Search for a Total (Integrated) Divertor Solution

The IFS-UT group

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IFS and Divertors

We, gratefully, acknowledge the coveted opportunity to participate in this ``event" that may, eventually, prove to be crucial for the future of fusion

It would appear to be a bit odd that the Chinese Organizers have invited two theorists to talk about a subject that is at least as much engineering as it is Physics

We have, however, devoted many years of our research in trying to isolate, formulate, and then attempt searching for solutions to the very challenging problems related to what could be generically called the ``divertor" of the upcoming generation(s) of high power density fusion machines.

Our provincial perception of CFETR
helping our hosts to formulate ``the Chinese MFE strategy"

- CFETR is a great idea- in fact, an indispensable one
- Building a fusion reactor will require a "lot more" to be be demonstrated than what even a highly successful ITER could accomplish
- Designing an appropriate Divertor for a DEMO is one of the biggest of those ``lot more"
- CFETR must create a solid foundation for such a divertor- the CFETR divertor must not be merely enough for its needs (more than ITER)-must be confidently extrapolatable to a DEMO
- Divertor solution has to be multifaceted- Heat handling is just one, though, a primary task
- Divertor problem is very very challenging- recent empirical scalings of the SOL width (consistent with what prompted us to get into this game) make the problem way harder
- CFETR must develop, implement and test the very very best divertor strategy- it might have to combine several ideas being investigated.

THE IFS TEAM WILL LOVE TO BE A PART OF DEVELOPING THIS STRATEGY

Physics and Technology issues of an advanced Divertor strategy follows

Context of the divertor for CFETR

- CFETR is intended as a bridge between ITER and a fusion DEMO

- **Necessarily, it will encounter new conditions more challenging than ITER in various respects**
  - ***Steady state operation – full non-inductive current sustainment as baseline scenario***
  - ***Unprecedented fluence of 14 Mev neutrons- serious material damage and hence likely component degradation in operation***
  - ***Availability 30%-50%- challenge to maintenance, component lifetimes***
  - ***Longer exposure of plasma facing components to plasma erosion before replacement***

- All of these conditions affect the divertor operation

Context of the divertor for CFETR

- To be a bridge, CFETR must demonstrate technologies **that could "work" in the challenging conditions of a DEMO and fusion reactor**

- **A DEMO has considerably more demanding conditions than CFETR or ITER**
  - *Much more heating power to exhaust*
  - *Considerably higher neutron fluence for components*
  - *Much higher helium production (from fusion) in the plasma- requiring higher helium exhaust*

- Thus, CFETR must select technologies **that plausibly extrapolate to operation in a DEMO**- the Demo demands are well beyond the requirements of CFETR itself

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Outline

- Some of the defining issues of the divertor challenge
  - *Neutron damage*
  - *Steady state operation*
  - *Plasma erosion*
  - *Extrapolation to fusion reactor parameters (DEMO)*
    - *Divertor heat flux*
    - *Limitations on the use of radiation to "save" the divertor*
    - *Helium exhaust*
  - *Uncertainty in extrapolation of SOL width-the width may be smaller than previously thought*
- Solutions being investigated in the US:
  - *Advanced divertor geometries- beyond ITER- Super-X divertor and Snowflake*
  - *Novel plasma facing materials- Li on porous substrate*
  - *Why such departures from ITER divertor technology may be needed for DEMO or CFETR*

How does neutron damage impact the divertor?

- Neutron damage to the divertor plates-Some details
  - ***Present ITER technology- Cu heat sink- tolerates 10 MW/m^2 steady state peak heat flux***
  - ***Cu has significant neutron degradation (embrittlement) at a few dpa (fission neutrons)***
  - ***Fusion neutrons likely cause more severe effects- produce He, which can increase embrittlement, swelling, etc.***
  - ***At 1 MW/m^2, 1 dpa is attained in only about a month of continuous operation***
  - ***Cu based divertor plates could have a much lower lifetime than other components, and may need to be replaced unacceptably often***
  - ***Other structural materials are under development in some countries (e.g. some form of ductile, radiation resistant tungsten) but it is unknown when or if they will be available***

How does steady state operation with current drive impact the divertor?

- Quote about ITER from the 2007 ITER physics basis (Nucl. Fusion **47**, special edition):

"The fusion gain in steady state maximizes at low density for constant β_N. The limitation on reducing the density in next generation tokamaks is set by the impact on the divertor."

