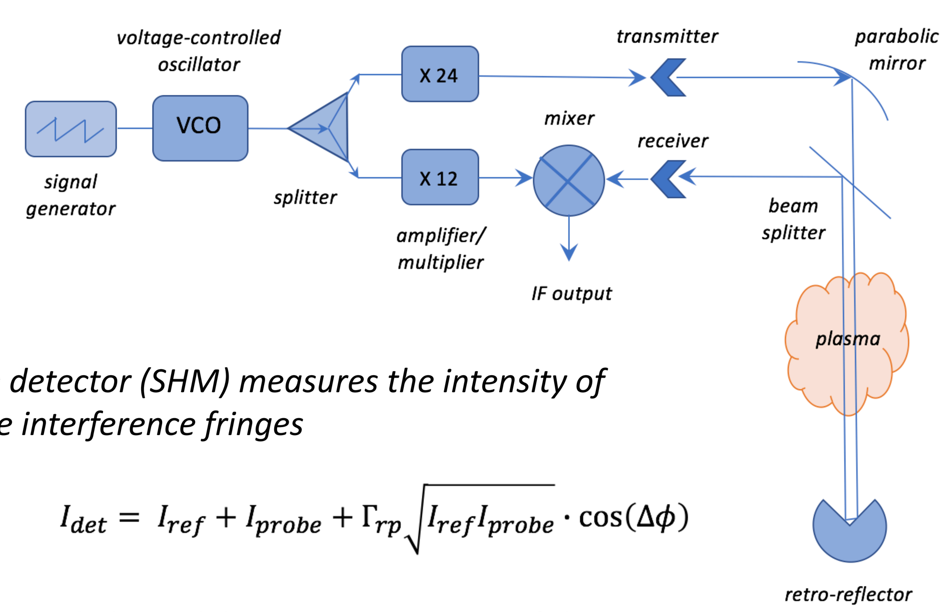
Interferometry in Plasma Diagnosis

BASICS

- Plasma retards mm-wave beam ~ density → phase modulation



- The detector (SHM) measures the intensity of the interference fringes

$$I_{det} = I_{ref} + I_{probe} + \Gamma_{rp}\sqrt{I_{ref}I_{probe}} \cdot \cos(\Delta\phi)$$

- The **total** phase delay written in terms of the line-averaged plasma density:

$$\Delta\phi = \frac{\omega}{c}\Delta l - \frac{e^2}{2m_e\epsilon_o\omega c}\int_0^{l_p} dl\, n_e$$

- 1 fringe shift → $\Delta\phi_{280GHz} = 2\pi$ → ~ 3.0×10^{18} electrons/m³

ADVANTAGES

- non-perturbative measurement
- subharmonic reference leg feeds directly into mixer – easy alignment of detector

