Mechanical and
Aerospace
Engineering

SPARC

Feasibility studies of the SPARC X-Point Target divertor

J.T. Wai[1], M.L. Reinke[2], A.Q. Kuang[3], D. Garnier[3], P. Rodriguez-Fernandez[3], E. Kolemen[1,4]

[1]*Princeton University, USA*
[2]*Commonwealth Fusion Systems, USA*
[3]*Massachusetts Institute of Technology, USA*
[4]*Princeton Plasma Physics Laboratory, USA*

E-mail: jwai@princeton.edu

APS-DPP Nov 8-12, 2021

Work supported by Commonwealth Fusion Systems

Executive summary (1 of 2)

SPARC is a high field tokamak aiming to leverage advances in magnet technology to achieve fusion gain (Q=2) in a compact (R=1.85m) machine.

Most SPARC divertor research effort has been on the primary scenario which uses strike point sweeping to mitigate enormous heat flux levels.

SPARC also aims to experimentally investigate the X-Point Target (XPT) scenario (Ip=5.7MA)

In this work we study feasibility of the XPT:

1. how to transition into the XPT scenario
2. operating space within power supply limits
3. sensitivity and control issues
4. compatibility with the standard scenario

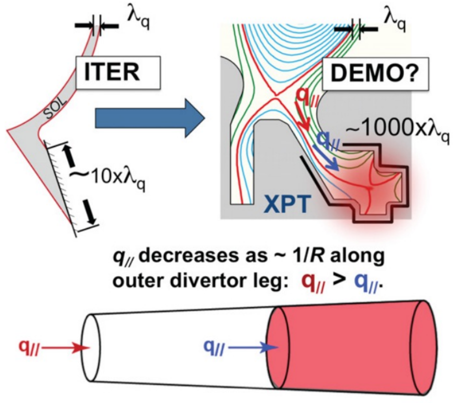


Fig 1: [Labombard, 2015] Illustration of the XPT concept which features a long strike leg terminating in an x-point and radiating volume.

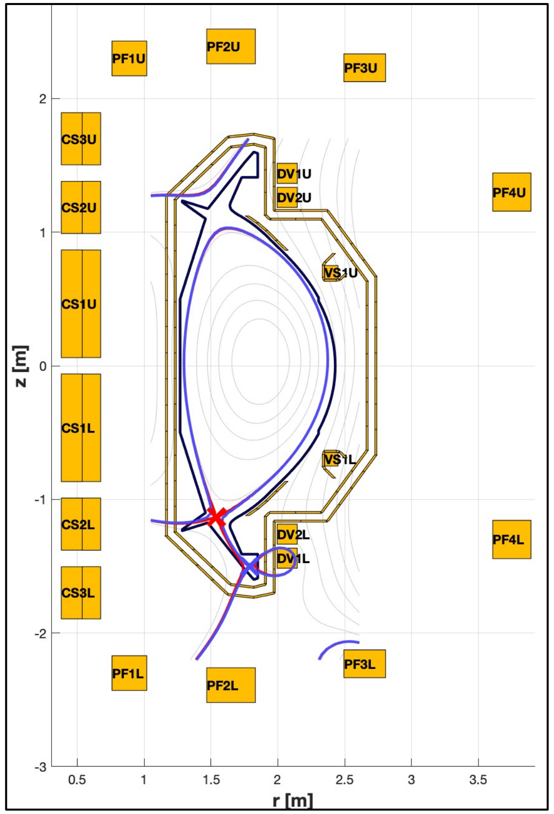


Fig 2: An XPT equilibria achieved within coil limits

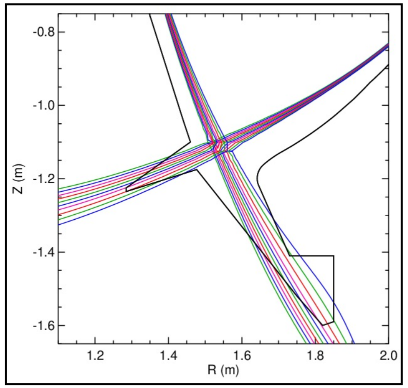


Fig 3: [P. Rodriguez-Fernandez] SPARC strike point sweeping.

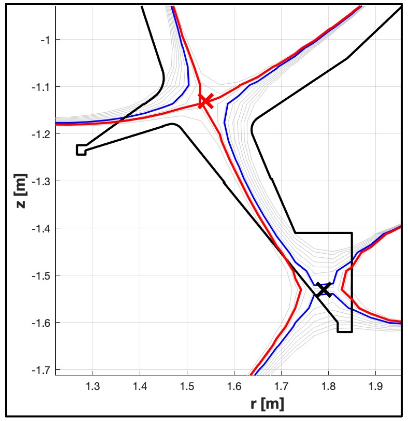
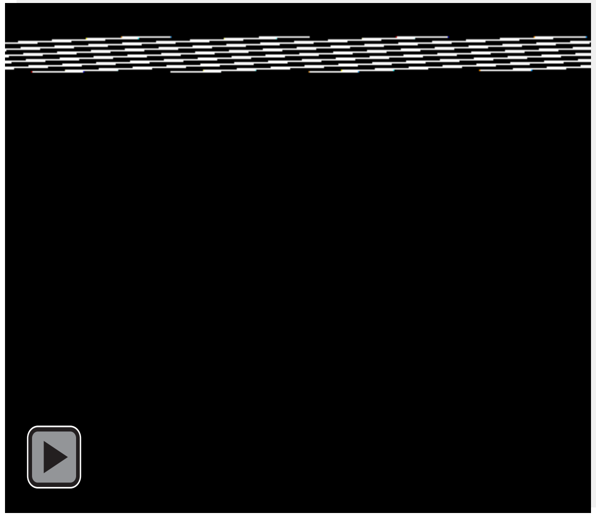


Fig 4: SPARC XPT divertor

Executive summary (2 of 2)

1. Is there a scenario for transitioning into XPT?

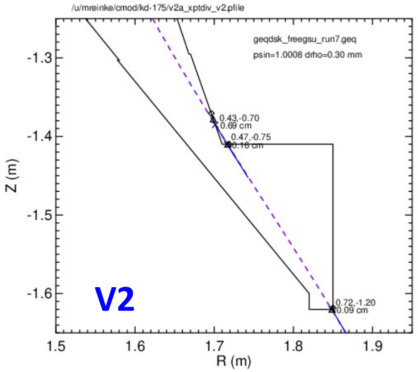
Dynamic trajectories found that respect coil/power supply limits and protect tiles during transition. Can transition from standard to XPT in ~2s. XPT scenario is at reduced Ip=5.7MA



2. What range of XPT equilibria are achievable?

Grid scans indicate reasonable operating space for placing the x-point Operating limits primarily determined by the PFC contour and PF4/DV1 coil currents.

Fig 1: Closed divertor geometry favorable to strike point sweeping.



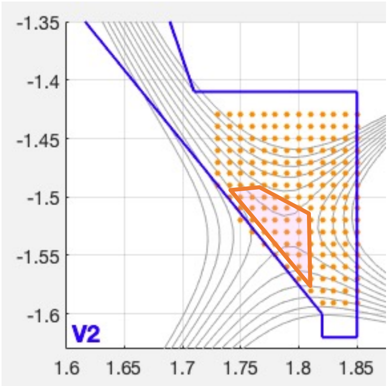


Fig 2: Operating space for xp2 position.

3. Can the divertor design handle the XPT and the primary strike point sweep scenario?

Strike point sweeping favors a closed divertor contour, and XPT favors an open divertor. At this stage, seems achievable but precise analysis is needed to identify a design that satisfies both.

4. Are the diagnostics, coil set, and power supplies sufficiently capable for good feedback control?

Reconstruction accuracy will probably be OK but control actuation difficult. DV coil actuators need <1% full scale accuracy.