- Why?
  - *For steady state driven current, the current drive efficiency increases as density decreases*
  - *At fixed β_N, as current increases, beta increases*
  - *Fusion power increases as beta increases*

- Hence, with steady state current drive, divertor performance is a crucial determining factor in the fusion performance of a tokamak
  - *Especially its ability to function acceptably as density is lowered*

How significant is plasma erosion?

- Erosion produces plasma impurities which could impact the core
- In addition, erosion produces dust - though the processes are not well understood
- Dust production should be expected to increase with increased plasma duration- hence it could be a more serious issue on CFETR compared to ITER
- Dust is the primary safety issue for ITER
  - ***Dust interaction with water can lead to chemical explosion***
  - ***Dust is radioactive, and its release in an accident can have serious very radiological consequences -especially tungsten dust***
- The amount of dust in ITER is limited by regulatory authorities, and **shutdown will result if too much dust is produced**
- Divertor surfaces can contribute to dust generation by sputtering, as well as, possibly, processes that are not well characterized or understood ("fuzz", blisters, etc.)
- Probably, dust generation is reduced by decreasing the plasma temperature at the surface as much as possible

Extrapolation to the divertor of a DEMO

- If CFETF is to be a bridge to a fusion DEMO, it must test a divertor ***that plausibly extrapolates to operation in a DEMO***
- A DEMO produces much more fusion power than ITER, in a device about the same size:

DEMO heating power is several times higher than ITER

- With baseline assumptions, the ITER divertor is already at about the limit of power exhaust- how can a such a divertor configuration handle several times more?
- In principle, core radiation could reduce power into the SOL
- In practice, the core radiation fractions needed are extremely high, and unlikely to result in satisfactory operation
- Let us examine the radiation requirements to allow the use of an ITER- like divertor for proposed fusion reactors

Can’t SOL radiation be increased to handle the extra power?

- The ITER divertor scenario **already** assumes puffing and impurities to reduce the divertor heat flux
  - ***Roughly 2/3 of the power into the SOL is dissipated before reaching the plate***
  - ***The divertor is in the “partially detached” regime***
- Extensive experimental and computational investigations have found that the **partially detached** regime is best- ***it gives the most radiation possible without confinement degradation to the H-mode***
- Of course, it is possible to increase this SOL radiation (e.g. puff more gas)- but this leads to **full detachment**, with consequent strong degradation of the H-mode barrier and core confinement
- With all these limits in mind, the best estimate is: **for the baseline ITER divertor and SOL width assumptions, at most, about 100 MW of power can be sent into the SOL**
- Of course, on can always increase radiation in the core, but probably at too high a cost-

Extrapolation of the ITER – like divertor to a DEMO: core radiation fraction required

- Consider how much core radiation is needed to give comparable power into the SOL as for ITER (the same P/R as ITER with 100 MW into the SOL)

Device	Core radiation fraction to give the same P/R as ITER
ITER	17%
ARIES -RS	83%
Slim-CS	86%
PPCS EU-C	85%

- With these radiation fractions, **confinement enhancement H over L-mode must be > 4**
- This is unrealistic
  - ***Considerably higher than in today's experiments (H ~ 2-3)***
  - ***Reactors and ITER have less velocity shear than present experiments***

Extrapolation of the ITER – like divertor to a DEMO: *total* radiation fraction required