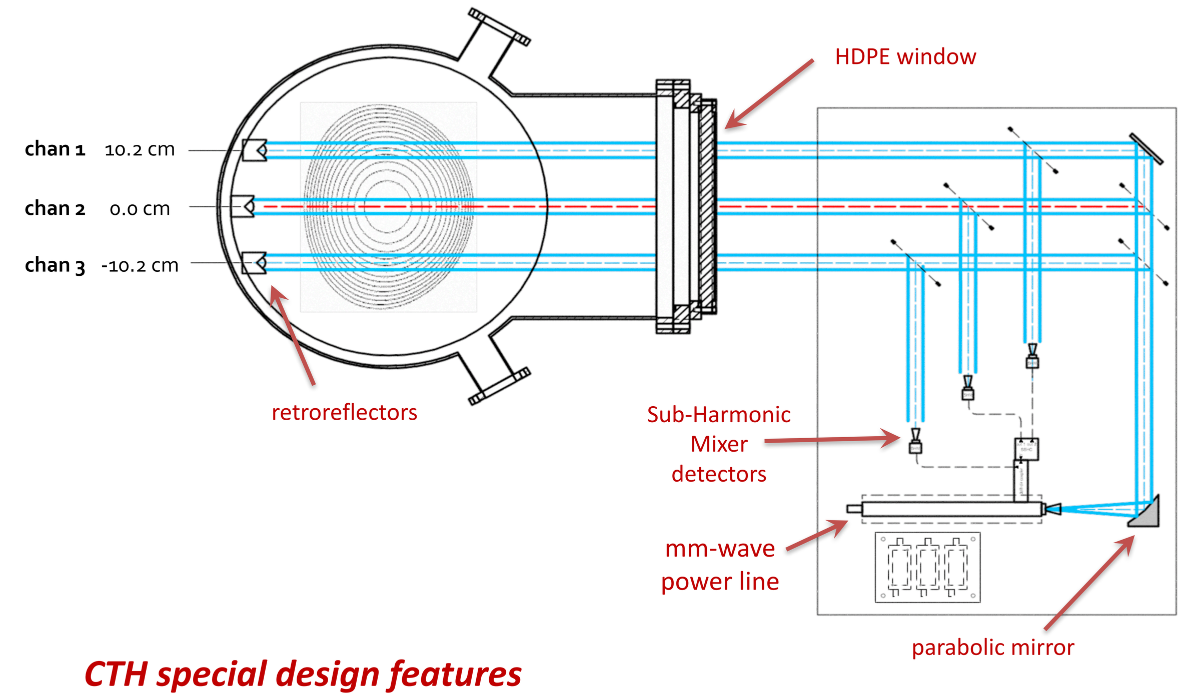
CHALLENGES

- refraction of beam out of retro-reflector → loss of signal
- rapid transient-induced errors in fringe counting (fringe jumps)

