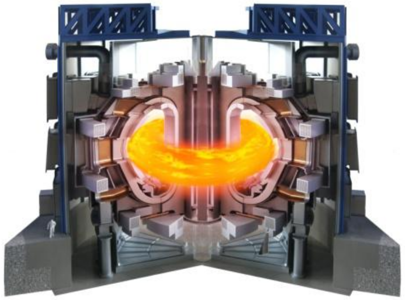

Australian National University

Dynamics of Fusion and Stellar Plasmas

M. J. Hole,
R. L. Dewar, B. Layden, Z. Qu, G. Bowden, A. Wright, L. H. Tuey, H. Hezaveh, G. A. Dennis, M. Fitzgerald[1], S. Sharapov[1], B. Breizman[2], R. Dendy[1], S. Hudson[3], J. Kim[4], A. Koenies[5], K. McClements[1] , J. Svensson[5], D. Terranova[6]

Plasma Theory and Modelling
Centre for Plasmas and Fluids

RSPE Seminar, 17 November 2016

Acknowledgement: Australian Research Council, ANU

1 CCFE CULHAM CENTRE FOR FUSION ENERGY

2 THE UNIVERSITY OF TEXAS AT AUSTIN

3 PPPL PRINCETON PLASMA PHYSICS LABORATORY

4 NFRI 국가핵융합연구소 National Fusion Research Institute

Dynamics of Fusion and Stellar Plasmas

5 IPP Max-Planck-Institut für Plasmaphysik

6 CONSORZIO RFX
Ricerca Formazione Innovazione

M. J. Hole,
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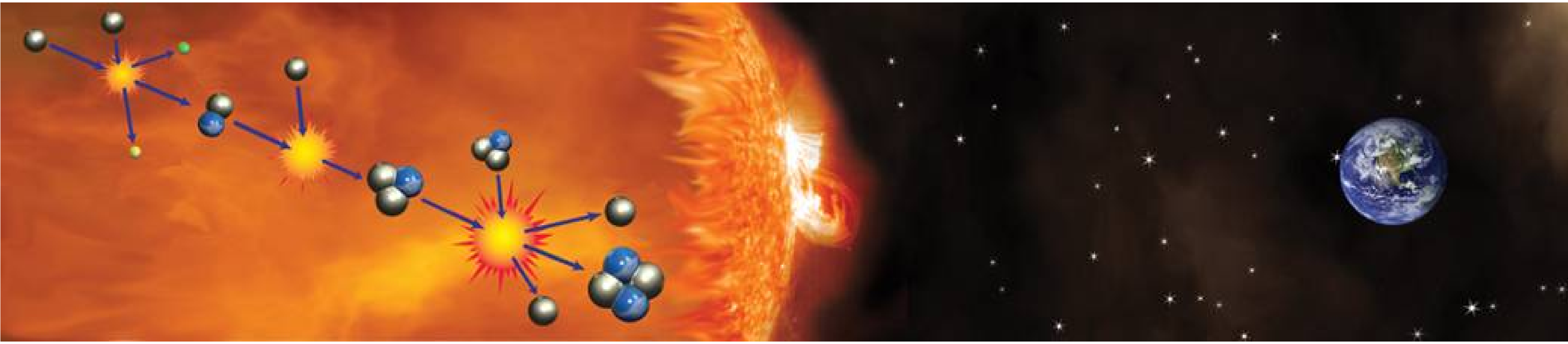
Fusion, the power of the sun and the stars, is one option

"…Prometheus steals fire from the heaven"



On Earth,

fusion could provide:

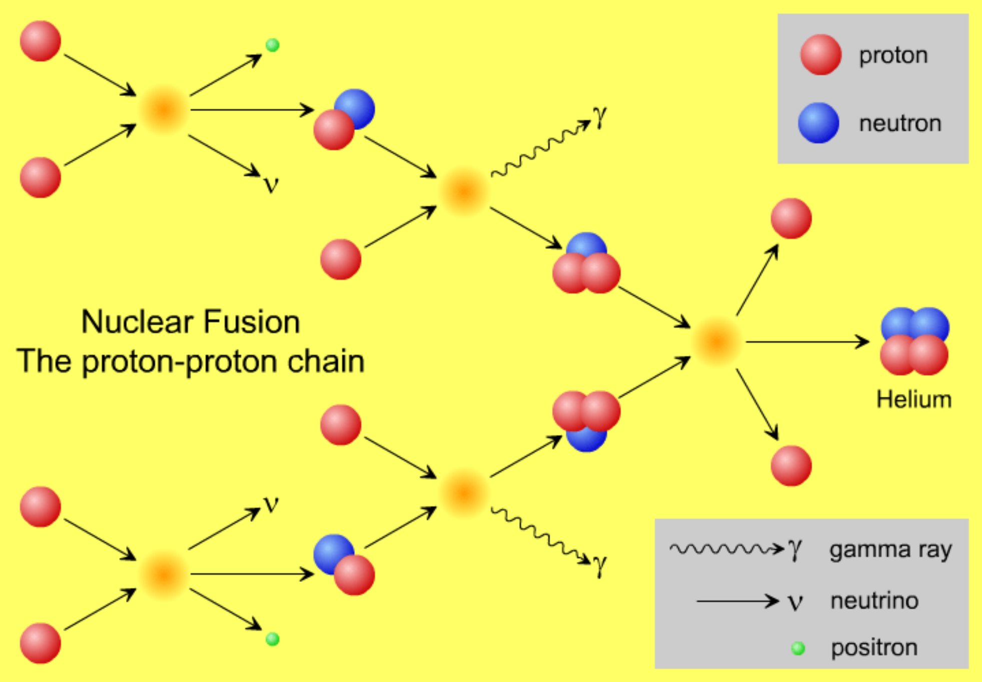
- Essentially limitless fuel, available all over the world
- No greenhouse gases
- Intrinsic safety
- No long-lived radioactive waste
- Large-scale energy production

Stellar cf terrestrial fusion

Proton-proton cycle

e.g. PP1 branch

Overall produces
26.732 MeV

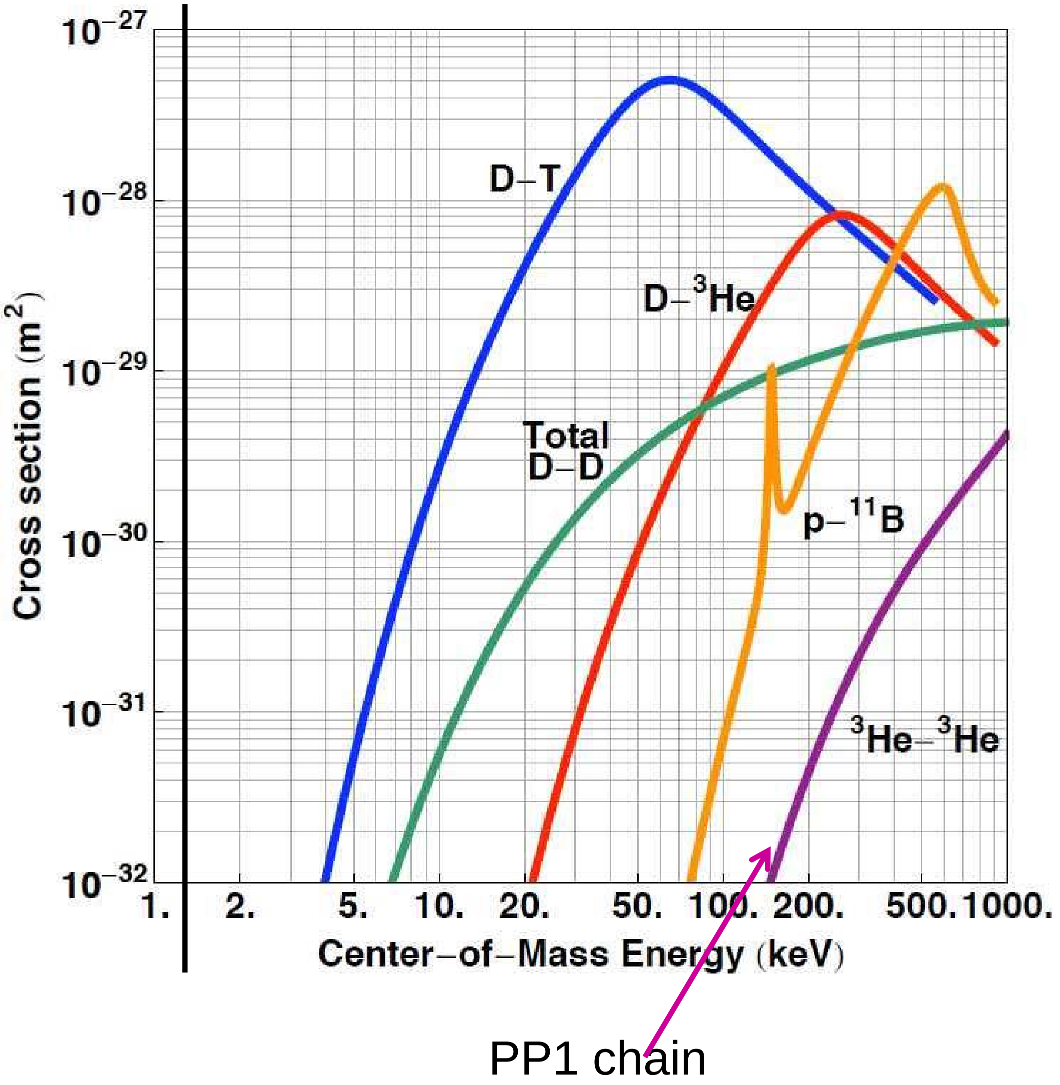


D-T and D-D reactions:

Fusion	$(D^2 + T^3 \rightarrow He^4 + n)$	17.6 MeV
	$(D^2 + D^2 \rightarrow He^3 + n)$	3.27 MeV
	$(D^2 + D^2 \rightarrow T^3 + H^1)$	4.03 MeV

D-T reaction co-discovered by Australian Sir Marc Oliphant 1932

Conditions for *stellar* fusion power



- Classically, the Sun shouldn't burn
- works by quantum tunneling of wavefunctions through the repulsive barrier
- Probability is small, but the Sun's volume is enormous

Sun's core temperature ~ 1.3keV (15C million)

Conditions for *terrestrial* fusion power

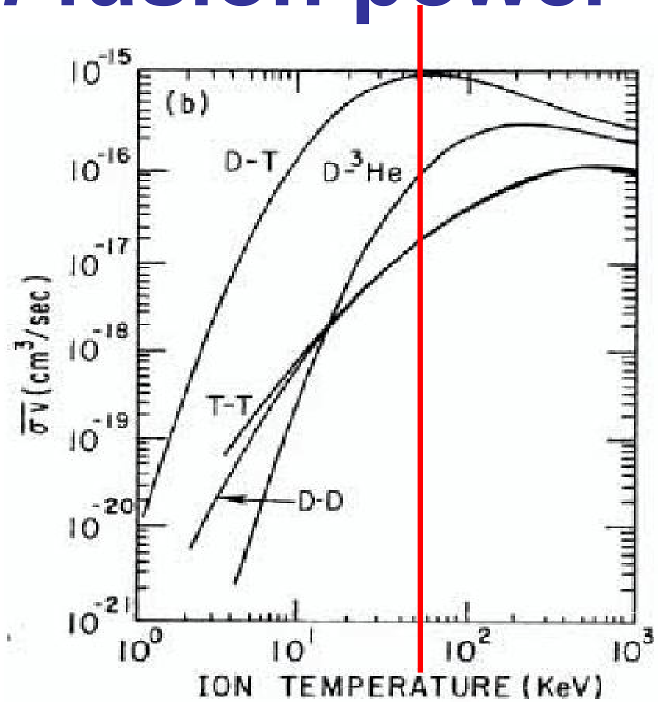
- Achieve sufficiently high

ion temperature T_i

$\Rightarrow$ exceed Coulomb barrier

density $n_D \propto$ energy yield

energy confinement time τ_E



≈600 million °C

τ_E = insulation parameter: e.g. time taken for a jug of hot water to lose energy to the surroundings

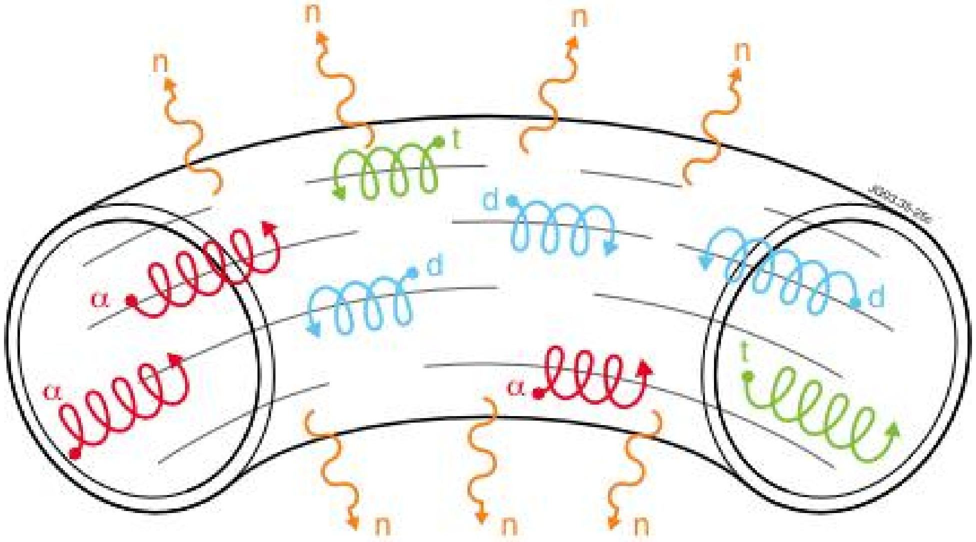
- “Lawson” ignition criteria : Fusion power > heat loss

Fusion triple product ⟶ $n_D \tau_E T_i > 3 \times 10^{21}\ \mathrm{m}^{-3}\ \mathrm{keV\ s}$

- Steady-state access requires confinement

Toroidal Magnetic Confinement

- Magnetic fields cause charged particles to spiral around field lines. Plasma particles are lost to the vessel walls only by relatively slow diffusion across the field lines

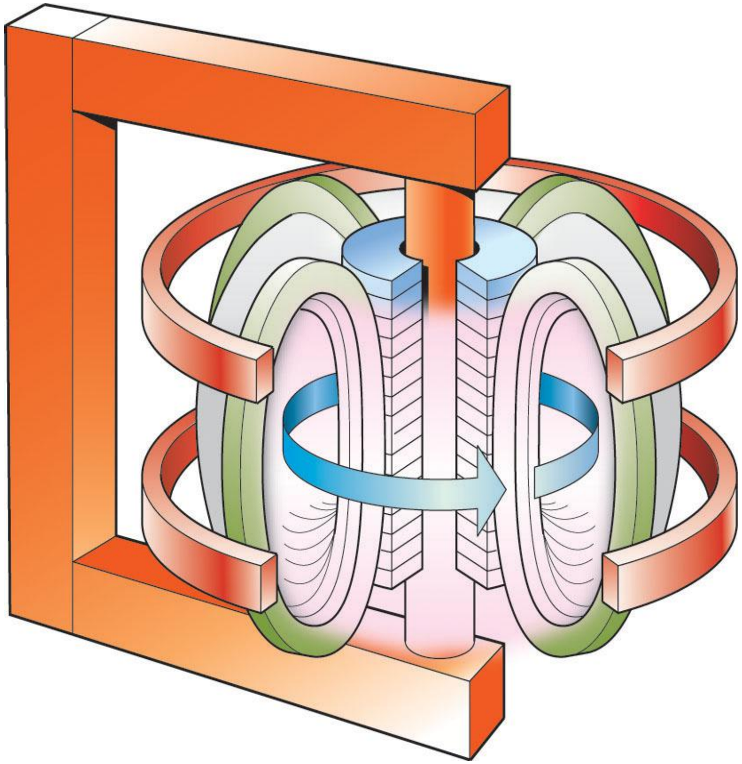


- Only charged particles (D^+, T^+, He^+…) are confined
  Neutrons escape and release energy

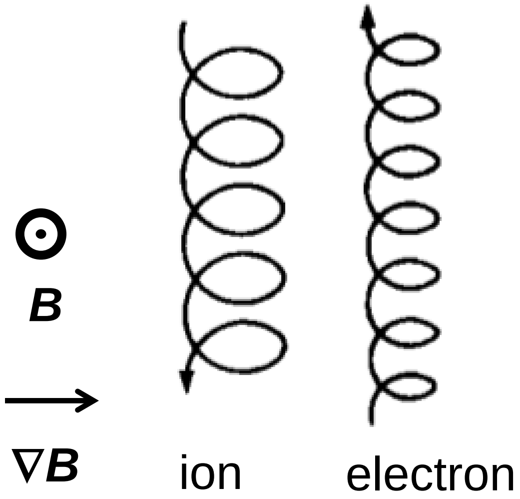
- Toroidal (ring shaped) device: a closed system to avoid end losses

