The physics of cold to burning plasmas

Plasma Theory and Modelling
group academics

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RSPE Seminar, 18 April 2013

Acknowledgement: Australian Research Council, ANU, DIISRTE
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International collaborators

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The plasma state: the fourth state of matter

- Plasma is an ionized gas
- 99.9% of the visible universe is in a plasma state

A Galaxy of Fusion Reactors.

- Fusion is the process that powers the sun and the stars
- Key concepts: magnetic confinement, physics models
Magnetic confinement

Focused target field, e.g. MAGPIE

Ripple magnetic field or mirror e.g.
LAPD [Zhang et al Phys. Plasmas 15, 012103 2008]

- Ions ($\text{D}^+$, $\text{T}^+$, $\text{He}^+$ …) confined
- Neutrons escape
- Toroidal (ring shaped) device
Several toroidal confinement concepts

MAST (UK)
compact

RFX-mod (Italy)
self-organising

H1-MNRF (Oz)
flexible shape

LHD (Japan)
steady-state

W-7X (Germany)
steady-state, reduced chaos
Physics regimes and physics models

- Dielectric tensor: often used for cold plasmas
- MHD: flowing plasma, single temperature for ions/electrons
- Particle in cell (PIC) simulation – individual particles
- Gyrokinetic simulation – simulate particle distribution functions
How is a plasma described?

- One approach: Through dielectric tensor in Maxwell's equations

\[ \nabla \cdot \mathbf{E} = \rho / \varepsilon_0 \quad \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \frac{\partial \mathbf{D}}{\partial t} \]

What is dispersion relation for a cold plasma with \( B_0, E_0=0, v_0=0 \)?

- Gauss's law requires charge neutrality \( \rho = 0 = \sum q_s n_s \)

- Solve momentum equation

\[ m \mathbf{\dot{v}}_1 = q \left( \mathbf{E}_1 + \mathbf{v}_1 \times \mathbf{B}_0 \right) \]

for wave field \( \mathbf{v}_1 \). Gives \( \mathbf{J}=n_0 q \mathbf{v}_1 \), and construct \( \varepsilon \) s.t. \( \mathbf{D} = \varepsilon \mathbf{E} \)

- Rearrange Gauss's law, Amperes law to give \( \nabla \times \nabla \times \mathbf{E} = \frac{\omega^2}{c^2} \varepsilon \cdot \mathbf{E} \)

- Search for wave like solutions \( \mathbf{E} = |\mathbf{E}(x)| \exp[i(k \cdot x - \omega t)] \)
giving dispersion relation \( \omega(k) \)
or... Magnetohydrodynamics (MHD)

- Single conducting fluid: \( J = n_i Z e v_i - n_e e v_e \) \( \rho \approx m_i n_i \)
  \[ v = (m_i v_i + m_e v_e) / \rho \approx v_i \]
  \( p = p_i + p_e \)

- Continuity: \( \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \)

- Momentum: \( \rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{J} \times \mathbf{B} \)

If \( \frac{d\mathbf{v}}{dt} = 0 \) \( \Rightarrow \) \( \mathbf{J} \times \mathbf{B} = \nabla p \)

- Generalised Ohm’s law: \( \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} \)

- Maxwells equations, Adiabatic equation: \( \frac{p}{\rho^\gamma} = \text{const.} \)
“MHD with anisotropy in velocity, pressure”

- Pressure different parallel and perpendicular to field due mainly to directed neutral beam injection

\[ \bar{P} = p_{\perp} \bar{I} + \Delta BB / \mu_0, \quad \Delta = \frac{\mu_0 (p_{\parallel} - p_{\perp})}{B^2} \]

- Momentum

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) = -\nabla \cdot \bar{P} + \mathbf{J} \times \mathbf{B} \]
equilibrium waves stability wave-wave wave-plasma nonlinearity

WOMBAT

MAGPIE

(LAPD)$^2$

KSTAR

MAST

MAST

RFX-mod

H1

configuration complexity

MHD

MRXMHD

MHD + flow, anisotropy

2 fluid

2 fluid + collisions

Maxwell’s equations Bayesian Inference

Data forward models

dielectric tensor (cold)
equilibrium waves stability wave-wave wave-plasma nonlinearity

- WOMBAT
- PCEN
- MAGPIE
- (LAPD)^2
- KSTAR
- MAST
- MAST
- RFX-mod
- H1

Maxwell's equations Bayesian Inference

- Data forward models, MHD, MRX, MHD + flow, anisotropy, 2 fluid, 2 fluid + collisions, dielectric tensor (cold)
What are predicted wave fields?

