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The He-I line ratio technique and its potential as SOL and separatrix electron density and temperature diagnostic for DIII-D

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4 Lawrence Livermore National Laboratory, Livermore, California, USA

Outline

- He-I line ratio technique at TEXTOR as introduction to basic principle
- Challenges for H-mode plasmas and expected radial coverage
- Assessment of feasibility for DIII-D:
  - Existing setups used
  - He-I intensity examples post boronization residual helium
  - He-I intensity examples from post helium glow residual helium neutrals
  - He-I intensity examples from low order He gas puffing into far SOL
- Proposed He-I line ratio setup for DIII-D
  - Upgraded filter scope system for $n_e(r,t)$, $T_e(r,t)$ and simultaneous $n_n(r,t)$ measurement
  - Proposed set of helium gas capillaries for SOL characterization
  - Modeling effort for adaptation of collisional radiative model for H-mode application

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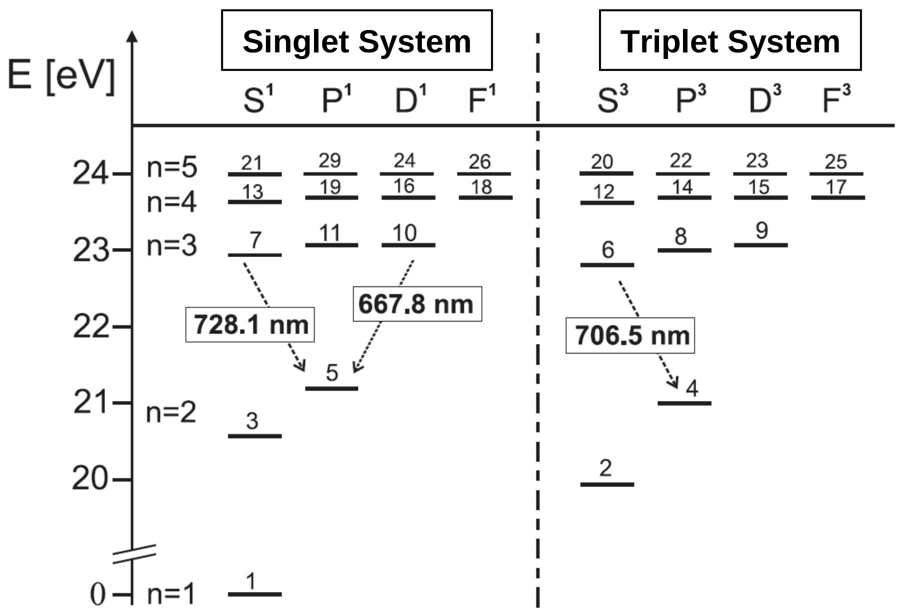
  - **Modeling effort for adaptation of collisional radiative model for H-mode application**

Technique is based on n_e and T_e dependence of the atomic level population densities in both spin systems

See e.g. [1] Hintz E and Schweer B 1995 *Plasma Phys. Control. Fusion* **37** A87



- **Suitable transitions:**

$3^1D \rightarrow 2^1P$ @ λ_1=667.8 nm

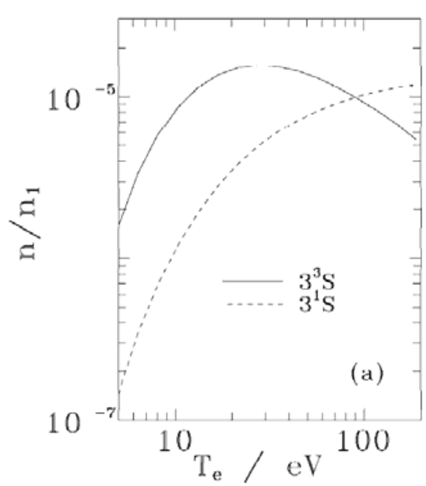
$3^1S \rightarrow 2^1P$ @ λ_2=728.1 nm

$3^3S \rightarrow 2^3P$ @ λ_3=706.5 nm

$n_e(r,t)$

$T_e(r,t)$

Electron temperature T_e sensitivity



Maximum of normalized population density at lower T_e for triplet system

(Result of different rate coefficients for spin forbidden transitions)

Comparison yields T_e sensitivity

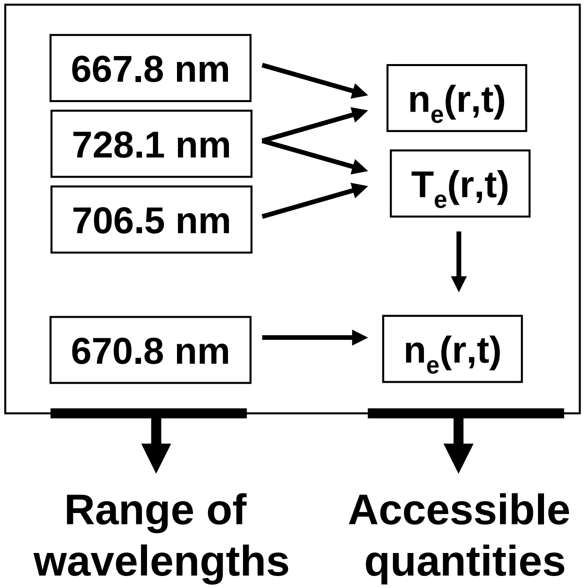
Electron density n_e sensitivity

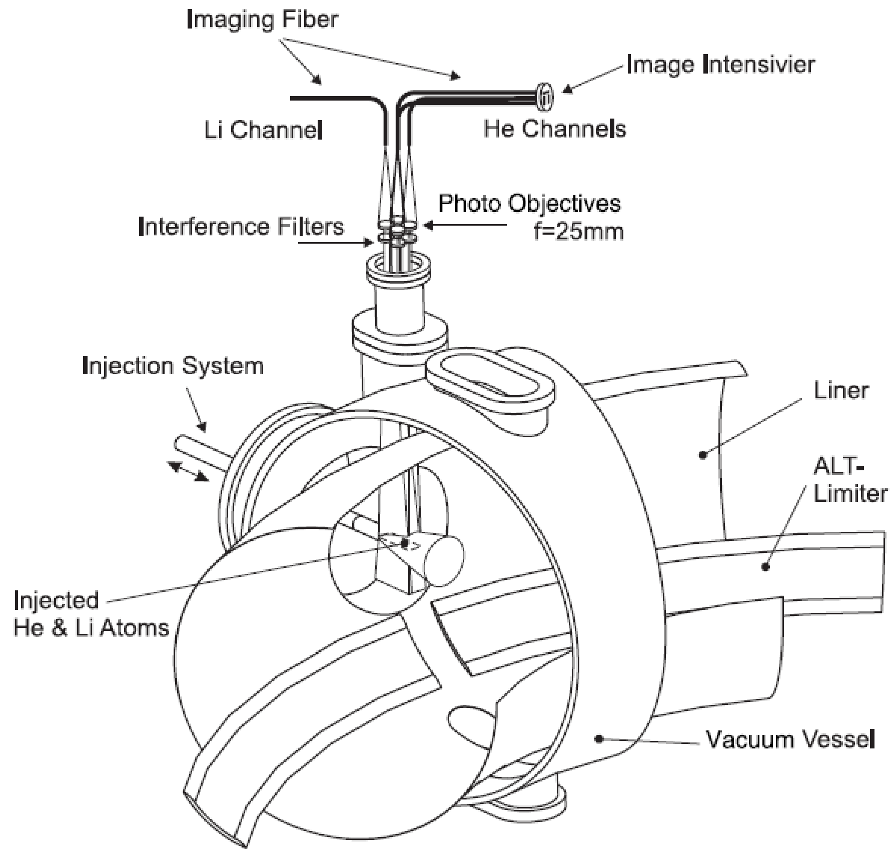
Employ ratio of levels predominantly depopulated by (a) collisions and (b) spontaneous radiation

Comparison yields n_e sensitivity

He-I line ratio spectroscopy is at TEXTOR a well established technique for SOL characterization

[2] O. Schmitz et al. PPCF **50** (2008) 115004





Standard system characteristics:

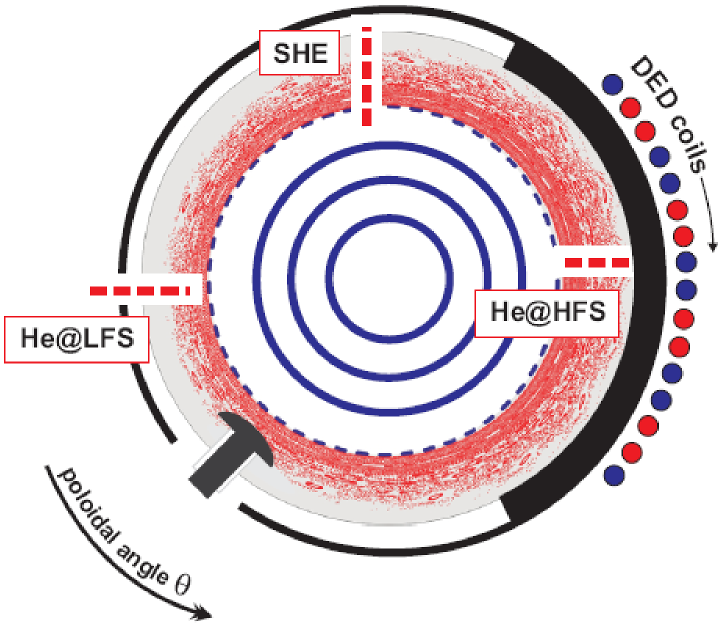
- **time resolution:** **> 100Hz**
- **digital resolution:** **12 bit or higher**
- **spatial resolution:** **15 cm coverage (0.7 < ρ < 1.1) with Δr=1.2mm**
- **He gas puff capability** **(rate needed < 8 x 10^{18} s^{-1})**
- **Lithium oven** **for beam attenuation on Lithium as n_e reference**

He-I line ratio spectroscopy is at TEXTOR a well established technique for SOL characterization

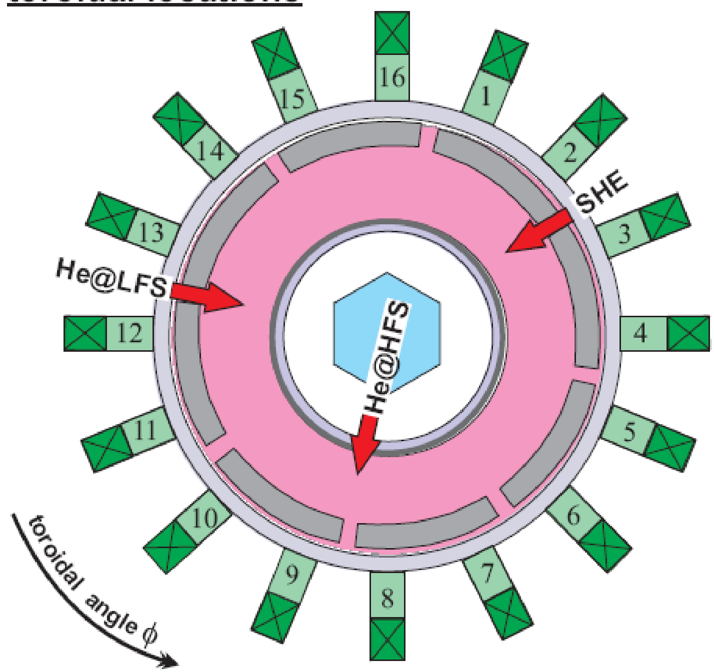
[3] O. Schmitz *et al* 2008 *AIP Conf. Proc.* **993** 135