Upgraded Interferometer Overview

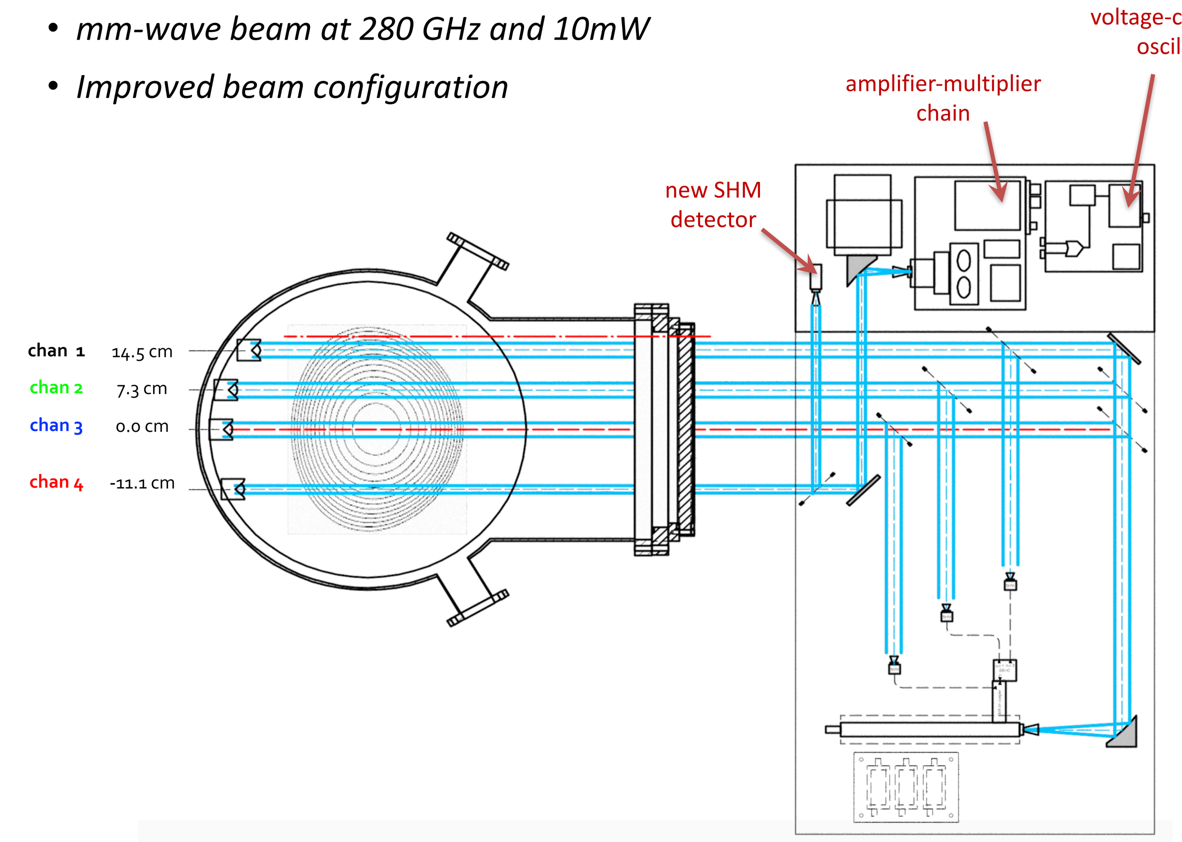
MOTIVATION

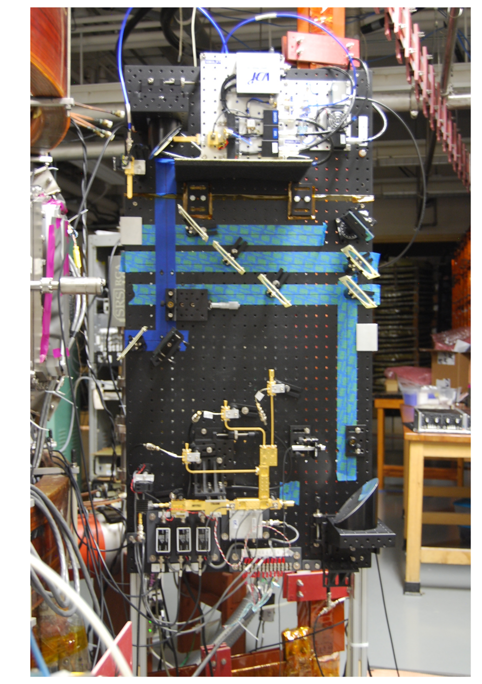
- new configuration provides 2 additional independent diagnostic signals which should provide much improved density profile resolution for studying MHD instabilities and disruptions



Upgrade Modifications

- mm-wave beam at 280 GHz and 10mW
- Improved beam configuration





CTH special design features

Subharmonic Mixer (SHM) design

- reference leg supplied direct to SHM facilitates alignment and reduces conversion loss

Double-pass horizontal launch

- allows single-port access to plasma

Chirping of frequency control

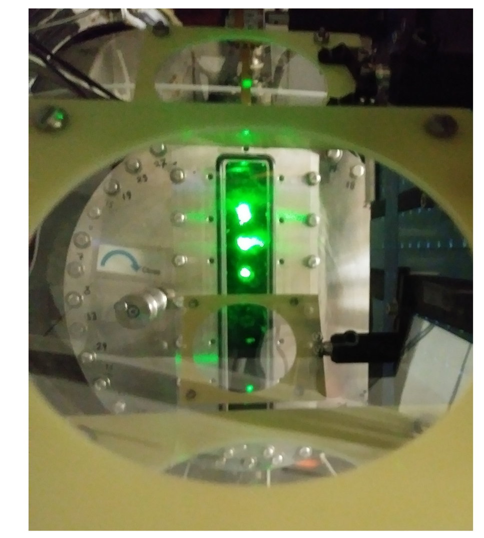
- frequency modulation required for phase shift calculation in single-source interferometer

Limitations of original design

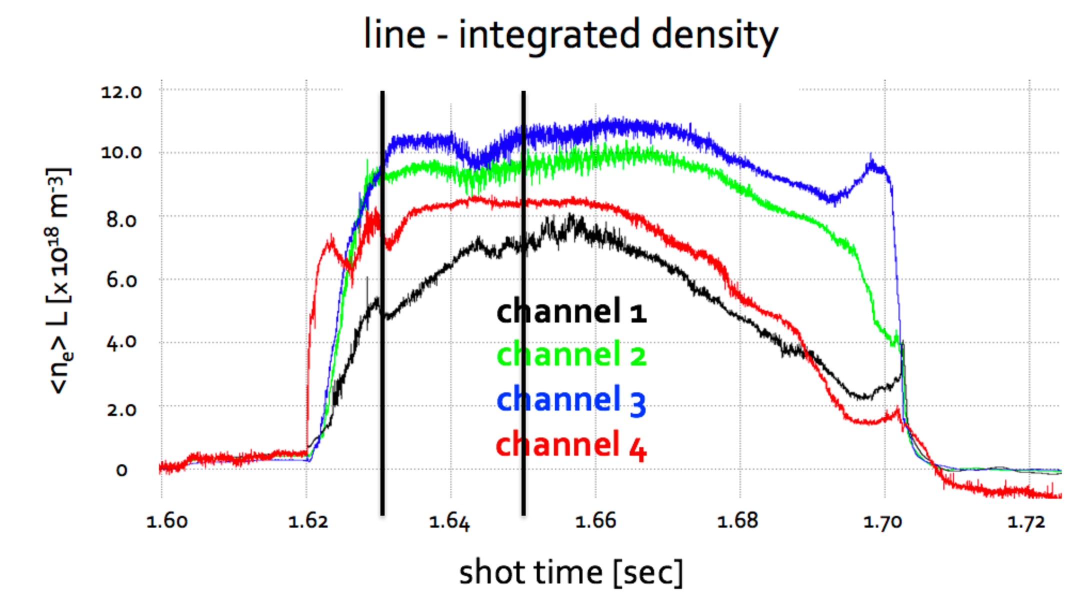
- symmetric off-axis beams are redundant data
- beams cover smaller fraction of plasma volume
- double-pass design imposes a limit on maximum density

