Plasma Diagnostics

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What do we want to measure, anyway?

n

- **Particle Density** (units = particles/m^3)
  - The more particles in the box, the more they run into each other

T

- **Temperature** (units = eV , 1 eV=11600K)
  - Ions need to smack into each other hard enough to overcome Coulomb repulsion

τ_E

- **Energy Confinement Time** (units = sec)
  - Magnetic fusion devices are typically *pulsed*.
  - Long τ_E means less energy leaking out

What kind of *resolution* do we need?

- ***Global parameters:***
  - Spatial scales ~ 1 m
  - Time scales ~ 1 s
  - Precision ~ 50%
- ***Local parameters:***
  - Spatial scales ~ 1-10 cm
  - Time scales ~ 1 ms
  - Precision < 10%
- ***Fluctuations:***
  - Spatial scales < 1 mm
  - Time scales < 1 μs
  - Precision < 1%

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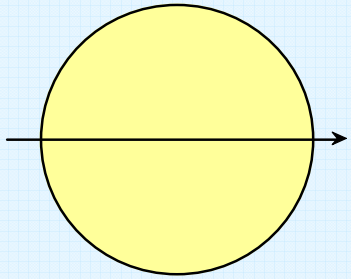
  - Spatial scales ~ 1-10 cm
  - Time scales ~ 1 ms
  - Precision < 10%
- ***Fluctuations:***
  - Spatial scales < 1 mm
  - Time scales < 1 μs
  - Precision < 1%

Code: GYRO

Authors: Jeff Candy and Ron Waltz

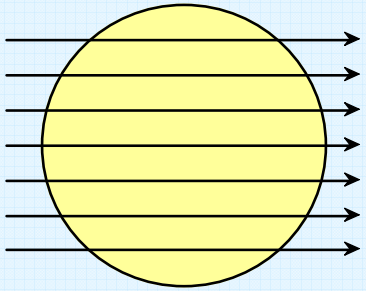
How about *Localization*?



Line-averaged measurement

Assumptions to convert to local information

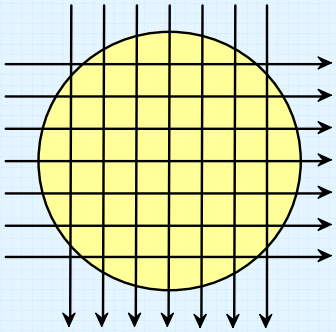
Spectroscopy, NPA, Interferometry



Multichord measurement

Can be converted to local info (Abel-inversion)

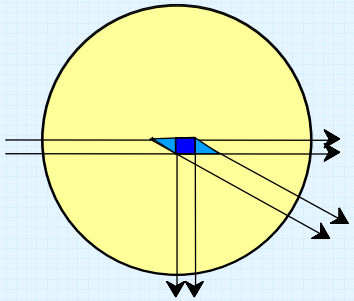
Interferometry/ polarimetry



Tomographic measurement

Local quantities by tomographic reconstruction routines

X-ray tomography



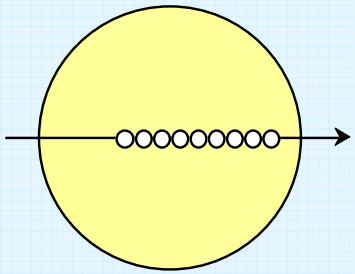
Scattering

Small angle: some spatial res.

Coherent Thomson scattering

90º good spat. res.

Incoherent Thomson scattering



Local measurement

Determined by spatial profile of ω_{ce}

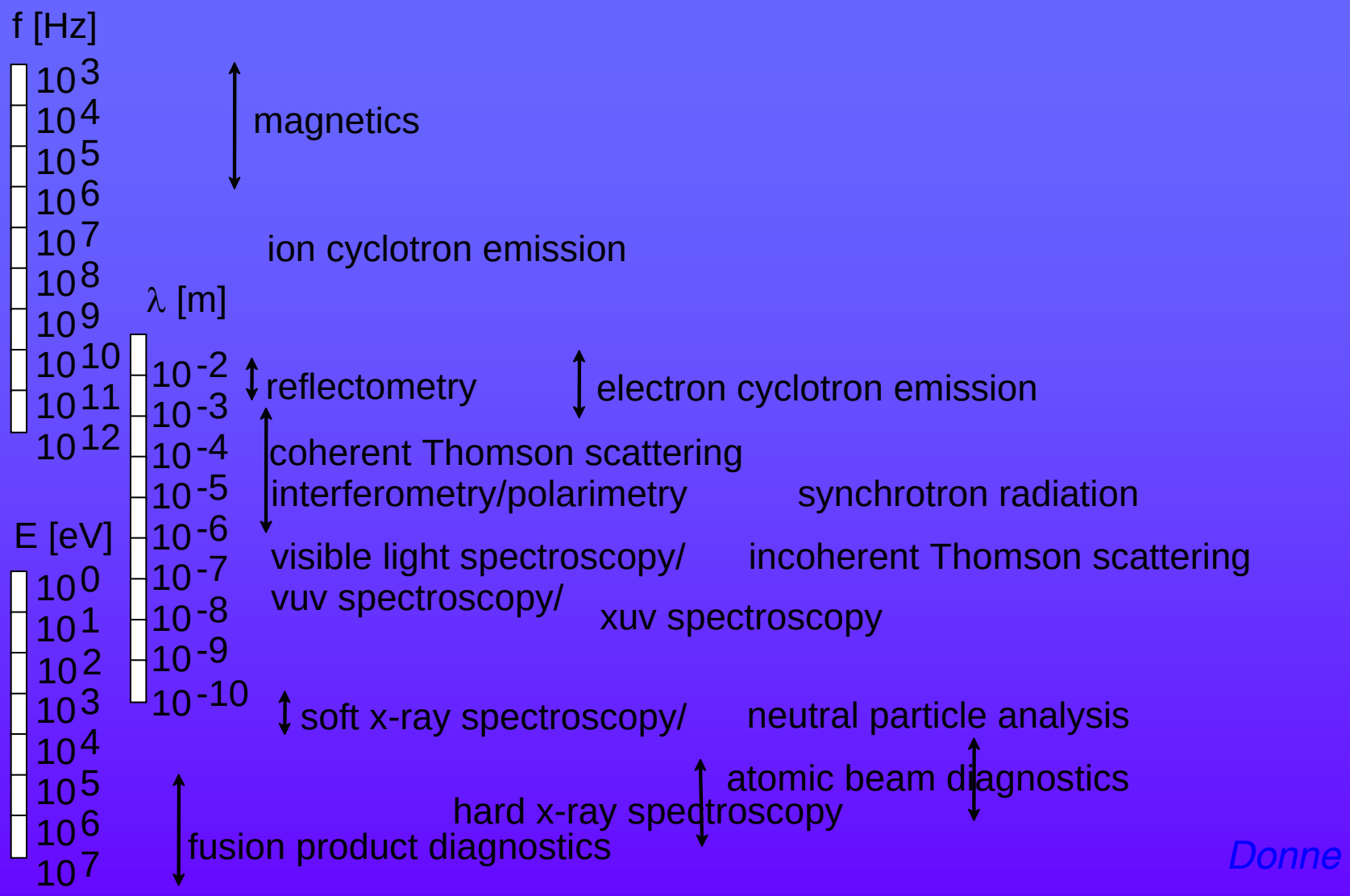
Electron Cyclotron Emission

& Reflectometry

Classification of Diagnostic Techniques

- Magnetics
- Microwave diagnostics
- Spectroscopy
- Laser diagnostics
- (Edge) probes
- Particle diagnostics
- Fusion product diagnostics

Frequencies / Wavelengths / Energy Scales



B-Field and Magnetic Flux Measurements

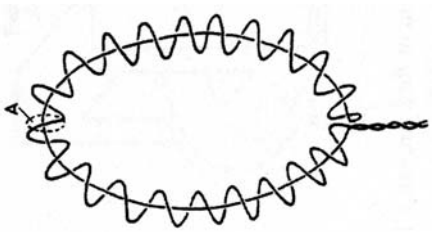
- **Typical freq. range: 100 Hz - 1 MHz**
- **Essential for machine operation**

– Rogowski coil	• Plasma current
– Pick-up coils (Mirnov coils)	• Plasma position and shape • B-field fluctuations
– Voltage loops	• Loop voltage • Ohmic input power
– Diamagnetic loops	• Plasma energy content

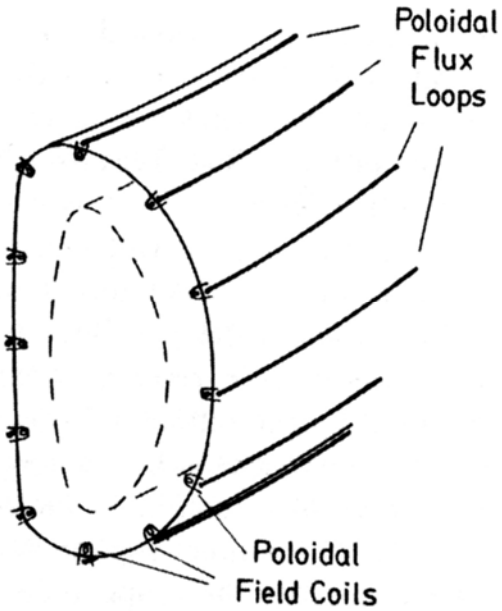
$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enclosed}$$

