Large Scale Data Analysis Case Study: NSTX-U Langmuir Probes

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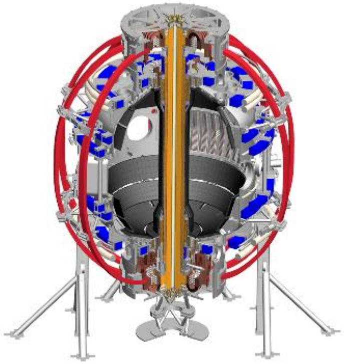
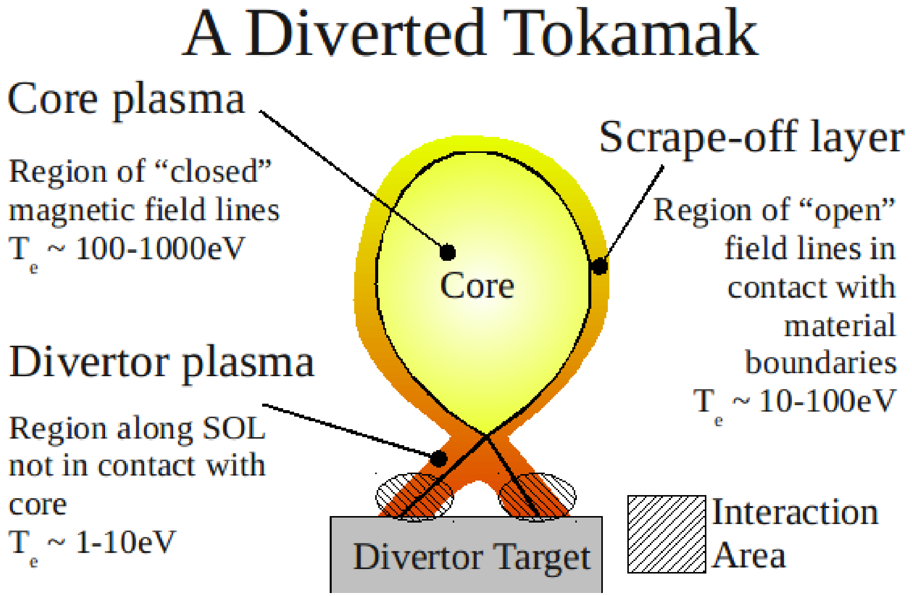


Outline of Material

- Will you have too much data and why that means you have to think
- Strategies for attacking your data
- Langmuir Probes as a case study of where things fall apart
- Extracting Electron Distribution Functions: practical aspects and recommended practices

Diverted tokamaks are the most developed concept for MFE

- Magnetic fields confine plasma in toroidal geometry
- Divertors developed to separate eroded material from core plasma



A Diverted Tokamak

Core plasma

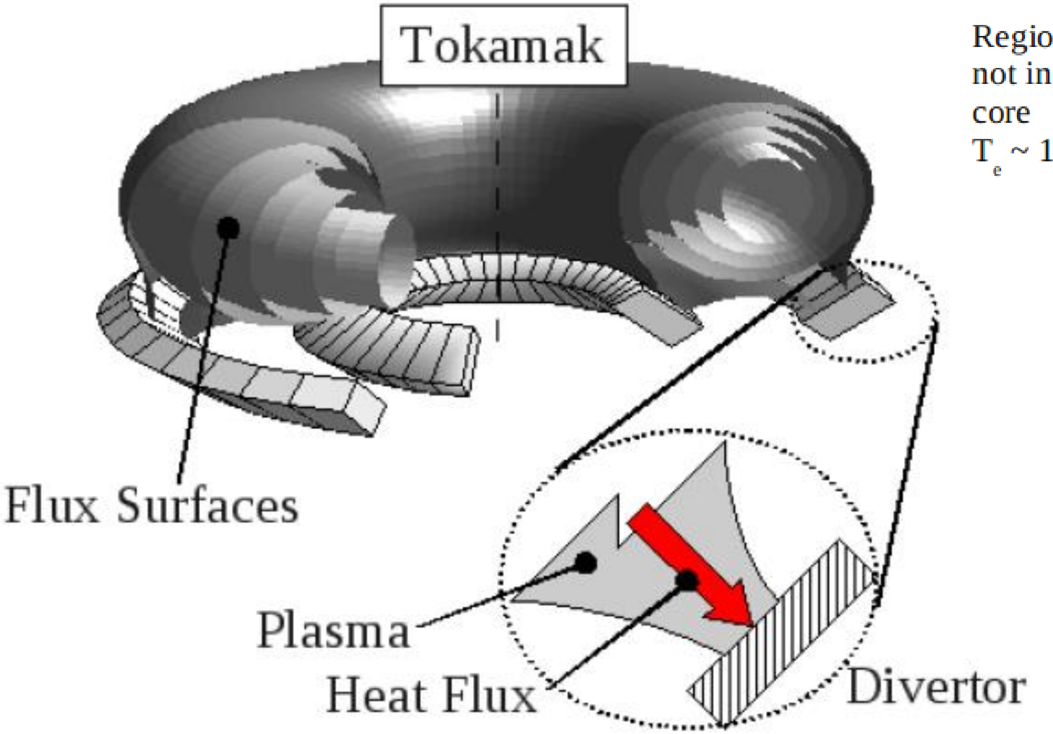
Region of “closed” magnetic field lines
T_e ~ 100-1000eV