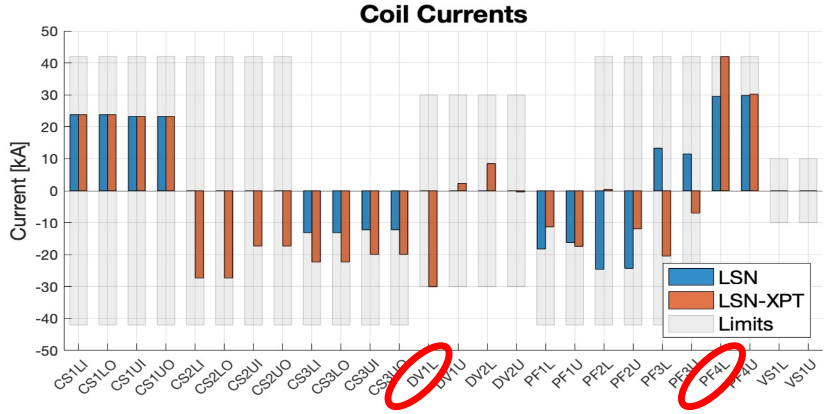


Fig 3: Start and end coil currents for creating the XPT

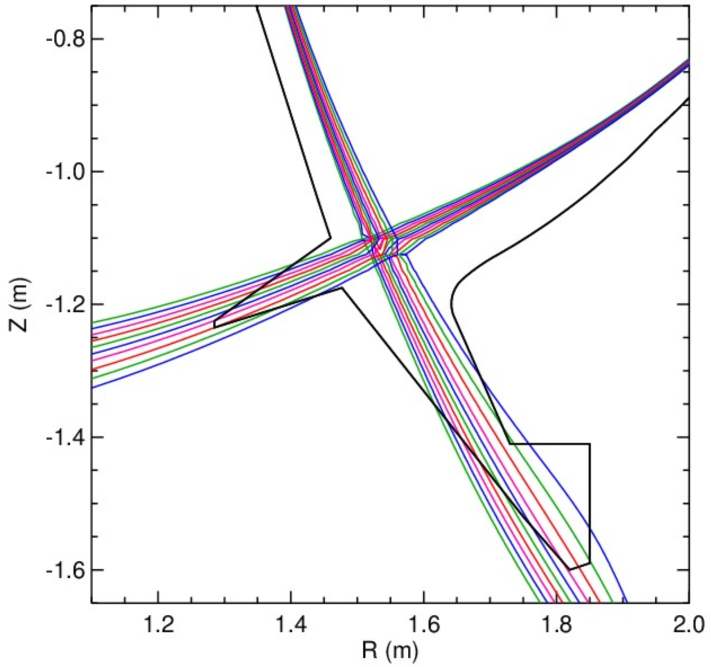
Motivation and background

Motivation

- The standard high-power scenario uses a combination of inertial cooling, angled targets, and strike-point sweeping to mitigate enormous heat flux levels ($q_{||}$ = 10 GW/m^2 , P_{SOL} = 29MW [Kuang, 2020]).

- This strategy does not to scale reactor size. Additionally, there is some question how standard detachment / partial-detachment scenarios (as on ITER) scale to pilot plants.

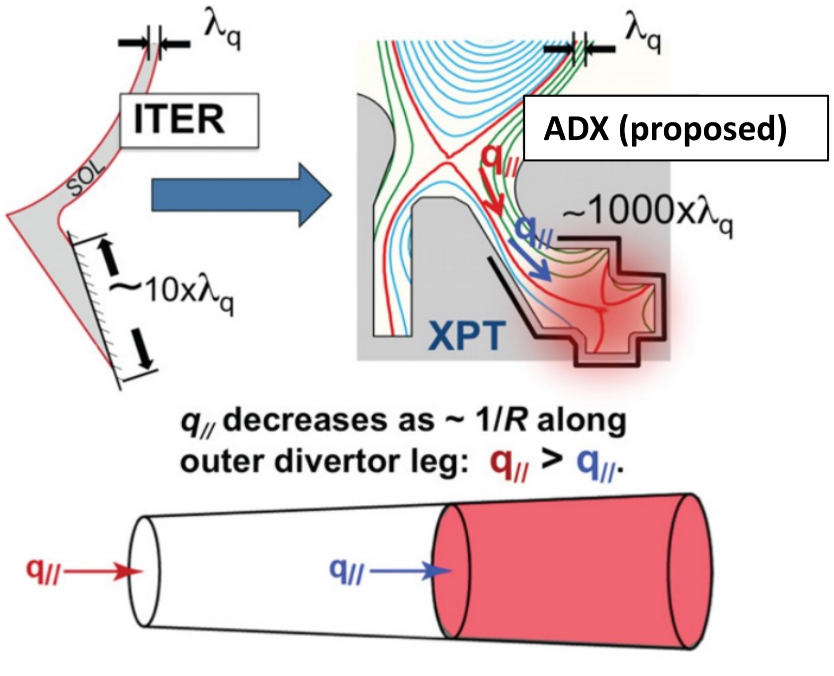
A design goal for SPARC is to investigate the X-Point Target divertor configuration for potential application to pilot-plant devices.



Strike point sweep equilibria [P. Rodriguez-Fernandez]

XPT divertor background

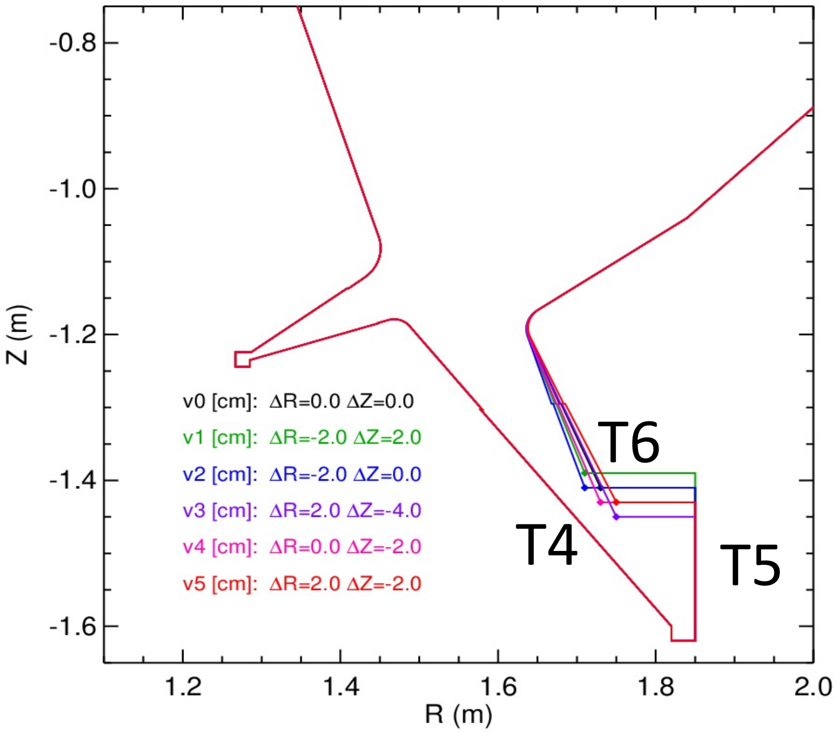
- Features of the XPT [B. Labombard, 2015]
  - Radially extended strike leg terminating in a secondary x-point
  - Large R increases A_{WET}
  - Large R reduces the effect of divertor impurities on core degradation, allows for higher impurity densities and detachment
  - Above a critical density, can form an x-point MARFE in divertor so that more heat transfer occurs via volumetric processes (radiation).
  - Toroidal (and to a lesser degree, poloidal) flux expansion is theorized to improve stability of the detachment front location. [Lipschultz, 2016]



XPT divertor concept. Figure adapted from [B. Labombard, 2015]

Equilibrium trajectory design

Operating constraints



- Observe coil limits
  - Also, CS1, CS3, and PF4 may not cross 0
  - Cannot use CS1 (used for Ip control)
- Keep the common flux SOL (2xλ_q) on HHF tiles as the 2nd XPT is moved into the common flux to < 2xλ_q (not T5!)
- Have at least 1xλ_q hitting T5 when 2nd XPT is at its 'final' position
- Protect tiles from excessive flux expansion leading to reduced A_{WET}

