The Super X-Divertor for high power density tokamaks

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The divertor: a serious challenge even for ITER

2007 ITER Physics basis:

"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*."

The divertor sets an upper bound on the fusion power in steady state mode

Also:

"It should be noted that presently developed advanced scenarios have not yet provided fully integrated scenarios and several issues remain to be solved, *such as edge compatibility with the divertor*.."

- For ITER (which has much lower power density than a reactor)
  - **Advanced scenarios are already at about the expected limit of standard divertor capability**

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Why lower edge density for higher power?

- Lower density increases driven current in steady state
- Profiles with lower edge density give more bootstrap current!
- Density gradients are substantially more effective than temperature gradients at driving bootstrap current
- **Density peaking gives much higher β for a given β_N**
- Density peaking implies the edge density is low

ARIES AT like profiles: beta vs. n(0)/n_ped for constant β_N

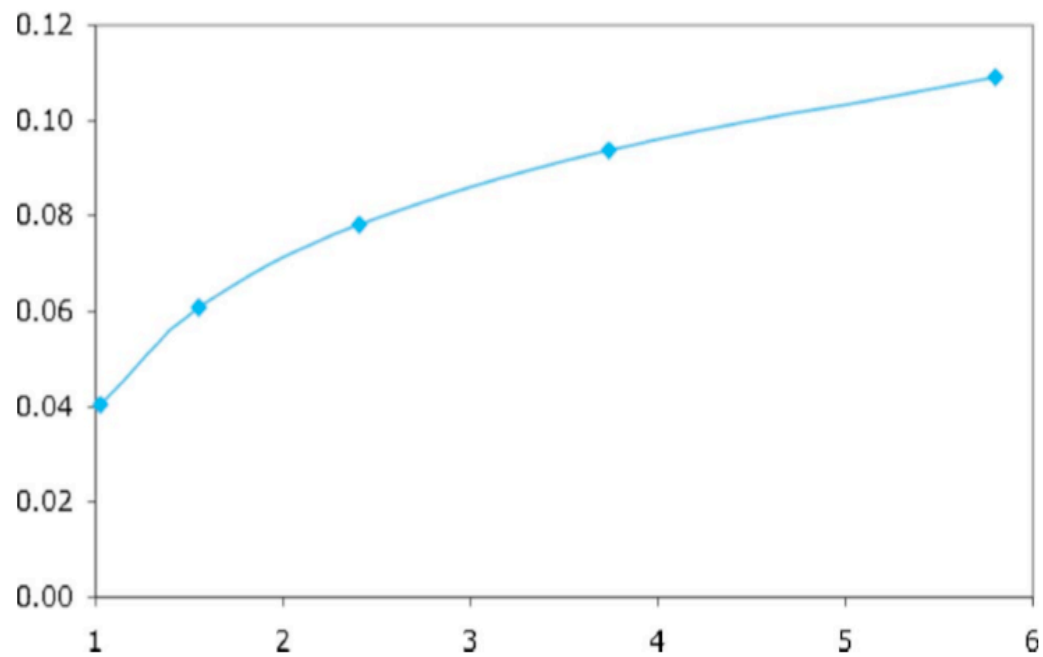

FIG. 1. (Color online) Beta vs the density peaking $n(0)/n_{ped}$ factor (for a fixed β_N) for the ARIES AT reactor. The ARIES AT design point has $n(0)/n_{ped} \sim 5$.

Limit on how low n_{ped} can be is set by the divertor

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Fraction of core radiation to get the same P_{SOL}/R as ITER

- ITER-like parameters: P_{SOL} = 100 MW, R = 6.2 m
- What *core* radiation fraction would reactors need for the same P_{SOL}/R ?
- ~ 60 % of ITER SOL power is estimated to be radiated in the divertor

Reactors	Heating Power	Major R [m]	Core f_{Rad}	Total f_{Rad}
ARIES AT	387	5.2	**78%**	**92%**
ARIES RS	515	5.5	**83%**	**93%**
ARIES AT	387	5.2	**78%**	**92%**
CREST	691	5.4	**87%**	**95%**
Slim-CS	645	5.5	**86%**	**95%**
EU-C	792	7.5	**85%**	**94%**
EU-D	571	6.1	**83%**	**93%**

•DIII-D experiments (close to reactor $\beta_N \sim 4$) have nowhere close to 92-95% radiation
•Is a radiation fraction ~ 95% consistent with 10^{-6} lower disruption freqeuncy?

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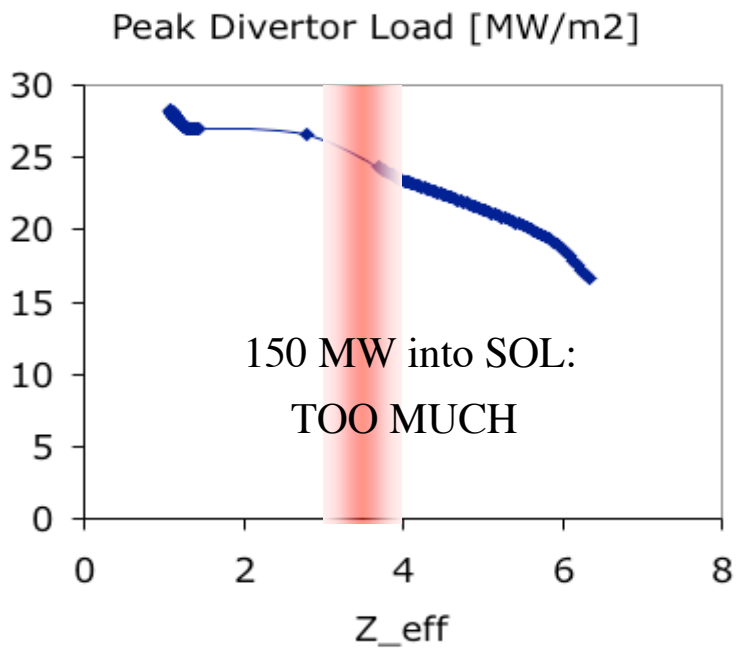
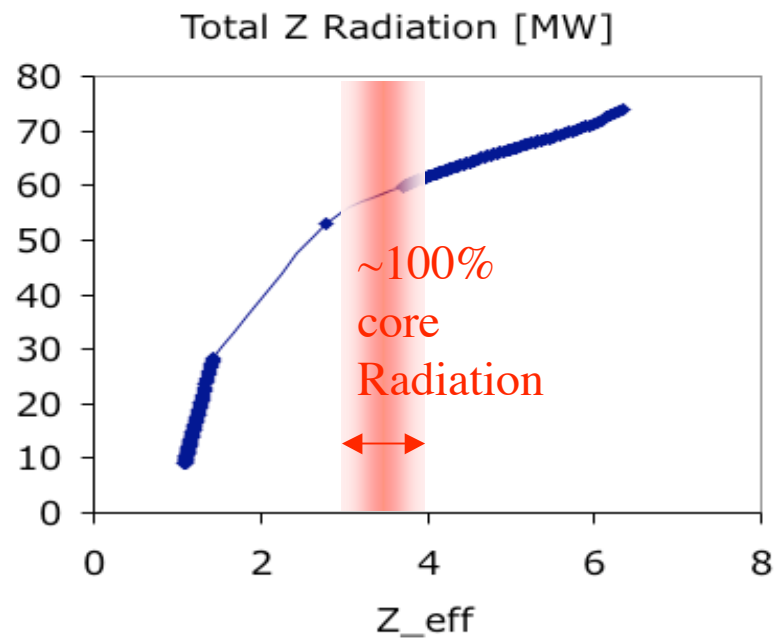
UEDGE results for 150 MW into SOL for ITER geometry

- Divertor Radiation nearly saturates with increasing impurities
- Core radiation would continue to increase linearly with Z_{eff}
- **No amount of impurities (up to Z_{eff}=6) brings divertor heat load below 10 MW/m^2**
  - **Depending on profiles, core heating is totally radiated at Z_{eff} ~ 3-4**

UEDGE Calculations for Reactor





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Need a divertor solution which can handle higher upstream $q_{||}$ and lower n_{sep}

- With the same core radiation fraction as ITER,

  Reactor upstream $q_{||}$ is ~ five times greater

- Divertor plate must have acceptable heat flux, ***and*** divertor plasma must not have unacceptably high T_e **and** it have acceptable He pumping
  - **E.g, must avoid the sheath limited regime**

- We will emphasize steady state heat flux here
  - Super-X divertor would also hopefully distribute ELM heat pulses over a larger area

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Problems at high divertor power/ low density

1. **Divertor plate heat flux Q_{plate}**
   - Technological limits of ~ 10 MW/m^2 , perhaps less at much higher neutron fluence than ITER
   - $Q_{plate} \sim P_{SOL}^{2.6}\, n_{sep}^{-2.4}$ (SOLPS runs for ITER)
2. **Helium pumping**
   - In simulations, degrades rapidly with higher power and lower density
   - $n_{He} \sim P_{SOL}^{3.3}\, n_{sep}^{-5.5}$ (SOLPS runs for ITER)
3. **Plasma temperature at the plate**
   - Unacceptable sputtering and plate lifetime, dust generation, etc.
   - High T => low n, low impurity screening, high plasma impurity levels
   - $T_{plate} \sim P_{SOL}^{2} n_{sep}^{-2}$ (Two point model, high recycling)

- **Many Solutions of 1 don't help 2 or 3**
- Need ***simultaneous*** solutions for 1,2 and 3 for devices beyond ITER (DEMO, CTF, commercial fusion reactor, fission-fusion hybrid, etc.)