Scrape-off layer

Region of “open” field lines in contact with material boundaries
T_e ~ 10-100eV

Divertor plasma

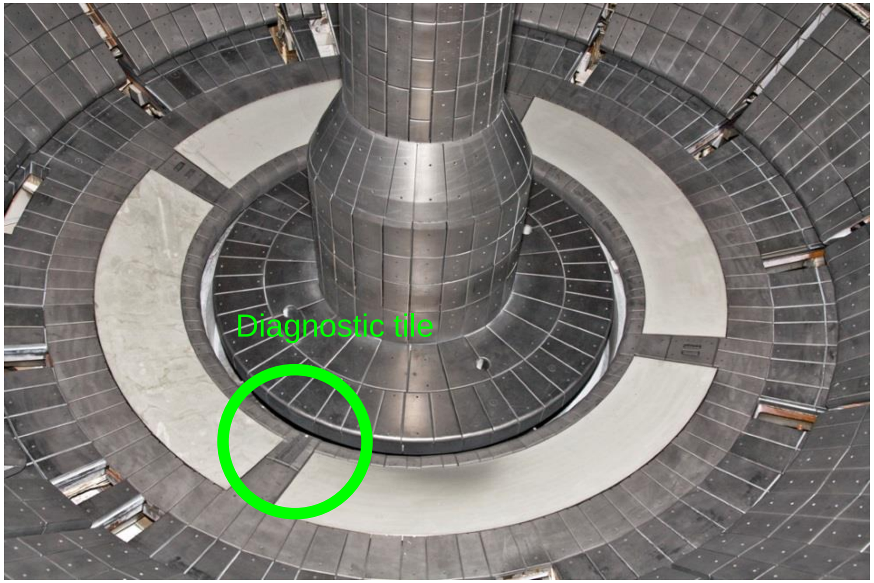
Region along SOL not in contact with core
T_e ~ 1-10eV

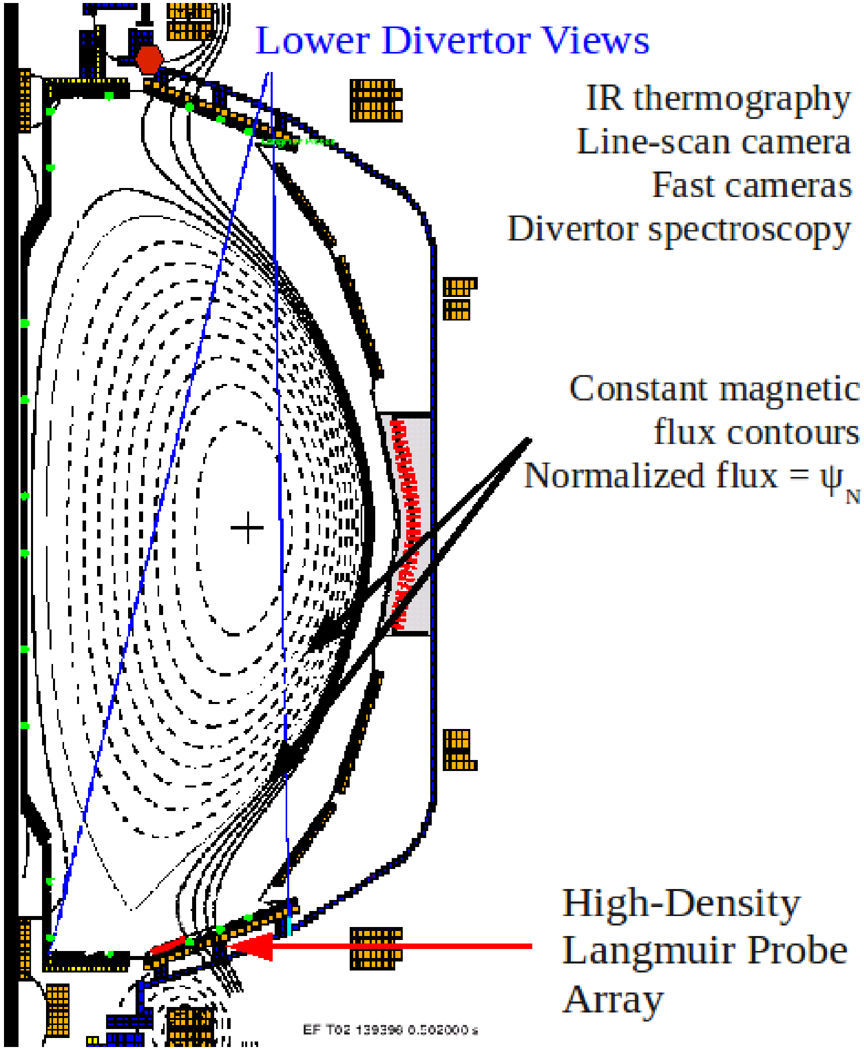


- A lot of processes happen in dense region at target plate – we need to diagnose it!

Array of plasma diagnostics utilized during experiments

- Local plasma conditions and PFC currents measured with Langmuir probe system
- 2D fast-cameras provide nearly full toroidal coverage of divertor





How much data is this?

- Each I-V characteristic can be a single “data set”
  - 250 kHz sampling frequency on digitizer
  - 500 Hz sweep rate, 2 V-sweeps per cycle
  - 1000 sweeps per 1s discharge per probe
  - 2000 shots per year

- **2000*1000*4 = 8 Million data sets in 1 year**

- What are the bigger picture questions and strategies needed to pare this down?

What if I just analyze all the data by hand?

- Just not practical, but even if it were: would you want to?

- Scientific reporting is to provide sufficient information to replicate the work
  - Hand analysis means *you* are making decisions during analysis
  - If *you* are integral to analysis, no one else can repeat it!