Three helium beam systems are available at TEXTOR

poloidal locations



toroidal locations



He@LFS ⇨ **Δt<10ms, Δr=1.2mm, 0.7<ρ<1.1, 12 bit linear CCD array**

He@HFS ⇨ **Δt<100ms, Δr=1.0mm, 0.6<ρ<1.0, 14 bit 2D CCD array with spectrometer**

SHE@top ⇨ **Δt<0.1ms, Δr=1.2mm, 0.7<ρ<1.1, 12 bit 2D CCD array and PMT**

Collisional radiative model (CRM) is needed to interpret measured line intensities

[2] O. Schmitz et al. PPCF **50** (2008) 115004

• Corona model (population density depends only on collisional excitation and radiative decay) not applicable here as population densities depend on variety of processes in a high density edge plasma

Population density n_i is established by:

• radiative transitions to and from other levels with Einstein coefficient A_{ij}
• electron impact excitation and de-excitation with rate coefficient $q^e_{j\to i}=\langle\sigma^e_{j\to i}\, v\rangle$ and $q^e_{i\to j}=\langle\sigma^e_{j\to j}\, v\rangle$
• ion impact excitation and de-excitation with rate coefficient $q^i_{j\to i}=\langle\sigma^i_{j\to i}\, v\rangle$ and $q^i_{i\to j}=\langle\sigma^i_{i\to j}\, v\rangle$
• electron and ion impact ionization with rate coefficients S^e_i and S^i_i

$$\frac{dn_i}{dt} = -n_i n_e S^e_i + \sum_{j>i}\left(n_j A_{j\to i} + n_j n_e q^e_{j\to i} - n_i n_e q^e_{i\to j}\right) + \sum_{i>j}\left(n_j n_e q^e_{j\to i} - n_i A_{i\to j} - n_i n_e q^e_{i\to j}\right) \quad .$$

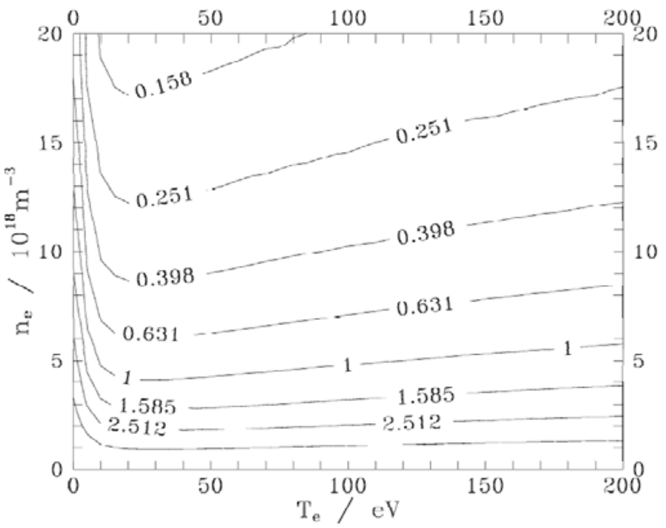
$$\frac{dn_i}{dt} = -C_{i,i} n_i + \sum_{j\neq i} C_{i,j} n_j$$

Set of 29 coupled, linear differential equations has to be solved for each data point

CRM solution can be delegated to lookup table for stationary conditions

[2] O. Schmitz et al. PPCF **50** (2008) 115004

Relaxation time of metastable 2^3S in µs



- Stationary set n_e and T_e sensitivity of line ratios can be calculated
- Validity depends on actual n_e values to be measured
- Beam atom velocity and spatial resolution of observation define stationary radial range

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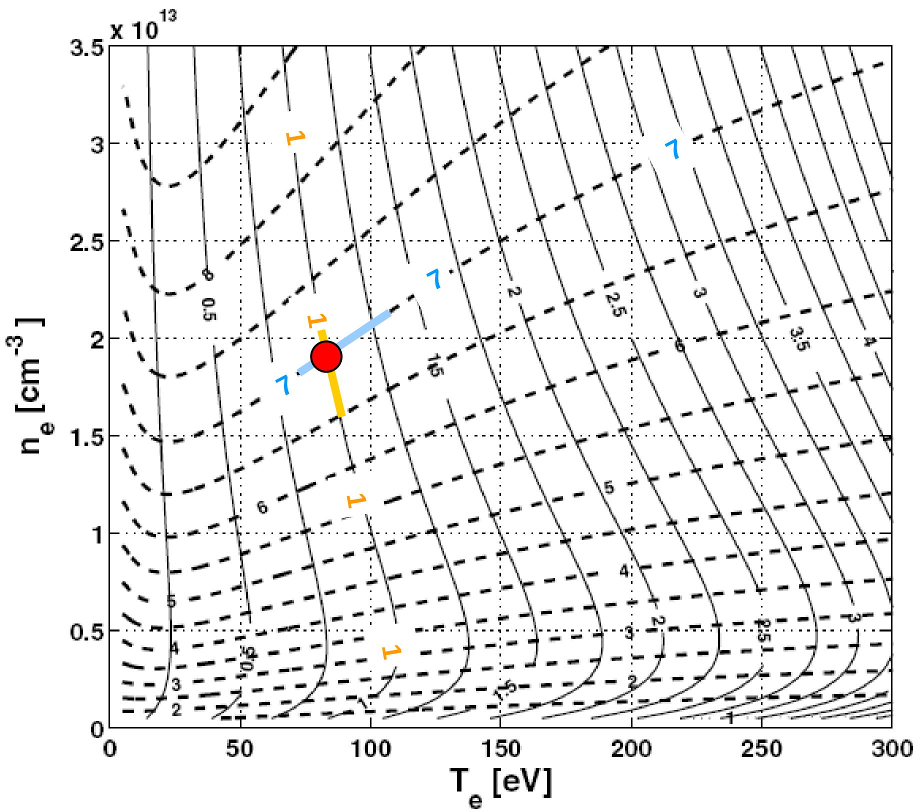
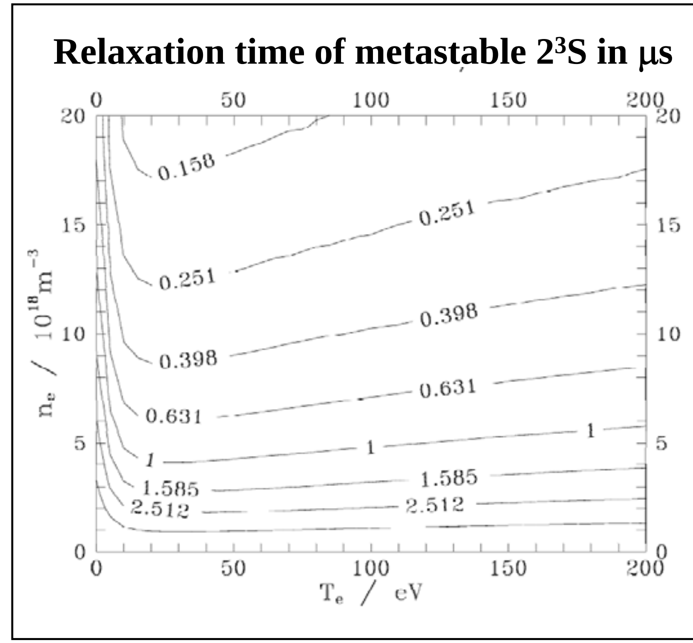




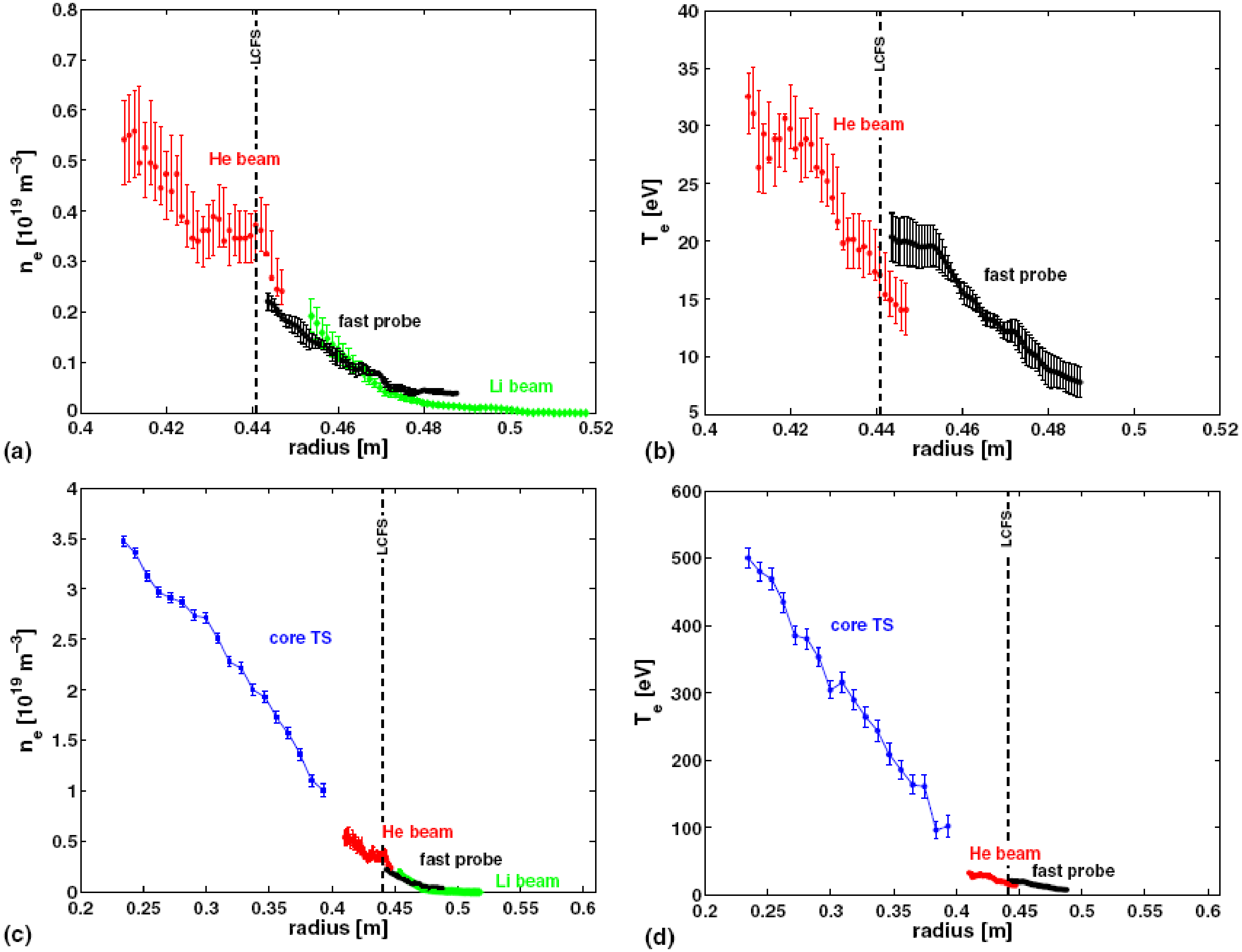
- **Stationary set n_e and T_e sensitivity of line ratios can be calculated**
- **Validity depends on actual n_e values to be measured**
- **Beam atom velocity and spatial resolution of observation define stationary radial range**

