Fast Ion Measurement in the Alcator C-Mod plasma: How, Why, and Who Cares*

**W. L. Rowan,[a] I. O. Bespamyatnov,[a] A. Bader,[b]
R. S. Granetz,[b] and Ken Liao[a]**

[a]Fusion Research Center, The University of Texas at Austin, Austin, TX 78712

[b]Plasma Science and Fusion Center, MIT, Cambridge, MA 02139

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Initiation into Fast Ions in Tokamaks

- **In a tokamak, there is an ion population that is in thermal equilibrium, and there is an electron population that is also in thermal equilibrium. Ion and electron distributions may have different temperatures.**
- **Sometimes there is another collection of ions that have energies well above the temperature of the themal ion population. These are called fast ions.**
- **In the current generation of tokamaks, fast ions are generated to heat the plasma, drive currents in the plasma, and drive mass flows in the plasma. We want to measure the density and energy of the fast ions to understand these processes.**
- **In a plasma that is hot and dense enough to support fusion, fast ions are generated by the fusion. When we see fusion in plasmas again, we will want to measure the fast ions so that we will know how much we are heating.**
- **If fast ions can be detected before they equilibrate or escape at the plasma edge, then they can contribute to our physics understanding of these processes.**
- **The tokamak described here is named Alcator C-Mod**

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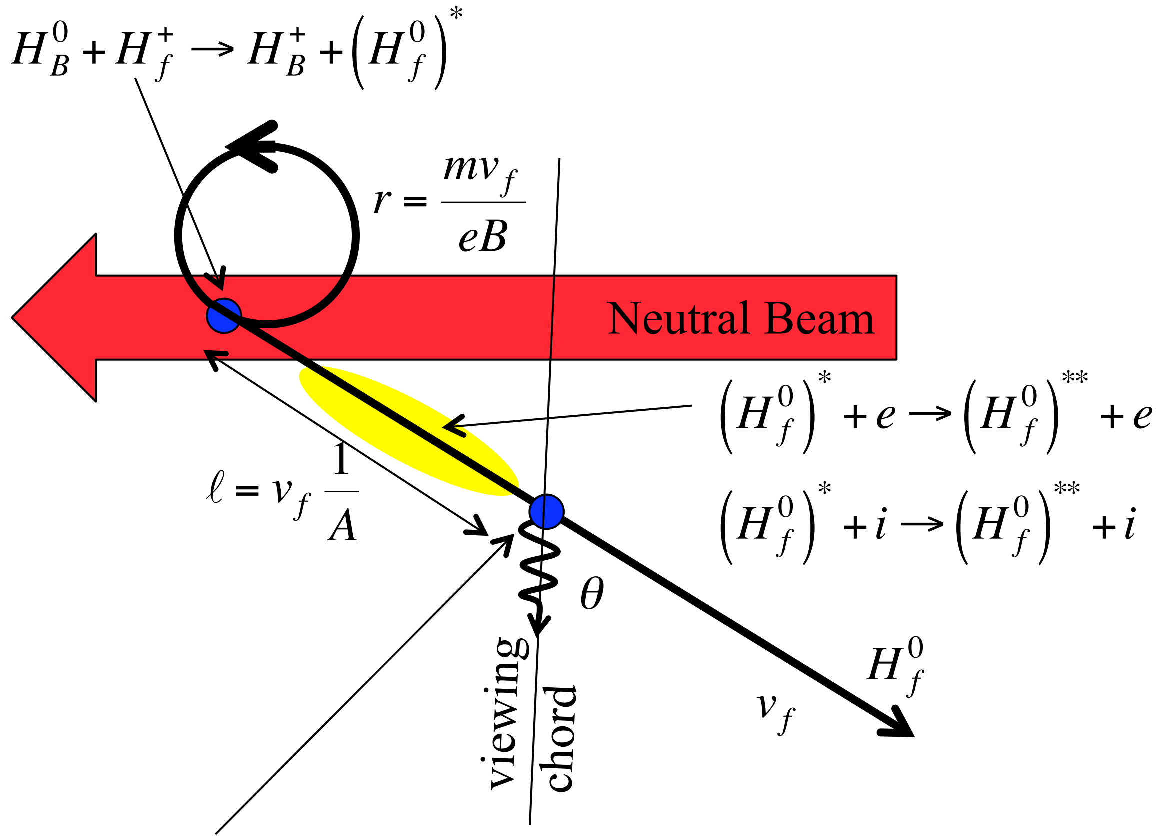
Fast Ions in Alcator C-Mod

