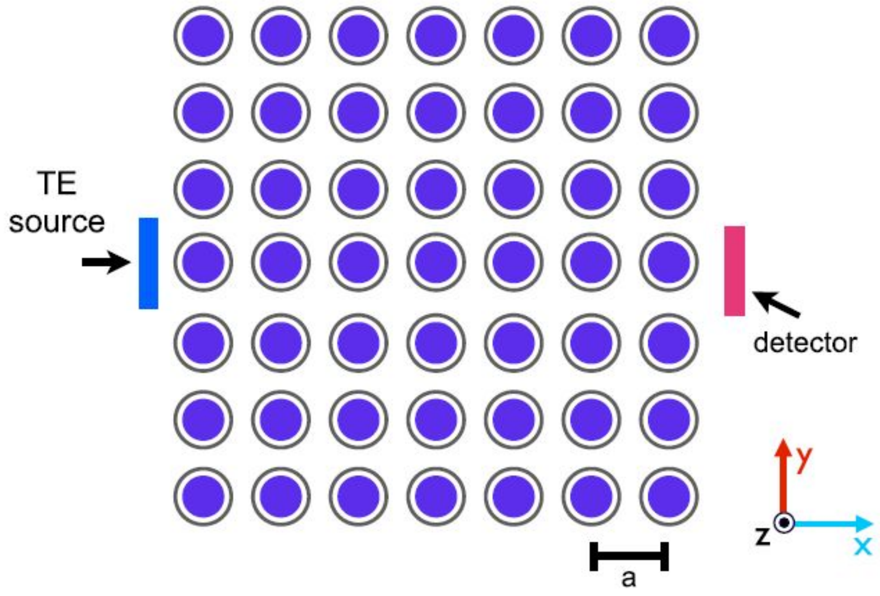


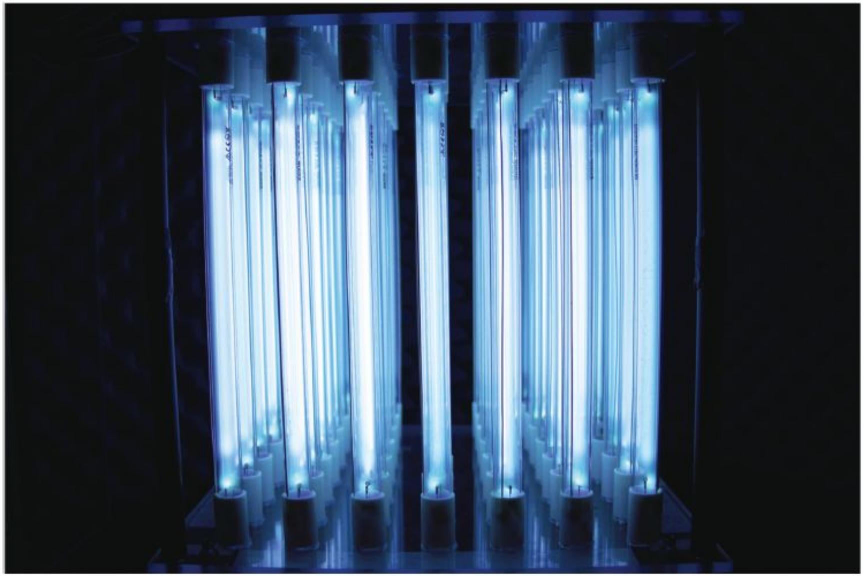
Plasma Tuning of Defect Transmission



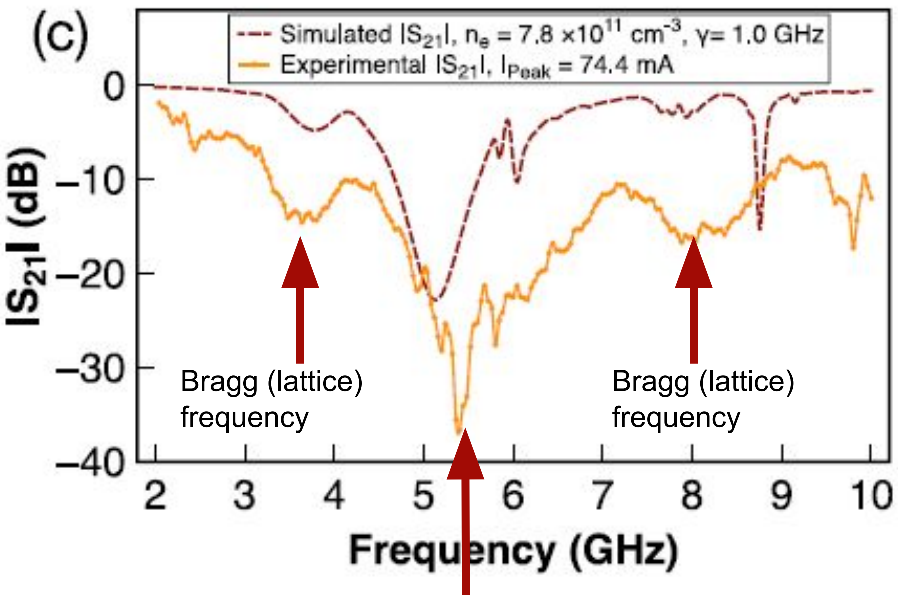


All-Plasma Photonic Crystal





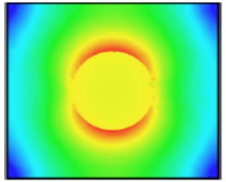
Multiple Gaps - Bragg and Surface Plasmons

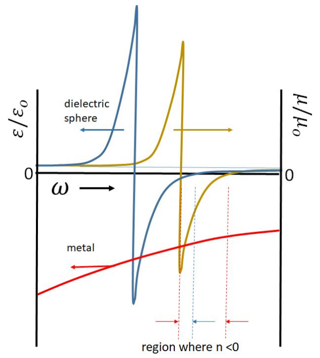