- **Fast lookup of measured line ratios possible**
  (typical time to process TEXTOR shot is 2 minutes)

667.8/728.1=7 | **728.1/706.5=1** ⇨ **n_e=1.82 10^{19} m^{-3}**, **T_e=78 eV**

Good agreement with other diagnostics in moderate n_e and T_e range obtained

[2] O. Schmitz et al. PPCF **50** (2008) 115004



Validity range of stationary model:

$1.0\ 10^{18} < n_e < 4.0\ 10^{19}$ m^{-3}

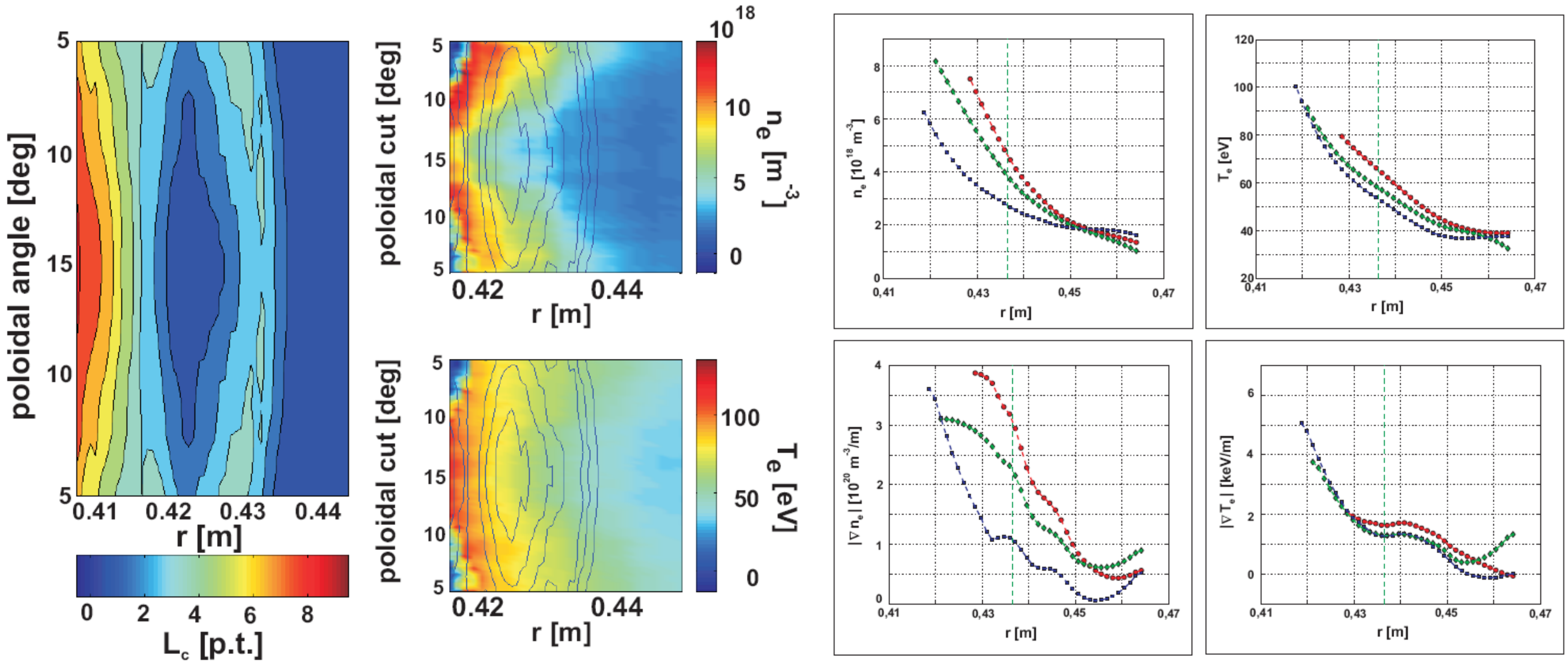
20 eV < T_e < 350 eV

Trends in deviations from other diagnostics

- **T_e lower than references with increasing heating**
- **at low n_e<1.0 10^{18} m-3, relaxation issues**

Applied for resolution of 3D helical SOL with application of resonant magnetic perturbations

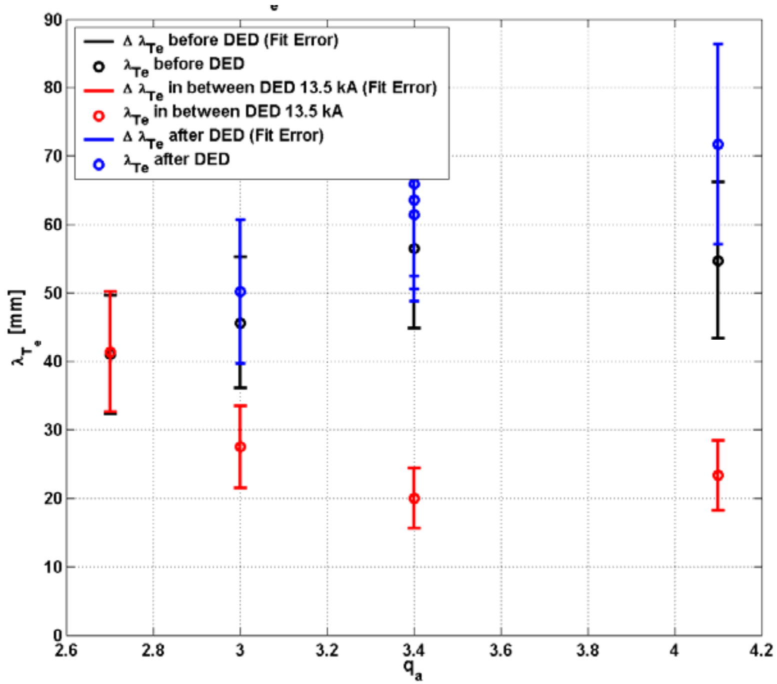
[4] O. Schmitz et al. Nuclear Fusion **48** 024009 (2008) **[5]** M. Jakubowski, O. Schmitz et al. Phys. Rev. Letters **96** 035004 (2006)



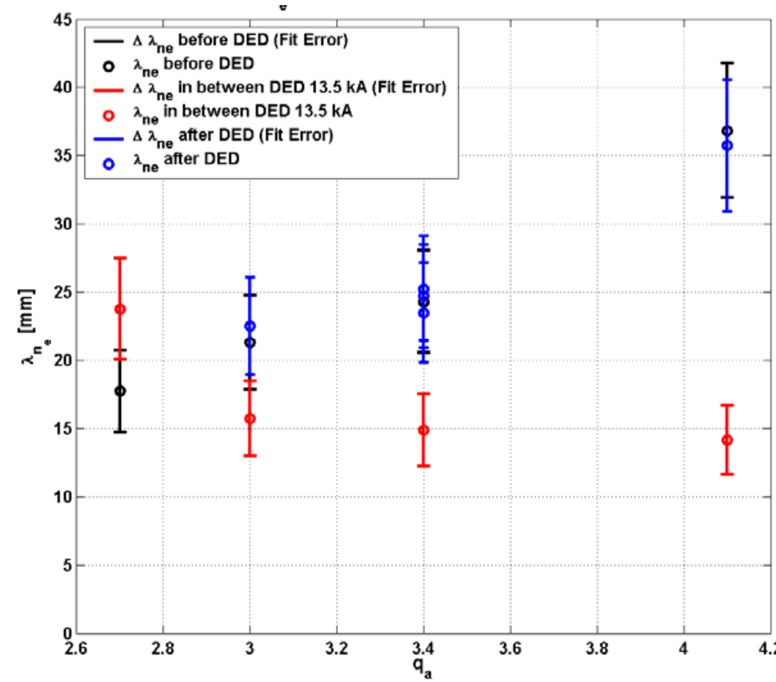
- **Short connection length flux tubes act as convective domain forming the 3D helical SOL**
- **Stochastic domains show diffusive transport characteristics due to enhanced outward transport**
- **High spatial resolution mandatory for investigation of these fine scale structures and the transport studies performed!**

He-I line ratio technique is the working horse for SOL characterization with and w/o RMP at TEXTOR