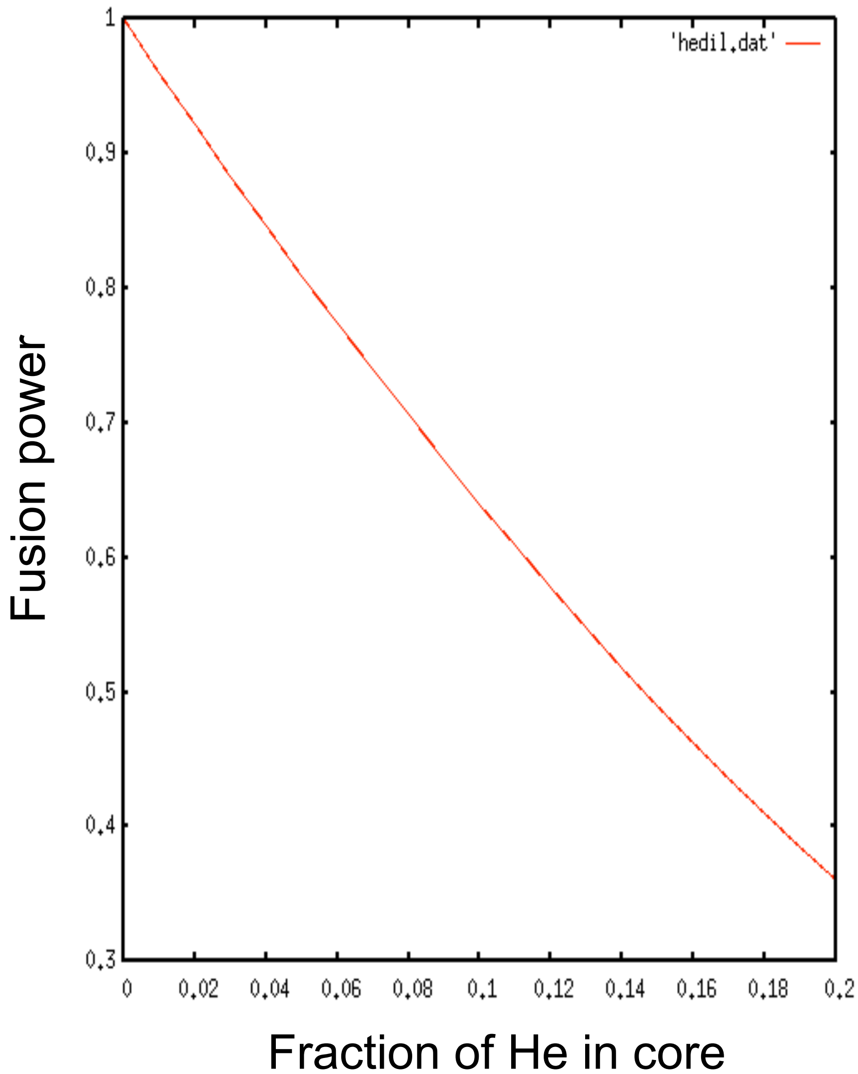
- Consider how much ***total*** radiation fraction is needed to give 10 MW/m^2 on the divertor plate, **assuming 5 mm SOL width (like ITER)**, and an ITER-like plate orientation

Device	Total radiation fraction to give 10 MW/m^2
ITER	66%
ARIES -RS	95%
Slim-CS	96%
PPCS EU-C	96%

- Plasmas with radiation fractions ~ 95% have little margin from a radiation collapse
  - ***Experimentally, such plasmas have a relatively high frequency of disruption***
  - ***Self-heated plasmas probably have an even higher chance of collapse/disruption***
- P. Rebut has recommended that, for acceptable disruptivity, radiation fractions should be limited to 75%
- **Radiation fractions for reactors are very far above such recommendations for a standard divertor**

Helium exhaust is more of an issue in a DEMO

- Helium production in a DEMO is several times higher than for ITER
- Helium exhaust potential of ITER divertor based on SOL-PS:
  - *On ITER, He exhaust expected to keep concentration of He in the core to ~ 1%*
  - *Helium exhaust decreases very rapidly as SOL exhaust power increases or density decreases*
  - *With several times higher He production in the core of a DEMO, and if He exhaust is degraded below ITER, He could be 10-20% or more*
  - *He dilution leads to a strong reduction in fusion power*



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How do recent predictions of SOL width impact divertors in future devices?

- The ITER divertor was developed using physics models that give an SOL width ~ 5 mm
- Recent dedicated experiments indicate that SOL widths might be substantially smaller
  - *JET and ASDEX- T. Eich et. al., Phy. Rev. Letters 107, 215001 (2011)*
  - *DIIID, Alcator C-MOD and NSTX*
  - *SOL widths in range 1- 2 mm*

ITER, CFETR and a DEMO should have comparable SOL widths

- This would lead to increases in peak heat flux- substantially above 10 MW/m^2
  - *Radiating significantly more power from the core could help the divertor, but would drop power below the H-mode threshold- UNACCEPTABLE FOR CORE CONFINEMENT*
- In addition to high heat fluxes, small SOL widths lead to sharp increases in the plasma temperature at the plate
  - *A large reduction in He exhaust*
  - *Much higher divertor sputtering erosion*
- Recall that a DEMO has much larger heating power to be exhausted- **if this challenge is combined with the challenge of SOL width far below 5 mm, the divertor problem for a DEMO becomes extraordinarily difficult**

Before considering possible solutions, we digress to consider the nature of the problems more closely

