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Measurement of the Effective Length of Laser-Plasma Channels by Guided Microwave Backscattering

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Abstract

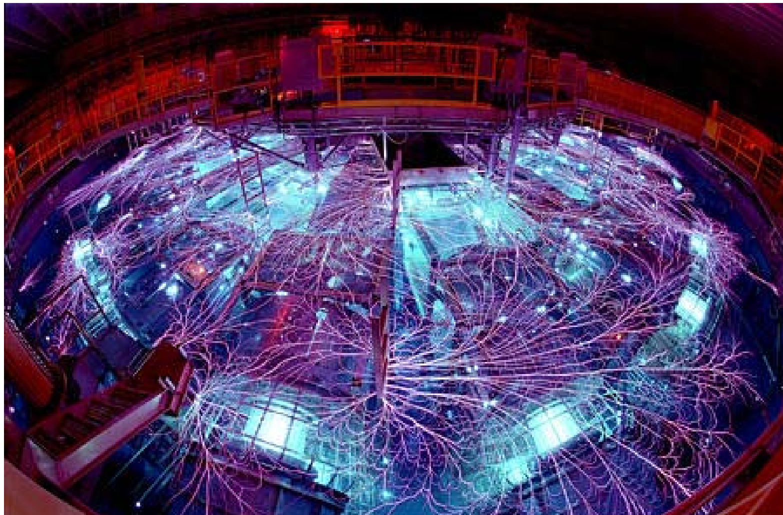
Laser triggered gas switches are critical components in many pulsed power driven systems, such as ZR at Sandia National Laboratories. Timing jitter is of concern is such systems, where power flow from multiple modules must be switched to a load simultaneously. Laser triggered gas switches utilize a laser-produced plasma channel (LPPC) to initiate breakdown between electrodes biased to ~ 80% of breakdown voltage. The effective length of the LPPC, as well as its conductivity and radius are important parameters affecting the breakdown timing. Forward- and backscattering of microwaves inside a waveguide by an LPPC, introduced by focusing the trigger laser through holes in the broad wall, has been used to characterize effective length, radius, and conductivity of the channel. Theoretical, computational, and initial plasma channel experimental results, as well as comparisons with other diagnostics, are presented.

* *Work supported by Sandia National Laboratories*

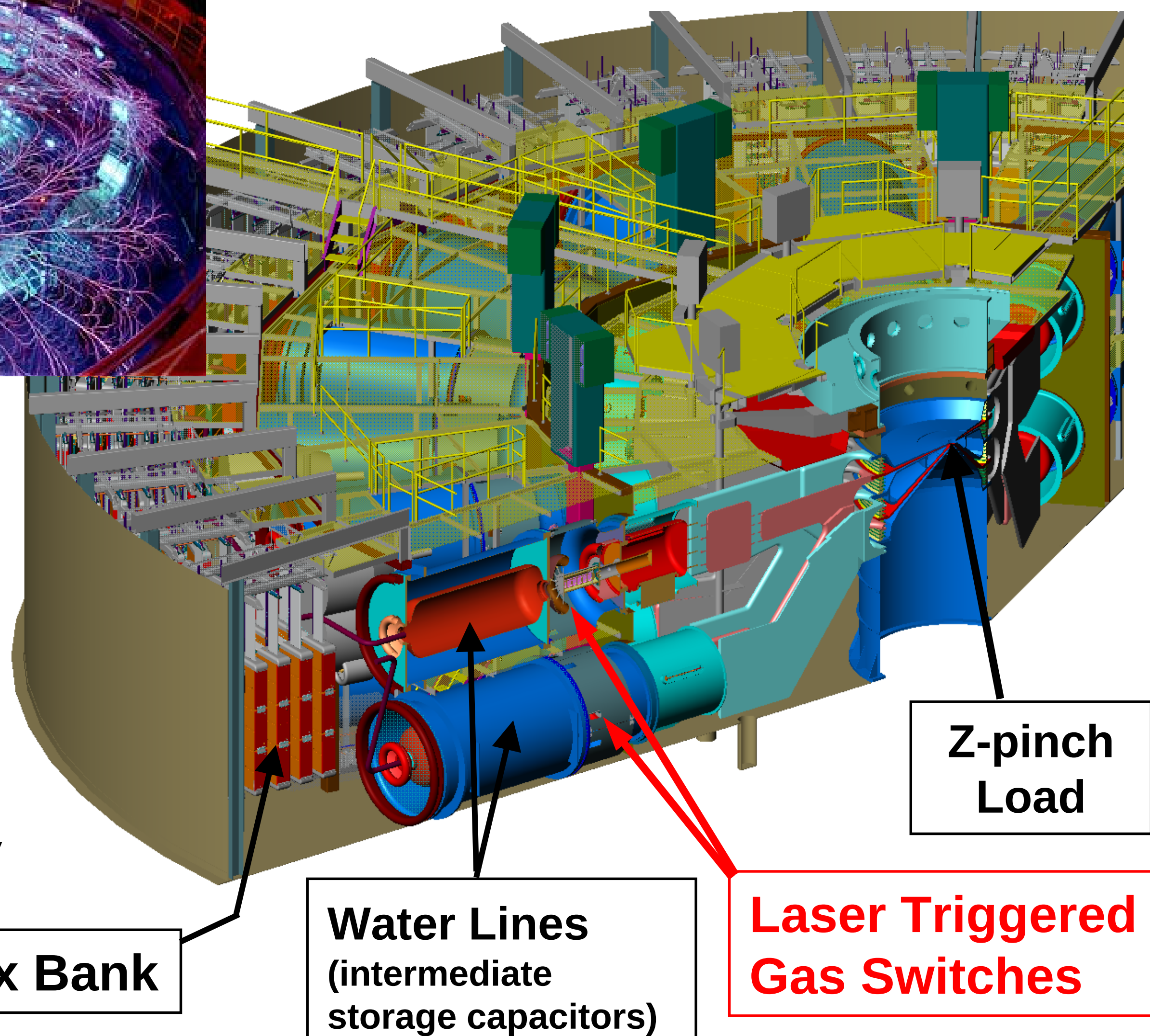
Overview

- Laser triggered gas switches are critical components in many pulsed power driven systems, such as ZR at Sandia National Laboratories. Timing jitter is of concern is such systems, where power flow from multiple modules must be switched to a load simultaneously.
- Laser triggered gas switches utilize a laser-produced plasma channel (LPPC) to initiate breakdown between electrodes biased to ~ 80% of breakdown voltage.
- The effective length, radius, and conductivity, of the LPPC are important parameters affecting breakdown timing.
- Multiple diagnostics, including guided microwave backscattering, D-dot probes, and visible and Shlieren imaging, are being used to characterize the effective length, radius, and conductivity of the LPPC vs. switch parameters such as SF_6 gas fill pressure, trigger laser focal length, beam waist position, and laser energy.

Pulsed Power Switching with Laser Triggered Gas Switches

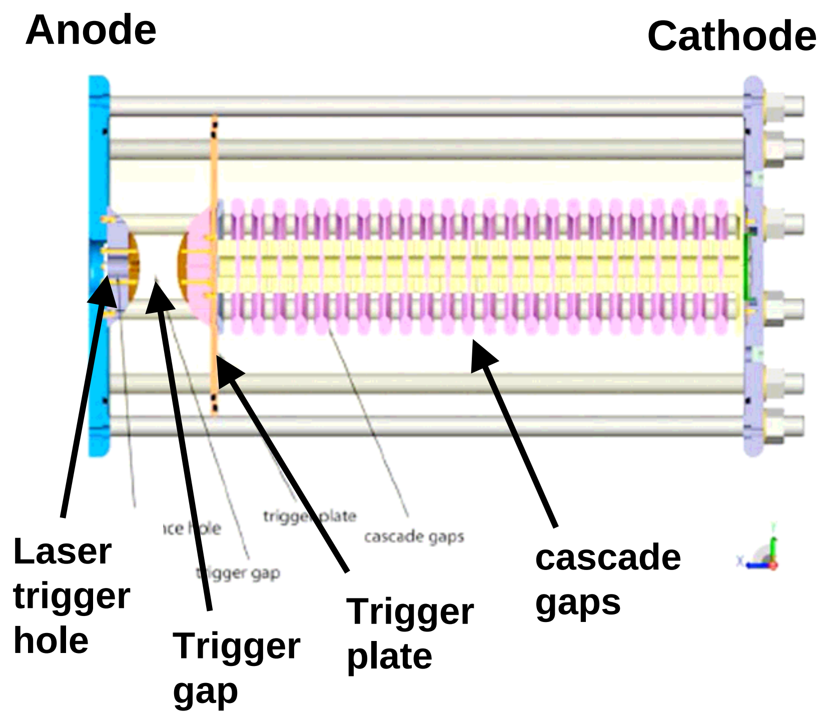


ZR at SNL



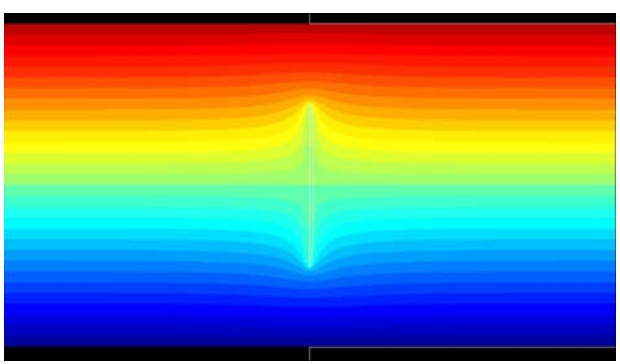
- On ZR, LTGS's are the only triggered (controlled) switch after the initial Marx bank discharge
- Prior to triggering, LTGS's hold off ~ 6 MV