Improvements in new design

- asymmetric positions eliminate redundancy
- beams cover higher fraction of plasma volume
- higher frequency mitigates density limit



System Performance



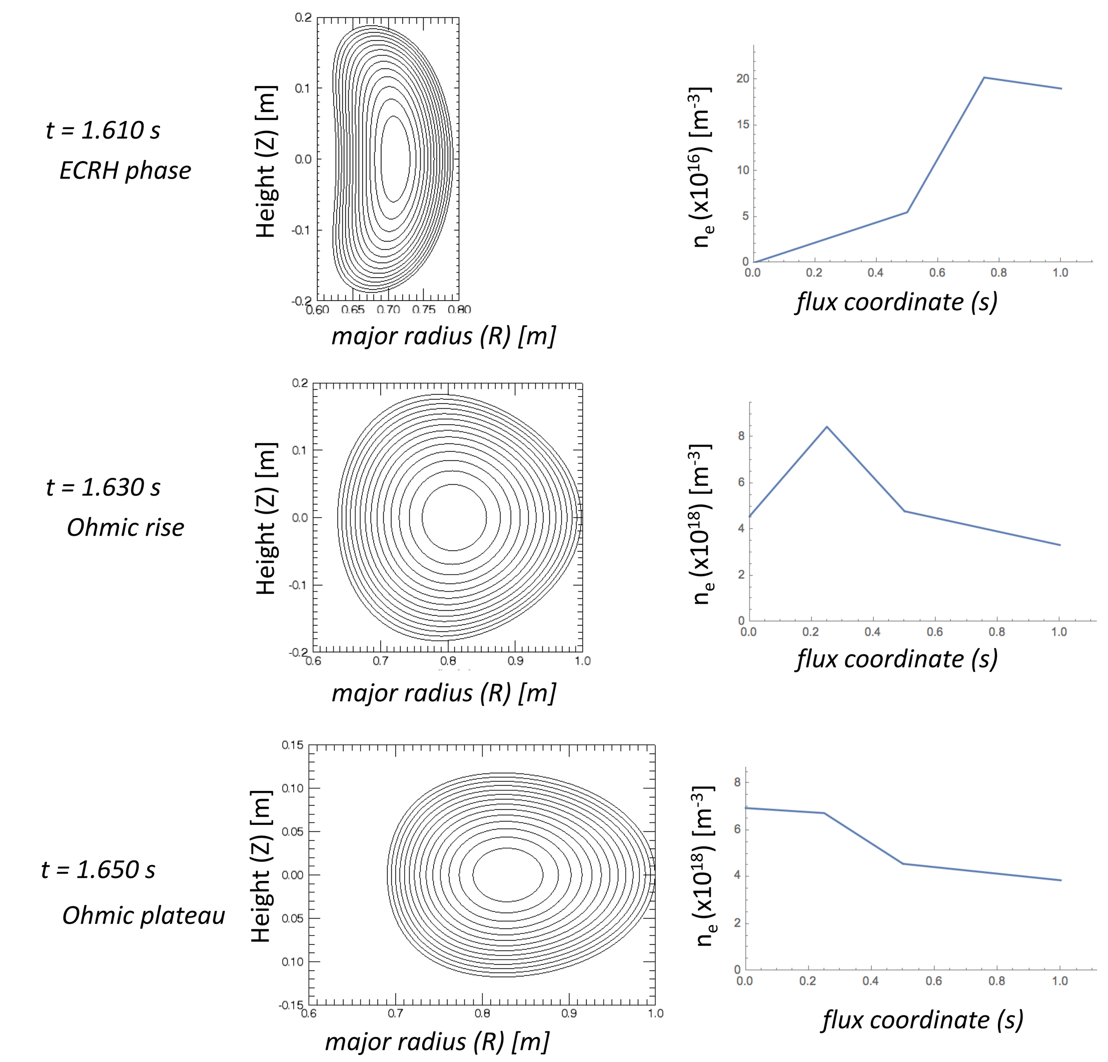
- channel 4 line-integrated density consistent with other channels assuming up-down symmetric discharge
- 4 independent beams give more details of shot evolution
- noise is a challenge for the new channel. (4) Now it is well-controlled.

