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Next Generation Fusion Experiments.

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Next Generation Fusion

High Power Density Experiment

HPDX

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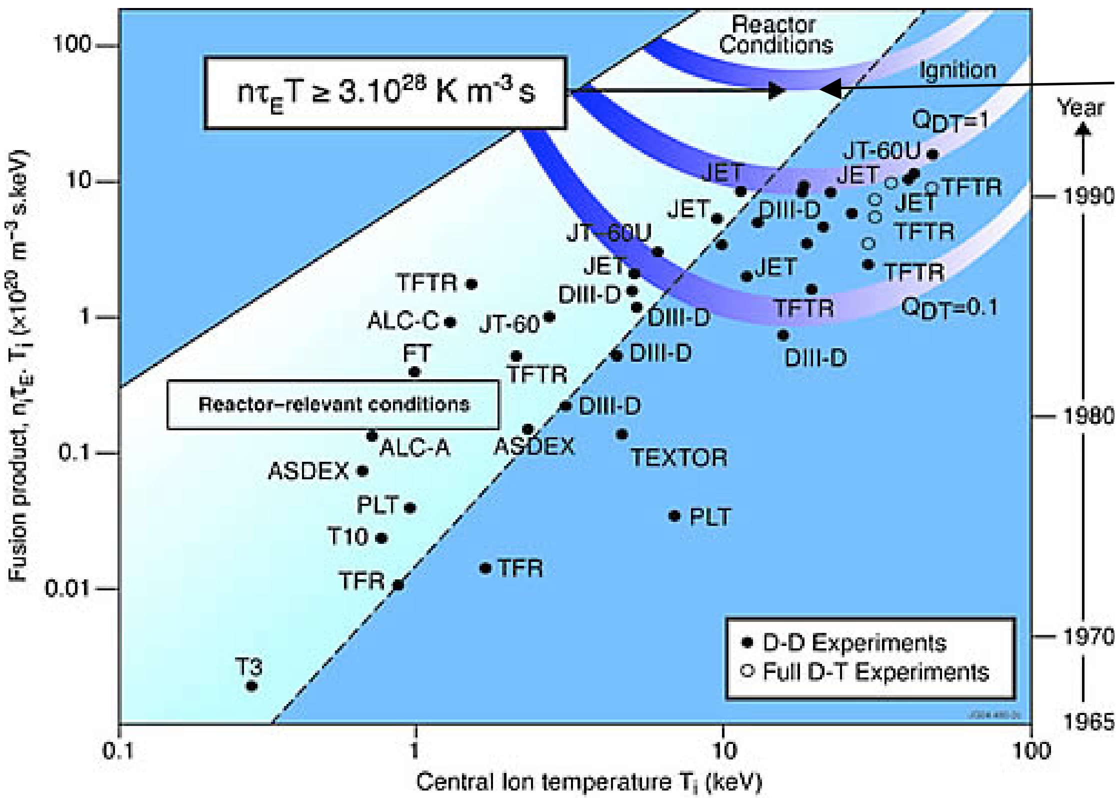
ICTP, 2008

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

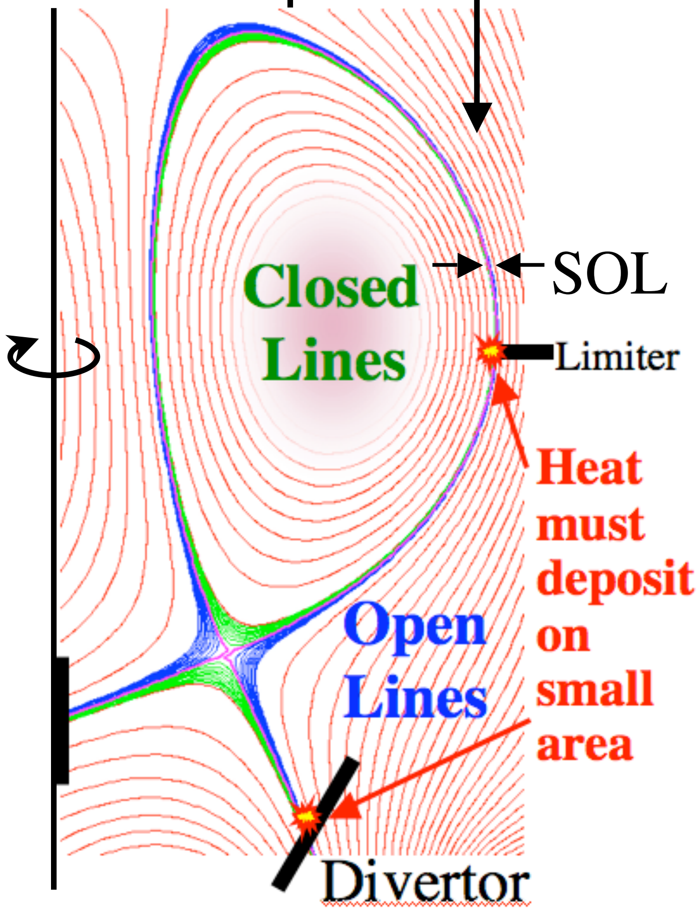
- Momentary Q ~10
- Q > 5 for 8 minutes
- Burning plasma

