Super X Divertor for NSTX

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Goals of this talk

Introduce Super-X Divertor (SXD):

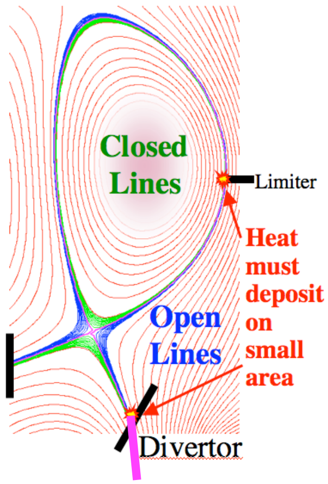
- SD to XD to SXD
- SXD basic idea (and differences between XD and SXD)
- SXD advantages
- Many SXD examples that we have designed so far

Start a discussion of NSTX constraints for SXD implementation:

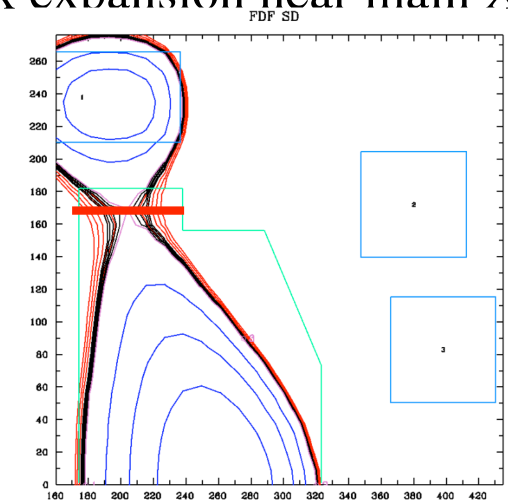
- Since SXD design is "easy", system goals and constraints dominate
- Physics goals for an SXD trial on NSTX
- NSTX engineering constraints that will limit SXD design flexibility
- Pumping, baffling, support structures, impurity isolation, …

Limiters to Divertors to X-Divertors to Super-XD

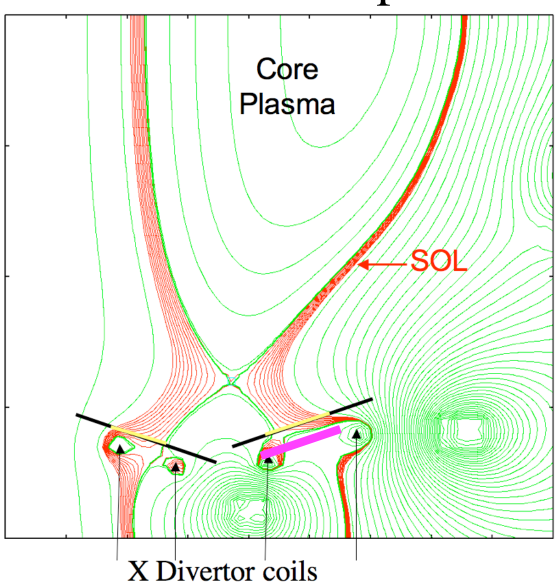
Limiter & Standard Divertor



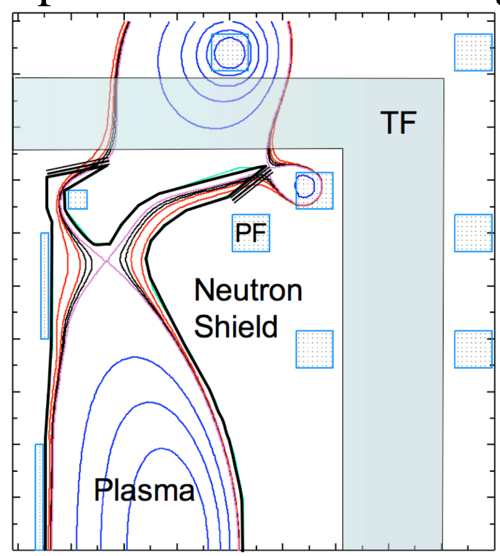
Flux expansion near main X-point



XD/snoflake to expand flux



Super X-Divertor at Large R



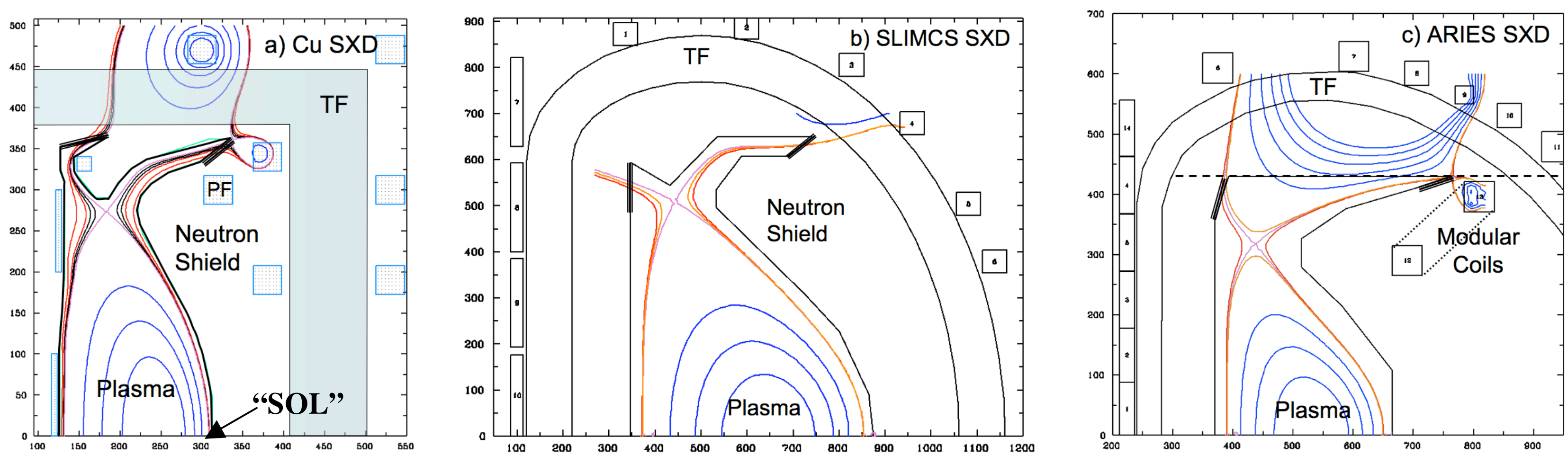
***All* flux expanders equally limited by 1 deg tilt limit**

