NSTX-U PF1B discussion – version 3

J. Menard

PPPL

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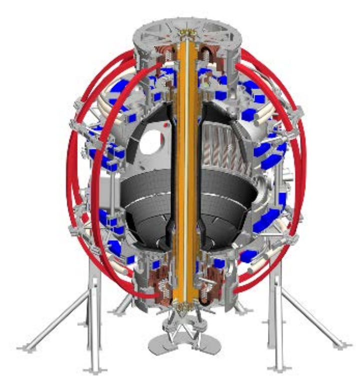
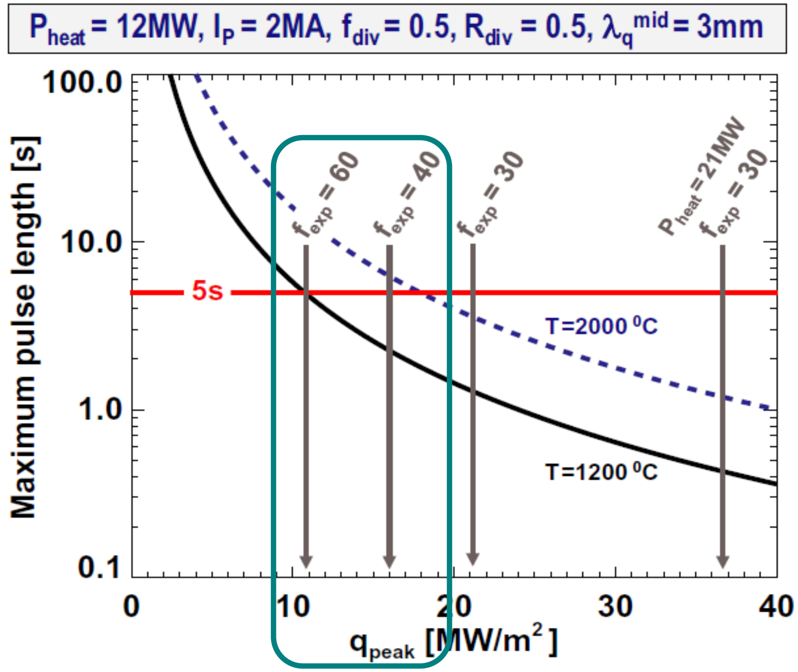


What are requirements for NSTX-U shape and divertor control – what are PF1 requirements?

- Simplistic version of roles of PF1 coils:
  - PF1A provides high-δ (up to 0.7) divertor for I_P = 2MA
  - PF1C → ability to control flux in divertor, have intermediate δ (δ = 0.4-0.5) higher than from PF2 alone (δ = 0.2-0.3)
  - PF1B assists in fine control of divertor flux – especially for maintaining stationary advanced divertors during OH swing

- Some form of advanced divertor (SFD- / X) is likely required to mitigate high heat flux in 2MA, 5s, 10-12MW pulses
  - Goal: such shapes should ideally also be compatible with cryo-pump for n_e control

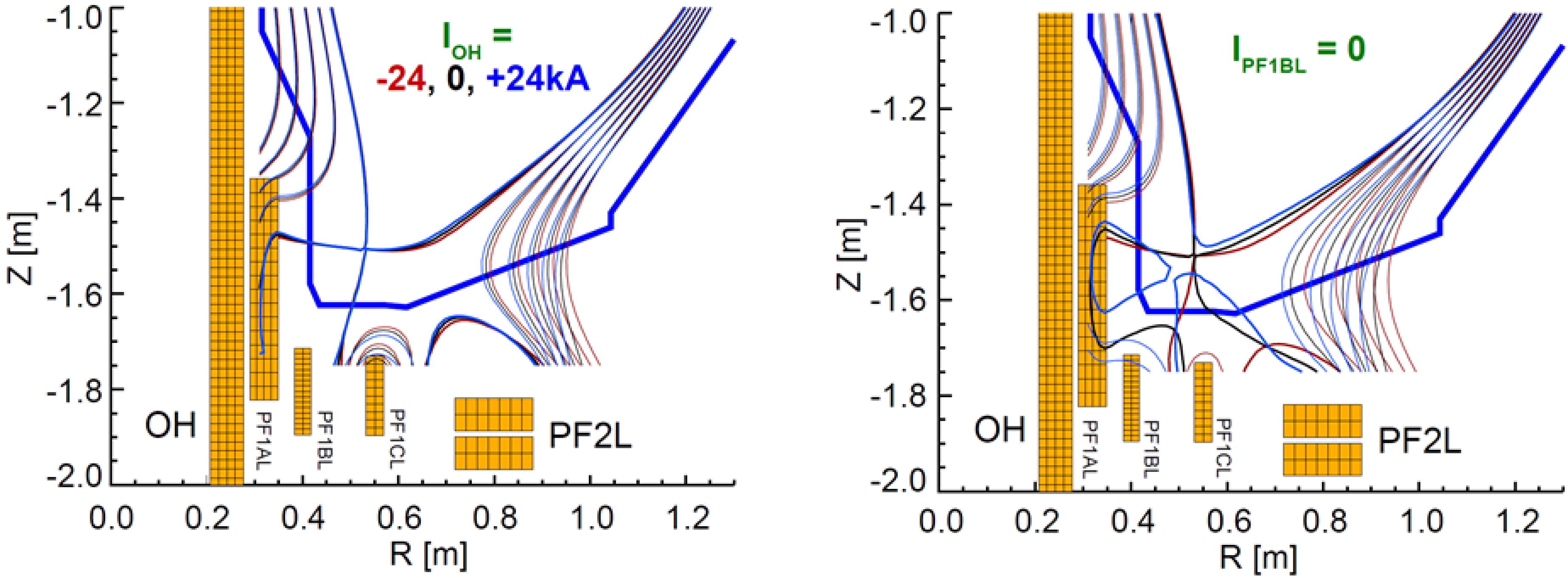


PF1B enables boundary shape, divertor flux / field, and power exhaust to be stationary during OH flux changes

- I_{OH} = +24kA causes largest variation in strike-point location
  - Impact may be larger early in shot at lower I_P → lower PF1A,C current
- Less variation between I_{OH} = 0 (~2MA SOFT) → -24kA (EOFT)

➢ Impacts ramp-up, 2MA flat-top may be ok for standard divertor

2MA equilibrium: PF1B current ≠ 0 **2MA equilibrium, PF1B current = 0**



From Figure 44 in J. Menard, et al., Nucl. Fusion 52 (2012) 083015

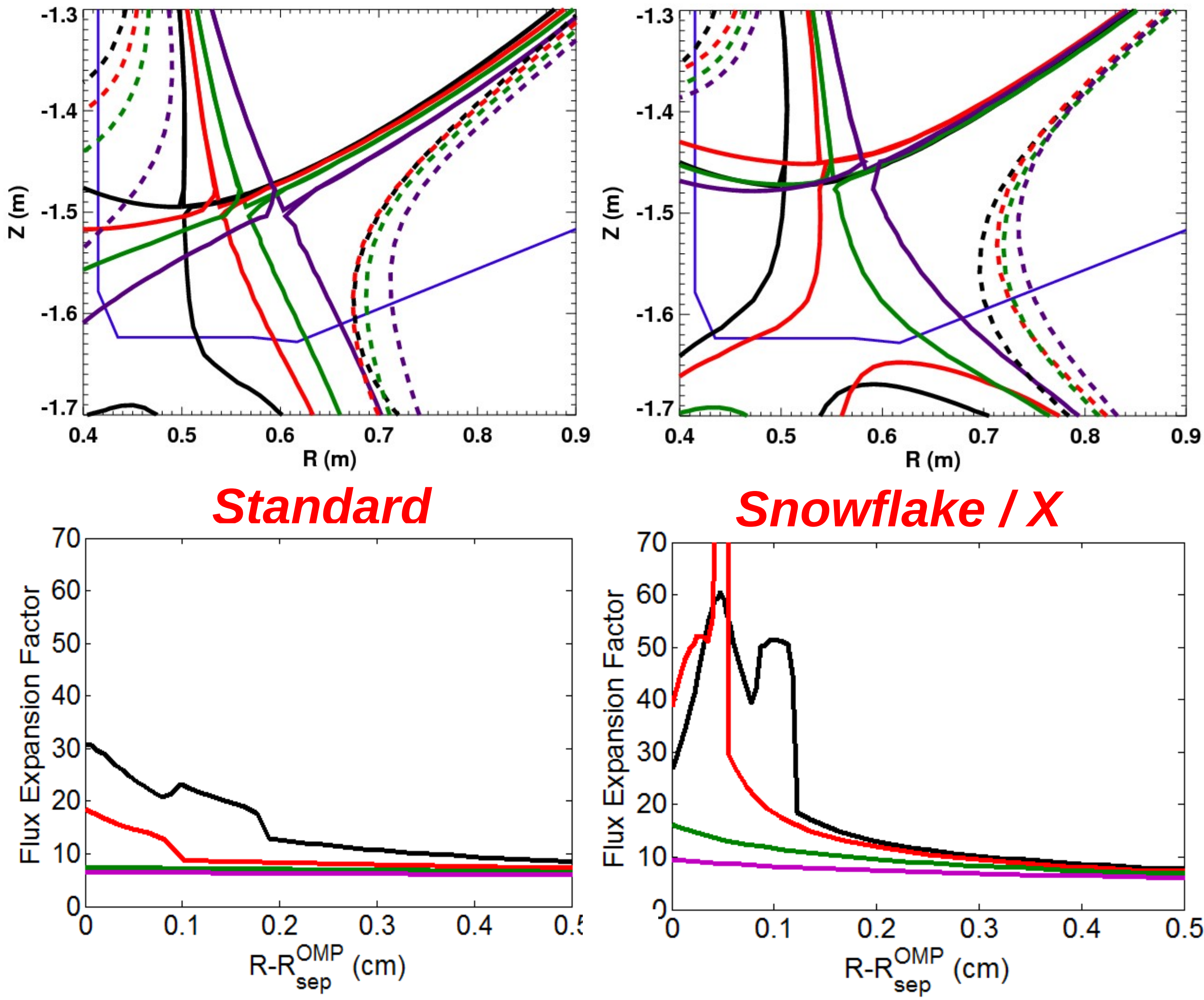
Are SFD-/X shapes cryo-pumpable w/o PF1B?

