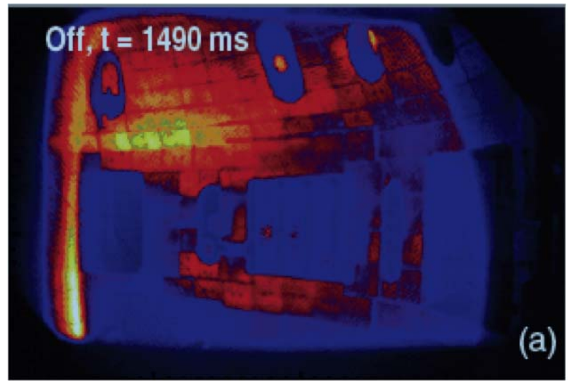
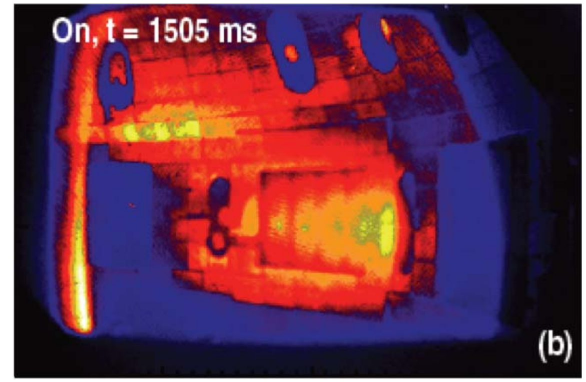
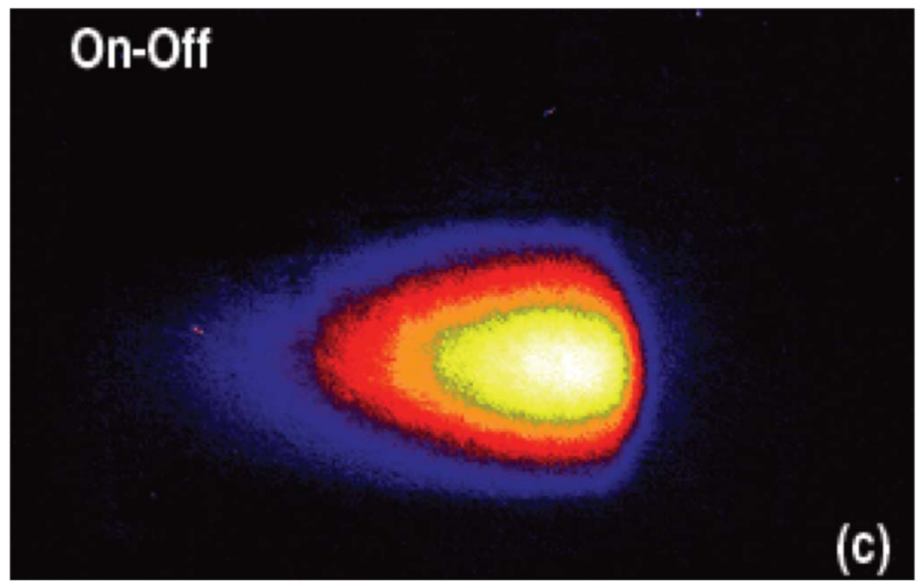
Beams, Brightness and Background — Using Active Spectroscopy Techniques for Precision Measurements in Fusion Plasma Research

By
D.M. Thomas
General Atomics





Presented at the
53rd Annual Meeting of the
APS Division of Plasma Physics
Salt Lake City, Utah



November 14-18, 2011

Prologue

- **Improvements in the performance of magnetically confined plasmas have been made via careful sculpting of the pressure, current, and radial electric field profiles**
  - Relies on detailed internal measurements of plasma parameters

- **Beam-based emission diagnostics can give us an immense amount of information about the internal structure of plasmas.**
  - Relies on injected neutral beams for collision partner
  - Depends on relevant atomic physics (well-known for most part)
  - Requires well-defined geometry, well-designed detection and analysis techniques

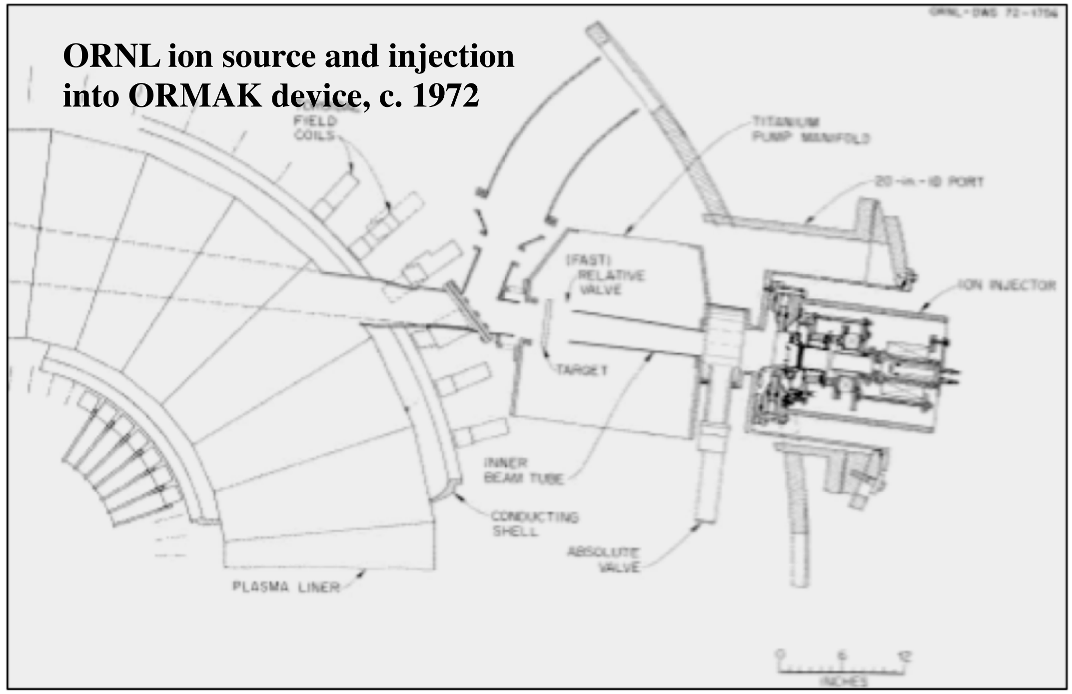
- **This tutorial will cover how we make these measurements**

Outline

- **What is active spectroscopy, and what it can do**
- **How do we do these measurements?**
  - Charge exchange spectroscopy
  - Beam emission spectroscopy
- **The use of non (H,D) beams in active spectroscopy**
- **Future developments for active spectroscopy**

Neutral Beam Injection was Recognized Early on as a Powerful Way to Heat and Fuel Magnetically Confined Plasmas

- **Required technology was developed & deployed in the early 1970s**
  - Plasma source, ion extraction and acceleration, gas cell neutralization. Extensive development since then



ORNL ion source and injection into ORMAK device, c. 1972

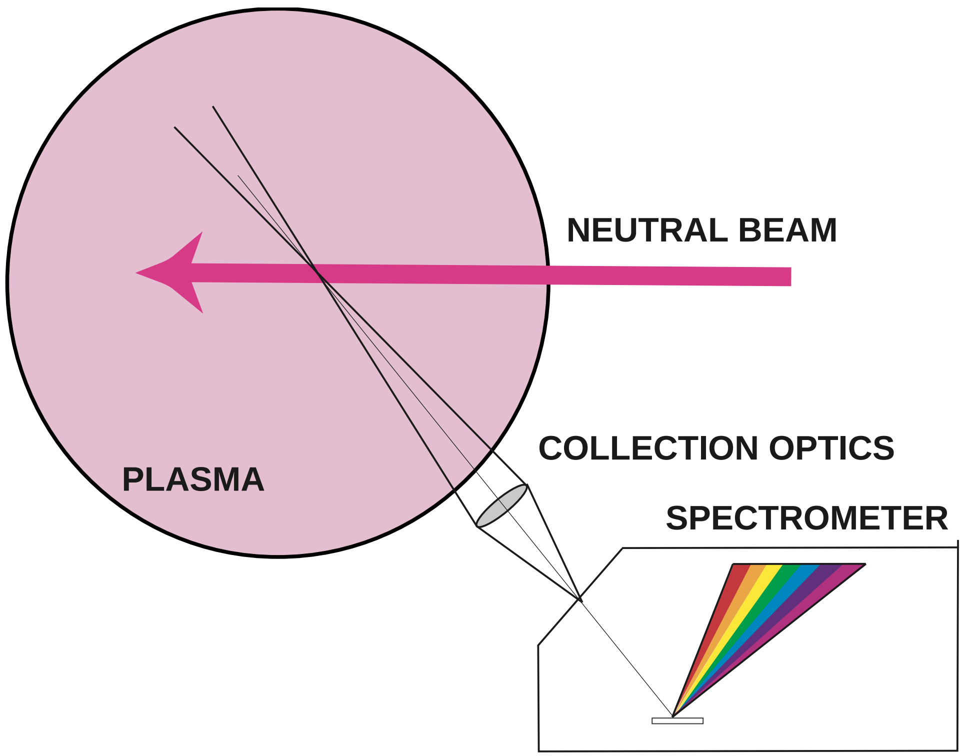
- **Neutrals can cross magnetic field lines and deposit their energy and momentum deep within the plasma.**

  Also their electrons…

- **Physicists were quick to exploit the diagnostic possibilities**

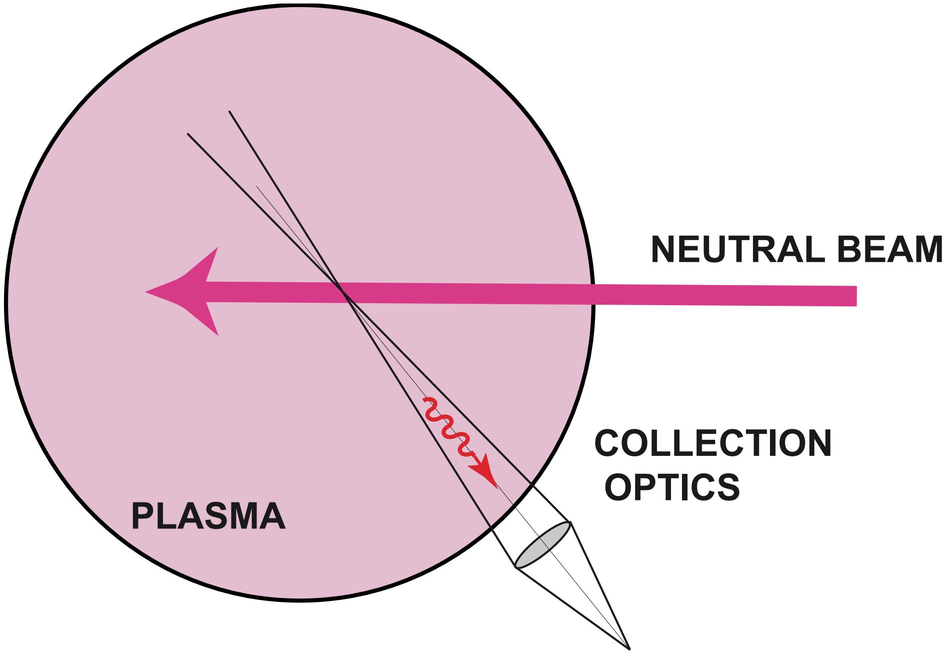
Active Spectroscopy Takes Advantage of the Emission from Beam-Plasma Interaction

- **Image beam with collection optics, analyze light**
- **Cross-beam view localizes measurement**
- **The details of beam-plasma physics enable a wide variety of measurements**

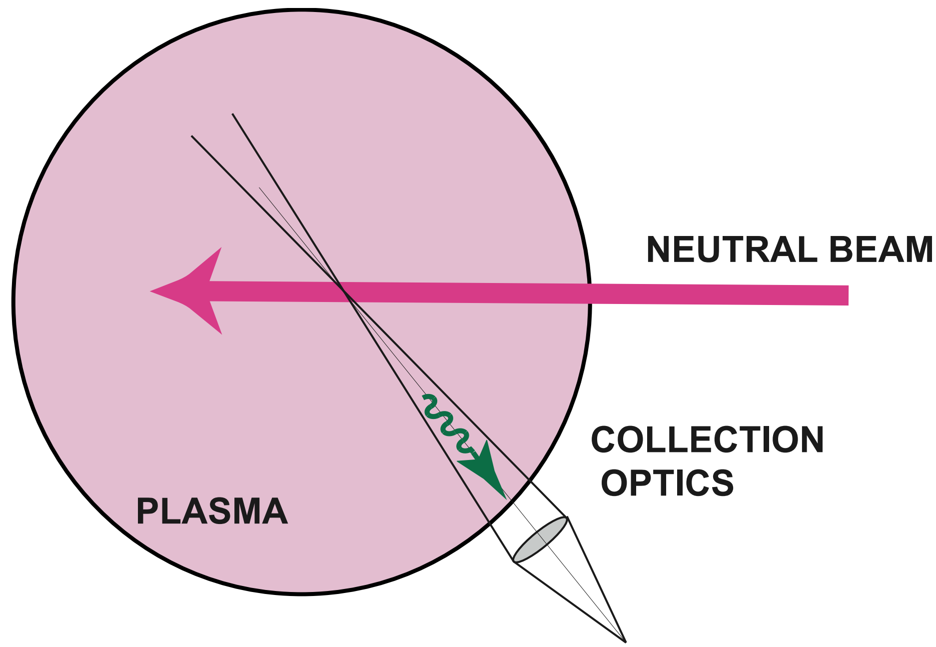


For this Talk I will Restrict the Scope to Techniques Using an Injected Neutral Beam and Collected Photons

- **Inject neutral beam, study fluorescence of excited beam neutrals**



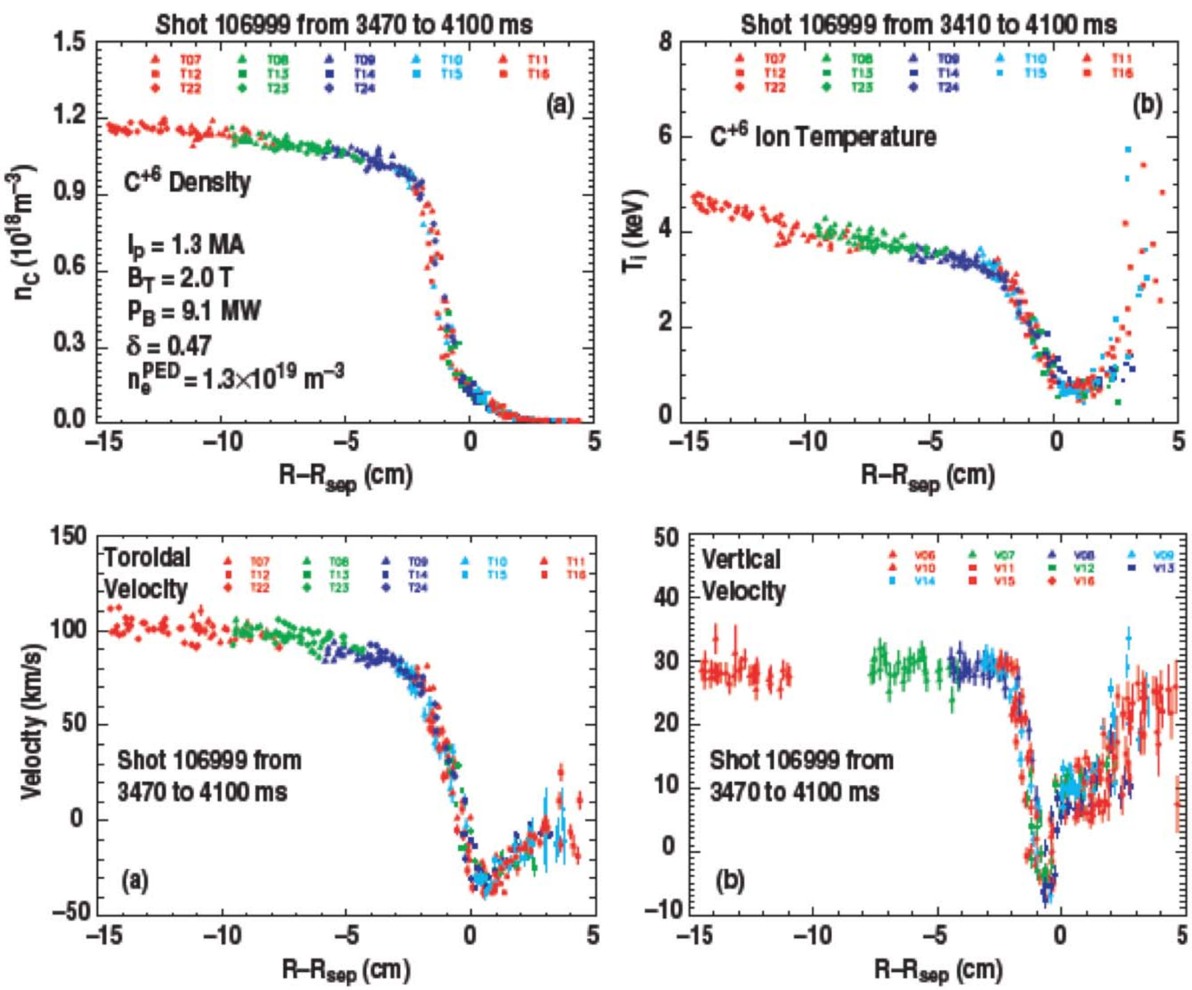
- **Collect light from excited states of recombined ions**



These Reactions can be Used for an Incredible Variety of Plasma Measurements

- **Beam deposition**
- **Ion temperature and rotation profiles**
- **ExB flow shear**
- **Plasma density and fluctuations, effects on turbulent transport**
- **Energetic particle/fast ion transport and confinement behavior**
- **Plasma safety factor profile for different current drive scenarios**
- **Impurity ion densities, helium ash buildup and transport**
- **Structure of H-mode pedestal, including edge current density**
- **Fuel ion ratios**
- **Ability to make these measurement has been a key factor in the development of fusion plasmas**

EXAMPLE: Exquisite Profiles of Edge Temperature and Rotation During QH-mode on DIII-D

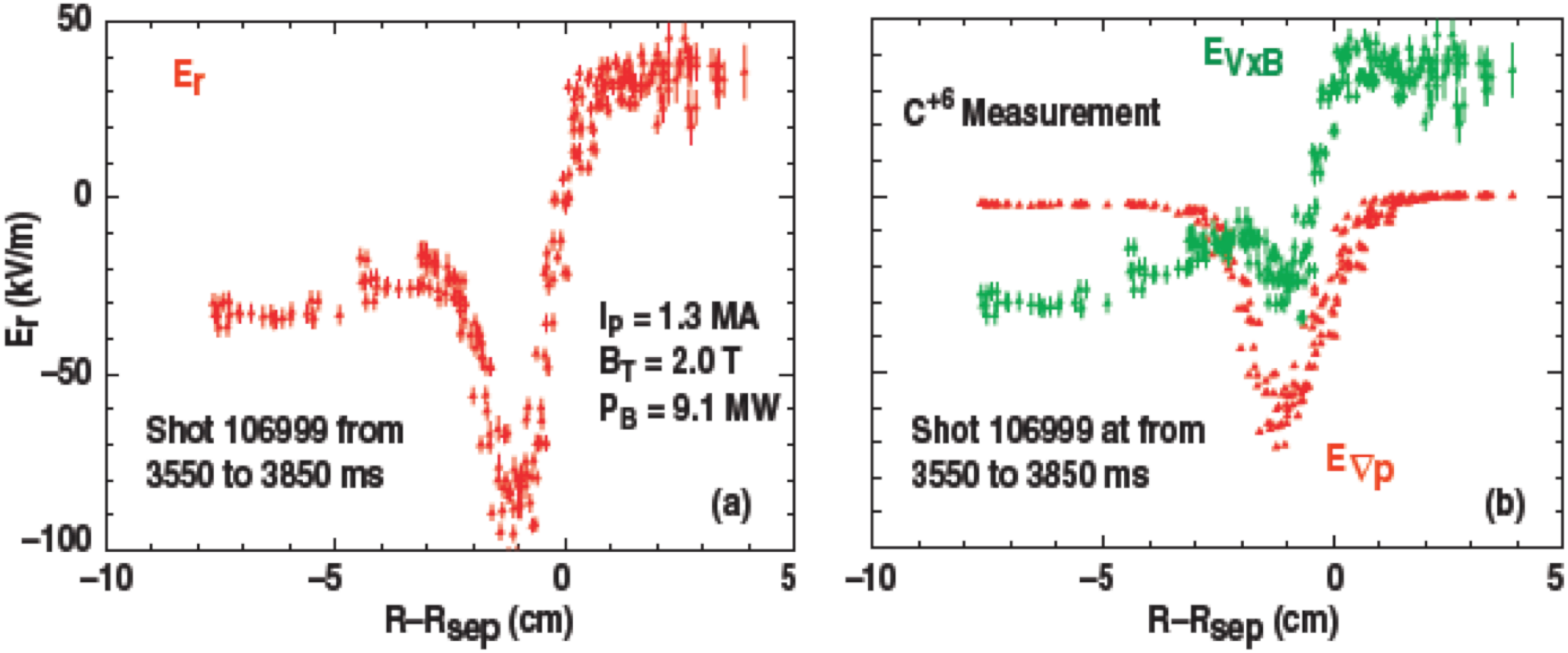


- **Radial resolution of a few mm**

[Burrell, *Plasma Phys. Control. Fusion* **46**, A165 *(2004)* (A24497)]

EXAMPLE: Self Consistent Analysis of Edge Radial Electric Field from Force Balance Equation

$$E_r = v_{\phi i} B_\theta - v_{\theta i} B_\phi + \frac{1}{Z_i n_i} \frac{dp_i}{dr}$$

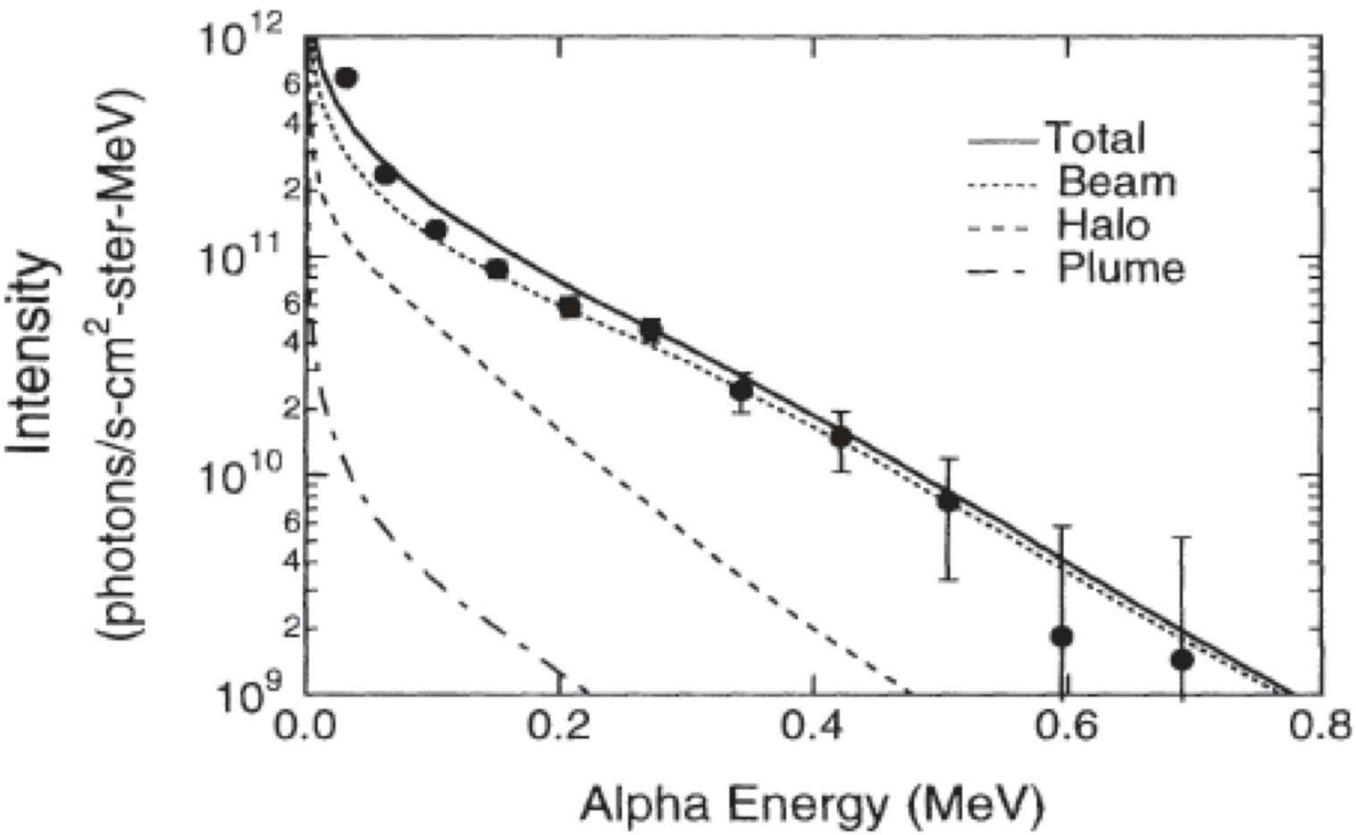


- E_r well width comparable to D+ gyro orbit

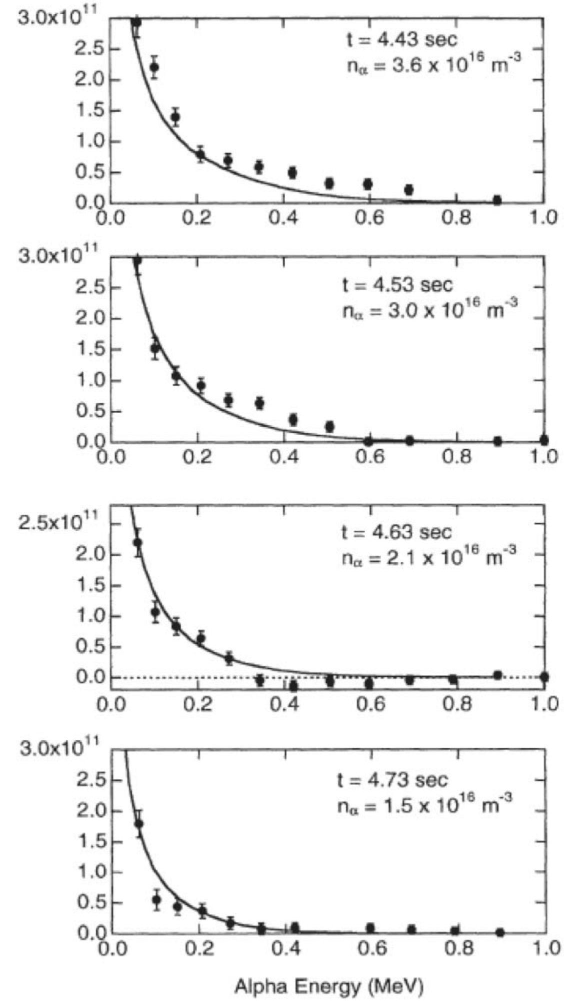
[Burrell, *Plasma Phys. Control. Fusion* **46**, A165 (*2004)* (A24497)]

