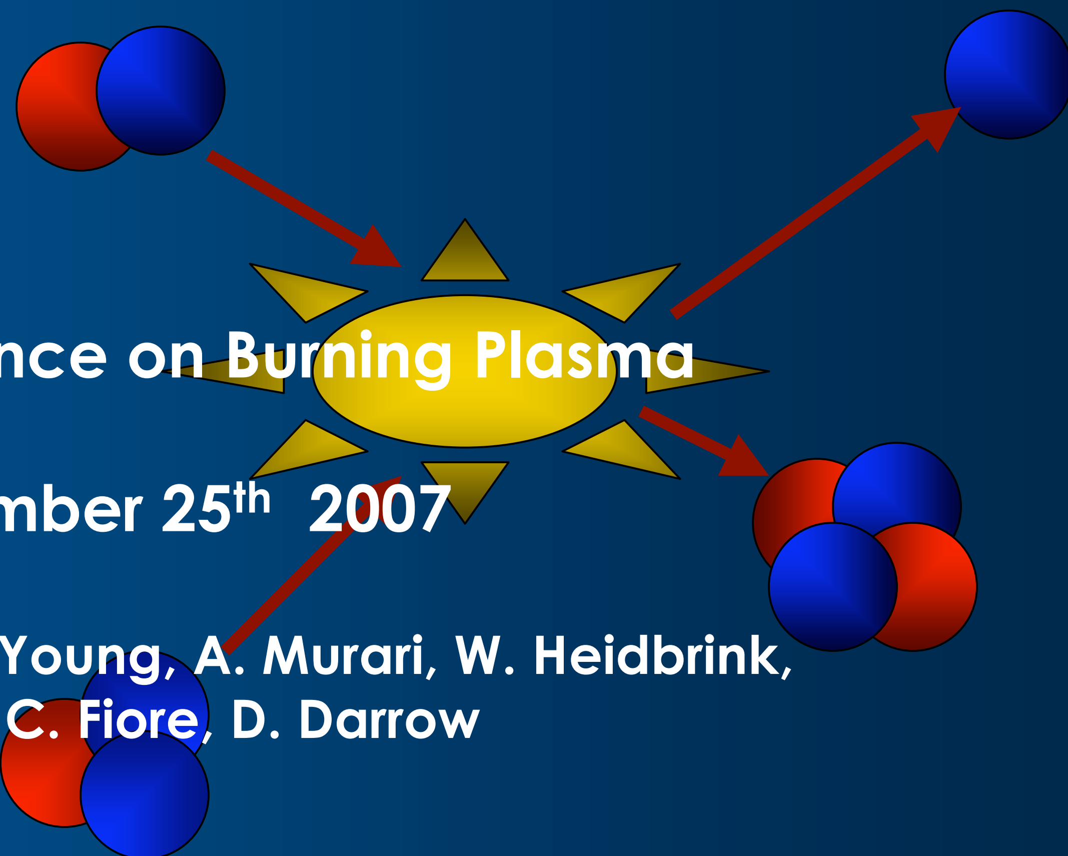
Role of Fusion Product Measurements in Physics Understanding of a Burning Plasma



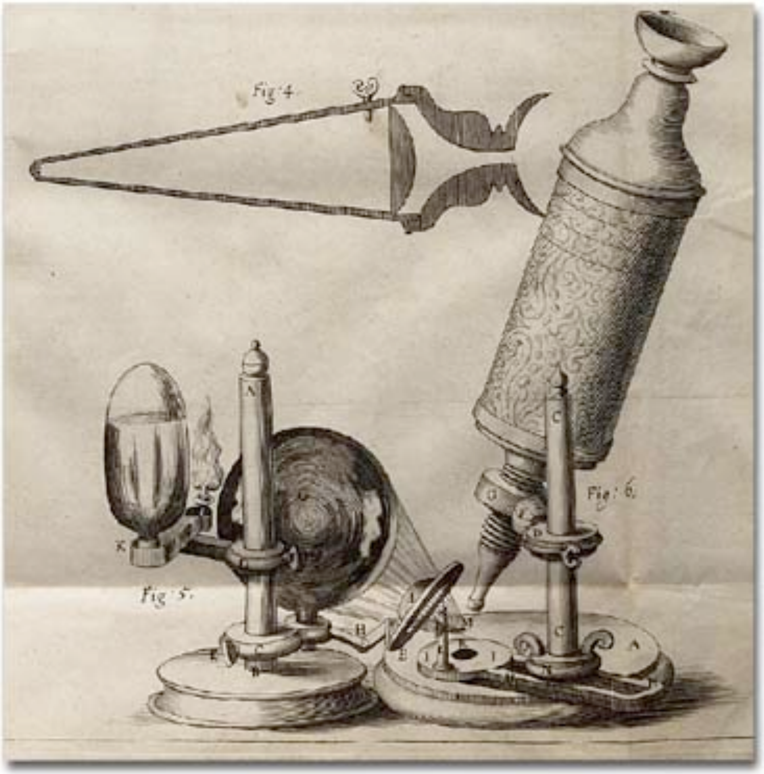
R.L. Boivin
General Atomics

International Conference on Burning Plasma Diagnostics
Varenna, Italy, September 25th 2007

With contributions from K. Young, A. Murari, W. Heidbrink, R. Fisher, M. Van Zeeland, C. Fiore, D. Darrow

Why do we Need to Measure Fusion Products?

- *"All I need is a camera, the loop voltage and a neutron counter!"*
- **There are multiple uses and needs beyond the simple, yet important, need to measure fusion performance**
  - Single particle physics
  - Collective effects
  - Advanced plasma control/Alpha Engineering/Burn Control
- **What are the scientific benefits from measuring fusion products for understanding and controlling burning plasmas?**



Early Fusion diagnostic

Outline

- Brief review of fusion products
- What do we need to measure and understand in order to create the proper conditions for fusion to occur?
- What do we need to measure and understand in order to create the proper conditions for burning plasmas?
- Brief outlook for DEMO and future

