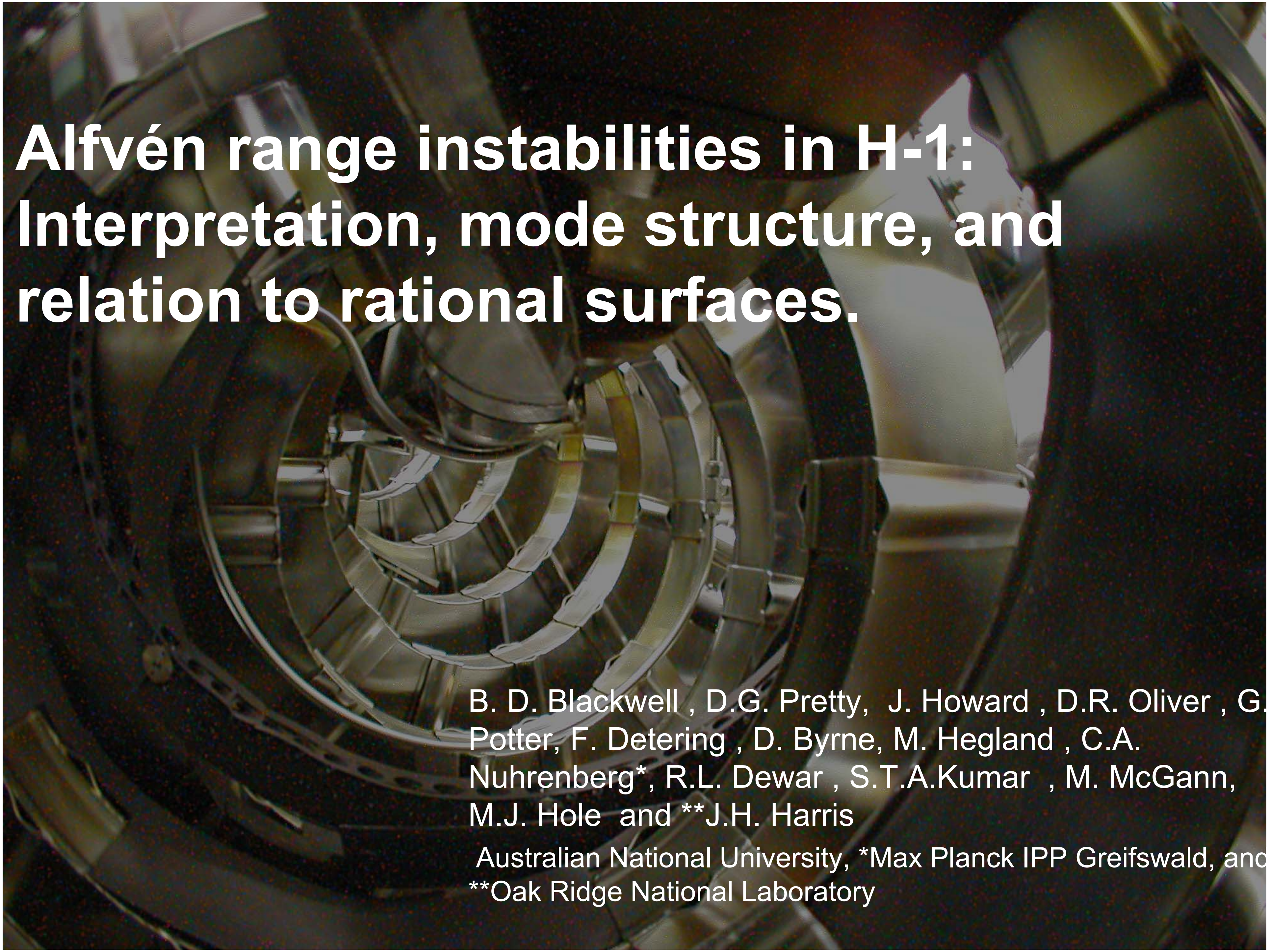


Alfvén range instabilities in H-1: Interpretation, mode structure, and relation to rational surfaces.

B. D. Blackwell , D.G. Pretty, J. Howard , D.R. Oliver , G. Potter, F. Detering , D. Byrne, M. Hegland , C.A. Nuhrenberg*, R.L. Dewar , S.T.A.Kumar , M. McGann, M.J. Hole and **J.H. Harris

Australian National University, *Max Planck IPP Greifswald, and
**Oak Ridge National Laboratory

Outline

- H-1 Heliac
- MHD Data
- Data mining
  - SVD, fluctuation structures
  - Clustering
- Interpretation
  - Alfvén Scaling
  - Iota an additional fit parameter
  - Radial location
  - Accurate iota confirmation
  - Scaling discrepancies
  - Beta–Induced modes, sound and drift modes
  - Helical Alfvén eigenmode
  - Radial Structure
- Summary

H-1NF: National Plasma Fusion Research Facility

NATIONAL PLASMA FUSION RESEARCH FACILITY

A Major National Research Facility established in 1997 by the Commonwealth of Australia and the Australian National University

Mission:

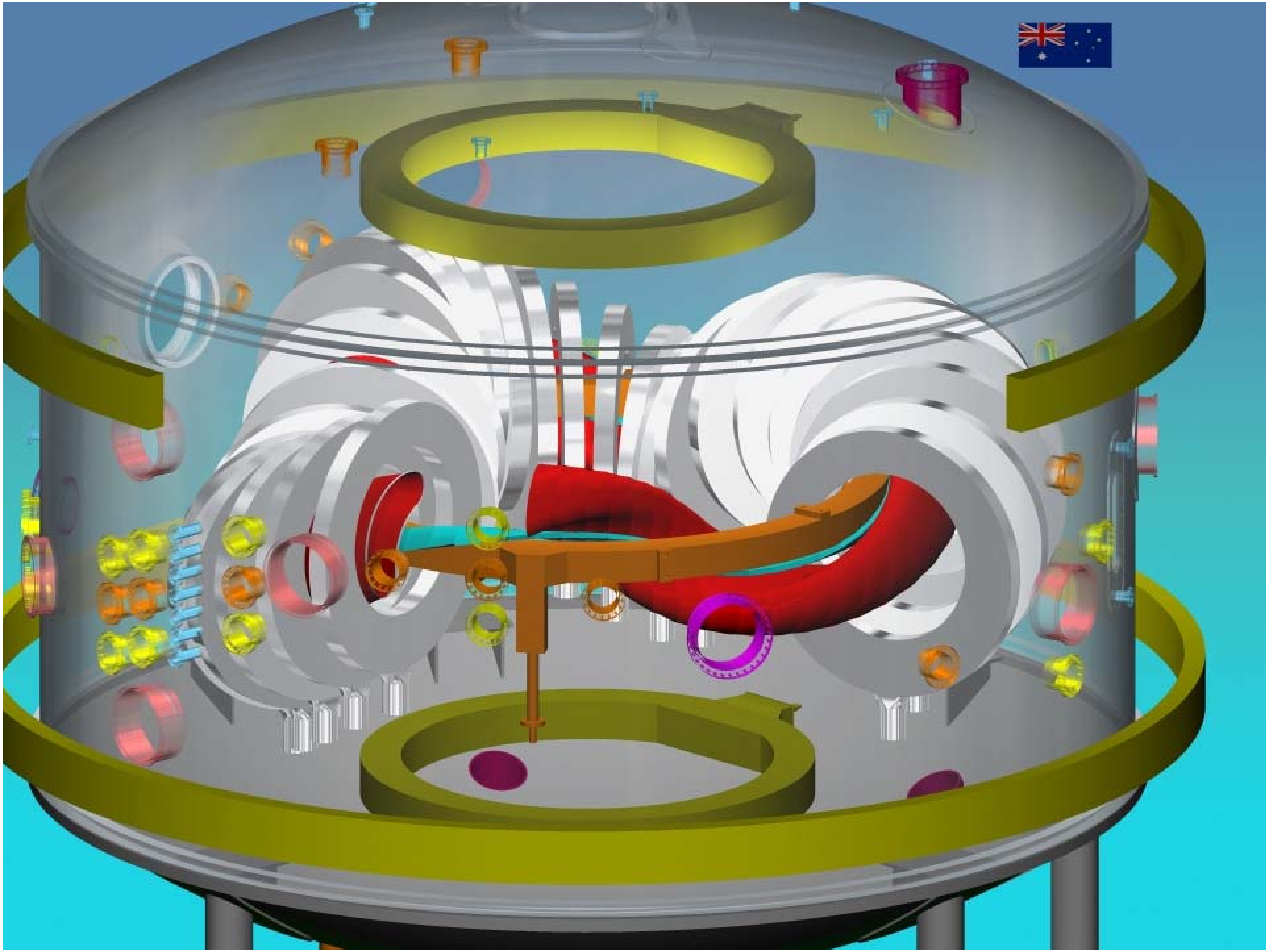
- Detailed understanding of the behaviour of magnetically confined hot plasma in the HELIAC configuration
- Development of advanced plasma measurement systems
- Fundamental studies including turbulence and transport in plasma
- Contribute to global research effort, maintain Australian presence in the field of plasma fusion power

Contract extended until 2010: includes some operational funding and limited collaborative funding

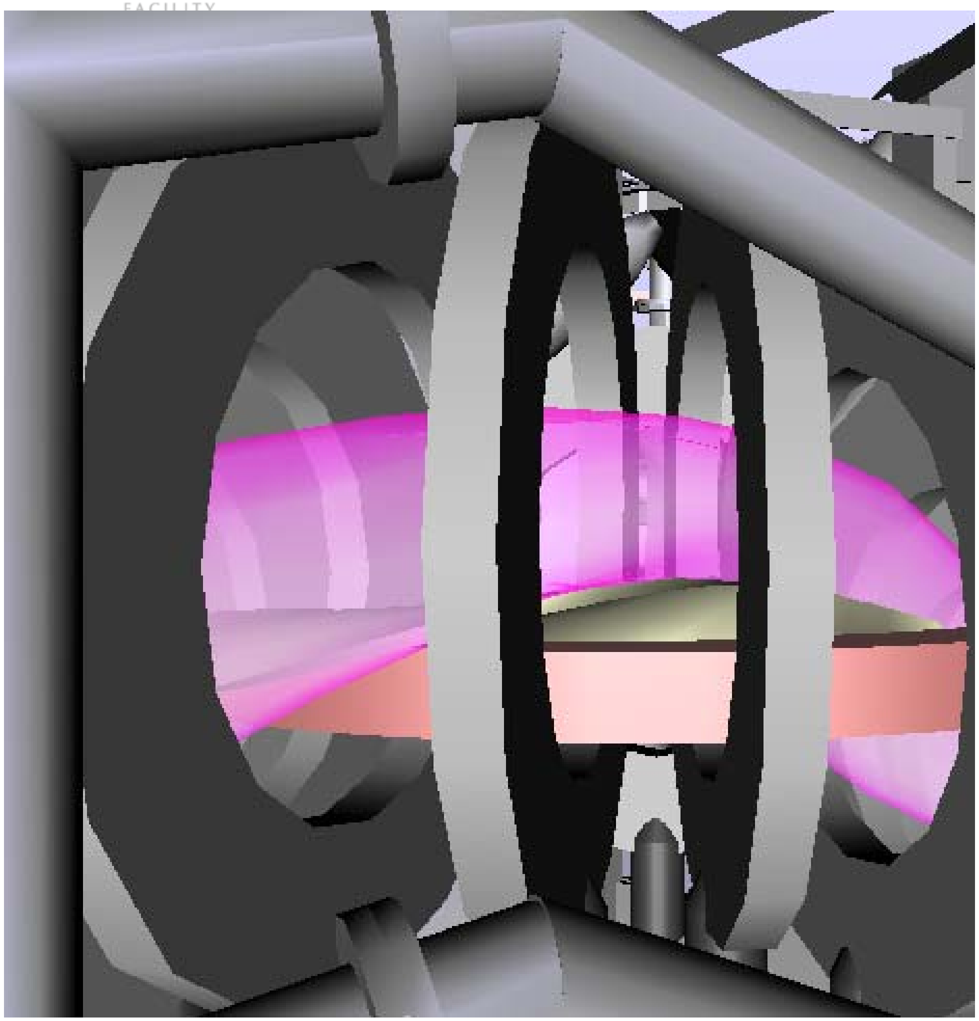
The facility is available to Australian researchers through the AINSE[1] and internationally through collaboration with Plasma Research Laboratory, ANU.