- Plasma shapes used in cryo-pump physics design allowed PF1B current, and had $I_{OH} = 0$
  - Equilibria were generated to vary strike point position for both conventional and SFD divertor configurations, since strike-point location vs. pumpability was the most critical trade-off in cryo-pump design
  - Did not study impact of OH swing since previous studies showed PF1B aided holding flux distribution during OH swing, and PF1B was assumed to be available when/if needed
- Need to revisit impact of time-varying OH and impact of no PF1B coil on controllability and pumpability of advanced shapes
  - Conventional shapes less impacted (?) and covered by SPG

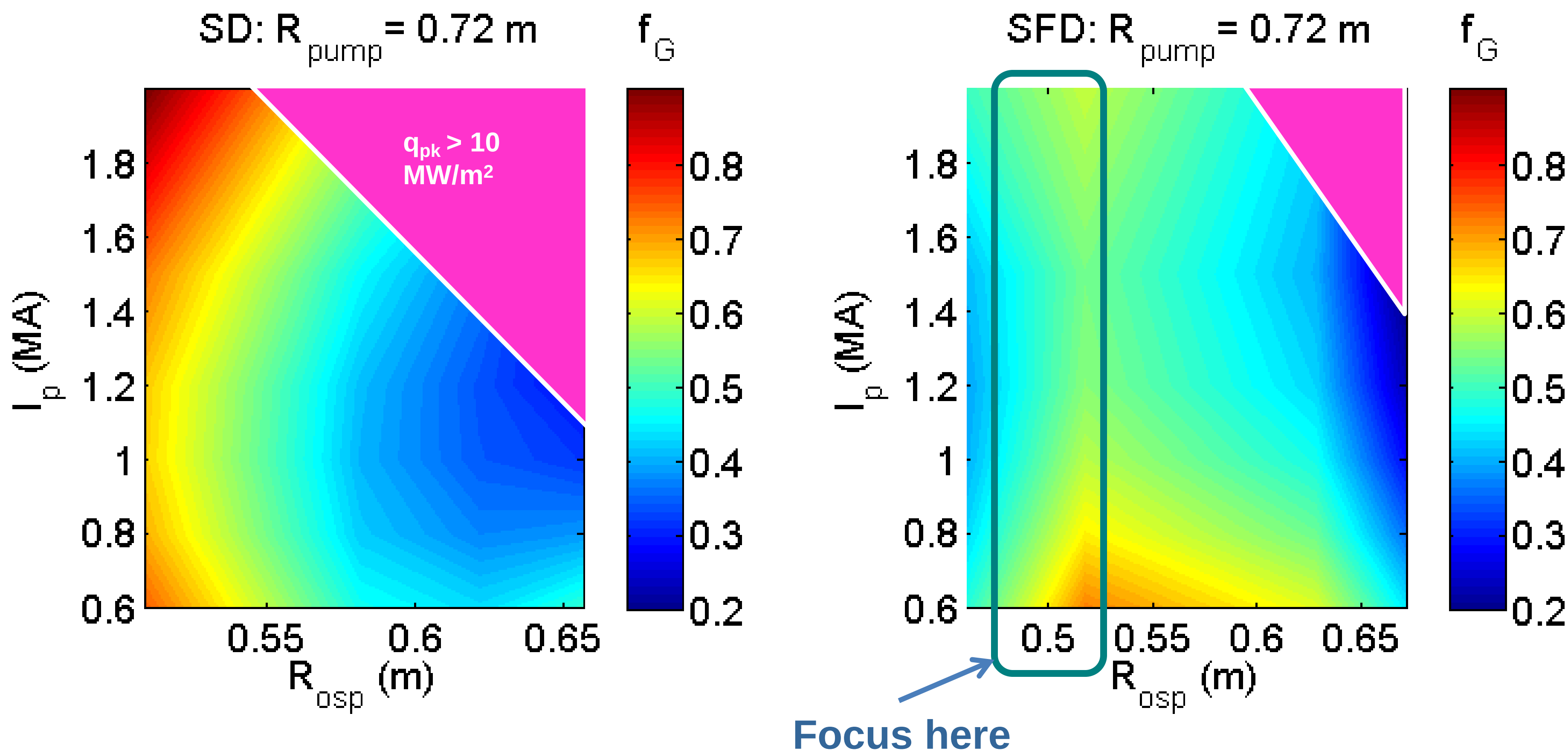
Cryo-study: Equilibria w/ range of R_{OSP} and flux expansion used to map heat flux profiles, assess candidate pump entrance locations

- Standard and snowflake divertors considered
  - Four R_{OSP} each
  - ψ_N=1.0,1.03 shown
  - Movement of ψ_N=1.03 strike line is much less than that of R_{OSP}

- Flux expansion, flux surface geometry used to convert midplane heat flux profile (from scaling) to divertor flux
  - As R_{OSP} is increased, flux expansion is decreased



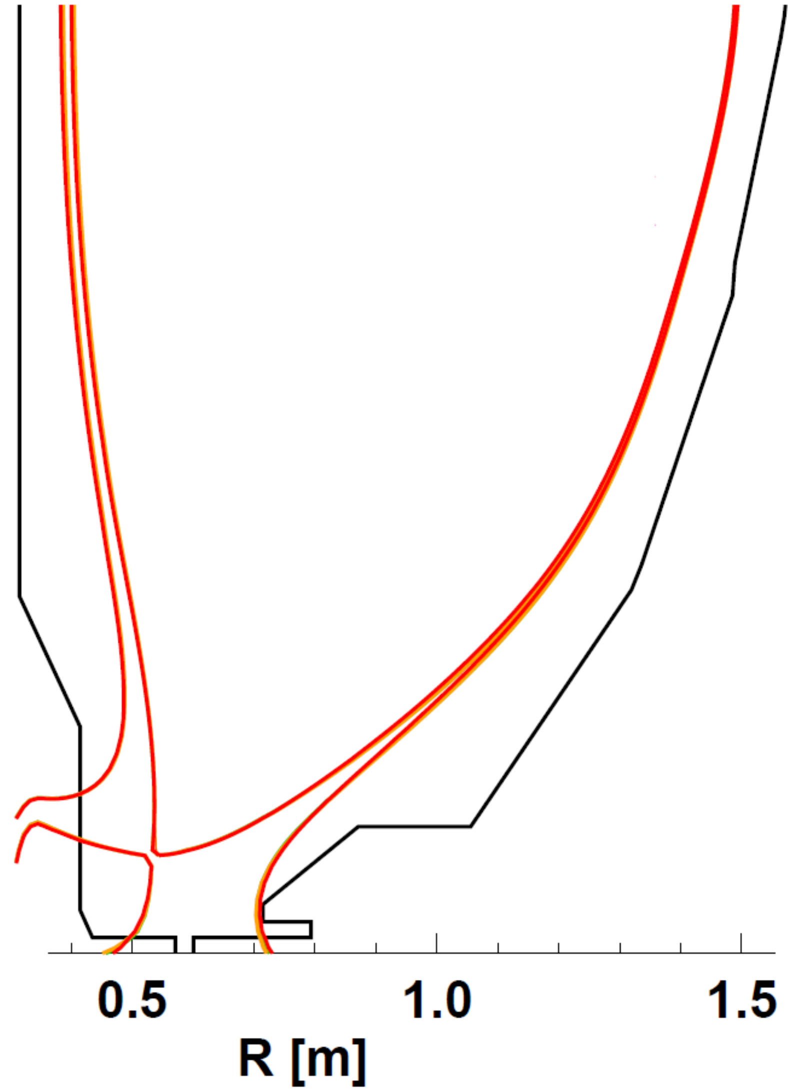
Optimized plenum geometry (R_{pump} = 0.72m) capable of pumping to low density n / n_G ~ 0.5 for a range of R_{OSP}, I_P



- **Equilibrium $f_{Greenwald}$ can be reduced down to < 0.5**
  - **Moving R_{OSP} closer to pump allows lower n_e, limited by power handling**

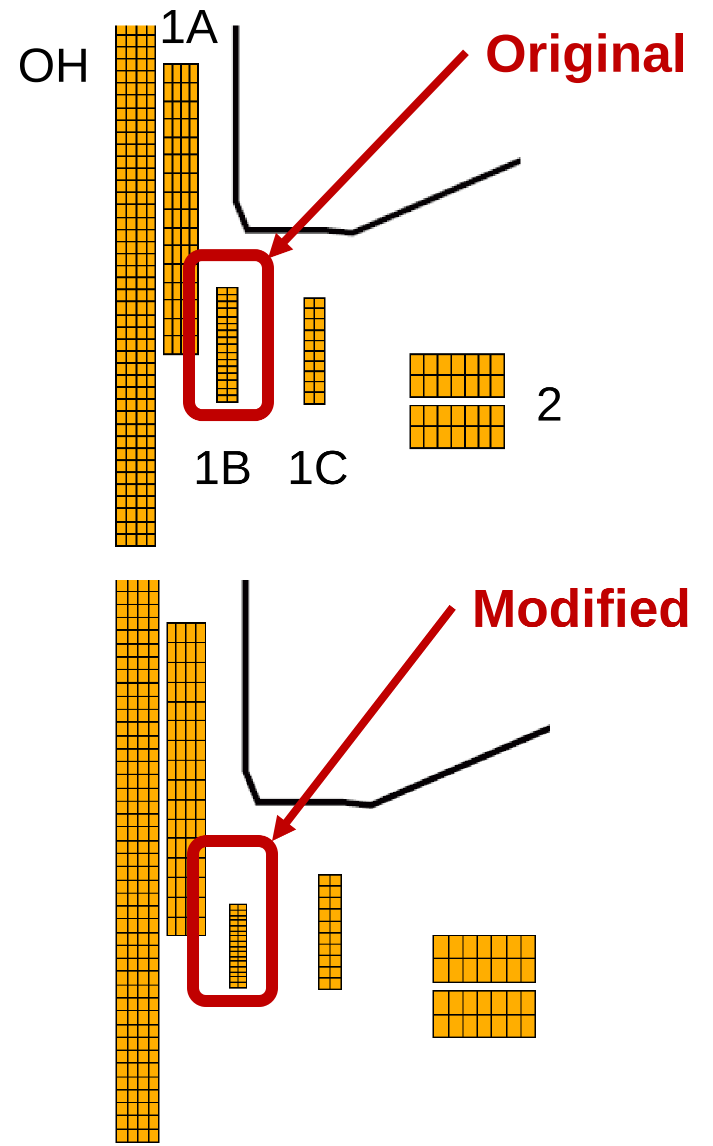
Equilibrium constraints

- Outboard strike-point R=0.5m
- Ψ_n = 1.03 near entrance of cryo-divertor: R=0.7-0.72m
- X-point location fixed
- Outboard boundary R=1.49m, outboard gap 8cm
- Outer squareness varied = 0.1-0.15 to achieve above → inboard gap and A vary