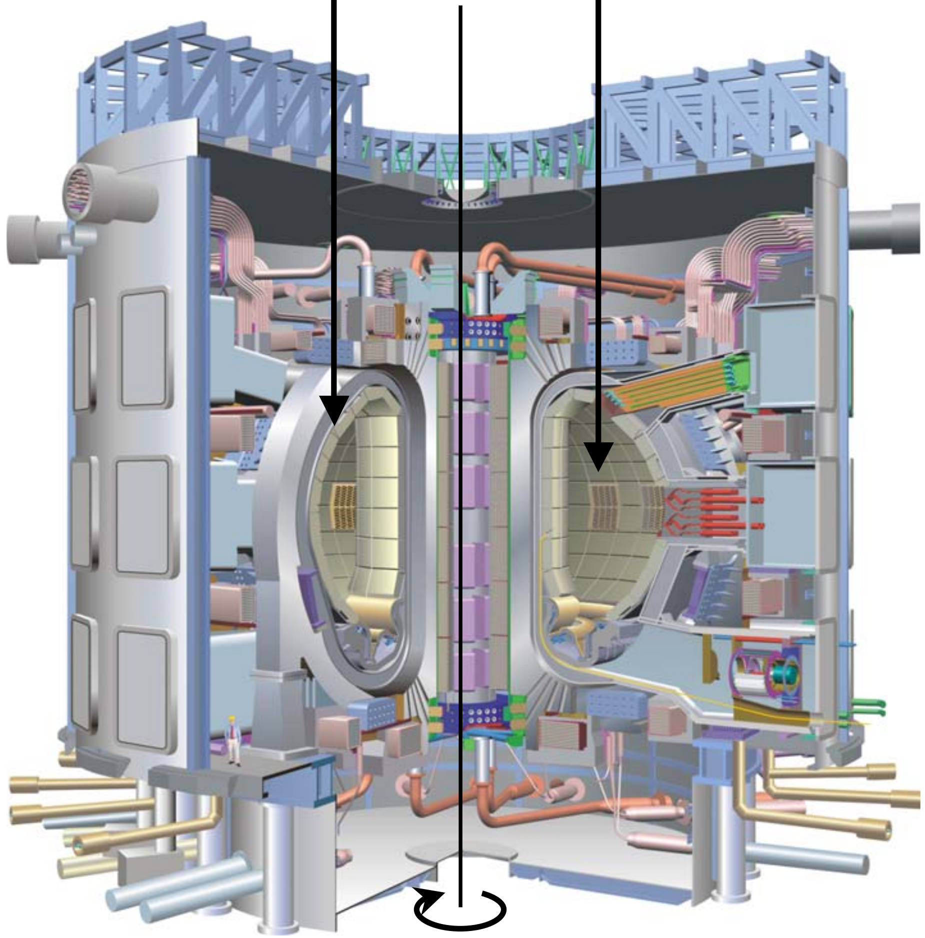
But then why is fusion still many decades away?

Fusion Reactor Schematic

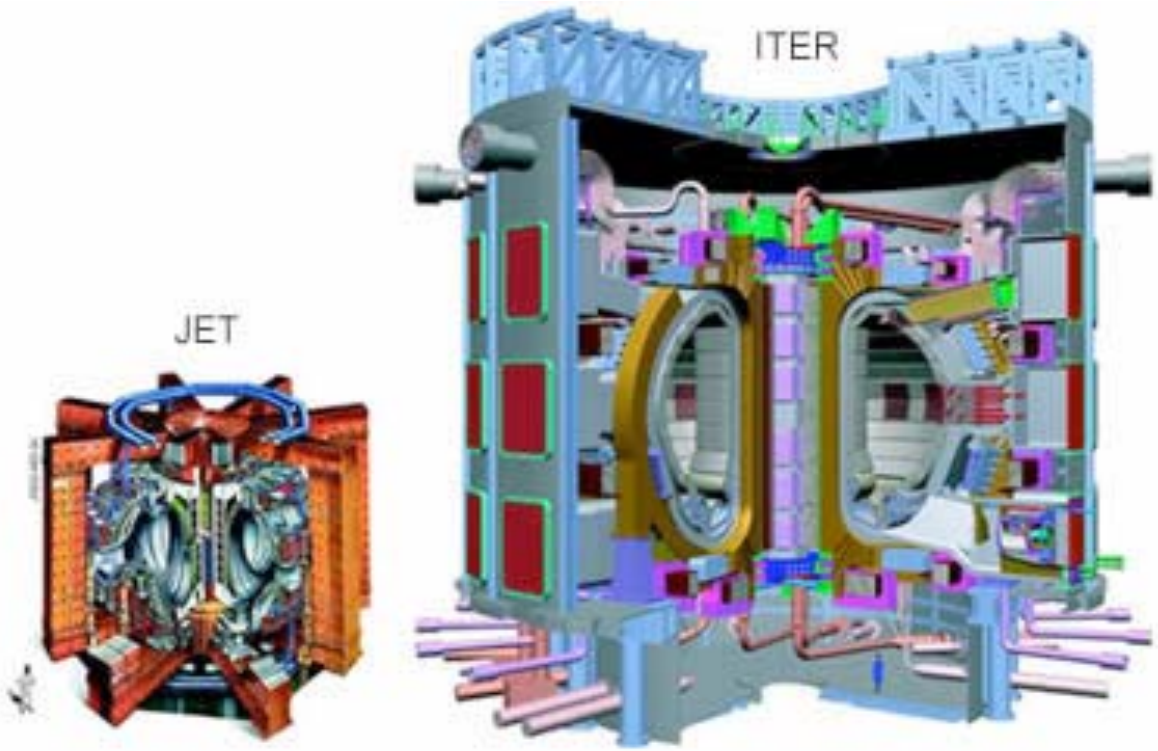
Core: High β -> high power density, hot confined plasma

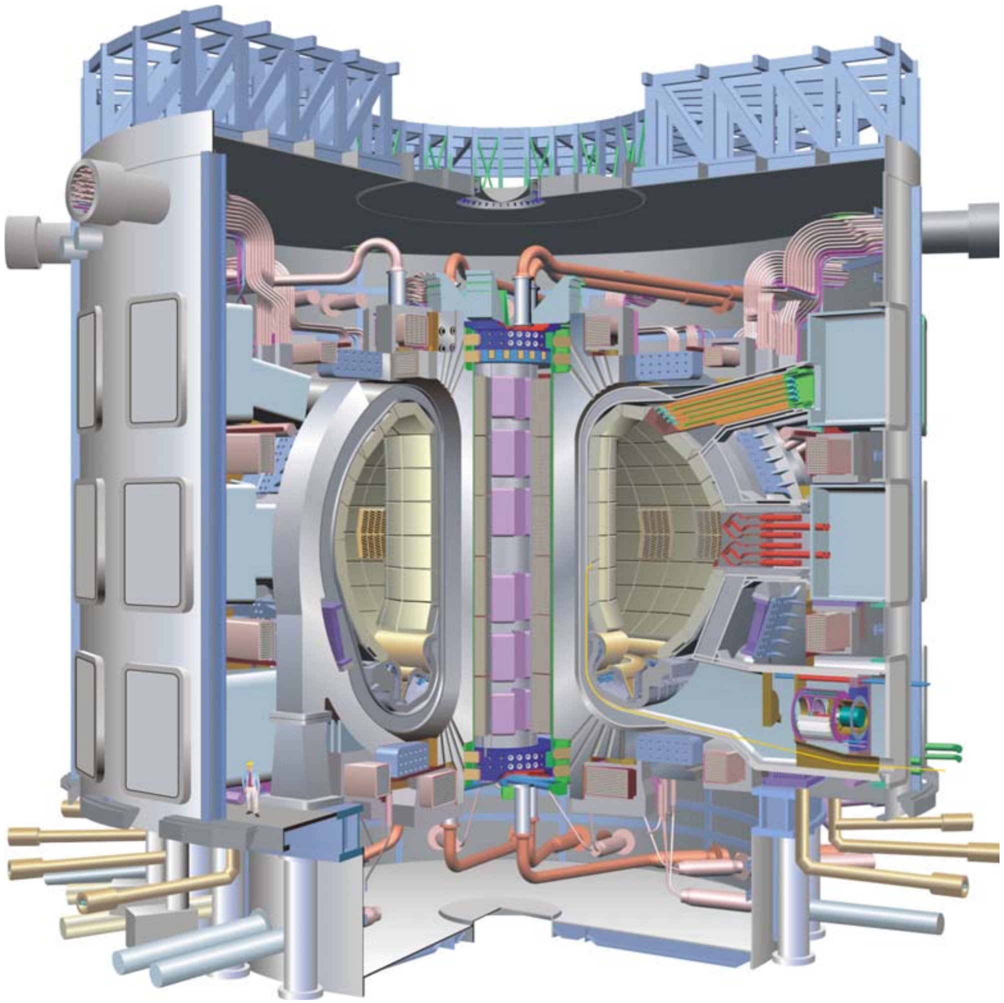
External world: open B lines, wall etc.

