Thomson Scattering Results from General Fusion's SPECTOR

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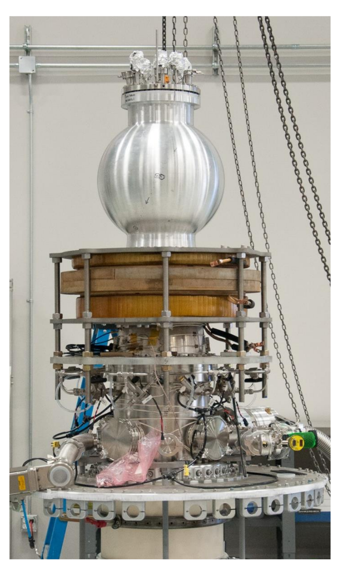
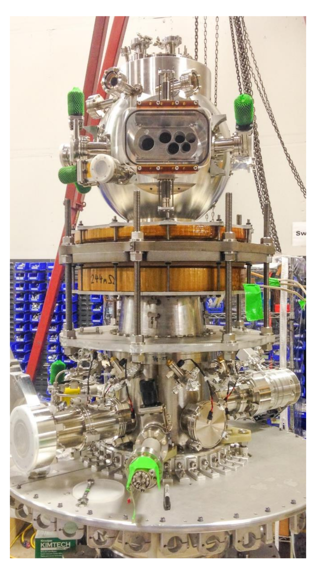
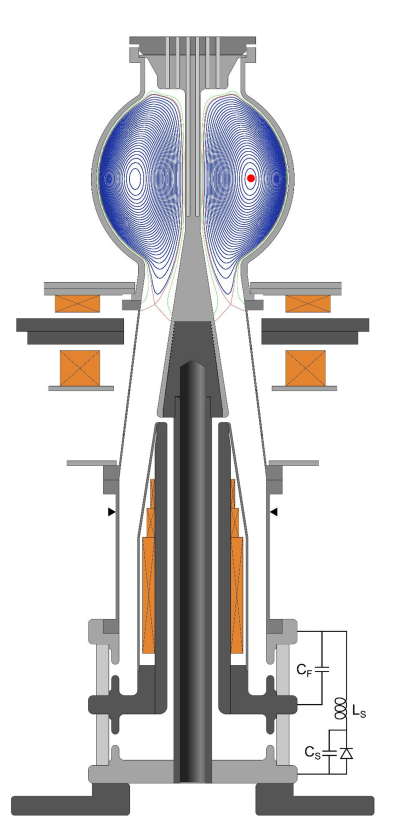
INTRODUCTION

Here we report details of the Thomson scattering diagnostic at General Fusion and electron Temperature measurements from its SPECTOR device that exceed 400eV at the plasma core. SPECTOR (SPhErical Compact TORoid) is the latest reduced-scale plasma injector at General Fusion designed to enable more spherical, self-similar compressions of candidate plasma targets for our MTF program. Two versions of SPECTOR have been built: a laboratory version for diagnosing the pre-compressed plasmas, and a version compatible with compression (PCS) tests. The Thomson scattering diagnostic is installed on the laboratory version only. Temperature and density measurements are made at four spatial positions, with plans to expand to six spatial positions. The diagnostic uses a 532 nm Nd:YAG laser and an imaging spectrometer with photomultiplier tube based detector. Other planned upgrades include camera and fiber based alignment monitoring and redesign of the collection optics and detectors.

Near Right: Compression version of SPECTOR during assembly
Far Right: Instrumented, lab version during assembly
Below: Cross-section showing equilibrium magnetic field lines and Thomson laser beam position.