Electron temperature decay length in SOL

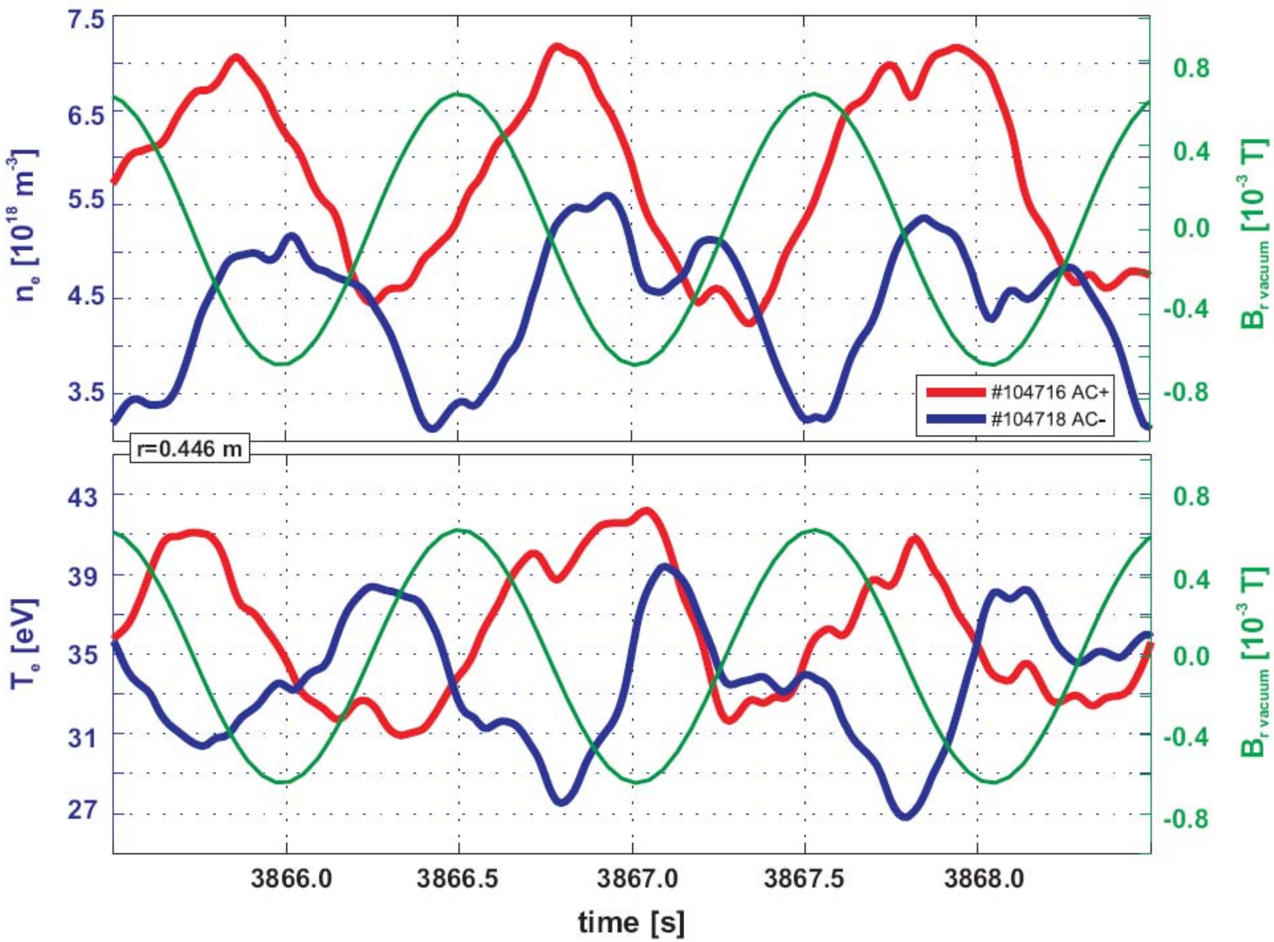


Electron density decay length in SOL



- **Trend for increase in λ_{ne} and λ_{Te} decay length with increasing q_a without RMP shown**
- **With RMP, λ_{ne} and λ_{Te} decrease with enhanced resonance, suggesting a strong channeling of particle and heat fluxes in well developed helical flux tube**

Supersonic beam gives better time and spatial resolution for fast measurements



+1kHz ~ 200Hz f_{rel}

-1kHz ~ 1.8kHz f_{rel}

- First time resolution of modulated n_e and T_e fields with high frequency rotating RMP fields shows existence of SOL flux tubes
- Phase delay between n_e and T_e wave forms measured for increasing relative rotation

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Atomic data set and solution methods in CRM have to be optimized for H-mode application

Trends in deviations from other diagnostics at TEXTOR

Analysis needs to be pushed beyond actual boundaries for good H-mode measurements

- **T_e lower than reference measurements with increasing heating**
  - Improve atomic data
  - Include high energy states by cascading and bundled solutions
  - Develop fast algorithm for automated non-stationary solution

- **at low n_e<1.0 10^{18} m-3, relaxation issues**
  - Develop fast algorithm for automated non-stationary solution
  - Include beam geometry and change in velocity distribution into CRM

We are aiming at n_e and T_e measurements in the SOL radial up to the separatrix under H-mode conditions at different poloidal positions

Use line ratio technique for 2D imaging and as divertor diagnostic

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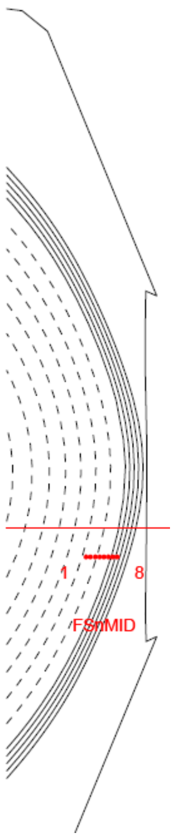
Use line ratio technique for 2D imaging and as divertor diagnostic

Can we obtain any suitable line intensities at all?

DIII-D OAK RIDGE National Laboratory TEC

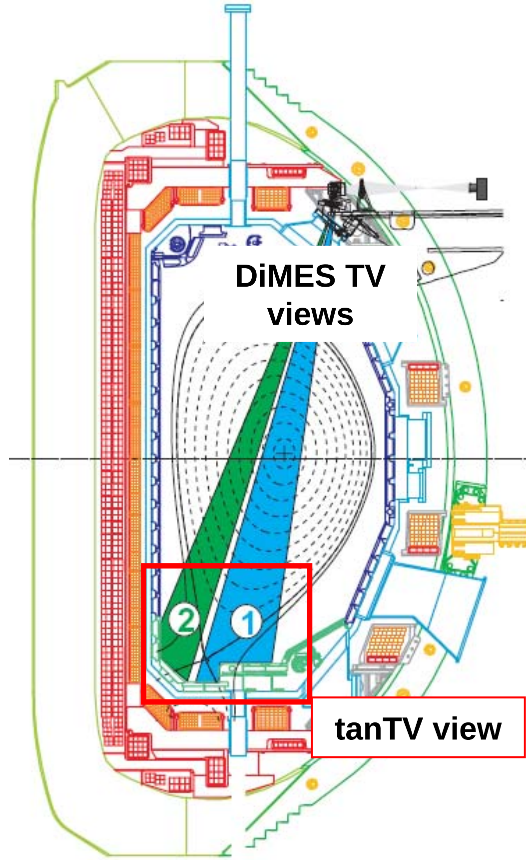
Result of piggy back testing with existing setups – nothing was optimized for the challenging task!

Midplane filter scope system



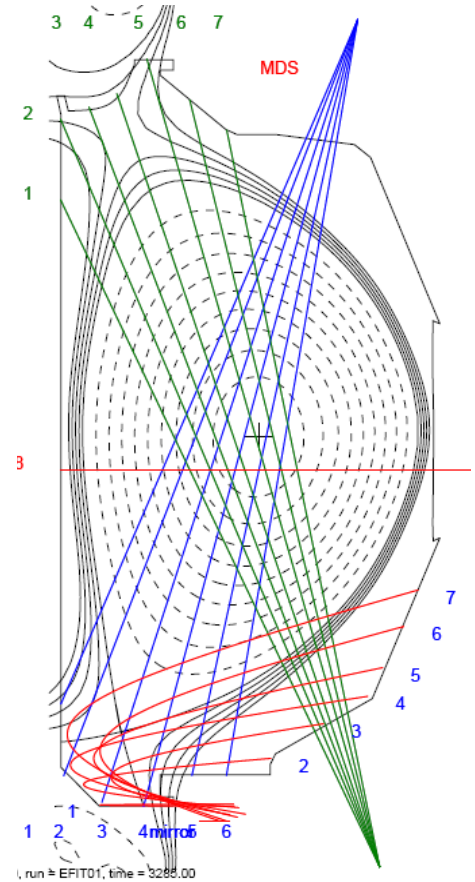
- One channel equipped with He-I filters and PMT
- Later: test of mockup for new FS system

Divertor video cameras



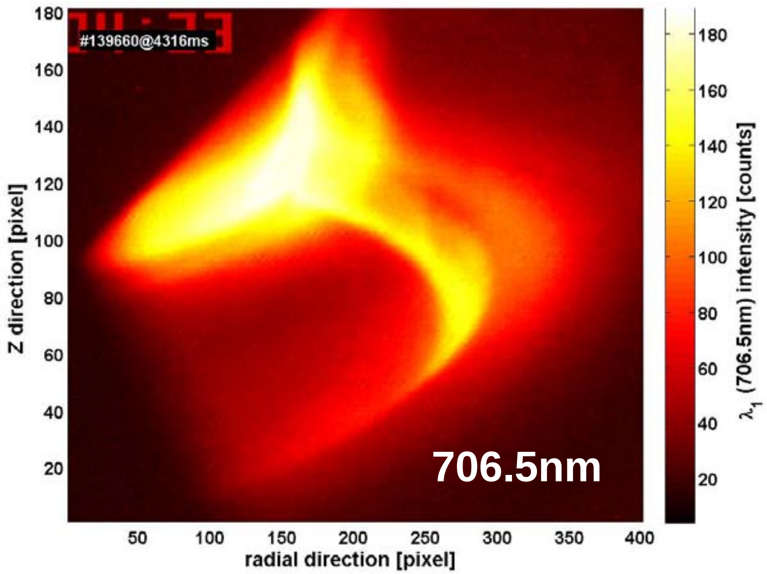
- He-I filters on cameras
- tanTV captured two lines simultaneously