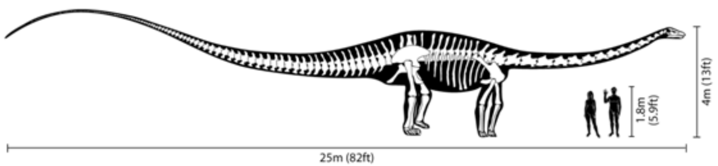




JET and ITER



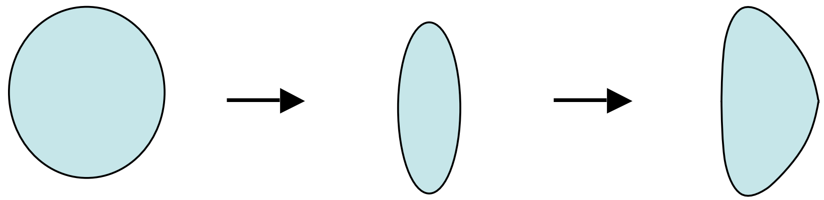




Diplodocus Drawn to scale

High β

- Modify core geometry
  - Elongation κ, triangularity δ, … (shape parameters)



- Increase plasma current
  - β goes up for a given β_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 Tranport Barrier (ITB)
- Confinement time
  - Semi-empirical scaling laws have been established
  - H_{89p} ~ ratio of observed confinement time to the standard H-mode τ

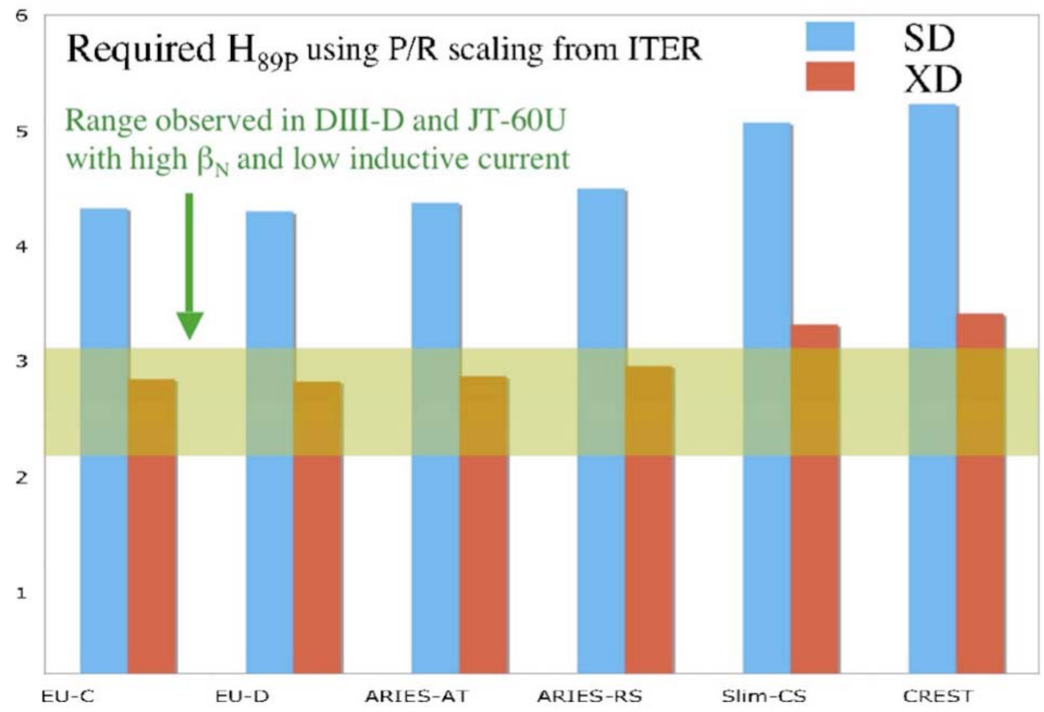


FIG. 2. (Color online) Confinement requirements for reactors as compared to the confinement range achieved in the present experiments. The net heating power is estimated to be $P_{heat}(1-f_{rad\text{-}core})$.