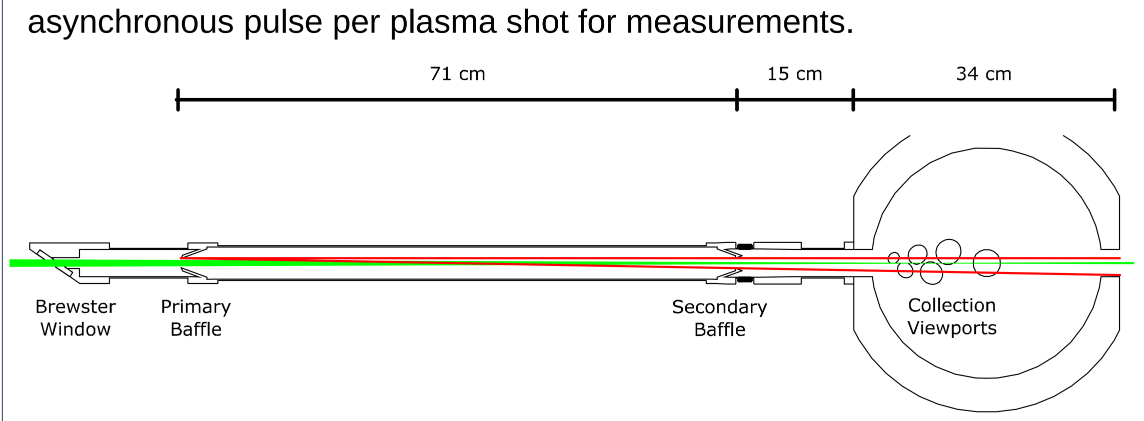


Typical Plasma Conditions

Lifetime:	1-2 ms
Species:	Deuterium
Inner Radius:	19 cm
Density:	0.2-1.5x10^{20} m^{-3}
T_e:	100-400 eV
Magnetic Field:	1 T Poloidal, 10 T Toroidal (At inner shaft surface)

BEAMLINE AND STRAY LIGHT REDUCTION

The diagnostic uses a frequency double Nd:YAG laser, with 1.3-1.8 J pulse energy at 532 nm. The laser operates at 10 Hz, with a single, asynchronous pulse per plasma shot for measurements.

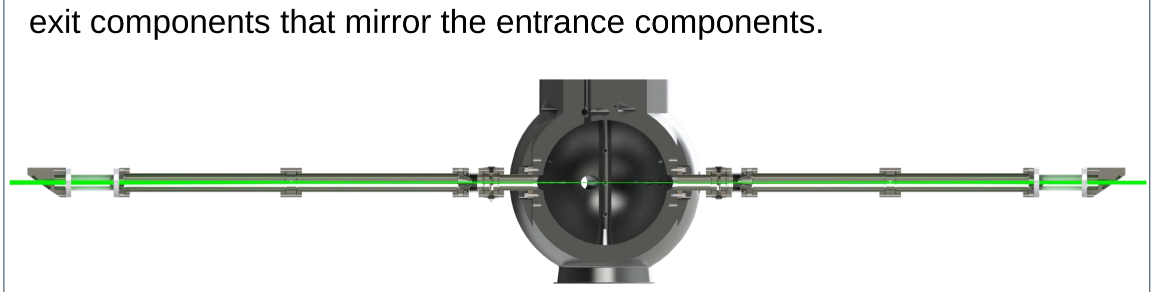


An illustration (above) shows beamline components at the vacuum entrance of the beamline. The beam passes through a f=1.5m lens (not shown) and enters the vacuum through a Brewster window.

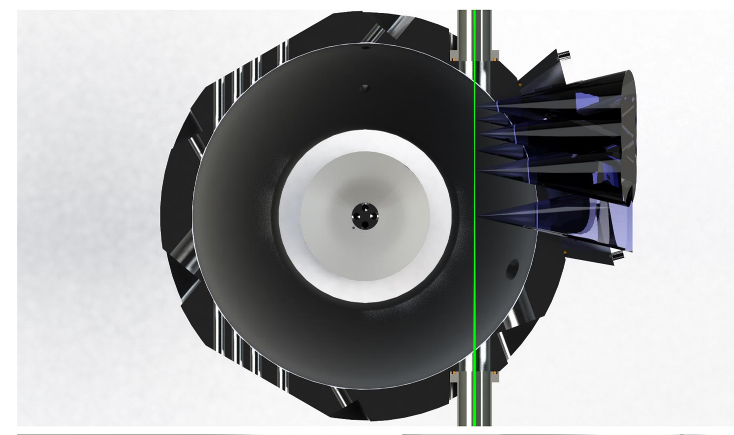
The combination of the two baffles block any direct ray from the window from reaching the inner surface of the main vacuum chamber, reducing laser light scattered by the window into the collection optics. Additionally, light scattered by the primary baffle (shown in red) is also blocked from the inner vacuum vessel.