Mie resonance frequency (localized surface plasmon)

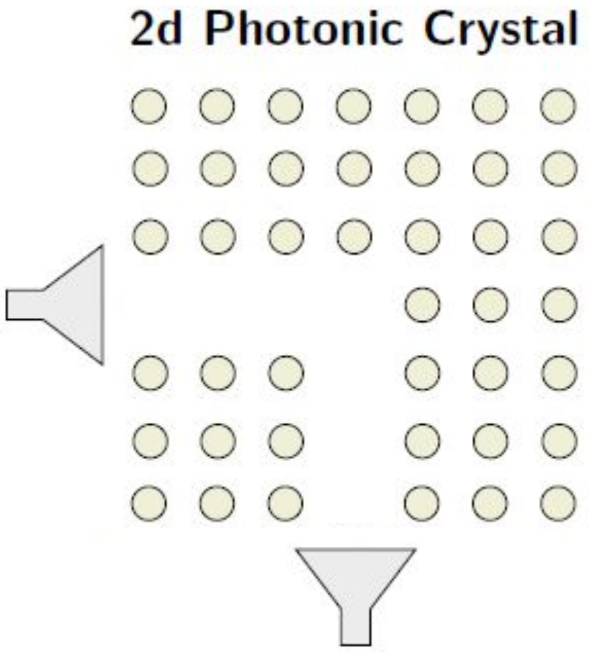
$$\omega_o = \omega_p/\sqrt{2}$$

- Bragg gap too weak to engineer for waveguiding
  - 7 x 7 crystal size too small
  - refractive index difference (at most 1) is too small
- Surface plasmon gap strong
  - dynamic waveguide?



