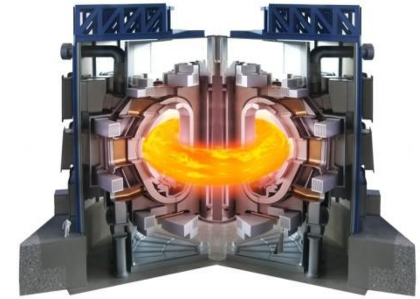
me

Australian National University



The physics of cold to burning plasmas

Plasma Theory and Modelling group academics

me

M. J. Hole,

R. L. Dewar, G. von Nessi, M. Fitzgerald, G. Dennis,

L. Chang, J. Bertram, (G. Bowden, Z. Qu, S. Cox, C. Callan, C. Bowie, M. McGann),

L. Appel[1], B. Breizman[2], R. Dendy[1], S. Hudson[3], J. Kim[4], A. Koenies[5], K. McClements[1], S. Sharapov[1], J. Svensson[5], D. Terranova[6]

B. D. Blackwell, C. Corr, J. Caneses, S. R. Haskey, J. Howard

students

RSPE Seminar, 18 April 2013

Acknowledgement: Australian Research Council, ANU, DIISRTE

1 CCFE CULHAM CENTRE FOR FUSION ENERGY

2

3 PPPL PRINCETON PLASMA PHYSICS LABORATORY

4 NFRI 국가핵융합연구소 National Fusion Research Institute

The physics of cold to burning plasmas

5 CONSORZIO RFX Ricerca Formazione Innovazione

6 IPP Max-Planck-Institut für Plasmaphysik

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International collaborators

RSPE collaborators

The Australian Plasma Fusion Research Facility

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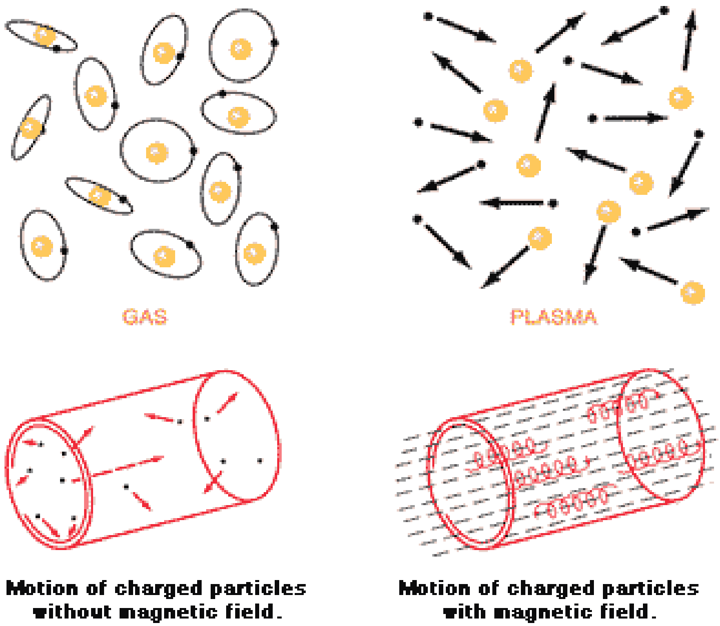
The plasma state : the fourth state of matter

- plasma is an ionized gas



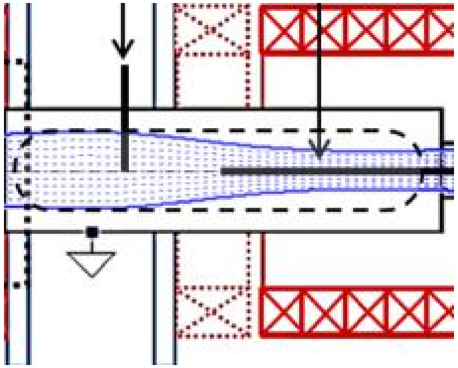
A Galaxy of Fusion Reactors.

- 99.9% of the visible universe is in a plasma state

Inner region of the M100 Galaxy in the Virgo Cluster, imaged with the Hubble Space Telescope Planetary Camera at full resolution.

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

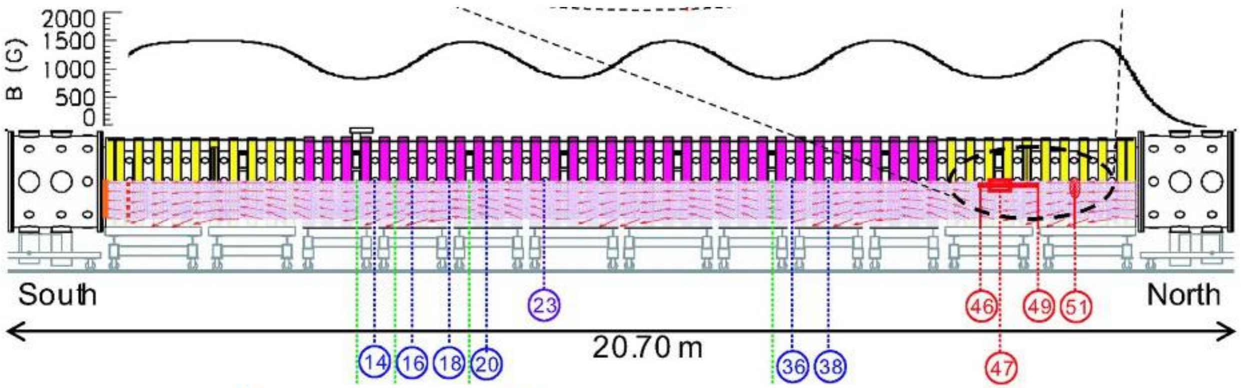
Magnetic confinement

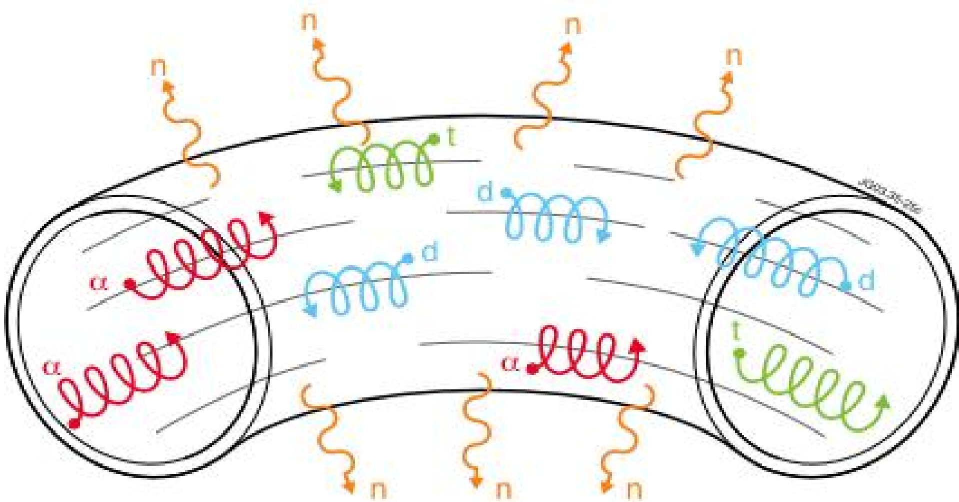


Focused target field, e.g. MAGPIE

[Blackwell *et al* 2012 *Plasma Sources Sci. Technol.* **21** 055033]

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

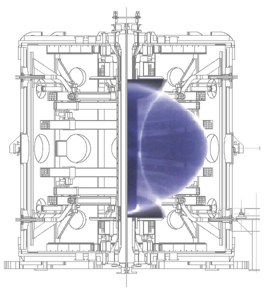




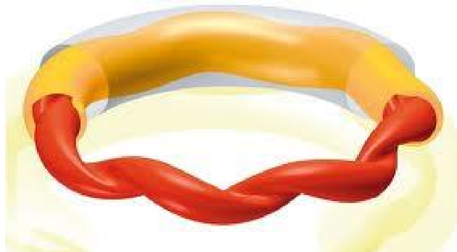
Toroidal Magnetic confinement

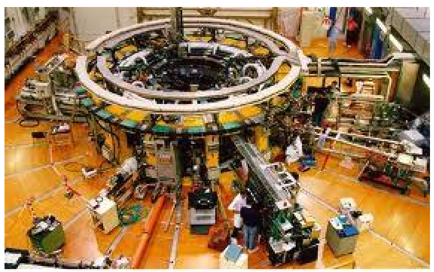
- Ions (D+, T+, He+…) confined
- Neutrons escape
- Toroidal (ring shaped) device

Several toroidal confinement concepts

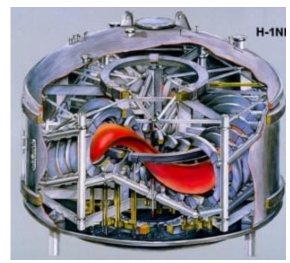


MAST (UK)
compact

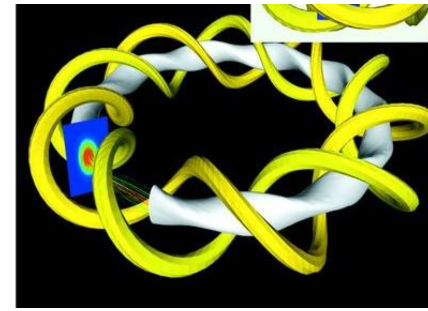




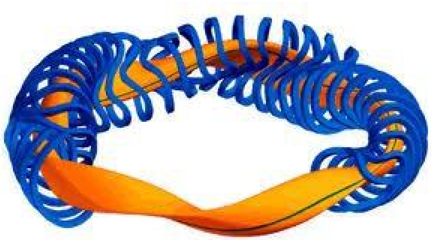
RFX-mod (Italy)
self-organising

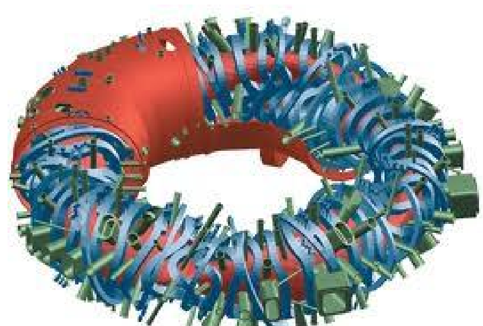


H1-MNRF (Oz)
flexible shape



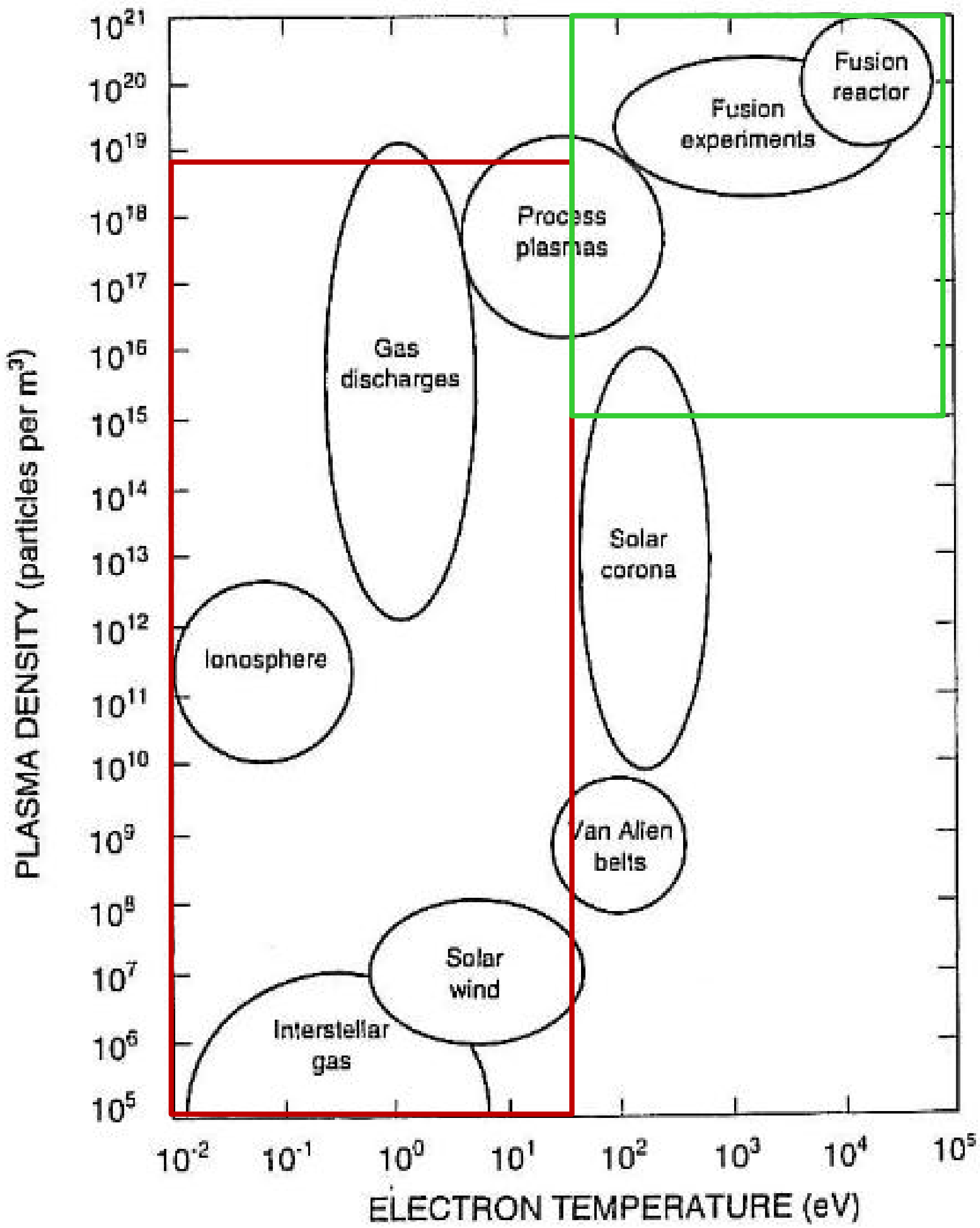
LHD (Japan)
steady-state





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

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0 \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \frac{\partial \mathbf{D}}{\partial t}$$

What is dispersion relation for a cold plasma with $\mathbf{B_0}$, $\mathbf{E_0}$=0, $\mathbf{v_0}$=0?

- Gauss's law requires charge neutrality $\rho = 0 = \sum_s q_s n_s$
- Solve momentum equation

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

for wave field $\mathbf{v_1}$. Gives $\mathbf{J}=n_0\, q\, \mathbf{v_1}$, and construct $\boldsymbol{\varepsilon}$ s.t. $\mathbf{D} = \boldsymbol{\varepsilon}\, \mathbf{E}$

- Rearrange Gauss's law, Amperes law to give $\nabla \times \nabla \times \mathbf{E} = \frac{\omega^2}{c^2} \boldsymbol{\varepsilon} \cdot \mathbf{E}$
- Search for wave like solutions $\mathbf{E} = |\mathbf{E}(\mathbf{x})| \exp\left[i\left(\mathbf{k}\cdot\mathbf{x} - \omega t\right)\right]$ giving dispersion relation $\omega(\mathbf{k})$

or… Magnetohydrodynamics (MHD)

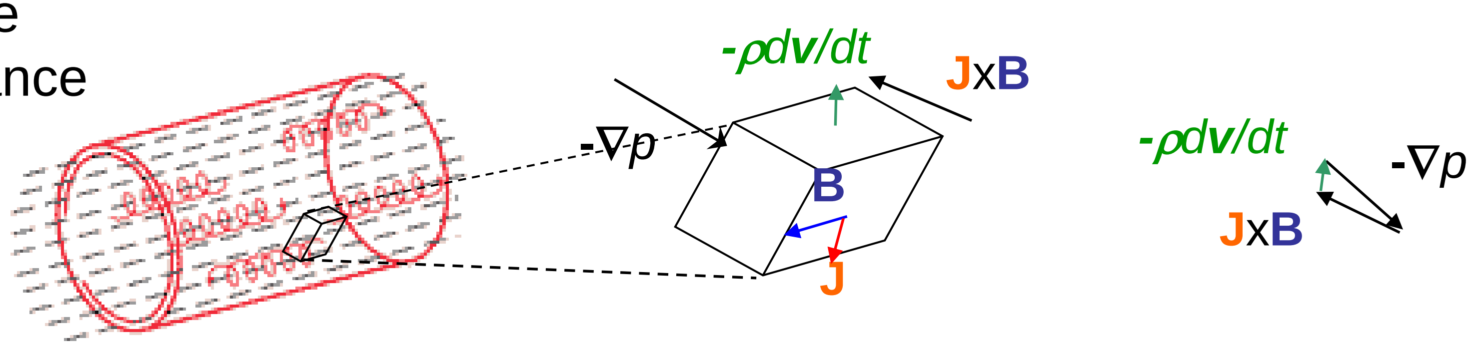
- Single conducting fluid: $\mathbf{J} = n_i Ze\mathbf{v_i} - n_e e\mathbf{v_e}$ $\qquad \rho \approx m_i n_i$

  $\mathbf{v} = \left(m_i \mathbf{v_i} + m_e \mathbf{v}_e\right)/\rho \approx \mathbf{v_i} \qquad p = p_i + p_e$

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

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

force balance



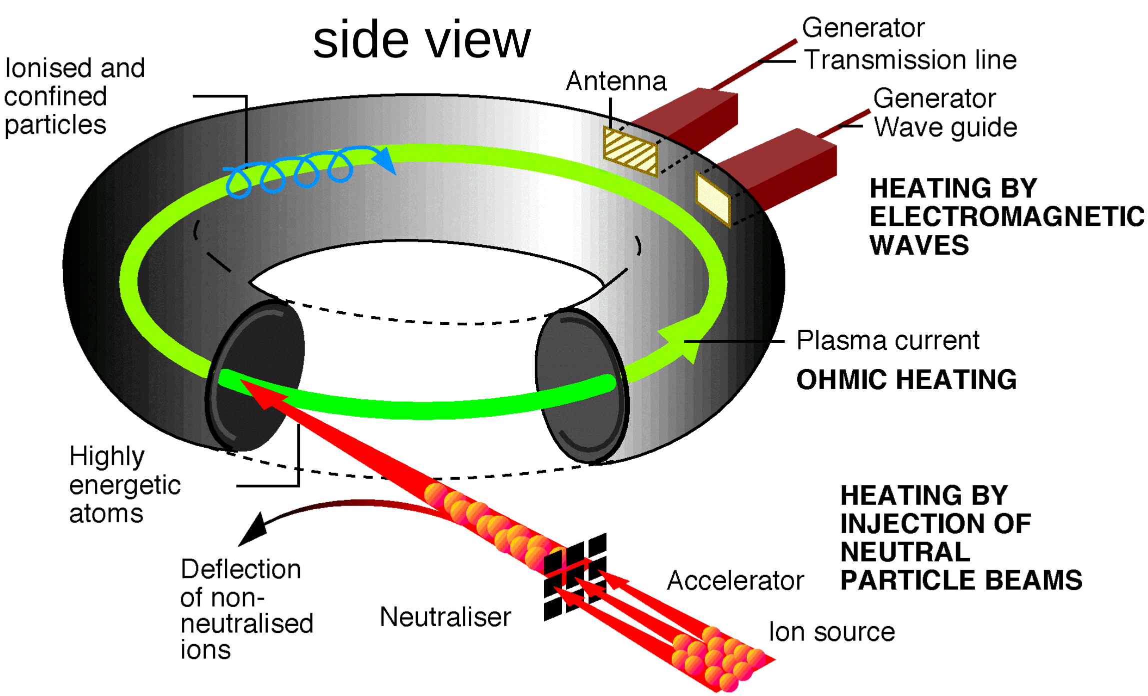
If d**v**/dt = 0 ⇒ $\mathbf{J} \times \mathbf{B} = \nabla p$

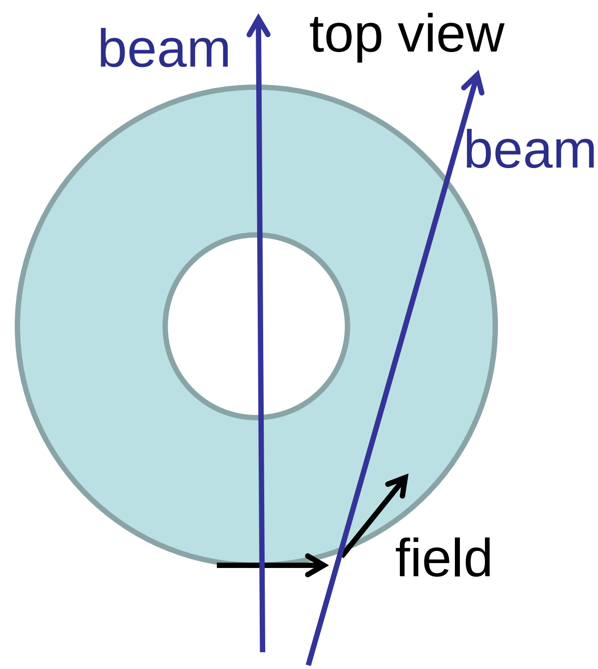
- Generalised Ohm's law: $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$