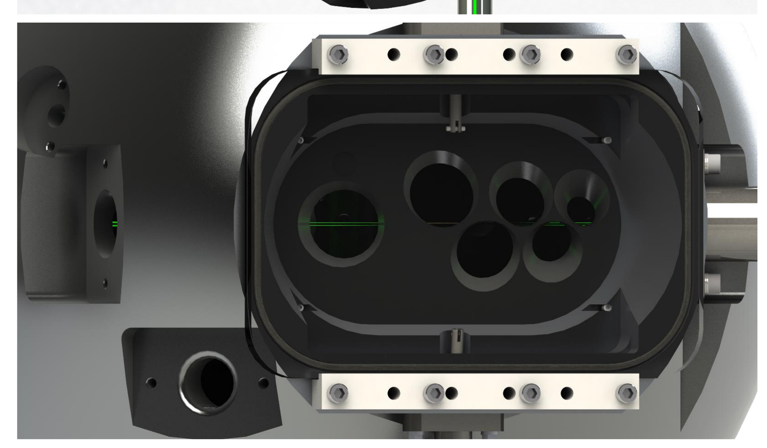
All inner surfaces of the beamline are coated in graphite using Aquadag, a suspension of colloidal graphite in water and ammonia. A minor upcoming upgrade to the beamline will install solid graphite baffles, as laser misalignment can strip the graphite coating off the current stainless steel baffles. Additionally, repositioning the primary baffle will create a critical baffle.

A rendering (below) shows the complete vacuum beamline, including the exit components that mirror the entrance components.



COLLECTION OPTICS





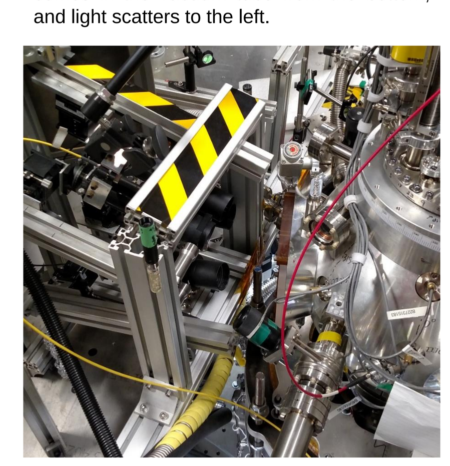
There are six viewports (overhead view: above, top), intersecting the beam with 1 cm radial spacing and 90 degree scattering angle. These views range from the plasma's magnetic axis at r=12 cm to 2 cm from the vacuum vessel at r=17 cm. Currently r=12,13,16, and 17 cm are in use.

Five of viewports are staggered vertical (side view: above, bottom), to maximize collection without using a single, large hole in the conducting vessel. All viewports are cones of the same angle and appear different sizes due to the angled, exterior face.

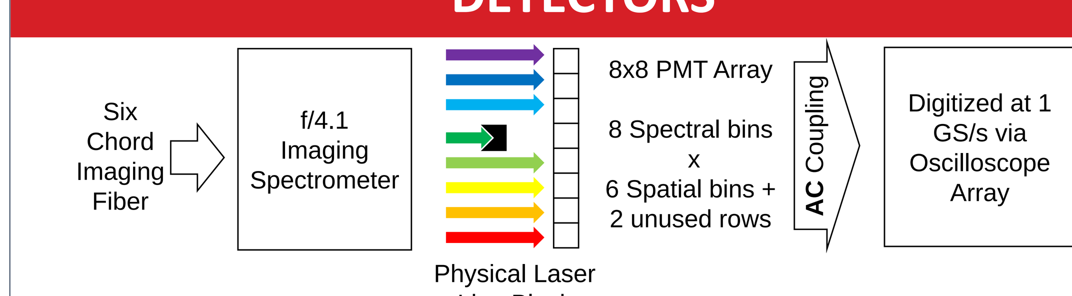
Current collection optics consist of a single f=15 cm converging lens per view, recycled from a previous machine. Space limitations (current lens mounts seen in photo to right) prevents using all six view ports with these optics.