Super X Divertor (SXD)

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

$$A_w = \frac{B_{p,sol}}{B_{div}} \frac{A_{sol}}{\sin(\theta)} \approx \left[\frac{B_p}{B_t}\right]_{sol} \frac{R_{div}}{R_{sol}} \frac{A_{sol}}{\sin(\theta)}$$

- **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 (Canik, Maingi)**



Flux expansion equivalent to plate tilt

- **One can increase wetted area by either tilting the plate or increasing flux expansion at the plate (i.e., tilting the field)**
- **Under the 1^0 limit, both yield the *same* max wetted area**
- **ITER engineering basis limit is 1^0, ITER plate is at ~ 2^0**
- **This limits *all* flux-expanders (SD, XD, SXD, Snowflake …)**
  - **The new key SXD idea is increasing R_{div}**
- **Whatever the minimum angle allowed, the larger R_{div} of SXD**
  => SXD does that much better than other flux expanders
- **One can use XD or snowflake to design an SXD**

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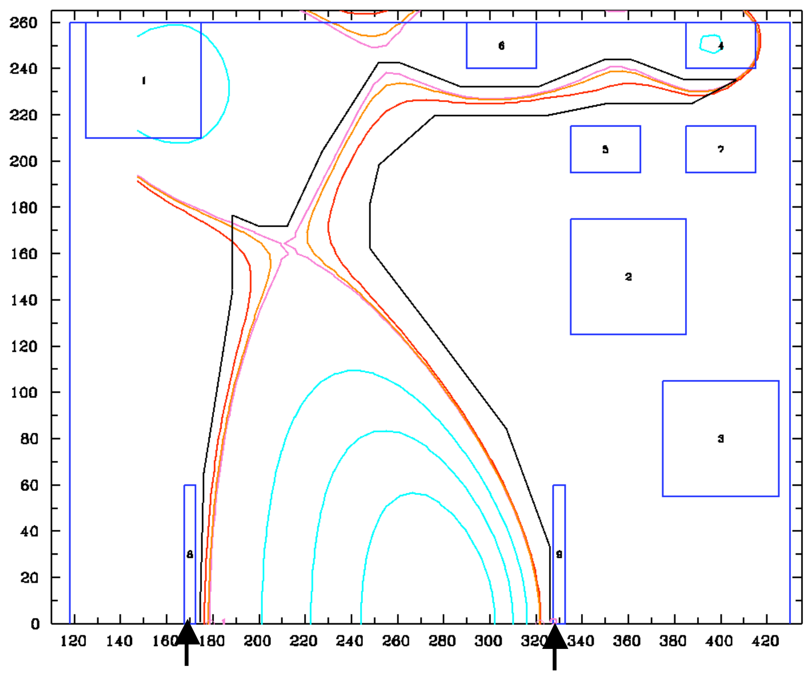
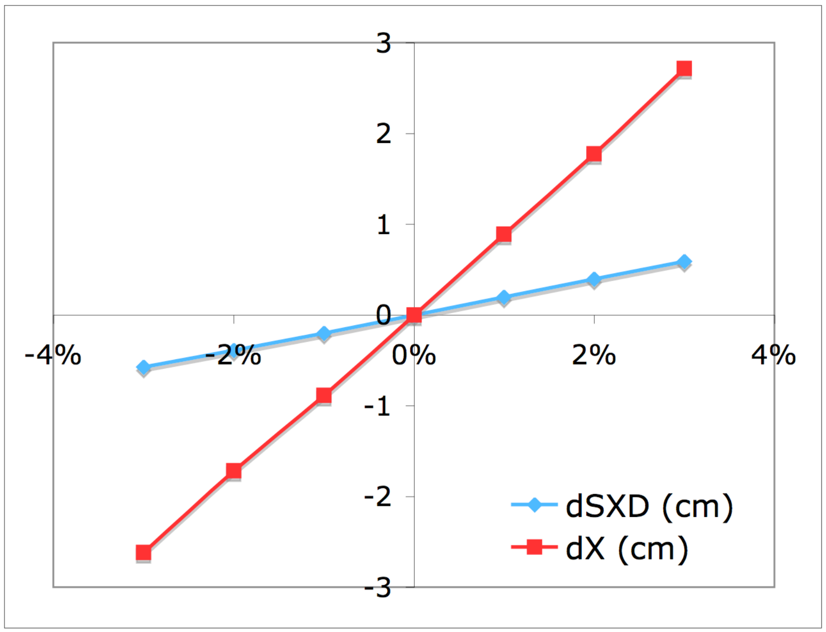
SXD is *very insensitive* to plasma changes

- 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_{plas}, R_0, a etc. by ±3% each and record main X and SXD shifts



FDF 7L0 with "wall coils"



Main X & SXD Shift (cm) vs dI_{plas} ±3%

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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
  - FDF walls must tolerate ~ 60 dpa (but at heat flux less than divertor)
  - Promising main chamber wall materials must be tested at ~ 60 dpa
  - ITER divertor technology deteriorates strongly at ~ 1 dpa (Cu-C)
- **Only *hypothetical divertor materials* (W-composites) might tolerate ~ 60 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)
  - Cannot credibly field a high duty cycle FDF without a divertor with a high chance of survival under ***simultaneous copious fusion neutron and SOL heat fluxes***.
- **SXD: substantial shielding of divertor plates for FDF and future CTF, DEMO**
  - With SXD, ITER divertor technology may well suffice for FDF high duty cycle DT
- **This alone may make SXD essential for all next generation fusion devices**

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SXD: Can it better survive disruptions?