1) Australian Institute of Nuclear Science and Engineering

International collaboration played an important role in the success of H-1 in obtaining facility funding

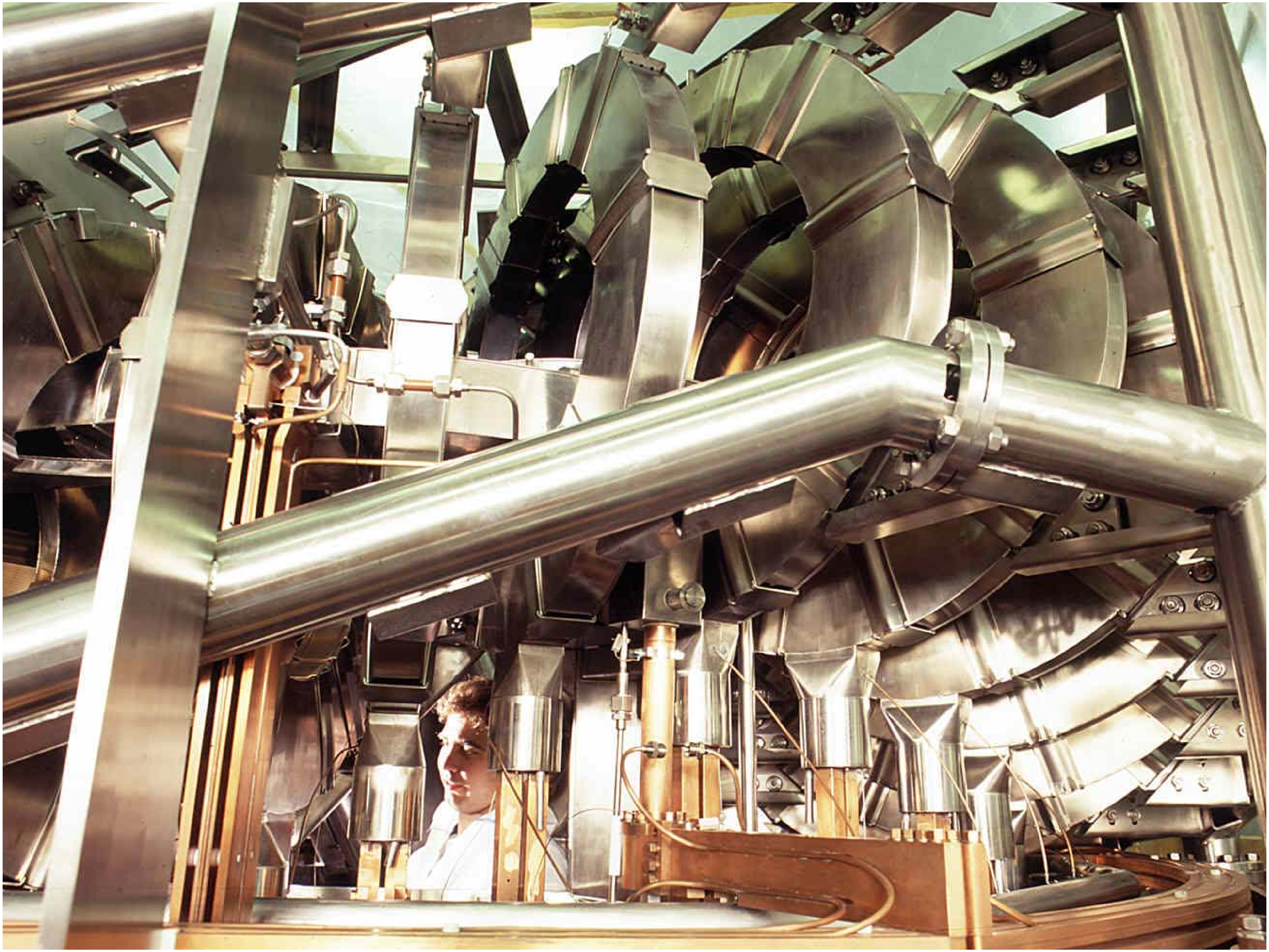


H-1 Heliac: Parameters

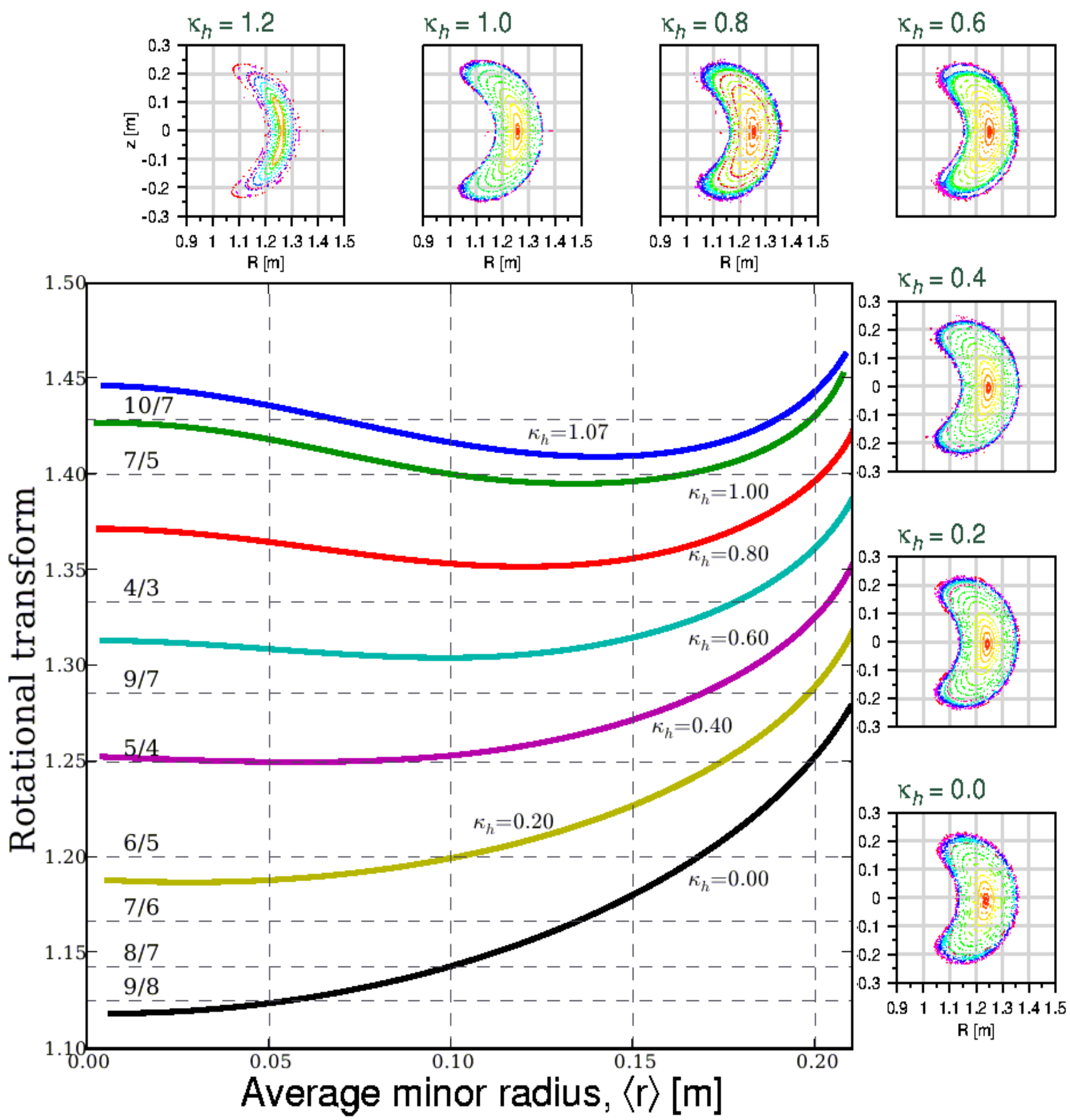


3 period heliac:	1992	
Major radius	1m	
Minor radius	0.1-0.2m	
Vacuum chamber	**$33m^2$**	**excellent access**
Aspect ratio	**5+**	**toroidal**
Magnetic Field	≤1 Tesla (0.2 DC)	
Heating Power	0.2MW 28 GHz ECH 0.3MW 6-25MHz ICH	

Parameters:	achieved to date::expected
n	3e18 :: 1e19
T	<200eV(T_e)::500eV(T_e)
β	0.1 :: 0.5%



H-1 plasma configuration is very flexible



- Original heliac:
  limited configuration range.
- ***"flexible heliac"*** :
  helical winding, with
  helicity matching the plasma,
  ⇒ 2:1 range of iota
- H-1NF can control 2 out of 3 of
  transform (ι)
  magnetic well and
  shear Δι
- **Reversed Shear, Normal Shear**

Santhosh Kumar

Experimental confirmation of configurations

Rotating wire array

- 64 Mo wires (200um)
- 90 - 1440 angles

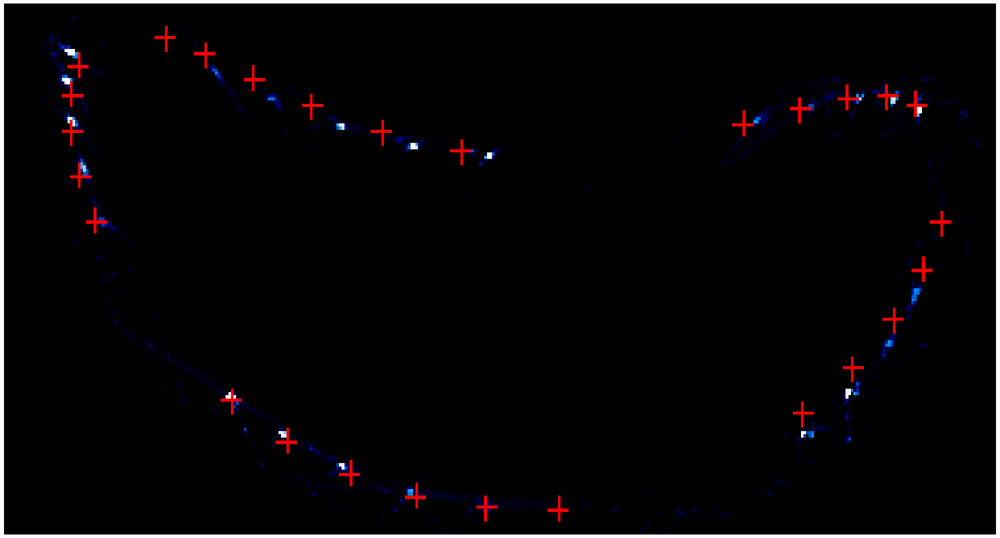
High accuracy (0.5mm)

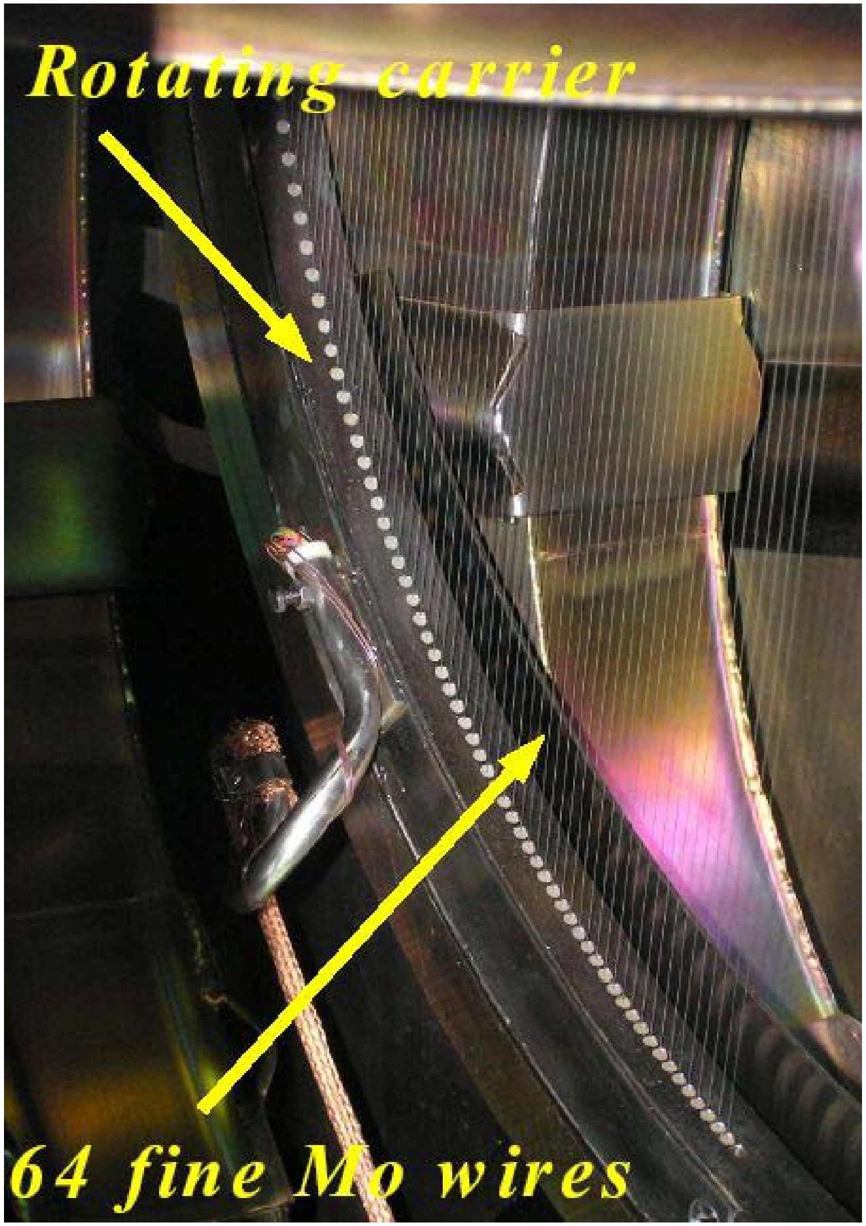
Moderate image quality

Always available

Excellent agreement with computation

T.A. Santhosh Kumar
B.D.Blackwell, J.Howard



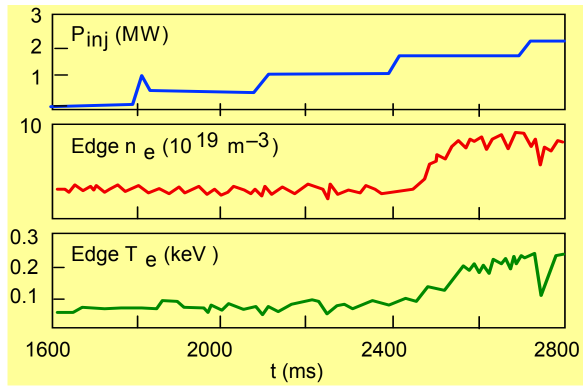


Large Device Physics on H-1

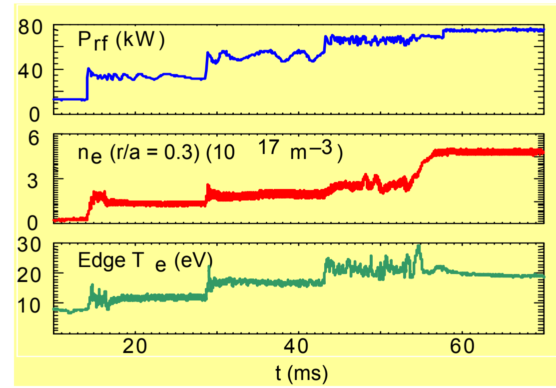
Confinement Transitions,
Turbulence (Shats, 1996--)

