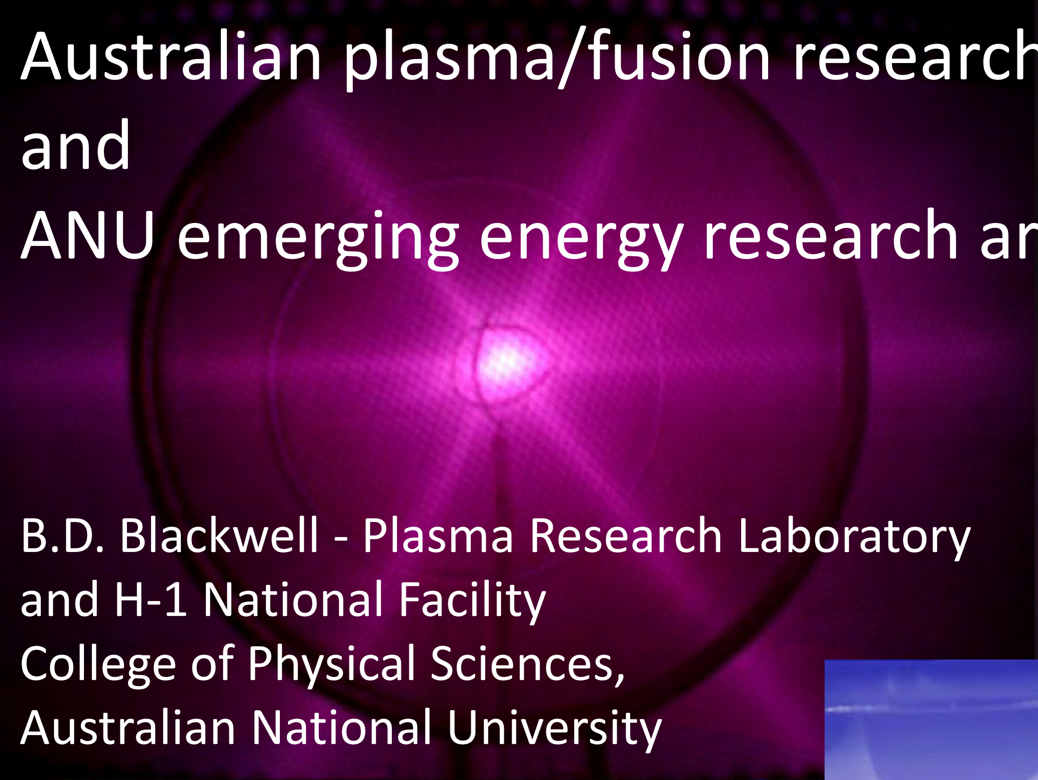
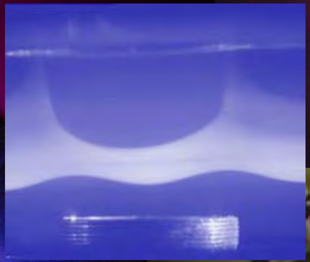
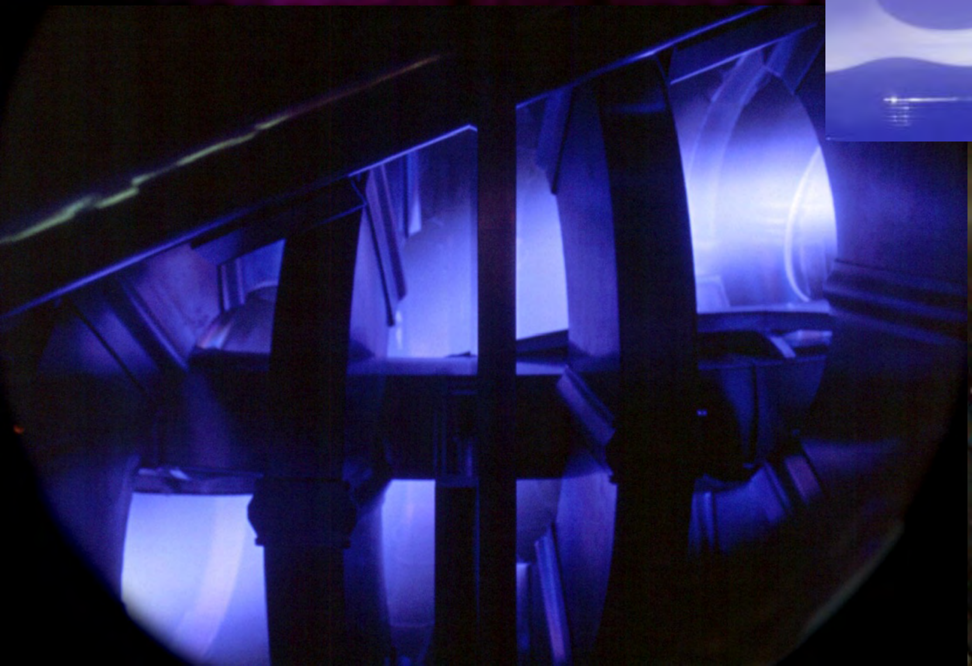
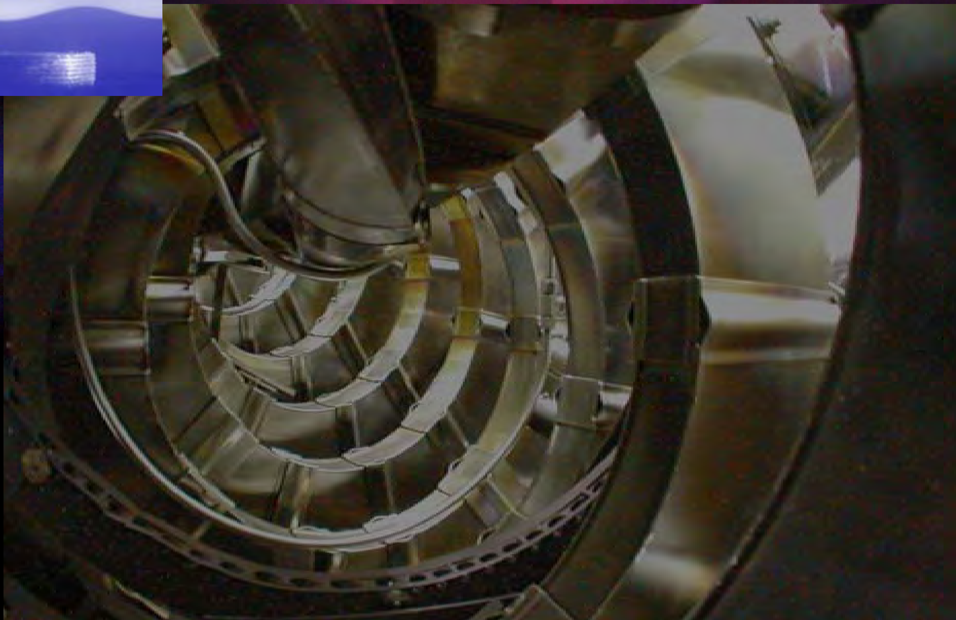
Australian plasma/fusion research
and
ANU emerging energy research areas



B.D. Blackwell - Plasma Research Laboratory
and H-1 National Facility
College of Physical Sciences,
Australian National University







NATIONAL PLASMA FUSION RESEARCH FACILITY

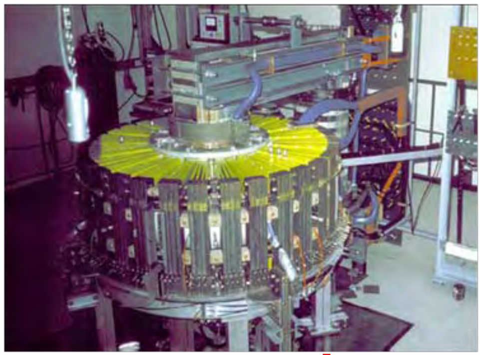
Outline

- Plasma/fusion research in Australia
  - Brief history
  - Main Themes
  - Examples
    - IEC, Dust in Fusion Plasma, Atomic Cross-sections, Theory, Materials, Diagnostics, Collaborations, H-1NF
  - Future – Energy Politics, the Australian ITER Forum

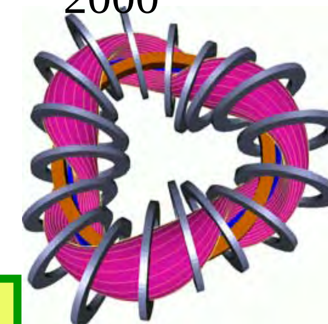
- The Australian National University Emerging Energy Initiative
  - (Fusion Research)
  - Solar – High/Low Temp Thermal, PV, Sliver Cells
  - Bio and Chemical Energy
  - Fuel Cell – Plasma nano fabrication
  - Artificial Photosynthesis/Bio Solar

Brief History of Australian Fusion Research

1960 1970 1980 1990 2000

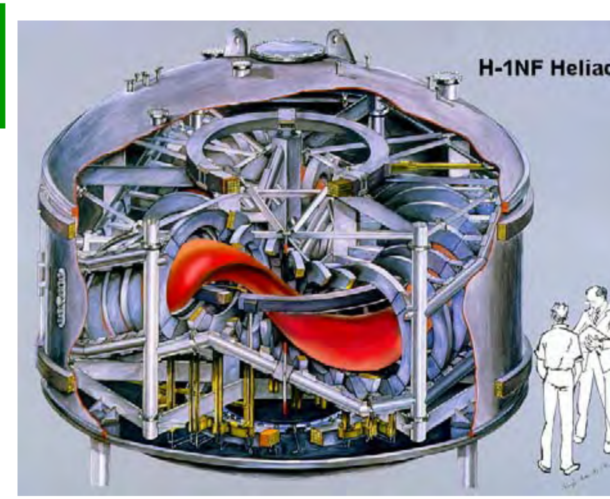


Liley Torus



First Heliac

SHEILA → H-1 Heliac

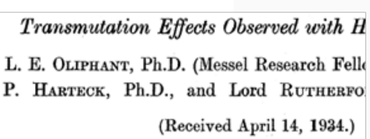


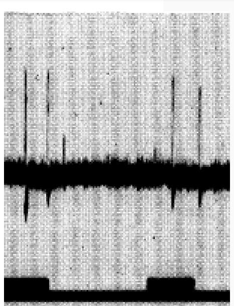
Oliphant: Discovery of Fusion (T)

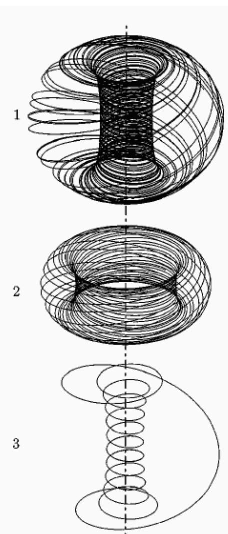
First Tokamak in West - Liley

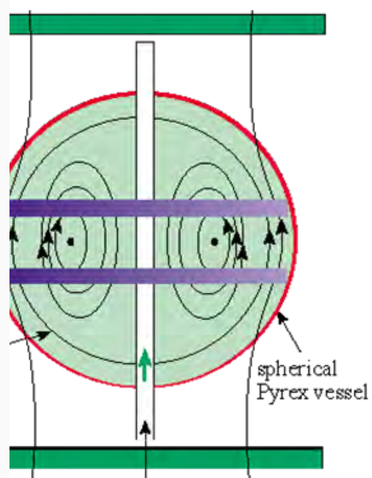
First Spherical Torus (ANSTO)

Rotamak (Flinders)


Transmutation Effects Observed with H
L. E. Oliphant, Ph.D. (Messel Research Fell
P. Harteck, Ph.D., and Lord Rutherfo
(Received April 14, 1934.)





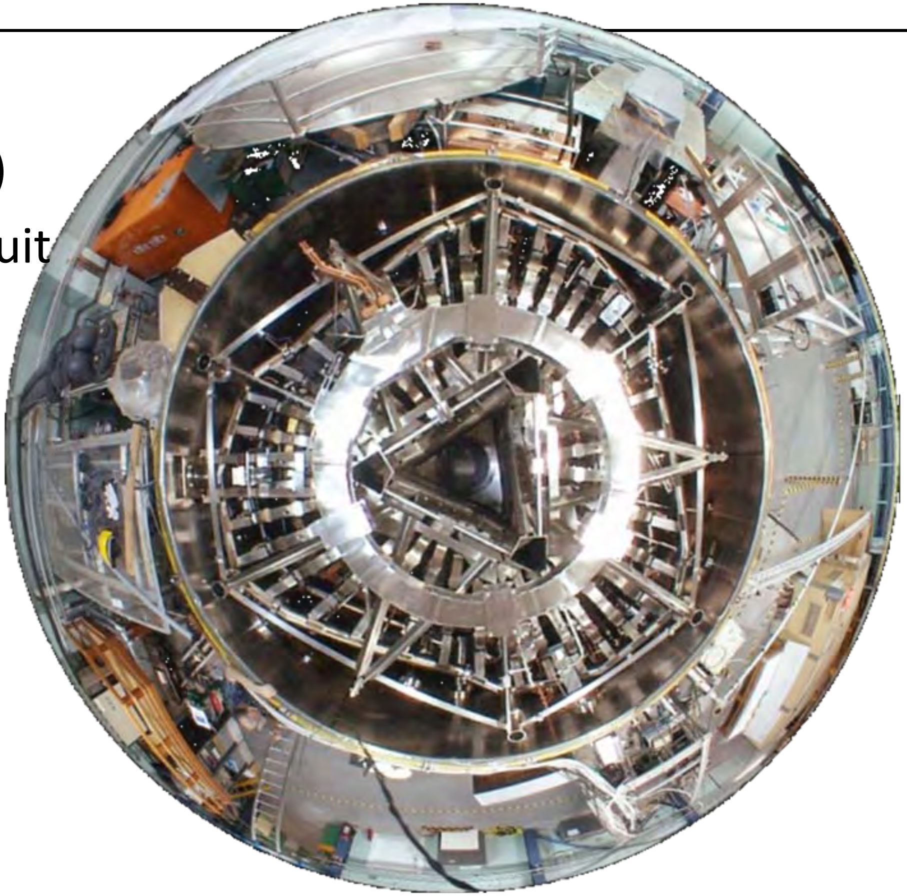


Core Australian fusion capability: The H-1NF heliac

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

H-1 National Plasma Fusion Research Facility

- Australia's major fusion-relevant facility
- $30 million (ANU contribution ~$20 million)
- Complementary theory and modelling pursuit



Recent accomplishments:

- H-mode behaviour in Ar plasmas

- Observation of zonal flows

- GAEs

- Test-bed for advanced diagnostics

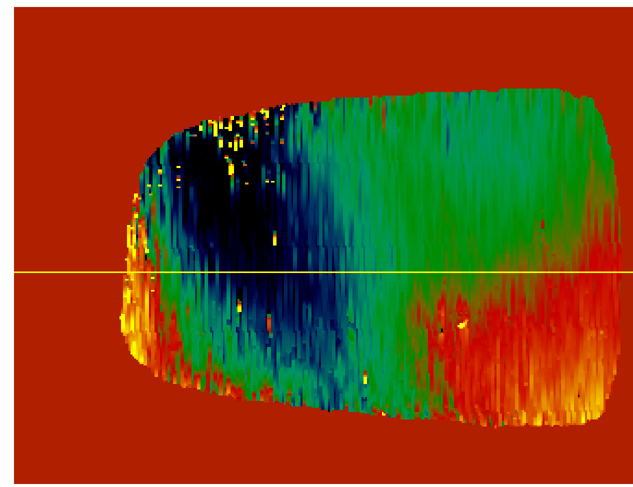
Mission:

- Study physics of hot plasma in a helical magnetic container
- Host development of advanced plasma measurement systems
- Contribute to global research, maintain Australian presence in fusion

Australia is a world leader in plasma measurement science and technology

- Advanced imaging systems (ANU)
  - International Science Linkages funding $700K (US, Korea, Europe, 2004-)
  - Systems developed under external research contracts for Japan, Korea, Germany, Italy ($480K)

World's first 2D image of internal plasma magnetic field on TEXTOR (Howard 2008)



- Signal processing, probabilistic data analysis, inverse methods (ANU)
  - International Science Linkages funding $430K (UKAEA 2008-)
- Laser-based probing (USyd, ANU)
- Atomic and molecular physics modeling (Curtin, ANU, Flinders)
- Complex and dusty plasmas (USyd)

Wider Australian fusion-relevant capabilities

Curtin University of Technology | Flinders University Adelaide • Australia | ANU

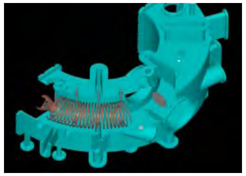
- Atomic and molecular physics modeling

The University of Newcastle Australia | The University of Melbourne | ANU

- High heat flux alloys
- MAX alloys synthesis
- Materials characterisation

The University of Sydney
AUSTRALIA

- Quasi-toroidal pulsed cathodic arc
- Plasma theory/ diagnostics
- Dusty Plasmas



Macquarie University ~ Sydney

- Plasma spectroscopy
- MHD and kinetic theory
- Materials science analysis

University of Wollongong
Faculty of Engineering

- joining and material properties under high heat flux

ansto
Australian Nuclear Science &Tec. Org.