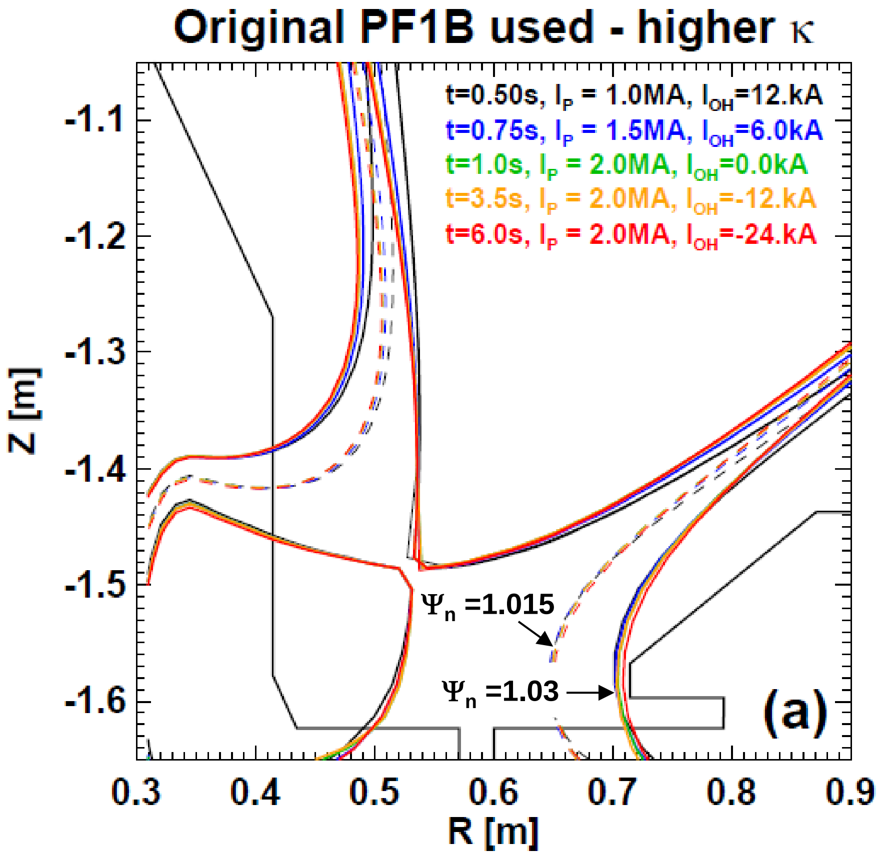
Equilibrium comparisons completed

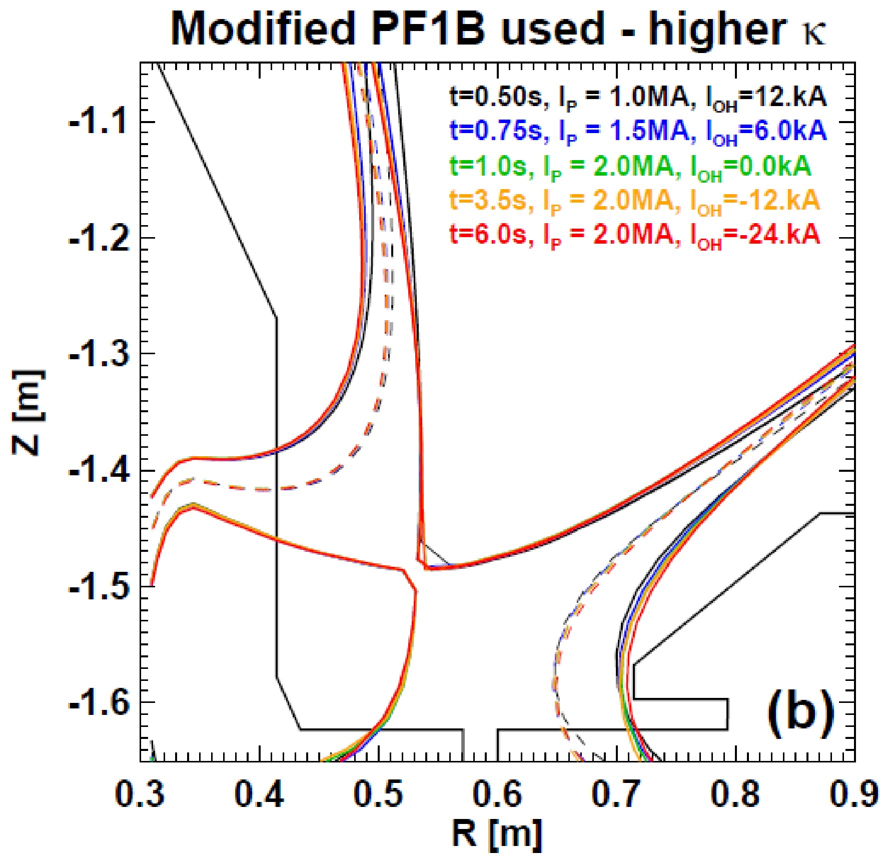
- Compare original and modified PF1B coil
  - Modified: 35% shorter, 25% narrower, shift: same OD, $|Z_{max}|$
  - Modified coil conductor area ~50% of original coil
- Compare cases with / without modified PF1B
- Compare lower and higher elongation
- 1MA and 2MA flat-top plasma currents



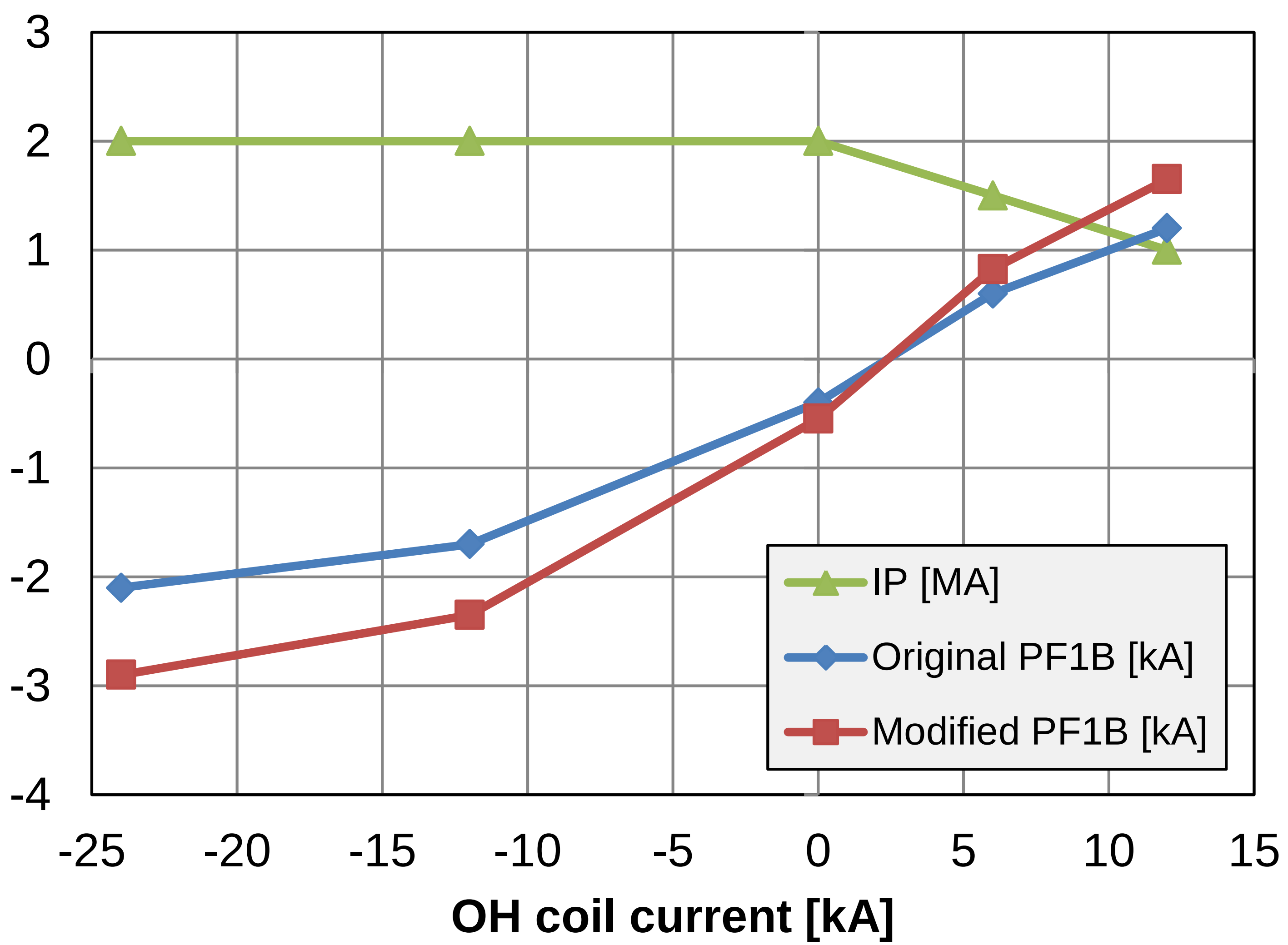
Modified PF1B coils generate poloidal flux pattern nearly identical to original PF1B coils

- Scenario: 2MA flat-top current, higher κ
- PF1B maintains flux pattern for $I_{OH} \leq +12$kA