- Recall there are three necessary functions of the divertor
    1. *Exhaust plasma power acceptably*
    2. *Exhaust helium ash acceptably*
    3. *Ensure acceptably low plasma erosion and low plasma impurities*
- Acceptable power exhaust entails staying below engineering limits on material heat fluxes
- Helium exhaust and low erosion essentially entail keeping the plasma temperature low enough at the plate
- The optimal regime is the so-called "partially detached" regime, which gives the maximum radiation (to lower the plate heat flux), the best helium exhaust, and the lowest erosion
- **The partially detached regime, in the standard divertor geometry, can be overwhelmed by**
    - *too much heating power*
    - *too small an SOL width*
    - *low a plasma density*
- **This is precisely the regime of a high fusion gain DEMO fusion reactor**

Heat flux

- Heat and particles in the SOL travel almost entirely along field lines

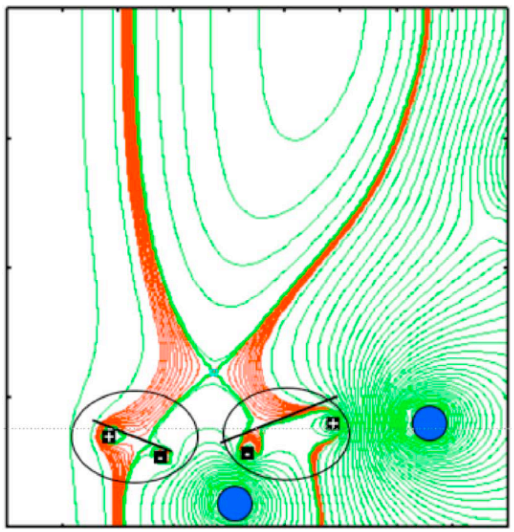
- The heat flux to a surface depends on the angle at which the field lines strike it

  - *A shallower angle spreads the heat over a larger area: $Q_{plate} = Q_{parallel} \sin(\theta)$*
  - *In principle, if the field line is sufficiently close to parallel to the plate, it is possible to spread the heat onto a large enough area*
  - *In practice, the angle is made shallower by EITHER tilting the plate, or poloidal flux expansion*
  - *Several new magnetic geometries have been developed in the last few years to increase flux expansion at the divertor*

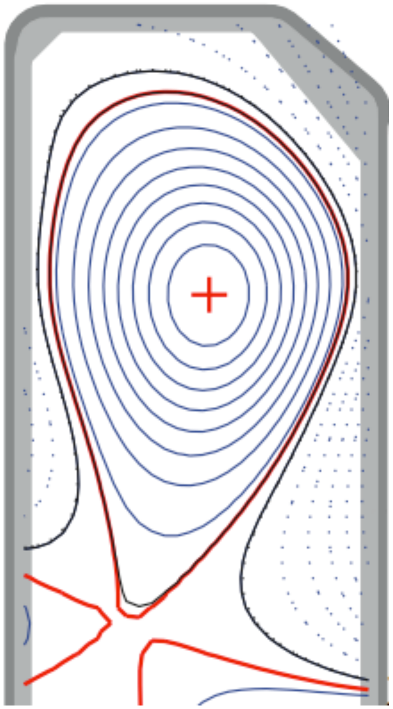
What are the new geometries?

- In historical order:

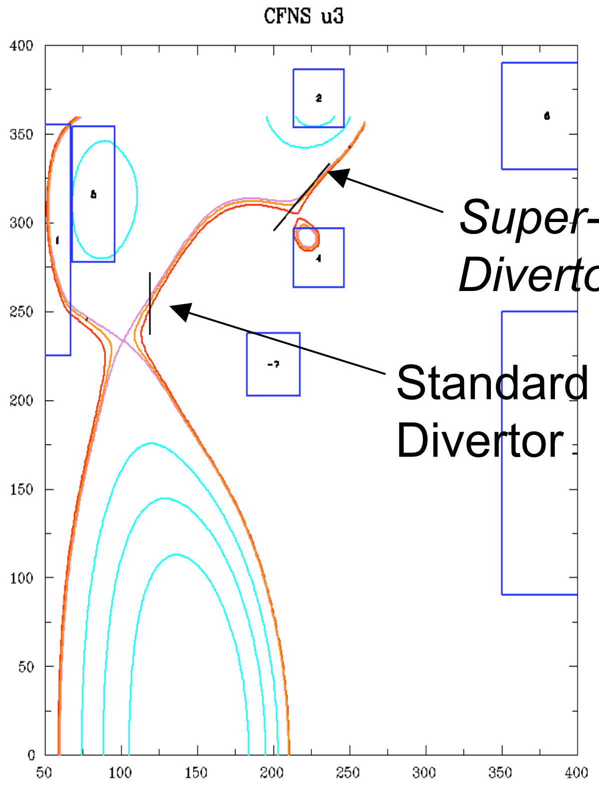
X-Divertor



Snowflake



Super-X



Plasma temperature- requires a different solution than just flux expansion of plate tilting

