Cost effective path to DEMO

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To

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Outline

• Maximizing the development-cost benefit from ITER knowledge
• Getting on cost effective path
• Requirements of smaller scale experiment
• Cost problems are helped with efficient current profile sustainment
• Discovery of a new current drive method with profile control potential
• Summary
Cost benefit of scaling results from ITER must be maximized

- Scaling studies will allow us to predict the performance of the DEMO using data from a smaller scale experiment.

  KSTAR ← Scaling laws → ITER

  1/3 scale D₂ experiment ← Scale up → DEMO

- Future fusion physics experiments only need to be ~1/3 the size of DEMO.
Need to get on a cost effective path to DEMO

- Have to get on cost effective path someday.
- Development costs are less if we do it now.
Scaling from ITER sets DEMO-PoP cost

- Cost of ITER $20 B
- Cost of KSTAR $330 M
- Cost scaling: 1/3 size without blanket and shield is 1/60 the cost. About \((1/3)^{3/2}\)
- Total cost of ARIES AT power plant $2.8 B
- Half of direct cost is the reactor $1.4 B
- Similar 1/3 scale size of DEMO can cost $1.4B/60 = $23 M
- First of a kind credit (60%) $37 M
Some specification of 1/3 scale PoP based on ARIES-AT

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Machine cost</td>
<td>$37 M</td>
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<tr>
<td>R</td>
<td>1.7 m</td>
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<tr>
<td>Aspect ratio</td>
<td>4</td>
</tr>
<tr>
<td>Beta</td>
<td>&gt; 9%</td>
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<tr>
<td>Exceed Greenwald</td>
<td>60%</td>
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<tr>
<td>Coil-1\textsuperscript{st} wall space</td>
<td>0.25 m</td>
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<tr>
<td>Boot strap frac.</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Plasma performance depends on scaling laws, perhaps like DIII-D</td>
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<tr>
<td>High temperature super con. coils</td>
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<tr>
<td>High temperature structure material</td>
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<tr>
<td>Control temperature gradient modes</td>
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<tr>
<td>Scalable divertor</td>
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<td>Scalable fueling</td>
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<tr>
<td>Steady state current drive</td>
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<tr>
<td>Solenoid free startup</td>
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<tr>
<td>Prevent disruption</td>
<td></td>
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<tr>
<td>Control ELMs</td>
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</tbody>
</table>

- Has to be the next experiment (s).
Efficient current drive with profile control solves many problems for 1/3 scale PoP

- Machine cost $37M
- R 1.7 m
- Aspect ratio 4
- Beta > 9%
- Exceed Greenwald 60%
- Coil-1st wall space 0.25 m
- Boot strap frac. > 90%
- Plasma performance depends on scaling laws. perhaps like DIII-D

- High temperature super con. Coils
- High temperature structure material
- Control temperature gradient modes
- Scalable divertor
- Scalable fueling
- Cost and power efficient steady state current drive with profile control
- Solenoid free startup
- Prevent disruption
- Control ELMs
Most of the remaining issues are addressed if the control is sufficient for removal of the TF coil

- Machine cost: $37M
- R: 1.7 m
- Aspect ratio: 4
- Beta: > 9%
- Exceed Greenwald: 60%
- Coil-1st wall space: 0.25 m
- Plasma performance depends on scaling laws, perhaps like DIII-D

- High temperature super con. Coils ⇒ Normal conductors
- High temperature structure material
- Control temperature gradient modes
- Scalable divertor
- Scalable fueling

- With efficient current drive and profile control external toroidal field may not be necessary for stable well-confined equilibria with acceptable beta

- Cost may be low enough that very high temperature nuclear materials are unnecessary
Newly discovered Imposed-Dynamo Current Drive might give the control

