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Next Generation Fusion Experiments.

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Next Generation Fusion

High Power Density Experiment

HPDX

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ICTP, 2008
Core Confinement- A Success Story

- Fusion research has made great strides in last 40 years
  - Momentary breakeven (Q~1) shown in JET & JT-60
- Tokamaks (axisymmetric magnetic bottles) in the lead

ITER to show
- Momentary Q ~10
- Q > 5 for 8 minutes
- Burning plasma

But then why is fusion still many decades away?
Fusion Reactor Schematic

Core: High $\beta$ -> high power density, hot confined plasma

External world: open B lines, wall etc.

Closed Lines

SOL

Limiter

Heat must deposit on small area

Open Lines

Divertor
JET and ITER
Diplodocus Drawn to scale
High $\beta$

• Modify core geometry
  – Elongation $\kappa$, triangularity $\delta$, … (shape parameters)

  ![Diagram](image)

• Increase plasma current
  – $\beta$ goes up for a given $\beta_N$ (set by stability)--- $\beta = \beta_N (I/aB)$

• Modify plasma profiles to increase bootstrap fraction
  – Reduces running cost
High core confinement

- Transport barriers improve confinement
  - H-mode barrier near the edge
  - Internal Transport Barrier (ITB)
- Confinement time
  - Semi-empirical scaling laws have been established
  - $H_{89p}$ ~ ratio of observed confinement time to the standard H-mode $\tau$

Should not expect future device $\tau$ to be much above the observed band

FIG. 2. (Color online) Confinement requirements for reactors as compared to the confinement range achieved in the present experiments. The net heating power is estimated to be $P_{\text{heat}}(1 - f_{\text{rad-core}})$. 
Magnetic bottles: A Fundamental Fusion Dilemma

- Good confinement: low cross-field transport in closed B inner region
- Power exhaust along “open” field lines which end on material “wall”
- Transport much faster along B field than across B field
- Scrape off layer (SOL) width $\lambda_q$ is small $\Rightarrow$ divertor focuses heat flux exhaust on very small “plasma wetted area” $A_w$ proportional to $R_{\text{div}}$ and $\lambda_q$
- Better core confinement $\Rightarrow$ higher flux on divertor plate (problems!!)
High Power Density (HPD)-consequences

- High power density => higher heat exhaust

- Needs the best design for the outer geometry (the SOL)
  - Inner (CORE) and outer (SOL) geometries must both be good
  - Either can be a show-stopper -the integral magnetic bottle has to be good

- Most fusion research has focused on optimizing the core
  - The inner geometry and physics-naturally

- New frontier: optimizing the outer geometry and physics

  but without damaging the core
Fundamental challenges for next generation experiments-HPDX

- How to get high confinement at high $\beta$ - core issue + plus

- Appropriate exhaust for the heating power - outer region issue

- Heating power $P_H = P_{ext} + (1/5) P_{Fusion}$
High Power Density (HPD) - a Perspective

• A standard measure of power density = P/R
  – ITER will have low P/R ~ 120MW/6m ~ 20
  – ITER wall loading ~ 10% of competing power reactors (fission, coal …)
  – This does not yield high enough system efficiency
  – Viable fusion reactors need P/R > 80

• HPDX must have high P/R- critical for viable fusion energy
  – Good news - “Core” confinement at high power density has been
    experimentally demonstrated, in principle, - however--------
  – Not so good news - handling high power exhaust is a severe challenge
HPDX vis a vis ITER

<table>
<thead>
<tr>
<th>Device</th>
<th>Heating Power (MW)</th>
<th>R (m)</th>
<th>P/R (MW/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER</td>
<td>120</td>
<td>6.2</td>
<td>19</td>
</tr>
<tr>
<td>NHTX (D-D, ST)</td>
<td>40</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>ST-CTF (ORNL)</td>
<td>60</td>
<td>1.2</td>
<td>50</td>
</tr>
<tr>
<td>FDF (GA)</td>
<td>110</td>
<td>2.5</td>
<td>44</td>
</tr>
<tr>
<td>HPDX (IFS)</td>
<td>120</td>
<td>2.5</td>
<td>48</td>
</tr>
<tr>
<td>ARIES-AT</td>
<td>390</td>
<td>5.2</td>
<td>74</td>
</tr>
<tr>
<td>ARIES-RS</td>
<td>510</td>
<td>5.4</td>
<td>93</td>
</tr>
<tr>
<td>ARIES-ST</td>
<td>620</td>
<td>3.2</td>
<td>195</td>
</tr>
</tbody>
</table>

We showed that radiating more power in core or edge will not solve this problem:


Core radiation destroys core confinement - Divertors must handle the heat flux
SOL width $\lambda_q$ is central to heat flux problem