$$\Delta V = -\frac{d\Phi}{dt}$$

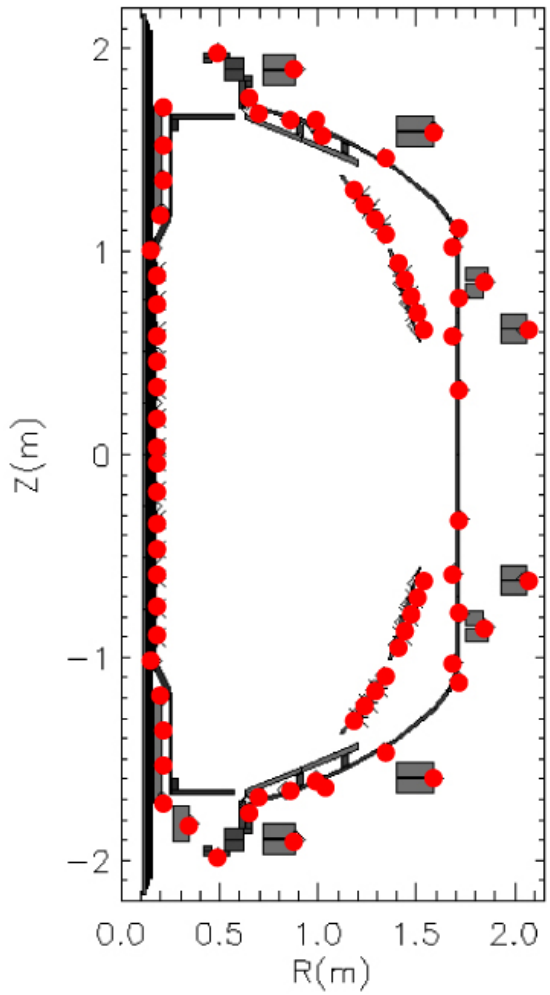
B-Field and Magnetic Flux Measurements

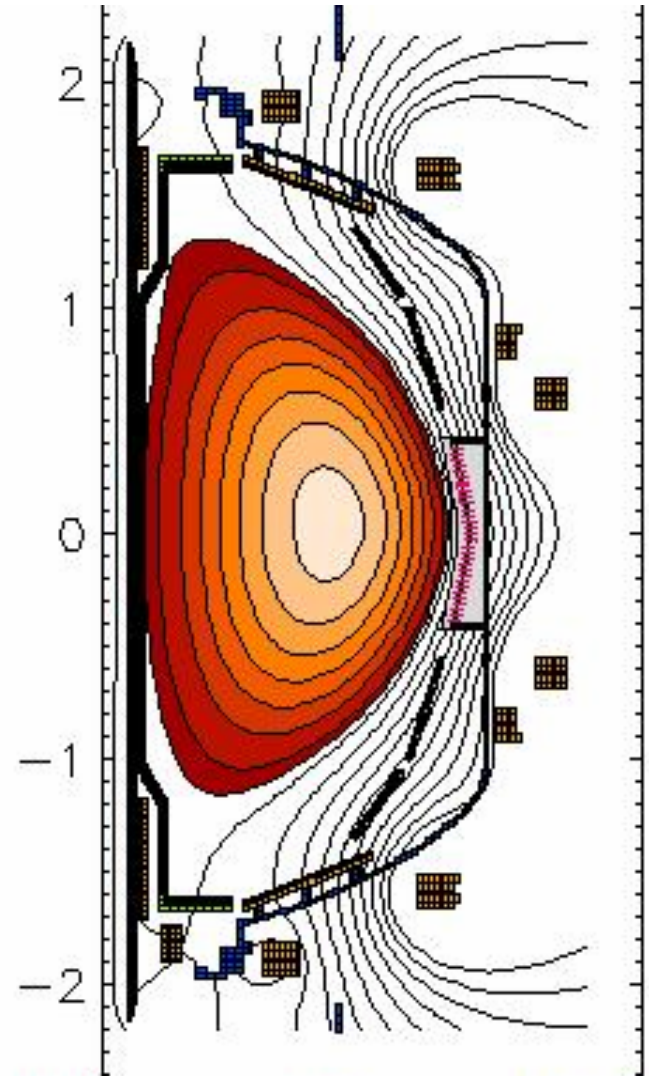


Rogowski coil



Each dot is a Mirnov coil or flux loop on NSTX

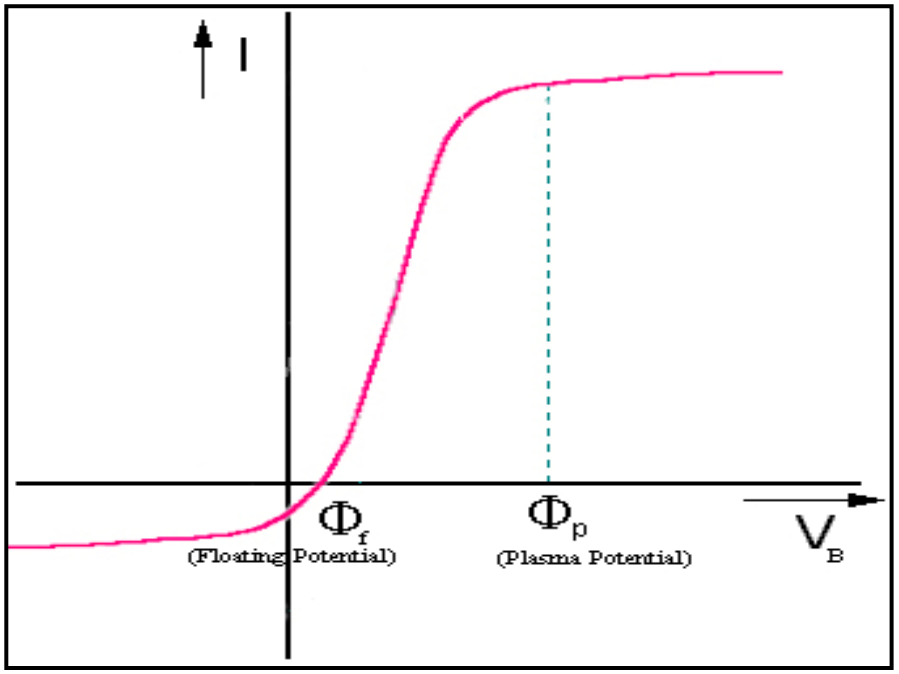




Langmuir Probes

- Simple hardware – stick a wire into a plasma
- Sweep voltage on tip, measure current "characteristic"
- Typically only good at edge (probe tips gets destroyed)

- Plasma is naturally positive with respect to vessel since e^- leave faster (Φ_P)
- $V = \Phi_P$: probe collects e^- (diffusively)
- $V > \Phi_P$: probe collects e^- (actively)
- $\Phi_F < V < \Phi_P$: probe retards some e^-
- $V = \Phi_F$: probe collects i^+ and e^- equally
- $V < \Phi_F$: probe collects i^+



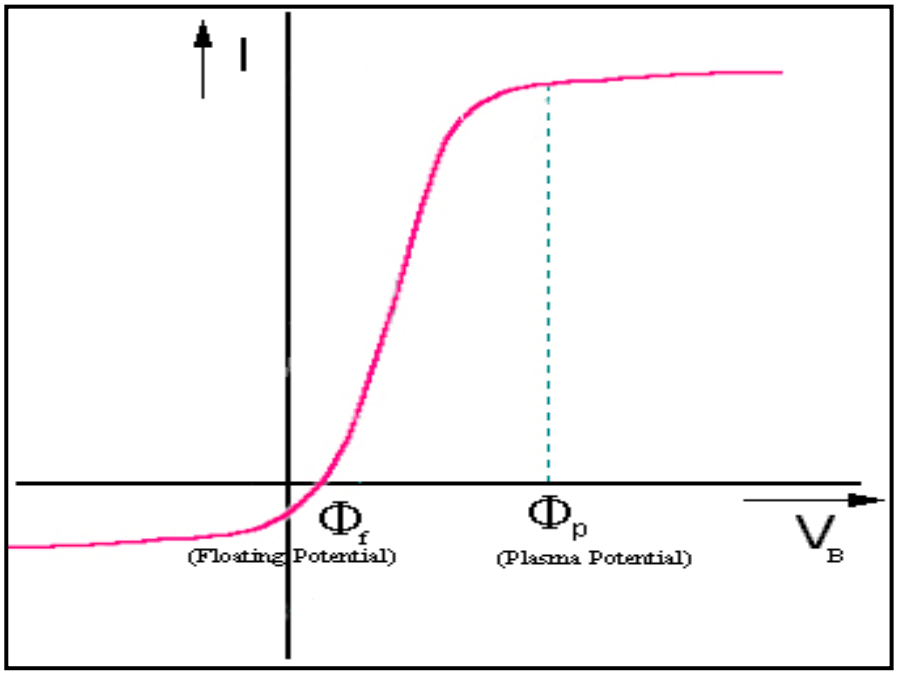
Langmuir Probes

- In electron retardation region:

$$T_e = \frac{e(I - I_{si})}{dI/dV}$$

- Ion saturation current:

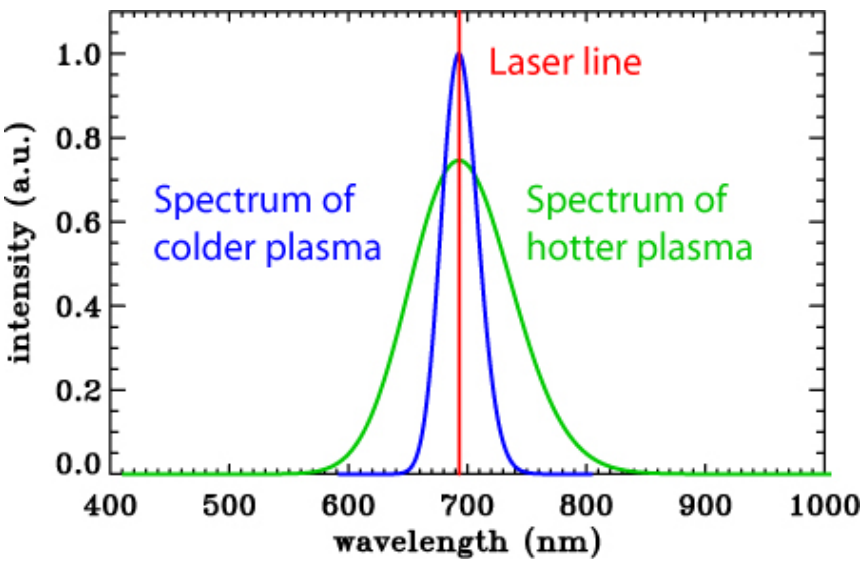
$$J_i = e^{-1/2} A_p n_e \sqrt{\frac{T_e}{m_i}}$$

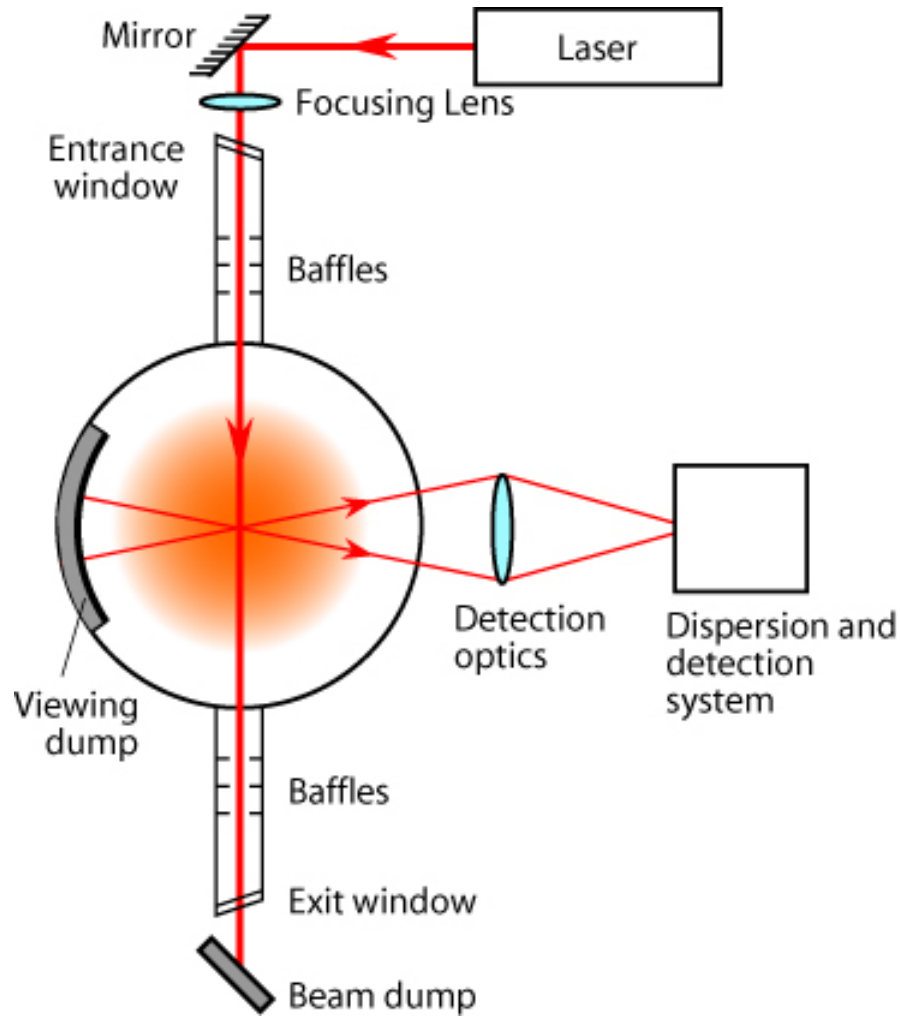


- Can use multiple probe tips with fixed or zero relative bias to eliminate the need for voltage sweeps or knowledge of plasma potential
  - Good for spacecraft (no “ground”) and instantaneous measurements

Thomson Scattering

- High-power laser vibrates electrons, which re-radiate
- Doppler shift turns velocity distribution into spectral distribution
- Width of distribution (spectrum) gives **electron temperature**





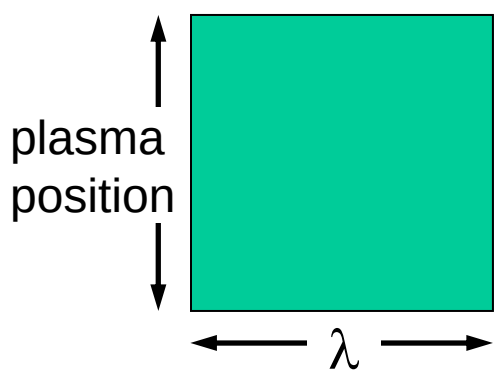
Thomson Scattering Considerations

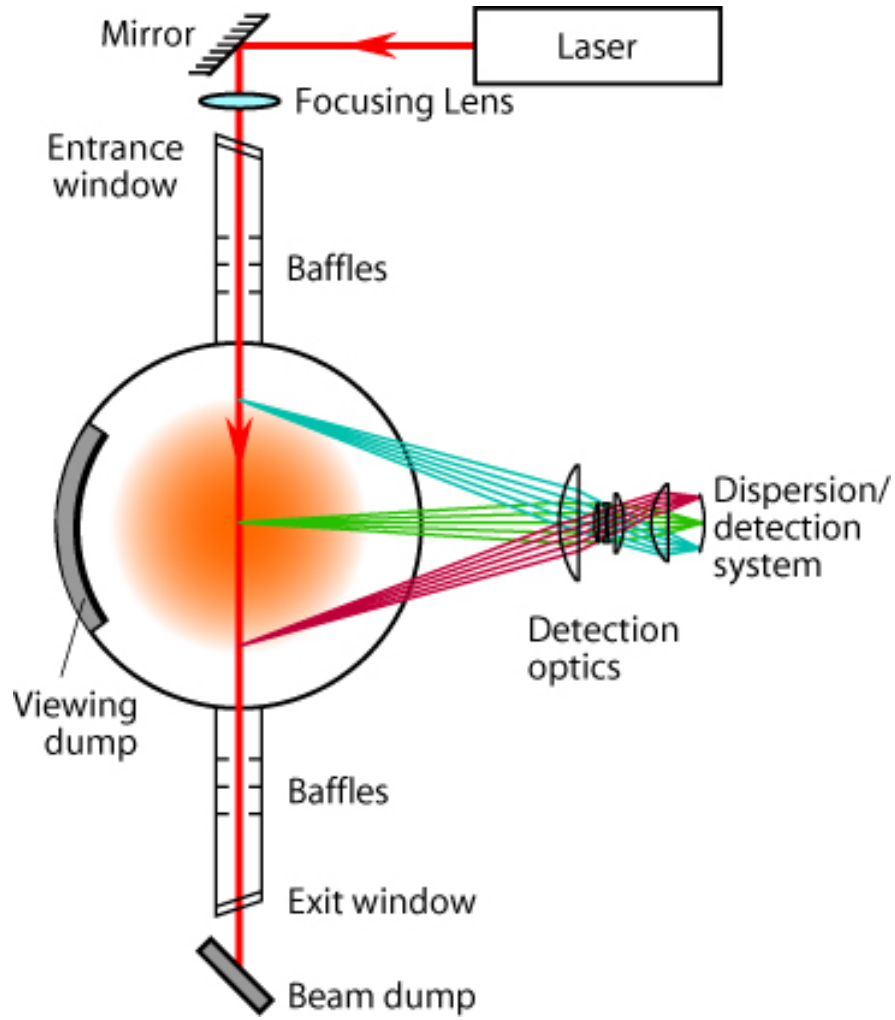
$$P_s = (P_i)(r_{e0}{}^2)(d\Omega)(n_e)(L)$$