- High Confinement mode ('96)
- Zonal Flows 2001
- Spectral condensation of turbulence 2005

D3D tokamak

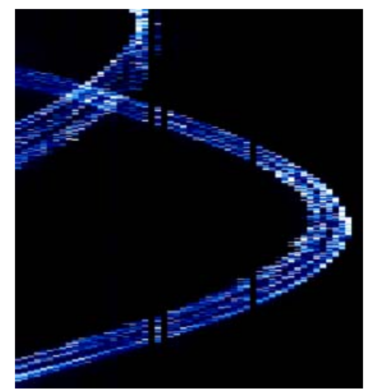


H-1



Magnetic Island Studies

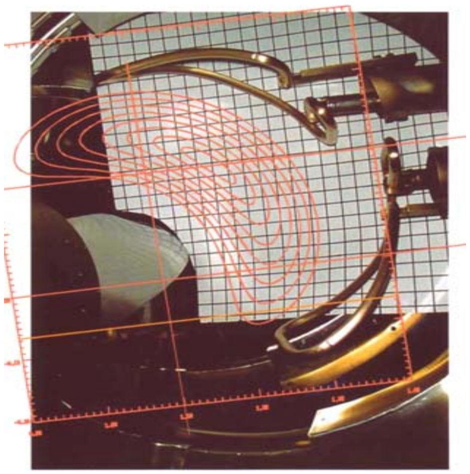
- H-1 has flexible, controlled and verified geometry
- Create islands in desired locations (shear, transform)
- Langmuir probes can map in detail



Alfvén Eigenmodes

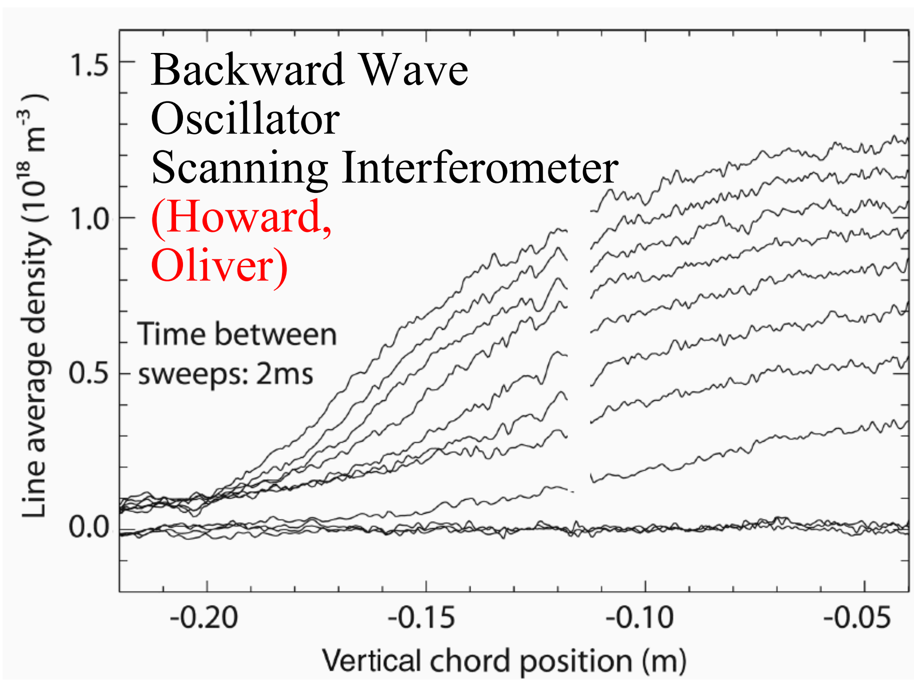
- May be excited in reactors by fusion alphas, and destroy their confinement
- (more)

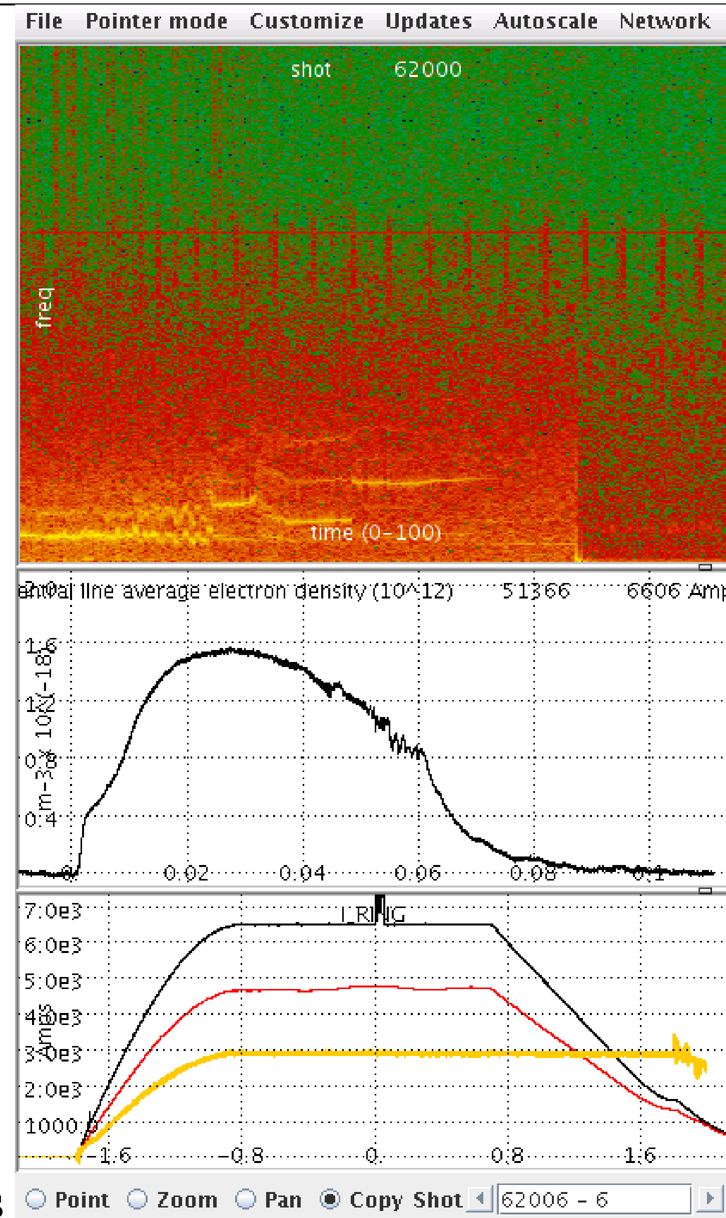
Plasma Production by ICRF



ICRF Heating:

- B=0.5Tesla, $\omega = \omega_{CH}$ (f~7Mhz)
- Large variation in n_e with iota





Axis

D. Pretty, J. Harris

Configuration scan: Magnetic Fluctuations

ICRF plasma configuration scan

Mode spectrum changes as resonances enter plasma

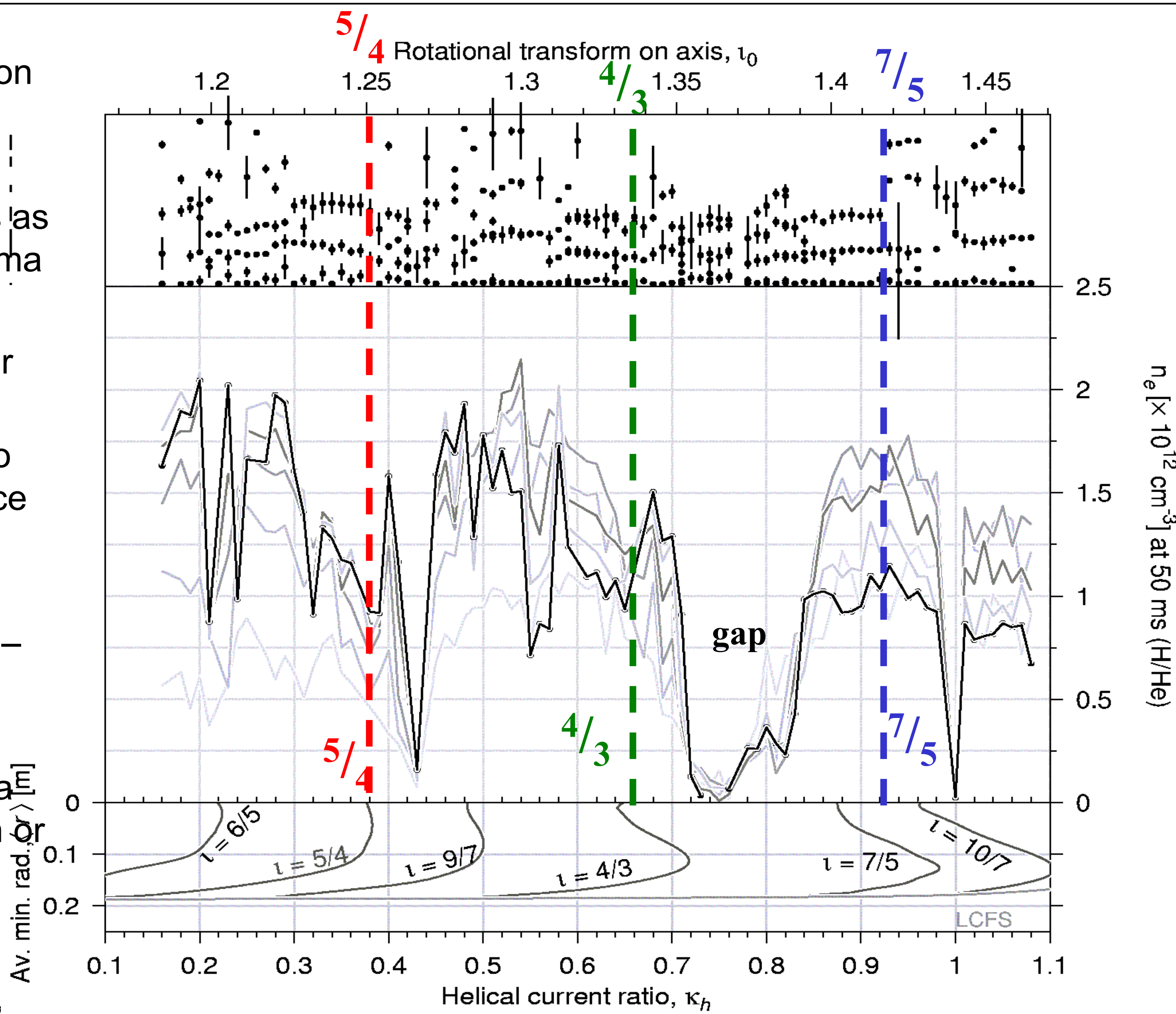
No simple explanation for "gap"

left side corresponds to zero shear at resonance

A clear connection with rational twists per turn – but what is it?

Resonant layer in plasma seems to aid formation or confinement.