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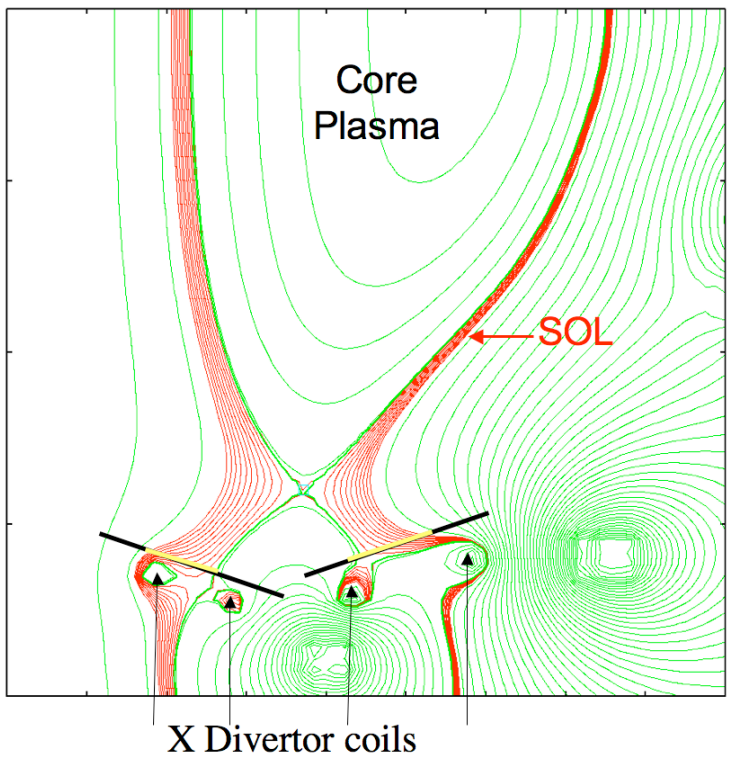
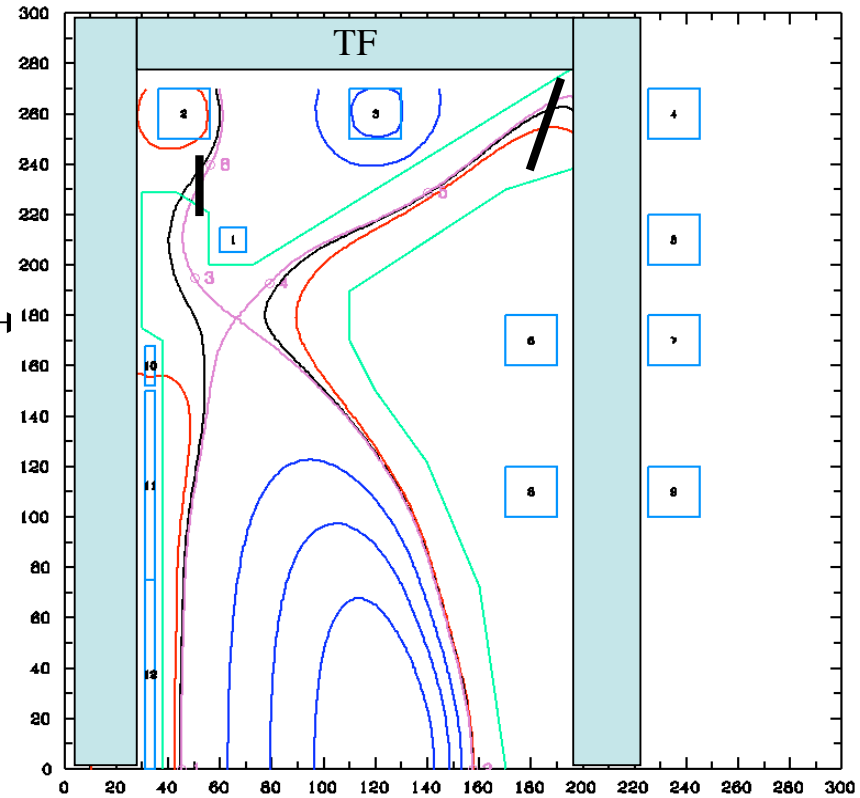
Solution:
Super X Divertor (SXD): evolution from X-Divertor

X-divertor /snowflake: expand flux



SXD: expand flux
PLUS maximally increase R_{div}



SXD greatly increases:
plasma wetted area, margin from sheath limited regime

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SXD- *combines flux expansion with larger major radius*

- Benefits of flux expansion are well appreciated
- SXD- Geometrically reduces $q_{||}$ from upstream value by having wall contact occur in a region of larger major radius (and lower B)
- Cross section of flux tube carrying exhausted heat increases as B decreases
- Lower $q_{||}$ reduces divertor plate heat flux Q_{plate}
  - for given plate angle
- Plate temperature ~ $q_{||}^2$ ~ $(B_{div}/B_{up})^2$ (two point model, high recycling)
  - NOTE: temperature is almost independent of angle (unlike Q_{plate})
  - Lower T_e in SXD leads to higher radiation, and even lower $q_{||}$
- SXD enables partially detached regime with several times higher power/ lower density than a standard divertor
  - Standard divertor would be in the sheath limited regime- unworkable for reactors

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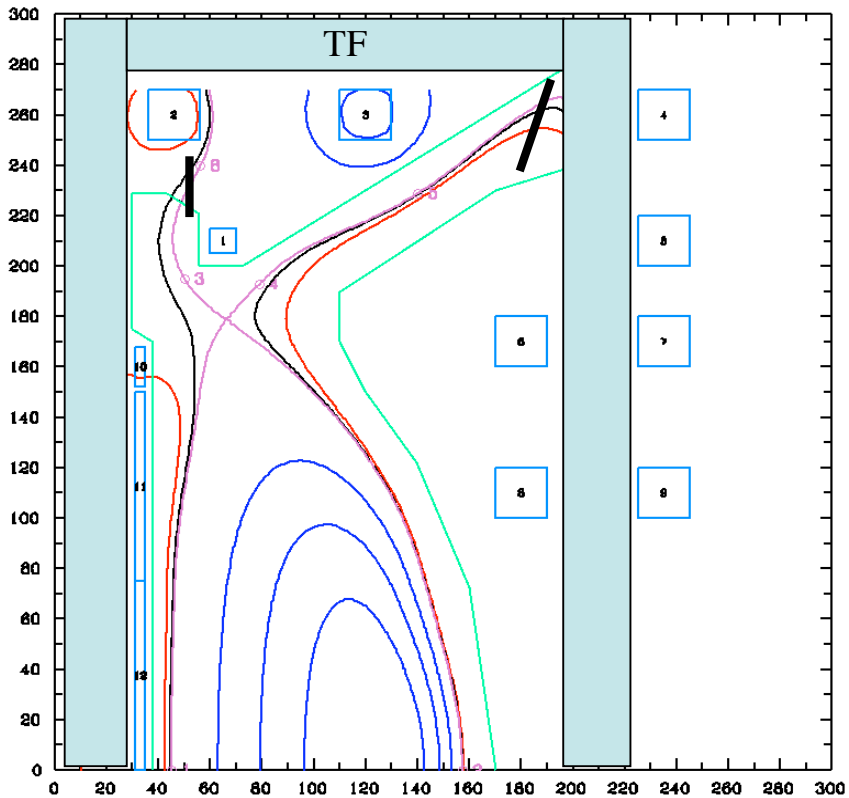
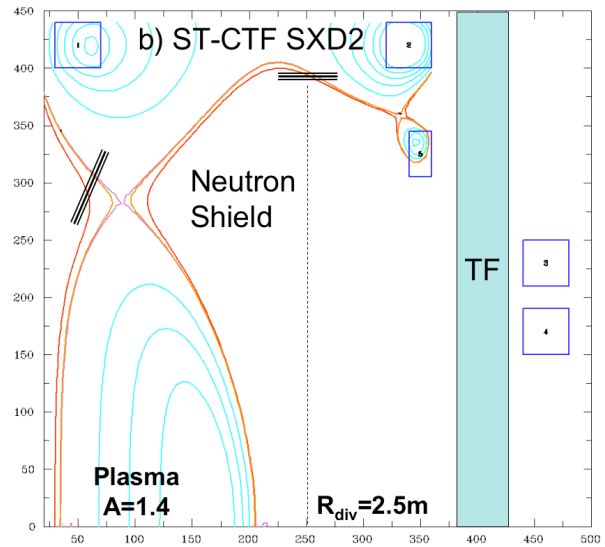
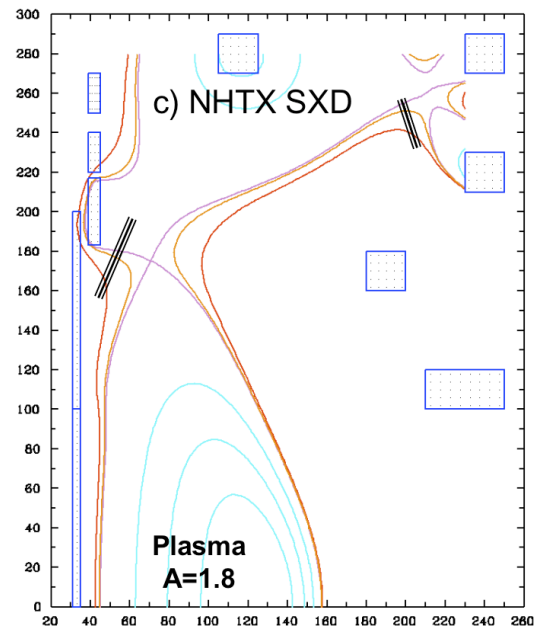
SXD Examples (CORSICA equilibria)