- Manages OPAL research reactor
- ~1000 staff

A sample of Material Science research in Australia – Newcastle Univ.
also University of Sydney, Melbourne

The University of Newcastle Australia

*The first wall of a fusion reactor has to cope with the ‘**environment from hell**’ so it needs a ‘**heaven sent surface**’.*

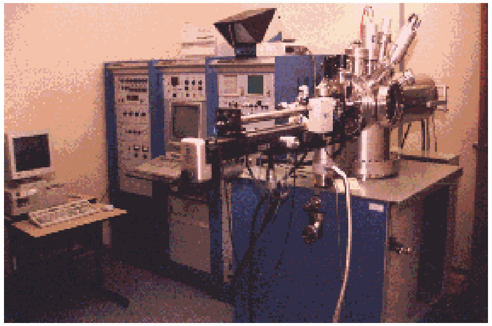
- heat load of 10-100 MW m^{-2}
- 14 MeV neutron irradiation
- 10 keV D, T, He bombardment

- Good thermal, electrical conductor
- high melting point
- ideally composed of low Z specie
- not retain too much hydrogen
- high resistance to thermal shocks

MAX alloys are one promising route :

M = transition metal (Sc, Ti, V, Cr, Zr, Nb, Mo, Hf, Ta)
A = Al, Si, P, S, Ga, Ge, As, Cd, In, Sn, Tl, Pb
X = either C or N

Spectroscopy lab



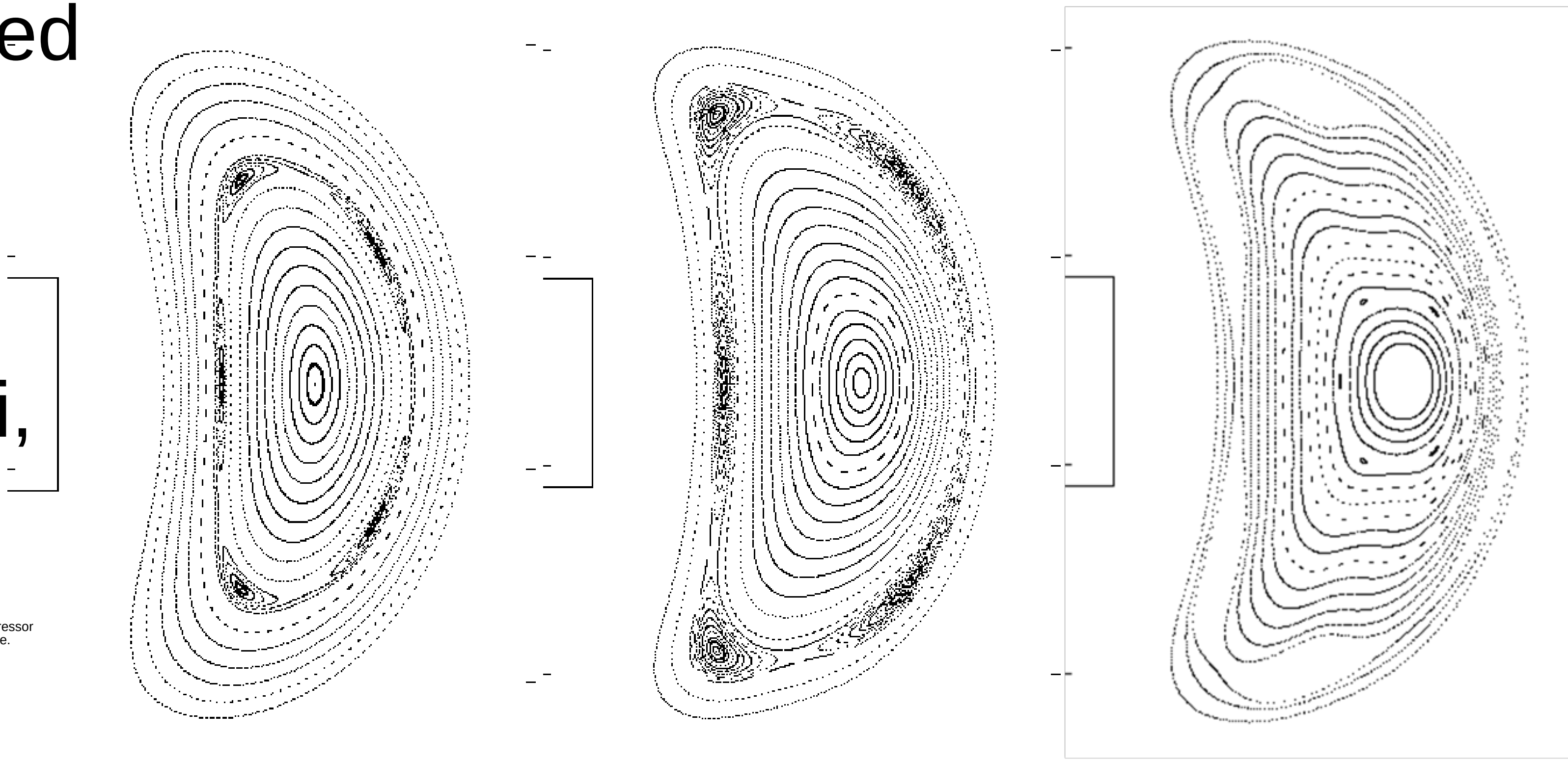
Different Stochiometries ⇒ over 600 potential alloys.

Finite-β equilibria in H-1NF

S. Lloyd (ANU PhD) , H. Gardner

Enhanced HINT code of late T. Hayashi, NIFS

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Vacuum $\beta = 1\%$ $\beta = 2\%$

Island phase reversal: self-healing occurs between 1 and 2% β

MRXMHD: Multiple relaxation region model for 3D plasma equilibrium

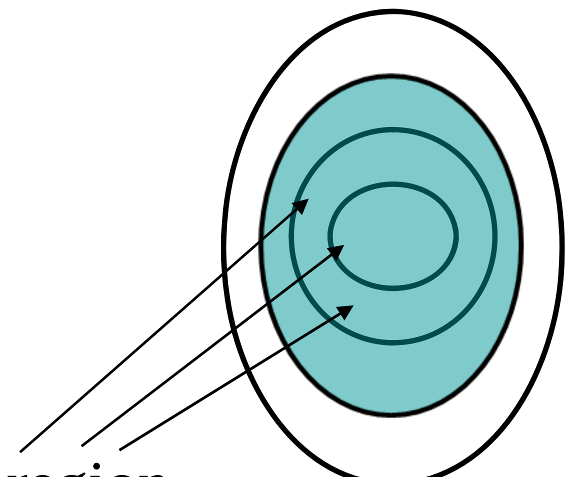
Motivation: In 3D, ideal MHD

(A) magnetic islands form on rational flux surfaces, destroying flux surface

(B) equilibria have *current singularities* if $\nabla p \neq 0$

Present Approach: ignore islands (eg. VMEC), or adapt magnetic grid to try to compensate (PIES). Latter cannot rigorously solve ideal MHD – error usually manifest as a lack of convergence.

ANU/Princeton project: To ensure a mathematically well-defined $J_{||}$, we set $\nabla p = 0$ over finite regions $\Rightarrow \nabla\times B = \mu B$, μ = const (*Beltrami field*) separated by assumed *invariant tori*.



Different μ in each region

Prof. I. Bray: Curtin University Presentation to IAEA 2009

Convergent close-coupling calculation of electron-impact ionisation of H-, He-, Na- and Mg-like ions.

I. Bray, C. Bostock, D. V. Fursa, A. Renwick

Institute of Theoretical Physics, Curtin University of Technology, Perth, Western Australia

4/3/09, IAEA, Vienna

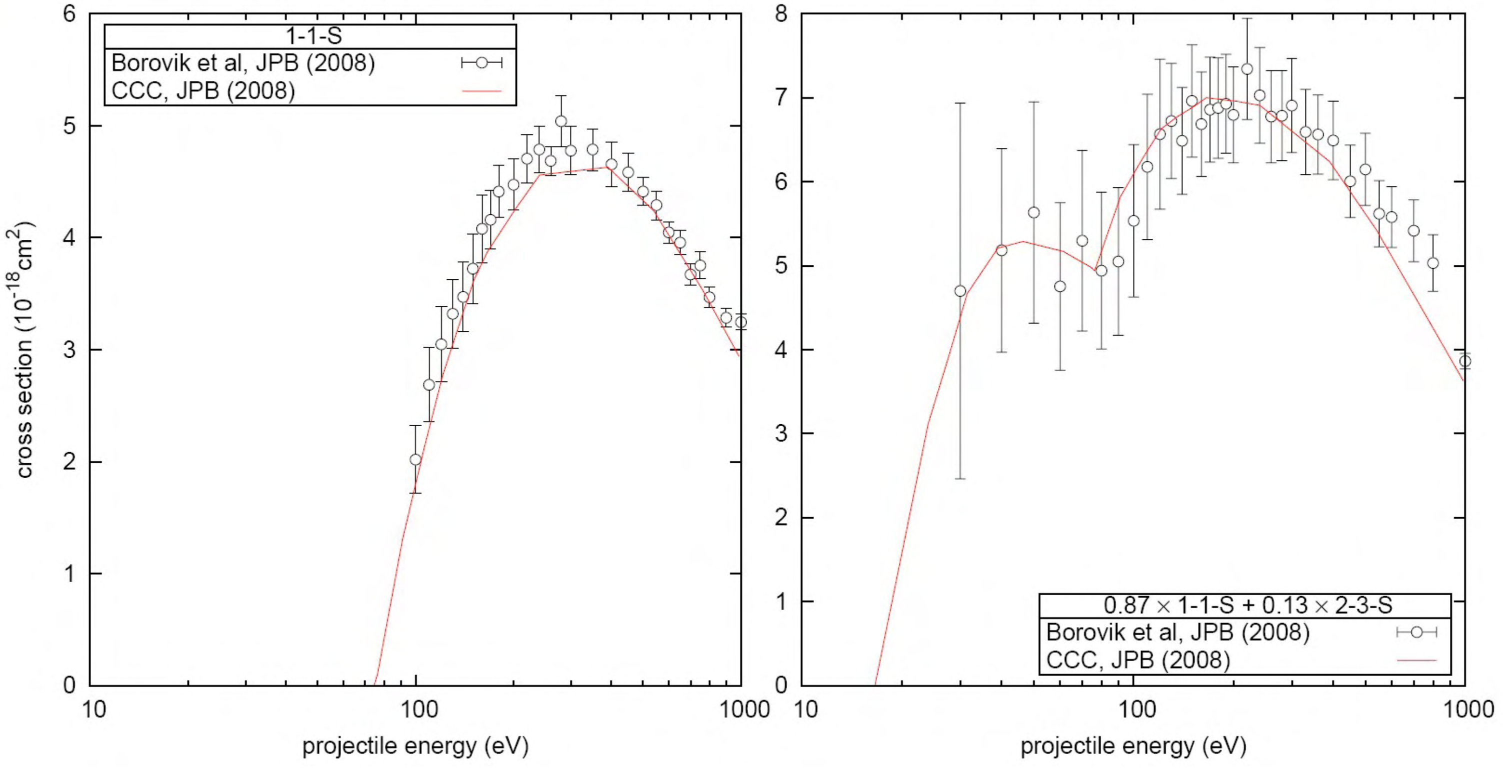
Curtin University of Technology

Atomic Cross-Sections for ITER

World-leading calculation of atomic cross-sections relevant to fusion using their "Convergent Close Coupling" (CCC) Method

Recent study of U^{91+}, Li, $^{B3+}$ and Tungsten (W^{73+}) for ITER

- e-Li^+ total ionisation cross sections



IEC: Doppler spectroscopy in H_2:

Predicting experimental fusion rates

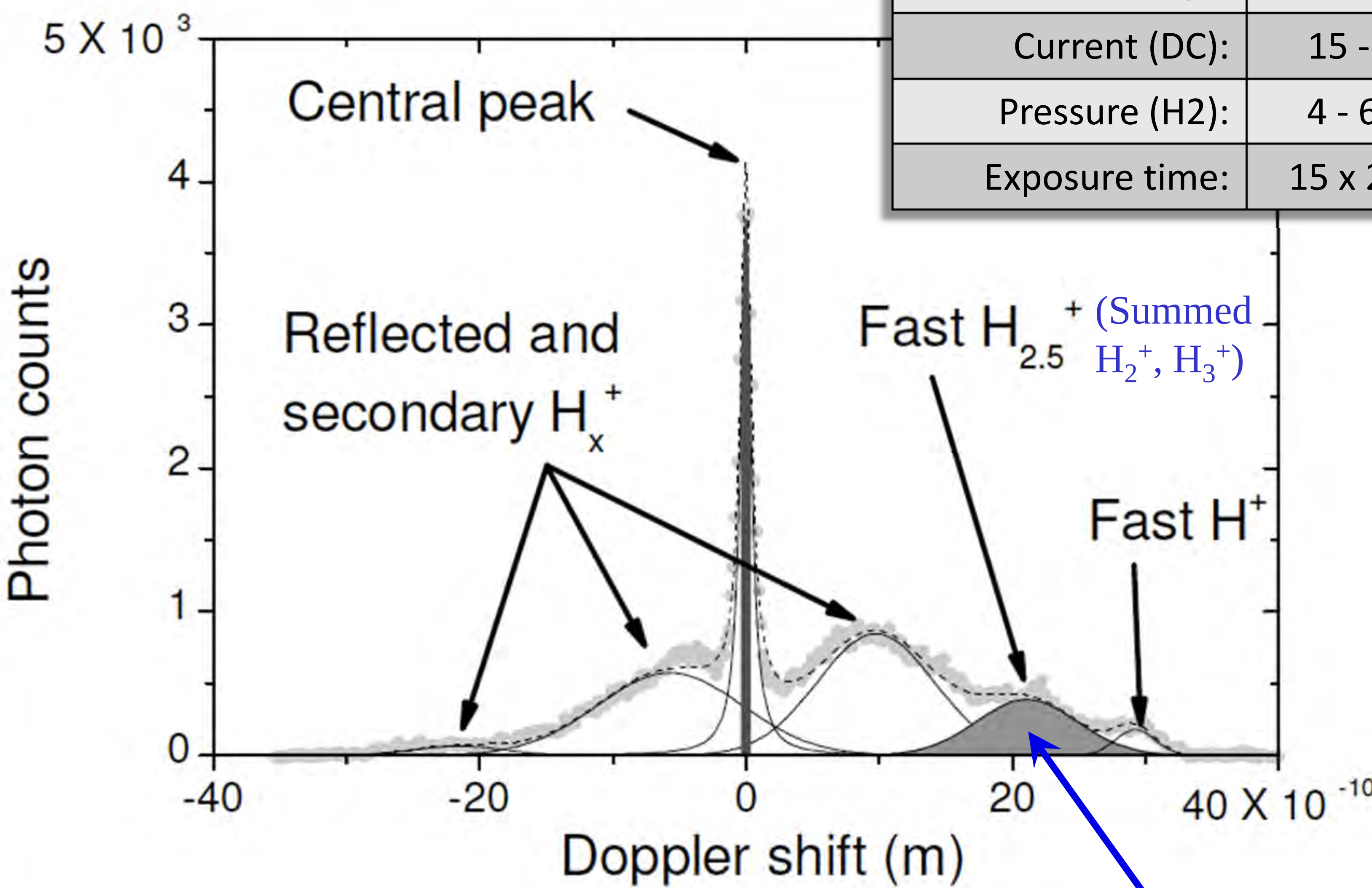
J. Kipritidis & J. Khachan

Applied and Plasma Physics
University of Sydney

The University of Sydney
Australia

Results: sample H_α spectrum at the anode wall

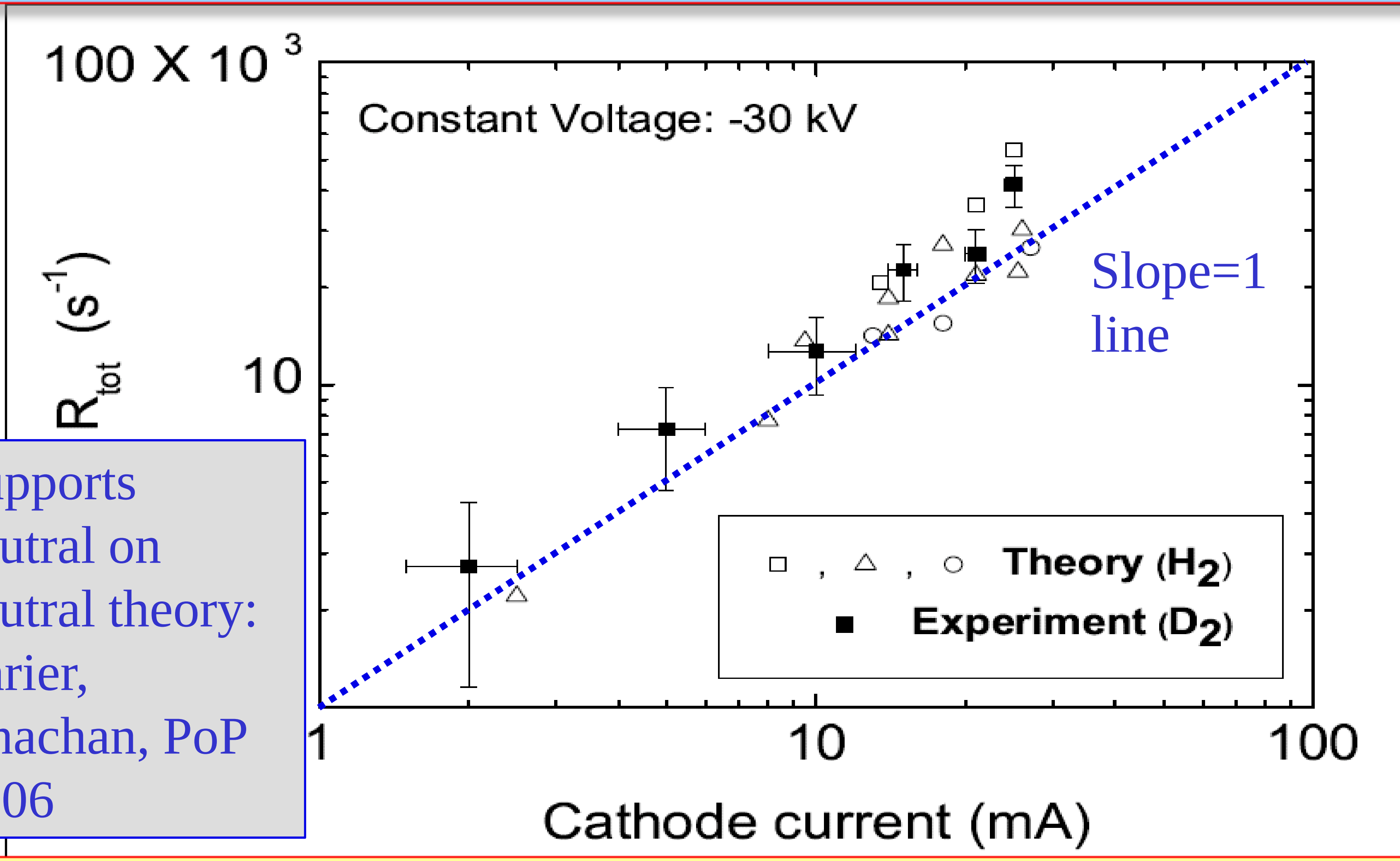
Cathode Voltage:	-30 kV
Current (DC):	15 - 25 mA
Pressure (H2):	4 - 6 mTorr
Exposure time:	15 x 2000 ms



This peak used for prediction

Results: neutron counts! (constant voltage) PhysRevE 2009

Dissociation fractions f_{fast} at apertures are ~ $\mathbf{10^{-6}}$ ***(increases with current!)***



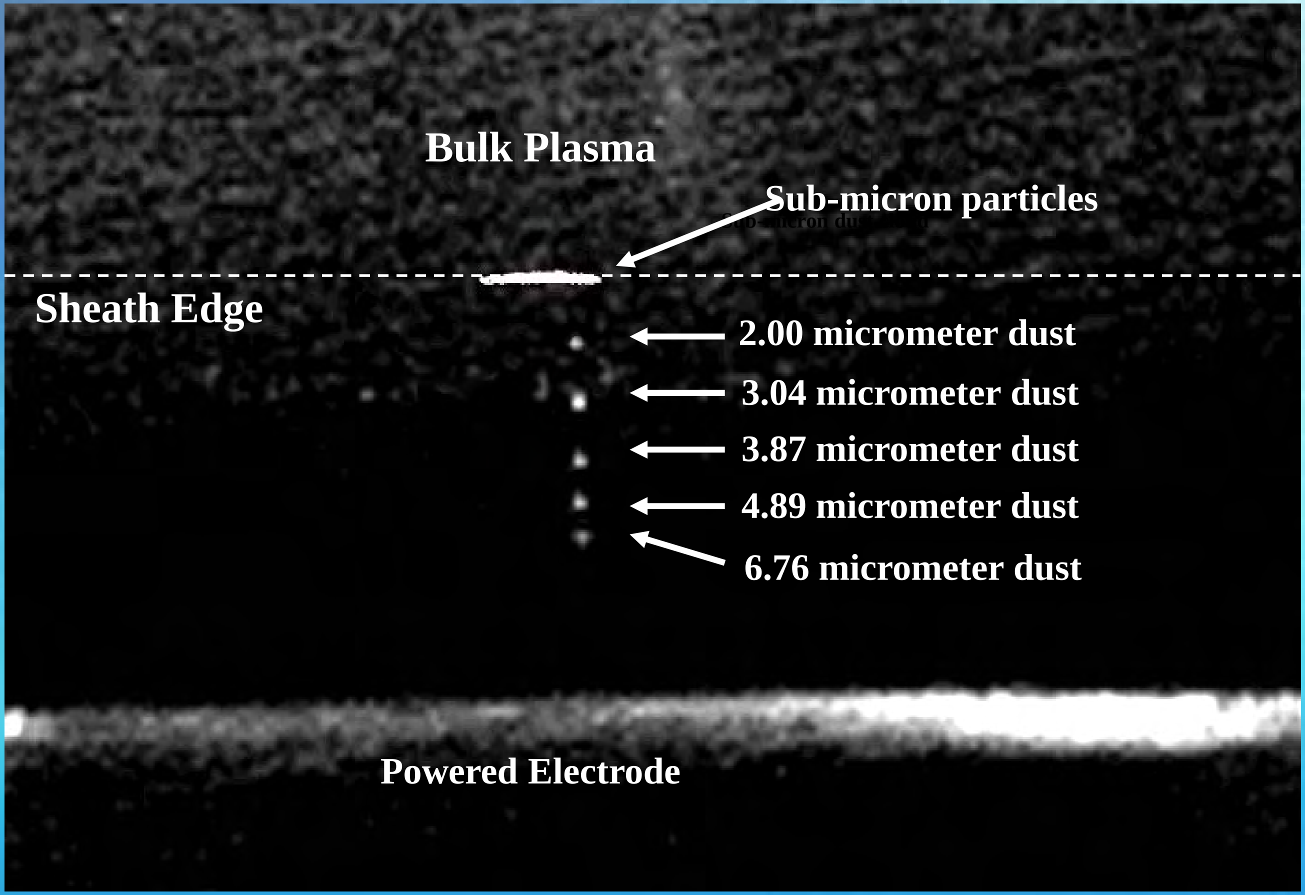
Supports neutral on neutral theory: Shrier, Khachan, PoP 2006

Densities of **fast $H_{2.5}^{+}$** at the cathode aperture are ~ $\mathbf{1\text{-}10 \times 10^{14}\ m^{-3}}$

(Summed H_2^+, H_3^+)

Levitation of Different Sizes Particles - Samarian

RF Sheath Diagnostic

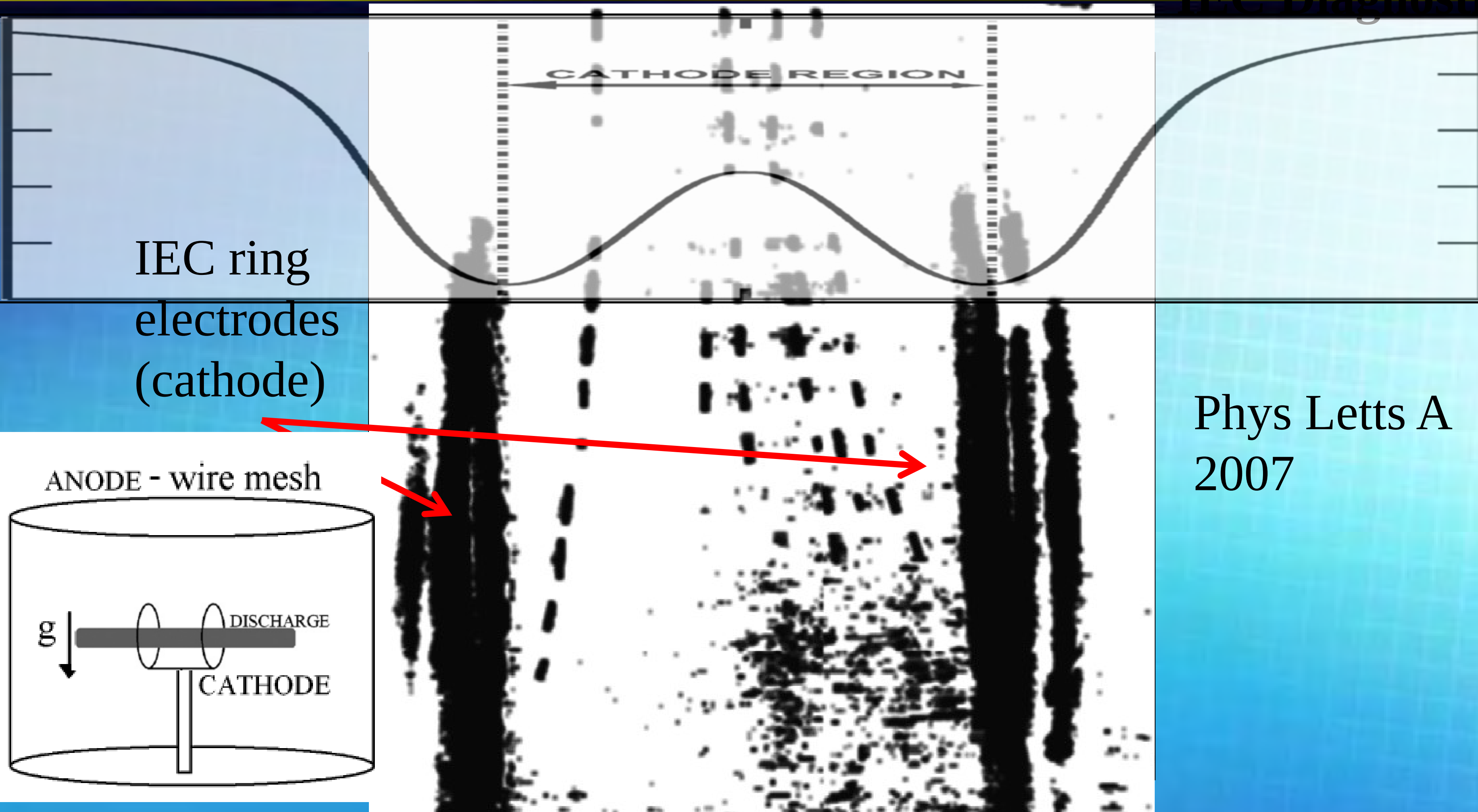


- Probing of sheath electric field on different heights

The University of Sydney
AUSTRALIA

Dust Deflection in IEC Fusion Device – Samarian/Khachan

IEC Diagnostic



Phys Letts A 2007

- Dust particle being deflected towards the rings are visible on the left hand side