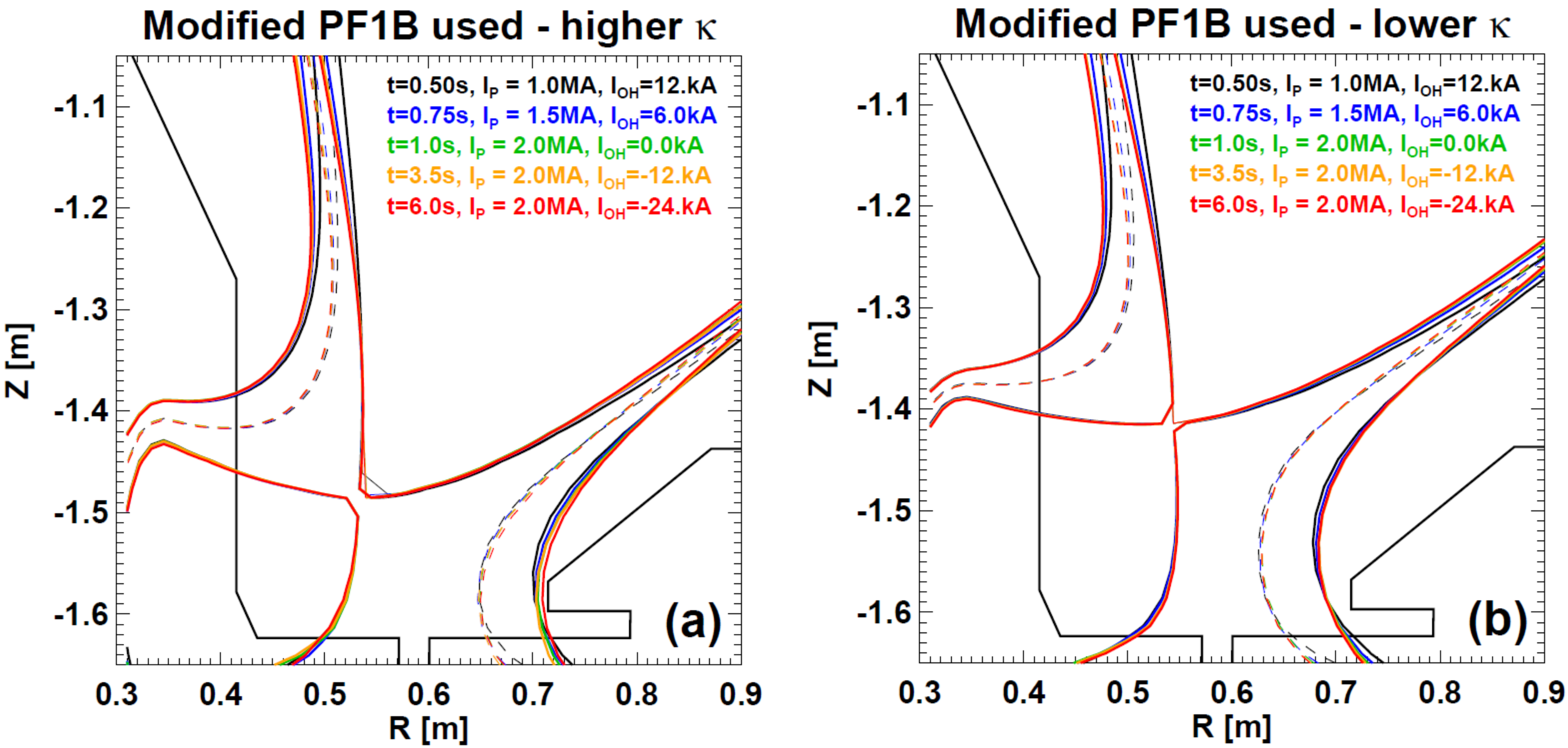


Modified PF1B current 1.4× original PF1B current



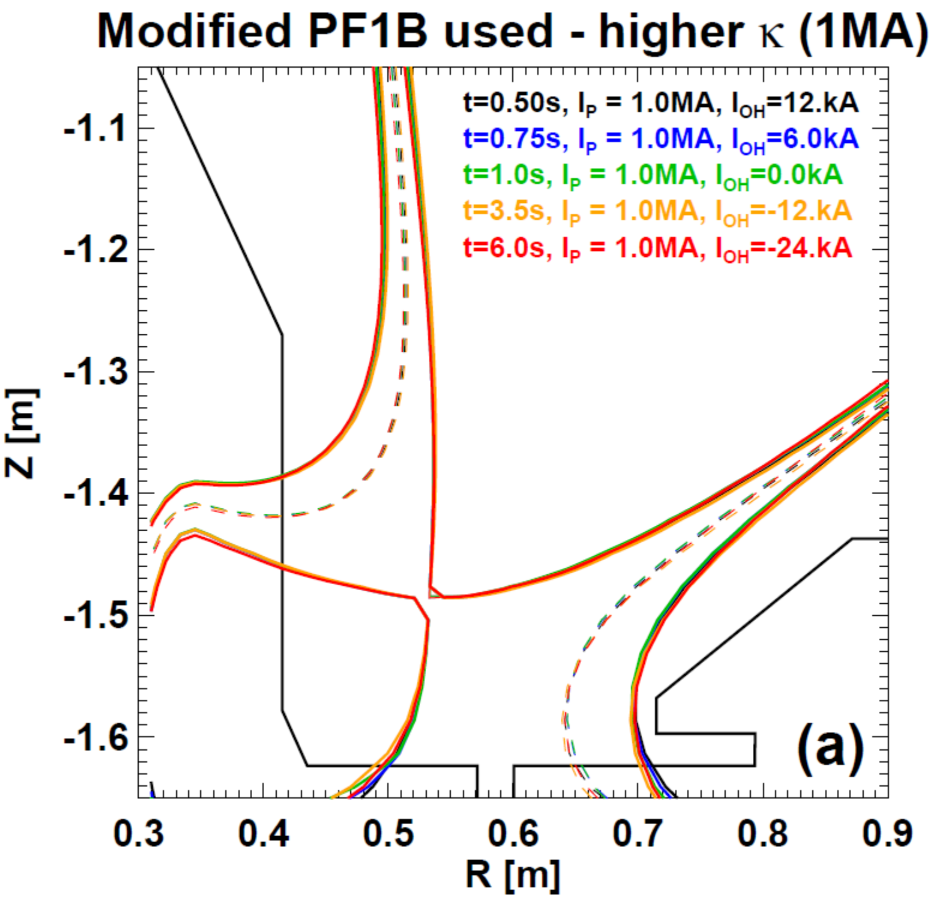
Modified PF1B coil supports both lower and higher elongation in **2MA** scenarios with flared divertor

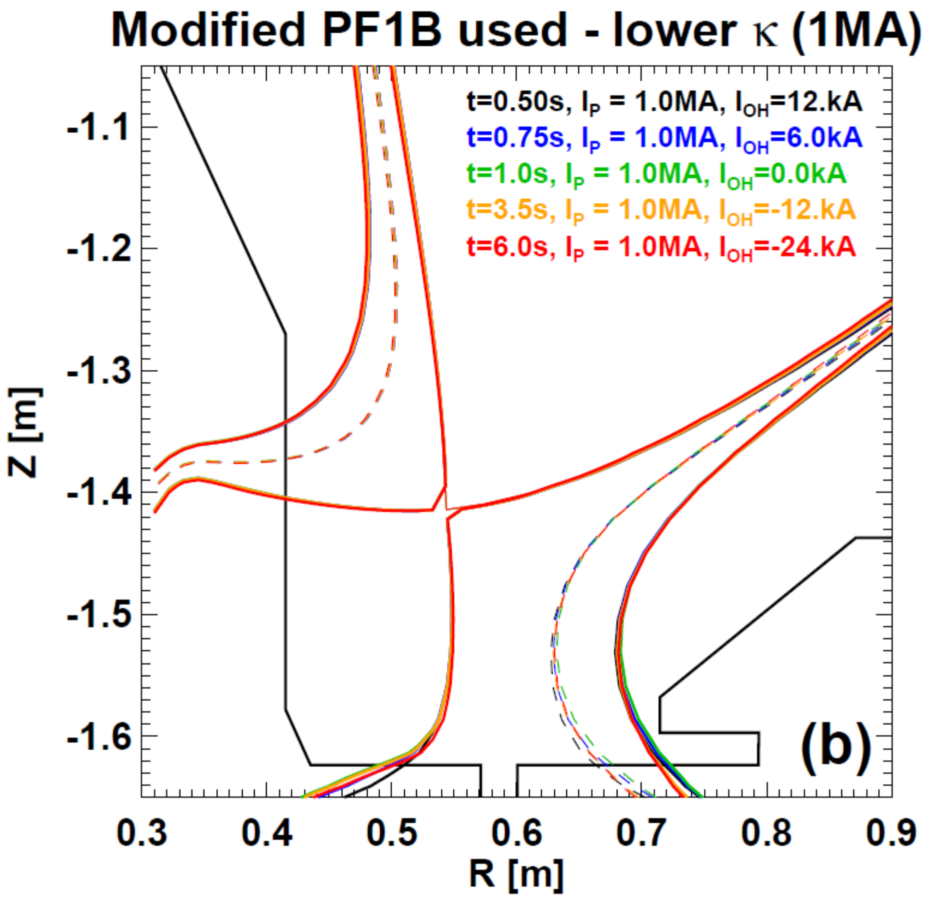
- Stationary poloidal flux profiles achievable for relevant OH coil current states



Modified PF1B coil supports both lower and higher elongation in **1MA** scenarios with flared divertor

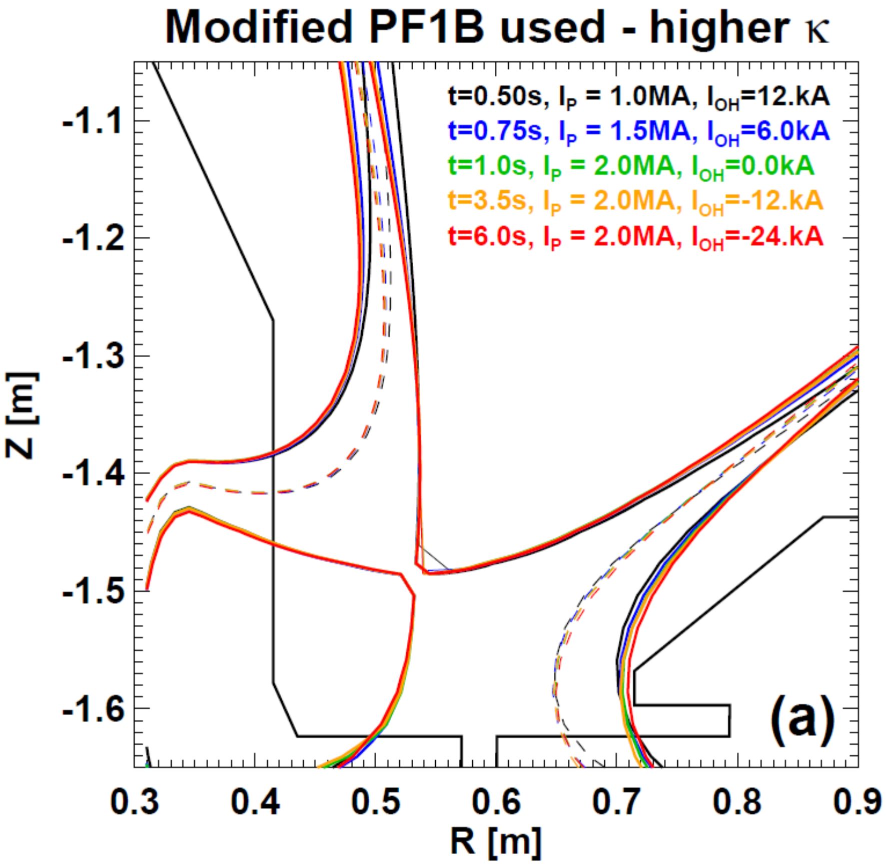
- Stationary poloidal flux profiles achievable for relevant OH coil current states

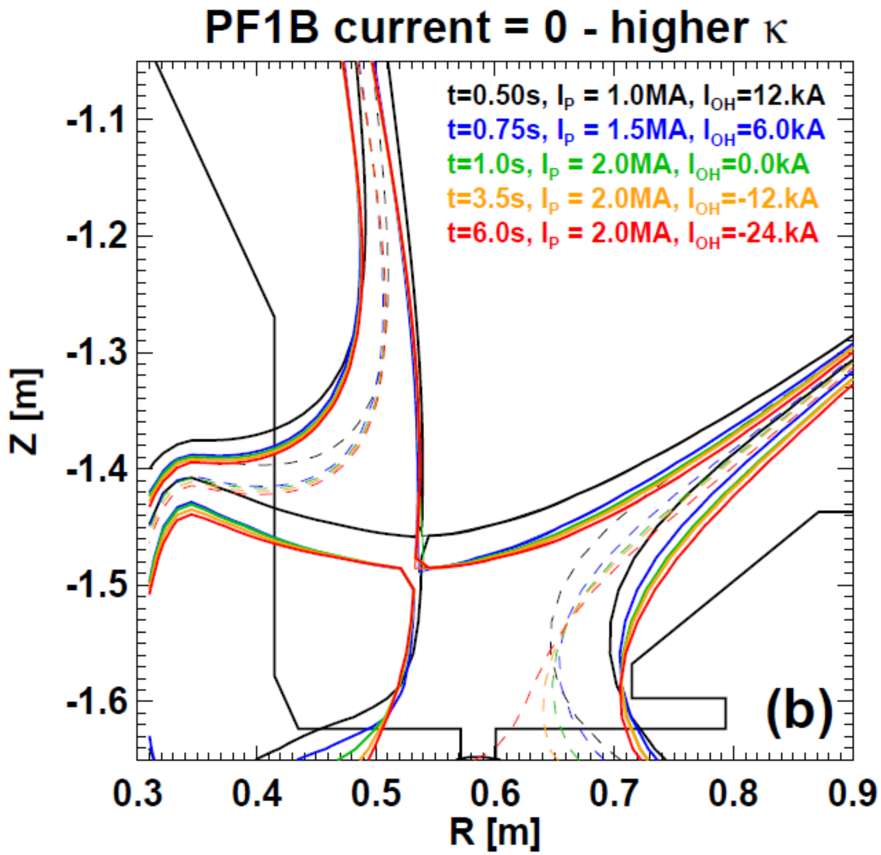




No PF1B → Ψ_n = 1.015 flux lines sweep 6-8cm across OBD as I_{OH} changes → heat flux profile would evolve