With 5% less Amp-m than SD







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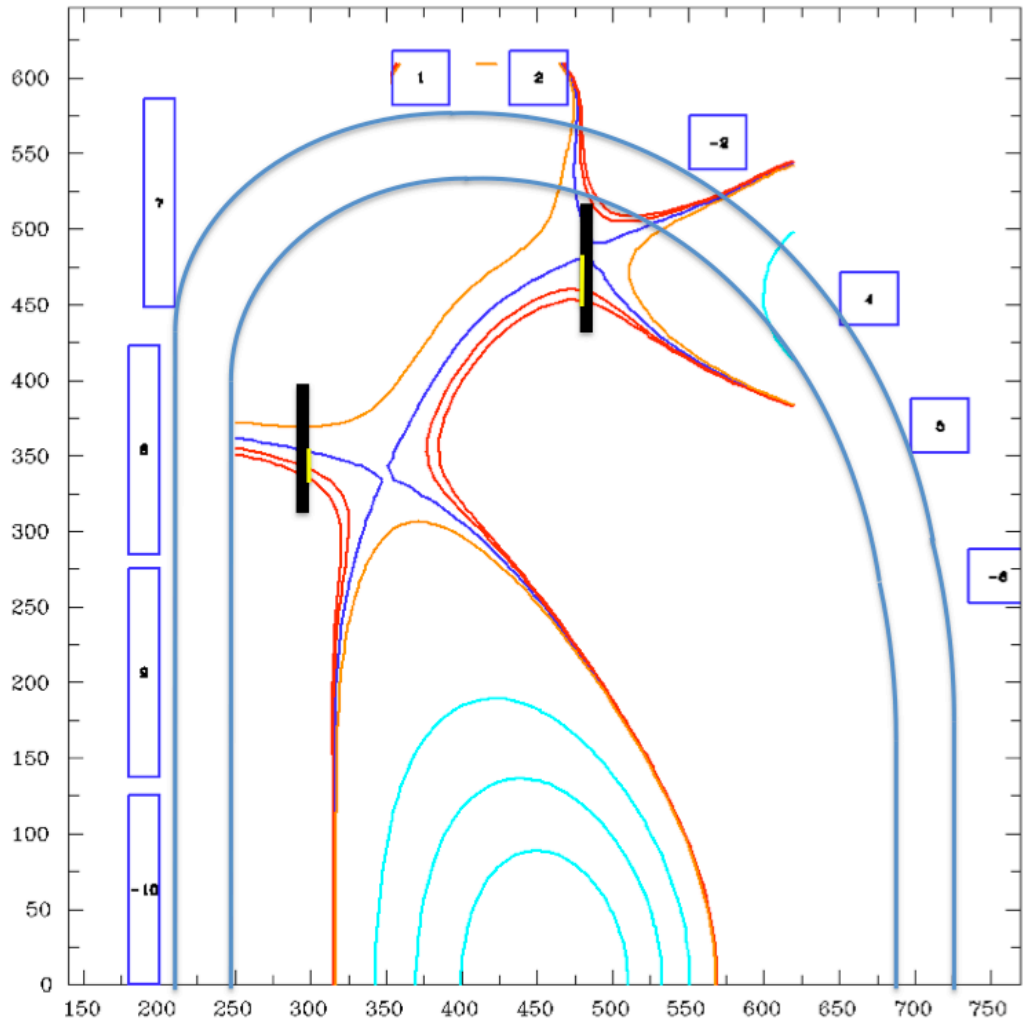
SXD Examples (CORSICA equilibria)

Slim CS



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SXD: lowers heat flux more than is possible with plate tilting or flux expansion

- Plate tilt (and flux expansion) strategies reduce plate heat flux by making the plate closer to tangent to the magnetic field

$$Q_{plate} = q_{||} \sin \theta$$

- ITER: angle θ between divertor plate and total magnetic field must be at least 1 degree- plate tilting and flux expansion are limited in practice
- By reducing the parallel heat flux geometrically, the SXD reduces heat flux more than is possible with plate tilting or flux expansion alone

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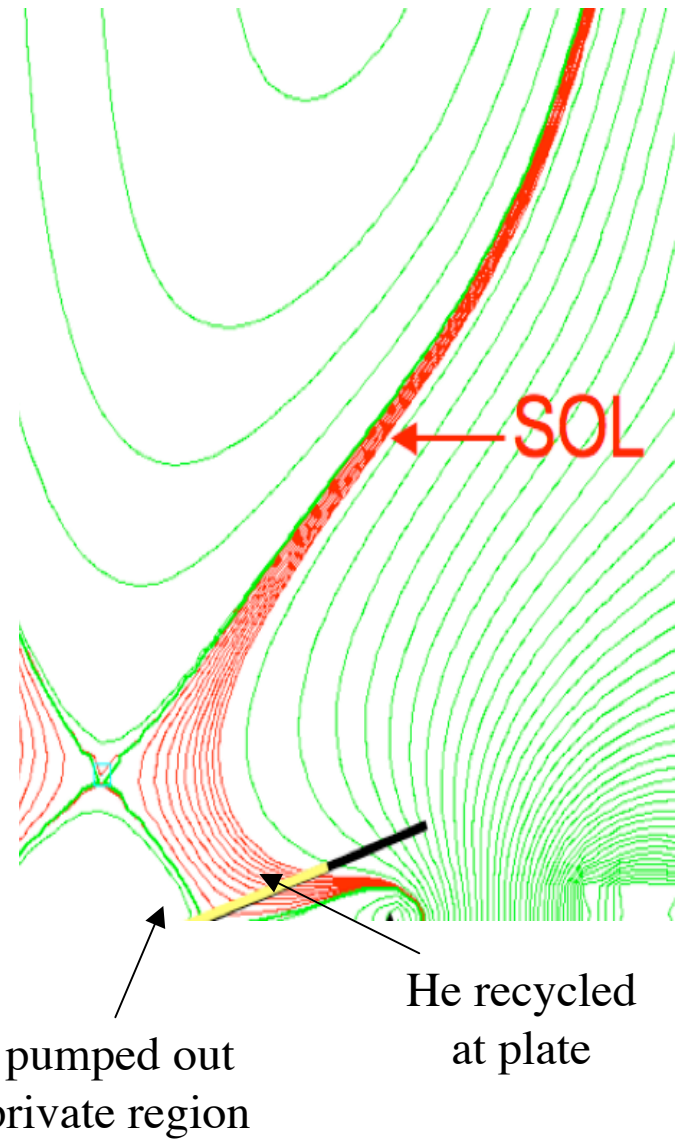
Erosion/Impurities

- Sheath boundary condition: plasma temperature on plate is a very rapidly increasing function of $q_{||}$, and plate tilt helps little
  - Sputtering increases (strongly) with plate plasma temperature, prompt re-deposion decreases (strongly) with lower plama plate density
  - Erosion/impurities are a rapidly increasing function of T_{plate}
- SXD advantage: Only method of geometrically reducing $q_{||}$
  - Other methods geometrically reduce Q_{plate}, BUT NOT $q_{||}$
  - Temperature at plate is determined by $q_{||}$, NOT BY Q_{plate}
  - SOLPS simulations of SXD: greatly reduces T_{plate} and increases n_{plate}
  - Expect SXD to greatly reduce erosion and impurities