EXAMPLE: Measurement of Slowing Down Confined Alphas in TFTR D-T Plasma

- **Good agreement with classical confinement predictions**

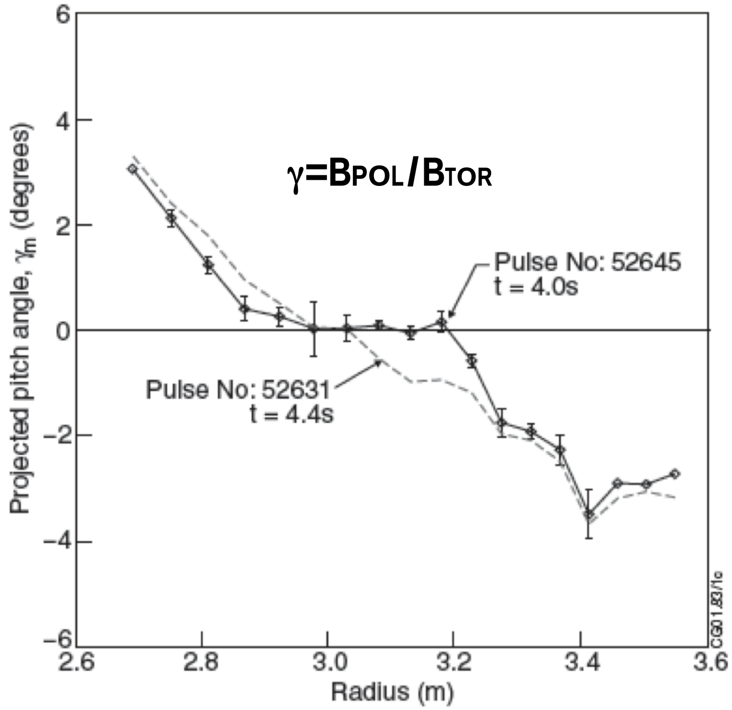


[McKee, *Phys. Rev. Lett.* **75**, 649 (*1995)]*

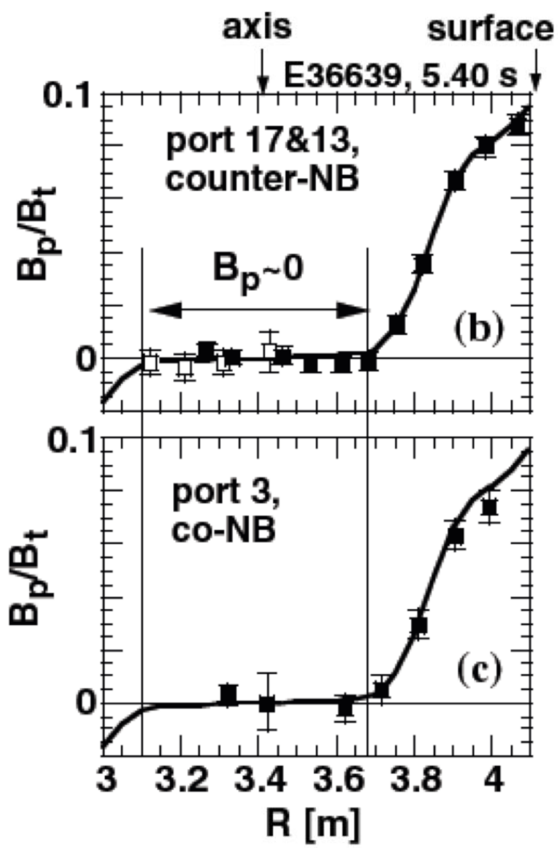


EXAMPLE: Measurement of "Current Holes"

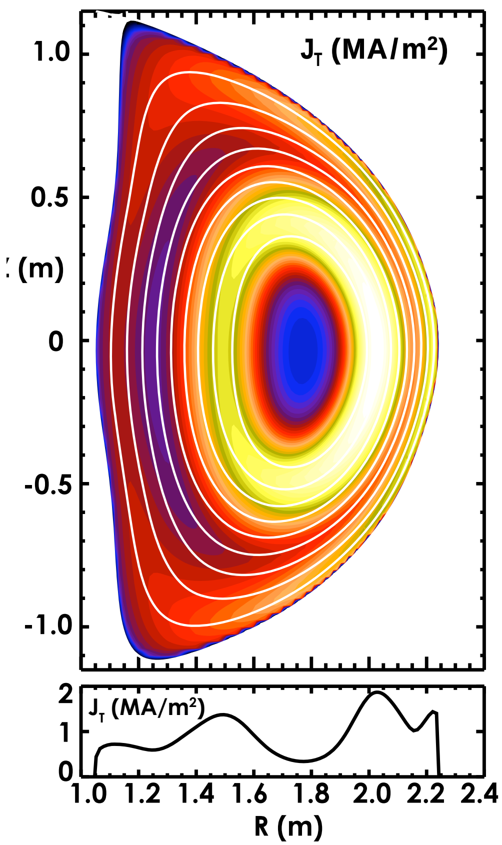
- **Excellent confinement despite near zero on-axis currents – formed through early heating and current drive**



JET: Hawkes, *Phys. Rev. Lett.* **87**, 115001 (2001)



JT60: Fujita, *Phys. Rev. Lett.* **87**, 245001 (2001)



DIII-D: Garofalo, *Phys. Plasmas* **13**, 056110 (2006)

Outline

- What is active spectroscopy, and what it can do
- **How do we do these measurements?**
  - Charge exchange spectroscopy
  - Beam emission spectroscopy
- The use of non (H,D) beams in active spectroscopy
- Future developments for active spectroscopy

To Make These Measurements, We Use Two Main Types of Atomic Collisions

I. Charge Exchange Spectroscopy

$$D^0 + A^{Z+} \rightarrow D^+ + A^{(Z-1)+*}$$

$$\rightarrow D^+ + A^{(Z-1)+} + h\nu$$

II. Beam Emission Spectroscopy

$$D^0 + \left\{A^{Z+}, D^+, e^-\right\} \rightarrow D^{0*} + \left\{........\right\}$$

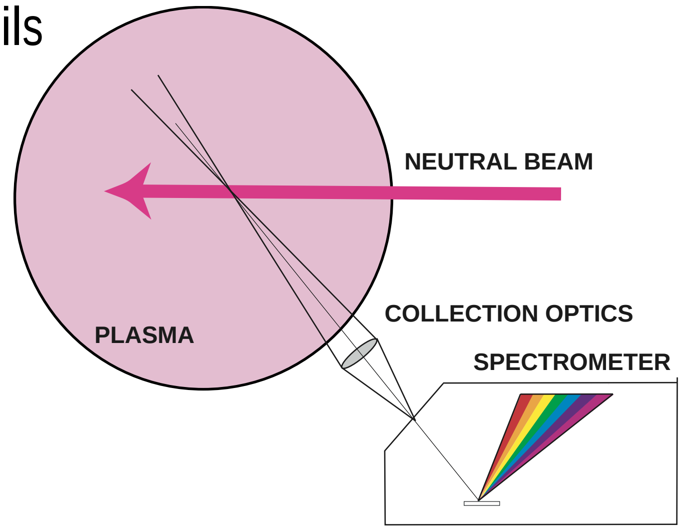
$$\rightarrow D^0 + h\nu\left\{L_\alpha, D_\alpha, D_\beta, ...\right\}$$

Key is appropriate analysis of the emitted photon

NOTE:
- Non-hydrogenic beams may be utilized
- Charge exchange partner may be main ions
- Polarization of emitted radiation may also be exploited

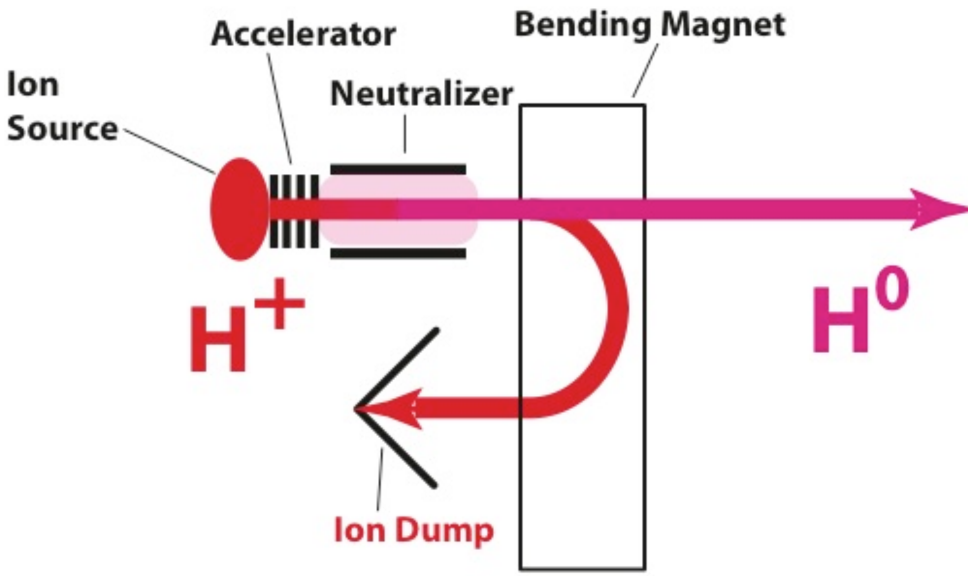
There Are Several General Principles for Exploiting Active Spectroscopy

- **Emission rate related to excitation environment**
- **Optical design must be matched to emission rate**
- **Exact viewing geometry must be carefully designed**
  - Beam/viewchord angle sets spatial resolution
  - Triad of beam/viewchord/magnetic field angles is also important
- **Tradeoff between time response and spatial resolution**
  - Need adequate resolution for spectral details
  - Helped by big improvements in detectors and dispersing elements
  - Historical increase in complexity as we have gone to larger, deuterium machines
- **Must control and correct for backgrounds**
  - Because chord integrated, views of wall



One Additional Consideration is Due to the Way We Make Neutral Beams

- Most neutral beams utilizes positive ion sources



- Molecular as well as atomic ions are extracted, accelerated and dissociated

  H^+, H_2^+, H_3^+, H_2O^+, ...

- Results in three (at least) energy components to final neutral beam

  E, E/2, E/3, E/18..

- Resulting ratios can have significant effects on measurements

I. Charge Exchange Spectroscopy

- Utilize collisions of type

$$
\begin{aligned}
\mathbf{D}^0 + \mathbf{A}^{Z+} &\rightarrow \mathbf{D}^+ + \mathbf{A}^{(Z\text{-}1)+*}(n,l) \\
&\rightarrow \mathbf{D}^+ + \mathbf{A}^{(Z\text{-}1)+} + \mathbf{h\nu}
\end{aligned}
$$

- Employ high resolution spectroscopy to measure the moments of ion velocity distribution
- A wide variety of ion species, transitions are available
- Key requirements: spectral resolution, adequate calibration, appropriate beam energy
- Rejection of or correction for background emission

Characteristics of the Charge Exchange Reaction

- **Is more properly a charge transfer reaction**

$$D^0 + A^{Z+} \rightarrow D^+ + A^{(Z\text{-}1)+*}(n,l)$$
$$\rightarrow D^+ + A^{(Z\text{-}1)+} + h\nu$$

- **Beam neutral is just acting as an electron donor**
  - **Allows us to examine fully stripped ions in plasma**
- **Cross section peaks at low relative velocity between beam atom and orbital electron of final state ion**
  - Optimizes around 40-50 keV/amu
- **Capture is primarily into high n-levels**
  - Has consequences for spectral range for observation

(A Short Aside on Acronyms)

- **One more characteristic is the historical, geographically driven proliferation of acronyms in the literature for this particular process:**

CES

CER

CERS

CXS

CXRS

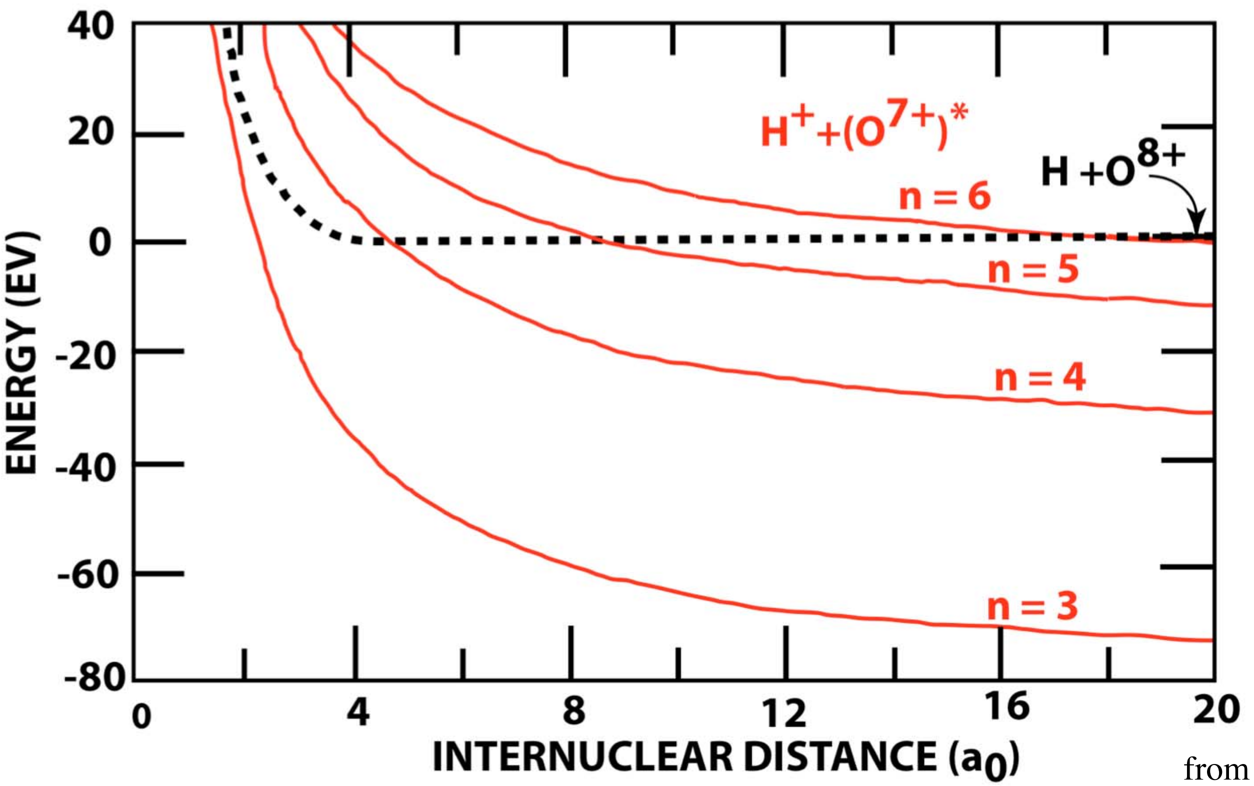
CHERS

ALL of these terms refer to the same process!

Charge Exchange Cross Sections Are Some of the Largest Known in Atomic Collision Physics

- "Quasi-molecular picture": Look at the potential curves of incoming (neutral + ion) and outgoing (ion+ion) states

Example: H plus fully stripped O



- **Charge exchange is most likely for channels that cross around 10-15 atomic units (5.3-8 Å) into high-n-levels**

$\sigma \sim 10E\text{-}15\ cm^2$

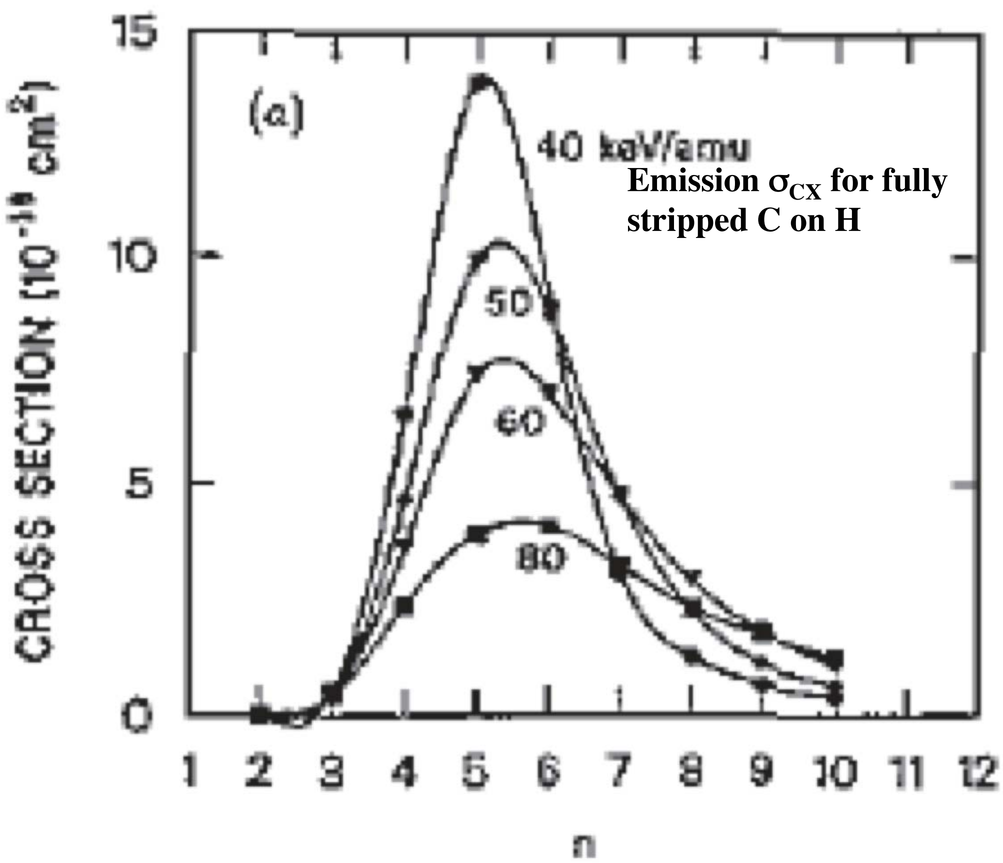
- **Direct emission from these highly excited states ranges from EUV to the visible**

from Isler, *Plasma Phys. Control. Fusion* **36**, 171 (1994)

Plasma Collisions Along With Finite Beam Energy Result in Wide Distribution of Excited Ion States

- **Cascades from higher n-levels, collisional l-mixing important**
  [Fonck, *Phys Rev A* **29**, 3288 (1984)]
- **Emission in visible, while not as strong as VUV, is efficient**
  - **High n, Δn = 1 transitions enable visible spectroscopy!**

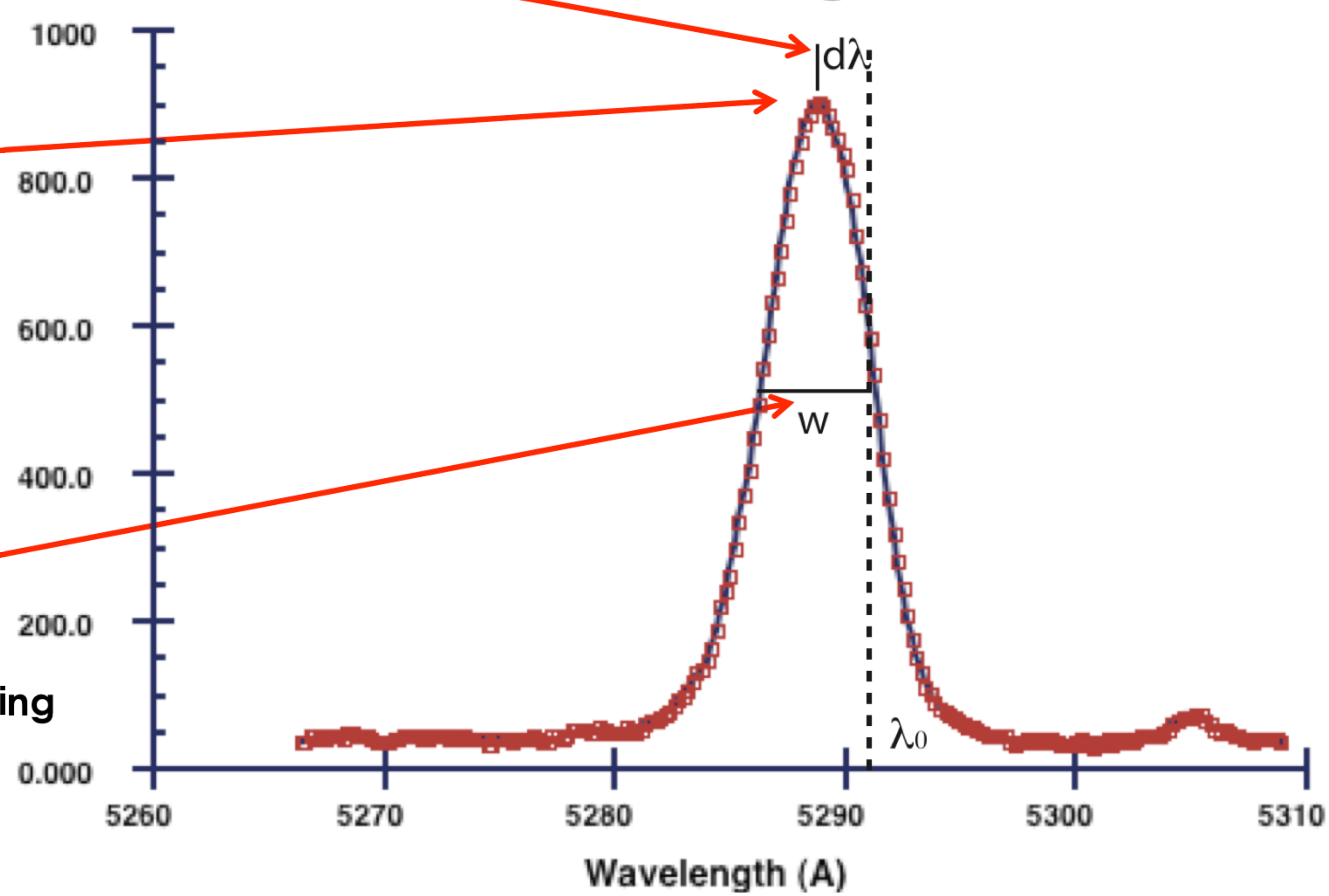
- **Emission cross section strong function of beam energy.**
- **Falls off around 40 keV/amu for H,D,T**
- **Optimum energy will depend on beam attenuation as well**



from Olson and Schultz, *Phys. Scr. T* 2871 (1989)

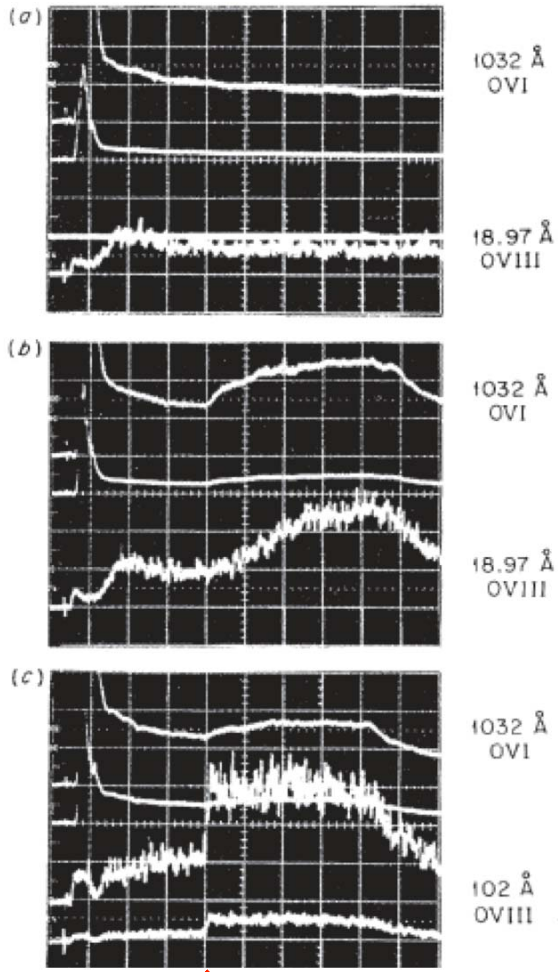
Spectroscopy of the Excited State Emission Allows Us to Examine Moments of Ion Velocity Distribution

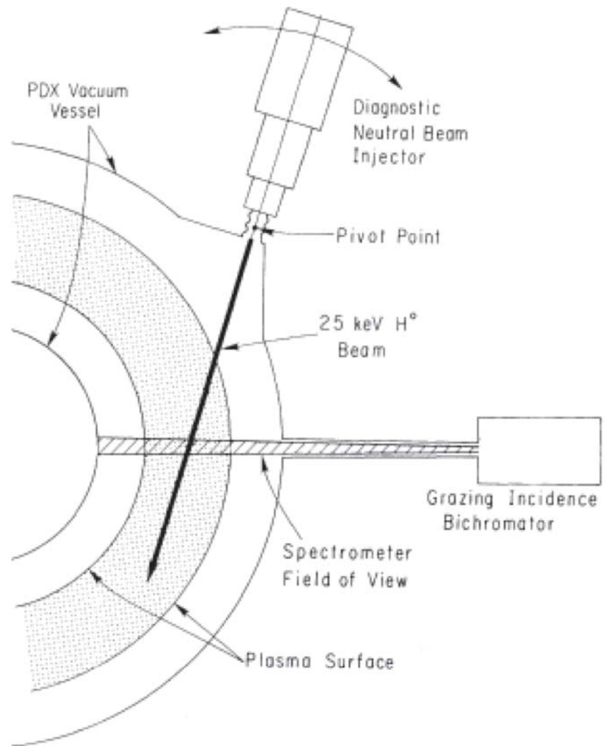
- **Dispersed emission line yields several key parameters**
- **Plasma rotation profile**
  - From Doppler shift of line emission
- **Impurity ion density**
  - From integral of line emission, absolute calibration, beam intensity modeling
- **Ion Temperature profile**
  - From Doppler broadening of line emission

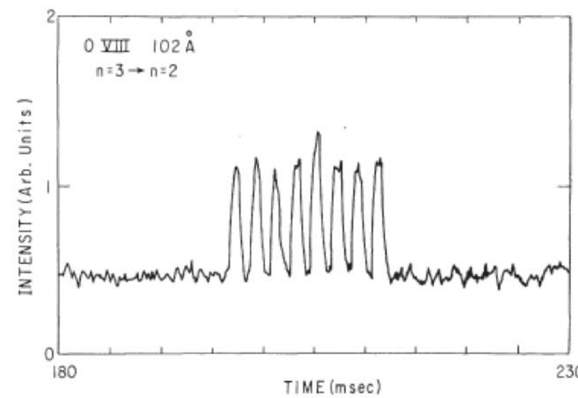


First CES Measurements Used EUV-VUV Transitions, Grazing Incidence Spectrometers

- **Observed prompt Balmer-α of hydrogen-like O**
- **Requires vacuum coupling to plasma**
- **Scanned point-to point**





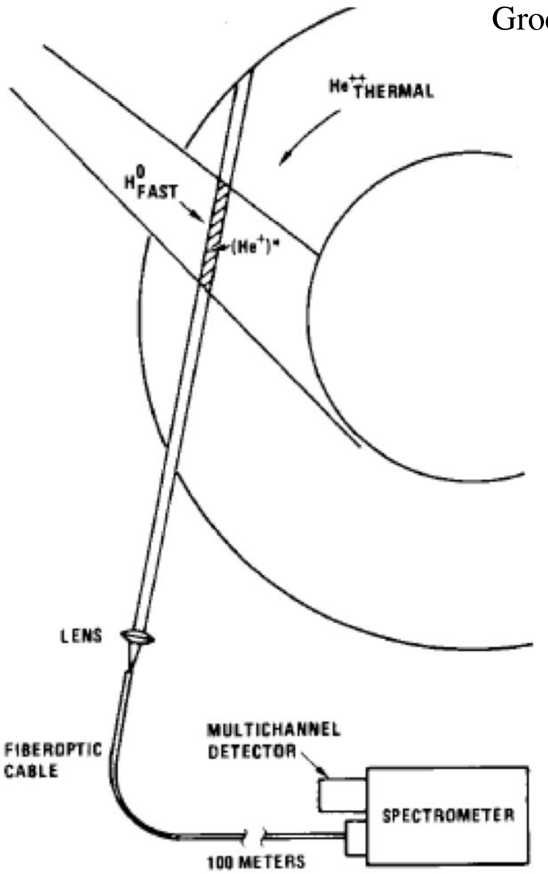


ORMAK: Isler, *Phys. Rev. Lett.* **38**, 1359 (1977)

