# Summary: Magnetic Fusion Experiments - I

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M.C. Zarnstorff
PPPL, USA
15 May 2021
ITER Construction – Fantastic Progress

- Major components being delivered
- First sector starting assembly
- Cryostat & coils being installed in pit
- Buildings & infrastructure being completed
- Incorporation of new developments, e.g. shattered pellets DM
- Research prep. progressing

1st plasma: late 2025

Community support is essential to success.

B.Bigot OV/1-1

Installation of the cryostat side-wall and PF-coil #6 in the tokamak pit
New & Upgraded Experiments Operating

**JT60-SA (JP, EU)**
- $R = 3\text{m}$, $A = 2.5$
- $B_T = 2.25\text{T}$, $I_P = 5.5\text{MA}$
- Superconducting Commissioning
- Long pulse adv.
- Y.Kamada

**MAST-U (UK)**
- $R = 0.85\text{m}$, $A = 1.3$
- $B_T = 0.92\text{T}$, $I_P = 2\text{MA}$
- First plasma: 2020
- Super-X Divertor
- ST performance
- J.Harrison

**HL-2M (CN)**
- $R = 1.78\text{m}$, $A = 2.8$
- $B_T = 2.25\text{T}$, $I_P = 2.5\text{MA}$
- First plasma: 2020
- High performance w/ adv. divertors
- X.Duan

**ST-40 (Tok. Energy)**
- $R = 0.4-0.6\text{m}$, $A = 1.6-1.8$
- $B_T = 3\text{T}$, $I_P = 2\text{MA}$
- First plasma: 2019
- ST performance, high T
- M.Gryaznevich OV/4-5

**JT60-SA (JP, EU)**
- $R = 3\text{m}$, $A = 2.5$
- $B_T = 2.25\text{T}$, $I_P = 5.5\text{MA}$
- Superconducting Commissioning
- Long pulse adv.
- Y.Kamada OV/2-4
New Experiment Projects/Upgrades

DTT (IT)
R=2.19m, A=3.1
B_T=6T, I_p=5.5MA
Exhaust physics, core-edge integration divertor test facility
P.Martin EX/P-1053

SPARC (CFS, Inc.)
R=1.85m, A=3.2
B_T=12.2T, I_p=8.7MA
Q > 2 short pulse
Long-leg divertor
P.Rodriguez -Fernandez
OV/P-856

RFX-mod2 (IT)
R=2m, A=4.1
I_p=2MA
Closer shell, double poloidal gaps, improved PFCs
L. Marrelli EX/P-1077
Core Confinement

- Predict-First Modeling
- Impact of fast ions
- Isotope scaling
- Stellarator transport & confinement
- High performance in JET
- ST confinement
Accurate Predict-First Models Developed

- Separatrix parameters from empirical model of gas puff & 2-pt model
- Pedestal from PB-stability & critical temperature gradient model
- Core plasma inside pedestal using TGLF
- More accurate than scaling laws for AUG!

See also J.Citrin TH/3-2 QuaLiKiz

Ding EX/1-3; J.McClenaghan TH/P8-1016

U. Stroth OV2-2; G.Tardini TH/P2-926
Impact of Fast Ions on Turbulent Transport Can Differ Between D & H

- FI impact studied in JET D and H L-mode by varying ICH $^3$He resonance

- Fast ion (FI) stabilization of turbulence can produce isotope effects can be large in regimes with high Fast Ion content, beta and rotation [J. Garcia, NF 2018].

- Isotope mass differences affects FI pressure gradient via:
  - Heating deposition profile
  - FI slowing down time

- GENE (GK) modelling shows that differences in FI in H vs D lead to strong deviations from GB scaling of thermal core transport

N. Bonanomi et al, NF 2019

J.Mailloux OV/1-2
A.Di Siena TH/4-1
**Dimensionless Identity Isotope Effect Experiments**

**L-mode**

- **H:** \( P_{\text{NBI}} = 6.24 \text{ MW} @ 82 – 91 \text{ keV} \)
- **D:** \( P_{\text{NBI}} = 2.56 \text{ MW} @ 64 – 71 \text{ keV} \)

<table>
<thead>
<tr>
<th>Isotope: pulse#</th>
<th>H: #91458</th>
<th>D: #89724</th>
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<td>( \Omega_i \tau_{E,\text{th}} [\text{T s}] )</td>
<td>0.27</td>
<td>0.28</td>
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\( \Omega_i \tau_{E,\text{th}} \) identical in H and D