Fusion Products are the Result of a Multitude of Reactions

$$D + D \rightarrow {}^{3}He\ (0.8\,MeV) + n\ (2.45\,MeV)$$

$$D + D \rightarrow T\ (1\,MeV) + p\ (3\,MeV)$$

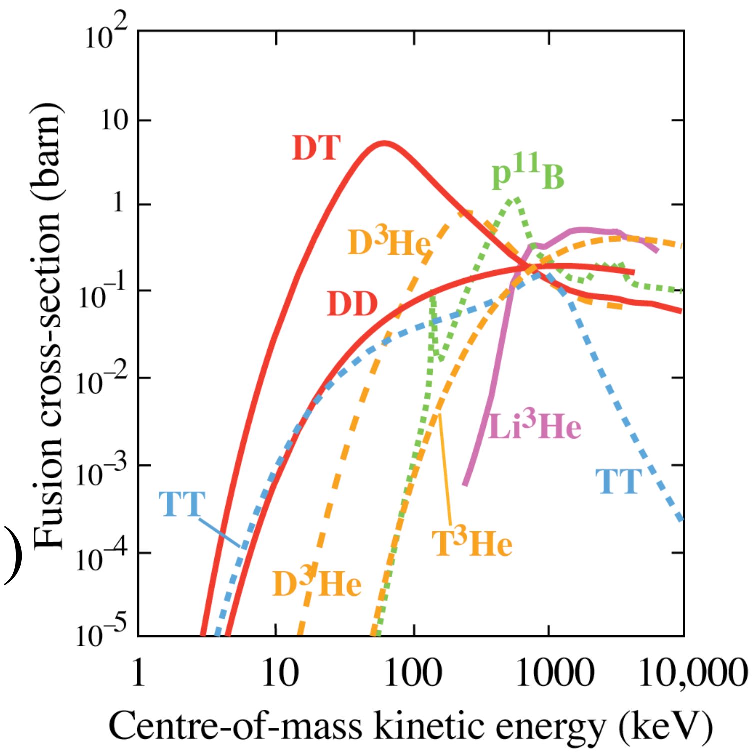
$$D + T \rightarrow \alpha\ (3.5\,MeV) + n\ (14.1\,MeV)$$

$$T + T \rightarrow \alpha + 2n(total\ of\ 11.3\,MeV)$$

- **Advanced fuels**

$$D + {}^{3}He \rightarrow \alpha\ (3.6\,MeV) + p\ (14.7\,MeV)$$

$$p + {}^{11}B \rightarrow 3\alpha\ (total\ of\ 8.7\,MeV)$$



- **Many reactions yielding gamma rays**
- **Proxies**
  - Beam ions, RF tail ions
- **But now we have to think in terms of large population of MeV ions!!!**

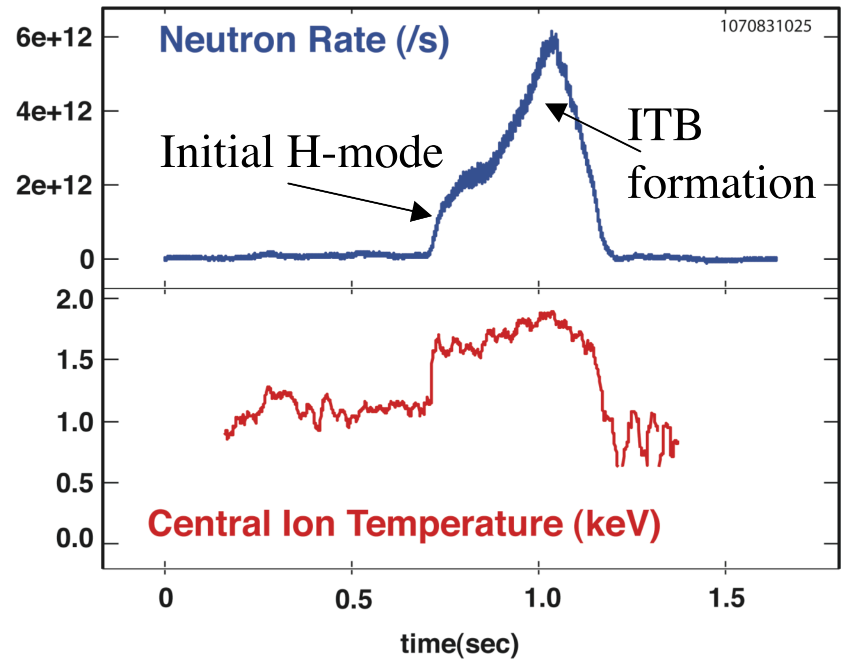
Create the Conditions for Fusion

Uses for Fusion Product Measurements Quickly Went Beyond Yield Derivation

- **Measure fusion production**
  - Measuring neutron 2.45 MeV yield
  - Measuring 15MeV proton yield for D+^{3}He reactions
  - Derive fuel/main ion temperature
- **Evaluate confinement by studying tritium and ^{3}He burnup**
  - Burnup is defined as the result of a secondary fusion reaction
    - E.g.

$$D + D \rightarrow T + p$$

$$D + T \rightarrow \alpha + n$$

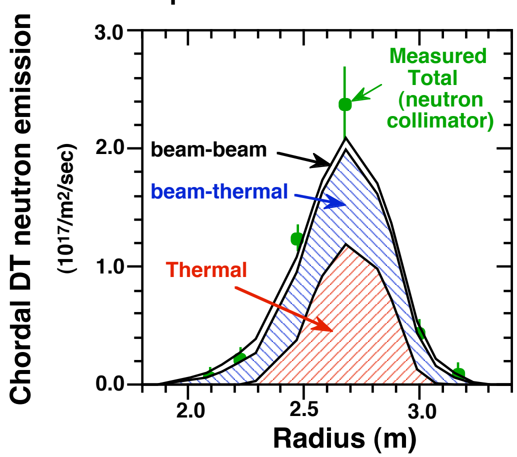


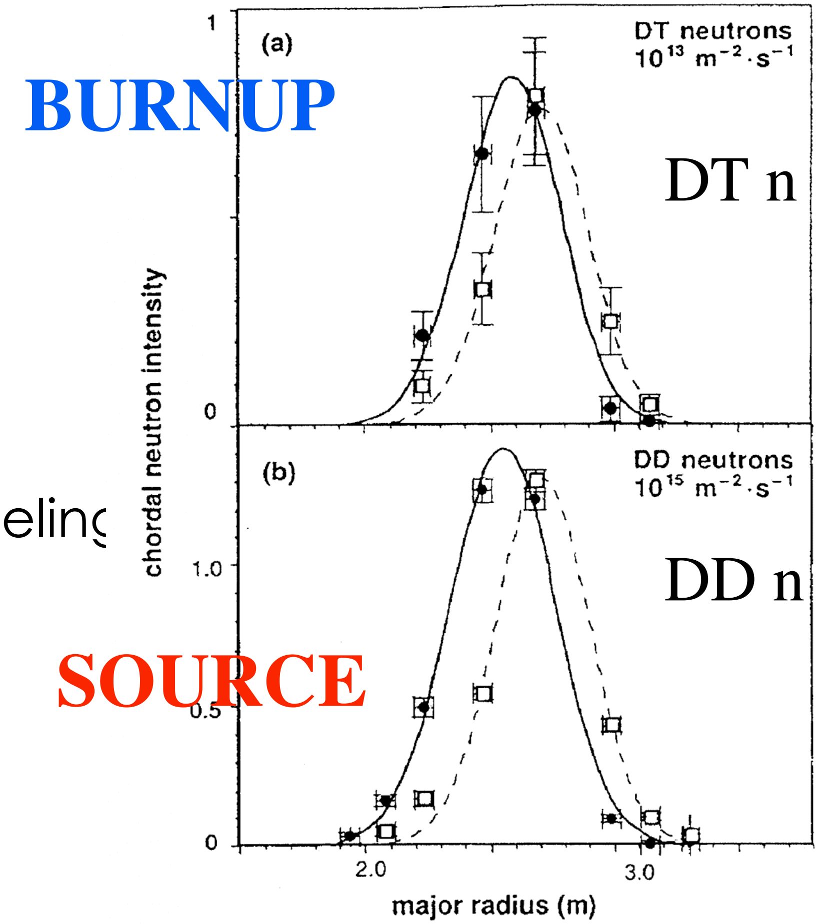
See Krasilnikov (Monday) and Nishitani (this session)