8×10^{-30} m^2 0.01 sr 10^{14} m^{-3} 1 cm

$$\frac{P_s}{P_i} \approx 10^{-13}$$

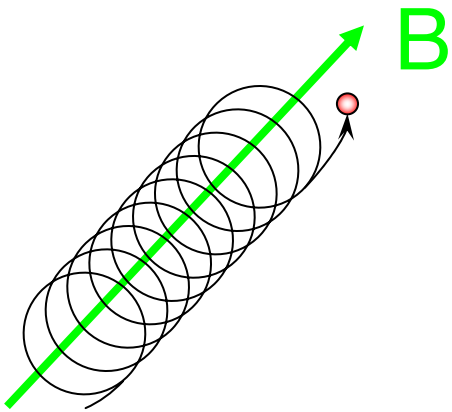
TVTS: Image multiple spectra onto CCD





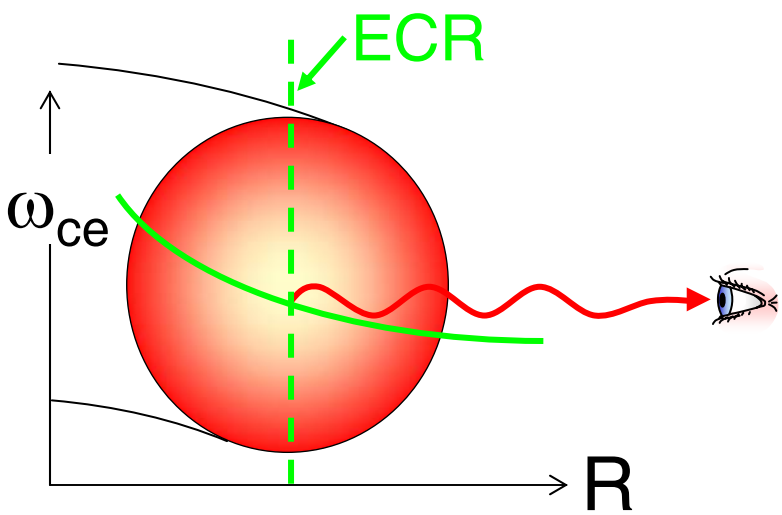
Electron Cyclotron Emission (ECE)

- Lorentz force ($q\mathbf{v}\times\mathbf{B}$) causes a gyration of charged particles



- **Electromagnetic waves are emitted at blackbody levels** from the electron cyclotron resonance layer (ECR)

- $\omega_{ce} \propto B \propto 1/R$



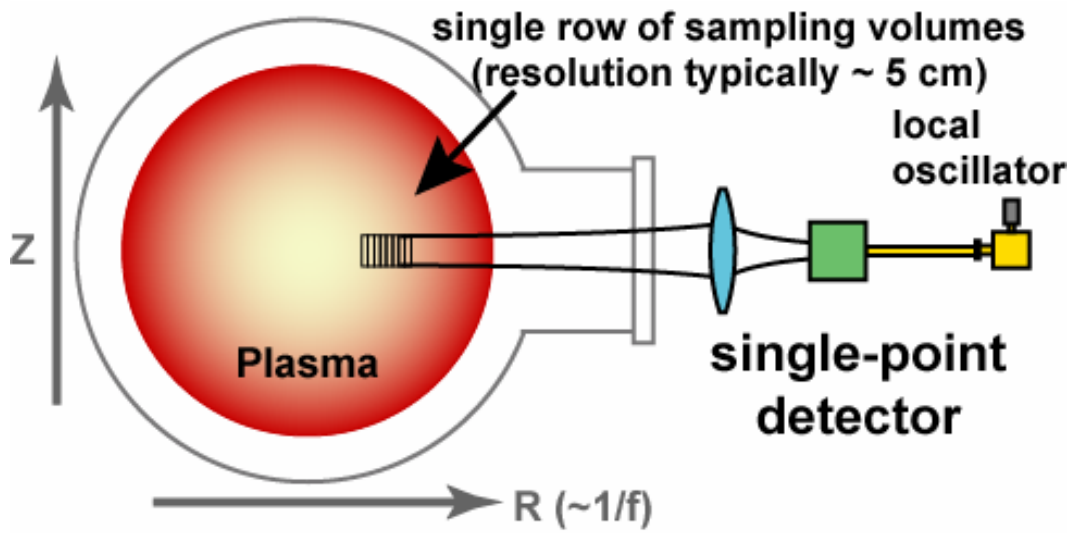
- Frequency range

  50 ~ 500 GHz

Electron Cyclotron Emission Imaging (ECEI)

ECE (conventional)

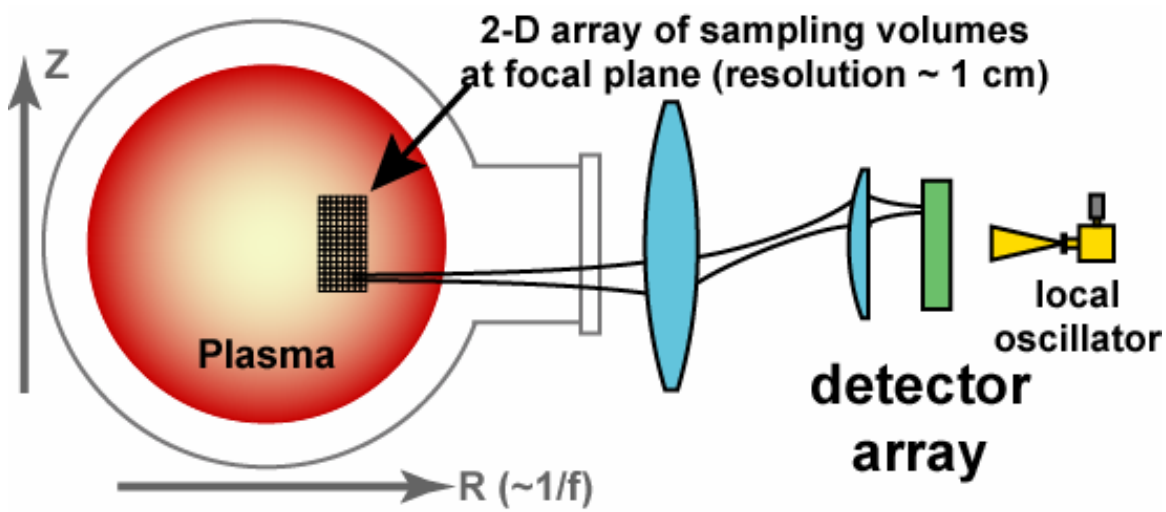
Radial localization from frequency



ECE Imaging

Radial localization from frequency

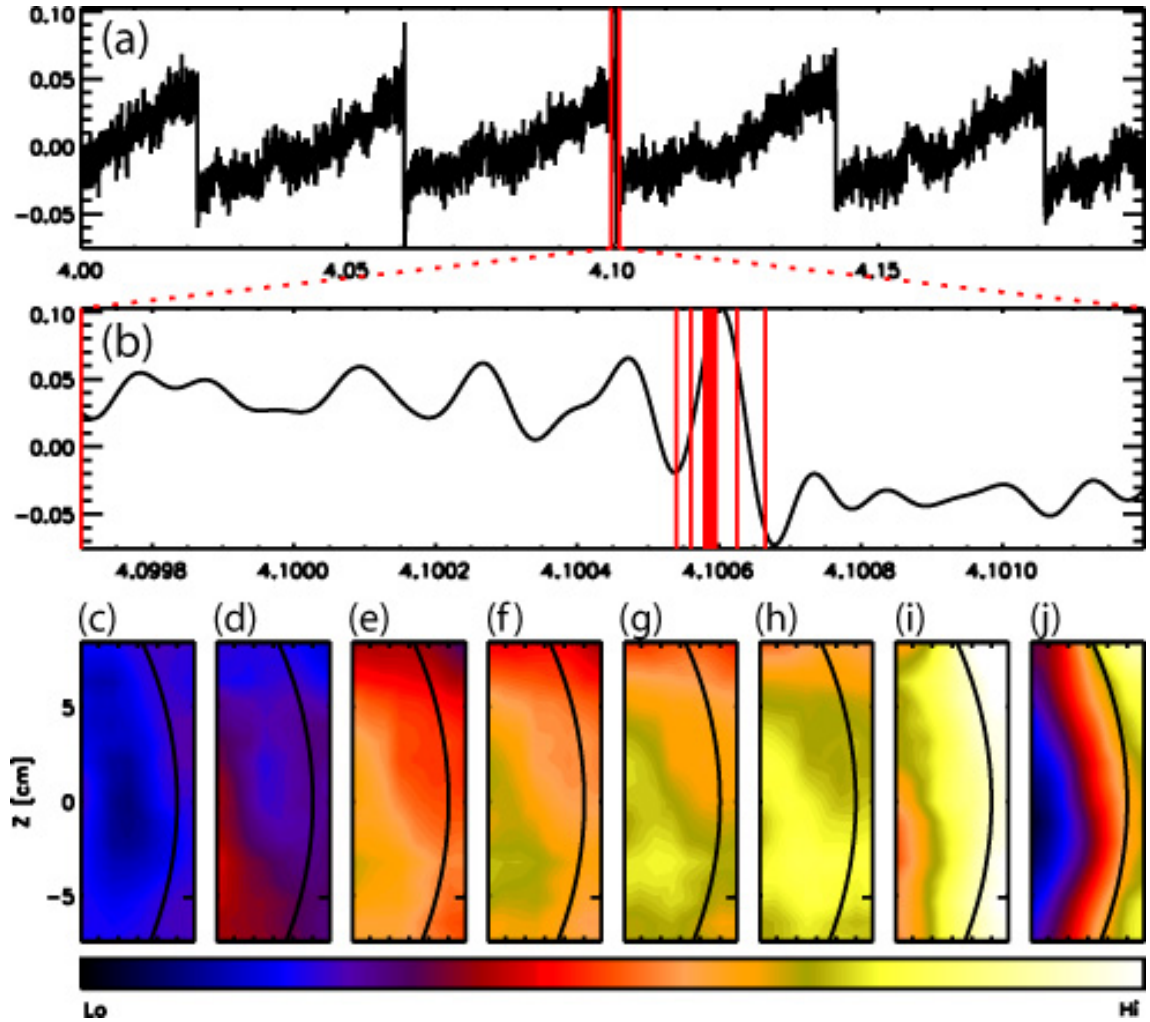
Vertical localization from optics



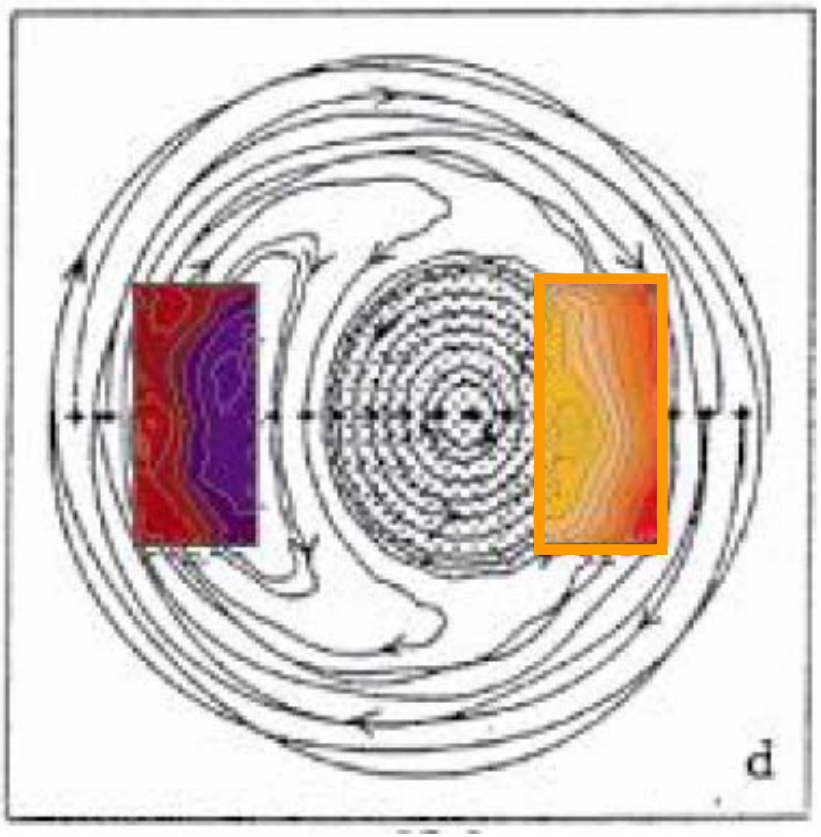
Sawtooth Studies with ECEI

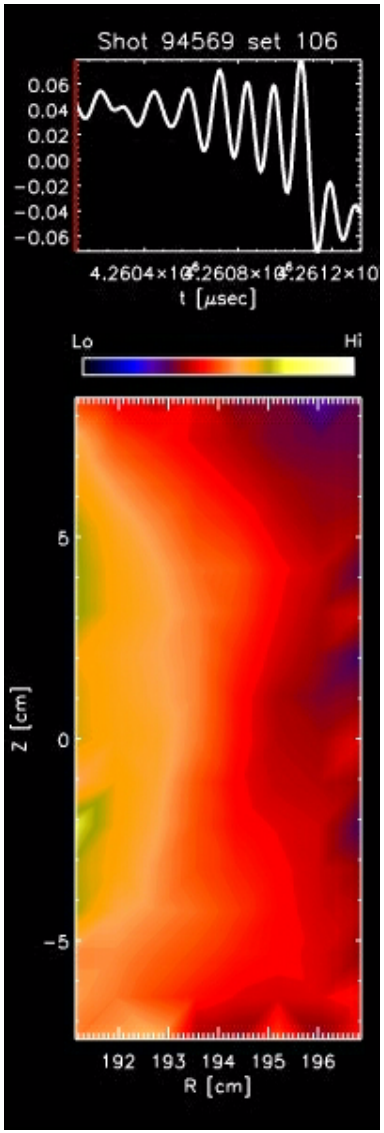
Single-channel ECE sawtooth signal:

2-D (8x16 channels) ECEI images:



Sawtooth Studies with ECEI





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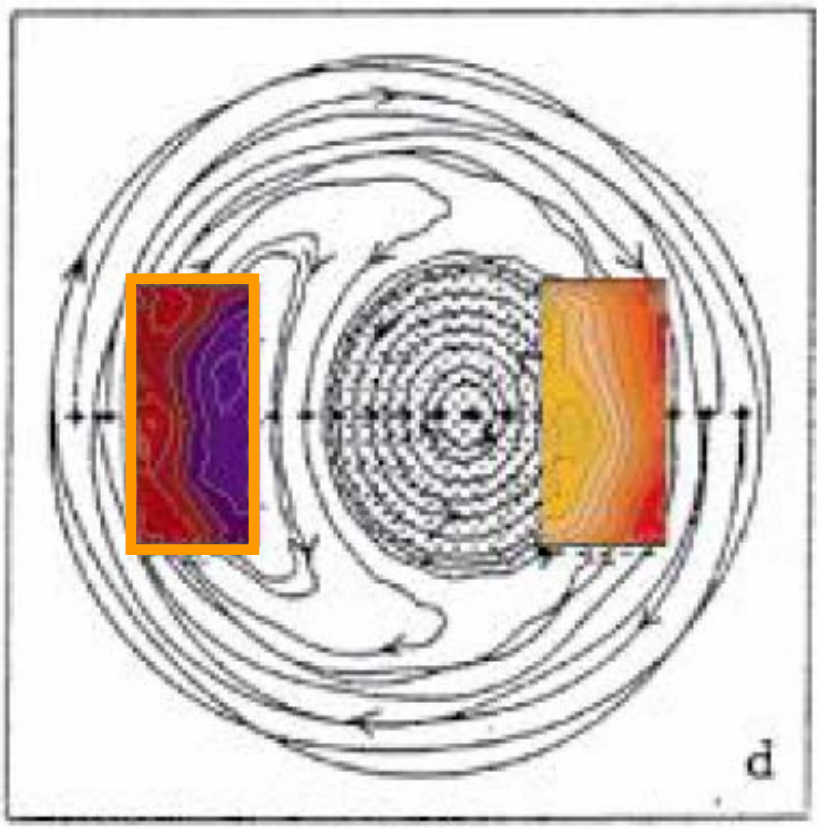
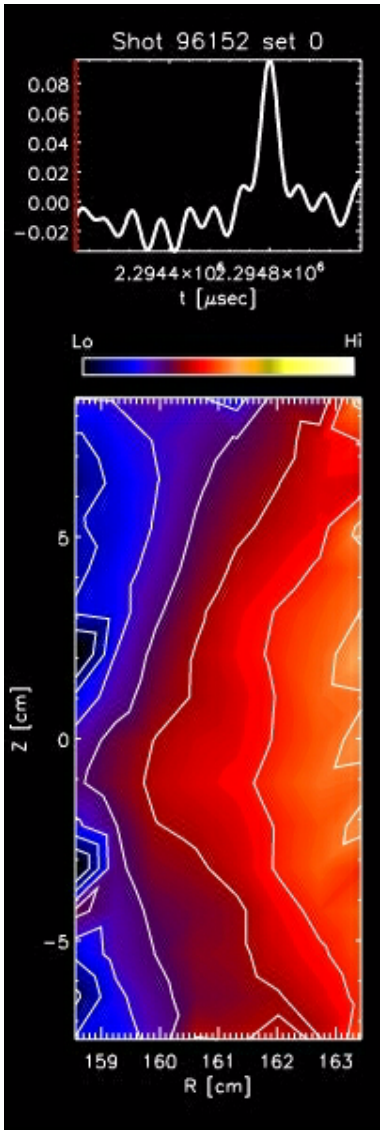
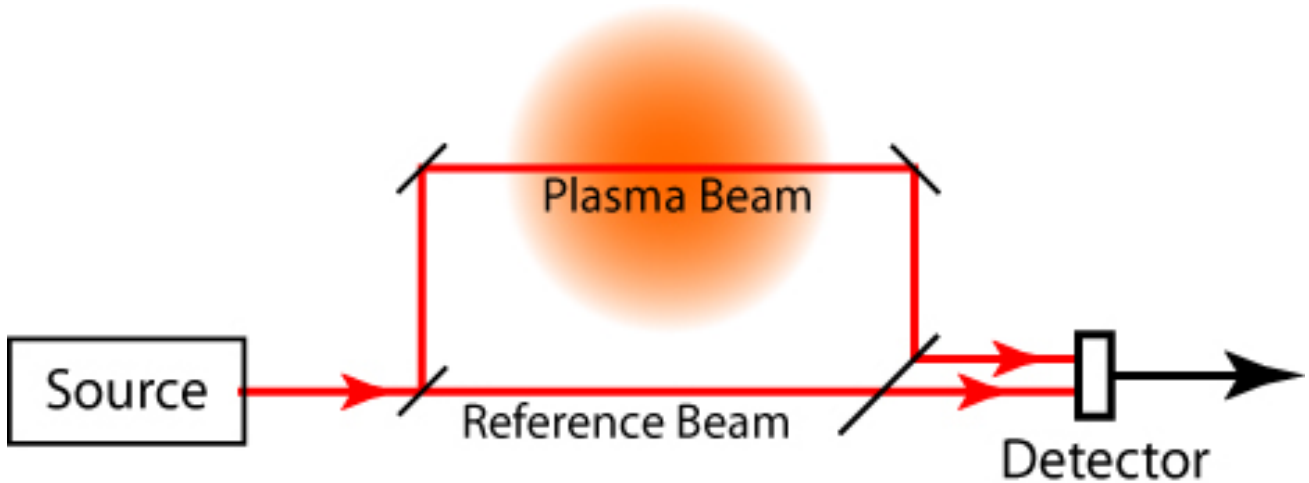




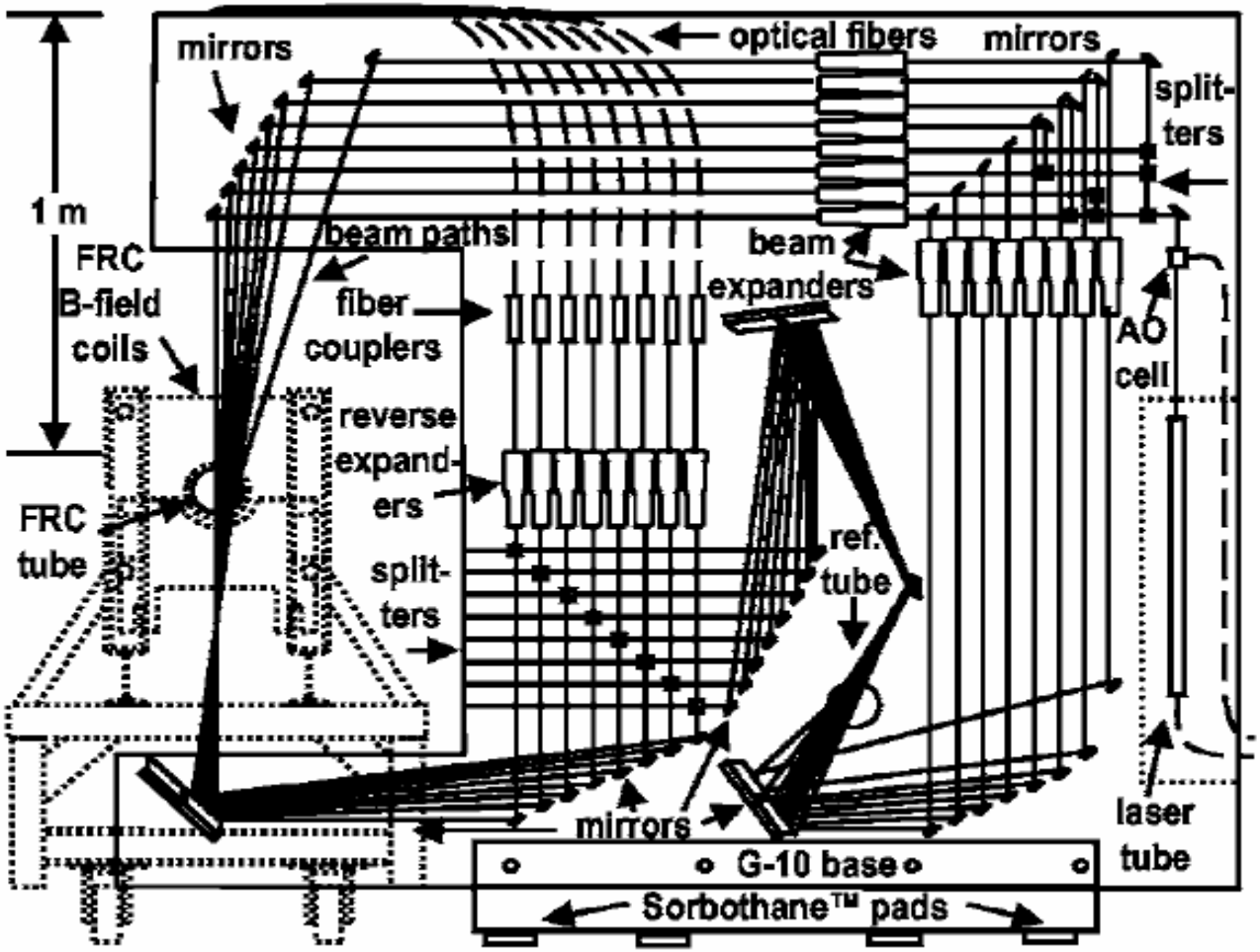
Interferometry

$$\Delta\phi = \frac{\omega}{c}\int\left[\sqrt{1-\frac{n_e e^2}{\varepsilon_o m_e \omega^2}}-1\right]dl \longrightarrow \boxed{\Delta\phi \approx \frac{e^2}{2c\varepsilon_o m_e \omega}\int n_e dl}$$

- Phase change gives **electron density** measurement
- Typical sources are mm-wave or infrared lasers



Interferometry

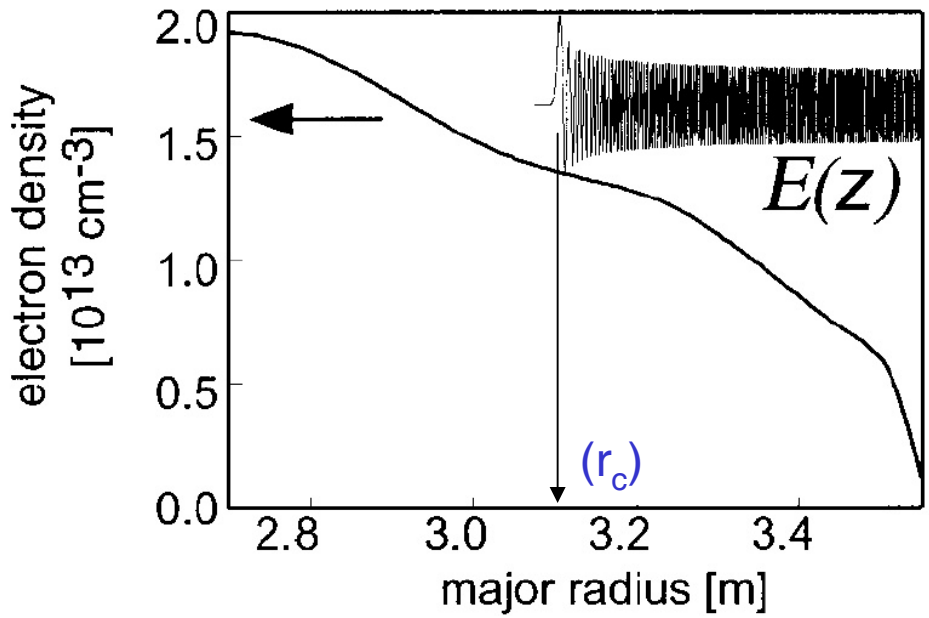


FRX-L Multichord Interferometer

Ruden RSI 2006

Microwave Reflectometry

- Probing wave is reflected at the cut-off layer
- Reflected waves contain information of the shape of the density cut-off layer.

