Development of tools for understanding, predicting and controlling fast ion driven instabilities in burning plasmas

M. Podestà[1], J. K. Anderson[2], W. Boeglin[3], B. Breizman[4], D. Brennan[5], D. Darrow[1], A. Fasoli[6], E. Fredrickson[1], G.-Y. Fu[1], N. Gorelenkov[1], Z. Lin[7], J. Menard[1], S. Pinches[8], J. Snipes[8], S. Tripathi[9], M. Van Zeeland[10], R. White[1]

1) PPPL, 2) UW Madison, 3) Florida International University, 4) UT Austin, 5) Princeton University, 6) CRPP/EPFL Lausanne CH, 7) UC Irvine, 8) ITER Organization, 9) UC Los Angeles, 10) General Atomics

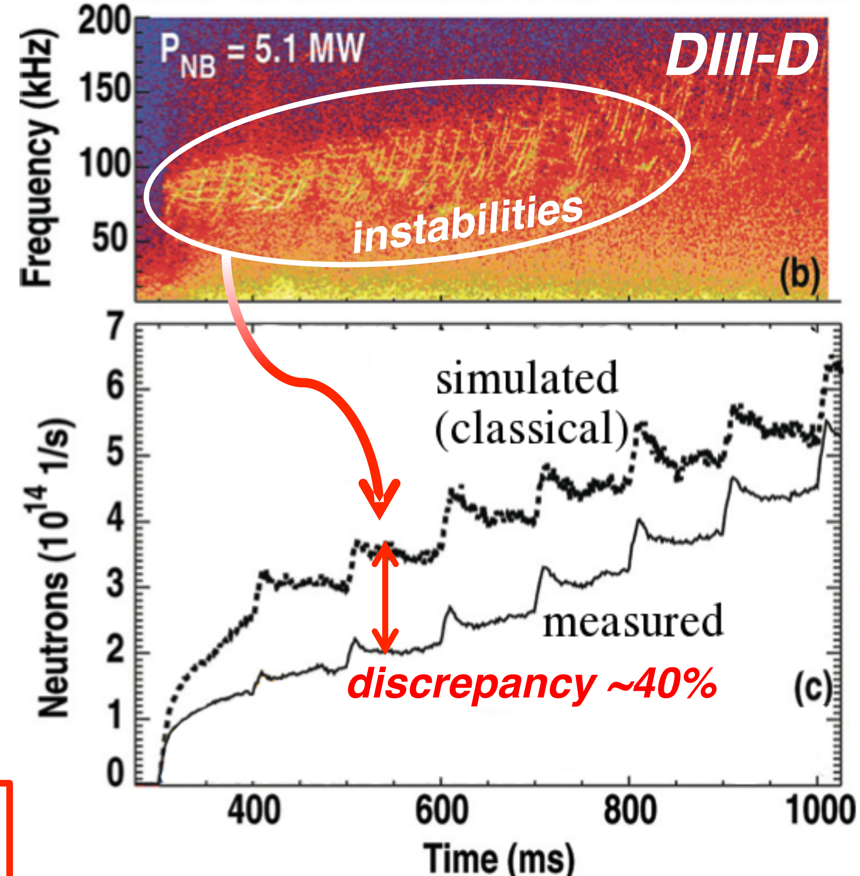
FESAC Meeting
July 8th-10th, 2014

Understanding and controlling energetic particle (EP) driven instabilities is crucial for ITER/FNSF mission

EP-driven instabilities affect alphas from fusion reactions, fast ions from neutral beam (NB) and RF injection

- –Enhanced transport
- –Effects on NB-driven current (presently) unpredictable
- –Losses can cause localized heat load to vessel wall

> *Possibly inaccurate predictions based on "classical" mechanisms if non-linear wave-particle interactions dominate*



*Van Zeeland et al., PoP **18** (2011) 056114*

Increased effort is required to understand, predict and ultimately control fast ion driven instabilities in burning plasmas