- Divertor heat flux $\sim (1 / \lambda_q)$, $\lambda_q =$SOL width

- Most projections give rather narrow SOL widths, e.g., for FDF (GA):
  - 2004 JET extrapolation: $4 \text{ mm}$ empirical
  - B2-Eirene extrapolation: $5 \text{ mm}$ numerical modeling
  - Connor-JET collisional $5 \text{ mm}$ semi-empirical (physics based)
  - Connor-JET low collisionality $5 \text{ mm}$
  - $1999 \lambda_q$ regression $14-23 \text{ mm}$ This is clearly an outlier

- For the small $\lambda_q$, heat flux on standard divertors will far exceed 10 MW/m$^2$ limit

- Can new physics ideas reduce uncertainty in the SOL width? Yes.
  - Assume similar H-mode barrier transport and SOL cross-field transport
  - This narrows the plausible range of SOL widths for next step devices

- Basic dilemma: good H-mode $\Rightarrow$ low edge transport $\Rightarrow$ small SOL width, so good core confinement makes divertor problem worse!
Estimating pedestal implications for SOL $\lambda_q$

- Parameterize transport in one of two ways:

1. Assume similar diffusion processes (i.e., $\chi$) operate in both near SOL and pedestal
   - compare the magnitude of $\chi$ in both regions
   - From the SOL width, estimate the $\chi$ needed to produce that width
   - Estimate $\chi$ in the pedestal using power balance and experimental data

2. Presume a marginal stability process from pressure gradients (as indicated by C-mod results)
   - Estimate $dp/dx$ for the pedestal
   - Estimate $dp/dx$ in the SOL
   - Compare the two
“Plausible” range of $\lambda_q$ for next step experiments

<table>
<thead>
<tr>
<th>$\lambda_q$ in mm</th>
<th>$\chi_{\text{SOL}}$ method</th>
<th>dp/dr$_{\text{SOL}}$ method</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER</td>
<td>3.1 - 5.4</td>
<td>3.2 - 4.3</td>
</tr>
<tr>
<td>NHTX</td>
<td>4.1 - 9.4</td>
<td>4.1 - 9.9</td>
</tr>
<tr>
<td>ST-CTF</td>
<td>2.7 - 6.2</td>
<td>1.8 - 4.4</td>
</tr>
<tr>
<td>FDF</td>
<td>5.2 - 9</td>
<td>3.0 - 4.9</td>
</tr>
<tr>
<td>ARIES AT</td>
<td>5.0 - 8.7</td>
<td>3.0 - 5.0</td>
</tr>
</tbody>
</table>

• Bottom line: $\lambda_q \sim 5$ mm, like ITER, for all next step HPD devices

• Hence P/R is a reasonable measure of divertor challenge

• *With such $\lambda_q$, heat flux on standard divertors will far exceed 10 MW/m$^2$ limit*

• ITER folks worried about divertor operation in steady state scenarios—substantially better divertors will be required for HPDX and Reactors
Radiative Solutions- Could heat be radiated away?

- **Two possible routes**
  - Radiate from the SOL (divertor region)
    - Detailed modeling shows limits to SOL radiation without destroying the main plasma- Maximum ITER SOL radiation fraction ~ 60%. SOL Radiation fractions, however, decrease with increasing parallel heat flux $Q_\parallel$, shorter line lengths, lower density
    - Compared to ITER, next step devices have: Substantially higher $Q_\parallel$, Substantially lower line length, and densities about the same. Elementary considerations imply that radiative divertor solutions are unlikely to solve the heat flux problem on next generation devices
  - Radiate from the core
    - Again limited to about 50%- Larger core radiation degrades confinement quite nonlinearly - not a reactor option
**Divertor Burdens- Heat flux way beyond ITER, and ----**

- Three distinct challenges crying for workable solutions:
  - **High heat flux on the divertor target plate**
    - **Solution:** spread heat out and/or radiate (some) before incidence on plate
  - **High plasma temperature at the divertor plate**
    - Can easily exceed 100 eV, leading to high sputtering (erosion, dust, plasma impurities, etc.)- high temperature $\Rightarrow$ low radiation (atomic physics)
    - **Solution:** increase line length along B from plasma to divertor plate
  - **Divertor neutron damage (along with high heat flux damage)**
    - ITER divertor technology: serious degradation at $\sim 1$ dpa
    - CTF: must test to dozens of dpa
    - Reactor: must run at $\sim 100$ dpa
    - **Solution:** place divertor plate where it can be shielded from neutrons
Limiters to Divertors to X-Divertors to Super-XD

Limiter & Standard Divertor

Flux expansion near main X-point

X-Divertor to expand flux

Super X-Divertor at Large $R_{\text{div}}$
Super X Divertor (SXD)

