EU Demo1 is Large & Low Power

- Demo must point to competitive COE
- $ > 1.5^2 \times$ price of ITER
- 0.5 GWe, pulsed
- Much more than fission $$/GWe?$
- How does this point to lower COE?

Wenninger et al.
EPS, 2015
The Problem is Power Handling

~ Reasonable cost steady state fusion power plant.

We need to understand this problem...
Outline

• Parallel heat flux
• Surface heat flux
• Simple detachment model
• Magnetic geometry
• Lithium vapor box divertor
Outline

• Parallel heat flux
• Surface heat flux
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• Magnetic geometry
• Lithium vapor box divertor
IR Data are Fit with “Eich Function”

- Convolve an exponential ($\lambda_9$) starting at the separatrix, representing the near SOL around the plasma, with a Gaussian ($S$) representing spreading along the divertor leg.

\[
q_{||}(x) = q_{||0} \int_0^\infty \exp\left(-\frac{x'}{\lambda_9}\right) \left\{ \frac{1}{\sqrt{\pi} S} \exp\left(\frac{-(x-x')^2}{S^2}\right) \right\} dx' \\
= \frac{q_{||0}}{2} \exp\left(\frac{S}{2 \lambda_9}\right)^2 \frac{x}{\lambda_9} \text{erfc}\left(\frac{S}{2 \lambda_9} - \frac{x}{S}\right)
\]

F. Wagner, NF 1985

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T. Eich, NF 2013
Data fit HD Model / 1.25 Well

\[ \lambda_q \text{ Data fit HD Model / 1.25 Well} \]

Scales with intensive variables, not system size.

Projections for ITER and Demo ~ 1 mm (!)
Individual Scalings fit HD Model

![Graph showing individual scalings fit for HD Model with variables B, q_cyl, P_SOL, R, and a/R. The graph indicates scaling coefficients for different models: HD Model, R/a ~ 3, R/a≈3 + MAST, and R/a≈3+MAST+NSTX.]
$S/\lambda_q$ Relatively Constant @ $\sim 0.5$

- $\lambda_{int,OMP} \equiv \int q\,dR/\hat{q}$
- $\lambda_{int}/\lambda_q$ varies with $S/\lambda_q$ in Eich fct.
- For $S/\lambda_q = 0.5$, $\lambda_{int}/\lambda_q = 1.79$
- $\lambda_{int} \sim 1.79\lambda_q$

- It is possible that turbulence will cause $\lambda_q$ or $S$ to scale with size from JET upwards... but much less than linearly, since JET fits HD model & $S/\lambda_q$.  

T. Eich, 2014
Let’s Evaluate $q_{||}$ for Demo1

\[ \lambda_q = 5671 \cdot P_{SOL}^{1/8} \left( 1 + \kappa^2 \right)^{5/8} \frac{a^{17/8} B^{1/4}}{I_p^{9/8} R} \times \left( \frac{2A}{1+Z} \right)^{7/16} \left( \frac{Z_{\text{eff}} + 4}{5} \right)^{1/8} \]

- Gives poloidal average width, $<\lambda_{q,HD}>$
- Map to OMP along flux surfaces, by fixing $\lambda \nabla \psi_p = \lambda_{HD} (R_0 <B_p>)$

\[ \lambda_{\text{int,HD,OMP}} = \frac{1.79 <\lambda_{q,HD}> R_0 <B_p>}{1.25 (R_0 + a) B_{p,OMP}} \]

- Demo1 assumes $P_{\text{sep}} = 154$ MW = 0.33 ($P_\alpha + P_{\text{aux}}$)
- Requires $Z_{\text{eff}} \sim 2.6$, $H = 1.0$
- $1.2 \times H$-mode threshold power.

\[ q_{||,R_0} \approx \frac{2 P_{\text{sep}}/3}{2\pi (R_0 + a) \lambda_{\text{int,OMP}}} \frac{B_{\text{OMP}}}{B_{p,OMP}} \frac{B_{t,0}}{B_{\text{OMP}}} = \frac{1.25 P_{\text{sep}} B_{t,0}}{3\pi \cdot 1.79 <\lambda_{q,HD}> R_0 <B_p>} \approx 3.6 \text{GW/m}^2 \]
Outline