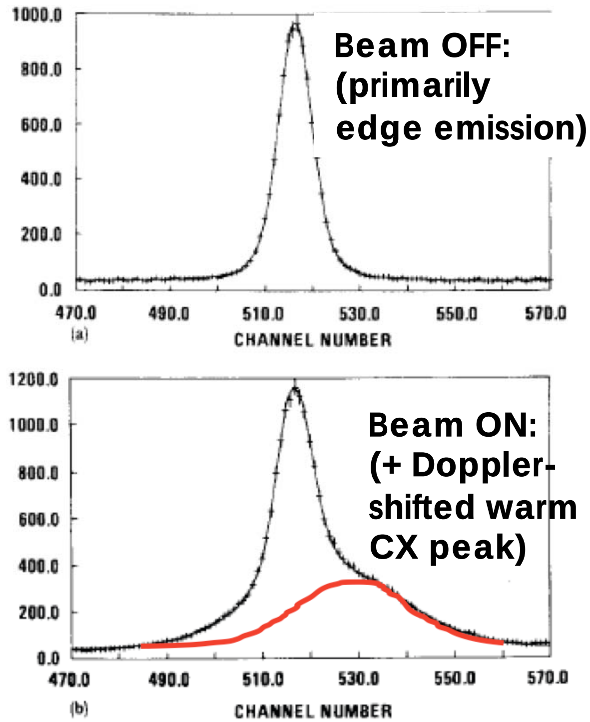
PDX: Fonck, *Phys. Rev. Lett.* **49**, 737 (1982)

Using Visible Transitions + Multichannel Detection Allows for Much Simpler Instrumentation

- **First attempt: HeII 4686 Å line from $H^0_{BEAM} + He^{++}_{THERMAL} \rightarrow H^+ + He^{+*}_{THERMAL}$**



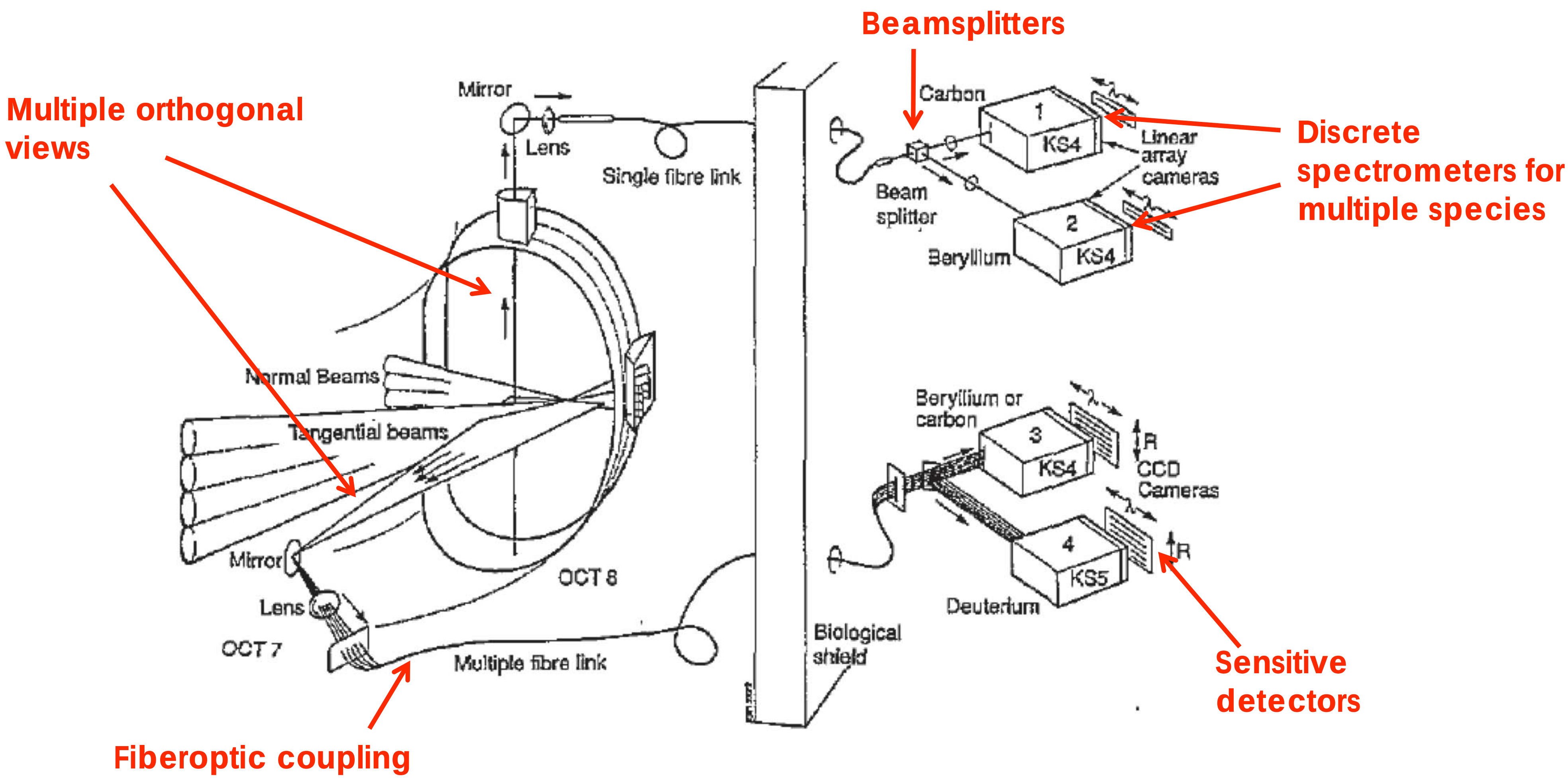
Groebner, *Appl. Phys. Lett.* **43**, 10 (1983)



- **Simple vacuum interface**
- **Visible optics**
- **High resolution spectrometers available**
- **Trivially extensible to multiple sightlines**
- **Multichannel detector**
  - Full line profile per timeslice
  - Enables timeslice subtraction for elimination of many background terms
- **Calibration significantly easier**

- **Visible CES has become <u>the</u> standard application for measuring T_i, V_{rot}, n_i**

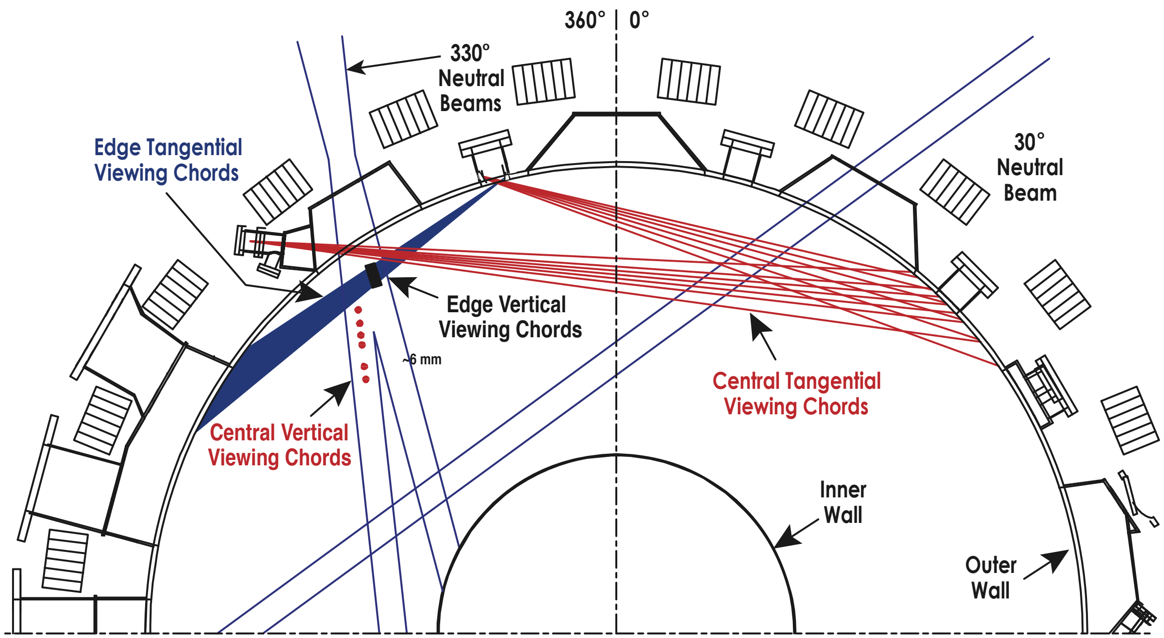
Keys for Implementing Charge Exchange Spectroscopy (JET c.1993)



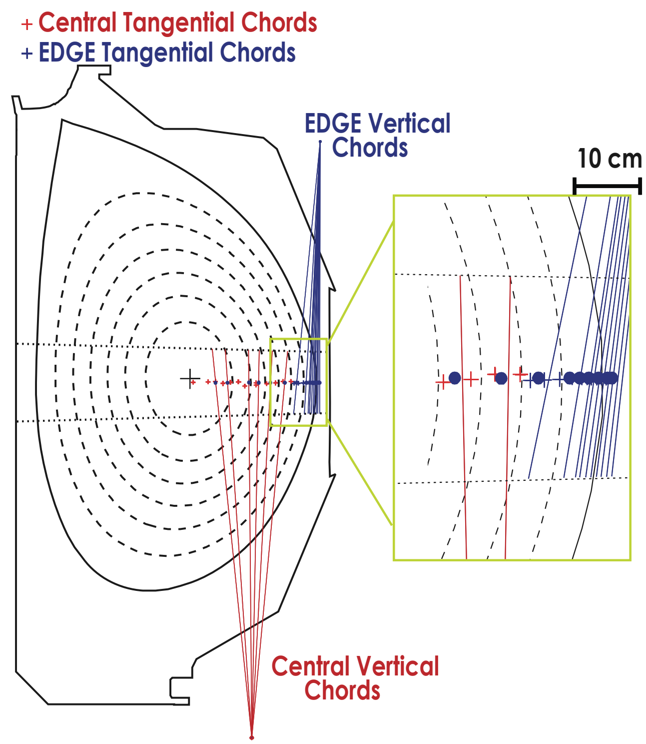
Von Hellerman, *Plasma Phys. Control. Fusion* **35**, 799-824 (1993)

Careful Choice of Viewing Geometry is Essential for the Best Spatial Resolution

- **Arrange optics to view tangent to magnetic flux surfaces, while maintaining maximal light collection efficiency. Typically requires multiple viewports**
- **Interleave vertical and horizontal views to determine both velocity components**



Plan View of DIII-D

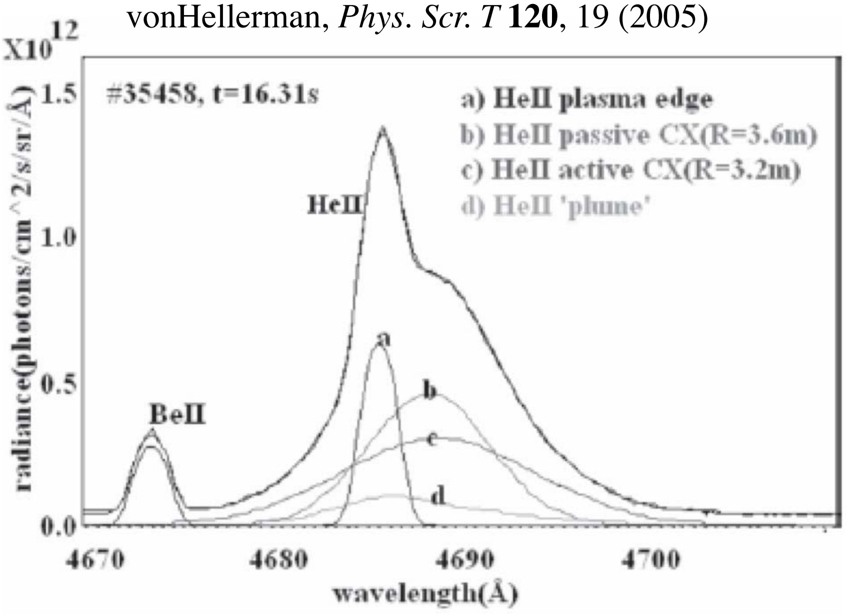


Cross Section View of DIII-D

Background Issues are Complex, But Manageable… in Most Cases

Desired signal competes with five main background components

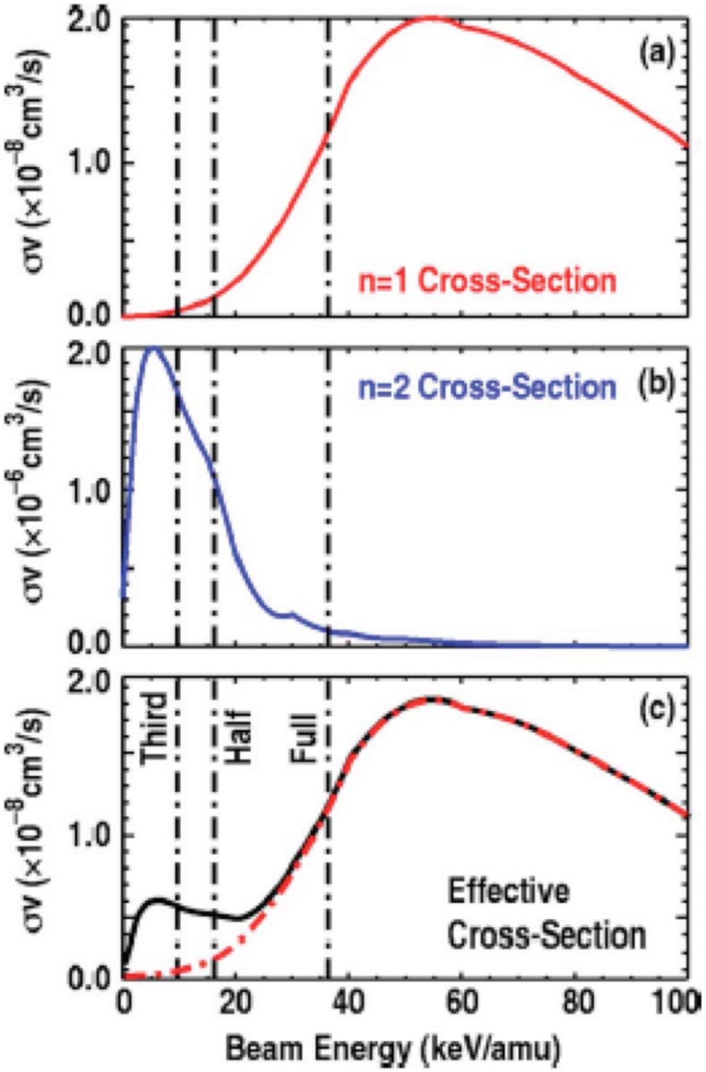
vonHellerman, *Phys. Scr. T* **120**, 19 (2005)



- **Chord-integrated bremsstrahlung**
- **Intense localized edge emission**
  - Either from collisional excitation of edge ions or charge exchange on edge neutrals
- **Emission from CX ions which drift along field lines into view region from other points ("plume")**
- **Emission from thermal "halo" neutrals which surrounds beam**
- **Nearby lines of other ions**

- **Three primary techniques for background handling are beam modulation, off-beam views and adequate spectral rejection**
- **An integrated fitting model is crucial**

High Beam Velocities and High Plasma Temperatures Lead to Significant Atomic Physics Corrections



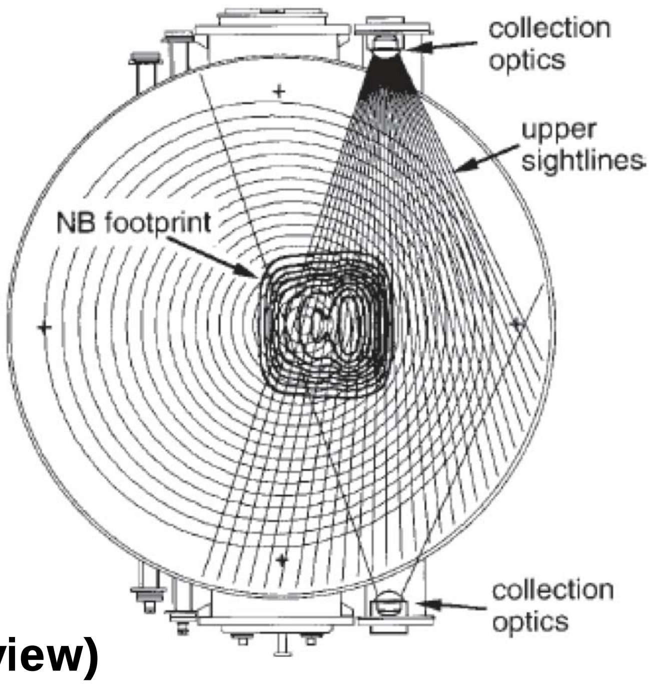
- **Early fitting models : de facto assumption of uniform emissivity across Doppler line**
- **BUT…Cross sections are energy dependent, so high plasma T or v lead to significant distortions of line profile**

Depends on beam velocity component along line of sight
Complicated by small excited state populations in beam
Complicated by gyroorbit and finite lifetime of emitting ion

Bell & Synakowski, *AIP Conf. Proc.* **547**, 39 (2000); vonHellerman, *Phys. Scr. T* **120**, 19 (2005); Solomon, *Rev. Sci. Instrum.* **75**, 3481 (2004)

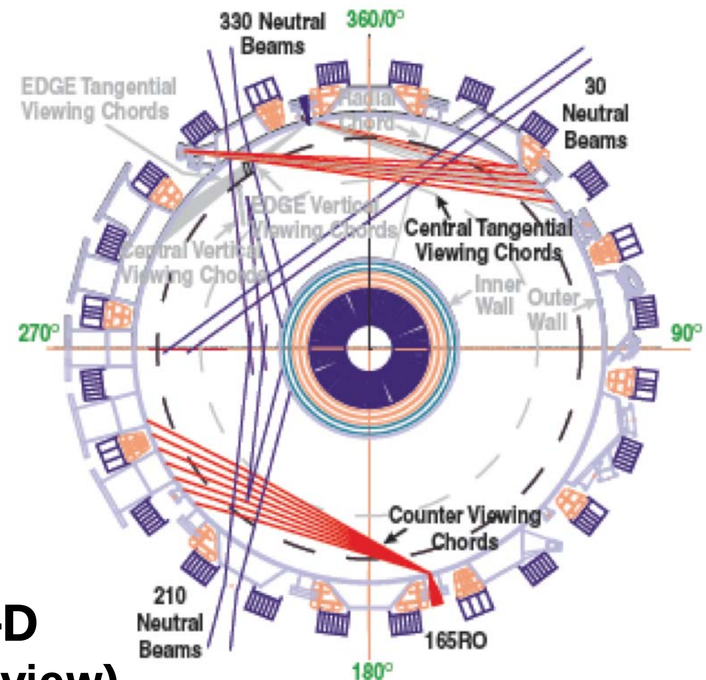
These "Cross-Section Effects" can be Handled in a Number of Fashions

- Use of symmetric up-down opposing views
- Views of co + counter beams
- Iterative correction of spectra based on T and v estimates
- Self-consistent evaluation using ADAS cross sections and beam modeling



TFTR (plan view)

Bell, *Rev. Sci. Instrum.* **70**, 821 (1999)

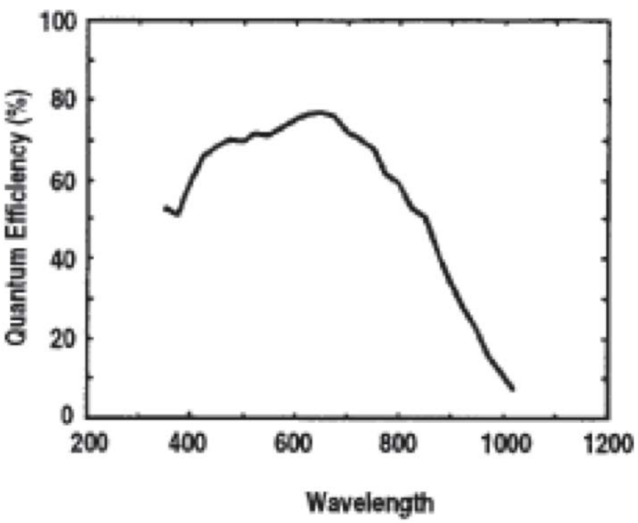


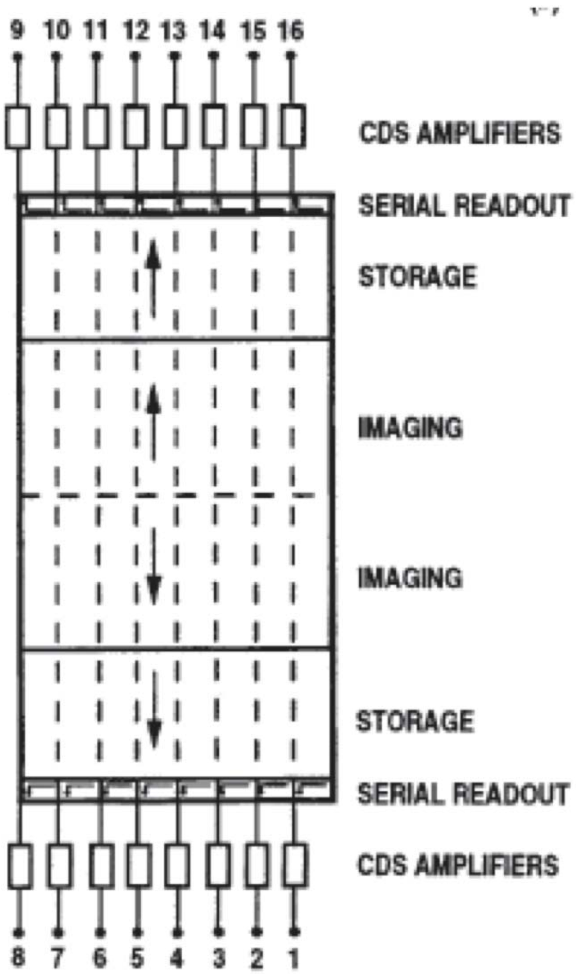
DIII–D (top view)

Solomon, *Phys. Plasmas* **13**, 05611 (2006); *Rev. Sci. Instrum.* **79**, 10F531 (2008)

Capability of CES Has Been Enhanced by Improvements in Detector Sensitivity and Readout

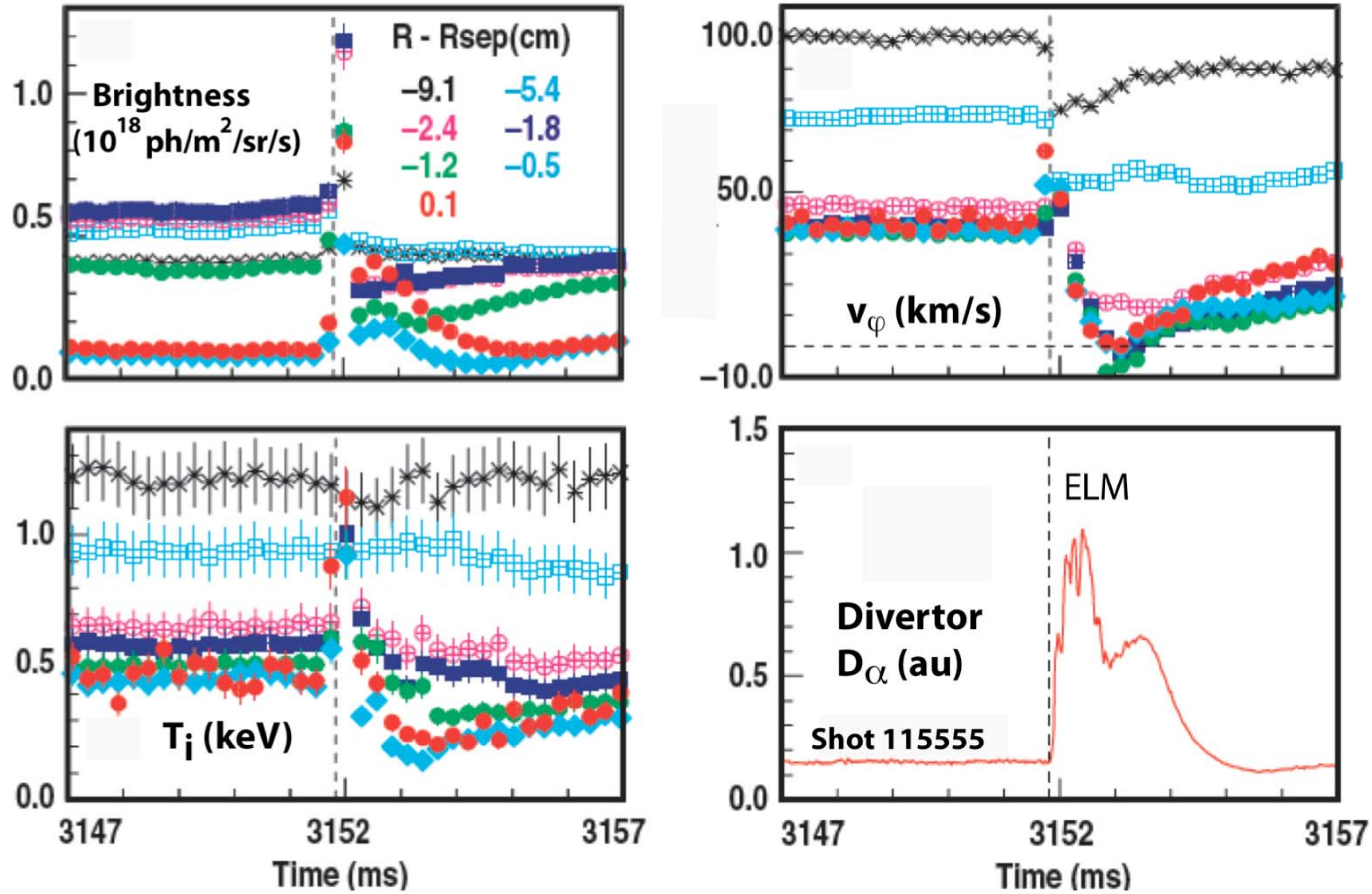
- **Detector technology has proceeded from single point detectors to high quantum efficiency, 2D-CCD arrays. Factors 16-20 improvement in signal**
- **Use split frame architecture of CCD chips to measure two spectra per chip; maintains high-speed readout.**
- **Simple optical coupling allows use of two CCD cameras per spectrometer**





Along With Improved Signal Levels, Time Resolution Has Improved As Well

- **Using CCD readout improvements and free streaming to PC memory, now routinely acquire full profile data with sub-ms time resolution**