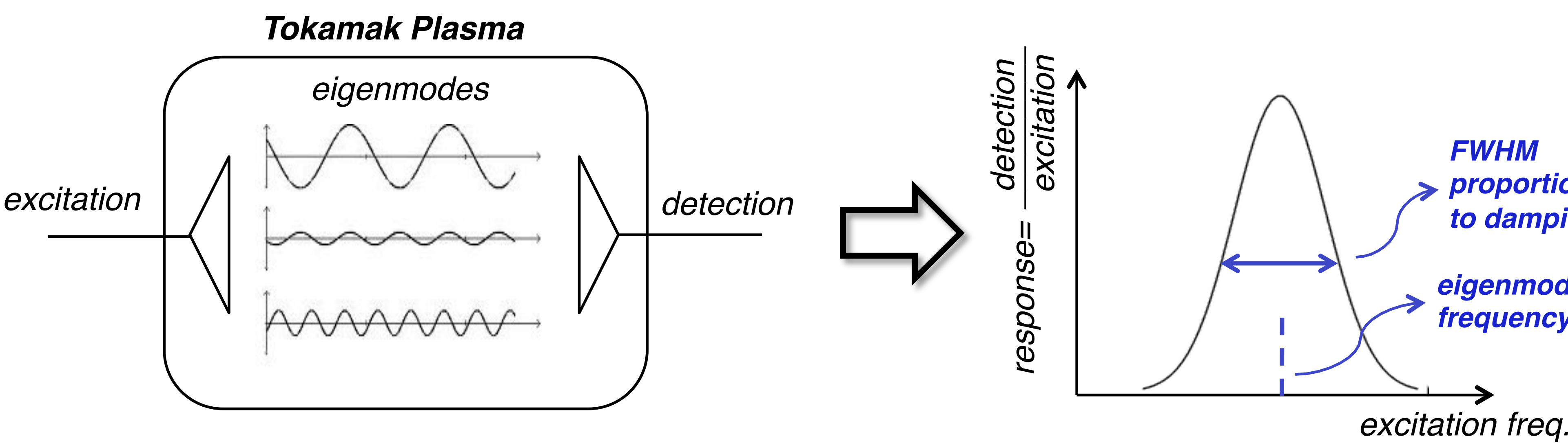
Experiments have shown *potential* for developing integrated detection, prediction and mode control within few years

- **Detection** in real time of EP-driven mode properties
  - Essential for mode control – but ***missing in present US facilities***
  - Implementation requires dedicated diagnostics to monitor/characterize mode evolution and effects on fast ion distribution

Example: real-time characterization of mode stability on JET via active spectroscopy -> enables early mode detection (before modes get unstable)

*Fasoli et al., PPCF **52** (2010) 075015*

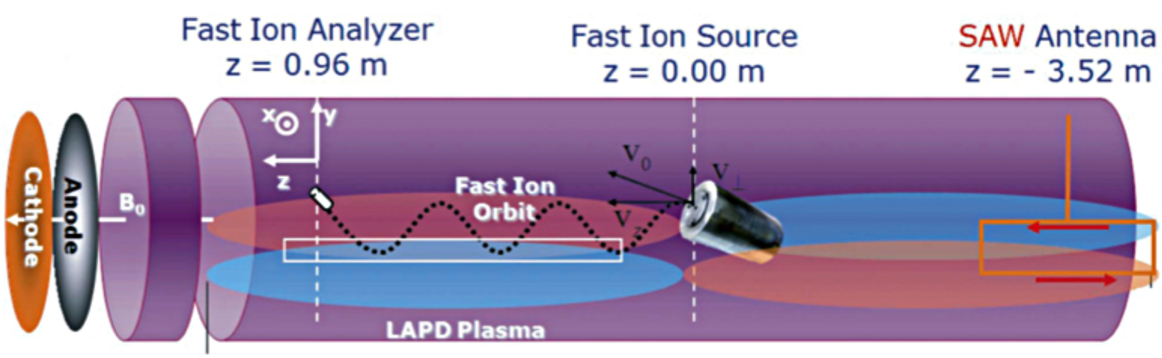
*Testa et al., EPL **15** (2010) 50001*



Experiments have shown *potential* for developing <u>integrated</u> detection, prediction and mode control within few years