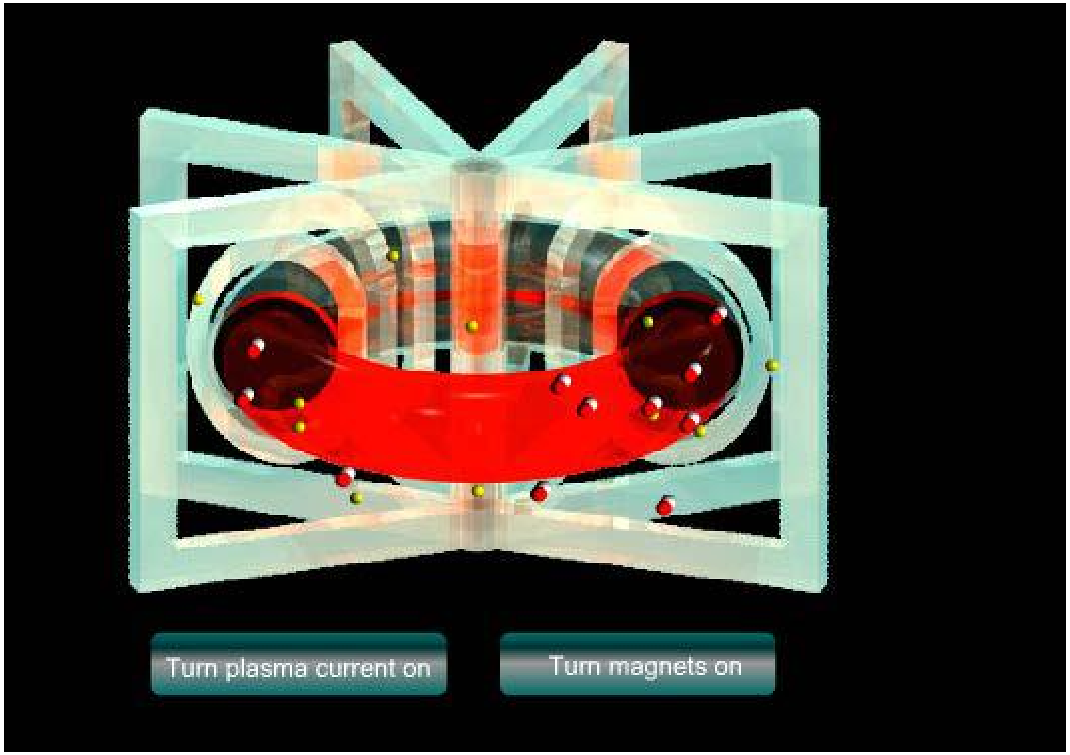
- The most successful Magnetic Confinement device is the TOKAMAK (Russian acronym for ‘Toroidal Magnetic Chamber’)

Components of a Tokamak

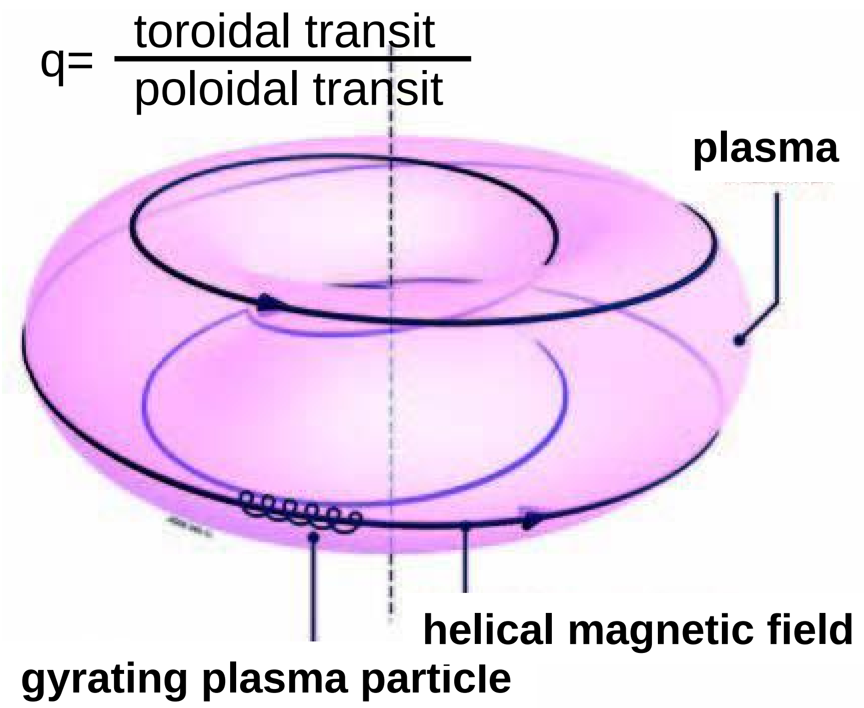


Fields in confining plasma





Fields lie in flux surfaces

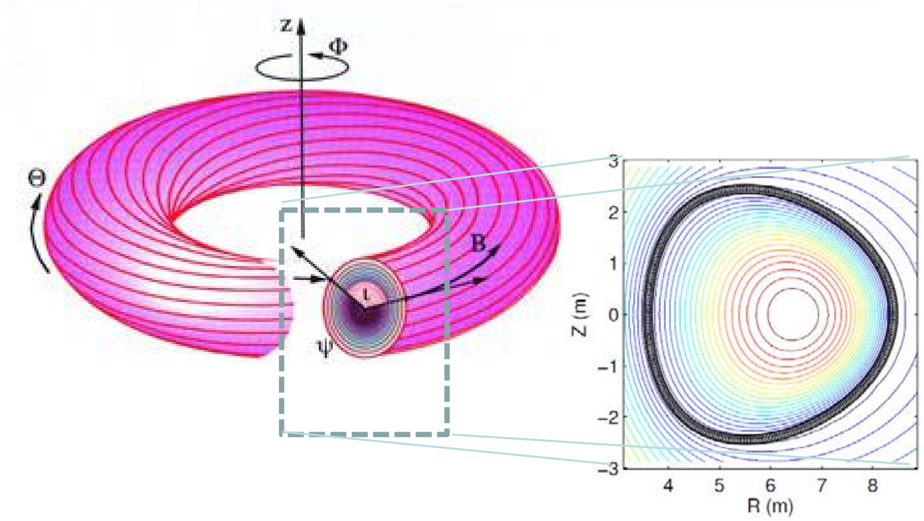


$$q = \frac{\text{toroidal transit}}{\text{poloidal transit}}$$

plasma

helical magnetic field

gyrating plasma particle

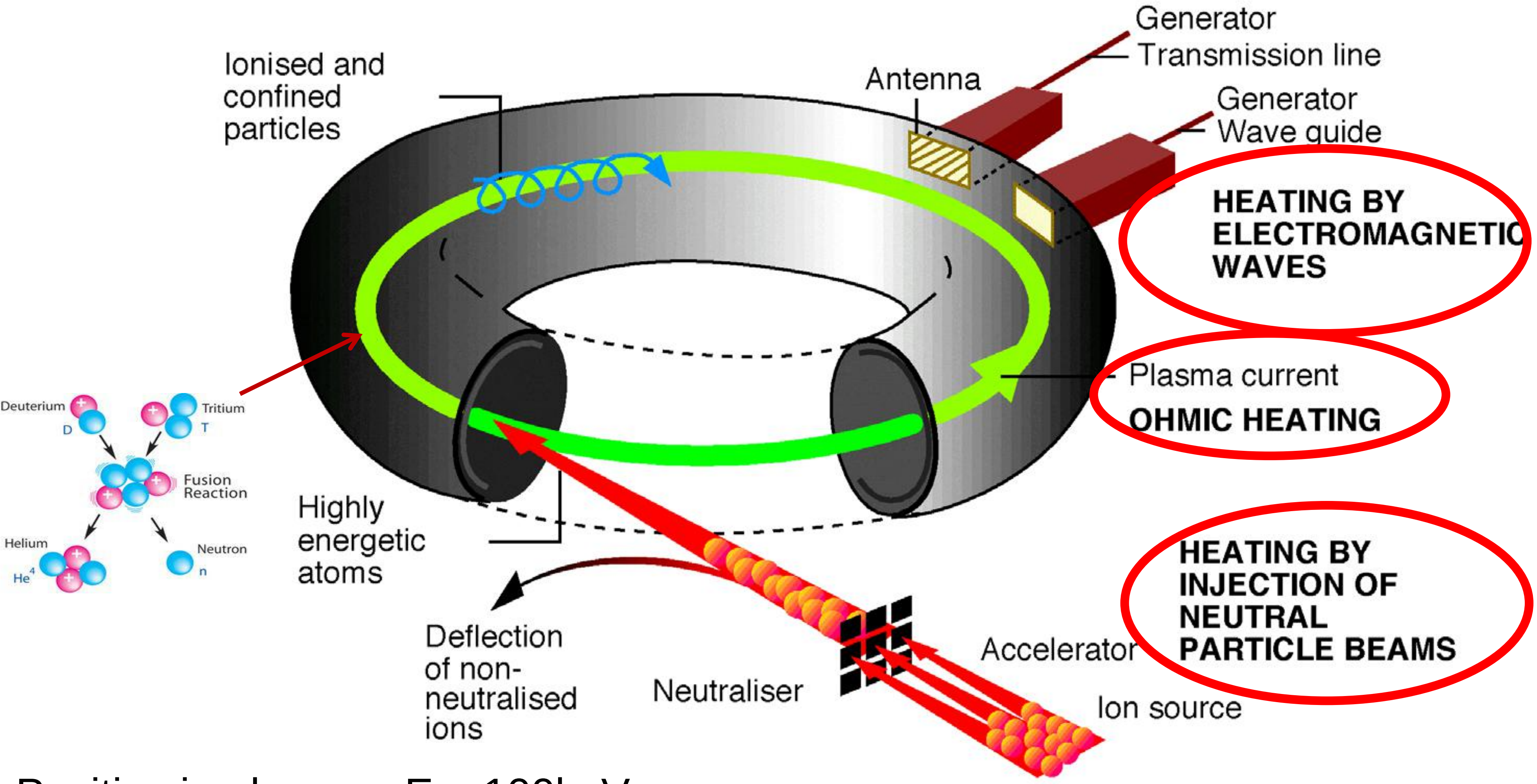


- In an “perfect” tokamak field lines lie in flux surfaces
- If magnetic field sufficiently strong ions and electrons bound to flux surfaces
- Different flux surfaces are ~ thermally insulated
- Flux surfaces support pressure gradient
- Tokamaks maximise core pressure, needed to initiate fusion

⇒ ***bottles*** **the plasma**

How to obtain the extreme temperatures?

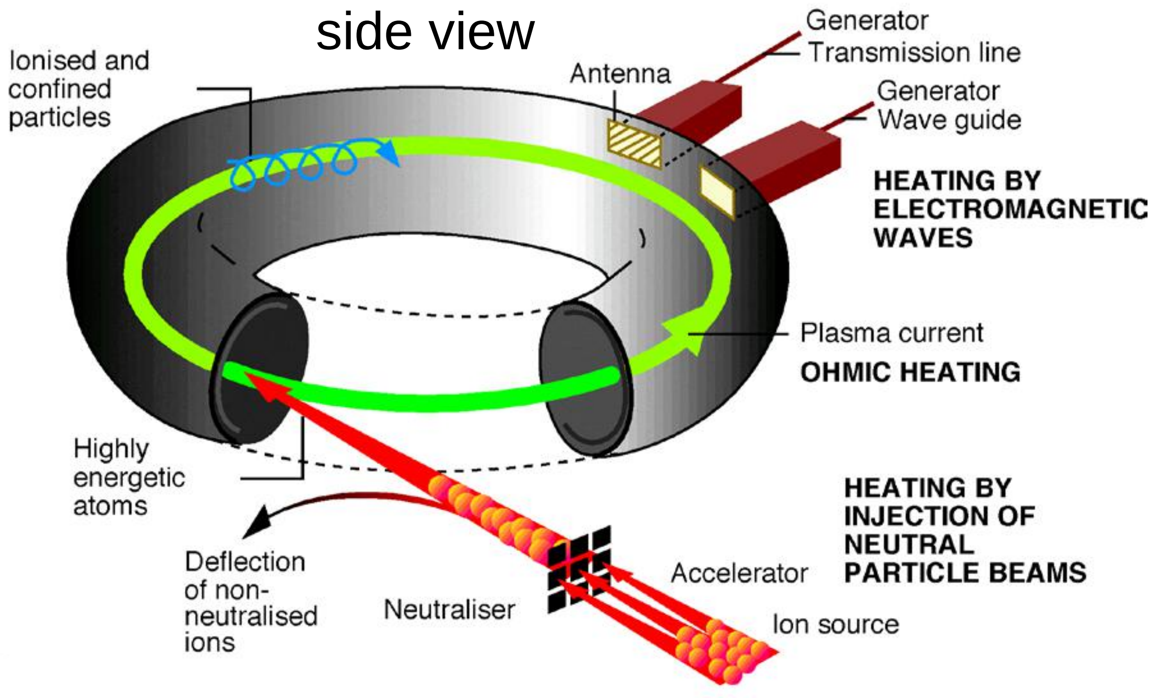
Ohmic heating: $\sigma \propto T^{3/2} \Rightarrow$ limited to T~ 3 keV,
additional heating needed, which also drives current:

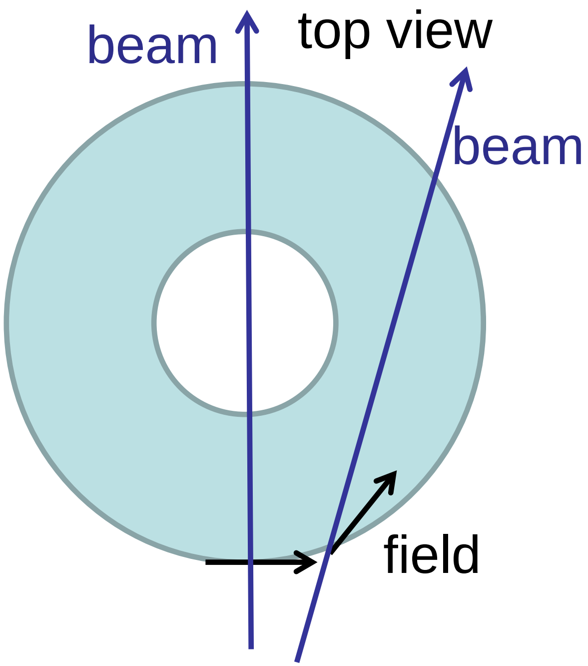


Positive ion beams: E ~ 100keV
Negative ion beams: E~ 1MeV

“MHD with anisotropy in velocity, pressure”

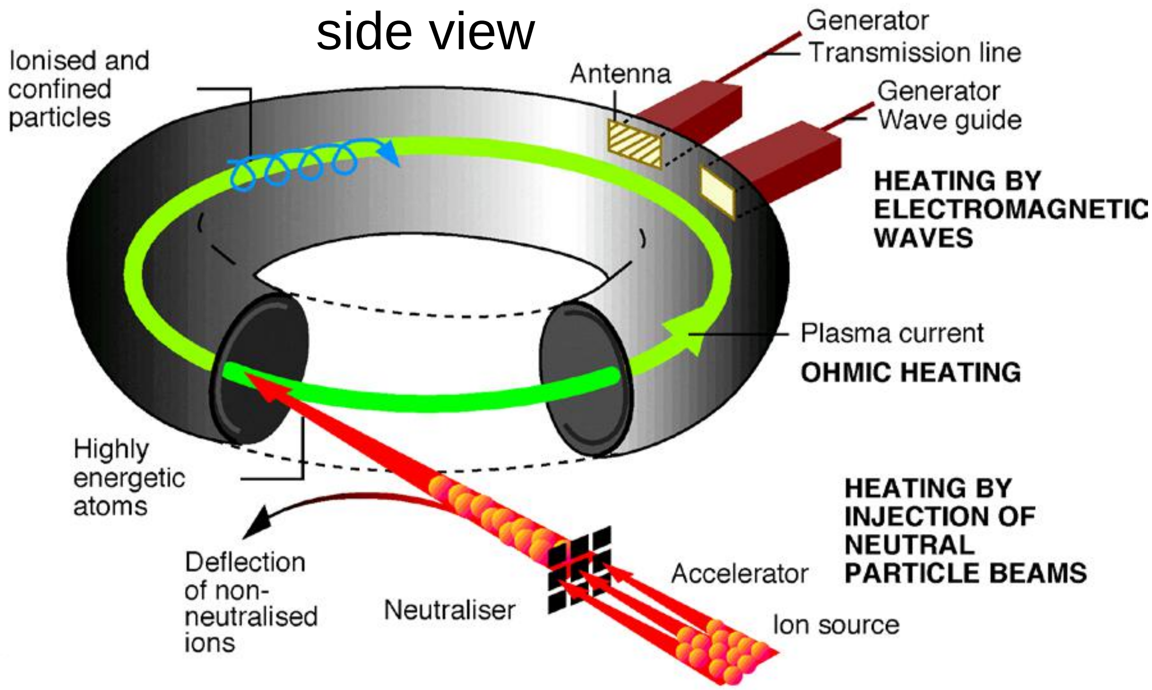
- Pressure different parallel and perpendicular to field due mainly to *directed* neutral beam injection

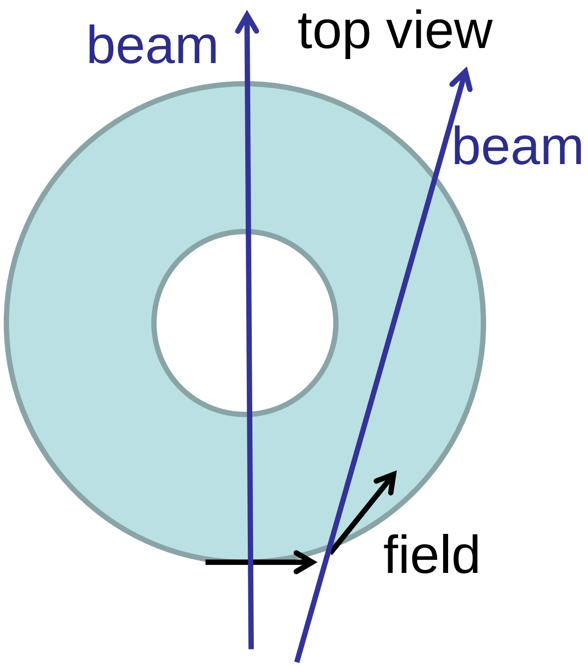




"MHD with anisotropy in velocity, pressure"

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





$\Rightarrow$ Pressure is a tensor $\mathbf{P} = p_\perp \mathbf{I} + \Delta \mathbf{B}\mathbf{B} / \mu_0$, $\quad \Delta = \dfrac{\mu_0 \left(p_{||} - p_\perp \right)}{B^2}$

- Inclusion of anisotropy and flow in equilibrium MHD equations

[R. Iacono, et al Phys. Fluids B 2 (8). 1990]

$$\nabla \cdot \left(\rho \mathbf{v} \right) = 0, \qquad \rho \mathbf{v} \cdot \nabla \mathbf{v} = \mathbf{J} \times \mathbf{B} - \nabla \cdot \overline{\mathbf{P}}, \qquad \nabla \cdot \mathbf{B} = 0$$

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}, \qquad \nabla \times \left(\mathbf{v} \times \mathbf{B} \right) = 0,$$

Tokamak Equilibria with anisotropy & flow

- New **EFIT TENSOR** reconstruction code
  - ➢ Add physics of flow/ anisotropy
  - ➢ Adds kinetic constraints to magnetic-only constraints of EFIT
  - ➢ Showed J_ϕ a strong function of transport model

[Fitzgerald, Appel, Hole, Nucl. Fusion **53** (2013) 113040]

- **HELENA+ATF** Add physics of flow/ anisotropy to fixed boundary & profile solver HELENA
  - ➢ Written to enable stability studies (Computes equilibrium in appropriate metric)
  - ➢ Decomposed J_ϕ into

$$J_\varphi = \underbrace{R\frac{B_p^2}{B^2}\left(\frac{\partial p_\parallel}{\partial \Psi}\right)_B}_{p_\parallel} + \underbrace{R\frac{B^2 - B_p^2}{B^2}\left(\frac{\partial p_\perp}{\partial \Psi}\right)_B}_{p_\perp} + \underbrace{\frac{1-\Delta}{2R}\left(\frac{\partial (RB_\varphi)^2}{\partial \Psi}\right)_B}_{toroidal\,field} - \underbrace{R\nabla \cdot \frac{\Delta \nabla \Psi}{R^2}}_{nonlinear}$$

    and showed $J_{p\perp}$ dominates of $J_{p||}$
  - ➢ Computed parametric scans of changes in to equilibrium with anisotropy – most significant change is to $\boldsymbol{J_{pol}}$.