He exhaust

- **ITER simulations: $n_{He} \sim P_{SOL}^{3.3} n_s^{-5.5}$**
  - He exhaust degrades very rapidly with increasing plate T/ lower plate n
  - We worry that tilt, flux expansion could degrade He exhaust, since recycled neutral He from plate must transport a longer distance through the plasma without being ionized to be pumped out
- SXD advantages:
  - Large reduction in T_{plate}/increase in n_{plate} to conditions which give good He exhaust
  - For a the same wetted area, increasing R by 2-3 decreases the width on the plate by 2-3 and so reduces the distance He must go to get to the private region

Older X- Divertor concept



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Analytical theory- SXD avoids the Sheath Limited Regime

- Use "two-point" criterion for sheath limited regime

$$q_{\|} / n_e^{1.75} L_{\|}^{0.75} > C_0 \quad (= 1 \times 10^{-27}\ W/m^{2.5})$$

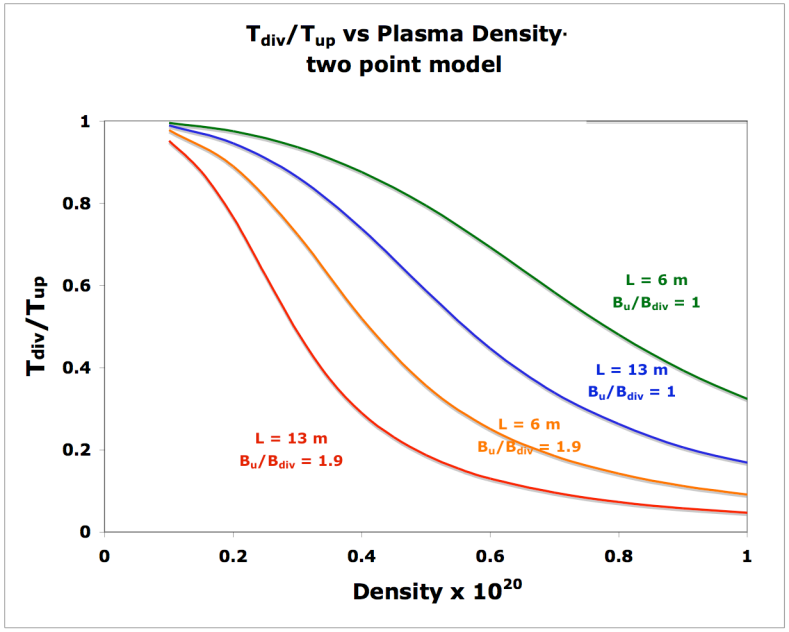
- Modify two point model to include $B_{div} < B_{up}$:

$$q_{\| up} (B_{div} / B_{up})^{1.75} / n_e^{1.75} L_{\|}^{0.75} > C_0$$

•SXD: reduces B_{div}/B_{up} by ~ 2

and increases $L_{\|}$ by ~ 2 =>

the sheath limited regime is avoided for ~ 5 times higher $q_{\|}$ or ~ 3 times lower density



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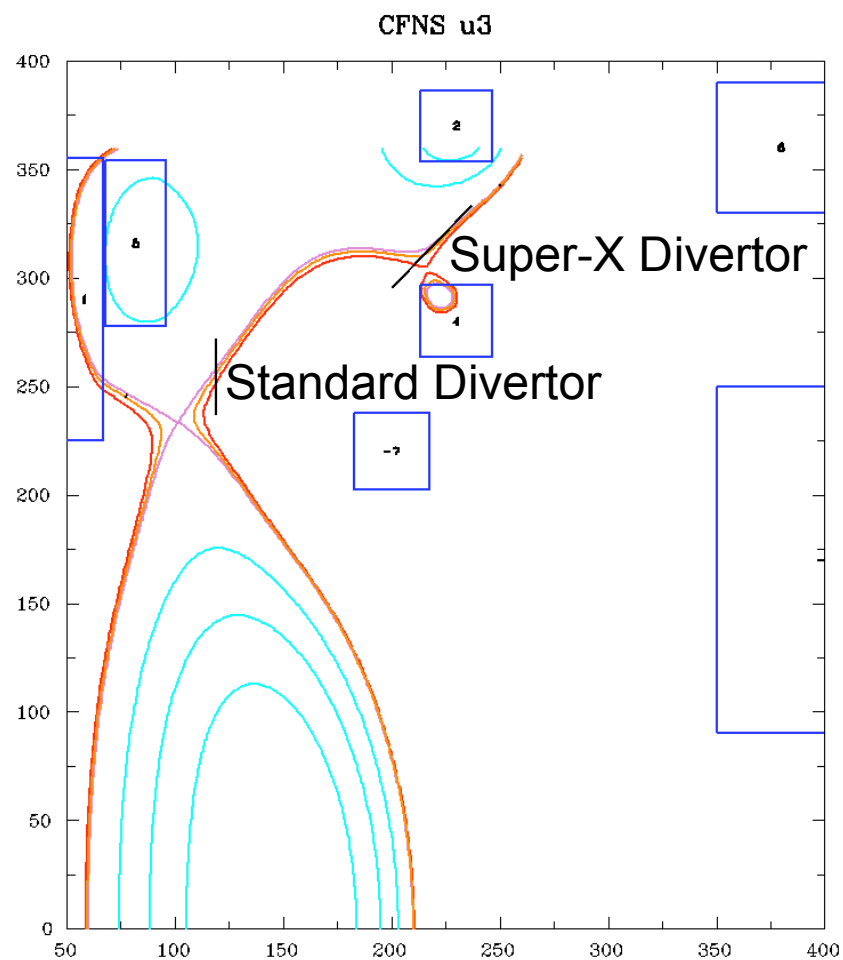
SOLPS simulations comparing SXD with standard divertor for CTF / CFNS

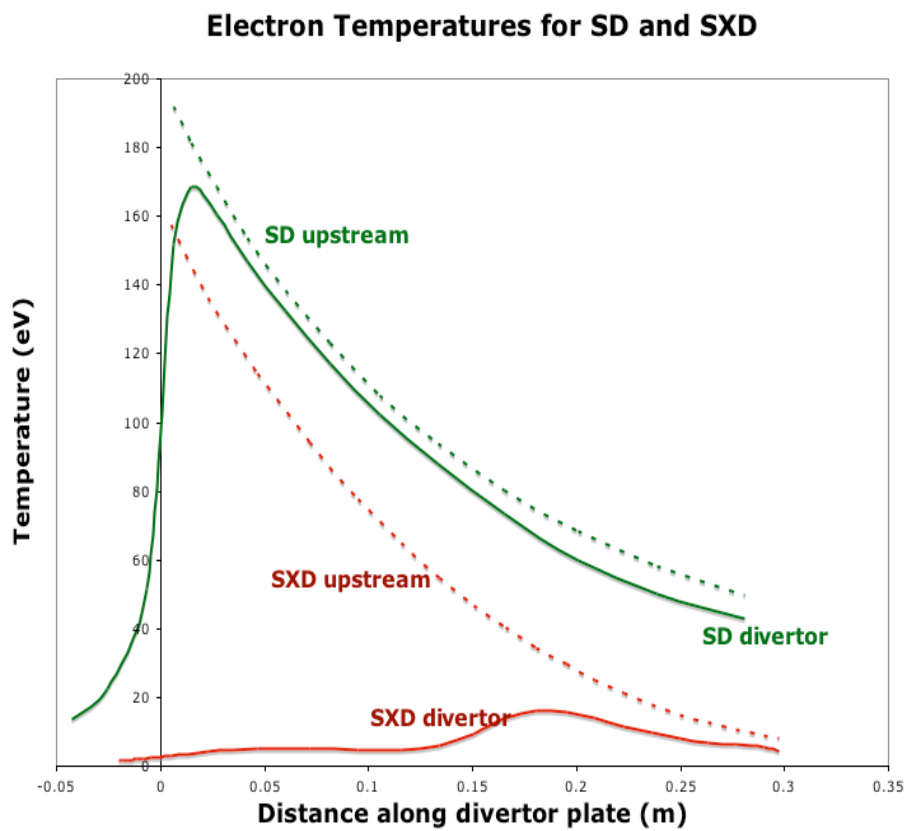
- Equilibrium A = 1.8, R = 1.35
- SXD - major radius of plate increased by factor of 1.9, $L_{||}$ increased by 2.1

- **Conclusions: SXD is in the partially detached regime when the standard divertor is in the sheath limited regime**



