SMALLER & SOONER:
EXPLOITING NEW TECHNOLOGIES
FOR FUSION’S DEVELOPMENT

Dennis Whyte
MIT Plasma Science and Fusion Center
MIT Nuclear Science and Engineering

With grateful acknowledgement to MIT colleagues and students
B. Sorbom, D. Sutherland, C. Kasten, C. Sung, T. Palmer, J. Ball, F. Mangiarotti,
J. Sierchio, P. Bonoli, L. Bromberg, J. Minervini, G. Wallace, E. Marmar, M. Greenwald,
B. Lipshcultz. Y. Podpaly, G. Olynyk, M. Garrett, Z. Hartwig, R. Mumgaard,
C. Haakonsen, H.S. Barnard

SOFE 2015
June 2015
It is self-evident that smaller, modular fusion devices will accelerate fusion’s development.

<table>
<thead>
<tr>
<th></th>
<th>Shippingport: 1954 “Pilot” Fission Plant</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{thermal}}$ (MW)</td>
<td>230</td>
<td>500</td>
</tr>
<tr>
<td>Core volume (m³)</td>
<td>60</td>
<td>~1000</td>
</tr>
<tr>
<td>Cost (2012 US B$)</td>
<td>0.6</td>
<td>~ 20</td>
</tr>
<tr>
<td>Cost / volume (M$/m³)</td>
<td>10</td>
<td>~ 20</td>
</tr>
<tr>
<td>Construction time (y)</td>
<td>~ 4</td>
<td>&gt; 20</td>
</tr>
</tbody>
</table>

- Cost & time $\propto$ unit volume and mass
It is self-evident that smaller, modular fusion devices will accelerate fusion’s development

<table>
<thead>
<tr>
<th></th>
<th>Shippingport: 1954 “Pilot” Fission Plant</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{thermal}} (\text{MW}) )</td>
<td>230</td>
<td>500</td>
</tr>
<tr>
<td>( \text{Core volume} (m^3) )</td>
<td>60</td>
<td>(~1000)</td>
</tr>
<tr>
<td>( \text{Cost (2012 US B$)} )</td>
<td>0.6</td>
<td>(~20)</td>
</tr>
<tr>
<td>( \text{Cost / volume} (\text{M$}/m^3) )</td>
<td>10</td>
<td>(~20)</td>
</tr>
<tr>
<td>( \text{Construction time (y)} )</td>
<td>(~4)</td>
<td>(&gt;20)</td>
</tr>
</tbody>
</table>

- Cost & time \( \propto \) unit volume and mass

- ITER is an invaluable science experiment for burning plasmas but is not an optimized size for modular fusion energy “pilots”
  - ITER is a trial of just one fusion concept, fission pilot tried four different cores!

- Small size and modularity are self-reinforcing: pilots of complex engineered systems as small as possible, yet sufficiently capable
It is self-evident that smaller, modular fusion devices will accelerate fusion’s development.

- Cost & time \( \propto \) unit volume and mass
- ITER is an invaluable science experiment for burning plasmas but is not an optimized size for modular fusion energy “pilots”
  - ITER is a trial of just one fusion concept, fission pilot tried four different cores!
- Small size and modularity are self-reinforcing, make pilots of complex engineered systems as small as possible, yet sufficiently capable

<table>
<thead>
<tr>
<th></th>
<th>Shippingport: 1954 “Pilot” Fission Plant</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{thermal}} ) (MW)</td>
<td>230</td>
<td>500</td>
</tr>
<tr>
<td>Core volume (m(^3))</td>
<td>60</td>
<td>~1000</td>
</tr>
</tbody>
</table>

Sounds like a reasonable strategy but how do you do it?
Confinement physics strongly favors high $B$ to produce fusion capable devices at smaller size.

Gain:
\[ nT \tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3 \]

\[ V \propto R^3 \]

\[ \frac{P_{\text{fusion}}}{S_{\text{wall}}} \sim \frac{\beta_N^2 \epsilon^2}{q_*^2} R B^4 \]

Power density

Copper coil pulse $\sim 10$ s

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (m)</td>
<td>2.14</td>
</tr>
<tr>
<td>$V$ (m$^3$)</td>
<td>30</td>
</tr>
<tr>
<td>$B_0$ (T)</td>
<td>10</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>$&gt;$10</td>
</tr>
<tr>
<td>Steady-state</td>
<td>No</td>
</tr>
<tr>
<td>Tritium breeding</td>
<td>No</td>
</tr>
<tr>
<td>$Q_{\text{electric}}$</td>
<td>0</td>
</tr>
</tbody>
</table>
Confinement strongly physics favors high B to produce fusion capable devices at smaller size.

