Beyond ITER: Neutral beams for DEMO

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Introduction

- DEMO is the next large fusion facility after ITER
- DEMO will link a fusion source with electricity generation.
  - it will solve the technical problems of running a power plant
- Building of DEMO is *most likely* determined by the success of ITER – specifically operation at Q=10!
- Use of neutral beam injection on DEMO is *most likely* determined by success of neutral beam injection on ITER!
- Neutral beams for DEMO will *probably* incorporate many features not in use on ITER
- This talk will describe some of the physics and technology issues which must be addressed for neutral beams on DEMO
European Fusion Roadmap

1. Plasma operation
   - Inductive
   - Steady state regimes
   - Medium Sized Tokamak
   - ITER Q = 10
   - ITER steady state

2. Heat exhaust
   - Baseline strategy
   - Advanced configuration and materials
   - Medium Sized Tokamak, linear plasma devices and Divertor Tokamak Test Facility (DTT)
   - ITER Q = 10

3. Materials
   - Early Neutron Source

4. Tritium breeding
   - ITER TBM programme
   - Parallel Blanket Concepts
   - Chinese Fusion Engineering Testing Reactor (CFTR) and Fusion Neutron Science (FNS) facility (US)
   - ITER Q = 10

5. Safety

6. DEMO
   - Components Design and Engineering Design
   - Construction
   - Operation

Timeline:
- 2010
- 2020
- 2030
- 2040
- 2050
Next step in fusion

International Tokamak Experimental Reactor (ITER)

First sustained burning plasma

BASIC PARAMETERS:

- Plasma Major Radius 6.2m
- Plasma Minor Radius 2.0m
- Plasma Current 15MA
- Toroidal Field on axis 5.3T
- Fusion Power 500MW
- Burn Flat Top >400s
- Plasma volume ~840m$^3$
- Power Amplification Q>10

Cost is > 14 Billion Euro
First plasma – 2020
D-T campaign - 2027

Neutral beam requirement

Heating: 2 x 1MeV, 40A D$^-$ ⇒ 17MW of D$^0$ injected into plasma per injector (3600s)
Diagnostics: 1 x 100keV, 60A H$, \sim$ 3MW of H$^0$
ITER Beamline

- Heating beam parameters
  - $D^-$
  - Energy 1MeV
  - Accelerated current 40A
  - Gas neutraliser
  - Injected power 17MW

- Accelerator
  - ~10MW of power dumped in accelerator
  - ~700kW of electrons exits accelerator
  - ~900kW of backstreaming positive ions

- Extensive development programme with test stands operating and being built
  - see talks/posters at this meeting
DEMO options

“Pulsed” – Main option

DEMO 1A

- Major /minor radius - 9/2.49m
- Plasma current - 16.8MA
- Toroidal field - 6.5T
- $<T_e> - 12.9$keV, $<n_e> - 9.3 \times 10^{19} m^{-3}$
- Current drive $\sim 0.35 \times 10^{20} \text{AW}^{-1}\text{m}^{-2}$
- Neutral beam energy - 1MeV
- Neutral beam power - 100/50MW
- Pulse length $\sim 2$hrs
- Net electrical power $\sim 500$MW

Snapshot as of July 2013 - likely to change!

Courtesy R Kemp

“Steady state” – Background option

DEMO 2

- Major /minor radius – 8.1/2.99m
- Plasma current – 19.85MA
- Toroidal field – 5.0T
- $<T_e> - 15.5$keV, $<n_e> - 7.7 \times 10^{19} m^{-3}$
- Current drive $\sim 0.35 \times 10^{20} \text{AW}^{-1}\text{m}^{-2}$
- Neutral beam energy - 1MeV
- Neutral beam power - 135MW
- Pulse length $\sim 300$hrs
- Net electrical power $\sim 500$MW

Courtesy R Kemp

Pulsed” – Main option “Steady state” – Background option
Choice of beam energy

Beam energy choice driven by current drive efficiency and shinethrough limits

DEMO 1 example for a peaked density profile

I Jenkins et al, SOFE (2013)

- **1MeV may be acceptable**
  - Good news for accelerator!
    - ITER experience is very important
    - Power loadings in accelerator and ion source
    - Power supply, HV bushing, HV holdoff in vacuum.....
Energy efficiency requirements

- Recirculating power in a power plant must be kept to a minimum

- For a 2.4GW fusion power reactor
  - 1.56GW electrical out
  - >1/3 (~0.56GW) is recirculating power
    - 300MW for heating and current drive