- Maxwells equations, Adiabatic equation: $\dfrac{p}{\rho^{\gamma}} = \text{const.},$

“MHD with anisotropy in velocity, pressure”

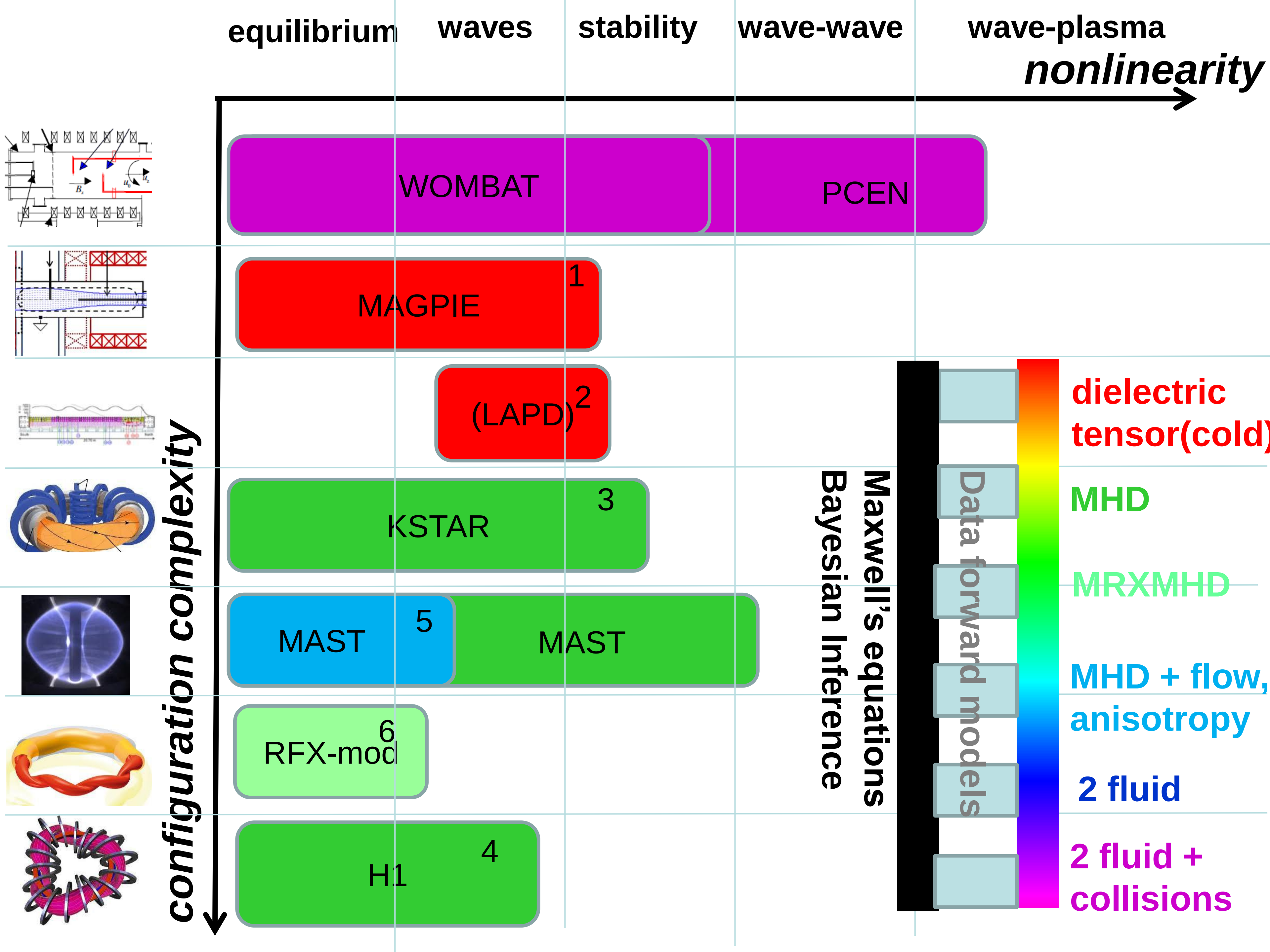
- Pressure different parallel and perpendicular to field due mainly to *directed* neutral beam injection

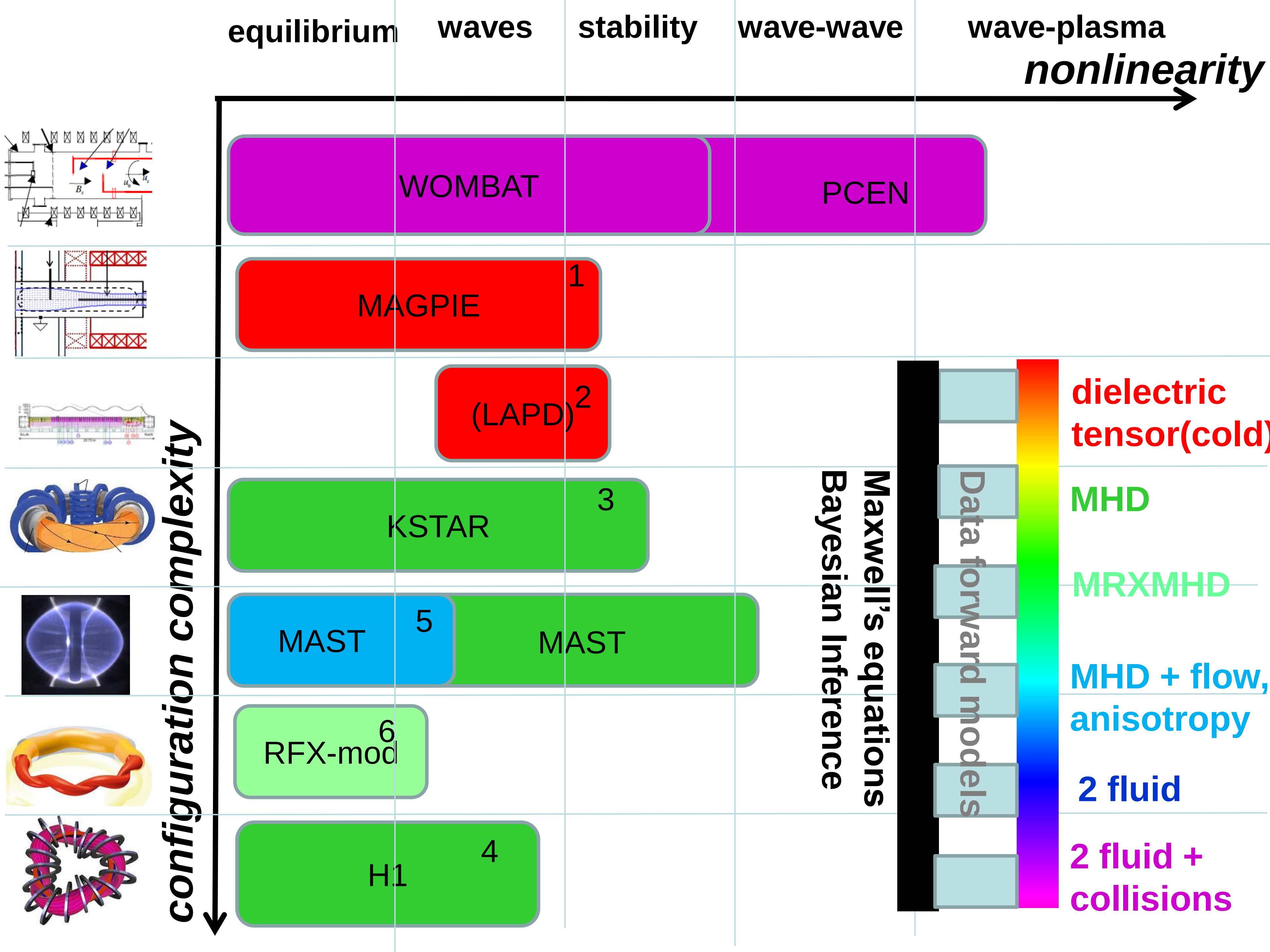




$\Rightarrow$ Pressure is a tensor $\quad \overline{\mathbf{P}} = p_{\perp}\overline{\mathbf{I}} + \Delta\mathbf{BB}/\mu_0 , \qquad \Delta = \dfrac{\mu_0\left(p_{\parallel} - p_{\perp}\right)}{B^2}$

- Momentum $$\boxed{\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \left(\mathbf{v}\cdot\nabla\right)\cdot\mathbf{v}\right) = -\nabla\cdot\overline{\mathbf{P}} + \mathbf{J}\times\mathbf{B}}$$


equilibrium
waves
stability
wave-wave
wave-plasma
nonlinearity
WOMBAT
PCEN
MAGPIE
1
(LAPD)
2
KSTAR
3
MAST
5
MAST
RFX-mod
6
H1
4
configuration complexity
Maxwell's equations
Bayesian Inference
Data forward models
dielectric
tensor(cold)
MHD
MRXMHD
MHD + flow,
anisotropy
2 fluid
2 fluid +
collisions



equilibrium
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H1
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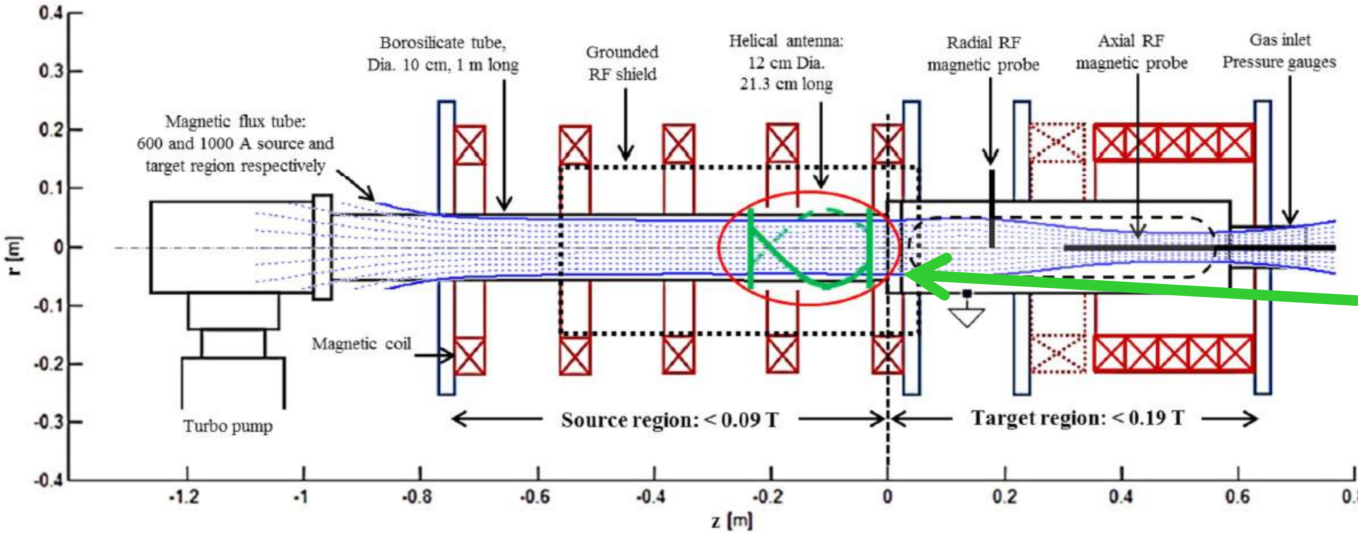
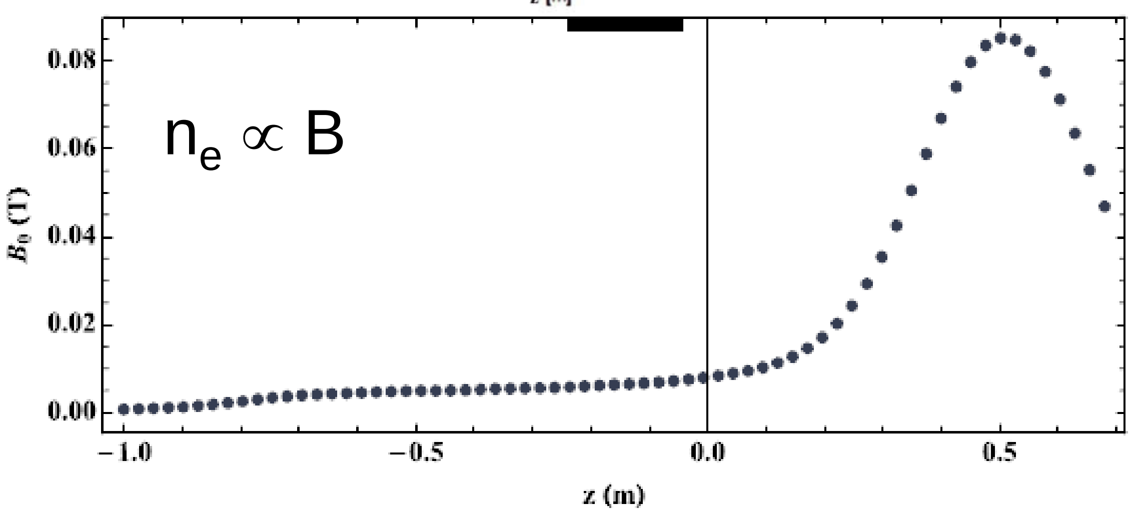
Bayesian Inference
Maxwell's equations
Data forward models
dielectric tensor(cold)
MHD
MRXMHD
MHD + flow, anisotropy
2 fluid
2 fluid + collisions

Helicon wave fields

Chang , Hole, Caneses,, Chen, Blackwell, Corr



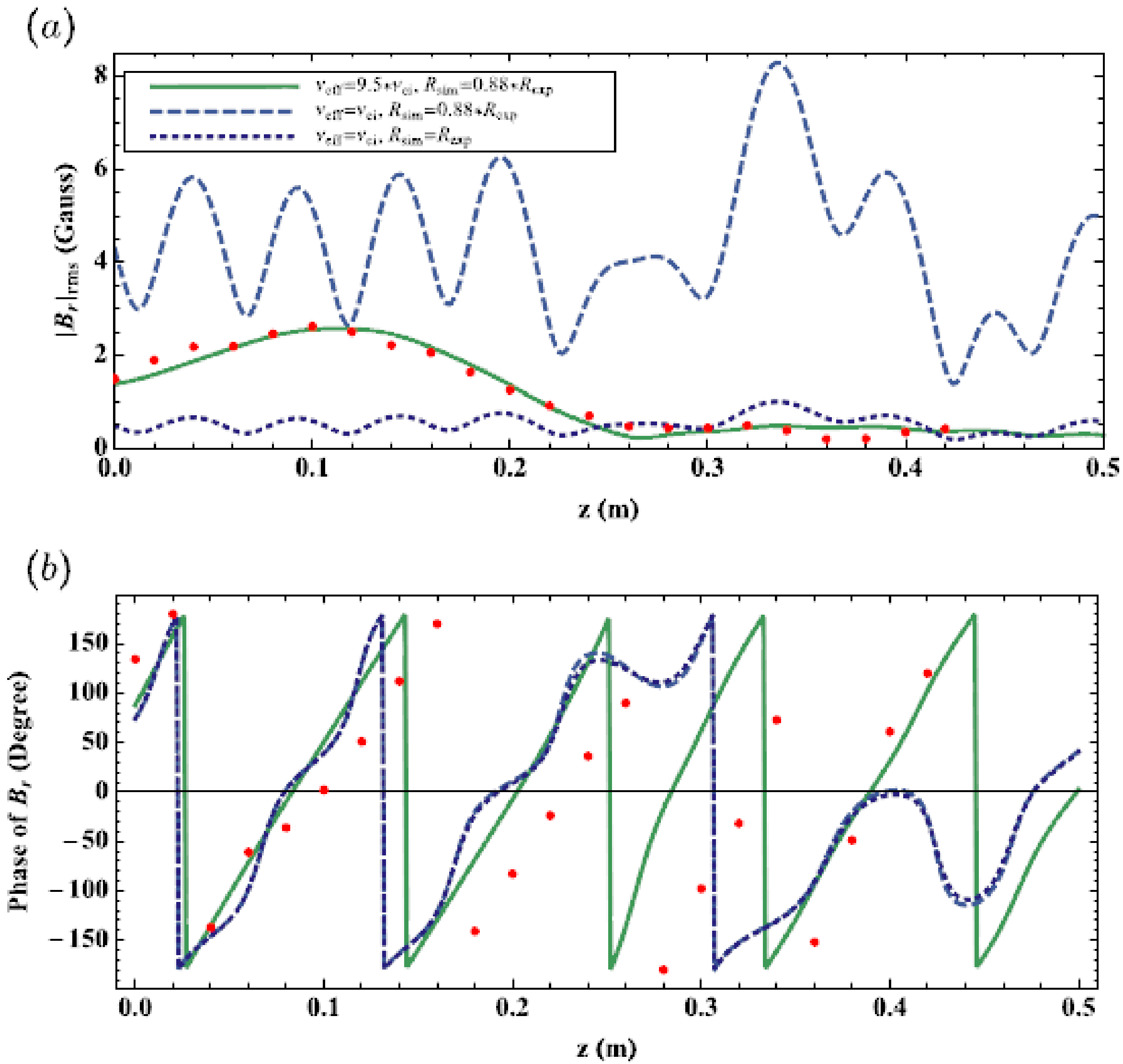
- Helical antenna generates plasma.



What are predicted wave fields?

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 ∠B(z) with enhancement in collision frequency to ~9.5 (ion-acoustic turbulence?)