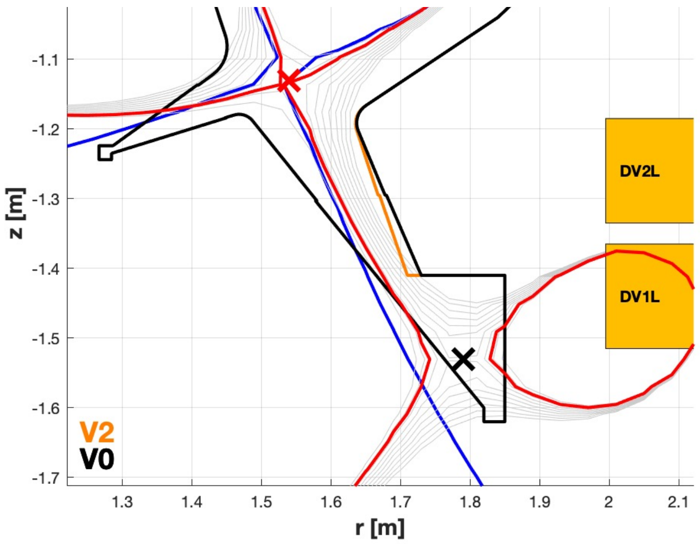
Coil	Max Current [kA/turn]	Max dI/dt [kA/turn-s]
CS1U/L	42	30
CS2U/L	42	30
CS3U/L	42	30
PF1U/L	42	19
PF2U/L	42	17
PF3U/L	42	25
PF4U/L	42	10
DV1U/L	30	100
DV2U/L	30	100

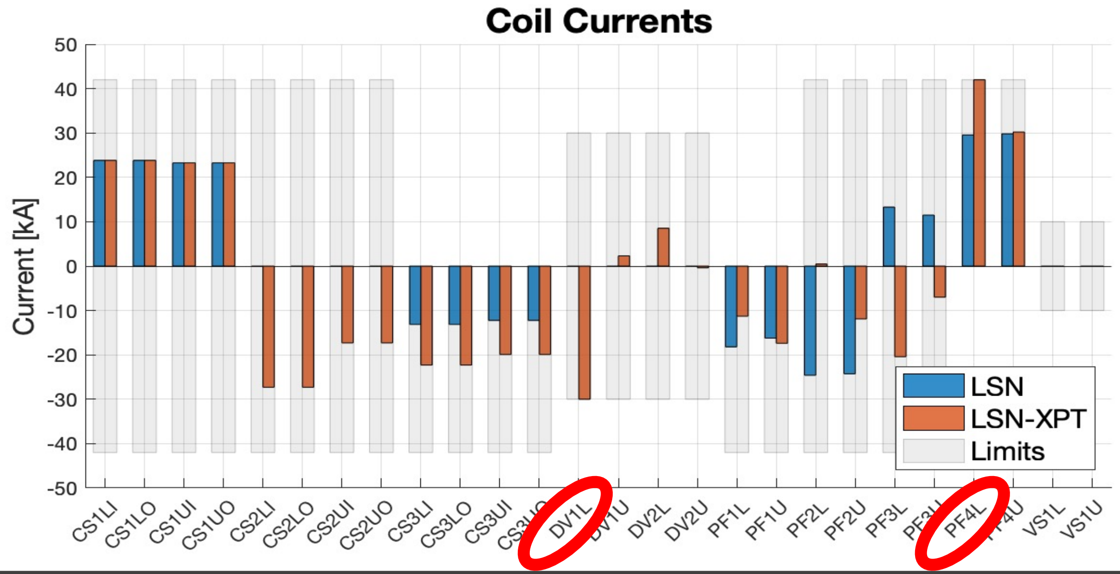
Coil and power supply limits

Note: Coil design is in-progress and at preliminary design stage.

Design procedure

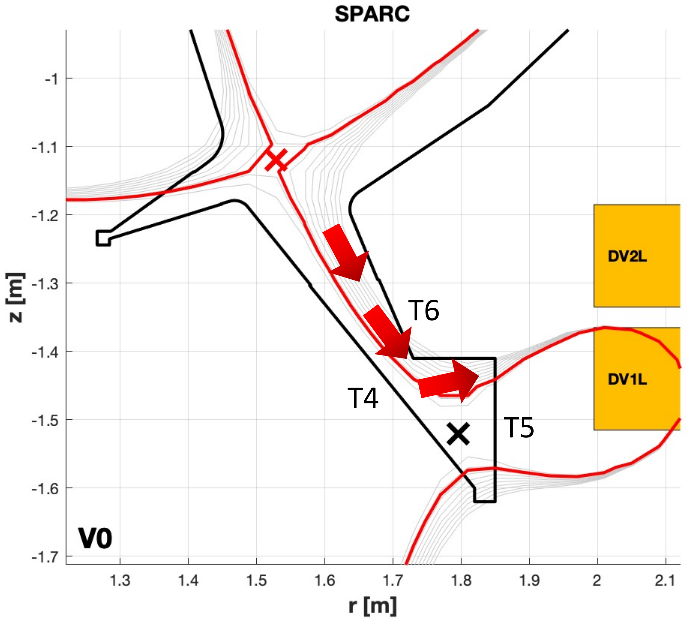
- Equilibria designed using gsdesign [Welander, 2019]
    - Weights to maintain core parameters (boundary, position, Ip=5.7MA, li=1.2, βp=0.4, elongation=2, internal profiles)
    - Design XPT equilibria by increasing weight on xp2
    - Weight to minimize dynamic interaction with Ip (i.e. that V_{LOOP}=0)
    - Once equilibria are found with corresponding change in coil currents, use the dI/dt limits to determine the fastest temporal evolution
    - Vessel currents post-verified to have minimal interaction with shape evolution
- Multiple starting points (from strike sweep equilibria) and paths explored



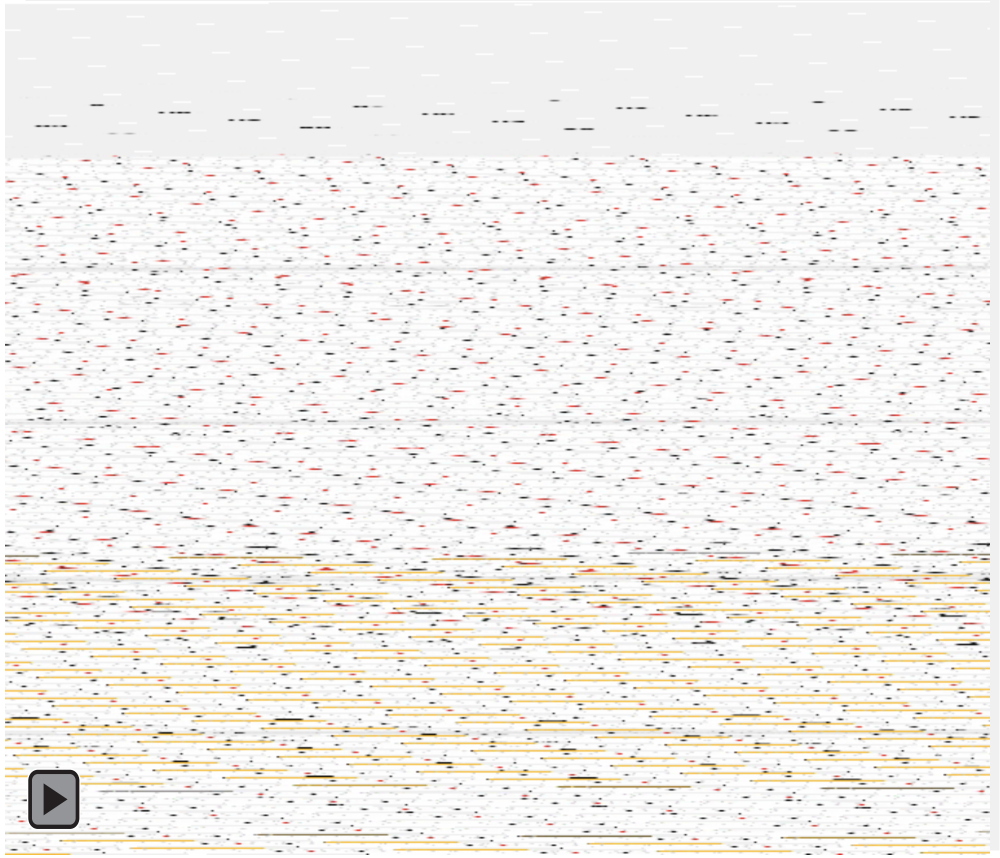


Poor design example: common flux delivers power directly to T5

- Goal was to have heat flux directed onto vertical target (T6) as xp2 crosses
- However, @t=2s, as separatrices cross back, strike leg delivers common flux power directly to T5



t=2s Power delivered directly to Tile5



Another poor design: excessive heat load from low angle of incidence

- Too low of an angle of incidence can cause overheating by reducing A_{WET} through shadowing.