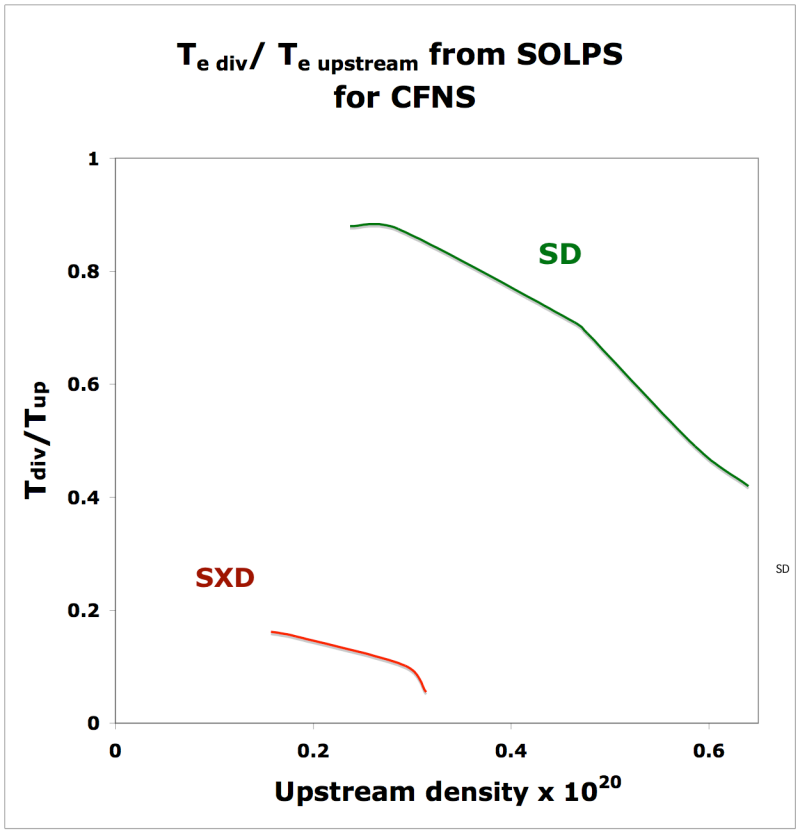
Super-X Divertor (SXD) provides the desired operation - unlike the standard divertor

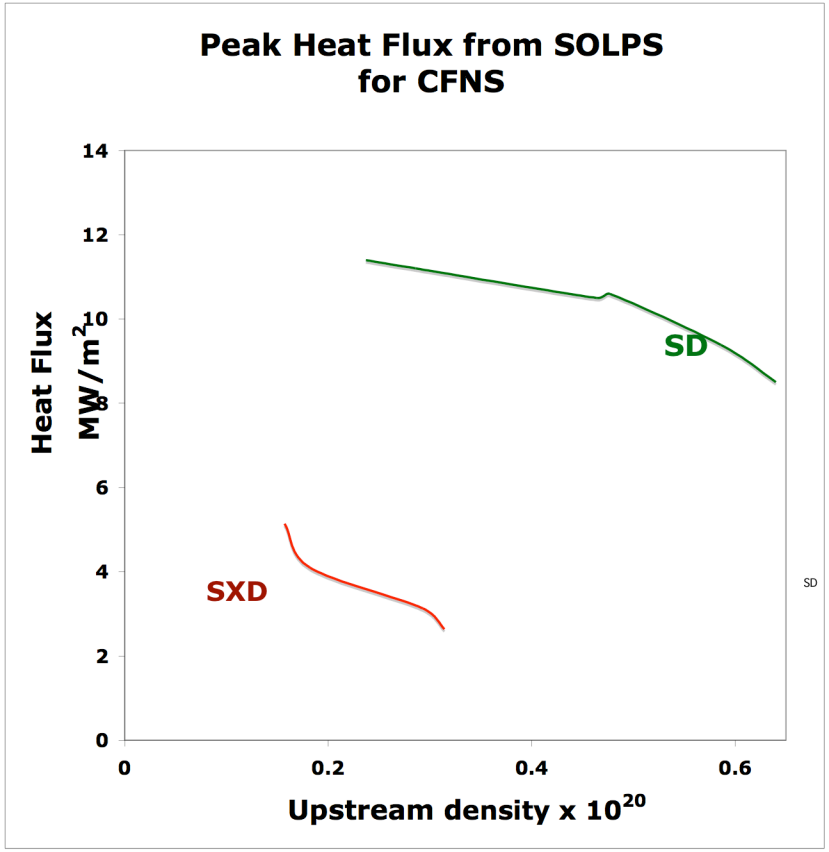
- Case with $n_s = 3 \times 10^{19}$, $P_{SOL} = 50$ MW
- **SXD- exhausted plasma is "partially detached"- what ITER design aims for**
  - **T < 10- 20 eV**
- **Standard divertor - strongly in the sheath limited regime**
  - **T ~ 100-150 eV**



Calculations by John Canik ORNL

Super-X Divertor (SXD) provides the desired operation

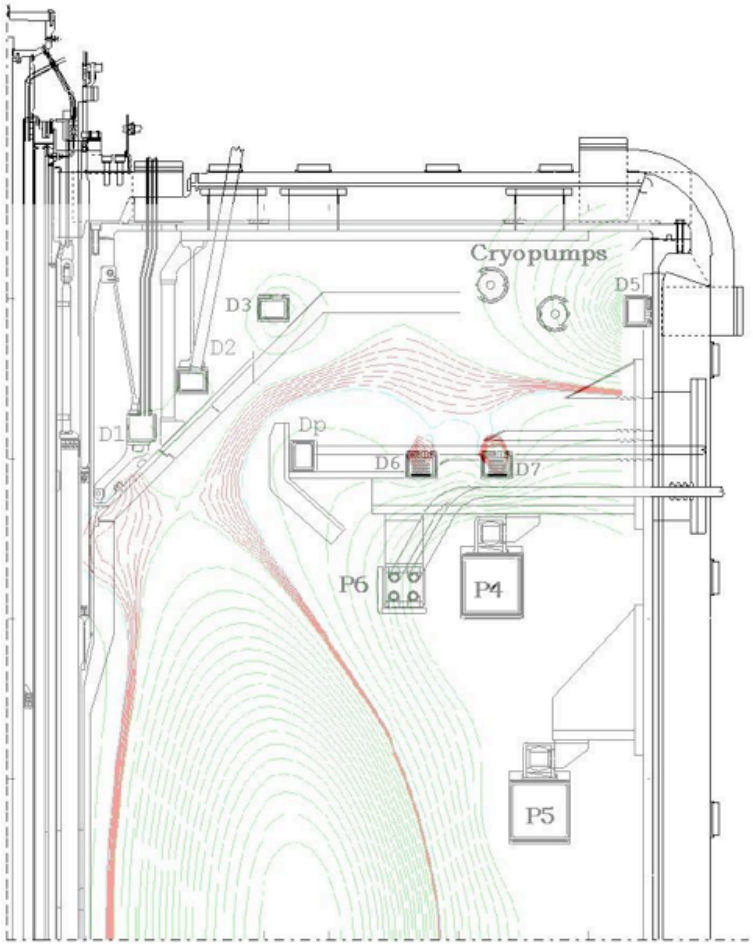




Calculations by John Canik ORNL

SXD-from theory to experiment

- **Worldwide plans are in motion to test SXD:**
  - MAST upgrade now includes SXD, now funded
  - Long-pulse superconducting tokamak SST in India designing SXD
  - NSTX: XD and future SXD?



SXD for MAST Upgrade

Neutron damage to divertor - serious issue

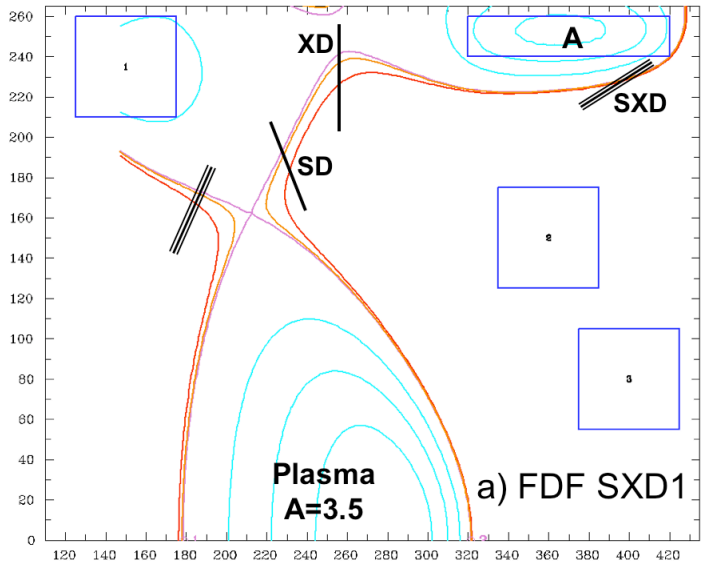
- **Only *hypothetical* high heat flux divertor materials might tolerate ~ 30-100 dpa**
  - Significant technology risk
  - Slow development would hamstring any high duty cycle DT device (CTF, DEMO)
- **SXD: substantial shielding of divertor plates for future CTF, DEMO**