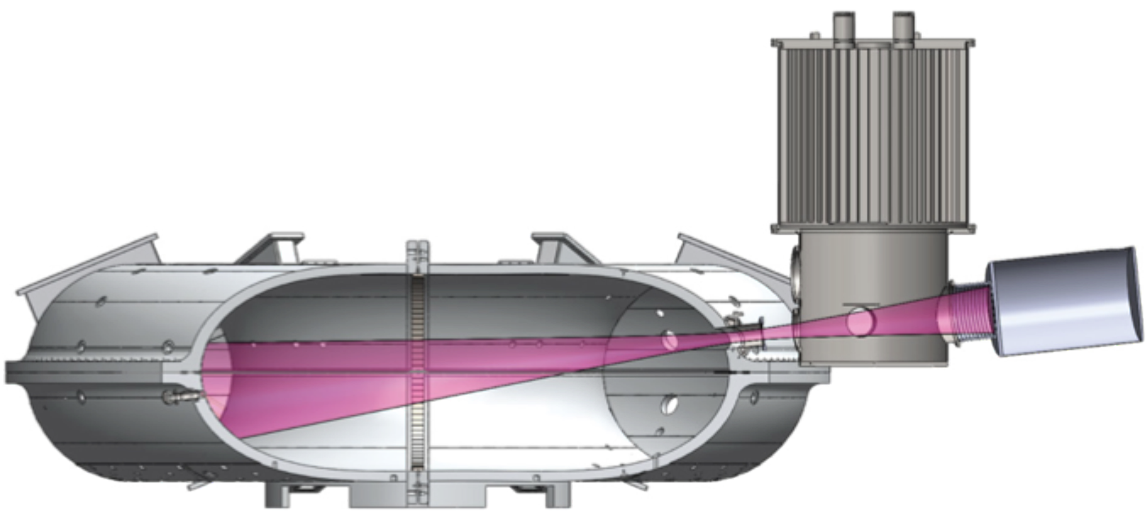
- **Detection** in real time of EP-driven mode properties (demonstrated on JET)
- **Prediction** of mode stability, effects on F_{ep} – *WPs by Fu, Guttenfelder, Hammett*
  - Exploit different configurations, well controlled experiments for validation of theory, models

Example: studies of Alfvénic Waves effects on energetic ions on LAPD (UCLA) and on MST (UW Madison)



LAPD: linear device, complete characterization of wave field, fast ion population

*Zhang et al., PoP **15** (2008) 102112*
*Heidbrink et al., PPCF **54** (2012) 124007*



MST: reversed field pinch, 1MW NBI for fast ion studies

*Anderson et al., PoP **20** (2013) 056102*

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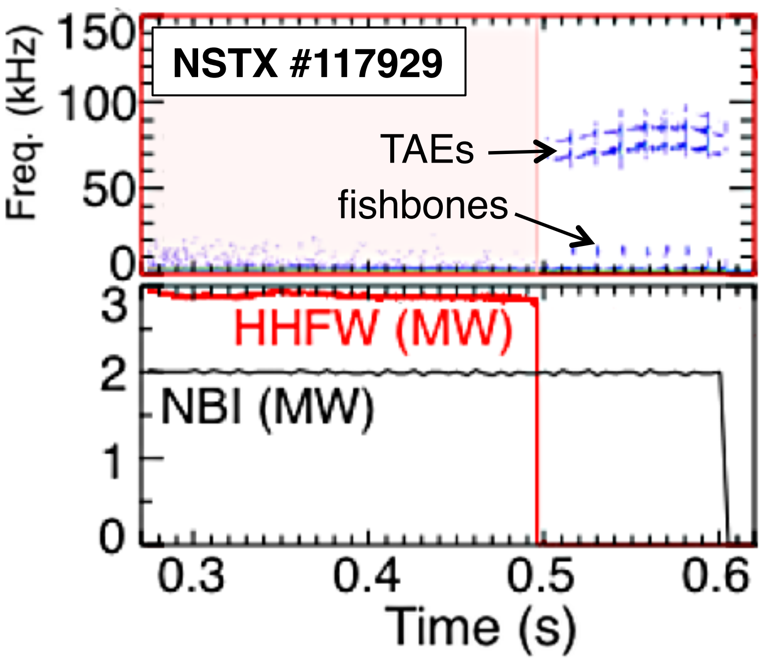
- **Detection** in real time of EP-driven mode properties (demonstrated on JET)
- **Prediction** of mode stability, effects on F_{ep} – *WPs by Fu, Guttenfelder, Hammett*
- **Control** – promising results obtained for mode suppression/mitigation
  - *Robust interpretation required to become practical control tool – WP by Fu*