- **The fast ions are high energy ions that are not in thermal equilibrium with the bulk plasma ions**
- **Fast ions are generated in tokamaks by**
  - **fusion** $_1D^2 + _1T^3 \rightarrow _2He^4(3.5MeV) + _0n^1(14.1MeV)$
  - **wave plasma interactions**
- **For C-Mod, the main interest is in wave plasma interactions**
  - **RF deposition: 6 MW at 80 MHz is absorbed by a few % H impurity in a D plasma**
  - **Absorption by a hydrogen minority in a deuterium plasma via Landau damping and transit time damping**
- **After formation, fast ions eventually come into equilibrium with the plasma via collisions or may escape the plasma.**
- **Fast ions detected in the plasma can be used to validate the physical models for RF deposition**
- **More ambitious experiments include study fast ion transport by unstable plasma waves**

Physics of Fast Ion Spectrum

- **In Alcator C-Mod, the fast ions are hydrogen ions.**
- **The fast ions are fully stripped and do not have a natural emission spectrum other that a bremsstrahlung continuum**
- **After the fast ions are born, they execute gyro orbits**
- **The fast ions charge exchange with the neutrals in an injected beam of high-energy neutrals to form a population of fast neutrals.**
- **The newly formed fast neutrals follow a straightline trajectory.**
- **The fast neutral is excited/de-excited by charge exchange and by collisions with thermal electrons and ions forming the plasma.**
- **The neutral emits a Doppler-shifted H_α spectrum which stands out against the wing of the broad ambient background spectrum of plasma D_α.**
- **Since the fast neutral retains the velocity vector of the fast ion, the emission spectrum for the fast neutrals contains detailed information on the kinetics and the density of the fast ion population.**