Laser Triggered Gas Switches

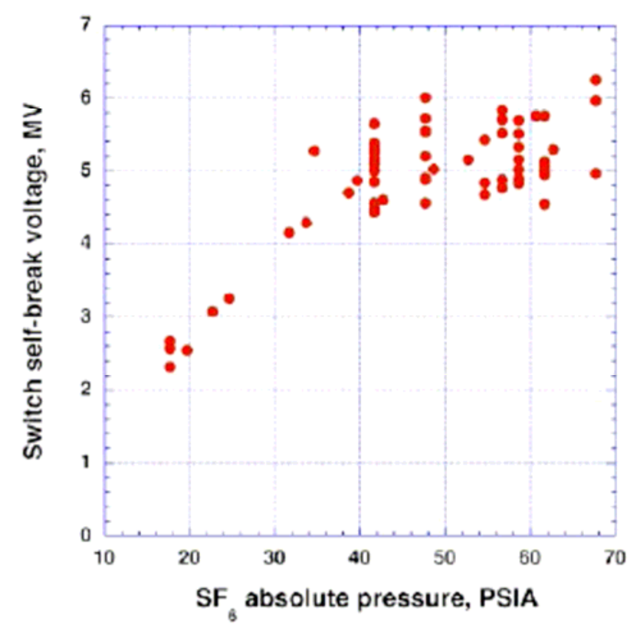


- LTGS trigger gap biased to ~ 80% of breakdown voltage
- Strongly electronegative SF_6 can stand off MV over cm's gap
- Trigger laser (4ω Nd:Yag, 266 nm, ~ 20 mJ) forms plasma channel in gap
- Plasma channel displaces equipotential contours ⇒ breakdown ⇒ switch closes

Deformation of equipotential contours by the laser plasma in the trigger gap, calc. by Electro



Self-break voltage vs. SF_6 pressure

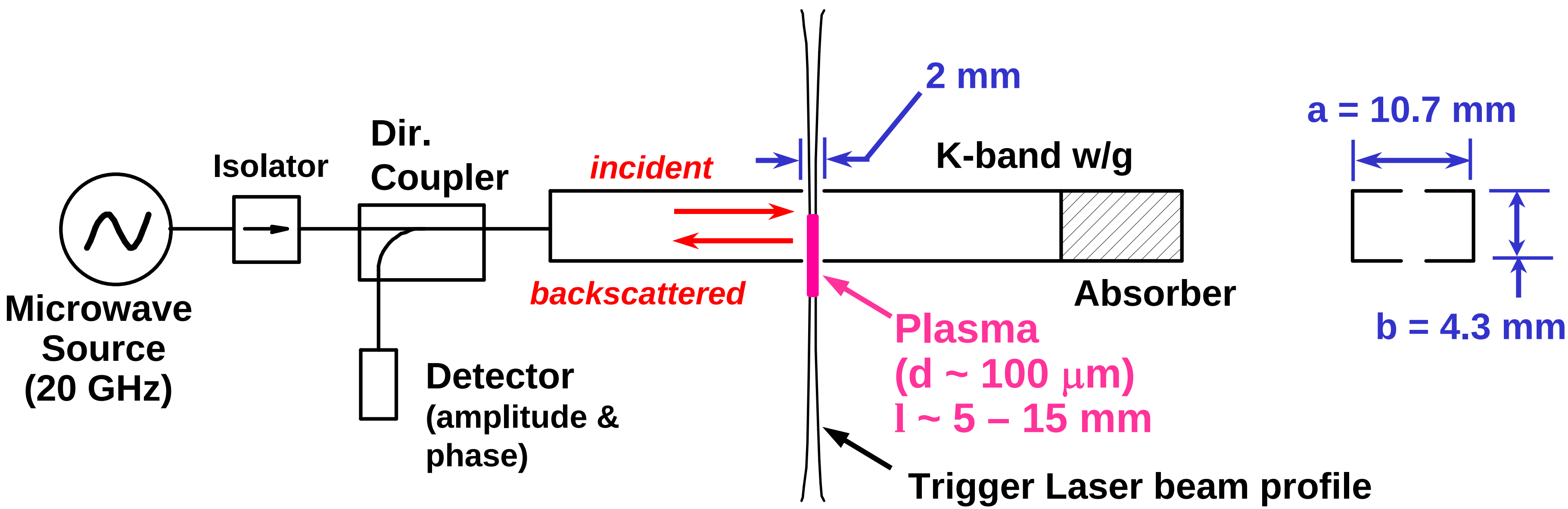


Principle of Guided Microwave Backscattering

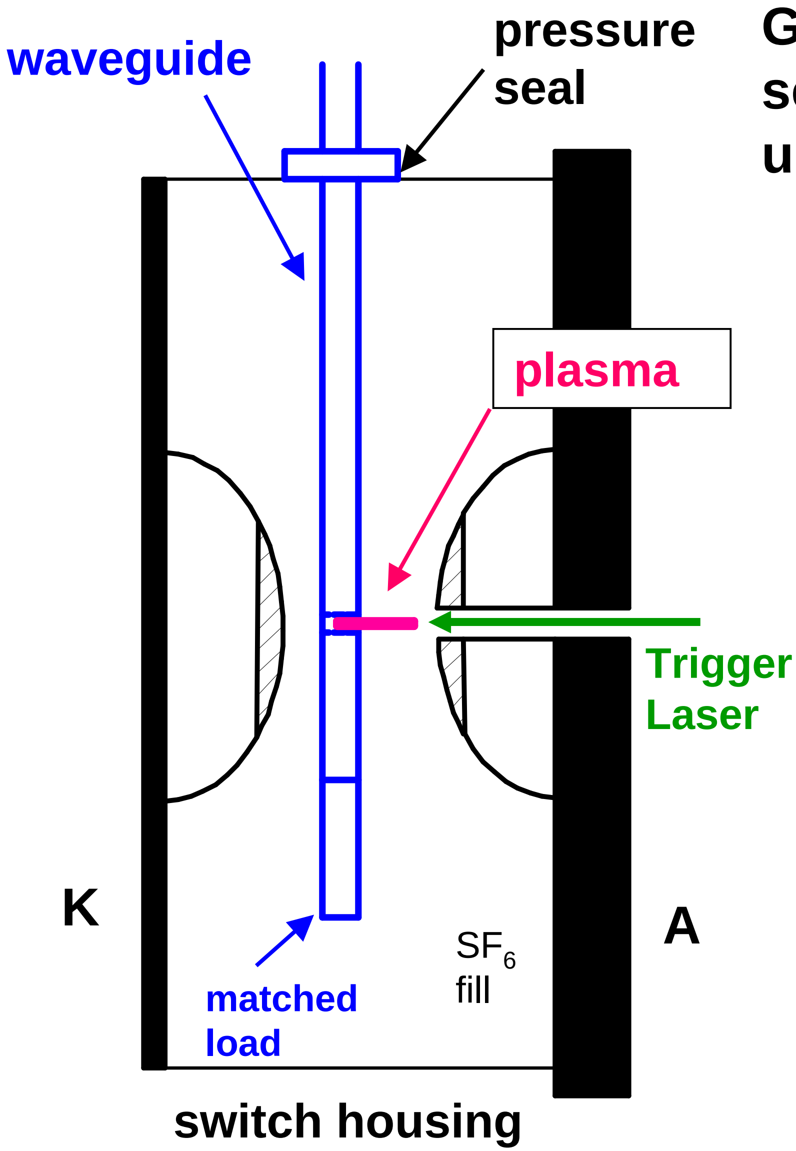
- **Standard rectangular waveguide with small holes in the broad wall is inserted into a LTGS mockup. The laser-produced plasma channel (LPPC) is formed partially inside the waveguide. The plasma can be translated by moving the trigger laser focus.**

- **Microwave power backscattered from the LPPC (a conductor) is measured. Theory and modeling indicate that backscattered power:**

  - is dependent on the length of the plasma, l
  - has a Re part dependent on the plasma radius, r (~ *ln*(a/r))
  - has an Im part dependent on the plasma conductivity, σ



Principle cont.



Guided wave backscattering setup in the gas switch mock-up (see below)

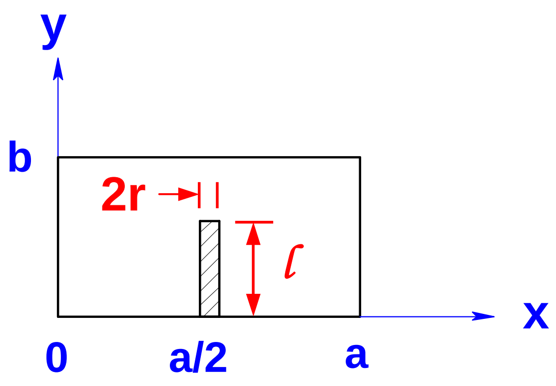
- Though a larger size waveguide, with b > *l*, would be better from a scattering point of view, the plasma has a risetime of τ ~ 500 ps . We want the microwave period T = 1/f << τ in order to have a stationary measurement. Furthermore, single mode (fundamental) waveguide operation is desirable.
- f = 20 GHz, and K-band waveguide (WR-42, a = 10.7 mm, b = 4.3 mm) was chosen as a good compromise.
- The plasma can be translated through the w/g to sample its total length

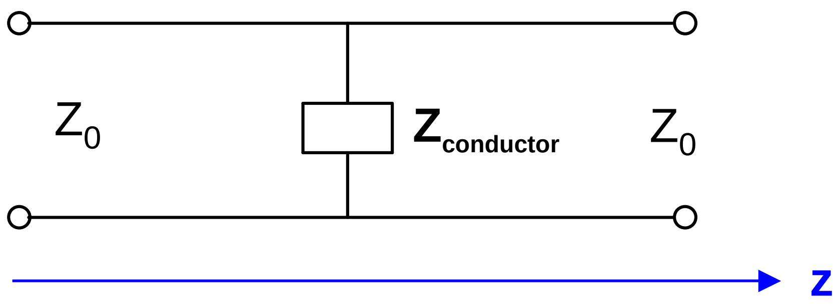
Analytical Model

- An analytical model is available only for the simplified case where the conductive post (plasma) is connected to one waveguide wall (the lower broadwall, in this case).

- Nevertheless, important conclusions can be drawn from this simple case.

- Following Lewin[1], this can be modeled as a transmission line of impedance Z_0, with shunt load of complex impedance $Z_{conductor}$





Backscattering is described by the *complex* reflection coefficient at Z:

$$\Gamma = \frac{Z_{conductor} - Z_0}{Z_{conductor} + Z_0}$$

Forward scattering is described by the *complex* transmission coefficient: $T = 1 + \Gamma$

[1] L. Lewin, *Theory of Waveguides*, chap. 5, J. Wiley & Sons, 1975

Analytical Model cont.