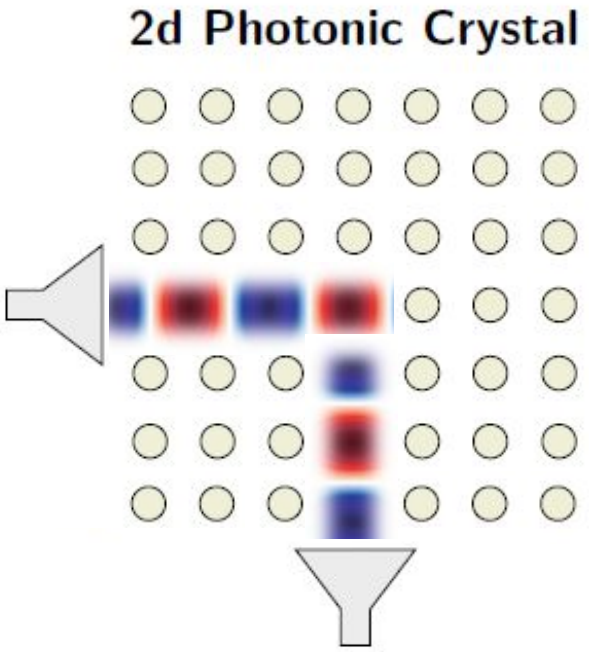


Waveguiding



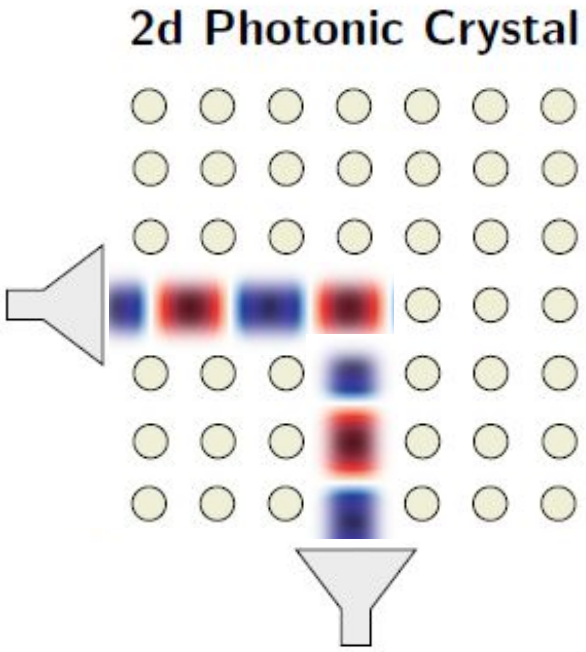
- line vacancies admit waves tuned to the defect state within the bandgap

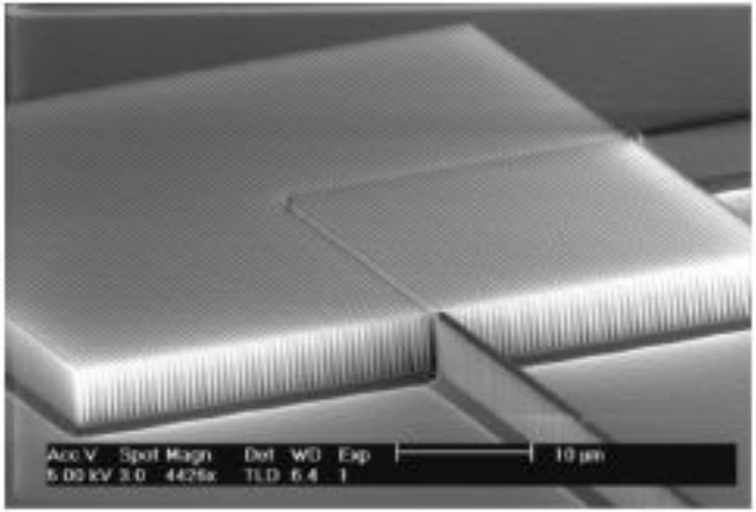
Waveguiding



- line vacancies admit waves tuned to to within the bandgap
- waves cannot propagate beyond the gap and are guided