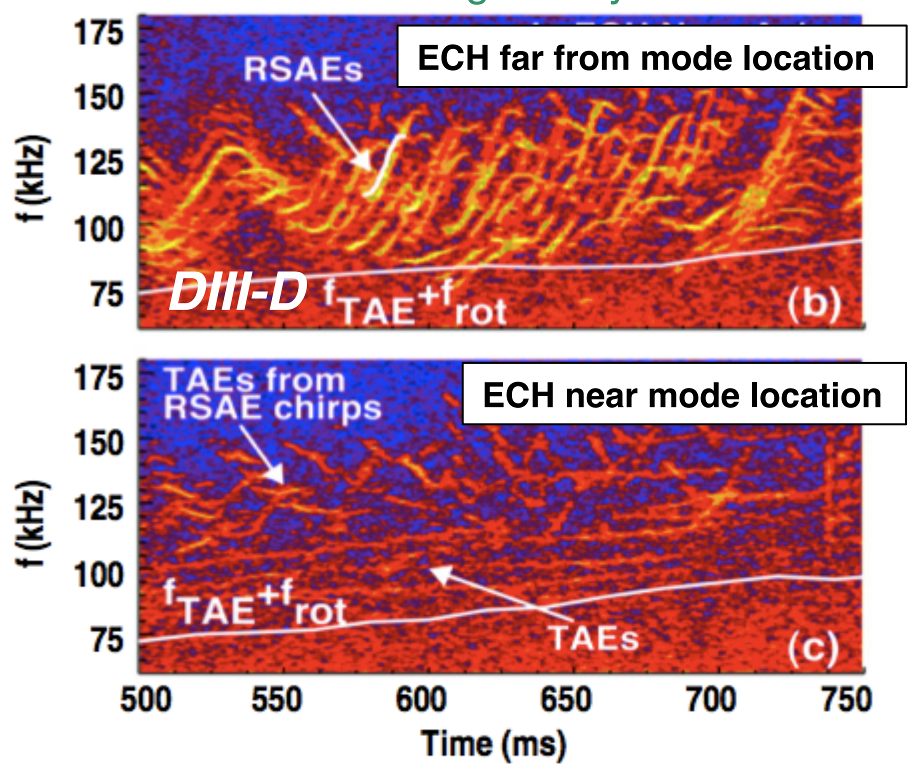
Example: mode suppression/mitigation using RF/HHFW, ECH, 3D fields

NSTX: Instabilities suppressed by 3MW of High Harmonic Fast Wave heating (HHFW)



Fredrickson (PPPL, 2014)
*Bortolon et al., PRL **110** (2013) 265008*

DIII-D: Instabilities mitigated by localized ECH



*Van Zeeland et al., NF **49** (2009) 065003*

Goal for next 5-year period: develop, demonstrate real-time mode detection & feedback control on existing devices

- Establish physics basis for "actuators"
  - From semi-empirical to integrated and validated understanding
  - Focus on mode stability and its dependence on fast ion distribution, F_{ep} (collaboration with theory)
  - Develop modules for integrated tokamak simulation codes (TRANSP, IMAS)
- Demonstrate mode control techniques using NBI, RF/ECH, 3D fields
  - Develop "reduced models" for mode stability, F_{ep} evolution to be included in real-time control schemes
  - Implement control schemes to close the loop *plasma-detectors-control-actuators*
- **Demonstrate in JET D-T campaign in FY17-18**
  - Target high-q_{min} scenario, *including ramp-up phase*
  - Characterize stability vs. F_{ep} – contribution from alphas, NB/RF tail ions
  - Explore "alpha channeling" processes

Goal for 10-year period and beyond: project mode control techniques to burning plasma devices (ITER, FNSF)

Reactors will present specific challenges

– *Limited diagnostics; reduced flexibility for actuators*

- Analysis based on actual diagnostics and actuators available on fusion reactors
  – Mode stability: complement measurements with validated reduced models
  – Actuators: NBI, RF/ECH, 3D fields – all available on major US facilities and JET
  > ***All this can be tested in present devices with proper enhancements***
- Assess optimum control schemes via integrated modeling
  – In line with ITER, ITPA priorities
  – Perform time-dependent simulations, *including current ramp*
  > ***Maximize performance, minimize risk***