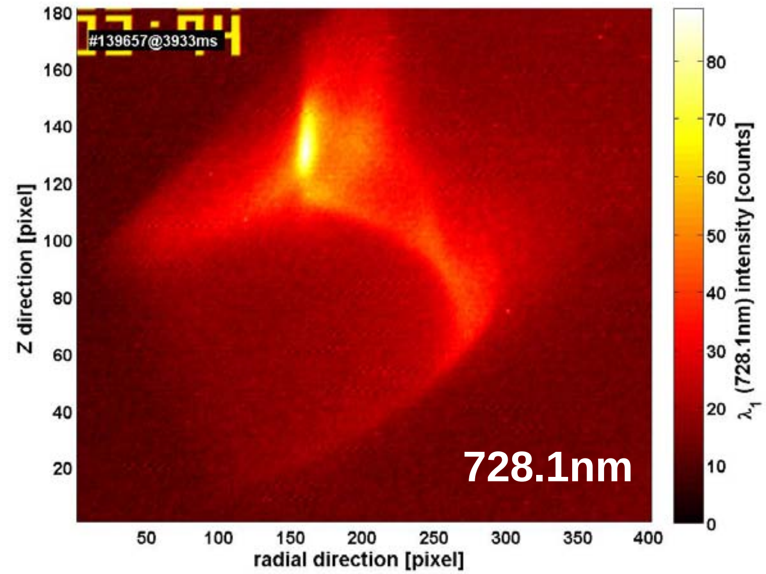
MDS spectrometer

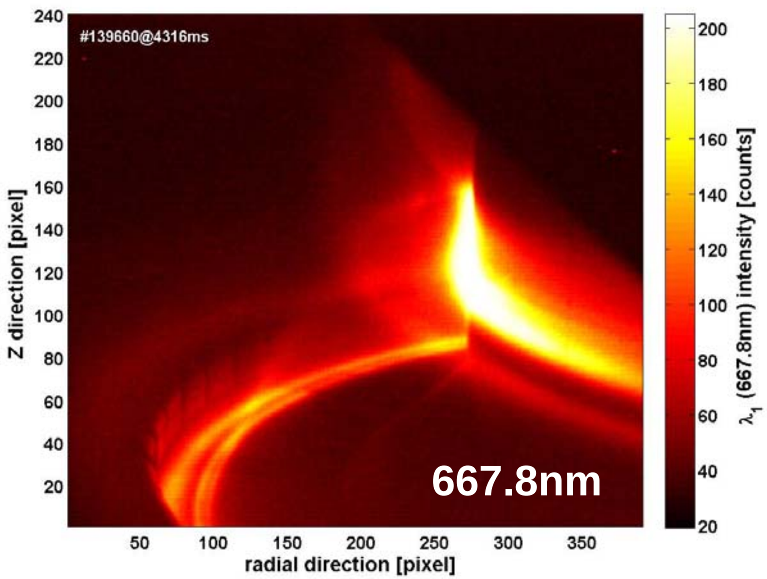


- Check carbon back-ground for He-I lines used

Residual helium after boronization gives sufficient signal for ~15 discharges







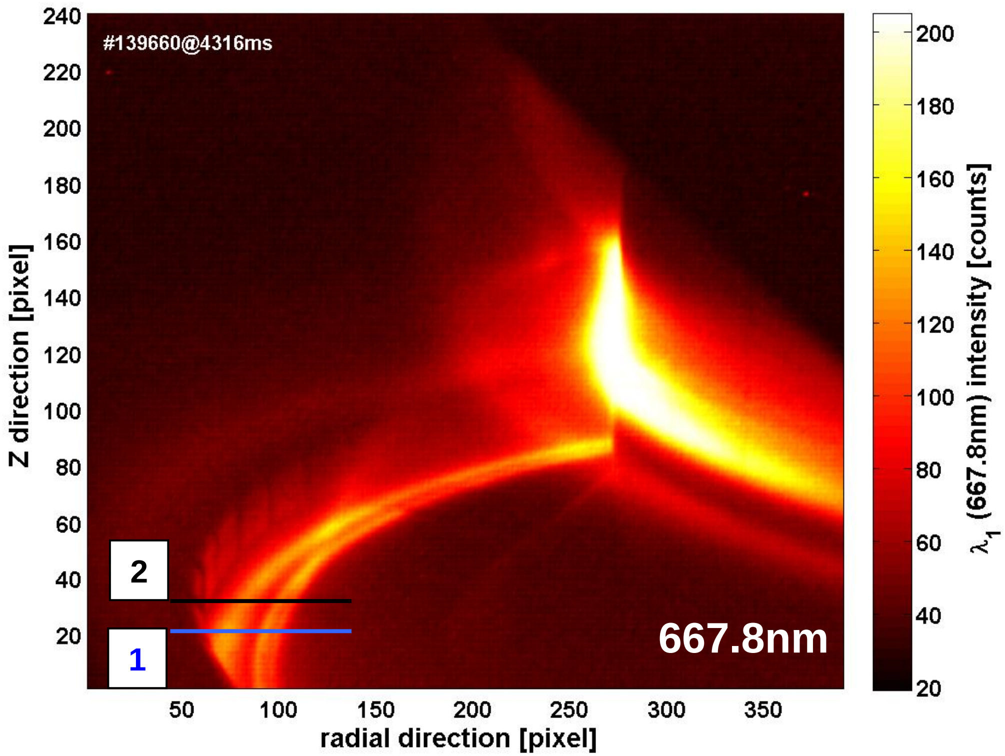
Signal from residual helium after boronization only, no puffing!

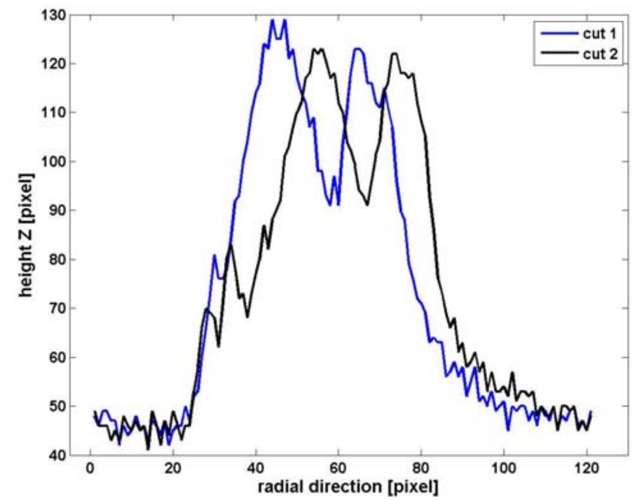
Discharge #15 after boronization recovery

Decays slowly but not eligible for quantitative evaluation by CRM

How much gas injection do we need for a robust signal?

Residual helium after boronization gives sufficient signal for ~15 discharges





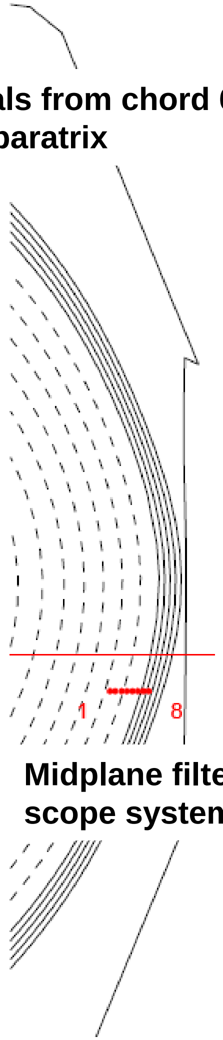
Strike line striation due to n=1 LM during TBM application observed in high contrast

High density and temperature dependence of level populations makes He attractive for imaging purposes

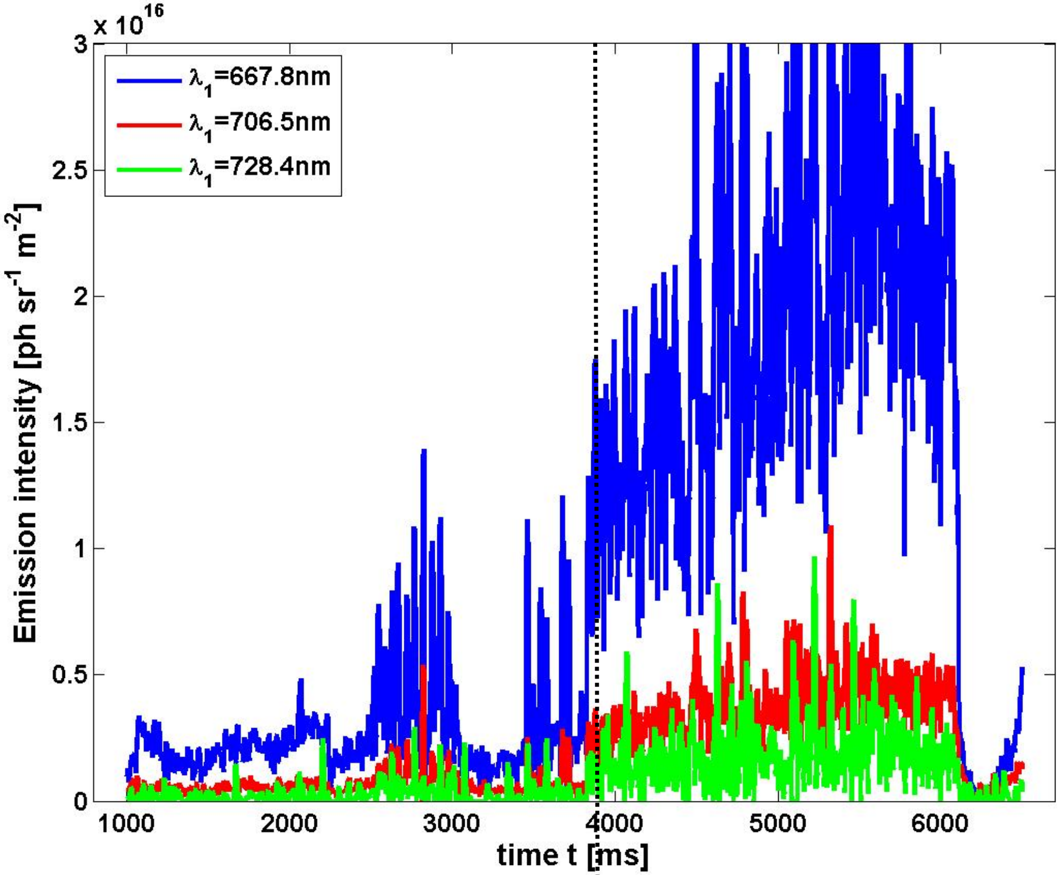
Camera views can be used as two dimensional n_e and T_e monitors in the divertor if calibrated

Midplane filter scope system shows sufficient intensities from residual helium and low flow gas puffing

Signals from chord 6 at separatrix



Midplane filter scope system



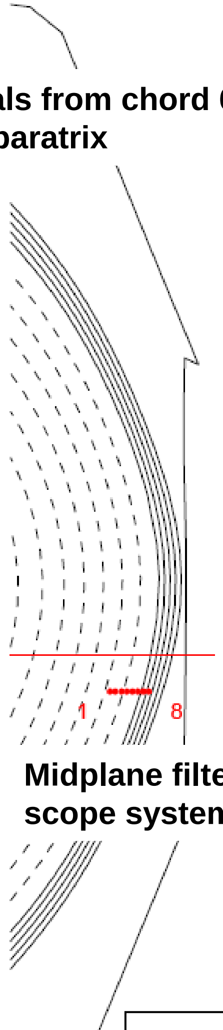
Signal from residual helium (GDC)

Signal from 0.2 torl s^{-1} helium gas puff into far SOL (gas_e)

The intensity from residual helium gas is marginal but a small He puff is enough to get sufficient data for n_e and T_e measurement

Analysis attempt with TEXTOR collisional radiative model suggests feasibility for n_e and T_e measurement

Signals from chord 6 at separatrix



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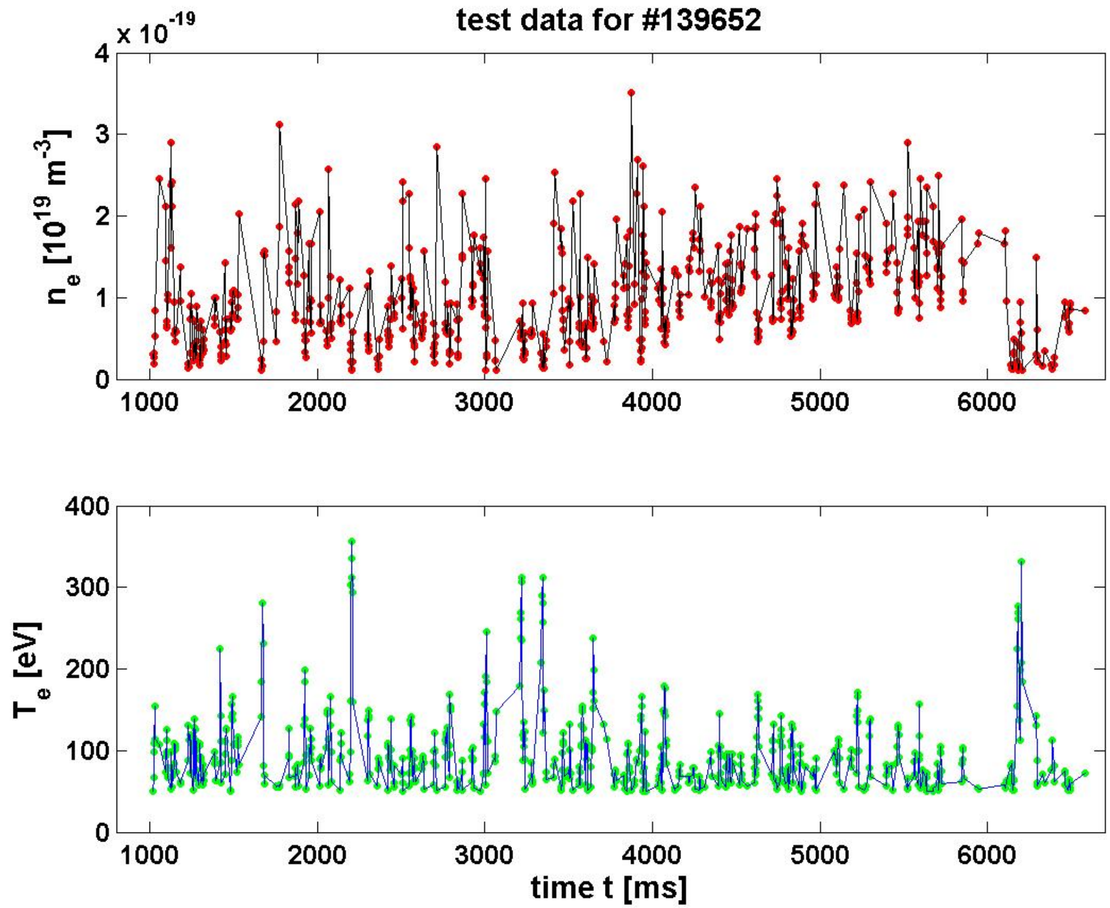