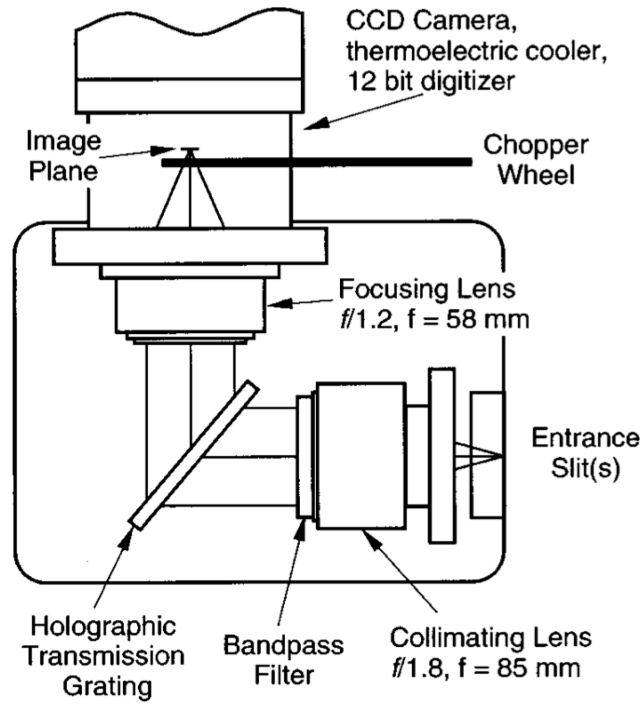


Measurements of CVI Doppler amplitude, shift, and broadening evolution during an Edge Localised Mode with 274 μs resolution

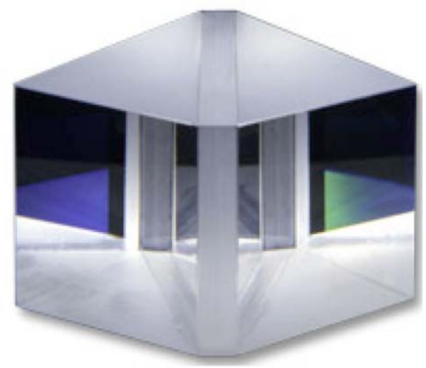
Burrell, *Rev. Sci. Instrum.* **75**, 3455 (2004)

CES Measurement Capability Has Also Advanced Through Use of High-throughput Spectrometers

- Using holographic transmission grating spectrometers, commercial camera lenses as inexpensive high-quality coupling optics. *f*/1.8 achievable. Pioneered by R. Bell of PPPL. First used on TFTR for hi-res v_{pol} measurements



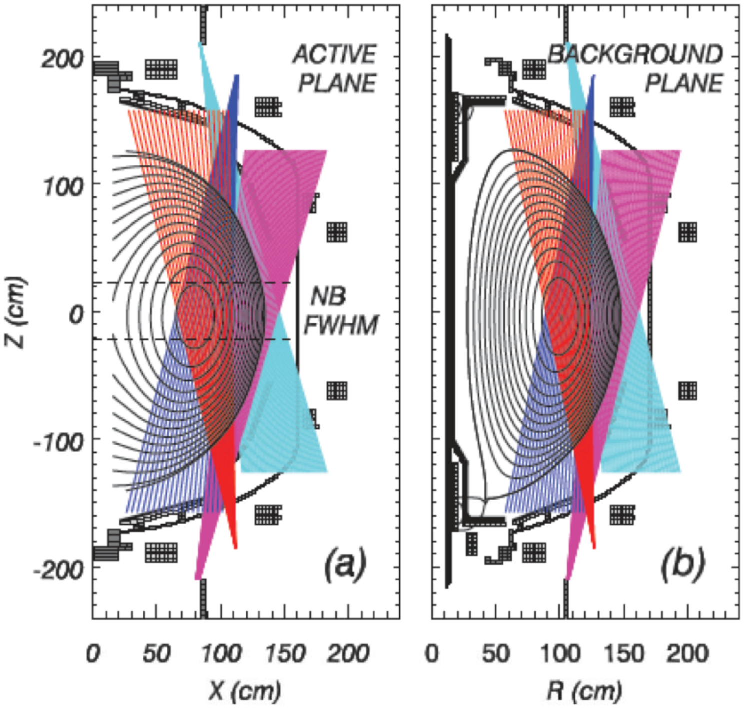
- This approach permits a large number of spatial chords per spectrometer
- Transmission grating development is present limitation on spectral resolution
- Can go to smaller detector elements, hybrid dispersion (grism)

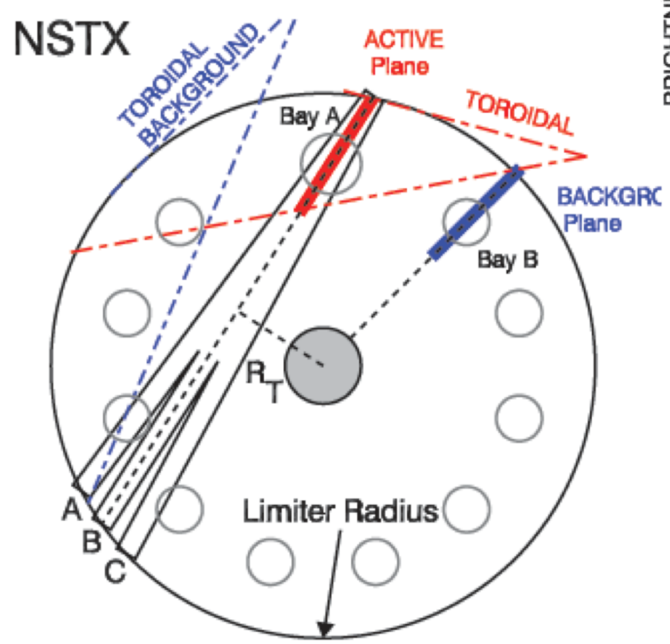


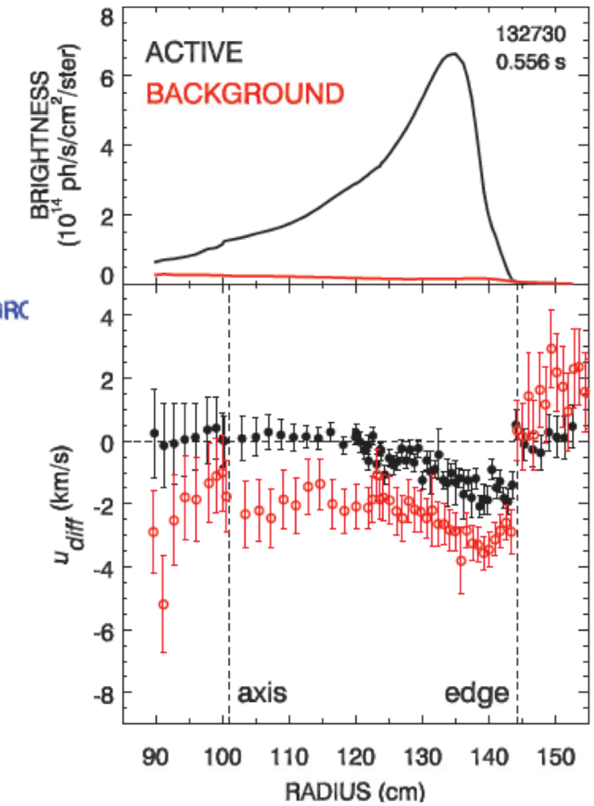
R. Bell, *Rev. Sci. Instrum.* **70**, 821 (1999); *Rev. Sci. Instrum.* **75**, 4158 (2004); *Rev. Sci. Instrum.* **77**, 10E902 (2006); *Rev. Sci. Instrum.* **81**, 10D724 (2010)

Utilization of High-throughput Spectrometers- Example from NSTX

- **NSTX system exploits large number of views to mitigate cross-section effects**
  - **(276 total fibers for poloidal system alone)**
  - **Symmetric sets of upward and downward views, precisely aligned**
  - **Complimentary active and passive view arrays for background subtraction**
  - **Poloidal and toroidal viewing arrays for velocity component determination**
  - **Can accommodate all 276 fibers on 6 spectrometers!**







Improvements in Spectral Analysis Have Enabled Main Ion Charge Exchange

- **Use the symmetric charge exchange reaction**

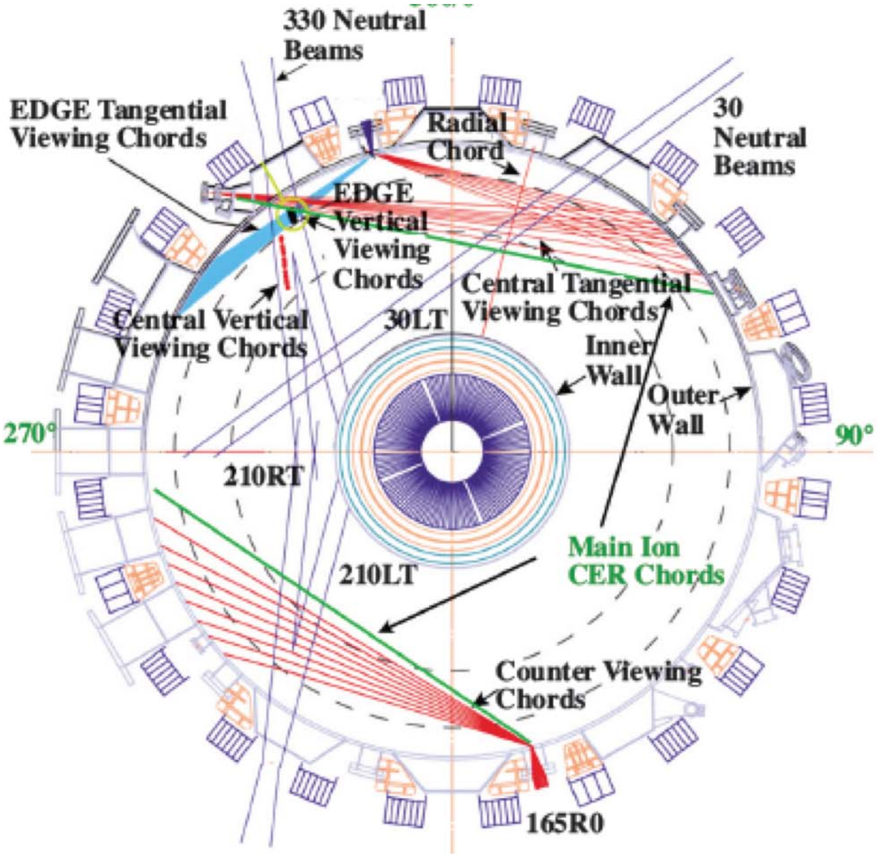
$$D^0 + D^+ \rightarrow D^+ + D^{0*}(n,l) \rightarrow D^+ + D^0 + \lambda\ 6561\ \text{Å}$$

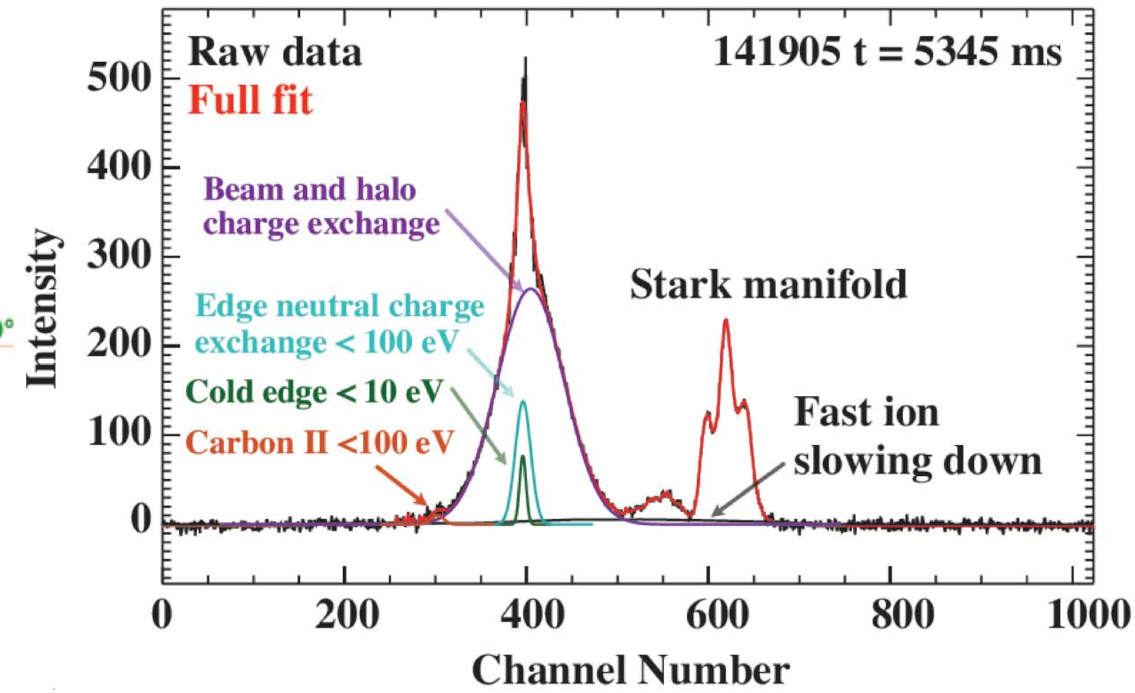
- **Poses extreme challenge with respect to modeling and background rejection**
- **Key elements are comprehensive fitting model, beam modulation, knowledge of beam components, absolute calibration**
- **Two-channel prototype installed on DIII-D in 2009** B. Grierson, *Rev. Sci. Instrum.* **81**, 10D735 (2010)

Example — Main Ion Charge Exchange on DIII-D

- **On DIII-D, 16 channel system (8 co- and counter- pairs) has begun producing new results with a comprehensive fitting model**

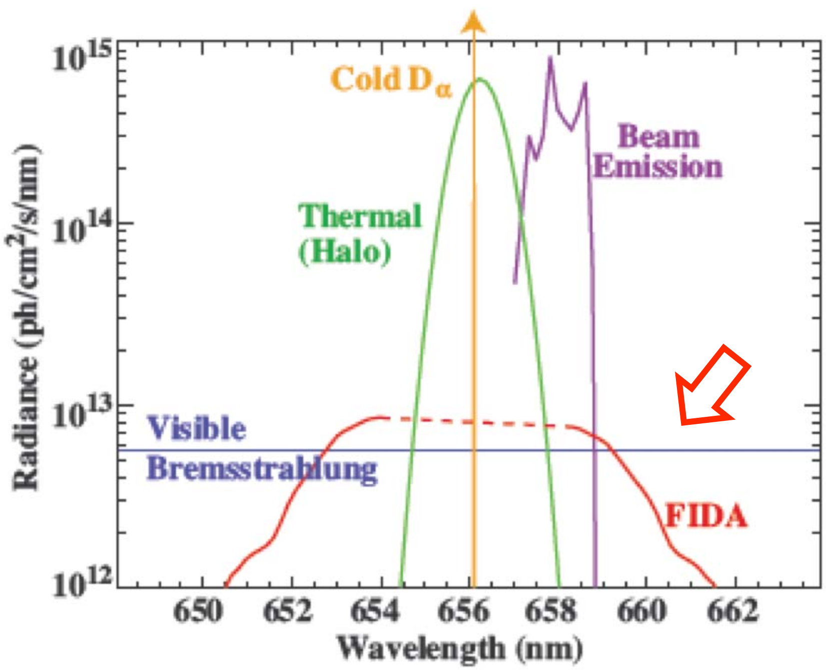
B. Grierson, paper NI2.00005 (Wed afternoon)





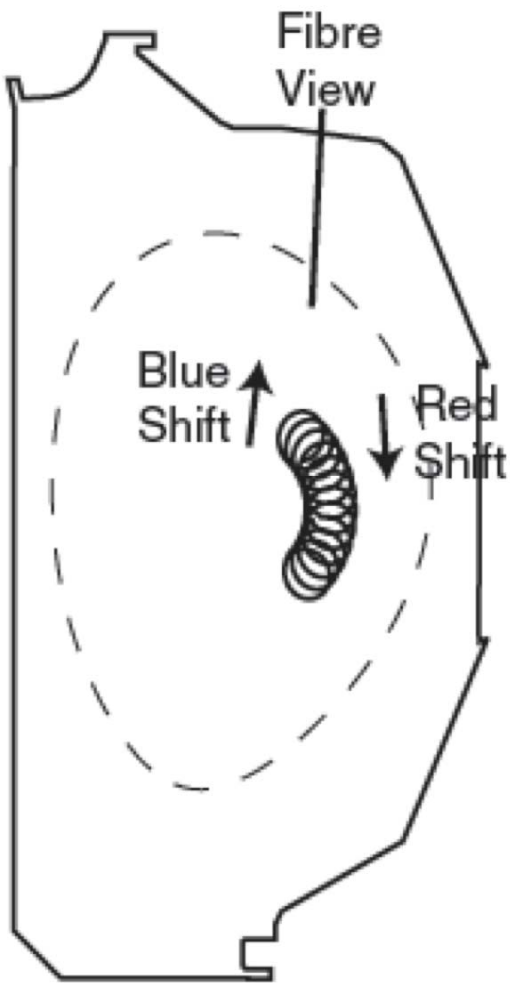
Analysis of Main Charge Exchange in Extreme Wings of D_α Profile Gives Information on Fast Ions (FIDA)

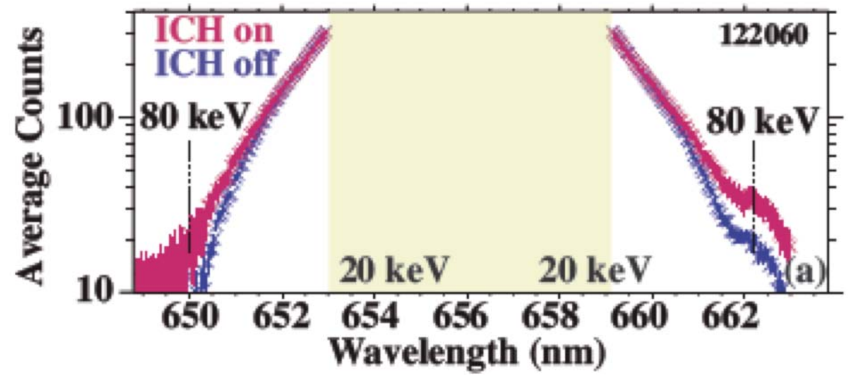
- **Due to charge exchange of the fast-ion distribution on beam**
- **FIDA technique is most sensitive to fast ions whose relative velocity to beam neutrals is near peak for charge exchange**
- **Requires proper choice of viewing angle, good discrimination**



Despite Large Backgrounds, FIDA Has Been Measured Successfully

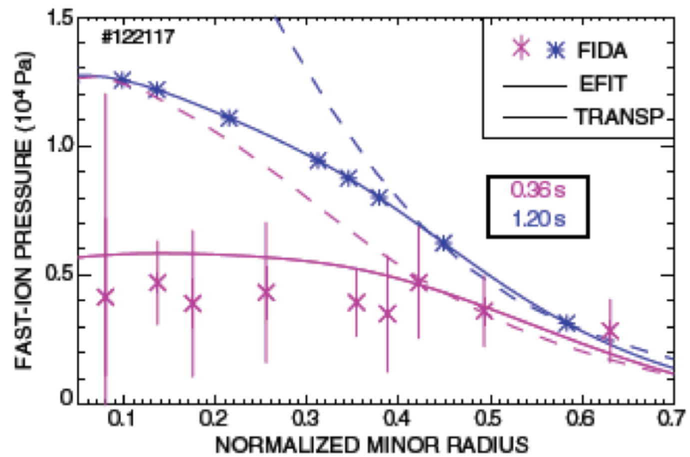
- **Strategy: image vertically for zero beam Doppler shift, look at extreme wings**
- **Gives information on one component of the fast ion velocity**





FIDA spectrum increases as ICH is applied

Heidbrink, *Plasma Phys. Control. Fusion* **49**, 1457 (2007)



FIDA profile indicates flattening of fast ion distribution correlated with Alfvén activity

Heidbrink, *Phys. Rev. Lett.* **99**, 245002 (2007)

II. Beam Emission Spectroscopy

- **Utilizes emission from excited states of beam**

$$\mathbf{D^0 + \{A^{Z+}, D^+, e^-\} \rightarrow D^{0*} \rightarrow D^0 + h\nu\{L_\alpha, D_\alpha, D_\beta, \ldots\}}$$

- **Emission rate related to excitation environment**
  - Density fluctuations will modulate beam emission
  - Therefore can use BES to study plasma turbulence directly
- **Emission wavelength also determined by environment**
  - Local electric field results in Stark shift
  - Due to intrinsic and motional (vxB) fields
- **Good diagnostic for beam penetration, fuelling, etc.**

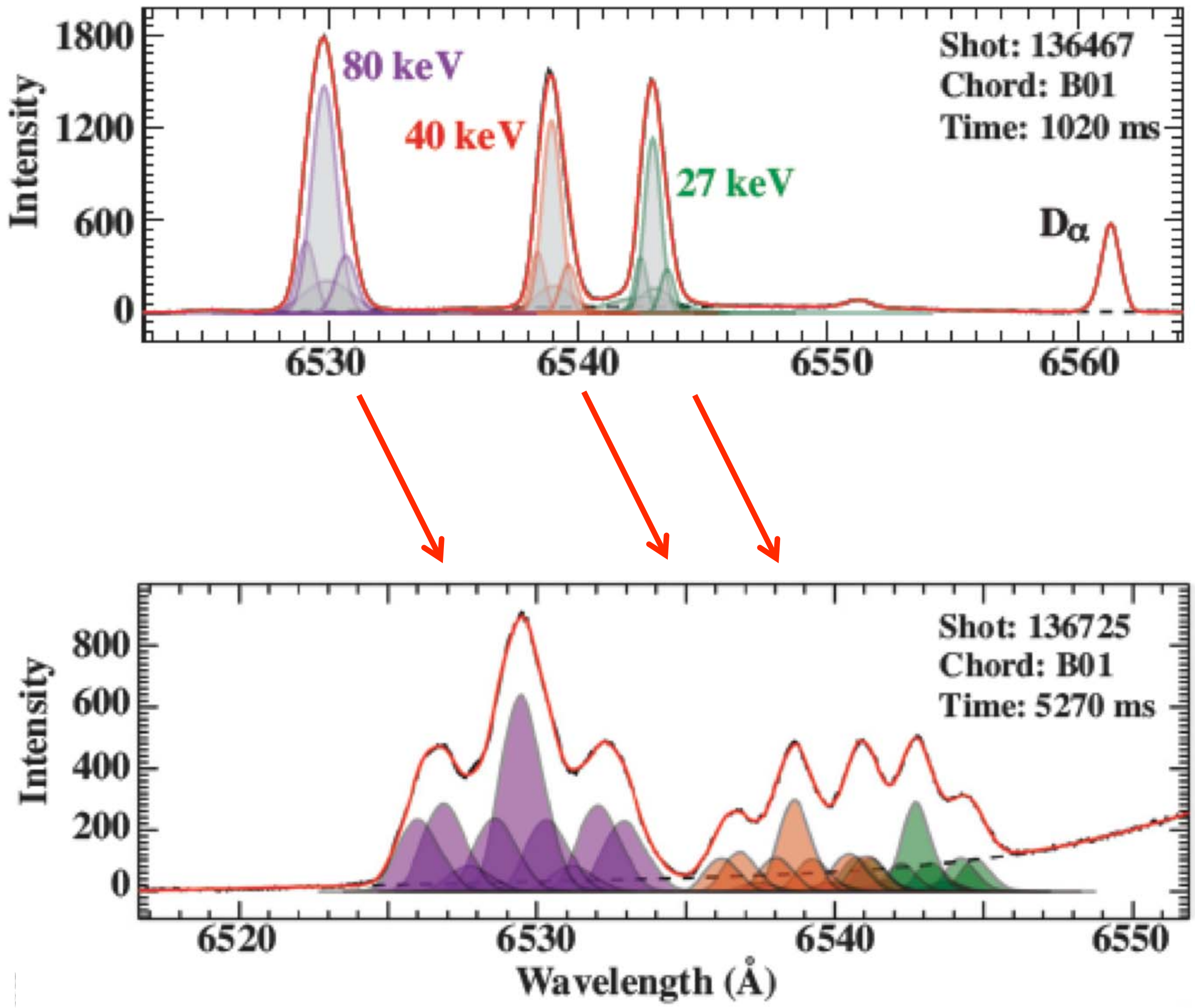
BES Applications are Based on Proper Collection, Analysis and Filtering of Hα(Dα) Spectral Region

- **Example: 80 keV D^0 injection on DIII-D, viewed at 57.3°**

- **Beam into gas (He) shows three energy components, small edge recycling peak**

- **Beam into plasma with fields shows Stark multiplets, high-energy wings**

- **Depending on specific measurement, may collect all light or concentrate on specific components**

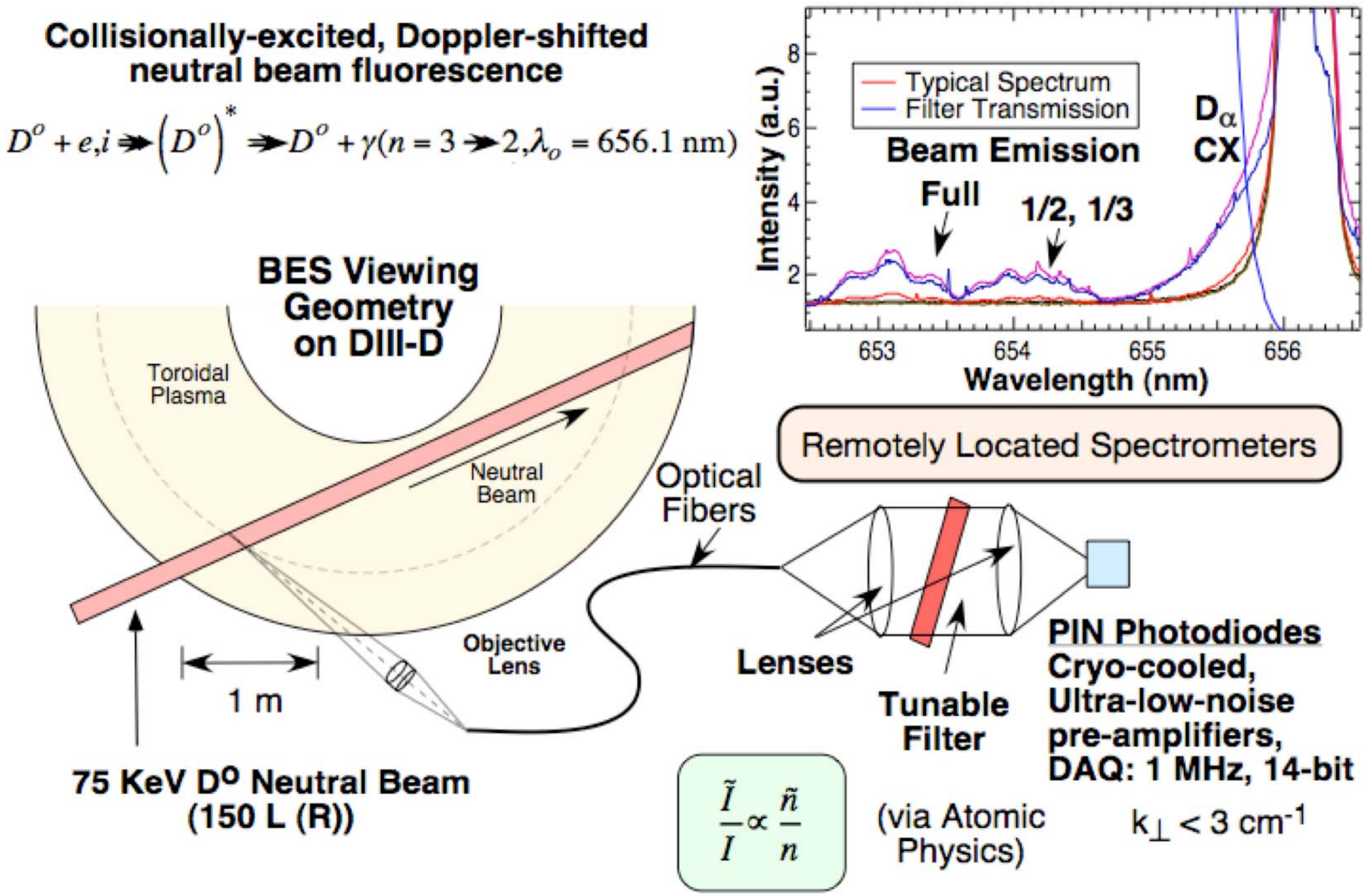


Beam Emission Spectroscopy Requirements — Density Fluctuations

- Key is to obtain highest possible photon flux consistent with spatial resolution – relatively low spectral resolution required. Use large lenses, large solid angles
- High speed requirements. Turbulent fluctuations are broadband, hundreds of kHz
- Need to reject background D_{α} : use non-normal view to utilize Doppler shift of beam emission
- Requires high sensitivity detectors, low noise, high bandwidth amplifiers