- **Next generation devices: high-β_N operation is desirable**
  - Must anticipate significant number of disruptions on the road to this goal
- **SXD can probably improve survivability to disruptions or ELMs:**
  - Heat flux is spread over a larger area further from plasma
  - Ions travel a much longer distance, so heat pulse could also be spread out significantly in time (material damage ~ $1/\text{time}^{1/2}$)
  - The divertor plate is not in the way of halo currents from a VDE
    - Wall can be made to be a more mechanically robust structure than a divertor plate, since it does not have to be designed to operate also near the engineering limit on high heat flux

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SXD Advantage Summary

- **SXD can lower peak heat flux significantly**
  - **With 1^0 tilt, wSOL = 5 mm, reduces need for impurity radiation**
- **Long Bline lowers T < 10 eV => more radiation possible**
- **SXD simultaneously shields from neutron + heat damage**
  - **Only SXD plate does not face the plasma neutrons directly**
- **SXD design space is large, insensitive to plasma changes**
  - **SXD isolation from plasma is generally good (ergodize, sweep …?)**

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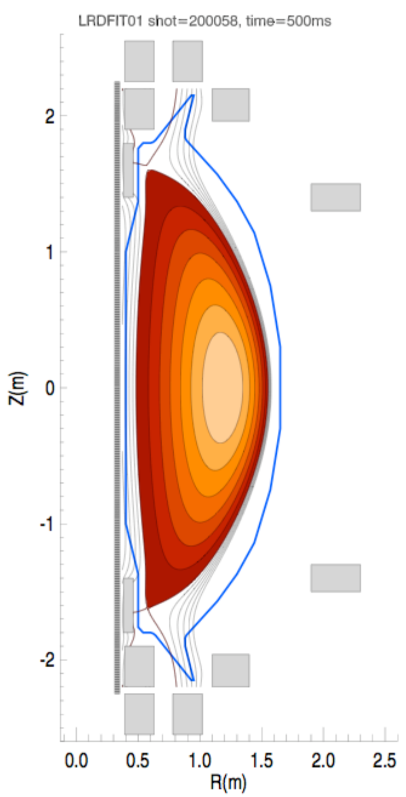
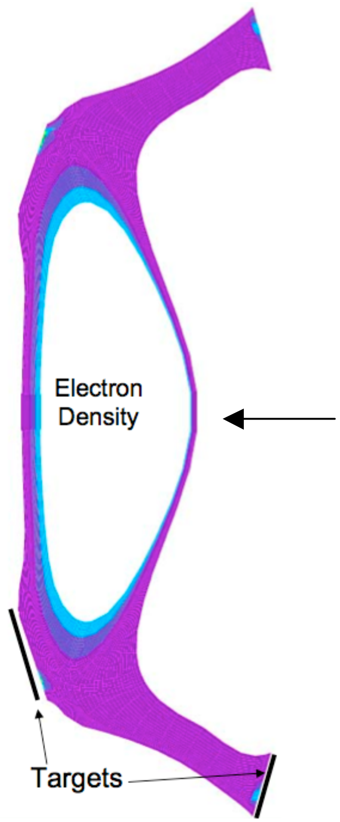
Example: Super XD saves NHTX from heat flux menace

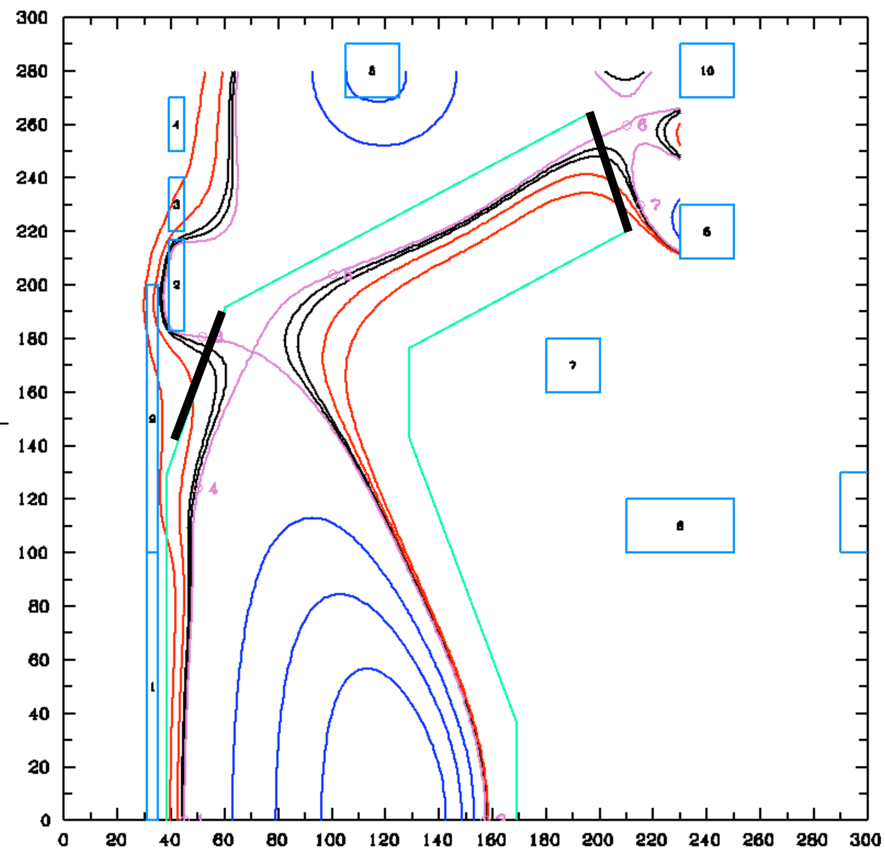
- With SXD & 30 MW, peak heat flux can be kept under 10 MW/m^2
- Not possible with standard divertor (peak stays at 30-40 MW/m^2)
- SOLPS 2-D calculations confirm what we expected from our 1-D code