Exact values (and trends) are matter of in vessel spectral calibration

MDS spectral survey showed no considerable C background within filter width of He-I line spectral filters

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Accompanying modeling effort in makes very good progress to tackle the particular H-mode challenges

J.M. Munoz Burgos

Population density n_i is established by:

- radiative transitions to and from other levels with Einstein coefficient A_{ij}
- electron impact excitation and de-excitation with rate coefficient $q^e_{j\to i}=\langle\sigma^e_{j\to i}\, v\rangle$ and $q^e_{i\to j}=\langle\sigma^e_{j\to j}\, v\rangle$
- ion impact excitation and de-excitation with rate coefficient $q^i_{j\to i}=\langle\sigma^i_{j\to i}\, v\rangle$ and $q^i_{i\to j}=\langle\sigma^i_{i\to j}\, v\rangle$
- electron and ion impact ionization with rate coefficients S^e_i and S^i_i

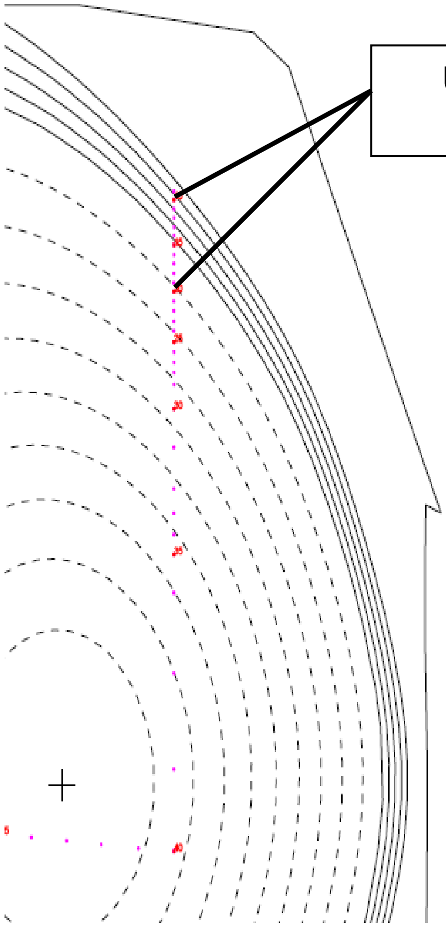
$$\frac{dn_i}{dt} = -C_{i,i}n_i + \sum_{j\neq i} C_{i,j}n_j$$

Same processes included but improvement towards H-mode challenges:

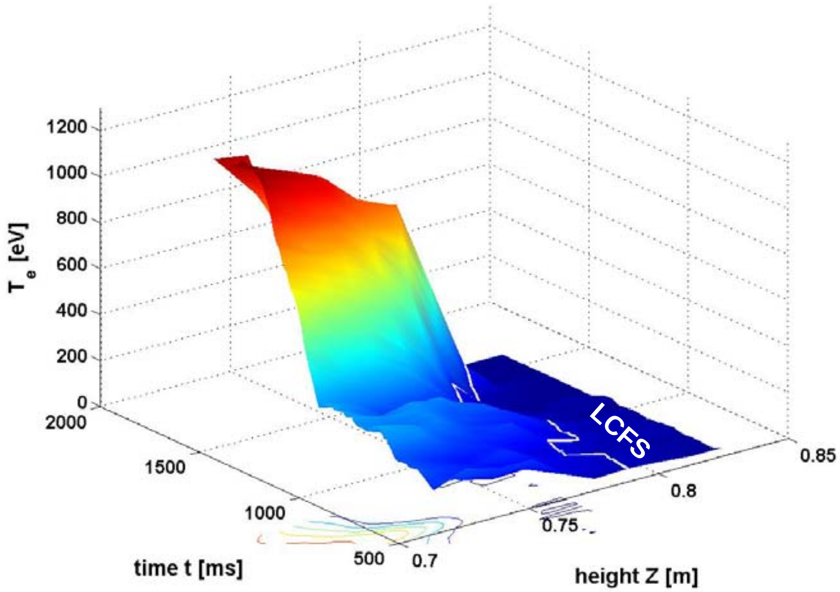
- Including pseudo states to calculate rate coefficients for high n levels
- Atomic data manufactured in particular for He problem with comparison to experiment
- Introduced linearization method for time dependent CRM solution to overcome relaxation issues
- Include line of sight effects of diagnostic setup for net line emission correction due to ionization

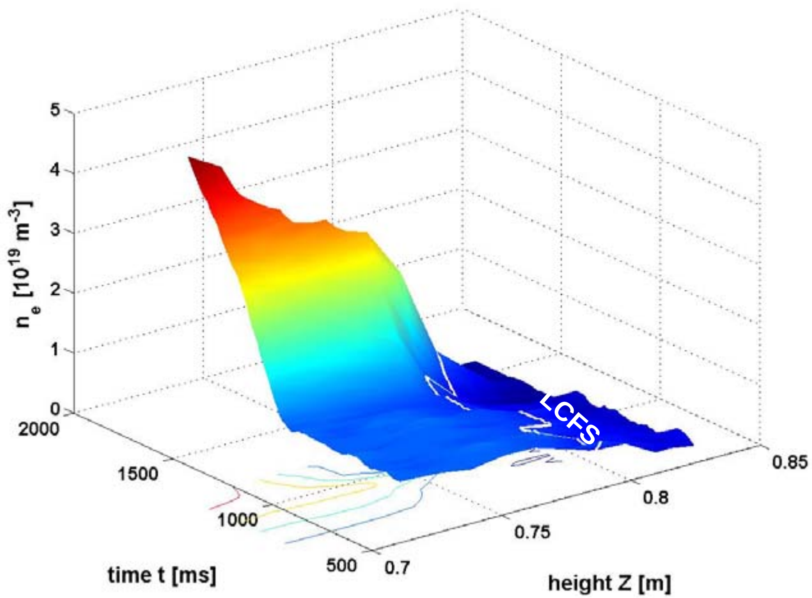
Further improvement ongoing but readily available for basic studies

Edge profiles used to study line emission distribution in L and H-mode



Use local Thomson Scattering profiles

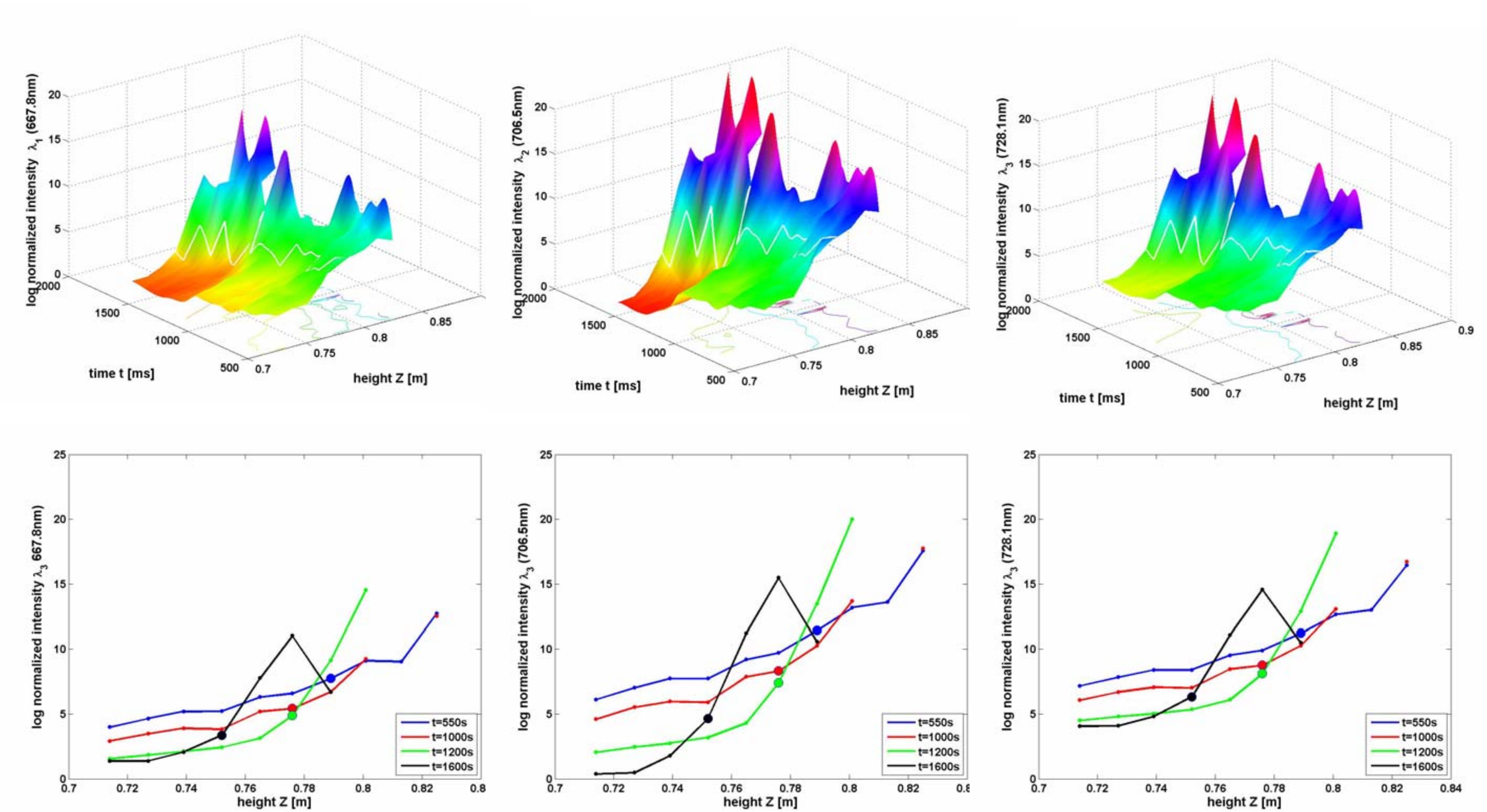




Simulates localized measurement at specific poloidal gas valve position for instance