[Chang et al Phys. Plas. 19, 083511 (2012)]

Modulation in B introduces mode gaps

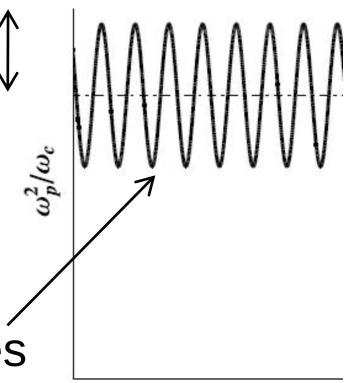
Chang, Breizman, Hole

- Helicon mode eigenfunction equation ⇔ continuous modes

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

- Apply periodic modulation to axial velocity through axial field

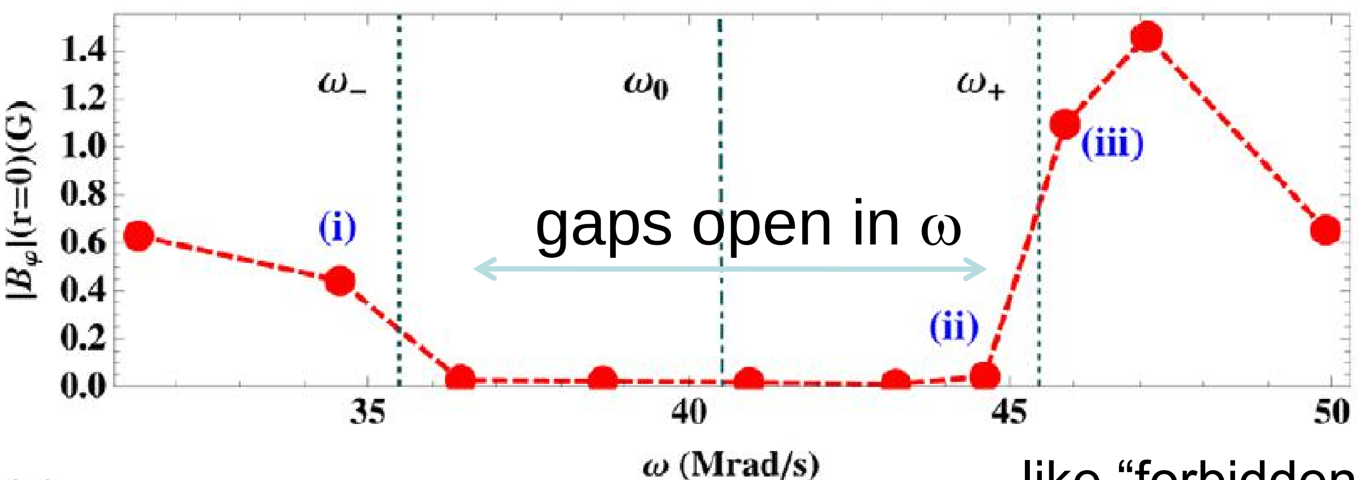
ε



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

modulation strength parameter

number of field ripples

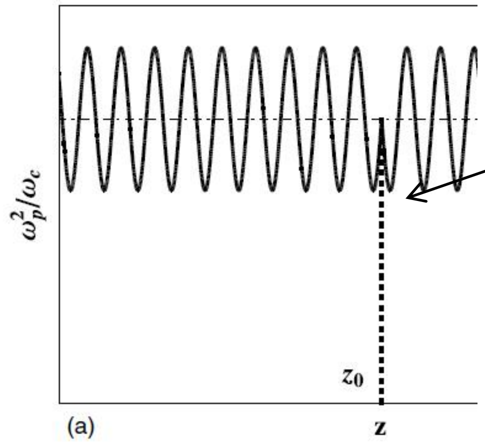


… like “forbidden frequencies”

Broken periodicity introduces gap modes

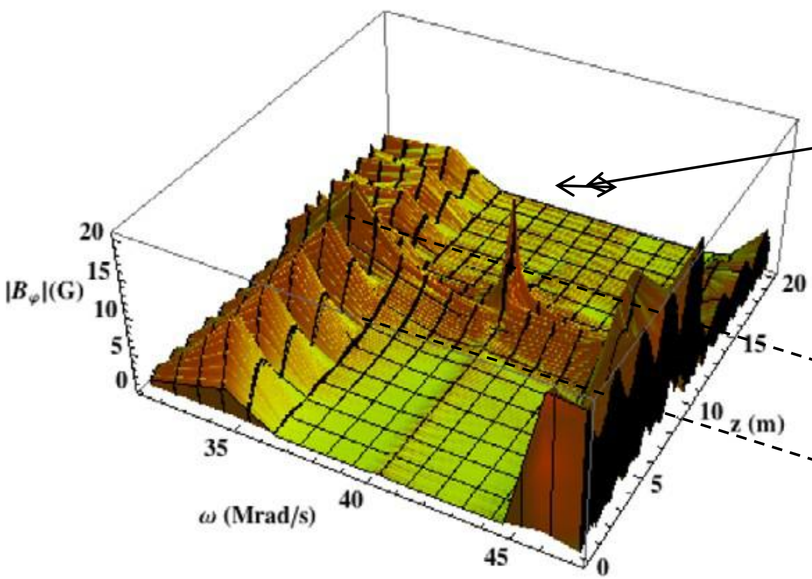
Chang, Breizman, Hole

- Introduce defect into periodicity



Conducting end plate: $E_{\vartheta}(r; z_0) = 0$

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



gap mode frequency

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

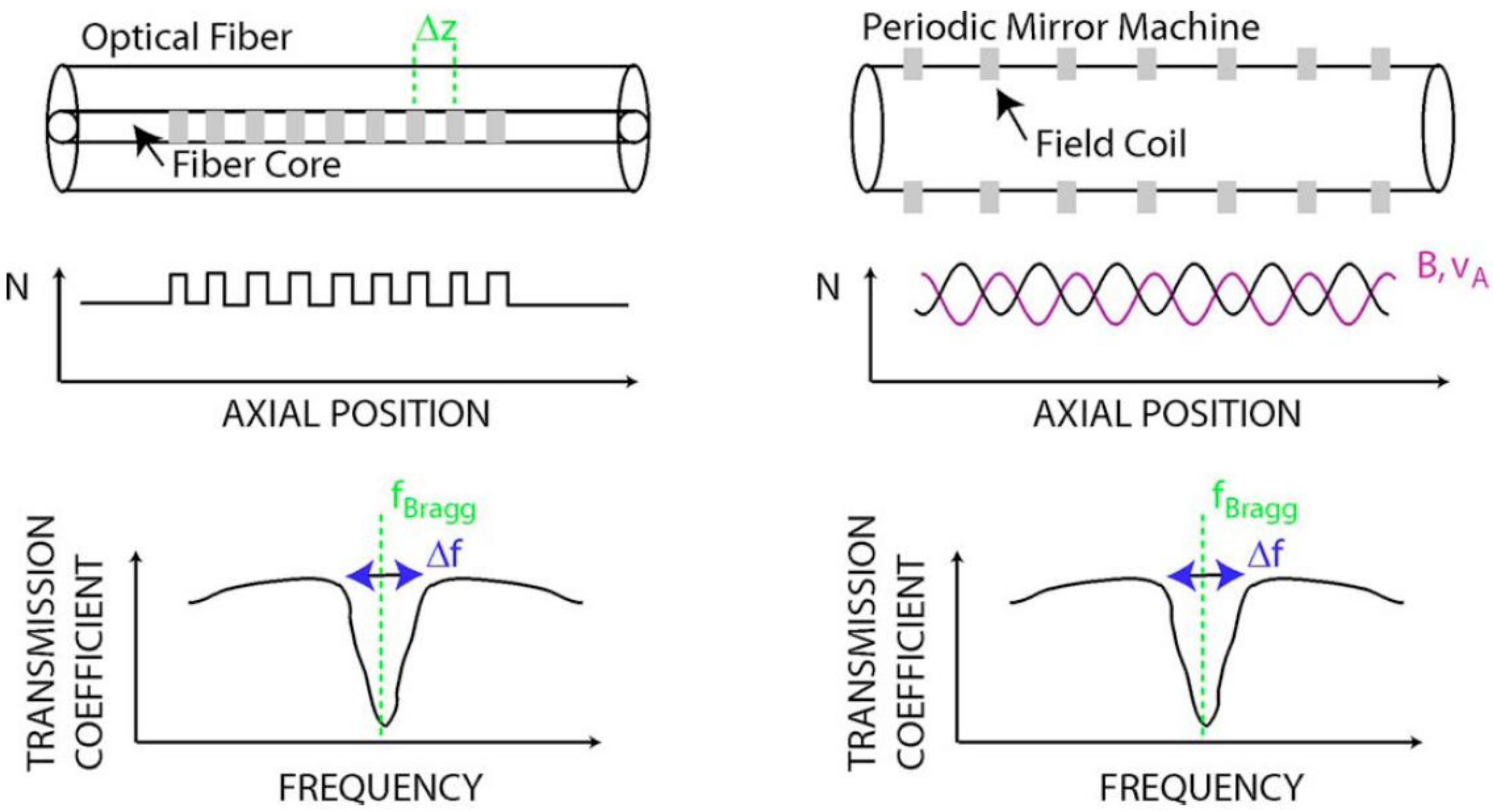
mode gap length

$$\lambda = \frac{\varepsilon}{8} q \sin qz_0$$

[Chang, Breizman, Hole, Plasma Phys. Control. Fusion 55 (2013) 025003]

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)



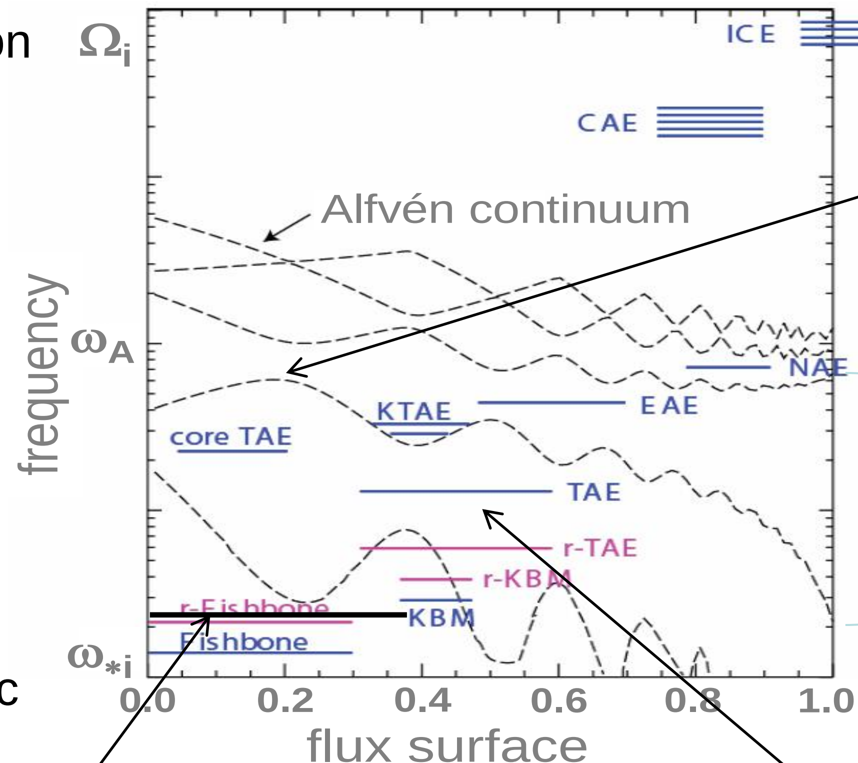
Gap modes also present in Tokamaks

- A zoo of gaps and gap modes

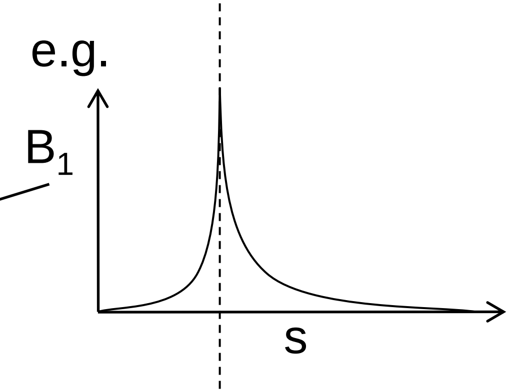
Ion cyclotron frequency

Alfven frequency

Thermal diamagnetic frequency



(radial coordinate)



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

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

Toroidial Alfven Eigenmode

[Spectrum of n=3 resonant singular frequencies Heidbrink Phys. Plasmas, Vol. 9, No. 5, May 2002]

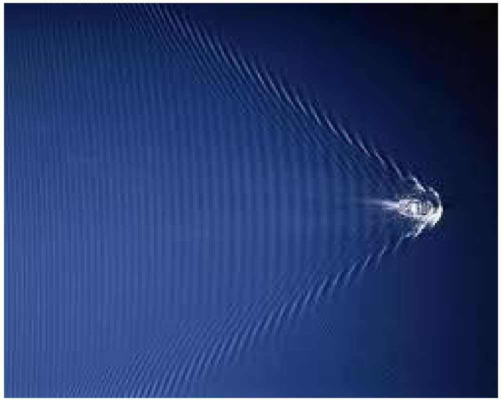
Who cares?… the impact of gap modes

- Alfvén eigenmodes are driven by wave-particle resonance.

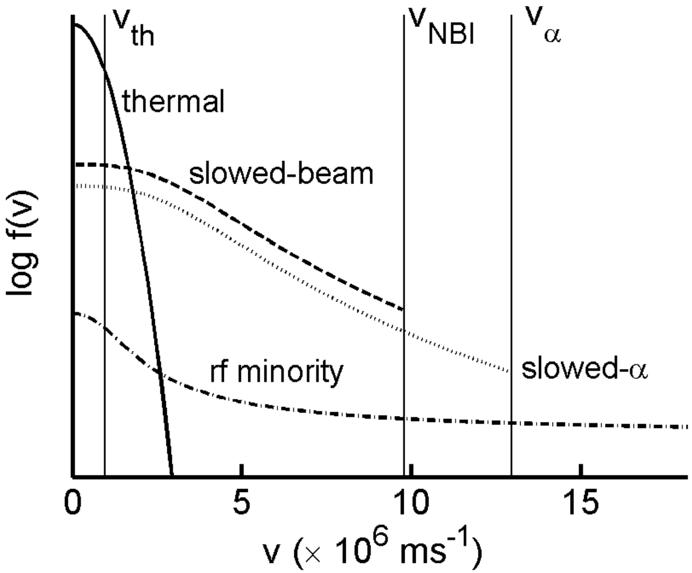
e.g. Wave-particle resonance

Surfer rides wave

Boat drives waves



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



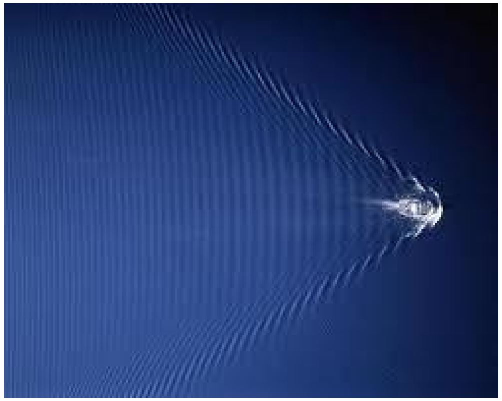
Who cares?… the impact of gap modes

- Alfvén eigenmodes are driven by wave-particle resonance.

e.g. Wave-particle resonance

Surfer gets dumped

Boat drives waves



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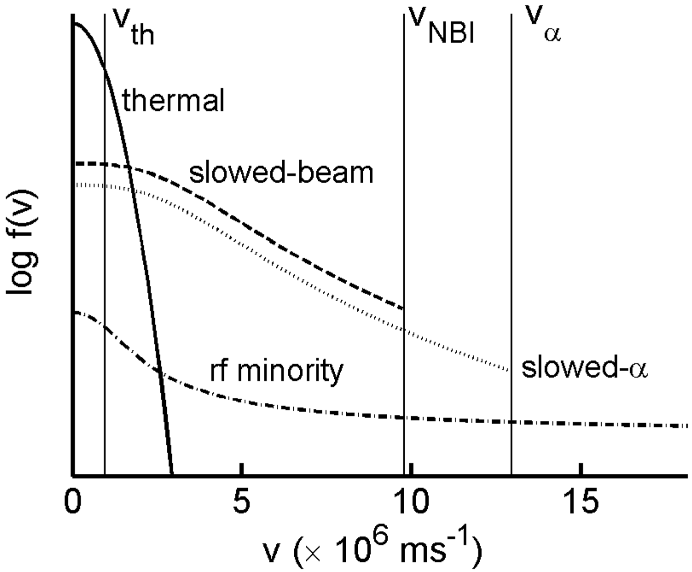
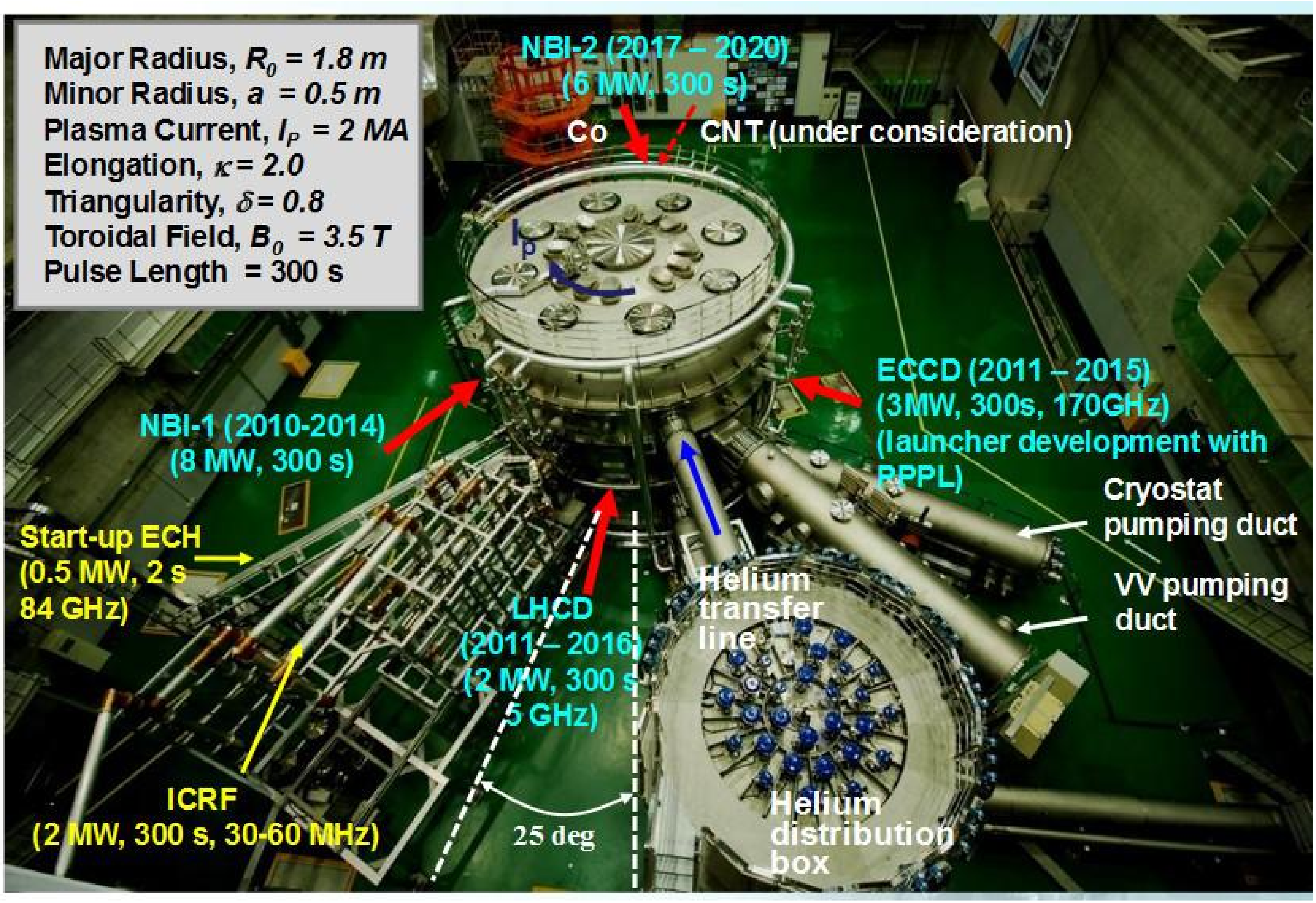


- At large amplitude, Alfven eigenmodes can eject the driving particles from confinement, damaging wall and extinguishing collisional heating

KSTAR

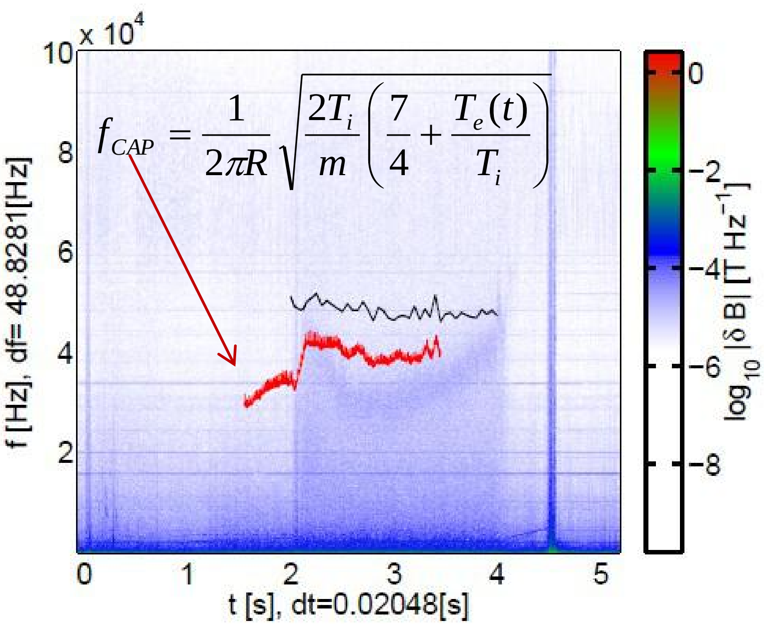
- KSTAR, a new ~$300m superconducting long pulse tokamak
- MOU between ANU and KSTAR



Suspected BAE mode activity in KSTAR

Hole, Ryu, Woo, Bak, Sharapov, Fitzgerald

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



Although ions have $v_{||} < v_A$ they can drive the mode through side band resonances