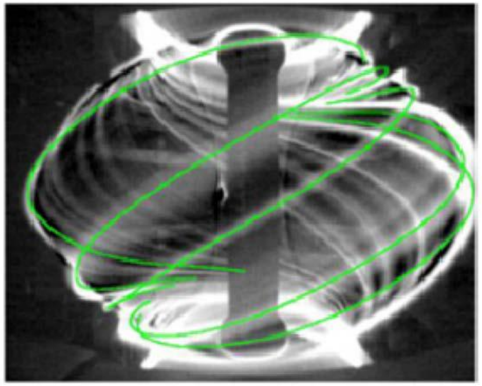
[Qu, Fitzgerald, Hole, Plasma Phys. Control. Fusion **56** (2014) 075007]

Tokamak Stability Zoo

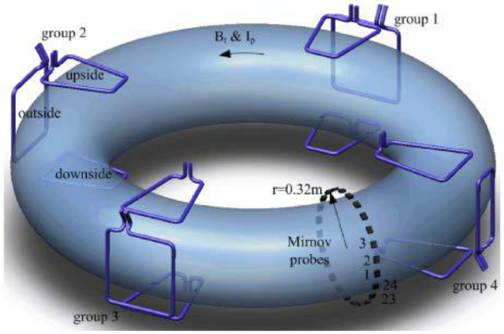
A whole zoo of modes. Can divide them as:

- Most-serious (disruptive): e.g. external modes such as the (n, m) = (1,1) *external kink*, driven by gradients in pressure and current density

- Serious but tolerable (performance-limiting):
  - *Sawteeth*, internal kink, (n, m) = (1,1) – reconnection of core. Periodic collapse of central temperature
  - **Alfven eigenmodes**, wave-particle resonance driven. Loss of fast particle confinement
  - *Edge-Localised Modes* (ELMs), which occur for moderately high *m* and *n*.



ELM mitigation / suppression demonstrated by application of resonant magnetic perturbation coils, that deliberately perturb edge



Stability: ANU single adiabatic model

ANU PTM postdoc M. Fitzgerald

- Compressional
  - ➢ *Double-adiabatic (CGL)*
    - Collisionless, $p_\parallel$ and $p_\perp$ do **independent** work
    - No streaming particle heat flow
    - Does not reduce to MHD in the isotropic limit

$$\frac{d}{dt}\left(\frac{p_\perp}{\rho B}\right) = 0,$$

$$\frac{d}{dt}\left(\frac{p_\parallel B^2}{\rho^3}\right) = 0.$$

  - ➢ *New ANU single adiabatic (SA) model*
    - $p_\parallel$ and $p_\perp$ doing **joint** work
    - Account for the isotropic part of the perturbation
    - Can reduce to MHD in isotropic limit

      [Fitzgerald, Hole, Qu, PPCF **57** (2015) 025018]

$$\widetilde{\mathrm{P}} \to \tilde{p}\mathrm{I} + \tilde{\pi}$$

$$\mathrm{Tr}\ \nabla \cdot \widetilde{Q} \to 0$$

$$\mathrm{Tr}\ \tilde{\pi} \to 0$$

- Incompressional

$$p_{\parallel 1} = -\xi_n \left[\frac{\partial p_\parallel}{\partial n} - (p_\parallel - p_\perp)\frac{\partial \ln B}{\partial n}\right] \qquad p_{\perp 1} = -\xi_n \left[\frac{\partial p_\perp}{\partial n} - (2p_\perp + \hat{c})\frac{\partial \ln B}{\partial n}\right]$$

*A B Mikhailovskii, Instabilities in a confined plasma, IOP publishing (1998)

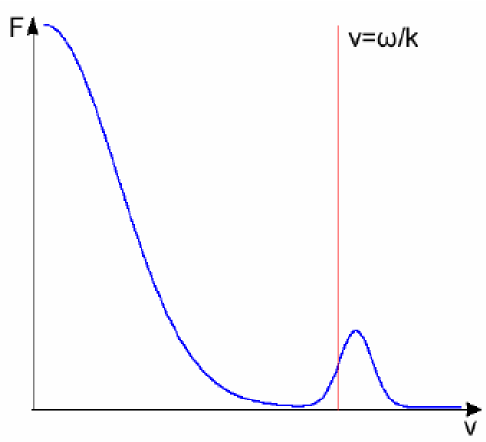
- Implemented in CSCAS (CSMIS-A) and MISHKA (MISHKA-A)

[Qu, Hole, Fitzgerald, PPCF **57** (2015) 095005]

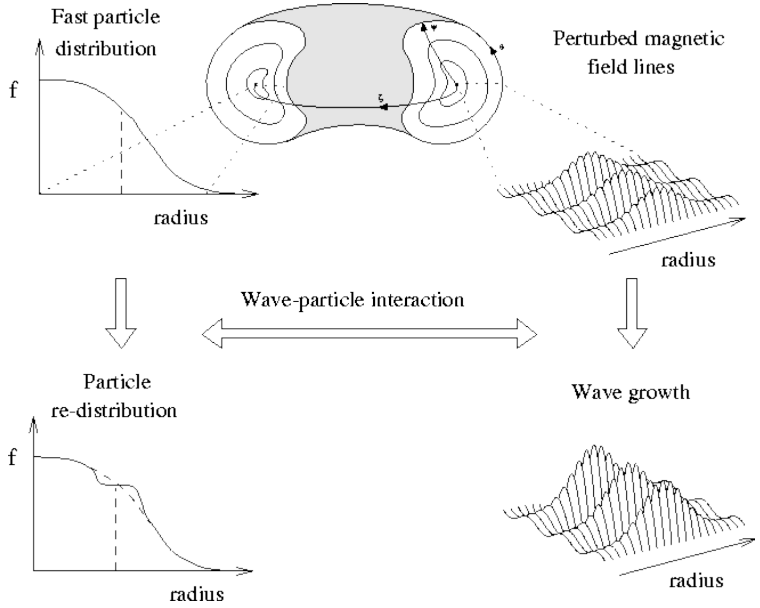
Wave-particle drive: (non)linear dynamics

Evolution of unstable modes in realistic geometry and with simulated distribution functions uses drift-kinetic wave-particle interaction codes, such as HAGIS.

[Pinches *et al,* Comp. Phys. Comm. 111 (1998) 133-149]



$$\left.\frac{\partial F_0}{\partial v}\right|_{\frac{\omega}{k}} > 0$$

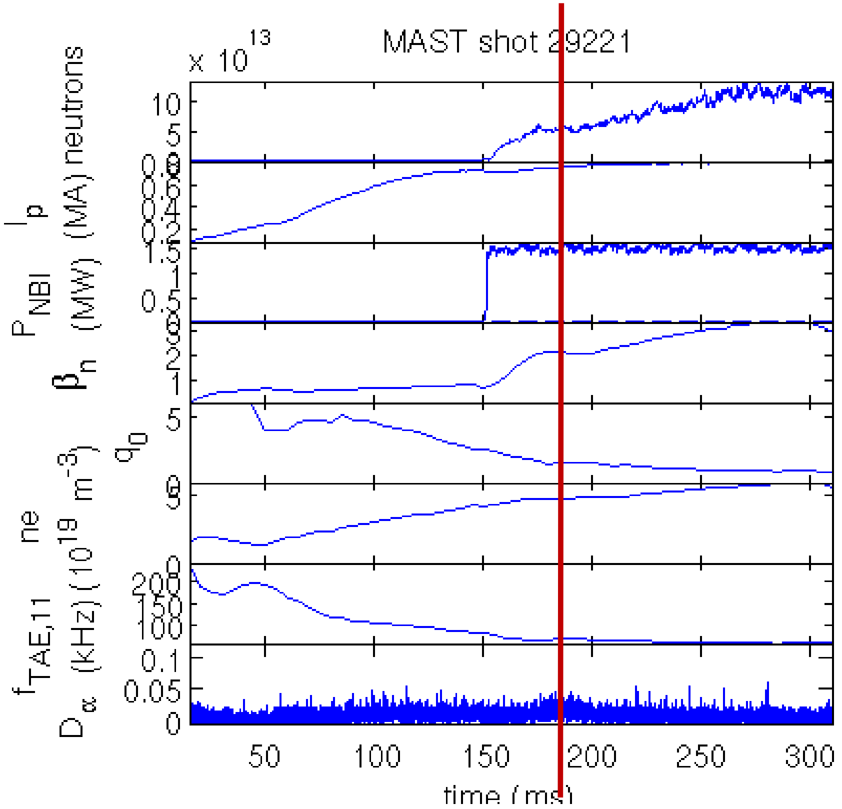


Inclusion of anisotropy:

- Formal: change the magnetic structure, equations of motion
- Approximate: use a mapping to match q(ψ) and I_{total}
  - ✓ Works provided particle orbits are similar.

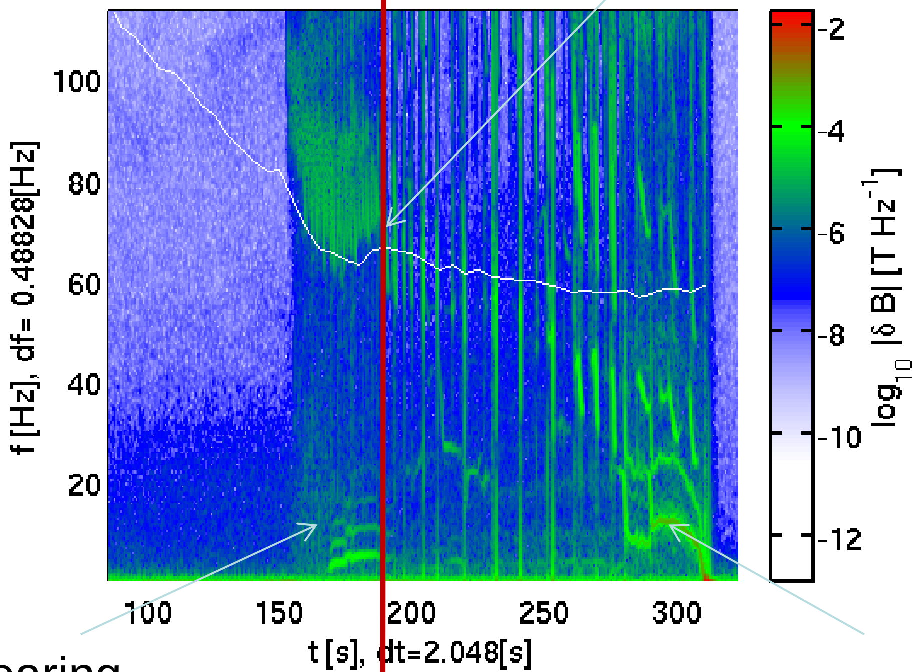
Anisotropy on MAST: #29221

- MAST #29221
- 1.6MW NB heating
- I_p = 0.9MA, β_n~3
- Magnetics shows TAEs, tearing modes fishbones, long-lived modes



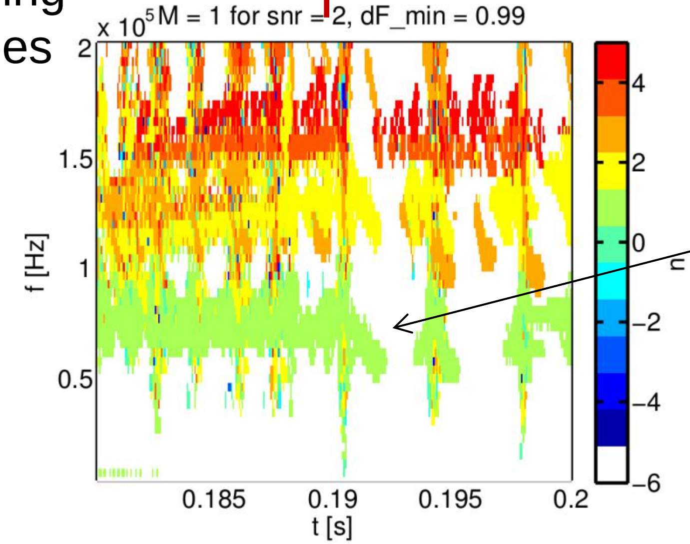
Magnetics

possible TAE



Tearing modes

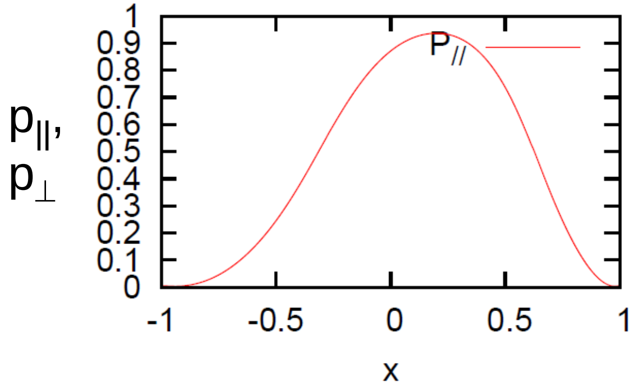
Long-lived modes

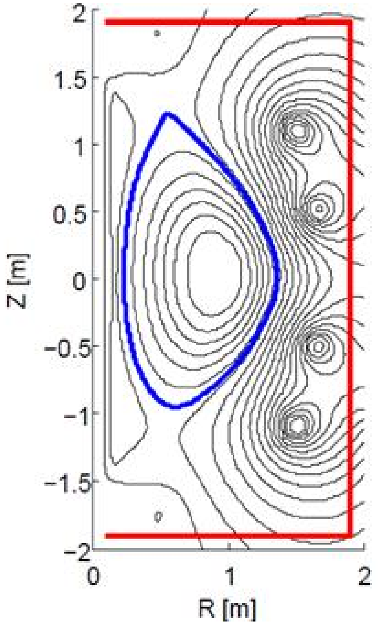


n=1

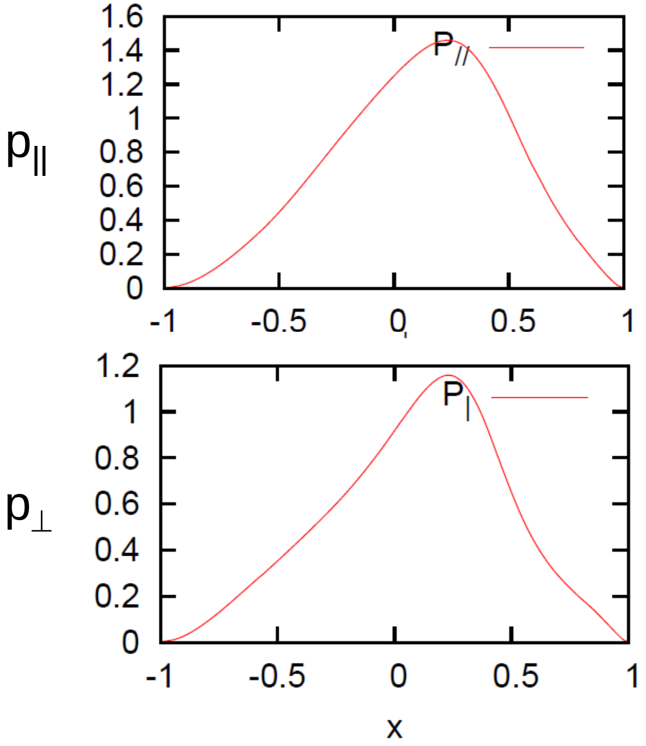
Beam + thermal population: $p_{||} / p_{\perp} \approx 1.7$

HELENA+ATF / EFIT TENSOR: **$p^* = (p_{||} + p_{\perp})/2$ (isotropic)**





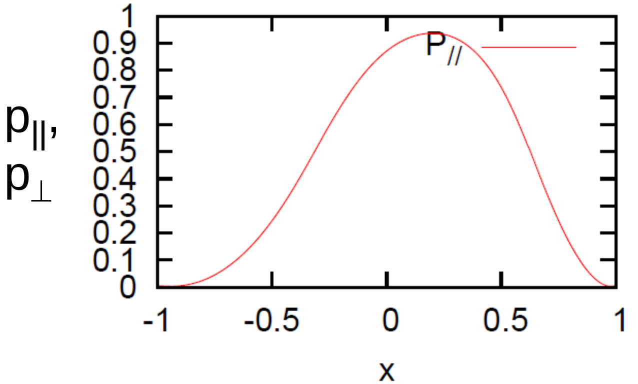
HELENA+ATF / EFIT TENSOR: **$p_{||}$, $p_{\perp}$ (anisotropic)**