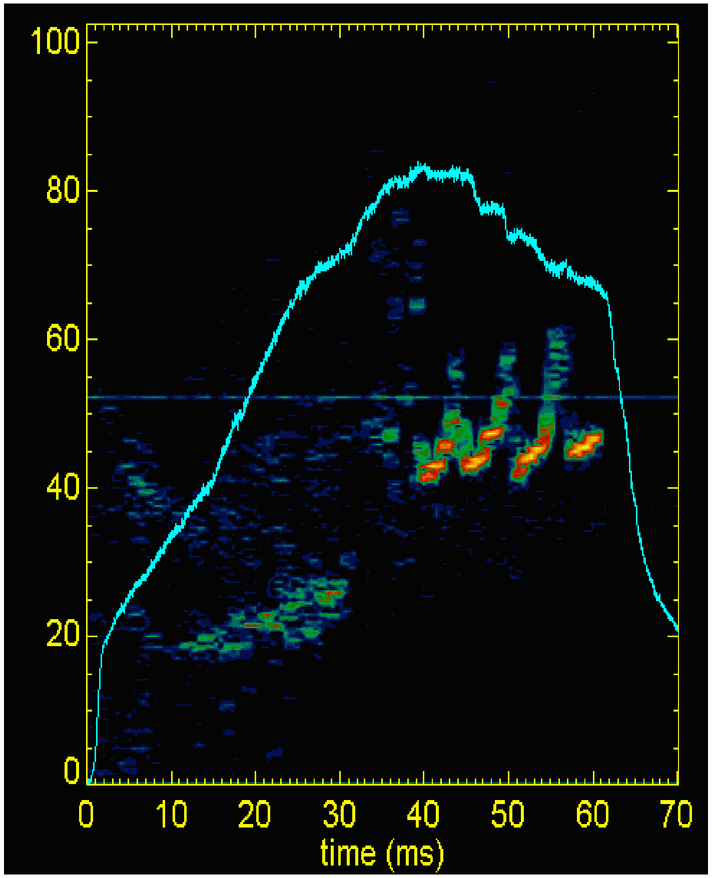
Variation with iota not pronounced in ECH.



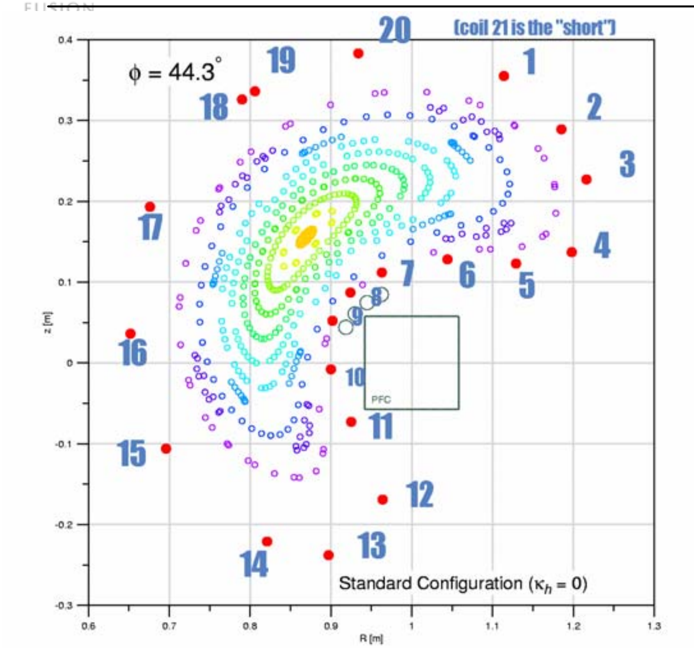
Magnetic fluctuations

approach “high temperature” conditions: H, He, D; B ~ 0.5T;
n_e ~ 1e18; T_e<50eV
$\rho_{i,e} \ll a$,
$\lambda_{mfp} \gg \ell_{conn}$

- spectrum in excess of 100kHz
- Low mode numbers: m ~ 0 - 7, n ~ 0 - 9
- $\delta b/\mathbf{B}$ ~ 2e-4
- both broad-band and coherent/harmonic nature
- abrupt changes in spectrum randomly or correlated with plasma events



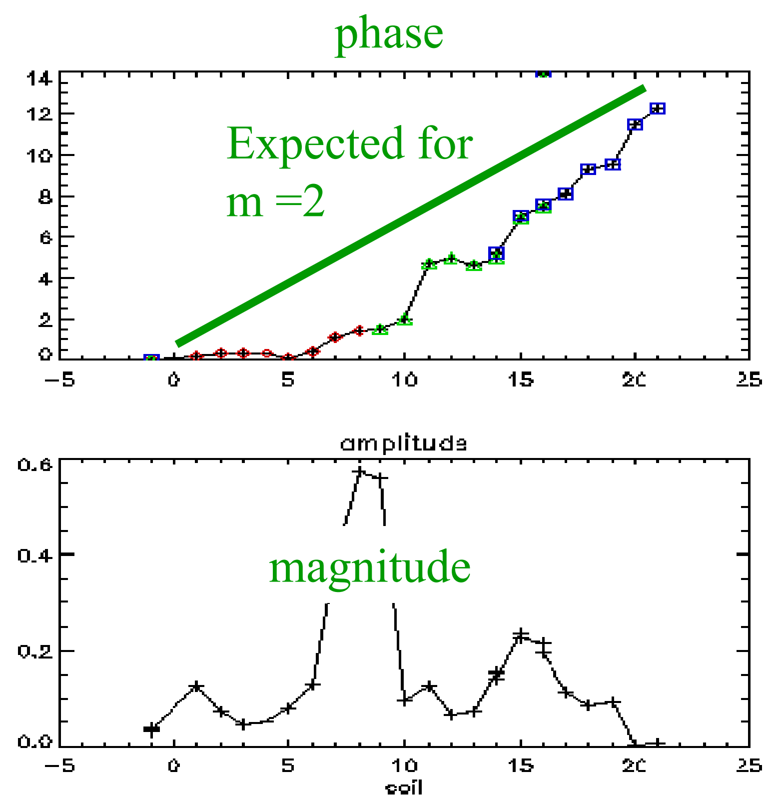
Poloidal mode number measurements



Two “bean-shaped” 20 coil Mirnov arrays

- Phase vs poloidal angle is not simple
  - Magnetic coordinates
  - External to plasma
    - Propagation effects
    - Large amplitude variation

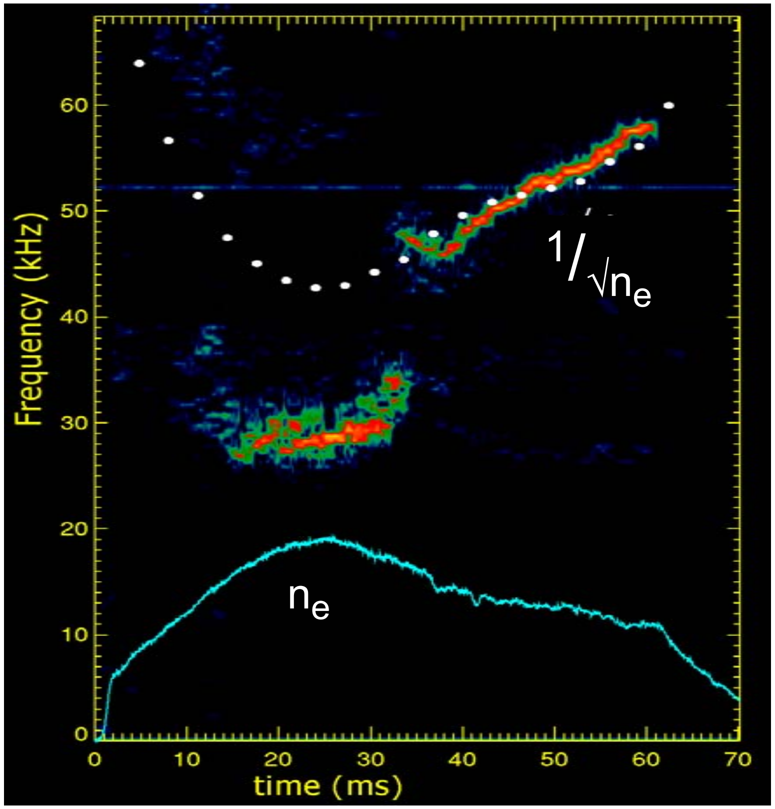
*Significant **interpretation** problem in advanced confinement configurations*

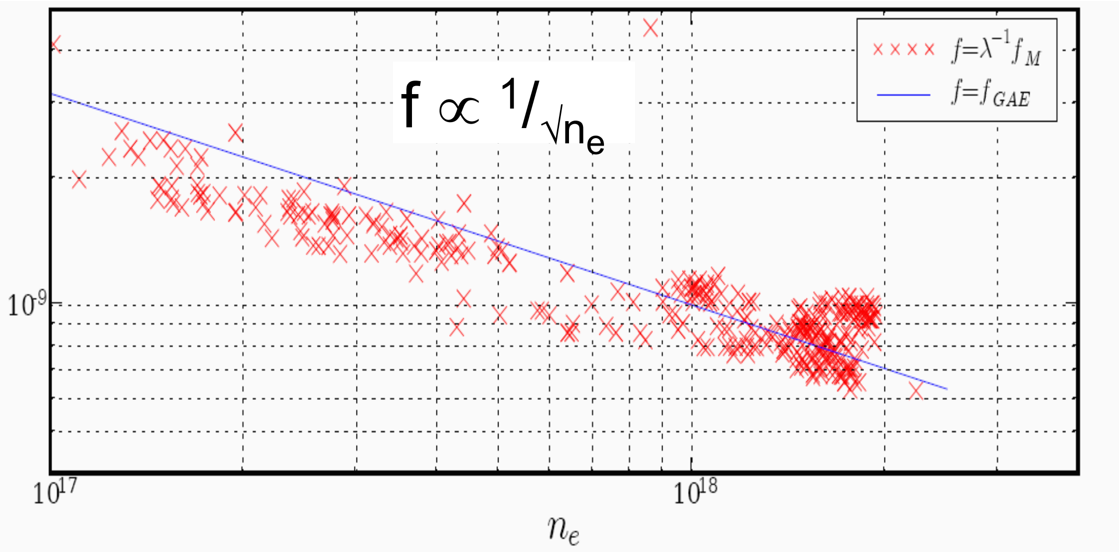


coil number (poloidal angle)

Identification with Alfvén Eigenmodes: n_e

- Coherent mode near iota = 1.4, 26-60kHz, Alfvénic scaling with n_e
- m number resolved by bean array of Mirnov coils to be 2 or 3.
- $V_{Alfvén} = B/\sqrt{(\mu_o \rho)} \propto B/\sqrt{n_e}$
- Scaling in $\sqrt{n_e}$ in time (right) and over various discharges (below)





H-1NF Data: MDSPlus + MySQL

gas properties

id	name	gauge fact	flow
1	hydrogen	2.2	2.9
2	helium	5.5	0.72
8	oxygen	0.99	8.0
18	argon	0.78	8.0

Machine and human generated data tables

Summary Database: one entry per shot - machine generated ~100 columns

Id	Shot	iring	Gas	flow_2	rf_power	p_iong	ne_18	p_iong	lenth	Comment
9001	45001	6500	He	0.0	59.1	1.1e-6	1.18	1.1e-6	.09	Test new MOSS camera
9002	45002	6500	He	2.0	57.4	2.5e-6	1.51	1.2e-6	.091	Test new MOSS camera
9003	45003	6600	H/He	0.5	59.4	1.1e-6	1.61	1.1e-6	.09	Test new MOSS camera
9004	45004	6700	H/He	0.5	55.1	1.1e-6	1.63	1.1e-6	.09	Test new MOSS camera
9005	45005	6800	H/He	0.5	61.7	1.2e-6	1.69	1.2e-6	.091	Test new MOSS camera
…..	….									

topics

id	topic	descript
1	operations	currents, tin
2	RF	RF heating
3	ECH	ECH system
4	MHD	equilibrium
5	MOSS	cameras, wh
6	probes	LP, TMT,

```
create table topics (
id int unique auto_increment,
topic enum('shotnote',
     'unknown','operations',
     'config','datasys','RF','ECH
```

Log Entry Database: many entries per shot, 21 columns

Id	Shot	topic	precis	Owner	Comment	script	Co
5001	45001	datasys		camac	Disk full error		
5002	45001	impurities	Ni impurity	bdb112	Possible line at 4047	plot_ccd_spectrum, sel-28	
5003	45001	shotnote	increase flow to 1.5	cam112			
5004	45001	MOSS	modulation voltage too low	cam112	need to modify analysis	fact=2.5 & anal_moss,foo,fact	nee ana
5005	45002	shotnote	He flow 2.0	cam112			
…..	….						

mySQL database server

php web interface

Graphic and textual queries

45002: 797A, κ_h=1.00, κ_v=1.00, Ar, 63kW, 0.43×10^{18} efuser] fix field at 1200A pressure 5e-6 28014, 15, 16 7.5e-6 017, 18,19 1.e-5 28020, 21, 22 1.6 e-5 23, 24, 25 2.e-5 26, 27, 28 2.5e-5 29,30,31 3e-5 32, 33, 34 4e-5 35, 36, 37 - two stage decay 5.1e-5 38, 39, 40 6e-5 41, 42, 43 - calibration has changed!! 7e-5 44, 45, 46 Now try changing B-field to see influence on decay pressure 7e-5 @1200 800A 47, 48, 49 - density jumps! 1000A 50(closer to 950A) 51, 52 jumps and modes - change in rf matching 1400A 53, 54, 55 1600A 56 - not taken current too high earth fault trip - finish today highest density so far is 1.5 e12 at 28050 - looks lower than overall highest wshow

highest densities -

6 5 fill highest deltaP is 45406 - 80ms 5.3e-6 - note CN26! [shotnote] [defuser] where G means Global mode, Q means quiet, H high ne, L low ne Of all these, the only one that is high power at 2 is 17, which is definitely 2sccm, and shows a deltaP of 1.6e-6, mainly H and CO, and seems to start from a relatively clean condition.