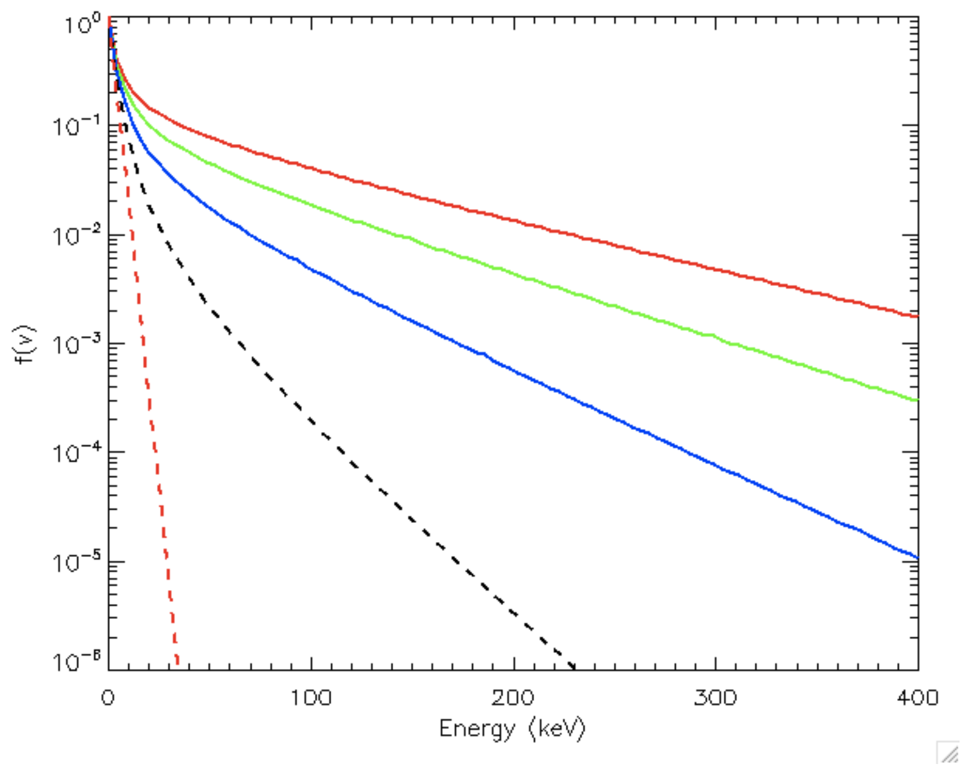
Physics of Fast Ion Spectrum



$$H_f^0(n=3) \rightarrow H_f^0(n=2) + h\nu$$

$$\lambda = \lambda_0\left(1 + \frac{v_f}{c}\cos(\theta)\right)$$

Fast Ion Distribution for Emission Simulation

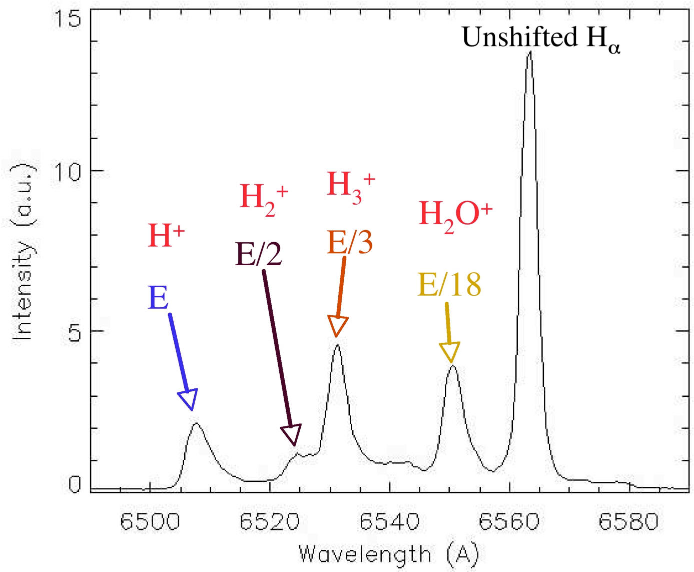


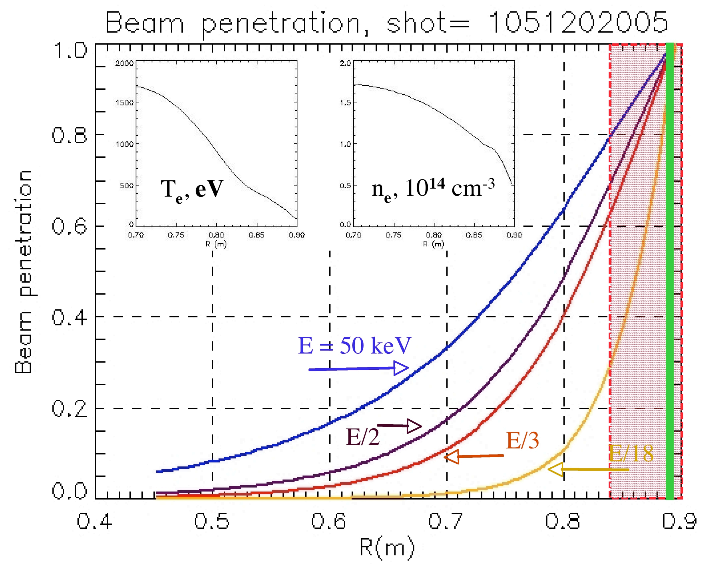
- **Distribution as computed in T. H. Stix, Nuclear Fusion 15, 737, 1975. Fast-wave heating of a two component plasma**
- **RF power varied between 0 red dashed curve (Maxwellian distribution) and 5 W/cm^3, solid red curve**
- **The emission spectrum is not unique, but we may be able to look at the spectrum and say that a particular f(v) is consistent or not**

Where will the real distributions come from?

- The goal of this research is the validation of the physics models used in simulations of fast ions created with ICRF minority absorption.
- Fast ions that are lost (those that escape the plasma) are measured with the Compact Neutral Particle Analyzer (CNPA) diagnostic
- The fast ions that remain in the plasma are measured with the CXRS-Fast-Ion (CXRS-FI)
- Compare with simulations based on AORSA (E. F. Jaeger, L. A. Berry, E. D'Azevedo, D. B. Batchelor, and M. D. Carter, Physics of Plasmas 8 (5), 1573 (2001).) AORSA is used to predict mode conversion and high harmonic fast wave heating in tokamak plasmas.
- Compare with CQL3D (R. W. Harvey and M. G. McCoy, presented at the Proceedings of the IAEA Technical Committee Meeting on Advances in Simulation and Modeling in Thermonuclear Plasmas, Montreal, 1992 (unpublished)) . CQL3D is a quasilinear Fokker-Planck code used to model distribution functions.
- Construct a synthetic diagnostic for interpretation.