ANU - University of Sydney collaboration

The University of Sydney

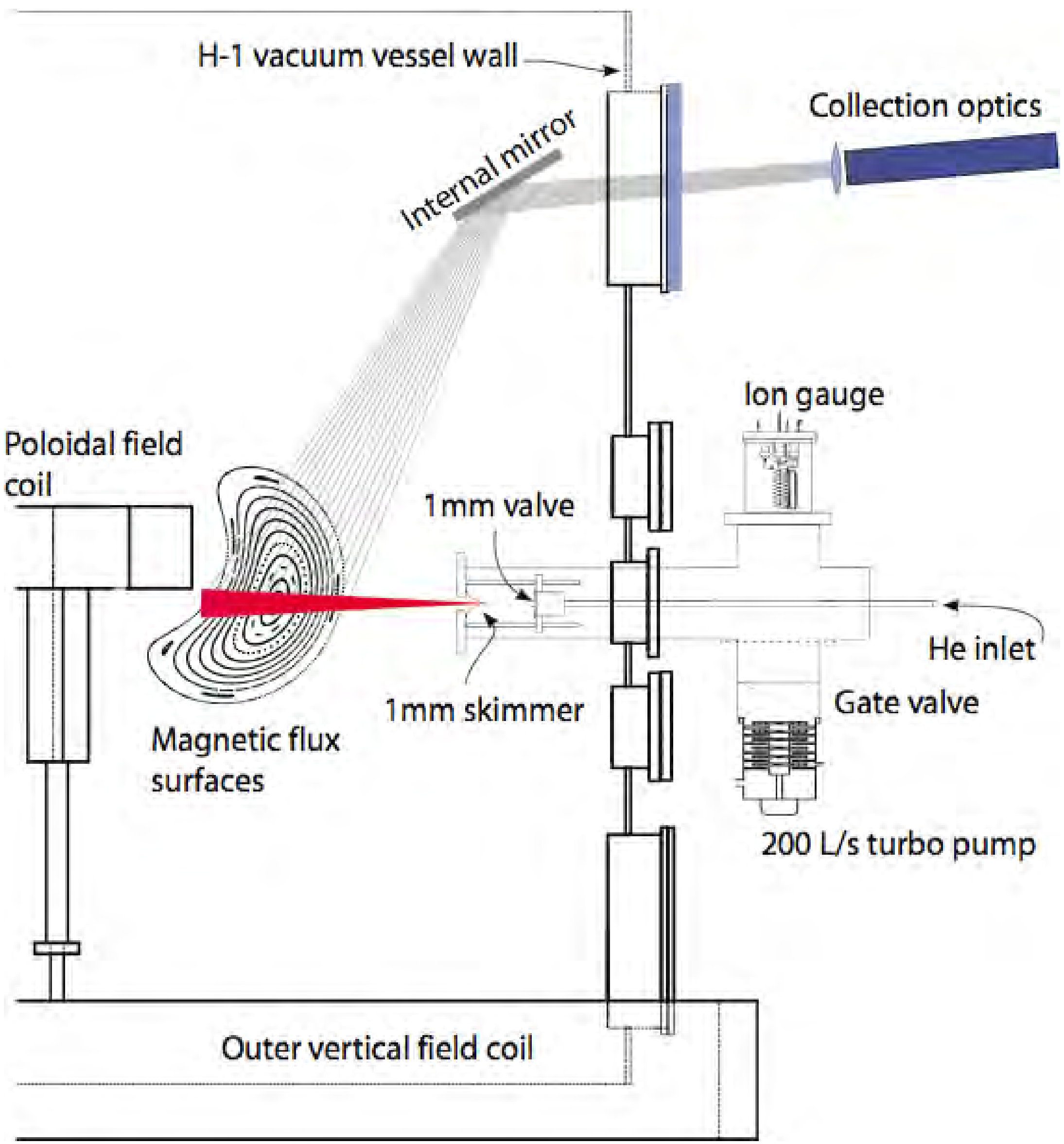
Brian James
Daniel Andruczyk

THE AUSTRALIAN NATIONAL UNIVERSITY

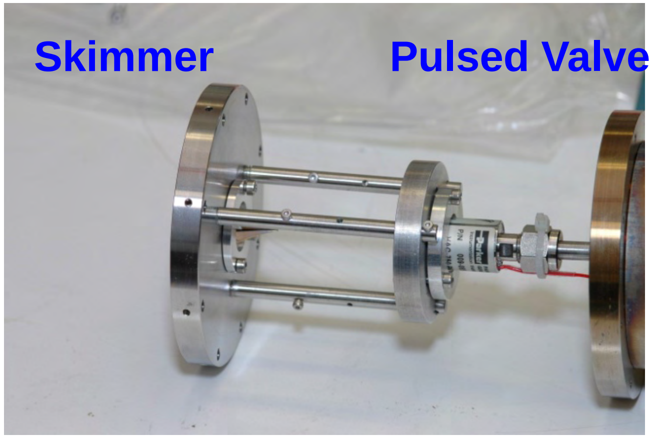
John Howard
Scott Collis
Robert Dall

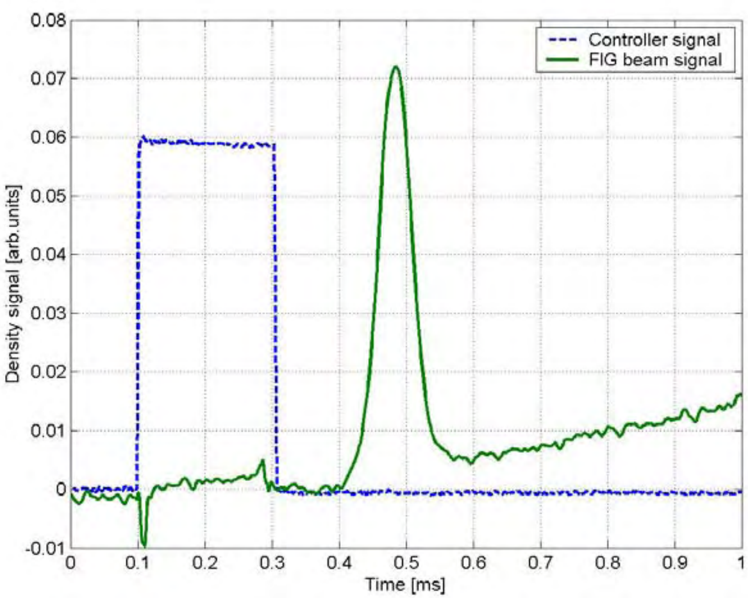
- Development of a He pulsed diagnostics beam
- Te profiles measured in H-1NF, from He line intensity ratios, with aid of collisional radiative model

Experimental set-up

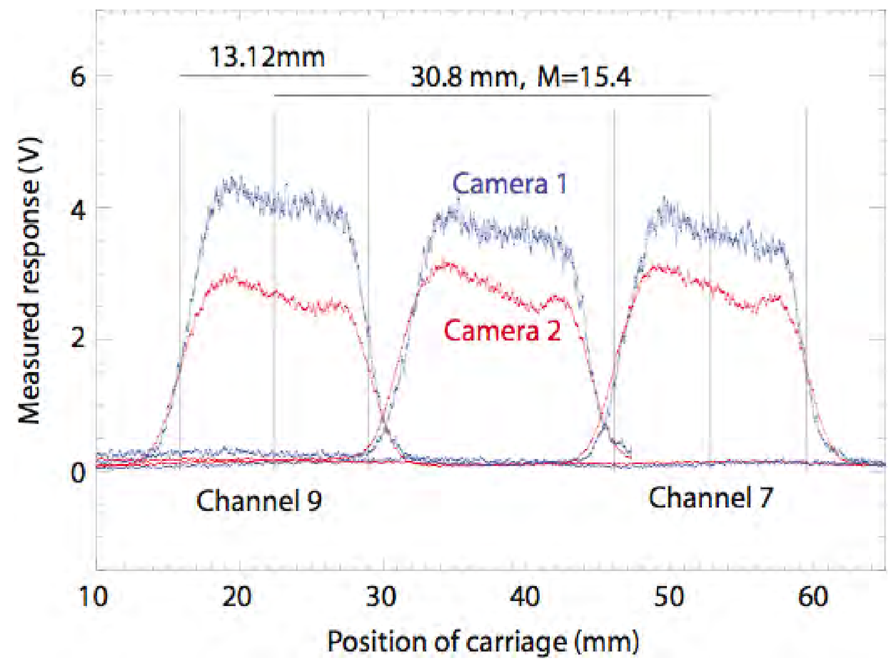


Pulsed He source

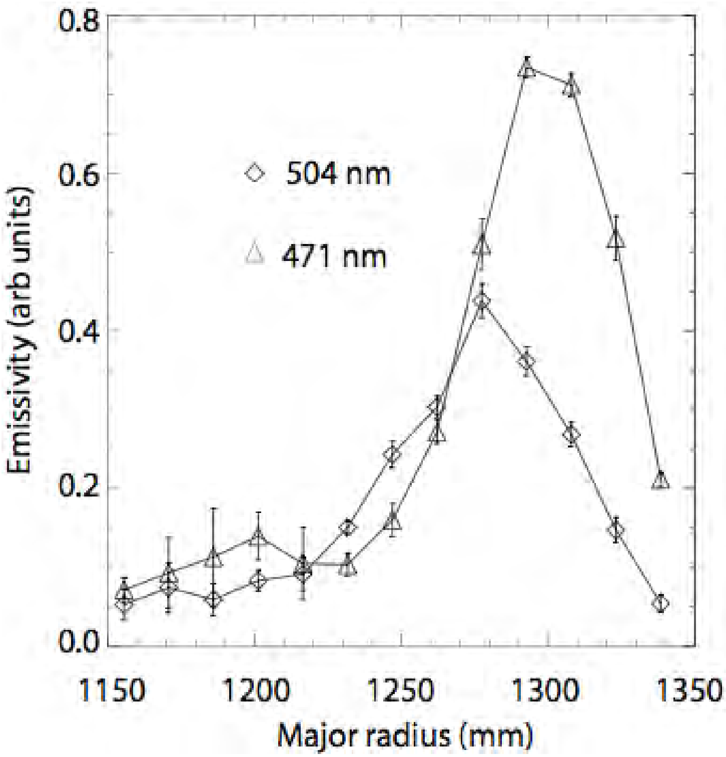




Collection optics



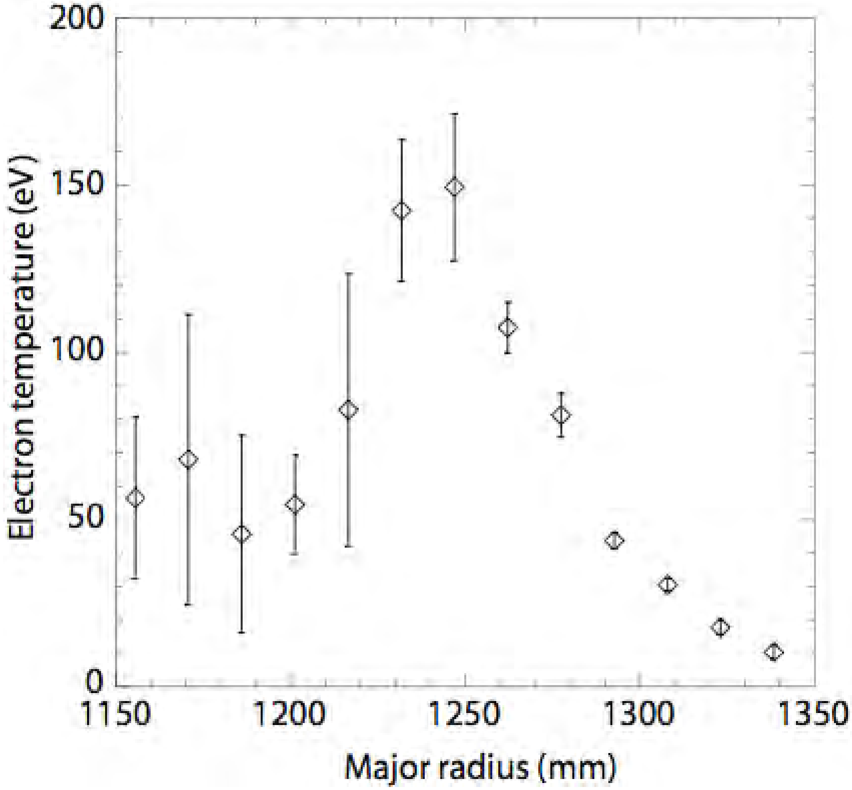
Spectral line emissivity vs radius



beam

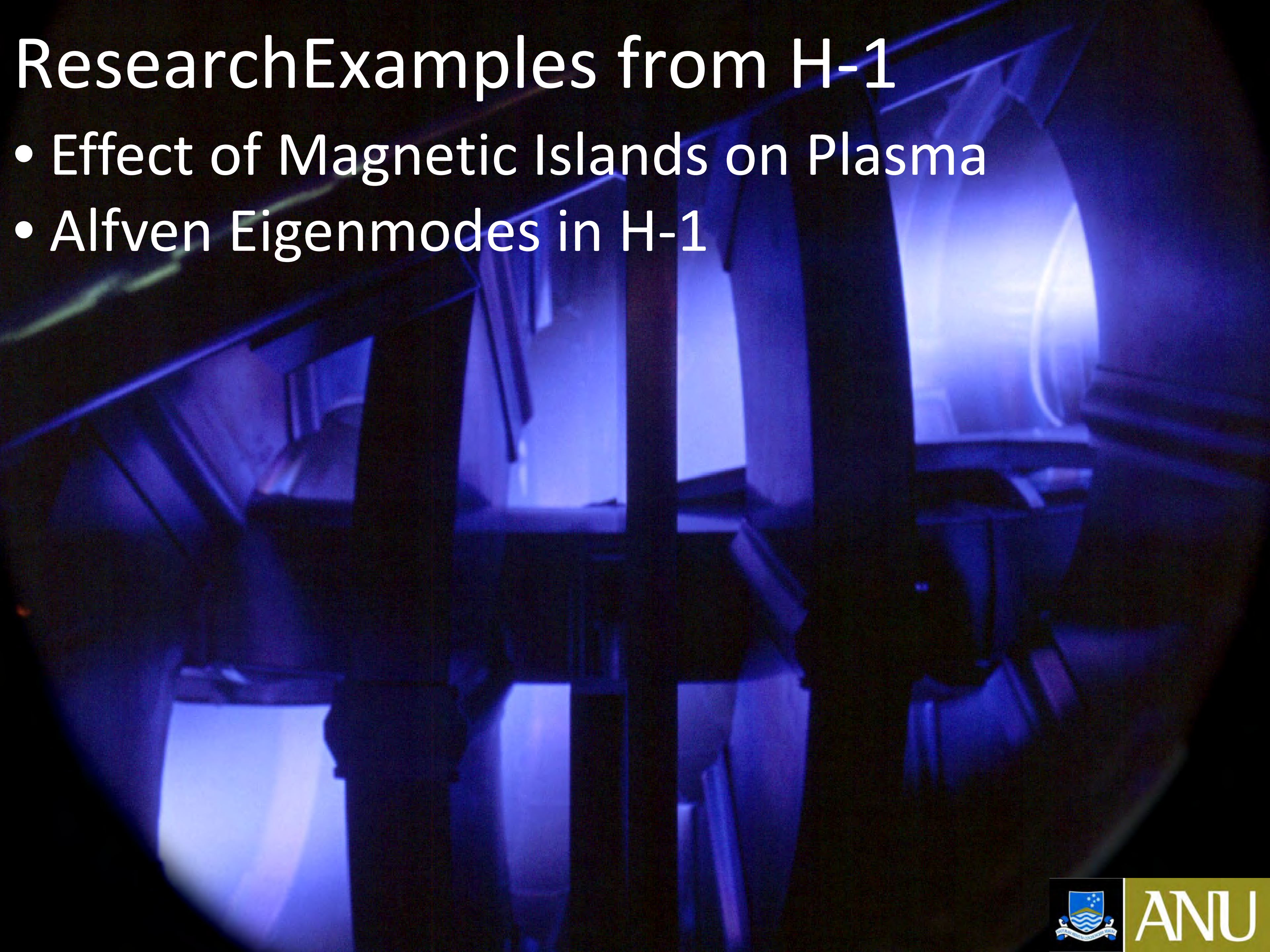
emissivity falls as beam moves into the plasma due to progressive ionization