\[ nT \tau_E \sim \frac{\beta N H}{q_*^2} R^{1.3} B^3 \]

\[ V \propto R^3 \]

\[ P_{\text{fusion}} \sim \frac{\beta N^2 \epsilon^2}{q_*^2} R B^4 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>2.14</td>
</tr>
<tr>
<td>V (m³)</td>
<td>30</td>
</tr>
<tr>
<td>( B_0 ) (T)</td>
<td>10</td>
</tr>
<tr>
<td>( Q_p )</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Steady-state</td>
<td>No</td>
</tr>
<tr>
<td>Tritium breeding</td>
<td>No</td>
</tr>
<tr>
<td>( Q_{\text{electric}} )</td>
<td>0</td>
</tr>
</tbody>
</table>

Copper coil pulse ~ 10 s

Continuous /w High-B Superconductors?
Basic geometry favors demountable magnets to provide modularity for internal components.
ARC conceptual design example of “smaller, sooner” fusion device using new superconductors

REBCO superconductor $B = 9.2$ T

Copper, $B = 3.5$ T

$P_{\text{fusion}} \approx 500$ MW

$\times B^4$

$P_{\text{fusion}} \approx 10$ MW

ARC: $R \approx 3.2$ m

JET: $R \approx 3$ m

~4 years construction
ARC conceptual design example of “smaller, sooner” modular fusion devices using new superconductors

- Demountable magnetic field coils
- Single-unit vertical lift

Small, modular design features generically attractive to your favorite MFE choice: ST, stellarator, liquid wall etc.

B. Sorbom et al FED 2015  SP6-62 Tue pm
Multiple, linked engineering design challenges to smaller, modular path

Challenges

$B_{\text{coil}} > 20 \, \text{T}$

SC Joints

Demountable coils

Small radial build neutronics

Internal components with small space + high power density
Multiple, linked engineering design challenges to smaller, modular path

**Challenges**

- $B_{\text{coil}} > 20 \, \text{T}$
- SC Joints
- Demountable coils
- Small radial build neutronics
- Internal components with small space + high power density

**Opportunities /w new technology**

- REBCO superconductors
- REBCO: tape form
- REBCO: $T \sim 25 \, \text{K}$
- Immersion liquid blanket
- Additive manufacturing of single-unit VV/PFC with advanced cooling capability
Multiple, linked engineering design challenges to smaller, modular path

Challenges

- $B_{\text{coil}} > 20$ T
- Superconducting joints
- Demountable coils
- Small radial build
- Neutronics

Opportunities /w new technology

- REBCO superconductors
- REBCO: tape form
- REBCO: $T \approx 25$ K
- Additive manufacturing of single-unit VV/PFC with advanced cooling capability

Internal components with small space + high power density

REBCO superconductors & Additive Manufacturing (3D printing) are new and rapidly developing technologies, so this is necessarily “work in progress”

Additive manufacturing of single-unit VV/PFC with advanced cooling capability
A revolution in superconductors in last 5 years:

REBCO (Rare-Earth Barium Cu Oxide) remain superconducting at VERY high B-field and above liquid He temperatures.
REBCO: coated superconductors in robust tape form, commercially available

- Strong in tension due to steel
- Flexible
- Outer Cu coating → simple solder low-resistance joint
- Stark contrast with NbSn superconductor strand & CIC!

REBCO tape composition (not to scale)
REBCO superconductors performance is constantly improving for application in high-B coils: E.g. Challenge of field anisotropy in $j_{\text{crit}}$
REBCO superconductors performance is constantly improving for application in high-B coils: E.g. Field anisotropy in $j_{\text{crit}}$ nearly eliminated last year.

Making coils from REBCO:
“No-insulator” tape winding highly attractive

• Steel is “internal” insulator for each turn

• Benefits
  ➢ Simple
  ➢ Improved mechanical strength
  ➢ Radiation resistance (insulators weakest link)
  ➢ Self-protecting in quenches

No-insulator coil self-heals via internal redistribution of $j \rightarrow \text{“Single-turn mode”}$ → Immediate drop in $B$, energy distributed in coil

“No-insulator” winding provides intrinsic quench protection in coil.

Quench at 9 Tesla: No damage to stacked double pancake coil (2014)

S. Hahn et al. Bitter Magnet Lab, MIT
Large coils made with REBCO actually require joints: Contact resistance at low-T is acceptable.