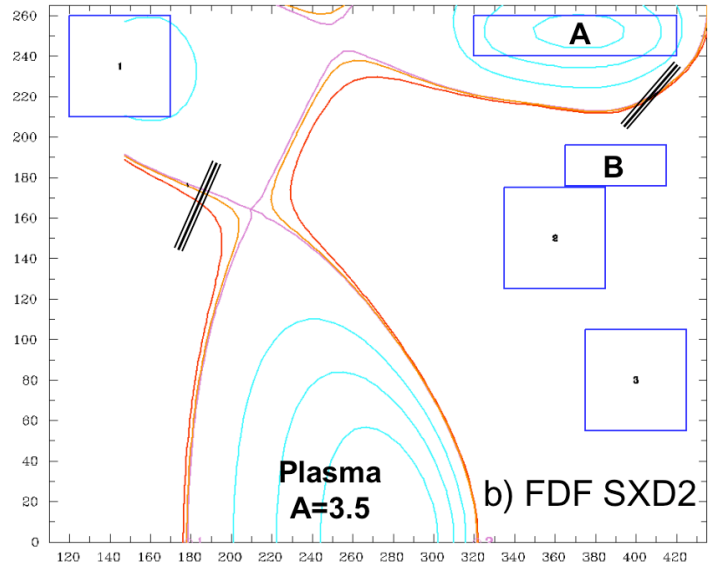
Initial MCNP calculations- damage rate reduced several times

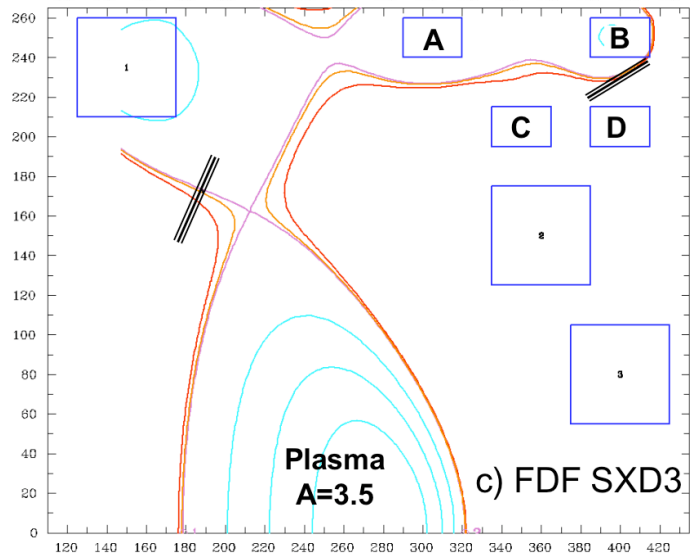
Summary

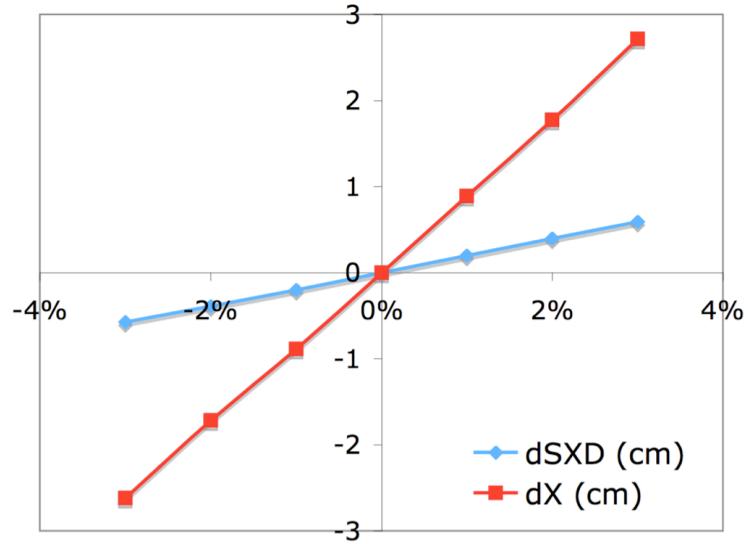
- The operating space of the divertor affects the operating space of the entire reactor
  - Density and edge density substantially affects β
  - Helium exhaust affects overall fusion power density
  - Extremely high radiation fraction probably impacts disruption probability
- The SXD combines both flux expansion and larger major radius to greatly increase the operating space of the divertor
- We hope and expect that this will commensurately improve overall plasma performance
- Overall engineering compatibility with fusion reactor designs requires more detailed analysis

SXD design space is smooth and large









SXD is insensitive to plasma changes possibly because the long SXD "leg" near the SXD coils is far from plasma current

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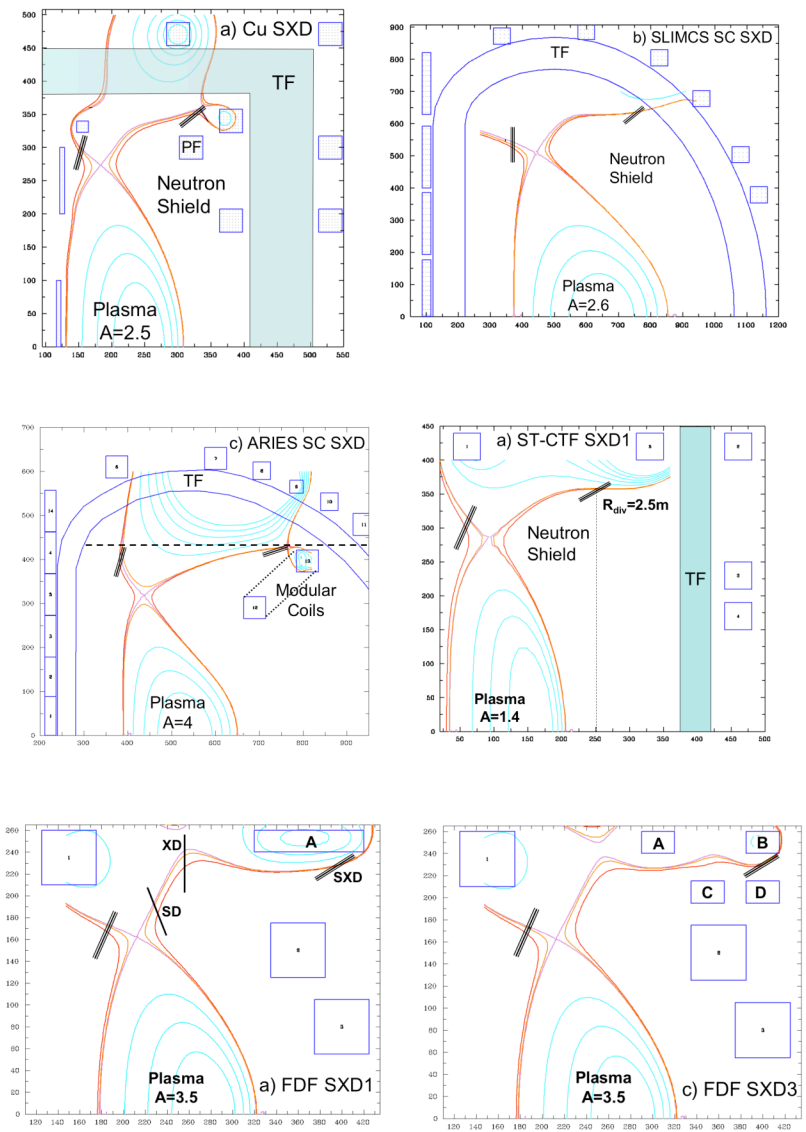
Gains for SXD equilibria



Case	Fig.	L [m]	L/L_x	R_{div}/R_x	A_w [m^2]
HPDX	1a	53.0	2.98	1.89	7.93
SLIMCS	1b	78.0	2.70	1.63	7.03
ARIES	1c	66.1	1.93	1.72	8.20
CTF 1	2a	26.6	2.08	2.74	10.35
CTF 2	2b	37.3	2.72	2.84	9.76
NHTX	2c	38.1	3.40	2.89	5.31
FDF 1	3a	61.9	3.99	1.86	5.57
FDF 2	3b	66.6	4.24	1.88	5.73
FDF 3	3c	73.6	4.69	1.85	5.57