T_e vs radius

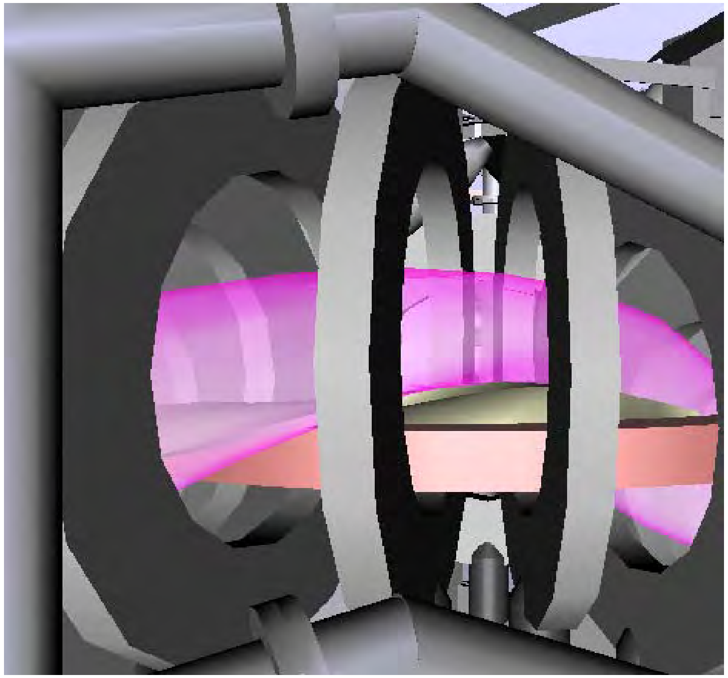


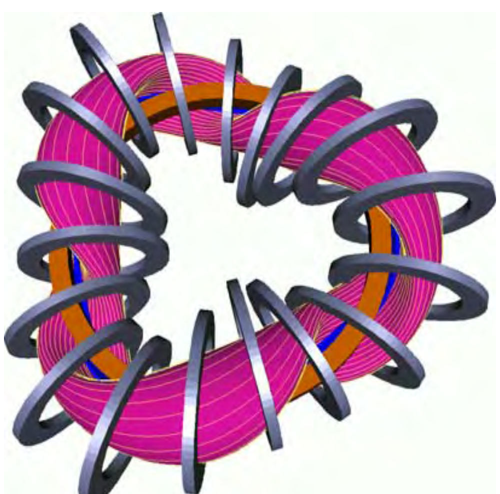
ResearchExamples from H-1

- Effect of Magnetic Islands on Plasma
- Alfven Eigenmodes in H-1



H-1 Heliac: parameters

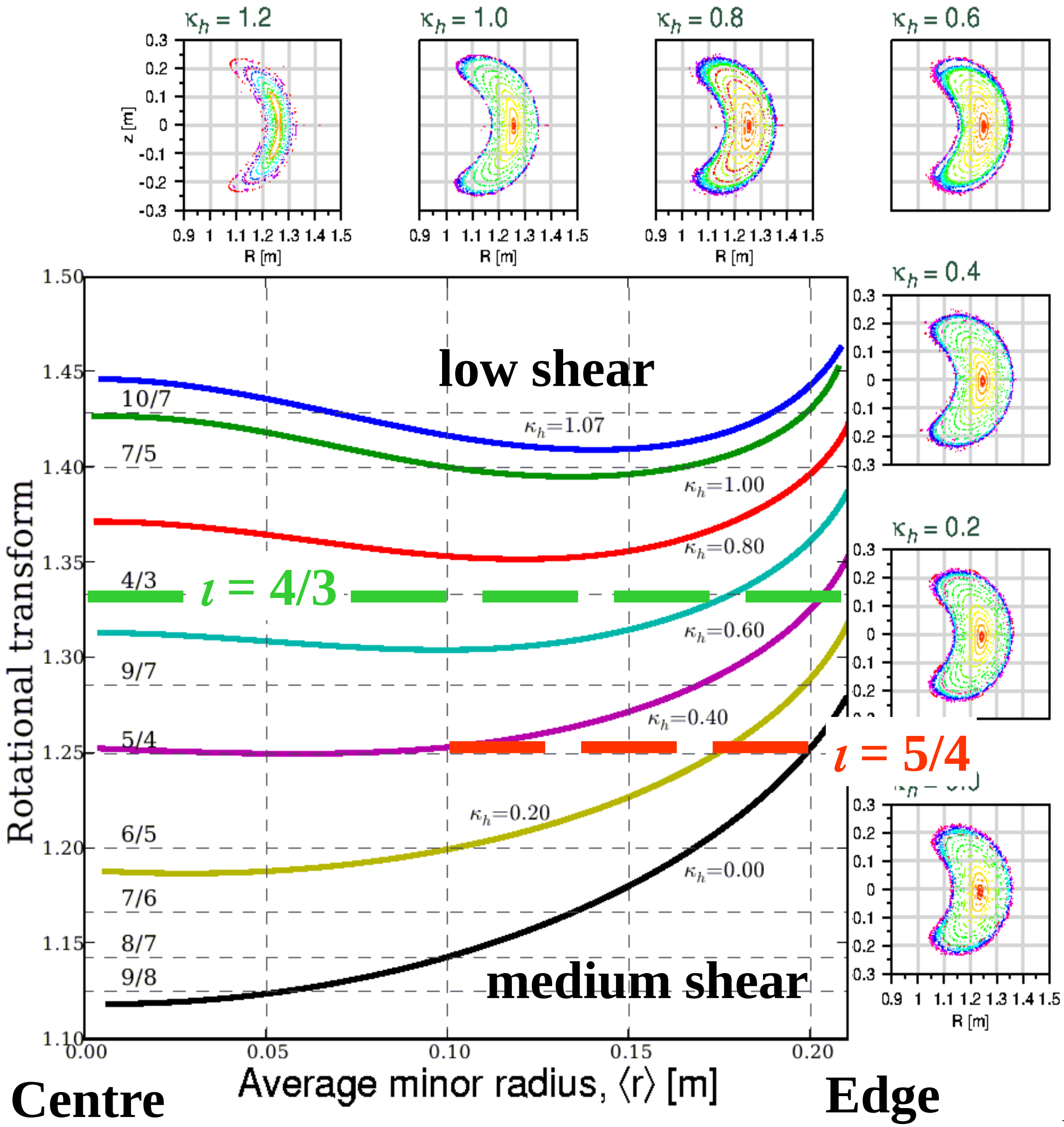




Machine class	3-period heliac
Major radius, *R*	1m
Minor radius, *a*	0.1-0.2 m
Vacuum volume, *V*	33 m^2 (excellent access)
Toroidal field, B_ϕ	≤1 Tesla (0.2 DC)
Aspect Ratio *(R/<a>)*	5 + (Toroidal > Helical)
Heating Power, *P*	0.2MW (28 GHz ECH) 0.3MW (6-25MHz ICH)

Plasma parameters	*Achieved*	*Design*
electron density	$3 \times 10^{18} m^{-3}$	10^{19} m^{-3}
electron temp., *T*	150eV	500eV
Plasma beta, β	0.2 %	0.5%

H-1 configuration (shape) is very flexible



- ***"flexible heliac"*** :
  helical winding, with
  helicity matching the plasma,
  $\Rightarrow$ 2:1 range of twist/turn

- H-1NF can control 2 out of 3 of
  - **transform (ι)**
  - **magnetic well and**
  - **shear Δι (spatial rate of change)**

- **Reversed Shear**
  → Advanced Tokamak mode of operation

Santhosh Kumar

Experimental confirmation of configurations

Rotating wire array

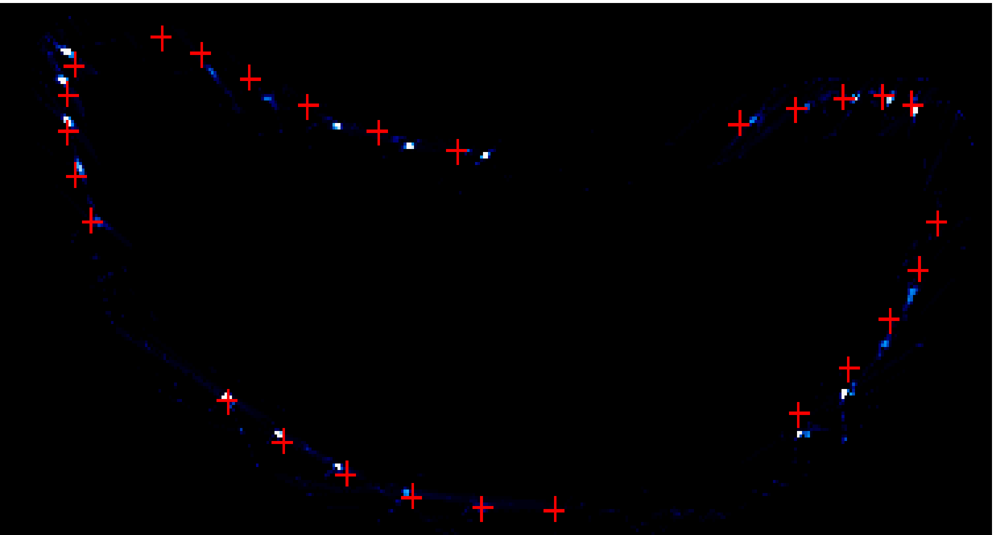
- 64 Mo wires (200um)
- 90 - 1440 angles

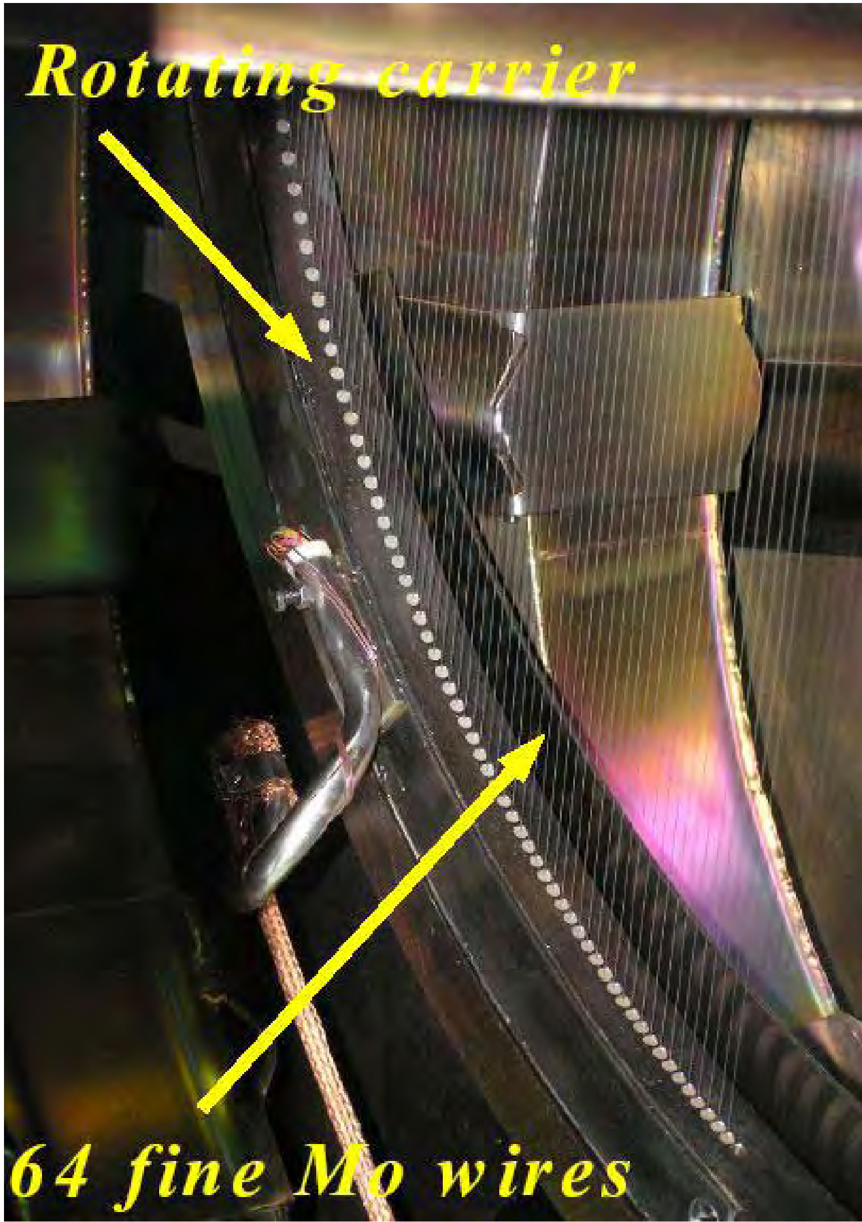
High accuracy (0.5mm)