$v_A/3$, $v_A/5$, $v_A/7$

Suspected BAE mode activity in KSTAR

Hole, Ryu, Woo, Bak, Sharapov, Fitzgerald

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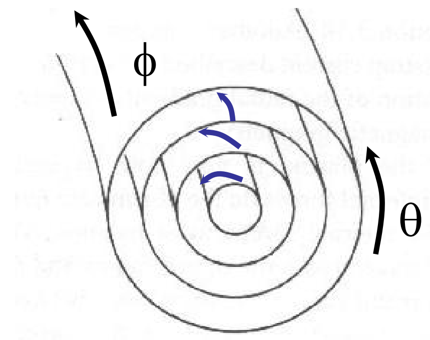
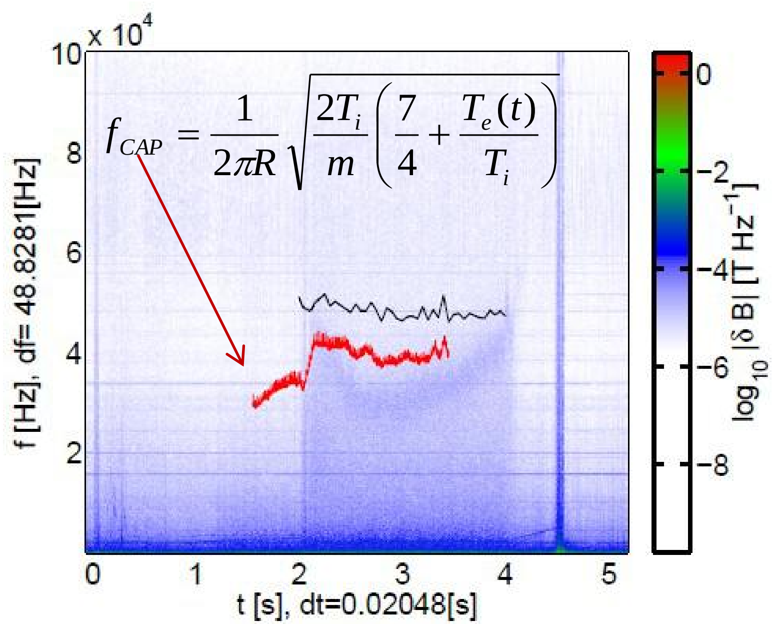
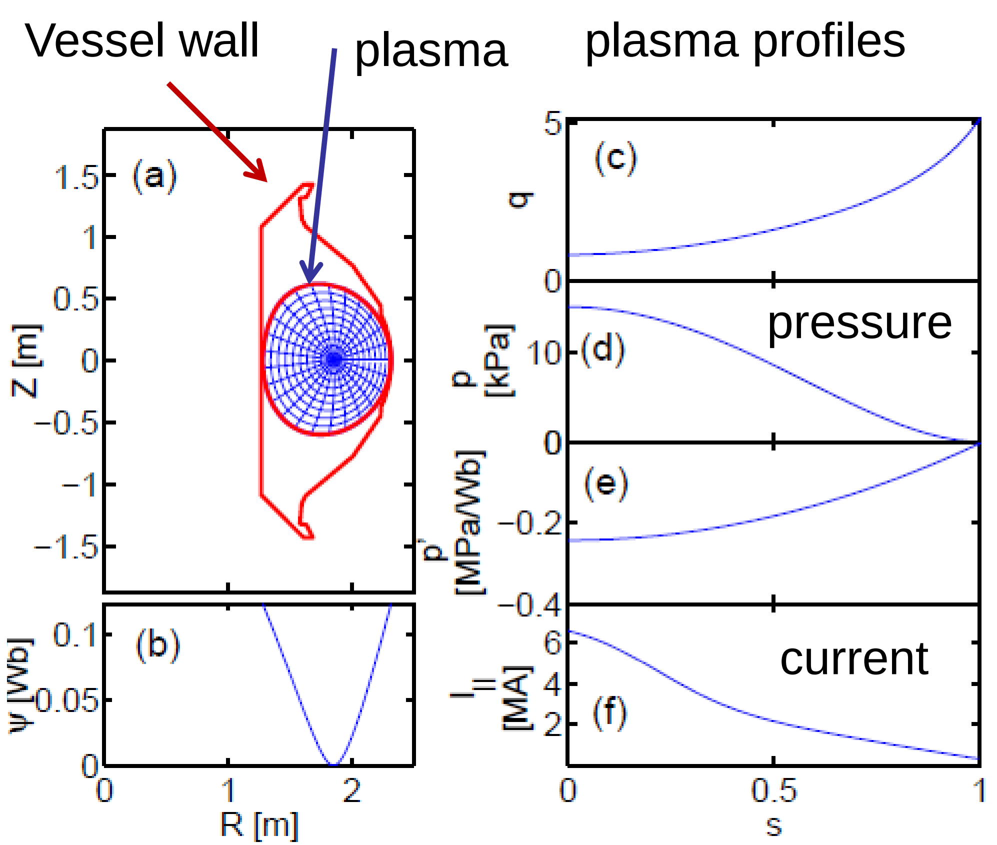


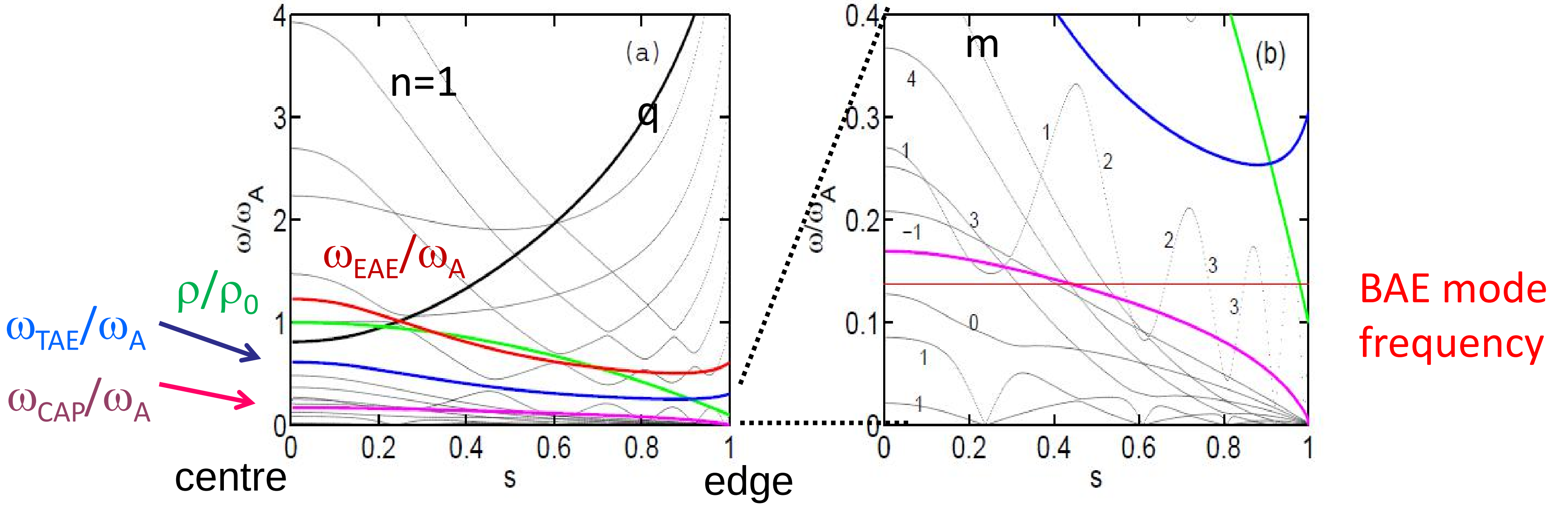
$$q = \frac{\text{toroidal transit}}{\text{poloidal transit}}$$



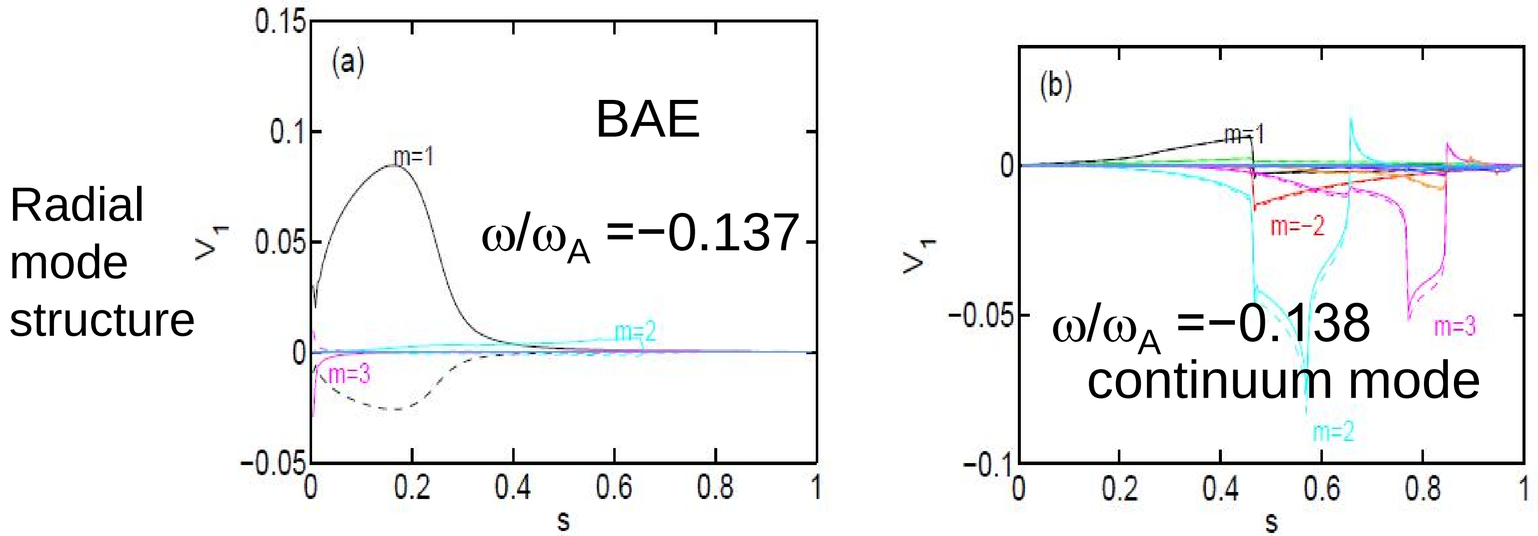


Global mode with reduced damping

- Computed ion sound, shear Alfven wave continuum (CSCAS)



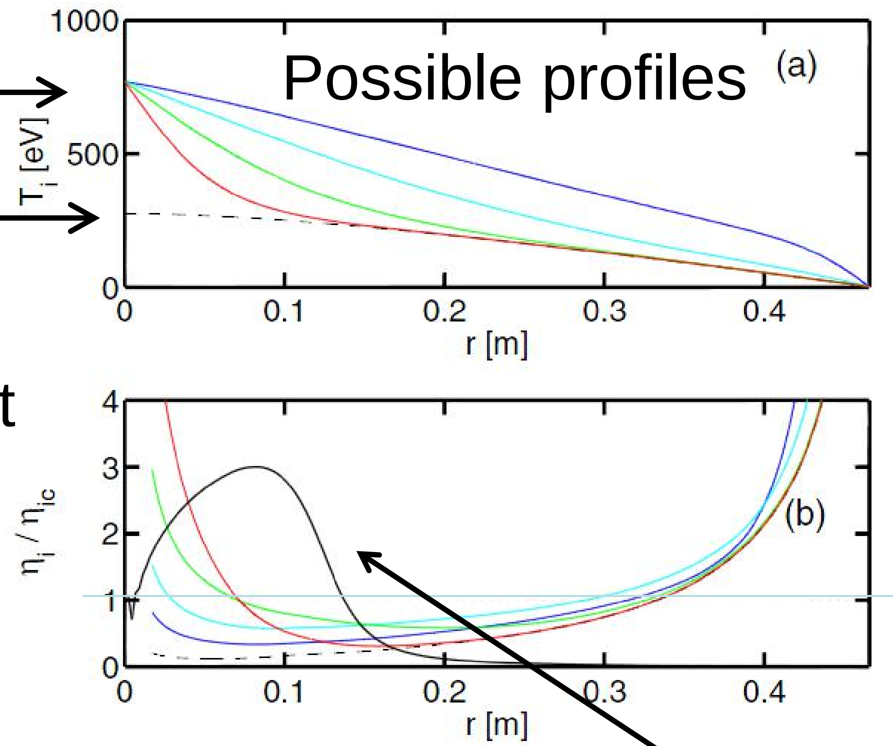
- n=m=1 global & continuum modes (MISHKA)



Beam changes threshold to BAE drive

Beam heated core T_i

Ohmic core T_i (no heating)



- Thermal temperature gradient drive stability parameter

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

- Critical gradient = η_c

n=1, m=1 eigenfunction

- Increasing core localisation $\Rightarrow$ lowered instability threshold
- Mode driven by beams through $v_A/3$ resonance

[Hole *et al* Plasma Phys. Control. Fusion 55 (2013) 045004]

BAE modes in H-1

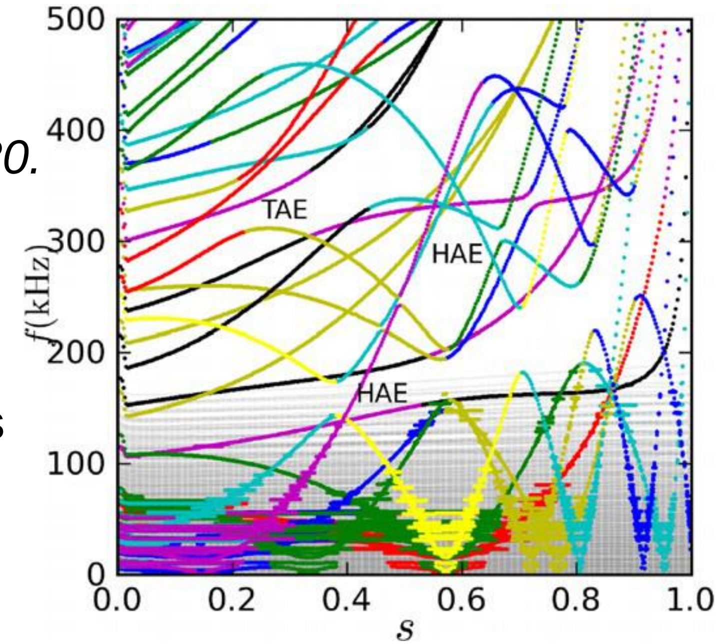
Bertram, Blackwell, Hole

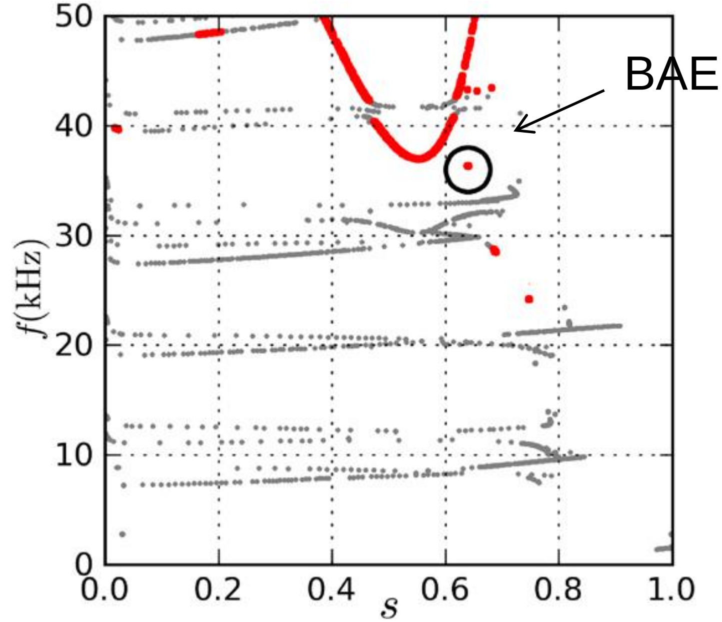
- H-1 has similar modes, but more complex because fully 3D

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

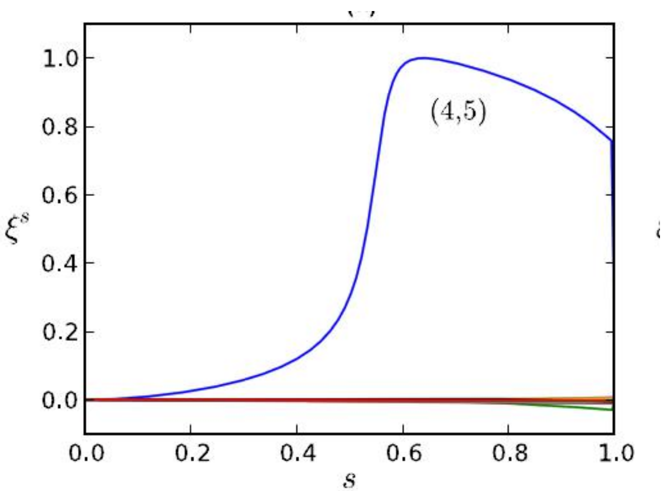
Alfvén branches (colour)

Sound branches (grey)



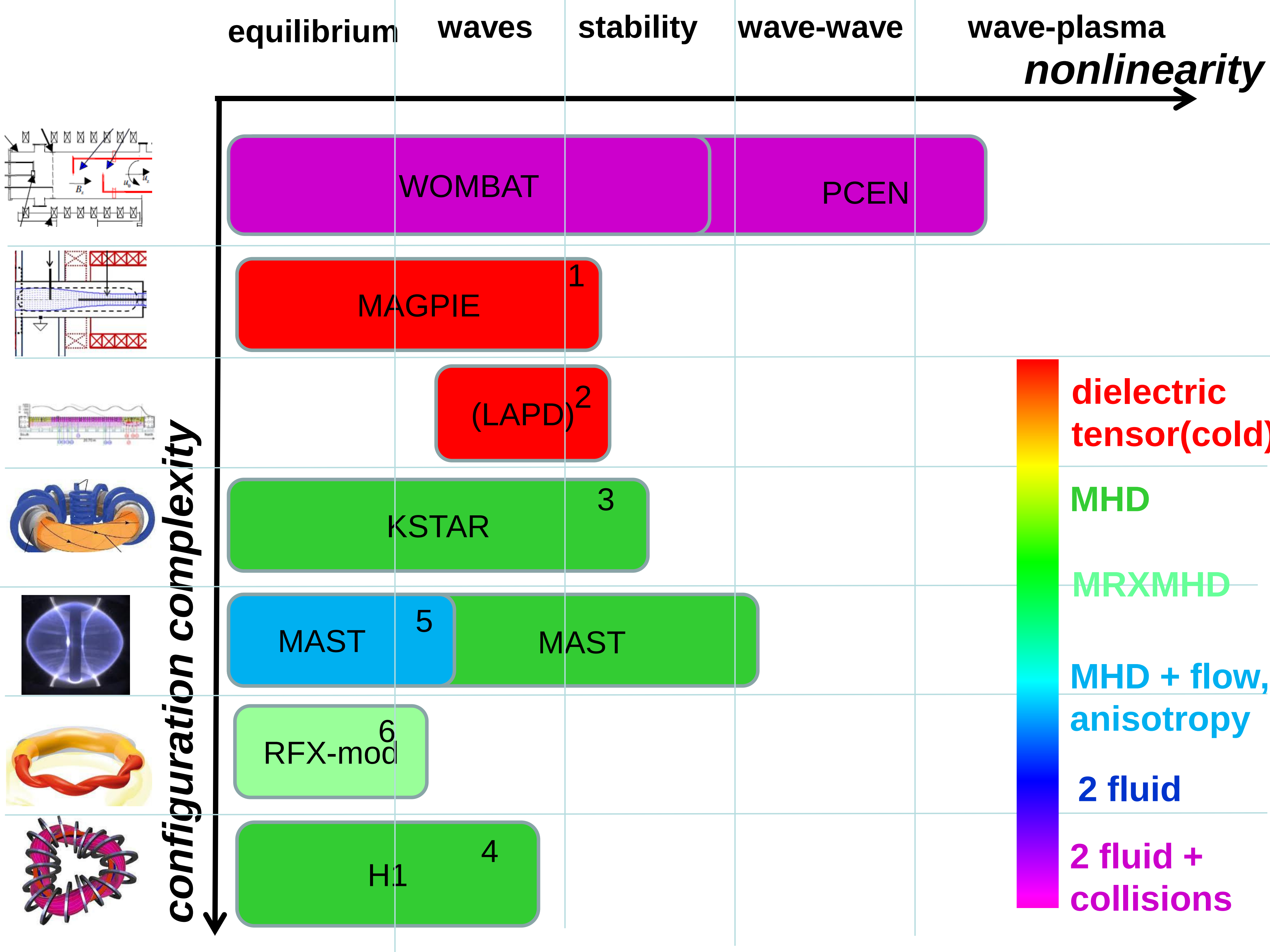


- CAS3D computed eigenmode for candidate BAE



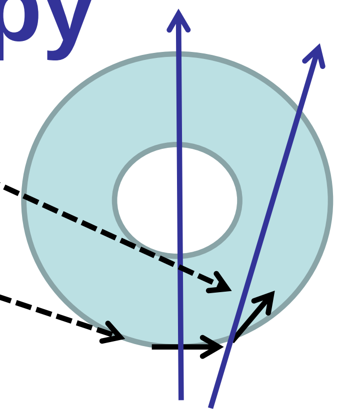
- Mode postulated to be driven by inverted (hollow) temperature profile