NHTX Standard Divertor



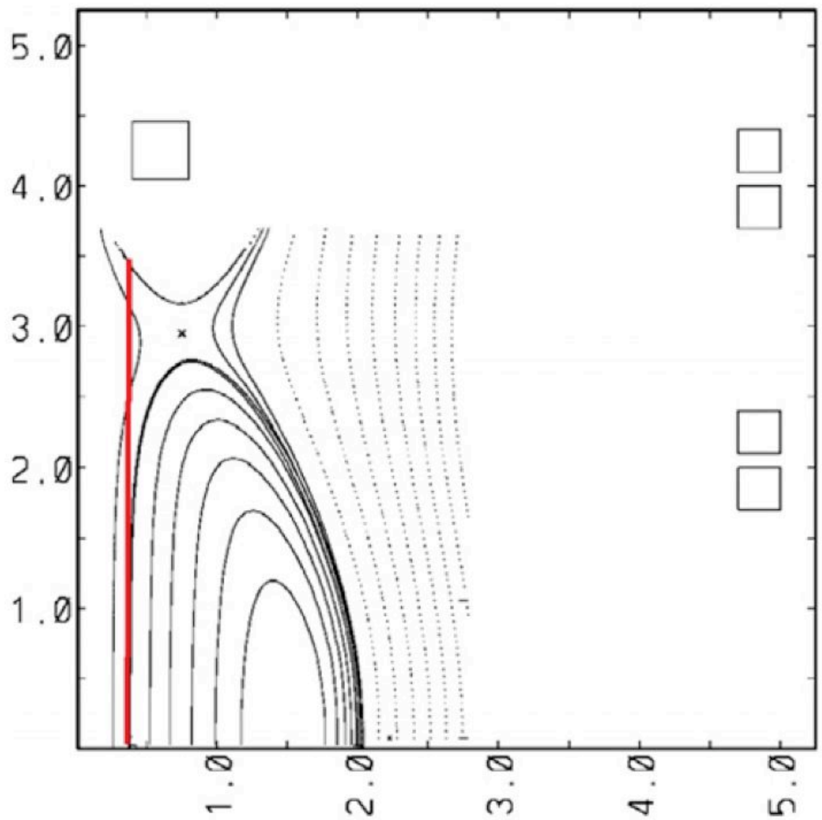
SOLPS SXD Calculation

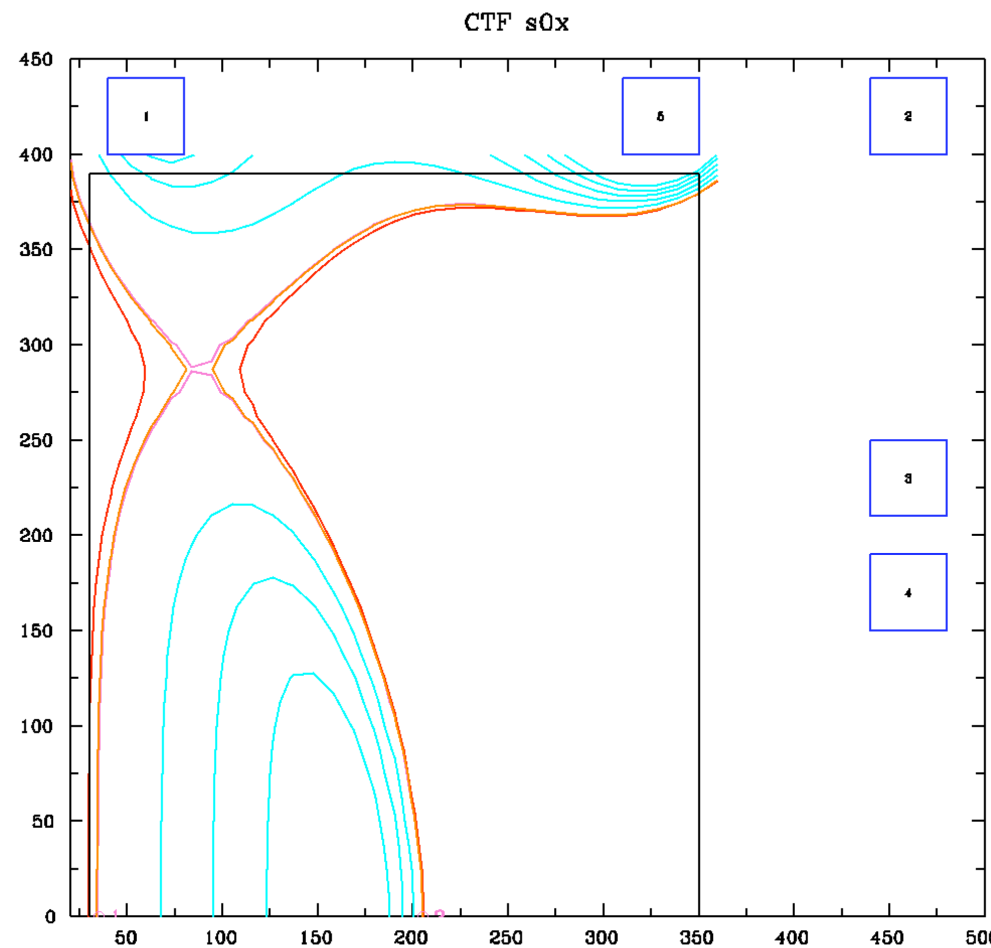


NHTX Super-X Divertor (Corsica Equilibrium)

Very First SXD for CTF

- Only had to move one coil. No extra coils were needed.
- **SDX MA-m actually lower than for SD!**