shot # 18102253

Equilibrium Reconstruction

- first equilibrium reconstructions using upgraded interferometer based on simple line segment model for density

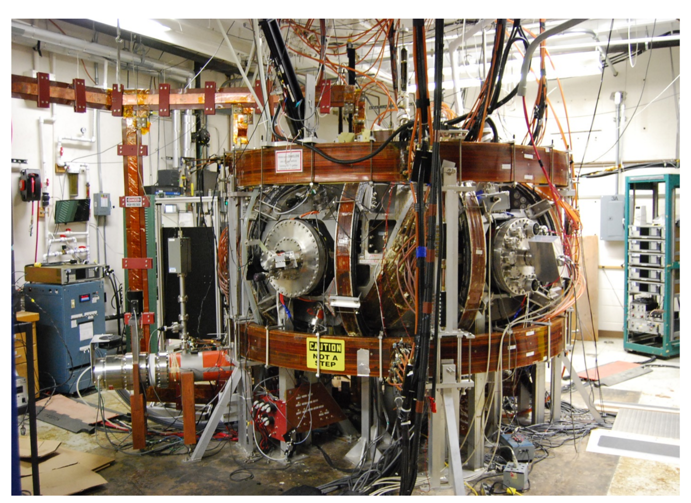
shot # 18102253



The Compact Toroidal Hybrid Experiment

DESIGN

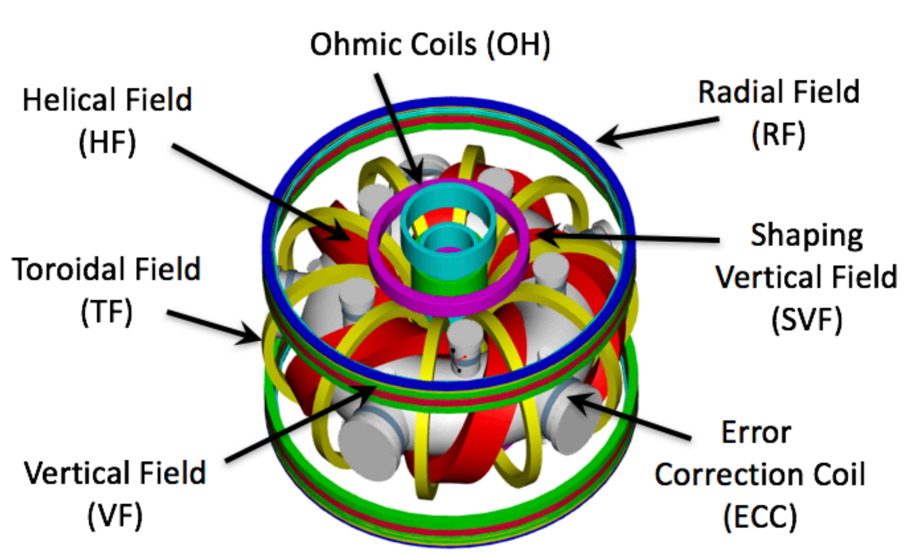
R_o = 0.75 m
a_v = 0.29 m
$a_p \le$ 0.20 m
$B_o \le$ 0.7 T
$I_p \le$ 80 kA
P_{ECRH} = 15 kW
P_{OHM} ~ 200 kW



PLASMA PARAMETERS

shot time ~ 0.1 s
$n_e \le 5\times10^{19}$ m⁻³
$T_e \le$ 200 eV
<β> ≤ 0.2%
$0.02 \le \iota_{vac} \le 0.35$