- Systematic analysis allows study of the method itself

- Avoids “cherry-picking” if its systematic

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Strategies for data analysis

1. Know what you want to get from the data!
   - E.g. I want the most accurate Ne and Te in divertor
   - E.g. I want the post-ELM evolution in the divertor

2. Know what you don’t want in your data sets!
   - E.g. I don’t want to analyze turbulent plasmas
   - E.g. I *do* want to analyze turbulent plasmas

3. Be Selective using 1 and 2!
   - Large data sets means you can “afford” to throw some things away
   - Don’t slow yourself down analyzing every single case

4. Build in consistency checks (recommended practice)
   - Ensure your systematic analysis is being correctly implemented

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Langmuir probes as case study

- The (almost) original plasma diagnostic (I. Langmuir 1881-1957)
- “Simple to implement; hard to interpret”
- Integrated measure of charged particles in plasma
- LP theory is deep and complex, lots of regimes of operation (see Demidov 2002)
- Perturbative diagnostic (at least locally)

Irving Langmuir (source: wikipedia)

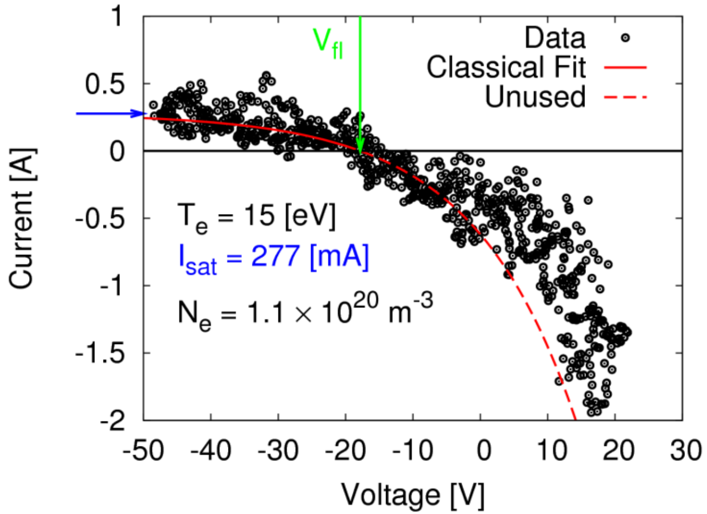
Many assumptions in “text-book” theory fall down

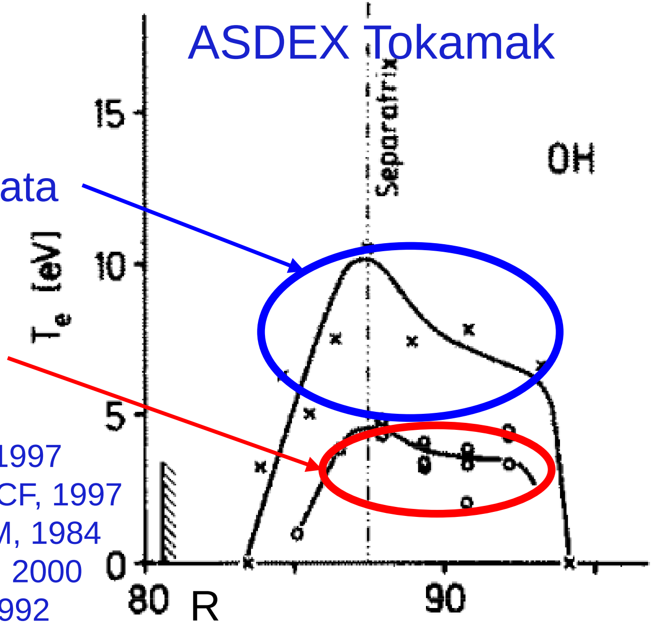
- Typical method:
  - Subtract ion saturation; fit exponential curve to electron current
  - Derive Ne from Te + Isat + plasma species

- Most derivations do not include magnetization
- Collisionality can be accounted for (see Laframboise method)
- Assumptions of Maxwellian distribution not always good to make

Classical interpretation often yields higher temperatures relative to other diagnostics

- Classical interpretation makes use of data up to floating potential
  - Assumes single Maxwellian distribution
  - Only uses ~5% of distribution
- Independent measurements often indicate lower temperatures
  - Thomson scattering on ASDEX had some indications of non-Max. pops.
  - Thomson scattering on DIII-D consistently lower T_e
  - Anomalously low sheath heat transmission coeff. on numerous machines





ASDEX Tokamak

LP Data

Thomson Data

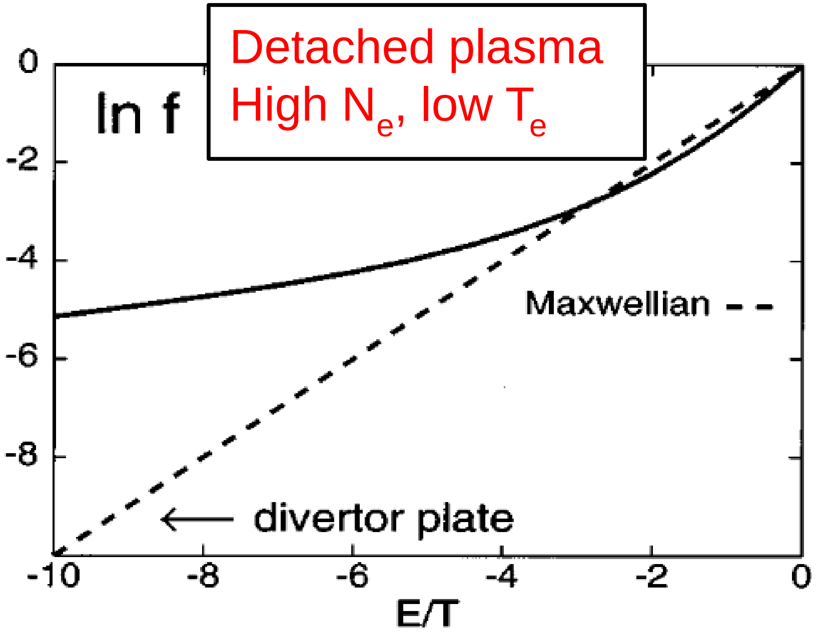
Tagle, PPCF, 1997
Matthews, PPCF, 1997
Fussman, JNM, 1984
Watkins, JNM, 2000
Futch, JNM, 1992

Why expect a Maxwellian distribution?