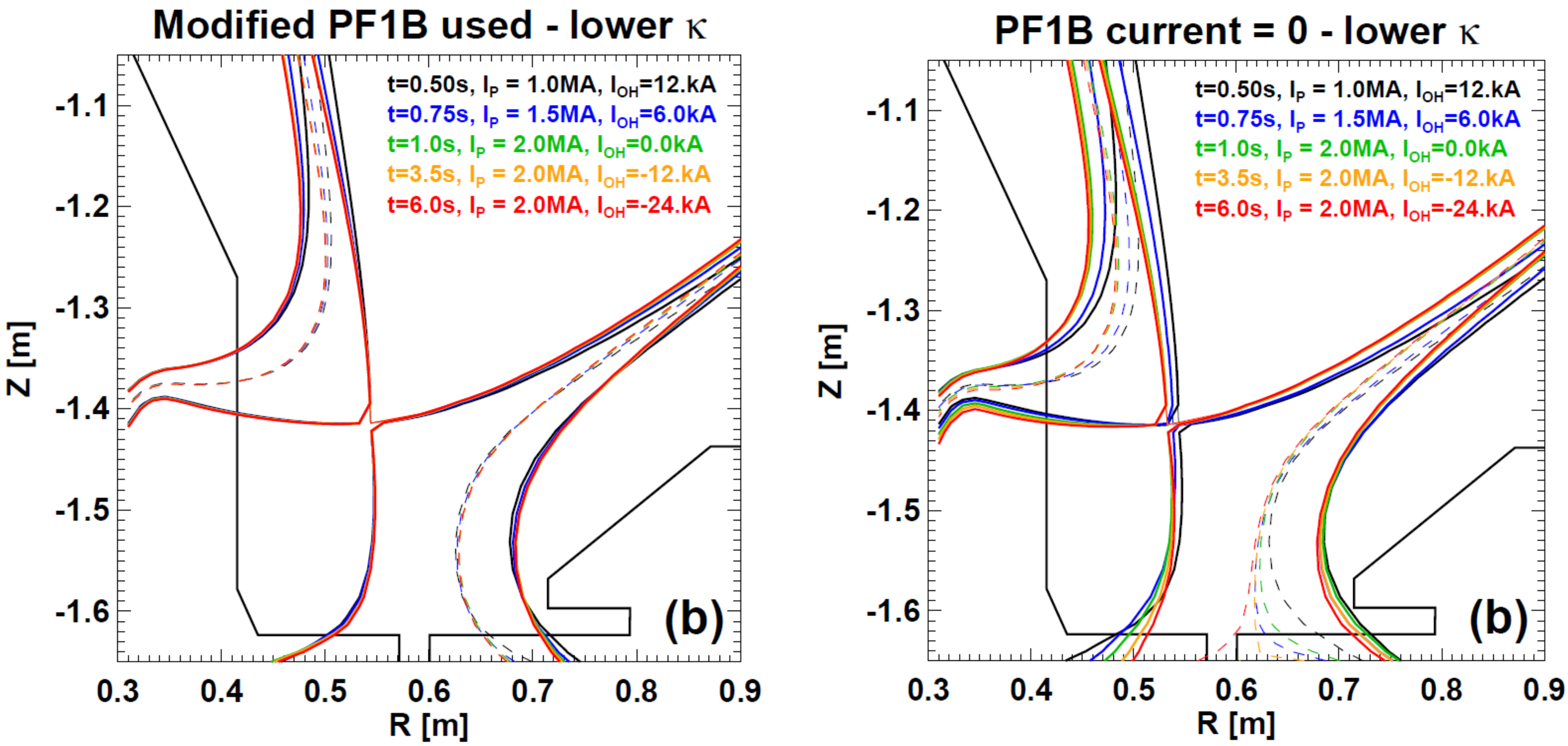
- Scenario: 2MA flat-top current, **higher κ**
- I_{PF1B} = 0 → need higher x-point height for I_{OH} = 12kA state, but shape more stationary for I_{OH} ≤ 6kA





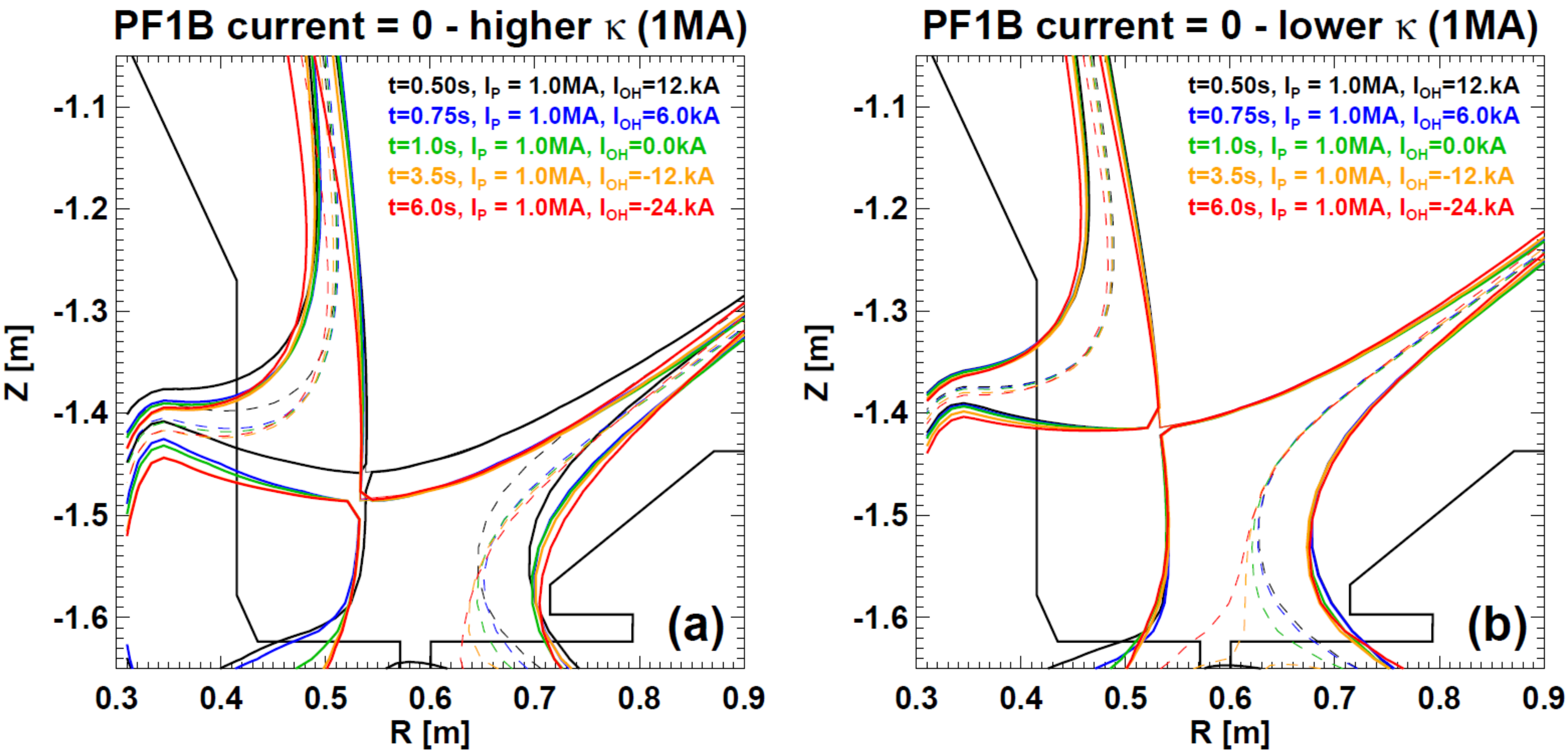
No PF1B → Ψ_n = 1.015 flux lines sweep 8-10cm across OBD as I_{OH} changes → heat flux profile would evolve

- Scenario: 2MA flat-top current, **lower κ**
- I_{PF1B} = 0 → larger shape changes required to maintain divertor

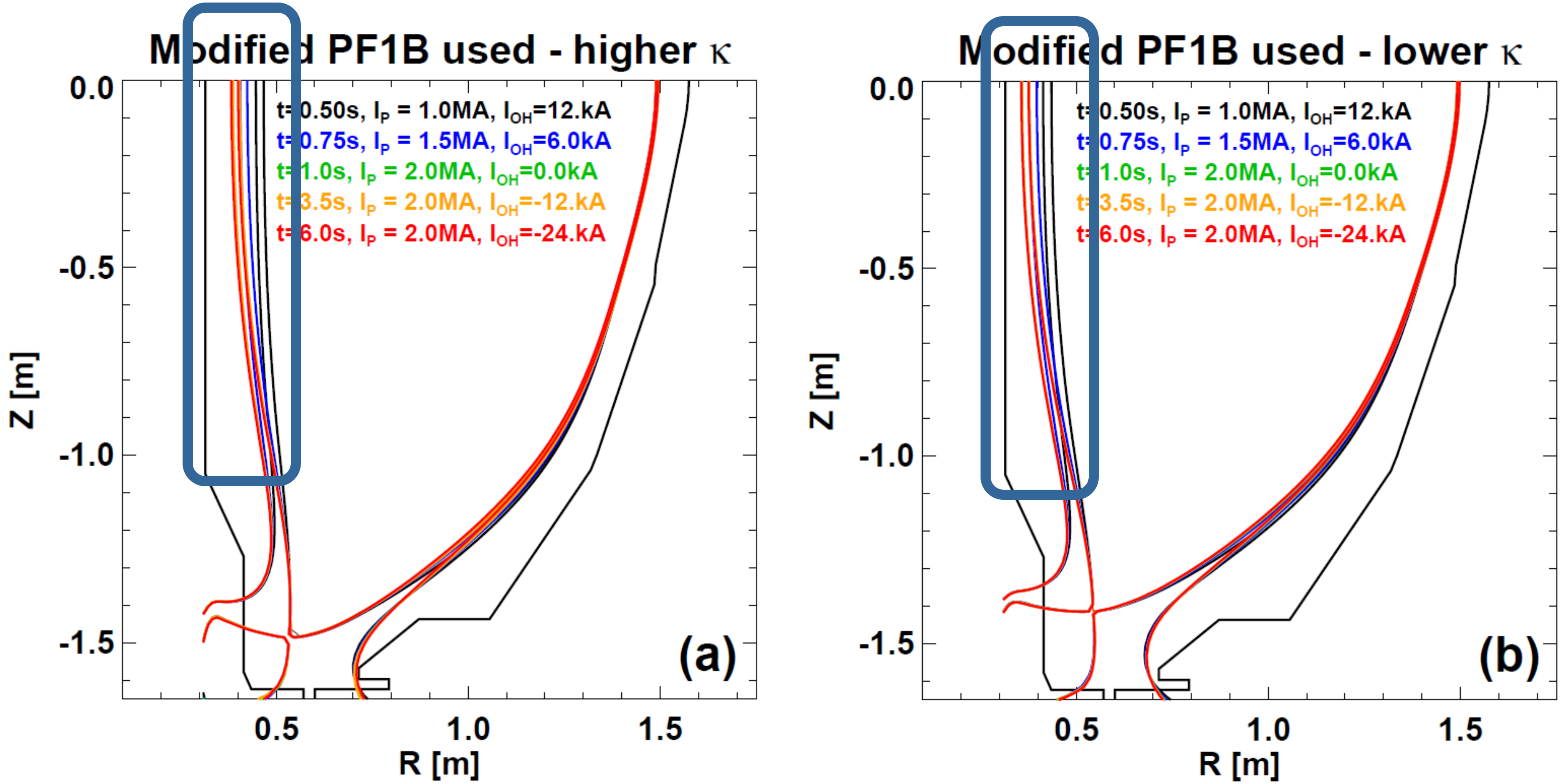


1MA flat-top, no PF1B → Ψ_n = 1.015 flux line sweeps for both elongation cases

- Scenarios: 1MA flat-top current, **higher and lower κ**
- Lower elongation scenario has more stationary boundary