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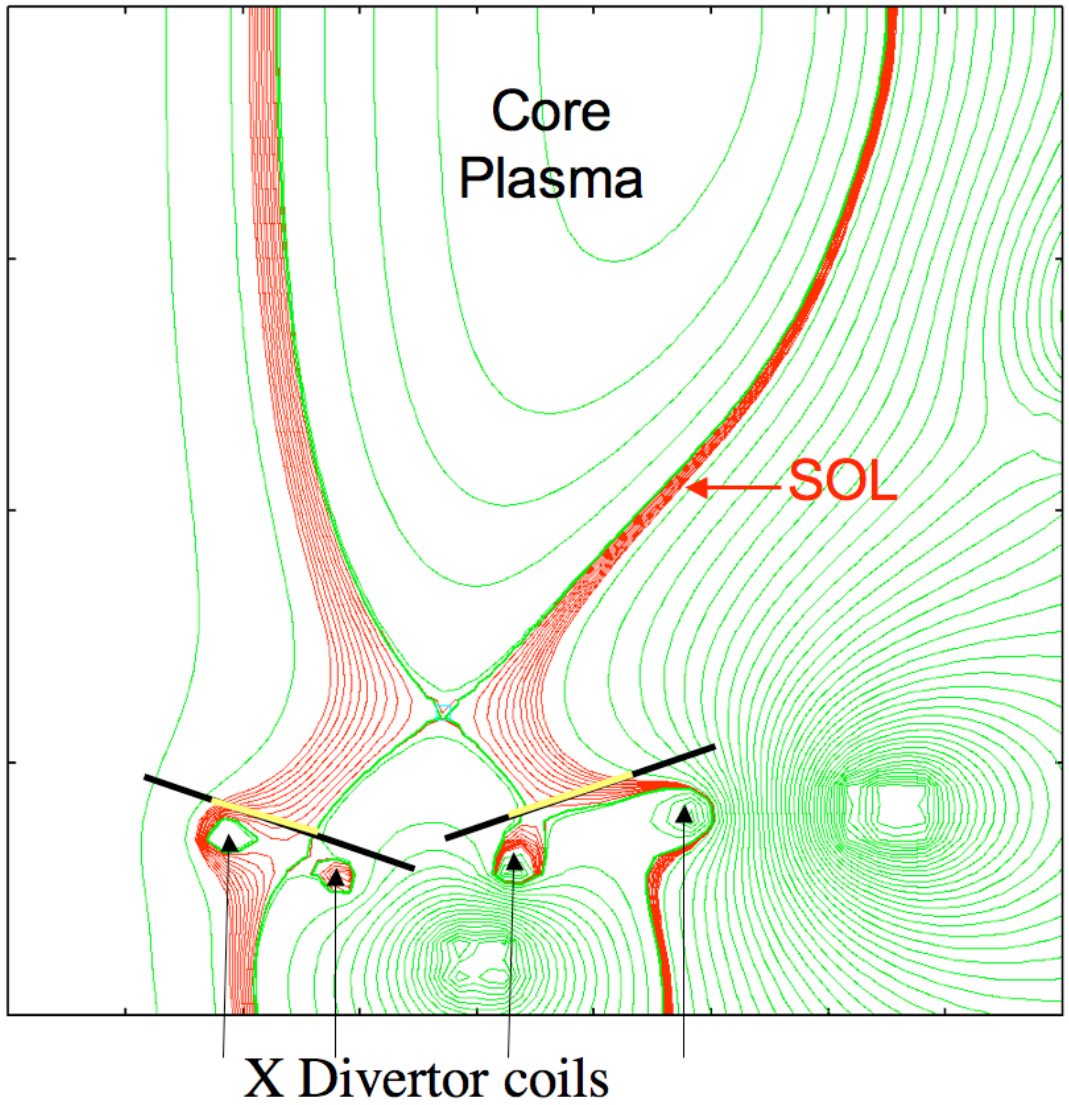

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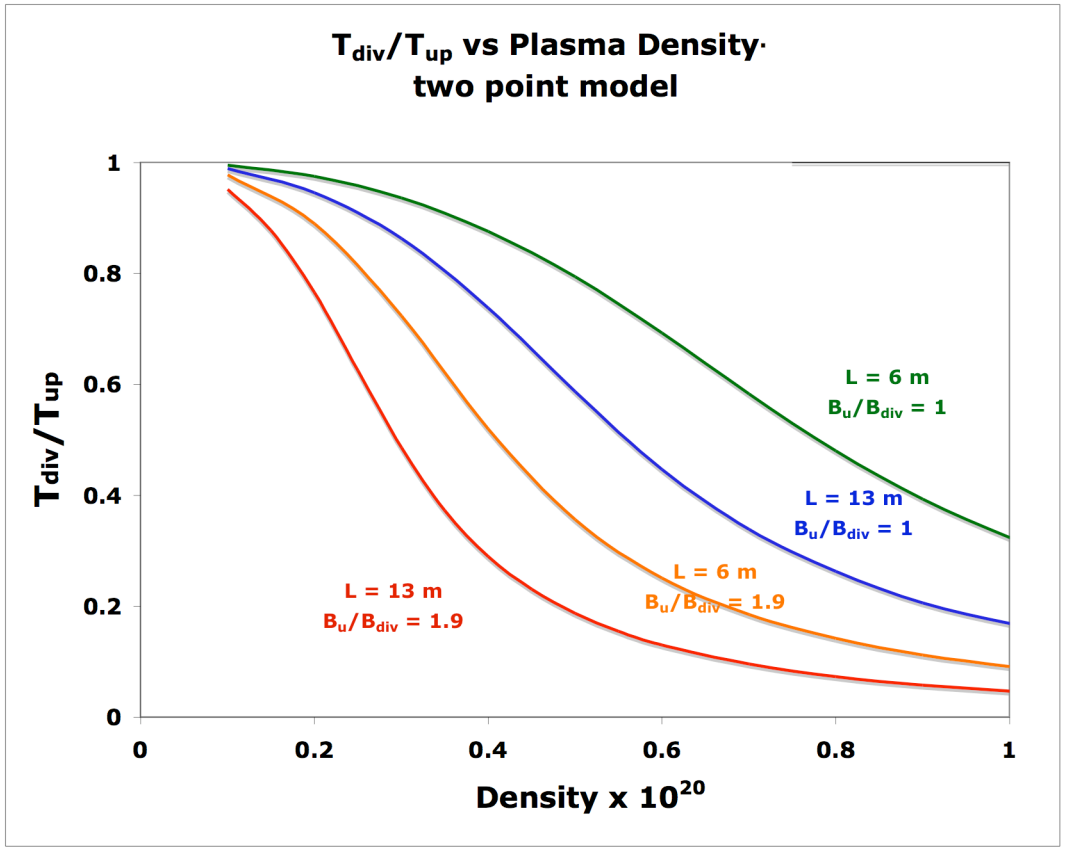
T_{div}/T_{up} vs Plasma Density·
two point model
T_{div}/T_{up}
Density x 10^{20}
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
L = 6 m
B_u/B_{div} = 1
L = 13 m
B_u/B_{div} = 1
L = 6 m
B_u/B_{div} = 1.9
L = 13 m
B_u/B_{div} = 1.9

