US Contributions to ITER Physics

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The US Fusion Energy Sciences Community is actively working to ensure a successful ITER research program

- **Device design is mostly settled, with a few areas still needing attention**
  - Disruption prediction, avoidance, and mitigation
  - ELM suppression or mitigation
  - Requirements for error field correction coils
  - The US community has always been proactive in addressing new questions as they come up (helium operation, test blanket modules, etc.)

- **The emphasis is gradually moving from “how to build it” to “how to operate it”**
  - Controlling a burning plasma
  - Preparing burning plasma relevant operating scenarios
  - Predicting the boundary heat flux
  - Energetic particle behavior
  - Measurement in a burning plasma environment

**ITER is not a diversion detracting from our research program, rather it inspires us to address issues that must be considered to successfully proceed to a burning plasma step**
ITER physics tasks are a communal responsibility (all seven parties)

- Usually identified by ITER Organization
  - Could be addressed through ITPA
  - Could be organized directly with individual facilities
- Communication with ITER Science and Operations Division has been excellent
  - We expect this to continue under new leader Tim Luce (formerly of GA)
- In many areas, different facilities/parties work together
  - ITER personnel frequently participate

ITER physics tasks are often carried out in a collaborative manner, crossing borders between partners. This talk focuses on work done by and in the US FES community.
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2016 FES Joint Research Target: Explore disruption avoidance and mitigation

Mitigation techniques inject particles into plasma to radiate away energy content
- MGI: Massive Gas Injection
- SPI: Shattered Pellet Injection

- Compared MGI mitigation of “sick” and “healthy” plasmas (C-Mod, DIII-D)
- Tested and installed 3 ITER-like MGI valves (NSTX-U)
- Runaway physics studied (C-Mod and DIII-D)
- Develop and install multi-machine disruption warning algorithm (NSTX/NSTX-U)
- Explored advanced MHD control techniques (DIII-D)
Shattered Pellet Injection (SPI) selected as ITER’s day 1 DMS

- **Wine-bottle-cork-scale pellet fired into the tokamak, shattering on the way in**
  - Tested with D$_2$ and Ne (high-Z better)

**Recent results (PRELIMINARY)**

- **Shallow (ITER upper port) trajectory reduces SPI effectiveness vs. core directed injection**
- **Effectiveness of multiple SPI depends on injection timing**
  - 2$^{nd}$ smaller pellet leads to less radiation than single large pellet
  - New experiment with two identical 400 torr-L pellets performed, results pending interpretation
- **Work is continuing...**
Collaboration on JET Shattered Pellet Injector will inform ITER disruption mitigation requirements

Status of U.S. Contributions

- D pellet injector from ORNL tested successfully
- Mechanical punch designed to dislodge high-Z pellets in the largest barrel requires further development, works in the two smaller barrels
- Cold zone for large barrel may be reduced to achieve desired performance
- Shipment to JET is imminent

Also being deployed in J-TEXT, HL-2A, MST

JET SPI has ITER-like 3-barrel injector and injection trajectory

Large Collaborative effort involves JET/EUROfusion, ORNL, USIPO, ITER Org, EC, and US DOE
Alternative DMS approaches under study

- ITER DMS can be upgraded if better alternatives are available and developed to maturity by ~2029
- Two options currently under study in the US

**Low-Z dust-filled shell**
(N. Eidietis, GA)

"Inside-out" thermal quench mitigation + stochastic runaway electron deconfinement & high n_e suppression + maintains moderate current quench rate

**Electromagnetic Particle Injector**
(R. Raman, U Washington)

Rapid delivery of impurities deeper into the plasma with fast time response
Prototype tested, time response and velocity consistent with predictions

![Diagram](image-url)
Disruption Event Characterization and Forecasting
innovation to enable disruption avoidance

Automated disruption event chain analysis

- Physics-based disruption forecasting models begun
- Prediction quantitatively compared to experiment
- Collaborative (inter)national multi-device studies starting (incl. NSTX/-U, KSTAR, DIII-D, TCV)

Disruption forecasting

Global kinetic MHD mode growth

Analysis aimed to cue disruption avoidance systems
- Physics-based disruption forecasting models begun
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DECAF code

ELM control with magnetic perturbations produced by internal coils is planned for ITER

Resonant Magnetic Perturbations (RMP)

- Full suppression demonstrated on ASDEX-U through collaboration with DIII-D
- Result on DIII-D suggested lower collisionality on AUG is key
- Follow on experiment on AUG achieved ELM suppression
- Encouraging result for ITER
Multi-mode RMP lowers threshold current for ELM suppression in DIII-D

- Multi-mode RMP with mixed $n=2$ and $3$ lowers total coil current to access ELM suppression compared with pure $n=3$ case

- Maximal current
  \[2.28 + 0.87 = 3.15 \text{kA} < 3.50 \text{kA}\]

- \(\propto \) Energy\(^{1/2}\)
  \[(2.28^2 + 0.87^2)^{1/2} = 2.44 \text{kA} < 3.50 \text{kA}\]

Multi-spectral tailoring of applied field made possible by new power supplies from ASIPP/EAST
Does ITER need to rotate the RMP perturbation?