• Observed to do current drive and should allow profile control.
• Similar to the way magnetic perturbations cause a force in a plasma rotating next to a resistive wall, perturbations also produce a force on differential flows in the electron fluid giving current drive.
• Sheared electron flow distorts almost any perturbation into cross-field current driving force. (B-field is frozen in the electron fluid.)
• Imposed perturbation profile $\Rightarrow$ defined current drive profile
• Only requires $\delta B/B \approx 10^{-4}$ in a reactor.
Imposed Dynamo Current Drive needs high electron fluid velocity at the edge and imposed fluctuations

Maxwell stress on mean flux surface = current driving force inside flux surface

\[ \int \frac{\delta B \delta B}{\mu_0} da = \int ne(\eta j - E) dvol \]
HIT-SI meets the requirements for imposed dynamo

- Injectors take turns driving edge current and imposing perturbations.
- Imposed dynamo was discovered on this first experiment to meet both requirements.
Imposed dynamo predicts current vs time

\[ \int \frac{\delta B \delta B}{\mu_0} da = \int n e(\eta j - E) dvol \]

\[ \dot{I}_{\text{tor}} = \frac{C_3}{n} I_{\text{inj}}^2 - \frac{I_{\text{tor}}}{\tau_{L/R}} \]

- \( \delta B \) from \( I_{\text{inj}} \).
- \( \eta \) from helicity decay time.
- Calculation starts at 1ms.
- Imposed dynamo accurately predicts current drive in edge flux surface.

Applying imposed dynamo to all flux surfaces \( \Rightarrow \) Imposed current profile
A good goal is to learn the physics and control needed to eliminate the TF coil

- May be only way to get on a cost effective path to DEMO.
- Private investment is only in TF-coil free ideas, demonstrating the cost point.
- Confinement has been demonstrated in transient low TF operation.
- The way to efficient formation and sustainment with profile control is now well lighted.
- In case we cannot afford the luxury of a TF-coil in a reactor, we must develop the profile control needed to eliminate it.
- Better control is valuable even with a TF-coil.
Summary

• Scaling data from ITER is extremely valuable.

• We need to get on a cost path that leads to DEMO NOW.

• Imposed dynamo may provide the control needed to solve many cost problems including the TF-coil.
Data over wide range of parameters agrees with model

- Applying theory to more shots

![Graph showing data and model comparison](graph.png)

Using $C_3 = 1.5 \times 10^{19}$ for all data
Current amplification of 3 is a spheromak record

- The injector currents are added in quadrature and smoothed over an injector cycle.
- The toroidal current is smoothed over an injector cycle.
- Shows a sustained current amplification greater than 2 with a peak value of 3.
- Up to 0.65 ms toroidal current persistence.

![Diagram showing current profiles and time progression](image-url)
Model predicts injector impedance

- IDCD model predicts
  \[
  \frac{V_{inj}}{I_{inj}} \propto \frac{j}{n}
  \]

- Measurements show
  \[
  \frac{V_{inj}}{I_{inj}} = (2.8 \times 10^{-12} \pm 0.7 \times 10^{-12}) \frac{j}{n}
  \]

- Amazing agreement
Model predicts injector impedance

- IDCD model predicts

\[
\frac{V_{\text{inj}}}{I_{\text{inj}}} \propto \frac{j}{n}
\]

- Measurements show

\[
\frac{V_{\text{inj}}}{I_{\text{inj}}} = (2.8 \times 10^{-12} \pm 0.7 \times 10^{-12}) \frac{j}{n}
\]

- Shows agreement
Model predicts $I_{tor}$ vs time

\[ \int \frac{\delta B_{\perp} \delta B_{\parallel}}{\mu_o} da = \int \nu (\eta j_{||} - E_{||}) dvol \]

- For a mean flux surface of minor and major radii of $r$ and $R$ this can be approximated as:

\[ \frac{\delta B_{rms}^2}{2 \mu_o} 2\pi R 2\pi r = (\eta j_{||} - E_{||}) ne \pi r^2 2\pi R \]