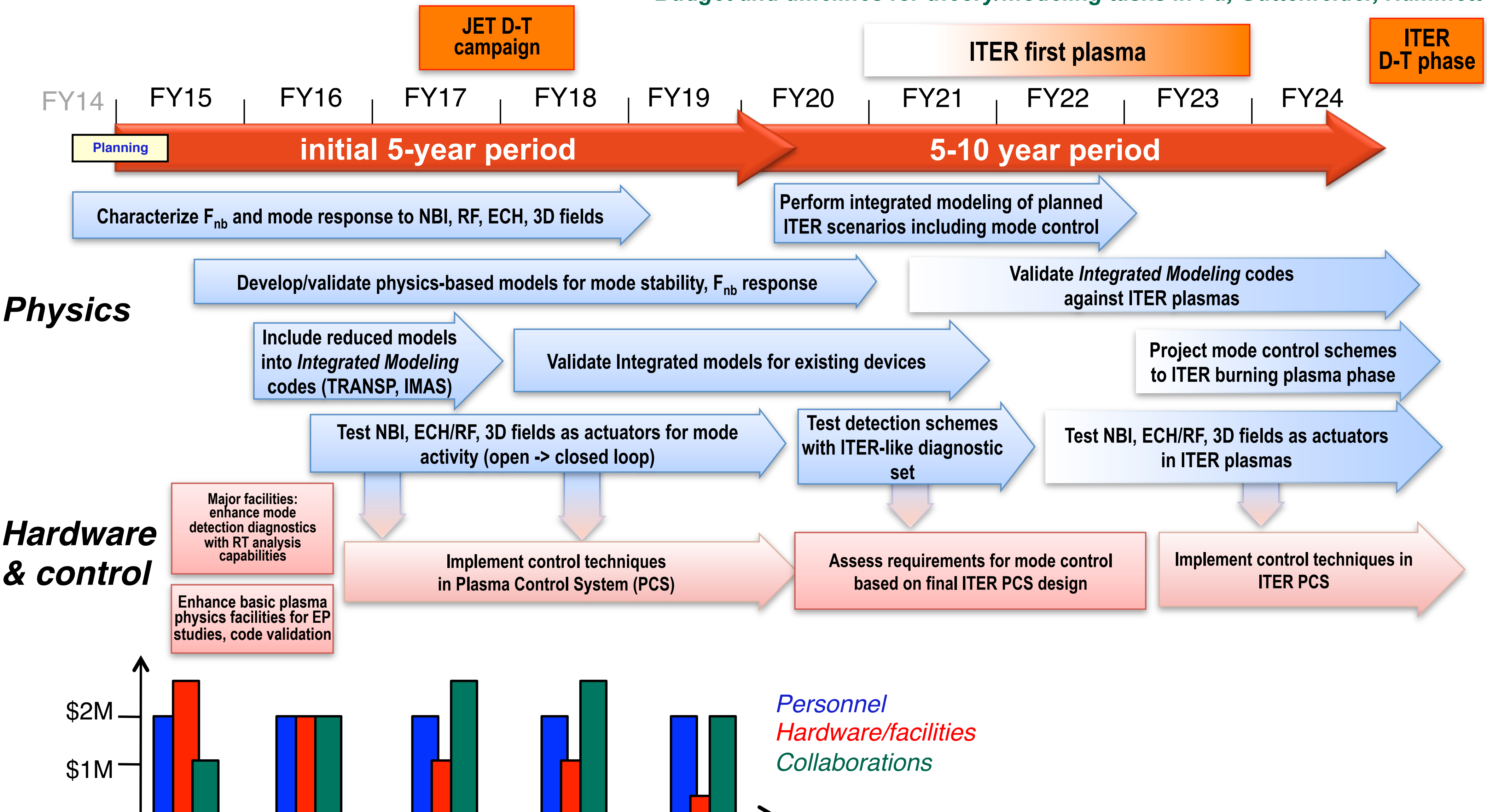
Incremental resources for EP research are needed to meet the proposed goals

- Need additional FTE's on major facilities, university-based experiments for coordinated initiatives
- Enhance present facilities with hardware for real-time characterization of modes, F_{ep}
- Support theory/modeling effort for successful achievement of *predictive capability*
  - Collaboration between National Labs and Universities
  - Leverage on complementary facilities for improved Verification&Validation tasks
- Strengthen collaboration with JET and other international institutions
  - Build Team for ~2020 (ITER era) and beyond