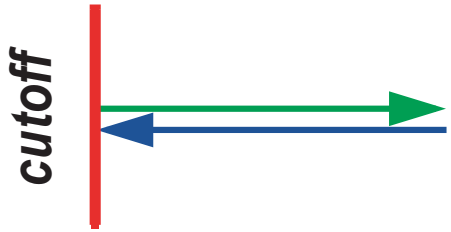


$$\omega^2 = \omega_p^{\ 2} + c^2 k^2$$

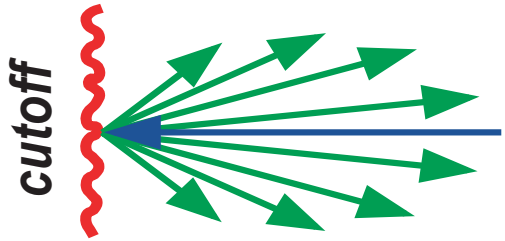
$$\omega_p^{\ 2} = \frac{n_e e^2}{\varepsilon_0 m_e}$$

⇒ reflectometry is extremely sensitive to density fluctuations!

Microwave *Imaging* Reflectometry

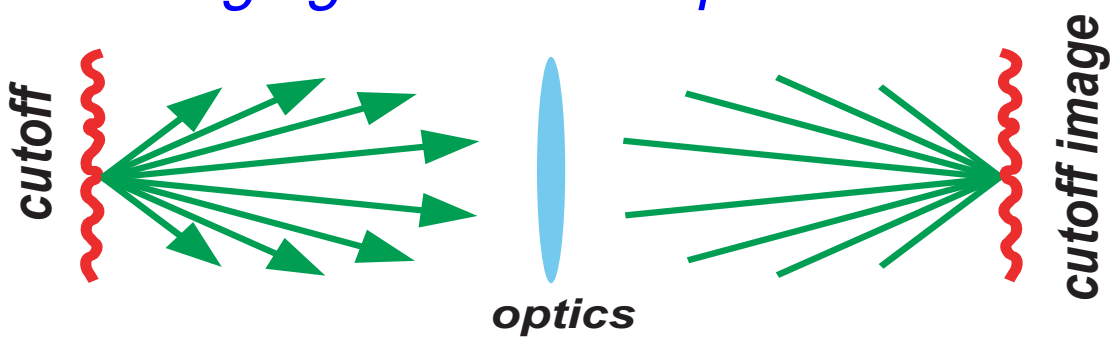


1-D fluctuations: straightforward interpretation



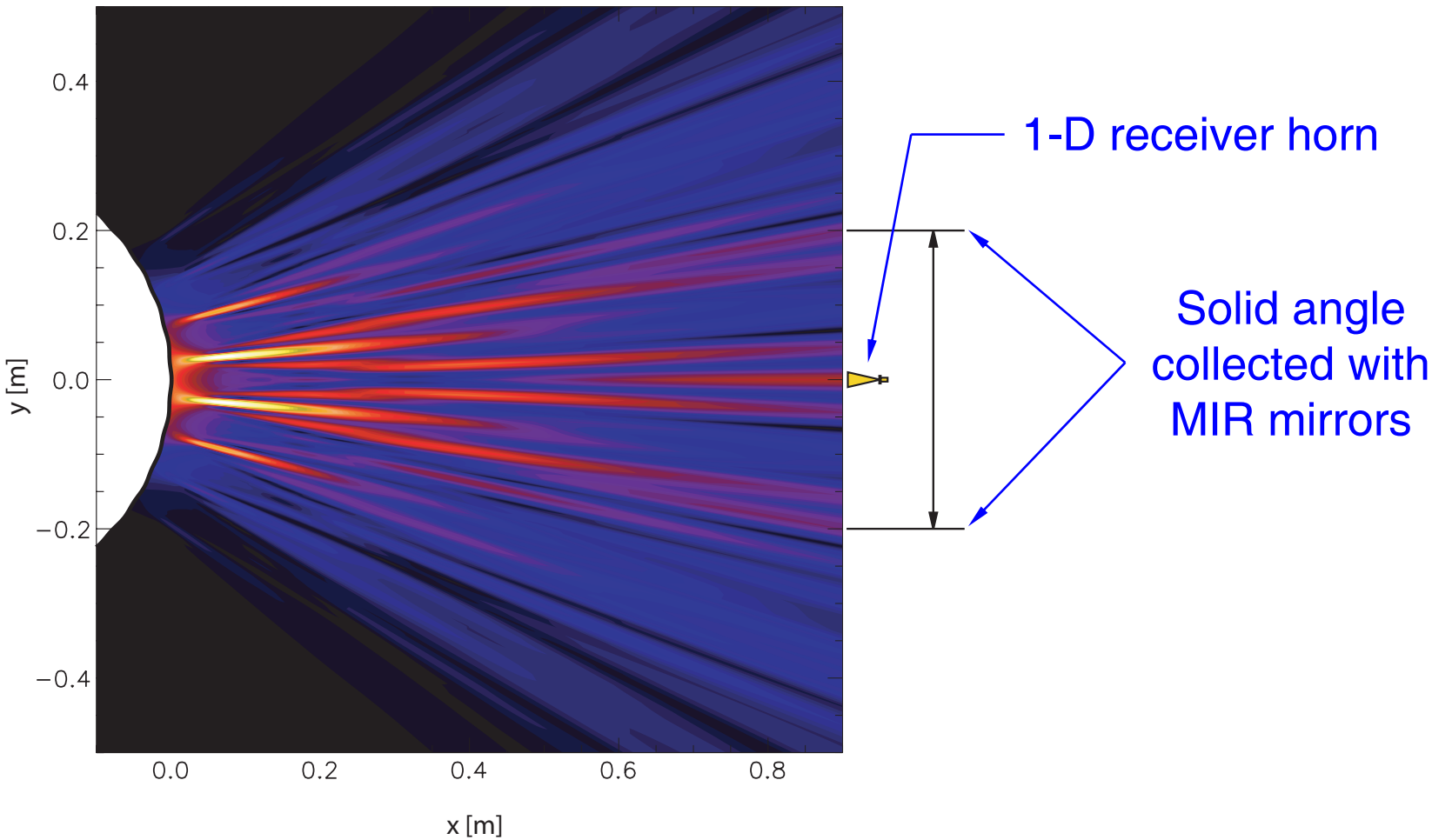
2-D fluctuations can lead to interference

Imaging can restore phase front

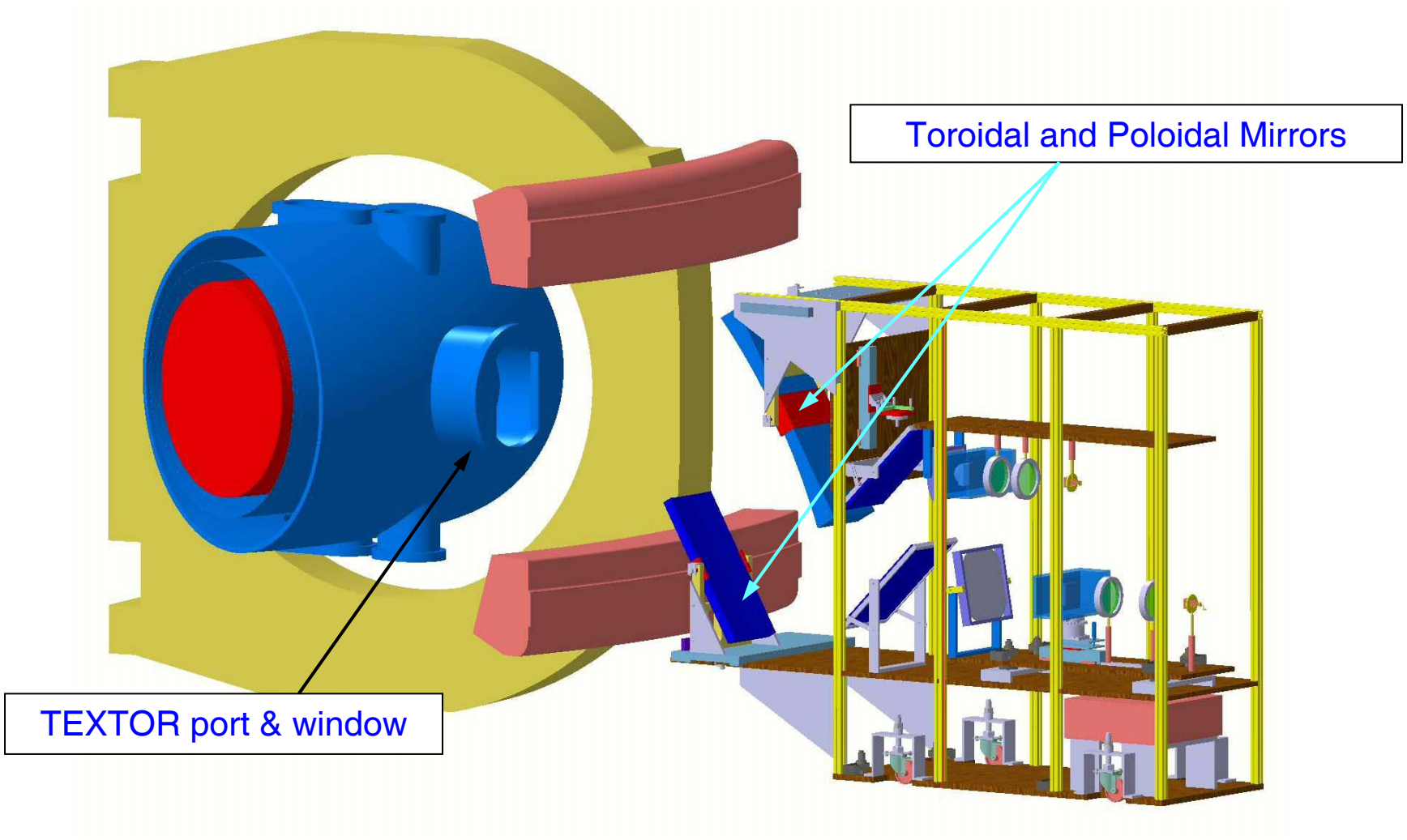


Analytic Solution of Reflected Field

$k_\theta = 1.25\ cm^{-1}$, $\delta\phi = 1.8\pi$

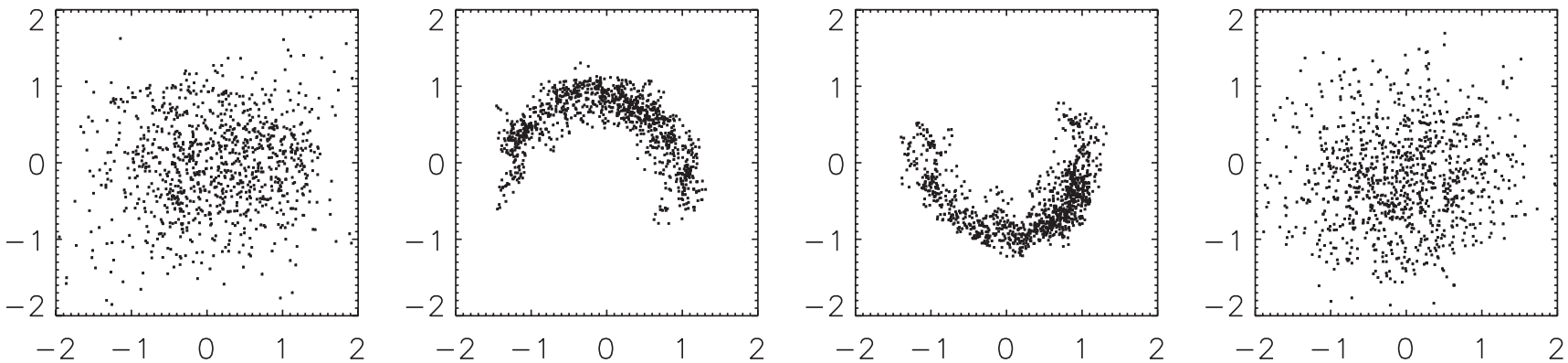


Combined MIR/ECEI System for TEXTOR

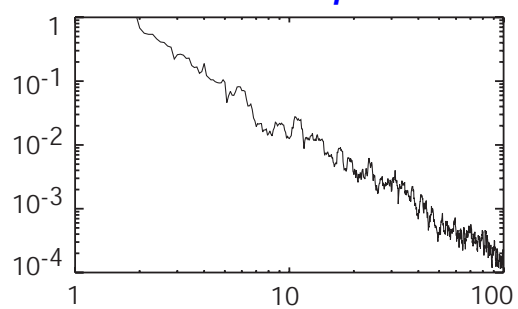


MIR Results from TEXTOR

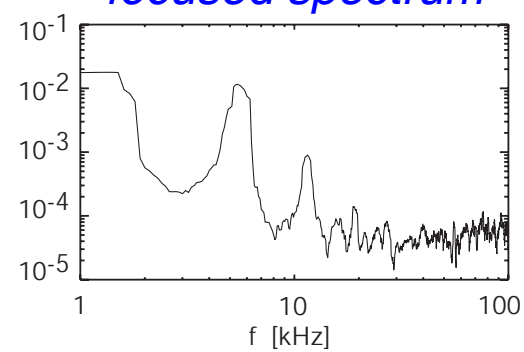
TEXTOR quadrature signals into focus back out of focus