- Power should not be delivered to xp2 while it is crossing PFC's, because the x-point creates a region high flux expansion and low strike angles.

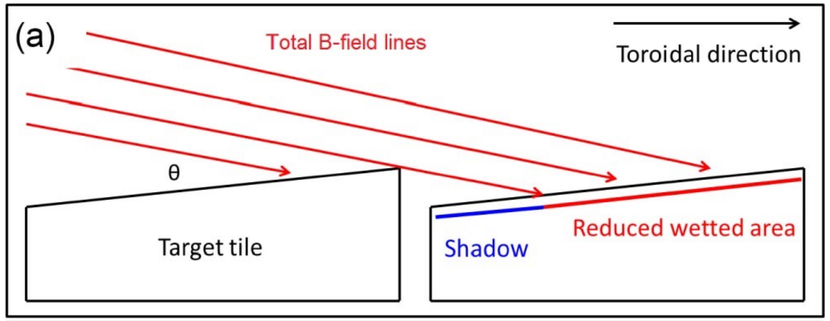
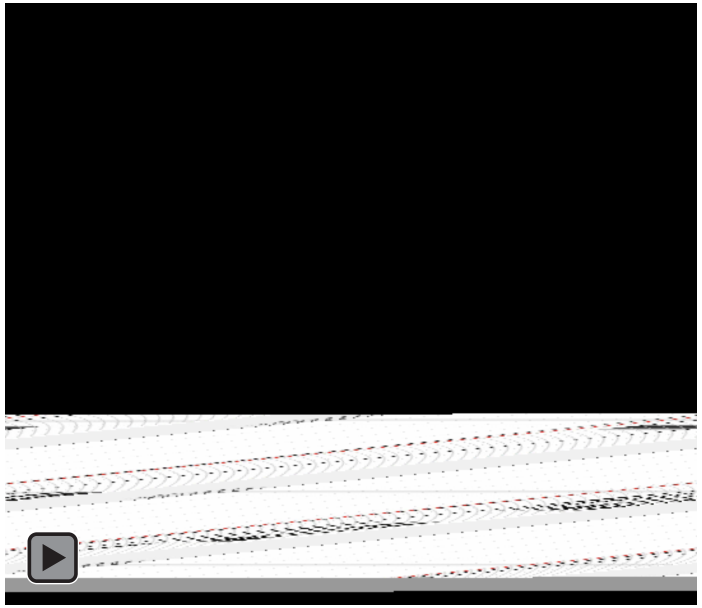
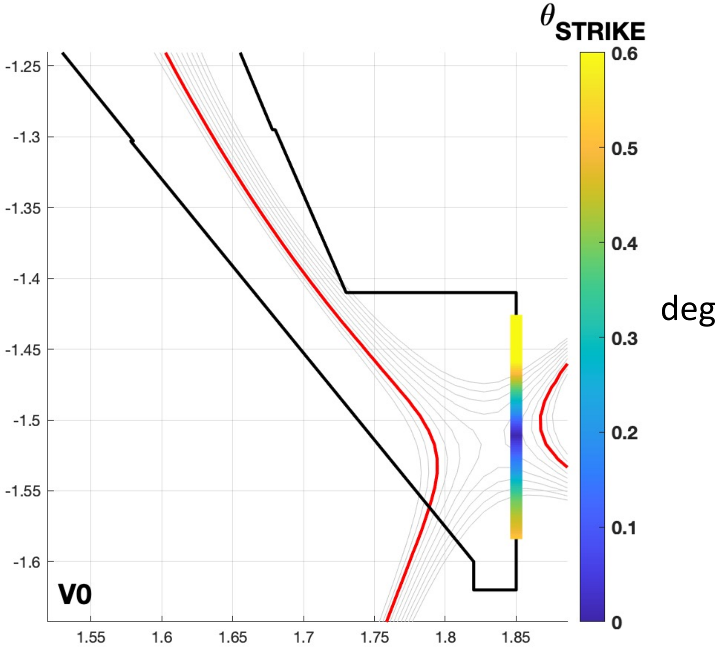


Figure from B Covele *et al* 2014 *Nucl. Fusion* **54** 072006



Transition with low angle of incidence

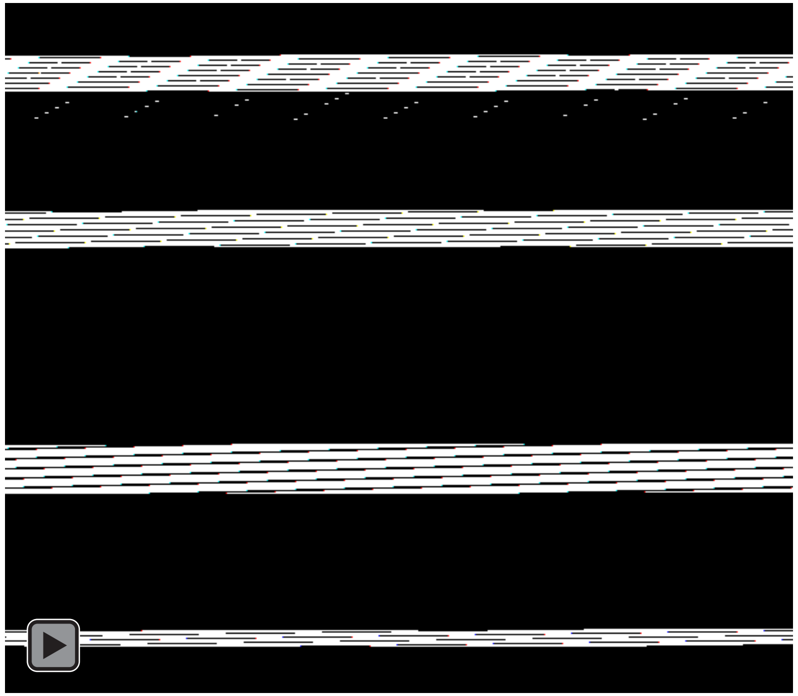


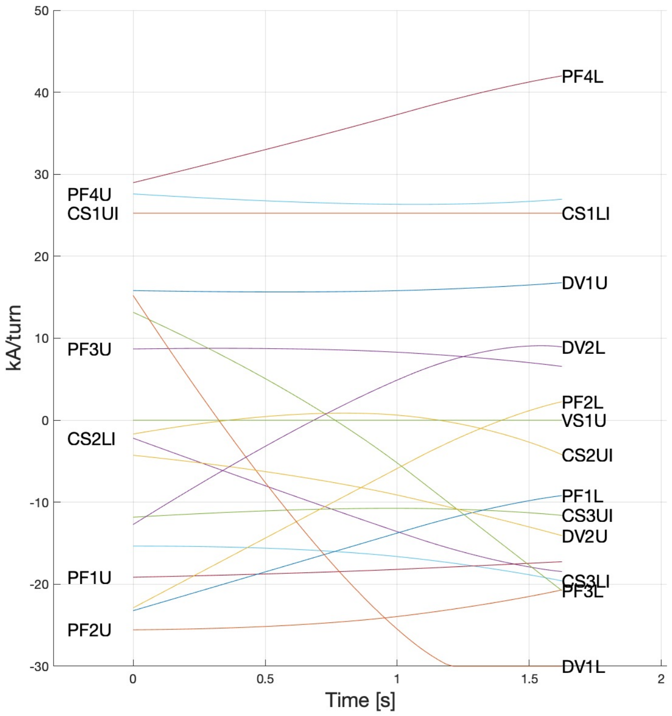
t=1.65: The strike lines are active and hit T5 with extremely low angle of incidence