- Maxwellian plasmas assumed due to plasma collisionality
  - Collisionality often calculated based on system length[1]
- Numerous modeling studies indicate non-Maxwellian distributions
  - Target plasmas result in low T_e and high N_e – yield large collisionalities in the divertor
  - Non-Maxwellian distributions still obtained
- Temperature scale length requires consideration as well

$$\lambda_{ee} \approx 1 \times 10^{16} \frac{T_e^2}{N_e} \qquad \nu_{ee}^* = \frac{L}{\lambda_{ee}}$$

$$L_{\parallel} \text{ vs. } \lambda_{Te}$$



Detached plasma
High N_e, low T_e

Batischev, PoP, 1997

Other exmples:
Fokker-Planck: Chodura, CPP, 1992
PIC modeling: Tskhakaya, JNM, 2011

[1] PC Stangeby, "The Plasma Boundary of Magnetic Fusion Devices", IoP, 2000.

Collisionality Must Be Calculated with the Correct Scale Length

- Chodura, in 1992, pointed out the importance of local temperature scale length
- Application of Chodura criterion suggests simple limits for thermal conduction
  - Based on moments of electron distribution function
  - Most heat-carrying electrons have 3-5x thermal velocity
- **NSTX divertor plasmas indicate T_e>15eV for fluid conduction to hold**

Temperature gradient scale length

$$L_{T_e} = \frac{T_e}{T'_e} \approx \frac{\kappa_{0e} T_e^{7/2}}{q_e}$$

Chodura criteria due to energetic electrons carrying heat

$$\frac{\lambda_{ee}}{L_{T_e}} < \frac{1}{100}$$

Scaling of minimum temperature to satisfy Chodura collisionality req.

$$T_e^{3/2} \gtrsim \frac{10^{18} q_e}{\kappa_{0e} N_e}$$

Jaworski JNM 2013

Kinetic probe interpretation provides more complete analysis of IV characteristics

- When electron energy scale length much longer than probe perturbation scale, velocity “diffusion” term negligible
  - f(r,v) ⟶ f(x,W)
  - W is total energy
  - f_0 is distribution far from probe
- Solution for probe characteristic determined by geometry and diffusivity
  - In magnetized plasma, cross-field diffusivity scales with Larmor radius
  - Diffusivity parameter takes form $\psi(W)=\psi_0 W^{-1/2}$ in this case
- When ψ_0 >> 1, first derivative becomes proportional to distribution function
- Demonstrated on CASTOR tokamak

$$x = r \qquad W = \frac{1}{2}mv^2 + e\phi(x)$$

$$\lambda_\epsilon \gg r_s$$

$$\nabla_x D_x(W)\nabla_x f_0 = 0$$

$$j_e(V) = \frac{8\pi e}{3m^2\gamma}\int_{eV}^{\infty}\frac{(W-eV)f_0(W)\mathrm{dW}}{1+\frac{W-eV}{W}\psi(W)}$$

$$\psi(W) = \frac{1}{\gamma\lambda(W)}\int_a^{\infty}\frac{D(W)\mathrm{dr}}{\left(\frac{r}{a}\right)D(W-e\phi)}$$

$$\boxed{\frac{\mathrm{d}j_e(V)}{\mathrm{d}V} \propto \frac{(eV)^{3/2}}{\psi_0}f_0(eV)}$$

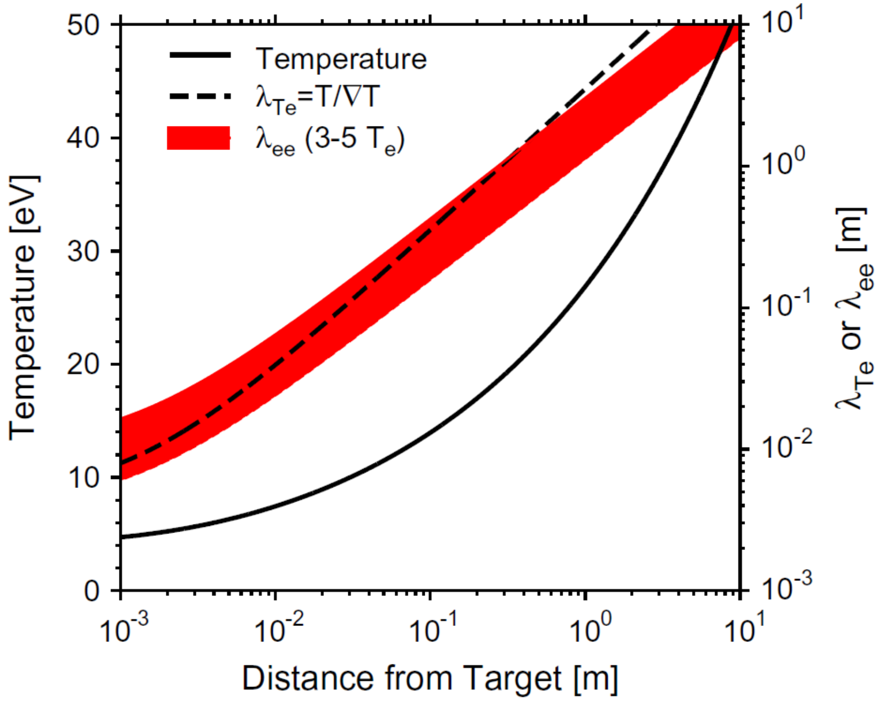
Bernstein, Phys.Rev., 1954
Golubovskii, Sov.J.Plasma Phys, 1981
Arslanbekov, PSST, 1994
Demidov, PoP, 1999
Popov, PPCF, 2009
Godyak, Demidov, J.Phys:D, 2011