Alcator C-Mod

Detailed Information can be Gained with Neutron Flux and Profile Measurements

- **Neutron profile measurements can yield information on:**
  - Heating (NBI, RF, etc)
  - Fuelling
  - Transport
    - Isotopic transport (H,D,T, etc)
  - Importance of fast ions
  - Impact of instability
  - Independent constraint on modeling



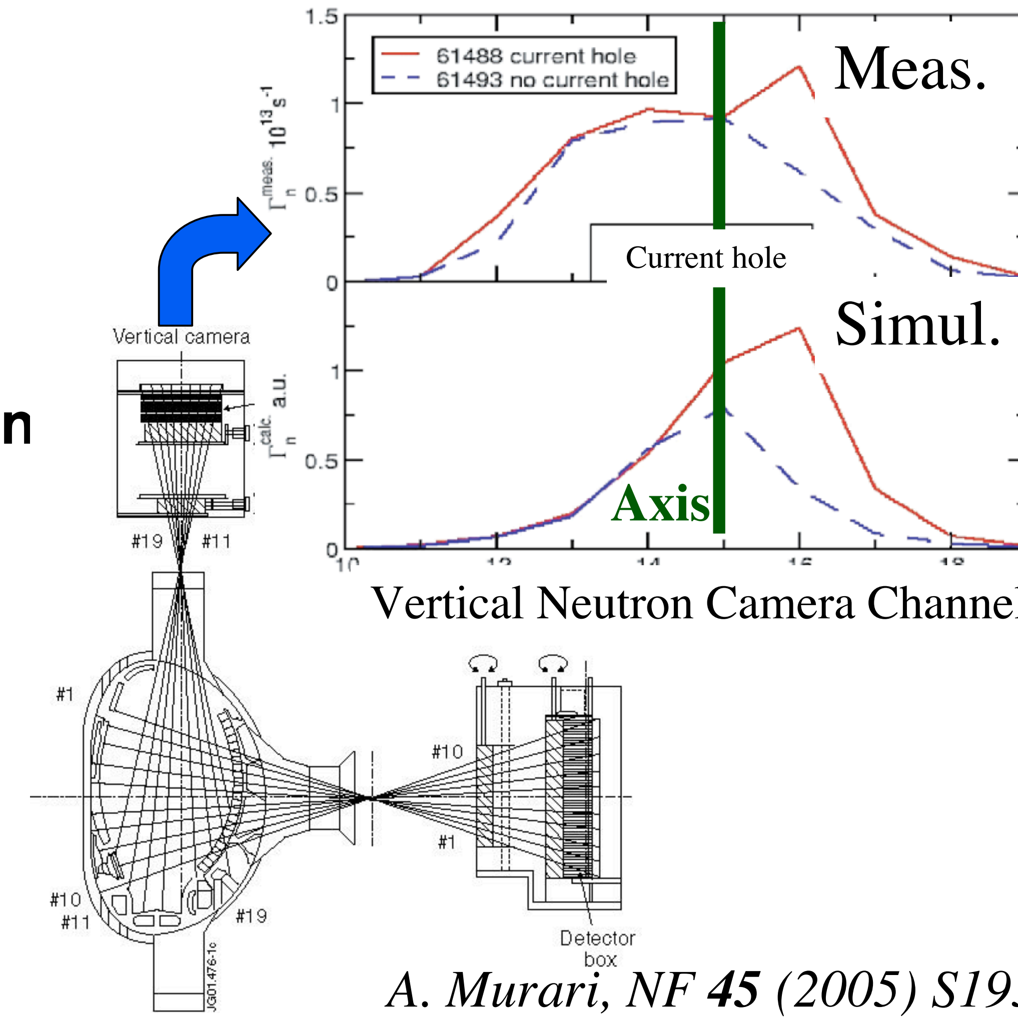


*J. Strachan, NF **36** (1996) 1189*

TFTR

Advanced Scenarios and Non-Standard Discharges Require Additional Information

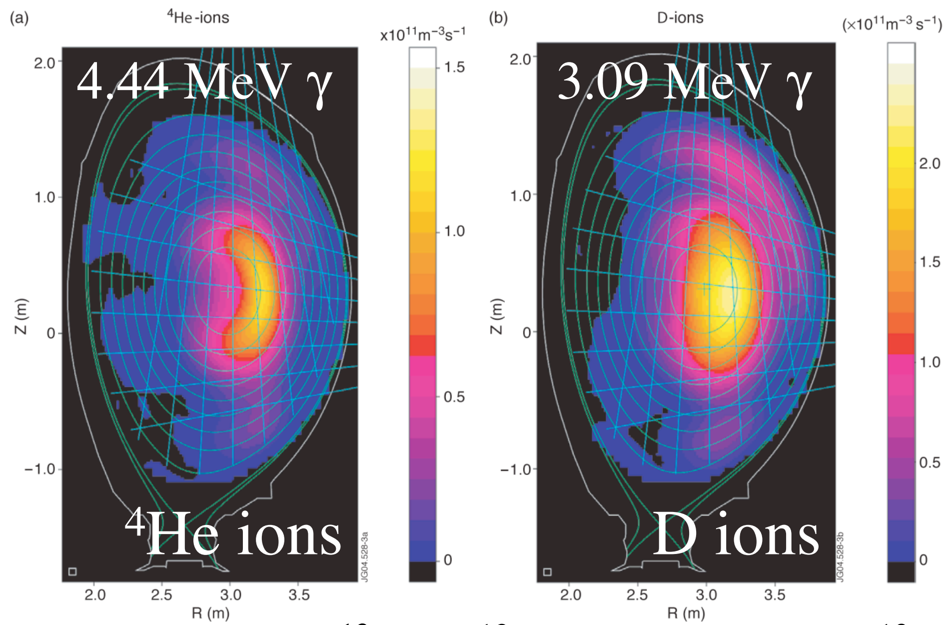
- **Tomographic neutron emission is required in advanced scenarios**
  - Reversed Shear
  - Current holes
- **Conventional ion/fast ion confinement does not necessarily hold**
  - Impacts on alphas as well



*A. Murari, NF **45** (2005) S195*

Unexpected Results Were Seen with 2-D Neutron and Gamma Source Profile Measurements

- **High energy gamma emission can help identifying the physcial mechanism**
  - Not poloidally symmetric
  - Clear examples in RF heating experiments
  - Also some other cases with strong edge localized fuelling
- **ITER should include 2D capability - even partial**
  - Neutrons and/or γ's
  - No need to be in one poloidal plane
- **See Kiptily (this session)**