- For the centered vertical (inductive) post, Lewin gives:

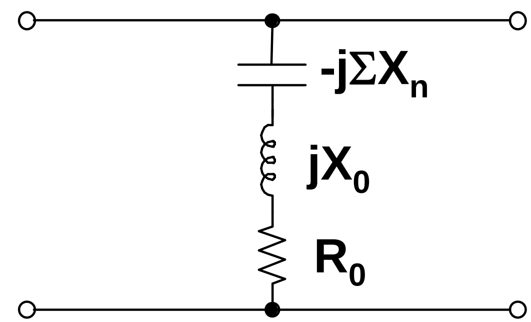
$$Z_{conductor} = R_0 + jX_0 - j\sum_{n=1}^{\infty} X_n$$

post resistance (R_0)

reactance of full length post (jX_0)

negative reactance (capacitance) due to post-upper wall gap (scattering into higher order w/g modes) ($-j\sum X_n$)

$\Rightarrow$ crkt model



- Lewin gives the following approximate expressions:

$$R_0 = \pi r^2 l \sigma(\omega)$$, σ(ω) is the conductivity per unit length of the post

$\Rightarrow$ Real part of Z (R_0) depends on conductivity of post (plasma)

$$X_0 \approx \frac{a}{2\lambda_g}\left\{\underbrace{\ln\left(\frac{2a}{\pi r}\right)} + 2\left[-1 + \sum_{m=2}^{\infty} \sin^2\left(\frac{m\pi D}{a}\right)\left[\left(m^2 - \frac{k^2a^2}{\pi^2}\right)^{-1/2} - \frac{1}{m}\right]\right]\right\}$$

a >> r $\Rightarrow$ weak dependence of X_0 on conductor (plasma) radius

Analytical Model cont.

$$\sum_{n=1}^{\infty} X_n = \frac{a}{4\lambda_g} \int_0^l \int_0^l I(y) I(y') G(y,y')\, dy dy' \left[\int_0^l I(y)\, dy \right]^{-2}$$

where $I(y)$ is the induced post current, and the Green's Function G(y,y′) is given by:

$$G(y,y') = \pi Y_0(kr) + b \sum_{-\infty}^{\infty} \left[F_n(y+y') + F_n(y-y') \right]$$

with
$$F_n(\xi) = \left[1 + k^{-2} \frac{\partial^2}{\partial \xi^2} \right] \frac{\cos\left[k\left(r^2 + (2nb+\xi)^2 \right)^{1/2} \right]}{\left(r^2 + (2nb+\xi)^2 \right)^{1/2}}$$
(where ξ is a dummy variable)

very weak variation with r, if r << l, in the integral of G(y,y′)

- Since $k = 2\pi/\lambda_g$, $k r << 1$ for low order modes, we can use the small argument approximation for $Y_0(kr)$:

$$Y_0(kr) \approx \frac{2}{\pi} \ln\left(\frac{1.781 kr}{2} \right) = \frac{2}{\pi} \ln\left(\frac{1.781 \pi r}{\lambda_g} \right) \sim \frac{2}{\pi} \ln\left(\frac{2.8 r}{a} \right)$$

r <<a $\Rightarrow$ strongly dependent on r

Analytical Model cont.

- Real part of Z depends on post (plasma) conductivity, σ, and radius, r
- Im part of Z is independent of conductivity, σ, but depends on plasma radius, r
- Therefore, **Re{Γ} = function of conductivity** and radius

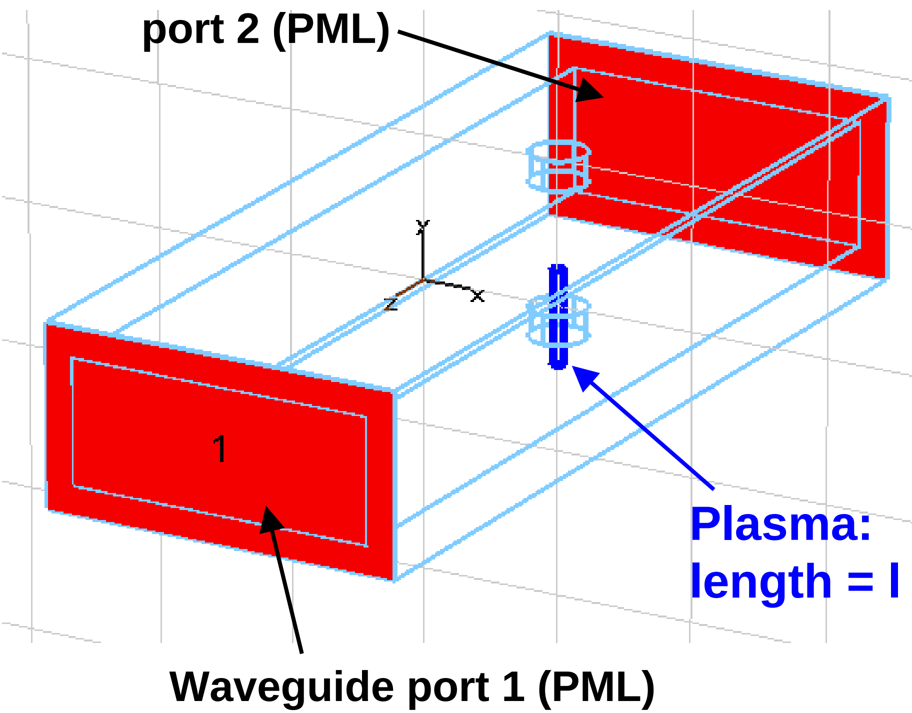
  Im{Γ} = function of conductor radius only
- By measuring both the backscattered power amplitude and phase (I/Q measurement), the Re and Im parts of Γ (= S_{11}) can be determined

Therefore, in principle, the conductivity and radius of the conductor (plasma) can both be determined from an I/Q backscatter measurement

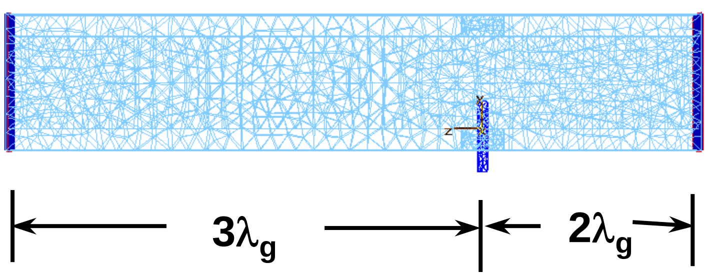
- Additionally, the plasma length can be measured by translating the laser focal spot through the waveguide, provided the plasma length *l* > *b* (short waveguide dimension (4.3 mm here))

Numerical Modeling

- Backscattering is calculated using commercial microwave engineering CAD software (***CST Microwave Studio***). Solver is finite element, frequency domain, with adaptive meshing.
- Plasma channel is modeled as a conducting post.
- TE_{10} mode launched from port 1. Scattering characterized by (complex) scattering parameters S_{11} and S_{12}.



Adaptive Meshing

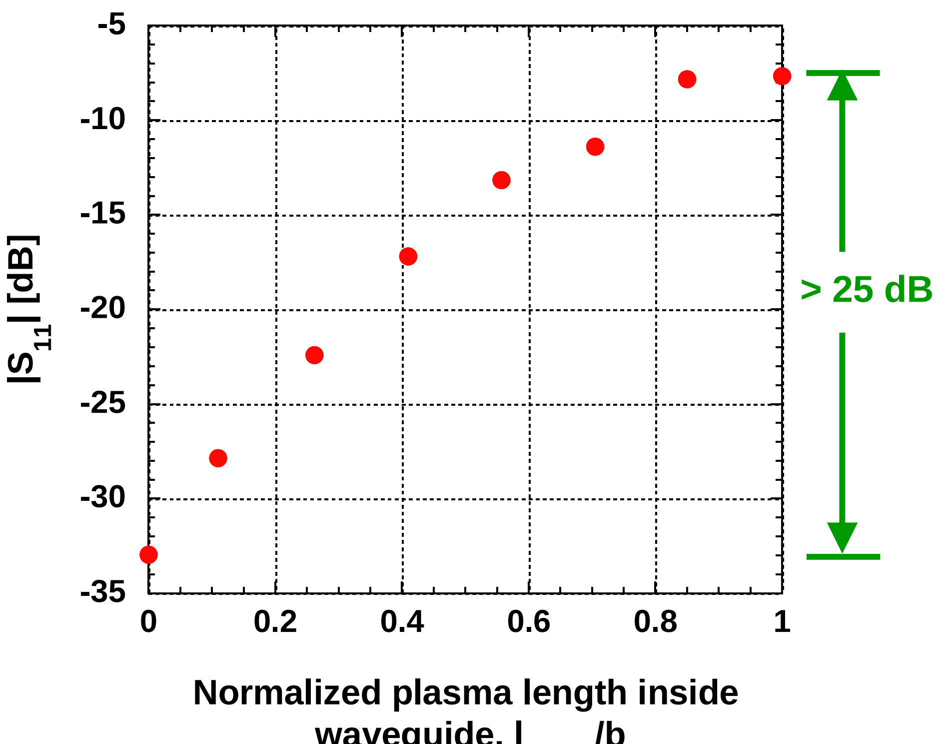


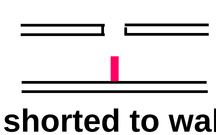
Higher order modes damped in less than $3\lambda_g$