• Parallel heat flux
• Surface heat flux
• Simple detachment model
• Magnetic geometry
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Fish-scaling Hides Leading Edges

Misalignments are inevitable

\[ a/b = \sin(\alpha + \alpha_0); \quad q \perp b = q \parallel a \]

\[ q \perp = q \parallel a/b = q \parallel \sin(\alpha + \alpha_0) \]
There are limits to both $\alpha$ and $\alpha_0$

- To reduce $\alpha$ requires
  - reducing poloidal field at target and/or
  - inclining target plate nearly tangential to B

- To reduce $\alpha_0$ requires
  - very high-precision alignment and
  - very little degradation of alignment over time

- $\alpha + \alpha_0 = 2^\circ$ would constitute major success

- $3.6 \text{ GW/m}^2 \times \sin 2^\circ = 126 \text{ MW/m}^2$
  A factor of 12.5 – 25 too high!
  Requires essentially full detachment
Outline

• Parallel heat flux
• Surface heat flux
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Simple Detachment Model

• Parallel heat flux is reduced by impurity cooling

\[q_\parallel = \kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial z}\]

\[\frac{\partial q_\parallel}{\partial z} = n_e n_z L_z = n_e^2 c_z L_z; \quad c_z \equiv \frac{n_z}{n_e}\]

• Multiply these:

\[\frac{1}{2} \frac{\partial q_\parallel^2}{\partial z} = n_e^2 c_z L_z \kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial z}\]

• Integrate and assume \(\rho_e = n_e T_e = \text{const.}\)

\[\Delta q_\parallel^2 = \int_{T_{det}}^{T_{sep}} 2n_e^2 c_z L_z \kappa_0 T_e^{5/2} dT_e = 2\left(n_e,\text{sep} T_e,\text{sep}\right)^2 \int_{T_{det}}^{T_{sep}} c_z L_z \kappa_0 T_e^{1/2} dT_e\]

Lengyel, 1981
$q_{\parallel} / (n_{e,\text{sep,20}} \sqrt{f_{z\%}})$ using ADAS

Demol $n_{GW} = 0.74 \cdot 10^{20} m^{-3}$

$q_{\parallel}$ that can be detached $\propto \sim n_{\text{sep}} \sqrt{c_z T_{\text{sep}}^{3/2}}$
Can we Increase $n_{sep}/n_{GW}$?

- Experiments run with $n_{sep} \sim \bar{n}/3$
- HD model consistent with ballooning limit in SOL at $n_{sep} \sim \bar{n}_{GW}/3$

![Graph showing electron density decay length and electron pressure gradient length against SOL electron temperature decay length, with $\eta_e = 1.4$ and $n_{sep} \sim \bar{n}/3$.](image)

- Strong pedestal $\nabla T_e$ with low $\nabla n_e$ impossible?

H.J. Sun, PPCF 2015
Bring in Spitzer $T_{e, \text{sep}}$ & GW Density

\[ q_{\|, \text{det}} = n_{e, \text{sep}} T_{e, \text{sep}} \sqrt{\frac{T_{\text{sep}}}{T_{\text{det}}}} \int_c L z \kappa_0 T_e^{1/2} dT_e \sim n_{e, \text{sep}} T_{e, \text{sep}}^{3/2} c_z^{1/2} \]

- Assume Spitzer $\chi_{\| e}$, Greenwald density scaling

\[ T_{e, \text{sep}} \propto \left( q_{\|, q_{\text{cyl}} R_0} \right)^{2/7} \quad \ell_{\|}^* \equiv \frac{L_{\|}}{\left( \pi q_{\text{cyl}} R_0 \right)} \quad n_{e, \text{sep}} \propto f_{GW, \text{sep}} \frac{\langle B_p \rangle}{a} \left( 1 + \kappa^2 \right)^{1/2} \]