Line emission shell moves and gets compressed during L-H transition

Solution of equilibrium model ➡ **Emission will increase and penetrate deeper for localized beam**

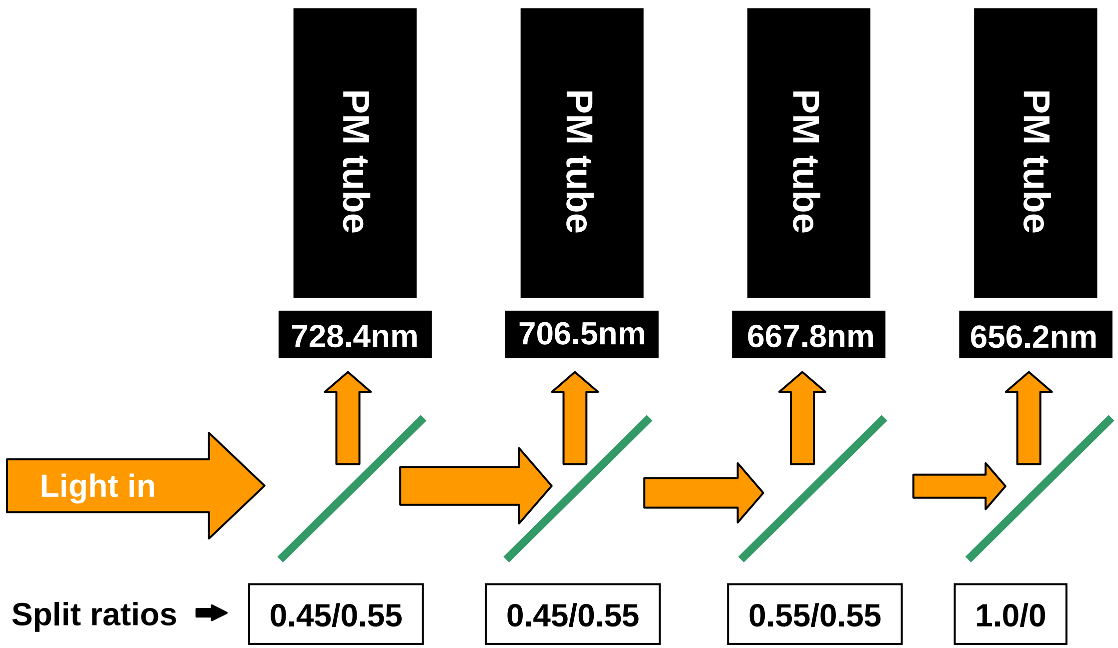


Expected measurement volumes: **Detection volume will move from separatrix region in L-mode towards SOL in H-mode plasmas**

New filter scope design for a compact SOL characterization tool

ORNL-TEXTOR collaboration

- **Measure line intensities with high time resolution**
- **Include D_α measurement for neutral density calculation**
- **Take advantage of filter scope system capabilities**
  - **Single chord gain adjustment**
  - **High sensitivity**
  - **High time resolution**
  - **Universal spectroscopic measurement for any optical setup**



12 channel system is under construction and will be tested at TEXTOR this summer

Design as compact tool which can be flexibly applied

Optical coupling possible with standard, off-the-shelf optical components

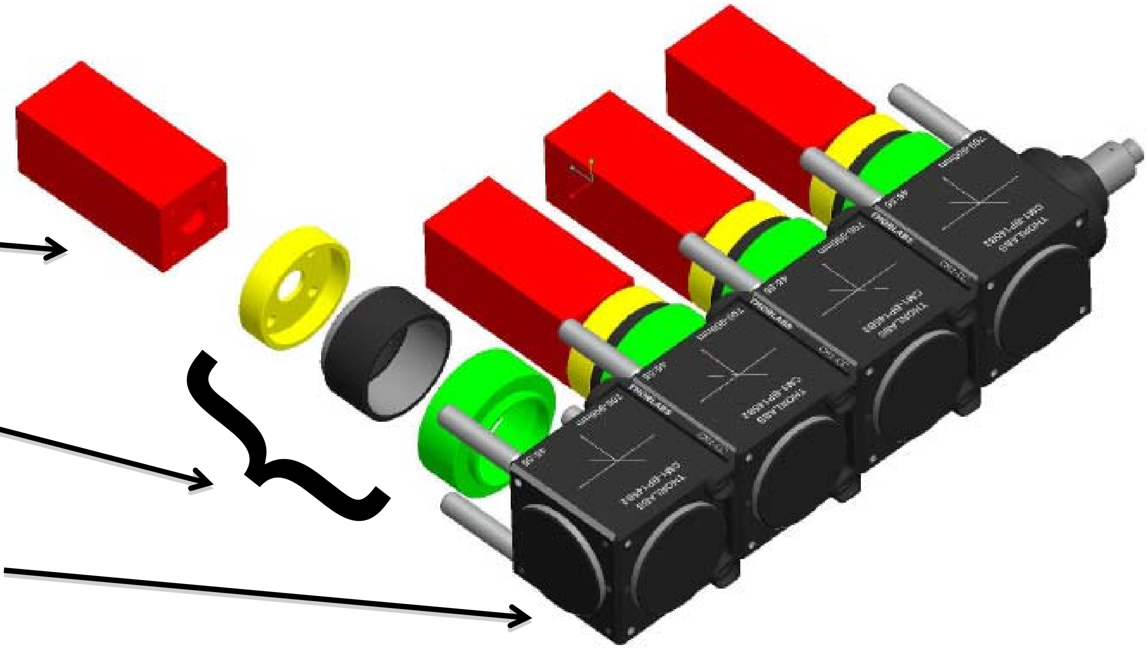
Test setup as used at DIII-D was very handy to assemble and adjust

Hamamatsu PMT near-IR sensitive

Thorlab components and

Andover He-I and D_α filters

Pellicle Beamsplitter ‘Cube’



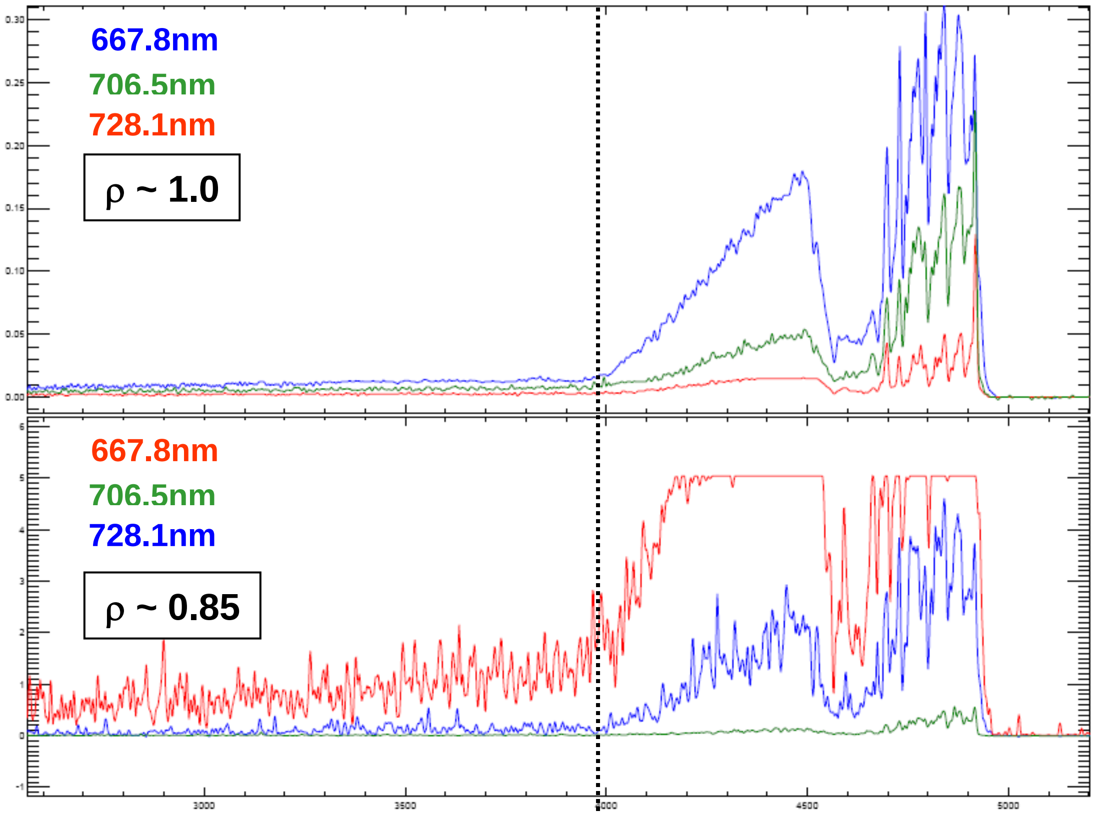
30mm

- Off-the-self parts allow reproducible chord-to-chord setup for light splitting

Application for initial tests during last days of campaign showed very promising results

Two channel system tested shows promising results

DIII-D #142099



- **Stronger sensitivity due to smaller loss along optical path**
- **Improved coupling of fiber guides from pit to system**
- **Reproducible set-up and handy implementation**
- **Compatible with existing filter scope set-up (light guides)**

Signal from residual helium (GDC)

Signal from 0.2 torl s^{-1} helium gas puff into far SOL (gas_e)

Successful initial test of adapted filter scope system set-up

Best case is observation of local gas puff - a suggestion

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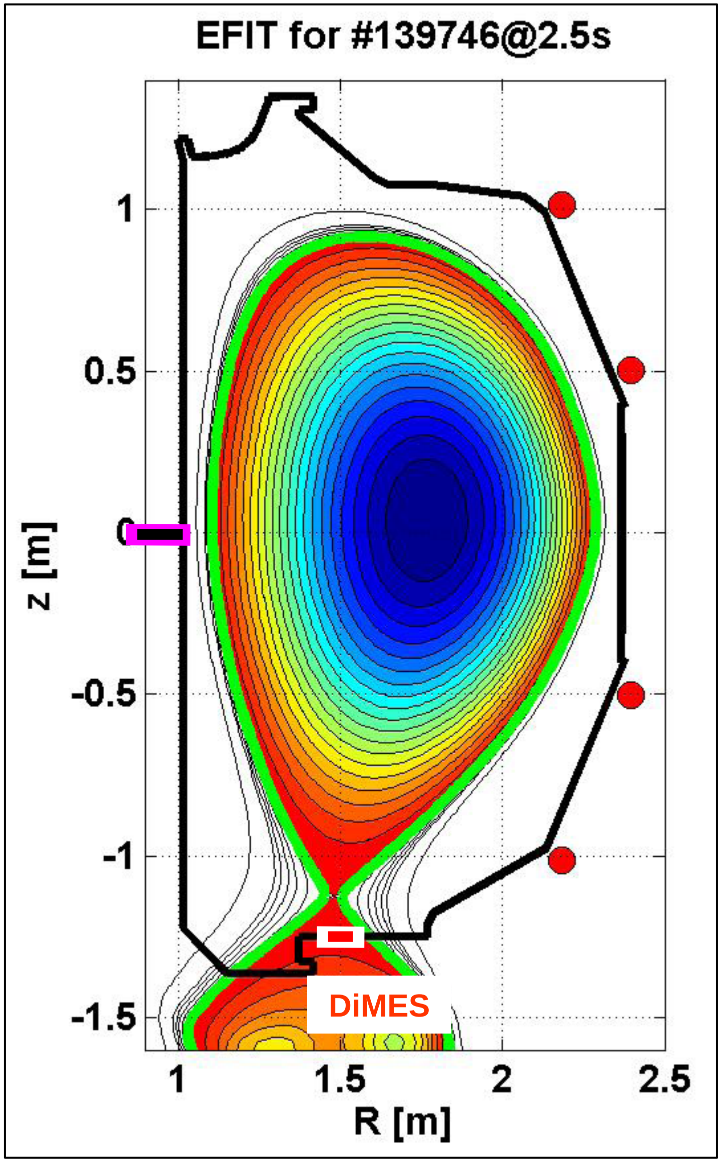

Local gas puff with direct tangential/perpendicular observation if the way to go!