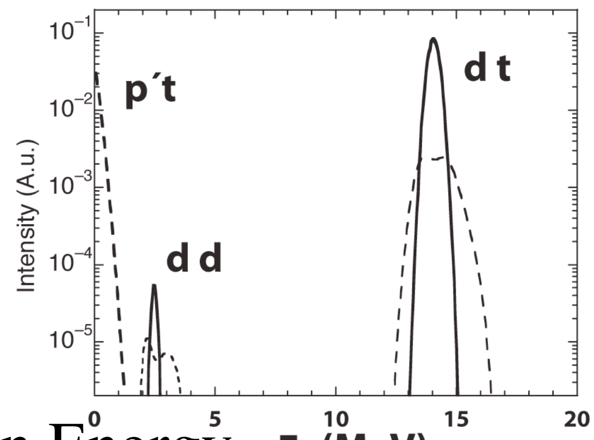


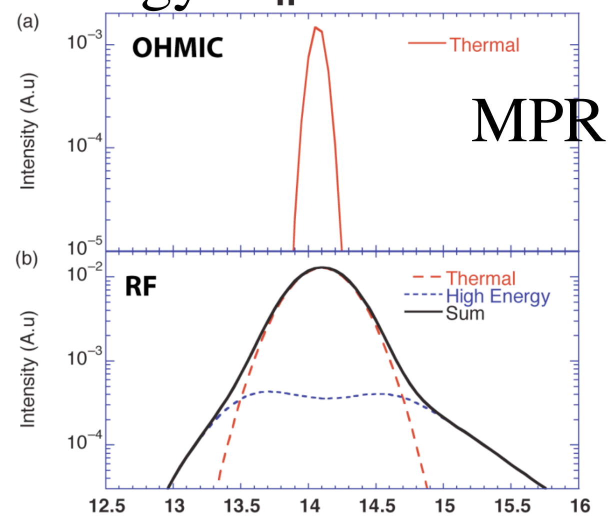
$$^{9}Be + \alpha \rightarrow n + \gamma + {}^{12}C \qquad {}^{12}C + D \rightarrow p + \gamma + {}^{13}C$$

V.G. Kiptily, NF ***45*** *(2005) L21*

Neutron Spectroscopy Adds a very Powerful Tool for Studying Confinement and Fusion Performance

- **The energy spectrum contributes in identifying the "source" of fusing particles and their energies**
  - Contribution from thermal, beam, tail and other fast ions
    - Presence of alpha-D/T knock-ons can be used advantageously for fast-ion diagnosis of self-heating
    - High energy end of spectrum particularly useful/interesting
  - Comparison of the 14 MeV versus the 2.45 MeV can also give valuable information of the isotopic composition of the plasma and its fuelling
  - Can be part of the advanced plasma and burn controls
- **See Popovichev (this session)**



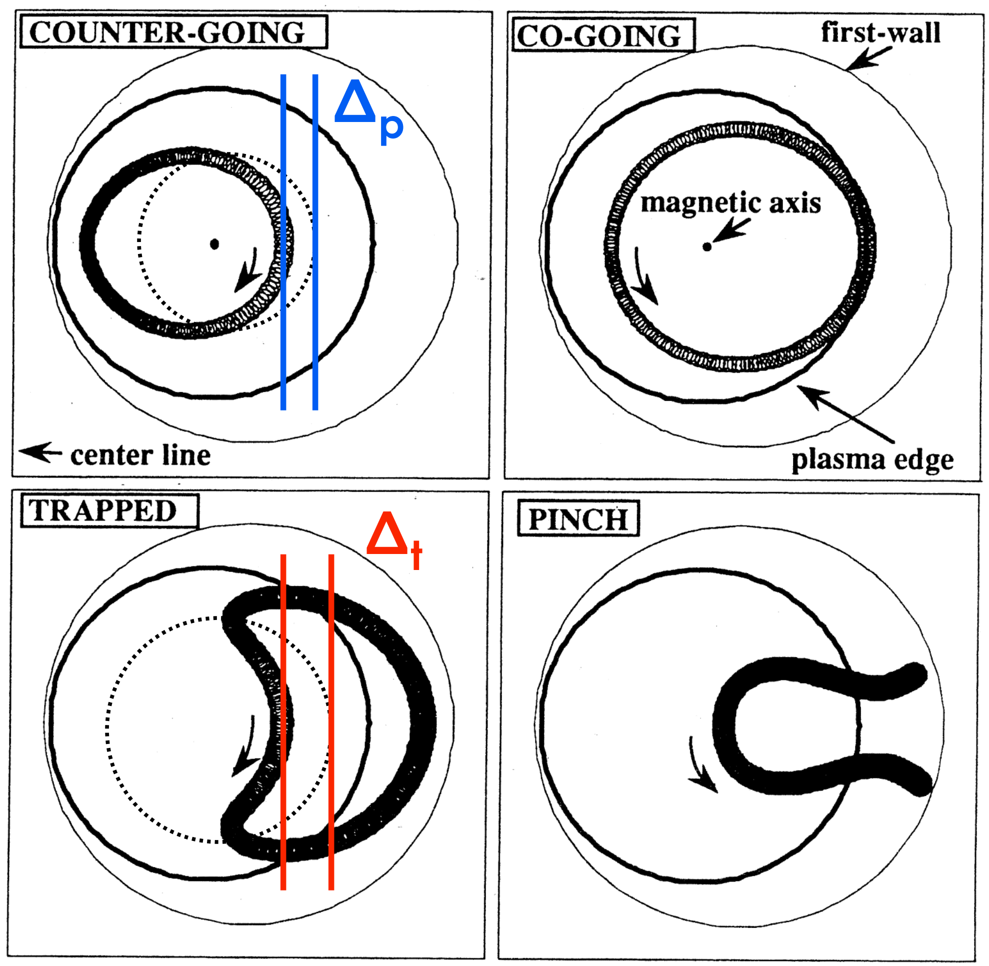


*H. Henriksson, et al, PPCF, **44** (2002) 1253*

Create the Conditions for Burning Plasmas

The Study of Charged Fusion Products (CFPs) Requires a Detailed Understanding of Orbits

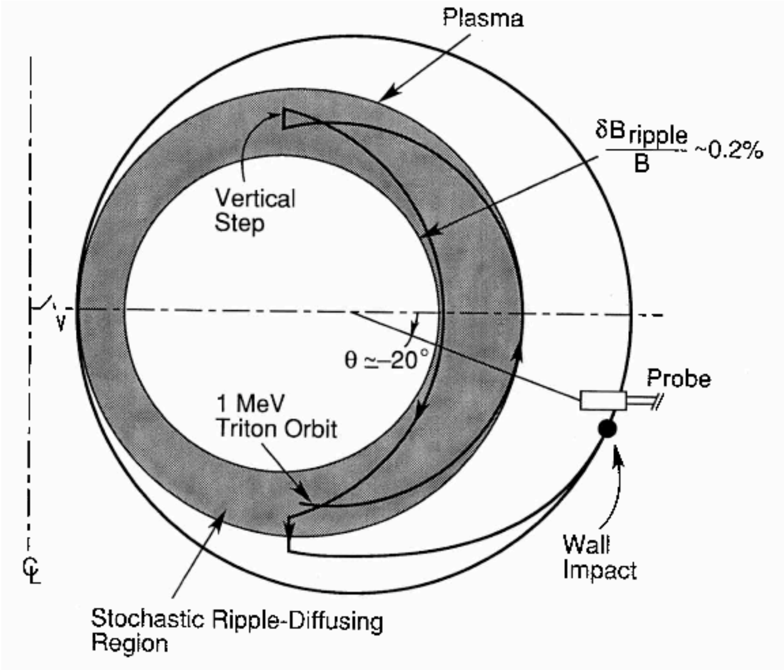
- **In toroidal geometry:**
  - Gyroradius: $\rho \sim Ze(E/m)^{1/2}/B$
  - Orbit shift from flux surface:
    - Passing $\Delta_p \sim 2q\rho$
    - Trapped $\Delta_t \sim 2q\rho/(\varepsilon)^{1/2}$
- **For alpha particles in ITER**
  - $\rho \sim 5$ cm
  - $\Delta_t \sim$ 15-20cm
- **Need to also know**
  - Current and source profiles!!!
  - 3-D first wall geometry