- Plug these into equation above

\[ q_{\| R_0} \propto f_{GW, \text{sep}} \frac{R_0}{a} \langle B_p \rangle \left( 1 + \kappa^2 \right)^{1/2} \left( q_{\|, q_{\text{cyl}} R_0} \right)^{3/7} c_z^{1/2} \]

\[ c_z f_{GW, \text{sep}}^2 \propto \frac{\left( q_{\| R_0} \right)^{8/7}}{\left( \ell_{\| q_{\text{cyl}}} \right)^{6/7} \left( \frac{R_0}{a} \right)^2 \langle B_p \rangle^2 \left( 1 + \kappa^2 \right)} \]

No size scaling!
Now Bring in HD $\lambda_q$ to get $q_{\parallel}R_0$

$$q_{\parallel}R_0 \propto P_{sep}^{7/8} B_{t,0}^{3/4} \left\langle B_p \right\rangle^{1/8} \frac{R_0}{a} \left(1 + \kappa^2\right)^{-1/16} \left(\frac{\overline{A}}{1 + \overline{Z}}\right)^{-7/16} \left(\ell^*_{\parallel}\right)^{-1/8}$$

• Substitute this into result from last slide

$$c_z f_{GW,sep}^2 \propto \frac{P_{sep} B_{t,0}^{6/7} \left(\frac{\overline{A}}{1 + \overline{Z}}\right)^{-1/2}}{\left(\frac{R_0 q_{cyl}}{a}\right)^{6/7} \left\langle B_p \right\rangle^{13/7} \left(1 + \kappa^2\right)^{15/14} \ell^*_{\parallel}}$$

$$c_z \propto \frac{P_{sep}}{\left\langle B_p \right\rangle \left(1 + \kappa^2\right)^{3/2} f_{GW,sep}^2 \ell^*_{\parallel}} \left(\frac{1 + \overline{Z}}{\overline{A}}\right)^{1/2}$$

OMG!
NO SIZE SCALING!
We Should not be Surprised

- Look at the simplest model possible

\[ q_\parallel \propto P_{sep} B / a \quad \text{from} \quad \lambda_{int} \propto (a/R_0) \rho_p \sim a/(R_0 B_p) \]

\[ p_{rad} \propto c_z n_c^2 \propto c_z f_{GW}^2 \left< B_p \right>^2 a^2 (1 + \kappa^2) / a^4 \]

\[ q_\parallel \propto P_{rad} L_\parallel \propto c_z f_{GW}^2 \left< B_p \right>^2 a^{-2} (1 + \kappa^2) q_{cyl} R_0 \ell_\parallel^* \]

\[ q_{cyl} \propto a B_0 (1 + \kappa^2)^{1/2} / R_0 \left< B_p \right> \]

\[ c_z \propto \frac{P_{sep}}{\left< B_p \right> (1 + \kappa^2)^{3/2} f_{GW,sep}^2 \ell_\parallel^*} \]