Moderate image quality

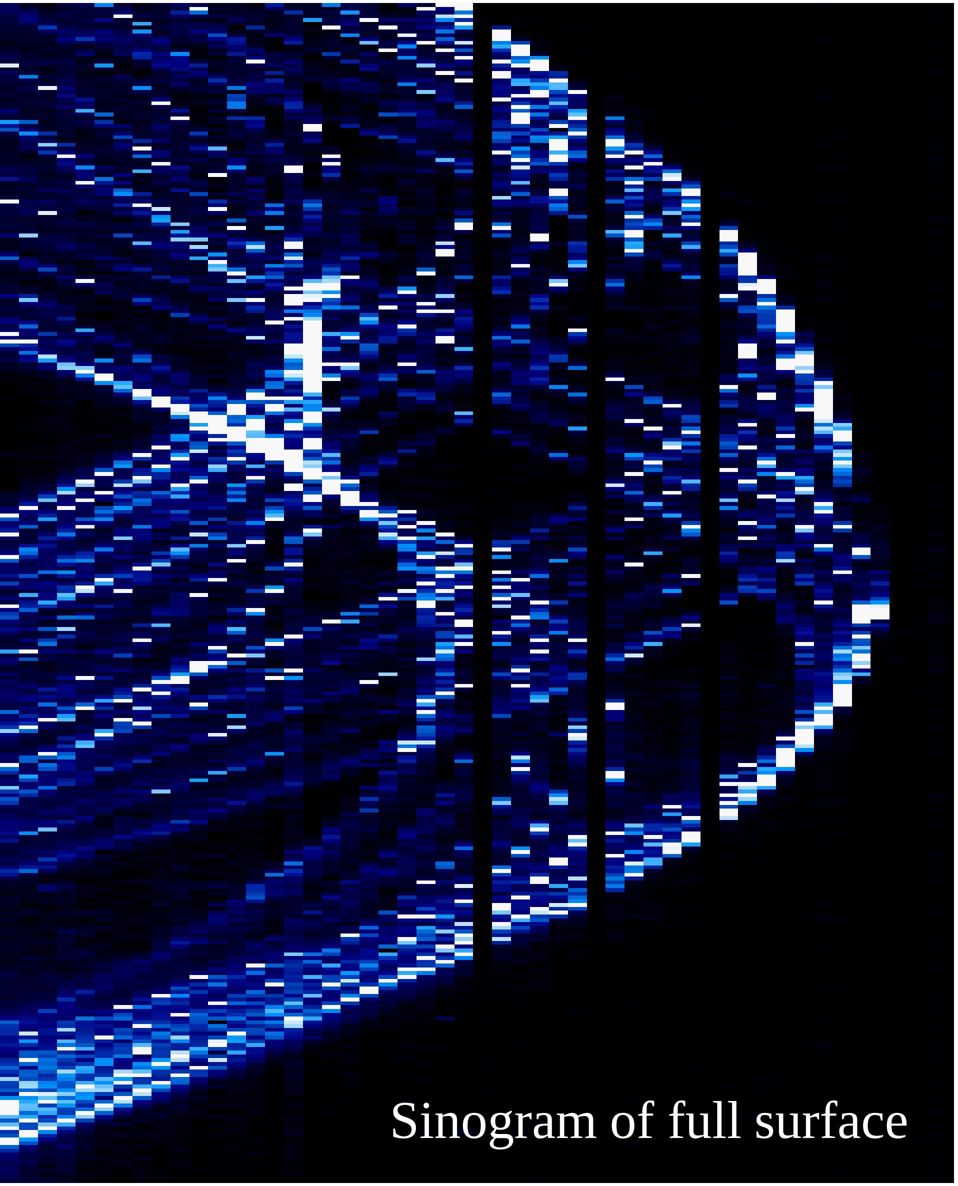
Always available

Excellent agreement with computation





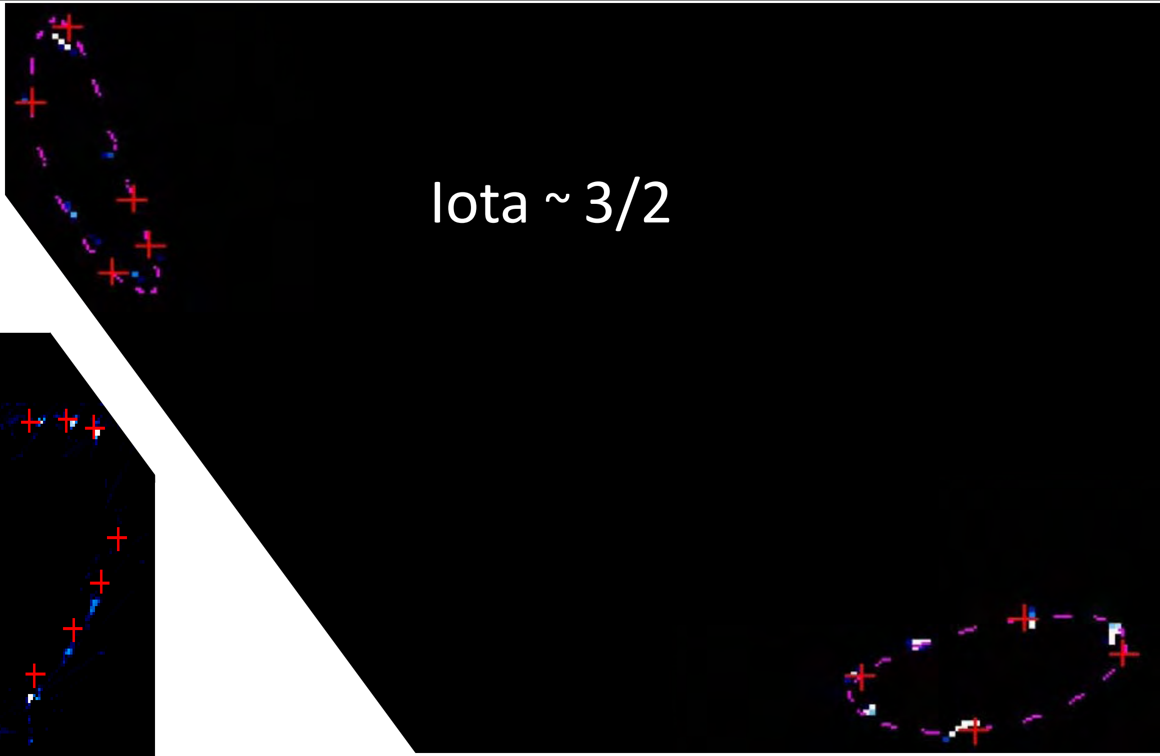
Mapping Magnetic Surfaces by E-Beam Tomography: Raw Data

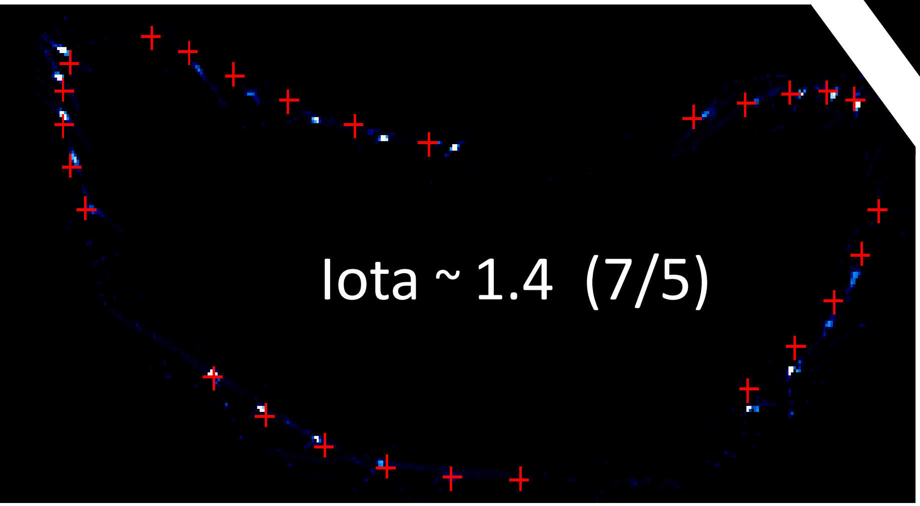


For a toroidal helix, the sinogram looks very much like part of a vertical projection (top view)

Good match confirms island size, location

computed +
e-beam mapping (blue/white)

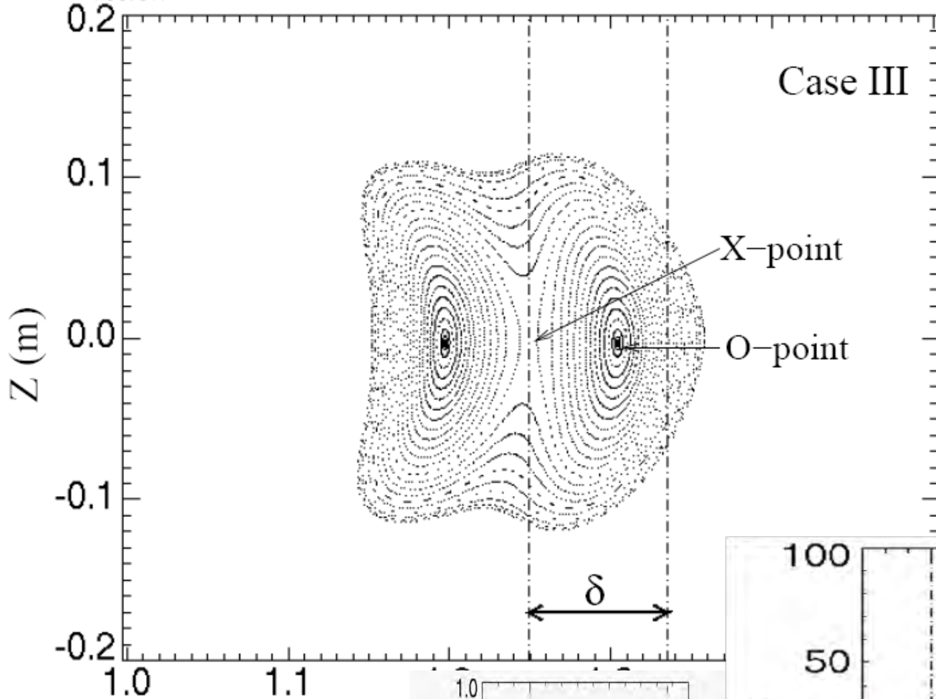


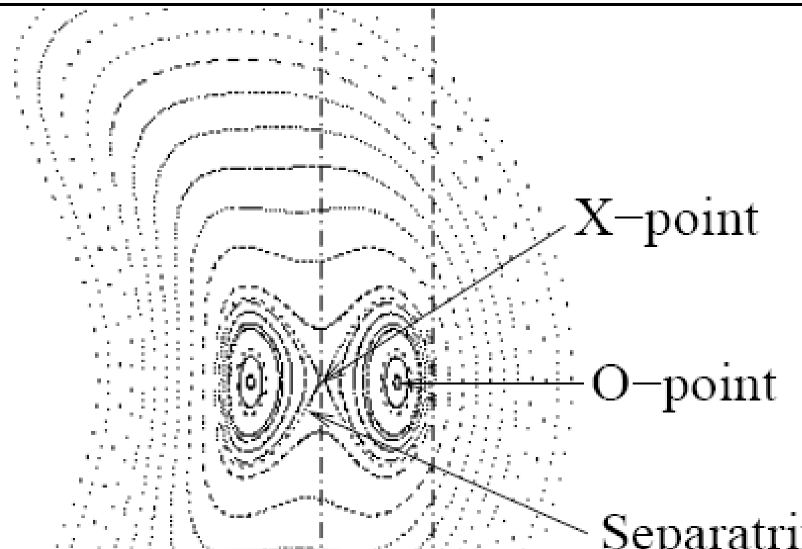


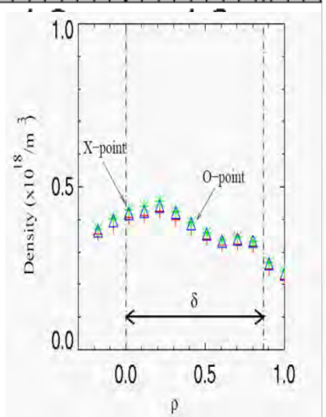
Good match between computed and measured surfaces

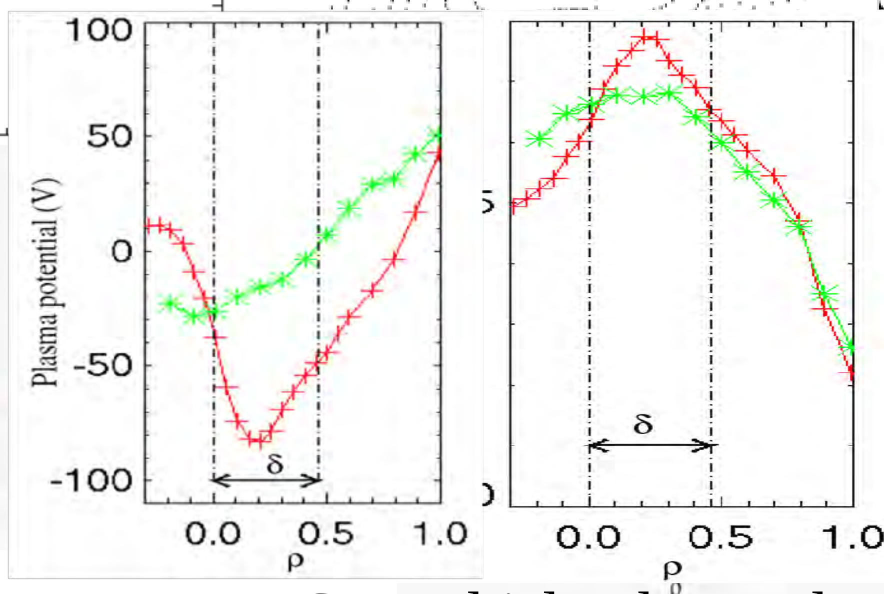
- Accurate model developed to account for all iota (NF 2008)
- Minimal plasma current in H-1 ensures islands are near vacuum position

Effect of Magnetic Islands









Giant island →"flattish" density profile

Possibly connected to core electron root enhanced

Central island – tends to peak

Spontaneous Appearance of Islands

Iota just below 3/2

– sudden transition to bifurcated state

Plasma is more symmetric than in quiescent case.

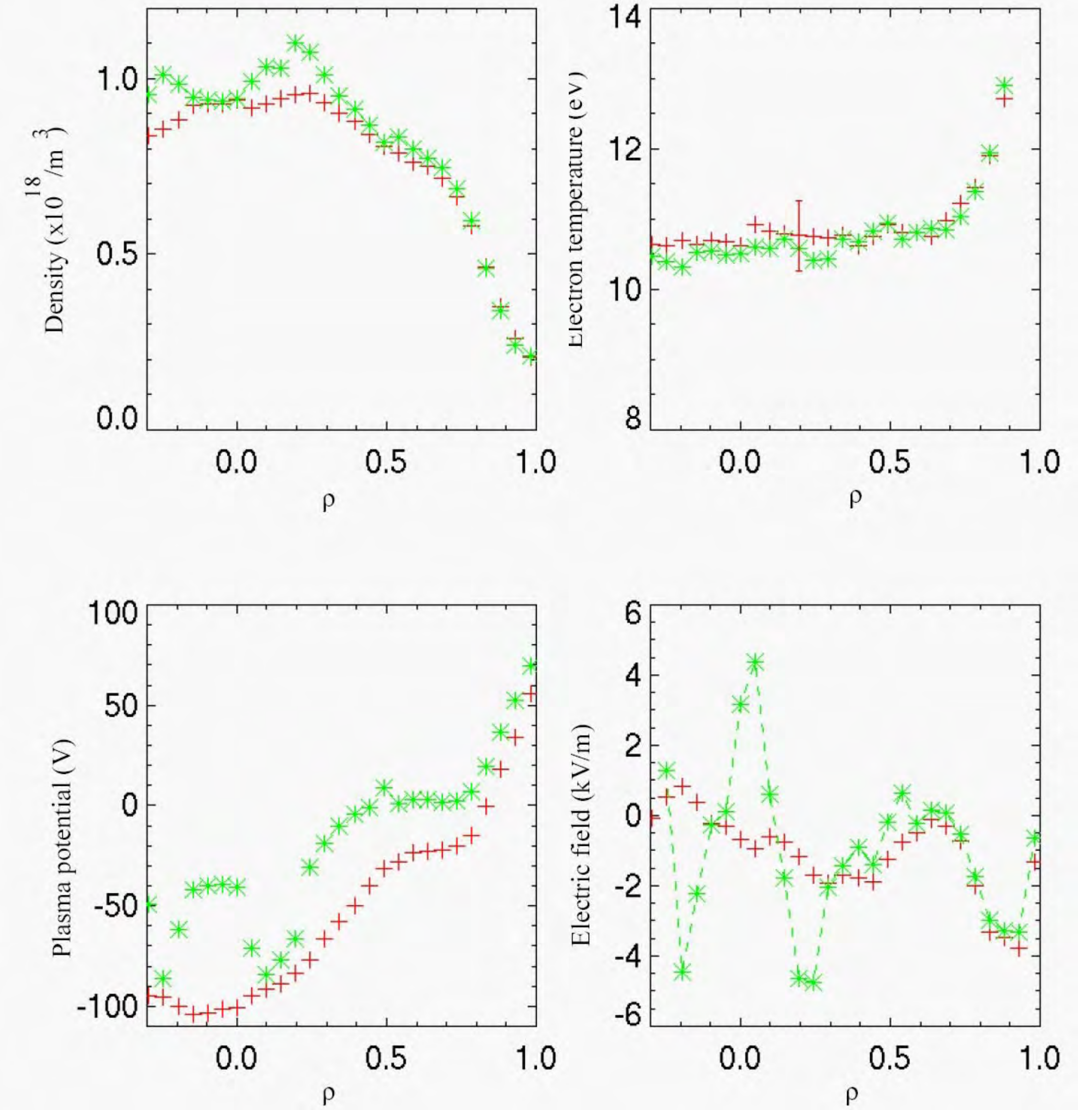
Uncertainty as to current distribution (and therefore iota), but plausible that islands are generated at the axis.

If we assume nested magnetic surfaces,
→then we have a clear positive Er at the core – similar to core electron root configuration?