Standard Orbits

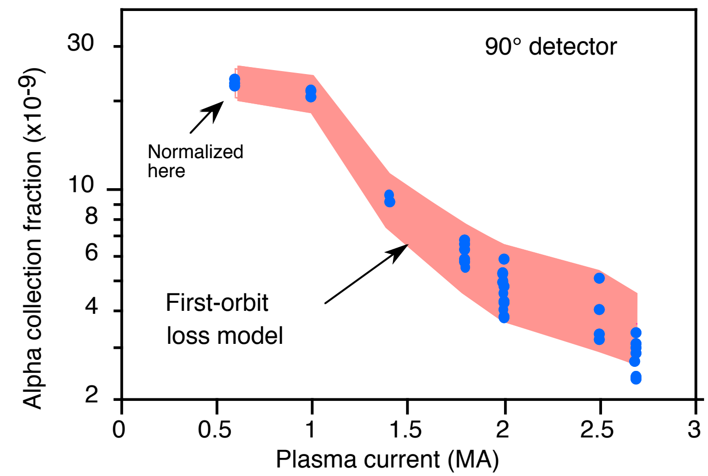
CFP Measurements offer the Possibility of Diagnosing Confinement Properties - *External Perturbations*

- **The effects of TF ripple are especially important for the confinement of CFPs (and other fast ions)**
  - Loss of confinement/Apparent diffusion
  - Localized heat load on first wall
- **Stochastic Ripple Diffusion acts on a class of trapped particles, mostly on outer minor radius, diffusing them rapidly to the edge/first wall**
- **Ripple trapped particles are a class of fast particles trapped in the well created by the ripple itself, creating a very fast vertical drift**
  - Very hard to diagnose directly
- **The effects of error fields are also not well known for CFPs/alpha confinement**

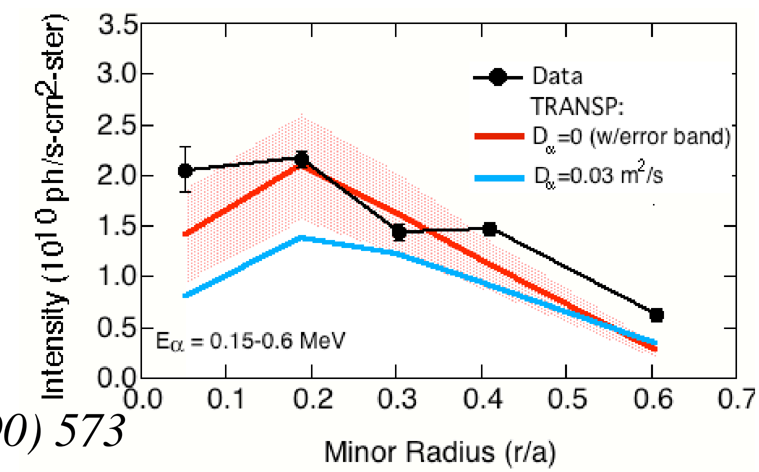


CFP Measurements offer the Possibility of Diagnosing Confinement Properties - *Internal Perturbations*

- **The presence of turbulent diffusion can also lead to non-optimized alpha heating (loss or non central heating)**
  - Slowing down time ~ 1 sec
  - Diffusion from center to mid-radius (ITER) in a slowing down time consequently is ~0.5m^2/sec



- **On TFTR, measurements of CFP losses due to turbulent/anomalous diffusion showed an upper limit of 0.1m^2/sec**
  - Important to validate the results for a burning plasma experiment
  - Measurements made on confined particles (using α- CHERS) indicated a 0.03m^2/sec upper limit
  - Why is it favorable compared to a thermal diffusivity of ~1m^2/sec



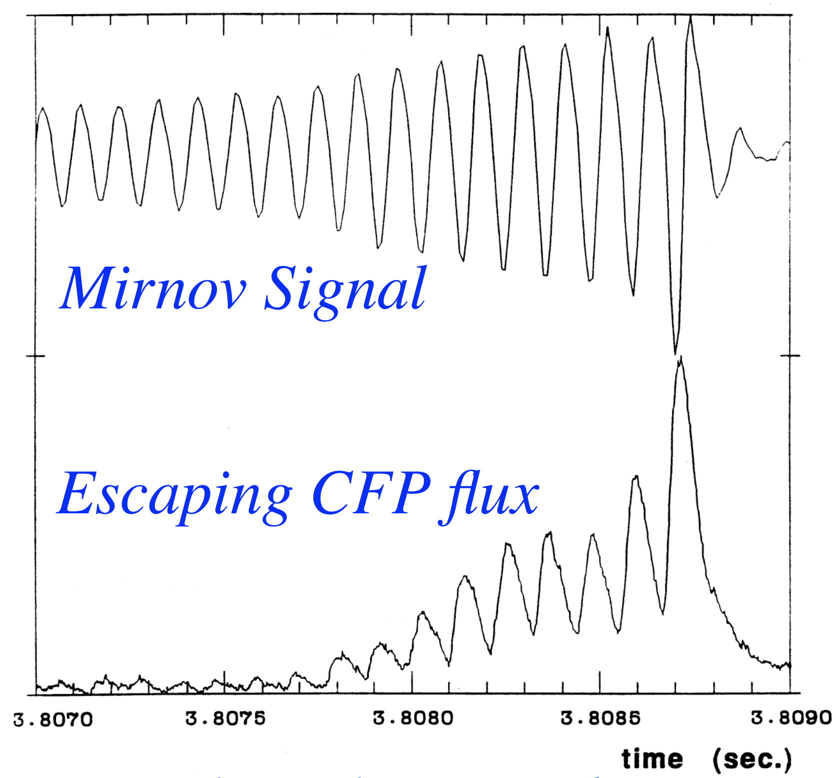
*S.Zweben, NF **31**, (1990) 573*

G. McKee, PRL 75, (1995) 649

TFTR

CFP Measurements offer the Possibility of Diagnosing Confinement Properties - *Internal Perturbations*