[Betram, Blackwell, Hole, Plasma Phys. Control. Fusion 54 (2012) 055009]



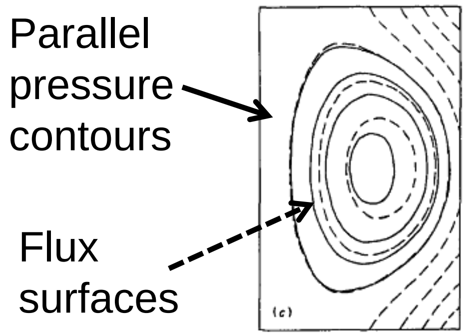
equilibrium
waves
stability
wave-wave
wave-plasma
nonlinearity
configuration complexity
WOMBAT
PCEN
MAGPIE
1
(LAPD)
2
KSTAR
3
MAST
5
MAST
RFX-mod
6
H1
4
dielectric
tensor(cold)
MHD
MRXMHD
MHD + flow,
anisotropy
2 fluid
2 fluid +
collisions

Expected impact of anisotropy



- Small angle θ_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 :

  [R. Iacono, A. Bondeson, F. Troyon, and R. Gruber, Phys. Fluids B 2 (8). August 1990]

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

  [M J Hole, G von Nessi, M Fitzgerald, K G McClements, J Svensson, PPCF 53 (2011) 074021]

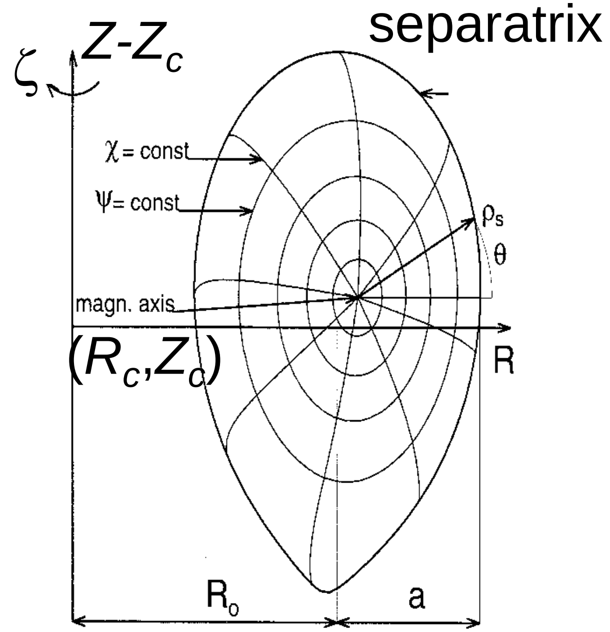
- Infer $p_{\perp}$ from measured diamagnetic current $\mathbf{J}_{\perp}$ using $\nabla p = \mathbf{J} \times \mathbf{B}$

  [see V. Pustovitov, PPCF 52 065001, 2010 and references therein]

Equilibrium in toroidal symmetry

$$\mathbf{J}\times\mathbf{B}=\nabla p \quad \begin{cases} \mathbf{B}\cdot\nabla p=0 & \therefore \text{No pressure gradient along B} \\ \mathbf{J}\cdot\nabla p=0 & \therefore \text{ Current flows in magnetic surfaces} \end{cases}$$

$$\nabla\times\mathbf{B}=\mu_0\mathbf{J}, \qquad \nabla\cdot\mathbf{B}=0$$



- Assume toroidal symmetry.
- Introduce
  - ➢co-ord. system (R, ζ ,z)
  - ➢poloidal flux function ψ, $\mathbf{B}\cdot\nabla\psi=0$
  - ➢toroidal flux function $f(\psi)=RB_\zeta(\psi,R)/\mu_0$
- Can reduce to Grad-Shafranov equation

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

- 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: $\boxed{\rho\mathbf{v}\cdot\nabla\mathbf{v} = \mathbf{J}\times\mathbf{B} - \nabla\cdot\overline{\mathbf{P}}}$ $\overline{\mathbf{P}} = p_\perp\bar{\mathbf{I}} + \Delta\mathbf{BB}/\mu_0\,,\quad \Delta = \frac{\mu_0\left(p_\parallel - p_\perp\right)}{B^2}$

- Frozen flux $\Rightarrow$ $\mathbf{v} = -R\phi_E'(\psi)\mathbf{e}_\varphi = R\Omega(\psi)\mathbf{e}_\varphi$ Force balance becomes …

$$\boxed{\nabla\cdot\left[(1-\Delta)\left(\frac{\nabla\psi}{R^2}\right)\right] = \underbrace{-\frac{\partial p_\parallel}{\partial\psi} - \rho H'(\psi) + \rho\frac{\partial W}{\partial\psi}}_{\text{Pressure gradient}} \underbrace{- \frac{f(\psi)f'(\psi)}{R^2(1-\Delta)}}_{\text{Lorentz}} \underbrace{+ R^2\rho\Omega(\psi)\Omega'(\psi)}_{\text{centrifugal}}}$$

Bernoulli equation:

$$H(\psi) = W(\rho,B,\psi) - \frac{1}{2}\left[R\phi_E'(\psi)\right]^{2\,2}$$

Set of 5 profile constraints $\left\{F(\psi),\Omega(\psi),H(\psi),\frac{\partial p_\parallel}{\partial\psi},\frac{\partial W}{\partial\psi}\right\}$

- ∂W/ ∂ ψ: different for MHD/ double-adiabatic/ guiding centre
- If two temperature Bi-Maxwellian model chosen

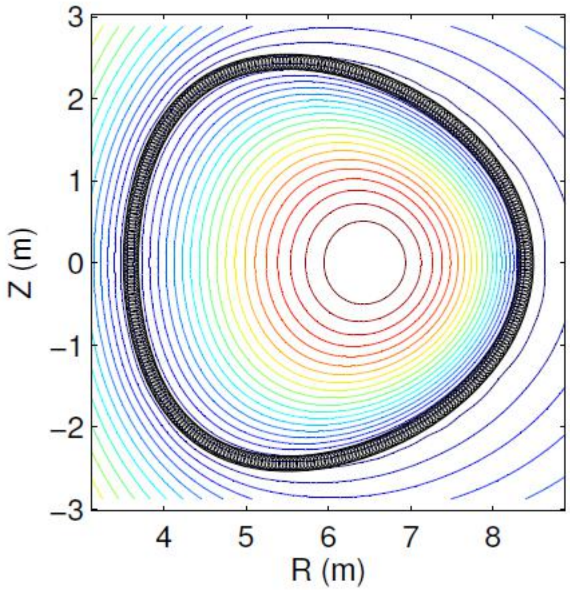
$$p_\parallel(\rho,B\psi) = \frac{k_B}{m}\rho T_\parallel(\psi) \qquad p_\perp(\rho,B\psi) = \frac{k_B}{m}\rho T_\perp(\psi) = \frac{k_B}{m}\rho T_\parallel(\psi)\frac{B}{B-\theta(\psi)T_\parallel}$$

$\left\{F(\psi),\Omega(\psi),H(\psi),T_\parallel(\psi),\theta(\psi)\right\}$ We have solved this problem!

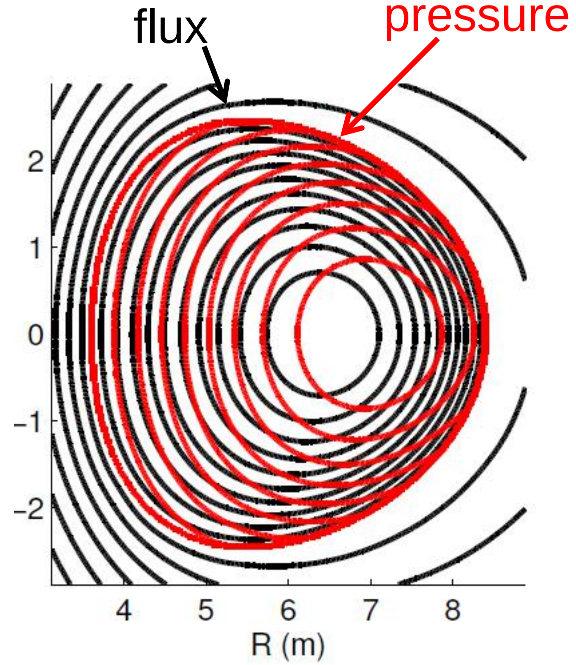
New code written and benchmarked

Fitzgerald, Hole, Appel

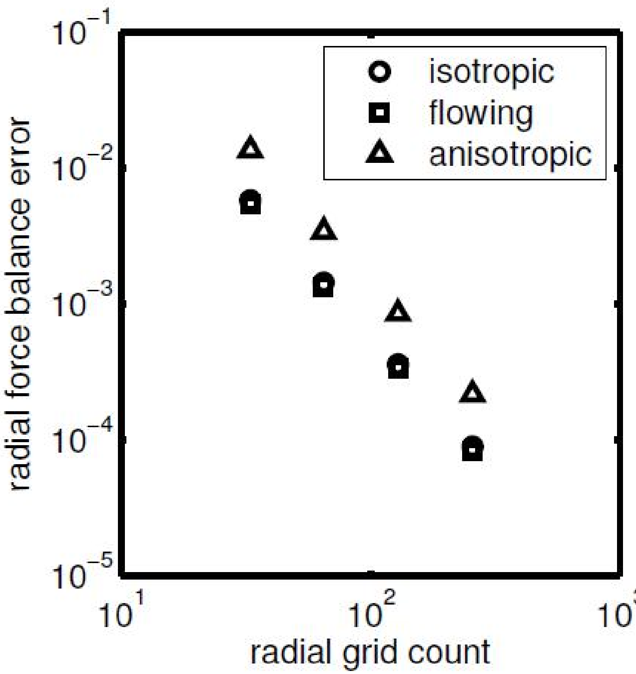
- New code EFIT TENSOR written to solve force balance with flow and anisotropy
- “Soloviev” analytic and real data benchmarks (MAST #13050, #18696) have been computed for isotropic, anisotropic and flow cases



Soloviev:
β_t=0.07



Extended Soloviev:
β_t=0.07, M_ϕ=0.8, Δ=0.004,



Solution Convergence

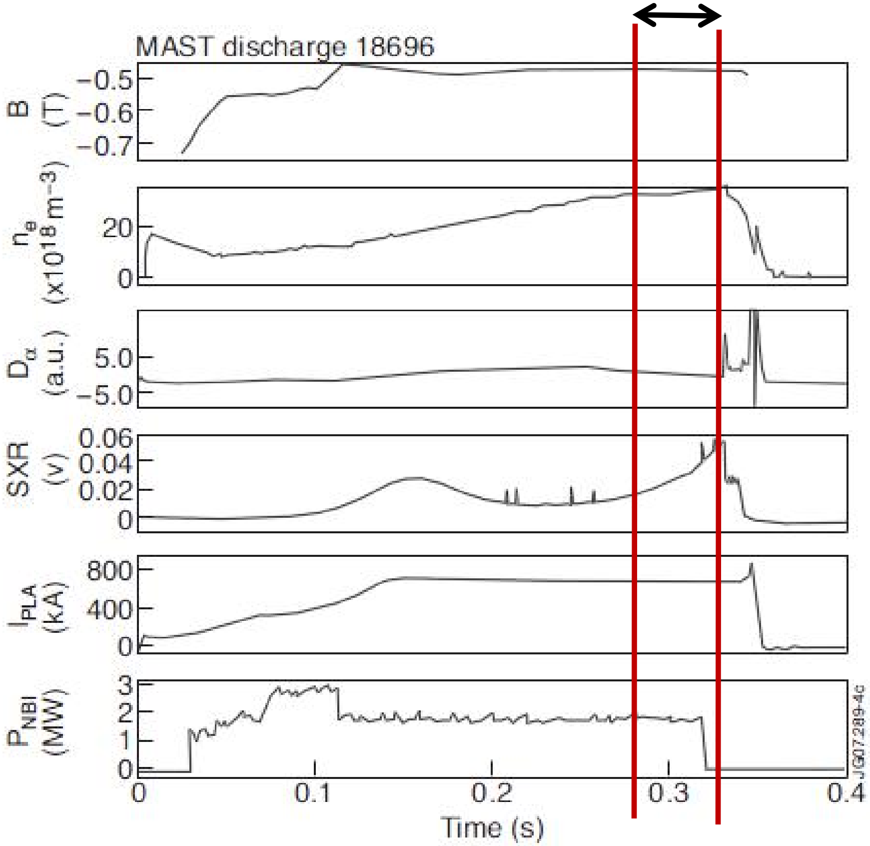
[M. Fitzgerald, L.C. Appel, M.J. Hole *submitted 10/04/2013* Nuc. Fusion]

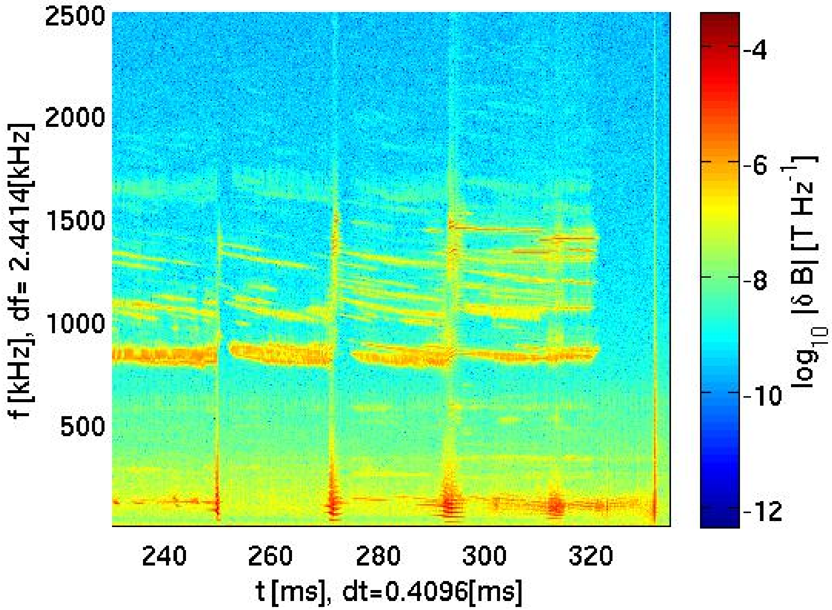
Effect of anisotropy on MAST

Hole, Fitzgerald, von Nessi

- MAST #18696
- 1.9MW NB heating
- I_p = 0.7MA, β_n=2.5
- Magnetics shows wave activity

Magnetics

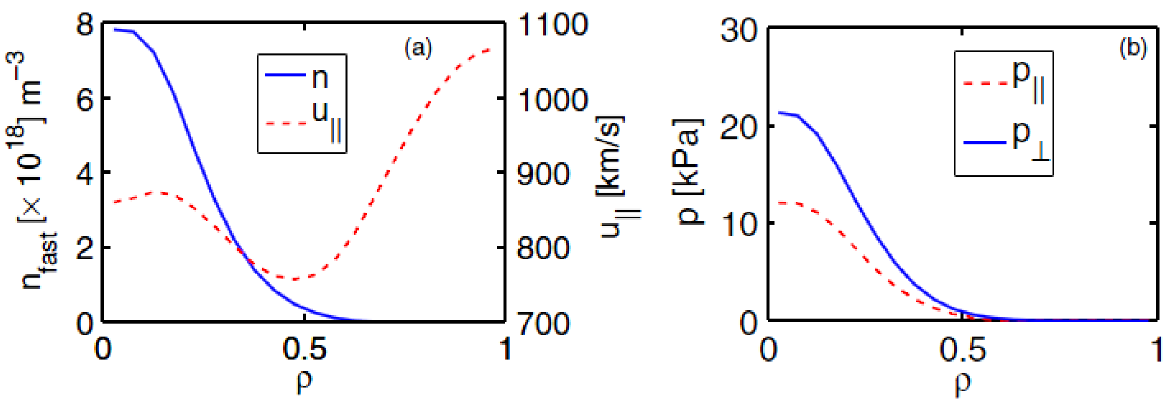




[M.P. Gryaznevich et al, Nuc. Fus. 48, 084003, 2008]

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

Monte Carlo collision code gives $p_{||}$, $p_{\perp}$, v



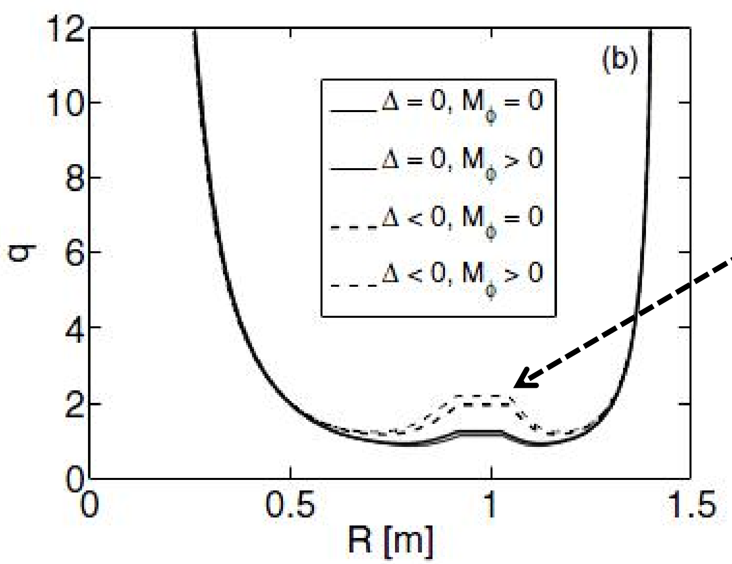
$p_{\perp}/p_{||} \approx 1.7$

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

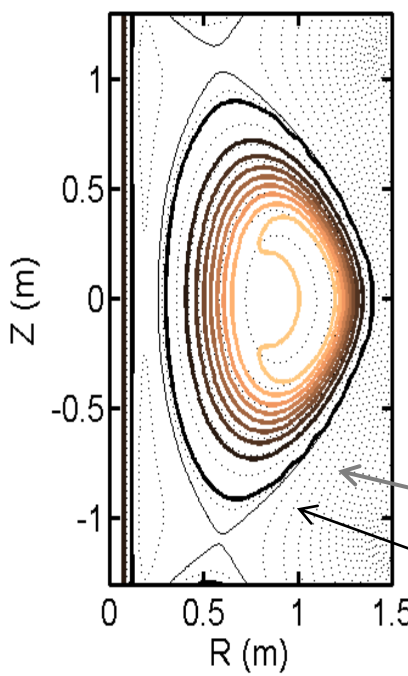
Φ = toroidal flux

$M_{\phi,max} = 0.3$

Impact on plasma computed with EFIT TENSOR



Increase in central q due to anisotropy



Calculation of MAST #18696 at 290ms.

$p_{\perp} / p_{||} \sim 1.7$

(slowing down beam particles)

poloidal flux

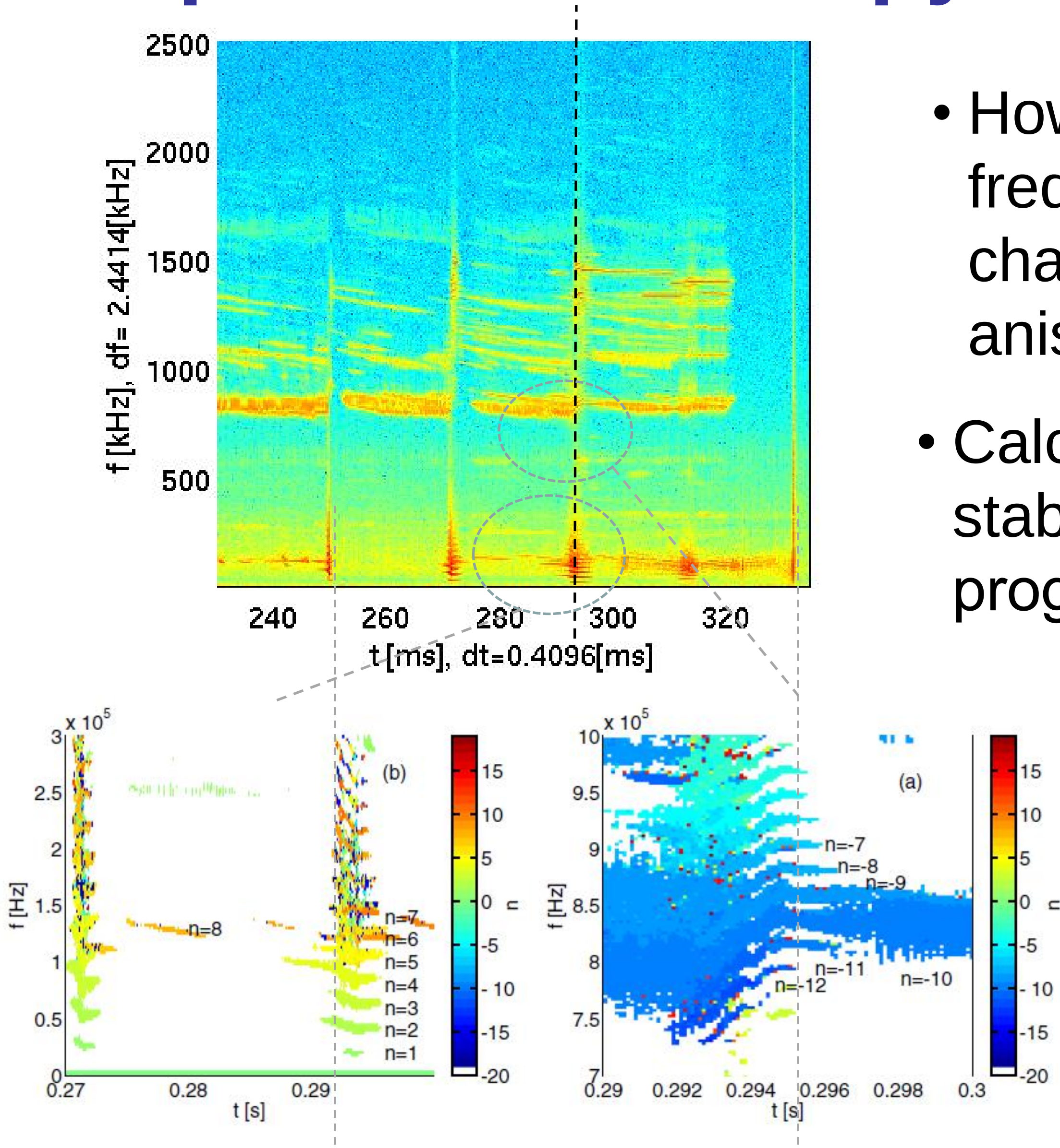
surfaces of constant $p_{||}$.