Timeline of deliverables & budget estimate

A budget increment* of $4-6M/yr over ten years is needed
to maintain/strengthen forefront US position in experimental EP physics

**Budget and timelines for theory/modeling tasks in Fu, Guttenfelder, Hammett*



Summary

- Control of EP-driven instabilities is required to **minimize risk, maximize performance** in future fusion reactors

- **Development of control tools is achievable** in next few years with modest increase in resources for EP research
  - Main program elements already present in *incremental* 5-year EP Research Plans for most facilities (e.g. NSTX-U, DIII-D, MST)

- **JET D-T** campaign provides **unique opportunity** to demonstrate mode control in conditions closer to ITER/FNSF

> *Combining expertise in EP physics (experiments, theory, modeling) and plasma control would enable US leadership in this area*

Backup slides

Proposed Initiative is well aligned with US Fusion Program priorities as summarized by ReNeW Themes

- Theme#1: Burning plasmas in ITER
  - "... develop improved methods for **controlling key aspects** of burning plasmas"
  - "... incorporating **validated theories** for alpha particle behavior into integrated simulation tools"
- Theme#2: Predictable, high-performance, steady-state plasmas
  - "... integrate development of [systems] needed to maintain plasma state seeking to **maximize performance**"
  - "... **understand the highly integrated dynamics** of dominantly self-heated and self-sustained burning plasmas"
- Theme#5: Optimizing the magnetic configuration
  - "Develop the ST to advance fusion nuclear science" for FNSF
  - "Power handling, **controlled stability, and sustainment** issues would be studied"

Must develop integrated set of tools

*for **detection, prediction and control** of EP-driven instabilities*

ITER diagnostic set provides means to detect core mode activity, proxies for EP evolution