Should not expect future device τ to be much above the observed band

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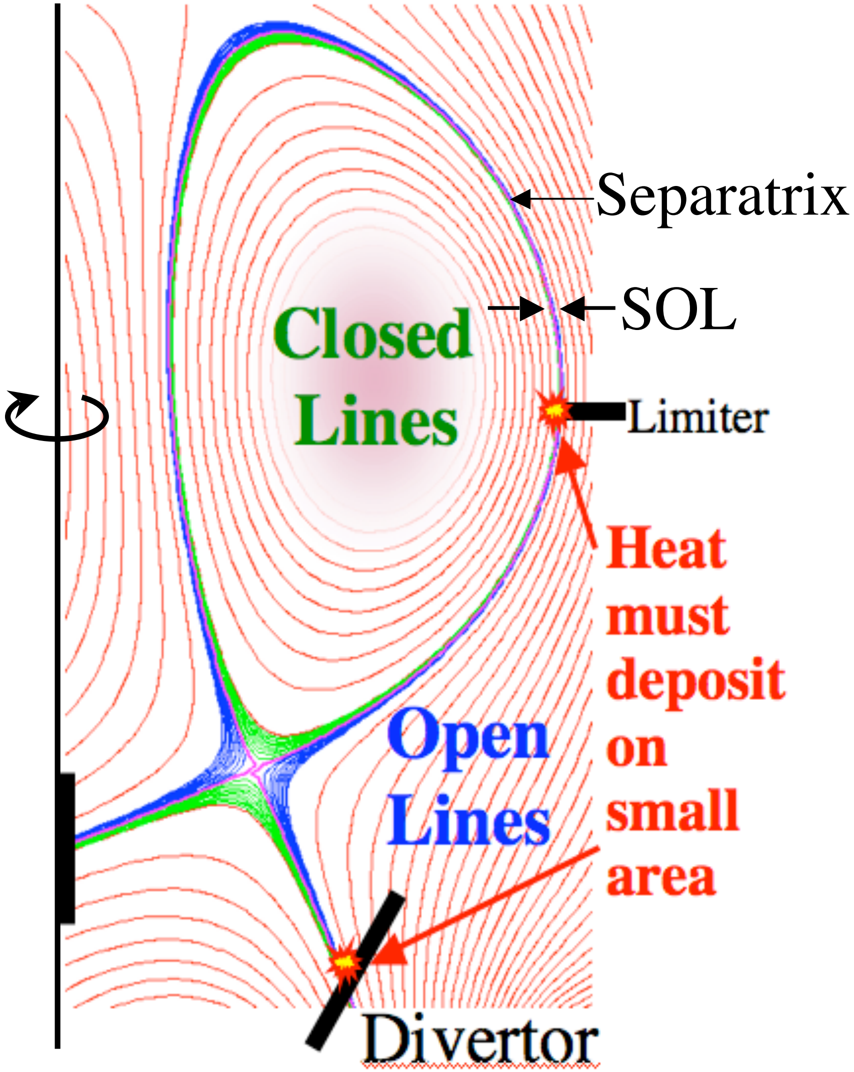
Magnetic bottles: A Fundamental Fusion Dilemma

- 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 λ_q is small => divertor focuses heat flux exhaust on very small "plasma wetted area" A_w proportional to R_{div} and λ_q
- Better core confinement => 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

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Fundamental challenges for next generation experiments-HPDX

- How to get high confinement at high β - 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

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

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

On heat loading, novel divertors, and fusion reactors, M. Kotschenreuther, P. Valanju, and S.M. Mahajan, Phys Plasmas 14, 7, pp. 072502-25 (2007)

Core radiation destroys core confinement - Divertors must handle the heat flux

SOL width λ_q is central to heat flux problem

- Divertor heat flux ~ (1 / λ_q), λ_q =SOL width
- Most projections give rather narrow SOL widths, e.g., for FDF (GA):
  - **2004 JET extrapolation: 4 mm empirical**
  - **B2-Eirene extrapolation: 5 mm numerical modeling**
  - **Connor-JET collisional 5 mm semi-empirical (physics based)**
  - **Connor-JET low collisionality 5 mm**
  - **1999 λ_q regression 14-23 mm This is clearly an outlier**
- ***For the small λ_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 => low edge transport => small SOL width, so good core confinement makes divertor problem worse!**

Estimating pedestal implications for SOL λ_q

- Parameterize transport in one of two ways:

1. **Assume similar diffusion processes (i.e., χ) operate in both near SOL and pedestal**
   - compare the magnitude of χ in both regions
   - From the SOL width, estimate the χ needed to produce that width
   - Estimate χ 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 λ_q for next step experiments

λ_q in mm	χ_{SOL} method	dp/dr_{SOL} method
ITER	3.1 - 5.4	3.2 - 4.3
NHTX	4.1 - 9.4	4.1 - 9.9
ST-CTF	2.7 - 6.2	1.8 - 4.4
FDF	5.2 - 9	3.0 - 4.9
ARIES AT	5.0 - 8.7	3.0 - 5.0

- **Bottom line: λ_q ~ 5 mm, like ITER, for all next step HPD devices**
- Hence P/R is a reasonable measure of divertor challenge
- ***With such λ_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

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Radiative Solutions- Could heat be radiated away?

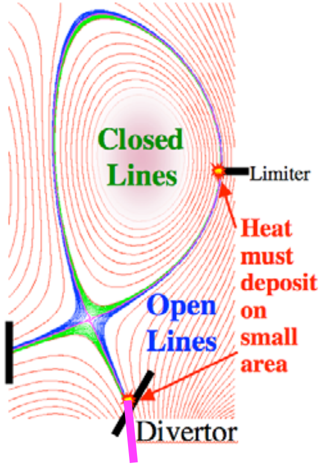
- **Two possible routes**
  - Radiate from the SOL (divertor region)
    - Detailed modeling shows limits to SOL radiation without destroying the main plasma- Maximum ITER SOL radiation fraction ~ 60%. SOL Radiation fractions, however, decrease with increasing parallel heat flux $Q_{||}$, shorter line lengths, lower density
    - Compared to ITER, next step devices have: Substantially higher $Q_{||}$, 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 ----

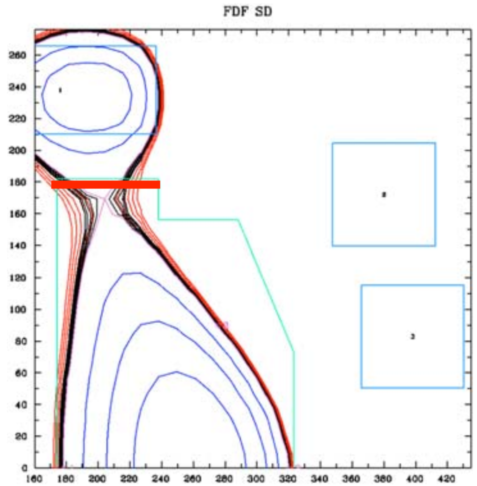
- **Three distinct challenges crying for workable solutions**:
  - **High heat flux on the divertor target plate**
    - **Solution: spread heat out and/or radiate (some) before incidence on plate**
  - **High plasma temperature at the divertor plate**
    - Can easily exceed 100 eV, leading to high sputtering (erosion, dust, plasma impurities, etc.)- high temperature => 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 ~ 1 dpa
    - CTF: must test to dozens of dpa
    - Reactor: must run at ~ 100 dpa
    - **Solution: place divertor plate where it can be shielded from neutrons**