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

$\Delta = 0$: $p_{\perp}/p_{||} = 1$ $M_\phi > 0$ $M_{\phi,max} = 0.3$

[M J Hole et al, PPCF 53 (2011) 074021]

Impact of anisotropy on wave modes

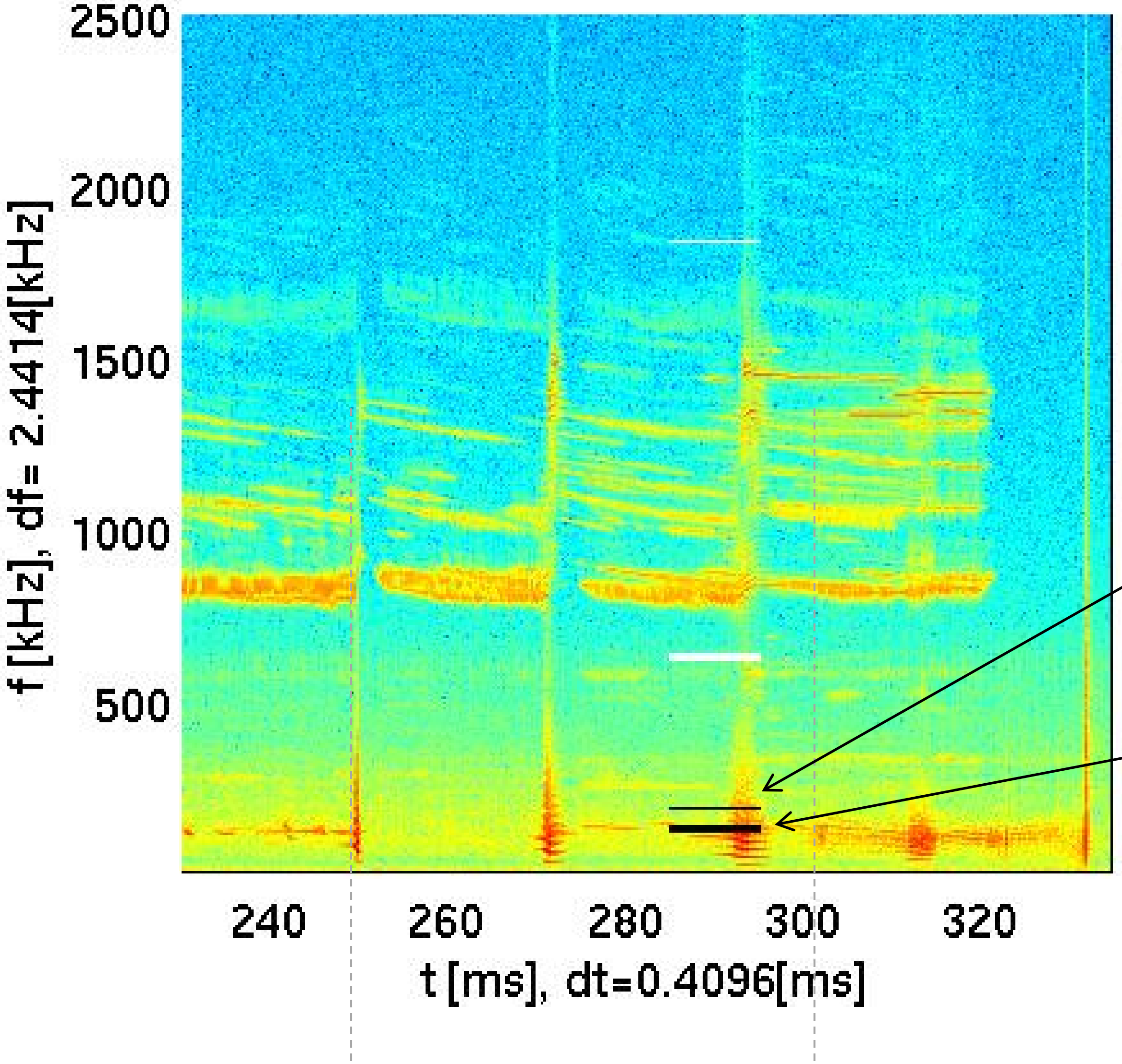


Toroidal mode number identification

- 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

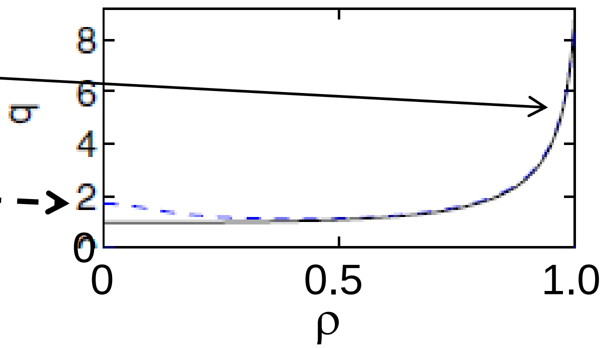
f_{TAE} flow, anisotropic
+ creates new eigenmodes

[M J Hole, G von Nessi, M Fitzgerald, PPCF 55 (2013) 014007]

Increased shear gives multiple TAEs

Isotropic, no flow:
Flat shear, dq/dr

Anisotropic, flow
Reverse shear, dq/dr<0



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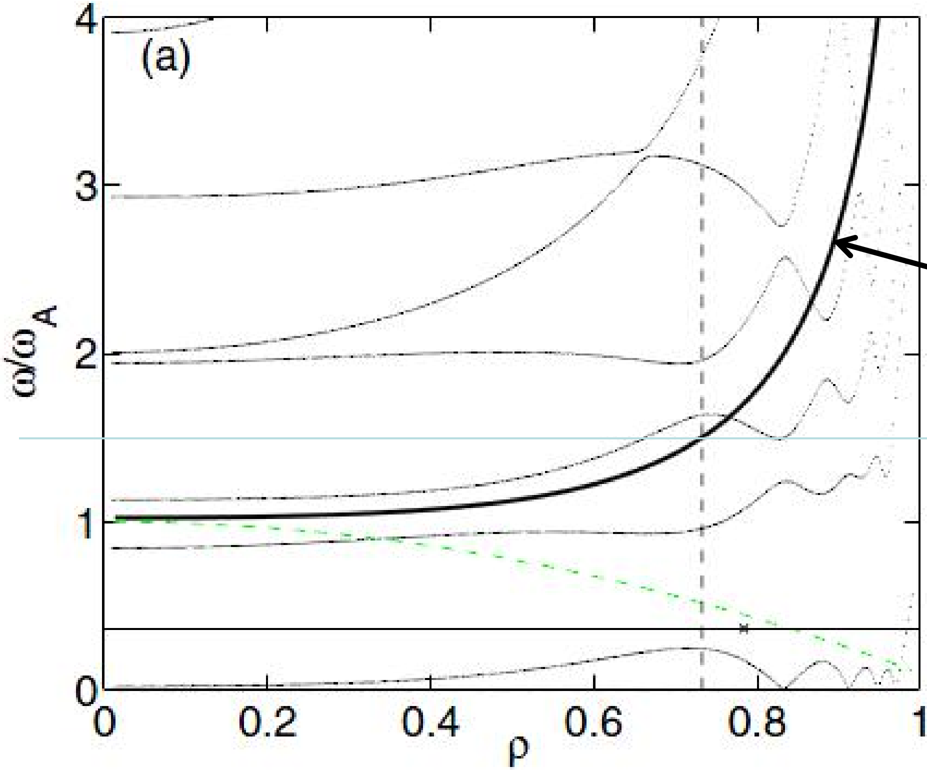
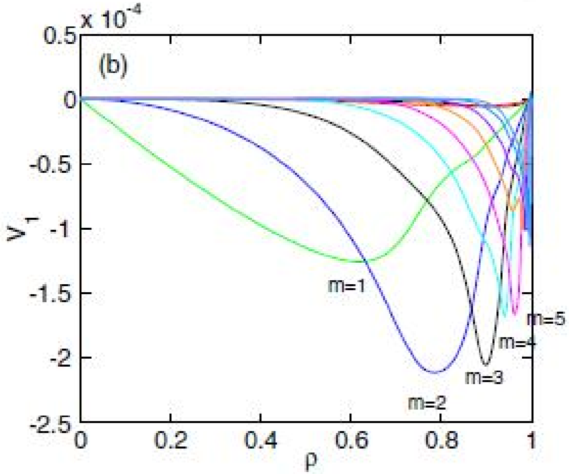


Flat shear continuum

q profile

q=1.5

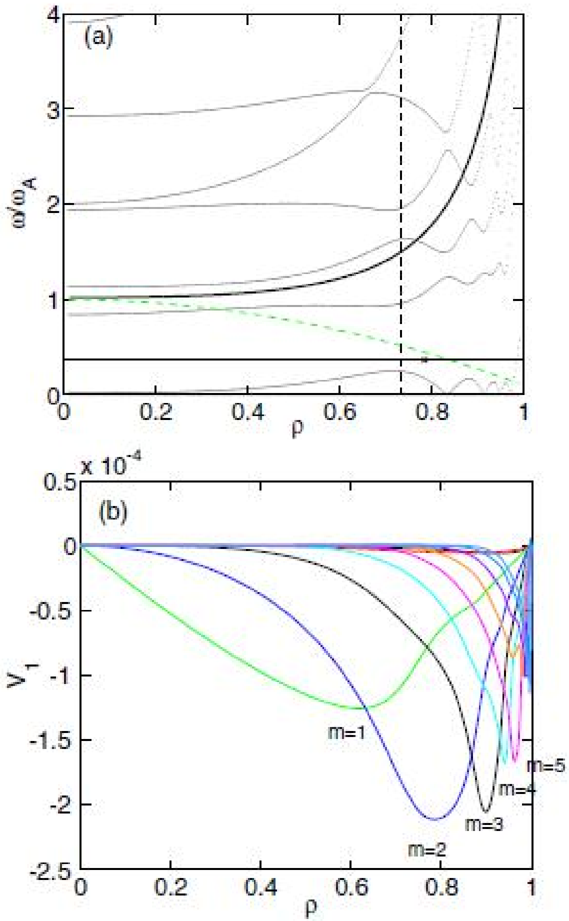
TAE mode



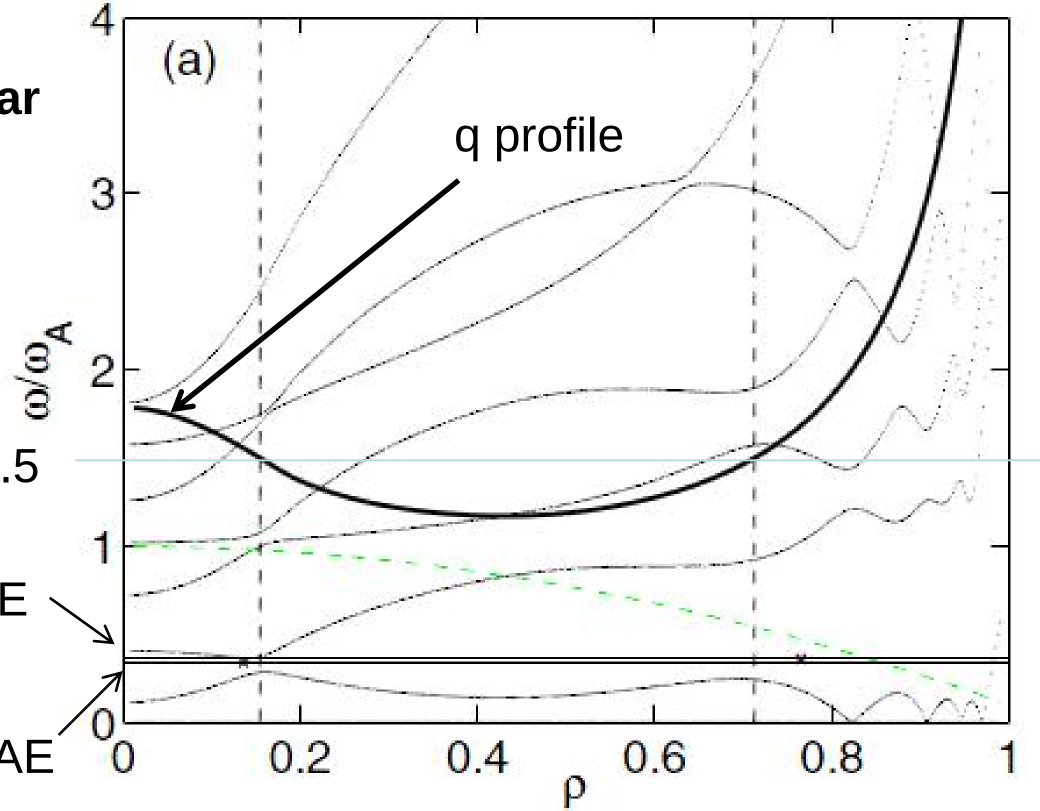
Single
global TAE
(m,n) = (1,1)

Increased shear gives multiple TAEs

Flat shear continuum



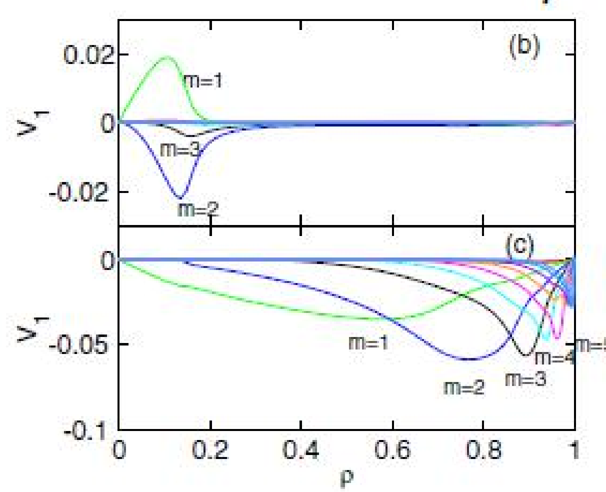
Reverse shear continuum



q=1.5

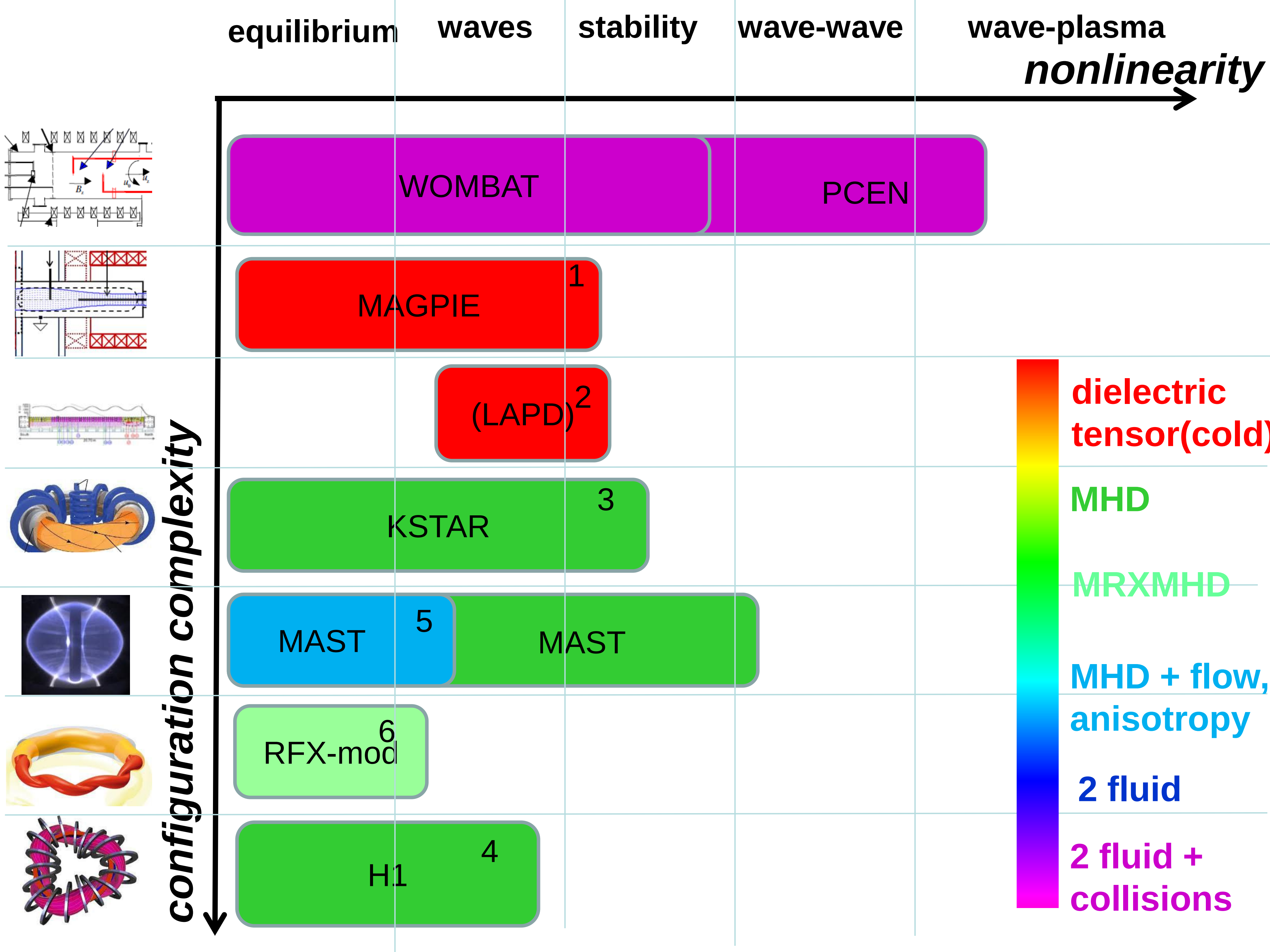
Core TAE

Global TAE



Odd core TAE

Global TAE



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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,** ∇p.

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

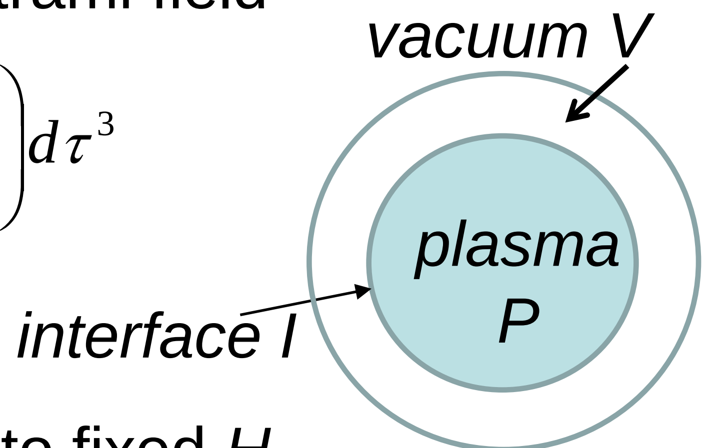
- Numerical implementation, SPEC, by S. Hudson (PPPL).