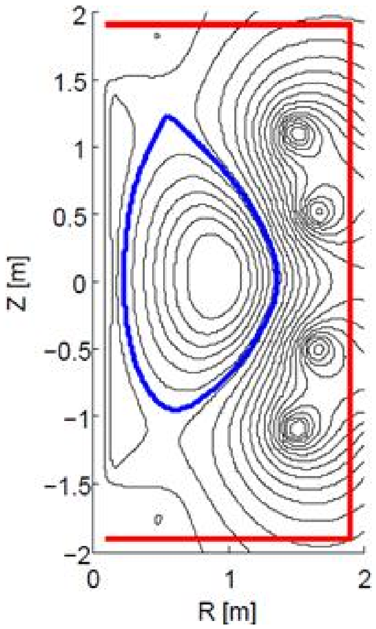


$p_{||}/p_{\perp}$ = 1.7 at s=0.5 outboard

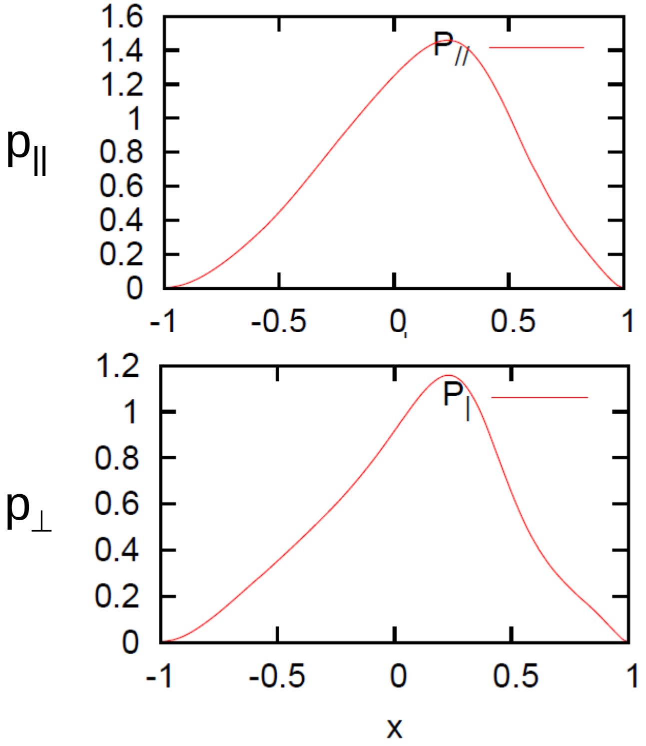
Beam + thermal population: $p_{||}/p_{\perp} \approx 1.7$

HELENA+ATF / EFIT TENSOR: **$p^* = (p_{||} + p_{\perp})/2$ (isotropic)**





HELENA+ATF / EFIT TENSOR: **$p_{||}$, $p_{\perp}$ (anisotropic)**



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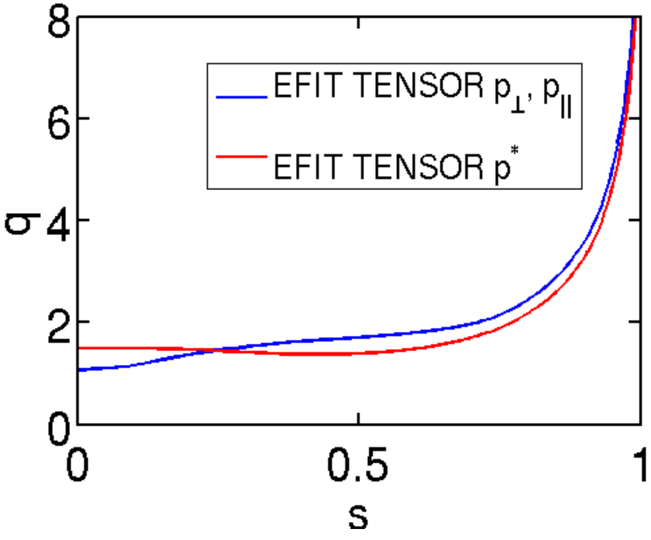


- What is the impact on stability due to this q profile?

Incompressible continuum for MAST

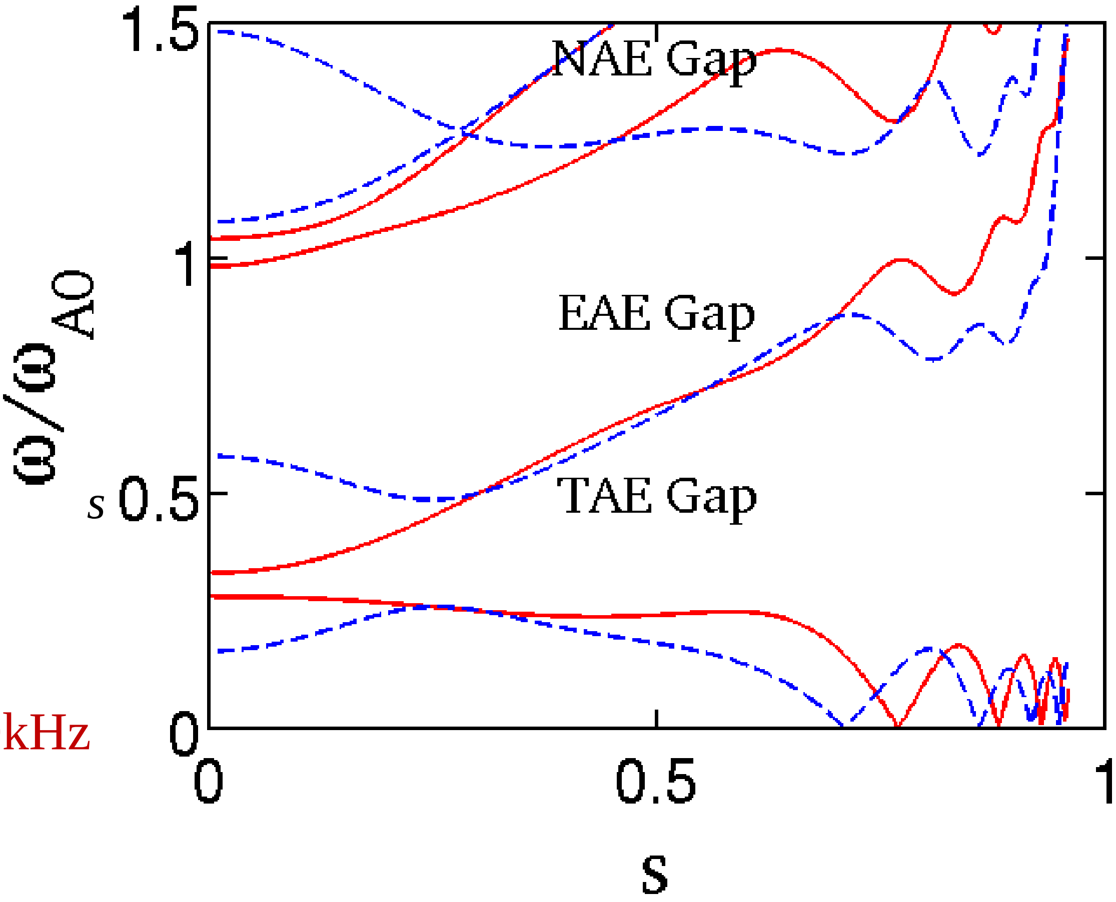
ANU PTM student Z. Qu

MAST #29221 at 290ms.

n=1, γ=0

isotropic

anisotropic



$p_{\|}/p_{\perp}$ = 1.7 at
s=0.5 outboard

R_{mag} = 0.914
f_A (R_{mag})= 280kHz

R_{mag} = 0.928
f_A (R_{mag})= 260kHz

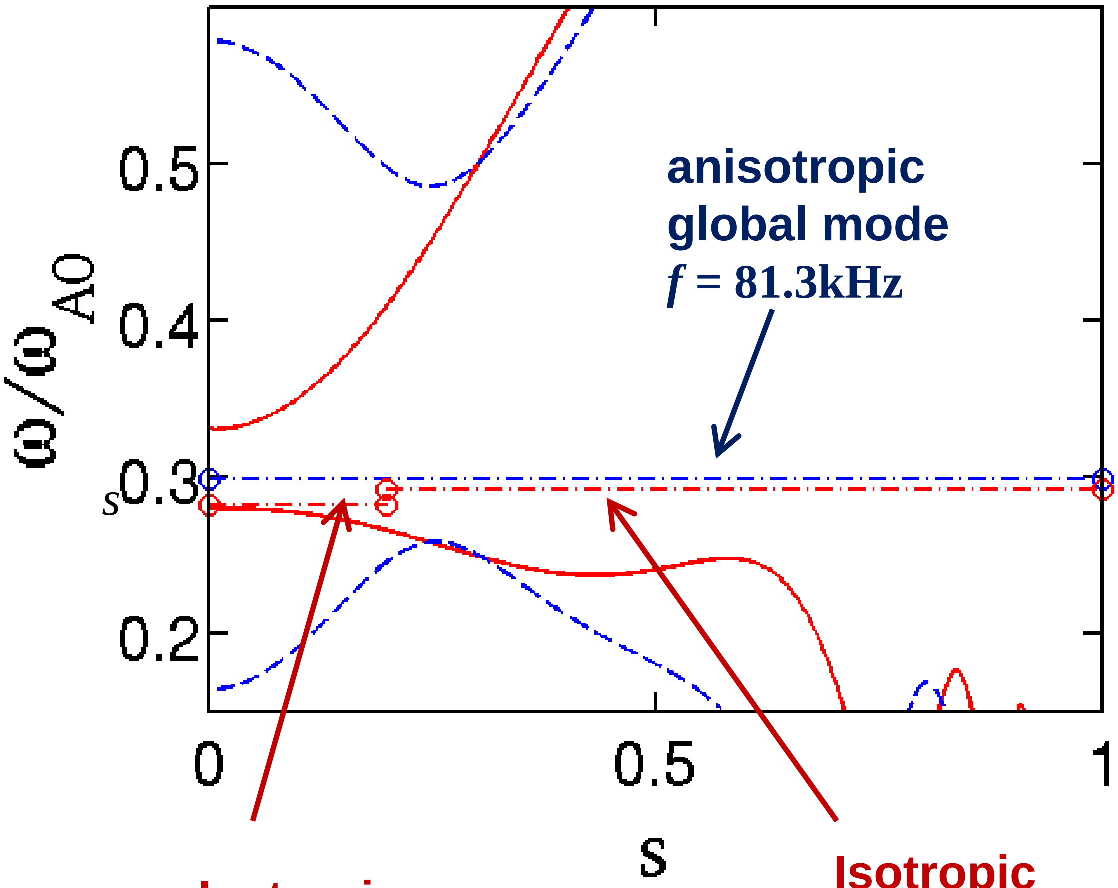
isotropic Δf_{TAE} < anisotropic Δf_{TAE}
$\Rightarrow$anisotropic modes less susceptible to continuum damping

Incompressible continuum for MAST

Z. Qu

MAST #29221 at 290ms.

n=1, γ=0

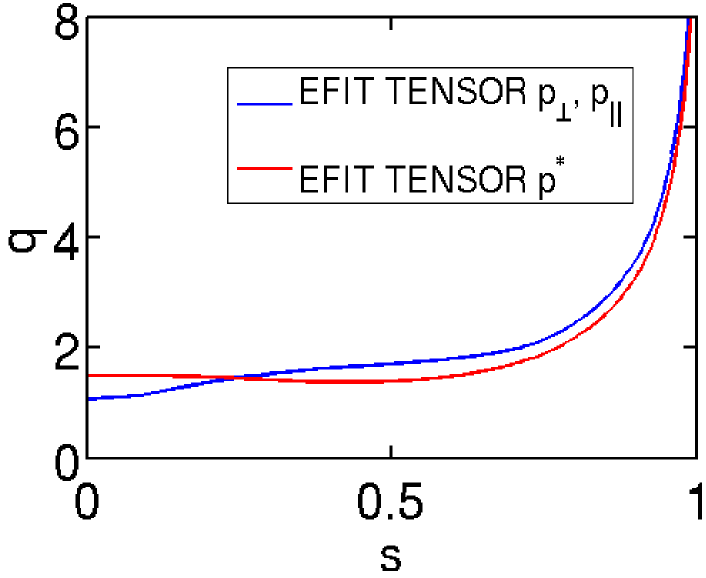


anisotropic global mode
***f* = 81.3kHz**

Isotropic core mode
***f* = 83.5kHz**

Isotropic global mode
***f* = 88.9kHz**

f_{A0} = 260kHz

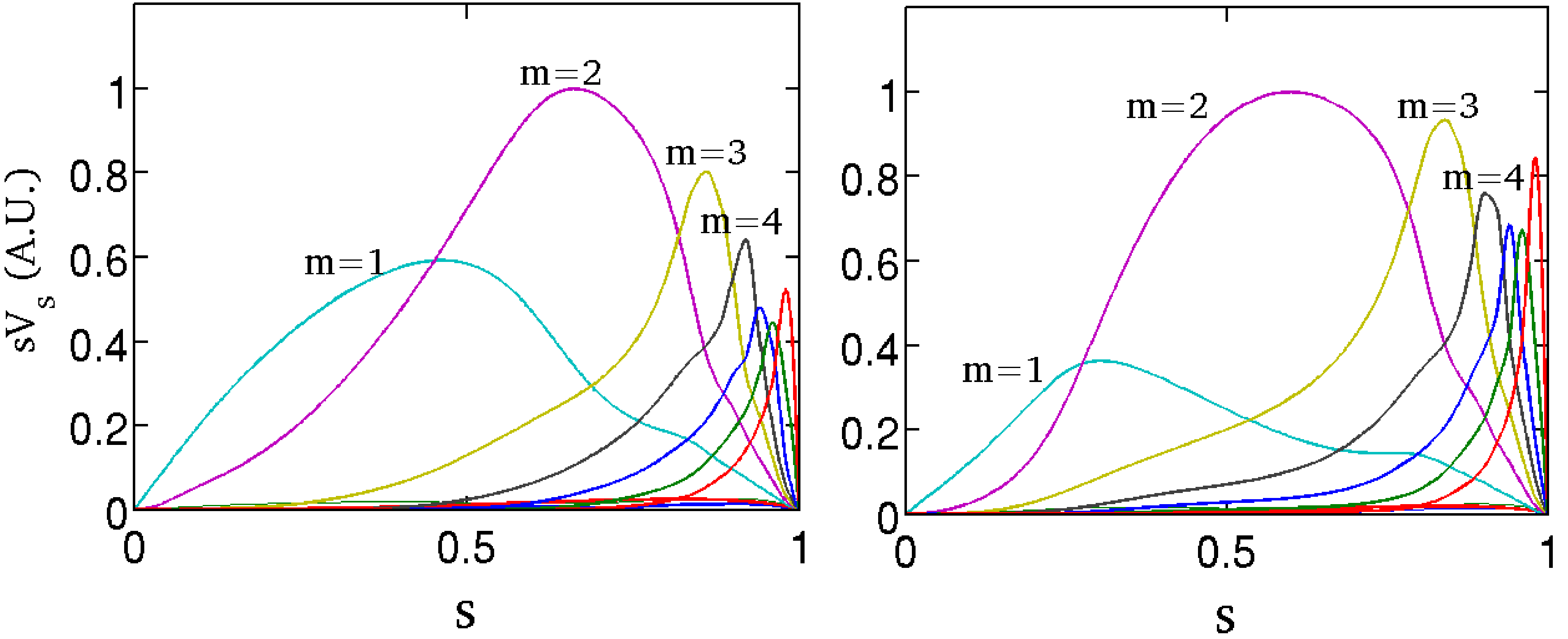


f_{A0} = 280kHz

Mode profile broader with anisotropy

Z. Qu

isotropic MAST #29221 at 290ms. **anisotropic**



- Might saturation level be different for two cases ?