Limiters to Divertors to X-Divertors to Super-XD

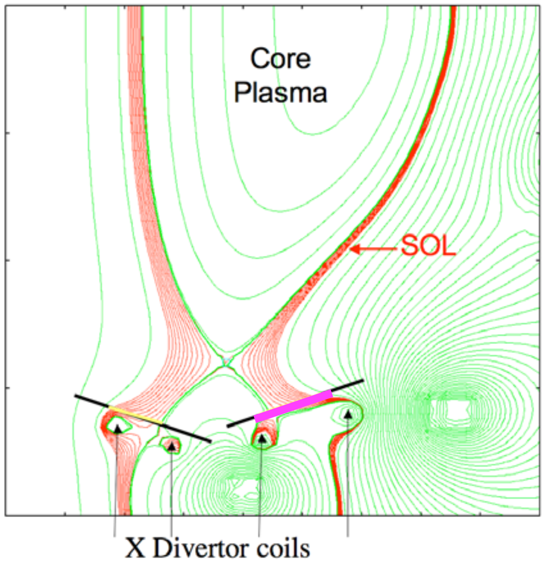
Limiter & Standard Divertor



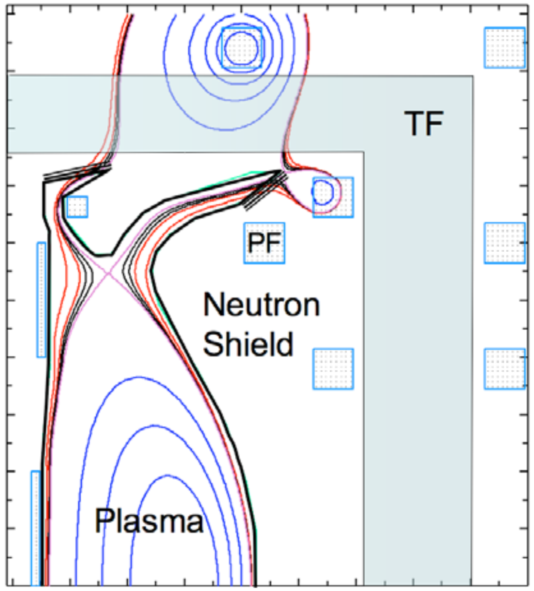
Flux expansion near main X-point



X-Divertor to expand flux



Super X-Divertor at Large R_{div}

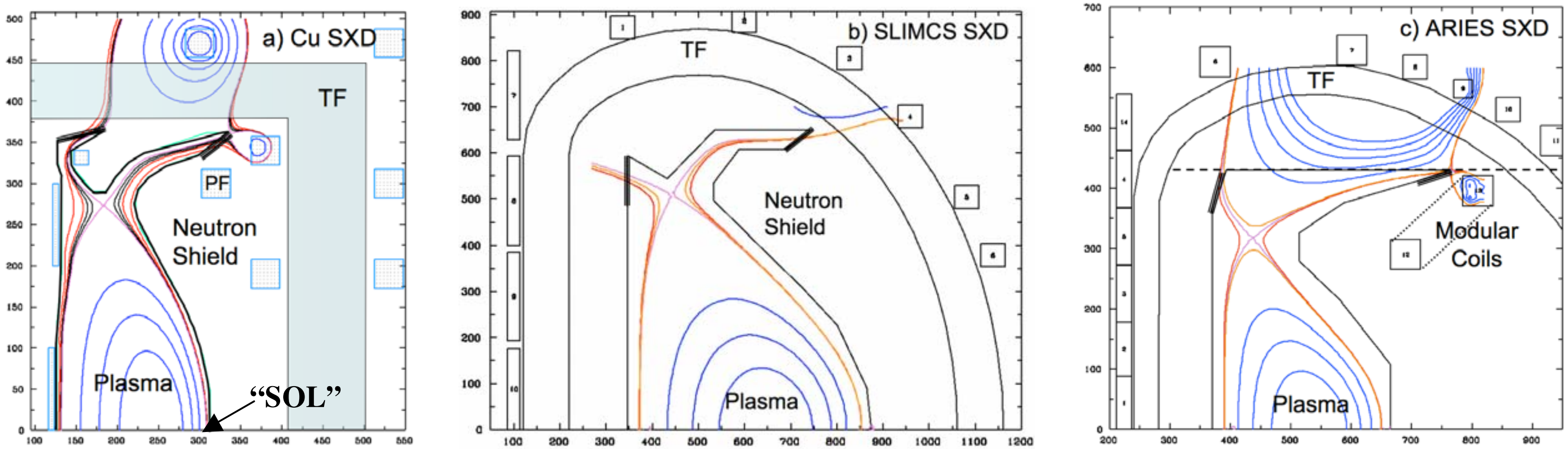


Super X Divertor (SXD)

- **Key idea: θ > 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**



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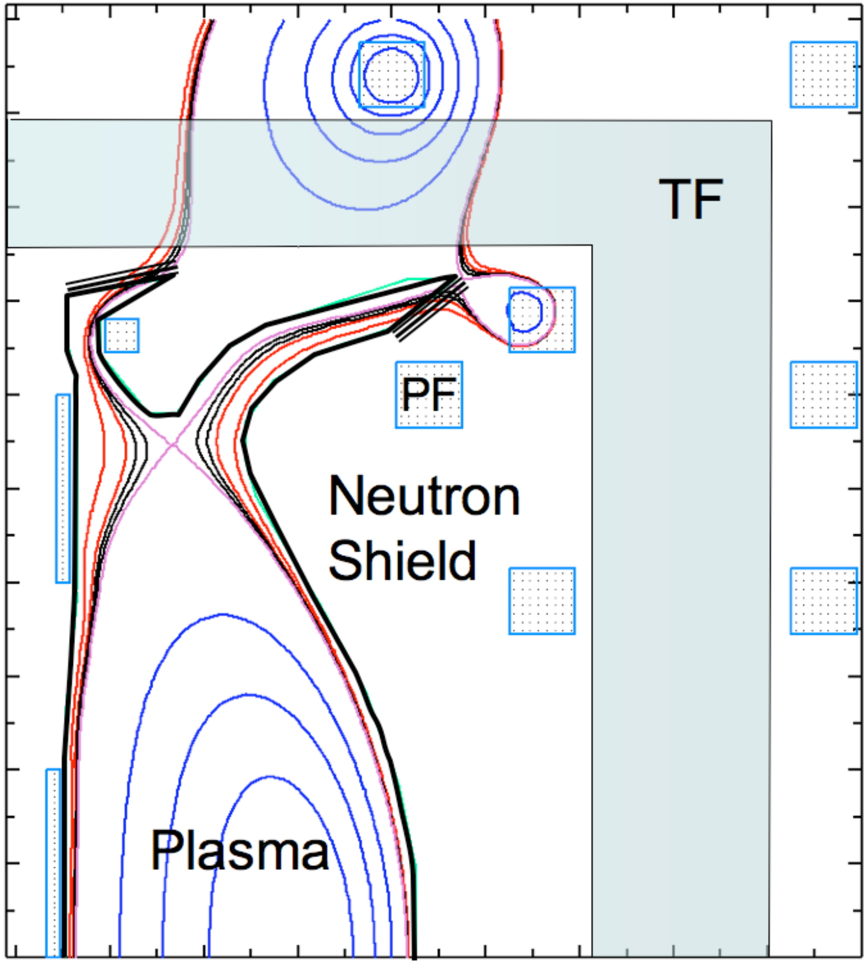
Super XD: Divide (Plasma-SOL) & Conquer

