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
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


Liley Torus

First Tokamak in West - Liley

First Spherical Torus (ANSTO)

First Heliac

SHEILA → H-1 Heliac

Oliphant: Discovery of Fusion (T)
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

ANU
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)

- 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

<table>
<thead>
<tr>
<th>Institution</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curtin University of Technology</td>
<td>• Atomic and molecular physics modeling</td>
</tr>
</tbody>
</table>
| The University of Newcastle | • High heat flux alloys  
• MAX alloys synthesis  
• Materials characterisation |
| The University of Sydney | • Quasi-toroidal pulsed cathodic arc  
• Plasma theory/ diagnostics  
• Dusty Plasmas |
| Macquarie University | • Plasma spectroscopy  
• MHD and kinetic theory  
• Materials science analysis |
| Macquarie University ~ Sydney Faculty of Engineering | • joining and material properties under high heat flux |
| ANSTO | • Manages OPAL research reactor  
• ~1000 staff |
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

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

Different Stochiometries ⇒ over 600 potential alloys.
Finite-$\beta$ equilibria in H-1NF

S. Lloyd (ANU PhD), H. Gardner

Enhanced HINT code of late T. Hayashi, NIFS

Vacuum $\beta = 1\%$
Island phase reversal: self-healing occurs between 1 and 2% $\beta$
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 equilibrium

(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 $J_\parallel$, we set $\nabla p = 0$ over finite regions $\Rightarrow \nabla \times B = \mu B$, $\mu = \text{const}$ (*Beltrami field*) separated by assumed *invariant tori.*
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
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, B$^{3+}$ and Tungsten (W$^{73+}$) for ITER

- e-Li$^+$ total ionisation cross sections
IEC: Doppler spectroscopy in H₂: Predicting experimental fusion rates

J. Kipritidis & J. Khachan

The University of Sydney

Applied and Plasma Physics
University of Sydney
**Results:** sample $H_\alpha$ spectrum at the anode wall

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Voltage</td>
<td>-30 kV</td>
</tr>
<tr>
<td>Current (DC)</td>
<td>15 - 25 mA</td>
</tr>
<tr>
<td>Pressure (H2)</td>
<td>4 - 6 mTorr</td>
</tr>
<tr>
<td>Exposure time</td>
<td>15 x 2000 ms</td>
</tr>
</tbody>
</table>

This peak used for prediction
Results: neutron counts! (constant voltage) PhysRevE 2009

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

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

(Summed $H_2^+$, $H_3^+$)

Supports neutral on neutral theory: Shrier, Khachan, PoP 2006
Levitation of Different Sizes Particles - Samarian

- Probing of sheath electric field on different heights

- RF Sheath Diagnostic

- 2.00 micrometer dust
- 3.04 micrometer dust
- 3.87 micrometer dust
- 4.89 micrometer dust
- 6.76 micrometer dust

Bulk Plasma

Sheath Edge

Sub-micron particles

Powered Electrode

The University of Sydney

AUSTRALIA
Dust Deflection in IEC Fusion Device – Samarian/Khachan

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

Phys Letts A 2007
ANU - University of Sydney collaboration

The University of Sydney

Brian James
Daniel Andruczyk

John Howard
Scott Collis
Robert Dall

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

Diagram of experimental set-up with various components labeled:
- H-1 vacuum vessel wall
- Collection optics
- Internal mirror
- Poloidal field coil
- Magnetic flux surfaces
- 1mm valve
- 1mm skimmer
- Ion gauge
- Gate valve
- He inlet
- 200 L/s turbo pump
- Outer vertical field coil
Pulsed He source

Collection optics
Spectral line emissivity vs radius

emissivity falls as beam moves into the plasma due to progressive ionization
Research Examples from H-1

- Effect of Magnetic Islands on Plasma
- Alfven Eigenmodes in H-1
## H-1 Heliac: parameters

<table>
<thead>
<tr>
<th></th>
<th>Achieved</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine class</strong></td>
<td></td>
<td>3-period heliac</td>
</tr>
<tr>
<td><strong>Major radius, R</strong></td>
<td>1m</td>
<td></td>
</tr>
<tr>
<td><strong>Minor radius, a</strong></td>
<td>0.1-0.2 m</td>
<td></td>
</tr>
<tr>
<td><strong>Vacuum volume, V</strong></td>
<td>33 m$^2$ (excellent access)</td>
<td></td>
</tr>
<tr>
<td><strong>Toroidal field, $B_\phi$</strong></td>
<td>$\leq$ 1 Tesla (0.2 DC)</td>
<td></td>
</tr>
<tr>
<td><strong>Aspect Ratio ($R/&lt;a&gt;$)</strong></td>
<td>5 + (Toroidal &gt; Helical)</td>
<td></td>
</tr>
<tr>
<td><strong>Heating Power, $P$</strong></td>
<td>0.2MW (28 GHz ECH)</td>
<td>0.3MW (6-25MHz ICH)</td>
</tr>
</tbody>
</table>