Non-Maxwellian distributions likely: motivates kinetic Langmuir probe interpretation

- Fluid-based reconstruction (OEDGE) indicates conduction-limited regime violates Chodura conditions

- Kinetic Langmuir probe interpretation theory developed over 30 years ago
  - Golubovsky 1981 – first application to high-pressure discharges
  - Arslanbekov 1994 – application to high-pressure and magnetized discharges
  - Popov 2009 – application to tokamak edge region at midplane

- **In the right conditions, *first derivative* becomes proportional to distribution function**



$$\nabla_x D_x(W)\nabla_x f_0 = 0$$

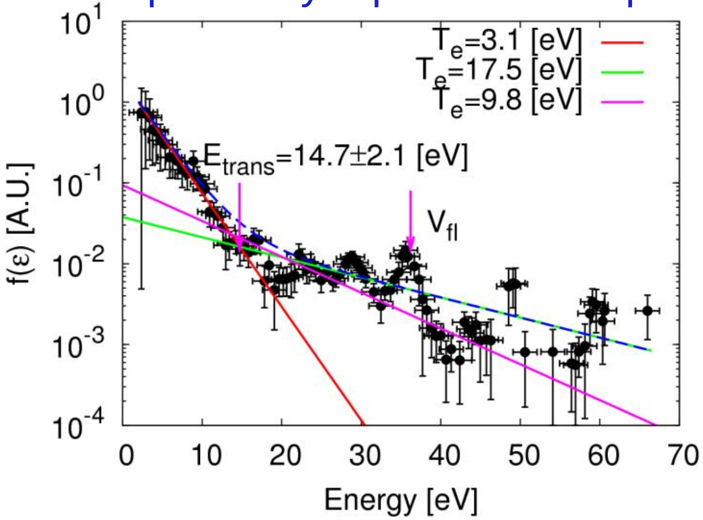
$$\boxed{\frac{\mathrm{d}j_e(V)}{\mathrm{d}V} \propto \frac{(eV)^{3/2}}{\psi_0} f_0(eV)}$$

Popov, PPCF, 2009; Jaworski FED 2012, Jaworski JNM 2013

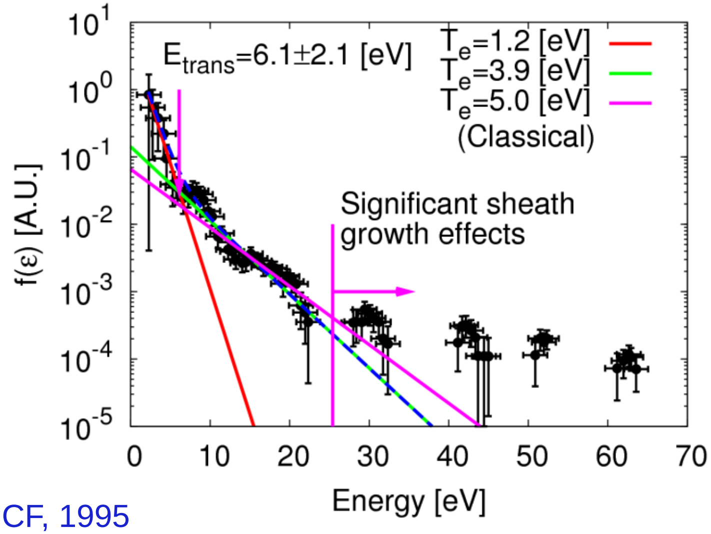
Bi-modal distributions observed in NSTX divertor

- Typical distributions shown
    - Scrape-off layer plasma where classical T_e~15eV
    - Private plasma example demonstrating T_e~1eV
- Ion current effects due to sheath growth estimated to avoid including in fits[1,2]
- Bi-modal distribution often "best" model
- Total density calculated from I_{sat}
    - Sound speed calculated using mixture of both plasma populations[3]

Scrape-off layer plasma example



Private plasma example



[1] Gunn, RSI, 1997; [2] Godyak, Demidov, J.Appl.Phys.D, 2011; [3] PC Stangeby, PPCF, 1995

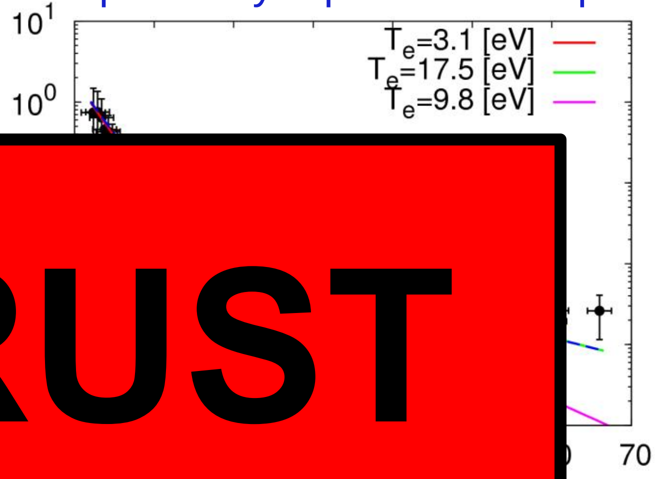
Bi-modal distributions observed in NSTX divertor