A new collection optics setup is being designed to increase the fill of collection fibers and to use all six views at the same time.

Below: A photo of the current collection lens setup shows the Spector vacuum head on the right, and black collection lens tubes to the left, behind support structures. The laser comes in the vacuum tube from the bottom, and light scatters to the left.



DETECTORS

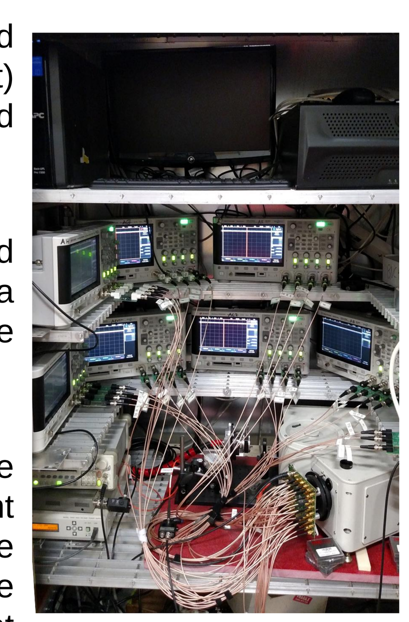


A spectrometer and PMT based system (outlined in above diagram and photo shown to right) provides spectral measurement of scattered light.

The numerical aperture of the fibers is matched to the spectrometer. The spectrometer, a Horiba iHR320 f/4.1 imaging spectrometer, is the ultimate etendue bottleneck of the system.

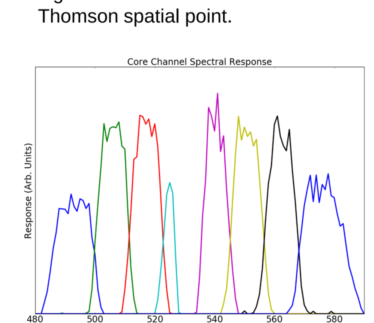
A physical block is used to remove the laser line from the spectrum. This block can scatter light within the spectrometer, so plasma-free reference shots are taken to subtract out the scattered light. However, with current stray light reduction, typically only a couple photons of stray laser light bypass the block. Some useful scattered light is not blocked (see spectral response to right).

A Hamamatsu H7546A-20 photomultiplier tube array, with 8x8 channels, measures 8 spectral bins for each chord. To preserve dynamic range when strong background light is present, the photocathode is switched on only a couple microseconds before the laser pulse and the output is AC coupled to digitizers.

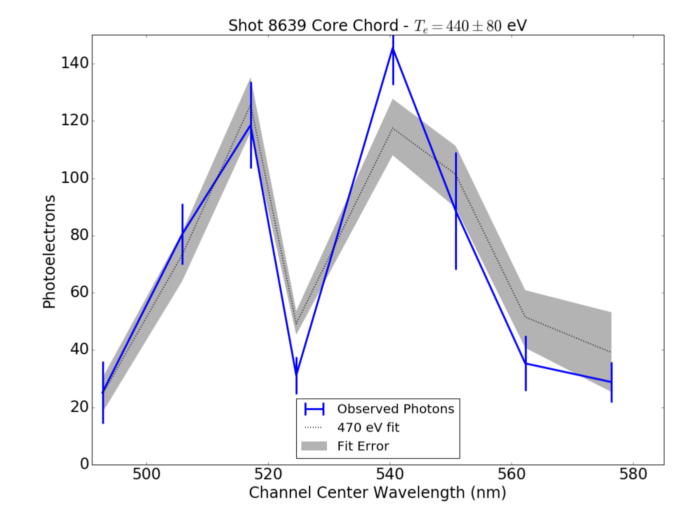


Above: A photo of the Thomson scattering detector setup, all located within a shielded box.