- 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



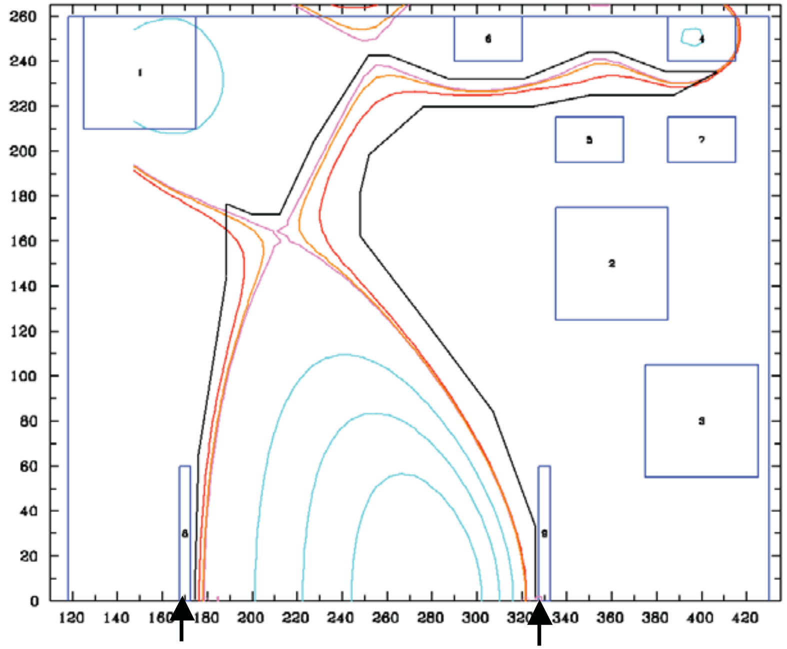
HPDX - CORSICA Equilibrium

SXD: Easy and Robust

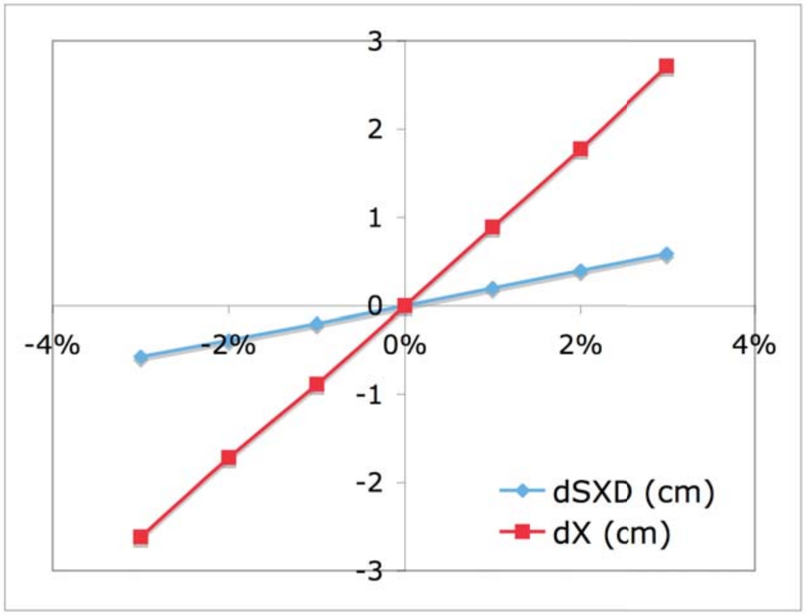
- **Surprisingly, the SXD is rather easy to implement:**
  - **Just need to move the poloidal field (PF) coils around a bit**
  - Coil currents & locations are not very different from standard divertor case.
  - This is so for a variety of machines that we have investigated
- **Increased distance from 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_{plas}, R_0, a etc. by ±3% each and record main X and SXD shifts



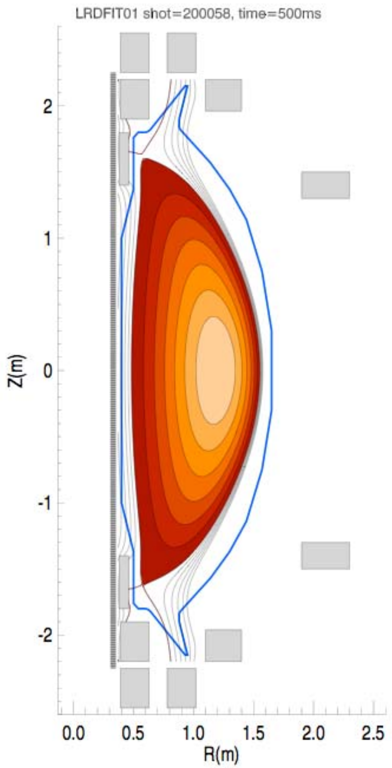
FDF with "wall coils"



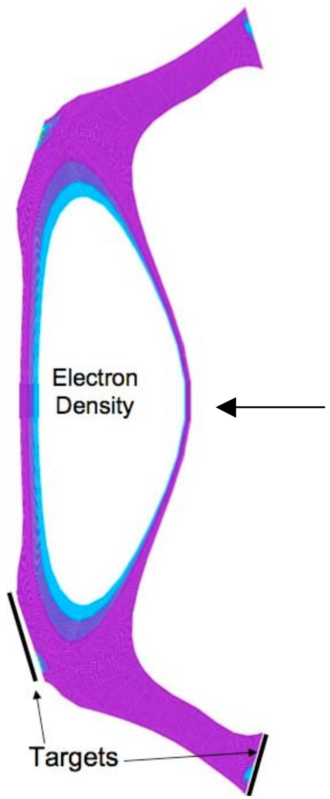
Main X & SXD Shift (cm) vs dI_{plas} ±3%