- **MHD activity has been observed to expel fast ions (including CFPs)**
  - NTMs, Fishbones, Sawteeth, Alfvén Eigenmodes,
  - ELMs? Could be significant in ITER
  - Largest effect is believed to be caused by passing particles forced into a trapped orbit - largest effect in low aspect ratio experiments
  - Another effect is believed to be caused by energetic particles trapped in a local well - either TF or MHD ripple
  - For AEs, the mechanism is not well established

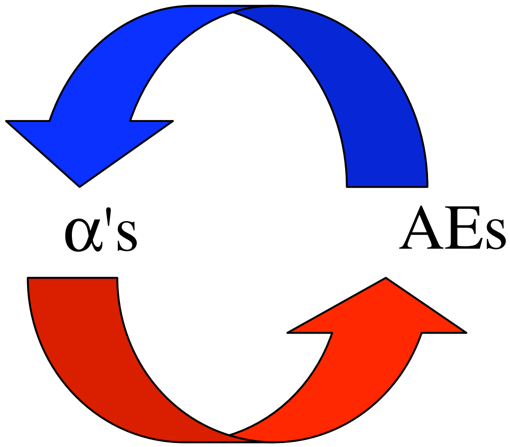


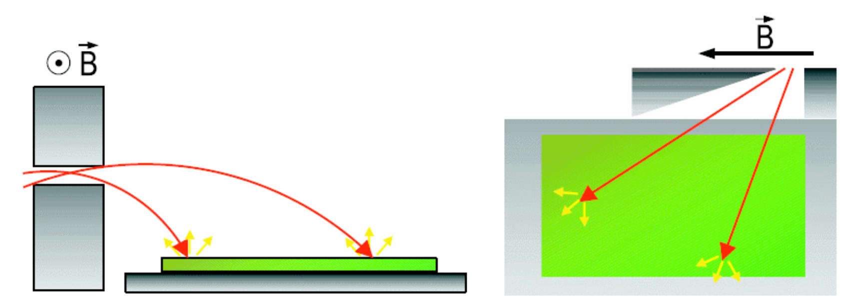
m=1, n=1 sawtooth precursor, passing/trapped boundary

TFTR

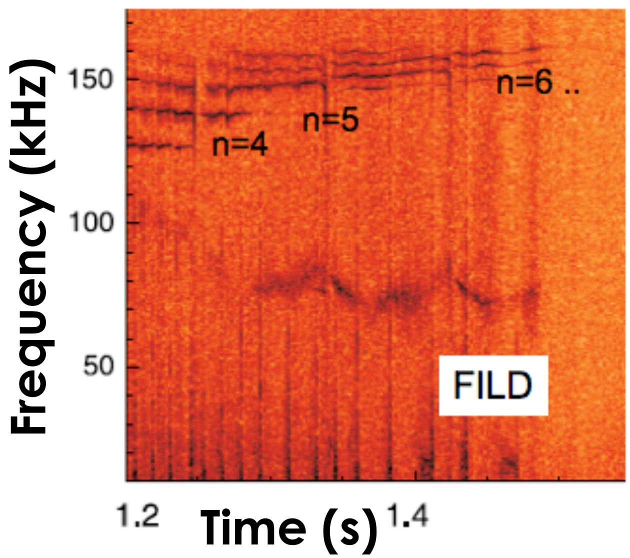
Diagnosing CFP Behavior during Alfvén Eigenmode Activity is Especially Important in a BPX

- A sufficiently large population of fast ions (e.g. CFPs) can drive AE activity
- This activity can, in turn, produce additional CFP transport
- This non-linear mechanism acts in space, and phase space
- Knowing mode structure is part of the picture
- See Van Zeeland, Wednesday AM





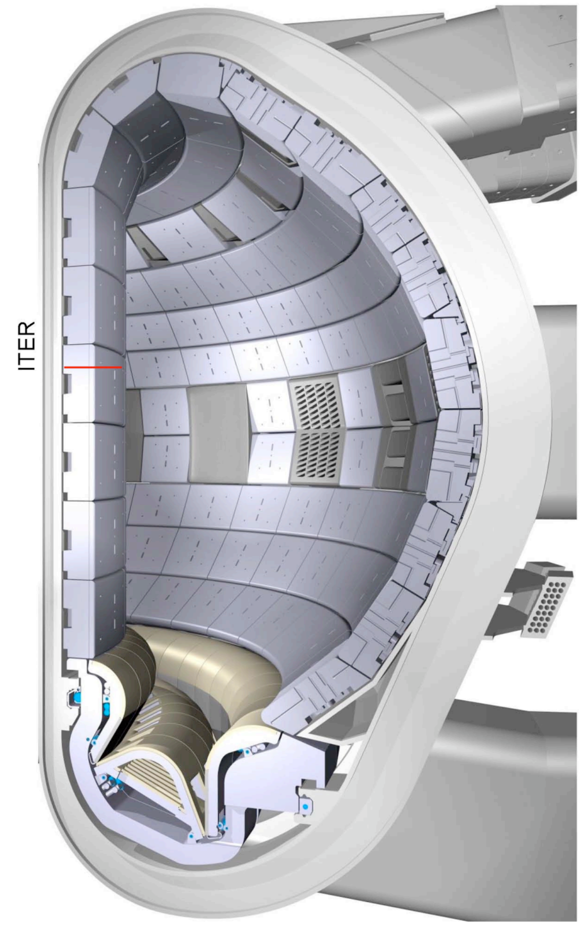
M. Garcia Muñoz APS-DPP (2006)



ASDEX-Upgrade

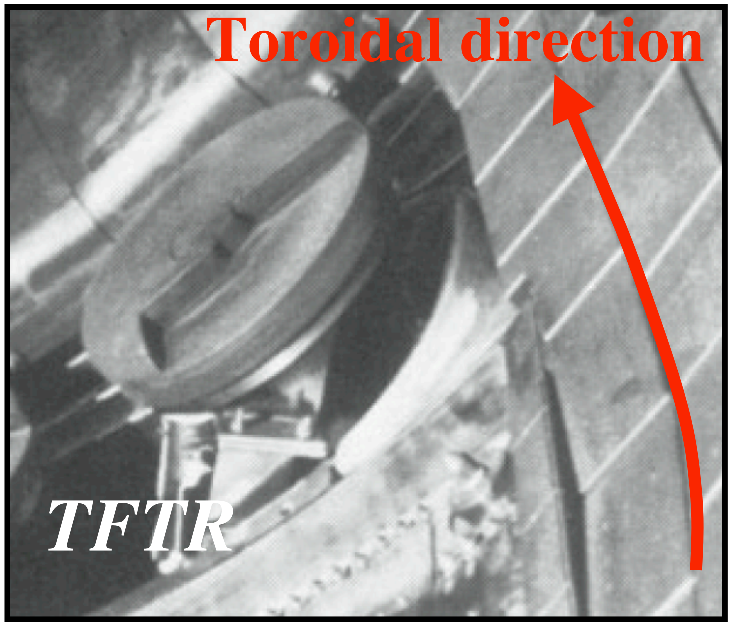
ITER will Require a Suite of CFP/Alpha Diagnostics