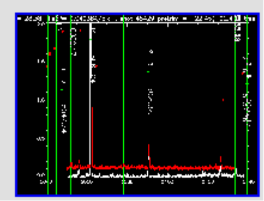
45445: lab not found shot 45445 not found

RGA sens turned up by 10x - now 28 peak is off scale. [shotnote] [defuser] ------------ 45440-49 Hy/He 0.5 Tesla just to test ABB supply The density was a little low compared to before - e.g. 1e12 and rising for he1,hy1, 60ms 6500 e.g. 44023 is the highest under these conditions 1.6e12, but it used 4sccm He, also 44013, but it is strange too - looks like std fill (1,0.6), but 7000A, and a little puff and ECH Not surprising that it behaves differently - lots of cleaning, and > 4 weeks since the last shot.

[plot_ccd_spectrum,sh=45429,sel=[1,2,6,7,14,17,18],tri=-22.45,en=2128,yr=[0,2],yty=0&plot_ccd_spectrum,sh=45429,/opl,col=2] larry has data up to 2128 - need to increase digitizer length

45545: lab not found shot 45545 not found

72.5kV DS, 5.17 - this might be the highest so far - dn/dt=121, cf 150 at 1.9e12 [shotnote] [defuser]



D. Pretty

Mode Decomposition by SVD and Clustering

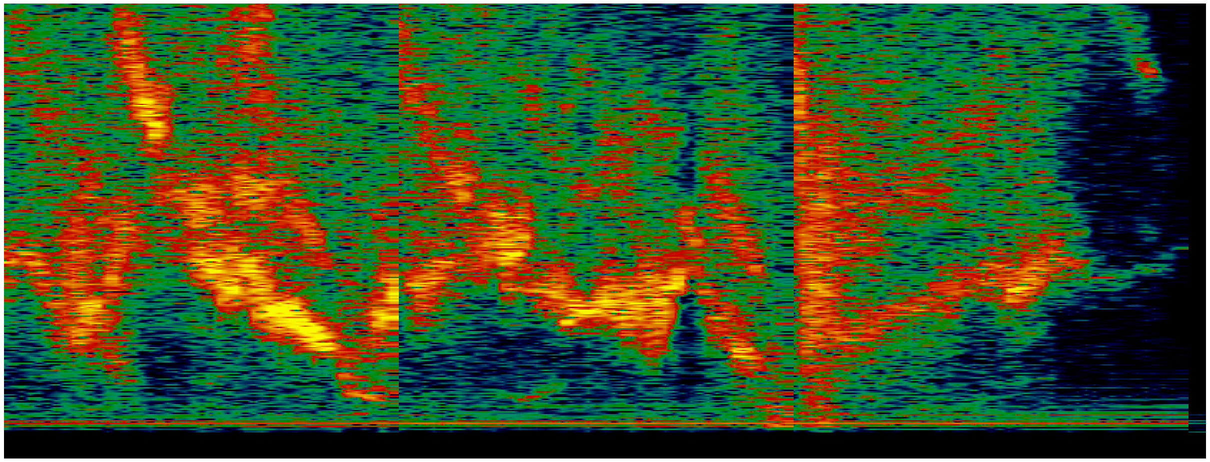
- Initial decomposition by SVD → ~10-20 eigenvalues
- Remove low coherence and low amplitude
- Then group eigenvalues by spectral similarity into fluctuation structures
- Reconstruct structures to obtain phase difference at spectral maximum
- Cluster structures according to phase differences (m numbers)

→ reduces to 7-9 clusters for an iota scan

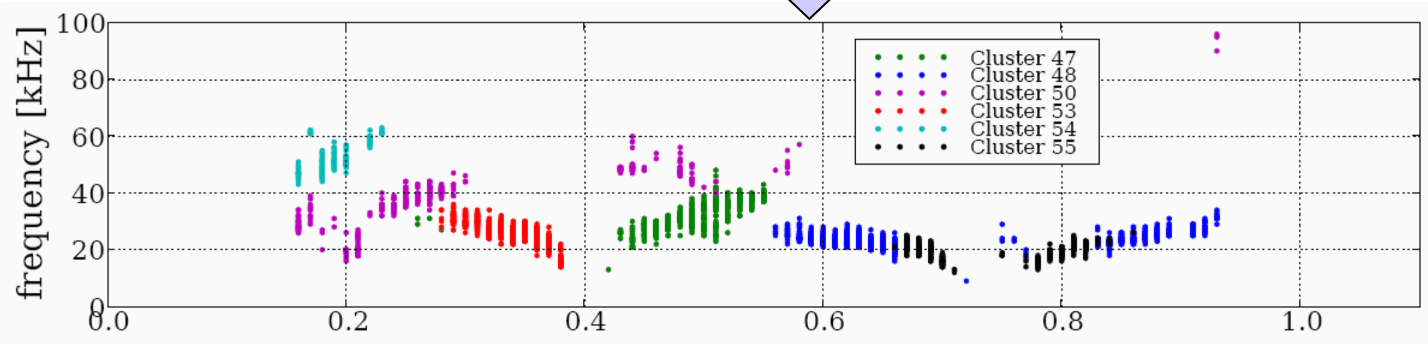
Grouping by clustering potentially more powerful than by mode number

- – Recognises mixtures of mode numbers caused by toroidal effects etc
- – Does not depend critically on knowledge of the correct magnetic theta coordinate

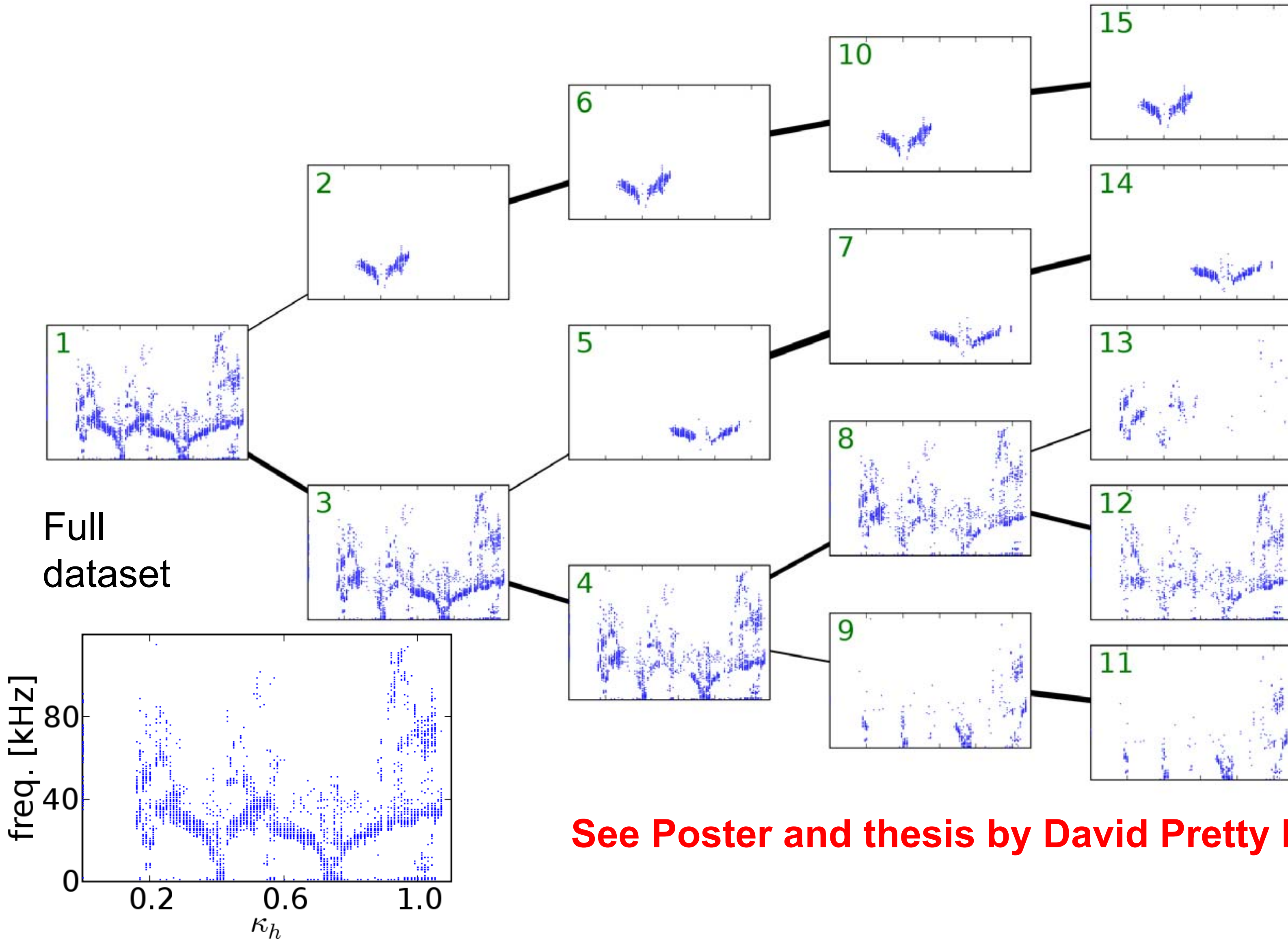
- 4 Gigasamples of data
  - – 128 times
  - – 128 frequencies
  - – $^2C_{20}$ coil combinations
  - – 100 shots



Data mining



Data Mining Classification by Clustering

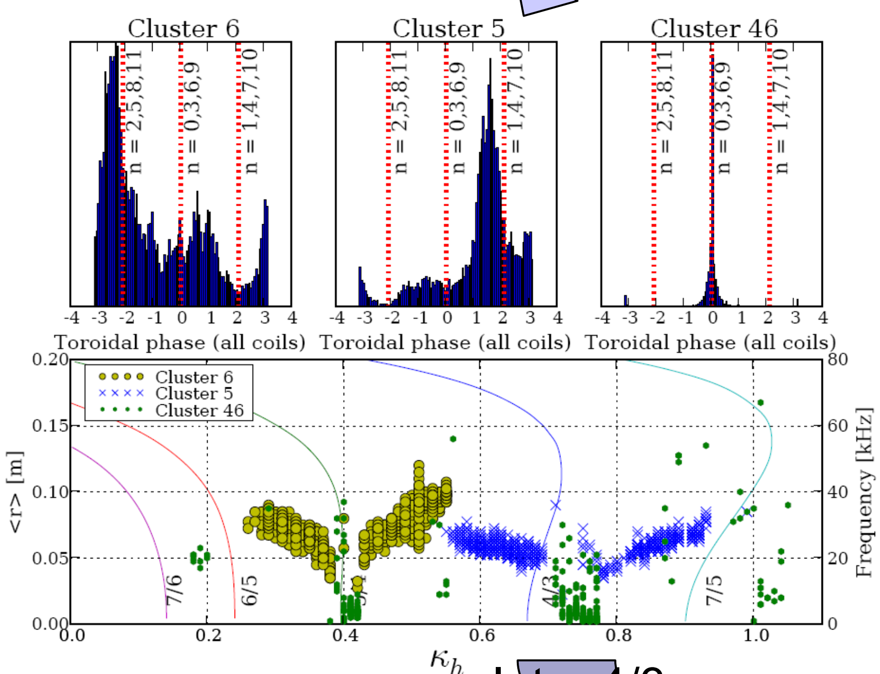


See Poster and thesis by David Pretty P2: 83 Wed.