* angle of incidence calculated assuming axisymmetric tile surfaces

Characteristics of good transition

- Easiest to start with outer strike point at low R
- Maintains a gap of ~4λ_q between separatrices as xp2 crosses PFCs, so that power is not delivered to xp2
- xp2 is 4cm inside limiter before gap drops to 3λ_q
- Vertical target helps shield power
- This type of transition is also faster 1.6s (less coil current changes)



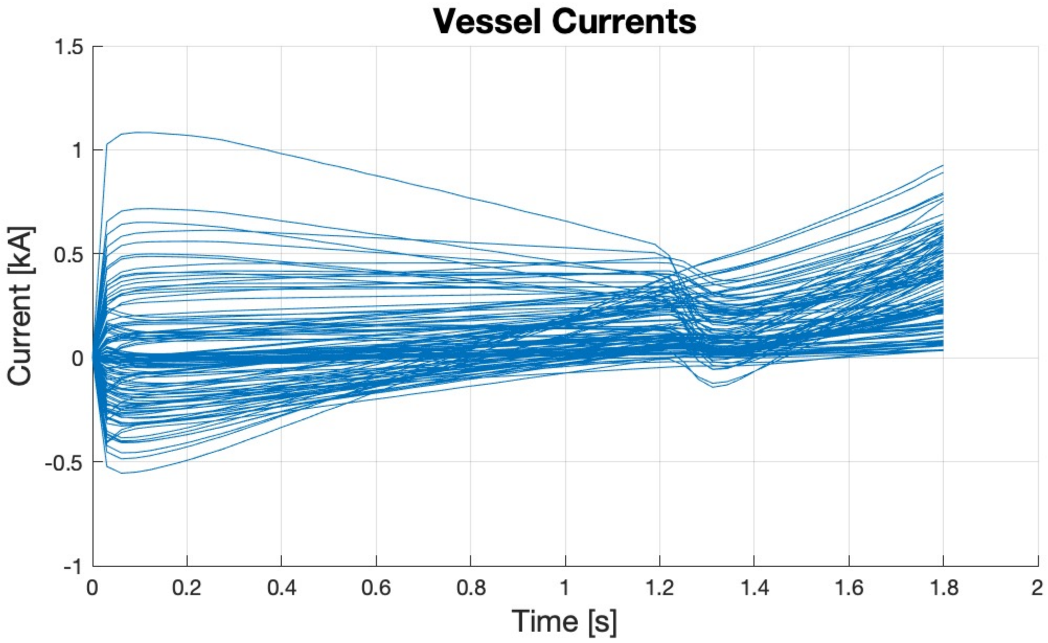


Vessel currents negligible during “slow” transition from standard to XPT

- Vessel currents found by integrating circuit equation, given the coil current trajectories

$$M_{vv}\dot{I}_v + M_{vc}\dot{I}_c + R_v I_v = 0$$

- Vessel currents are negligible (order 1kA, vs coil currents 30-40kA/turn).
- At final time, changes the optimal coil currents by 0.2%
- Currents decay quickly compared to the transition timescale due to vessel resistivity $\rho_{\text{stainless steel}} = 6.9 \times 10^{-7}$ Ohm-m

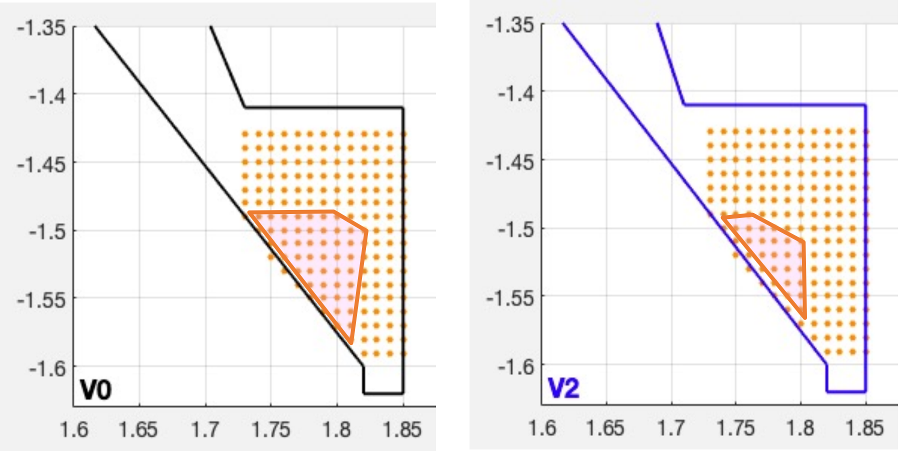


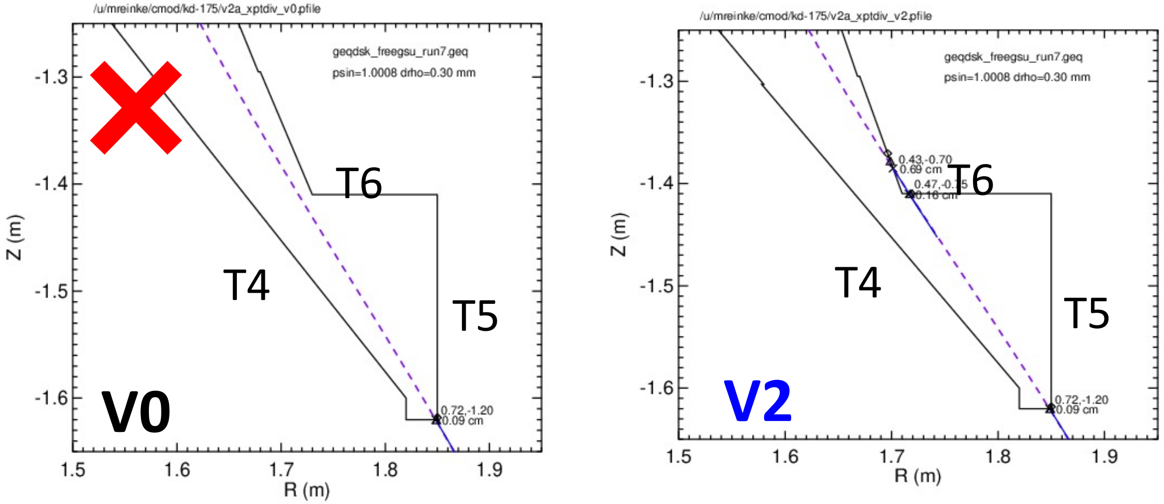
SPARC

Operating space for secondary x-point

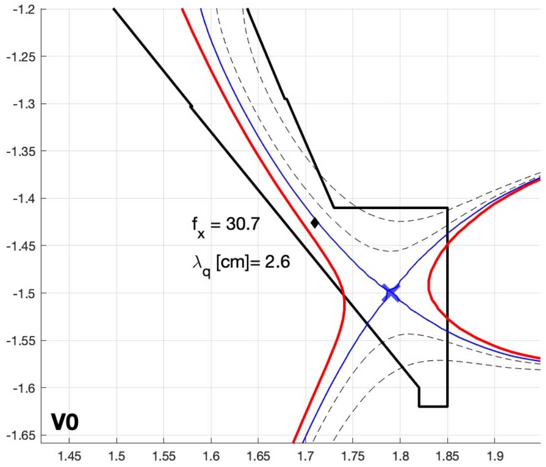
Competition between strike point sweep and XPT divertor design reqs

- **Strike point sweep**, want to close the gap between T4 and T6 (the HHF tiles), so that T5 never receives power
- **XPT**, want to keep the gap open so that power is directed into chamber.
  - Performed grid scan of xp2 placement.
  - Closing gap reduces operating space