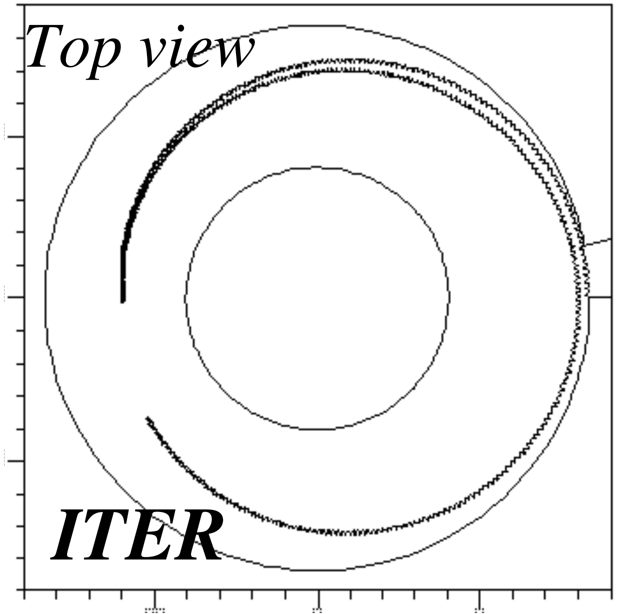
- **ITER and other burning plasma experiments will have large fast ions populations, especially alphas**
- **Very difficult to directly measure loss to first wall**
  - IR cameras remain base diagnostic
- **Redistribution of energetic particles can have impacts on alpha heating and protection of first wall/divertor**
- **Many approaches/techniques in measuring confined population distributions are needed to cover ranges and to increase chance of success**

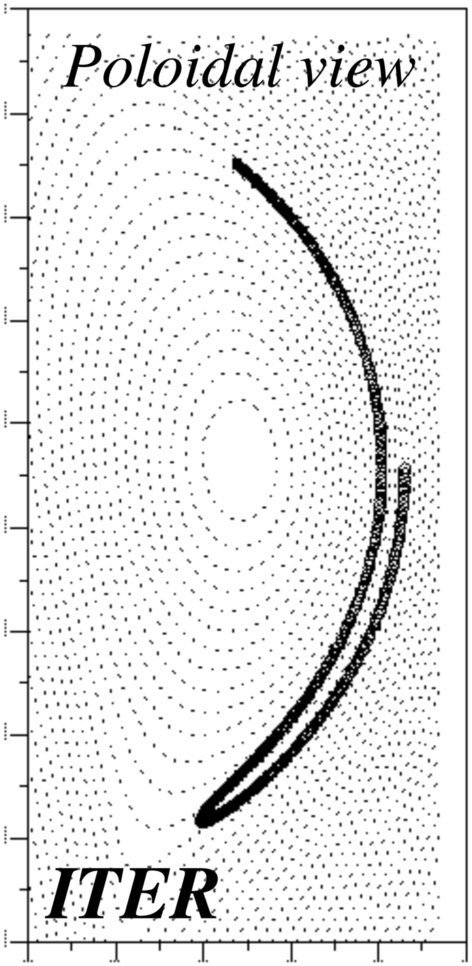


Diagnosing Alpha Losses to the First Wall in a Burning Experiment is a Non-Trivial Task

- **Alpha particles and energetic ions will circulate many times before hitting a solid surface**
  - Travel mostly toroidally (dependent on q_{edge})
  - Will sample the first wall and find the proud edge
  - The impact location can change with plasma shape and current, and ion drift direction

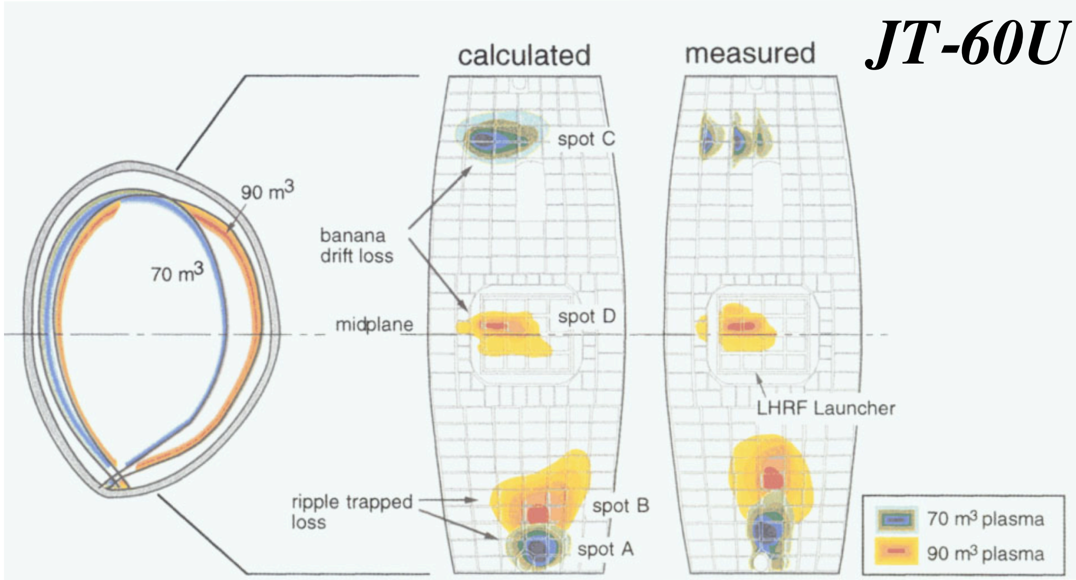






Diagnosing Alpha Losses to First Wall is a Non-Trivial Task How to Circumvent that?

- **IR and visible cameras will monitor the first wall and could help identifying direct alpha impacts**
  - No other information (such as energy, flux and pitch angle) available
- **Will require a proxy**
  - Ion Cyclotron Emission
  - Local gas puffing/neutral detection
  - Gamma detection from local impact/fusion(e.g. JET)
  - Most techniques imply a prior knowledge of impact location!
- **And a full orbit code is required for ITER with full FW geometry**