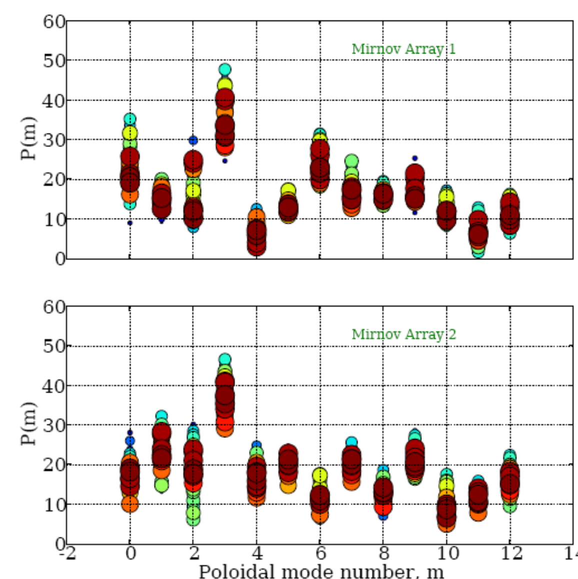
Mode numbers consistent with iota

- Mode analysis of the clusters found is complex, but is consistent with the rotational transform

dominant n=4



Iota=4/3



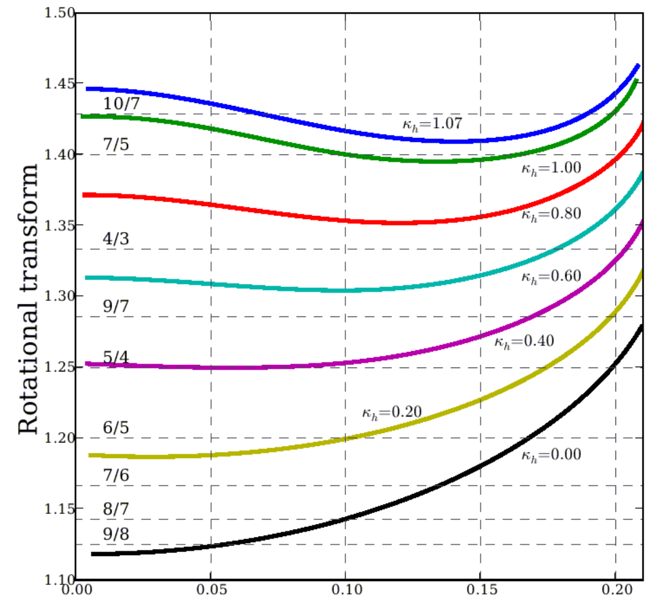
dominant m=3

Identification with Alfvén eigenmodes: $k_{||,}$ iota

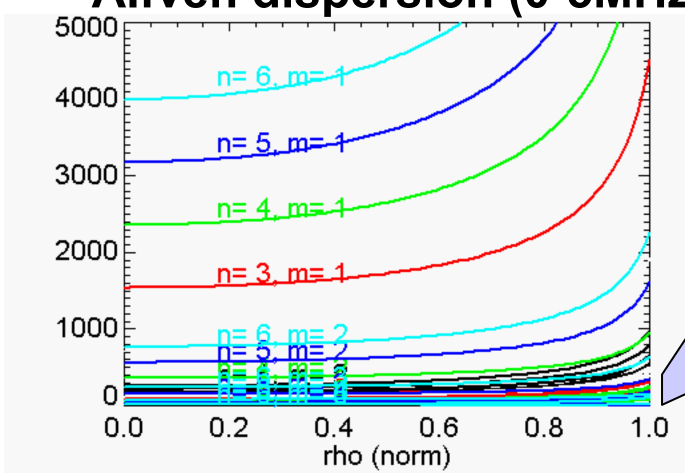
- $\omega_{res} = k_{||} V_{Alfvén} = k_{||} B/\sqrt{(\mu_o \rho)}$
- $k_{||}$ varies as the angle between magnetic field lines and the wave vector
- for a periodic geometry the wave vector is determined by mode numbers n,m
- Component parallel to B is $\propto \iota - n/m$

  $k_{||} = (m/R_0)(\iota - n/m)$

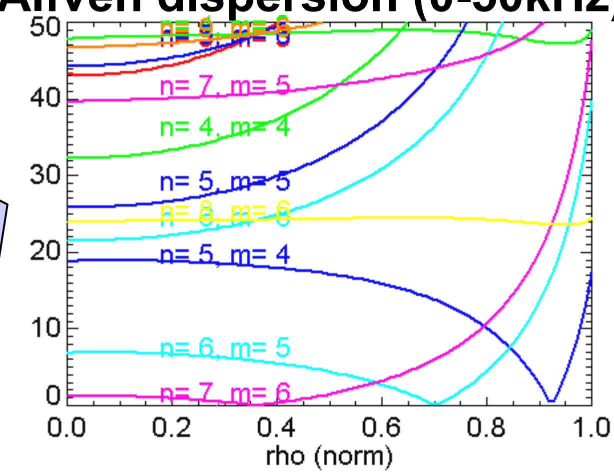
  $\omega_{res} = (m/R_0)(\iota - n/m)\, B/\sqrt{(\mu_o \rho)}$
- Low shear means relatively simple dispersion relations



Alfvén dispersion (0-5MHz)



Alfvén dispersion (0-50kHz)



Near rationals, resonant freq. is low

David Pretty

Identification with Alfvén eigenmodes: $k_{||}$, iota

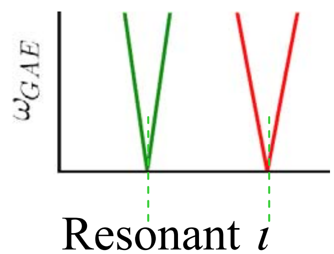
$$\omega_{res} = k_{||} V_A = (m/R_0)(\iota - n/m)\ B/\sqrt{(\mu_o \rho)}$$

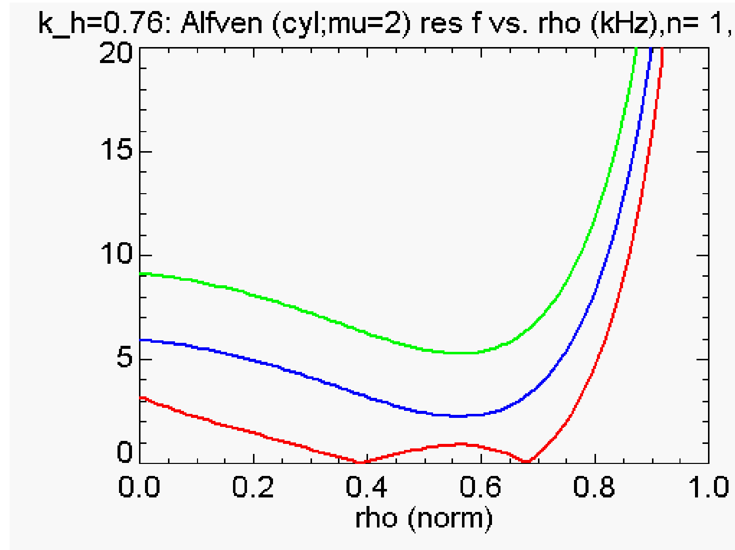
- $k_{||}$ varies as the angle between magnetic field lines and the wave vector

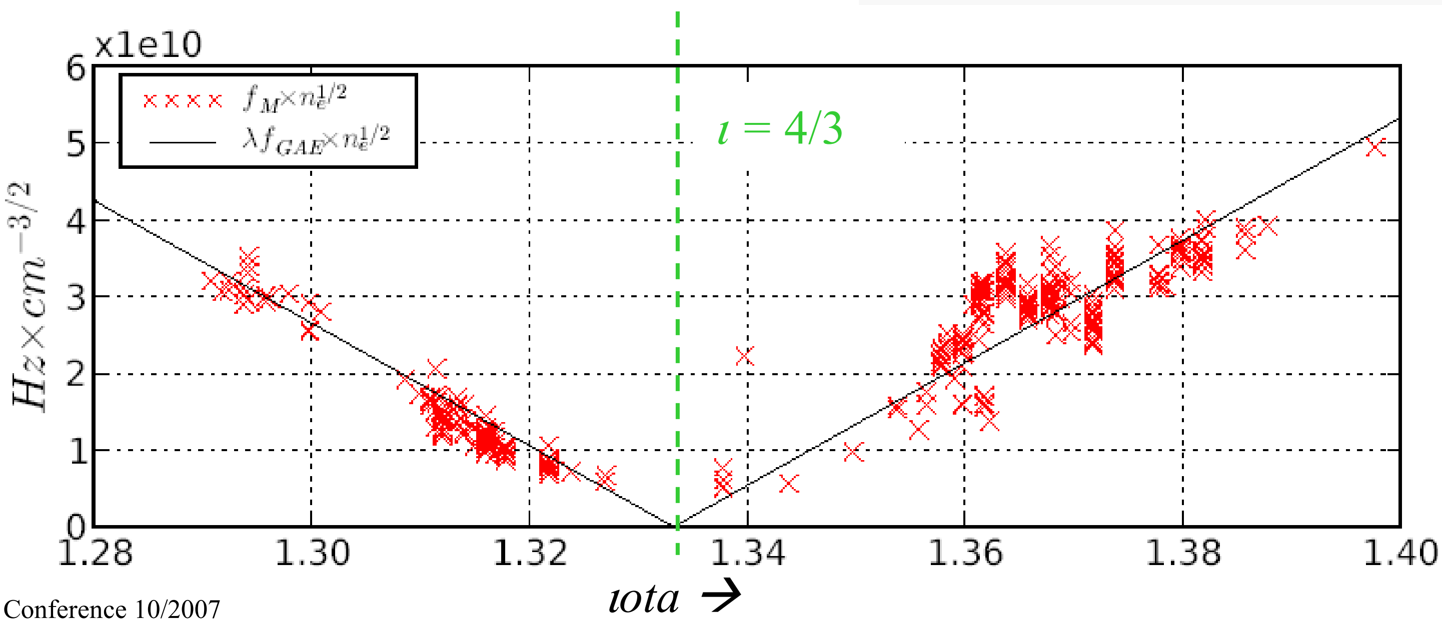
$$k_{||} \propto \iota - n/m$$

- iota resonant means $k_{||}, \omega \rightarrow 0$

Expect F_{res} to scale with δ iota



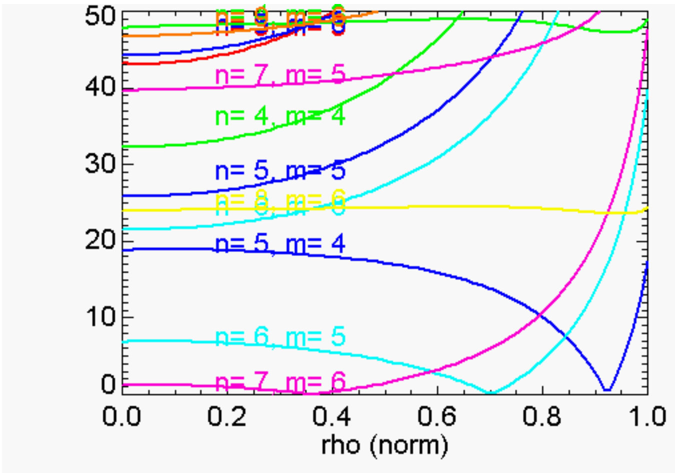




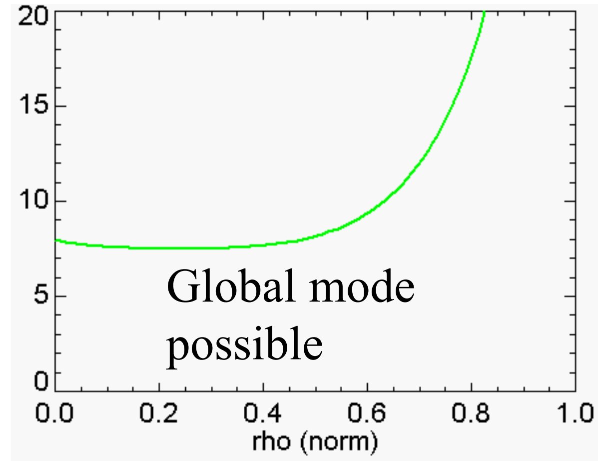
Blackwell, ISHW/Toki Conference 10/2007

Alfvén eigenmode frequency: radial variation

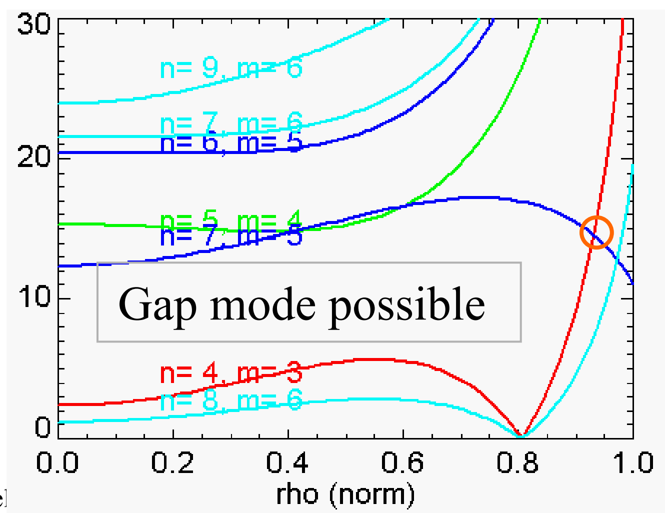
$$\omega_{res} = k_{||} V_A = (m/R_0)(\iota - n/m)\, B/\sqrt{(\mu_o \rho)}$$