26 stacked coils
~300 m/coil consistent with maximum continuous length of high-performance tape

- Soldered joints!
- Mechanical attachment lowers resistance
April 2015: New record of 26.5 Tesla with REBCO-only, “no-insulation” coil

4.2K Magnet Operation

S. Hahn, J.M. Kim, et al.
NNFML, FSU, SUNAM, MIT
Scaled-down REBCO coil matches most requirements for ARC design

<table>
<thead>
<tr>
<th>B_{coil}(T)</th>
<th>26.5</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_{e} (A/mm^2)</td>
<td>400</td>
<td>400-500</td>
</tr>
<tr>
<td>T (K)</td>
<td>4.2</td>
<td>25</td>
</tr>
<tr>
<td>Materials</td>
<td>REBCO, SS316L</td>
<td></td>
</tr>
<tr>
<td>σ_{max} (MPa)</td>
<td>593</td>
<td>660</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>0.03</td>
<td>~ 6</td>
</tr>
</tbody>
</table>
Large-bore challenge for high-B MFE magnet: requires optimized geometry & superstructure

Peak stress ~ 0.67 Gpa
~65% of limit for 316SS LN

1. Support ring, 2. Top TF leg
4. Mechanical joint
6. Epoxy enforcement

\[ B_{\text{coil}} = 23 \, \text{T} \]
Demountable TF coil: Evolving strategy ➔ Separation of mechanical and electrical joints

F. Mangiorotti, J. Minervini
MIT Ph.D. thesis
One design example:
Plate terminations with edge joints
One design example:
Plate terminations with edge joints

F. Mangiortt, J. Minervini
MIT Ph.D. thesis
Operation of joints above 4 K liquid He temperatures is highly advantageous

- Greatly reduces required cooling power (Carnot).

- Thermal stability due to higher heat capacity.

- Operation or ARC at T~25 K
  - Small power to joints
  - Liquid H or Ne for cooling options

R/a=3.5

Copper FNSF-AT
Coil $P_{\text{coil}} \approx 500$ MW

ARC: Resistive joints /w REBCO superconductors
Coil $P_{\text{coil}} \approx 1$ MW
Demountability seems complicated…
is it really worth it? Yes, for FNSF/Pilot

- Demountable design transfers complex, integrated risk away from the speculative nuclear components and places it on “non-nuclear” mechanical/electrical engineering.

- Nuclear components have “Catch-22” problem: needs FNSF to test its own components!

- Can demonstrate demountable joints at small scale.

- Device maintenance with modular coils: single leg failure of TF can be tolerated.
Demountable coils have a profound effect on modularity and design of interior fusion “core”

- Core is designed as a single integrated unit
  - PFCs, vacuum vessel, blankets
  - Synergy with keeping design of small total mass and volume

- Fabrication + qualification done completely off-site
  - Vacuum
  - Heating
  - Cooling

- No connections made inside TF
Modular core can have a profound effect on fusion design: e.g. the immersion blanket

- VV is right beside plasma
- VV is immersed in liquid blanket

Advantages

- Simple
- Neutronics/nuclear engineering at atmospheric pressure.
- No gaps
- Energy & tritium extraction with single-phase low-velocity flow
- No DPA limits in blanket
- Minimized solid waste
- Tub is robust safety boundary
Immersion blanket: Many liquid choices & lack of internal structure optimize neutron thermalization, energy capture and tritium breeding → Small radial build

Heating with 2mm W first wall, 2.54cm Inconel-625 vessel

![Graph showing Heating (GW) vs Distance into the 200 cm blanket (cm)]

- Li$_{17}$Pb$_{83}$
- Li$_{17}$Pb$_{83}$ (E=90%)
- FLiBe
- FLiBe (E=90%)
- Li (nat)
- Li (E=90%)
- LiH
- LiD

MCNP
Immersion blanket: Many liquid choices & lack of internal structure optimize neutron thermalization, energy capture and tritium breeding → Small radial build

TBR with 2mm W first wall, 2.54cm Inconel-625 vessel

Distance into the 200 cm blanket (cm)

TBR (tritons/source neutron)

MCNP
Immersion blanket: Solid, replaceable components (plasma-facing materials, vacuum vessel) receive minimized neutron damage immersed in low-Z fluid.