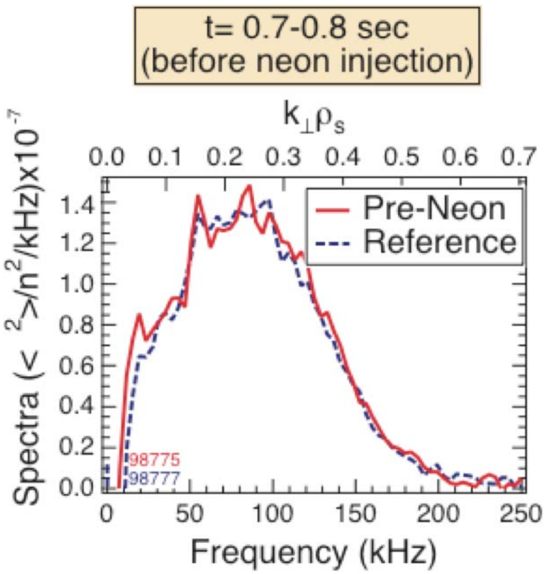
Components of a BES System

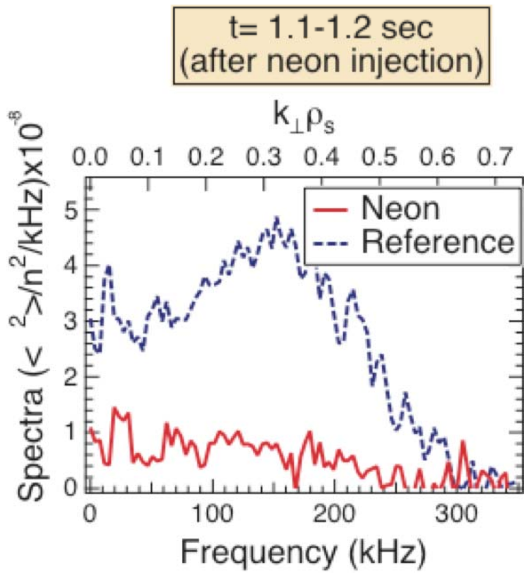
- **Multiple tangential views of blue-shifted beams, poloidal and radial arrays with very high spatial resolution. High etendue**



These Measurements Allow Us to Directly Test the Connection Between Turbulence and Transport

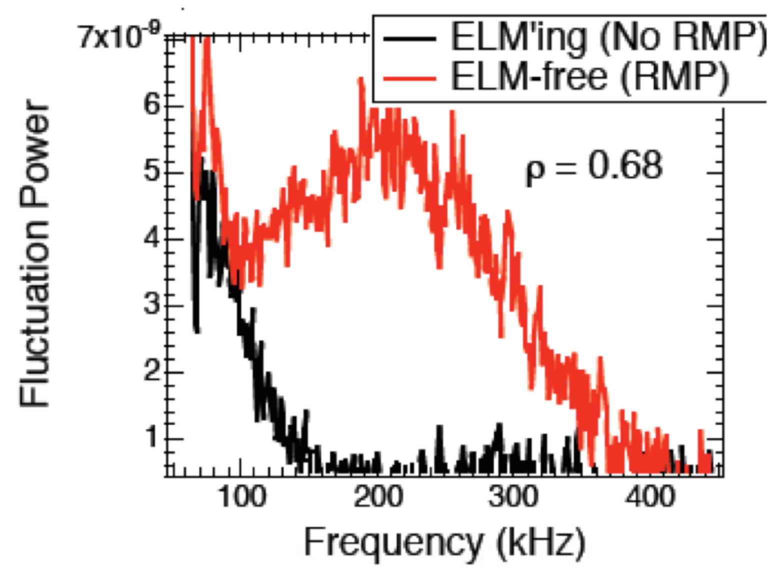
- **Using BES, find broadband turbulence is dramatically suppressed during Neon injection** McKee, *Phys. Rev. Lett.* **84**, 1922 (2000)





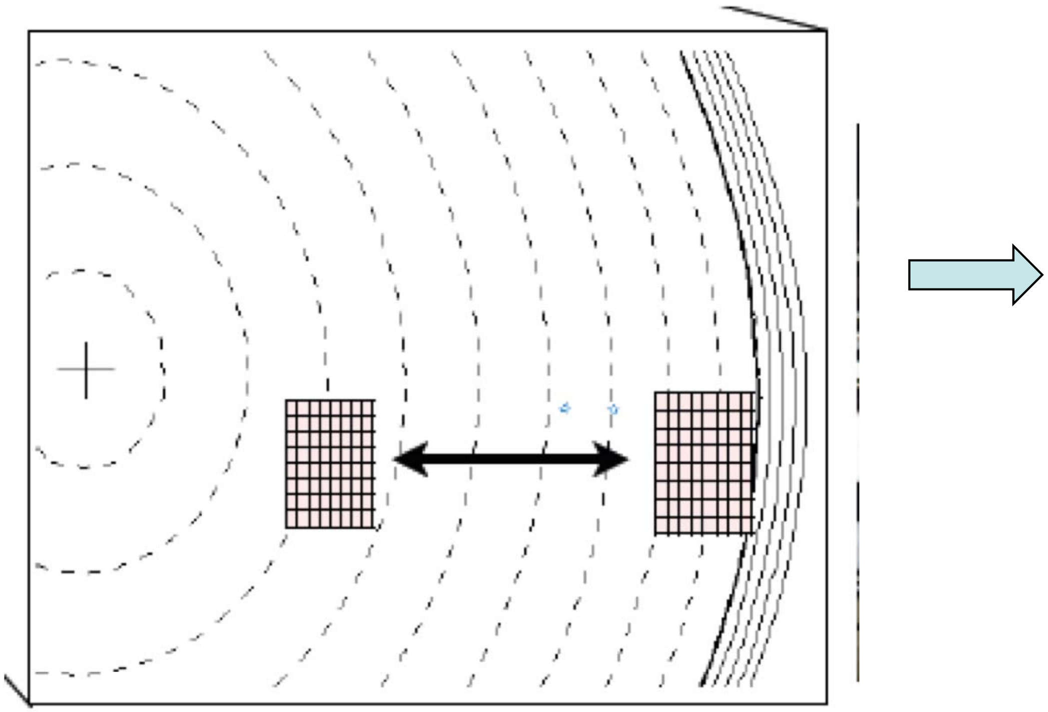
- **Broadband core turbulence increases with resonant magnetic perturbations applied for ELM suppression**

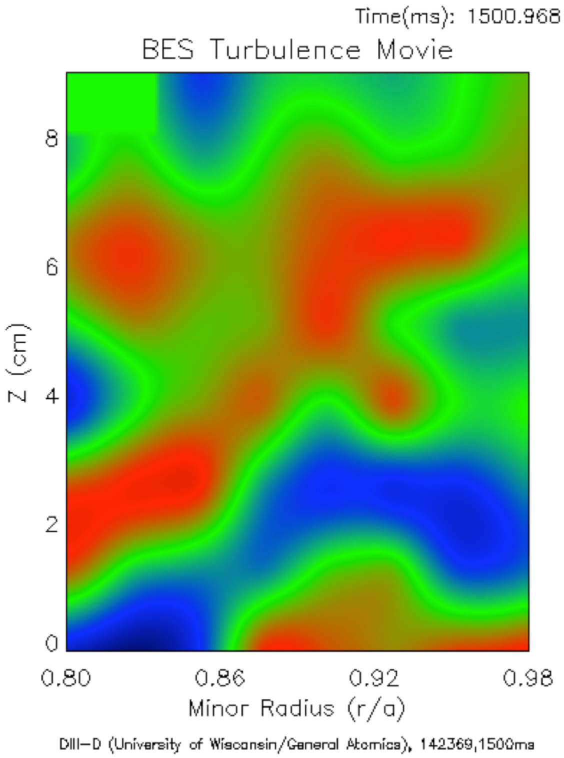
McKee (2010)



BES: Time-Resolved Images Yield 2D Time-Resolved Velocity Field

8x8 sampling array allows visualization of turbulent eddys, characterization of correlation lengths

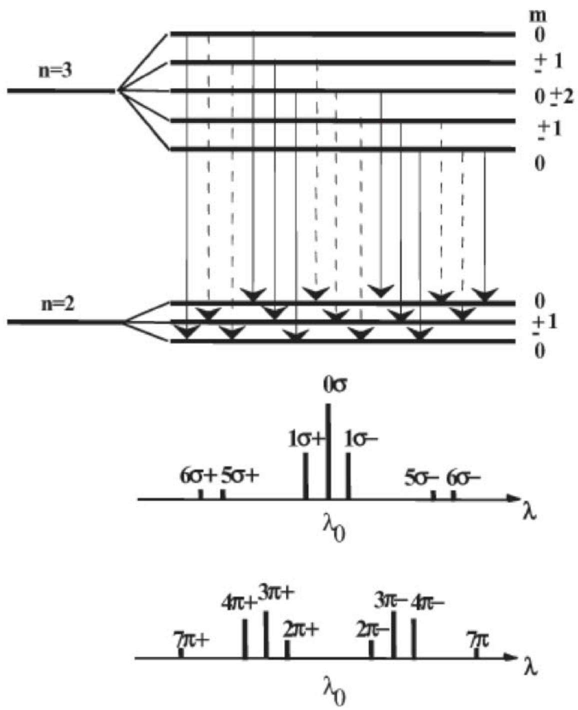




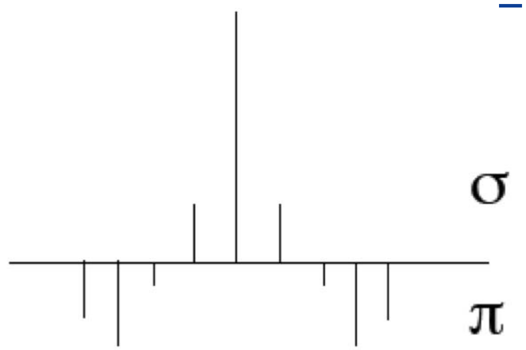
Size of Current 8x8 BES view: ~7x9 cm2

Higher Spectral Resolution Allows Us to Exploit Motional Stark Effect (MSE) on Beam Emission

- **As beam atoms propagate across B field, they experience a large Lorenz electric field** ***$E = v_{BEAM} \times B$***
- **This results in Stark splitting of beam quantum states, separation of emission lines**
  - Effect is linear in E for hydrogenic species, quadratic for others
  - **Individual transitions are now polarized relative to E**
    - **π (Δm=0) transitions; linearly polarized parallel to E**
    - **σ (Δm=±1) transitions linearly polarized perpendicular to E**



E.U. Condon and G.H. Shortley, *The Theory of Atomic Spectra*, Cambridge University Press, Cambridge (1963)

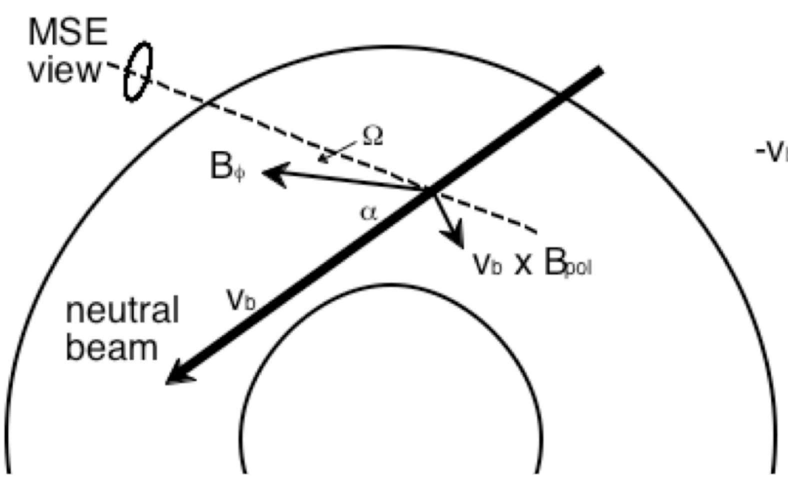


- **Note: static electric fields in plasma will have the same effect**

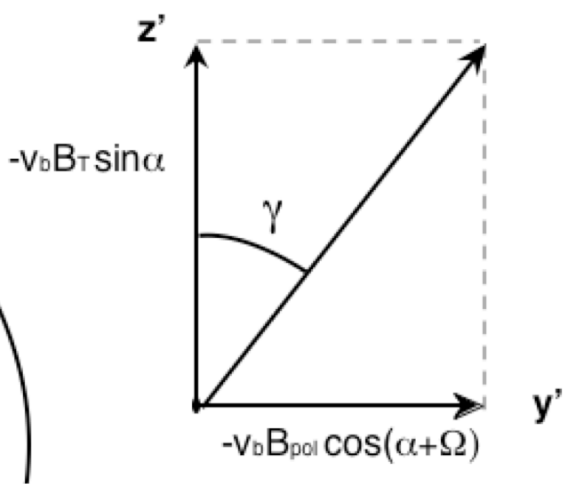
MSE: Spectral + Polarization Analysis Gives Internal Magnetic Field and Details Of Current Density J

- **Choose proper view: desire Doppler shifted beam emission, tangent to flux surfaces. Note premium now set on higher energy beam.**
- **Filter emission to pick out π or σ manifold**
  - **Key is to minimize the Doppler broadening due to geometric effects**
- **Perform polarimetry on filtered light to determine projected polarization angle and hence the magnetic pitch angle $\gamma \sim (B_{POL}/B_{TOR})$**

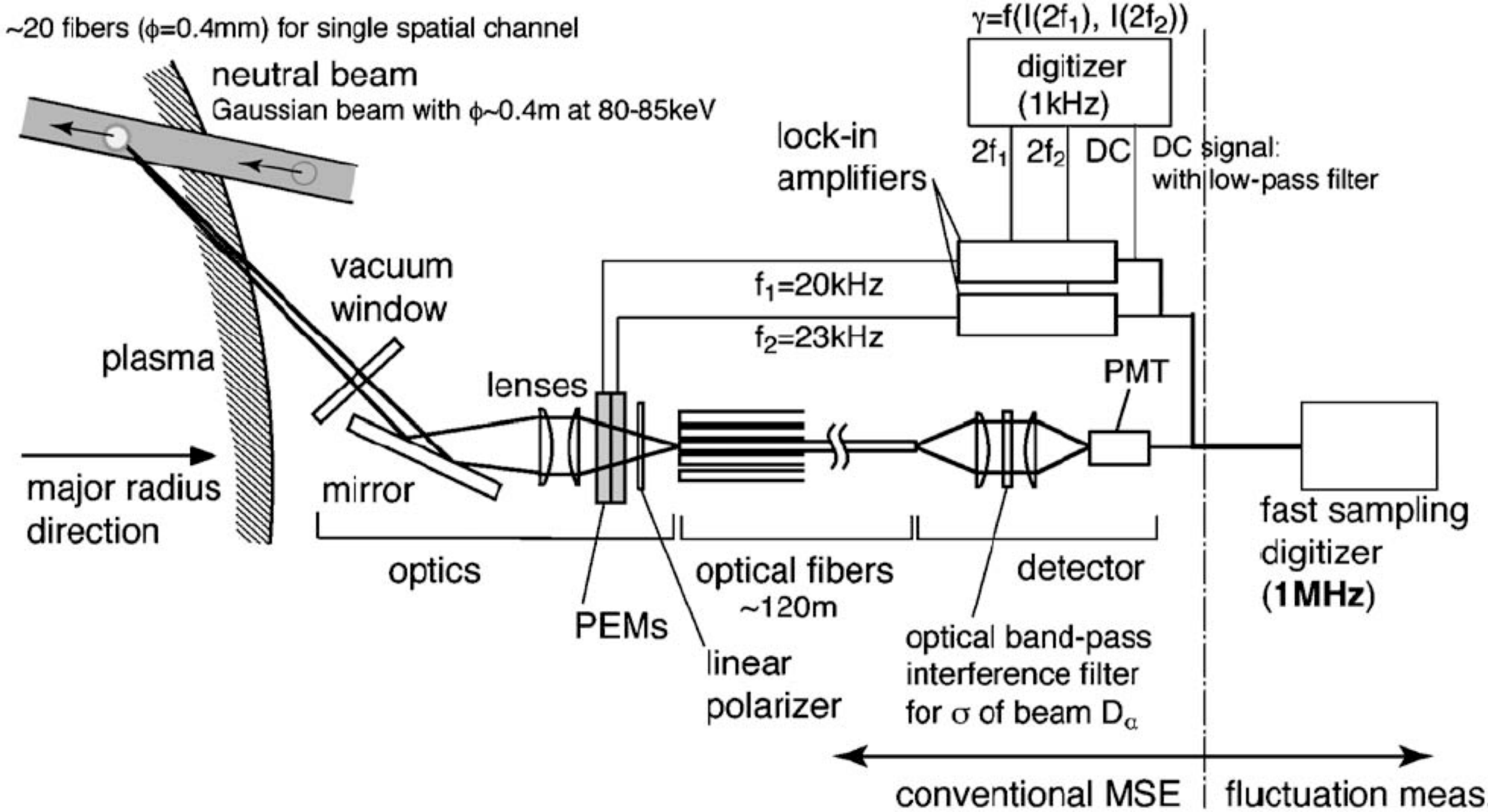
Top view of torus



View from MSE optics

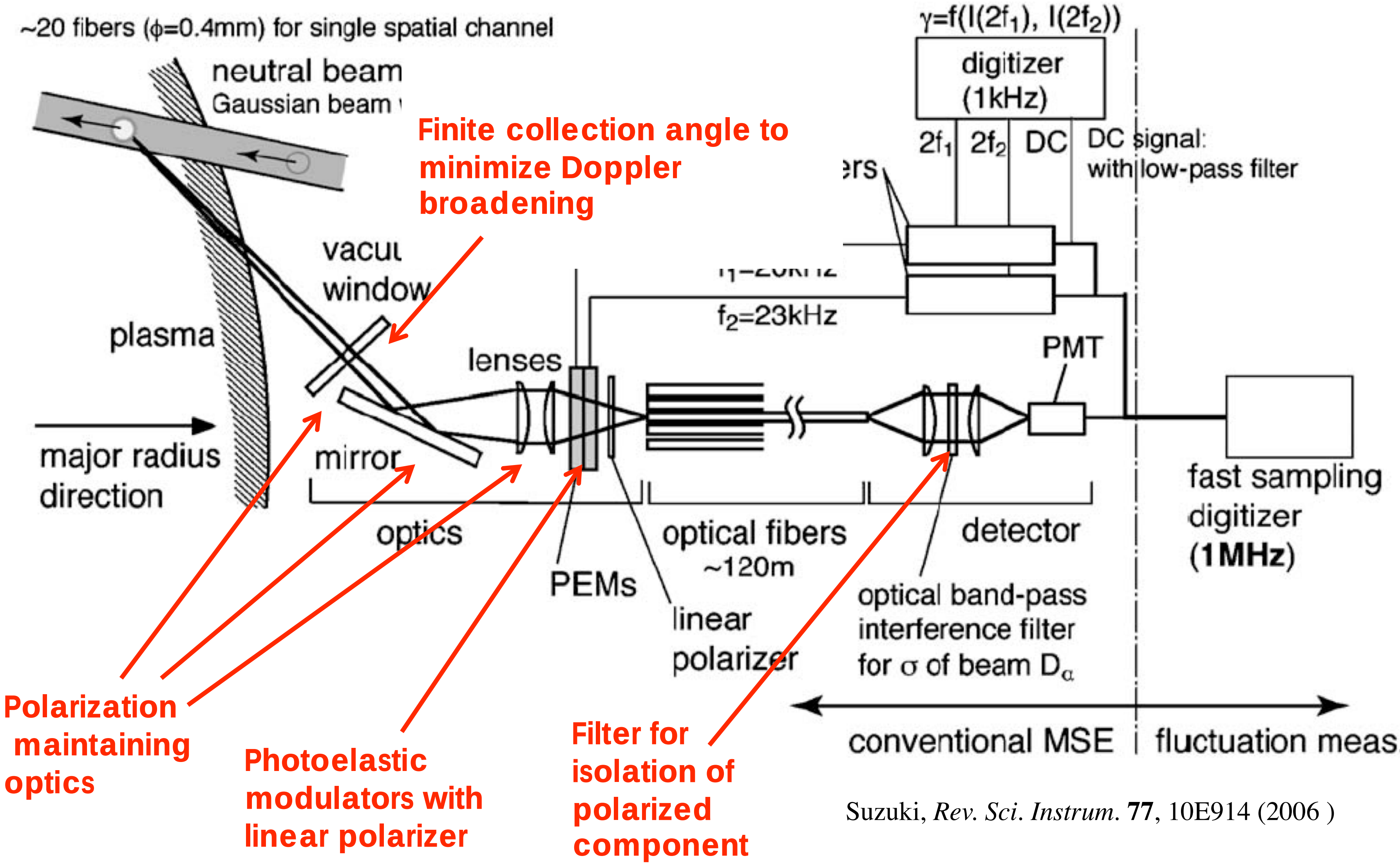


Components of A MSE Analyzer (JT-60U)



Suzuki, *Rev. Sci. Instrum.* **77**, 10E914 (2006)

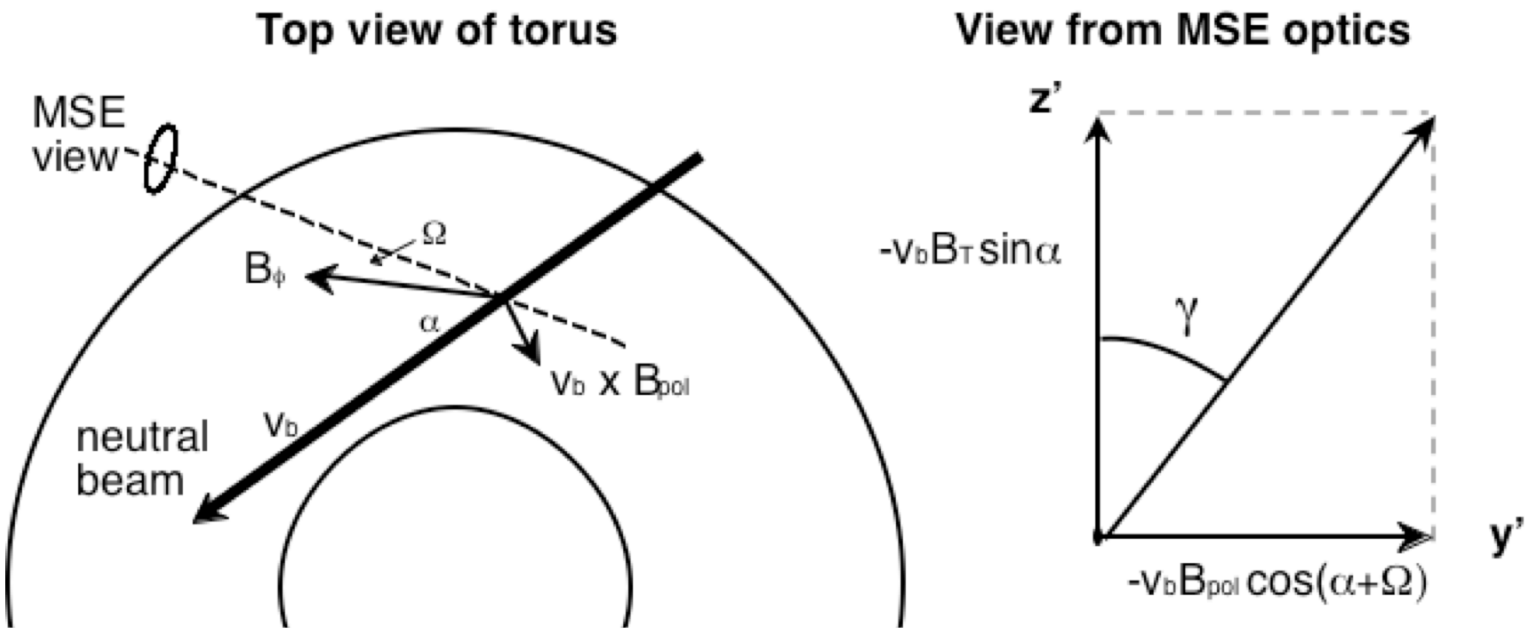
Components of A MSE Analyzer (JT-60U)



Suzuki, *Rev. Sci. Instrum.* **77**, 10E914 (2006)

MSE: Poloidal Field Measurements can be Compromised by Large Local Electric Fields

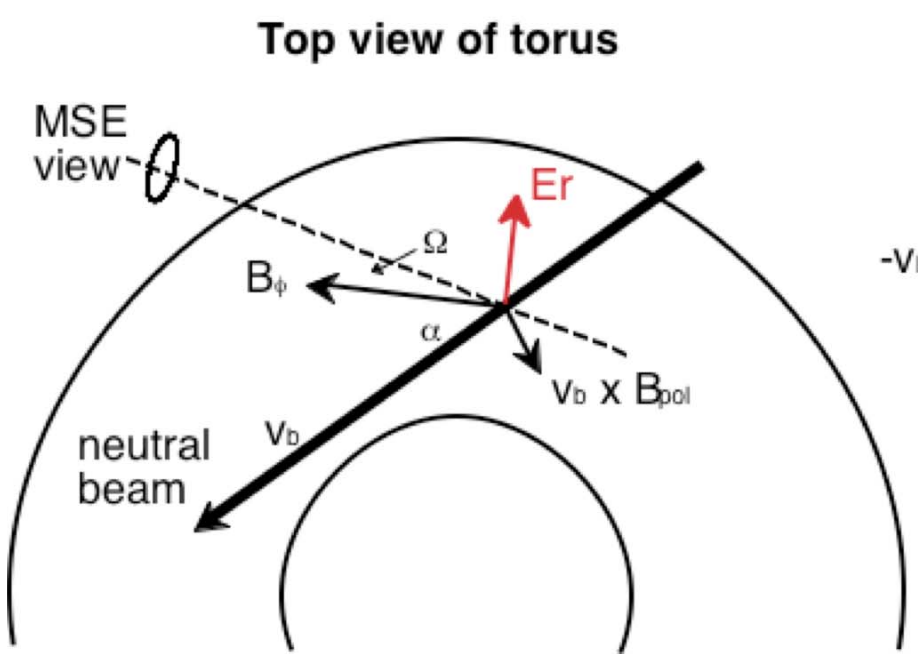
- **Intrinsic Stark effects will combine with MSE; can cause large systematic errors on γ**