Modeling Suggests that Plasma Length Changes < 1 mm Can be Resolved

Reflection coefficient (S_{11}) at port 1 vs. conductor length inside w/g

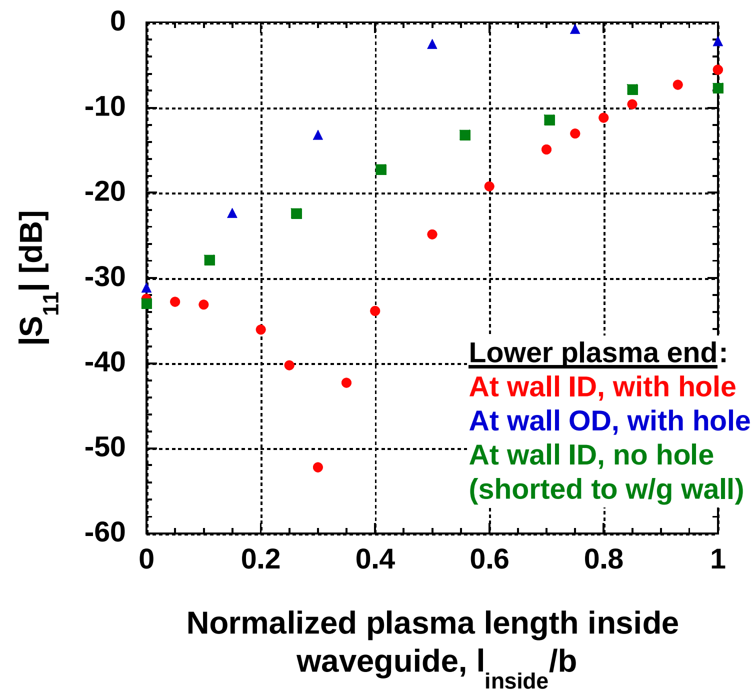
(conductor shorted at lower w/g wall, $l_{inside}/b = 0$)

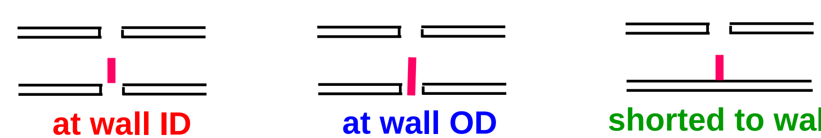




(b = 4.3 mm)

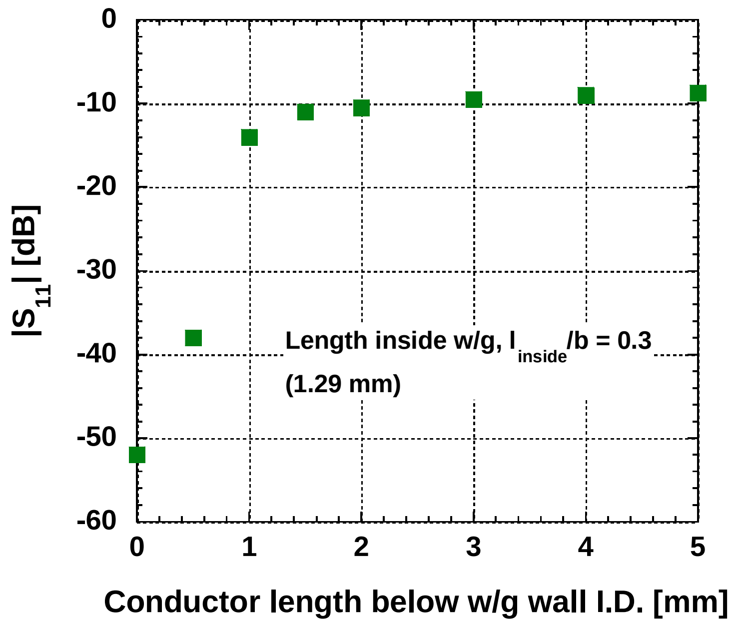
- **However, backscattering depends on the length of the conductor <u>outside</u> the w/g as well as <u>inside</u>**

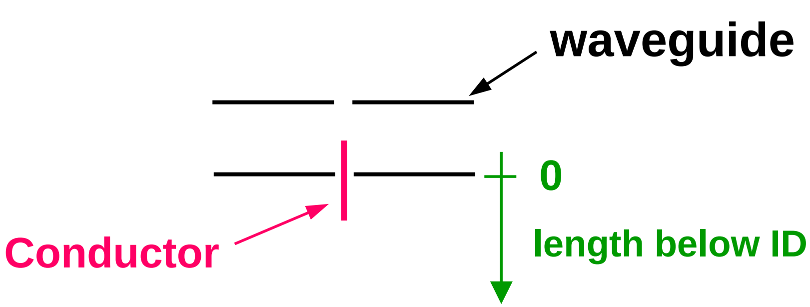




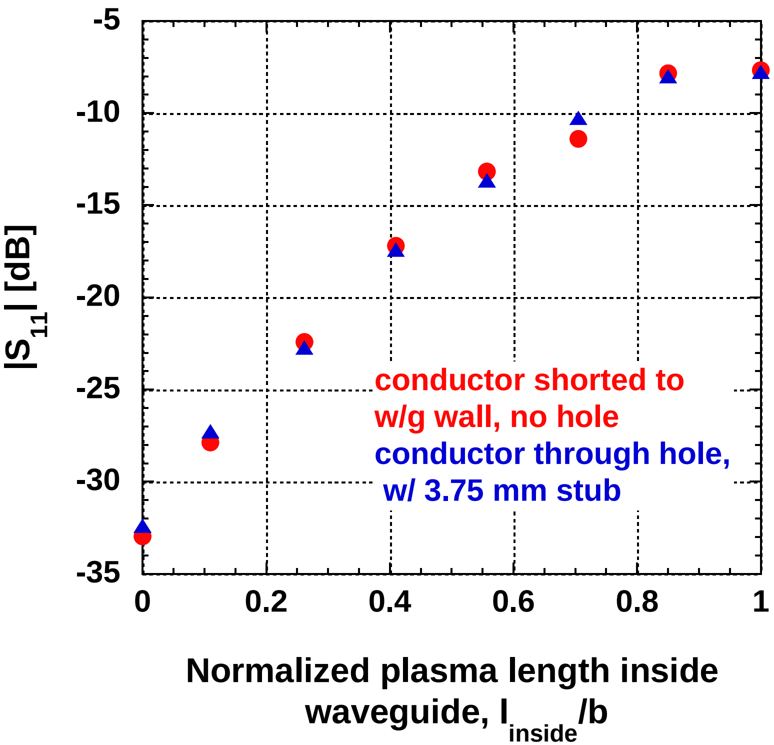
Modeling Indicates that $\lambda/4$ Coaxial Stub Makes Back-scattering Insensitive to Plasma Outside Waveguide

S_{11} vs. conductor length outside of the waveguide with **no $\lambda/4$ stub**



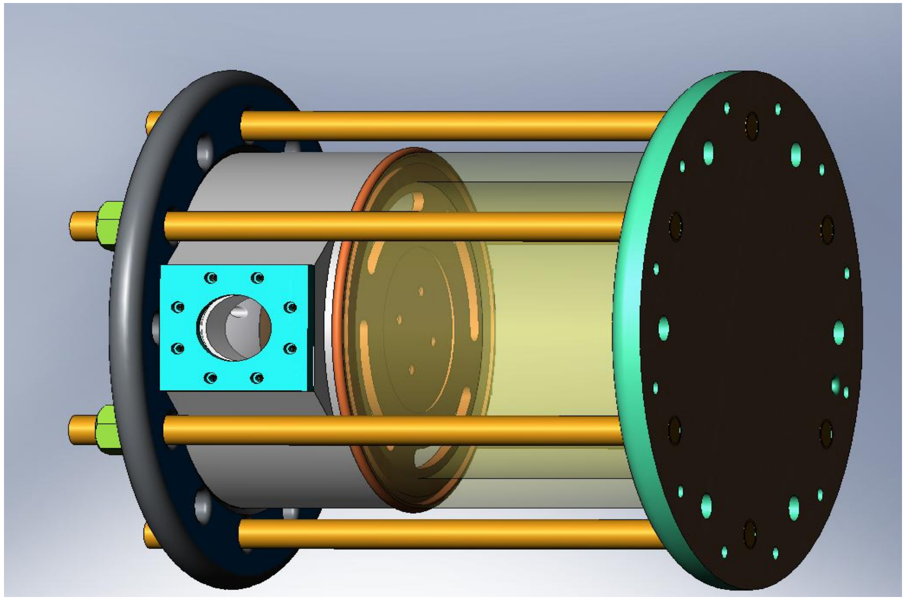


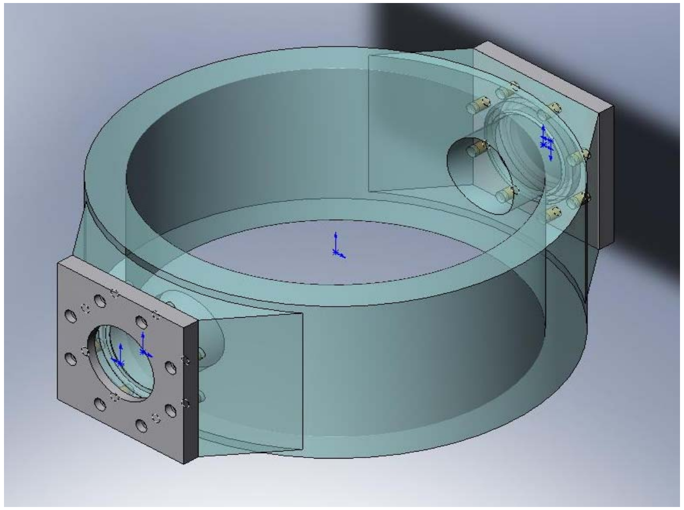
- Essentially no difference in backscattering between case where conductor shorted to w/g wall *versus* plasma through hole w/ $\lambda/4$ stub