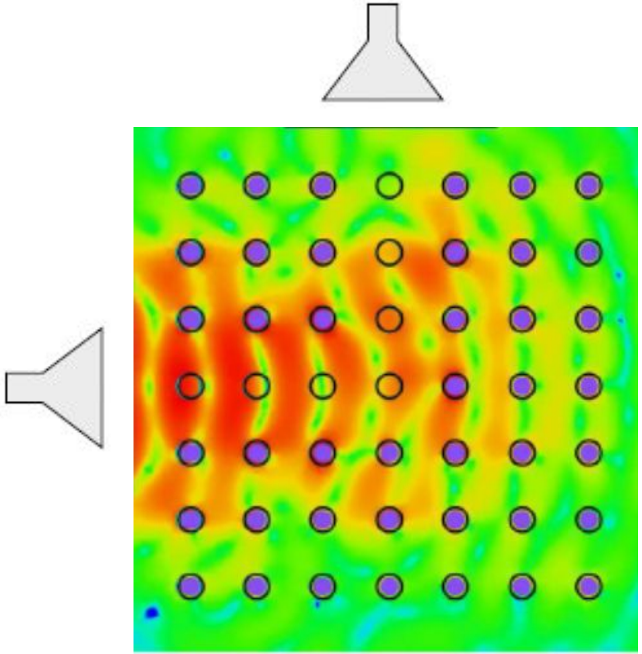
Waveguiding



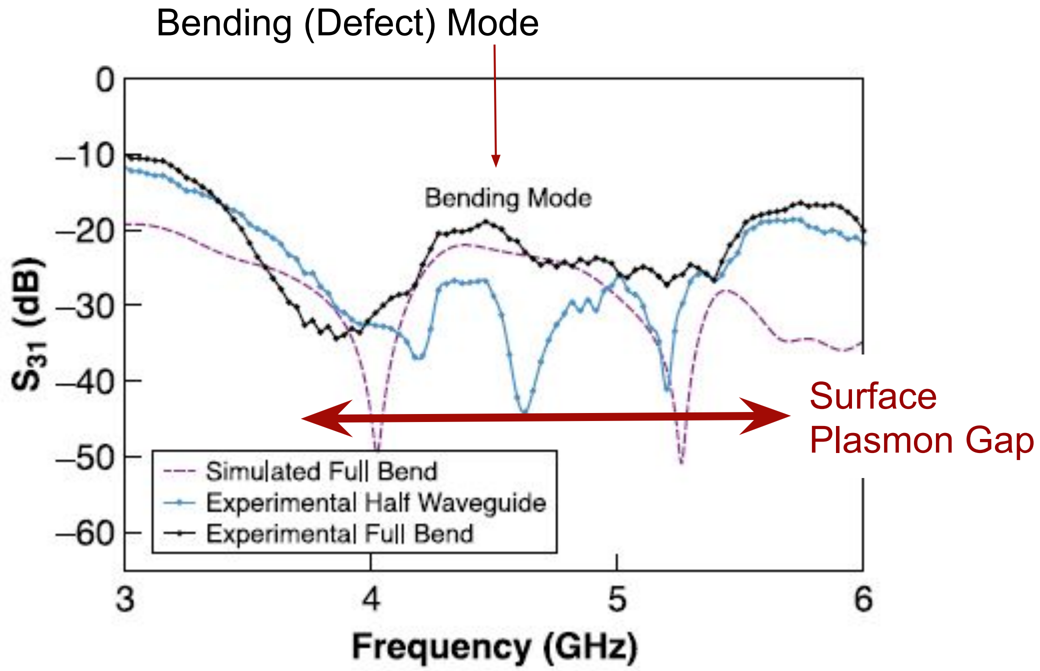


- line vacancies admit waves tuned to the defect state within the bandgap
- waves cannot propagate beyond the vacancy and are guided
- basis for on-chip optical devices

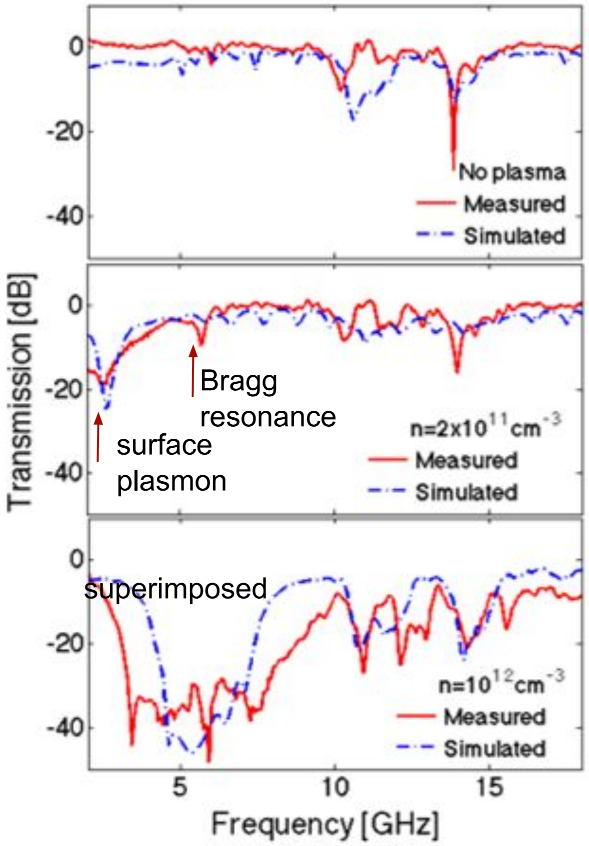
Multiple Gaps - Bragg and Surface Plasmons