Fixed divertor & OB gap and shape → inner gap varies with OH flux state for higher and lower κ

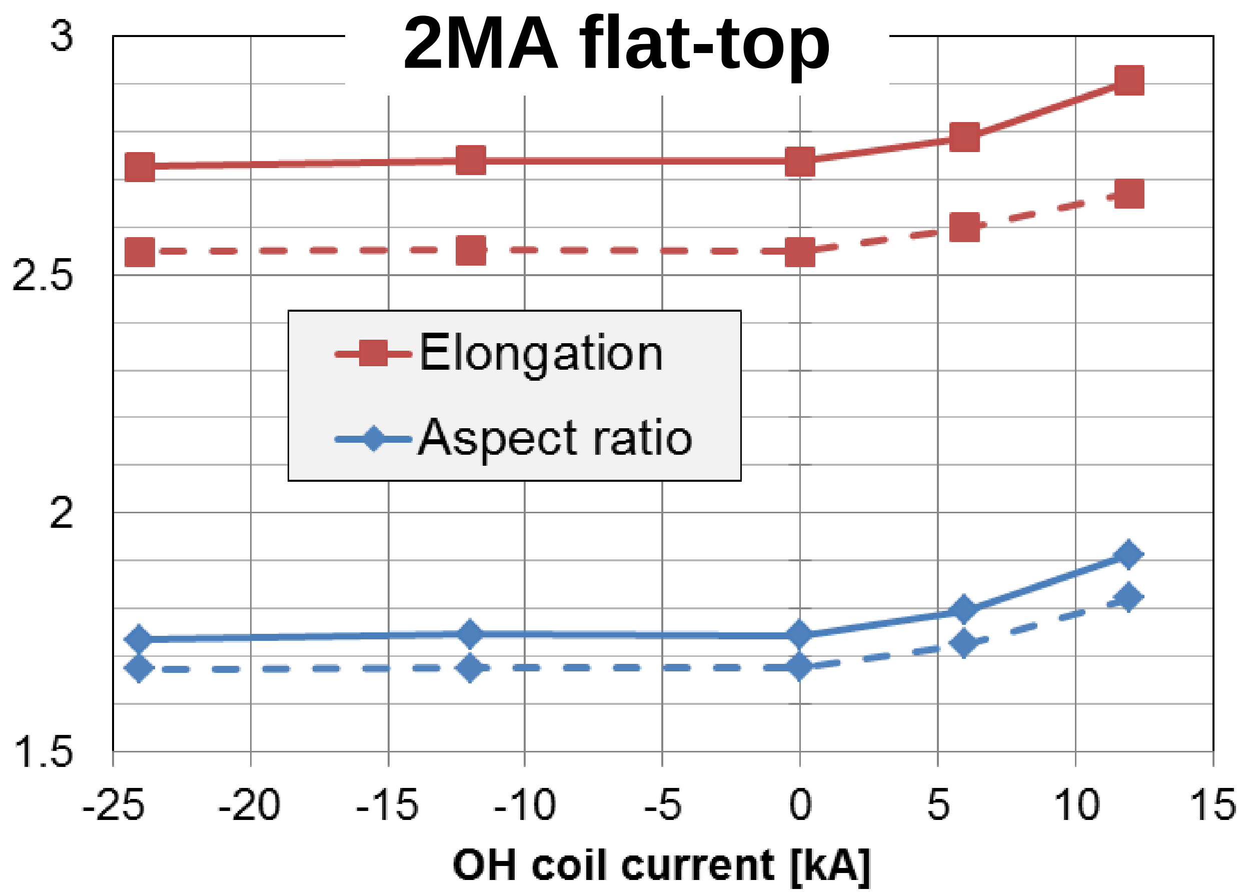


- I_{OH} = 12kA state (I_P=1MA) has highest A and κ

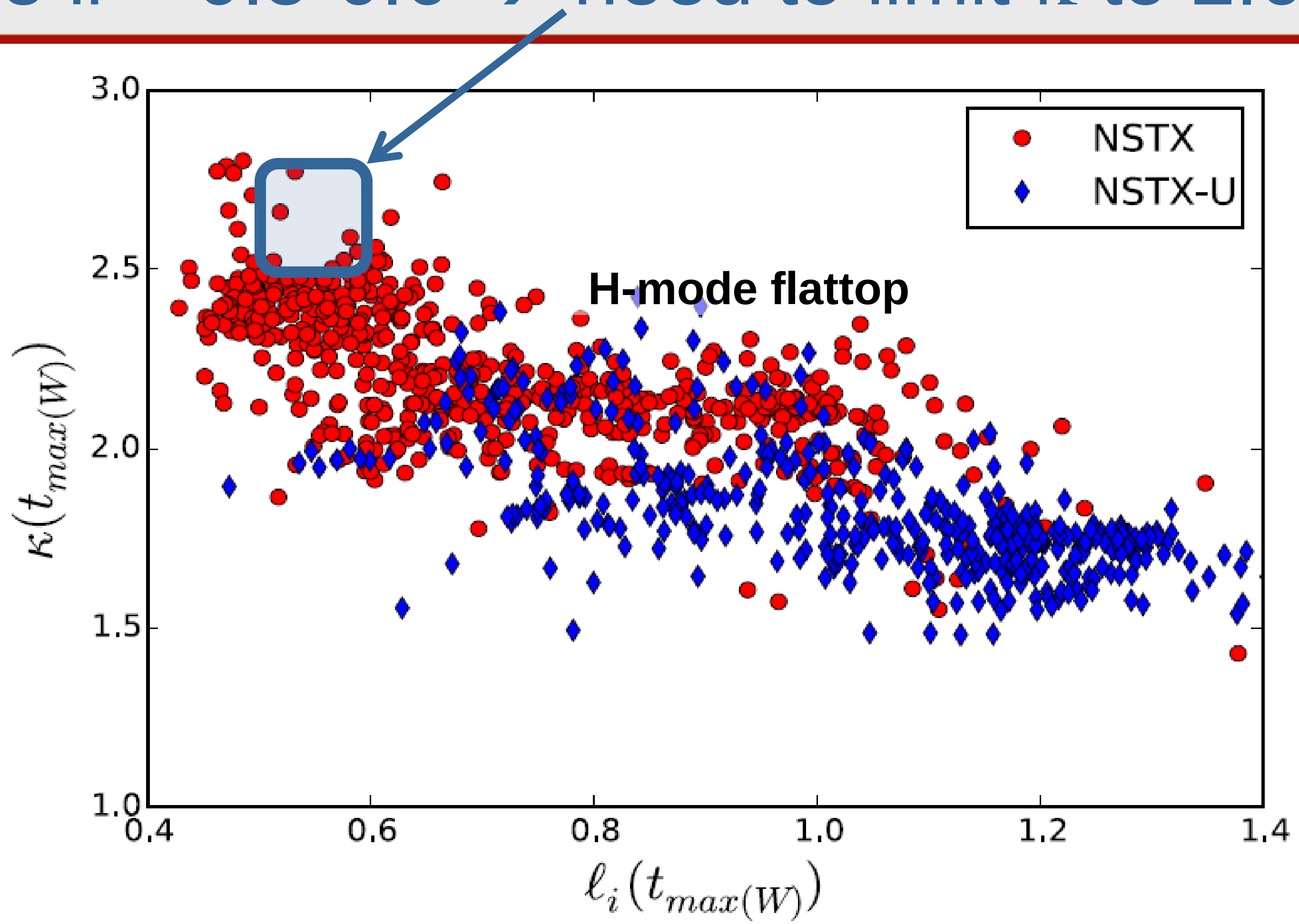
Fixed divertor & OB gap and shape → inner gap varies with OH flux state for higher and lower κ

- I_{OH} = 12kA state (I_P=1MA) has higher A and κ
  - More prone to vertical instability?

Modified PF1B included



Advanced divertor scenario cases studied have li = 0.5-0.6 → need to limit κ to 2.6-2.8