Many unanswered questions……

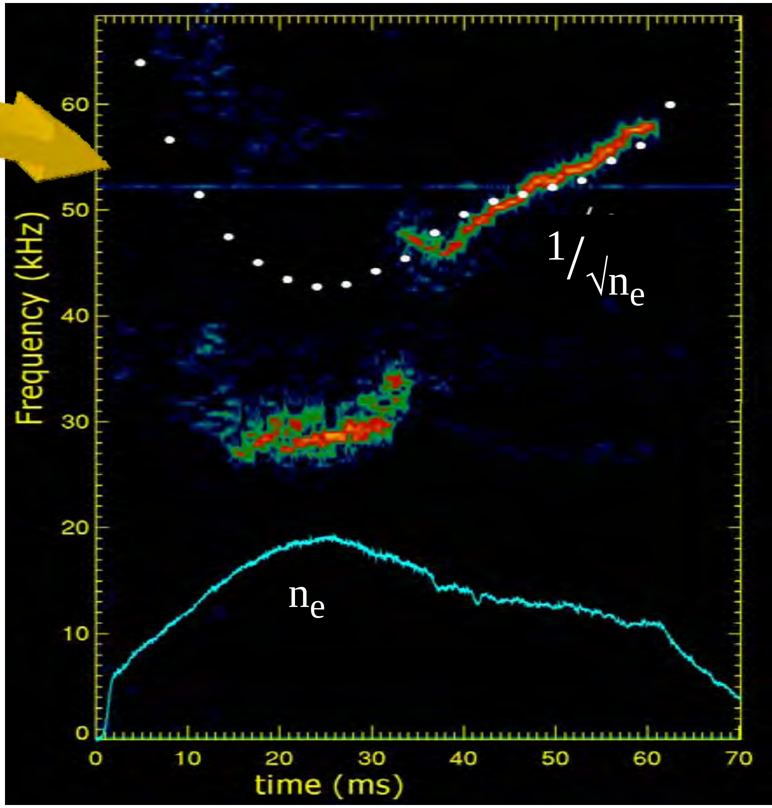
Symmetry?

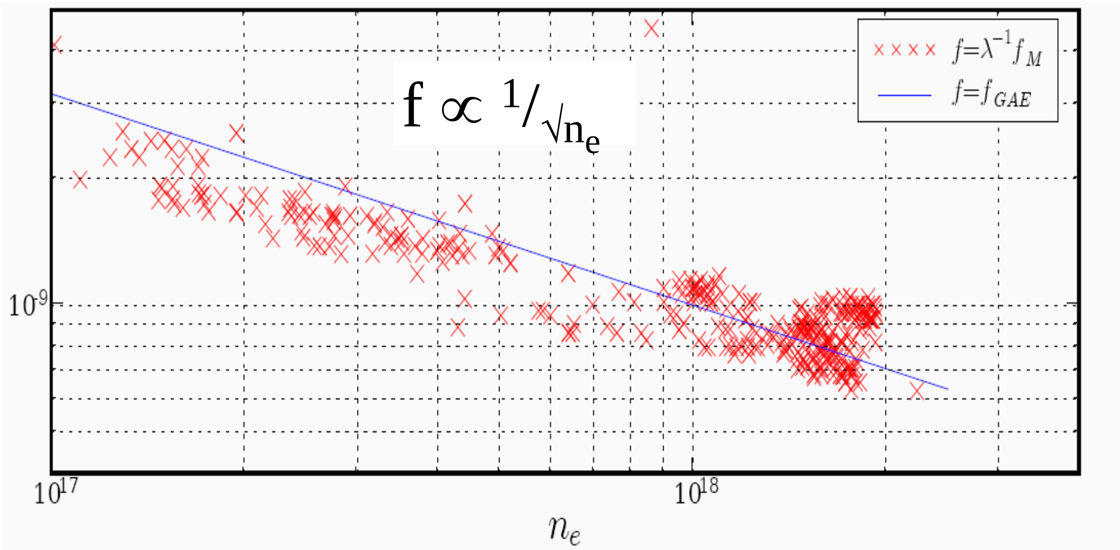
How to define Er with two axes?



Identification with Alfvén Eigenmodes: n_e

- Coherent mode near iota = 1.4, 26-60kHz, Alfvénic scaling with n_e
- Poloidal mode number (m) 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)

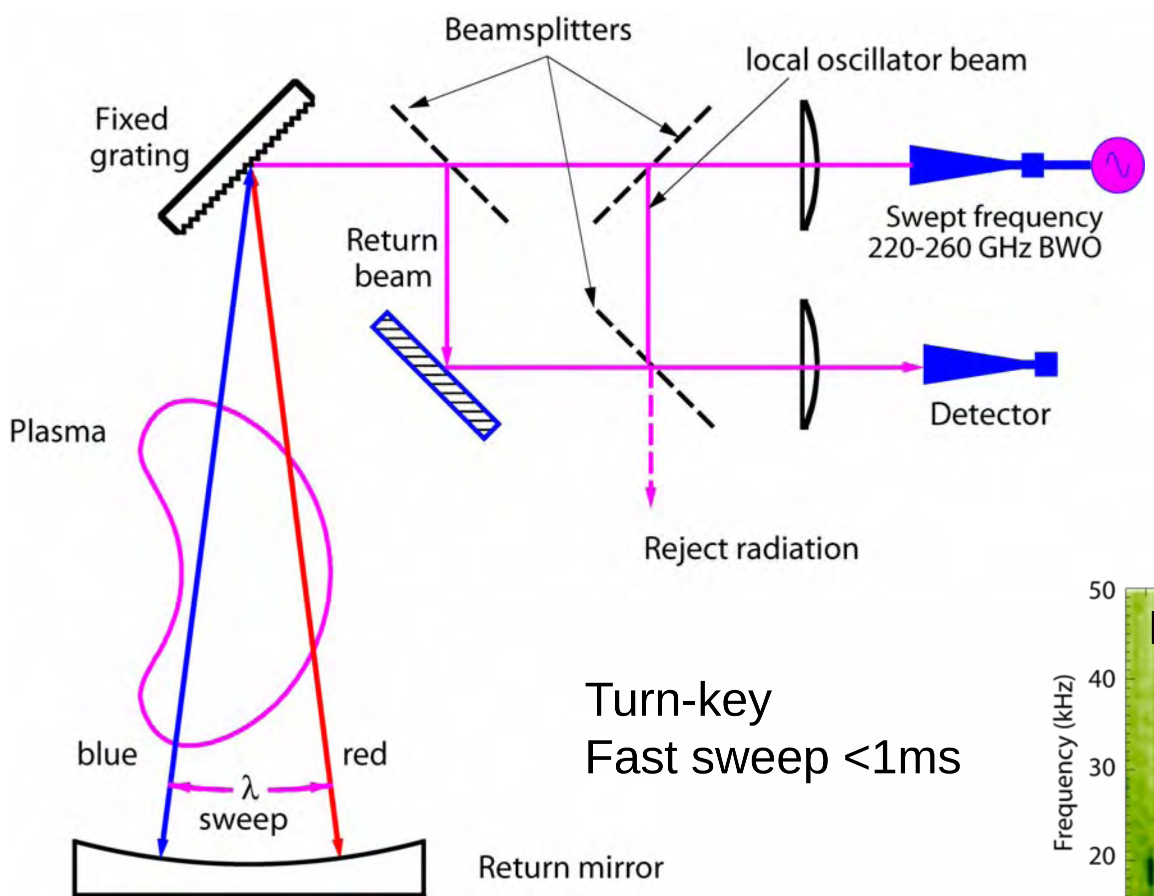


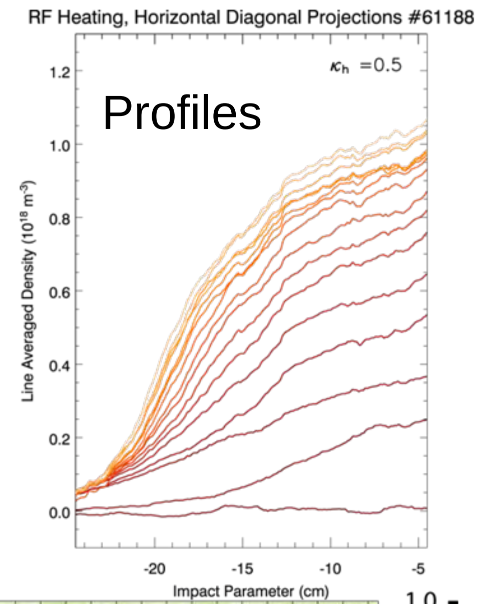


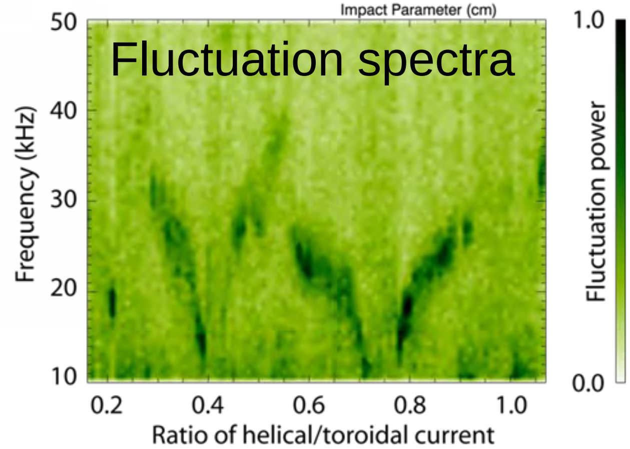
Critical issue in fusion reactors:

$V_{Alfvén}$ ~ fusion alpha velocity
→ fusion driven instability!

Fluctuation Spectra Data from Interferometer upgrade:
(Rapid electronic wavelength sweep)







Turn-key
Fast sweep <1ms

D Oliver

Alfven Mode Decomposition by SVD and Clustering

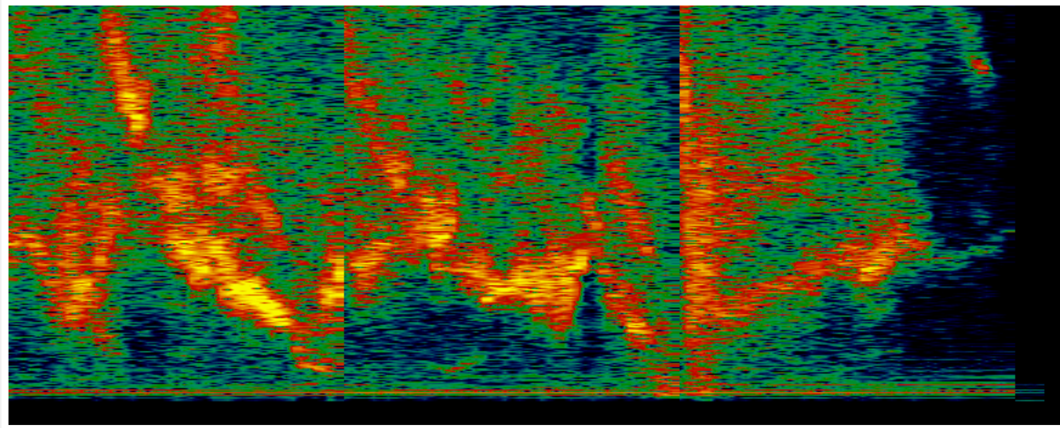
- Initial decomposition by SVD → ~10-20 eigenvalues
- Remove low coherence and low amplitude
- Then group eigenvalues by spectral similarity into fluctuation structures
- Reconstruct structures to obtain phase difference at spectral maximum
- Cluster structures according to phase differences (m numbers)

→ reduces to 7-9 clusters for an iota scan

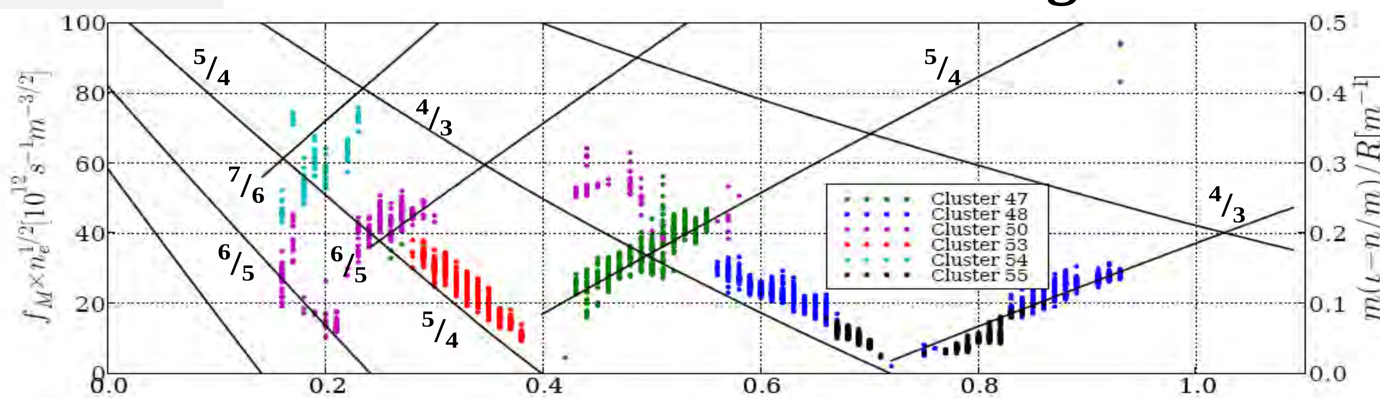
Grouping by SVD+clustering potentially more powerful than by mode number

- 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
  - ${}^{2}C_{20}$ coil combinations
  - 100 shots

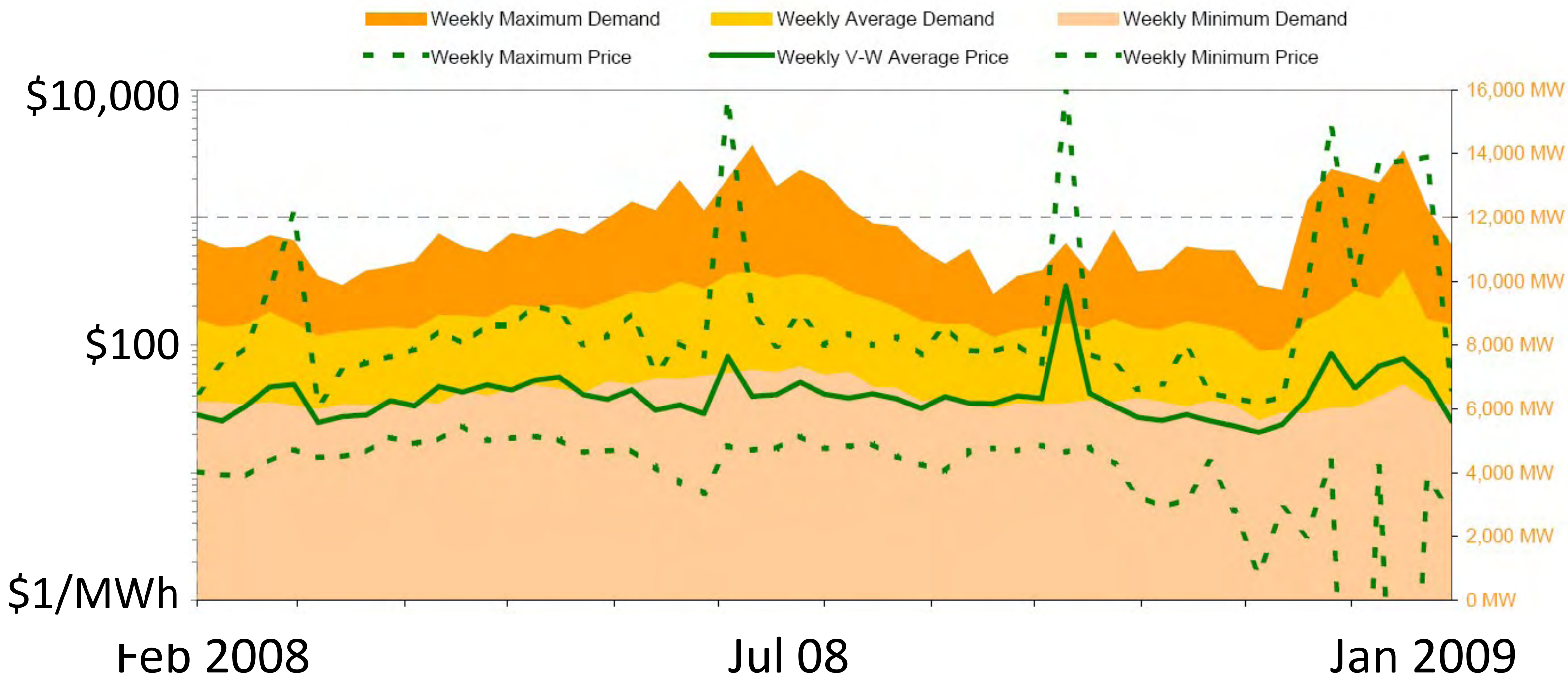


increasing twist →



Energy Politics: Energy Consumption (NSW)