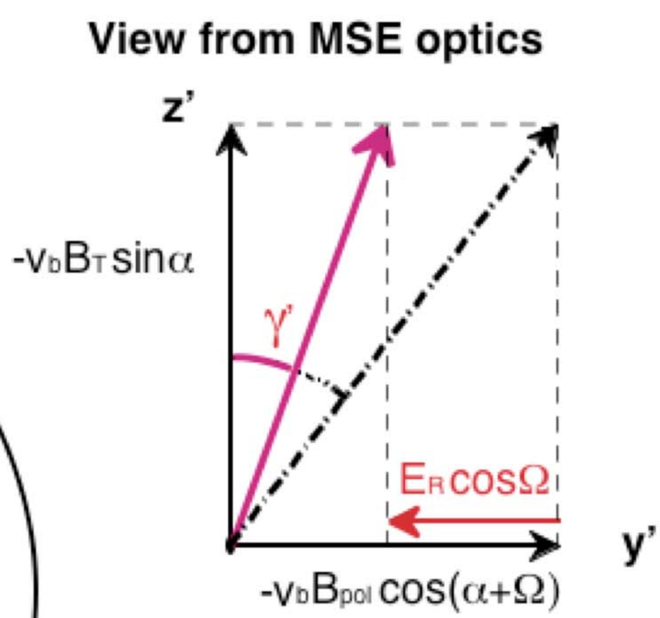


MSE: Poloidal Field Measurements can be Compromised by Large Local Electric Fields

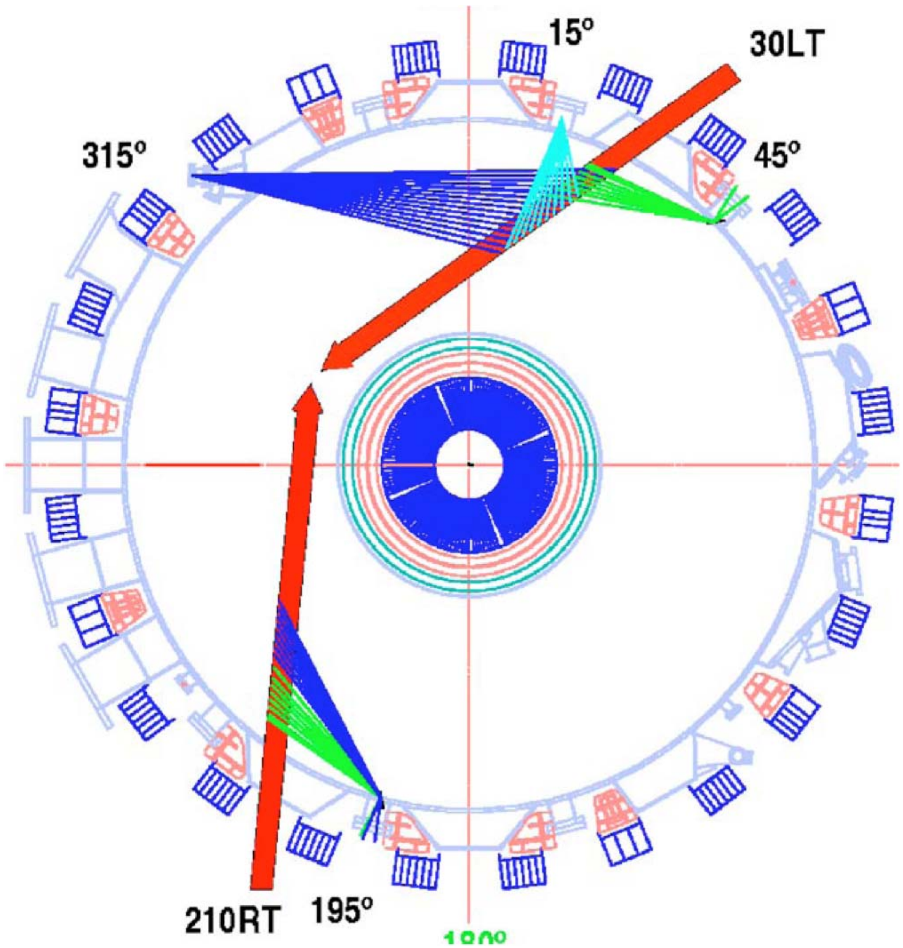
- **Intrinsic Stark effects will combine with MSE; can cause large systematic errors on γ**
  - E_r vector adds to smaller $V_b \times B_{pol}$ field

- **Can be ameliorated by properly matched pairs of views**





Resolve E_r Ambiguity Using Paired Views

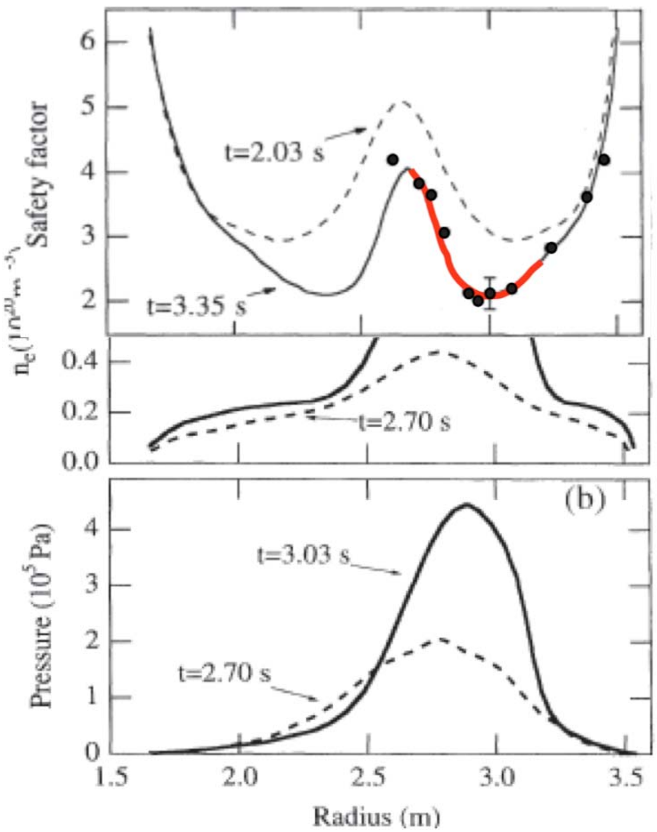


Holcomb, *Rev. Sci. Instrum,* **77**, 10E506 (2006)

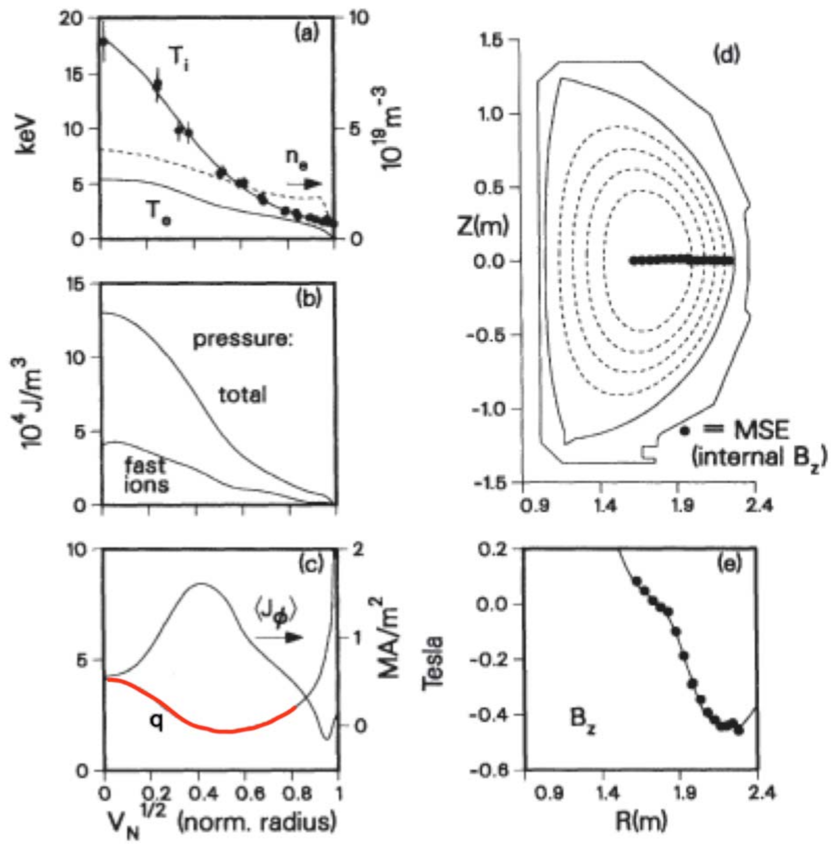
- **Example: DIIID-system as of 2006**
- **64 total views**
- **Utilizes multiple ports to obtain a range of intersection angles with beam**
  - Tradeoff on radial resolution
- **Opposing views to resolve E_r ambiguity**
- **Also complementary views of counter-going beams**

MSE Measurements Gave First Indication that Reversed Magnetic Shear *dq/dr* Led to Increase in Performance

- **Using early NB heating to form hollow current density profile → *dq/dr* < 1**
- **New reversed shear operating regime led to highly peaked density and pressure profiles. Free of MHD despite record pressure gradients**



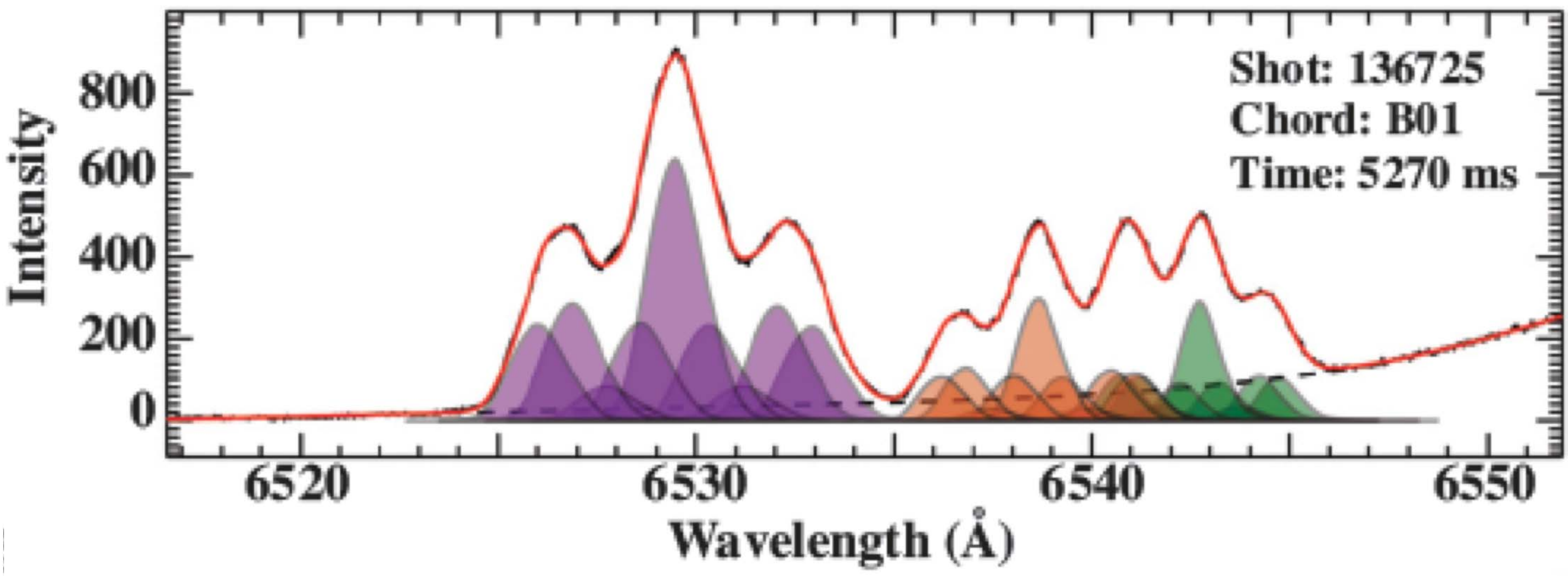
TFTR: Levinton, *Phys. Rev. Lett.* **75**, 4417 (1995)



DIII-D: Strait, *Phys. Rev. Lett.* **75**, 4421 (1995)

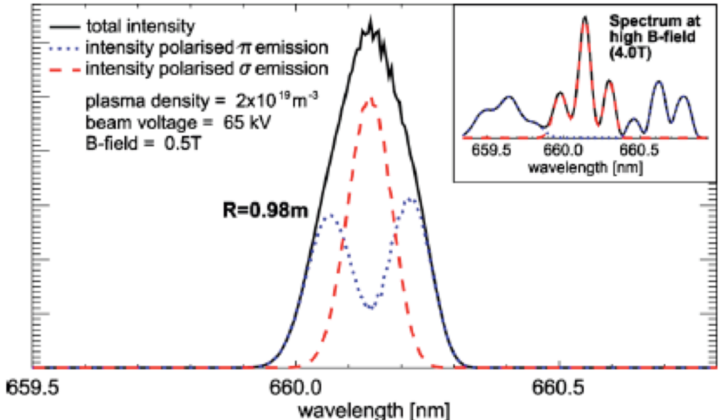
An Alternative MSE Method Uses High Resolution Spectroscopy Instead of Polarimetry (BSTARK)

- **Development of comprehensive fitting model permits measurement of mod|B| directly at viewing location, based on peak splitting.**
- **Eliminates need for polarization analysis, amplitude modulation.**

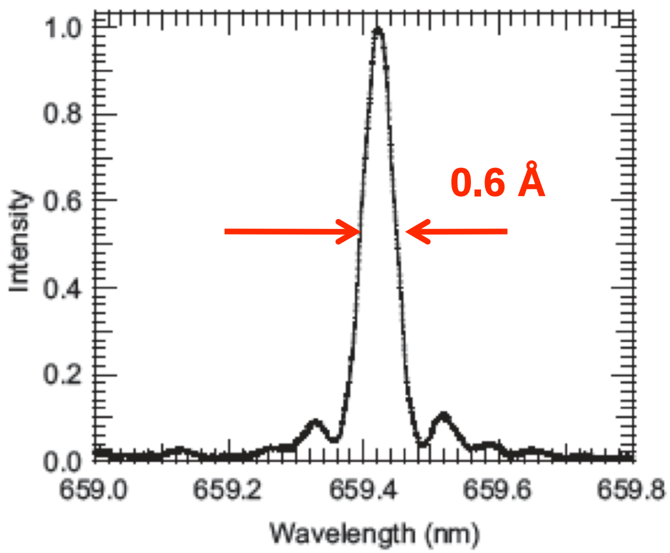


Pablant, *Rev. Sci. Instrum.* **81**, 10D729 (2010)

With Proper Care, MSE Measurements can be Implemented on STs, Other Lower Field Devices



MAST: Conway, *Rev. Sci. Instrum.* **81**, 10D738 (2010)
Implemented 35 channels, 2.5 cm spatial resolution 1ms, ang resolution 0.5°



NSTX: Levinton, *Rev. Sci. Instrum.* **79**, 10F522 (2008)

- **Stark multiplets are blended & washed out by Doppler width**
  - Finite temperature beam
  - Finite collection angle
- **Much higher constraint on achieving net polarization in transmitted light**
  - **Key is proper filtering**
- **Need well-constrained optics**
- **Need well-matched interference filters (MAST) or Lyot filters (NSTX)**
  - Narrowband, tunable bi-refringent filters with wide acceptance angles

A.M. Title and W.J. Rosenberg, *Appl. Opt.* **18**, 3443 (1979)

Outline

- What is active spectroscopy, and what it can do
- How do we do these measurements?
  - Charge exchange spectroscopy
  - Beam emission spectroscopy
- **The use of non (H,D) beams in active spectroscopy**
- Future developments for active spectroscopy

Other Light Atoms can be Used for Beams

- **A fast helium neutral beam** has several advantages over hydrogenic beams
  - Better penetration (~ 50% transmission into TFTR)
  - Good α-particle proxy for helium ash measurements
  - No fractional energy components
  - Reduced beam halo
  - More efficient charge exchange cross sections in certain energy regions

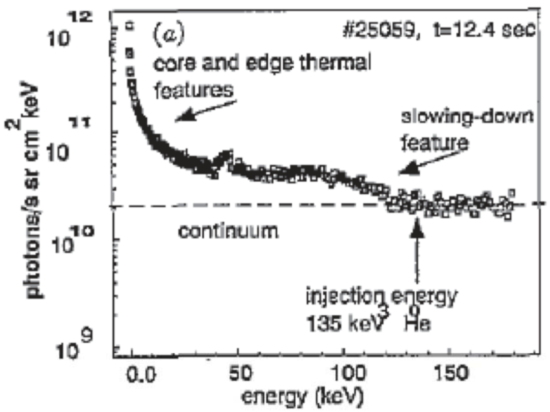
See: **Recent integrated modeling improvements**

J. M. Muñoz Burgos, paper UP9.00065 (Thurs afternoon)

Examples: Helium Beams

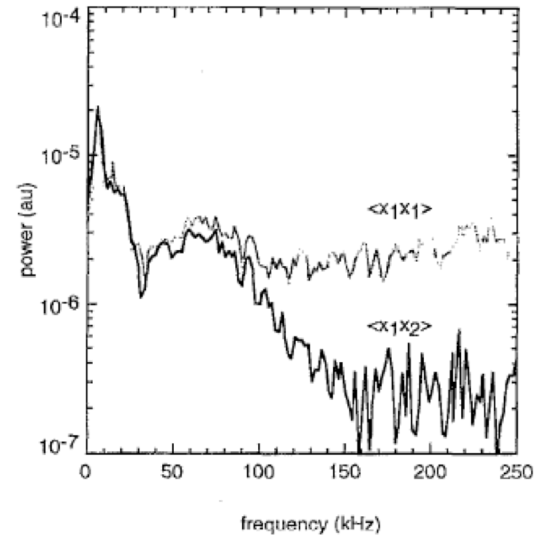
Slowing down spectra on JET using 135 keV He heating beams

Von Hellerman, *Plasma Phys. Control. Fusion* **35**, 799-824 (1993)



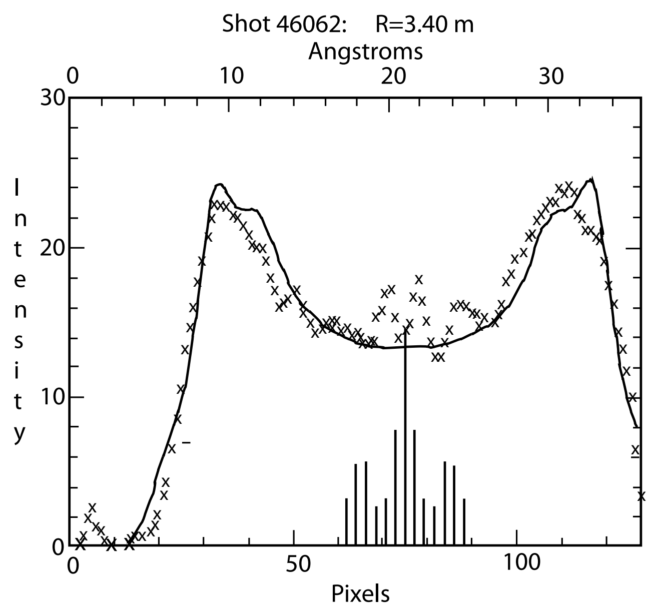
Fluctuation spectra on TEXT-U using 40 keV He DNB

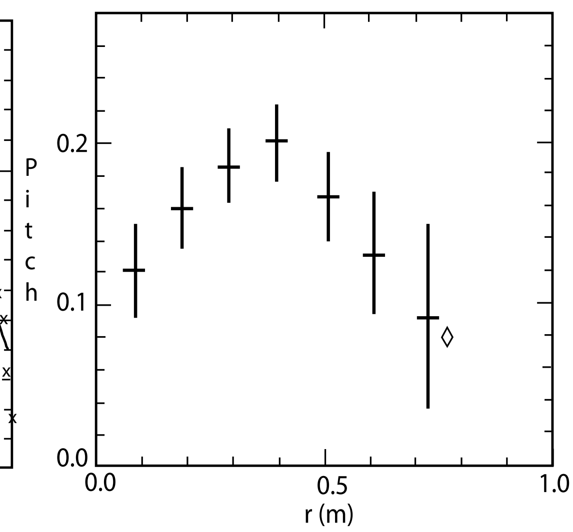
Durst, *Rev. Sci. Instrum.* **66**, 842 (1995)



Measurement of magnetic pitch angle profile on TFTR using emission from orbiting 60 keV He+ from He DNB

Jobes, *Rev. Sci. Instrum.* **61**, 2981 (1990)



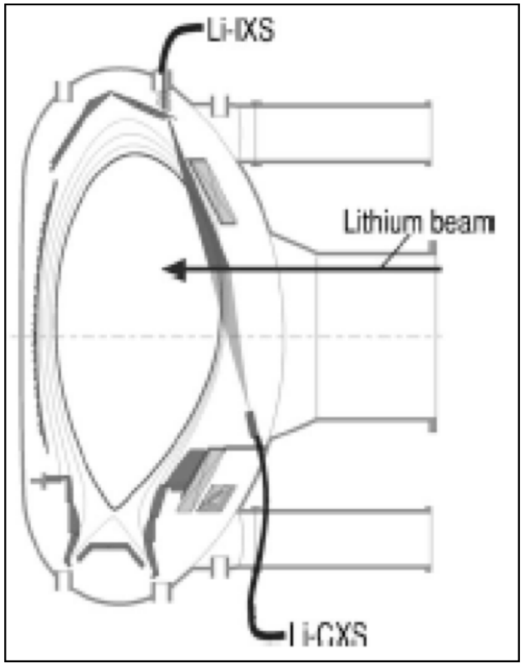


Lithium Beams Have Several Advantages

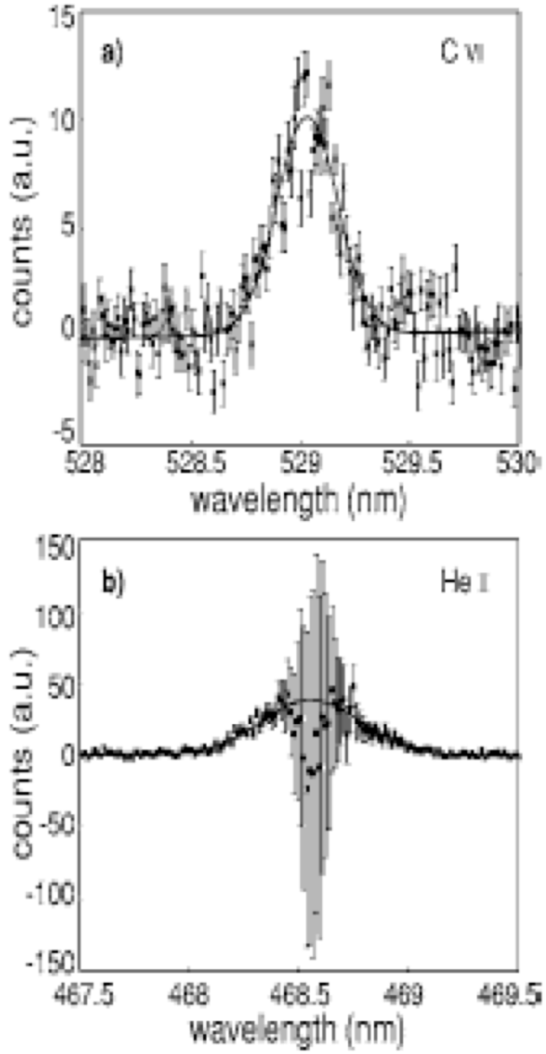
- Li 2S-2P 6708Å resonance line is split by Zeeman effect in a magnetic field. Lines are polarized relative to B
- States have negligible Stark effect – eliminates electric/ magnetic ambiguity that occurs with MSE
- Cross section for collisional excitation is large (500 x D_α) thus can use a very small beam, permitting very fine spatial resolution
- Correspondingly large charge exchange cross sections (100xH^0), preferentially into higher n-shells of target ions, makes effective small-scale measurements
- Correspondingly large ionization cross sections increase attenuation, limit use to edge plasma diagnostics

Examples: Lithium Beam Charge Exchange

- **ASDEX system**

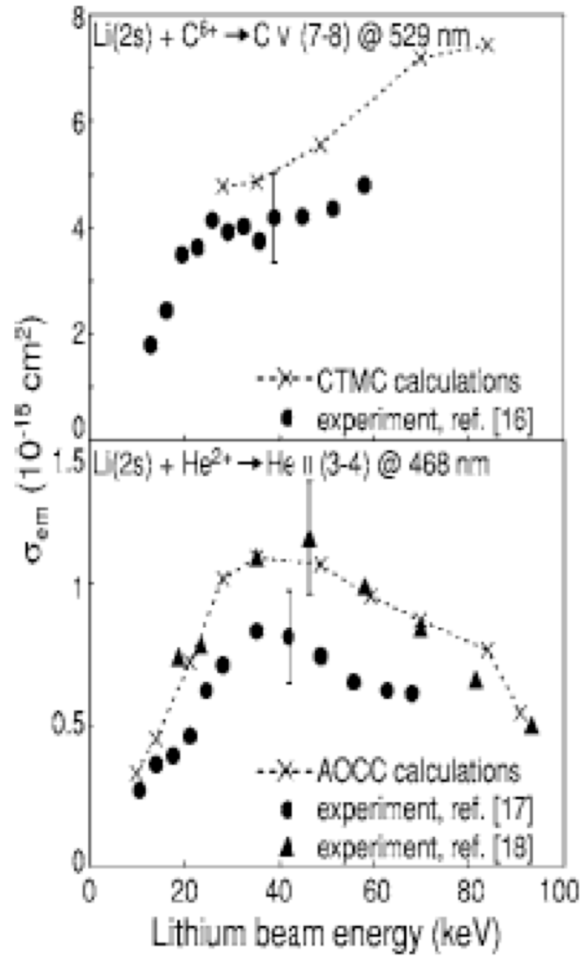


Simultaneous LI-BES helps with absolute calibration of impurity densities



Fits to C and He ions

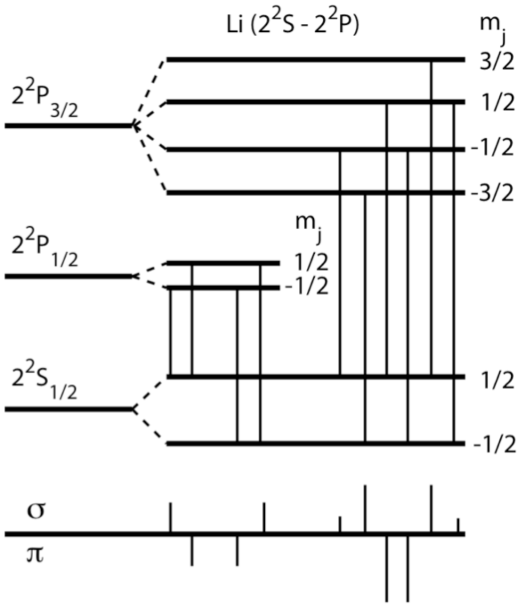
Cross sections are ~100x equivalent H ones



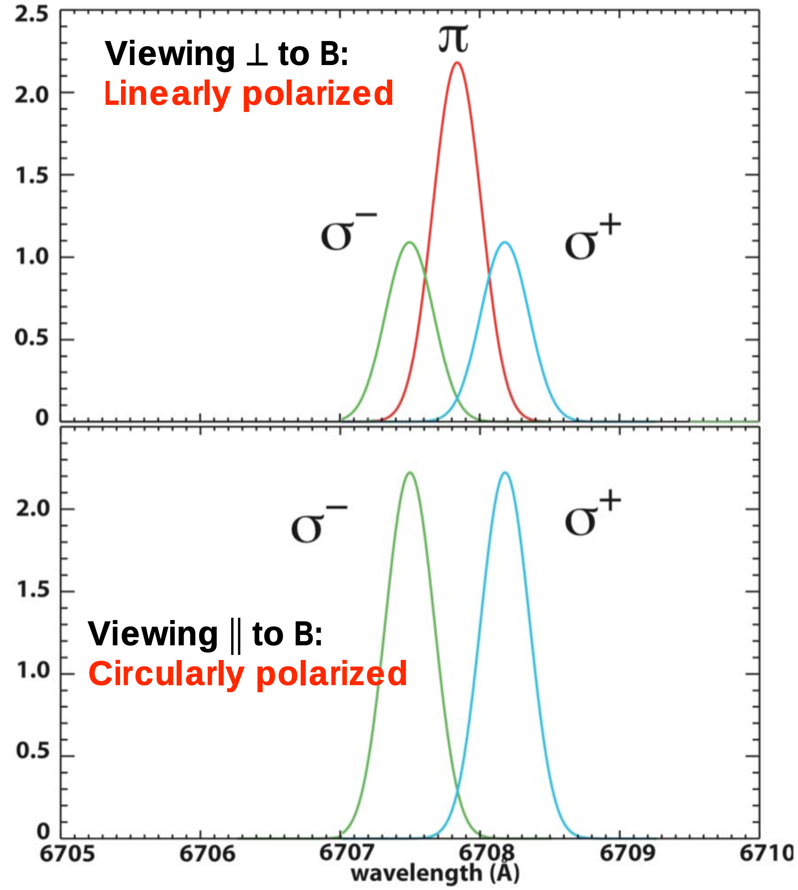
from Wolfrum, *Rev. Sci. Instrum.* **77**, 033507 (2006)