L-mode dimensionless energy confinement independent of isotope mass: \( \Omega_i \tau_{E,\text{th}} \sim A^{0.05\pm0.1} \)

where \( \Omega_i \) is the ion cyclotron frequency.
Dimensionless Isotope Effect Experiments

L-mode

D: (3.0T/2.5MA)  
$P_{NBI} = 6.24 \text{ MW} @ 82 - 91 \text{ keV}$

H: (1.74T/1.44MA)  
$P_{NBI} = 2.56 \text{ MW} @ 64 - 71 \text{ keV}$

L-mode dimensionless energy confinement independent of isotope mass:  
$\Omega_i \tau_{E,th} \sim A^{0.05\pm0.1}$

H-mode

$\Omega_i \tau_{E,th} \sim A^{0.51}$  
H-mode difference identified as coming from pedestal
Stellarator Isotope Scaling

- Database of H and D plasmas at fixed magnetic configuration (R=3.6m)
- NBI heated, dominantly heating electrons
  \[ P_e/P_i = 3.9 \pm 2.0 \]
  \[ T_e(0)/T_i(0) = 1.79 \pm 0.37 \]

- Fit to operational parameters

  \[ \tau_{E,th}^{R360\text{NBI}} \propto M^{-0.07 \pm 0.01} B^{0.85 \pm 0.01} n_e^{-0.73 \pm 0.01} P_{abs}^{-0.81 \pm 0.01} \]

- Fit to dimensionless parameters

  \[ \tau_{E,th}^{R360\text{NBI}} \Omega_i \propto M^{0.94} \rho^{* -3.02} \nu^{* 0.15} \beta^{-0.23} \]

  *gyro-Bohm with a separate Mass-dependence*
Isotope Mixing and Non-Mixing

- Isotopic densities measured by bulk ion charge-exchange recombination.
- Mixing plasmas have $n_e > 2-3 \times 10^{19} \text{ m}^3$, hollow density profile
- Non-mixing plasmas have low density $n_e < 2-3 \times 10^{19} \text{ m}^3$, peaked density profile

- Gyrokinetic analysis suggests strong correlation with ITG-TEM
  - Mixing: core ITG unstable, TEM stable ($\rho = 0.5$)
  - Non-mixing: core ITG stable, TEM unstable
W7X: Neoclassical Optimization Successful

Calculated neoclassical energy transport for W7X profiles in other stellarator shapes

- Pellet peaked density profile to reduce ITG
- Other configurations scaled to same volume and B=2.5T as W7X
- Neoclassical losses calculated using W7X density and temperature profiles
- Other configurations: losses exceed W7X heating power => temperature inaccessible!

T. Pedersen OV/3-2
W7X: Highest Performance with Pellets

- ECH heating only, 4.9 MW, B=2.5T
- From GENE calculations, need $a/L_n \sim a/L_{Ti}$ to suppress ITG & TEM
- Confinement enhancement of $1.3 \times$ ISS04 scaling
- Accessible using multi-pellet fueling

- Highest $n(0) \ Ti(0) \ \tau_E$ for a stellarator

Growth rate vs density and temperature scale lengths
**W7X and AUG see** $T_i \sim 1.5$keV **clamping**

for gas-fueled ECH L-mode

- $T_i$ clamps with only electron heating, independent of magnetic configuration
- ITG stronger for $T_e > T_i$ enforces marginal stability
  - Very difficult to increase $T_i$ from an initial condition of $T_e >> T_i$
- Ion-electron thermalization $\sim (T_e-T_i)/T_e^{3/2}$ weakens as $T_e$ increases
- Enhanced confinement usually requires ITG suppression or weakening (ETB, ITB)
JET: High Performance for DT Baseline and Hybrid Scenarios

Ion transport reduced by:
- Edge impurity dilution (reducing $n_i$)
- Reduced gas puff + pellets (incl. Ne)
- $T_i / T_e \sim 1.6$ including pedestal top
- Strong ExB shear
- Strong rotation to centrifuge W & Ni
- Core $P_{rad}$ stable
- Pedestal collisionality approaching ITER

Low-gas puff, ELM-free initial period
- $T_i > T_e$ including pedestal
- Increased rotation
- Core $P_{rad}$ stable
- Record peak and average DD reaction rate
Spherical Torus Confinement Advances