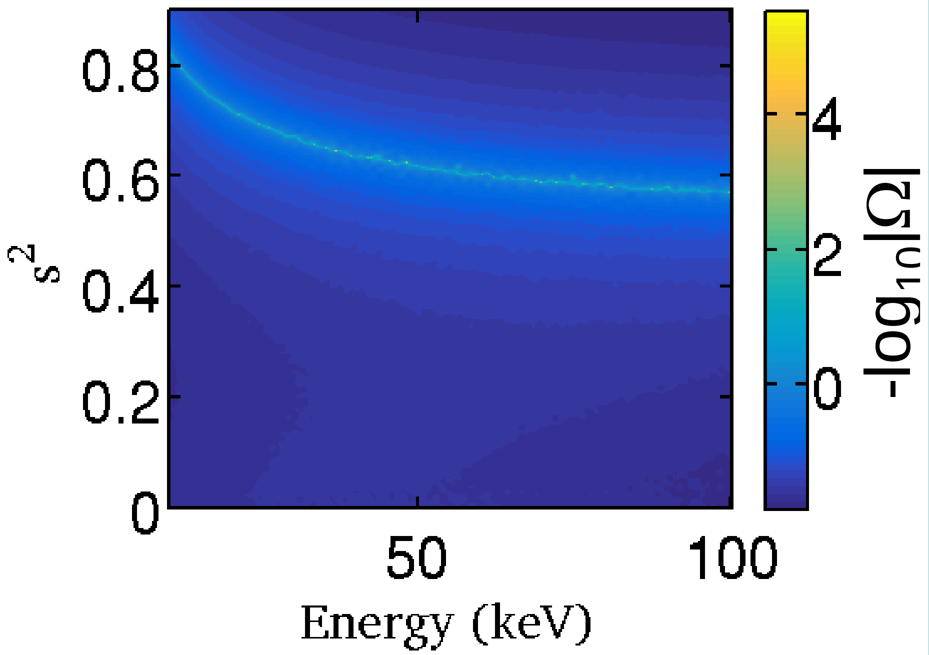
Resonance maps from HAGIS

ANU PTM postdoc B. Layden

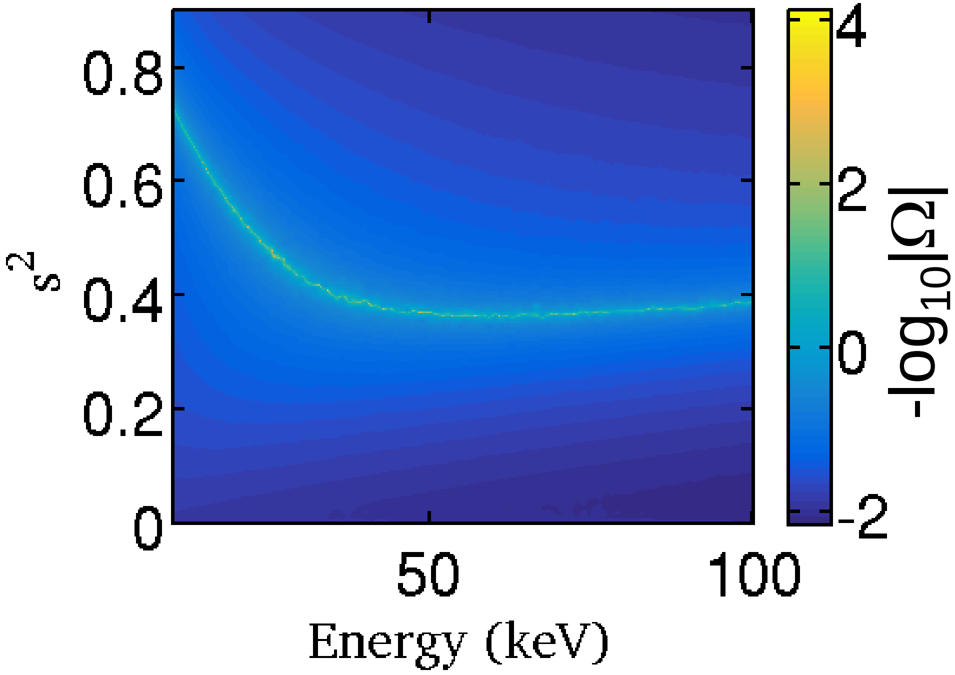
- Use linear eigenfunction from MISHKA+ATF to compute resonance maps (Ω=0) of wave/ particle evolution

$$\Omega = \omega - n\omega_\phi - p\omega_\theta$$

isotropic,
n=1, p=1,
f = 88.9kHz, Λ = 0.3



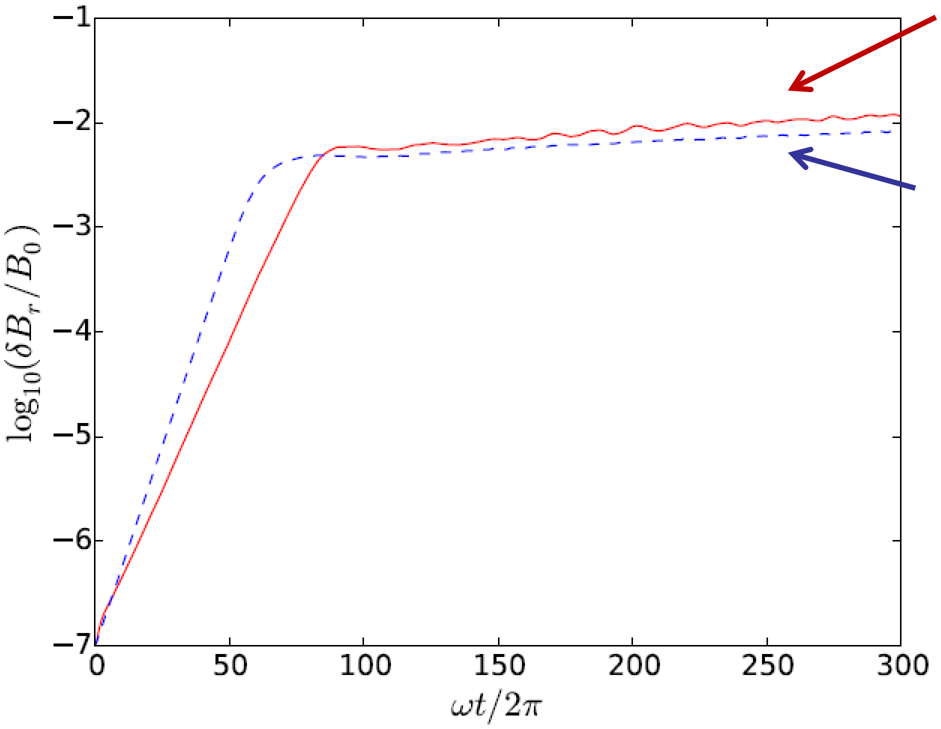
anisotropic,
n=1, p=1,
f = 81.3kHz, Λ = 0.3



Saturation level for (an)isotropic cases

B. Layden

- Distribution function is slowing down in energy, Gaussian in s (centred at s=0) and delta function in Λ (Λ = 0.3).



isotropic

anisotropic

- Anisotropic drive 35% larger than isotropic mode
- Anisotropic saturation 15% weaker than isotropic mode

- First wave-particle interaction study in anisotropic plasmas
- *Lots more to do*: relax delta function in Λ

Other Burning Plasma Results

- Hole and Fitzgerald, Topical Review, “Resolving the wave–particle–plasma interaction”, Plasma Phys. Control. Fusion 56 (2014) 053001

Other Burning Plasma Results

- Hole and Fitzgerald, Topical Review, “Resolving the wave–particle–plasma interaction”, Plasma Phys. Control. Fusion 56 (2014) 053001
- Demonstrated perturbative approach used for last 20 years to compute continuum damping does not converge [G. W. Bowden, A. Könies, M. J. Hole, N. N. Gorelenkov,G. R. Dennis Phys. Plas. **21**, 052508 (2014)]
- First calculation of continuum damping in a realistic stellarator (W7X, H-1). [G. W. Bowden, M. J. Hole, and A. Könies, Phys. Plas. **22**, 092114 (2015)]
- Used singular finite elements (a first) to compute continuum damping. [G. W. Bowden and M. J. Hole, Phys. Plas. **22**, 022116 (2015)]

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- Energetic geodesic acoustic modes associated with two-stream like instabilities in tokamak plasmas, [Z.S. Qu and M.J. Hole, M. Fitzgerald, 116, 095004, PRL]
  - ➢ Discovered a new instability (EGAM)
  - ➢ Describes wave activity during DIII-D after beam switch-on.
  - ➢ one of the referees noted “the work will open up a new way to study and understand energetic particle-driven instabilities in fusion plasmas and make a big impact in fusion research.”

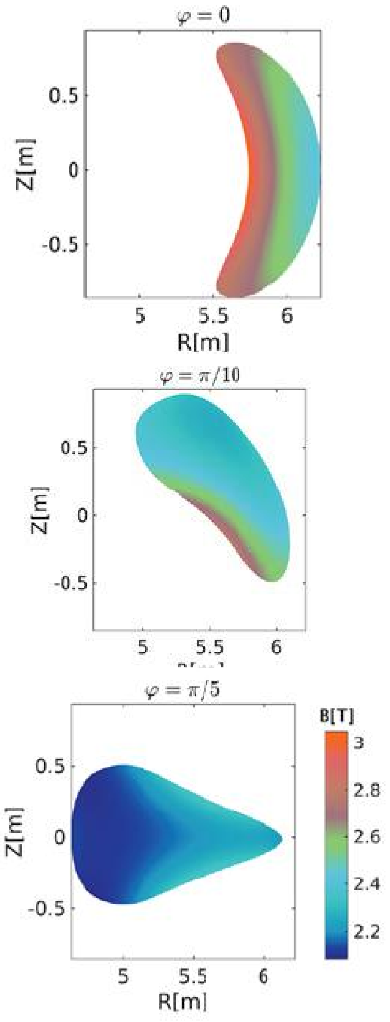
Components of a Stellarator

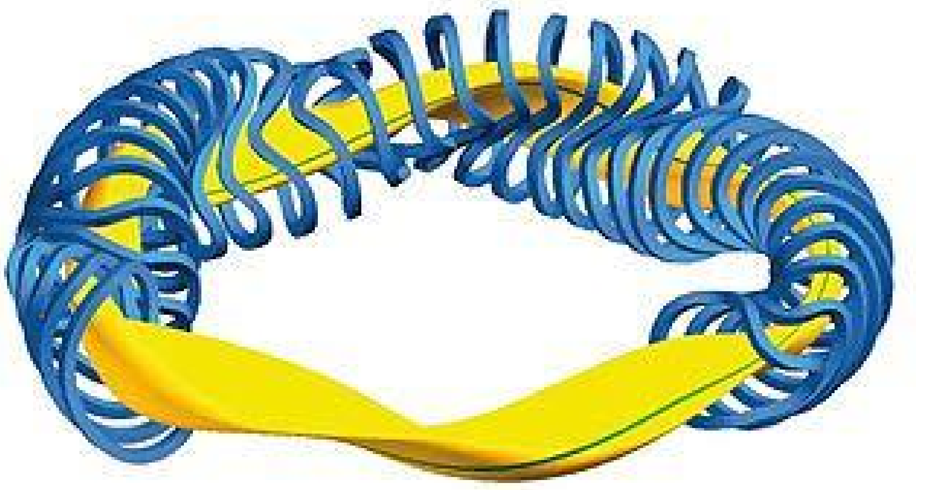
Principle:

- Confining field nearly all produced by external coils
- Twists the field so as to eliminate ∇B drift
- Intrinsically 3D (no continuous symmetry)

Consequence:

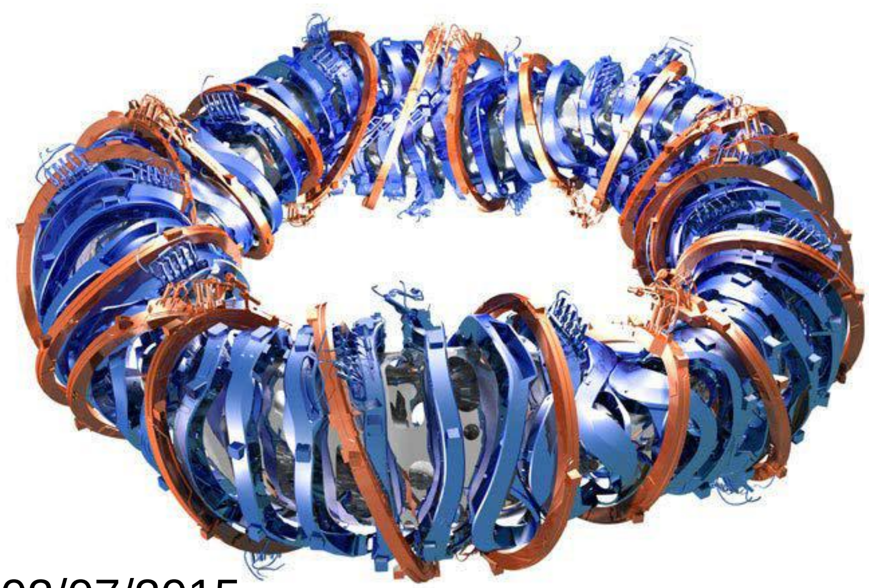
- Large toroidal current removed (stability ✓)
- Cross section changes shape with toroidal position (confinement ×)





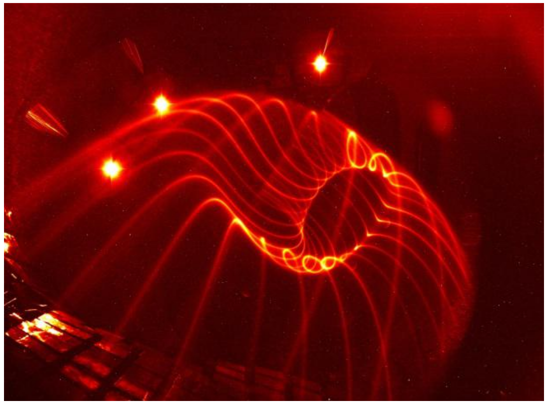
Wendelstein 7-X

- € 1 billion experiment. Construction started in ~2000.
- Aim: evaluate future fusion reactor potential of stellarator
- Quasi-symmetry (lines of constant B^2 in natural field coords)
- Opened by Chancellor Merkel in February 2016



03/02/2016

02/07/2015



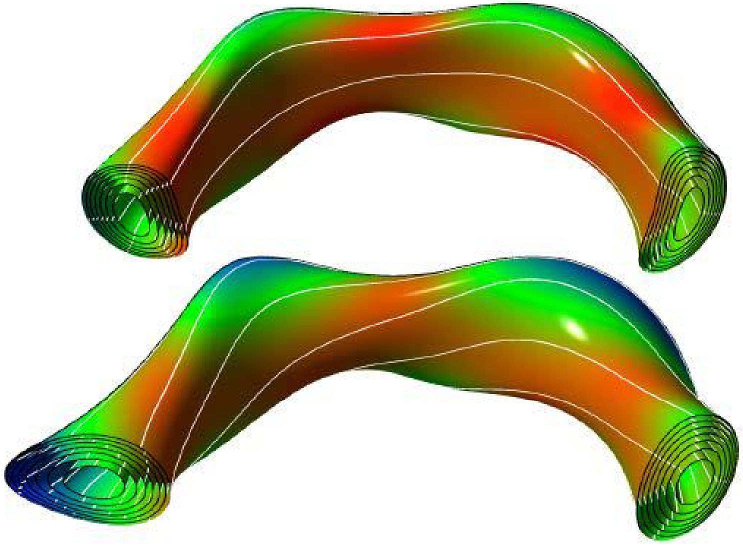
06/07/2015: electron beam in full vacuum field

New ANU approach to 3D equilibria

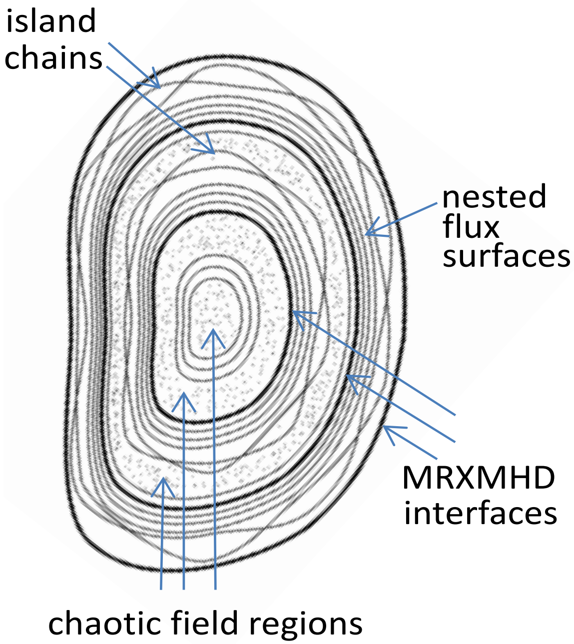
- Simplest model to approximate global, macroscopic force-balance is magnetohydrodynamics (MHD).

$$\nabla p = \mathbf{J} \times \mathbf{B}, \qquad \nabla \times \mathbf{B} = \mathbf{J}, \qquad \nabla \cdot \mathbf{B} = 0$$

- Non-axisymmetric $\Rightarrow$ field does **not** lie in nested flux surfaces **unless** surface currents allowed.
- Existing 3D solvers (e.g. VMEC) assume nested flux surfaces.



[CTH stellarator, Hanson et al, IAEA 2012]



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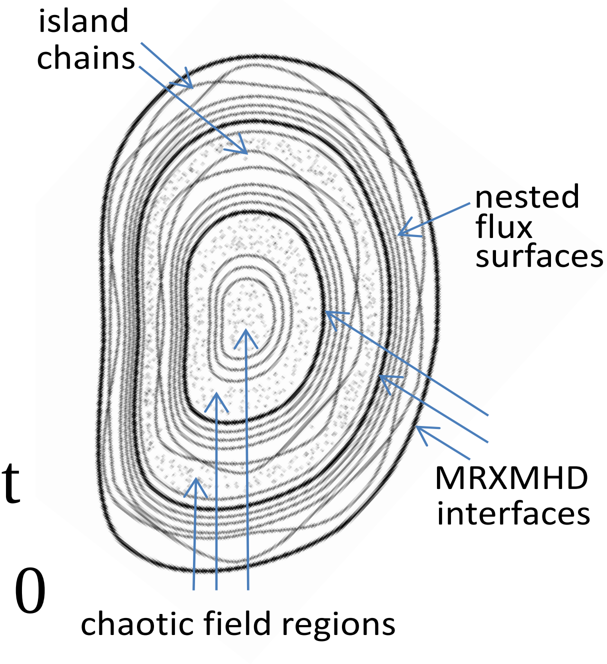
- Existing 3D solvers (e.g. VMEC) assume nested flux surfaces.
- Generalised Taylor relaxation model: Multiple Relaxed Region MHD (MRxMHD) supports full complexity of field: nested flux surfaces, magnetic islands, chaotic regions.