Helical antenna generates plasma.

\[ n_e \propto B \]
Wave fields indicate anomalous resistivity

Chang, Hole, Caneses, Chen, Blackwell, Corr

- Add external antenna in dielectric tensor formulation and solve for wave fields (EMS code)
  - match to $|B(z)|$ and $\angle B(z)$ with enhancement in collision frequency to $\sim 9.5$ (ion-acoustic turbulence?)

[Chang et al Phys. Plas. 19, 083511 (2012)]
Modulation in B introduces mode gaps

Chang, Breizman, Hole

• Helicon mode eigenfunction equation \( \Leftrightarrow \) continuous modes

\[
k_z^2 \left( \frac{\partial}{\partial r} r \frac{\partial}{\partial r} r E_\varphi - m^2 E_\varphi \right) = -E_\varphi m \frac{\omega^2}{c^2} r \frac{\partial g}{\partial r} \quad \Leftrightarrow \quad \omega \sim \omega_c \frac{k_z^2 c^2}{\omega_p^2}
\]

• Apply periodic modulation to axial velocity through axial field

\[
\frac{\omega_p^2}{\omega_c} = \frac{\omega_{p0}(r)}{\omega_{c0}} \left[ 1 - \varepsilon(z) \cos qz \right]
\]

modulation strength parameter

number of field ripples

... like “forbidden frequencies”
Broken periodicity introduces gap modes

- Introduce defect into periodicity

Conducting end plate: \[ E_g(r; z_0) = 0 \]

- Can be cast as *time-independent Schrödinger system*, and admit localised solutions \((\propto e^{-\lambda z})\), with

\[
\frac{\omega - \omega_0}{\omega_0} = -\frac{\varepsilon}{2} \cos(qz_0)
\]

\[
\lambda = \frac{\varepsilon}{8} q \sin(qz_0)
\]

Gap formation: a generic wave phenomena

Existence of frequency gaps generic wave phenomenon: (e.g. electron band gap in conductors, Bragg reflection in optical interference filters)
Gap modes also present in Tokamaks

- A zoo of gaps and gap modes

Ion cyclotron frequency

Alfven frequency

Thermal diamagnetic frequency

Beta induced Alfven eigenmode (BAE):
Low frequency mode that exists due to finite beta (pressure)

Elliptical Alfven Eigenmode band gap first discovered by Em. Prof. R. L. Dewar in 1974: due to ellipticity of plasma cross-section

Toroidal Alfven Eigenmode

Who cares?... the impact of gap modes

- Alfvén eigenmodes are driven by wave-particle resonance.
  
  *e.g.* Wave-particle resonance
  
  Surfer rides wave

- As energetic particles from beams, radio-frequency heated or fusion alphas collide with thermal population they slow and hit resonances

---

![Boat drives waves](image)

---

![Graph showing log f(v) vs. v (× 10^6 ms^-1)](image)
Who cares?... the impact of gap modes

• Alfvén eigenmodes are driven by wave-particle resonance.

  e.g. Wave-particle resonance

  Surfer gets dumped

• As energetic particles from beams, radio-frequency heated or fusion alphas collide with thermal population they slow and hit resonances

• At large amplitude, Alfvén eigenmodes can eject the driving particles from confinement, damaging wall and extinguishing collisional heating
KSTAR

- KSTAR, a new ~$300m superconducting long pulse tokamak
- MOU between ANU and KSTAR
Suspected BAE mode activity in KSTAR