- **Key idea:** $\theta > 1^0$ limit $\Rightarrow$ only “knob” is increased $R_{\text{div}}$

  $$A_{w} = \frac{B_{p,\text{sol}}}{B_{\text{div}}} \frac{A_{\text{sol}}}{\sin(\theta)} \approx \left[ \frac{B_{p}}{B_{t}} \right]_{\text{sol}} \frac{R_{\text{div}}}{R_{\text{sol}}} \frac{A_{\text{sol}}}{\sin(\theta)}$$

- **Key surprise:** Generally easy to design SXD
  - Small PF coil modifications are needed for a variety of devices
  - We have SXDs for HPDX, NHTX, FDF, CTF, ARIES, SLIM-CS …

- **SOLPS shows it works for NHTX & FDF**
Super XD: Divide (Plasma-SOL) & Conquer

- Moves the plates to larger major radii
- With 1 degree min B-plate angle limit,
  - Increases wetted area by ~ 2-3
- Decreases B_{pol} to increase line length
  - B-Line length increases by up to 5
  - Increases maximum divertor radiation fraction from 10-15% to > 50%
    - Increases P_{SOL} by ~ 2
    - Also increases SOL width for all common models of SOL diffusive processes by ~ 1.5
- Together, these gains increase maximum tolerable P_{SOL} by a factor over 5
- Decreases need to radiate power from core
- Long leg isolates divertor from plasma
SXD: Easy and Robust

• Surprisingly, the SXD is rather easy to implement:
  – Just need to move the poloidal field (PF) coils around a bit
  – Coil currents & locations are not very different from standard divertor case.
  – This is so for a variety of machines that we have investigated

• Increased distance from plasma isolates SXD from plasma changes.
  – The relative isolation makes SXD strike point insensitive to plasma fluctuations - we have tested this in a variety of studies.

• Main plasma is also more immune to SXD changes, so one may be able to:
  – Operate in a fully detached mode without damaging the main plasma.
  – Or “sweep” the strike point without affecting the main plasma
**SXD is very insensitive to plasma changes**

- In general (for NHTX, FDF …), SXD strike point, wet area, line length, B line angle, ALL are insensitive to sudden changes in plasma current
- Possible reason: plasma is far, while SXD coils are near the SXD plate
- Preliminary snowflake studies (NHTX case) show greater sensitivity
  - Because higher-order main X point near plasma easier to perturb?
- Simulated by adding two “wall simulator coils” & fixing all others
- Vary $I_{\text{plas}}$, $R_0$, $a$ etc. by $\pm 3\%$ each and record main X and SXD shifts

![FDF with “wall coils”](image1)

![Main X & SXD Shift (cm) vs d$I_{\text{plas}}$ ±3%](image2)
SXD can save NHTX from heat flux menace

- With SXD & 30 MW, peak heat flux can be kept under 10 MW/m²
- Not possible with standard divertor (peak stays at 30-40 MW/m²)
- Plasma temperature (only) at SXD plate stays low (< 10 eV)
- SOLPS 2-D calculations confirm what we expected.
**SXD fits inside TF coils - no TF real estate issues**

- For NHTX, FDF, and Reactors the Super-XD does not require larger TF coils
- SXD uses available space (in the corner of TF coils) which is normally unused
- FDF, ARIES RS, ARIES AT, and ARIES ST are similar in this respect
- SXD coils & currents very similar to NHTX coils with standard divertor
SXD: essential & enabling for ST-CTF

- Heat flux problem is even more critical for low-A HPD Spherical Tori (STs)
- SXD is a high-A divertor for low-A core
- With SXD, the many expected low-A core advantages can be actualized
- SXD gains in $R_{\text{div}}$ are higher at low-A
- SXD designs for ST-CTF are easy
- Hence, SXD has now become the “presumptive nominee” for HPD STs
SXD can make SST a long-pulse HPD device

- Divertor heat flux limits maximum input power on SST long pulse
- This is a central limit on potential impact of SST on fusion science
- SXD can increase this limit by to 2 to 5 times \((R_1/R_2=2200/1100)\) !
- Enough room in vacuum vessel
- Dwell on coils that already exist
- Only a small extra coil may be needed
- Because of SST structure, same coils can make standard or super divertors
- Right now may be an opportunity for SST SXD design modification

Super-SD separatrix in red
Compare with NHTX coils

SST-1 figure from Bora et. al., Brazil 2001
Bonuses

- Spectacular Increase in Line Length - A significantly lowering of $B_{pol}$ in the long leg $\Rightarrow$ increase in line length by up to 10x. Long line length leads to:
  - A jump in divertor radiation fraction - from insignificant to substantial - 10-15% to $>50%$.
  - An expected result validated by calculations using an elaborate 1D model. 2-D runs (SOLPS) *a fortiori* verify these advantage (IFS collaboration with ORNL/PPPL)
  - A strong lowering of plasma temperature at plate (this lowers impurities)
  - A widening of SOL width for usual models of SOL diffusive processes by $>1.5$