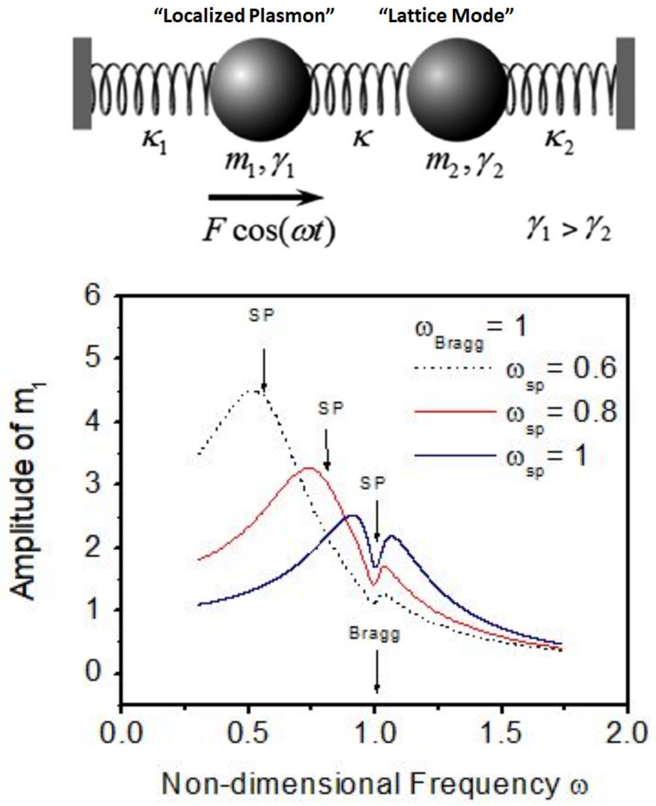


Simulated Fields



Fano (Lattice) Resonance Enhancement



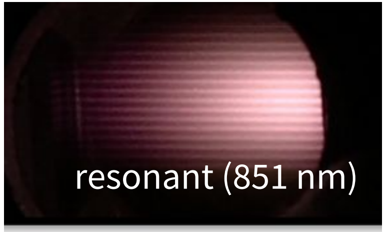


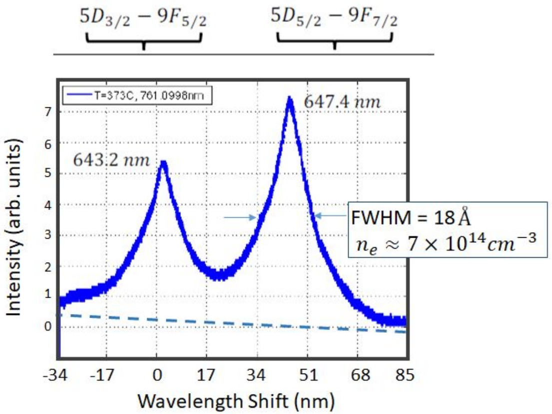
What’s on the Horizon?

- THz All-Plasma PCs (Higher Plasma Density)
- 3D Plasma Photonic Crystals

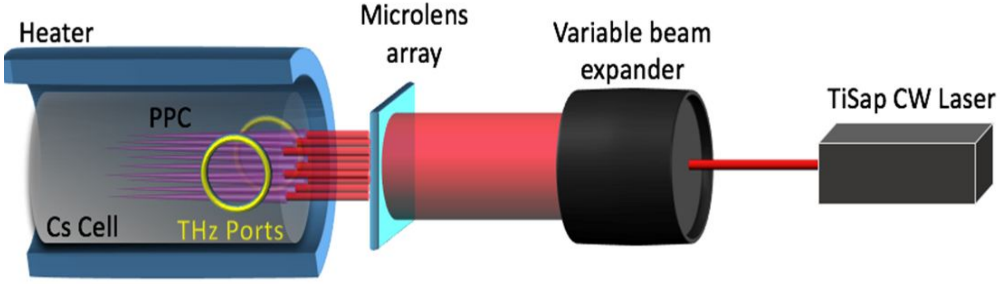
THz All-Plasma Photonic Crystal?