SXD can save NHTX from heat flux menace

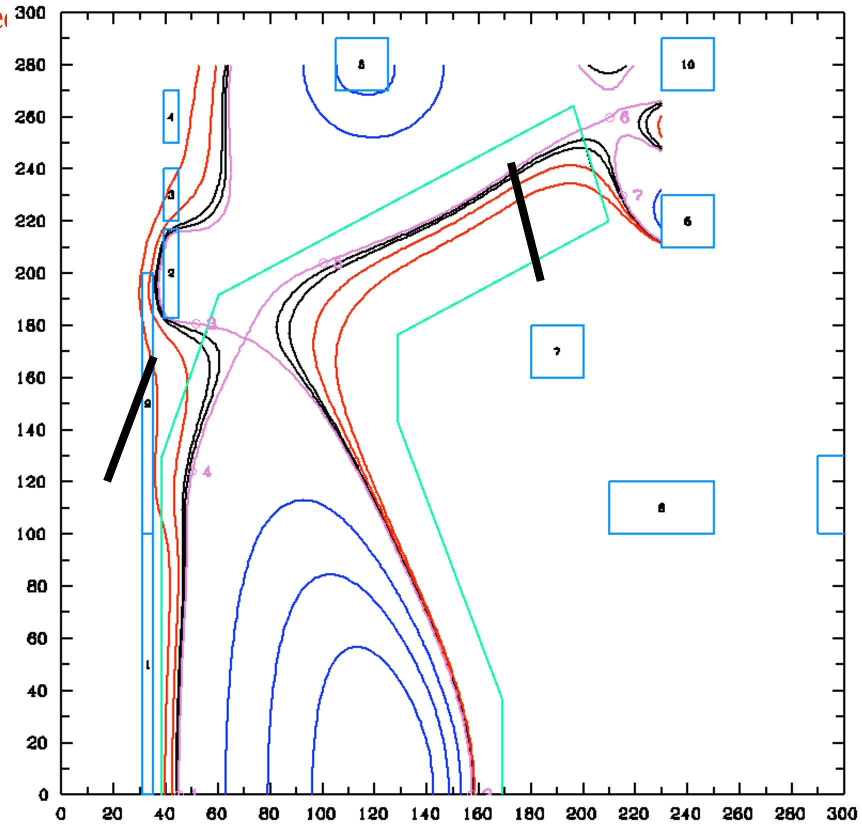
- **With SXD & 30 MW, peak heat flux can be kept under 10 MW/m²**
- **Not possible with standard divertor (peak stays at 30-40 MW/m²)**
- **Plasma temperature (only) at SXD plate stays low (< 10 eV)**
- **SOLPS 2-D calculations confirm what we expe**



NHTX Standard Divertor



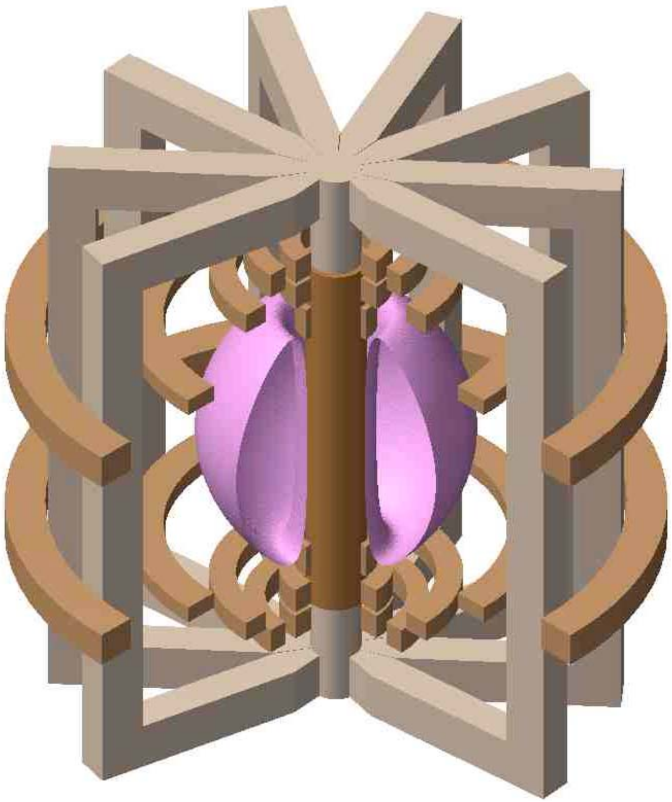
SOLPS SXD Calculation



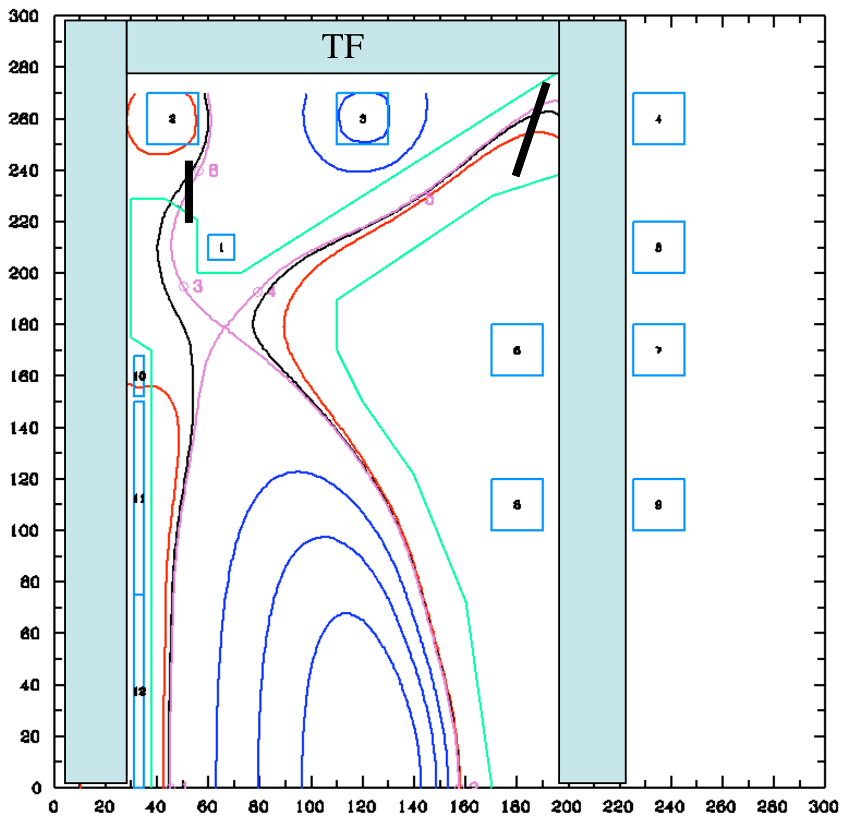
NHTX Super-X Divertor (Corsica Equilibrium)