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



Taylor solved for minimum *W* subject to fixed *H*

i.e. solutions to δF=0 of functional $F = W - \mu H \quad / 2$

$$P: \qquad \nabla \times \mathbf{B} = \mu \mathbf{B}$$

$$I: \qquad \left[\left[\frac{B^2}{2\mu_0} + p \right]\right] = 0$$

$$V: \qquad \nabla \times \mathbf{B} = 0$$

Model very successful for toroidal pinches, multipinch, and spheromaks

discretised $\mathbf{J} \times \mathbf{B} = \nabla p$

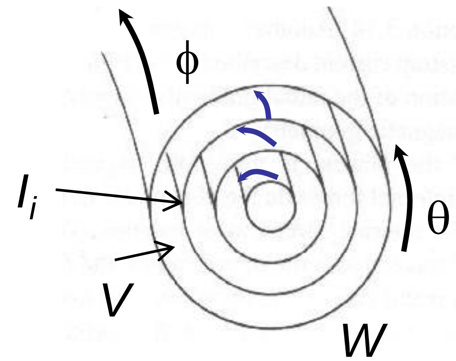
Generalised Taylor Relaxation: MRXMHD

R. L. Dewar, S. R. Hudson, M. J. Hole, G. Dennis, G. von Nessi

- 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



$$W_l = \int_{R_i} \left(\frac{B_l^2}{2\mu_0} + \frac{P_l}{\gamma - 1} \right) d\tau^3$$

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

Seek minimum energy state:

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

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

$P_l = \text{constant}$

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

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

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

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

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

Example: DIIID with n=3 applied error field

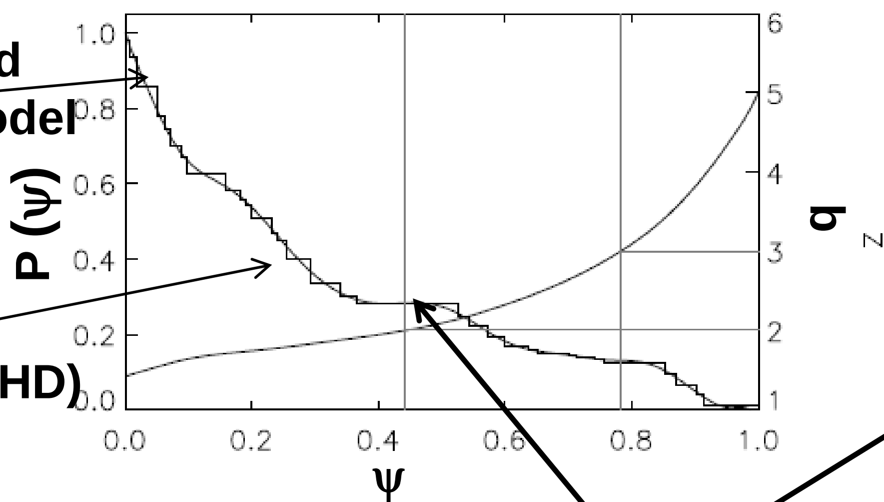
[S. R. Hudson et al Phys. Plas. 19, 112502 (2012)]

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

- Irrational interfaces chosen to coincide with pressure gradients.

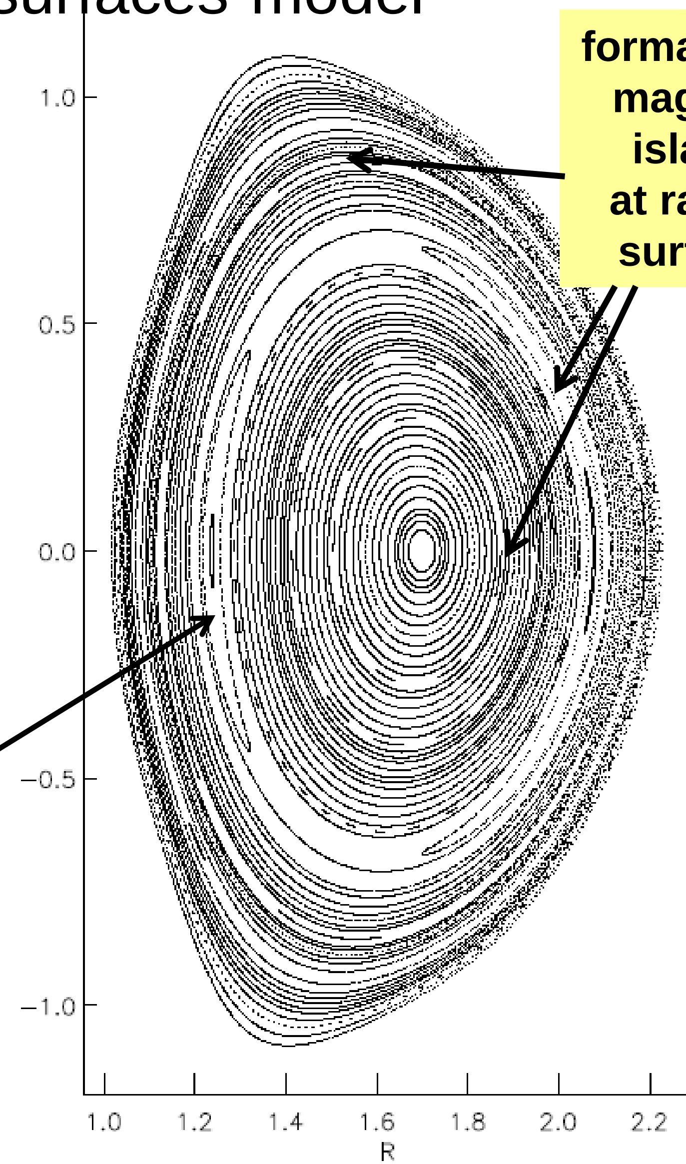
Standard MHD model

SPEC (MRXMHD)



- Islands are now resolved

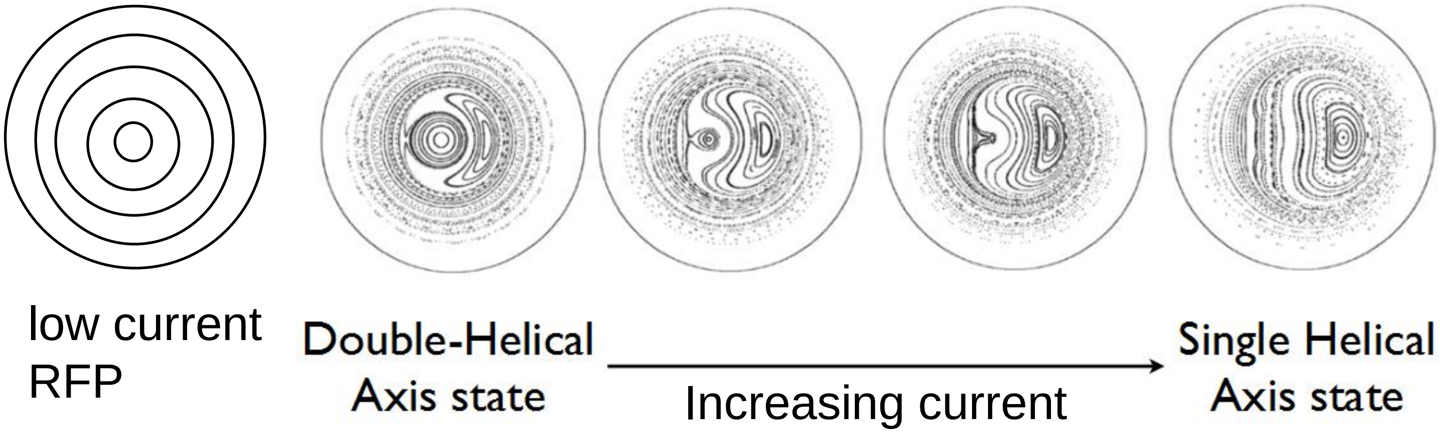
formation of magnetic islands at rational surfaces



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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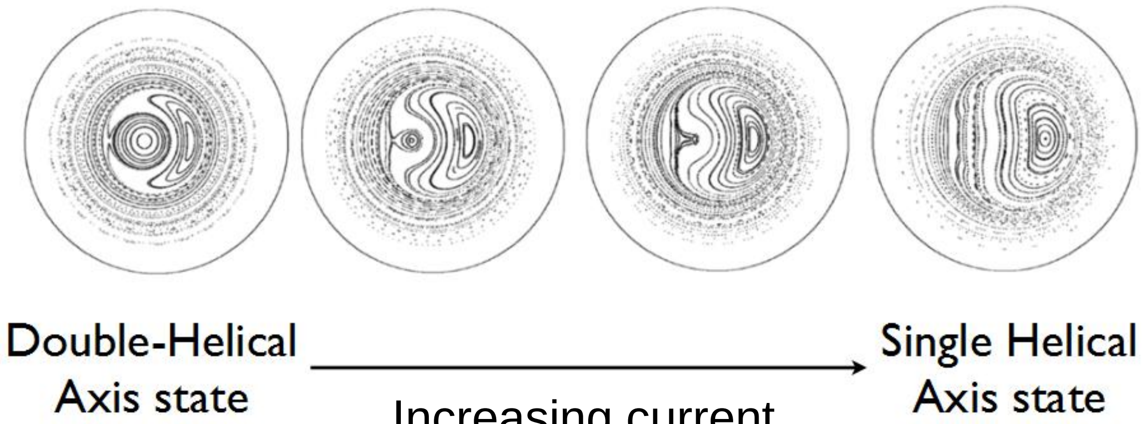

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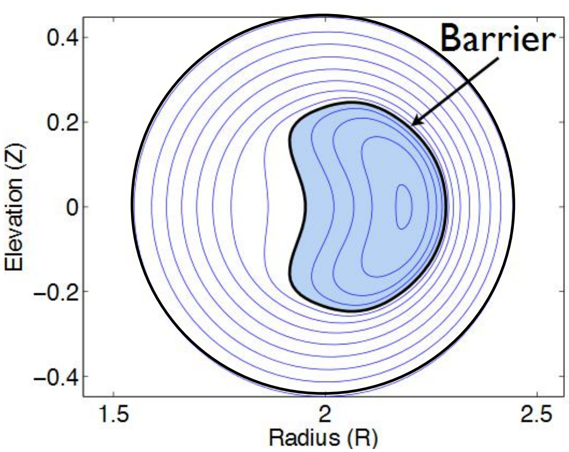

- Model RFX-mod QSH state by a 2-interface minimum energy MRXMHD state.

[G. R. Dennis submitted Phys. Rev. Lett. 22/02/2013 http://arxiv.org/abs/1302.5458]

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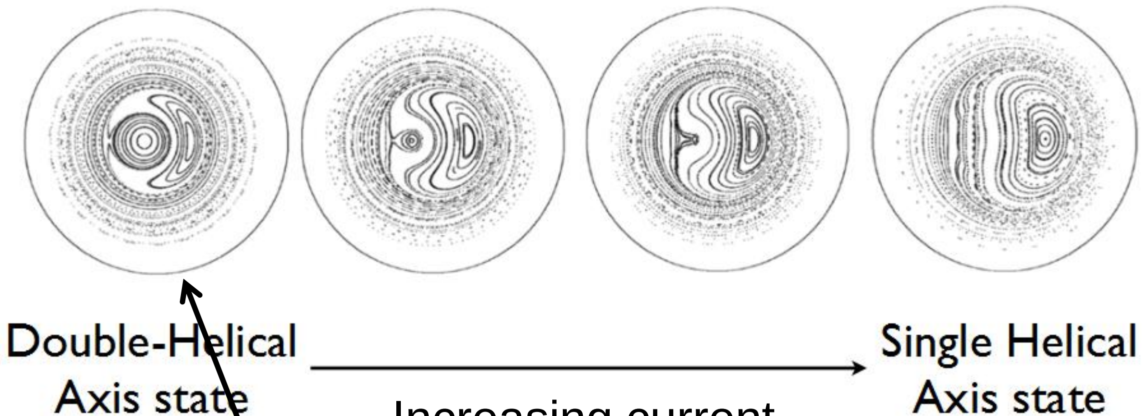

Increasing current

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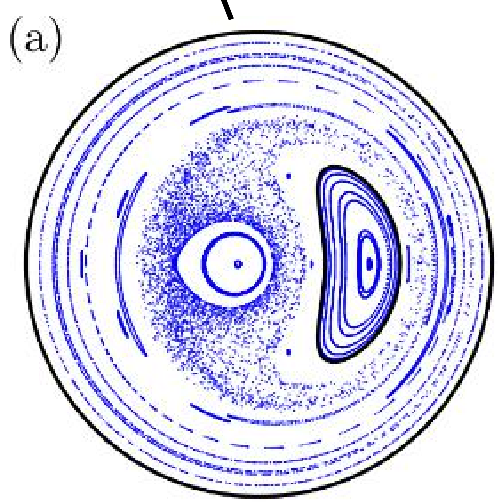
[Fig. 6 of P. Martin et al., Nuclear Fusion 49, 104019 (2009)]



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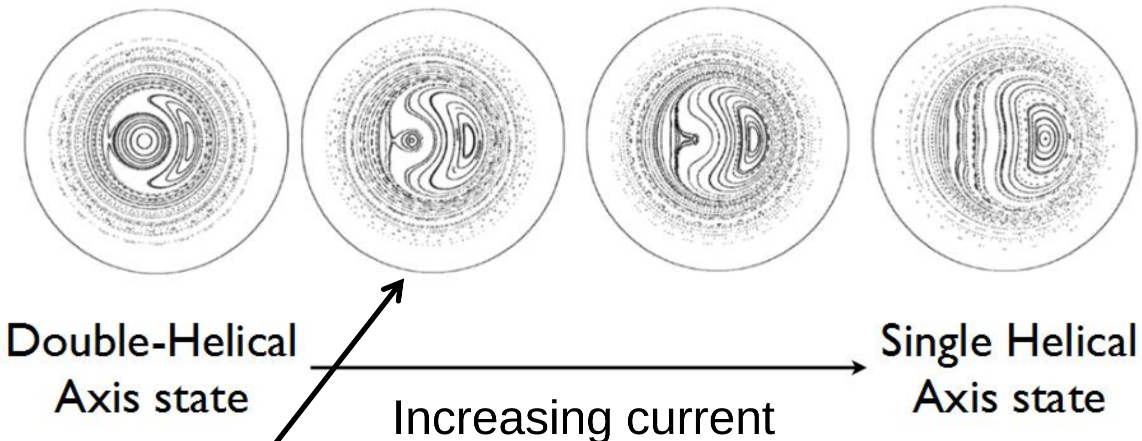

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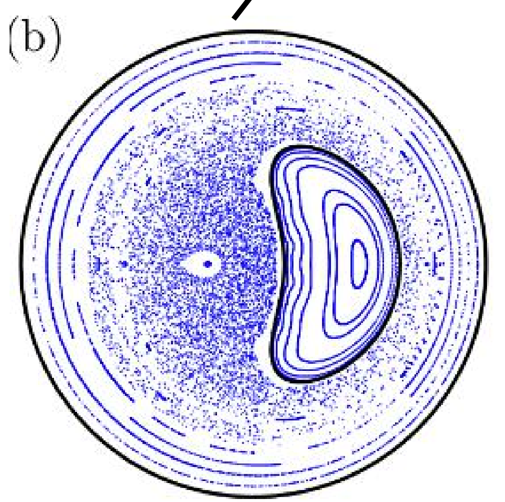

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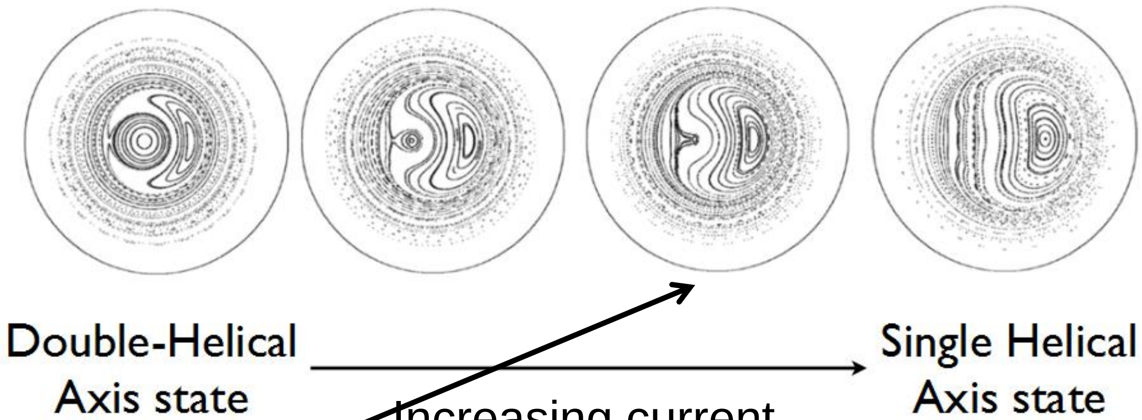

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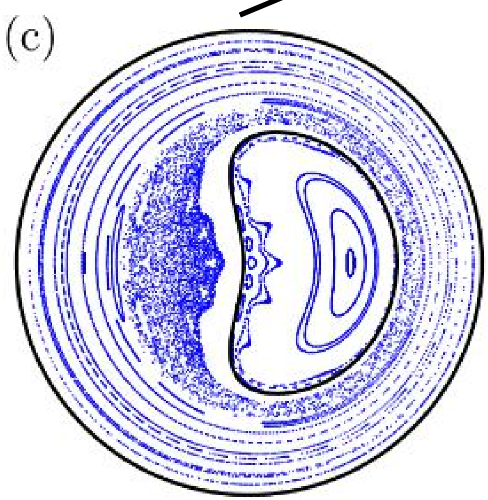

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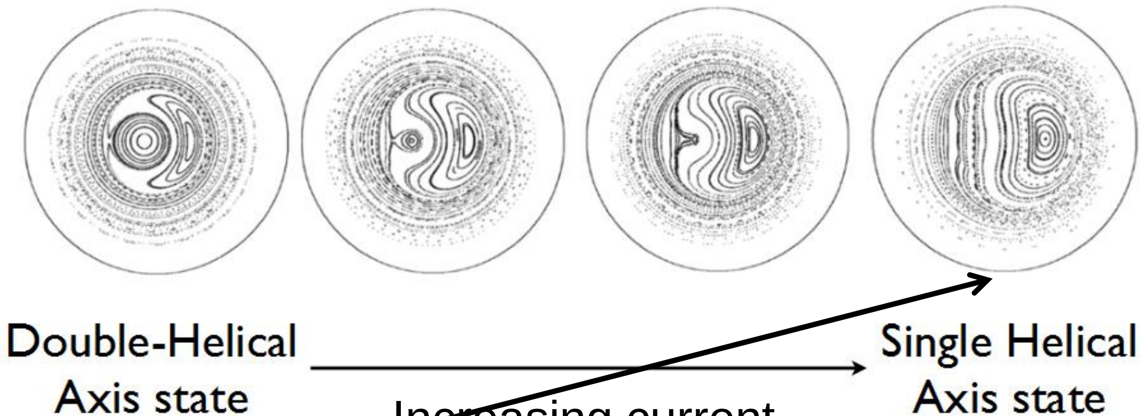

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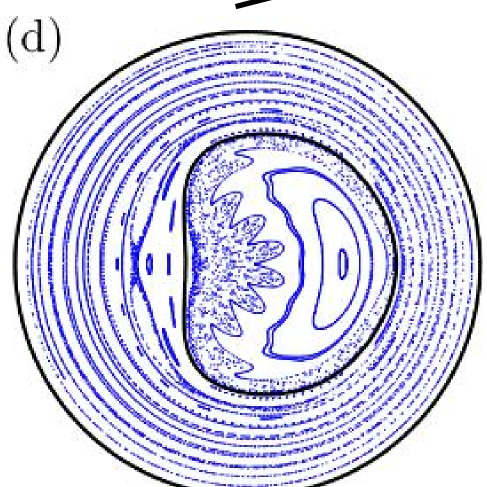