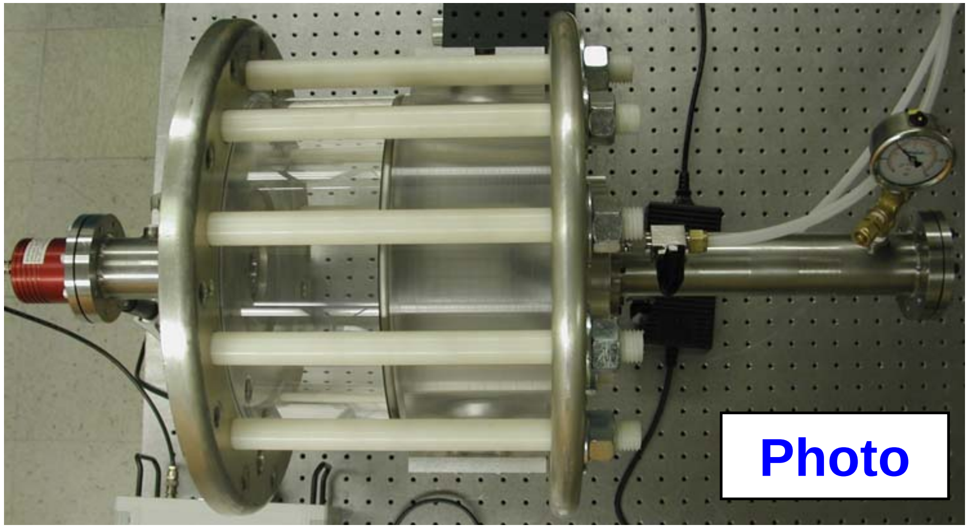


Experimental Setup: Gas Switch Mock-Up

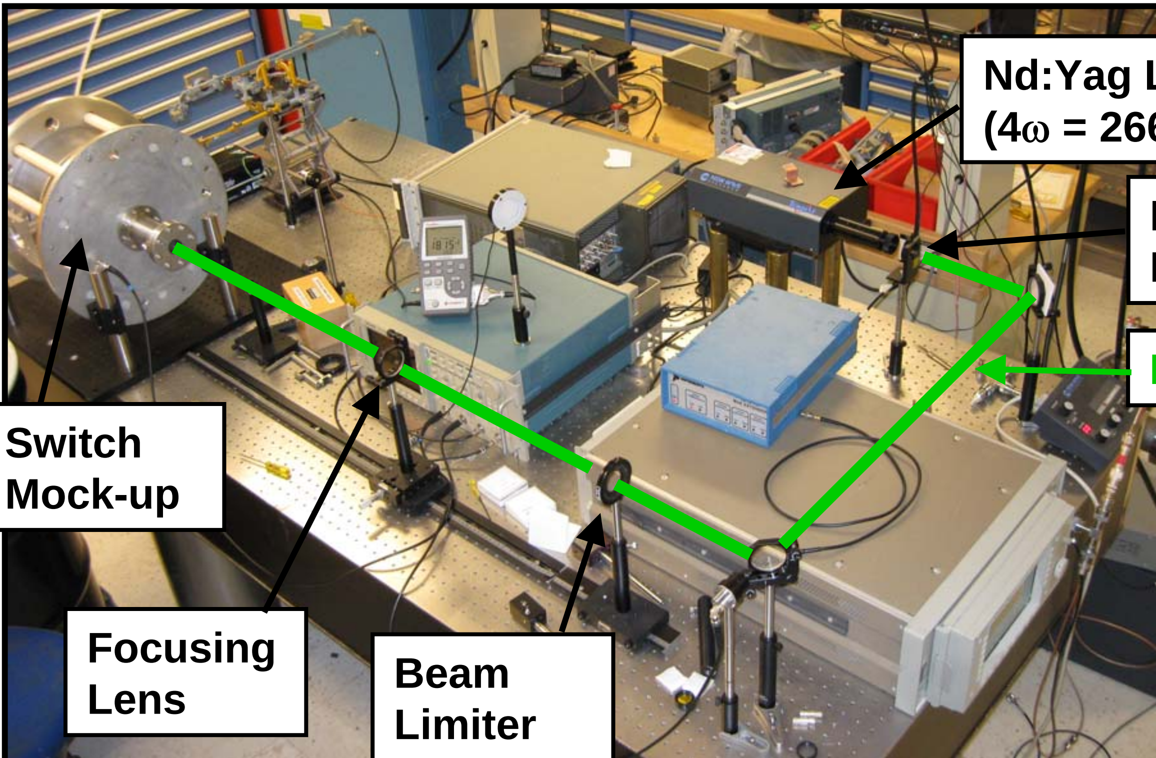
- A scaled down gas switch mock-up has been constructed for laboratory measurements (25 cm diameter, no cascade gap section)
- Pressure-sealed ports for optical windows or waveguide feedthrus added
- Optical windows: BK7 & UV grade fused silica. Viewing diameter: ~ 5 cm

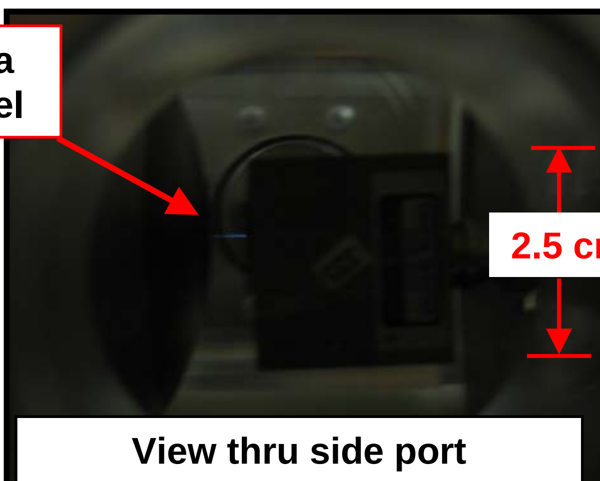


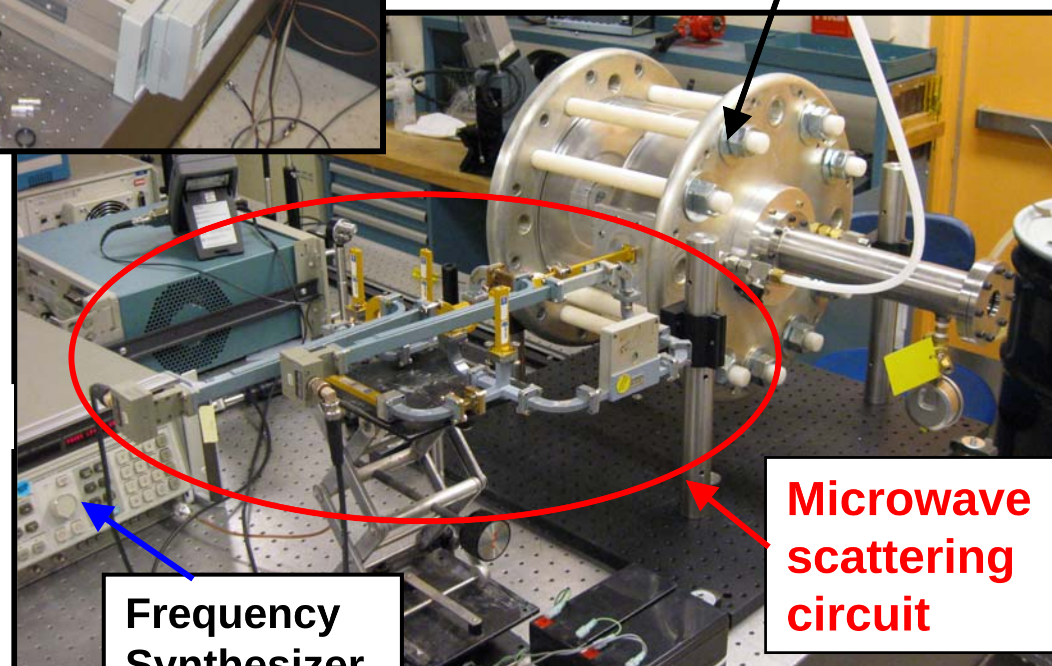




Experimental Setup cont.