*From A. Donné et al., NF **47** (2007) S337*

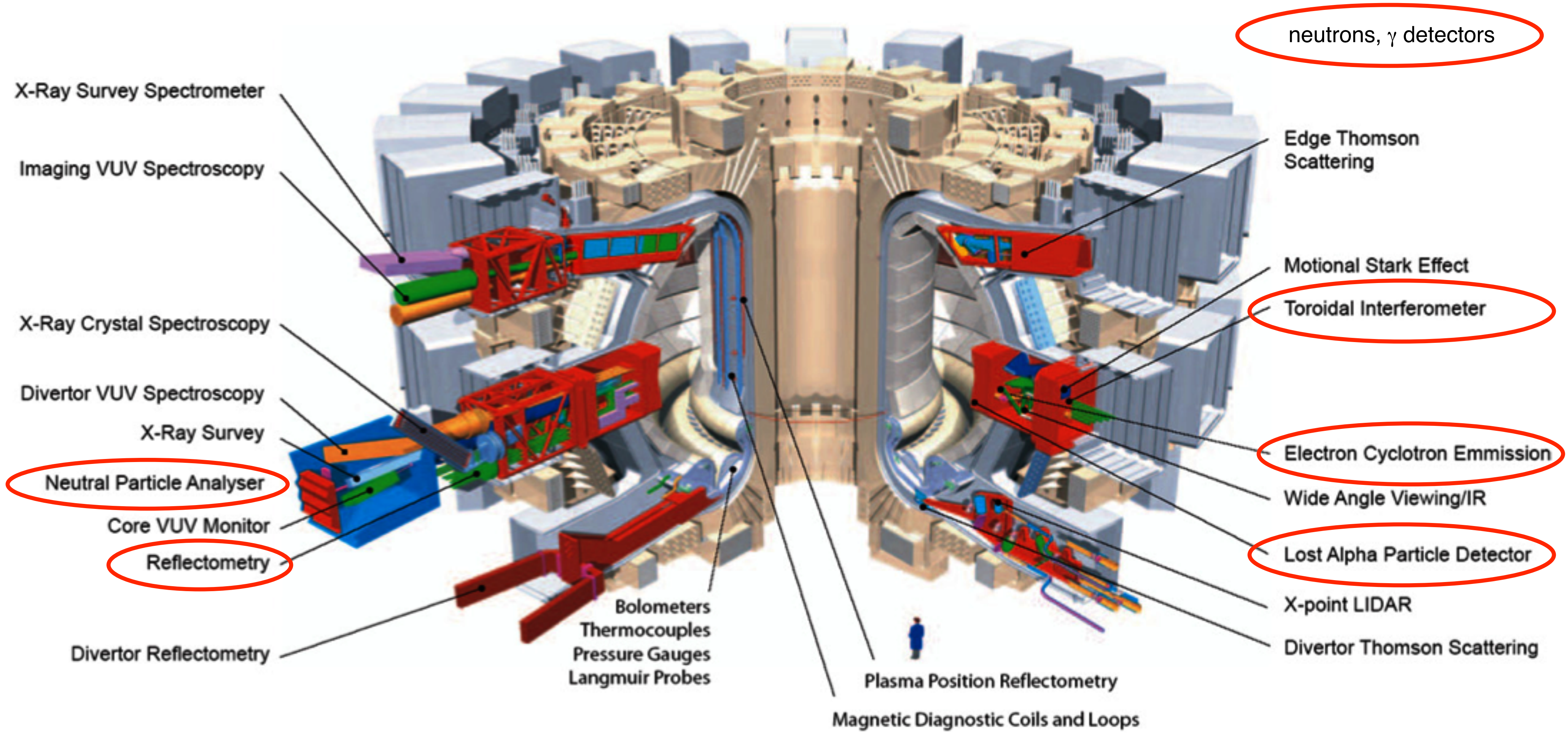


Figure 15. Cut-out view of ITER to visualize some typical diagnostics in upper and equatorial ports, as well as in the diagnostic divertor cassettes.

Some diagnostics may require improved bandwidth to cover frequency range of EP-driven instabilities

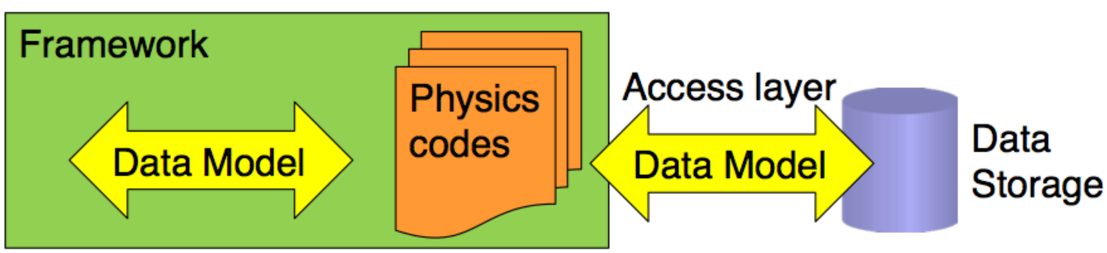
ITER integrated modeling programme
Integrated Modeling and Analysis Suite - IMAS

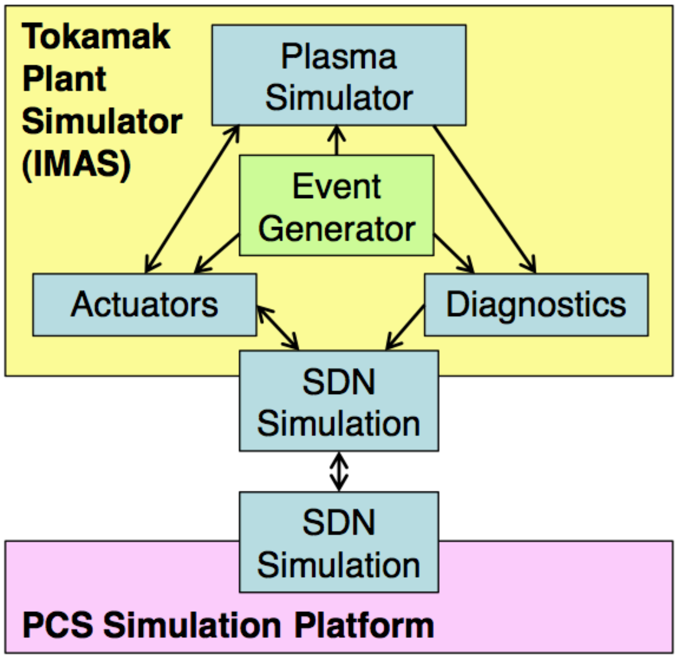
From S. Pinches, APS-DPP 2013 Denver (CO)

- A programme on integrated modelling and control of fusion plasmas, including benchmarking and validation activities, co-ordinated by the ITER Organization, but developed using relevant expertise within the Members' fusion programmes
- Overall aims of programme are to meet initial needs of ITER Project for more accurate predictions of ITER fusion performance and for efficient control of ITER plasmas, to support the preparation for ITER operation and, in the longer term, to provide the modelling and control tools required for the ITER exploitation phase