**ST-40**

Sharp increase in confinement for $B_T > 1\,\text{T}$

M.Gryaznevićh OV/4-5.4

**GLOBUS-M2**

Extended $B_T$ to 0.8T, Ip to 0.4MA

$B \tau_E \sim \nu_*^{-0.74}$ extended to lower $\nu_*$

Yu.Petrov OV/4-5.3

**NSTX-U**

- Using novel synthetic diagnostic, nonlinear gyrokinetic simulations (GYRO) reproduce electron transport & high-k microwave scattering spectra for moderate-$\beta$ NSTX H-mode
- Parameter scans ($\nabla n$, $\nabla T$, q, s) used to quantify sensitivity of predicted fluxes and synthetic high-k spectra

W.Guttenfelder OV/4-5.2

- Consistent with previous ST studies
- Not like IPB98(y,2)
MHD, Stability, and Fast Ion Transport

- Shaping: Reversed Triangularity
- Quasi-Symmetric Magnetic perturbations
- Magnetic flux pumping
- Fast Ion Instabilities & Transport
Diverted Negative Triangularity Is Advantageous (TCV, DIII-D)

- $H(98y,2) \sim 1$, $\beta_N = 3$, without power threshold
- L-mode edge maintained. H-mode threshold drastically higher.
- SOL heat-flux width $\sim 1.5 \times$ H-mode width
- $\tau_P \sim \tau_E$ from laser blow-off

- Average $\delta \sim -0.2$
- Energy confinement improves for more negative triangularity, linearly
- Observed for OH, ECH, NBI heating
- Improvement maintained for $q_{95} < 3$, up to $\beta_N = 3$
- Density fluctuations reduced inside LCFS
- Reduced SOL turbulence on low-field side, due to shorter connection length

A. Marinoni EX/6-6.1  L. Porte EX/6-6.2
Quasi-Symmetric Magnetic Perturbations (QSMP)

- QSMP in a tokamak: 3D magnetic perturbation that induces the minimum neoclassical 3D torque (NTV) and transport. Compared to RMP (resonant MP) or NRMP (non-resonant MP)
- Optimization for QS perturbation uses self-consistent torque response matrix
- QSMPs do not show confinement degradation in high-β flattop, or impact on L-H transition power in KSTAR and DIII-D, despite large amplitude perturbations
- Thus: Error fields can be modified towards quasi-symmetry, minimizing resonant and no-resonant effects, and minimizing confinement impact.
Experimental Evidence of Magnetic Pumping at AUG

- Experimentally test new theoretical model of flux pumping at high $\beta$ with (1/1) mode [I. Krebs, PoP 2017]
- Possible way to reduce needed current drive in reactors
- Cases where q-profile evolution does follow neoclassical current diffusion
- Or, central co-ECCD cannot drive $q(0)$ down, below $q=1$ (IMSE measurements, without sawteeth)
- Stronger effect at high $\beta$ (like theory)
- At high non-inductive current, effect may not be strong enough to keep $q(0)=1$
- Qualitative agreement with theory, but model gives more peaked current than measurements.

Average current density inside 1/1 mode
Scenario prepared to assess $\alpha$-driven instabilities in JET-DT

- $\alpha$-driven instabilities are potentially an issue for burning plasmas, including ITER. Unambiguously identified only in TFTR-DT plasmas so far.
- A dedicated scenario was developed and tested to observe $\alpha$-Toroidal Alfven Eigenmodes (TAE) in JET-DT, including:
  - Good fusion performance from Internal Transport Barrier
  - Elevated central q-profile, to lower threshold
  - Real-time control trigger to switch to afterglow at peak performance
  - NBI-only before afterglow, to not generate other fast ions
  - ELM pacing by pellets
  - Core-localised TAEs when ICRH heating used (as test)

- Extrapolations to DT using integrated modeling (TRANSP & CRONOS) predict $\beta_\alpha(0) \sim 0.15\%$ and $\sim 9$ MW of fusion power. This is larger than extrapolations for previous JET pulses, and than the TFTR-DT $\alpha$-instability experiments.
- JET / TFTR comparisons included in plans for coming JET DT campaign
Control of Fast-Ion Alfvénic Modes in Advanced Steady-state Scenarios

- Energetic ion driven Alfvénic Eigenmodes (AE) are common in advanced scenarios with elevated $q_{\text{min}}$, causing transport of the energetic ions.