Damage to the Inconel-625 primary vacuum vessel

Neutron wall loading: 4 MW/m²
Wall area = 533 m²
Uptime: 2.9e7 s (11 months)

MCNP

Z. Hartwig, C. Haakonsen   MIT
While in many ways, immersion blanket is ideal (see fission!) it does limit areal access to plasma

- Heating, pumping, diagnostics must wind through supports

- ARC: Total ~ 4-5 m$^2$
  - RF heating: ~1 m$^2$
  - Support: ~ 1-2 m$^2$
  - Pumping ~ 0.5 m$^2$

- Tradeoff: more port area vs. TBR, neutron streaming
Immersion blanket: Very large heat sink in close proximity to internals provides fundamental improvement in heat exhaust
Immersion blanket: high-T molten salt FLiBe
Single-phase, low-pressure flow with minimum MHD effects

<table>
<thead>
<tr>
<th>Property</th>
<th>FLiBe [7]</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point (K)</td>
<td>732</td>
<td>273</td>
</tr>
<tr>
<td>Boiling Point (K)</td>
<td>1700</td>
<td>373</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1940</td>
<td>1000</td>
</tr>
<tr>
<td>Specific Heat (kJ/kg/K)</td>
<td>2.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m/K)</td>
<td>1</td>
<td>0.58</td>
</tr>
<tr>
<td>Viscosity (mPa-s)</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

- TBR ~ 1.14
- High thermal efficiency ~ 0.4 - 0.5
- Shielding: ~10 FPY coil lifetime
Immersion blanket: high-T molten salt FLiBe
Single-phase, low-pressure flow with minimum MHD effects

- TBR ~ 1.14
- High thermal efficiency ~ 0.4 - 0.5
- Shielding: 10 full-power coil lifetime
- Exploit FLiBe + Immersion blanket + Additive manufacturing to address high heat flux regions?
Preliminary study: Improved surface heat removal with FLiBe + 3-D printed cooling channels

Next major design study: ARC divertor & cooling

2 mm thick W tile

2 mm thick W tile + Internal Fin

10 m/s

~ 1 bar pressure drop

L. Zhou, R. Vieira  MIT
Strong benefits of 3D printing for actively cooled launchers too

Example RF antennae strap
Integrated, near-surface cooling channels impossible /w standard manufacturing

S. Wukitch
Tue pm
SO15
New technologies provide access to synergistic physics design advantages at high-B and small size: High-field side launch $\Rightarrow +$ 50% CD efficiency
New technologies provide access to synergistic design advantages at high-B and small size:
Robust steady-state far from disruptive limits

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>ARIES-AT</th>
<th>ARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>q_{95}</td>
<td>6.3</td>
<td>3</td>
<td>7.2</td>
</tr>
<tr>
<td>H_{98}</td>
<td>1.5</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>\beta_N</td>
<td>3.7</td>
<td>5.4</td>
<td>2.6</td>
</tr>
<tr>
<td>G = \beta_N H_{98}/q^2</td>
<td>0.14</td>
<td>0.90</td>
<td>0.09</td>
</tr>
<tr>
<td>f_{bootstrap}</td>
<td>0.65</td>
<td>0.91</td>
<td>0.63</td>
</tr>
<tr>
<td>n / n_{Greenwald}</td>
<td>0.5</td>
<td>0.9</td>
<td>0.65</td>
</tr>
</tbody>
</table>

\[
\frac{P_{\text{fusion}}}{S_{\text{wall}}} \sim \frac{\beta_N^2 \epsilon^2}{q_*^2} R B^4
\]

\[
nT \tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3
\]

- Steady-state scenario using high safety-factor, moderate Beta approach
- Scenario ACHIEVED in present moderate-B devices (e.g. DIII-D)
Modularity and small size should be enabling to solving critical issue of divertor heat exhaust

- Large linear size, low B unfavorable for heat exhaust
  - At fixed fusion power density, Eich scaling \( q// \sim R B \)
  - Lawson criterion: \( R \sim 1/B^{2.3} \)
  - \( q// \sim 1 / B^{1.3} \)

- Advanced divertor coils built into modular core as replaceable components
  - Exploit physics advances from expanded volume divertors

**ADX presentations**
LaBombard SO10-3 Tue AM
Posters: SP3 Tue PM
Near-term, *small-scale* research can pursue this exciting path for fusion energy.
The disruptive innovation of high field, high-T superconductors

Demountable High-B coils

Superconductor

Liquid blanket

Smaller, sooner Viable fusion energy

Steady-state

Operation robustness

Small & Modular
Summary

• Fusion is hard …as a community we need to be continually looking for both technology and science innovations that will accelerate fusion’s development

• Exciting technology opportunities recently available: High-temperature, high-field superconductors Additive manufacturing

• Conceptual reactor design shown here give a sense of technology limits and integrated effects on magnetic fusion…those effects appear to be positive and revolutionary

• The near-term pace of fusion science development will also be accelerated by exploiting these technologies