- From basic sheath physics, plasma temperature is predicted to depend only on the heat **flux parallel to the field lines, and only very weakly on the angle θ**
  - *SO UNLIKE HEAT FLUX, plasma temperature at plate is almost independent of θ*
  - *Neither tilting the plate, NOR POLOIDAL FLUX EXPANSION, can DIRECTLY REDUCE THE PARALLEL HEAT FLUX*
- **If parallel heat flux is too high, (or SOL density is too low), the plasma will "burn through" the partially detached regime and enter the so called "sheath limited" regime**
- The "sheath limited" regime combines multiple unacceptable features at once:
  - *High plasma temperature near the plate (~ 200eV) – very high plate erosion*
  - *Low plasma atomic radiation – little reduction of heat flux from atomic processes*
  - *Very low helium exhaust*
- So, even if the angle θ could be small enough to give acceptable plate heat flux, the "sheath limited" regime would still be unacceptable due to inadequate helium exhaust and excessive erosion

A different solution is needed!

Reducing parallel heat flux-Super X divertor

- There are only two ways to reduce **parallel** heat flux:

1. Atomic processes- often invoked:
   - ***Gas puffing and impurity seeding to radiate the power- the usual approach, but only a limited amount of dissipation is anticipated without confinement degradation***
   - ***The ITER divertor is roughly at the limit of atomic processes (assuming 5 mm SOL width)***
2. Unusual geometries for the SOL flux tube:
   - ***Engineer the SOL flux tube so that it guides the plasma to a divertor plate located where the TOTAL B FIELD is SMALLER***
   - ***Consequence: the area of the flux tube expands, while the heat stays constant- parallel heat flux is reduced GEOMETRICALLY***
   - ***In practice, this means causing the SOL flux tube terminate at larger major radius***
   - ***Amongst the geometries, currently in the literature, ONLY THE SUPER-X DIVERTOR REDUCES THE PARALLEL HEAT FLUX PURELY GEOMETRICALLY***
   - ***by the ratio of the major radius increase of the position of the divertor plate***

SXD- allows operation in the partially detached regime- analysis using the "two point" model*

- If the SOL power is too high (or density is too low), the partially detached regime becomes impossible to achieve- **the plasma goes into the so called "sheath limited regime" with very high plate temperatures (~ 200 eV), and much lower helium exhaust**
- To model the effect of **flux tube terminating in a low B region**, we modify the classic "Two Point" formula via the factor B_{div}/B_{up}. The criterion for avoiding the sheath limited regime, then, becomes:

$$Q_{||\,up}\,(B_{div}/B_{up})^{1.75}\; n_e^{-1.75} L_{||}^{-0.75} < 1 \times 10^{-27}\ \text{(MKS)}$$

- The SXD, Snowflake and X-divertor all increase $L_{||}$ by 2-3 times
  - ***$Q_{||up}$ can be increased by a factor of ~ 2***
- The SXD, in addition, uniquely reduces B_{div}/B_{up} ~ 2
  - ***$Q_{||up}$ can be increased by an additional factor of ~ 3 - 4***

The SXD can avoid the sheath limited regime for several times higher $Q_{||\,up}$ /lower SOL density

* Peter Stangeby's Textbook

The implications of an engineering limit on shallowness of the field angle

- Engineering restrictions on θ, the angle between the divertor plate and the magnetic field
  - ***precision of the divertor plate, and the precision of the magnetic field***

- Restrictions apply to all geometries- including the advanced divertor geometries

- Since $Q_{plate} = Q_{parallel} \sin(\theta)$, with the same engineering limit (i.e, θ), flux expansion and a highly tilted plate have a similar limit on how much they can spread out the heat

- Since the Super-X divertor uniquely reduces $Q_{parallel}$ purely geometrically, with the same restriction on θ, it can reduce the plate heat flux by an additional factor

Equivalently, with the same engineering limit on θ, the SXD gives a larger wetted area (by the ratio of the divertor major radius increase)

The SXD Bonus- Built-in Neutron Shielding

- The geometry allows for a natural shielding of the divertor plate to neutrons

- Simulations with Monte-Carlo neutron transport code (MCNP) find that neutron damage is strongly reduced
  - Dpa reduced by about 1 order of magnitude
  - Helium production reduced by 1 ½ order of magnitude