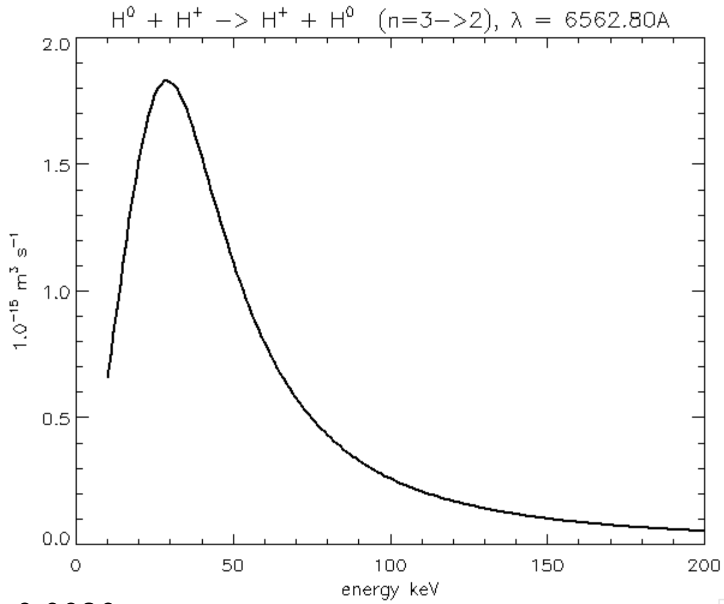
Diagnostic Neutral Beam

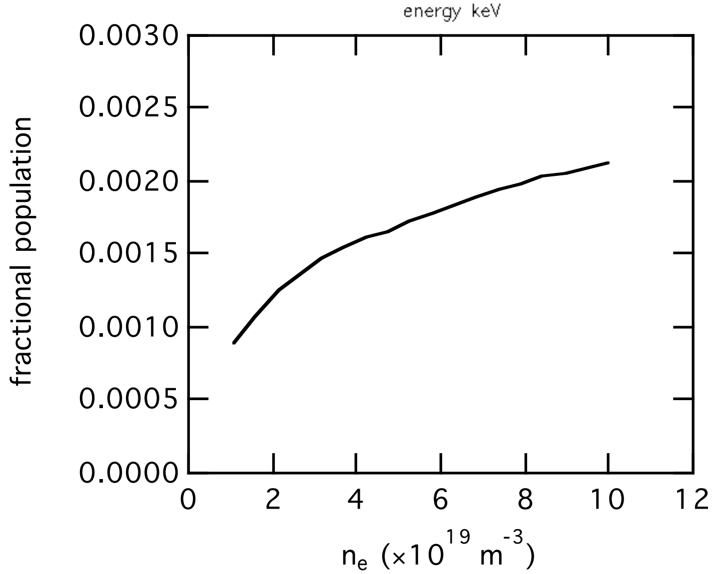




- **DNB: 50 kV H neutral beam. 6A accelerated current. 3.5 A neutrals into plasma**
- **The beam emission spectrum on the left illustrates that the beam is consists of 4 high energy components. Only the full energy (E) component contributes to this simulation of the fast ion spectrum.**
- **The beam penetration for a typical tokamak discharge is shown at right. Signal to noise will decrease for locations nearer the plasma core.**

Photon Emission Cross Section





- **Fast neutrals are generated by charge exchange in a diagnostic neutral beam**
- **The charge exchange event produces and excited neutral and is followed by cascade; usually well described as a Seaton cascade.**