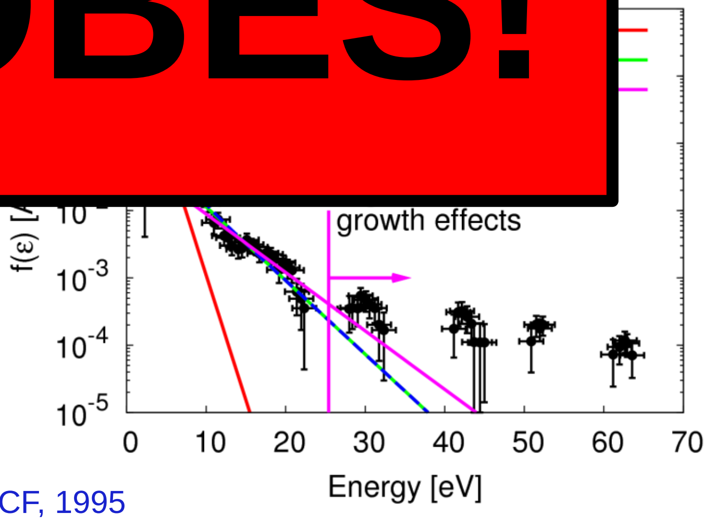
- Typical distributions shown
  - Scrape-off layer plasma

DON’T TRUST THE PROBES!

- Ion c
  growt
  fits[1,2]
- Bi-mo
  mode
- Total
  - Sound speed calculated using mixture of both plasma populations[3]

Scrape-off layer plasma example





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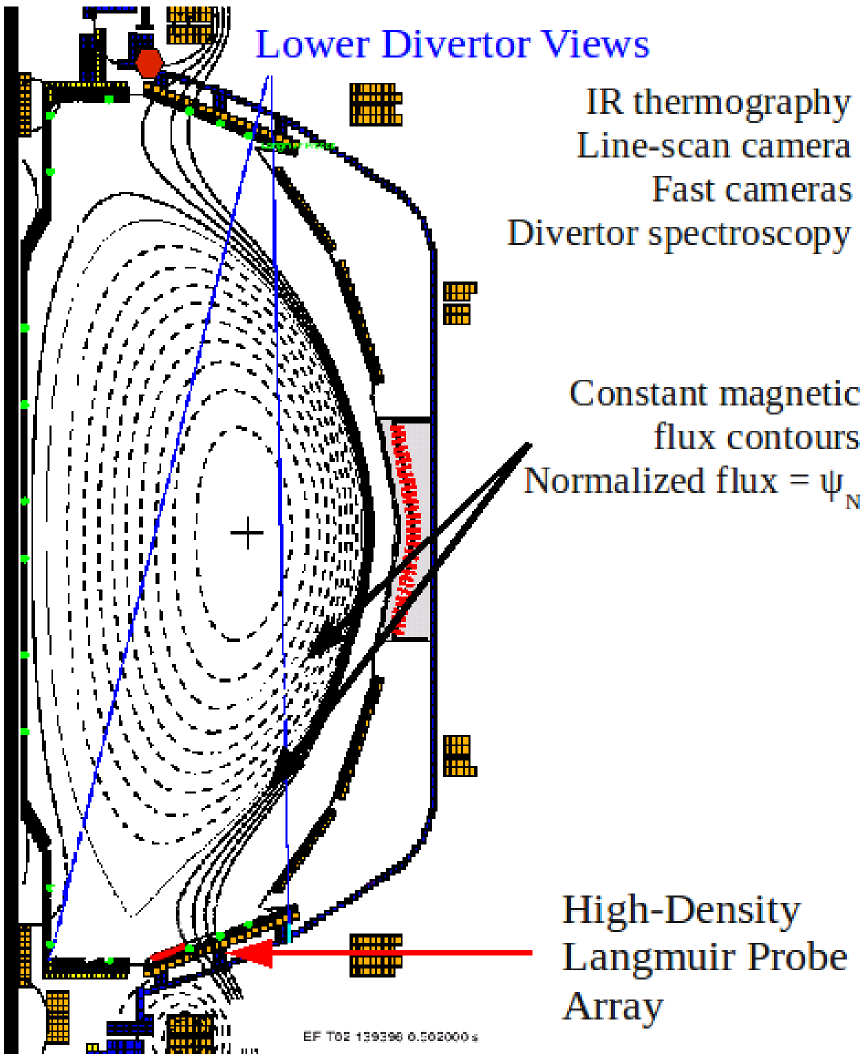
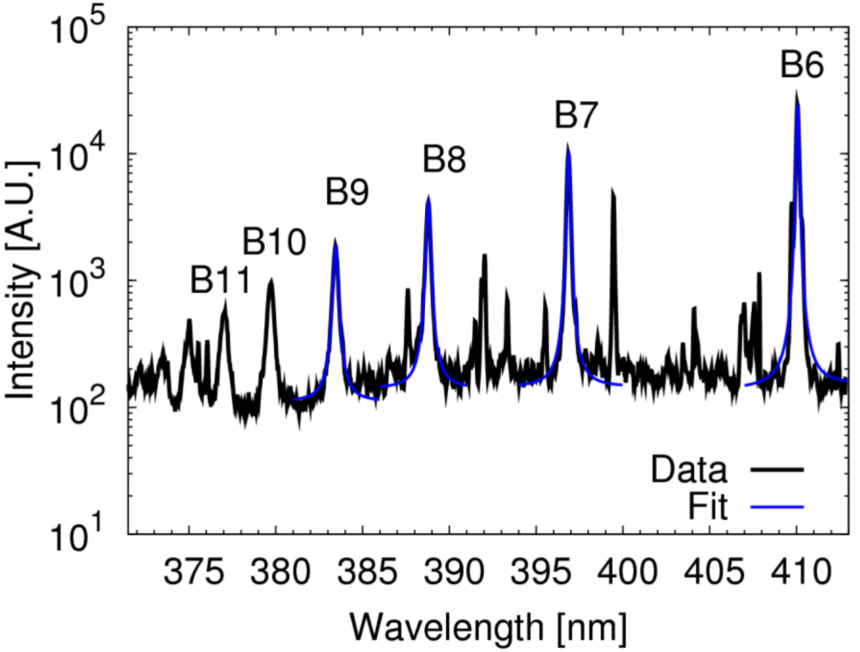
Empirical plasma reconstruction provides framework for checking consistency between diagnostics