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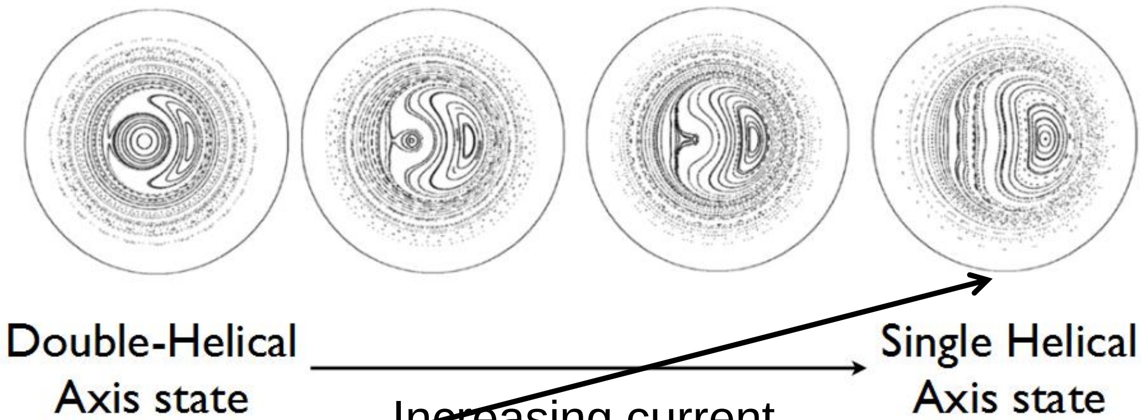

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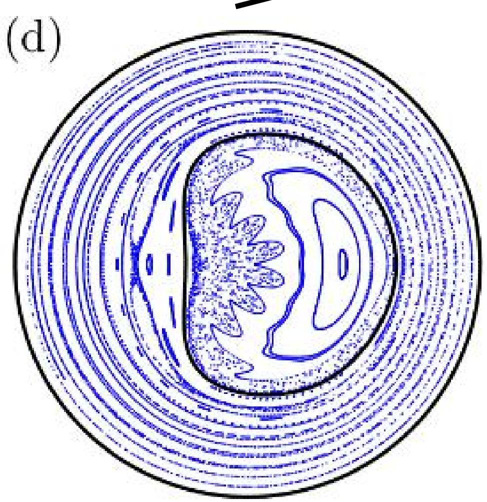

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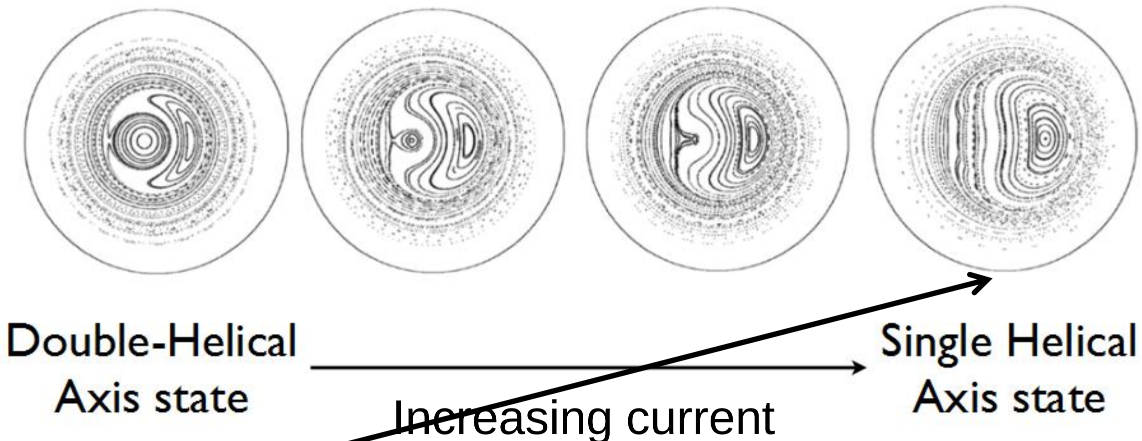
- RFP bifurcated state has lower energy (preferred) than comparable axis-symmetric state

[G. R. Dennis submitted Phys. Rev. Lett. 22/02/2013 http://arxiv.org/abs/1302.5458]

Spontaneously formed helical states

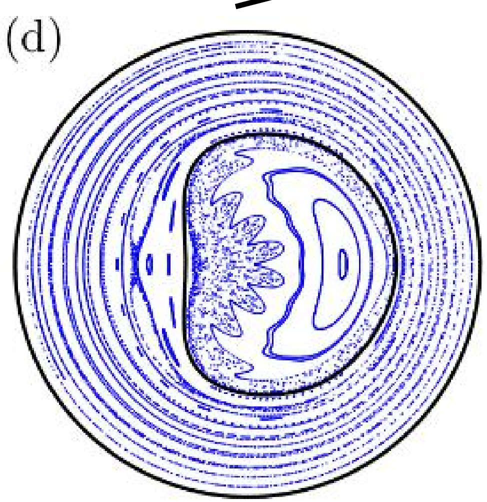
Dennis, Hudson, Terranova, Dewar, Hole

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

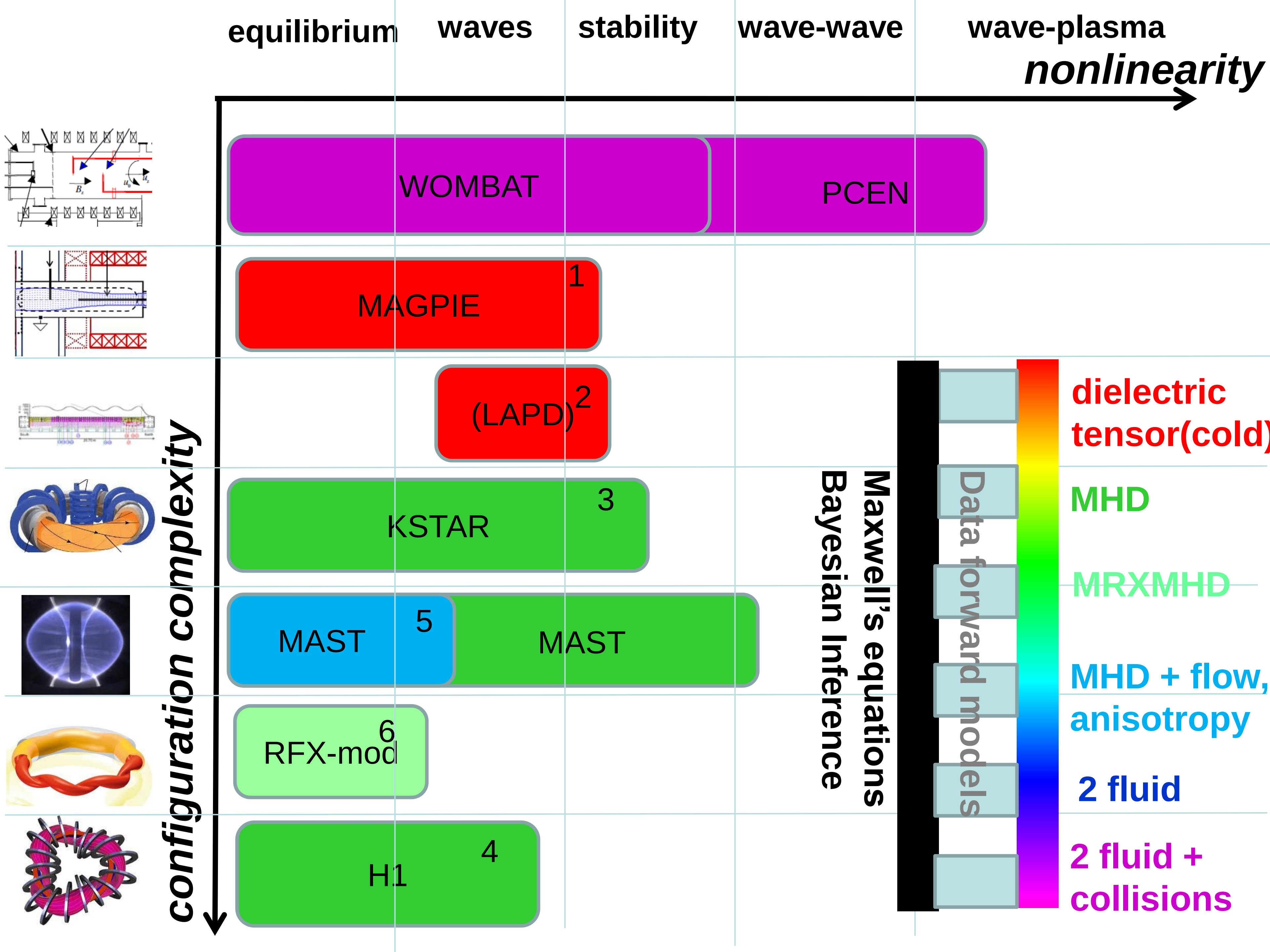


"Experimental" Poincaré plot

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



- Model RFX-mod QSH state by a 2-interface minimum energy MRXMHD state.
- Theoretical Poincare plots match experiment as barrier is changed
- 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
configuration complexity
WOMBAT
PCEN
MAGPIE
1
(LAPD)
2
KSTAR
3
MAST
5
MAST
RFX-mod
6
H1
4
Bayesian Inference
Maxwell's equations
Data forward models
dielectric tensor(cold)
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,

$$P(\mathbf{H}|\mathbf{D}) = P(\mathbf{D}|\mathbf{H})P(\mathbf{H}) / P(\mathbf{D})$$

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

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

Pick-up coils | Flux loops | MSE signals | Plasma current | TS spectra | CXRS spectra

Aims

(1) Improve equilibrium reconstruction

(2) Validate different physics models

Two fluid with rotation

[McClements & Thyagaraja Mon. Not. R. Astron. Soc. 323 733–42 2001]

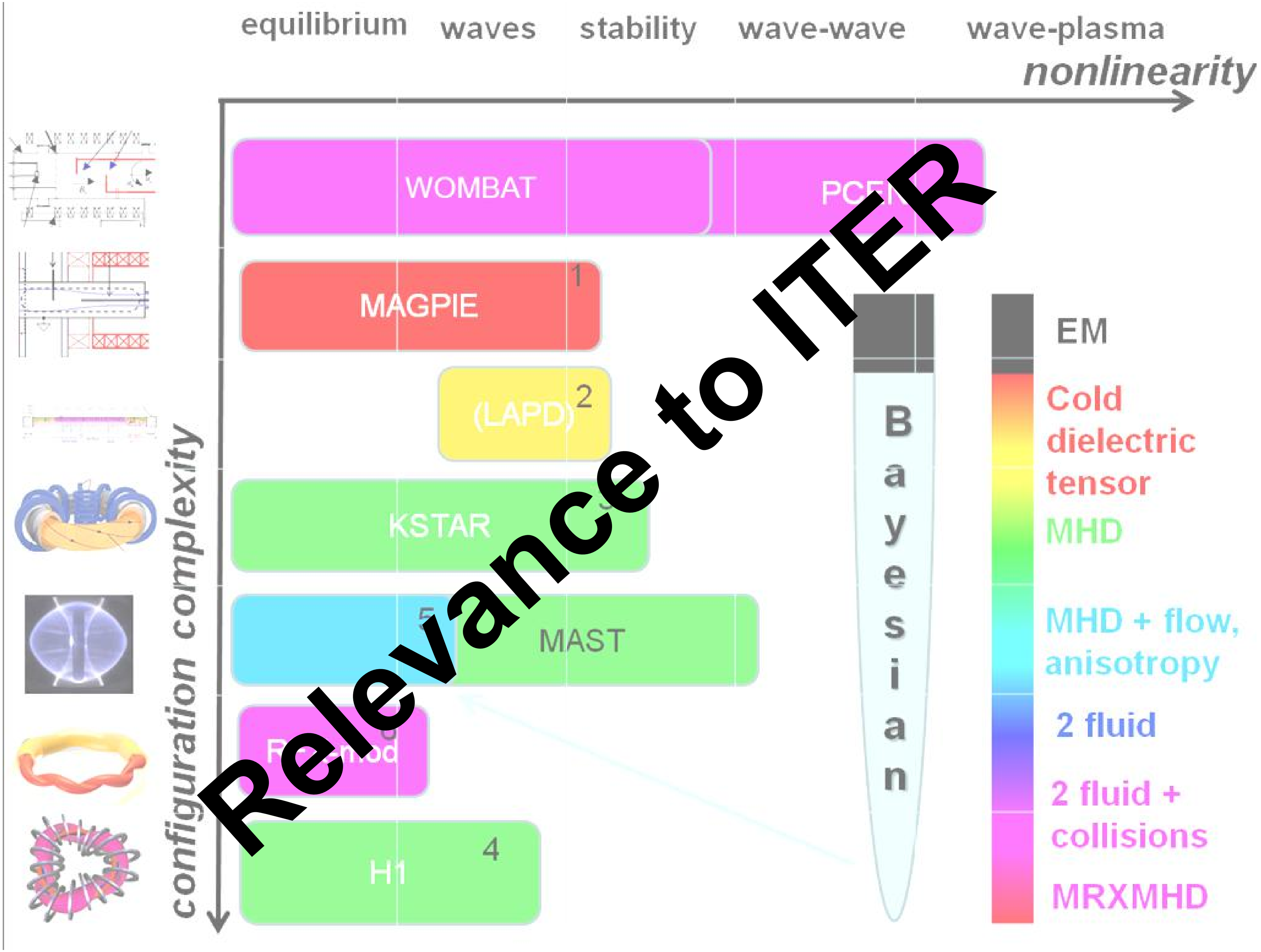
Ideal MHD fluid with rotation

[Guazzotto L et al, Phys. Plasmas 11 604–14, 2004]

Energetic particle resolved multiple-fluid

[Hole & Dennis, PPCF 51 035014, 2009]

(3) Infer poorly diagnosed physics parameters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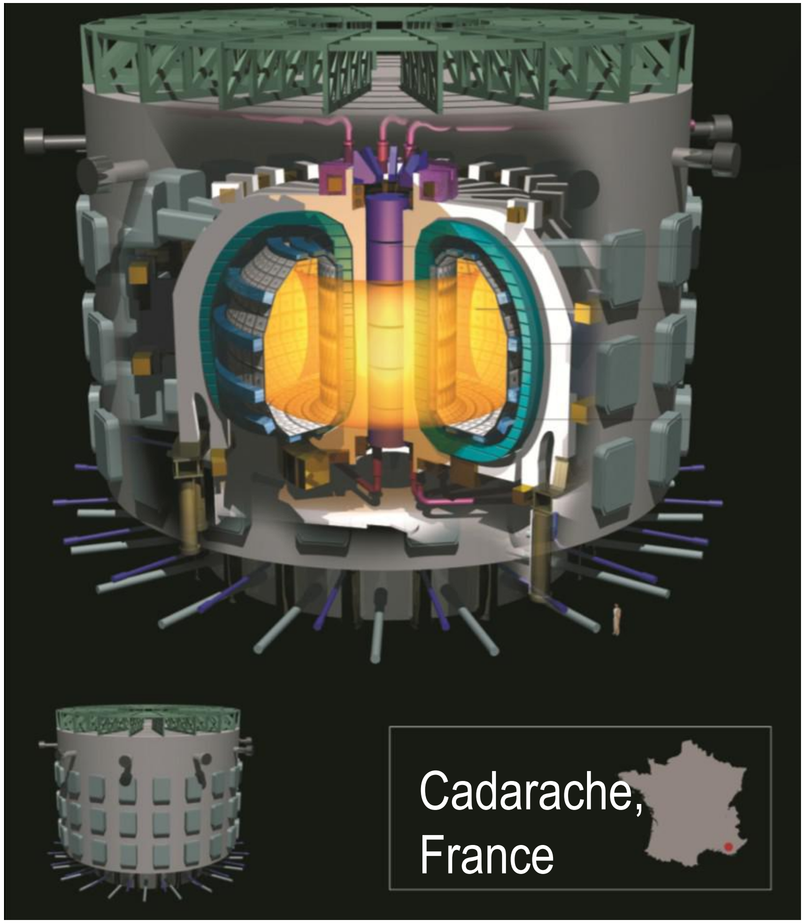
Cold dielectric tensor
MHD
MHD + flow, anisotropy
2 fluid
2 fluid + collisions
MRXMHD
Relevance to ITER

ITER: The next step for fusion power



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

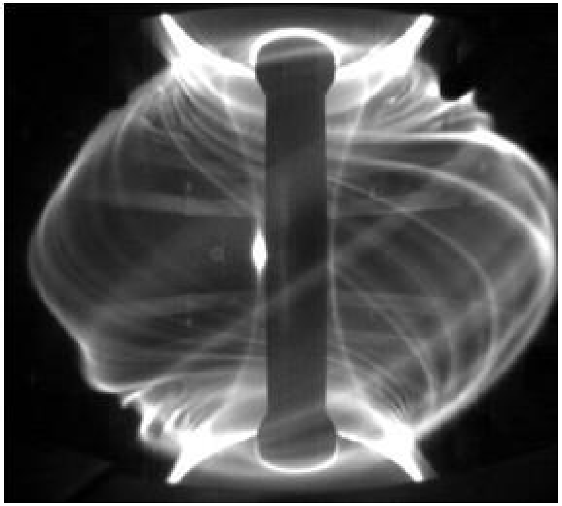
- Growing Consortium

- 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

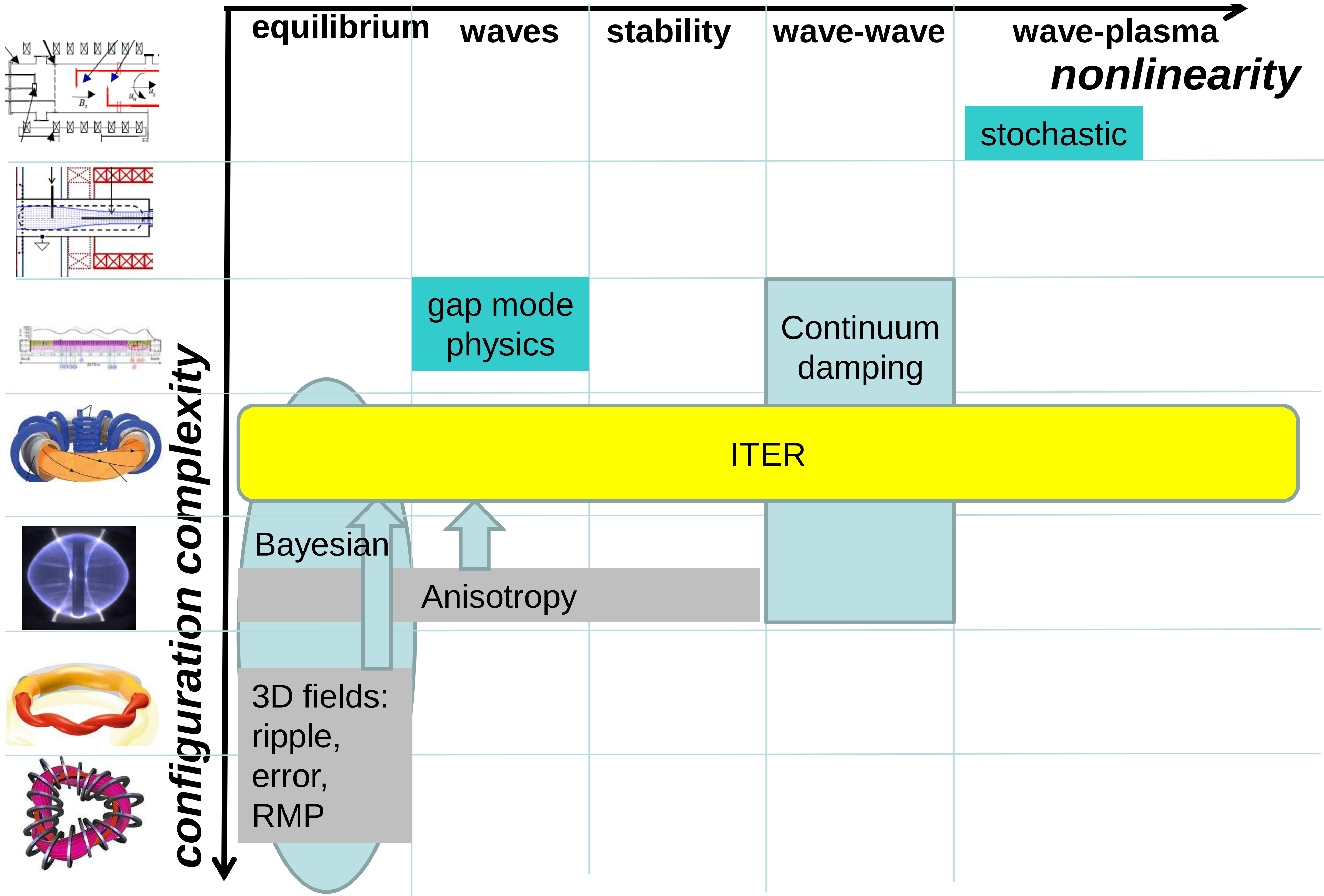
Plasma Physics Challenges

- 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 αs 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^{α} camera of MAST plasmas

Physics contributions to ITER



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.