- $P_{\text{NBI}} \sim 1.2\text{MW},$
- $P_{\text{ECRH}} \sim 200\text{kW},$
- 80keV injection energy:
- $1/3 < v_{\parallel}/v_A < 1, \quad v_{\parallel} = v \cdot B$
- $210 < I_p < 407 \text{ kA},$
- $3 < \langle n_e \rangle < 6 \times 10^{19} \text{ m}^{-3}.$

Although ions have $v_{\parallel} < v_A$ they can drive the mode through side band resonances $v_A/3, v_A/5, v_A/7$
Suspected BAE mode activity in KSTAR

- $P_{NBI} \approx 1.2 \text{MW}$,
- $P_{ECRH} \approx 200 \text{kW}$,
- 80keV injection energy:
  - $1/3 < \nu_\parallel / \nu_A < 1$, $\nu_\parallel = v \cdot B$
  - $210 < I_p < 407 \text{kA}$,
  - $3 < \langle n_e \rangle < 6 \times 10^{19} \text{ m}^{-3}$.
Global mode with reduced damping

- Computed ion sound, shear Alfven wave continuum (CSCAS)
- $\omega / \omega_A = -0.137$ (BAE)
- $\omega / \omega_A = -0.138$ (continuum mode)

Radial mode structure

BAE mode frequency

$n=m=1$ global & continuum modes (MISHKA)
Beam changes threshold to BAE drive

Beam heated core $T_i$

Ohmic core $T_i$ (no heating)

• Thermal temperature gradient drive stability parameter

$$\eta_i = \frac{\partial \ln T_i}{\partial \ln n_i} = \frac{\partial \ln n_i}{\partial r}$$

• Critical gradient = $\eta_c$

• Increasing core localisation $\Rightarrow$ lowered instability threshold

• Mode driven by beams through $v_A/3$ resonance

BAE modes in H-1

• H-1 has similar modes, but more complex because fully 3D

continuous spectrum for $N = 1, \kappa_h = 0.30$.

Alfvén branches (colour)

Sound branches (grey)

• CAS3D computed eigenmode for candidate BAE

• Mode postulated to be driven by inverted (hollow) temperature profile

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Expected impact of anisotropy

- Small angle $\theta_b$ between beam, field $\Rightarrow p_{||} > p_{\perp}$
- Beam orthogonal to field, $\theta_b=\pi/2 \Rightarrow p_{\perp} > p_{||}$
- $p_{||}$ surfaces can be distorted and displaced inward relative to flux surfaces (i.e. Plasma)
  
  [Cooper et al, Nuc. Fus. 20(8), 1980]

- If $p_{\perp} > p_{||}$, an increase will occur in centrifugal shift :
  

- Compute $p_{\perp}$ and $p_{||}$ from moments of distribution function, computed by Monte-Carlo collision code
  

- Infer $p_{\perp}$ from measured diamagnetic current $J_{\perp}$ using $\nabla p = J \times B$
  
  [see V. Pustovitov, PPCF 52 065001, 2010 and references therein]
Equilibrium in toroidal symmetry

\[ \mathbf{J} \times \mathbf{B} = \nabla p \]
\[ \begin{cases} \mathbf{B} \cdot \nabla p = 0 \\ \mathbf{J} \cdot \nabla p = 0 \end{cases} \]

\[ \therefore \text{No pressure gradient along } \mathbf{B} \]
\[ \therefore \text{Current flows in magnetic surfaces} \]

\[ \mathbf{J} \times \mathbf{B} = \mu_0 \mathbf{J}, \quad \nabla \cdot \mathbf{B} = 0 \]

- Assume toroidal symmetry.
- Introduce
  - co-ord. system \((R, \zeta, z)\)
  - poloidal flux function \(\psi\), \(\mathbf{B} \cdot \nabla \psi = 0\)
  - toroidal flux function \(f(\psi) = RB_\zeta(\psi, R)/\mu_0\)

- Can reduce to Grad-Shafranov equation

\[
\nabla \cdot \frac{1}{R^2} \nabla \psi = -\mu_0 \frac{J_\zeta}{R} = -\mu_0 p'(\psi) - \frac{\mu_0^2}{R^2} f(\psi) f'(\psi)
\]