- Heat (IRTV) and particle flux (Fastcam visible imaging) splitting measured in DIII-D RMP ELM suppressed discharges with ITER similar shape and operating conditions shows
  - clear splitting in particle flux
  - no clear splitting seen in heat flux

**Divertor strike point particle flux splitting exceeds vacuum predictions by 3x-5x**
- challenges linear plasma response models which result in predominantly screening

- Partial HFS strike point heat flux detachment achieved with mid-Z puffing.
  - RMP ELM suppression maintained over wide range of collisionalities

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R. Moyer, D. Orlov (UCSD)
ELMs Eliminated in EAST Using PPPL Impurity Dropper in Scenarios with Tungsten Divertor

R. Maingi, Nucl. Fusion (2017) submitted

ELMs suppressed
On-going effort to predict error field (EF) tolerance of ITER operation (MDC-19)

- Using 3D MHD response metrics
- Resonant n=1 EF criterion (2017):
  \[(\delta B/B_T)_{pen} = 0.0006(n_e)^{1.3}B_T^{-1.7}R_0^{0.7}\beta_N^{-0.78}\]
- New resonant n=2 EF criterion is due on 2018 March ITPA MHD meeting
- Two more EF criteria on NTV and heat flux splitting are under investigation

MDC-19 will provide final report and recommendation for 3D coils by 2019, based on each EF correction capability

- In particular, on top and bottom ex-vessel coils (EFCT, EFCB), which are found 10 times less efficient to control n=1,2 resonant fields

Error field penetration thresholds vs. density

10 times higher currents are required to avoid EF-resonant disruption when using EFCT/B

J.-K. Park, et al.
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US contributions to ITER control

- Development of ITER-relevant controls on US tokamaks
  - Plasma shape, current, & vertical position control
  - Non-axisymmetric (e.g., RWM, NTM) stability control
  - Current profile control
  - ELM control
  - Off-normal event detection and handling
  - Divertor control
  - Alfvén Eigenmode control

- Participation in design of ITER real-time framework and PCS

- Support for development of ITER Plasma Control System Simulation Platform (PCSSP)
  - PCSSP is a software platform for development and validation of ITER PCS
Effective remote experiments demonstrated during EAST 3rd shift operations

Scientific Achievements in 2017:

- Remote technology challenges addressed (audio, data transfer)
- Four expt’s carried out over 5 shifts (1 wk)
- New EAST capabilities demonstrated
  - Divertor detachment
  - Fast rampdown without disruption
- Prototype for remote participation in ITER
- Remote control rooms now available at
  - GA (EAST, KSTAR)
  - PPPL (KSTAR, W7-X)
  - MIT (in preparation)
Modeling framework aims to accelerate ramp-up scenario and control development

TOKSYS: Matlab code used to develop actuator and plasma models for testing PCS algorithms (supported by GA)

Two major development efforts
- Design and validate plasma model using experimental data and simulations (i.e. TRANSP, DCON)
- Develop non-linear models and/or switching between linear models
  - Flattop modeling typically uses linearized model around a reference case

Ultimate goal: develop, test and optimize scenarios and control in the ramp-up phase in offline simulations
Update and reanalysis of international H-mode database for ITPA Transport and Confinement TG

- Add data closer to ITER baseline conditions + hybrids, including data from high-Z wall devices
- Expand parameter range and explore new variables (torque, $n_{e,SOL}$ and $n_{e,sep}$, improved fast ion content)
- Separate core and pedestal scalings, provide a more realistic density dependence
- 2 devices included so far: JET and ASDEX-Upgrade
  - AUG: 613 W-wall ITER baseline discharges
  - JET: 630 data points with ILW

S. Kaye, PPPL
Stable zero-torque ITER Baseline Scenario discharges achieved

\[ \beta_N, I_N, H_{98y2} \]

\[ n_e \left(10^{19}/m^3\right) \]

\[ \tilde{B}(n=1) \quad (G) \]

\[ I \quad (MA) \]

\[ \ell_1, \text{Div. } D_\alpha \quad (\text{a.u.}) \]

\[ P_{NB} \quad (MW) \]

\[ f(q=2) \quad (kHz) \]

\[ T_{NB} \quad (Nm) \]
Experiments in DIII-D have applied ELM suppression to a high-β, fully noninductive scenario