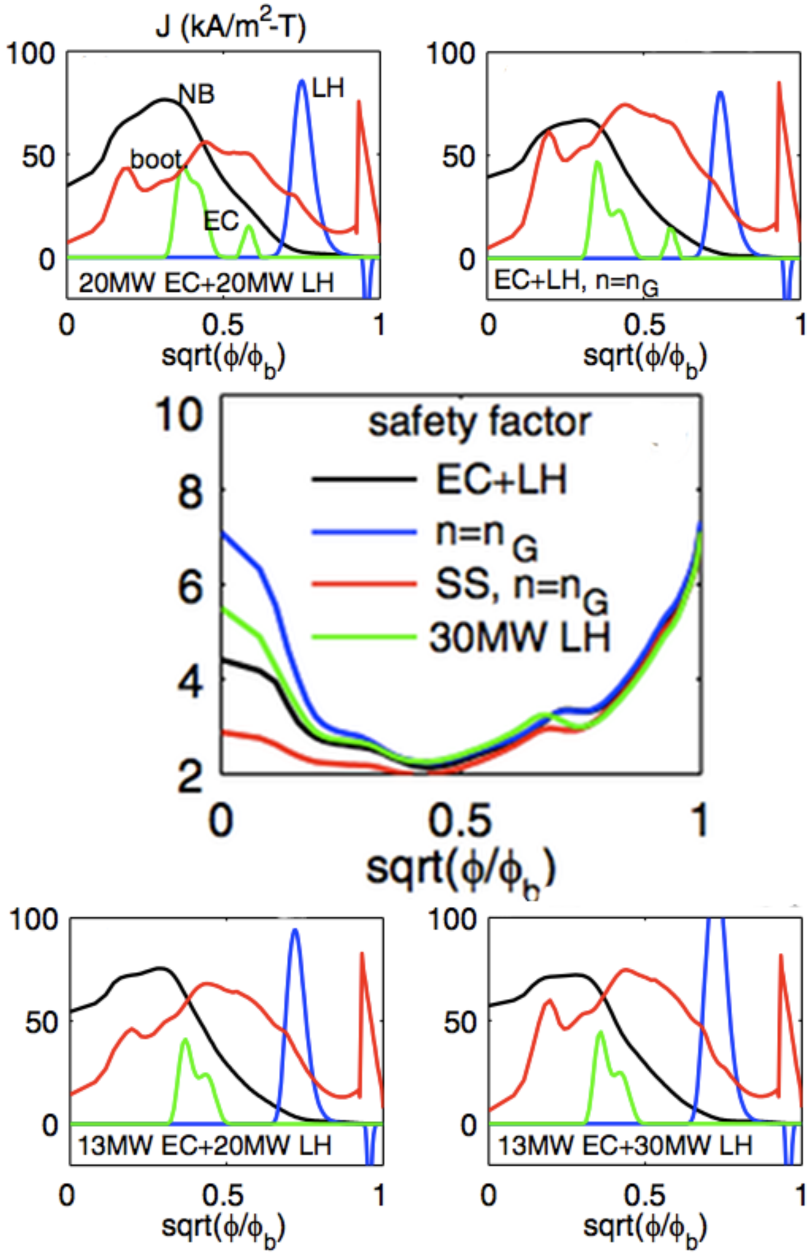
IMAS:

- ITER Physics Data Model
  - Applicable for all physics usages
- Physics Codes
  - To support Plasma Operations and Plasma Research
  - Contributed and validated by ITER Members
- Workflow Engine
  - To orchestrate execution of integrated modelling workflows





Advanced Scenarios in ITER to achieve Q up to ~5 may require reversed shear with elevated q_{min}



*F. M. Poli et al., NF **54** (2014) 073007*

- ITER steady-state (SS) scenarios with Q~5 and Ip~9MA require high H_{98}~1.6
- High confinement may imply internal transport barrier (ITB)
- For electron-heating-dominated plasmas expected in ITER, ITBs require reversed shear
- q_{min}~2 or larger for ideal MHD stability

> *Stability properties of Alfvénic modes in this phase (including trajectory to achieve SS) still unexplored*