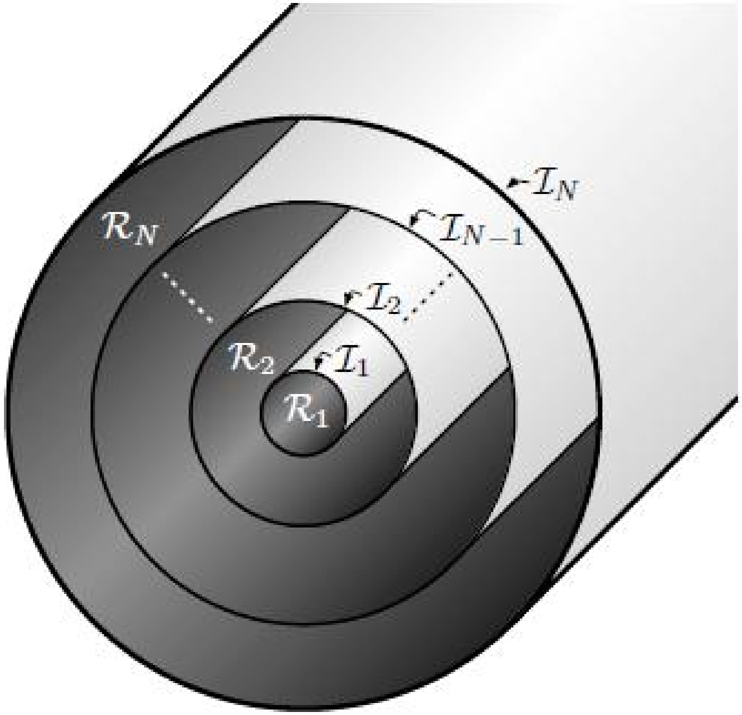


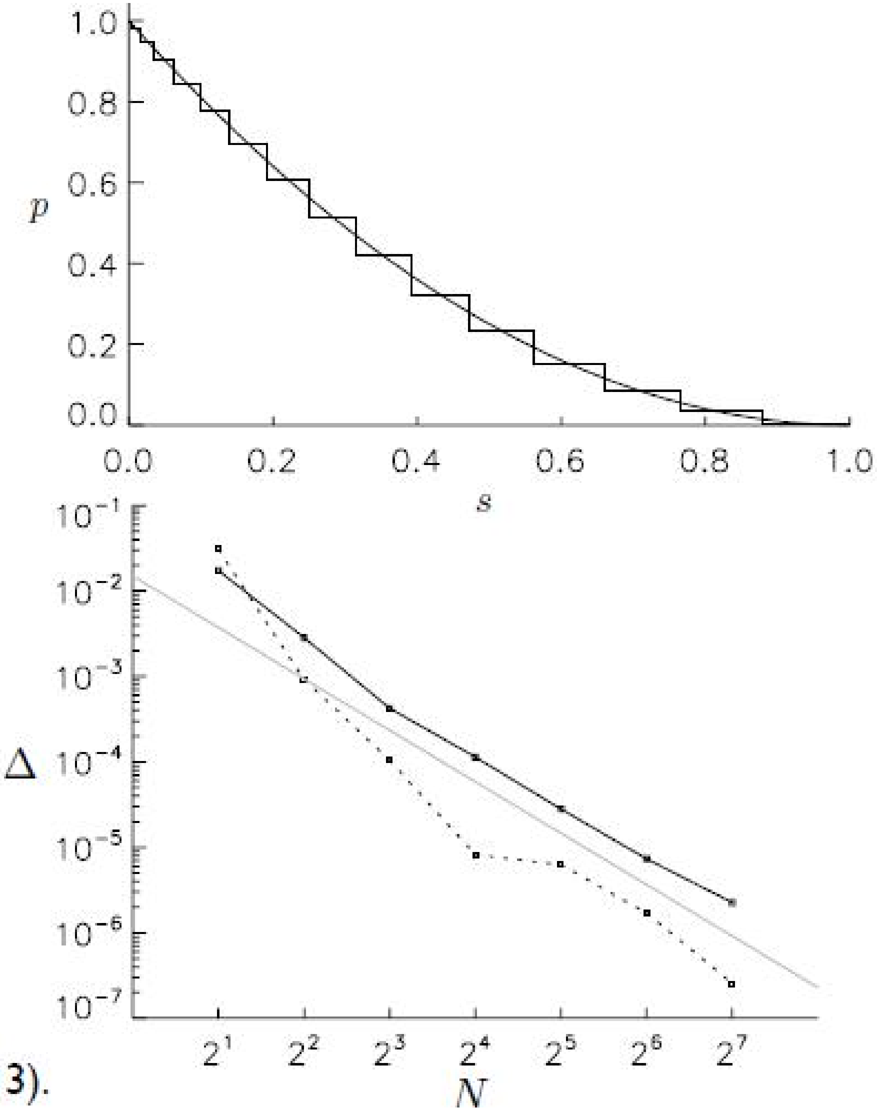
Volume: $\nabla \times \mathbf{B} = \mu_l \mathbf{B} \qquad P_l = \text{constant}$

Interfaces: $[[P_l + B^2/(2\mu_0)]] = 0 \qquad \mathbf{B} \cdot \mathbf{n} = 0$

MRXMHD approaches ideal MHD as N→∞

ANU PTM postdoc G. Dennis





[1] G. Dennis et al., *Phys. Plasmas* **20**, 032509 (2013).

Stepped Pressure Equilibrium Code, SPEC

[Hudson et al Phys. Plasmas 19, 112502 (2012)] **ANU PTM alumnus S. Hudson**

Vector potential is discretised using mixed Fourier & finite elements

- Coordinates (s,φ, ζ)
- Interface geometry $R_i = \sum_{l,m,n} R_{lmn} \cos(m\vartheta - n\zeta),\ Z_i = \sum_{l,m,n} Z_{lmn} \sin(m\vartheta - n\zeta)$
- Exploit gauge freedom $\mathbf{A} = A_\vartheta(s,\vartheta,\zeta)\nabla\vartheta + A_\zeta(s,\vartheta,\zeta)\nabla\zeta$
- Fourier $A_\vartheta = \sum_{m,n} \alpha(s)\cos(m\vartheta - n\varsigma)$
- Finite-element $a_\vartheta(s) = \sum_i a_{\vartheta,i}(s)\varphi(s)$

& inserted into constrained-energy functional $F = \sum_{l=1}^{N} (W_l - \mu_l H_l / 2)$

- Derivatives wrt **A** give Beltrami field $\nabla \times \mathbf{B} = \mu \mathbf{B}$
- Field in each annulus computed independently, distributed across multiple cpu's
- Field in each annulus depends on enclosed toroidal flux, poloidal flux, interfaces ξ

Force balance solved using multi-dimensional Newton method

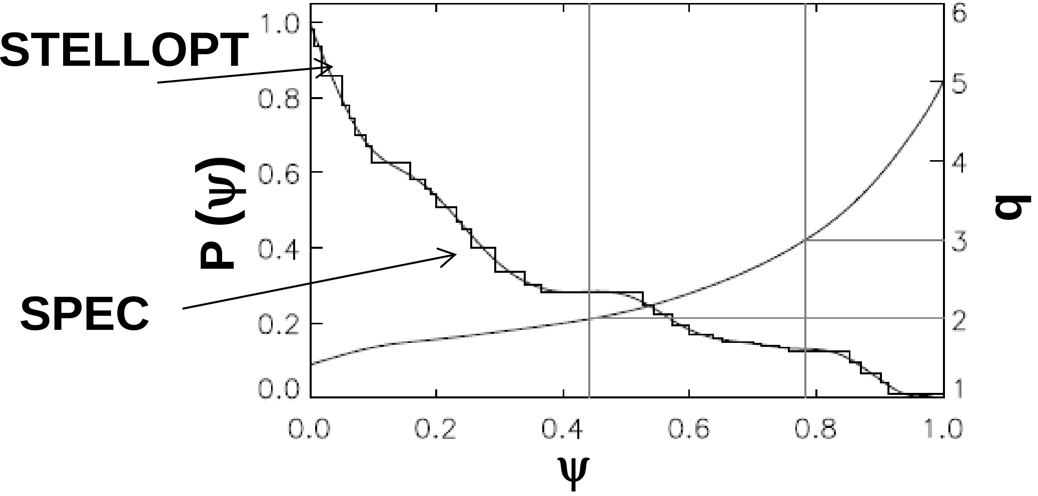
- Interface geometry adjusted to satisfy force balance $\mathbf{F}[\xi] = \{[[p + B^2/2]]_{m,n}\} = 0$
- Angle freedom constrained by spectral condensation,
- Dertivative matrix ∇F[ξ] computed in parallel using finite difference

Example: DIIID with n=3 applied error field

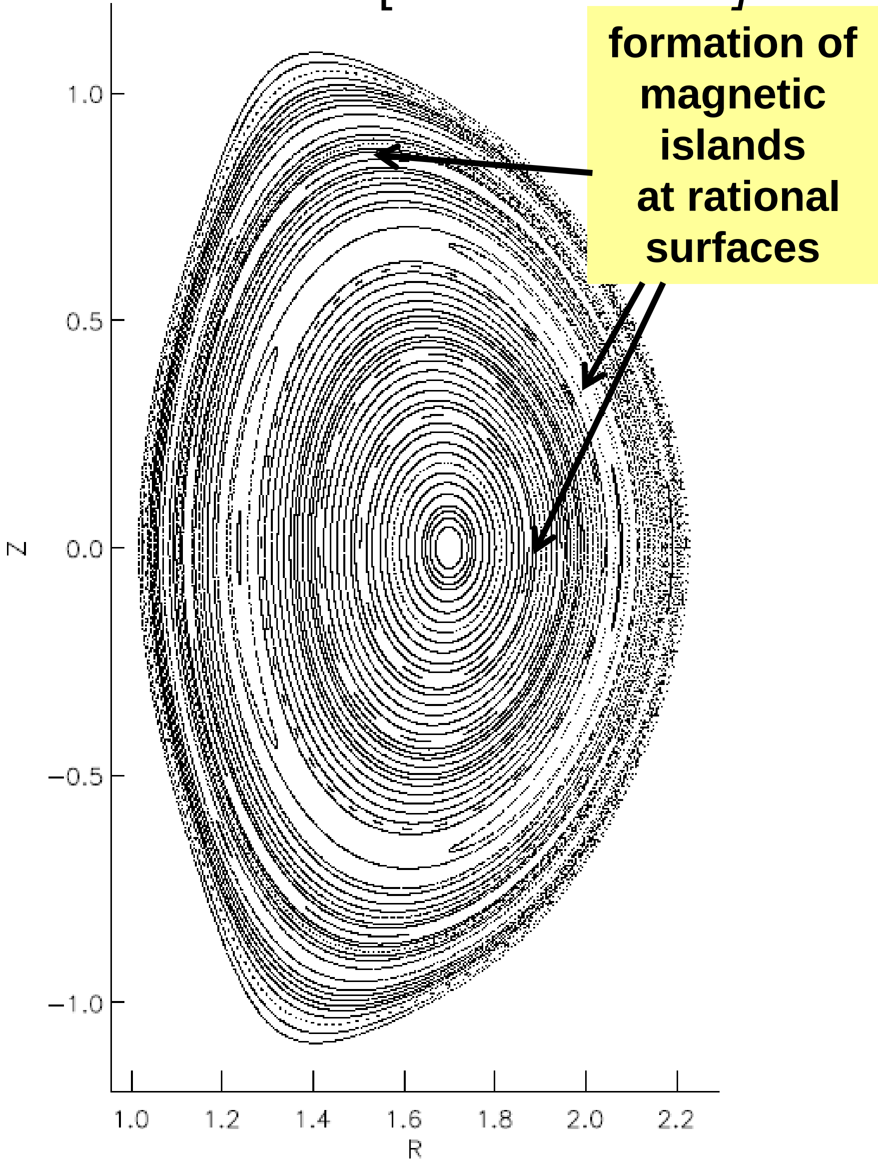
[Hudson et al Phys. Plasmas 19, 112502 (2012)]

Hudson

- 3D boundary, p, q-profile from STELLOPT reconstruction [*Sam Lazerson]*
- Irrational interfaces chosen to coincide with pressure gradients.


STELLOPT

SPEC

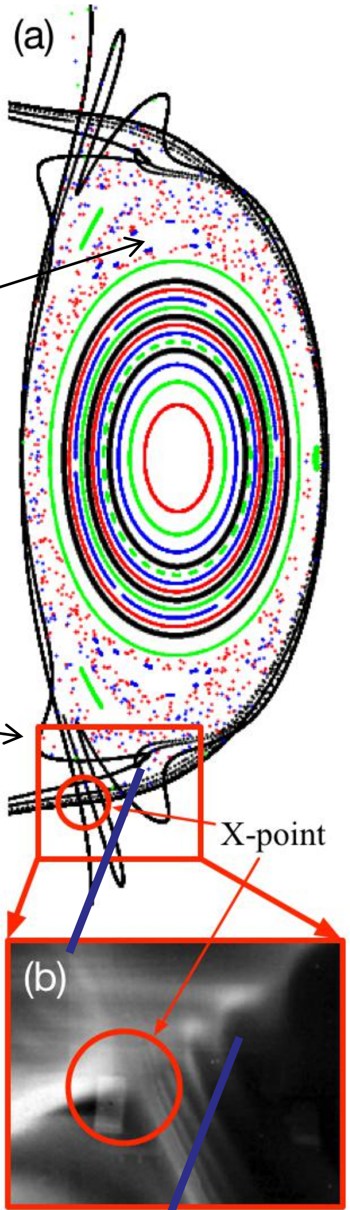

formation of magnetic islands at rational surfaces

- Island formation is permitted
- No rational “shielding currents” included in calculation.

SPEC extended to vacuum and X points

Hudson

- a prototype calculation performed for an illustrative (MAST-like) cross-section with a large perturbation applied in the vacuum



edge field region chaotic by generating intersecting unstable manifolds’ (a homoclinic tangle) about the X-point

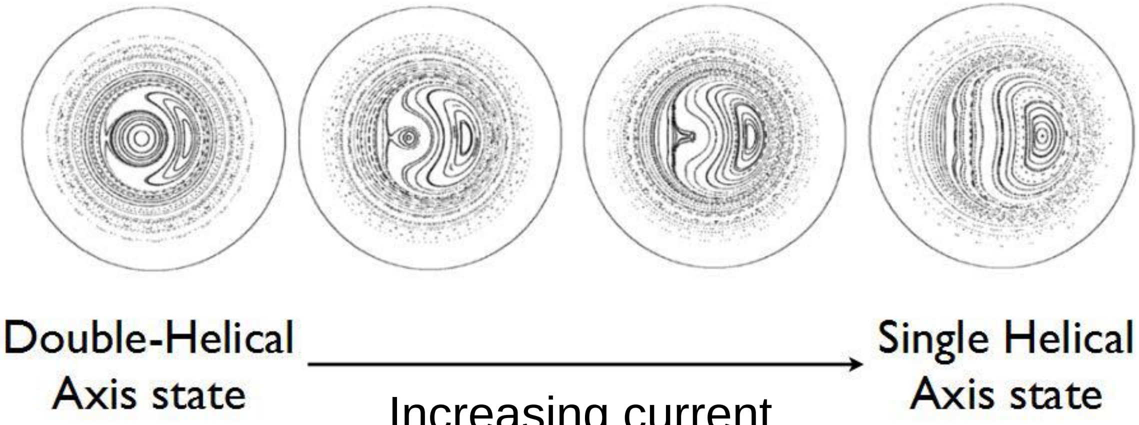
some lobes can intersect the divertor target and result in the strike point splitting often observed during RMP experiments

[A. Kirk *et al*, Plasma Phys. Control. Fusion **55**, 124003, 2013]

Spontaneously formed helical states

Dennis, Hudson, Terranova, Dewar, Hole, Escande

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



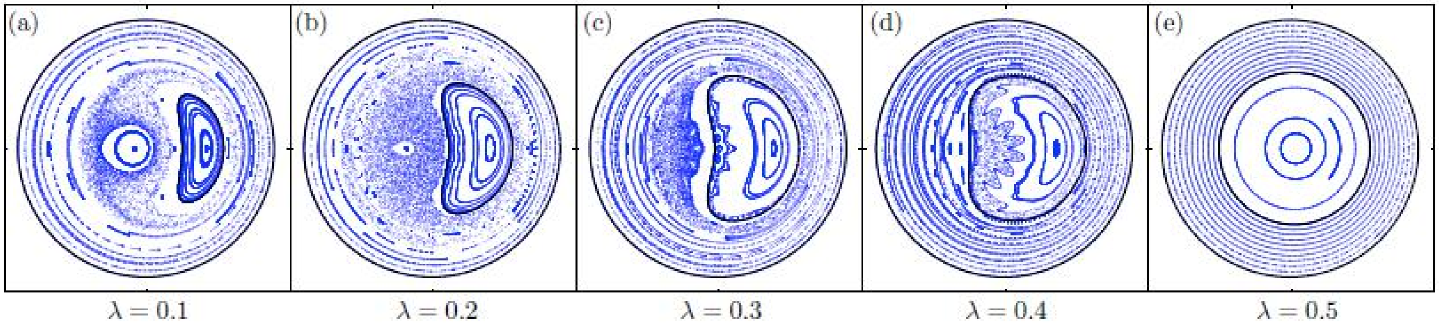
Increasing current

“Experimental” Poincaré plot

[Fig. 6 of P. Martin et al., Nuclear Fusion 49, 104019 (2009)]

- State can be described by a sequence of SPEC solutions, which are in a minimum energy state

[G. R. Dennis *et al* , Phys. Rev. Lett. **111**, 055003, 2013]