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



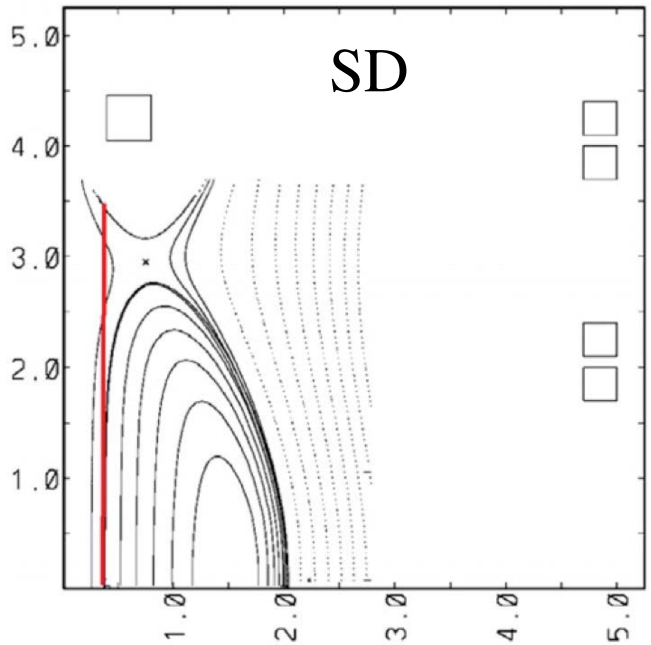
NHTX (PPPL/ORNL)

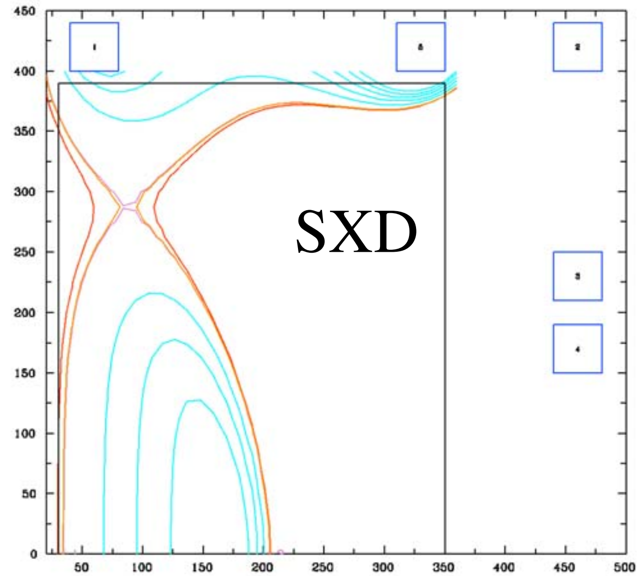


CORSICA Equilibrium for NHTX-SX

SXD: essential & enabling for ST-CTF

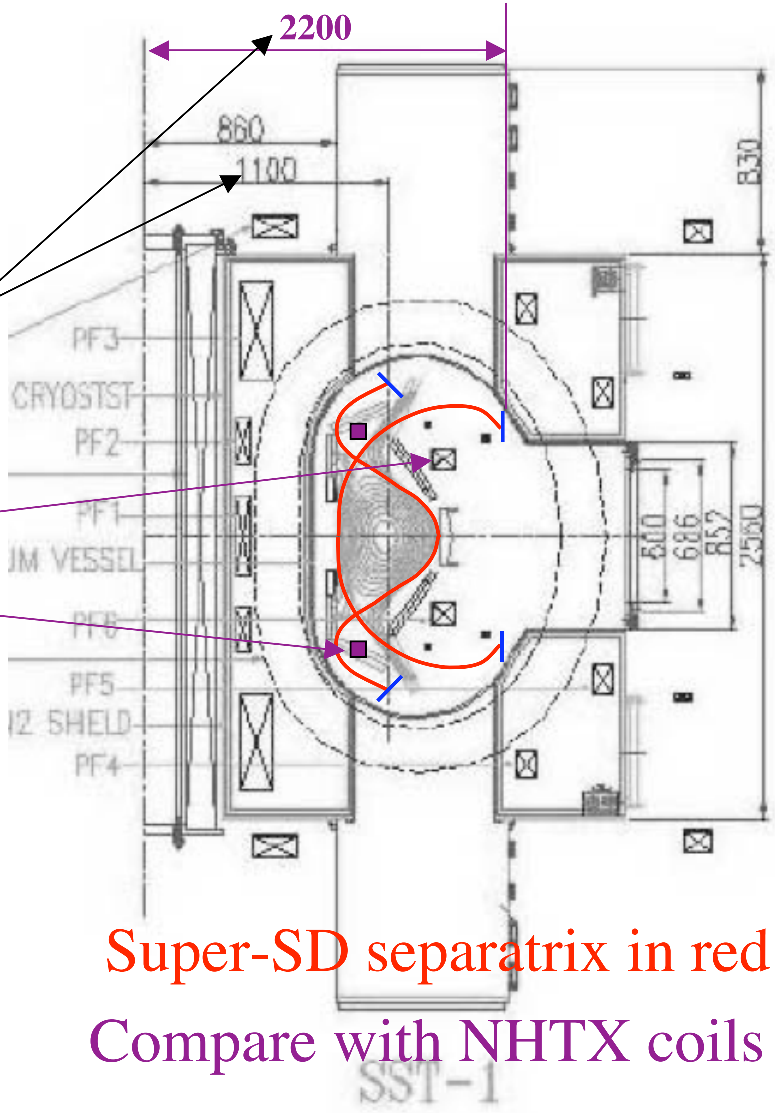
- Heat flux problem is even more critical for low-A HPD Spherical Tori (STs)
- SXD is a high-A divertor for low-A core
- With SXD, the many expected low-A core advantages can be actualized
- SXD gains in R_{div} are higher at low-A
- SXD designs for ST-CTF are easy
- Hence, SXD has now become the “presumptive 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 => 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 ~ $1/\text{time}^{1/2}$)
  - 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 ~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.