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

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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
• 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

\[ D + D \rightarrow ^3\text{He} \ (0.8 \text{ MeV}) + n \ (2.45 \text{ MeV}) \]
\[ D + D \rightarrow T \ (1 \text{ MeV}) + p \ (3 \text{ MeV}) \]
\[ D + T \rightarrow \alpha \ (3.5 \text{ MeV}) + n \ (14.1 \text{ MeV}) \]
\[ T + T \rightarrow \alpha + 2n (\text{total of } 11.3 \text{ MeV}) \]

- **Advanced fuels**
  \[ D + ^3\text{He} \rightarrow \alpha \ (3.6 \text{ MeV}) + p \ (14.7 \text{ MeV}) \]
  \[ p + ^{11}\text{B} \rightarrow 3\alpha \ (\text{total of } 8.7 \text{ MeV}) \]

- **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)
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

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**TFTR**

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

\[ ^9\text{Be} + \alpha \rightarrow n + \gamma + ^{12}\text{C} \]
\[ ^{12}\text{C} + D \rightarrow p + \gamma + ^{13}\text{C} \]

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)

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 $\Delta_t \sim 2q\rho/(\epsilon)^{1/2}$

- **For alpha particles in ITER**
  - $\rho \sim 5 \text{ cm}$
  - $\Delta_t \sim 15-20 \text{ cm}$

- **Need to also know**
  - Current and source profiles!!!
  - 3-D first wall geometry
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
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 ~0.5m²/sec

On TFTR, measurements of CFP losses due to turbulent/anomalous diffusion showed an upper limit of 0.1m²/sec

- Important to validate the results for a burning plasma experiment
- Measurements made on confined particles (using \( \alpha \)-CHERS) indicated a 0.03m²/sec upper limit
- Why is it favorable compared to a thermal diffusivity of ~1m²/sec

\[ S. \text{Zweben, NF 31, (1990) 573} \]
\[ G. \text{McKee, PRL 75, (1995) 649} \]
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

**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

\[ \alpha' \text{'s} \rightarrow \text{AEs} \]

Time (s) Frequency (kHz)

\[ \text{M. Garcia Muñoz APS-DPP (2006)} \]

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 $q_{\text{edge}}$)
  - 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 2\textsuperscript{nd} 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 Phase Space 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

*S.S. Medley et al, NF 38 (1998)1283*
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 many roles in controlling burning plasma performance (e.g. burn control) in DEMO and future reactors
  – Require full vetting in ITER and similar experiments