- Utilizes measured data points as starting point in constraining plasma models
- Solution improves as more and more data constrains background
- OEDGE code suite used here: Onion-Skin Method (OSM2)+EIRENE+DIVIMP
    - OSM2 fluid solver
    - EIRENE neutral hydrogen
    - DIVIMP Monte Carlo impurities
- Utilized here to provide fluid background and identify candidate diagnostics for comparison

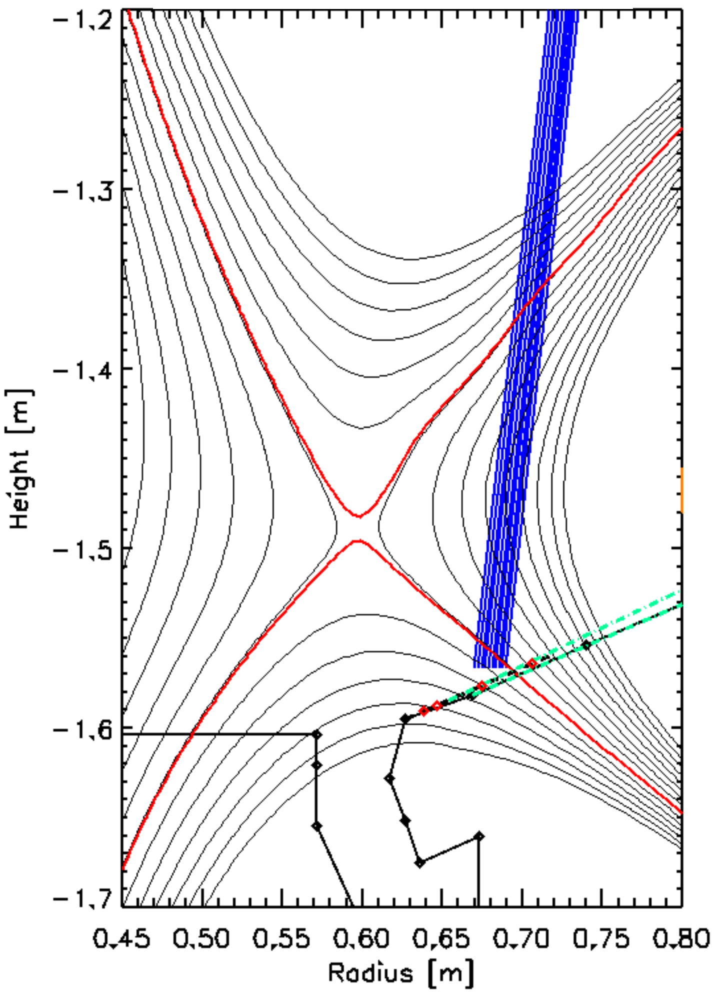


Spectroscopy provides independent checks on density and temperature

- Divertor spectrometer viewing strike-point region during discharge
- Deuterium Balmer lines shown in this spectra
- Pressure broadening analysis indicates density of $3.6\text{x}10^{20}$ m^{-3} (mean, 2.1-5.5x10^{20}m^{-3} min/max)
  - Existence of high-n Balmer lines indicates low temperature