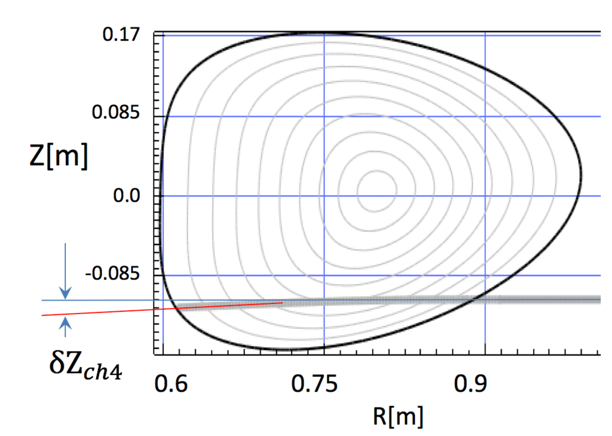
The CTH Coil Set



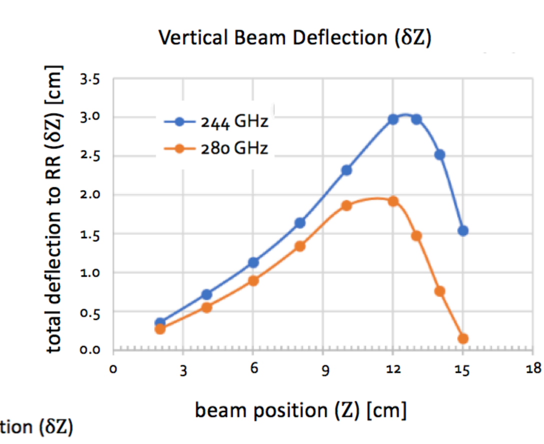
- CTH is a **5 field-period torsatron** designed to investigate plasma instability and disruptions over a wide range of operating conditions
- The hybrid feature of CTH is the ability to add toroidal current, which gives significant control over the transform profile.

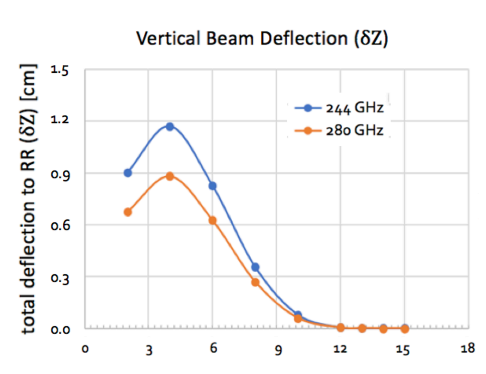
TRAVIS Beam Refraction Study

- **TRAVIS code** was used to analyze possible beam locations to minimize the deflection of the beam from retro-reflector (δZ)



- beam refraction analysis was done on three general classes of profiles - broad, peaked and hollow
- higher frequency beam has lower refraction





- beam deflection tends to be highest wherever there is both a higher density and a strong density gradient
- new higher f beam placed where beam loss by deflection is minimized for full system

V3FIT Multi-Beam Comparison

Started with the assumption that more data is better.

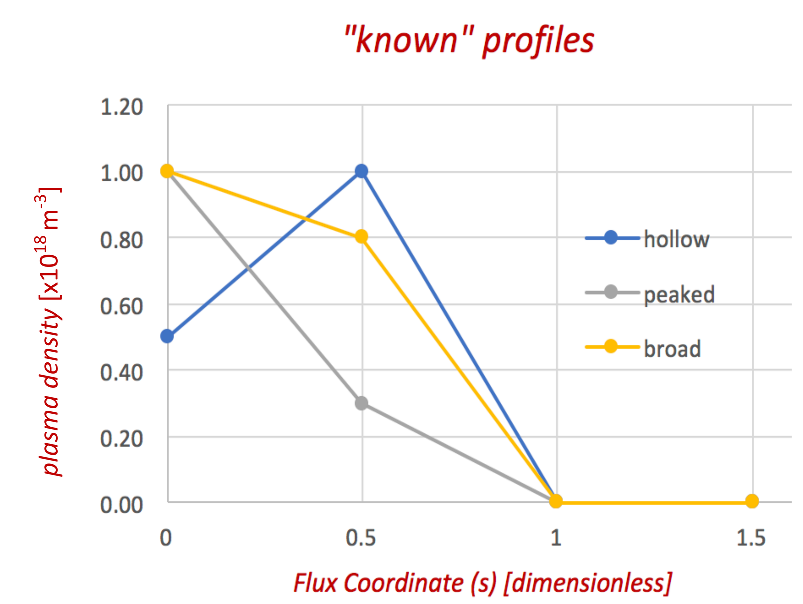
Compared 3, 4 and 5-beam configurations

- We estimated potential reduction in the errors in equilibrium reconstruction in expanding signals to a 4 and 5-beam system
- Computed "**fractional error**" (α) based on known and reconstructed density profiles

$$\alpha \equiv \frac{\int_0^1 ds\,|n_{known}(s) - n_{recon}(s)|}{\int_0^1 ds\, n_{known}(s)}$$

	fractional error		
# beams	broad	peaked	hollow
3	0.33707	0.01683	0.38148
4	0.00039	0.00607	0.00023
5	0.00045	0.00638	0.00025
	% improvement		
3 ➤ 4	99.88%	63.93%	99.94%
3 ➤ 5	99.87%	62.09%	99.93%