$$e^- + H^0 \rightarrow e^- + H^{0*}$$

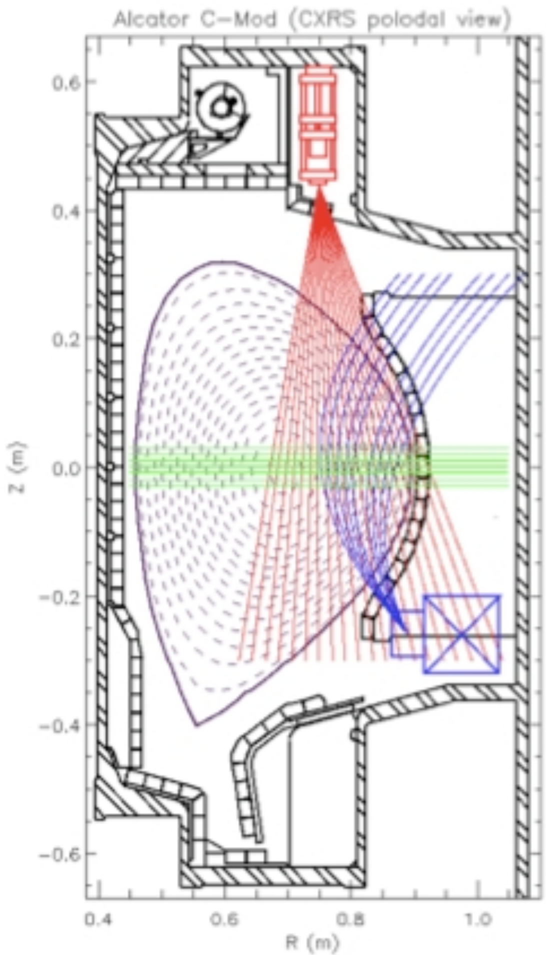
$$p^+ + H^0 \rightarrow p^+ + H^{0*}$$

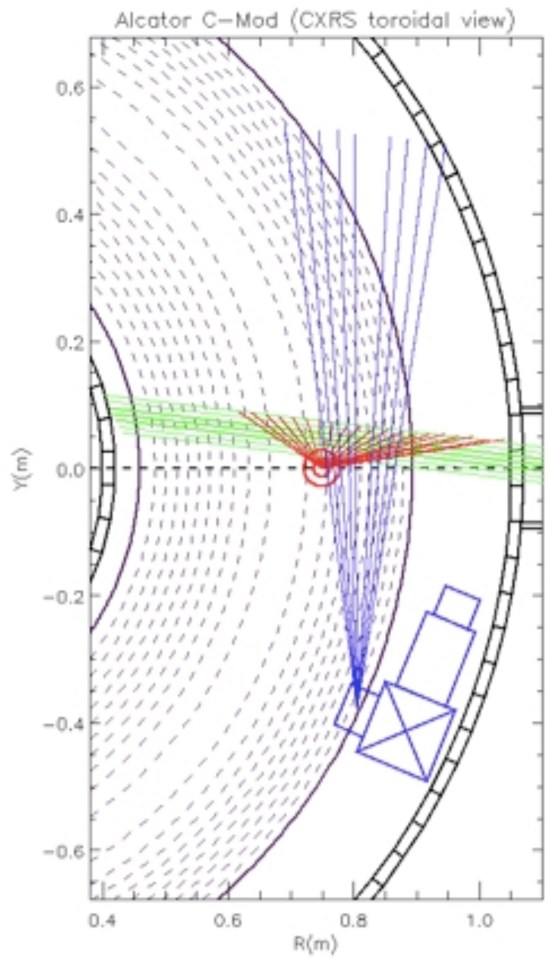
$$A^q + H^0 \rightarrow A^q + H^{0*}$$

$$H^{0*} \rightarrow H^0 + h\nu$$

- **Population of upper levels including n=3 continue to evolve between charge exchange and emission due to collisions with plasma constituents: electrons, ions, *and* impurities**
- **A cross section is typically devised to include all these in one chunk.
M. vonHellerman et al., PPCF 37, 71 (1995).**