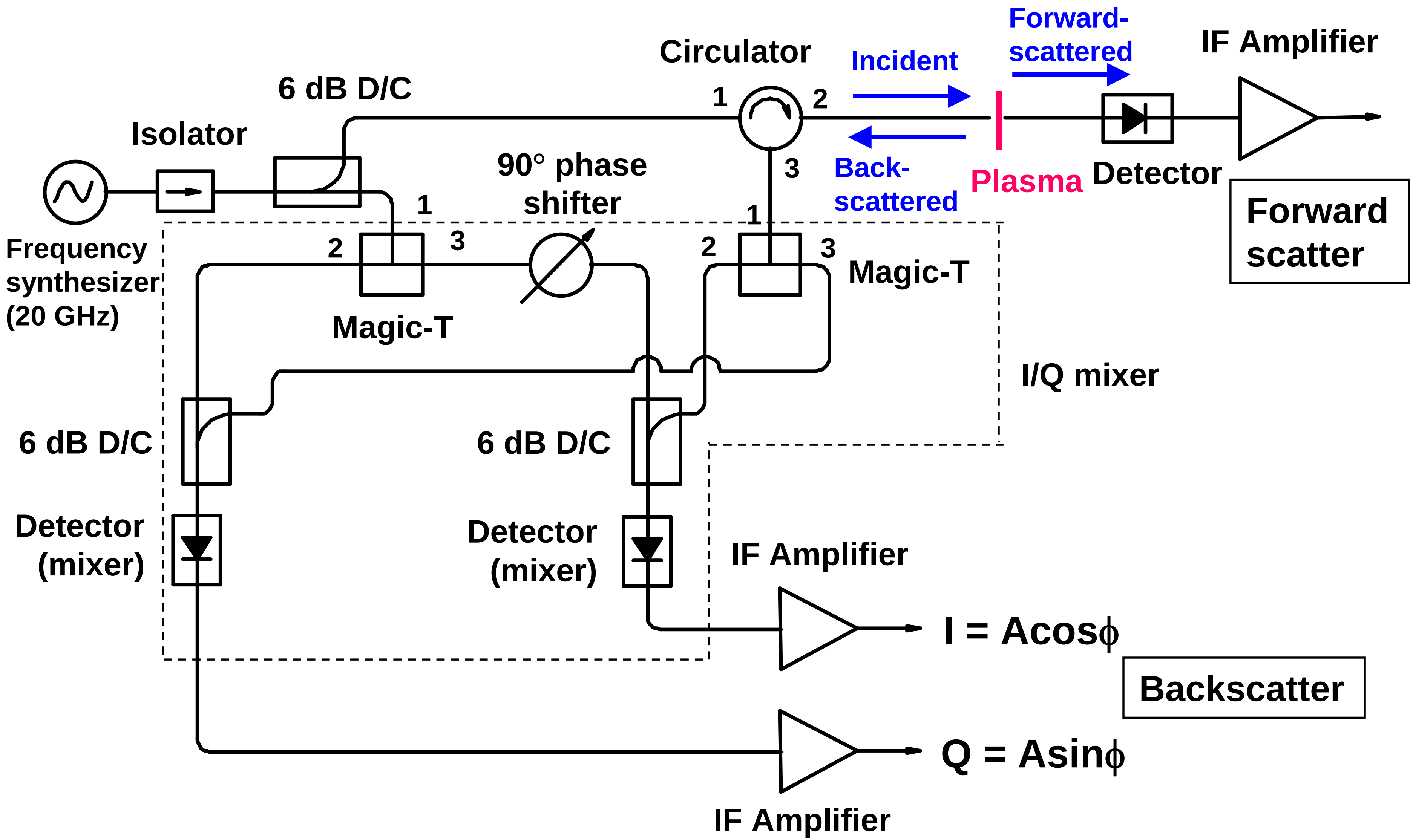






Microwave Circuit

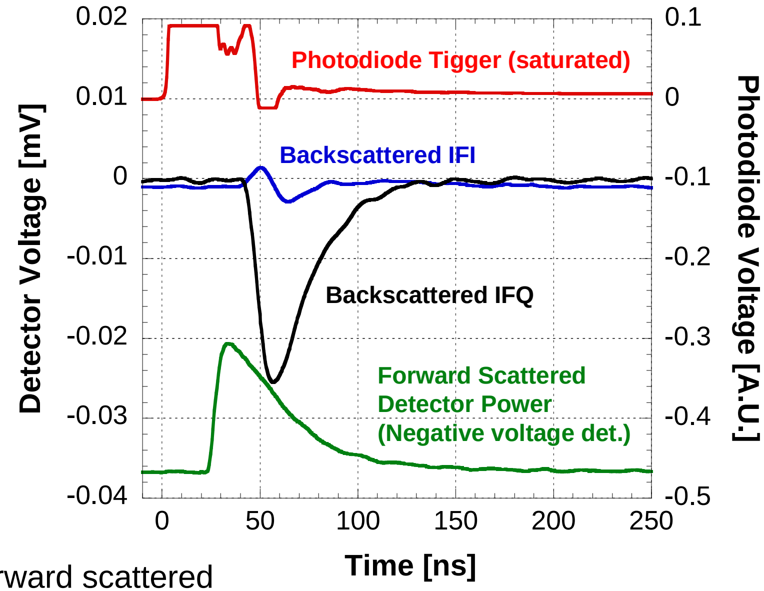
- I-Q detection to measure backscattered amplitude and phase
- Detector to measure forward scattered power



Experimental Results: Raw Data

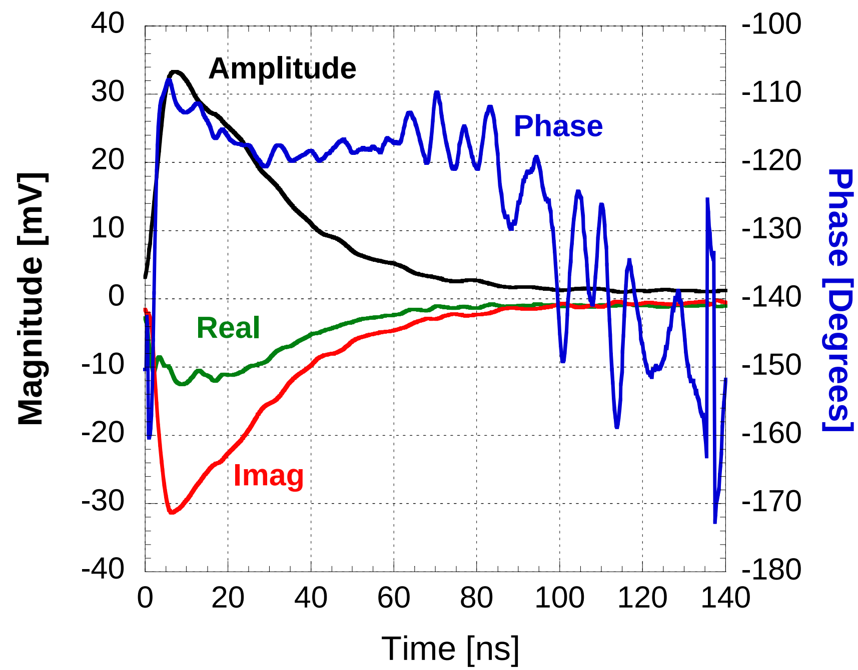
Example Raw Signals

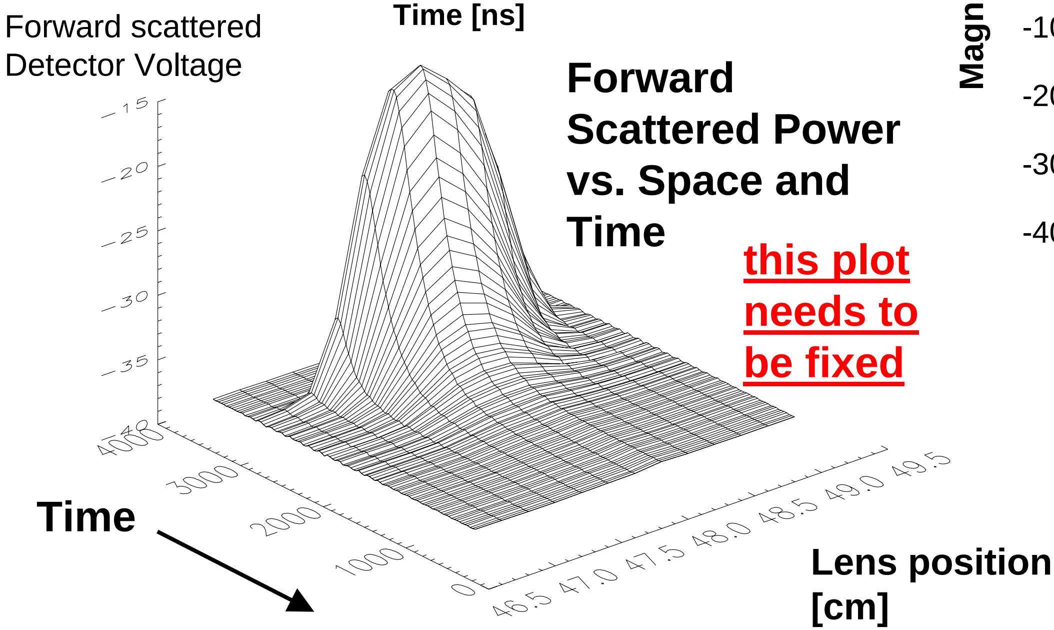
shot 368, 700 mm lens, 18 mJ, 30 psi



Backscattered Detector Amplitude, Phase, Re and Im parts Derived from I/Q Data

shot 422, 700 mm lens, 10 psi



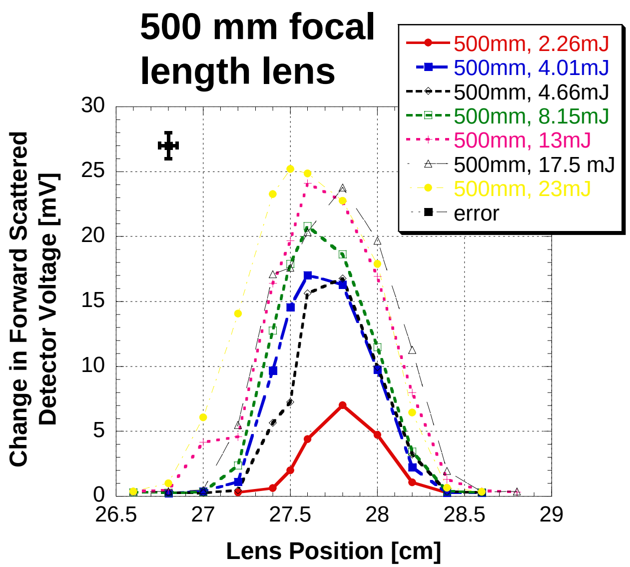


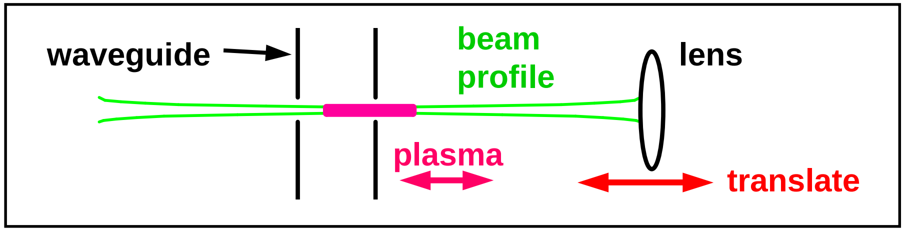
Forward Scattered Power vs. Space and Time

<u>this plot needs to be fixed</u>

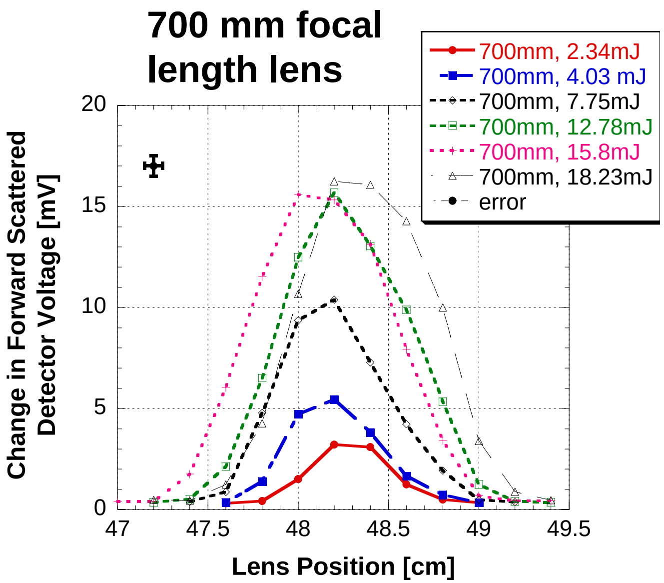
SF_6

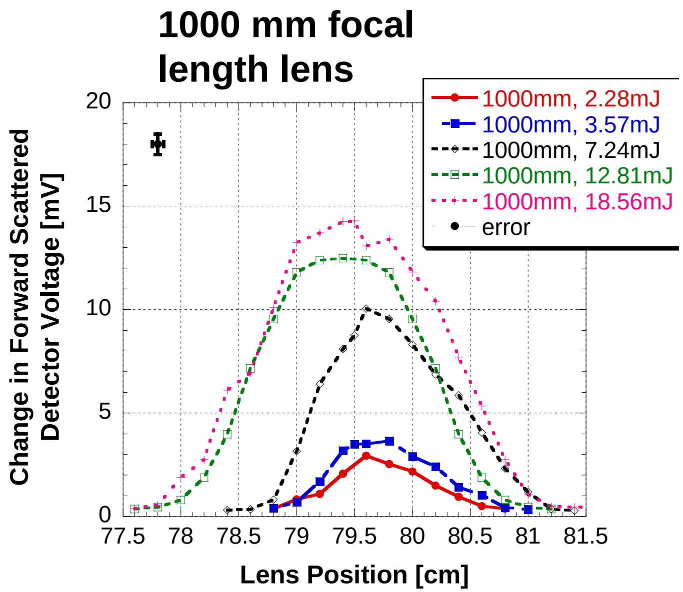
Plasma Channel Length Measured by Translating Focal Lens