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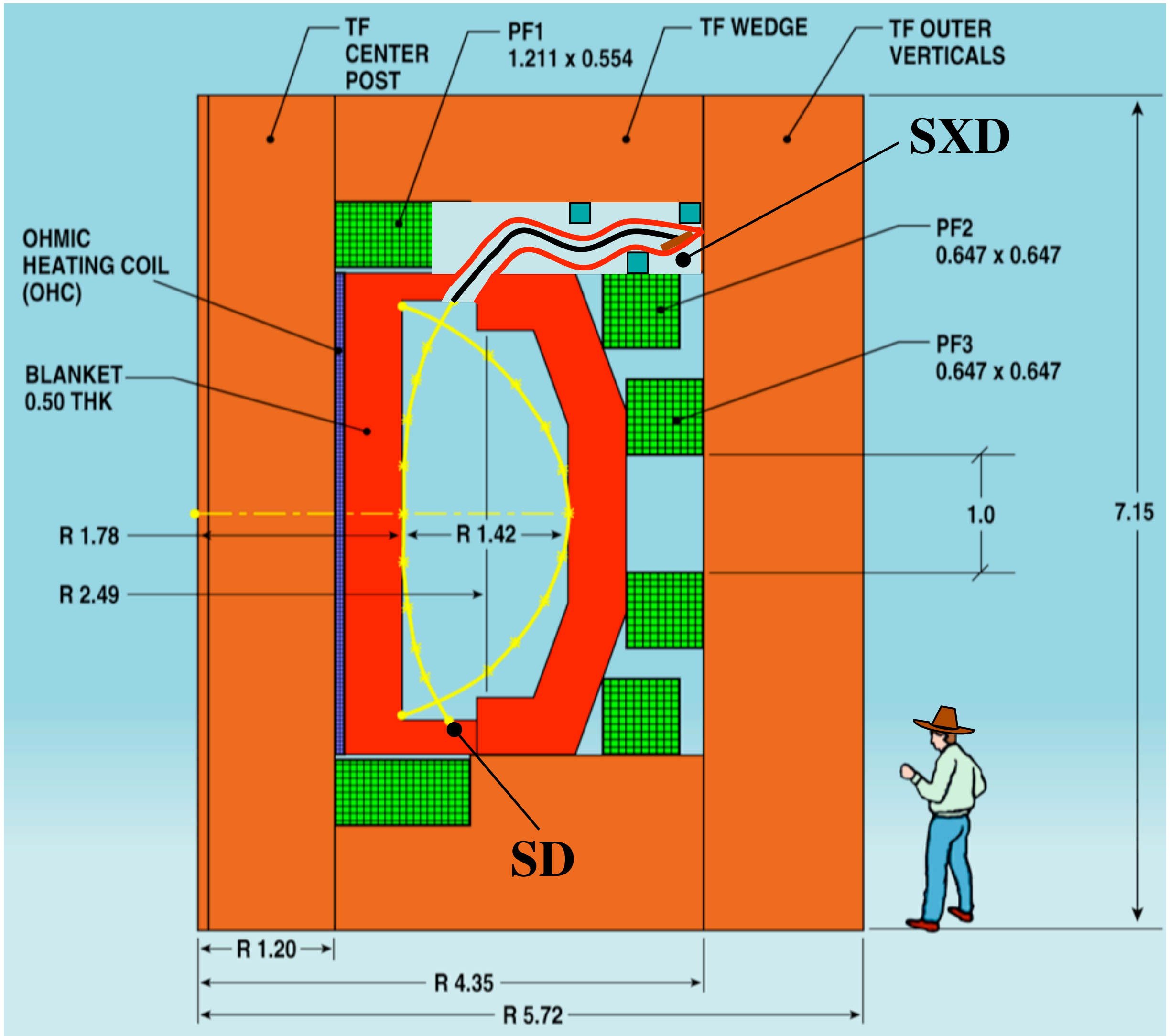
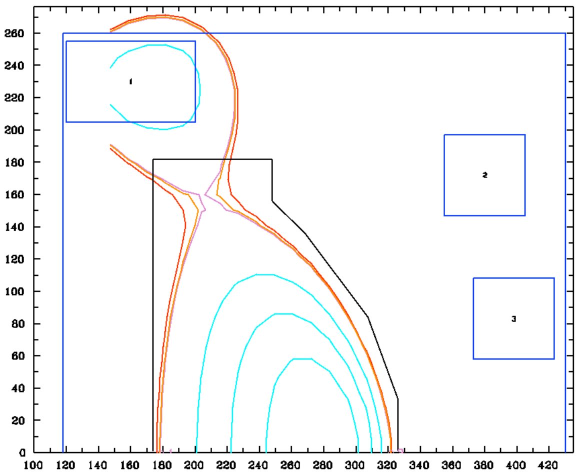
FDF SD case used in these SXD Designs

Best place to fit SXD is in the TF corner - there is enough room





FDF-SD: CORSICA

used for all equilibria

(We thank Pearlstein,

Bulmer, LoDestro

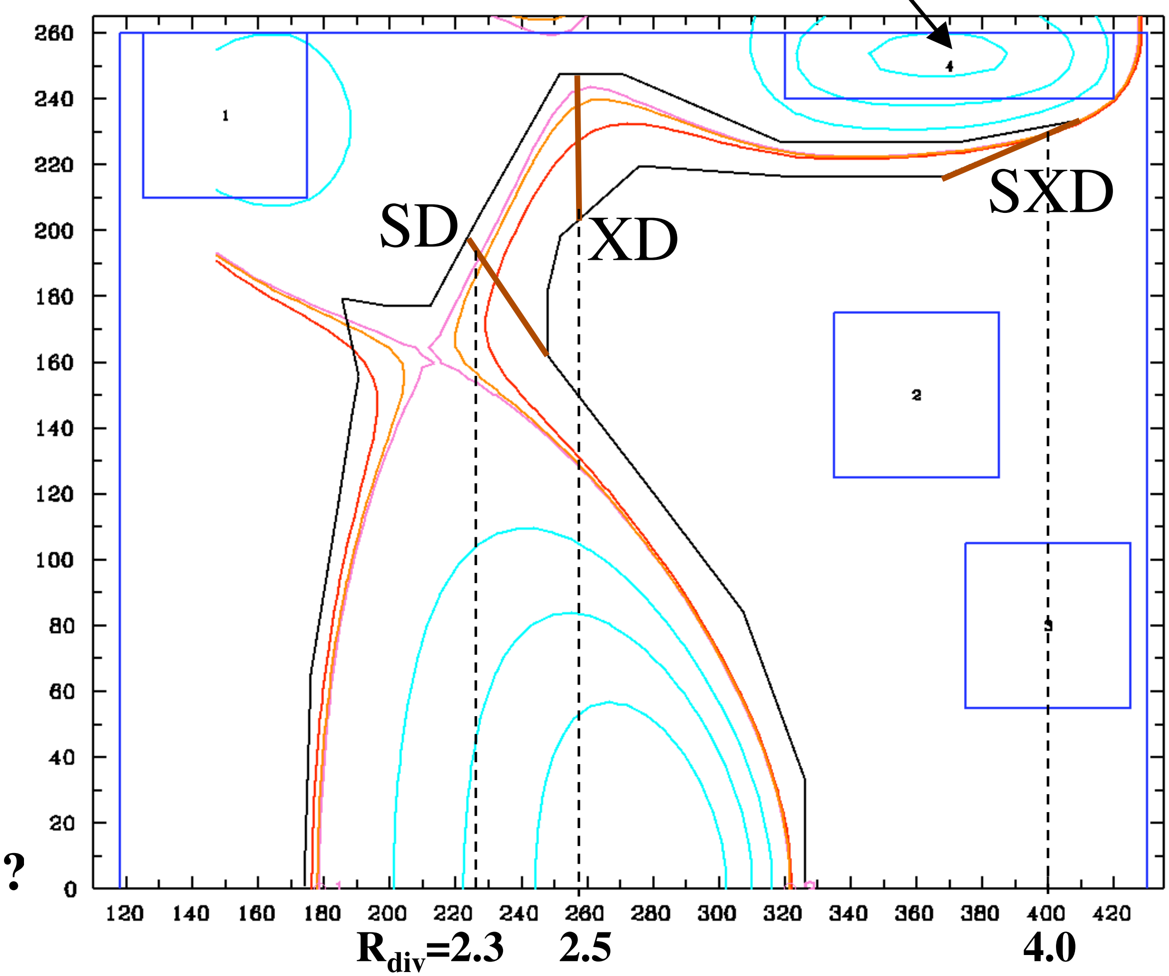
[LLNL] for kind help)