Examples: Lithium Edge Current Density Measurements

- **Based on Zeeman splitting of resonance line**
- **Emission polarized linearly perpendicular to B**
- **Circularly polarized parallel to B**
- **Analyze ratio of circular to linear, gives direction of B-field, or B_{POL}/B_{TOR}**

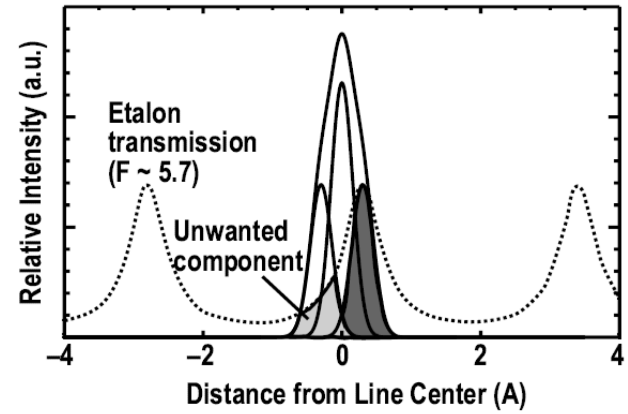


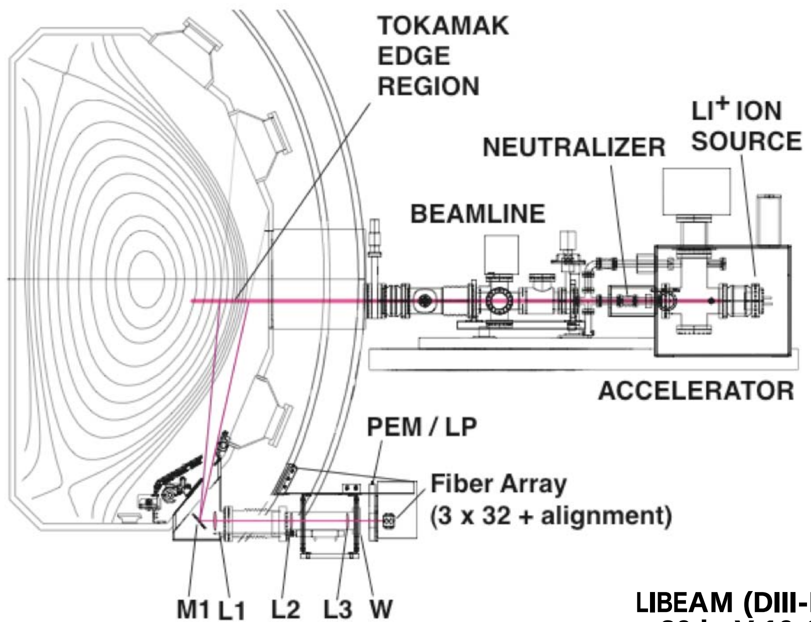
E.U. Condon and G.H. Shortley, *The Theory of Atomic Spectra*, Cambridge University Press, Cambridge (1963)



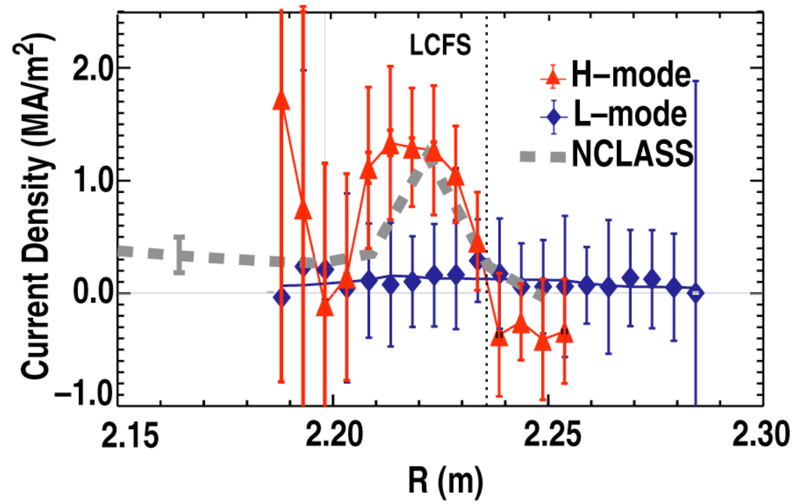
Examples: Lithium Edge Current Density Measurements

- Relative size of Zeeman splitting is a challenge (~0.3 Å)
- Need low-temperature beam – thermionic ion source, Na vapor neutralizer
- Use thermally tuned doubled etalons for 0.3Å passband
- Use PEMS and AM technique but utilize different harmonics to analyze circular and linear polarization
- Able to resolve cm-scale features in edge J_T





LIBEAM (DIII-D):
30 keV,10-20 mA Li0
1-2 cm dia



Thomas, *Phys. Rev. Lett*. **93**, 065003 (2004); *Phys. Plasmas* **12**, 056123 (2005)

Outline

- What is active spectroscopy, and what it can do
- How do we do these measurements?
  - Charge exchange spectroscopy
  - Beam emission spectroscopy
- The use of non (H,D) beams in active spectroscopy
- **Future developments for active spectroscopy**

Active Spectroscopy Developments are Focused in Two Areas

1. **Adapting active spectroscopy to the next generation of machine**
   - ITER raises a number of separate implementation challenges, both technically and with respect to basic physics

2. **Continuing to develop these techniques for the present class of experiments**
   - Lots of paths forward here, improvements will continue to contribute to physics programs

Measurements on Next Generation of Machines

- **Expectation:**

  Larger, hotter, denser, large α- and fast ion fraction. Also severe radiation environment.

- **Consequences:**

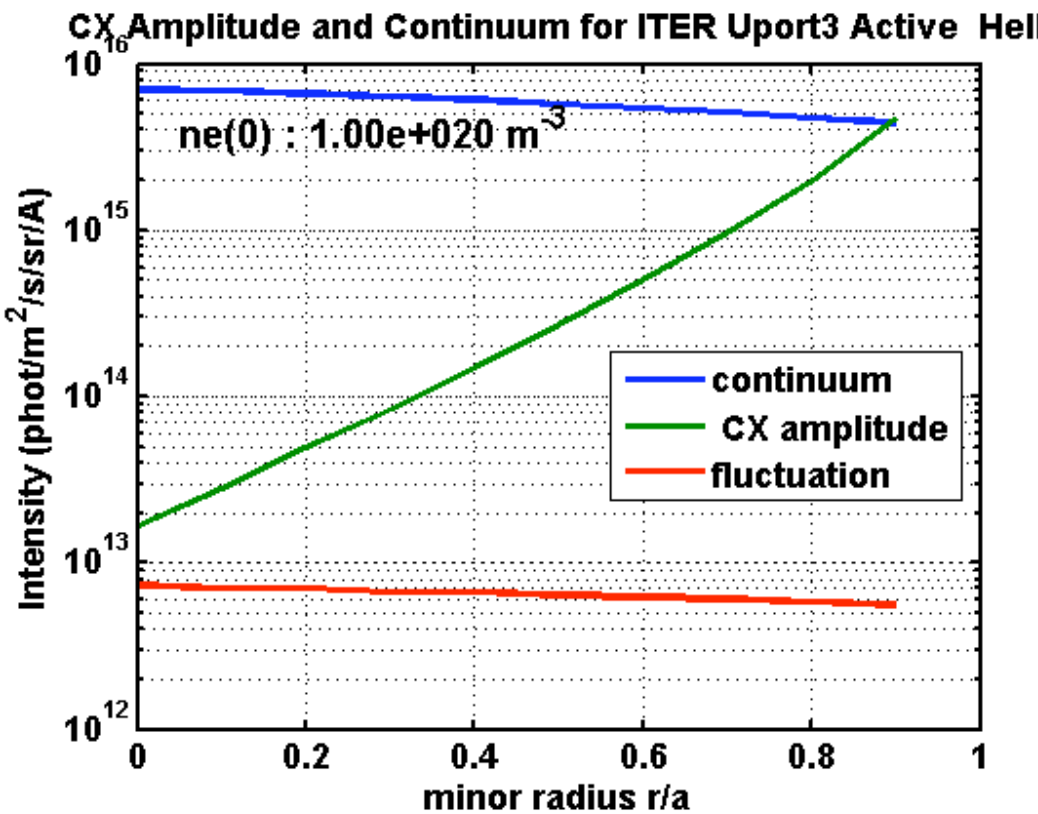
  Penetration requirements for heating beams drive beam energy up beyond peak for charge transfer

  - **Need negative ion beams since can't efficiently neutralize high energy positive ion beams**
  - **Good for MSE – CES measurements will require lower energy beam – dedicated Diagnostic Neutral Beam**

ITER Active Spectroscopy Measurements are a Critical Component of the Diagnostic Set

- **ITER Baseline specifies 90 parameters to be diagnosed**
- **Active spectroscopy is expected to contribute to determining almost a third of these**

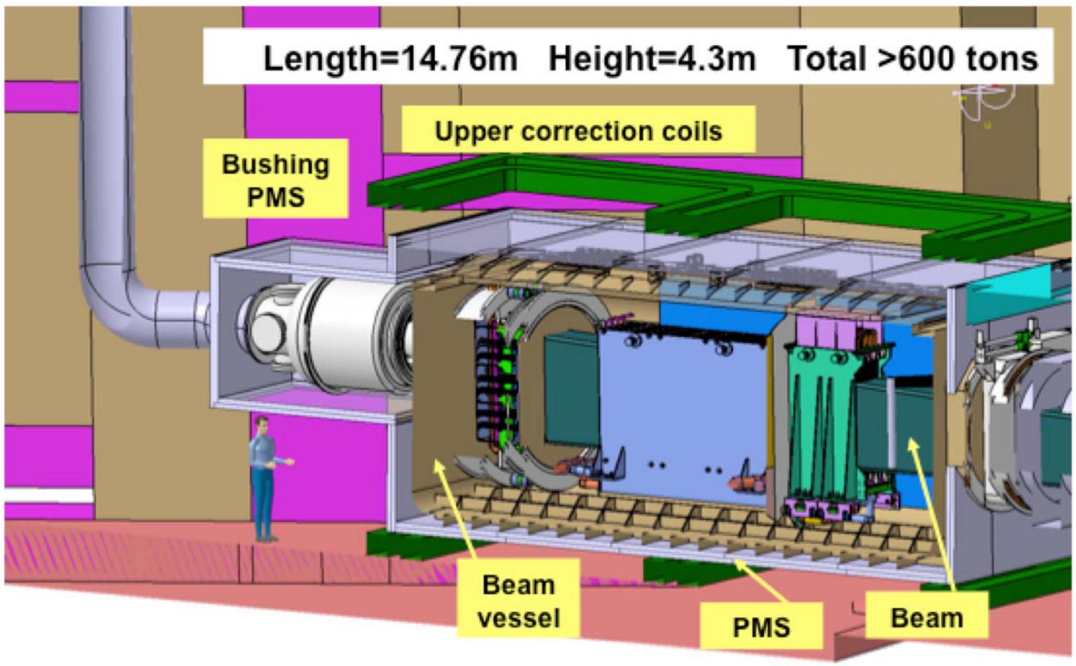
- **BUT…a two-fold challenge**
- **Must measure in the presence of large backgrounds**
- **Measurements must be conducted in a hostile environment**

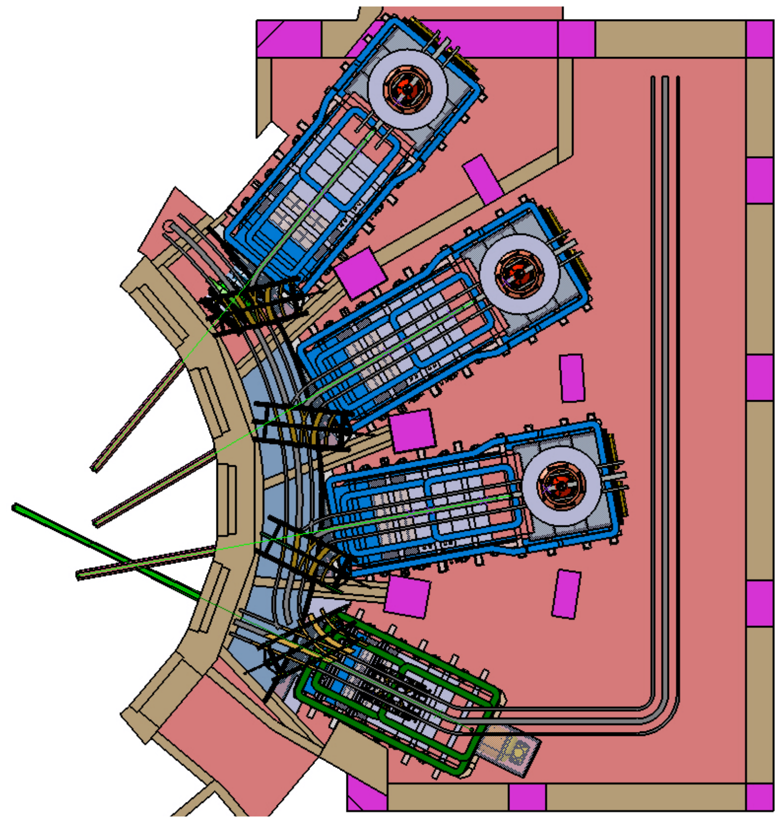


Thomas, *Rev. Sci. Instrum.* **68**, 332 (1997)

ITER DNB Uses Same RF Source as 1 MeV Heating Beams, But Simplified Accelerator Structure

- **Negative ion based, so single energy component**
- **100 keV H0 ~2 MW to plasma, (60A extracted H- current)**





ITER Plan Calls for 4 Active Spectroscopic Systems, All Port-Plug Based

- **Must be engineered for robustness, neutron/tritium compatibility, and optics survivability <u>in addition to diagnostic requirements</u>**

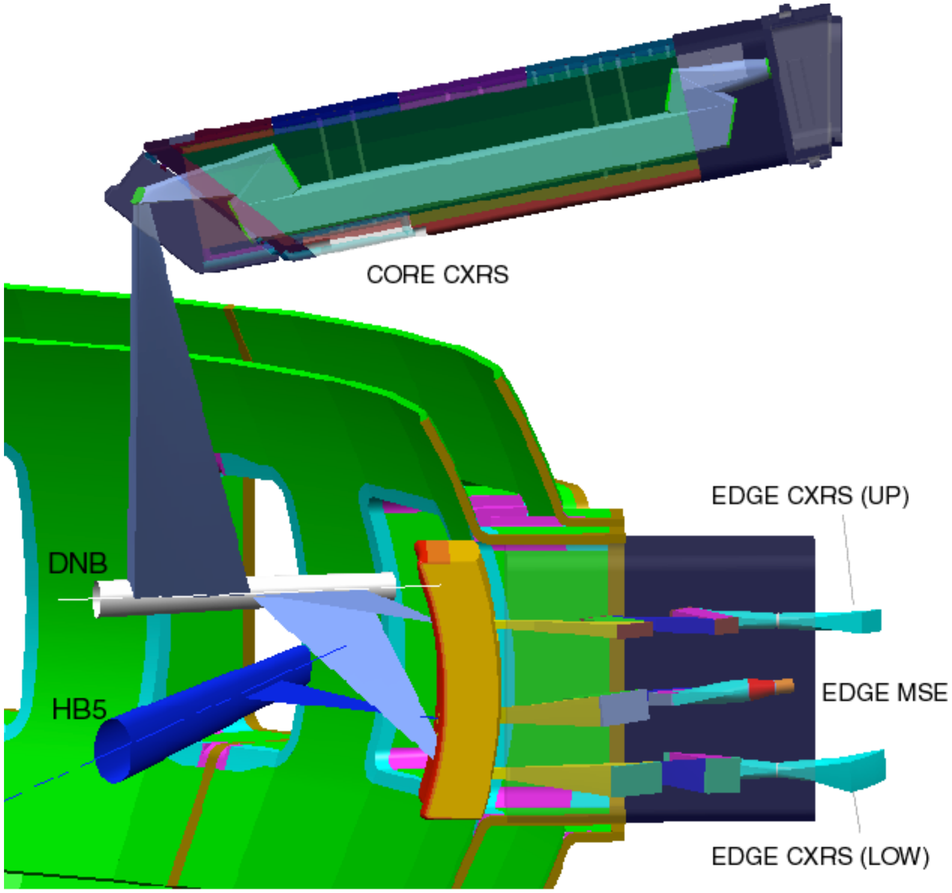
4 systems

CXRS+BES:CORE
: **UPP03**

CXRS+BES:EDGE
: **EQ03**

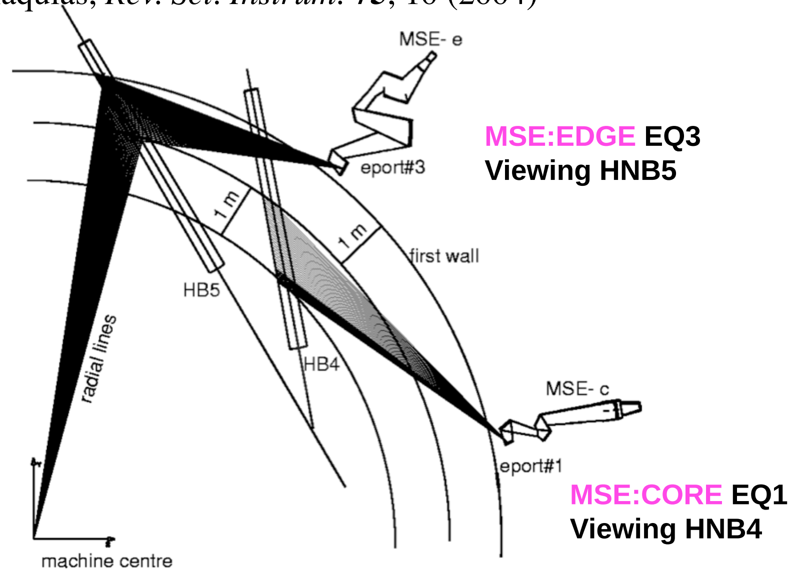
MSE:EDGE
: **EQ3**

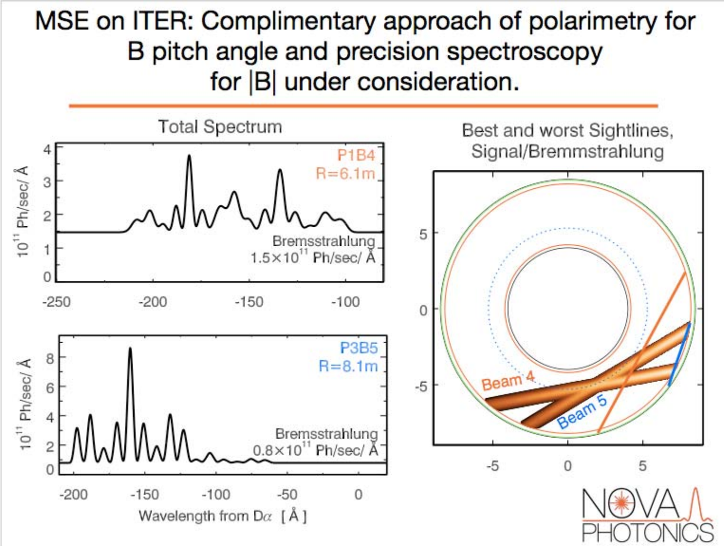
MSE:CORE
: **EQ01**



MSE Measurements are Based in Two Separate Equatorial Port Plugs

Edge and Core MSE views on HNB 4 and 5
A. Malaquias, *Rev. Sci. Instrum.* **75**, 10 (2004)



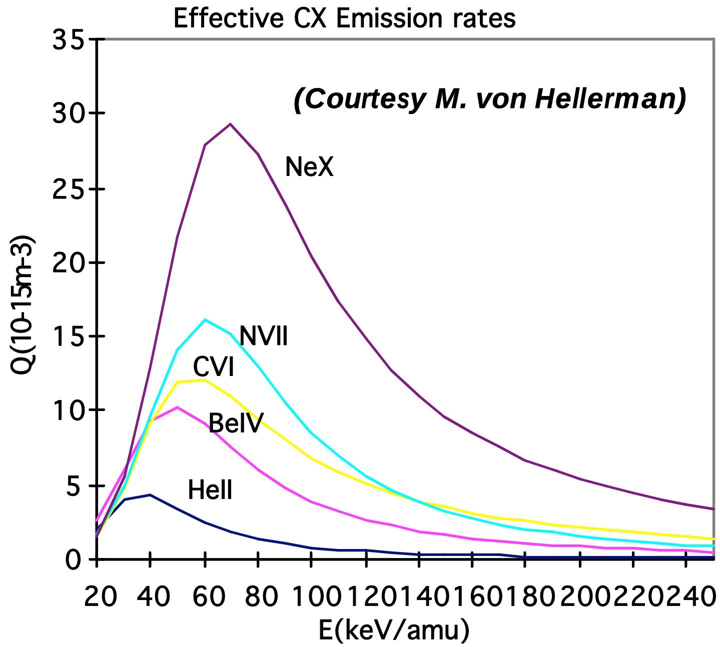


Calculated MSE spectra (extreme views)
(Courtesy F. Levinton, Nova Photonics)

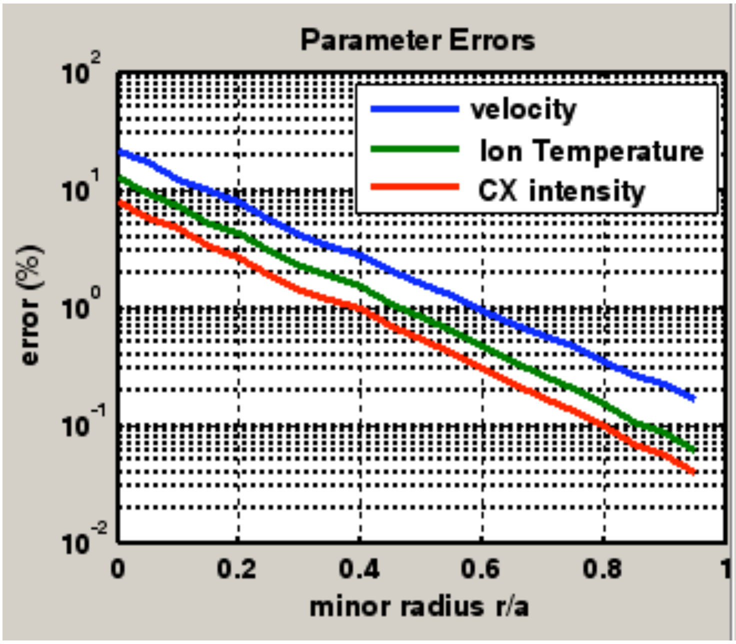
- **The main challenge is good characterization of polarization changes in optical system, particularly first mirror**
- **Probably pursue both polarization and mod|B|spectroscopic measurements for better consistency**
- **Option of alternate view which obtains whole profile from a single beam exists but is not in the baseline**

The CXRS Measurement Requirements Make Strong Demands on DNB and Spectrometer Performance

Parameter	Range	Time Res	Space Res	accuracy
v_{TOR}	5-200 km/s	10 ms	a/30	5 km/s
v_{POL}	5-50 km/s	10 ms	a/30	5 km/s
T_I	0.5-40 keV	10 ms	a/30	5%
n_z/n_e	0.05-5%	100 ms	a/30	10%
Core He concentration	1-10%	100 ms	a/10	10%

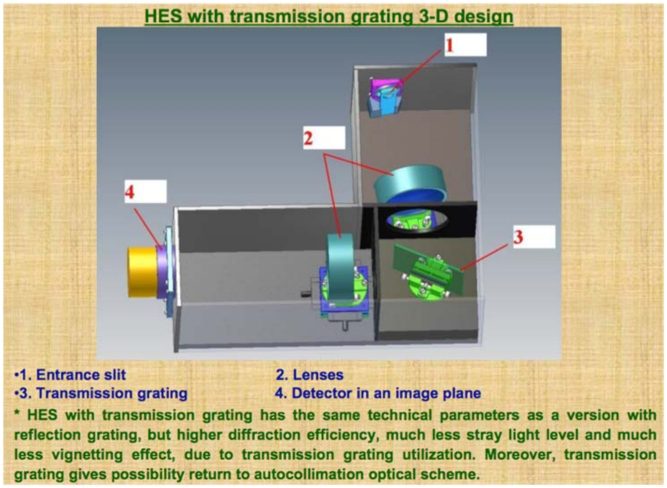


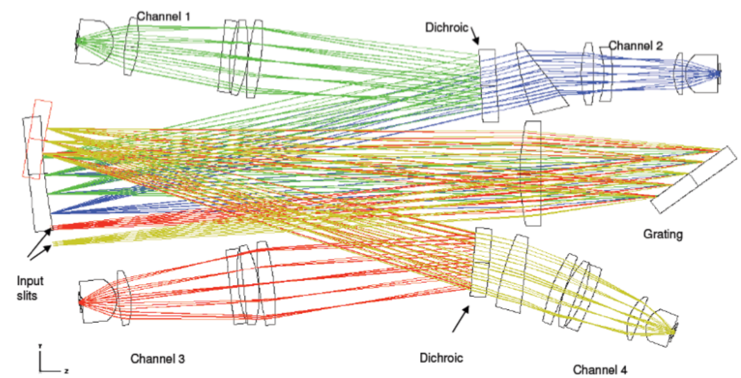
Form of charge transfer cross-section determines choice of beam energy….