- Direct $A_w$ gain, widening of SOL, and enhanced radiation working in unison boosts up the maximum tolerable $P_{SOL}$ by a factor over 5

- Decreases need to radiate power from core: allows better core performance
Neutron damage to divertor - critical issue

- **Tungsten “armor” on a high thermal conductivity actively cooled substrate**
  - High conductivity substrates (Cu or C) severely deteriorate after only a few dpa
  - Reactor walls must tolerate ~ 50-100 dpa (but at heat flux less than divertor)
  - Promising main chamber wall materials must be tested at 50-100 dpa

- **Only hypothetical high heat flux divertor materials might tolerate ~ 50-100 dpa**
  - Decades away with much material development effort in the EU and Japan
  - The US virtually does not have a fusion material development program anymore
  - Slow development would hamstring any high duty cycle DT device (CTF, DEMO)
    - A very real chance of this
      - Cannot credibly field a high duty cycle DT device without a divertor with a high chance of survival under copious fusion neutron and SOL heat fluxes.

- **SXD: substantial shielding of divertor plates for future HPD devices**
  - With SXD, ITER divertor technology may well suffice for high duty cycle DT
Disruptions, ELMs, and SXD

• Experimentally, disruptions are strongly correlated with plasma operation:
  – Near the density limit
  – With high radiation fractions
  – Near an ideal MHD limit

• Robust reactor relevant operation needs a significant margin in these parameters

• The super XD allows more margin in each from their disruptive boundaries

• A super XD probably also improves survivability to a disruption or an ELM:
  – Heat flux is spread over a longer area
  – Ions travel a much longer distance, so heat pulse could also be spread out significantly in time
    (material damage ~ 1/time^{1/2})
  – The divertor plate is not in the way of halo currents from a VDE
    • Wall can probably be made to be a more mechanically robust structure than a divertor, since it does not have to be designed to operate near the engineering limit on heat flux
Broad interest in implementing SXD

- IPR (India) has formed a group to design and implement SXD on SST
  - Can give SST a huge boost on the usable steady state heating power

- SXD for NHTX (the PPPL proposal)
  - Preliminary results are very encouraging: SXD may be necessary for NHTX

- SXD for ST-CTF (ORNL)
  - SXD is now the presumptive “standard” divertor for ST-CTF

- SXD for FDF (GA)
  - SXD is being evaluated for FDF, we think it will be necessary

- PRC-IFS collaboration already exploring SXD configurations
  - Preliminary designs being generated for testing SXD
Summing Up

This is the “Age of ITER”

- ITER does leave some “critical gaps” in the march to fusion reactors
  - ITER power density is too low for a competitive reactor (beta too low by \(\sim 1/3\))
  - ITER neutron fluence is too low for a CTF

- Raising the power density by the needed factor of 10 poses an enormous intellectual challenge, and a commensurate scientific and programmatic opportunity

- Of course this tremendous boost of power density must be done respecting all the physics and engineering (theoretical and empirical) constraints -a fundamentally trivial and obvious statement- but then this has been just the problem- the constraints have been really constraining.
Summing Up

Can one conceptualize (and hopefully design and build) a workable smaller, high power density AT-based device that:

- Significantly shortens the time to high power density fusion energy reactors
- Offers a credible, short-term, attractive goal
- Demonstrates $Q_{XT} = P_{fus}/P_{elec} > 1$ in a compact much cheaper machine fully extrapolatable to an economic reactor ($Q_{XT} > 1$, a major scientific and programmatic milestone, will be a great public relations coup)

  • **Reference:** NIF will claim Q~10 (but has $Q_{XT}~1/10$, like JET) in a few years!

- Yes we could, and partially have made nontrivial progress towards an HPDX
  - By building on multiple strengths of many programs that can productively collaborate
  - By being enabled by some recent (post-ITER-design) critical fusion discoveries
    (we shall not attempt to duplicate ITER advances (e.g., superconducting coils) but focus on critical fusion reactor issues that ITER will not or cannot address)
Summing Up

• This conceptual machine, if it is to deliver all the goodies, is not a “filling in the gaps” some niche machine - its reification will be a major undertaking and, though a bargain, will not be cheap- it is a mini reactor with power densities of a reactor.

• High power density => high heat flux- whatever is not radiated falls on the divertor. Must plan to handle enormous heat fluxes

• Radiative ability of the system (including the core) is limited. No purely or mostly radiative solutions - the divertor must bear the brunt of much of the heat-flux

• Standard divertor configuration falls way short of being able to handle the heat loads endemic to all high power density experiments(HPDX)

• If one is to continue and develop the vision of an HPDX further, one must make a better divertor- in fact a much better one! Only then can one plan for a high beta next generation machine.