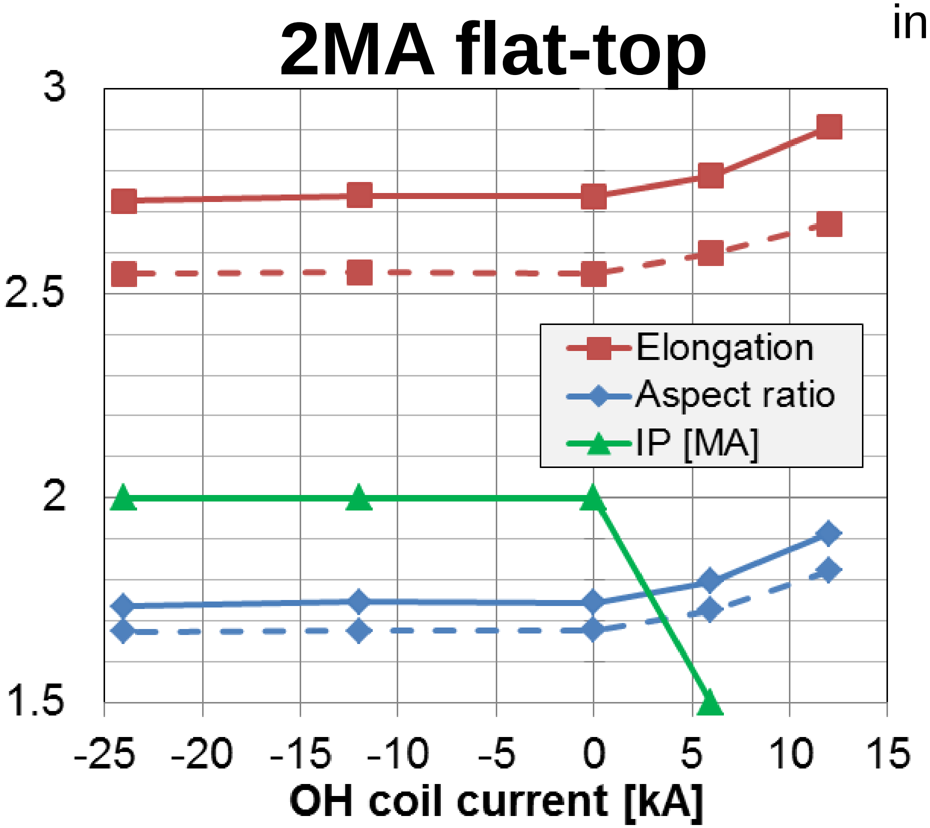


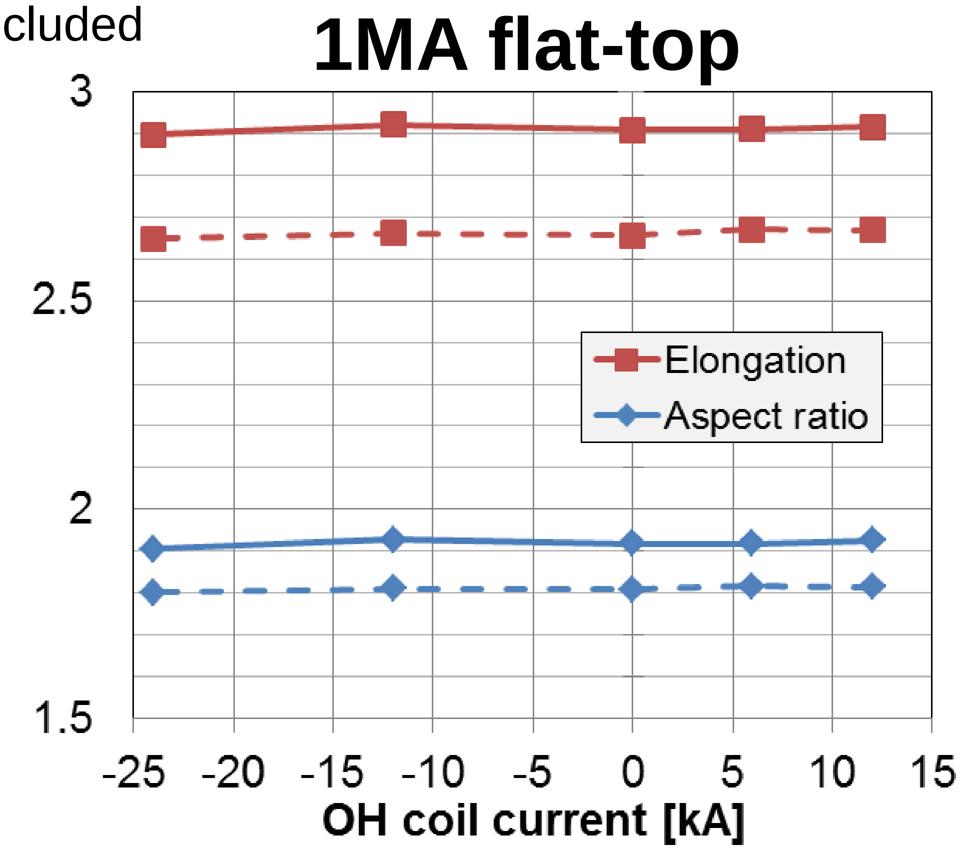
- **Goals for next NSTX-U run:**
  - **Access l_i = 0.5-0.7, κ=2.4-2.7, B_T = 0.75-1T, I_P = 1.5-2MA**

May need to develop additional high-κ advanced divertor configurations for 1MA flat-top scenarios

- I_P=1MA higher κ cases likely vertically unstable

Modified PF1B included

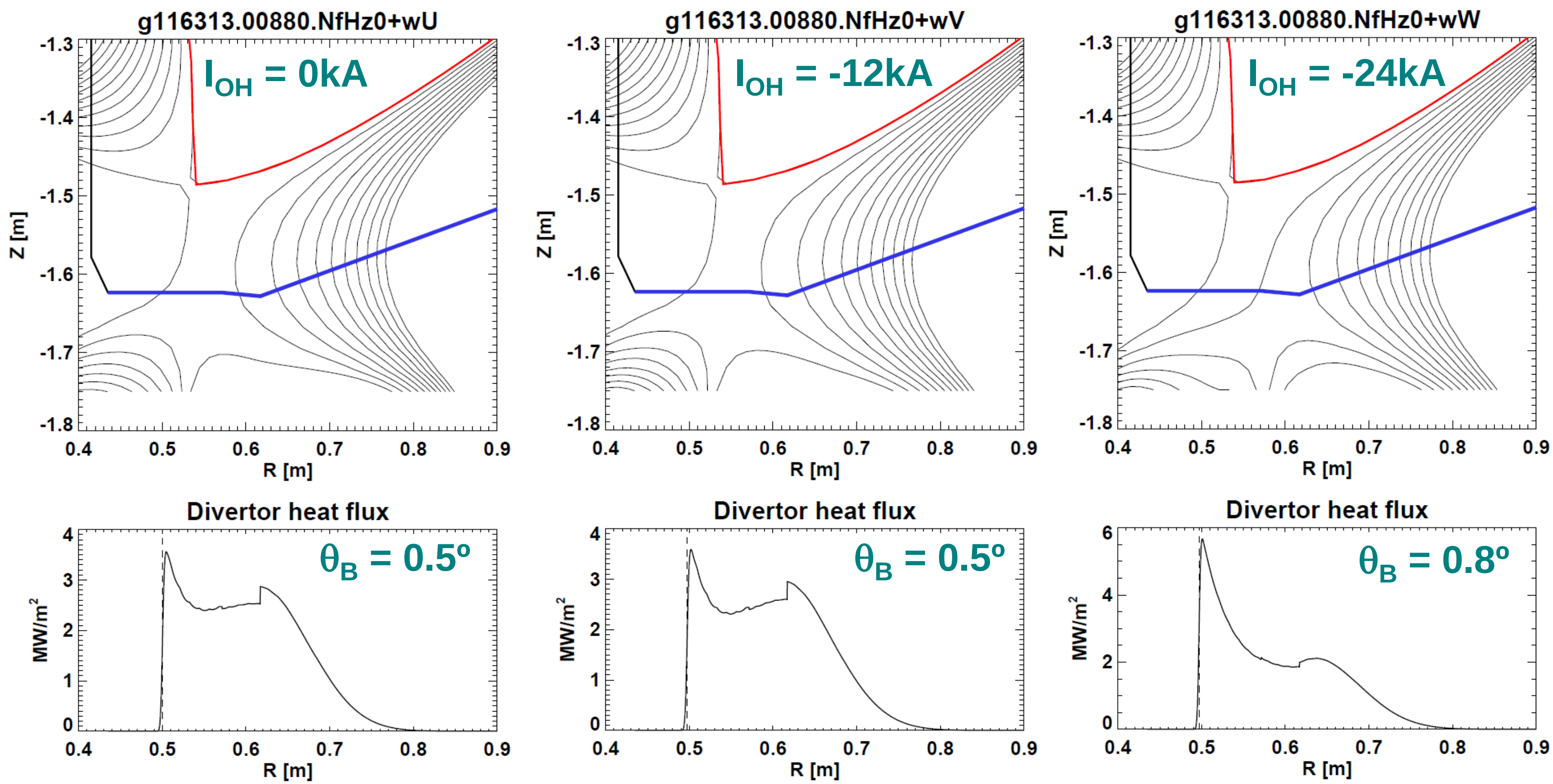




Higher κ with PF1B: stationary poloidal flux and (low) heat-flux profiles are achievable for ~several seconds

- I_P=2MA, P_{NBI}=10MW, modified PF1B, **higher-κ**
- f_{rad} = 0.5, f_{obd} = 0.8, N_{div} = 2, $\lambda_{q\text{-int}}$ ~ 2mm

$$Q_{out}^{peak} = \frac{P_{heat}^{SOL}(1 - f_{rad}) f_{obd} \sin(\theta_{plate})}{2\pi R_{strike} N_{div} f_{exp} \lambda_q}$$

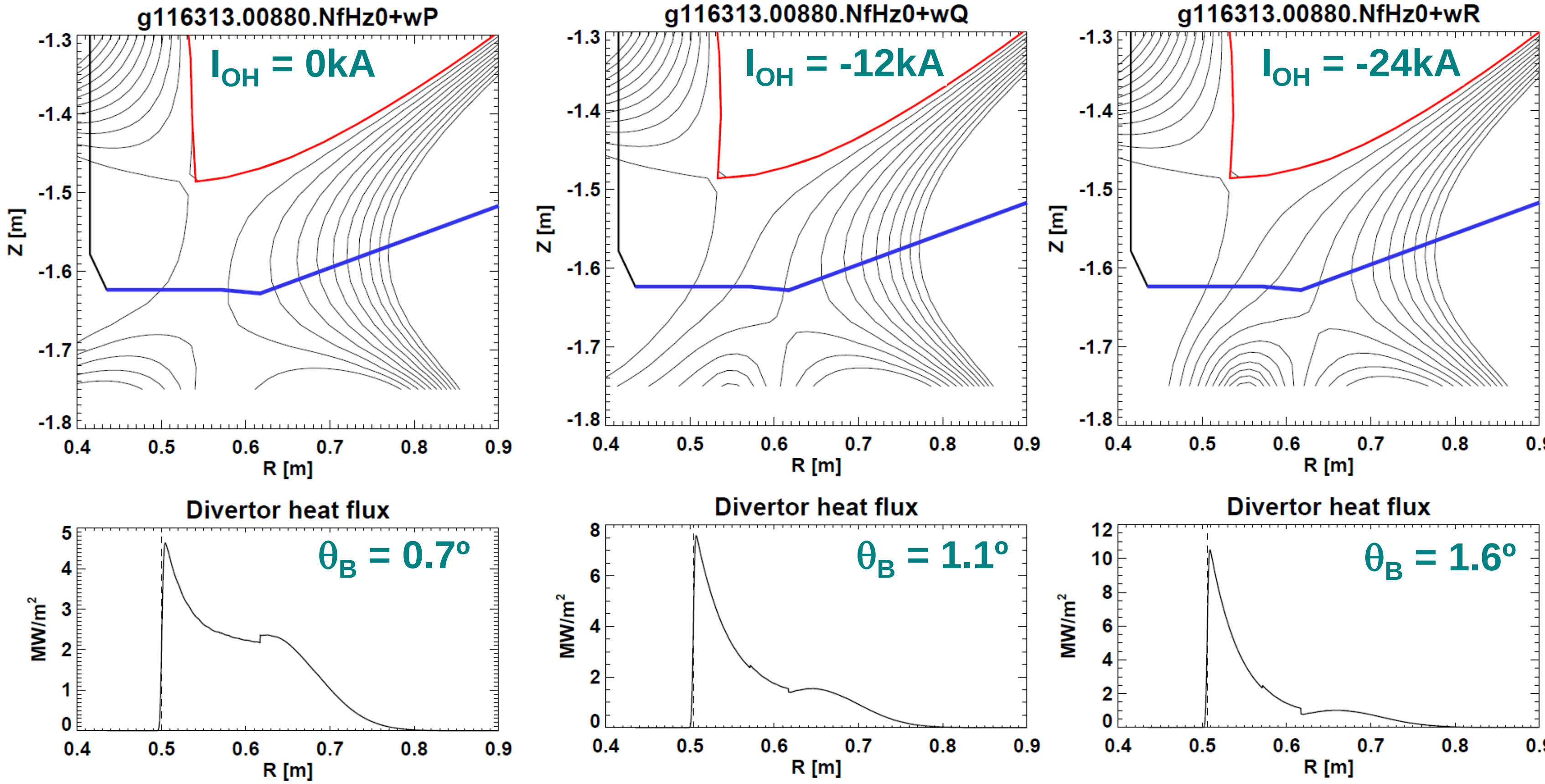


Heat flux profile stationary for -12kA ≤ I_{OH} ≤ 0 (Δt = 2-3s) [Note: θ_B = 1° heat flux ~6-7MW/m²]