- This should allow the use of copper for the divertor plate with a much longer component lifetime than any other divertor
  - ITER developed divertor technology might be applicable to CFETR and DEMO
  - This could allow operation of a fusion device without having to wait for new materials development (highly uncertain schedule)

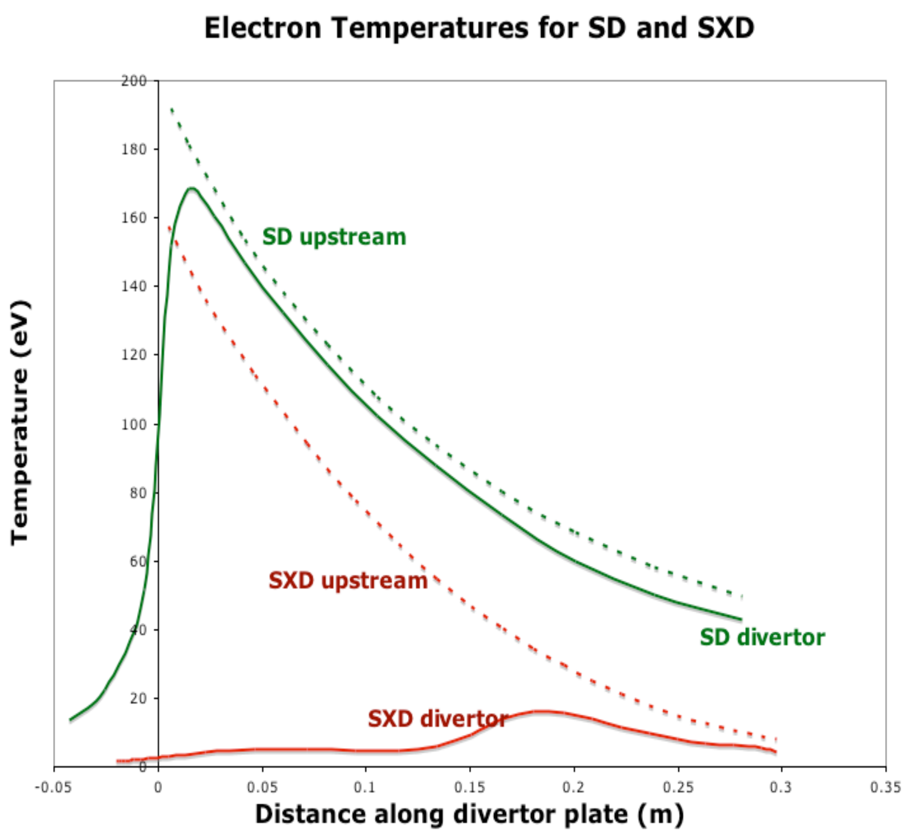
Summary of properties of the new geometries:

- X-divertor and Snowflake:
  - ***Flux expansion to increase wetted area and reduce heat flux- like more highly tilted plate***
  - ***But additional increased line length and radiating volume compared to tilted plate***
  - ***2D codes find some reduction in temperature from increased atomic radiation***

- Super-X has at least as much of these elements (flux expansion), **PLUS MORE**
  - ***Further increases wetted area and radiating volume (with same θ restriction)***
  - ***Geometrically reduces $q_{//}$- which substantially reduces plasma temperature at the plate***
    - ***Further increases radiation***
    - ***Reduces sputtering, erosion***
  - ***ALLOWS ACCESS TO PARTIALLY DETACHED REGIME AT HIGHER SOL POWER AND LOWER DENSITY***
  - ***Increases plasma neutral density, which increases helium exhaust***
  - ***Divertor plate is naturally substantially shielded from neutrons***

SOL-PS analysis for normal coil devices Compact Fusion Neutron Sources (CFSN: CTF and hybrid applications)- An example

- Examining both normal aspect ratio and ST geometries
- Results qualitatively bear out the analytical estimates
- With SXD, the exhausted plasma is "partially detached"- what ITER design aims for
  - $T_e \sim 10$ eV
- For the same parameters, standard divertor is strongly in the sheath limited regime
  - Divertor temperature is close to upstream plasma temperature
  - $T_e \sim 150$ eV