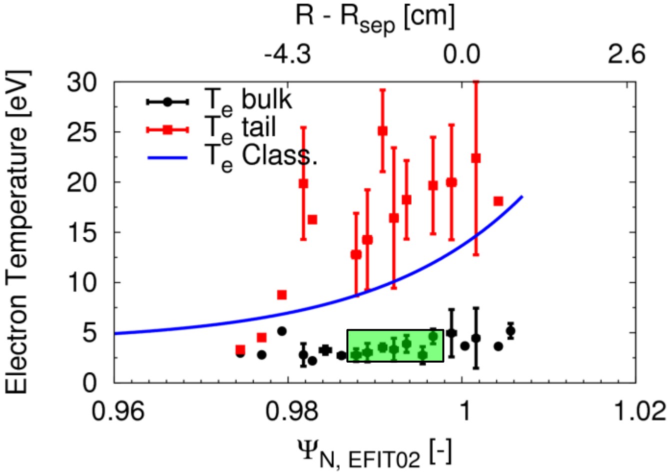


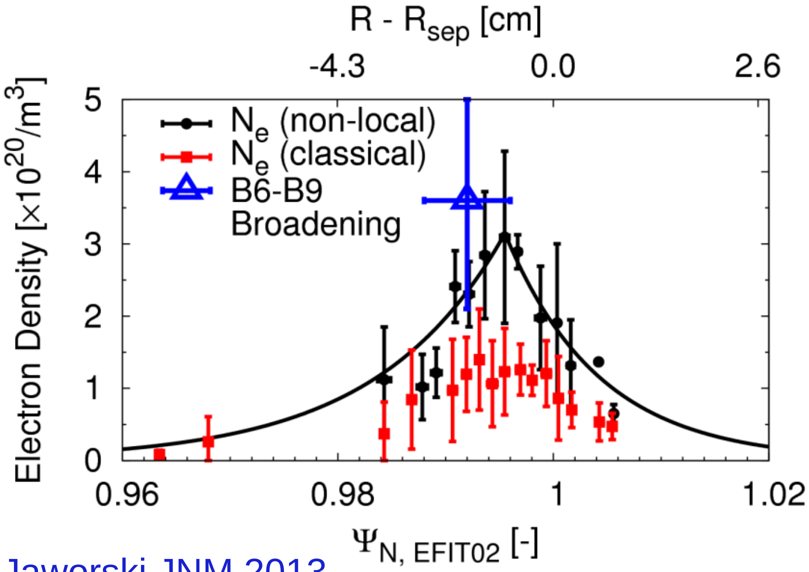
Divertor spectrometer view



Broadening measurement and CR modeling of hydrogen spectrum consistent with kinetic interpretation

- Pressure broadening yields density
- OEDGE plasma+neutral solution provides local parameters
- CR model calculates excited state populations for given background (Maxwellian!)
- Brightness ratios normalized to B6 consistent with 3-5eV





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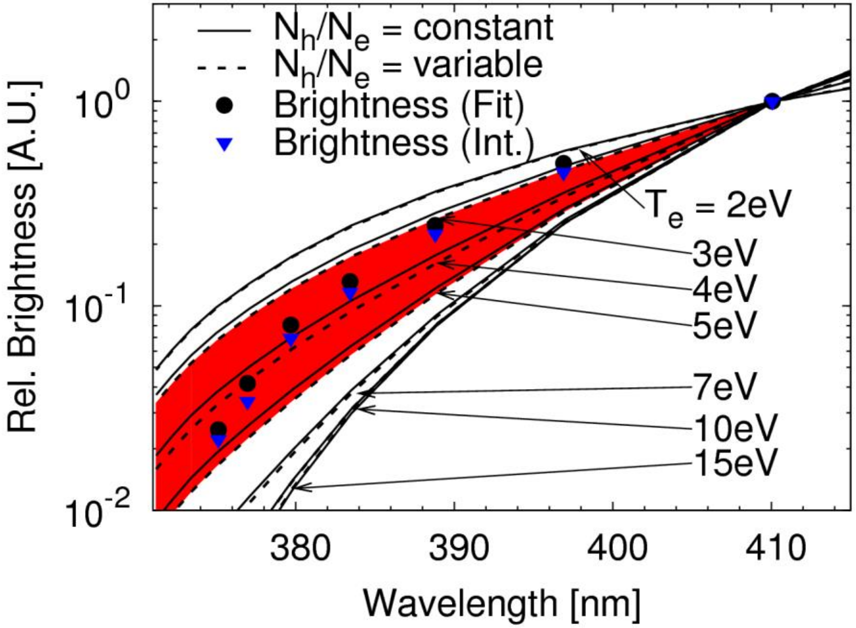

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Not all models have the same knowns and unknowns!

- Classical interpretation
  - Te, Ne, and Vf come out
  - Vf easily identified in I-V characteristic
  - Te extracted from exponential fit
  - Ne derived from Isat and Te

$$x = r \qquad W = \frac{1}{2}mv^2 + e\phi(x)$$

- Kinetic interpretation for EEDF
  - Entire distribution function is up for grabs!
  - Energy is referenced to **plasma potential** (not known ahead of time)
  - Psi transport function not really known ahead of time (but can be guessed)

$$j_e(V) = \frac{8\pi e}{3m^2\gamma}\int_{eV}^{\infty}\frac{(W-eV)f_0(W)\mathrm{d}W}{1+\frac{W-eV}{W}\psi(W)}$$

$$\psi(W) = \frac{1}{\gamma\lambda(W)}\int_{a}^{\infty}\frac{D(W)\mathrm{dr}}{\left(\frac{r}{a}\right)D(W-e\phi)}$$

$$\boxed{\frac{\mathrm{d}j_e(V)}{\mathrm{d}V} \propto \frac{(eV)^{3/2}}{\psi_0}f_0(eV)}$$

- If you don’t know/trust the value, find consistency checks!

The EEDF algorithm for NSTX-U

1. Get data from central storage
2. Determine simple IV characteristics for starting point (classical analysis)
3. Perform data smoothing (first-derivative noise)
4. Distribution function loop
    1. Construct model curve based on best guess of f(E)
    2. Determine best Vp from model curve chi-square
    3. Calculate new f(E) using new Vp (also solve Psi0)
    4. Calculate new I-V based on f(E) and check chi-square
5. Calculate derived parameters (bi-modal Te, Ne, etc)
6. Write data files

The value of chi-square (“goodness-of-fit”)

- Provides a quantitative value relating the model curve to the data set

- Not necessarily valuable as an absolute value
  - Should be ~1 if uncertainty correctly defined
  - Less free-parameters is better
  - Uncertainty not always well defined!
  - Should be minimized for best fits

- Be wary of “black box” fitting algorithms and traps

Consistency checks are critical!

- Make lots of plots during process development, verbose output is helpful
- Bug checking is critical – are you really applying the model you intended?
- Constantly ask yourself: is my model really better than another one?
- CHECK IT, BE QUANTITATIVE

Other recommendations

- COMMENT YOUR CODE
  - You won’t know when you’ll get back to it or put it down
  - Comment while its fresh in your mind

- Remember what research is: you get to learn when you are wrong!

Thank you!

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