SAME RESULT:
NO SIZE SCALING!
Scaling to ITER & Demo1

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>ASDEX-U</th>
<th>JET</th>
<th>ITER</th>
<th>FNSF (A=4)</th>
<th>EU Demo1</th>
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</thead>
<tbody>
<tr>
<td>$P_{sep}$</td>
<td>3.83</td>
<td>10.7</td>
<td>14</td>
<td>100</td>
<td>96</td>
<td>154.7</td>
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<tr>
<td>$B_t$</td>
<td>5.47</td>
<td>2.5</td>
<td>2.5</td>
<td>5.3</td>
<td>7.0</td>
<td>5.7</td>
</tr>
<tr>
<td>$R_0$</td>
<td>0.7</td>
<td>1.6</td>
<td>2.9</td>
<td>6.2</td>
<td>4.5</td>
<td>9.1</td>
</tr>
<tr>
<td>$P_{sep}/R$</td>
<td>5.5</td>
<td>6.7</td>
<td>4.8</td>
<td>16.1</td>
<td>21.3</td>
<td>17.0</td>
</tr>
<tr>
<td>$P_{sep}B_t/R$</td>
<td>29.9</td>
<td>16.7</td>
<td>12.1</td>
<td>85.5</td>
<td>149.3</td>
<td>96.9</td>
</tr>
<tr>
<td>$I_p$</td>
<td>0.82</td>
<td>1.2</td>
<td>2.5</td>
<td>15</td>
<td>7.5</td>
<td>20</td>
</tr>
<tr>
<td>$a$</td>
<td>0.22</td>
<td>0.52</td>
<td>0.90</td>
<td>2.00</td>
<td>1.13</td>
<td>2.94</td>
</tr>
<tr>
<td>$\kappa_{95}$</td>
<td>1.51</td>
<td>1.63</td>
<td>1.73</td>
<td>1.80</td>
<td>2.10</td>
<td>1.70</td>
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<tr>
<td>$&lt;B_p&gt;$</td>
<td>0.58</td>
<td>0.34</td>
<td>0.39</td>
<td>1.03</td>
<td>0.81</td>
<td>0.98</td>
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<tr>
<td>$q_{cyl}$</td>
<td>3.78</td>
<td>3.16</td>
<td>2.79</td>
<td>2.42</td>
<td>3.55</td>
<td>2.62</td>
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<tr>
<td>$n_{GW}$</td>
<td>5.39E+20</td>
<td>1.44E+20</td>
<td>9.82E+19</td>
<td>1.19E+20</td>
<td>1.89E+20</td>
<td>7.39E+19</td>
</tr>
<tr>
<td>Projected $c_N$ for detachment from AUG</td>
<td>1.0%</td>
<td>4.0%</td>
<td>4.1%</td>
<td>10.1%</td>
<td>8.6%</td>
<td>18.8%</td>
</tr>
</tbody>
</table>

Demo1 needs ~ 5x AUG’s $c_N$ ??
No Problem in ITER?

\[ x \sim \frac{7}{4} \]
No Problem for 8.25m Demo?

- Fix target conditions including $q_{\perp}$ & $\lambda q$
- Integrate along B up to OMP $\Rightarrow P \sim \propto R$
- But... $B_p$ is fixed, so $f_{GW}$ goes up x $\sim$ 3 even though $n_e$ falls a bit.
Outline

- Parallel heat flux
- Surface heat flux
- Loss power / detachment
- Magnetic geometry
- Lithium vapor box divertor
Magnetic Geometry Can Help 3 Ways

• Reduce $q \perp \propto B_p \perp$ at the target plate: (XD)
  • Limited by $\alpha + \alpha_0$

• Reduce $q \parallel \propto |B|$ at the target plate: (SXD)
  • Requires access to high $R$
  • May also help with stability of detachment

• Increase $L \parallel$ to the target by reducing $<B_p>$: (SFD)
  • *This directly decreases* $c_z \propto L \parallel / \pi q R$
Significant Effects May be Available

Fig. 6: (a) Reference configuration and alternative configurations including (b) an X divertor, (c) a Super-X divertor and (d) a snowflake divertor.

<table>
<thead>
<tr>
<th>Costs</th>
<th>SND</th>
<th>XD</th>
<th>SXD</th>
<th>SFD</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max $\Sigma</td>
<td>I_{PF}</td>
<td>(Ma \text{ turns})</td>
<td>160</td>
<td>194</td>
<td>164</td>
</tr>
<tr>
<td>Total $I_{PF,\text{internal}}$ (MA \text{ turns})</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Max. force on single coil $F_{z,PF}$ (MN)</td>
<td>145</td>
<td>301</td>
<td>451</td>
<td>439</td>
<td>&lt;450</td>
</tr>
<tr>
<td>Max. CS separation force $F_{z,CS}$ (MN)</td>
<td>130</td>
<td>244</td>
<td>284</td>
<td>329</td>
<td>&lt;350</td>
</tr>
<tr>
<td>Flux swing (Vs)</td>
<td>330</td>
<td>340</td>
<td>297</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>Norm. TF coil volume $V_{\text{TF}}/V_{\text{plasma}}$</td>
<td>2.9</td>
<td>3.6</td>
<td>4.2</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Benefits</td>
<td>$L_{1,\text{outer}} (r_u=3\text{mm})$ (m)</td>
<td>114</td>
<td>146</td>
<td>158</td>
<td>245</td>
</tr>
<tr>
<td>$f_{x,t}/f_{x,\text{min}}$</td>
<td>1</td>
<td>1.43</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$R_d/R_x$</td>
<td>1.04</td>
<td>1.14</td>
<td>1.34</td>
<td>1.19</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Cost and geometric characteristics of the reference SND configuration and several alternatives.