High power, high-β hybrid scenario

- \( n = 3 \) odd parity RMP excites edge kink modes that are marginally stable and amplifying
  - Benefits: modest RMP amplitude, wide \( q_{95} \) window, small effect on pedestal, ELM suppression at low rotation

- Integrated with Argon-based radiating divertor, reducing heat flux by 50%

- Scenario scales to steady-state in ITER with \( P_{\text{fus}} \approx 460 \text{ MW} @ Q_{\text{fus}} \approx 5 \) and \( H_{98y2} = 1.2 \) (further optimization possible)

C. Petty, IAEA16
Significant progress towards QH-mode startup with zero net NBI torque

- If QH-mode is to be used in future devices such as ITER, we need to demonstrate creation and sustainment with essentially zero NBI torque.

- Experiment in 2017 focused on reducing the input NBI torque needed for wide pedestal QH-mode:
  - Counter-$I_p$ torque from NTV from nonaxisymmetric $n=3$ fields was used to supplement NBI.

- Time integrated torque needed for wide pedestal was reduced by 90%.

- Next issue to confront is locking of core tearing modes.

K. Burrell APS17
Super H-mode Scenario Sustained in DIII-D & Applied in C-Mod to Achieve ITER-level Pedestal

- **Sustained in DIII-D for 2.5s with H_{98} \sim 1.6**
  - RMP-ELM mitigation
  - $\beta_N \sim 2.9$, 1.9MJ, $\tau_E = 200$-600ms

- **Possible record DIII-D P_{ped} = 30kPa**
  - $H_{98}$ reaches 2.5, $Q_{DT, EQUIV}$ reaches 0.35
  - On-axis $n$, $T_i$ similar to ITER mid radii

- **Understanding applied to achieve ITER-level pressure pedestal in C-Mod**
  - Demonstration of Super H-mode benefits at higher field
    - World record pressure achieved in three scenarios: Super H, EDA H-mode, I-mode

- **May be applicable to other devices**

Snyder APS17, Hughes APS17
First and only $\lambda_q$ measurements taken at ITER-level $B_p$ in Alcator C-Mod

- No major departure from inverse poloidal field scaling
- H- and I-modes at similar poloidal field have similar heat flux widths: similar physics controlling for both?
- Heuristic Drift model agrees with C-mod $\lambda_q$, although C-Mod has largest deviation in multi-machine database
- XGC1 prediction for ITER are $10 \times$ wider than empirical trend - due to turbulence broadening
  - Basis for exascale simulations

New C-Mod data: D. Brunner, APS17
XGC1 calculations: S.-H Ku and C.S. Chang
Energetic particle behavior is becoming increasingly predictable

- Tangential 2\textsuperscript{nd} neutral beam suppresses Global Alfvén Eigenmode (GAE) in NSTX-U
- **Consistent with HYM simulations**

E. Fredrickson, PRL (2017)

- HYM code: growth of n=10 counter-GAE from 1\textsuperscript{st} NBI
- HYM: suppression of n=10 counter-GAE by 2\textsuperscript{nd} NBI
- Most unstable $n$-number, mode $\omega$ consistent with HYM
Diagnostic development and exploitation is a strength of the present-day US Fusion Energy Sciences program

- Need to maintain leadership

New challenges for measurement

- Particle flux and fluence (neutrons, gammas, ions, neutrals)
- Very limited access (e.g. tritium blanket modules)
- Very long pulses and high duty factors
- Reliability, robustness, lack of maintenance
- Full set of real-time measurements
- Define minimal set of required diagnostic systems
- Develop and test new techniques

Follow-on devices (FNSF, DEMO,...) will be even more demanding

- All of the above - but more so
Prototype of ITER Toroidal Interferometer and Polarimeter (TIP) tested on DIII-D

Just one of many examples...

- Real-Time (1 kHz) control of density
- Crude density profiles
- Global constraints to Thomson scattering density profiles
- Measurement of density fluctuations from turbulence and coherent modes (0-1 MHz)
- Benefit of TIP: Recovery from temporary loss of signal
US Fusion Energy Science community is working with international partners to make ITER succeed

- The US community has been enthusiastic in its support of ITER physics
  - The US is responsible for 9% of ITER construction, but contributions to ITER science have far outpaced that number
  - The difficulty in preparing this talk was in deciding what to leave out
- Even eight years before ITER’s first plasma, the science is exciting and challenging

I would like to acknowledge the many contributions made to this talk by community members, and apologize for all of the material I had to leave out.