First try SXD for FDF - Only 1 SXD coil

- **With just one extra PF coil (well-shieldable, in TF corner)**
- **Very first solution looked quite good, was easy to get**

- **R_div = 4.01 m**
- **1^0 Wet area = 5.6 m^2**
- **B Length = 61.8 m**
- **B Length gain = 4.0**
- **MA-m ratio = 1.62**
- **For more line length:**

  split SXD coil into two?



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Very first case (1 SXD coil) is already close

Div Plate	B Angle Degrees	B Length [m]	R_{div} [m]	Max Area m^2 (at 1^0)	T eV at Peak	SOLPS MW/m^2
SD	1.28	27.4	2.34	3.27	**150**	**58**
XD	0.93	39.7	2.51	3.51	**150**	**28**
SXD	**1.2**	61.6	4.01	5.61	**10**	**18**

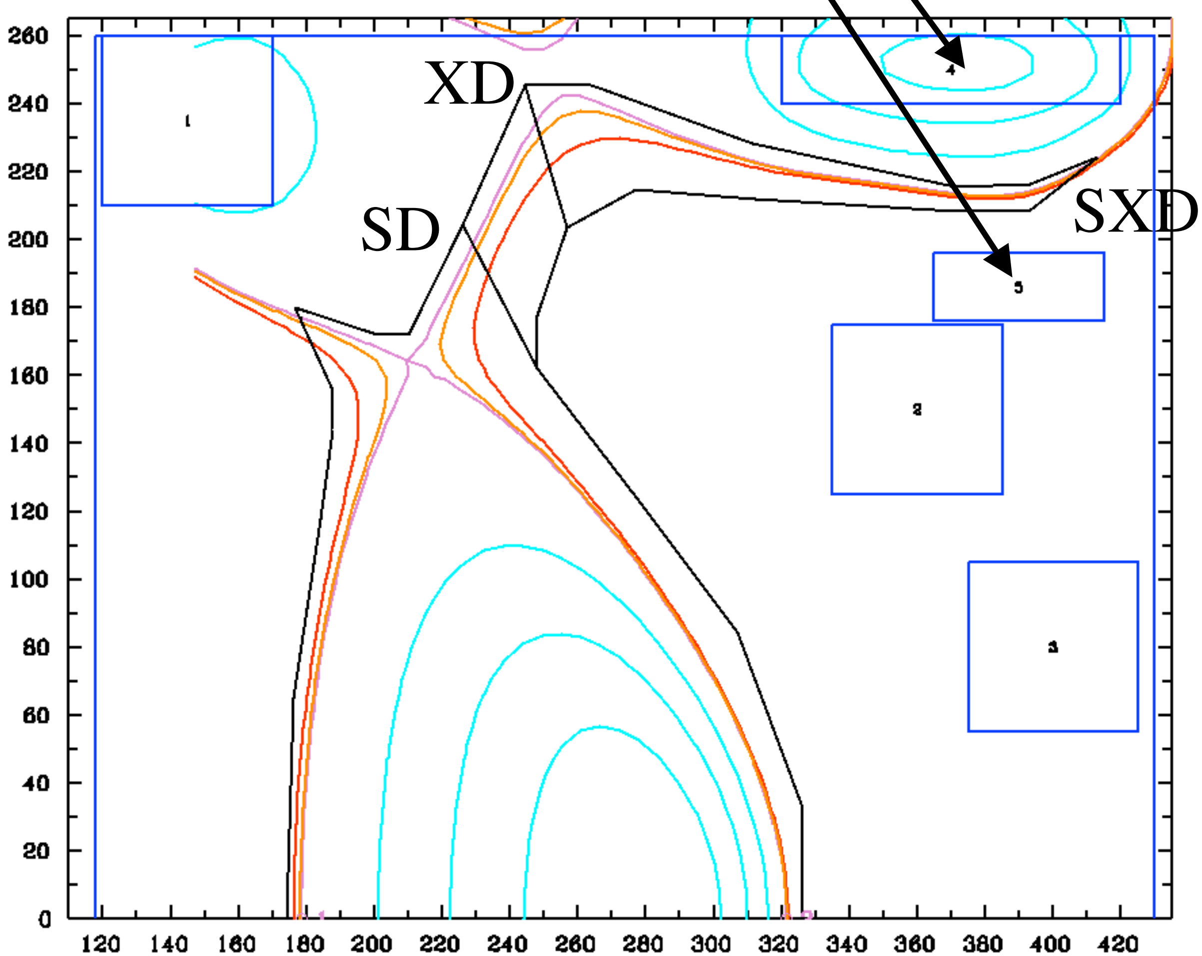
For 5 mm wSOL at z=0

- SXD MW/m^2 low due to large R_{div} , T low due to longer line length
- SXD peak is the lowest, need less radiation to reach 8 MW/m^2
- Grid issues near plate make it hard to tilt more in SOLPS code
  - just the first case we ran, can further optimize
- Try to get more SXD flux expansion by splitting the SXD coil
- Also try to use the split SXD coil to get even longer line length

Split one SXD coil into 2 coils

- **SXD with two extra PF coils (= one SXD coil split into 2)**
- **Another coil -> another extra X point -> more flux expansion & line length**

- **R_div = 4.04 m**
- **1^0 Wet area = 5.73 m^2**
- **B Length = 66.6 m**
- **B Length gain = 4.24**
- **MA-m ratio = 1.89**
- **SOLPS run not yet done on this case**



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2 SXD coils FDF case: longer line

Div Plate	B Angle Degrees	B Length [m]	R_{div} [m]	Max Area m^2 (at 1^0)	T eV at Peak	SOLPS MW/m^2
SD	1.14	28.0	2.33	3.30	150	58
XD	1.07	42.0	2.51	3.56	150	28
SXD	1.00	66.6	4.04	5.73	< 8?	<18?