Recent progress in MRxMHD

- Related helical bifurcation of a Taylor relaxed state to a tearing mode
  [Z. Yoshida and R. L. Dewar , *J. Phys. A: Math. Theor.* **45**, 365502, 2012]
- Explained spontaneously formed helical states in reverse field Pinch
  [G. R. Dennis, S. R. Hudson, D. Terranova, Franz, Dewar, Hole, PRL. **111**, 055003, 2013]
- Reproduced MHD in infinite interface limit [G. R. Dennis, S. R. Hudson, R. L. Dewar, M. J. Hole, Phys. Plasmas 20, 032509 (2013)]
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  [R. L. Dewar *et al*, Phys. Plas. **20**, 0832901, 2013.]
- Developed techniques to establish pressure jump a surface can support.
  [M. McGann, ANU PhD thesis, 2013]
- Extended MRxMHD to include non-zero plasma flow
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- Extended MRxMHD to include non-zero plasma flow and anisotropy
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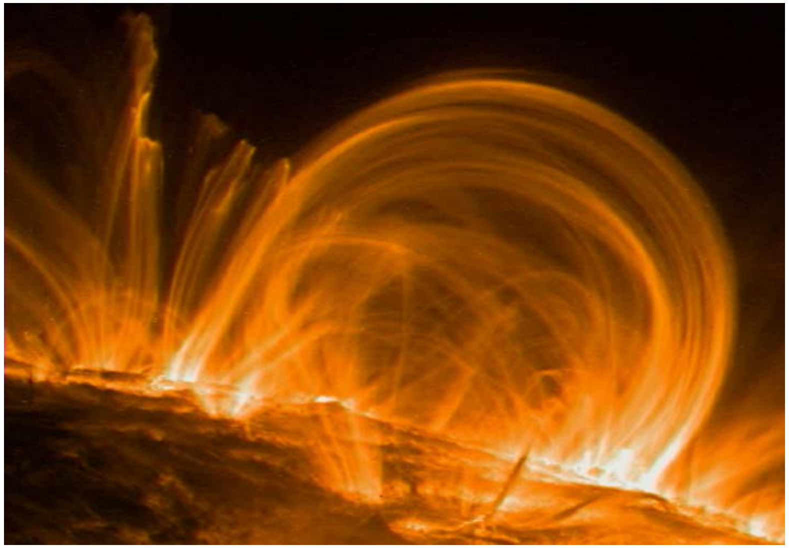
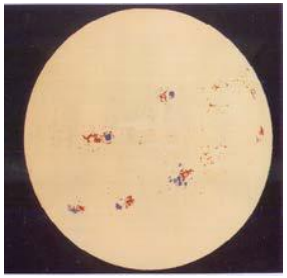
- **Stability of a two-volume MRxMHD model in slab geometry [L. H. Tuen, ANU Masters thesis, 2015]**
- *Stepped transform equilibria: transform everywhere irrational, arbitrary smooth pressure profile, continuously-nested flux surfaces. [Loizu, Hudson et al, Phys. Plas. 22, 090704, 2015]*

MRxMHD *equilibria* of stellar plasmas

- Most coronal solar flare models assume the field is force-free, and adjust the field pitch to match local measurements of the photosphere field footprint. (nonlinear force free fields)
- boundary conditions are line-tied (solar) cf toroidal (fusion)



Solar magnetogram



e.g. Polarization, intensity of radio thermal free-free emission

[*Iwai et al* Earth, Planets and Space, Volume 66:149, 10 pp.]

intensity

circular polarisation

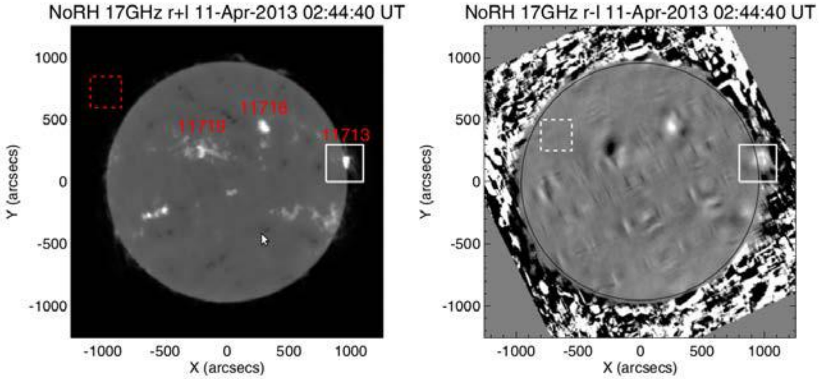


Figure 1 Radio intensity and circularly polarized component observed with NoRH. (Left) Intensity and (right) circularly polarized component of the radio emission at 17 GHz observed with NoRH on 11 April 2013 02:44:40 UT.

Current Sheets: Drivers of Nanoflares and Eruptive Flares in the Solar Corona

- Solar T_{core}~10^6 K, T_{edge}~ 10^4 K, T_{corona} ~10^6 K.

- Parker [E. N. Parker, Astrophys. J. **174**, 499 (1972)] suggested current density in the corona must be surface currents (if volume currents, Ohmic heating can not compensate due to radiation loss)

- Current sheets can release their energy through “nanoflares” (possibly magnetic plasmoids) heating the corona

- Currents sheets mediate fast reconnection during coronal mass ejections, possibly by “breakout model” in which a fully 3D coronal configuration is driven by photospheric footpoint motion to form an extended thin current sheet which becomes violently unstable [S. Antiochos et al , Astrophys. J. **510**, 485, 1999]

Multi-Region Relaxation *Dynamics*

DP170102606 Multi-Region Relaxation Dynamics — a new paradigm for fusion and stellar plasma physics, R. L . Dewar, M. J. Hole, S. R. Hudson; A. Bhattacharjee

Q1) What is the MRxMHD spectrum of normal modes, and what are the effects of field-line curvature and mass flow on their stability?

Q2) When are the MRxMHD current sheets topologically stable towards internal plasmoid formation?

Q3) When do unstable modes saturate at a low level or develop nonlinearly into explosive events?

- compare the effect of toroidal (fusion) and line-tied (solar) boundary conditions on wave spectrum and stability

- Develop codes to treat dynamics in full 3D:
  time-domain evolution code SPDC nonlinear numerical experiments and frequency-domain code SPECN to calculate linear normal modes

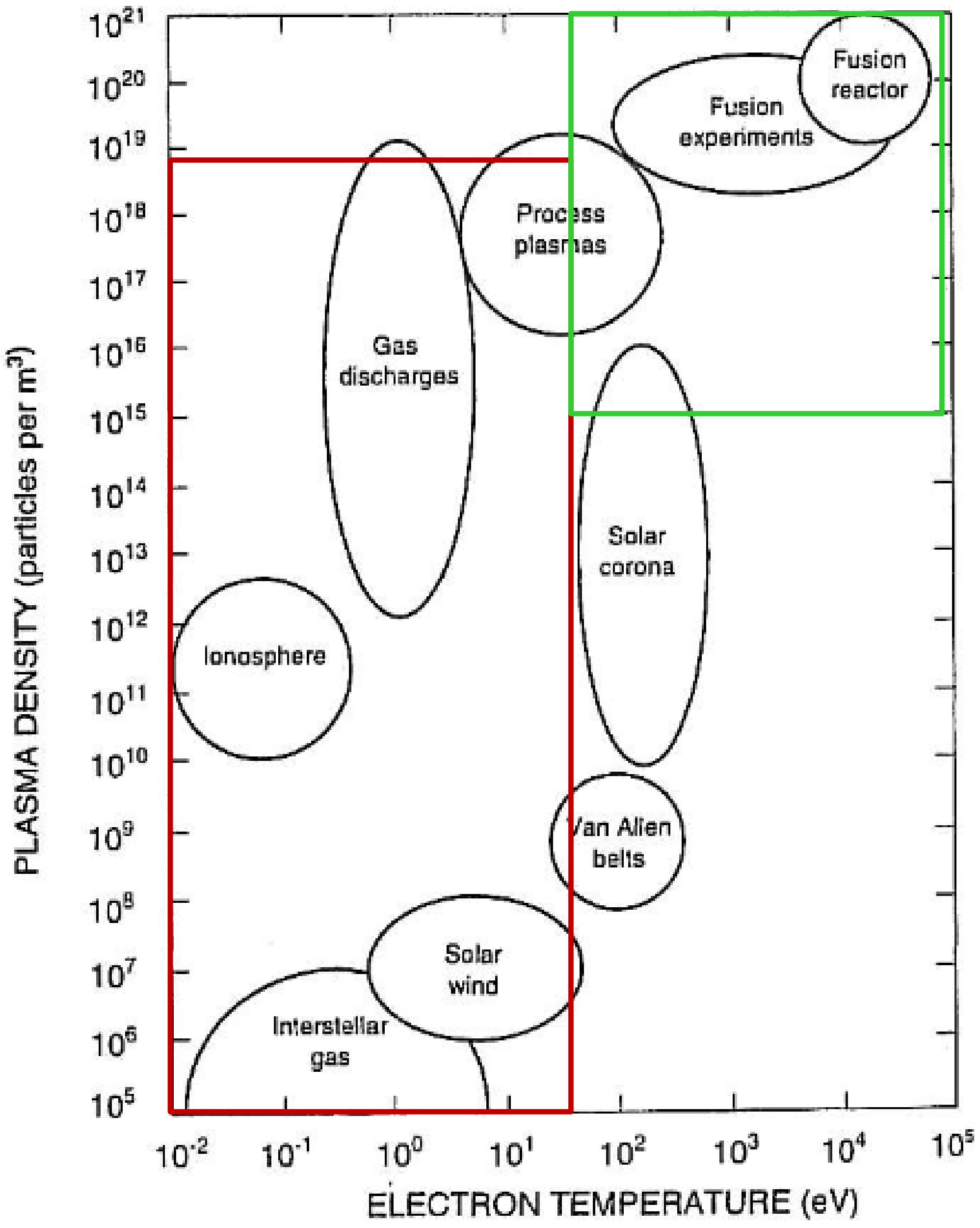
- Comparison of results with experimental and observational data

Some anticipated outcomes…

- Compute helical structure and magnetic islands induced by RMP coils, especially in the edge region. RMP fields are able to suppress ELMS, but there is still no accepted explanation.

- Use of SPECN to find “gap modes” in stellarators, *with* island / chaotic field structure
- Demonstration that a line-tied version of SPDC can simulate dynamics of solar flares,

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

What is *B* for a tokamak, stationary plasma?

$$(1)\quad \mathbf{J}\times\mathbf{B}=\nabla p \Rightarrow \begin{cases} \mathbf{B}\cdot\nabla p = 0 \Rightarrow \text{No pressure gradient along } \mathbf{B} \\ \mathbf{J}\cdot\nabla p = 0 \Rightarrow \text{Current flows within surfaces.} \end{cases}$$

$$(2)\quad \nabla\times\mathbf{B}=\mu_0\,\mathbf{J}$$

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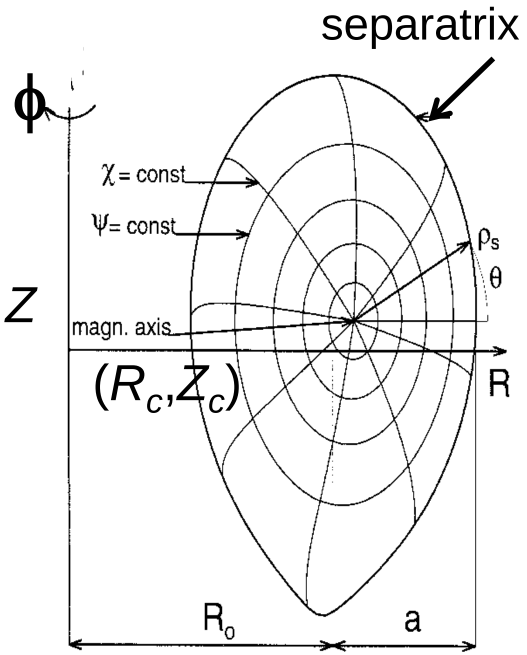

Introduce poloidal magnetic flux function ψ(R,Z) and co-ord. system (*R*, ϕ ,*z*). In axisymmetry Eq. (1), (2) become **Grad-Shafranov equation:**

$$\boxed{\nabla\cdot\frac{1}{R^2}\nabla\psi=-\frac{\mu_0 J_\phi}{R}=-\mu_0 p'(\psi)-\frac{\mu_0^{\;2}}{R^2}f(\psi)f'(\psi)}$$

second order PDE for field and currents.

With *f(ψ)* a toroidal flux function

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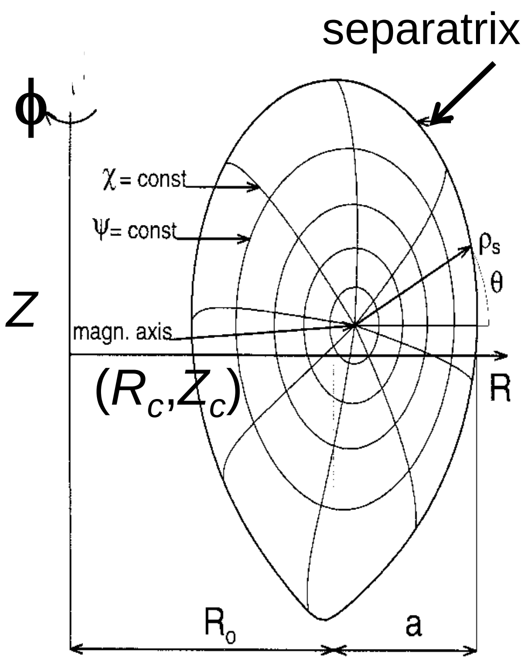

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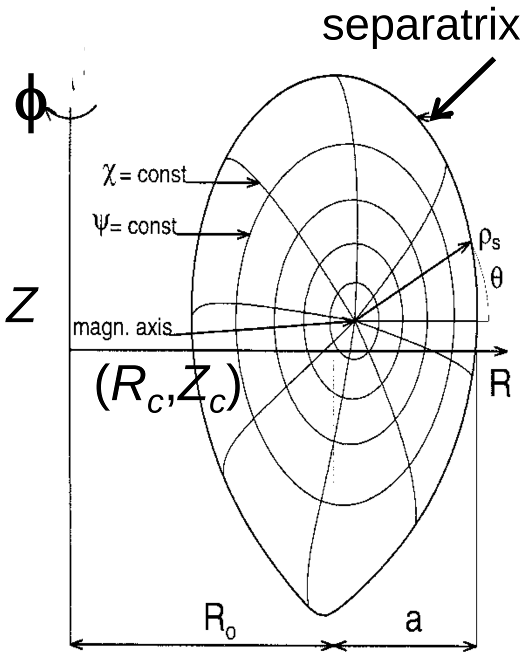

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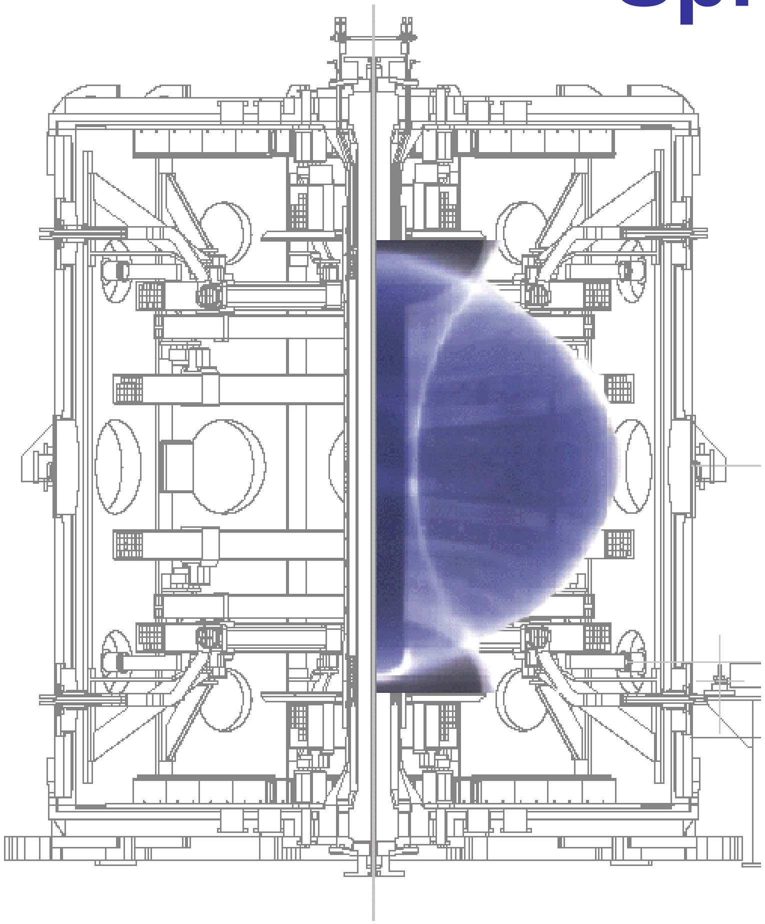
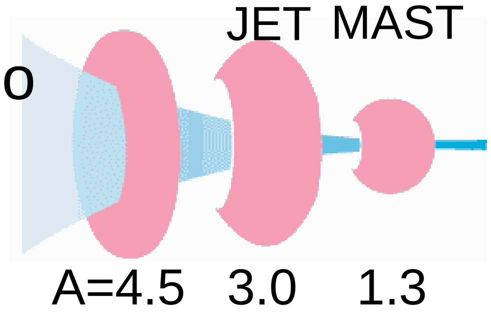
- What is the solution to ψ? *Choose an experiment...*

Mega Ampere Spherical Tokamak



	Achieved
Major Radius	0.85 m
Minor Radius	0.65 m
Aspect Ratio	1.3
Elongation	2.5
Triangularity	0.5
Plasma Current	1.5 MA
Toroidal Field	0.62 T
NBI Heating	3.8 MW
RF Heating	1 MW
Pulse Length	>0.5 sec

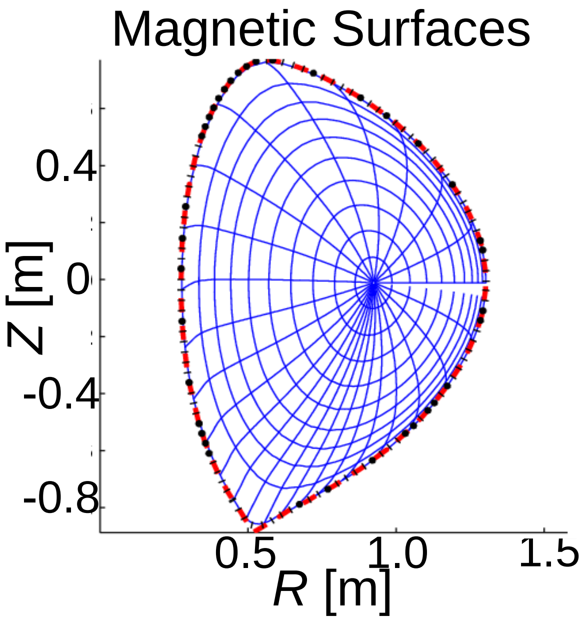
Aspect ratio (A=R/a)

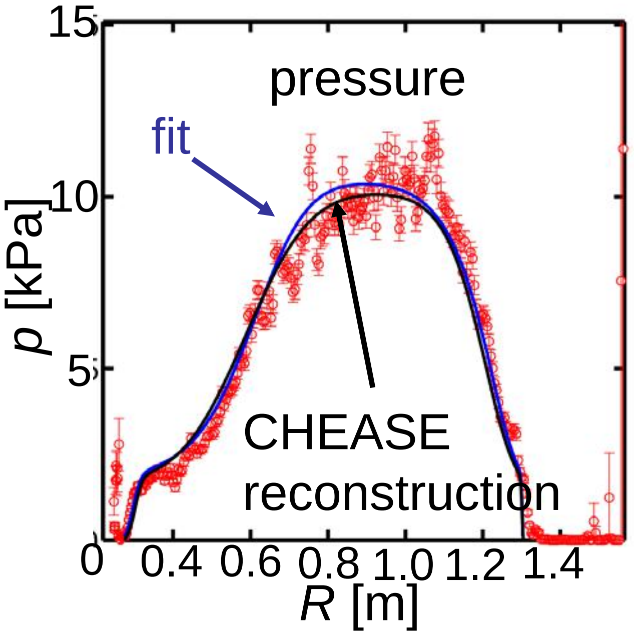


MAST's mission:

- to explore the ST concept
- test low aspect ratio physics to strengthen general tokamak understanding.