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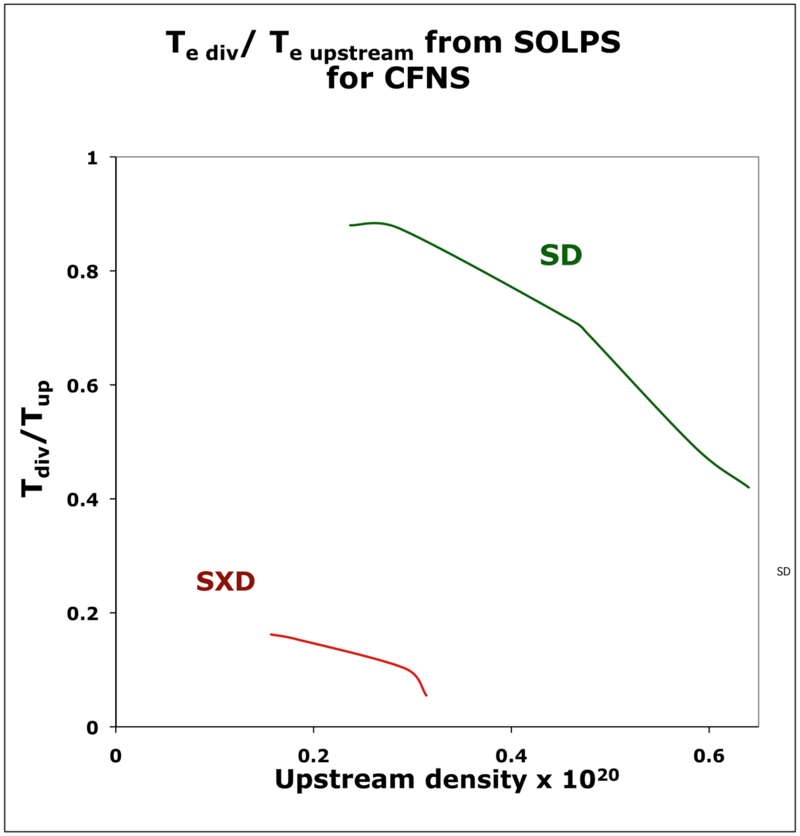
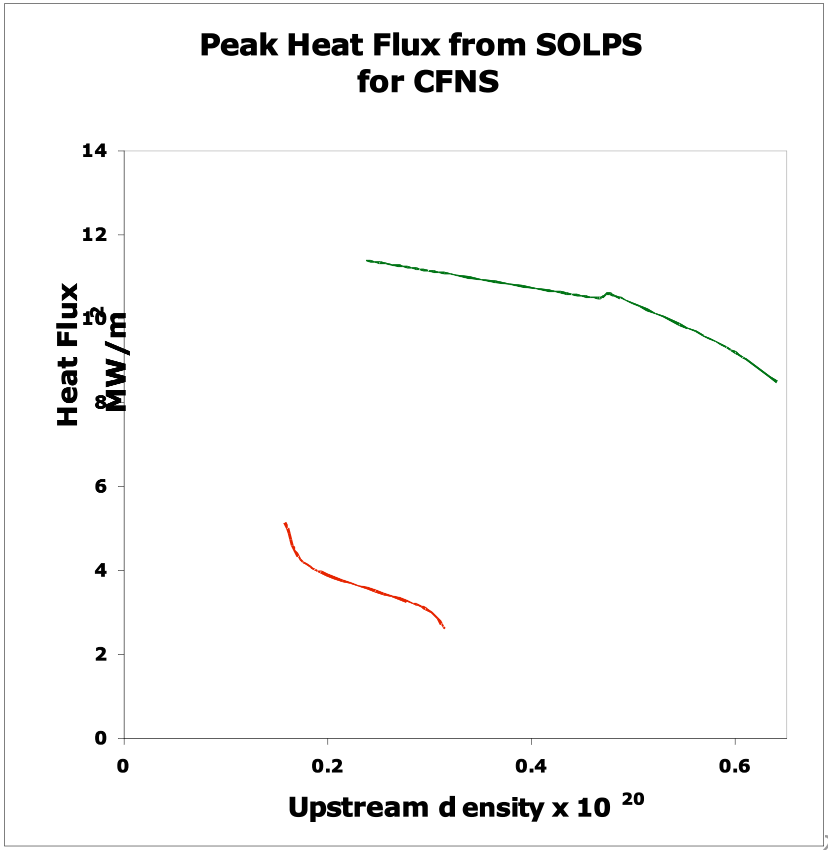
SOL-PS calculations: confirm theoretically motivated expectations