For 5 mm wSOL at z=0

- 2 SXD coils together carry ~ same net current as 1 SXD coil
- Each extra coil => another nearby X point => longer B Length
- Larger flux expansion at SXD => easier grids for SOLPS
- Coils appear to be still in neutron-shieldable corner locations
- So try even further coil splitting

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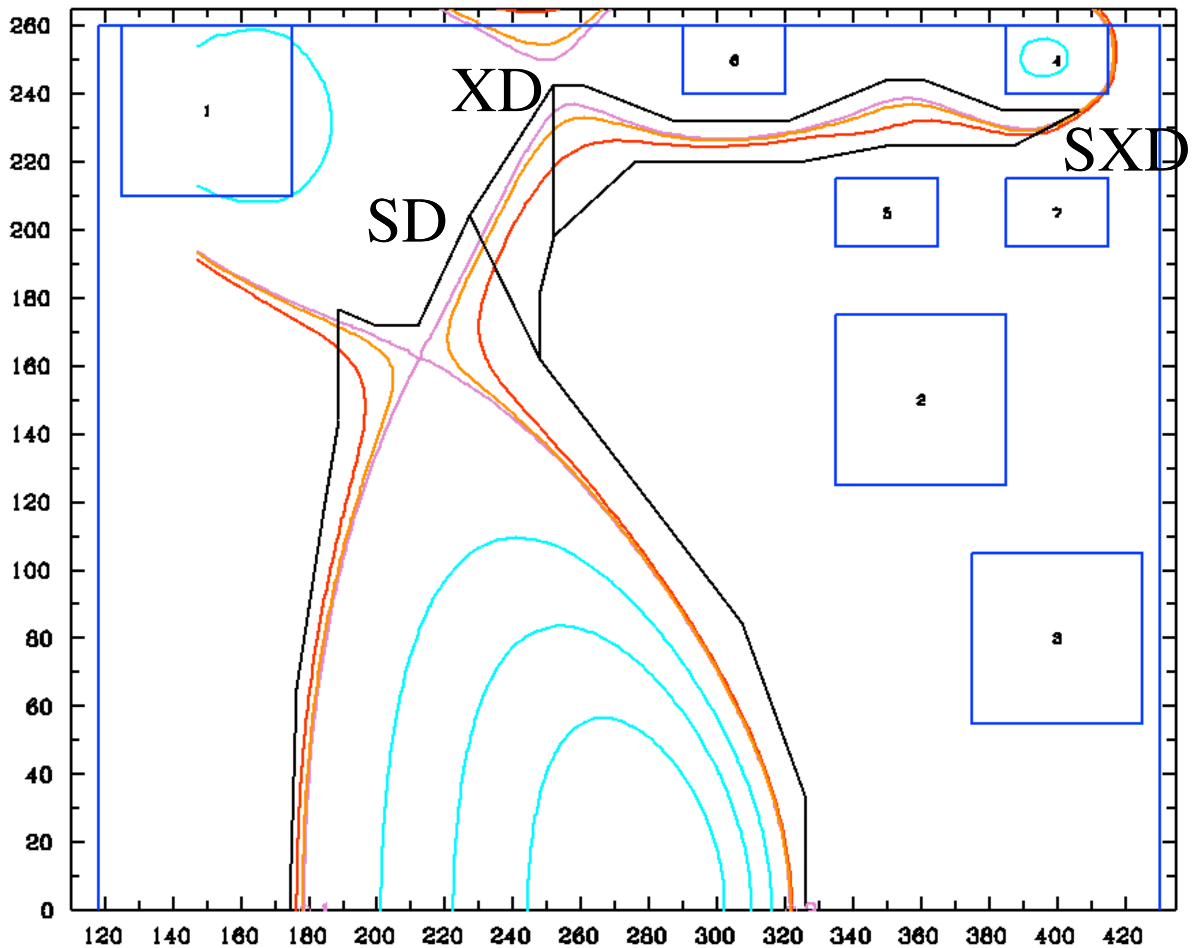
Split one SXD coil into 4 small coils

- With four extra PF coils (= one coil split into 4, carry ~ same total current)
- The pattern is now clear: extra coils -> extra X -> increase B Length
- R_div = 3.95 m
- 1^0 Wet area = 5.57 m^2
- B Length = 73.6 m
- BLen gain = 4.69
- MA-m ratio = 1.72
- Can get more R_{div}, BLength by further optimizing coils
- SOLPS run in progress



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4 SXD coils: even longer line, more flux exp

Div Plate	B Angle Degrees	B Length [m]	R_{div} [m]	Max Area m^2 (at 1^0)	T eV at Peak	SOLPS MW/m^2
SD	1.18	27.8	2.34	3.30	150	58
XD	0.92	40.3	2.51	3.54	150	28
SXD	1.0	73.6	3.95	5.57	< 5?	<18?