- Focusing lens translated to move beam waist thru waveguide. Fwd- and backscattered μwave power measured to produce plasma profiles as shown.
- Lens focal length and laser energy varied

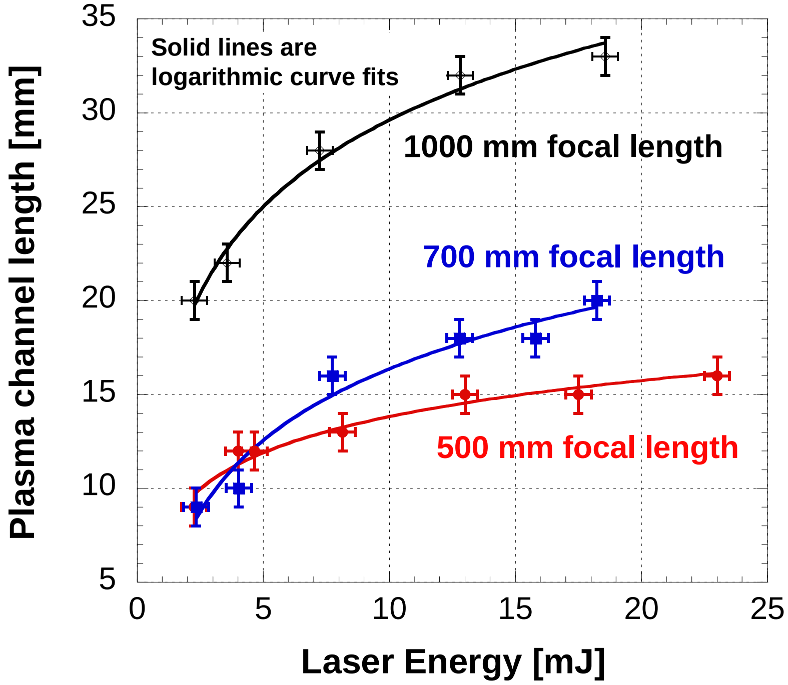




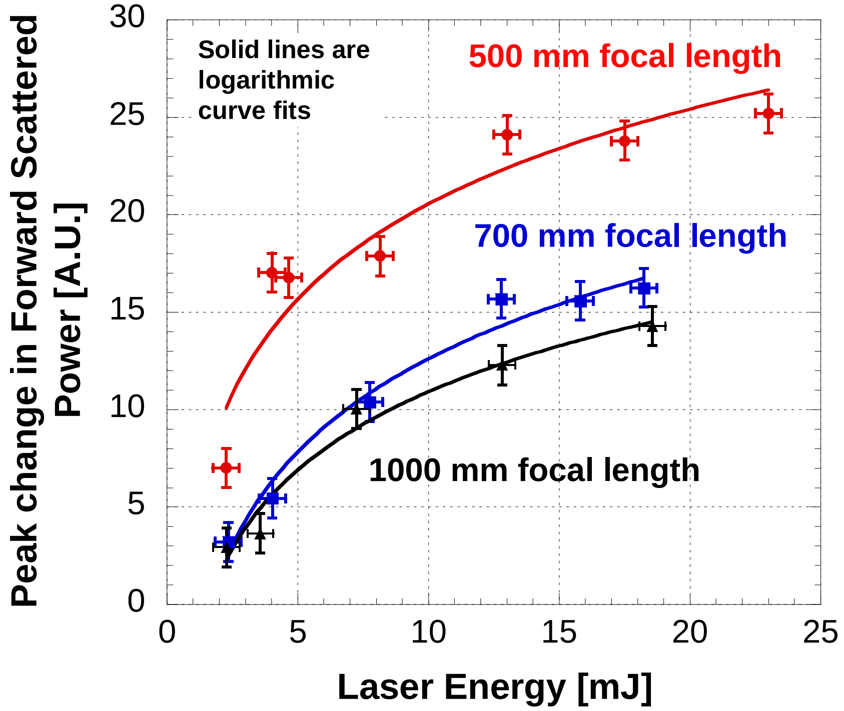
SF_6
30 psi

Plasma Channel Length and Peak Scatter Power vs. Laser Energy

Plasma Channel Length vs. Laser Energy



Peak Change in Forward Scattered Power vs. Laser Energy



- Plasma channel effective length shows an approximately logarithmic dependence on laser energy

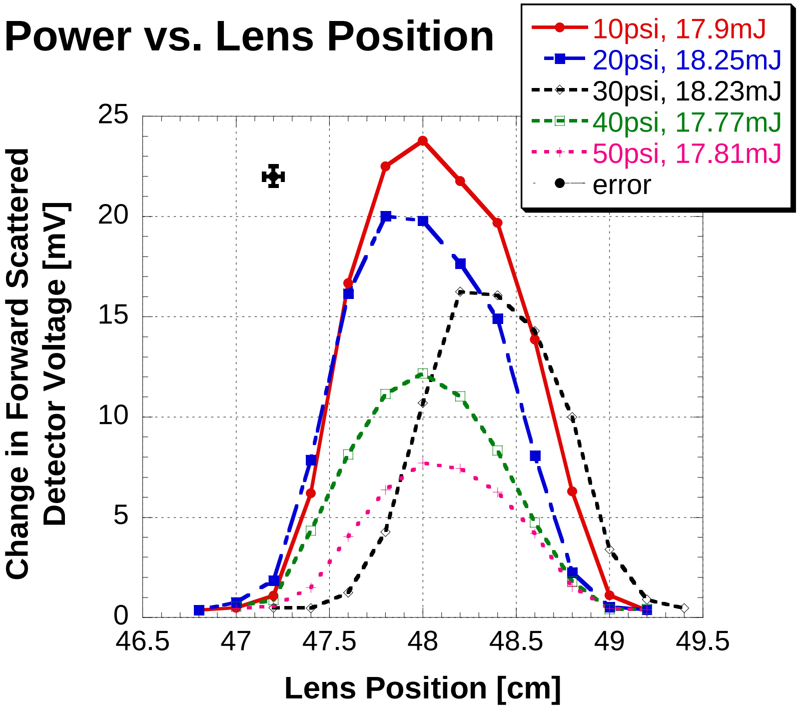
- Peak change in scattered power also shows an approximately logarithmic dependence on laser energy. This may indicate changes in plasma conductivity and radius.

SF_6 , 30 psi

Plasma Channel Length and Scattered Power vs. Fill Pressure

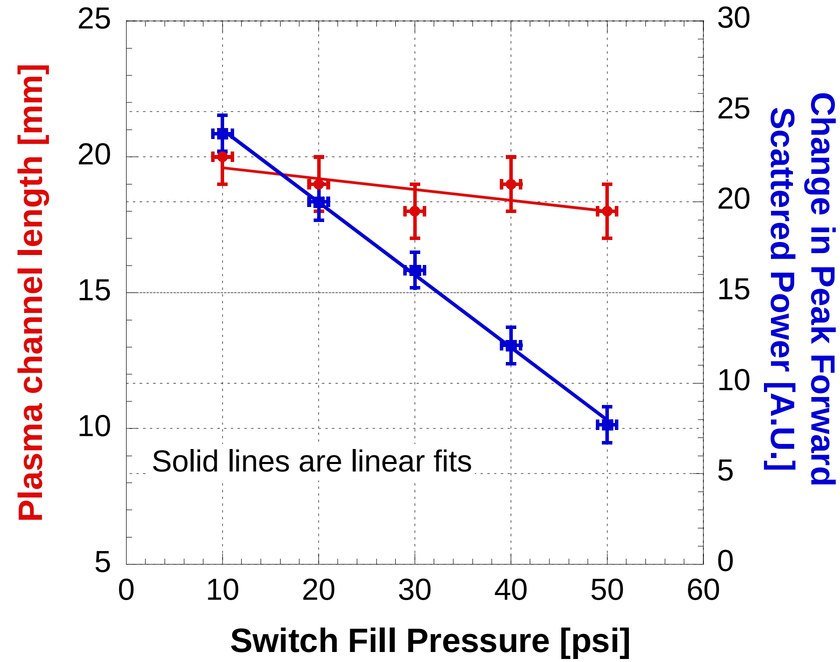
SF_6

Forward Scattered Power vs. Lens Position



Pressure Scan

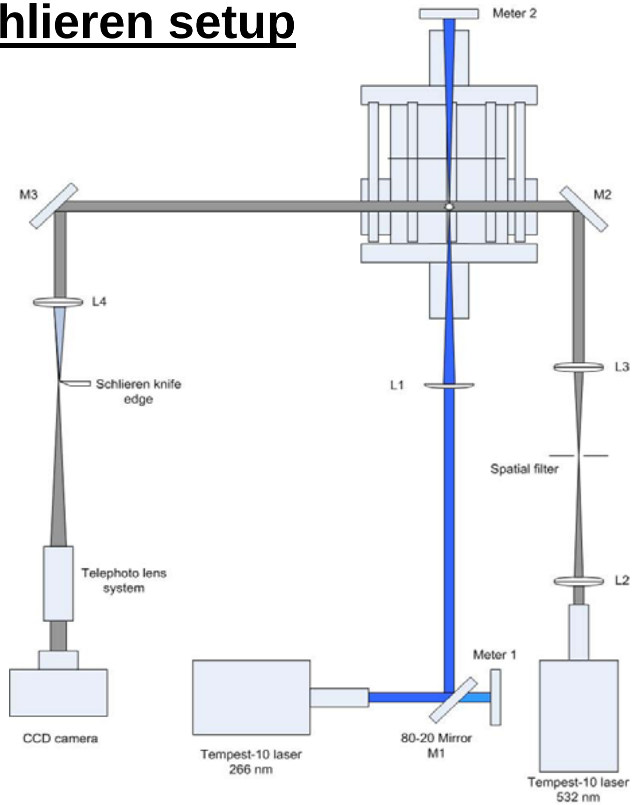
700 mm lens, ~ 18 mJ



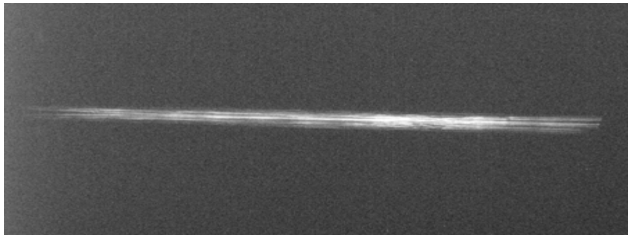
- Plasma channel effective length shows little or no change with SF_6 gas fill pressure (10 – 50 psig (1.8 – 4.9 atm)).
- Peak forward scattered power shows a strong linear dependence on fill pressure (backscattered power does also). This suggests that plasma conductivity and/or radius change significantly.