Below: The spectral response of the eight PMT channels is shown for one Thomson spatial point.

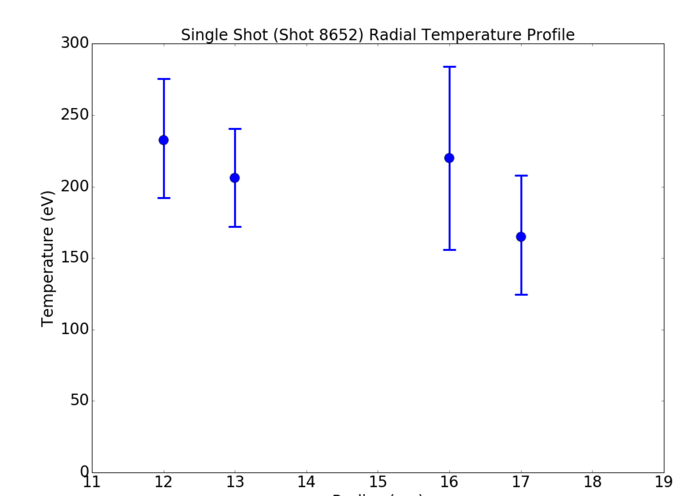


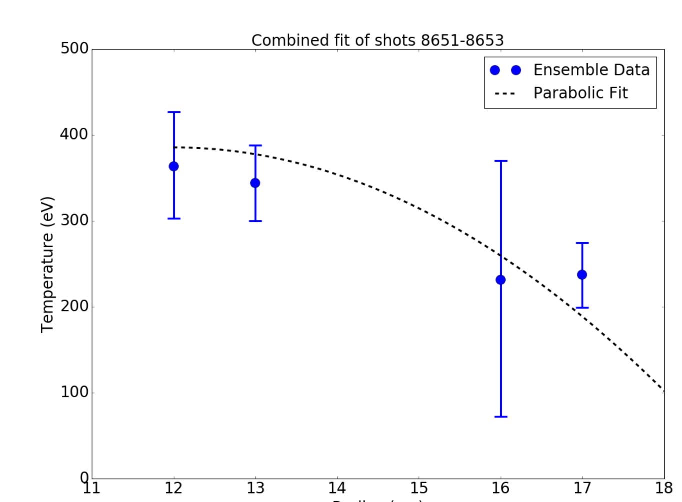
ANALYSIS AND RESULTS



A typical, high temperature spectral profile is shown above. The central channel is lower because it contains the laser line block, but allows some non-laser light (see spectral response in Detectors section). The channel centered at 550 nm is ignored from the fit, as a strong lithium spectral line saturates this channel.

With current signal levels, radial profiles are difficult to resolve on a single shot (example on top, below). But ensembling similar shots together does resolve some profile, and is in agreement with a parabolic profile (ensemble of 10 shots on bottom, below).





IN SITU PMT CALIBRATION

With reduced stray light, plasma-free reference shots were found to have only 0-2 photoelectrons/channel of stray laser light. With dozens of such shots, the PMT gain can be calibrated from the quantization of the signal.

Consider the forward model, with observed signal S_i for the i-th shot:

$$P(S_i|Parameters)=P_{Gaussian}(A_{X,i}|\mu=S_i,\sigma=\sigma_{Si})P_{Poisson}(A_{xi}/A_{2i}|\lambda=G_x)\,P_{Poisson}(A_{2i}/A_{1i}|\lambda=G_2) \times P_{Poisson}(A_{1i}/A_{0i}|\lambda=G_1)P_{Poisson}(A_{0i}/I_i|\lambda=G_0)$$

With free parameters:

G_0 – Quantum efficiency
G_1, G_2 – Gain of first and second dynode
G_x – Total gain of rest of dynodes
I_i – Incoming photon intensity of a given shot
A_{ji} – Amplitudes after various stages for each shot