### Plasma parameters

<table>
<thead>
<tr>
<th></th>
<th>Achieved</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron density</td>
<td>$3 \times 10^{18}$ m$^{-3}$</td>
<td>$10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>electron temp., $T$</td>
<td>150eV</td>
<td>500eV</td>
</tr>
<tr>
<td>Plasma beta, $\beta$</td>
<td>0.2 %</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
H-1 configuration (shape) is very flexible

• “flexible heliac”: helical winding, with helicity matching the plasma, ⇒ 2:1 range of twist/turn

• H-1NF can control 2 out of 3 of transform ($\iota$)
magnetic well and shear $\Delta \iota$ (spatial rate of change)

• Reversed Shear → Advanced Tokamak mode of operation
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

- 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 $E_r$ at the core – similar to core electron root configuration?

Many unanswered questions......
  Symmetry?
  How to define $E_r$ 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.

- $V_{\text{Alfvén}} = \frac{B}{\sqrt{\mu_0\rho}}$, $\propto \frac{B}{\sqrt{n_e}}$

- Scaling in $\sqrt{n_e}$ in time (right) and over various discharges (below)

Critical issue in fusion reactors:

$V_{\text{Alfvén}} \sim$ fusion alpha velocity
$\Rightarrow$ fusion driven instability!
Fluctuation Spectra Data from Interferometer upgrade:  
*Rapid electronic wavelength sweep*

Profiles

RF Hesting, Horizontal Diagonal Projections #61188

Profiles

Line Averaged Density (10^19 m⁻³)

Impact Parameter (cm)

-20
-15
-10
-5

D Oliver

Return mirror

Turn-key
Fast sweep <1ms

Fluctuation spectra

Frequency (kHz)

0.2
0.4
0.6
0.8
1.0

Ratio of helical/toroidal current

0.0
10
20
30
40
50

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

Increasing twist
Energy Politics: Energy Consumption (NSW)

Prices set by NEMMCO marketing software – updated every 5 minutes

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)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Australian EDR</th>
<th>Australian TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium (Li)</td>
<td>170 kT (4.1%)</td>
<td>257 kT</td>
</tr>
<tr>
<td>Vanadium (V)</td>
<td>2586 kT (19.9%)</td>
<td>5061 kT</td>
</tr>
<tr>
<td>Tantalum (Ta)</td>
<td>53 kT (94.6%)</td>
<td>154.2 kT</td>
</tr>
<tr>
<td>Titanium (Ti)</td>
<td>80.7 kT (21.5%)</td>
<td>158.7 kT</td>
</tr>
<tr>
<td>Zirconium (Zr)</td>
<td>14.9 kT (40.5%)</td>
<td>40.9 kT</td>
</tr>
<tr>
<td>Niobium (Ni)</td>
<td>194 kT (4.3%)</td>
<td>2147 kT</td>
</tr>
</tbody>
</table>

**Fusion Resources**

Lithium: 4% world

Vanadium: 20% resources

**Footprint**

Australia is the biggest CO₂ 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

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
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” 400m² 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”
Fusion Power

Advantages:

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

ANU Fusion

- H-1 Major National Research Facility - develop national fusion capacity
- Engage with ITER - world's first fusion reactor and largest science experiment

Fusion powers the sun
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 (H₂) from water, Carbohydrates from CO₂

\[
\text{H}_2\text{O} + \text{Energy} \Rightarrow \text{H}_2 + \text{Oxygen} \quad \text{CO}_2 + \text{Energy} \Rightarrow \text{Carbohydrates}
\]

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

\[
\text{H}_2 + \text{Oxygen} \Rightarrow \text{H}_2\text{O} + \text{Energy} \quad \text{Carbohydrates} \Rightarrow \text{CO}_2 + \text{Energy}
\]

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

Now

30 years

Perth

H₂ + O → H₂O + 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

Advantages:
- No CO$_2$ Emissions
- Utilises Abundant Raw Materials
- Carbohydrate Production via ‘Dry Agriculture’

ANU Artificial Photosynthesis
- Chemistry inspired by biology converting light to energy
- Linkages with CSIRO Industrial Physics and international institutions
BioSolar: Biofuels + solar-thermal

Advantages:
• sustainable and carbon neutral
• microalgae create oil for biofuels production
• biomass for H₂ generation or feed stocks

A biological process:

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

energy for processing
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
  - Discussion 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..