unfocused spectrum

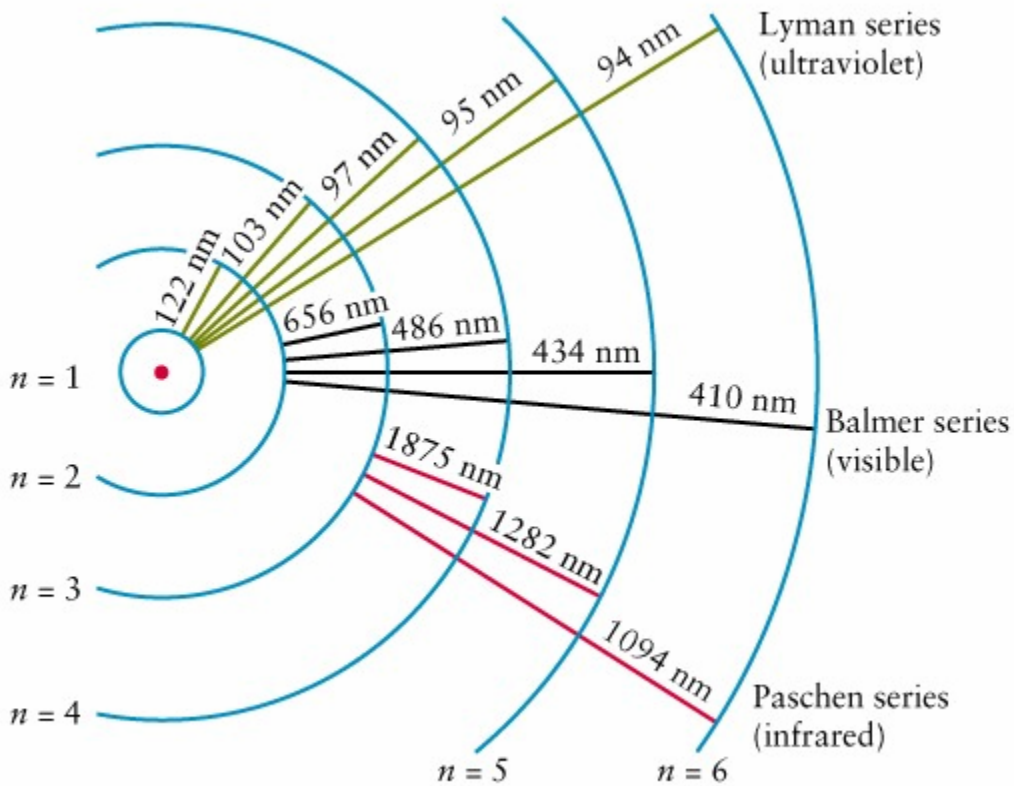


focused spectrum



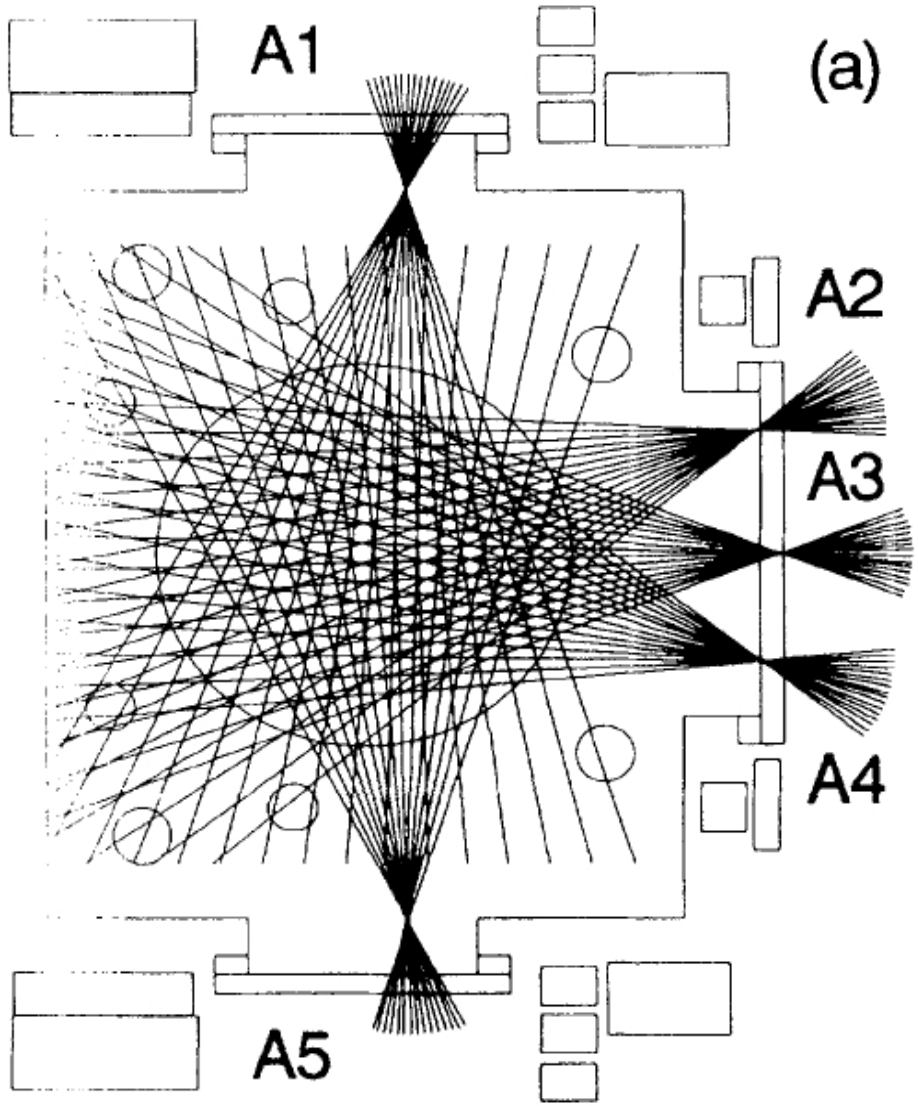
Plasma Spectroscopy

- Bremsstrahlung
  - acceleration from free electrons near ions
- Line emission
  - radiative energy-level transitions
  - visible to x-ray energies
  - working species and impurities
  - Intensity = $f(n_i, n_e, T_e)$
  - Doppler shift and width give $\mathbf{T_i}$ and $\mathbf{v_i}$



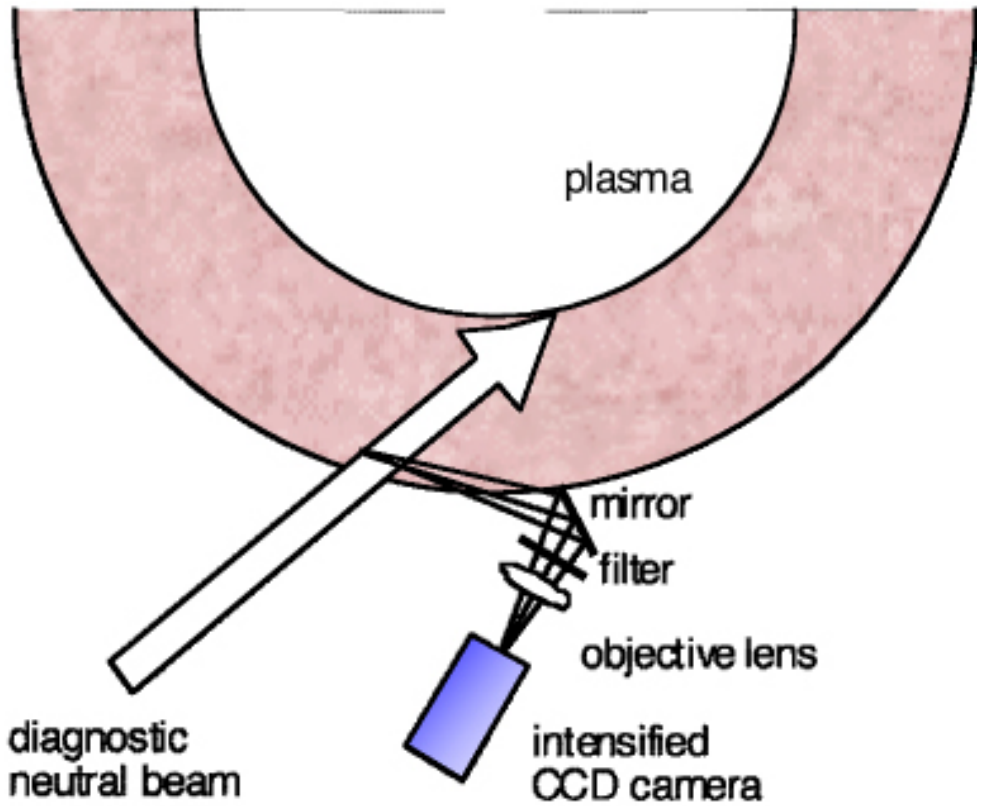
Soft X-Ray Arrays

- Often look at impurity lines (Carbon, Oxygen)
- $\lambda < 1$ nm
- Imprecise measure of T_e, n_e, and n_i from intensity
- Plasma is *optically thin* to this wavelength, so measurement is chord-integrated
- Tomographic reconstruction: high spatial resolution
- Fast detectors: high time resolution



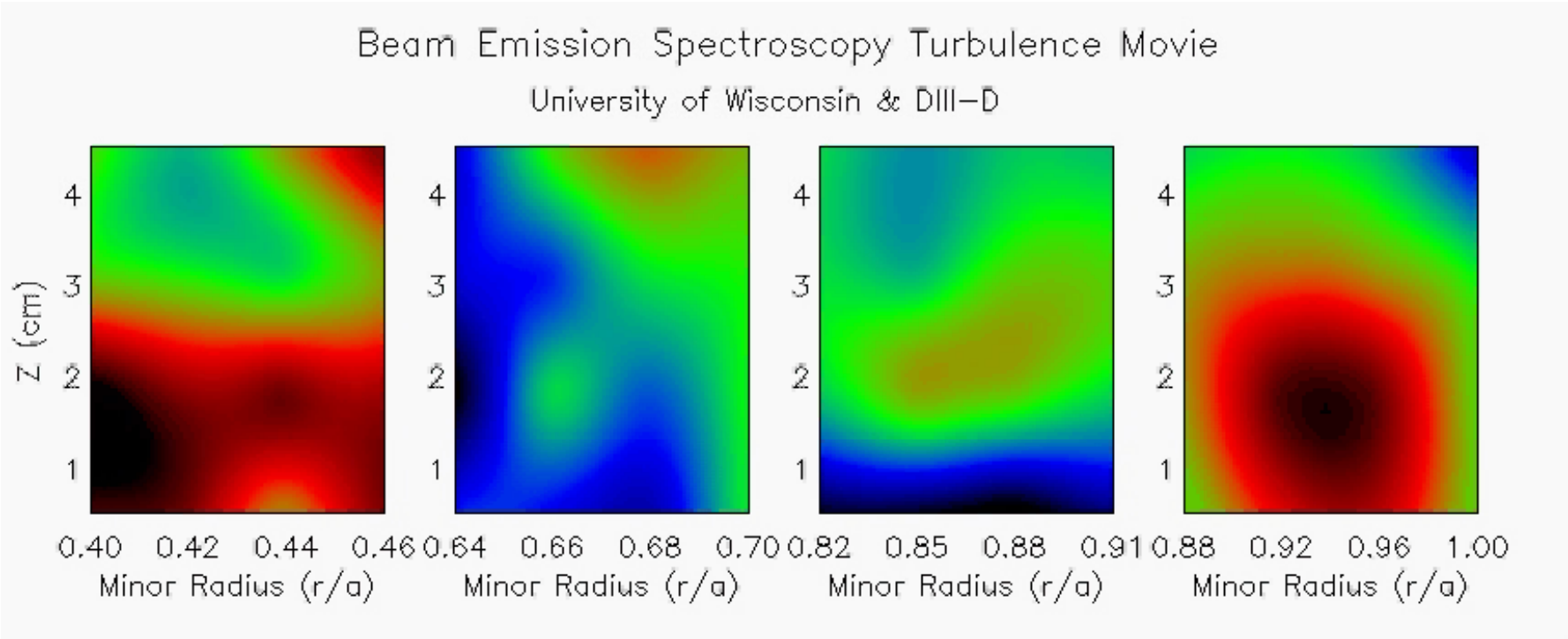
CHERS (or CXRS)