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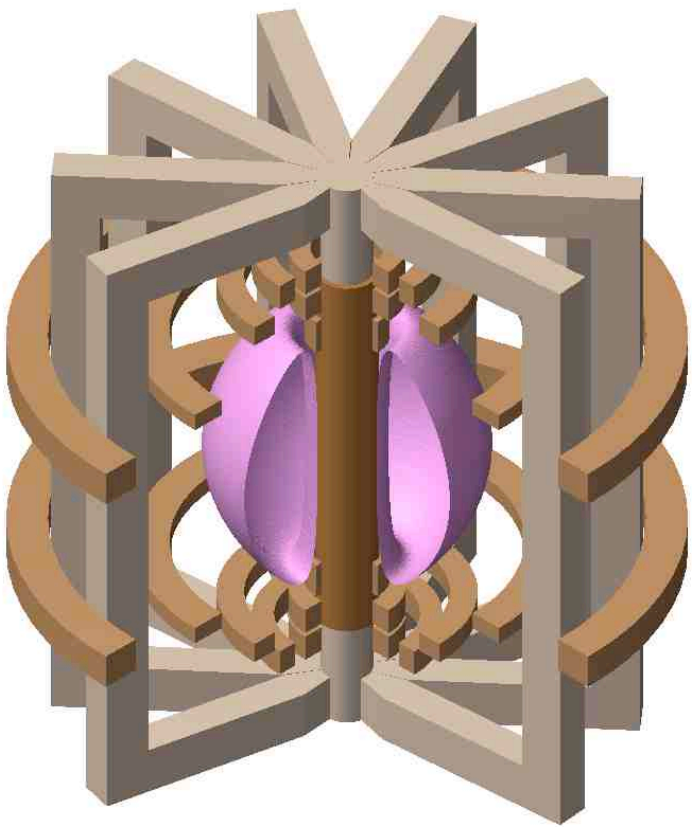
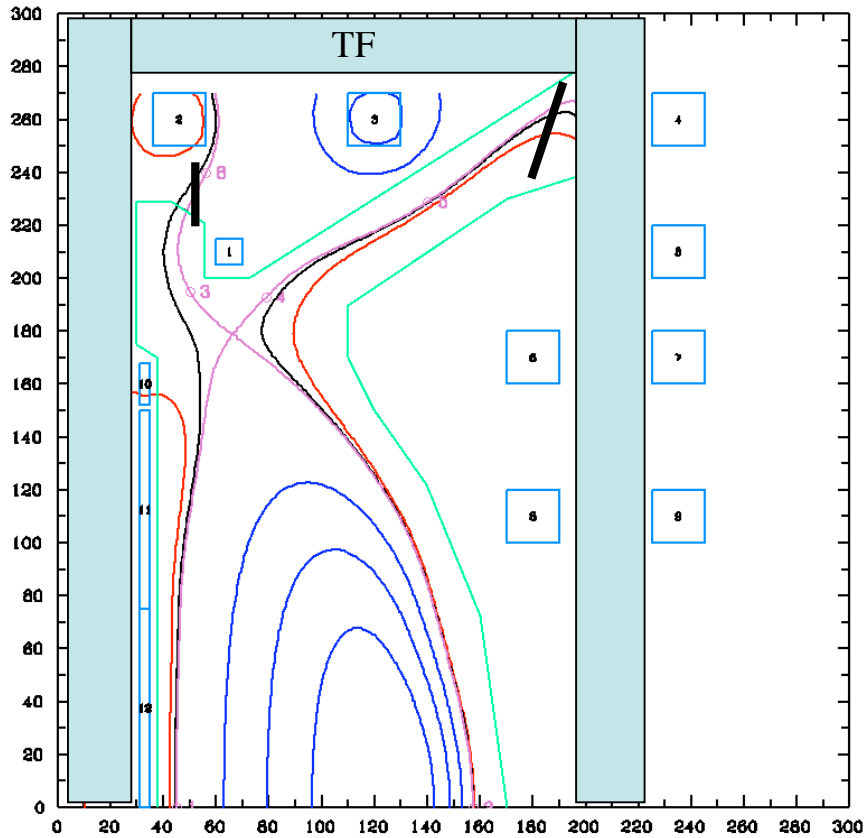
SXD fits in TF corners - no TF real estate issues

- For NHTX, FDF, and Reactors, SXD does not require larger TF coils
- SXD uses available space (in the corner of TF coils) which is normally unused



NHTX (PPPL/ORNL)



CORSICA Equilibrium for NHTX-SX

Further SXD issues to be investigated

- **Doesn't inner divertor now become the problem?**
  - No. Almost all HPDs are designed as double-null (DN) devices
  - In DN, heat flux on inner plate is order of magnitude less than outer
  - SXD does not increase heat flux on inner plate
  - So unless SXD decreases heat flux by more than ~5, this is no problem
- **Won't some instability increase cross-field transport?**
  - That would be good! It will further increase SXD capability.
  - The SXD leg does not go very near the extra X-point, so ergodic problems (hot spots etc.) are expected to be not bad
- **What about pumping, He pumping, etc.**
  - SXD is better isolated from plasma, lower T, higher n, so higher neutral pressure
- **TF ripple at SXD plates**? Solution: shape SXD plates
- **Is stable detached operation possible with SXD?** Need to simulate.

High radiation fractions likely unacceptable

Reactors	Core f_{Rad} to give same P_{SOL}/R as ITER	H_{89P} by subtracting core radiation
ITER (AT mode)	~50%	-
ARIES RS	83%	4.4
ARIES AT	78%	4.2
CREST	87%	5.2
Slim-CS	86%	5.1
EU-C	85%	4.3
EU-D	83%	4.3

- Core f_{Rad} ~ 85% qualitatively different from ITER value of core f_{Rad} ~ 50%
- **Reactor H_{89P} ~ 4.2-5.2**
- DIII-D: H_{89P} ~ 2.5-3 (for high β_N "reactor-like"experiments)
- Can we expect reactors with much less velocity shear to have much higher H_{89P}?
- Even if low core χ is possible, likely He build-up/collapse

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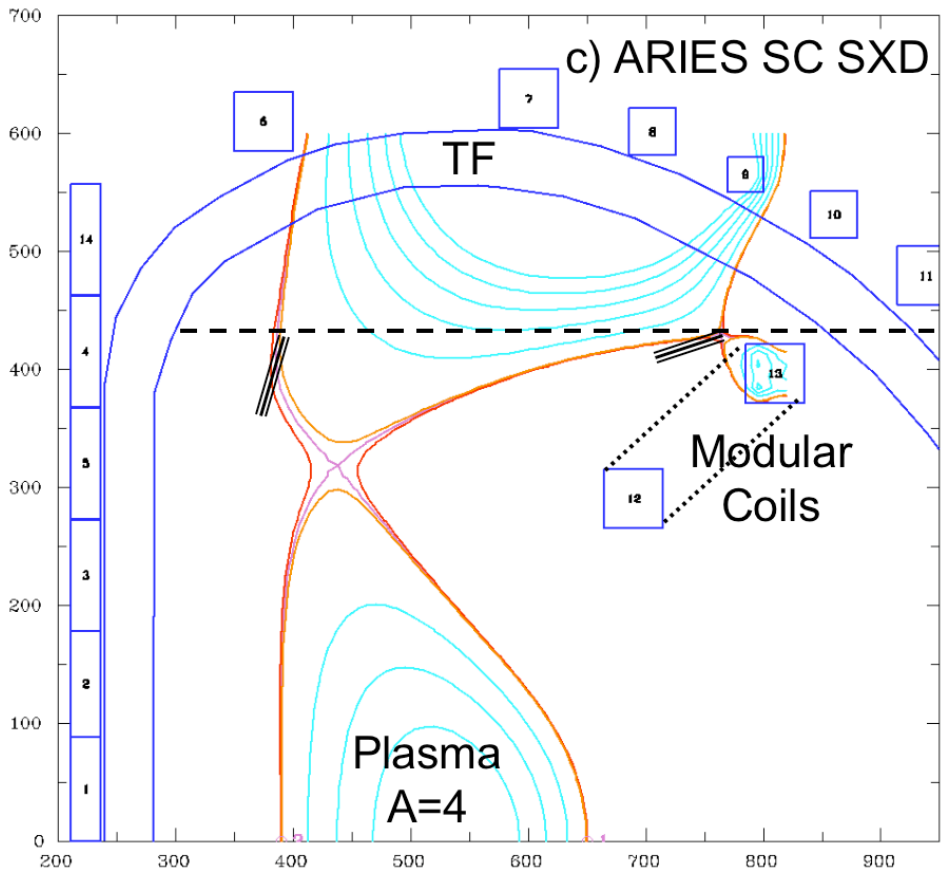
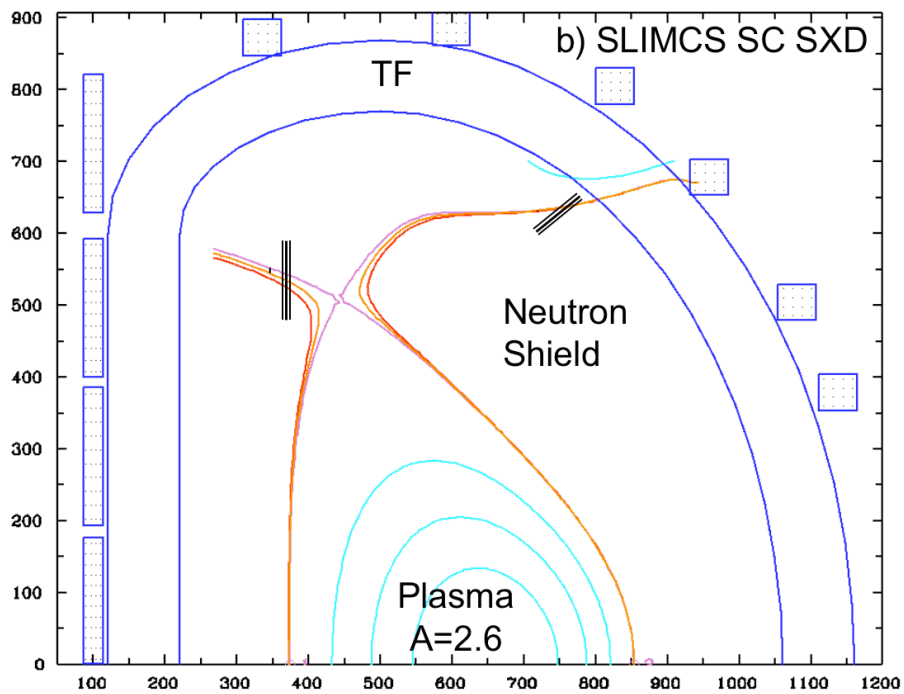
SXD Examples (CORSICA equilibria)





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