Iota ~ 7/6



just below iota ~ 5/4



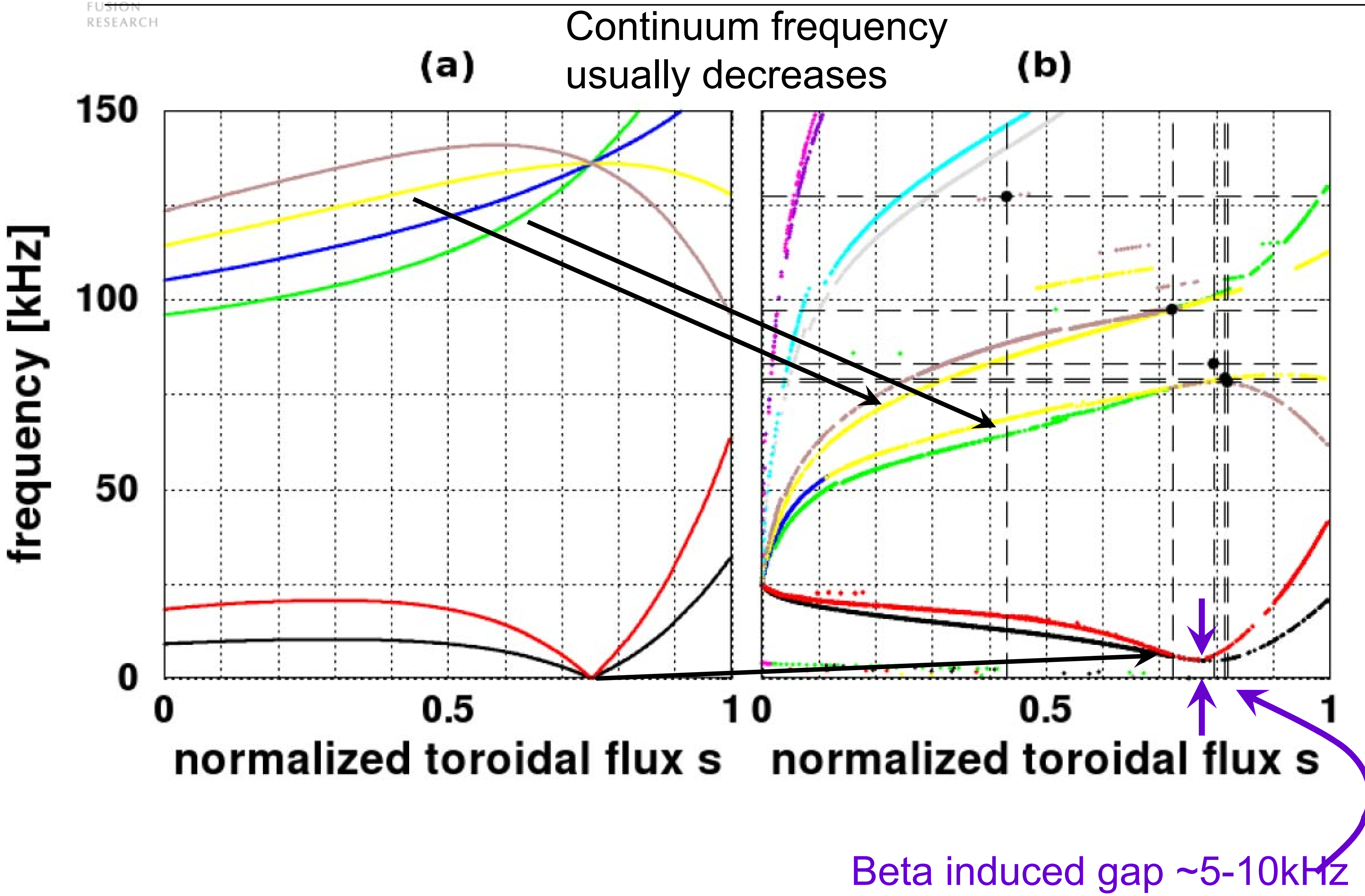
iota ~ 4/3

HAE gap likely as

$$\frac{n_1 - n_2}{m_1 - m_2} = \frac{3}{2}$$

Carolin Nuhrenberg

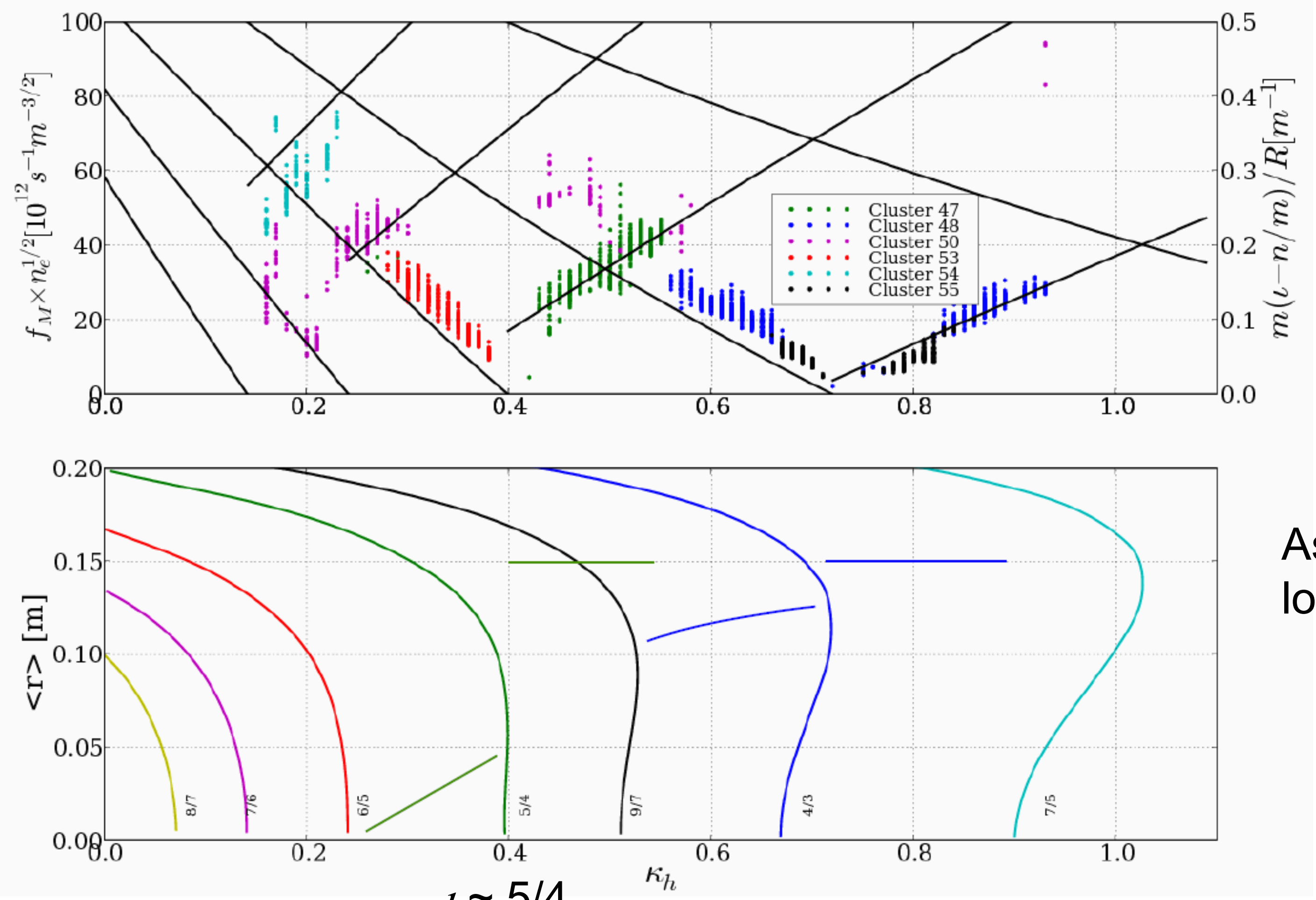
CAS3D: 3D and finite beta effects



David Pretty

Closer inspection → radial location

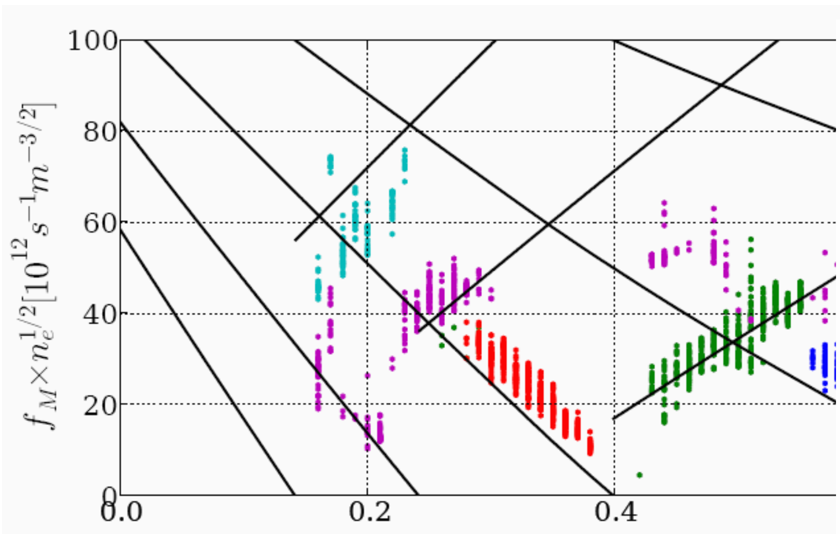
Better fit of frequency to iota, n_e obtained if the location of resonance is assumed be either at the zero shear radius, or at an outer radius if the associated resonance is not present.

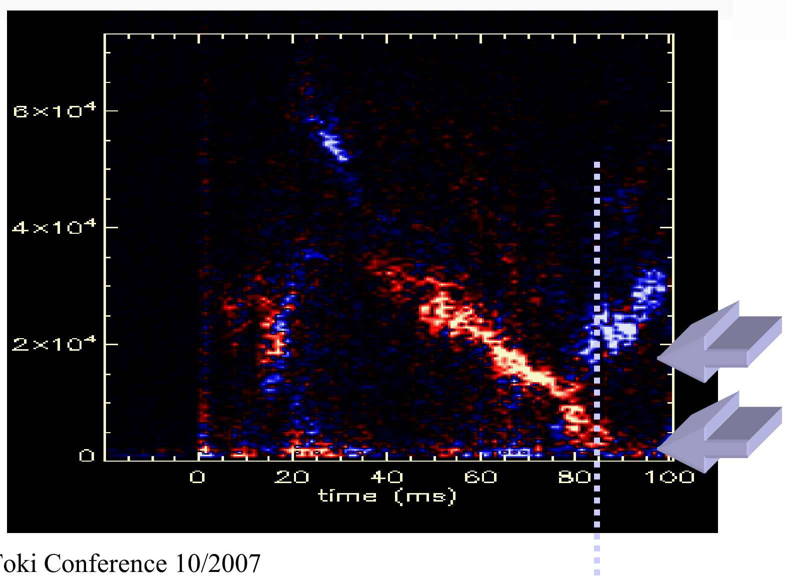


Assumed mode location

ι ~ 5/4

Two modes coexisting at different radii





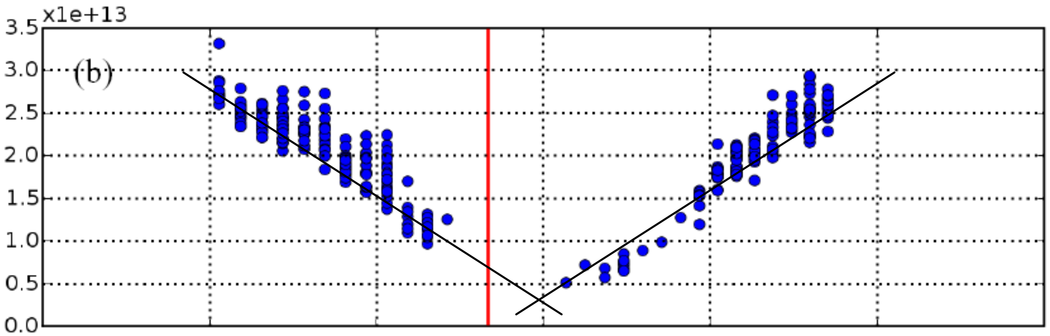
- Cross-power between n_e and Mirnov coils shows two modes coexisting
- Probably at different radii as frequency is different, mode numbers the same

Santhosh Kumar

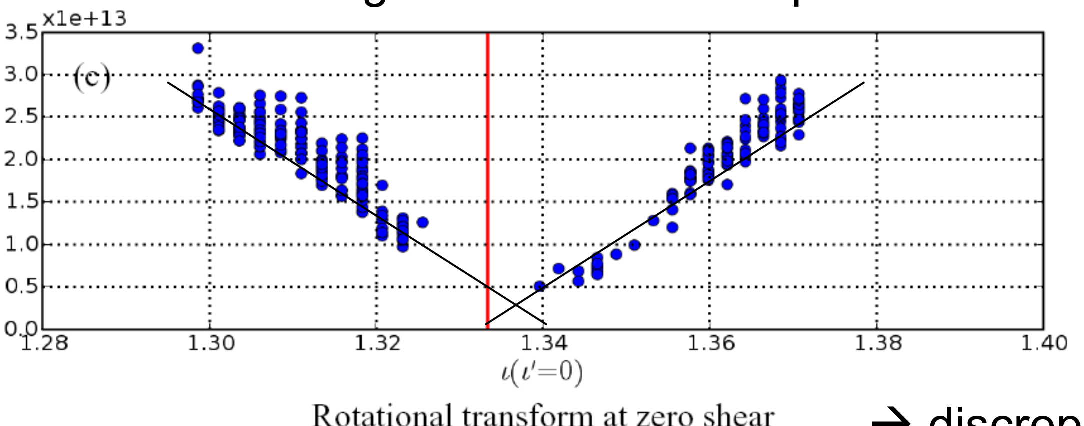
Accurate cross-check of iota

Potential to be iota diagnostic (if shear low)