- Density scans: for the same plate tilt (1 degree) standard divertor is well into the sheath limited regime, whereas the SXD is in the partially detached regime
- SXD allows operation for core plasma density ~ 1 x 10^{20}, allowing good current drive efficiency, whereas standard divertor requires much higher density (low fusion gain)





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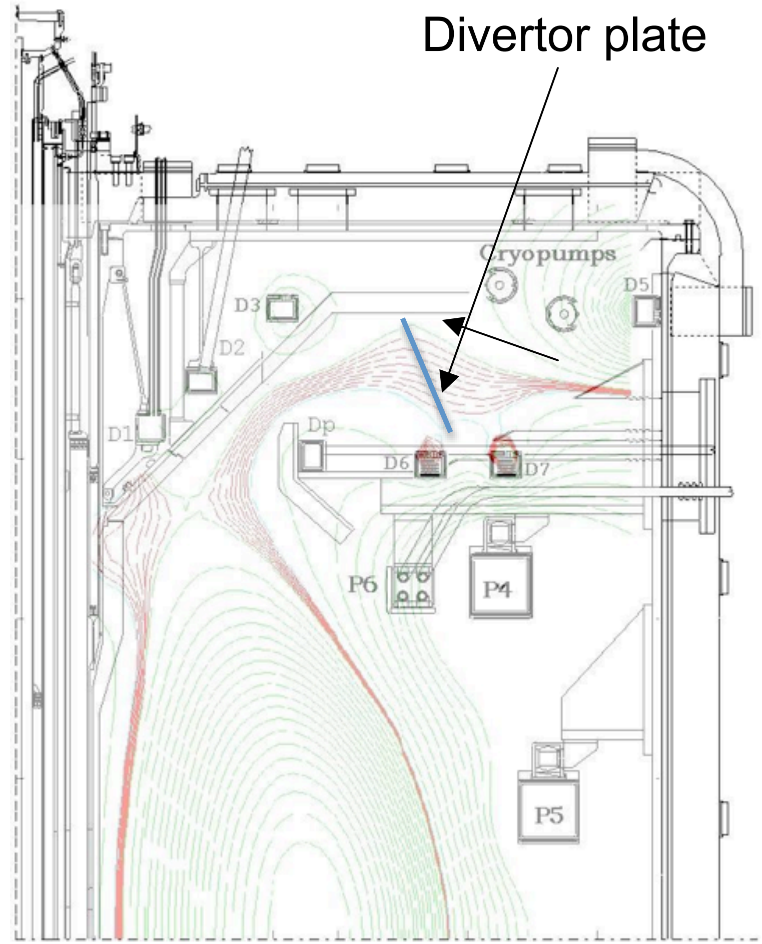
What about ELMs?

- By increasing the wetted area, the new divertor geometry should also spread ELM energy over a larger area
  - ***SXD would give the largest improvement within engineering tolerances on field angle θ***
- Increased line lengths should also increase the particle travel time to the divertor, spreading the ELM out in time as well
  - ***Potentially, line length could also probably be longest in the SXD geometry***
- Including all effects, perhaps a 3-5 reduction in the ELM damage potential metric
  - ***Joules/ meter^2 sec$^{1/2}$***

Experimental tests of the SXD

- MAST upgrade now includes SXD
- Long-pulse superconducting tokamak SST in India designing SXD
- DIII-D- could test SXD with internal baffling added
- Perhaps TCV could test as well????



SXD Engineering design for MAST Upgrade

Suggested preparatory Research for CFETR Divertor

- Develop magnetic geometries for all the divertor candidates, and perform SOL-PS simulations of CFETR:
  - *ITER-like divertor*
  - *Divertor with higher plate tilt*
  - *Snowflake divertor and X-divertor*
  - *Super-X divertor*
- Vary the SOL width so as to model the **range of smaller SOL widths** recent experiments seem to favor
- Perform the same sets of simulations for CFETR **and a pure fusion DEMO (with plausible core radiation fractions)**
- Develop divertor options that give the required **total performance** - **heat flux, helium exhaust and plate temperature (erosion)**
- The results of investigations (on CFETR and DEMO) should decide what divertors must be tested on CFETR- Divertors that CFETR will need – and The Divertors that we anticipate for DEMO

Conclusion

There is enough experimental data and calculation tools (and experience) to guide us in examining divertor strategies for CFETR and the DEMO

The problem is challenging , in fact, very challenging

Advanced divertor concepts are likely to hold a possible key to solutions

CFETR divertor strategy must transcend CFETR needs- Must get us ready for fusion DEMO