- **Strong active and therefore localized signal**
- **Well defined beam geometry and velocity distribution**
- **Pulsed system possible for optimized background subtraction**

Standard TEXTOR nozzle

- **340 micro tubes**
- **210 µm diameter each**
- **30 mm in length**

⇩

- **beam with +/- 10 degree divergence**
- **thermal velocity (1.4-1.6 km s^{-1})**
- **puff rate 0.3-4.0 10^{18} He atoms s^{-1}**
- **local beam density 0.2-2.0 10^{17} at. m^{-3}**
- **effect on local plasma parameters negligible (<5%)**

[2] O. Schmitz et al. PPCF **50** (2008) 115004

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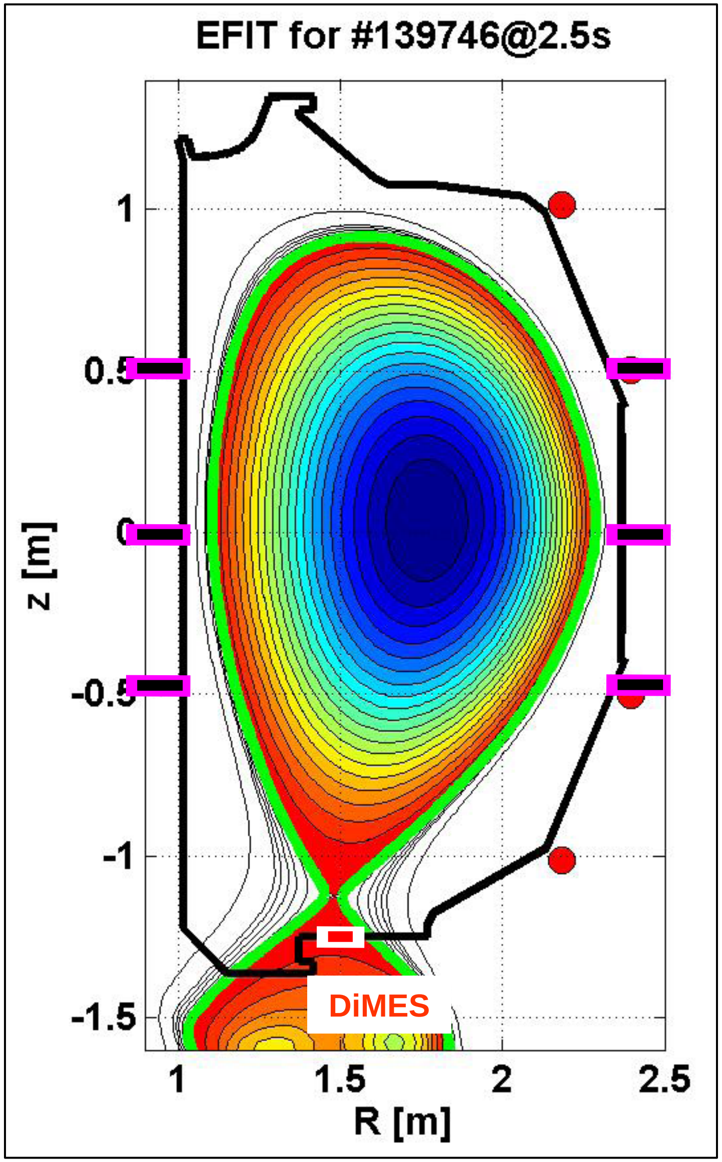
Best case is observation of local gas puff - a suggestion



Proposal for a complete SOL capillary set

System I: HFS and LFS profile diagnostic

- 1 filter scope system, 12 radial chords, Δr=3 mm with 2 mm spot size
- automated view adjustment to one of six puff locations
- tangential view with radial fine adjustment

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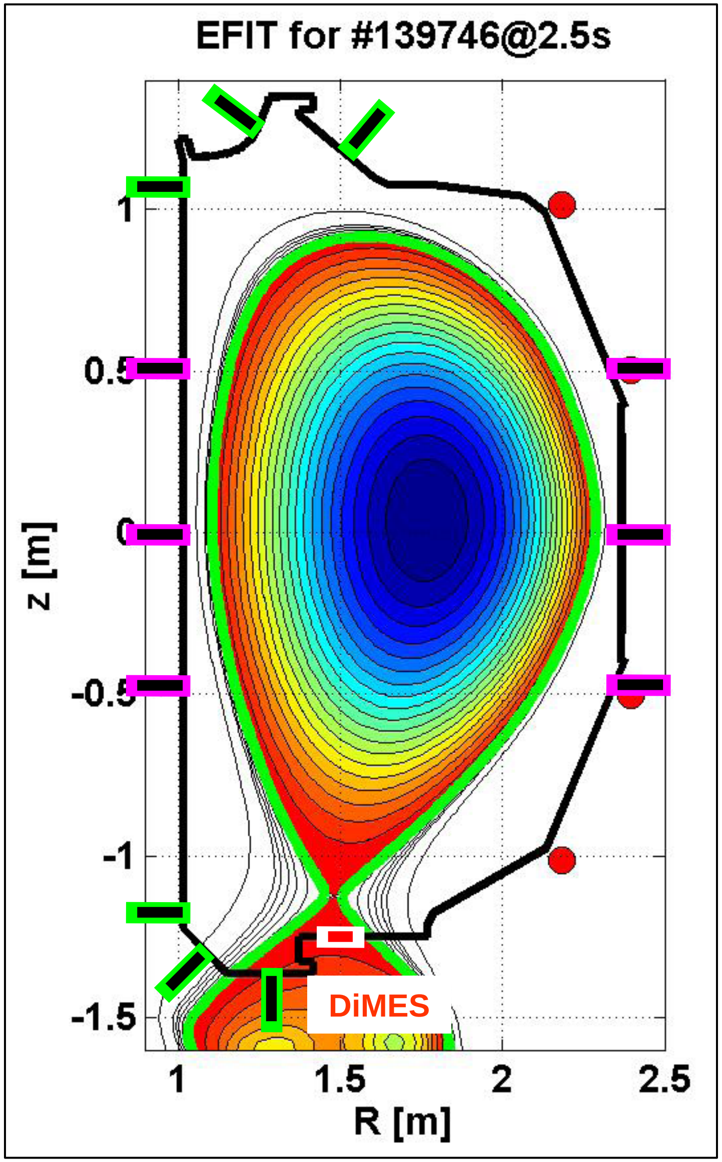

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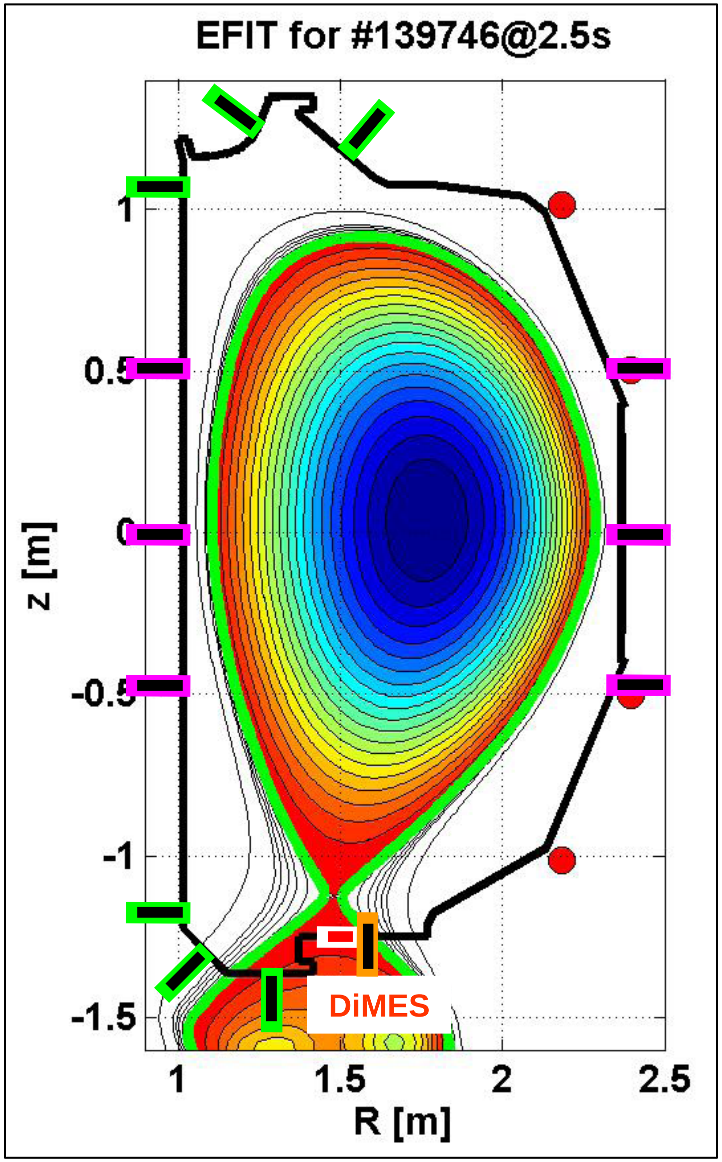

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System III: DiMES capillary

- 1 filter scope system
- 2-3 channel observation from UD on capillary
- 1 additional channel observation of DiMES sample (PPI)

Summary

Coherent test of He-I line ratio technique was performed showing promising path to a new SOL and plasma edge n_e and T_e diagnostic tool

He-I emission from low gas puff rate He influx gives sufficient intensity for the measurement

Design of ORNL filter scope based spectroscopic system is finished and system is under assembly to be tested at TEXTOR this summer

Modeling expertise available in house and CRM addressing specific H-mode needs is under development

Based on this feasibility test, we would like to work on an implementation strategy as a short notice LTOA activity