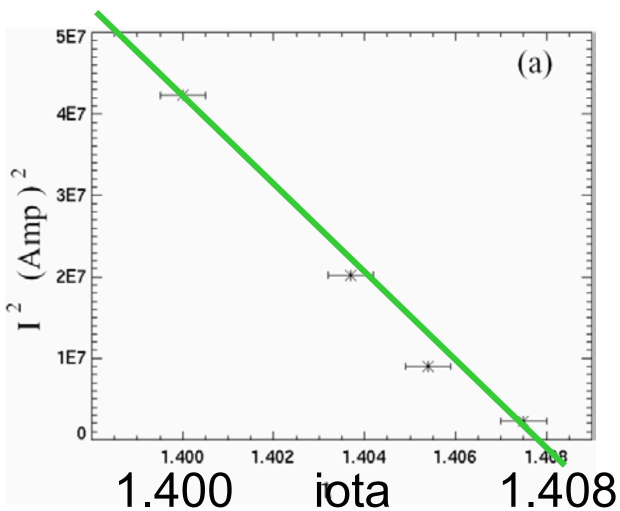
Original iota calibration at reduced field



Corrected iota agrees better with dispersion



Transform decreases by 0.5% at high field



δ iota $\propto I^2$

→ discrepancy halved

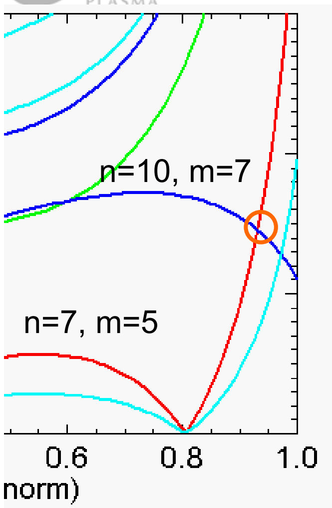
Scaling discrepancies

phase

- $\omega_{res} = k_{||} V_{Alfvén} \quad = k_{||} {}^{B}/_{\sqrt{(\mu_o \rho)}}$
- Numerical factor of ~ 1/3 required for quantitative agreement:
  - Impurities (increased effective mass) may account for 15-20%
  - 3D MHD effects ~ 20-40%
  - Still a factor of 1.5-2x required
- Magnetic field scaling is unclear
  - Ion cyclotron resonant heating with fixed frequency couples plasma preparation with magnetic field variation
  - Possible that expected scaling (f ~ B) applies, but indications of f ~ 1/B
- Unknown drive physics
  - V_A ~5e6 m/s – in principle, H+ ions are accelerated by ICRH, but poor confinement of perpendicular H+ at V_A and $V_A/3$ in the heliac configuration makes this unlikely.
  - Electron energies are a better match, but the coupling is weaker.
  - The bounce frequency of the higher energy thermal H+ is in the range of observed frequencies

David Pretty

Helical Alfvén eigenmode



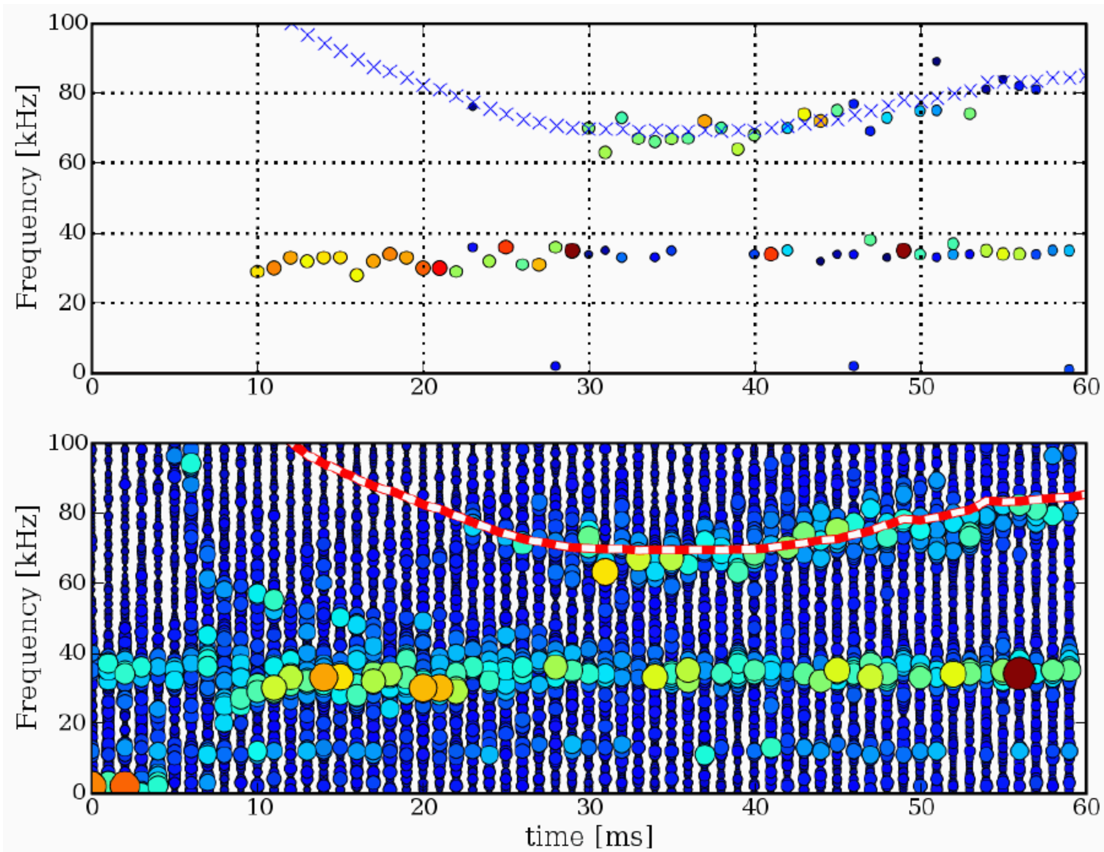
Helical gap mode likely at coalescence of 7/5 and 10/7

as

$$\frac{n_1 - n_2}{m_1 - m_2} = \frac{3}{2}$$

Good scaling with n_e,

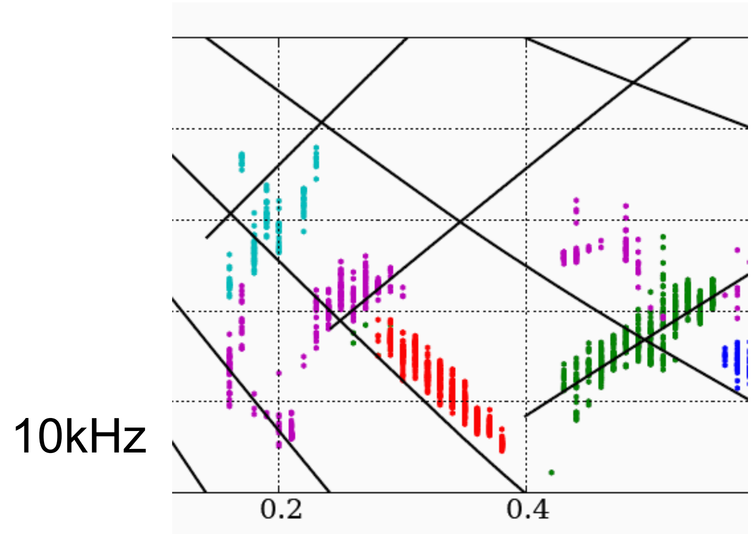
Correction is ~ 0.7 –
typical of 3D effect

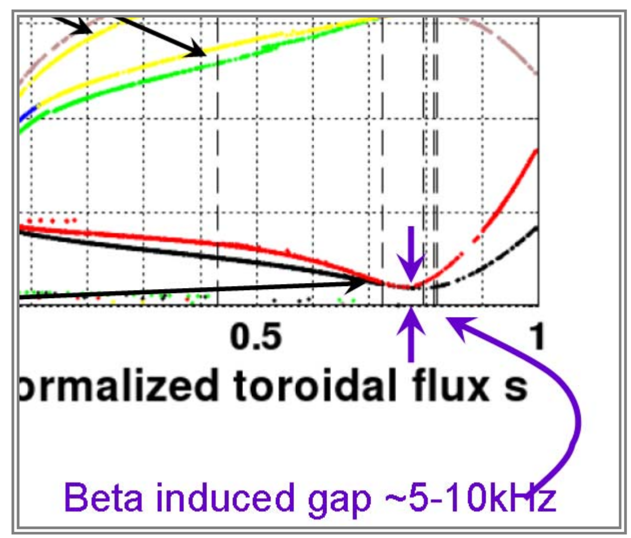


Blackwell, ISHW/Toki Conference 10/2007

Beta-induced Alfvén eigenmodes?

- At low beta in H-1 (10^{-4}), the beta-induced gap is in the range 5-10kHz.
- This is within the range of the modes near resonance, when iota-n/m is small
- Beta induced gap scales with temperature rather than magnetic field
- → interactions between the beta induced gap and Alfvén continuum could help explain the ambiguous B dependence.
- Scaling of f ~n/m (not ι- n/m) does not explain frequency dependence on ι.
- Evidence of electrostatic modes, but not at resonance where GAM-like behaviour may be expected.



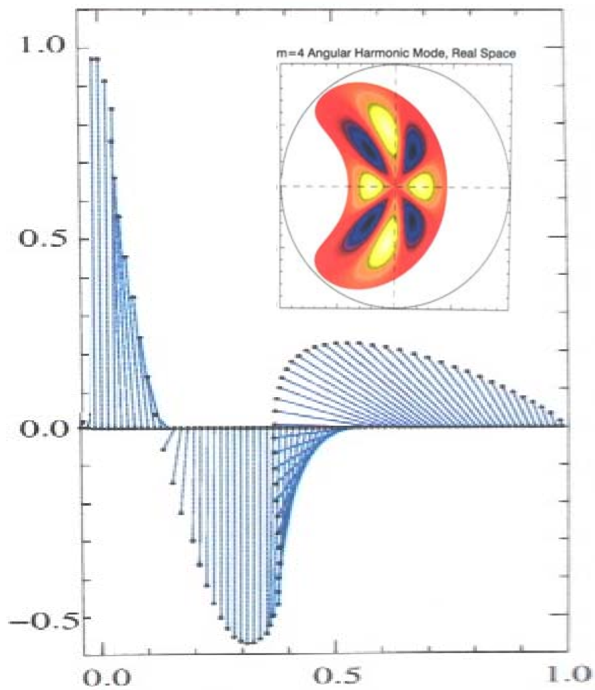


Howard, Byrne, Oliver

Radial Structure: interferometry and optical emission

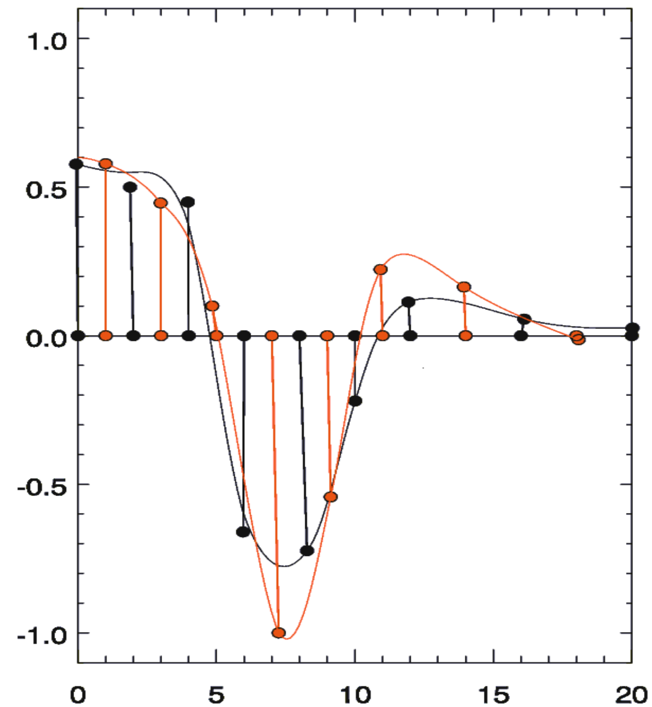
Mode simulated by rotating m=4 Fourier
Bessel object in magnetic coordinates

m=4 simulation



Average minor radius

Measured projections near iota=5/4



Height above magnetic axis

Mode is strong in outer region, indication that
the central amplitude is reduced.

Summary

See also
Michael Shats: Wed 14:10
David Pretty: P2: 83 Wed.
R. Numata: P2: 59 Wed.

H-1 National Facility

- Configurational flexibility
- Large device physics accessible
  Confinement Transitions, Alfvén Eigenmodes, Magnetic Islands
- Test Bed for Advanced Diagnostic Development
- H1 plasma can be used to develop reactor edge plasma diagnostics

Alfvénic modes observed

- Iota scan is a valuable additional test parameter, especially at low shear
- Increased dimensionality of data space (iota, ne, B, frequency, m, n) is handled by datamining
- Strong evidence for Alfvénic scaling in n_e, k||, f
- Unclear B scaling (resonant plasma production)
- Around resonance, frequency is low by a factor of ~ 3.
- Sensitive interferometer and PMT array → valuable mode profile information
- In low shear configurations, near resonant AEs can provide sensitive iota diagnostics under full plasma conditions.
- Will apply technique to Heliotron J and TJ-II data.