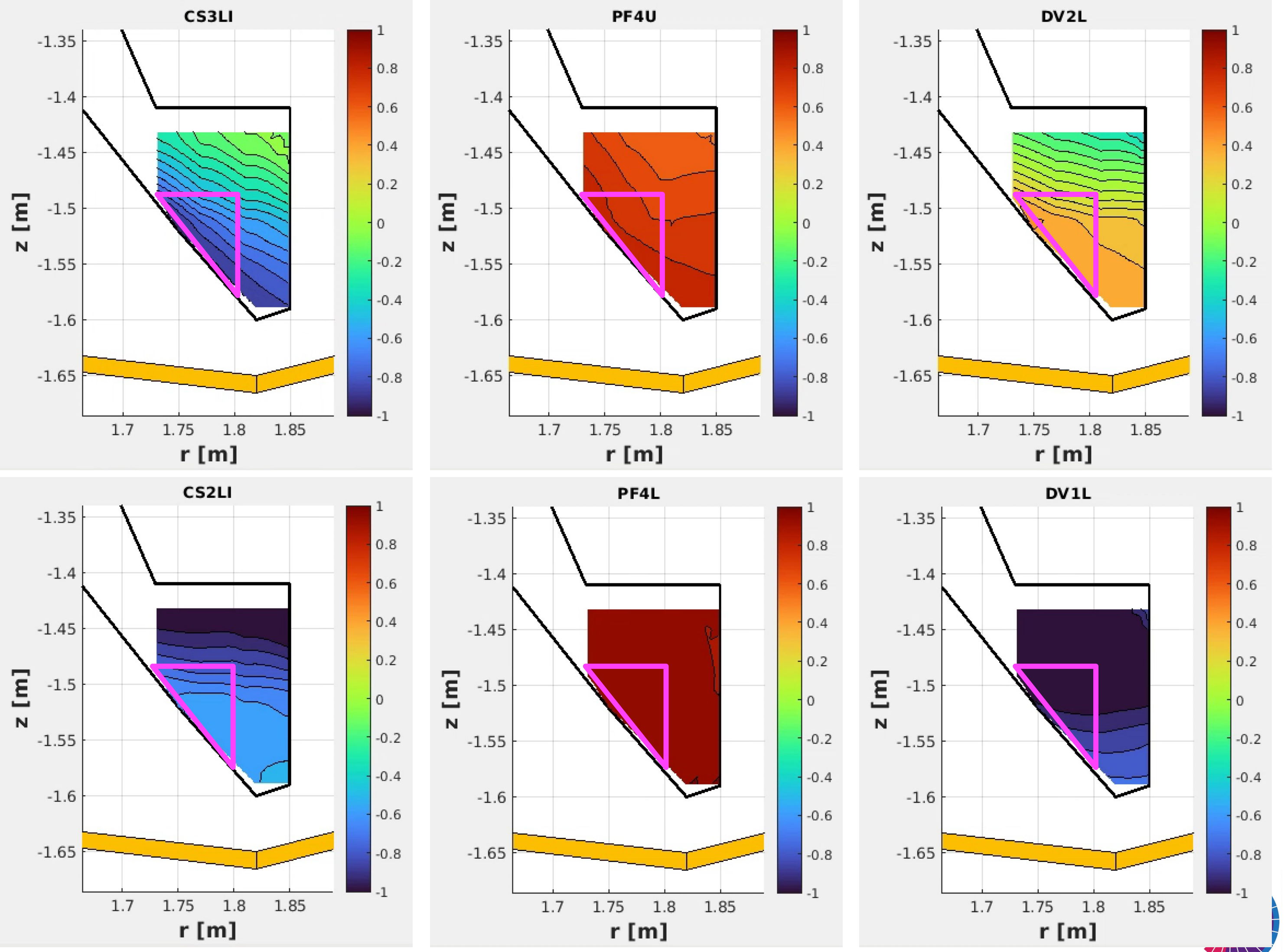
Above: V0 and V2 divertor contours which are a subset of the contours under design analysis. V2 features a smaller gap between T4 and T6.



Left: In XPT, high flux expansion makes it difficult for all the power to enter the chamber. The dashed lines are at $1\lambda_q$ and $2\lambda_q$.

Operating space constraints from coil currents

- cases are for 5.7 MA XPT shot. Ip can drop to create margin at ~10% level
- PF4L and DV1L are the most restrictive for creating these equilibria and are maxed out in nearly all cases
- PF4U also pushes limit when xp2 near lower T4
- Coils not shown have significant margin (~>40%) in meeting limits

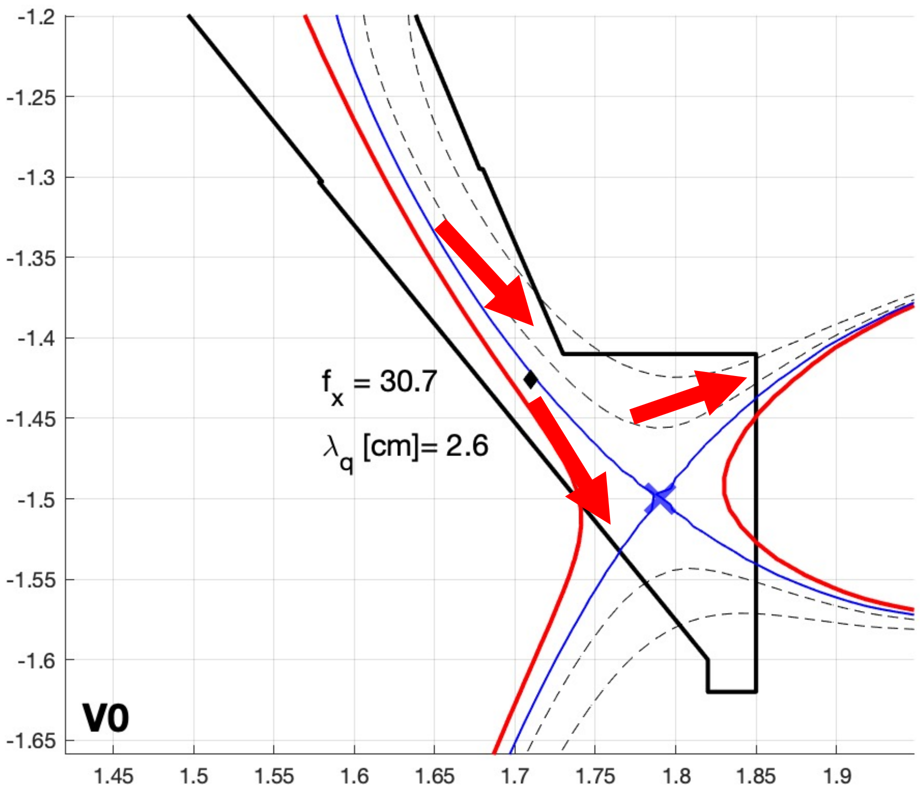


0D estimate of heat flux in attached XPT

- Simple energy balance indicates high heat flux levels as in standard scenario 16 MW/m^2
- This level is OK on short timescales <<1s (as in sweeping) but multi-second XPT pulses will only be enabled by accessing dissipative regimes.
- Picture will become more complex as drifts, turbulence are included. Detailed SOL modeling and simulation needed as next step.

$$P_{SOL} = 29MW$$
$$R = 1.8\ m$$
$$f_{out} = 0.6$$
$$L = (4.0 + 3.9 + 1.4)cm$$
$$A_{WET} = 2\pi \mathrm{RL}$$