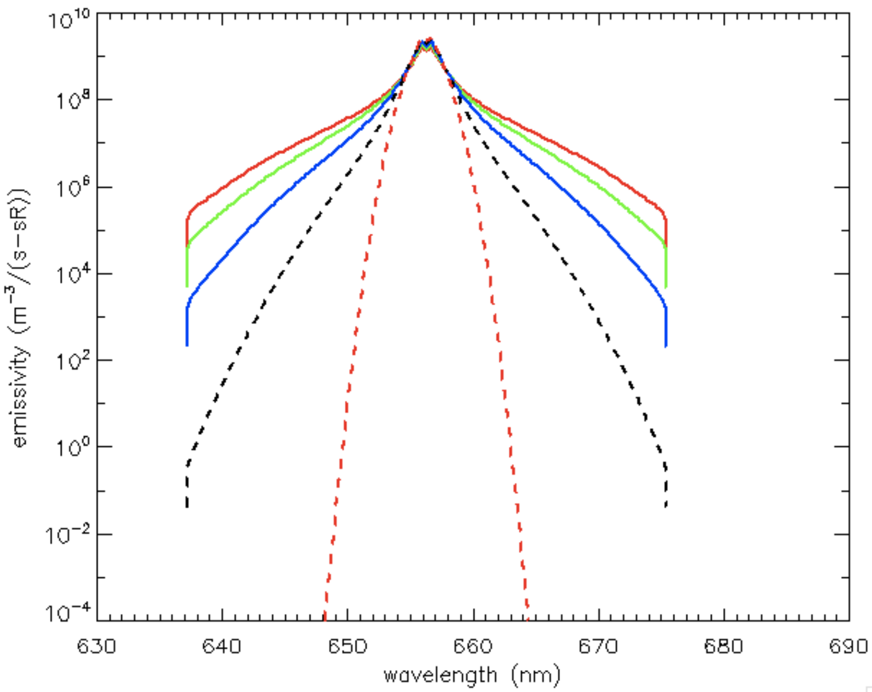
Plasma Views





- **There are two plasma views for this diagnostic.**
- **The blue chords are the toroidal system, the red chords are the poloidal system. The beam is shown in green.**
- **The proof of principle experiments and the simulation is for chords in the poloidal system.**
- **19 chords**
  0.67 m < R < 0.91 m
  ΔR ≈ 1.2 cm

Simulation of the Spectrum



RF power varied between 0 red dashed curve (Maxwellian distribution of ions) and 5 W/cm^3, solid red curve

- **The simulation using all the preceeding information is shown above.**
- **Simulated spectra are shown for the same range of RF power deposition as on the earlier distribution fcn graph.**
- **The wings clearly increase more than linearly as a function of the increase in RF power. The core is insensitive to RF power.**
- **Evidently, the region of primary interest is between the core and the far wing for sensitivity to the fast ion distribution function and to avoid competing spectral emission processes.**

Competing Processes

- **The simulated spectrum demonstrates that the measurement can be made but it also demonstrates that the emission is comparable to that from competing processes.**
- **Competing Processes**
  - **Line emission from the cold deuterium and hydrogen at the plasma edge**
  - **Doppler-shifted spectrum emitted by the neutral beam**
  - **Electron-ion bremsstrahlung**
  - **Halo emission**
- **The fast ion measurement can be made in a region sandwiched between the wing of the cold deuterium emission and the region where the fast ion spectrum it drops below the competing processes by a factor of approximately two.**

Halo Emission

- **What is it?**
  The halo is a region of neutral H in the vicinity of the neutral beam.
- **The source is charge exchange between beam neutrals and plasma ions.**
- **The neutrals are transported through convection and diffusion.**
- **The neutrals are destroyed through charge exchange with other ions and through ionization.**

$$\frac{\partial n_0}{\partial t} + \nabla \bullet \Gamma = -S_i^e n_e n_0 - S_i^i n_i n_0 + \sum_{j=1}^{ncmp} n_B^j C_x^j n_i = 0$$

- **In the mean time, halo neutrals undergo collisions which lead to emission of spectra. A simple analysis of the transport equation leads to a relation for the density of the halo. The factor f is simply the concentration of a beam component relative to the total concentration**

$$\frac{n_0}{n_B} = \frac{\sum_{j=1}^{ncmp} f_B^j C_x^j n_i}{S_i^e n_e + S_i^i n_i}$$

Measurement Validation and Plan

Measurement Validation

- The spectrum must be detected against a background that will be comparable in strength. The background may also include impurity spectra.
- The measurement validation will begin with acquisition of high resolution spectra with a sensitive detector, and then move toward higher temporal resolution and simpler spectral dispersion

Measurement Validation and Plan

Measurement Plan

- **Proof of principle experiment. Assure that the measurement can be made. Develop analysis. Accurately estimate expected errors from signal to noise ratios**
  - **Spectral Analysis: Kaiser f1.8 Holospec**
  - **Detection: PI Micromax**
- **Improve the temporal resolution**
  If signal levels are adequate from the proof of principle experiment, replace the detector with a photomultiplier array for improved temporal resolution.
  - **Spectral Analysis: Kaiser f1/8 Holospec**
  - **Detection: photomultiplier array**

Measurement Validation and Plan

Measurement Plan (continued)

- **Simplify the spectral analysis**
  If the spectrum is sufficiently simple, use a filter scope for spectral analysis. Note that a high resolution spectrometer will always be needed since spectra in tokamaks change due to appearance and disappearance of impurities.
  - **Spectral Analysis: Filter scope**
  - **Detection: photomultiplier array**

Role of the Diagnostic

- **This emission spectrum is the basis for just one of a complementary set of fast ion measurements.**
- **Its unique contribution is that it allows measurement of the fast ions inside the plasma.**
- **Escaping fast ions are measured independently.**
- **Each measurement contributes a different view of the fast ion distribution which must be combined for a complete description of fast ions.**