- Charge-Exchange Recombination Spectroscopy
- Neutral atoms CX with plasma ions
- Newly-neutral atoms moving at plasma thermal speeds
- Bound-electron spectroscopy gives **ion velocity distribution** (through Doppler shift and Doppler broadening)
- $\mathbf{T_i}$ and $\mathbf{v_i}$ (along sightline)



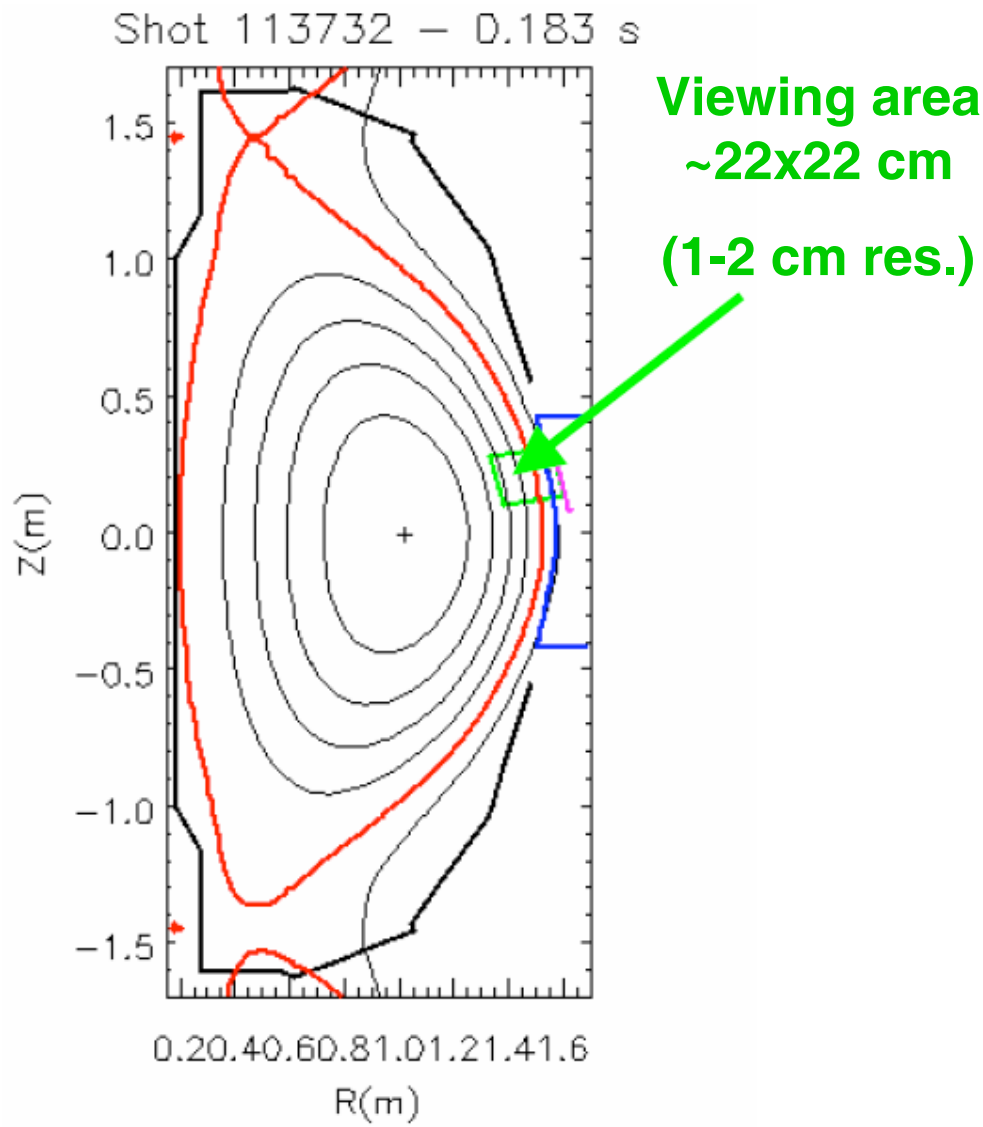
Electron Density Fluctuations with B.E.S.

- Beam Emission Spectroscopy: beam atoms *themselves* radiate…
- Absolute signal level proportional to local electron density
- Array of detectors : high-resolution map
- High time-resolution

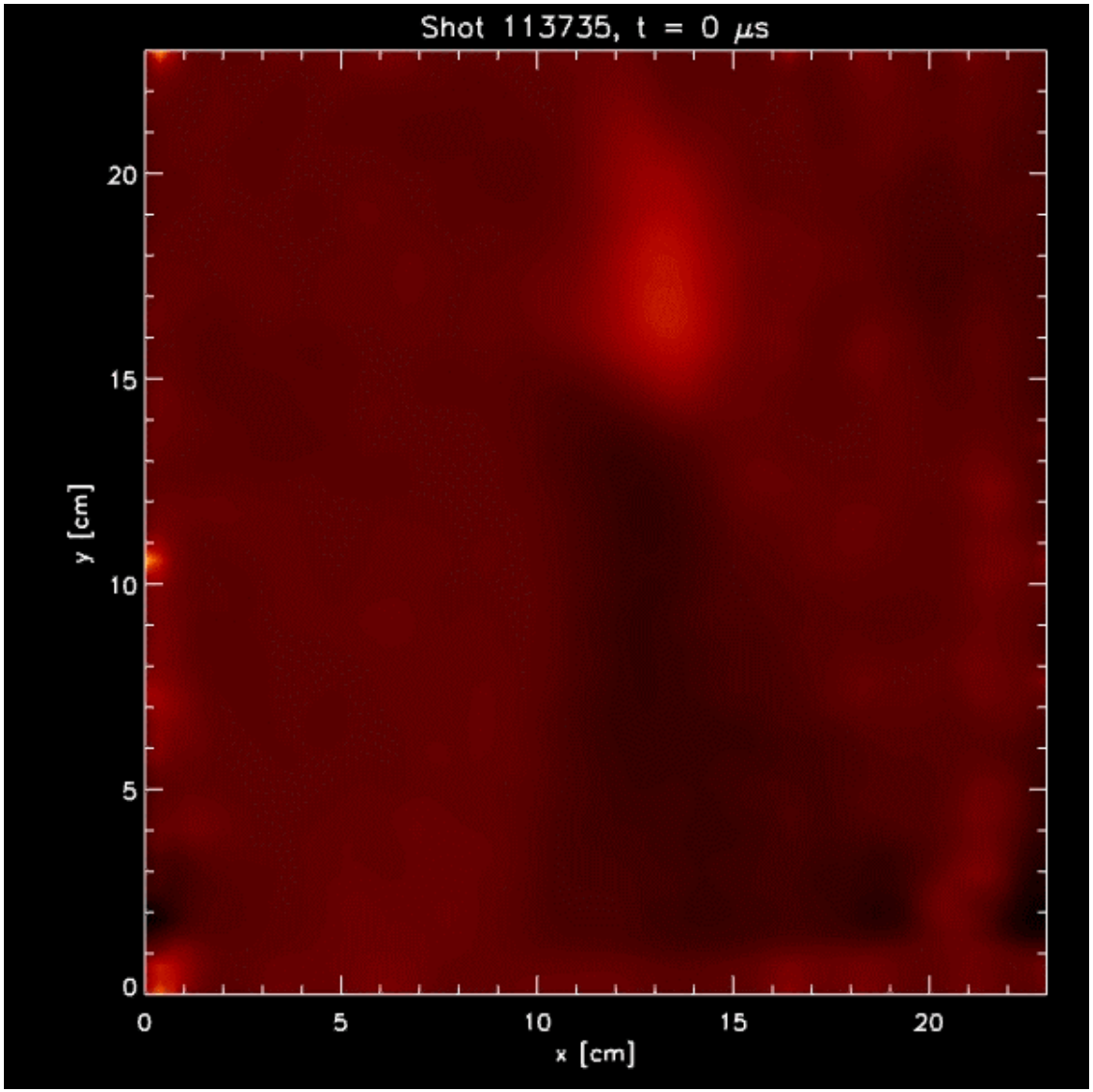


Electron Density Fluctuations with G.P.I.

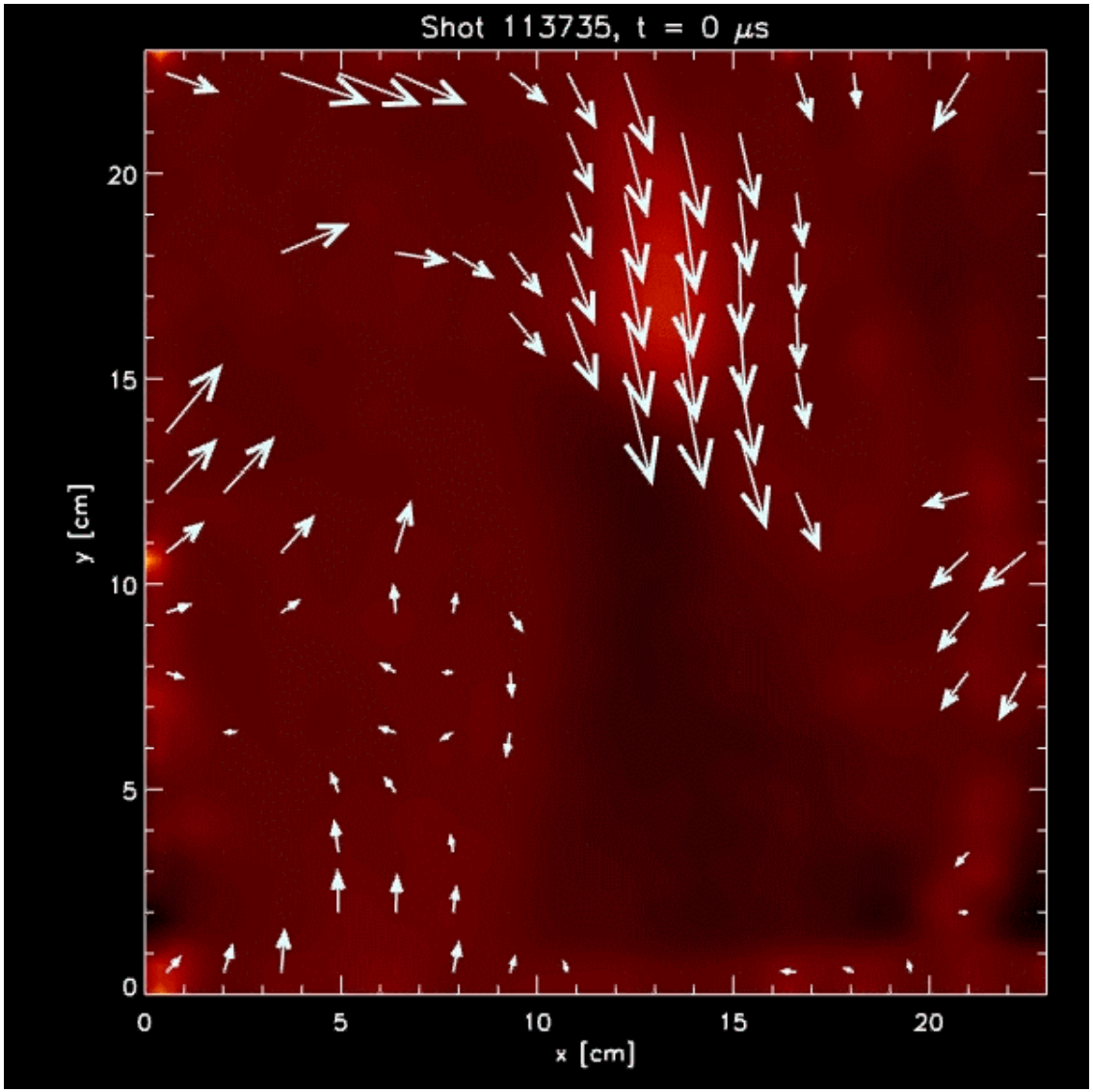
- Gas Puff Imaging
- D2 or He puffed into NSTX edge in sheet
- $I \propto n_n\, n_e\, f(n_e, T_e)$
- View ~ along B observes poloidal plane of line emission
- Images recorded by fast (250,000 frames/sec) camera