“Kinetic” MAST equilibrium

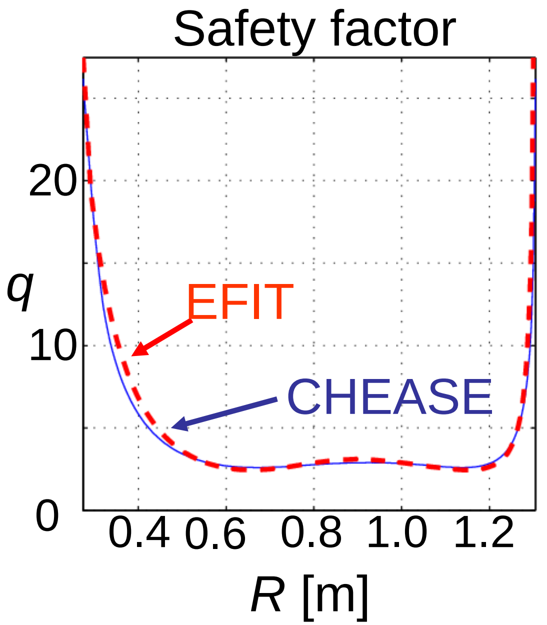


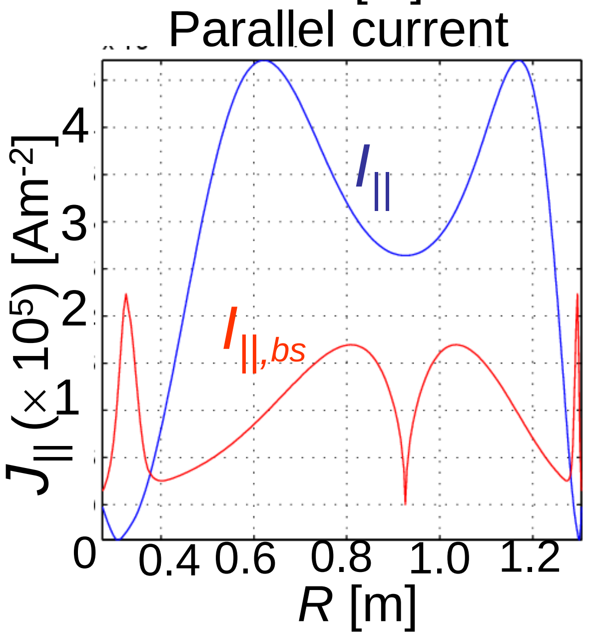


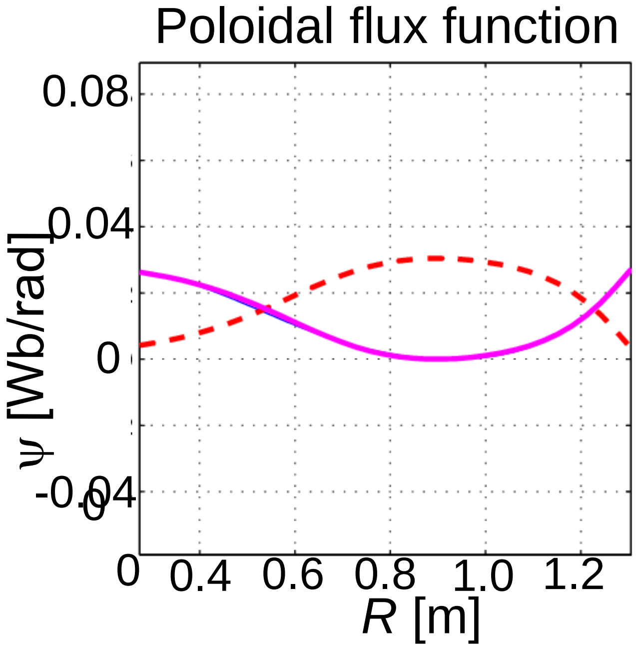
#7085 at 290ms

q_0=2.9, β_N=4.97,
q_{95}=11.69, β_t=5.03,
q_{100}=26.18, I_N=1.01,
l_I=1.00, $p(0)/\langle p\rangle$=1.98,

[M J Hole et al Plasma Phys. Control. Fusion 47 (2005) 581–613]







What is *B* for an accretion disc?

1. MHD/EM equations with gravity

$$\nabla \cdot (\rho \boldsymbol{v}) = 0 \,,$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} \boldsymbol{J} \,,$$

$$\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} = 0 \,,$$

$$\nabla \times \boldsymbol{E} = 0 \,,$$

$$\rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\nabla p + \rho \boldsymbol{g} + \frac{1}{c} \boldsymbol{J} \times \boldsymbol{B} \,,$$

$$\nabla \cdot \boldsymbol{B} = 0 \,,$$

2. Assume toroidal symmetry

$$\boldsymbol{B} = \boldsymbol{B}_p + \boldsymbol{B}_\phi \qquad \boldsymbol{B}_p = \frac{1}{r} \nabla\Psi \times \hat{\boldsymbol{\phi}} \,,$$

$$4\pi\rho \frac{|\boldsymbol{v}_p|}{|\boldsymbol{B}_p|} = F(\Psi) \,, \qquad = r\Omega(\Psi)\hat{\boldsymbol{\phi}} + \frac{F(\Psi)}{4\pi\rho} \boldsymbol{B} \,.$$

3. angular momentum conservation

$$-F(\Psi) r v_\phi + r B_\phi = H(\Psi) \,.$$

4. Energy Flow conservation

$$\int (d\rho/\rho)\Big|_{\Psi = \mathrm{const.}} + \tfrac{1}{2} |\boldsymbol{v}|^2 + \Phi_g - r v_\phi \Omega(\Psi) = J(\Psi) \,,$$

5. Assume flow is adiabatic

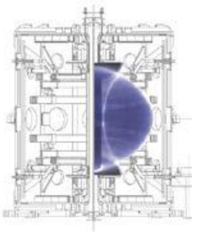
$$S(p, \rho) = k_{\mathrm{B}}(\Gamma - 1)^{-1} \ln(p/\rho^\Gamma) = S(\Psi)$$

6. Generalised, nonrelativistic, **Grad-Shafranov equation**

$$\left(1 - \frac{F^2}{4\pi\rho}\right)\Delta^*\Psi - F\nabla\left(\frac{F}{4\pi\rho}\right) \cdot \nabla\Psi = -4\pi\rho r^2 (J' + r v_\phi \Omega') - (H + r v_\phi F)(H' + r v_\phi F') + 4\pi r^2 p (S'/k_{\mathrm{B}}) \,,$$

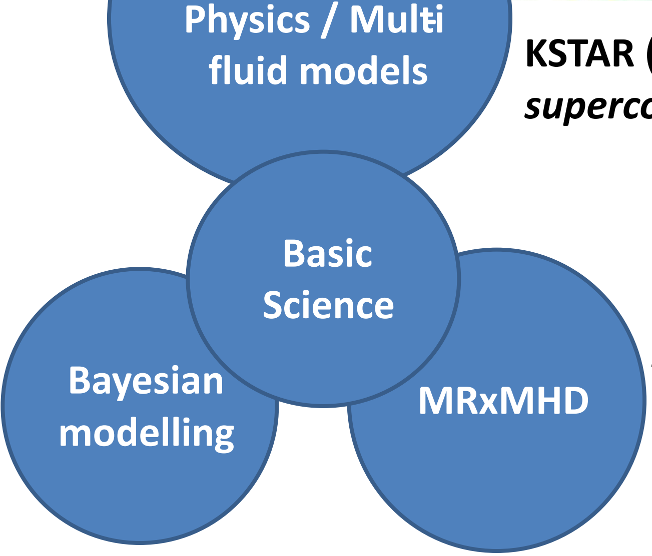
Contopoulos, Lovelace, ApJ, 429:129-152, 1994

ANU Theory and Modelling



MAST (UK)
compact

Local experiments

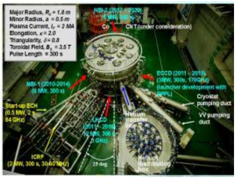


Burning Plasma Physics / Multi fluid models

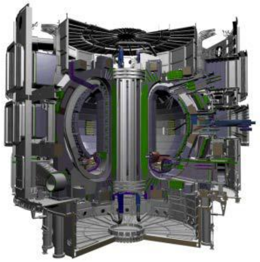
Basic Science

Bayesian modelling

MRxMHD



KSTAR (Korea)
superconducting



ITER (Earth)
ITPA

CCFE
CULHAM CENTRE FOR FUSION ENERGY

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

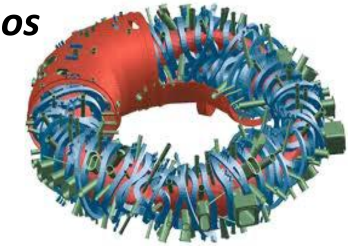
IPP Max-Planck-Institut für Plasmaphysik

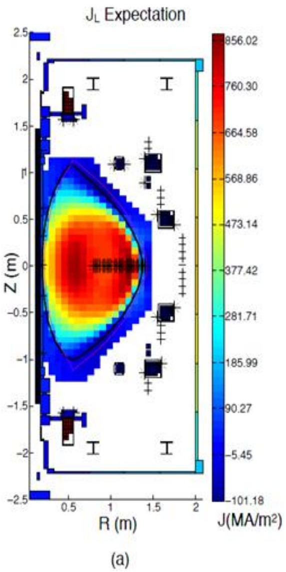
NFRI
국가핵융합연구소
National Fusion Research Institute

THE UNIVERSITY OF TEXAS AT AUSTIN

CONSORZIO RFX

W-7X (Germany)
steady-state, reduced chaos





RFX-mod (Italy)
self-organising

Stellar dynamics

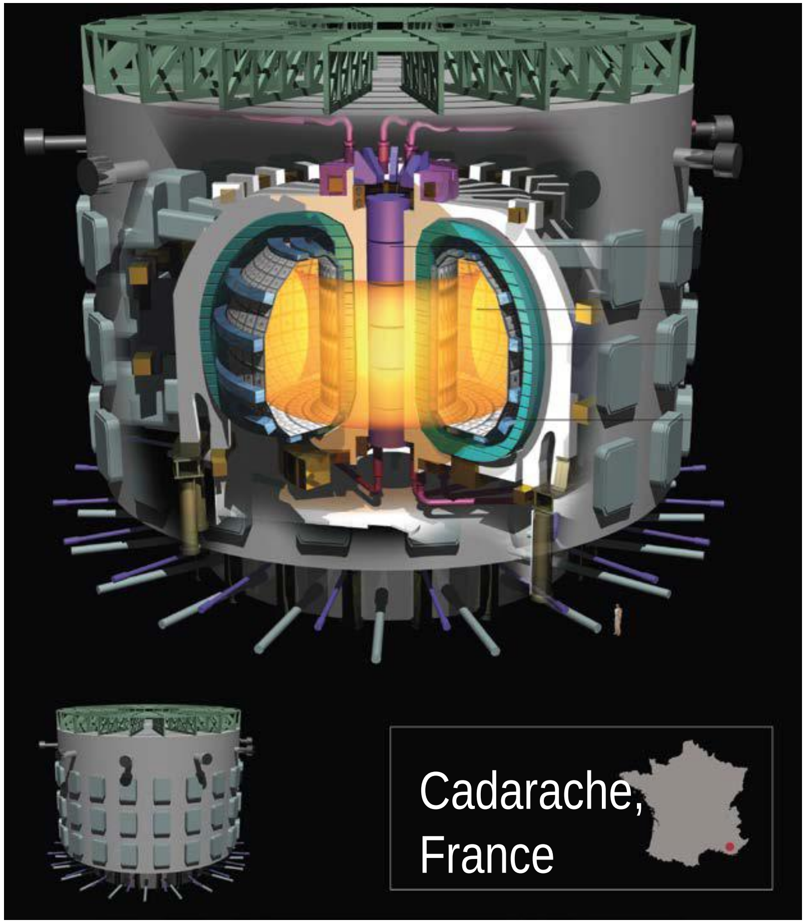
- Supported by ~$2.5m in funding over last 8 years (ARC, ISL)

Australian ITER Forum

- January, 2005. Formation of Australian ITER Forum at AIP Congress with objectives
  1. To promote an Australian involvement in ITER and articulate the benefits to Australia
  2. To promote the science of fusion energy.
  3. To advance the recognition of fusion science and plasma physics in the wider scientific community.

fusion.ainse.edu.au

ITER



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

- Growing Consortium

- Collaboration agreements with
  - ➢International Atomic Energy Agency
  - ➢CERN – world's largest accelerator
  - ➢Principality of Monaco
  - ➢Australia 30/09/2017
  - ➢*Iran (4 July 2016, High-level Iranian delegation visits ITER worksite)*

Construction +10 year operation cost ~$20 billion

Australian Fusion Science Strategic plan: "Powering Ahead" launched 10/07/2014

Powering Ahead

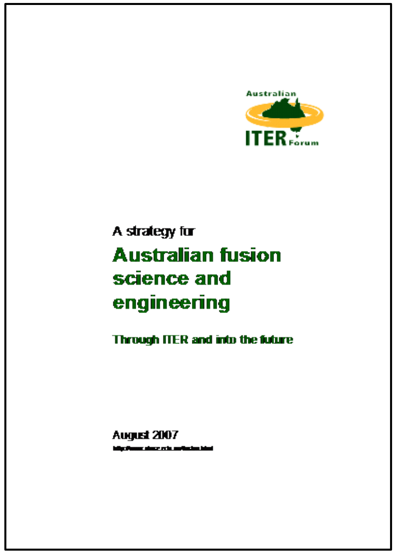
A National Response to the Rise of the International Fusion Power Program

"The problem I hope scientists will have solved by the end of the century is nuclear fusion. It would provide an inexhaustible supply of energy without pollution or global warming."

Stephen Hawking

Co-released by Australian ITER Forum, ANU, and ANSTO

Building on the success of the first fusion strategy, ***A Strategy for Australian Fusion Science and Engineering: Through ITER and into the Future*** (2007)



Australian ITER Forum

A strategy for

Australian fusion science and engineering

Through ITER and into the future

August 2007

Advisory committee

Dr Richard Garrett, ANSTO

Dr Barry Green, UWA (formerly ITER design team)

Em/Prof John Howard, ANU

A/Prof Matthew Hole, ANU

A/Prof Brian James, Univ Sydney (coordinator)

Prof John O'Connor, Univ Newcastle

Key recommendations

(1) That the Australian government supports a national fusion program that would provide:

- **A fusion program fellowships scheme – supporting ITPA**, stellarator physics and advanced materials
- **Funding for an Australian flagship contribution to ITER**
- Ongoing support for the Australian Plasma Fusion Research Facility
- **High-power enhancements to the MagPIE device**
- Support for ITER engagement through the ITER research program of the International Tokamak Physics Activity (ITPA)

(2) That the Australian fusion science community through ANSTO establishes a Memorandum of Understanding with the ITER to formally enable Australian participation in ITER and the ITPA.

- ✓ Cooperation agreement between ANSTO / ITER enabling collaboration and ITPA participation signed 30 Sep., 2016

International Tokamak Physics Activity

- ITPA is a framework for internationally coordinated fusion research.
- operates under the auspices of ITER.
- the participants in the ITPA are the members of ITER.
- 7 topical groups:

DIAGNOTICS: address issues that might arise both in plasma control and in the analysis of ITER plasmas and in reactor grade plasmas (e.g. DEMO)

ENERGETIC PARTICLE PHYSICS: tackle the qualitatively new physics element of ITER: dominant alpha particle heating.

INTEGRATED OPERATION SCENARIOS: establish operational scenarios in burning plasma experiments

MHD, DISRUPTIONS & CONTROL: establish β-limiting MHD instability thresholds and their active control; address disruption mitigation

PEDESTAL & EDGE PHYSICS: improve understanding of pedestal, focus on H-modes and suppression of ELMs

SCRAPE-OFF-LAYER & DIVERTOR: plasma-material interactions and their dependence on materials, hydrogen isotope recycling and their storage

TRANSPORT & CONFINEMENT develop a fundamental understanding of transport and confinement physics governing plasma performance,

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
  - Fully 3D toroidal physics and MRxMHD.
    Impacts of 3D structure on plasma.
    Dynamics of MRxMHD plasmas,
    linkage to solar and toroidal fusion plasmas
  - *Bayesian inference of configurations*
    Bayesian inference (inversion) for fast particle velocity distribution
  - Interpretation/modelling of international and domestic experiments
  - *Not mentioned… wakefield accelerator physics, ELM statistics*
- Research synergies identified with ITER and ITPA. These align with Australian strategic planning for fusion science.

“CSIRO child care 2017 aims…”

Black Mountain Laboratory, CSIRO Care

17/11/2016

A	Acknowledging theorists
I	Interpersonal relationships
M	Managing performance and mentoring