$$q_{\perp,out,avg} = \frac{P_{SOL} f_{out}}{A_{WET}}$$
$$= 16\ MW/m^2$$



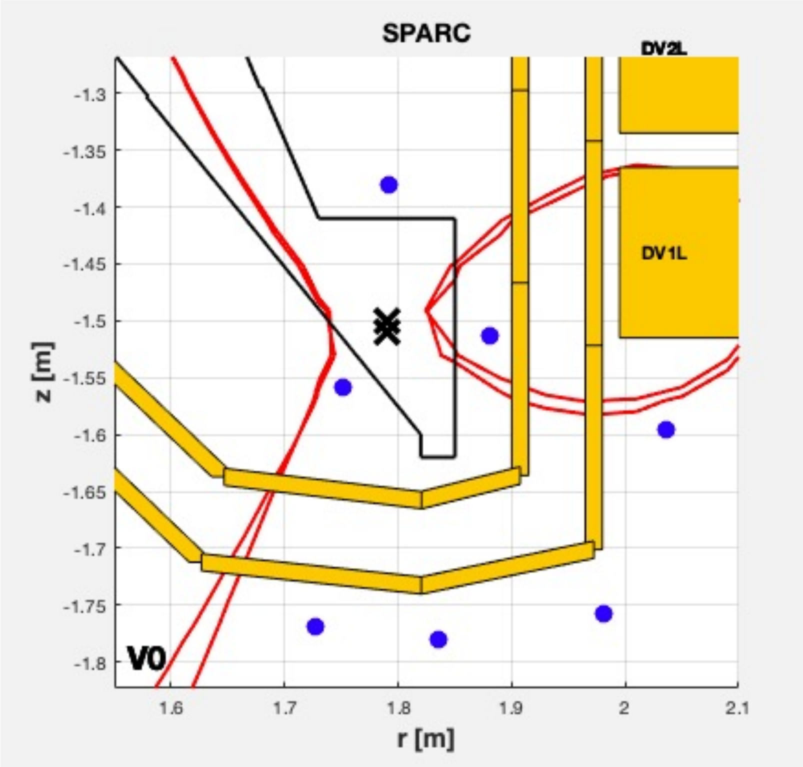
Control and sensitivity

Diagnostics probably support x-point position resolution <1cm

- Measured B-field strengths at possible probe locations for perturbed equilibria, with xp2 separation of 1cm

- ΔB_p ranges from .005-0.03 T at the probes (significantly larger than the Bp measurement noise on e.g. DIII-D (noise amplitude 10μT)
    - $\frac{|\Delta B_p|}{B_p}$ = 5-25%

- This precision, not accuracy! Does not account for model or bias errors. DIII-D IRTV measurements indicated larger reconstruction errors in snowflake divertor of several cm [Wai, 2020]



Probe locations used for this calculation only, diagnostics still in design phase

Need <1% coil current tracking for accurate flux gap, xp2 control

- Control requirements on flux gap between primary and secondary separatrices, target tracking of xp2, and high sensitivity of these parameters, indicate need for high accuracy on DV coils.
- Sensitivities are calculated with respect to DV coils since these are the dedicated actuators.
- The sensitivities are evaluated using both a vacuum model and nonrigid plasma response model (gspert) and give similar estimates for magnitudes.
- Coil accuracy will probably need to be lower than 1%, since target flux gap accuracy will probably be less than **1λ_q**

*Calculations for L-mode λ_q , H-mode λ_q is ½ L-mode

Coil currents for keeping flux separation <1λ_q

$$\lambda_{q,OMP} = 0.87mm \leftrightarrow 0.0267Wb$$

$$\Delta I_{DV1L,DV2L} = 0.0267 \text{ Wb} \ / \frac{\partial(\psi_{xp1} - \psi_{xp2})}{\partial I_{DV1L,DV2L}}$$

$$\begin{aligned}\Delta I &= 250A,\ 440A \\ &= 0.8\%,\ 1.5\% \text{ of full scale current (30kA)}\end{aligned}$$

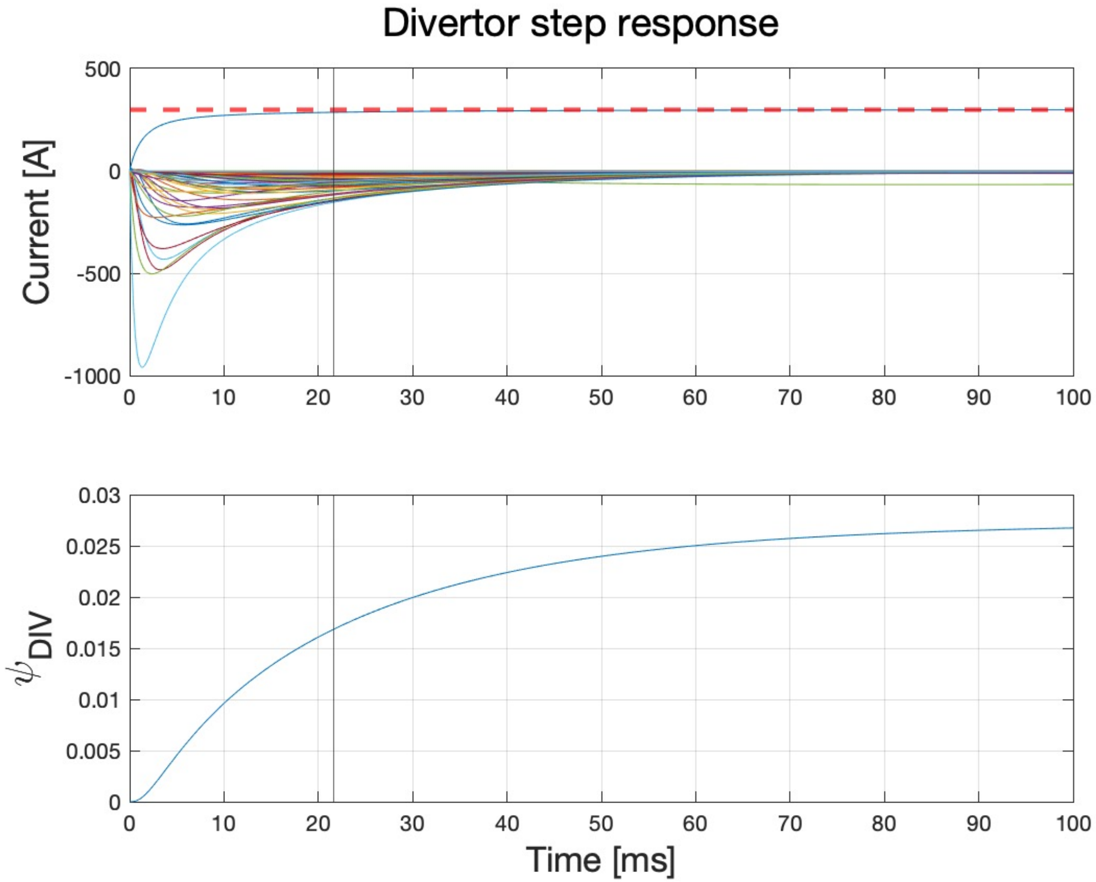
Coil currents for keeping xp2(r,z) within 1cm

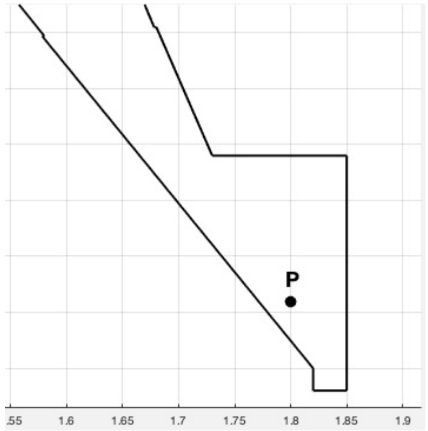
$$\Delta I_{DV1L,DV2L} = 0.01m / \frac{\partial r_{xp_2}}{\partial I_{DV1L,DV2L}}$$

$$\begin{aligned}\Delta I &= 350A,\ 600A \\ &= 1.1\%,\ 2\% \text{ of full scale current (30kA)}\end{aligned}$$