- Normally solved by iterating calculation of field from current and current from field with prescribed boundary and \(\{p'(\psi), f(\psi)\}\)
Equilibrium with rotation & anisotropy

- Inclusion of anisotropy and flow in equilibrium MHD equations

  **Momentum:**
  \[
  \rho \mathbf{v} \cdot \nabla \mathbf{v} = \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{P}
  \]
  \[\mathbf{P} = p_\perp \mathbf{I} + \Delta \mathbf{B} \mathbf{B} / \mu_0, \quad \Delta = \frac{\mu_0 (p_\parallel - p_\perp)}{B^2}\]

- Frozen flux \( \mathbf{v} = -R \phi'_E (\psi) \mathbf{e}_\phi = R \Omega (\psi) \mathbf{e}_\phi \)

Force balance becomes...

\[
\nabla \cdot \left( (1 - \Delta) \left( \frac{\nabla \psi}{R^2} \right) \right) = -\frac{\partial p_\parallel}{\partial \psi} - \rho H'(\psi) + \rho \frac{\partial W}{\partial \psi} - \frac{f(\psi)f'(\psi)}{R^2(1 - \Delta)} + R^2 \rho \Omega(\psi) \Omega'(\psi)
\]

Bernoulli equation:

\[
H(\psi) = W(\rho, B, \psi) - \frac{1}{2} [R \phi'_E (\psi)]^2
\]

- \( \partial W / \partial \psi \): different for MHD/ double-adiabatic/ guiding centre

- If two temperature Bi-Maxwellian model chosen

\[
p_\parallel (\rho, B \psi) = \frac{k_B}{m} \rho T_\parallel (\psi) \quad p_\perp (\rho, B \psi) = \frac{k_B}{m} \rho T_\perp (\psi) = \frac{k_B}{m} \rho T_\parallel (\psi) \frac{B}{B - \theta(\psi)T_\parallel}
\]

\[
\{F(\psi), \Omega(\psi), H(\psi), T_\parallel (\psi), \theta(\psi)\}
\]

We have solved this problem!
New code written and benchmarked

- New code EFIT TENSOR written to solve force balance with flow and anisotropy
- “Soloviev” analytic and real data benchmarks (MAST #13050, #18696) have been computed for isotropic, anisotropic and flow cases

Soloviev:
\[ \beta_t = 0.07 \]

Extended Soloviev:
\[ \beta_t = 0.07, M_\phi = 0.8, \Delta = 0.004, \]

Solution Convergence

Effect of anisotropy on MAST

- MAST #18696
- 1.9MW NB heating
- \( I_p = 0.7 \text{MA}, \beta_n = 2.5 \)
- Magnetics shows wave activity

- What is the impact on q profile due to presence of anisotropy and flow?
- How would this change wave activity?

[M.P. Gryaznevich et al, Nuc. Fus. 48, 084003, 2008]
Monte Carlo collision code gives $p_{\parallel}$, $p_{\perp}$, $v$.

$\rho = \sqrt{\Phi / \Phi_0} \approx s$

$\Phi = \text{toroidal flux}$

$M_{\phi,max} = 0.3$

Impact on plasma computed with EFIT TENSOR.

$\Delta < 0$: $p_{\perp}/p_{\parallel} \approx 1.7$

$\Delta = 0$: $p_{\perp}/p_{\parallel} = 1$

$M_{\phi} > 0$ $M_{\phi,max} = 0.3$

Impact of anisotropy on wave modes

- How do predicted mode frequencies change due to changes in $q$ produced by anisotropy and flow?
- Calculation of change in stability due to anisotropy in progress…

*can address*: What is the change in ideal MHD modes of $n=1$ TAE?
Impact of anisotropy on wave modes

$ f_{TAE} $ no-flow, isotropic

$ f_{TAE} $ flow, anisotropic

+ creates new eigenmodes

Increased shear gives multiple TAEs

Isotropic, no flow:
Flat shear, $dq/d\rho$

Anisotropic, flow
Reverse shear, $dq/d\rho<0$
Increased shear gives multiple TAEs