- Power for neutral beam system
  \[ P_{NB} = \frac{P_{CD}}{\eta_{coup}\eta_{conv}\gamma_{CD}} \]

- System studies show for “economic” power
  - \( \eta_{conv}\gamma_{CD} > \sim 0.25 \) with \( \gamma_{CD} \sim 0.45 - 0.6 \)
  - so we require \( \eta_{conv} > \sim 0.45 \)

- DEMO designs assume \( \eta_{conv} = 40\% \)
  - \( \eta_{conv}\gamma_{CD} \sim 0.14 \)

Challenges for NBI on DEMO

Improved wallplug efficiency

• Number of methods proposed
  – improvement in transmitted neutral beam power
    • reduced stripping
    • improvement in divergence
  – improvement in neutralisation efficiency
    • photo-neutraliser
    • plasma neutraliser
  – improvement in use of electrical power
    • energy recovery

• One solution may not be enough in itself
  – technological challenge
  – risk mitigation
Beam halo and transmission

- Beam halo is relatively small in volume sources
- Halo increases with the addition of caesium to the source
- Halo also increases with increasing tank pressure

H de Esch et al

Surrey and Holmes

ITER modelling considers halos of up to 30mrad containing 15% of the beam

Halo formation possibly due to surface produced negative ions, space charge effects and magnetic fields
Beam halo formation


• Compensation of magnetic deflection and space charge effects
Towards 1MeV!

**Status**

- ITER programmes will provide important data
  - current density
  - beam divergence
  - effects of magnetic fields addressed in accelerator design
  - use of caesium

- Modelling plays an important role due to lack of facilities!
  - 2D and 3D starting to produce results

- Ionic plasma in front of plasma grid

- Virtual cathode in front of plasma grid

**Research priorities**

- Surface production
  - influence of D⁻ production site on extraction probability and trajectory

- Magnetic field effects

- Production of D⁻ on accelerator grids due to Cs migration and aberrated trajectories

- Space charge effects

- Role of caesium
  - Replacement?
  - Caesium management
Gas neutralisation

- Use of positive ion or negative ion source depends on size and plasma density of fusion device
  - need to penetrate to the core of plasma
  - determines beam energy
  - neutralisation efficiency determined by beam energy

- Gas neutralisation is the usual method

- Improvements in neutralisation can have a big effect on efficiency
Improved neutralisation - photoneutraliser

- Photo-detachment of negative ion beam by laser radiation
- Potential for high degrees of neutralisation
- Lower gas requirement
  - reduced stripping

Laser power requirement

\[ P = -\frac{hc}{\lambda} \frac{\ln(1-f)}{\sigma} \sqrt{\frac{2E_b}{M_b}} \frac{w}{G} \]

- \( f \) - degree of neutralisation
- \( \lambda \) - laser wavelength
- \( \sigma \) - photodetachment cross-section
- \( E_b, M_b \) - beam energy and mass
- \( w \) - average beam width
- \( G \) - number of laser passes through ion beam ("gain")

Laser power requirement for \( f=0.95, w=0.25 \text{m} \) and \( G = 500 \)
(M Kovari and B Crowley Fus, Eng. Des. 85 745, 2010)
Laser neutraliser proposals (recent)


A Simonin et al, Negative Ions, Beams and Sources, AIP Conf. Proc 1515, 532 (2011)
Improved neutralisation – plasma neutraliser

- Take advantage of higher neutralisation cross-sections for collisions with positive ions and electrons compared to gas

- Lower gas requirement

\[ \chi = \frac{n_i}{n_i + n_g} \]

K Berkner et al, Production and Neutralisation of Negative Ions and Beams (1980)
Some plasma neutraliser proposals

ECR plasma neutraliser

Arc discharge plasma

Ar at 5x10^-5 Torr
~10% ionisation


Beam driven plasma neutraliser

- Gas neutraliser $n_e \sim 10^{14}\text{m}^{-3}$ or 0.001% ionisation

- Beam generated plasma
  - stripping of $D^{-}$ produces fast electrons (272eV for 1MeV)
  - ionisation of background gas by beam particles ($D^{-}, D^{+}, D^{0}$)
    - electron energy distribution peaks at $\sim 62\text{eV}$ leading to further ionisation

- Plasma density enhancement by multipole confinement

E Surrey and A Holmes, Negative Ions, Beams and Sources, AIP Conf. Proc 1515, 532 (2012)
Neutraliser development

Status

- Initial studies only
- Some experimental tests planned

Technology development

- Photo-detachment neutraliser
  - High power dc lasers
  - Retaining mirror and cavity reflectivity
  - Cooling
  - Stability
  - Radiation damage

- Plasma neutraliser
  - Driven plasma
    - Some experiments with relatively low ionisation
  - Beam driven plasma
    - Initial idea only
  - Higher ionisation
  - High cusp fields
  - Effect of multipole field on beam divergence
  - End losses
Improved electrical efficiency - energy recovery

- Use recovery power supply to collect fraction $g$ of residual negative ions.
- Negative ions decelerated by $V_b$-$V_r$ to an energy of $eV_r$.
- Drain current in HV PS reduced by $g\eta$.