Vessel shielding limits response time to >20ms

- Step response applied to DV1L coil using proportional control and response simulated for all currents. Gain increased until DV1L response is at fastest allowed (dI/dt limit)
- Vessel currents shield the change of flux in the divertor, giving an **e-fold time of 21ms**. Value will probably increase further when considering all power supply constraints.
- A feedback system could compensate for slow disturbances (current diffusion, shape evolution) but not higher frequency disturbances (ELM effects, fast vertical motion)





$$\Delta\psi_p = [M_{pc}\ M_{pv}] \begin{bmatrix} I_c \\ I_v \end{bmatrix}$$

Conclusions

Conclusions

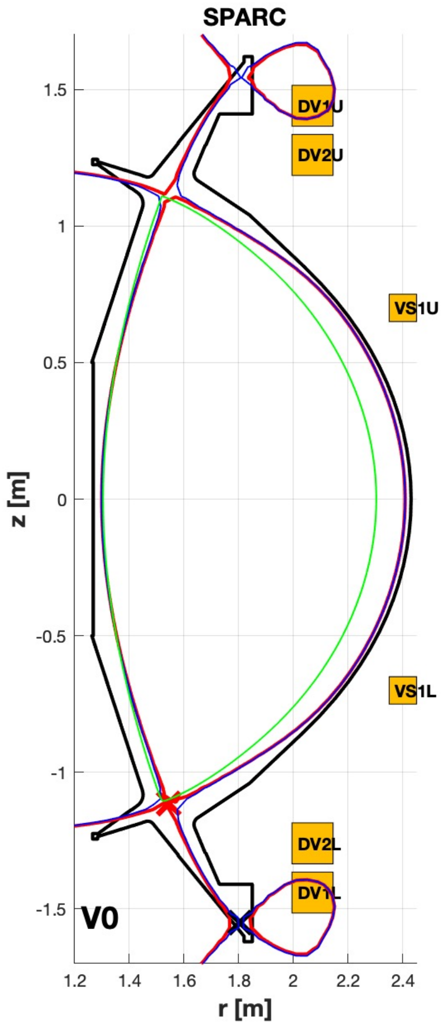
- Operating space and initial trajectories found for transitioning into XPT while protecting tiles. Transitions can happen in a reasonable time <2s.
- There is competition between meeting requirements for strike point sweeping (closed divertor) and the XPT (more open divertor). Generated scans will be useful for quantifying tradeoffs. At this design stage, a reduced XPT operating space is still available in the more closed geometries.
- Control will likely be a challenge, need <1% full-scale tracking accuracy in DV coils, vessel shielding limits dynamic responses to slower than 20ms

SPARC

Bonus: additional studies on Double Null Divertor-XPT

Double-null XPT is predictably more difficult

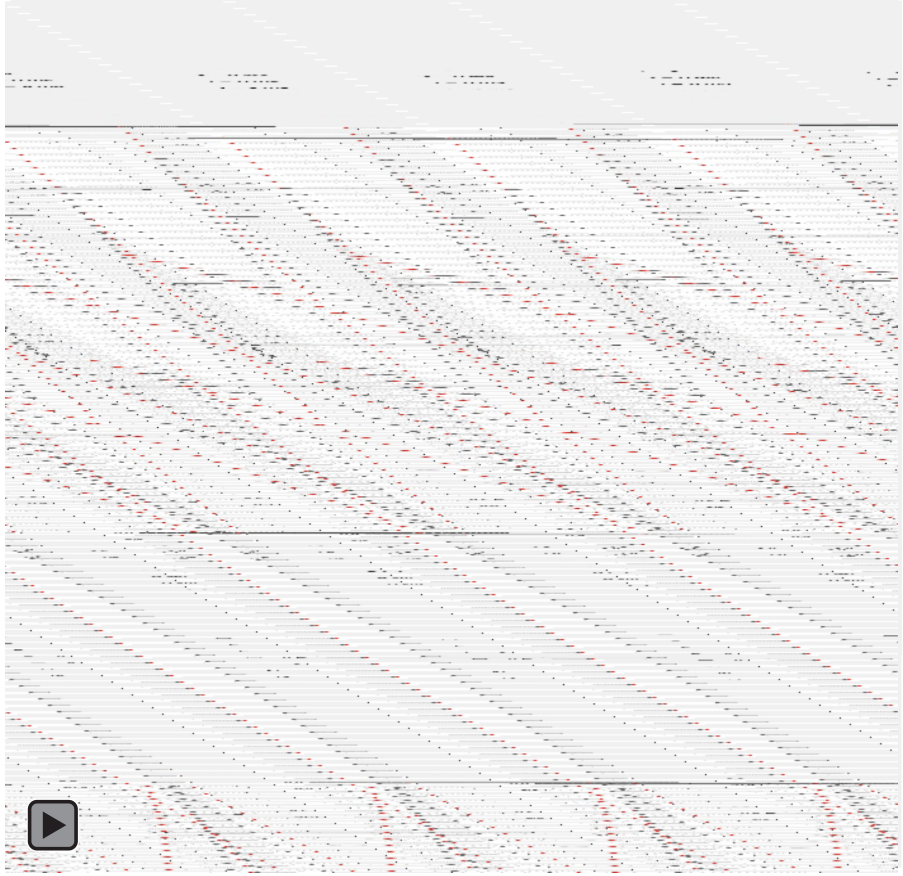
- Challenge is maintaining core shape with high Ip (since coil currents scale with Ip). In LSN XPT can get around this exploiting some up/down asymmetry
- In particular, elongation increases with Ip/XPT formation. Requires more use of CS coils
- Can create transition with coil set but less headroom in multiple directions (profiles, coil constraints, xp positions, Ip, core shape).
- Physics goals for DND-XPT are less ambitious and can probably scale Ip significantly to achieve headroom

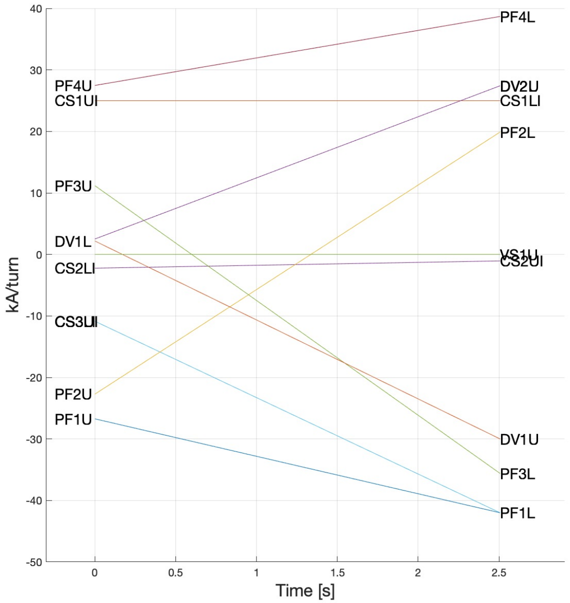


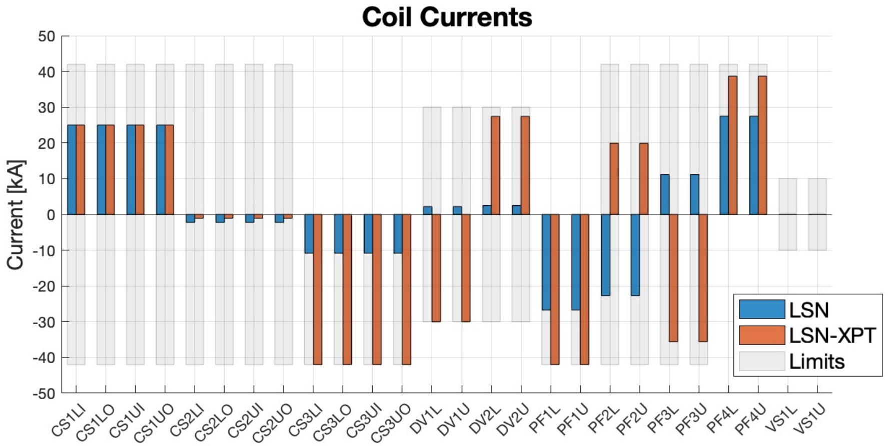
Elongation tends to increase significantly in DND-XPT but can be avoided to some extent with CS coil usage

Some initial DND-XPT trajectories found

- Difficulties
  - secondary x-point cannot be placed too far inside divertor due to current limits
  - CS3, DV1, PF1 are maxed out with DV2, PF3 and PF4 not far behind
  - Ip will likely need to reduce well below the 5.7MA case to realize this in an experiment







References

References

A.Q. Kuang *et al* 2020, *Journal Plasma Physics*, **86** 865860505

B. LaBombard *et al* 2015 *Nuclear Fusion* **55** 053020

B. Lipschultz *et al* 2016 *Nuclear Fusion* **56** 056007

A. Welander *et al* 2019 *Fusion Engineering & Design* **146** 2361-2365

B. Covele *et al* 2014 *Nuclear Fusion* **54** 072006

J.T. Wai *et al* 2020, *Nuclear Material & Energy,* **25** 100835

Acknowledgements:

Work supported by Commonwealth Fusion Systems