- Broadened energetic ion profile gives better control of AE stability in elevated $q_{\text{min}}$ scenarios. Key factor is moving $\rho_{q_{\text{min}}}$ towards region of reduced $\nabla \beta_{\text{fast}}$

- In DIII-D NBI experiments, this was done by switching from central to off-axis neutral beams
  - Accessed 15% higher $\beta_N$
  - Ratio of expected to measured neutron emission increased by ~25% in flattop
  - TGLF-EP + ALPHA critical gradient model reproduces energetic ion transport trends. MATCHES measured neutron rate within 12%>

- Provides basis for understanding how to avoid AE-induced energetic ion transport in ITER and future burning plasmas.
Divertor & Scrape-off-layer

• Super-X divertors
• Controlled Detachment
• Stellarator divertors
• Divertor experiments and modeling
Heat Flux Reduced in Super-X Divertor

MAST-U

Substantial reduction in the outer divertor heat flux observed in the Super-X vs. conventional divertor

Initial studies have focused on moving the outer strike points to large major radius and reducing the poloidal field there to produce Super-X configurations.
New Methods to Control Detachment

- Metal-wall devices need (low Z) seed-impurity injection for detachment radiator. Previously Nitrogen was best, but:
  - Complicates tritium processing chemistry

- New gasses are successfully integrating a detached edge with core confinement without confinement degradation
  - Neon JET High Performance Scenarios J.Mailloux OV1-2
  - Neon DIII-D High-$\beta_p$ Scenario J.Giroud EX/P3-977
  - Neon,Argon EAST High-$\beta_p$ Scenario L.Wang EX/7-1
  - Argon AUG EDA H-mode L.Wang EX/7-1
  - Neon EAST, J sat, $T_e$, div, $P_{rad}$ A.Kallenbach EX/2-5

- New feedback control methods of detachment for reliable operation
  - AUG Location of emission M.Bernert EX/7-3
  - DIII-D, EAST $J_{sat}$, $T_e$, div, $P_{rad}$ L.Wang EX/7-1
W7X Island Divertor Is Highly Effective

- Core plasma surrounded by helical island chain (typ. 5/5) that interfaces to divertor baffles.

- Wetted area up to 1.5 m² to spread exhaust heat, increases with $P_{\text{SOL}}$

- Islands shield against impurity sources, e.g. hot spots on divertor tile edges

- Stable, complete detachment in many scenarios achieved, for up to 26 sec. Detachment density $\sim 10^{20}$ m⁻³

- Below detachment, observe high recycling regime, enabled by counter-streaming flows in islands.
TCV with Baffles – a Divertor Testbed

- Divertor baffles increase neutral pressure ~5x, increase divertor dissipation. Facilitates detachment in L- and H-mode.
- Detachment density ~25% lower with baffles
- Flexible coil-set enables divertor leg steering
- SOLPS drift simulations predicts key features and trends. E.g, potential structure, currents.
- Reduction of detachment threshold for Super-X (large radius target) lower than originally predicted with baffles. May be due to details of geometry.
DIII-D SAS is a Divertor Testbed

- SAS: Small Angle Slot divertor
- Interaction between drift flows and divertor geometry has important effects on dissipation
- SOLPS-ITER with drifts reproduces trends found in experiments
  - Lower $T_e$ and detachment density with drift away from divertor.
  - Drifts are comparable to geometry in effects on recycling flux and neutral density
- Experiment and modeling both found that geometry+drift can alter variation of dissipation
  - Including $T_e$ bifurcation and $J_{sat}$ reduction
Thank You
A Comprehensive Study of Energetic Particle Transport due to Energetic Particle Driven MHD Instabilities in LHD Deuterium Plasmas

Beam ion and DD fusion born triton transport due to energetic-particle-driven MHD instabilities (EIC) is simultaneously studied in the Large Helical Device (LHD).

- Drop of total neutron emission rate \( (S_n) \) by EIC shows enhanced beam ion transport due to EIC.
  - Experiments in full D and H/D beam conditions shows that EIC induces up to 8% of passing transit beam ion losses and up to 60% of helically-trapped beam ion losses.
- Drop of secondary DT neutron emission rate \( (S_{n\_DT}) \) increases substantially with the EIC amplitude to the third power and reaches \( \sim 30\% \).
  - 1 MeV tritons are largely transported because the tritons are barely confined in LHD.
Dimensionless-identity comparisons
Controlled Pedestal Height (AUG,JET)

Matched edge profiles by adjusting $\delta$, keeping source profiles similar

**H: $\delta = 0.37$  D: $\delta = 0.25$**

Low NBI power:
core profiles similar, good agreement with TGLF

High NBI power:
$T_i$ higher in D => reduced ion heat
Transport

- Nonlinear GENE simulations: higher fast ions pressure in D-plasmas stabilizes turbulence (slowing-down time)
- Similar experiments in JET