For 5 mm wSOL at z=0

- Net MA-m actually went a bit lower than 2 SXD coils case
- B Line further increased to ~ 74 m, R_{div} was kept about same
- Flux expansion at SXD also up to 4.64 => easier on SOLPS
- SOLPS run in progress: expected results in red
- These 3 cases show the great flexibility of SXD design space
  - Need to know other constraints & goals to optimize further

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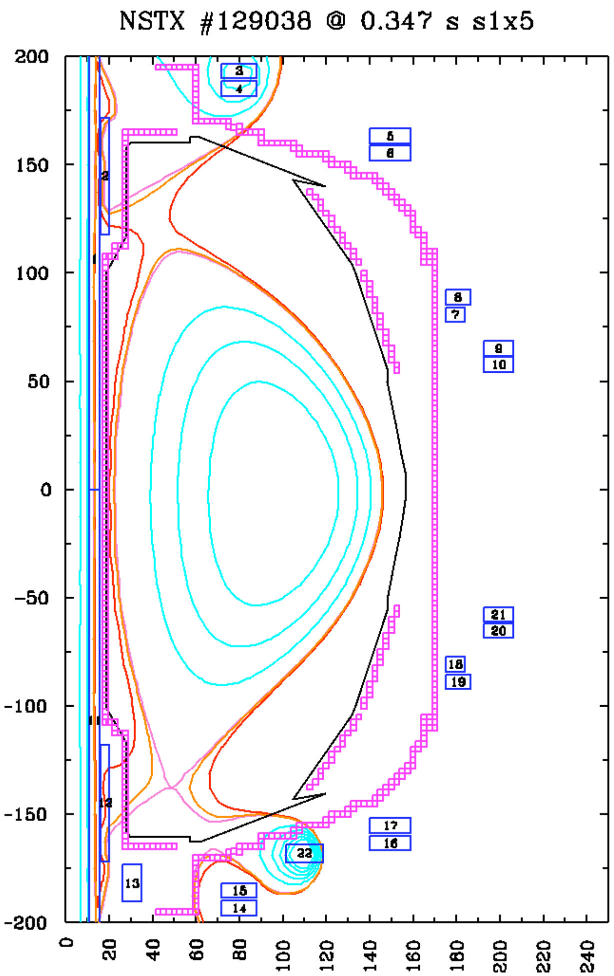
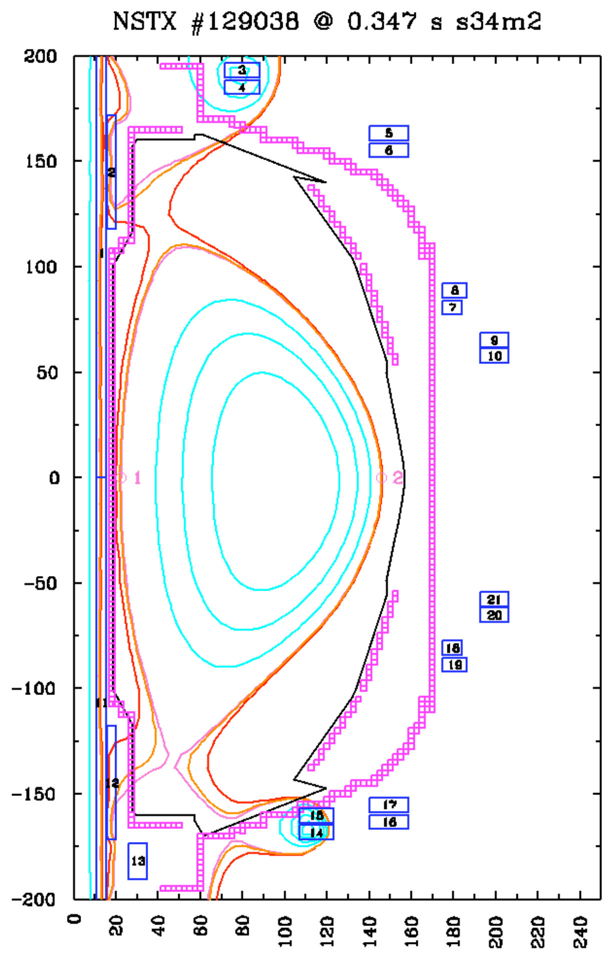
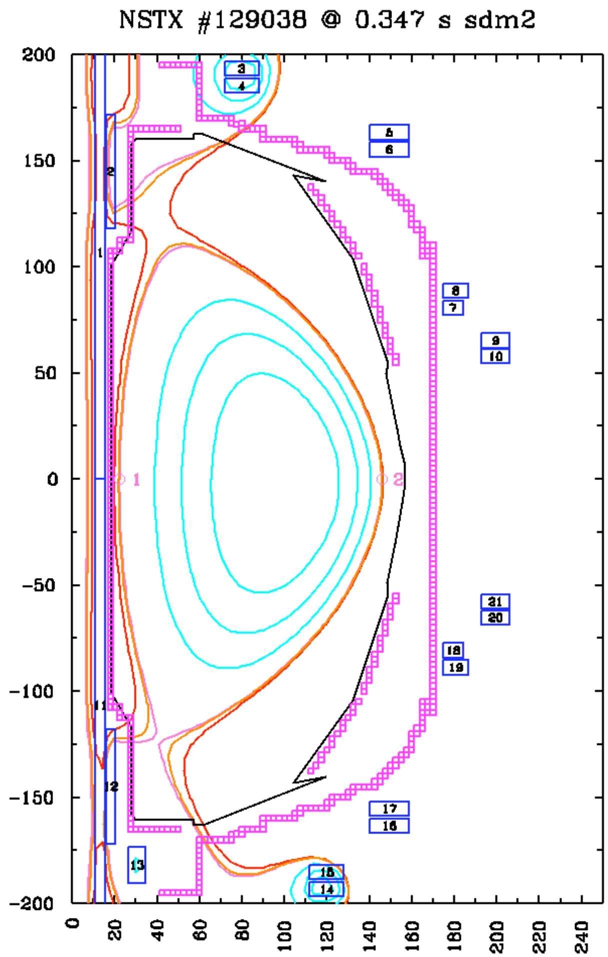
Very Preliminary SXDs for NSTX

- **Shown just to give an idea of what NSTX SXDs may look like**
- **No NSTX constraints yet on NSTX-SXD design - to be discussed here**







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NSTX SXD Test Issues

SXD should be tested on NSTX - soon, but …

SXD Test on NSTX should not be "half-hearted"

- **Should not test an XD or "Partial SXD" - with the risk of passing premature judgments on SXD**

For further SXD Design, together we need to:

- **Better specify specific physics goals for such a test**
- **Better specify NSTX Constraints & Flexibility**
- **Design a few SXD configurations that fit these constrains**
- **Calc SOLPS results to see if substantial gains are predicted**
- **Calc pumping, baffling, impurity isolation, etc …**