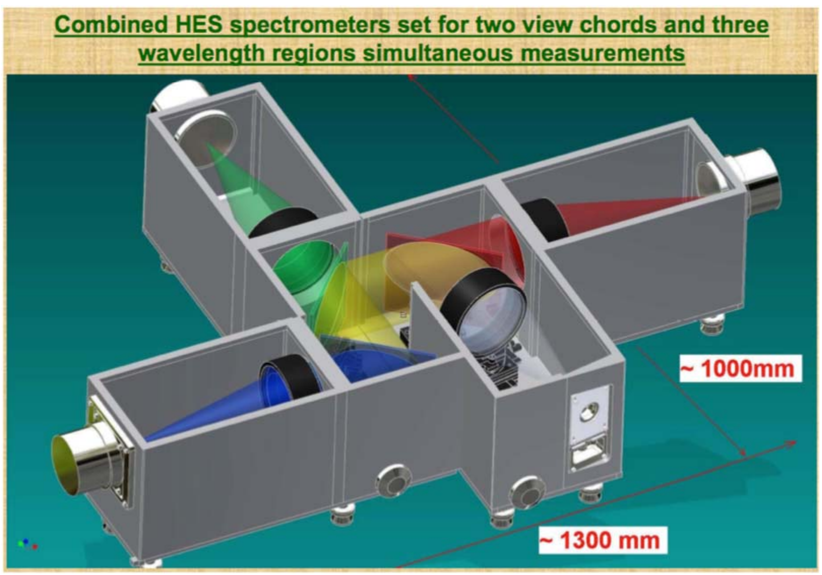
…But ITER size, extreme attenuation determines ultimate signal levels and diagnostic performance

Compact, Efficient Spectrometers are Being Developed for the Core and Edge CXRS Systems

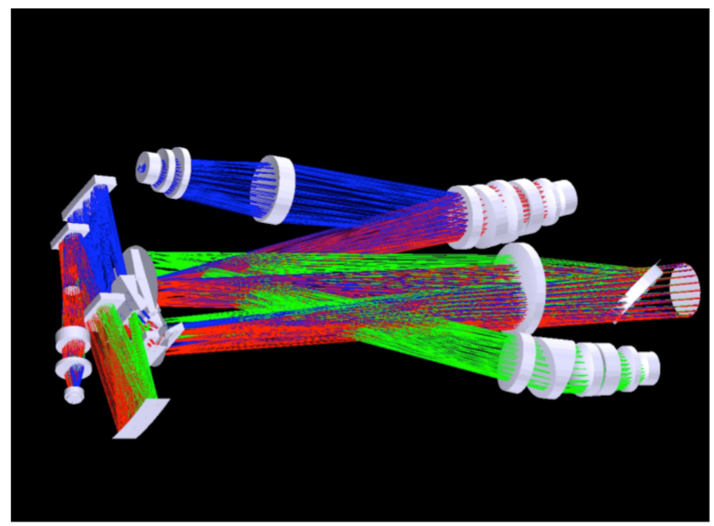




Prototype 4-wavelength Core system (EU)

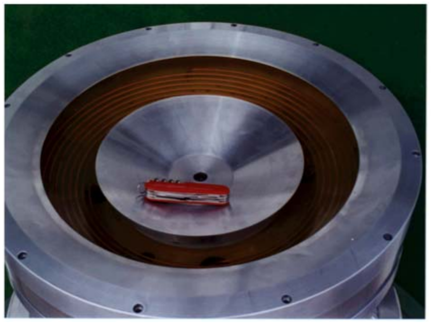


3 wavelength Edge system (RF)

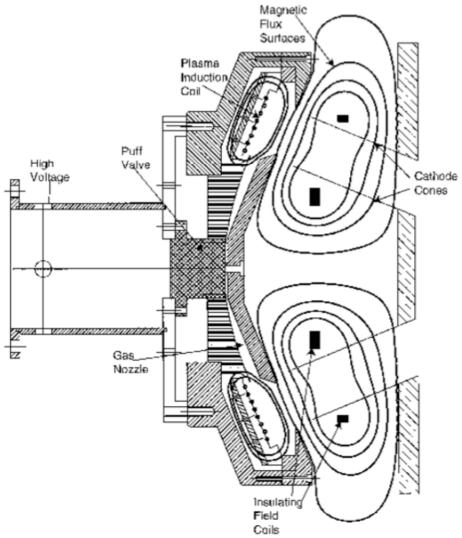


Development of an Intense, Pulsed Neutral Beam Could Enhance ITER CXRS Measurements

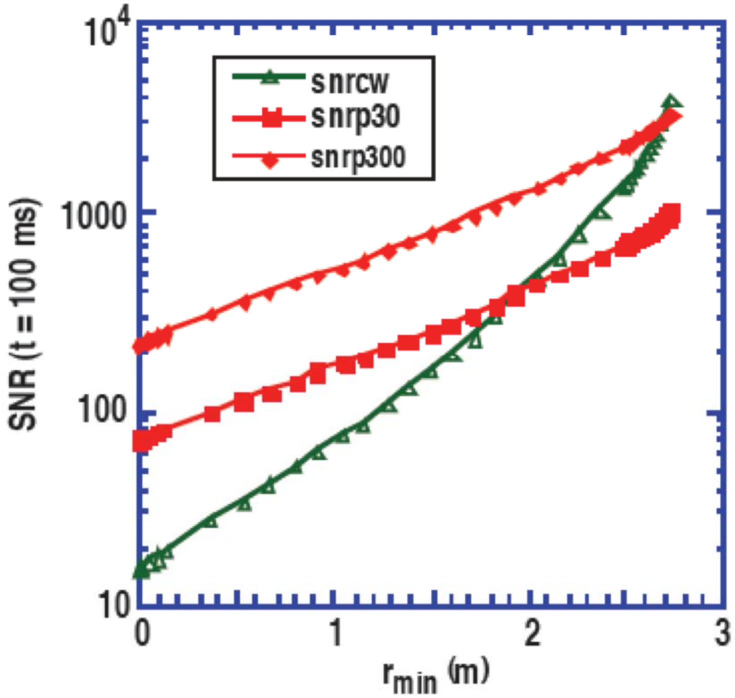
- **Uses magnetically insulated diode as pulsed plasma source**
- **~100 keV, ~50 kA, pulse length 1 μs, rep rate 30-300 Hz**
- **Gating detectors in phase would eliminate most background**



LANL MID hardware and schematic



Davis, et al., *Rev. Sci. Instrum.* **68**, 332 (1997)

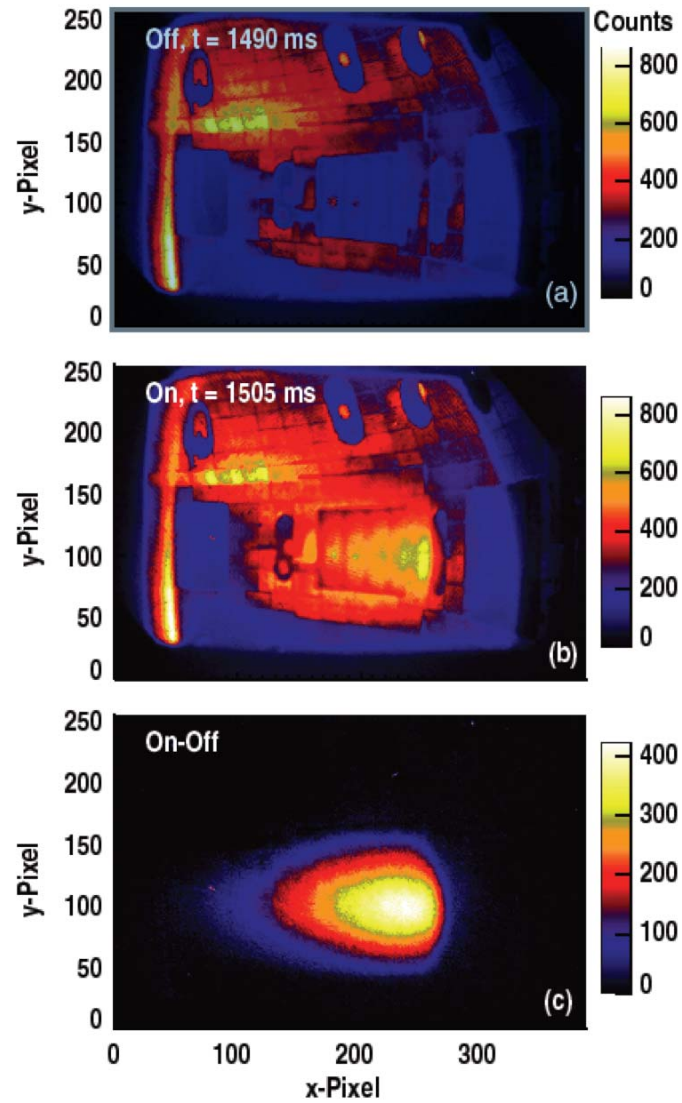


ITER simulations using CW and pulsed beam: 8-20x improvement

Thomas, et al., *Varenna.* (1998)

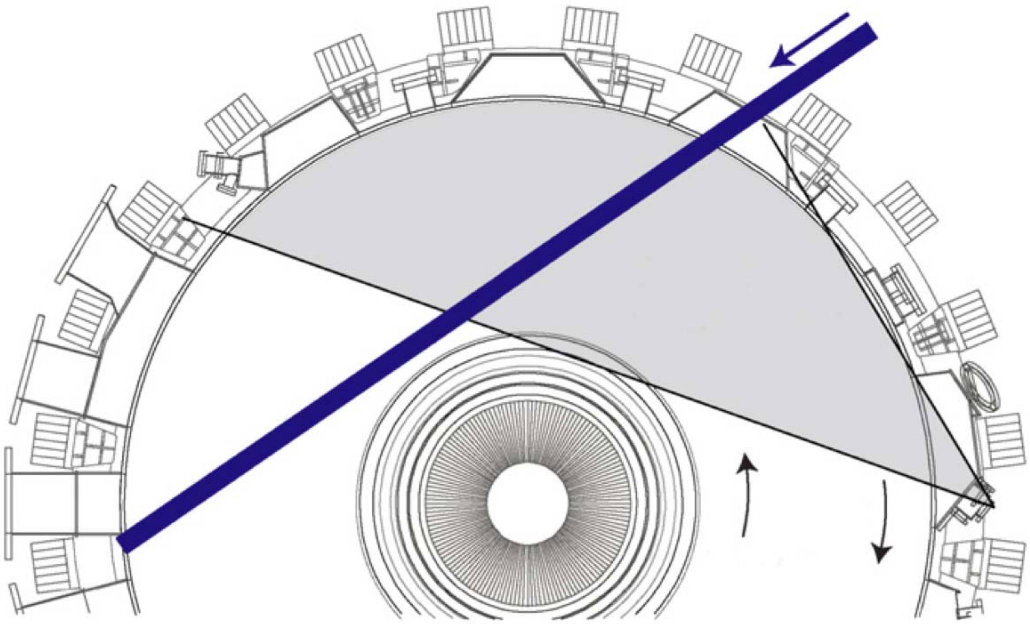
Near Term Developments: Using High Performance CCD Cameras for Active Spectroscopic Imaging

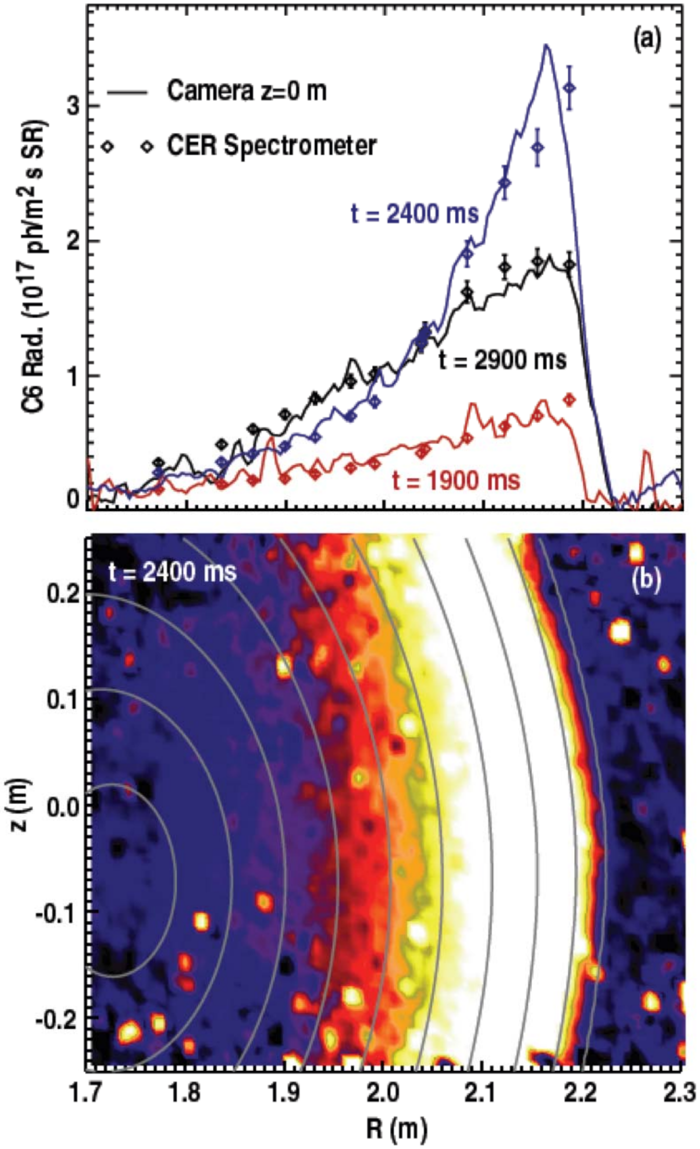
- **Example: Imaging BES using narrowband filters, exposure time synced with beam modulation** [Van Zeeland, *Plasma Phys. Control. Fusion* **52**, 045006 (2010)]
- **Here the tradeoff is on spectral resolution for spatial resolution**
- **Increases in sensitivity and well characterized gain allow improvements in exposure times/frame rates. Can image coherent structures in plasma**
- **Careful crafting of filter passband and intensity calibration is important. Existing filters can set limits on field of view**



Example: Imaging CER

- Initial tests using transmission filters
- Same caveats on FOV
- When calibrated, got good agreement with point CER measurements

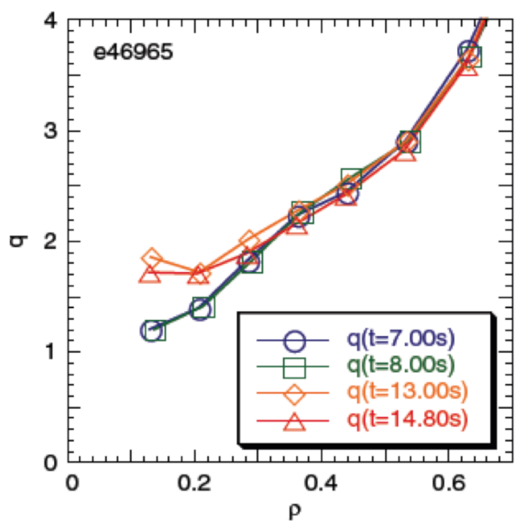


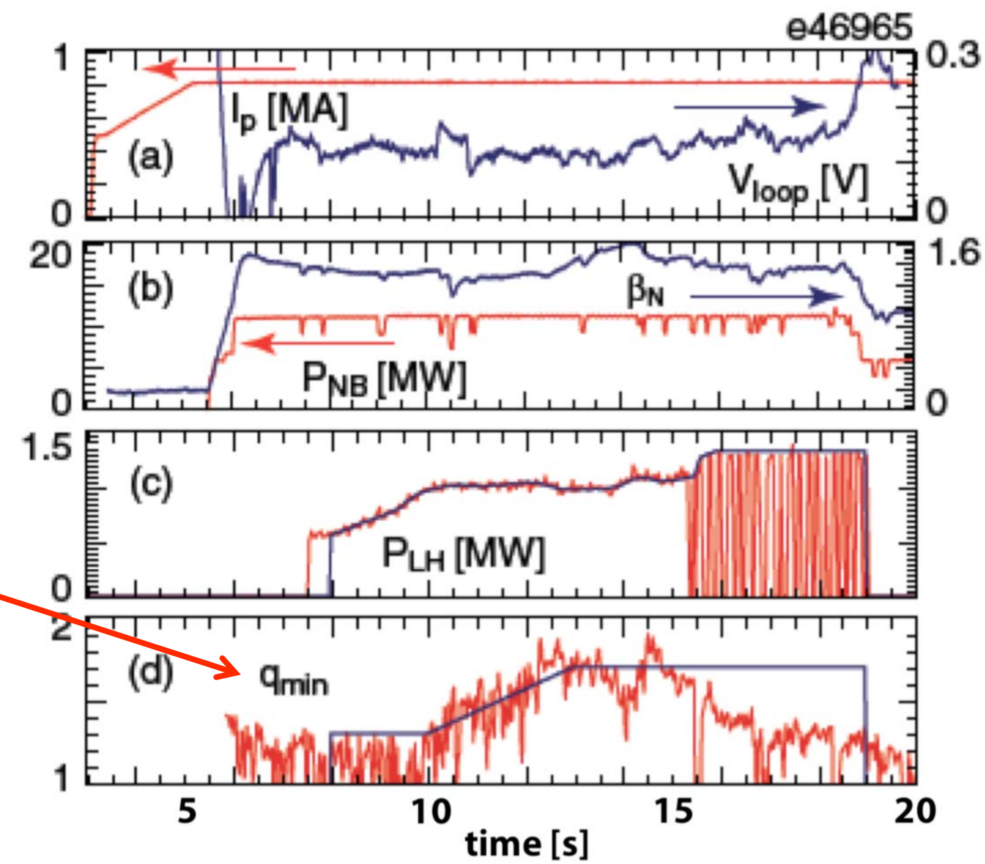


[Van Zeeland, *Plasma Phys. Control. Fusion* **52**, 045006 (2010)

Another Near-Term Development is the Use of Active Spectroscopic Inputs for Feedback Control

- **Example: use of MSE and near real time analysis to control q_{min} in JT-60U using off-axis LHCD**
- **Safety factor profile determined from 9 spatial MSE points (10 ms averaging**
- **Demand q_{min} used to throttle P_{LH} and keep real q_{min} below 2**

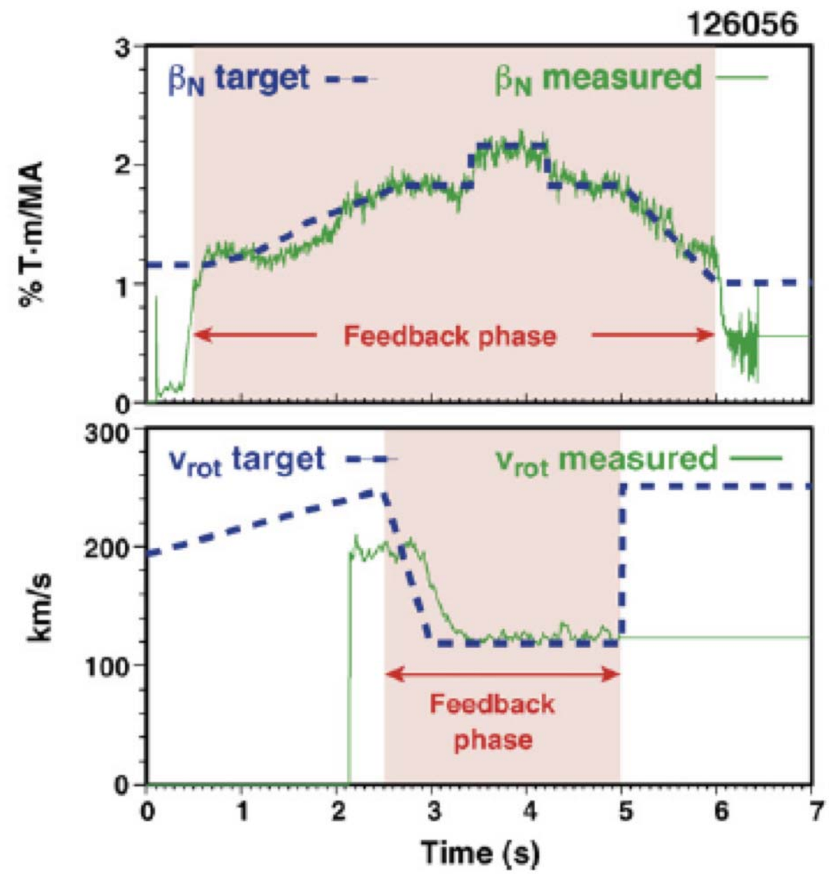




Suzuki, *Nucl. Fusion* **48**, 045002 (2008)

Another Near Term Development is the Use of Active Spectroscopic Inputs for Feedback Control

- **Example: use of CER and near real time analysis to control rotation in DIII-D using co and counter NBI**
- **Modified Plasma Control System for multiple feedback loops**
- **Allows simultaneous control of plasma rotation and stored energy**
- **Exciting future for performance control**



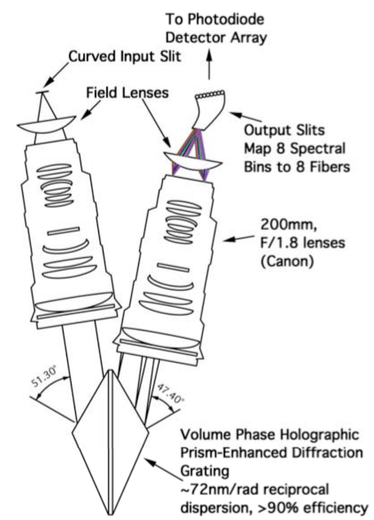
Scoville, *Fusion Eng. Design* **82**, 1045 (2007)

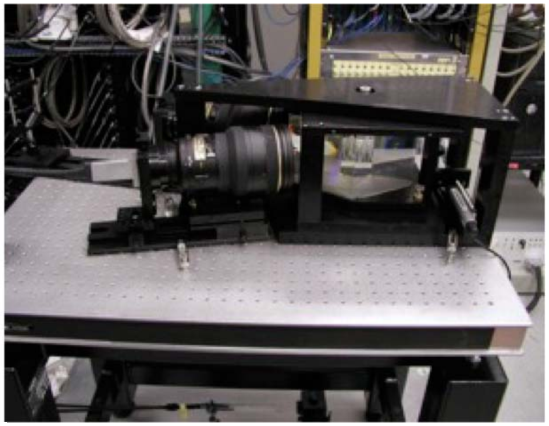
Other Recent Developments in Active Spectroscopy

- **Through Advances in Throughput**

  T_I fluctuations using UF-CHERS on CVI line

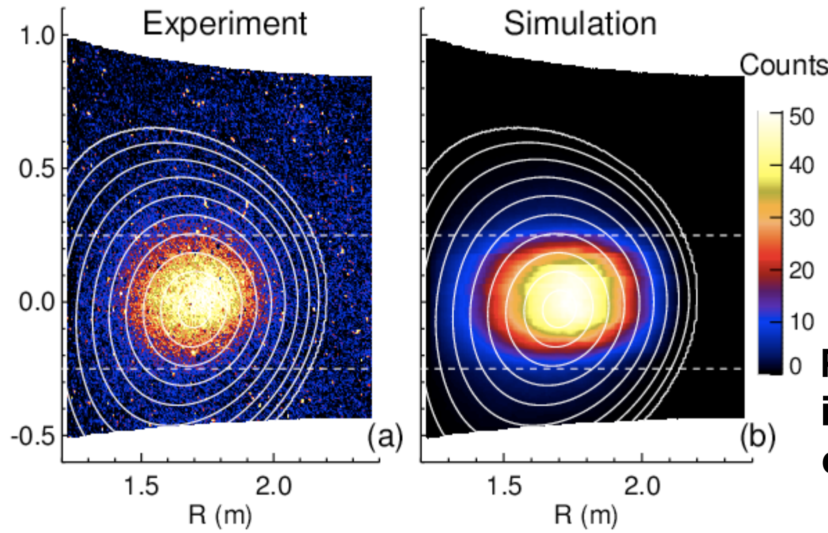
  Uzun-Kaymak UP9.00064 Thurs PM





- **Through Advances in Spatial Resolution**

  Imaging FIDA using fast camera, tilt-tuned D_α filter [Van Zeeland, *Plasma Phys. Control. Fusion* **51**, 055001 (2009)]

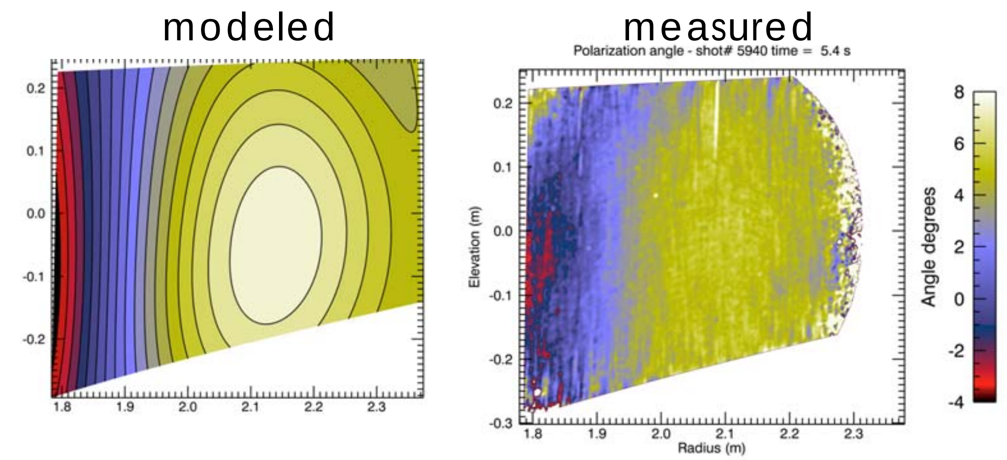


FIDA intensity on DIII-D

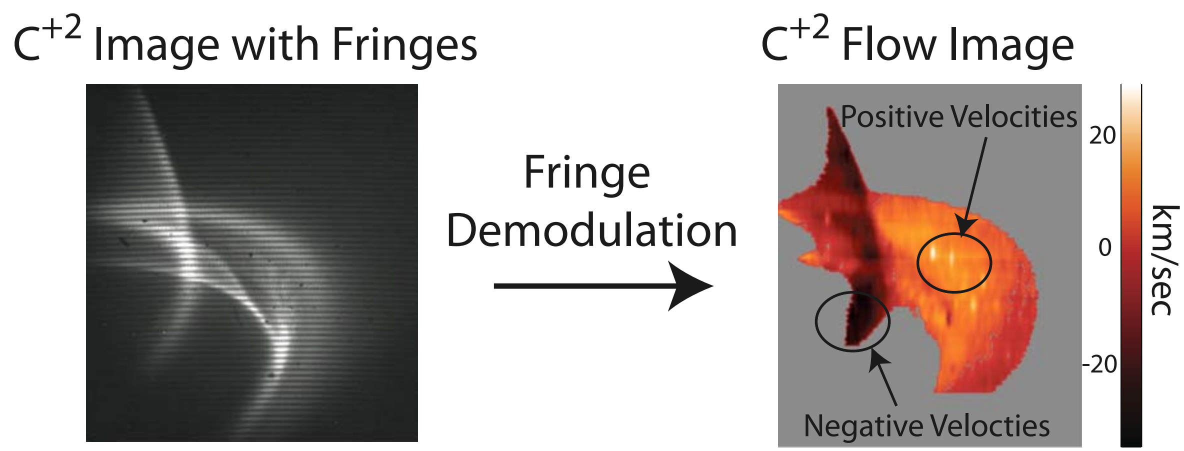
Other Recent Developments in Active Spectroscopy: Adaptation of Coherence Imaging Systems

- **Based on polarization-dependent interferometry, phase shift of image yields a velocity or polarization field** [Howard, *J. Phys. B* **43**, 4010 (2010)]

- **Polarization analysis: Pitch angle imaging on KSTAR**



- **Doppler spectral analysis:**
- **Flow visualization of C^{2+}**
- **Weber,G04.00010 Tues AM**



Conclusions

- **Active spectroscopic diagnostics based on beam-plasma collisions provide a wide range of unique information from the interior of fusion grade plasmas**

- **They take advantage of the presence of heating beams on modern day experiments, advances in spectroscopic capabilities, and our knowledge of the underlying collision physics**

- **They serve a vital role for improving our understanding of these devices, and help in developing the potential of magnetic confinement fusion as a future energy source**

Many Thanks To...

General Atomics: K.H. Burrell, R.J. Groebner, E.J. Strait, M.A. Van Zeeland

University of Wisconsin Madison: G.R. McKee

LLNL: C.T. Holcomb, M.A. Makowski, S.L. Allen, T.R. Weber

Oak Ridge National Laboratory: R.C. Isler, T.C. Jernigan, M. Murakami

iter-nl: M. Von Hellerman

iter: B. Schunke

ANU: J. Howard

PPPL: B.A. Grierson, W.M. Solomon