Flat shear continuum

q profile

q = 1.5

TAE mode

Single global TAE
(m, n) = (1, 1)
Increased shear gives multiple TAEs

- Reverse shear continuum
- Flat shear continuum
- Core TAE
- Global TAE
- Odd core TAE
- Global TAE
- \( q \) profile
- \( q = 1.5 \)
equilibrium waves stability wave-wave wave-plasma

nonlinearity

WOMBAT

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(LAPD)$^2$

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H1

configuration complexity
dielectric tensor(cold)
MHD
MRXMHD
MHD + flow, anisotropy
2 fluid
2 fluid + collisions
Toroidal plasma equilibrium in 3D

• In ideal MHD non-axisymmetric magnetic fields generally do not have a nested family of smooth flux surfaces, unless ideal surface currents are allowed at the rational surfaces.

• If the field is non-integrable (i.e. chaotic), then any continuous pressure that satisfies $\mathbf{B} \cdot \nabla p = 0$ must have an infinitely discontinuous gradient, $\nabla p$.

• Instead, solutions with stepped-pressure profiles are guaranteed to exist. Variational principle called MRXMHD (R. L. Dewar).

• Numerical implementation, SPEC, by S. Hudson (PPPL).
Taylor Relaxed States: Relaxed MHD

- Zero pressure gradient regions are **force-free** magnetic fields:
- In 1974, Taylor argued that turbulent plasmas with small resistivity, and viscosity relax to a Beltrami field

**Internal energy:**

\[ W = \int_{P \cup V} \left( \frac{B^2}{2\mu_0} + \frac{p}{\gamma - 1} \right) d\tau^3 \]

**Total Helicity:**

\[ H = \int_V (A \cdot B) d\tau^3 \]

Taylor solved for minimum \( W \) subject to fixed \( H \)

i.e. solutions to \( \delta F = 0 \) of functional \( F = W - \mu H / 2 \)

**P:** \( \nabla \times B = \mu B \)

**I:** \( \left[ \left( \frac{B^2}{2\mu_0} + p \right) \right] = 0 \)

**V:** \( \nabla \times B = 0 \)

Model very successful for toroidal pinches, multipinch, and spheromaks

\[ \text{discretised} \quad J \times B = \nabla p \]
Generalised Taylor Relaxation: MRXHMHD


- Assume each invariant tori $I_i$ act as ideal MHD barriers to relaxation, so that Taylor constraints are localized to subregions.

New system comprises:

- $N$ plasma regions $P_i$ in relaxed states.
- Regions separated by ideal MHD barrier $I_i$.
- Enclosed by a vacuum $V$,
- Encased in a perfectly conducting wall $W$

$$W_i = \int_{R_i} \left( \frac{B_i^2}{2 \mu_0} + \frac{P_i}{\gamma - 1} \right) d\tau^3$$

$$H_i = \int_V (\mathbf{A}_i \cdot \mathbf{B}_i) d\tau^3$$

Seek minimum energy state:

$$F = \sum_{l=1}^{N} \left( W_l - \mu_l H_l / 2 \right)$$

At each $P_i$:

$$\nabla \times \mathbf{B} = \mu_l \mathbf{B}$$

$$P_i \text{ = constant}$$

At each $I_i$:

$$\mathbf{B} \cdot \mathbf{n} = 0$$

$$[[P_i + B^2 / (2 \mu_0)]] = 0$$

At $V$:

$$\nabla \times \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

At $W$:

$$\mathbf{B} \cdot \mathbf{n} = 0$$
Example: DIII-D with $n=3$ applied error field


- 3D boundary, $p$, $q$-profile from flux-surfaces-model

- Irrational interfaces chosen to coincide with pressure gradients.

- Islands are now resolved

Standard MHD model

SPEC (MRXMHD)

formation of magnetic islands at rational surfaces
Spontaneously formed helical states

Dennis, Hudson, Terranova, Dewar, Hole

• The quasi-single helicity state is a stable helical state in RFP: becomes purer as current is increase

“Experimental” Poincaré plot

[Fig. 6 of P. Martin et al., Nuclear Fusion 49, 104019 (2009)]
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“Experimental” Poincaré plot

- Model RFX-mod QSH state by a 2-interface minimum energy MRX MHD state.