Using Bayes theorem with uniform priors, a Monte-Carlo Markov Chain generation of the probability above for all channels, and marginalizing all of the per shot intensities produces fits for the various gains:

G_0 – 0.21±0.02 (QE from spec sheet: 0.22)
G_1 – 3.0±1.0, G_2-5.5±0.6
$G_0G_1G_2$ – 136000±11000 (calculated value, 139000)

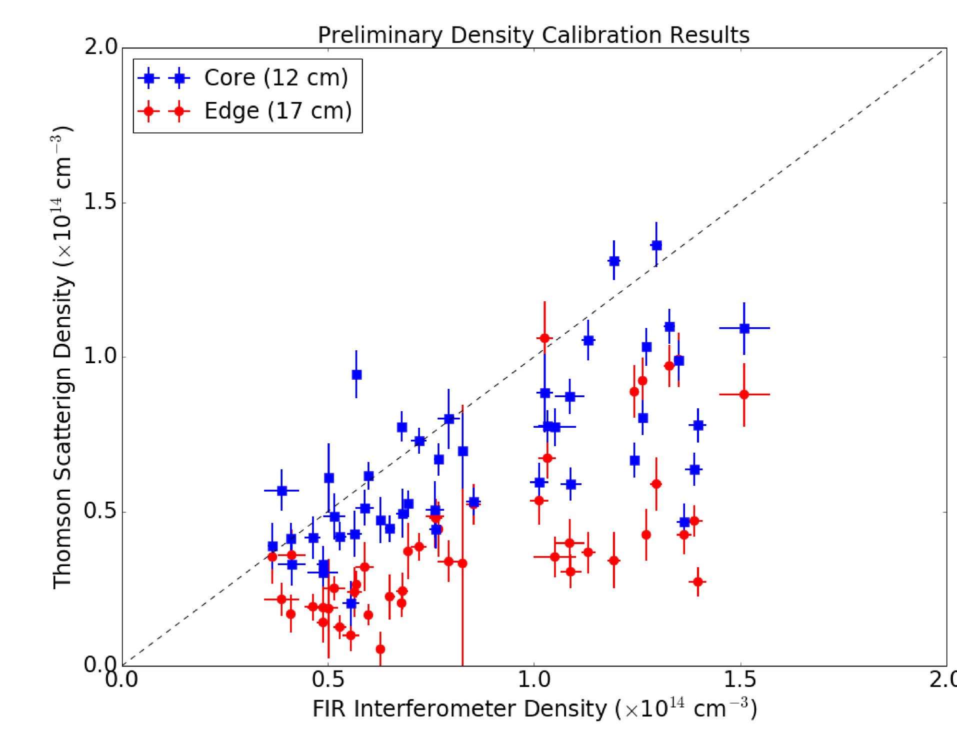
By using not only the signal strengths, but the distribution of the noise, the gains of early stages can individually be fit along with total gain.

With further accumulated data, per pixel gains can be calculated (above data bins all pixels together).