Example at 1MeV

$\eta_0 = 0.6$, $\eta_- = \eta_+ = 0.2$

For $g=0.9$, $i_d = 0.82i$

$i_d = i(\eta_0+2\eta_+ - \eta_+ + (1-g)\eta_-) = i(\eta_0+\eta_+ + \eta_- - g\eta_-)$

$= i(1-g\eta_-)$

$i_r = i\eta_-$

Need to keep $V_r/V_b$ as low as possible.

Deceleration and collection

- Input parameters
  - 1MeV beam
  - 2A in each channel
    - 80% of beam
    - core beam only (no halo)

- Modelled after magnetic separation of residual ions
  - Twiss parameters
    - $\alpha = 1.057$
    - $\beta = 5.31 \text{ m/rad}$
    - $\epsilon_{4\text{rms}} = 552 \times 10^{-6} \text{ m rad}$

- Staged deceleration with secondary particle suppression

- Single channel (x-x') shown

Power from the residual positive ions!

- Because the positive ions are created in the neutraliser their current cannot be re-circulated.

- Proposal for direct conversion of positive ion energy to electrical power:
  - Positive ions decelerated to low energy (say ~25kV).

- Resonant modular convertor:
  - Capacitors in modules charged initially to recovery voltage.
  - Drivers of each module switched alternatively.
  - Capacitors discharged through transformer and rectifier circuit.
  - Recovery current acts to charge capacitors.

- Module outputs connected in parallel or series.

Energy recovery development

**Status**

- First proposed back in 1970's
- Tests with positive ion beamlines
  - CEA Cadarache
- Tests with negative ion beamline
  - CEA Cadarache/JAERI
- No working systems in use!

**Technology development**

- 1 accelerator/ 1(2) ~ full energy decelerators
- Separation of residual ion beams (D^-/D^+)
  - Electrostatic/magnetic
- Recovery efficiency
  - beam losses in separation and deceleration
  - beam halo!
- Development of positive ion energy conversion and integration
Calculation of wallplug efficiency based on scaling for basic ITER beamline

<table>
<thead>
<tr>
<th>Ion source and beam</th>
<th>Efficiencies and transmission</th>
<th>Neutralisation and energy recovery</th>
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</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>1.0</td>
<td>DC efficiency 0.9</td>
</tr>
<tr>
<td>D⁺ current (A)</td>
<td>59.1</td>
<td>RF efficiency 0.9</td>
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<tr>
<td>Electron/D⁺ ratio</td>
<td>1</td>
<td>Stripping 0.29 0.24</td>
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<td></td>
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<td>No laser Laser</td>
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<td>Electron extraction</td>
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<td>Core divergence 3-7</td>
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<tr>
<td>voltage (kV)</td>
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<td>(mrad)</td>
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<tr>
<td>Electron suppression</td>
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<td>Halo divergence 15</td>
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<tr>
<td>voltage (V)</td>
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<td>(mrad)</td>
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<td>Electron suppression</td>
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<td>Re-ionisation BTR code Laser power</td>
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<td>current (A)</td>
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<td>Filter field voltage</td>
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<td>(V)</td>
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<td>(A)</td>
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<td>Incidentals (MW)</td>
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<td>No Laser</td>
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<td>Conversion efficiency 0.9</td>
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<tr>
<td>Laser</td>
<td>4.4</td>
<td>for positive ions</td>
</tr>
</tbody>
</table>

(BTR: Beam Transmission and Re-ionisation)
Wallplug efficiency for different neutralisation scenarios
Wallplug efficiency under different improved neutralisation and energy recovery scenarios

Wallplug efficiency

5 mrad core divergence
15 mrad halo
Summary

• DEMO represents an aggressive programme on the road to fusion energy

• The success of DEMO and the neutral beam system is predicated on the success of ITER

• Studies of options for improvement of neutral beam system efficiency are commencing now

• There is plenty of room for good ideas!
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Thank you for your attention