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- RFP bifurcated state has lower energy (preferred) than comparable axis-symmetric state.

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• RFP bifurcated state has lower energy (preferred) than comparable axis-symmetric state

• Looks similar to H-1 (next step), indeed … next stellarator conference is joint with RFP’s
equilibrium waves stability wave-wave wave-plasma nonlinearity

WOMBAT

MAGPIE 1

(LAPD)\(^2\)

KSTAR 3

MAST 5

MAST

RFX-mod 6

H1 4

Maxwell’s equations Bayesian Inference

MHD

MRXMHD

MHD + flow, anisotropy

2 fluid

2 fluid + collisions
Bayesian equilibrium modelling: integrating data with theory

J. Svensson, G. von Nessi, M. Hole, L. Appel,

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

$$H = \{J_\phi(R, Z), p'(\psi), f(\psi), \rho(\psi, R), \Omega(\psi)\}$$

$$D = \{P_i(R, Z), F_i(R, Z), \tan \gamma_i(R, Z), I_p, P_{s,e}, S_e(k, \omega), S_C(v)\}$$

Aims
(1) Improve equilibrium reconstruction
(2) Validate different physics models

Two fluid with rotation

Ideal MHD fluid with rotation

Energetic particle resolved multiple-fluid
[Hole & Dennis, PPCF 51 035014, 2009]

(3) Infer poorly diagnosed physics parameters
Relevance to ITER
ITER: The next step for fusion power

- Fusion power = 500MW
- Power Gain > 10
- Temperature ~ 100 million °C

Growing Consortium

- Collaboration agreements with
  - International Atomic Energy Agency
  - CERN – world’s largest accelerator
  - Principality of Monaco

Construction +10 year
operation cost ~$20 billion

Fiscally, world’s largest science experiment
Plasma Physics Challenges

- Production and study of a plasma dominated by self heating. *Burning Plasma Physics.*

- New instabilities in burning plasmas: possibilities energetic particle modes driven by beam ions, fusion $\alpha$-s could “short-circuit” heating of thermal plasma

- Edge Localised Modes: Control of field lines that erupt through plasma edge

- Better disruption mitigation (e.g. massive gas puff injection).

- Real time mode control and identification

- Measurement and “integrated modelling” of plasmas under extreme conditions.

Difference images from D$^\alpha$ camera of MAST plasmas
## Physics contributions to ITER

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Australian contributions to ITER science

Powering ahead:

* a national response to the rise of the international fusion power program

B. James (coordinator), R. Garrett, B. Green, M. J. Hole, J. Howard, J. O’Connor

- Successor to a strategy for fusion science in Australia released in 2007
- Outcomes: H-1 upgrade, influence Future Fellowship Scheme

Exposure draft available at

http://www.ainse.edu.au/fusion/iter/australian_fusion_strategy2

- Proposed participation in the International Tokamak Physics Activity, coordinated by the ITER Organisation. ITPA topical groups in
  - Diagnostics
  - Energetic Particle Physics
  - Integrated Operating Scenarios
  - MHD, Disruption and Control
  - Pedestal and Edge
  - Scrape-off Layer and Divertor
  - Transport and Confinement

- Construction of a pilot coherence imaging divertor diagnostic

- Country level agreement proposed through ANSTO
Summary

• Plasma Theory and Modelling: a vibrant ANU pursuit developing theory for next generation fusion experiments, and supporting physics interpretation of existing experiments.

• Very strong international collaboration

• Research areas
  - Burning plasma physics: anisotropy and flow, energetic particle driven modes
  - 3D MHD physics (e.g. MRXMHD). Impacts of 3D structure on plasma.
  - Bayesian inference of configurations
  - Interpretation/modelling of international and domestic experiments
  - Not mentioned… continuum damping, pulsar modelling, ELM statistics

• Research synergies identified with ITER and its strategic research community, the International Tokamak Physics Activity ITPA. These align with Australian strategic planning for fusion science.