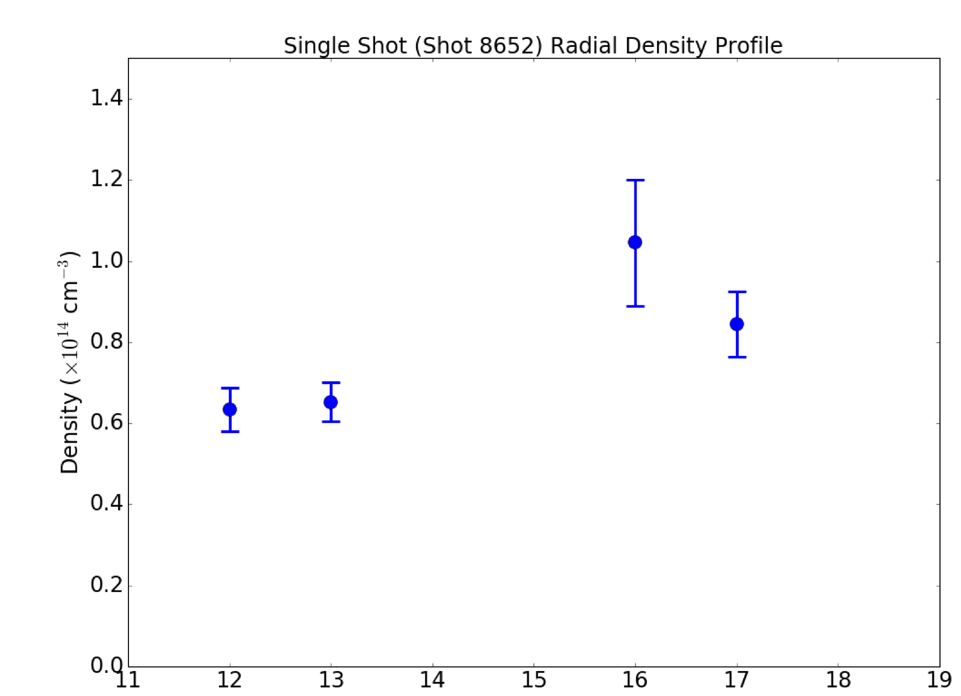
DENSITY CALIBRATION

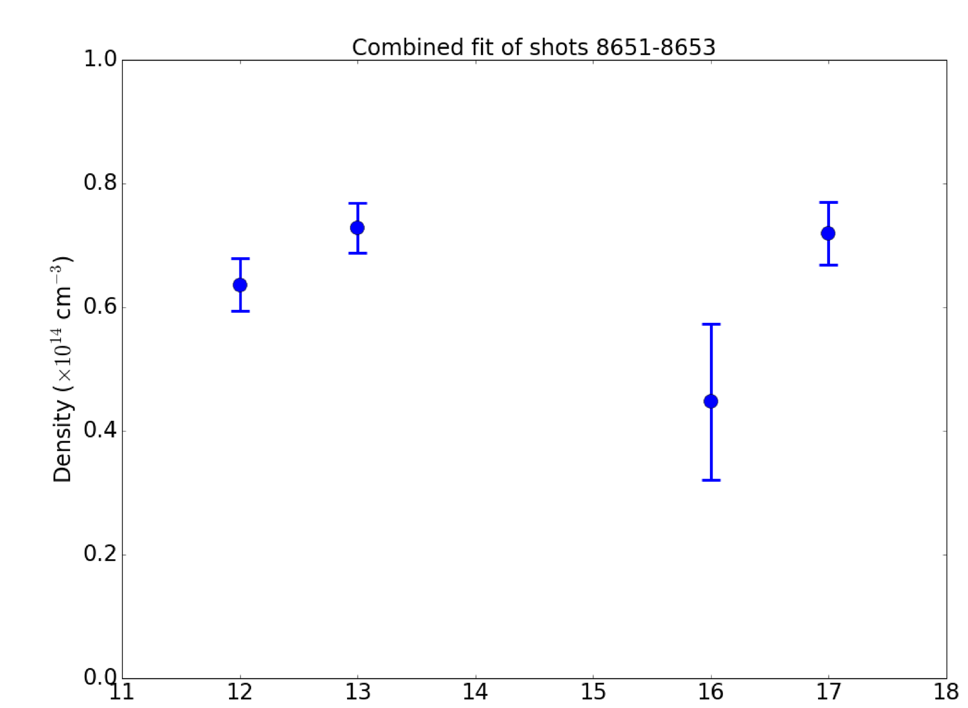
With a FIR polarimeter and interferometer coming online, density information from Thomson scattering would be useful for validating other diagnostics measuring, or depending on, density.

Recently, a density calibration was performed using Rayleigh scattering from a 90% He – 10% Ar blend that pumps efficiently. Nitrogen was avoided due to possible contamination of lithium coating within the machine. The initial calibration results show a correlation with single chord FIR interferometer density measurements (plotted below).



Preliminary density measurements provide some of the first density profile estimates of Spector (shown below), especially when ensembling together multiple shots.





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