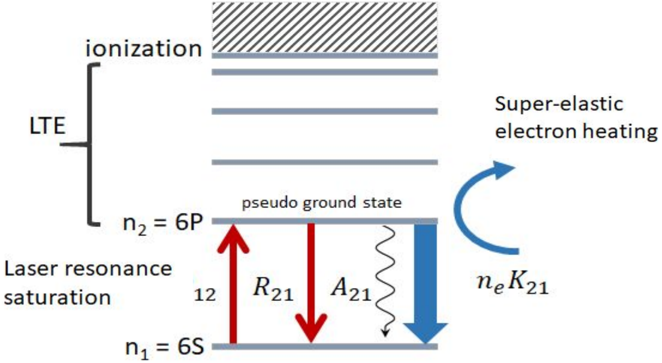
- Requires high plasma densities
  - $n_e = 10^{15} – 10^{16}\ cm^{-3}$
- Small lattice constant (<300 μm)
- Continuous generation



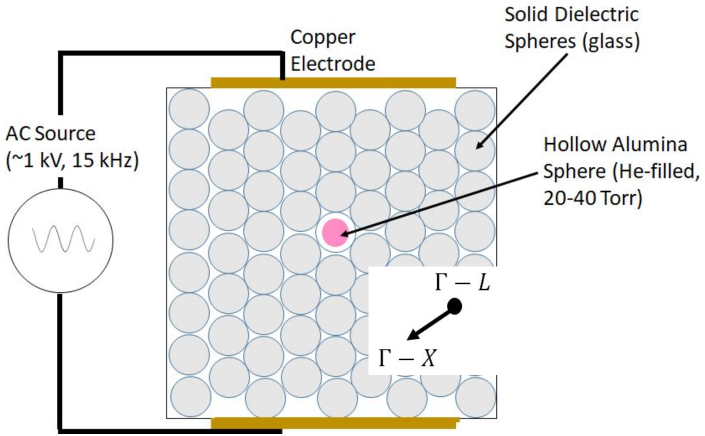


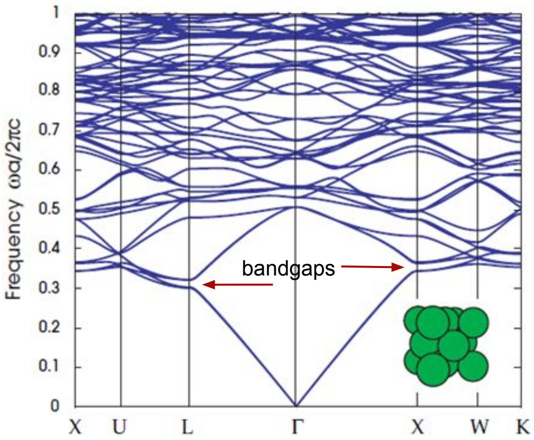
Laser shaping and ionization

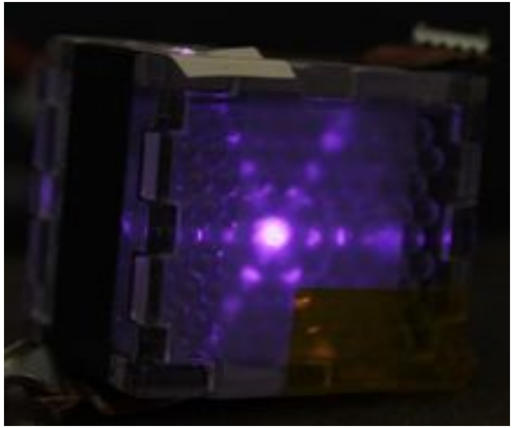




3D Photonic Crystal with Plasma-Filled Defect?







- closed-packed dielectric spheres (glass) with plasma-filled defect
- hollow alumina (He-filled) core excited with a DBD
- band-gaps expected but weak for glass ($n_{glass}/n = 1.3$)
- demonstrate plasma excitation
- redesign for solid alumina spheres with hollow-core defect

Thank you for your attention and patience!

Questions?