"known" profiles

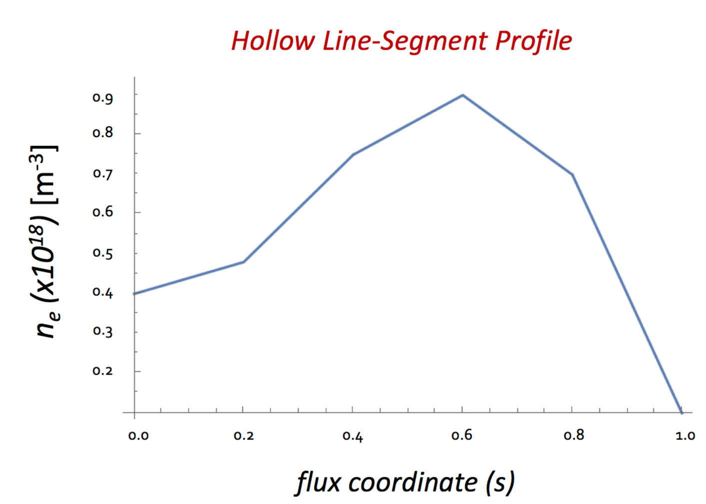


- **main result** is there is very little difference between the 4-beam and 5-beam systems in terms of reducing errors in reconstruction

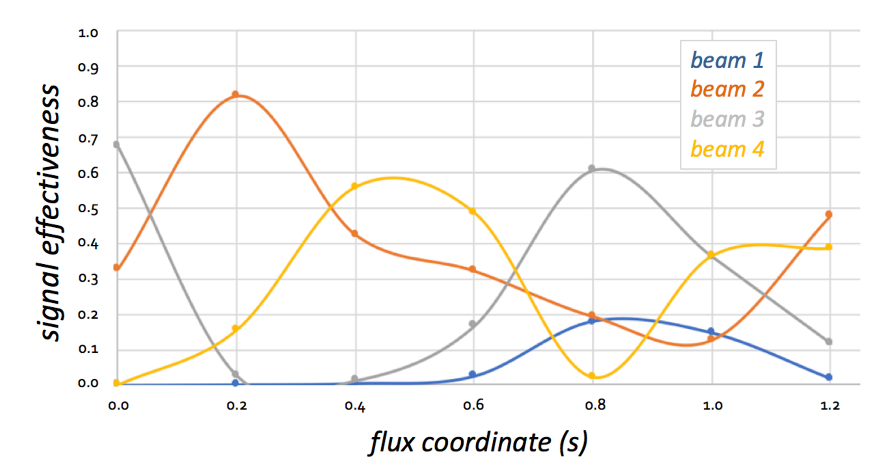
V3FIT Sensitivity Analysis

- for a given density profile, **V3FIT shows** how sensitivity of reconstruction depends on the new locations of the beams

Hollow Line-Segment Profile



$$E_{ij} \equiv \frac{d(ln\sigma_j^P)}{d(ln\sigma_i)}$$



- **signal effectiveness** (E_{ij}) is a measure of the sensitivity of model parameters to variations in a given signal.
- **RESULT** - full analysis shows beam spacing provides coverage with good sensitivity over full plasma volume for broad, peaked and hollow density profiles.

Summary

- interferometer upgrade has been successfully designed, built and demonstrated.
- new channel is incorporated in equilibrium reconstructions
- planning to use new density model to analyze vertical instability
- performance issues of the new channel will be addressed by further refining the frequency modulation program

References

- M. C. Miller et al., Rev Sci. Instrum. **83**, 10E332 (2012)
- Marushchenko et al., Comput. Phys. Commun. **185**, 165 (2014)
- Hanson et al., Nucl. Fusion **49**, 075031 (2009)
- I. H. Hutchinson, Prin. of Plasma Diagnostics (2e), CUP

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