The divertor plasma in the reference and the alternative configurations is simulated using models with various degrees of sophistication. Following scoping studies in WP2014 the suite of codes was reduced to TECXY, OSM-Eirene, SOLPS (SND, XD and SXD only) and SOLEDGE2D and a set of criteria developed:

1. Seed impurity concentration (Ar) needed for the onset of detachment;
2. $I_{mp}$ purity concentration for required divertor power loss $q_{\perp,t,max} = 10 \text{ MW/m}^2$;
3. Robustness of detachment;
4. Max. divertor power loss before loss of stability/convergence.

Calculations of these criteria are ongoing.
Outline

- Parallel heat flux
- Surface heat flux
- Loss power / detachment
- Magnetic geometry
- Lithium vapor box divertor
Three Modalities for Liquid Metals

- Heat Conduction to Substrate: Liquid protects surface
- Heat Convection by Liquid Metal: Liquid carries away heat
- Evaporation & Radiative Cooling: Steady vapor shielding
Steady Lithium Vapor Shielding

Golubchikov
1996

Ono
2013, 2014
Lithium Vapor Shielding Promising

Estimate $\sim 250 \text{ eV/particle } e^-$ cooling.

J. Schwartz
Lithium injected into plasma as vapor
• Multiple boxes to localize Li cloud
  • Lined with Li CPS
  • Cooler towards the top, less vapor
  • Heat-pipe-like Li recycling
• Bottom box for 2.5 GW ITER, 580 °C
  • Depth 50 cm, aperture 20 cm
• Efflux from bottom box
  • 18 g/s, ~ 1/10 reduction per box
• Lithium inventory:
  • $2\pi R \times 2m \times 0.25mm = 10$ kg Li
Lithium Radiation $\sim 1/2 \, N$
In NSTX, L pulled relatively weakly upstream & into plasma core.
Thermal Force Much Weaker on Lithium

Simple balance between $\nabla \rho_z$ and thermal force:

$$\frac{T_z}{n_z} \frac{dn_z}{ds} + \frac{dT_z}{ds} = \alpha_e \frac{dT_e}{ds} + \beta_i \frac{dT_i}{ds}$$

$$\frac{L_T}{L_z} = \alpha_e + \beta_i - 1$$

$\alpha_e = 0.71Z^2$

$$\beta_i = \frac{3(\mu + 5\sqrt{2}Z^2(1.1\mu^{5/2} - 0.35\mu^{3/2}) - 1)}{2.6 - 2\mu + 5.4\mu^2}$$

$\mu \equiv m_z/(m_z + m_i)$. 

Stangeby 2001
Conclusions - 1

• A very large, low power Demo does not even point to cost-effective fusion power.
  • Due to the problem of power handling.
  • Even with 2/3 core radiated power and 500 MWe @ R = 9.1m, still must detach.
  • The measure for difficulty in detachment is more likely $P/B_p$ than $P/R$ – no size scaling!
• Should validate with 2-d codes & experiments – but it makes simple sense.
Conclusions - 2

- Steady lithium vapor shielding is attractive
- Substantial dissipation per atom
- Lithium vapor can be localized
- Thermal force << than for N, Ne, Ar
- Neoclassical inward pinch $\propto Z$
- Demo designs should study increasing $B_\rho$ and $\ell^*_\parallel$, rather than $R$, to foster detachment.
- The community should develop self-consistent scenario(s) for liquid metals in Demo.