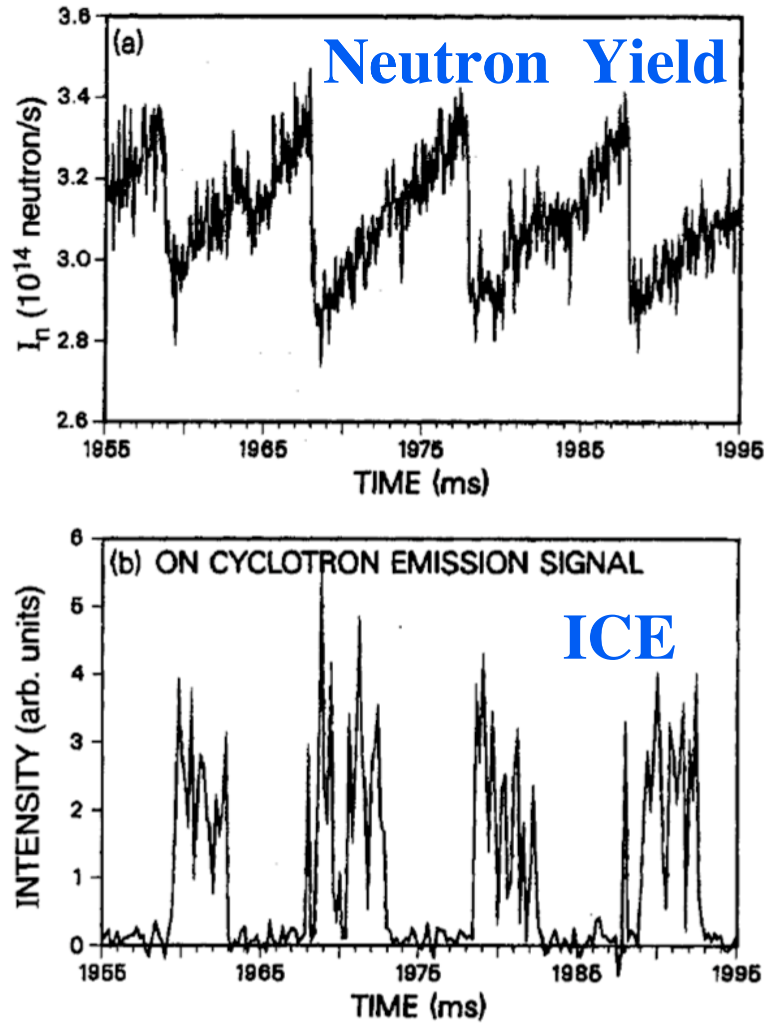


K. Tobita, NF ***35*** *(1995) 1585*

Example: Measurements of Ion Cyclotron Emission May Act as a Sensitive Fast-Ion Loss Diagnostic

- **ICE and CAE are driven by a bump-on-tail in the fast ion velocity distribution (edge/SOL)**
  - AE can redistribute fast ions
- **During fast ion redistribution/loss events, strong 2nd Harmonic ICE has been observed on many devices (~ 50 MHz on ITER)**

- **Measured using RF/magnetic pickup loops, FIR/microwave scattering and reflectometry (conventional and fast-wave)**
- **Full study is required**



*H.H. Duong, et. al. NF **33** (1993)749*

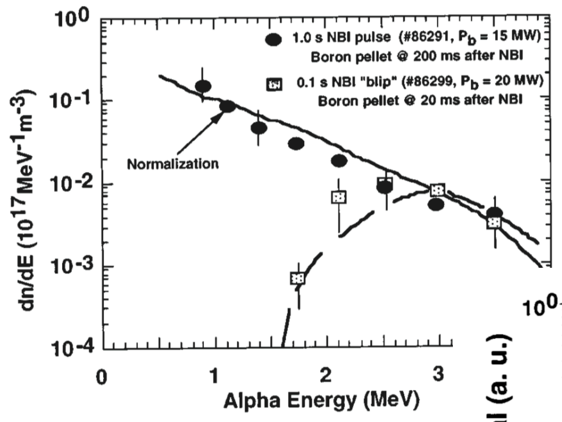
The Direct Diagnosis of Confined CFPs is Crucial for Two Major Aspects of Burning Plasma Physics

- **Alpha Heating**
  - An efficient and central alpha heating is crucial in low Q conditions
- **Instability Drive**
  - High energy particles can drive instabilities (e.g. AE s)

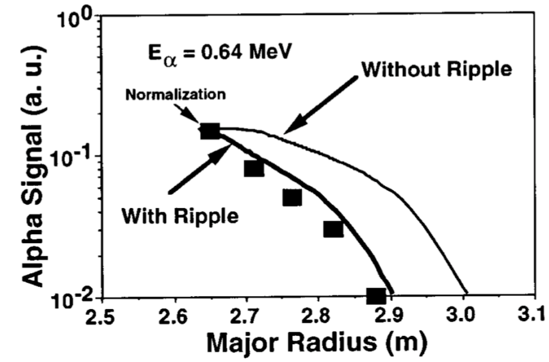
- **Temporal, Spatial and <u>Phase Space</u> distributions are critical to obtain physical picture**
  - Measurement requirements do not reflect these needs adequately at the moment

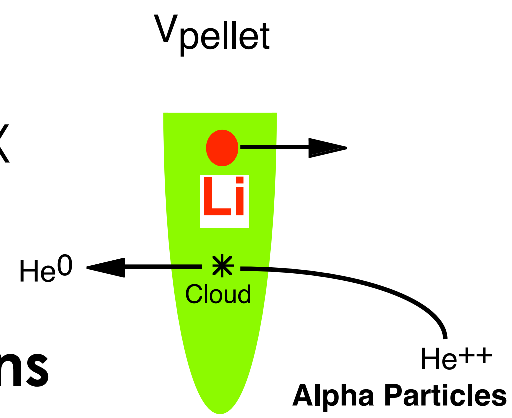
The Measurement of Confined CFPs Has Brought Much Insight into Potential Loss/Diffusion Mechanisms

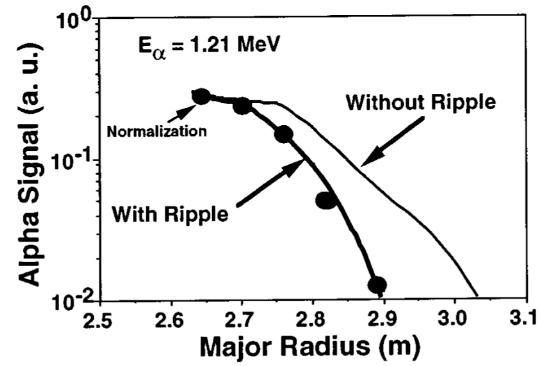
- **One basic technique lies on particle detection through CX/neutralization with beams or pellets**
  - NBI, pellets, lithium beam are candidates
  - Penetration and attenuation serious drawbacks for ITER/BPX
- **Other candidates: CTS (see Bindslev), spectroscopy, knock-ons**



PCX data







*S.S. Medley et al, NF **38** (1998)1283*

TFTR

DEMO and other BPX will Bring Additional Roles to FP Measurements

- **Alpha Channeling**
  - Channel alpha energy preferably to ions through wave interaction
- **Advanced control**
  - Burn control
  - Source profile optimization
    - Thermal, fast ions, spatial distribution
  - Control of limiting AE MHD activity
  - Efficient and uniform fuelling
    - Pellet, etc
- **Advanced fuels**
  - Polarized fusion
  - Aneutronic reaction
    - Test the $p+^{11}B$ and CFP diagnostics during hydrogen phase?

Summary

- **Diagnostics based on Fusion Products measurements can yield comprehensive and vital information of the behavior of burning plasmas**
  - Optimize fusion production
  - Optimize self-heating conditions
- **They can be made compatible with nuclear environment (some are naturally!)**
- **Due to their nature, they will be also called to serve may roles in controlling burning plasma performance (e.g. burn control) in DEMO and future reactors**
  - Require full vetting in ITER and similar experiments