Prices set by NEMMCO marketing software – updated every 5 minutes



NSW (including ACT) demand and spot price (NEMCO, ESAA)

http://www.nemmco.com.au/

Capacity: ~ 45GW on Grid + 4.5GW off grid (mines, smelters) 2005 report ESAA

Generation: 58% Black Coal, 26% Brown, 9% gas, 7% Hydro

Usage: Residential – 28%, Commercial – 24%, Metals/Mining 20%, Aluminium smelting – 13.6%, Manufacturing – 12%, Transport 1%

Energy Politics in Australia

Energy security

Brown coal: Australia has 24% of world total (EDR)
Uranium: Australia has 36% of world total (24% is in one mine)

Fusion Resources
Lithium: 4% world
Vanadium: 20% resources

Mineral	Australian EDR [1] (% world)	Australian TOTAL [2]
Lithium (Li)	170 kT (4.1%)	257 kT
Vanadium (V)	2586 kT (19.9 %)	5061 kT
Tantalum (Ta)	53 kT (94.6 %)	154.2 kT
Titanium (Ti) [3]	80.7 kT (21.5%)	158.7 kT
Zirconium (Zr) [3]	14.9 kT (40.5%)	40.9 kT
Niobium (Ni)	194 kT (4.3%)	2147 kT

Footprint
Australia is the biggest CO_2 producer per capita – 28 Tonnes pa/person

New Government ratifies Kyoto, $150M in Clean Energy Research
Government policies delayed by Financial Crisis and bushfires

Economically Demonstrated Resource = EDR
Source: Geoscience Australia, Australia's Identified Mineral Resources, Australian Government (2006).

The Australian ITER forum: Strategic Plan for Australian Fusion Science and Engineering

An association of > 130 scientists and engineers interested in plasma fusion energy science:

International Workshops held in 2006 and 2009

Proposal: Formation of an "Australian Fusion Initiative", that would enable development of expertise and industry capabilities to meet the nation's long-term needs.

$27M over 5 years, $63M over 10 years. Principal components:

- **A fellowship program:** to develop a broad national capability; focused on early to mid-career researchers;
- **An ITER instrument/diagnostic contribution:** – would be a flagship for Australia's effort
- **Enabling infrastructure:** to develop ITER contribution and enable broader capability (e.g. H-1 facility)

ITER Forum Strategic Plan has wide support

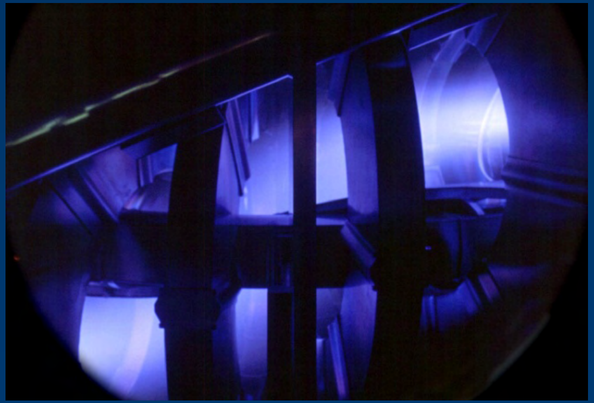
Letters of support from:

- *Australian National University,*
- *University of Sydney,*
- *University of Newcastle,*
- *University of Wollongong,*
- *Curtin University,*
- *Flinders University*
- *Macquarie University,*
- *Australian Nuclear Science and Technology Organisation,*
- *Australian Institute of Nuclear Science and Engineering,*
- *H1 Major National Research Facility,*
- *The Australia Institute*
- *Australian Institute of Physics*
- *Australian Institute of Energy,*
- *Australian Academy of Technological Sciences and Engineering*
- *The ITER organization*
- *The Hon. Martin Ferguson, Minister for Resources, Energy and Tourism*

and endorsement from a Parliamentary Standing Committee on non-fossil fuel energy (Prosser Report, 2007)

ANU Initiative on Emerging Energy Sources

Part of the Climate Change Institute, an interdisciplinary grouping of researchers across the Australian National University

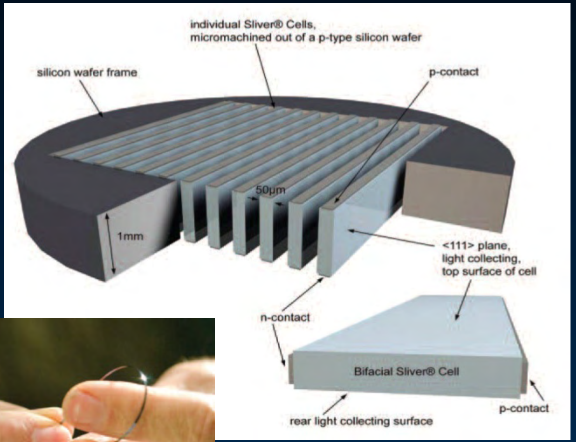


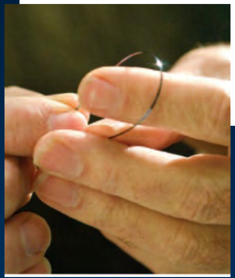
- The ANU is Australia's leading research university and unique among its peers as the only one formed by an Act of the Federal Parliament.
- We have the largest portfolio of research into Emerging Energy Sources (c.f. existing sources) of any university in Australia: ~$100M in facilities and over 150 researchers
- We collaborate and provide leadership with the other major players in Australia and internationally

Solar energy

ANU Centre for Solar Energy Systems:

- Photovoltaics
  - Sliver cells are very efficient and flexible (A. Blakers)
    - Single crystal, 100mm x 15-40um
      >20% efficiency
- Solar thermal
  - High and low temperature
  - Steam conversion (engine or turbine)
  - Chemical storage – e.g. ammonia
- Solar concentrators
  - "Big dish" 400m^2 at ANU (K. Lovegrove)
  - New Project: array of "lower cost" dishes for >1MW by ANU in South Australia with ANU ammonia storage technology
    - $7.4M Govt funding
    - commercial partner "Wizard"





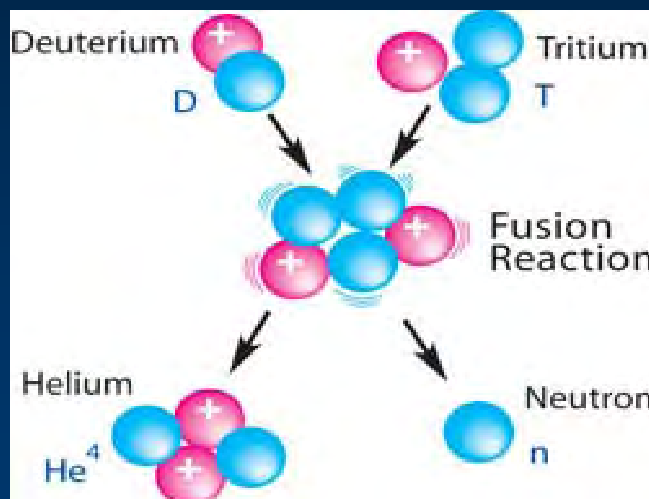
ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

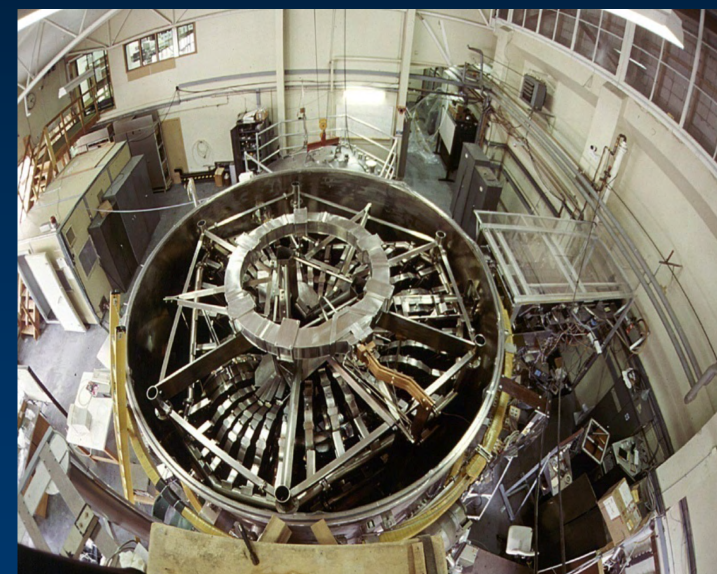
Fusion Power

Now — 30 years

- Advantages:
  - low carbon emissions and very low (long lived) radioactive waste
  - millions of years fuel abundantly available

Fusion powers the sun





- ANU Fusion
  - H-1 Major National Research Facility - develop national fusion capacity
  - Engage with ITER - worlds first fusion reactor and largest science experiment

Bio & Chemical Energy Systems

- Bio- & chemical-based research activity - aimed more at transportable energy:
  - Fuel Cells
  - Artificial Photosynthesis
  - BioSolar

- Bio & chemical energy systems can use renewable energy.
  They produce fuels: Hydrogen (H_2) from water, Carbohydrates from $C0_2$

H_2O + Energy => H_2 + Oxygen

CO_2 + Energy => Carbohydrates

- Hydrogen can be burnt to produce energy.
  Carbohydrates can be be used both for fuels and chemical feedstocks.

H_2 + Oxygen => H_2O + Energy

Carbohydrates => CO_2 + Energy

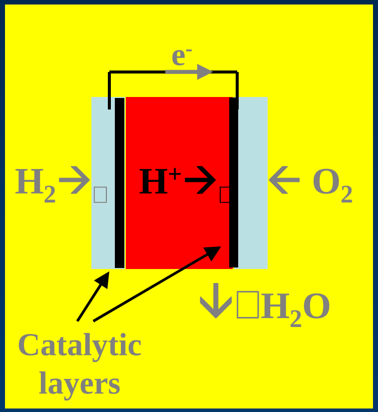
- These processes can be carbon neutral if the energy used in the first process is derived from non-fossil fuel sources e.g. sunlight

Fuel Cell Energy

Now — 30 years

Hydrogen energy trials in Western Australia

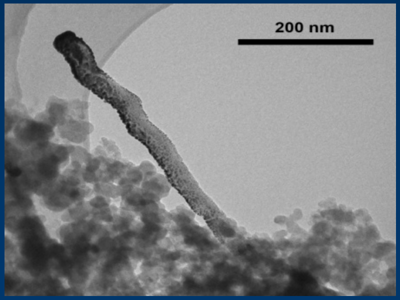
Perth



$H_2 + O$

$=$

H_2O + energy

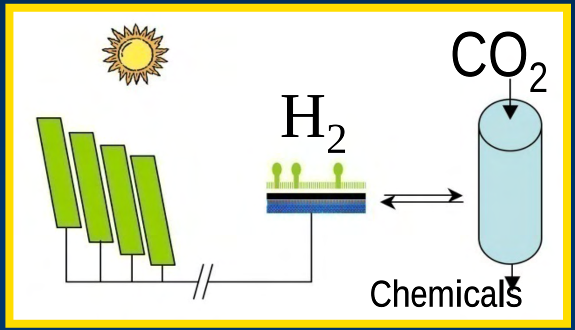


- ANU Fuel Cells
  - Uses plasmas to make carbon nano-fibres with clusters of platinum for electrodes
  - Sole national plasma fabrication for fuel cells - national/international collaborations

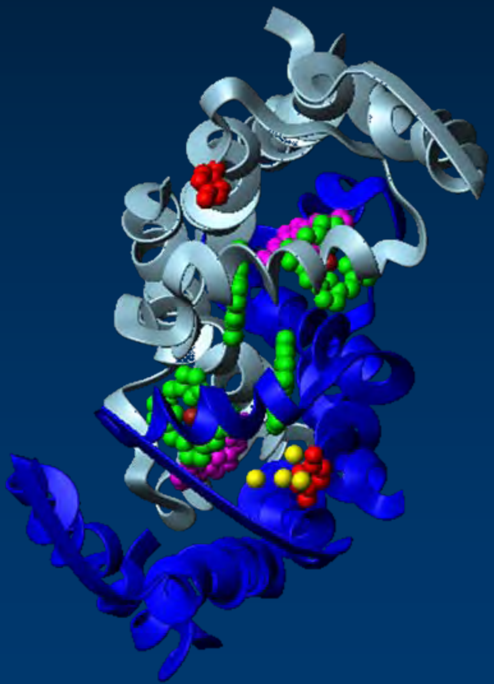
Artificial Photosynthesis

Now — 10 to 20 years — 30 years

- Advantages:
  - No CO_2 Emissions
  - Utilises Abundant Raw Materials
  - Carbohydrate Production via 'Dry Agriculture'



a process that mimics biology

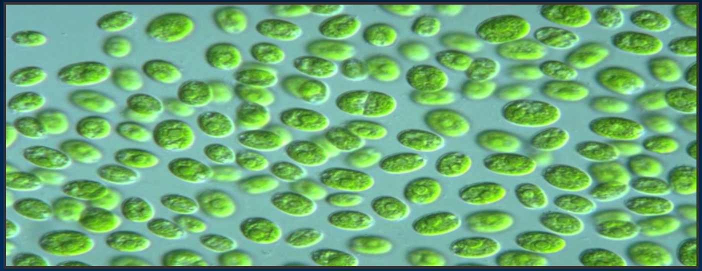


- ANU Artificial Photosynthesis
  - Chemistry inspired by biology converting light to energy
  - Linkages with CSIRO Industrial Physics and international institutions

BioSolar: Biofuels + solar-thermal

Now | 5-10 years | 30 years

- Advantages:
  - sustainable and carbon neutral
  - microalgae create oil for biofuels production
  - biomass for H_2 generation or feed stocks



A biological process :

CO_2

energy for processing

- ANU BioSolar
  - 2 ARC Centres of Excellence (Legume Research and Energy Biology)
  - Harnessing biotechnology and ANU thermal solar power for energy production

Closing Thoughts

- Australian plasma fusion research has had a very strong record
- Future of fusion research is linked to ITER and Energy
- New Government show promise
  - Increased internationalization of research
  - Clean energy initiatives
  - Dicussion of support of “full cost” of research

but financial crisis and bushfires have delayed white papers, policies

Solar energy is the biggest project, but many others..