Time-resolved movies

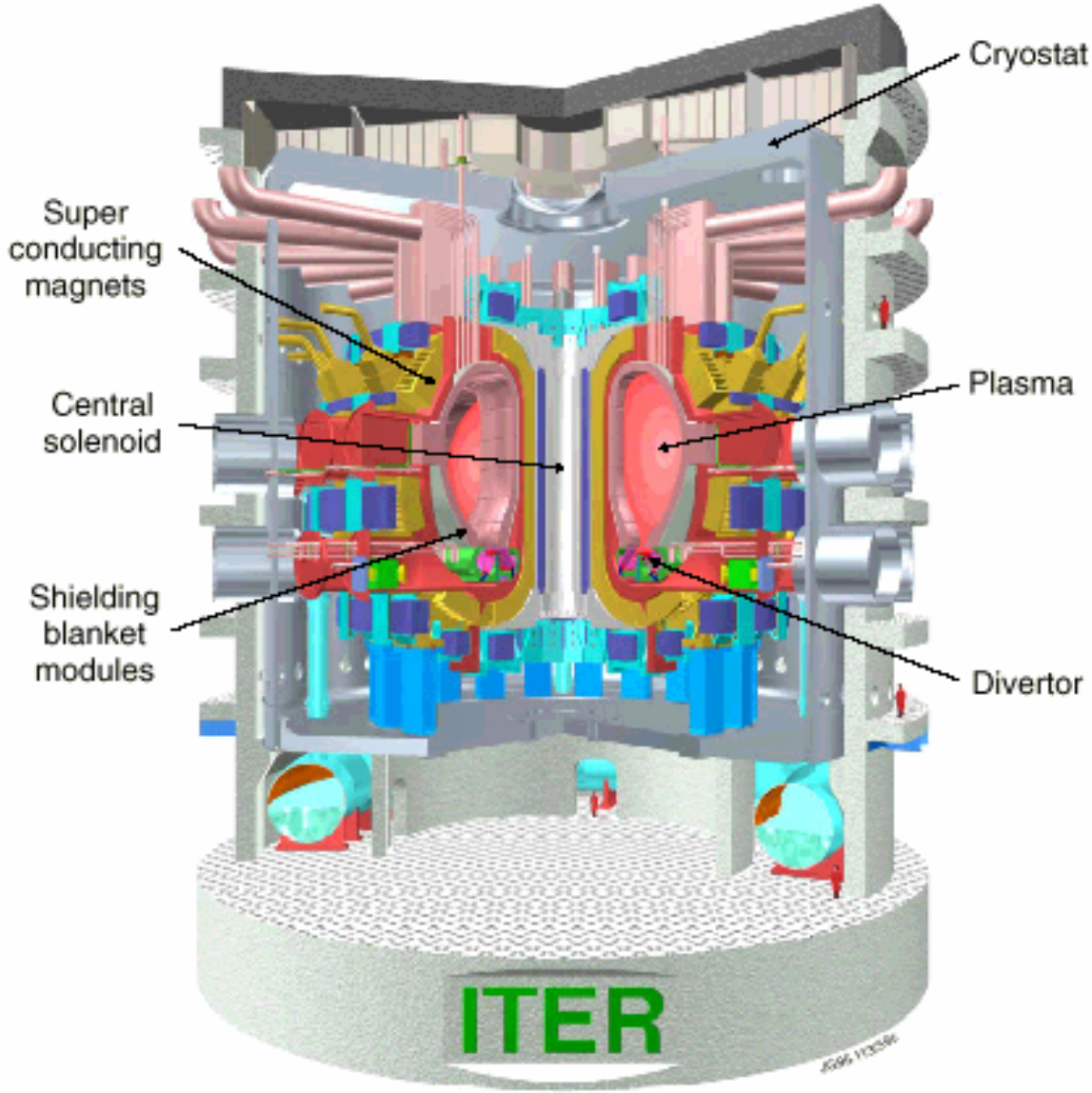


Dynamic v-field analysis

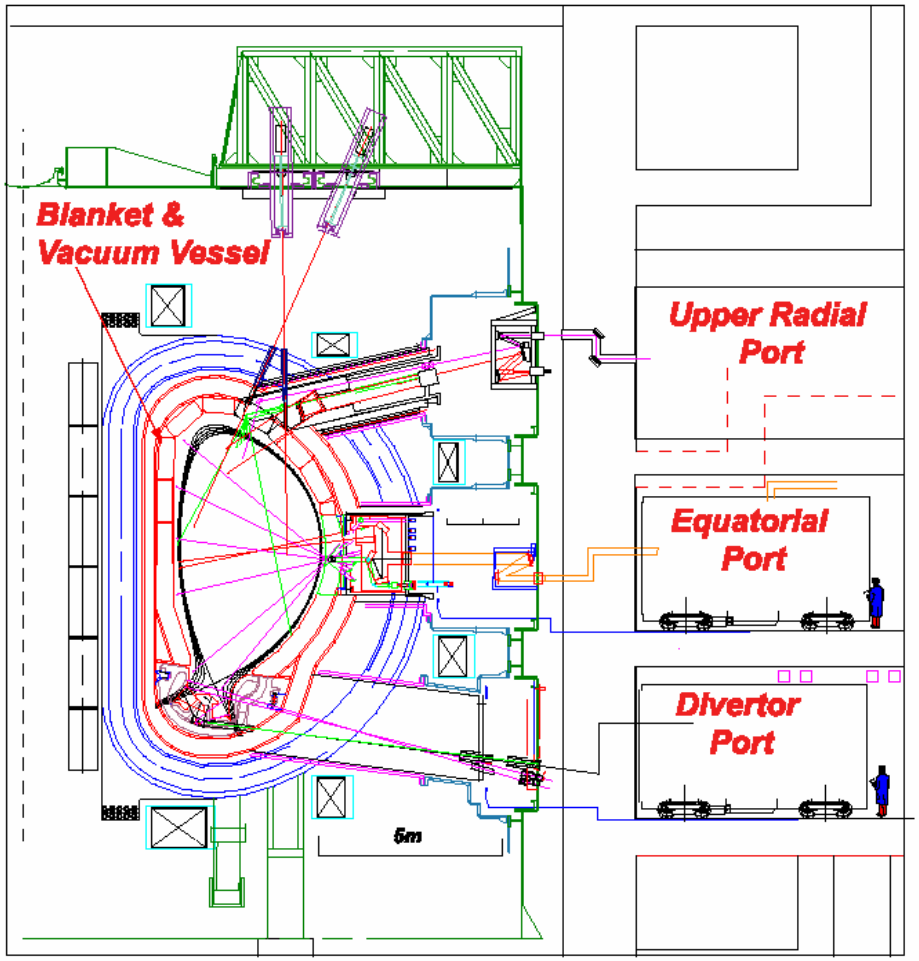


ITER Diagnostics Considerations

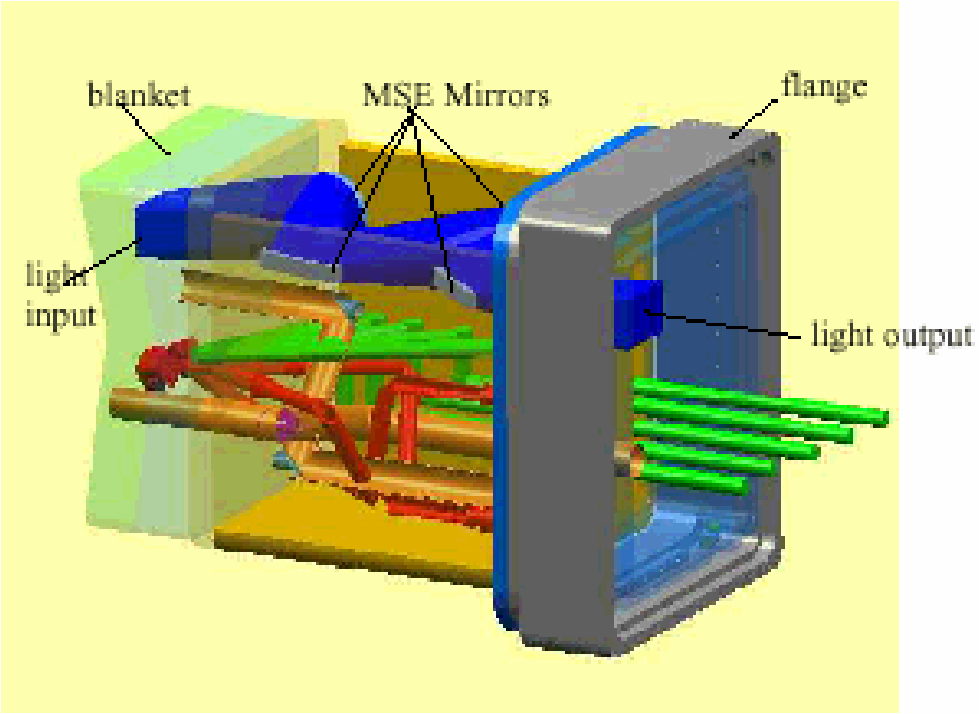
- ITER design well underway
- Projected to achieve Q>5
- Need multiple systems working in concert for profile controls
- Radiation hardness critical
- Remote handling required!



Cartridge system for cryostat / blanket penetration

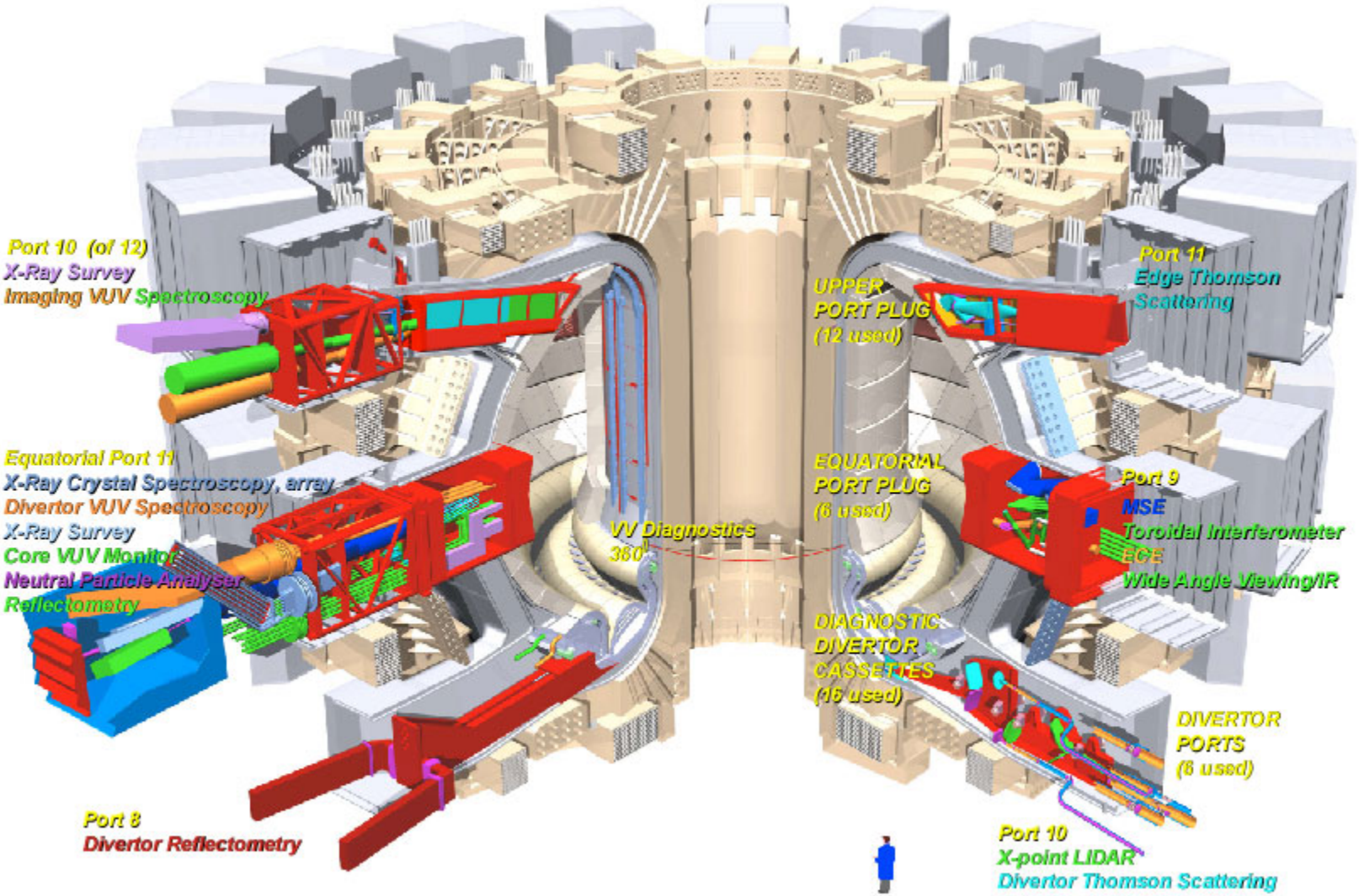


Example: MSE optical diagnostic



Radiation effects on diagnostics

Effect	Of concern …
Radiation-induced conductivity (RIC)	When using insulators
Radiation-induced electrical degradation (RIED)	When using insulators held at electric field
Radiation-induced electromotive force (RIEMF)	For any small voltage or current
Radiation-induced thermoelectric sensitivity (RITES)	
Radiation-induced absorption	For optical transmission
Deposition	For any first mirror or any thin metal window close to the plasma
Erosion of any first mirror	
Radioluminescence	For fibers and windows
Nuclear heating	For most front end components with complex consequences
Change in other properties due to transmutation and swelling	

Vayakis

ITER Diagnostics Layout