Visible Light and Shlieren Imaging Measurements of Channel Length

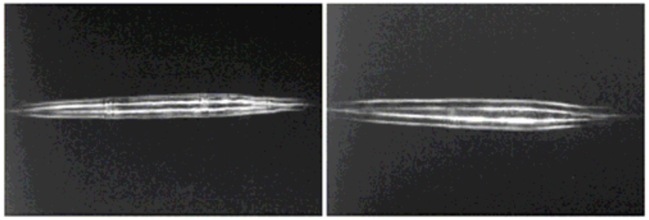
Schlieren setup



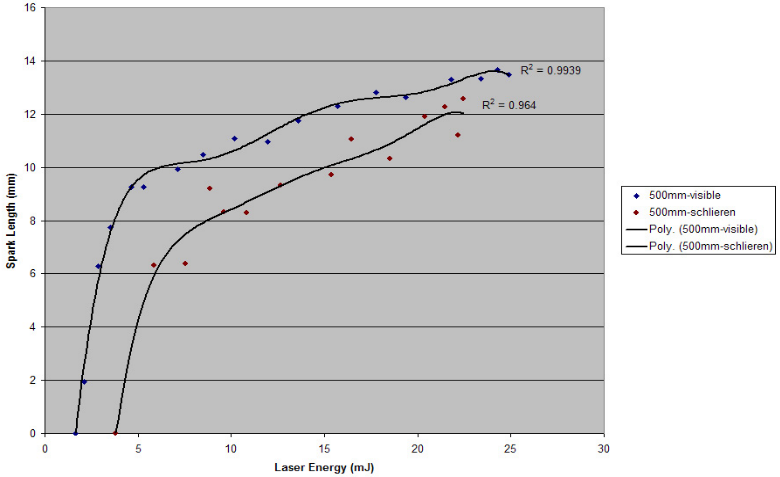
Schlieren plasma channel image



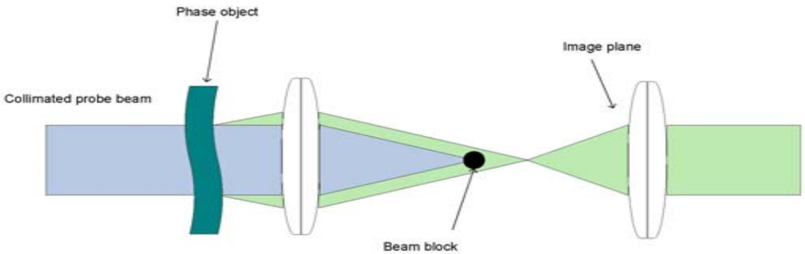
Schlieren image of shock waves expanding late in time



Spark length derived from Schlieren image is less than that derived from visible light

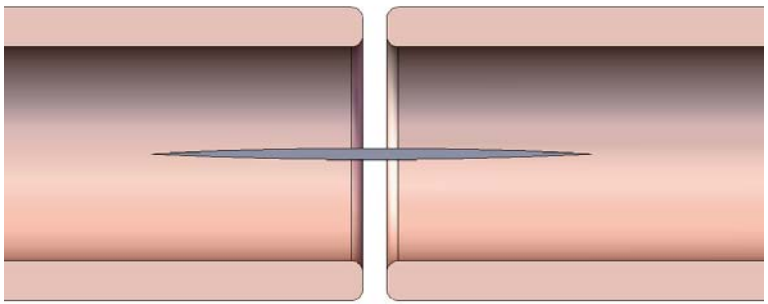


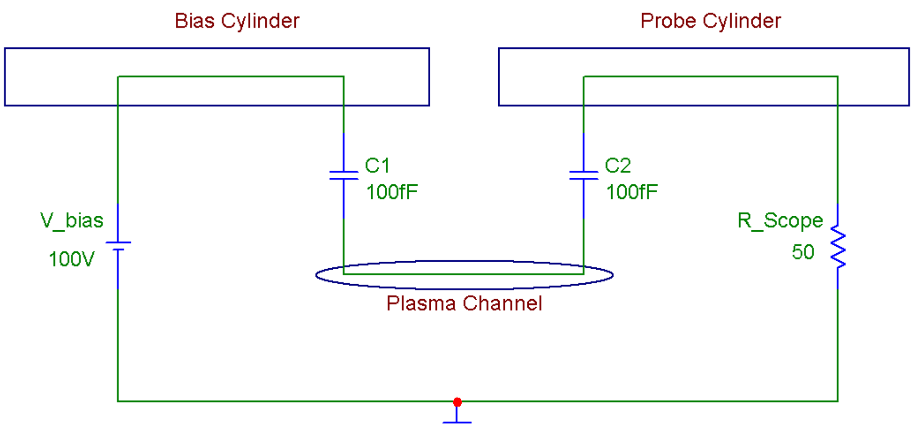
Schlieren detail



D-dot Probe Measurements of Channel Length

- Laser beam path surrounded by separated conducting shells. One shell biased. Plasma causes change in capacitance.





- At a given bias voltage, the output signal will be proportional to the rate of capacitance change over time.

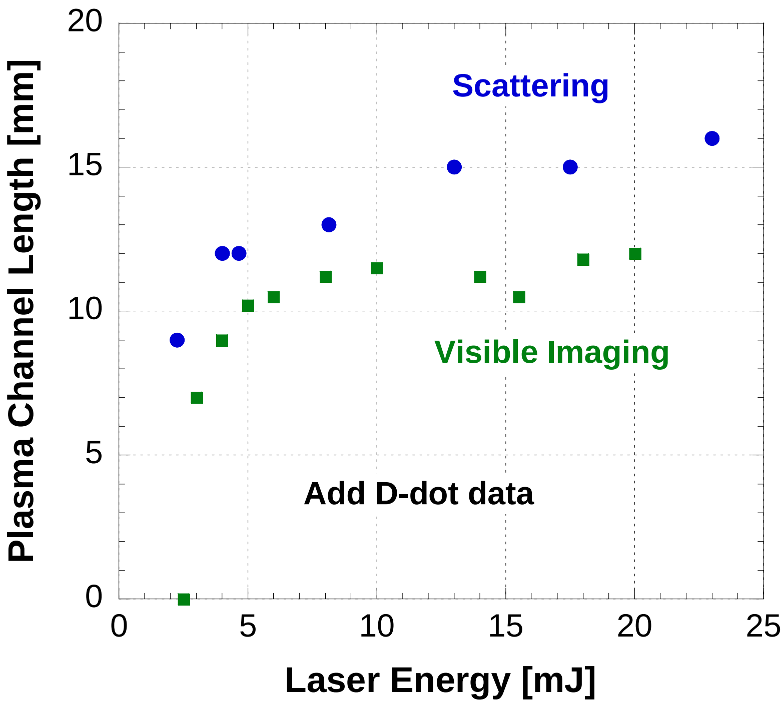
$$Q = V_{bias} C$$

$$\frac{dQ}{dt} = i = \frac{d(V_{bias} C)}{dt}$$

$$V_{probe} = iR = RV_{bias} \frac{dC}{dt}$$

Comparison of Scattering, D-dot Probe, and Visible Measurements of LPPC Effective Length

need correct D-dot data from Brian



- profound comments here about scattering and D-dot in good agreement, visible shorter, and Schlieren shorter still

SF_6 , 30 psi

Summary

- Measurements of laser plasma channel length in the LTGS mockup have been made, **demonstrating the success of the guided wave back-scattering technique**.
- These scattering measurements of effective plasma channel length show good agreement with D-dot probe measurements, and indicate that **visible imaging measurements of the plasma tend to underestimate its length**.
- Plasma channel length increases with laser energy, and the dependence is reasonably well fit by a logarithmic function (in the range ~ 2 – 20 mJ).
- Plasma channel length show little or no dependence on gas fill pressure in SF_6. However, there is a strong linear dependence of scattered power with fill pressure (SF_6), suggesting strong changes in plasma conductivity and/or radius.
- Future measurements will utilize different fill gases (N, N/SF_6 mix, Ar/ SF_6 mix)

Summary cont.

- Theory indicates a strong dependence of ***Im*{ Γ }** on plasma radius, and a linear dependence of ***Re*{ Γ }** on plasma conductivity ($\Gamma = (Z_{plasma} - Z_0)/(Z_{plasma} + Z_0)$) is the complex reflection coefficient). **Therefore, I/Q measurements of backscattered power should be able to give at least relative measures of plasma conductivity and radius**. This analysis is currently underway.
- Thus far, modeling shows qualitative agreement with the dependence of forward- and backscattered power on effective plasma channel length.
- Modeling work to attain better quantitative agreement with measured scattered power is continuing. It is hoped that modeling will allow a ***quantitative* determination of plasma radius and conductivity**.
- Modeling indicates that adding a λ/4 coaxial stub removes sensitivity of backscattering to plasma outside of the waveguide. This sensitivity is not observed in experiments, and is likely due to a numerical boundary condition issue.