Using:

\[ \frac{B \lambda}{\mu_o} = j_{||}; \quad \tau_{L/R} = \frac{\mu_o}{\eta \lambda^2}; \quad B = \frac{C_1 \mu_o I_{tor}}{2\pi a}; \quad E_{||} = -\frac{\dot{B}}{\lambda}; \quad \delta B_{rms} = \frac{\mu_o I_{inj}}{C_2 a}; \quad r = a \]

Yields:

\[ \frac{\delta B_{rms}^2}{\mu_o} = C_1 \frac{\mu_o ne I_{tor}}{2\pi \lambda} \left( \frac{I_{tor}}{\tau_{L/R}} + \dot{I}_{tor} \right) \]

Solving for $dI_{tor}/dt$ yields:

\[ \dot{I}_{tor} = \frac{C_3}{n} I_{inj}^2 - \frac{I_{tor}}{\tau_{L/R}} \]

Where $C_3 = \pi \lambda / C_1 C_2 a^2 e$. Using $a = 0.22$ m, $\lambda = 10.3$ m$^{-1}$ from for HIT-SI and estimating $C_1 = 2$ and $C_2 = 4\pi$ gives $C_3 = 2.6 \times 10^{19}$ in SI units.
Future Plans

- Place three injectors on one side.
  - Drives plasma rotation for stability
  - Injectors have same preferred direction
  - Injectors easy to shield from DC spheromak fields
- Thicker plate gives better injector opening
- Using higher power surface treatment
- Try perforated plate backed by a pumped chamber for density control
Office of Nuclear Energy is developing ARIES-AT relevant materials

- Very High Temperature Reactor (VHTR) concept
- Developing high temperature structural material that can tolerate the nuclear environment.
- The temperature (1000°C) and DPA requirements are similar to the most difficult materials demands of ARIES-AT
- We need to keep abreast with these developments in NE
- It is not cost effective for us to do it
Specification of 2/3 scale CTF based on ARIES-AT

- $415 \text{ M machine cost}$
- CTF requirements
- Tritium gain
- Many blanket modules
  - High temperature nuclear certified materials
  - Do 14 MeV R & D (try top candidates)
- Pre-DEMO
- R = 3.4 m
- 0.5 m thick blanket and shield
Small CTX Spheromaks achieved 400eV temperatures [Jarboe 90]

- Temperature is taken at 310 μs.
- MeV runaway electrons observed [Chrien 91]
- Ohmically heats to beta limit –Best it can do.
Goal of ohmically heating to the β-limit was achieved in the CTX large solid flux conserver experiment. [Wysocki 88]

- Results are from Multi-point Thomson scattering. Peak temperature was 150eV.
- With $T_e = T_i$ peak local $\beta \approx 60\%$, ($\beta_{\text{tor}} = \infty$)
- $\Delta t$ is time the relative to a rapid loss of density at the magnetic axis (from the instability)
- If resistivity and confinement scale as Spitzer, result independent of size and T.
- Confinement cannot get any better than this and should be sufficient for reactor.
Achieving large separatrix region is a three step process

1. A large non-symmetric configuration is formed (matches injector symmetry)
2. A self-organizing reconnection event forms separatrix
3. Separatrix current is increased by imposed dynamo current drive

[Calculations performed by George Marklin (Plasma Science and Innovation Center)]
Data show three step process

1. A large non-symmetric configuration is formed (injector symmetry)
2. A self-organizing reconnection events forms separatrix
3. Separatrix current is increased by imposed dynamo current drive (IDCD)
Equation without density fails to fit

\[ \dot{I}_{\text{tor}} = C_3 I_{\text{inj}}^2 - \frac{I_{\text{tor}}}{\tau_{L/R}} \]
Simple roadmap to DEMO

- Cost and science scalable CTF might entice private funding.
references

F. Najmabadi et al. / Fusion Engineering and Design 80 (2006) 3–23

KSTAR: Nuclear Engineering International 10 August 2009