Higher κ with no PF1B: stationary heat flux profiles achievable for ~several seconds, but heat fluxes higher

- I_P=2MA, P_{NBI}=10MW, no PF1B, **higher-κ**
- f_{rad} = 0.5, f_{obd} = 0.8, N_{div} = 2, $\lambda_{q\text{-}int}$ ~ 2mm

$$Q_{out}^{peak} = \frac{P_{heat}^{SOL}(1 - f_{rad}) f_{obd} \sin(\theta_{plate})}{2\pi R_{strike} N_{div} f_{exp} \lambda_q}$$

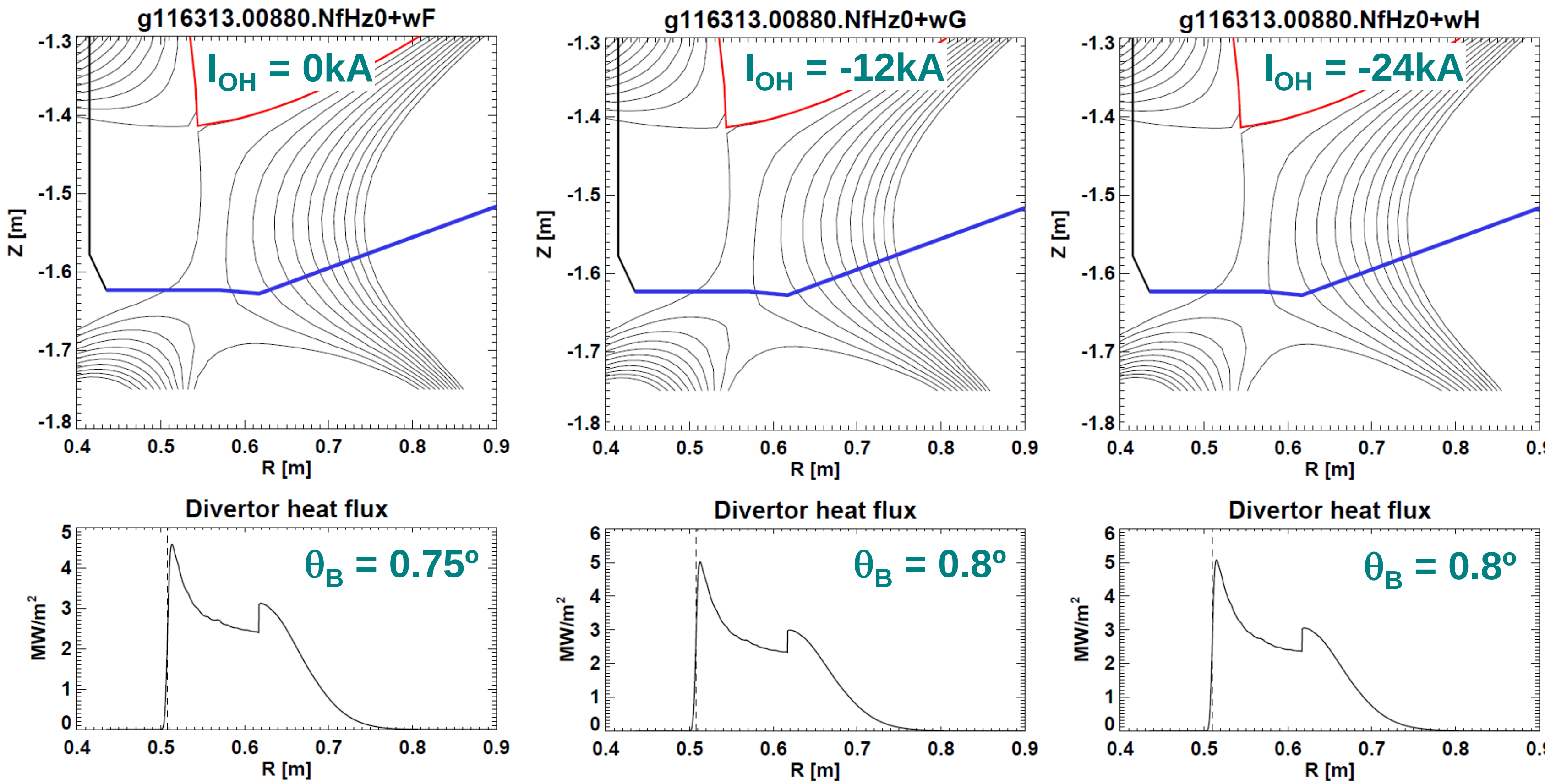


Heat flux profile stationary for I_{OH} ≤ -12kA (Δt = 2-3s), θ_B increases for more negative I_{OH}

Lower κ with PF1B: moderate heat flux (~5-6MW/m²) and stationary heat-flux profiles

- I_P=2MA, P_{NBI}=10MW, modified PF1B, **lower-κ**
- f_{rad} = 0.5, f_{obd} = 0.8, N_{div} = 2, $\lambda_{q\text{-}int}$ ~ 2mm

$$Q_{out}^{peak} = \frac{P_{heat}^{SOL}(1 - f_{rad}) f_{obd} \sin(\theta_{plate})}{2\pi R_{strike} N_{div} f_{exp} \lambda_q}$$

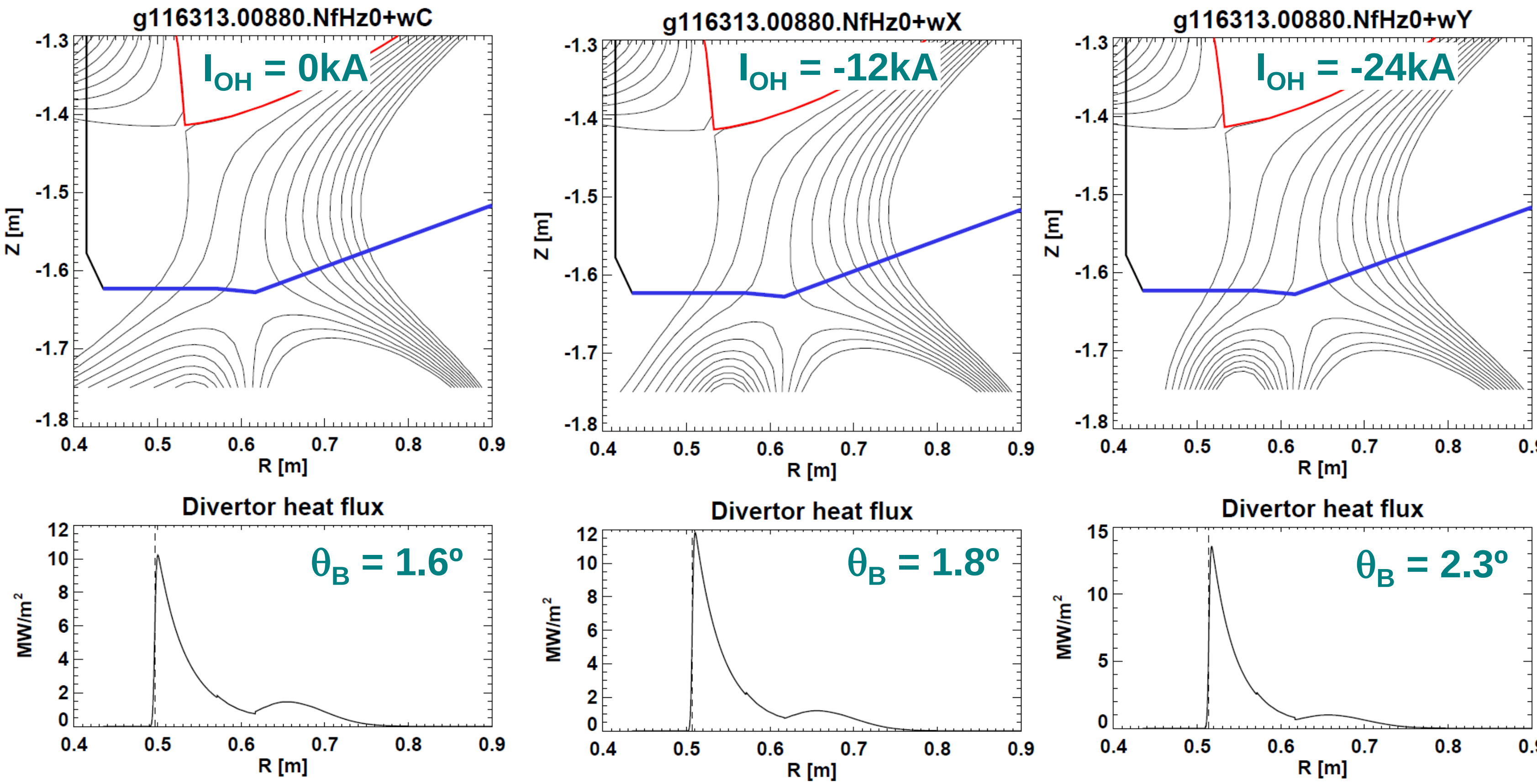


Heat flux profiles stationary for ~full flat-top duration

Lower κ with no PF1B: higher heat flux (~10-13MW/m²) due to reduced f_{exp}, stationary heat-flux profile shapes

- I_P=2MA, P_{NBI}=10MW, no PF1B, **lower-κ**
- f_{rad} = 0.5, f_{obd} = 0.8, N_{div} = 2, $\lambda_{q\text{-}int}$ ~ 2mm

$$Q_{\rm out}^{\rm peak} = \frac{P_{\rm heat}^{\rm SOL}(1 - f_{\rm rad}) f_{\rm obd} \sin(\theta_{\rm plate})}{2\pi R_{\rm strike} N_{\rm div} f_{\rm exp} \lambda_q}$$



Heat flux profile shape stationary for ~full flat-top duration, $\theta_B \geq 1.6^o$ for all I_{OH} in I_P flat-top

Conclusions

- Modified / smaller PF1B performs similarly to original PF1B, but requires 40% higher current per turn (assuming same # turns)
  - Modified coil current density for SFD- / X still likely ok
- Heat-flux reduction + cryo-pumpability appear feasible
  - True for several κ values and with or w/o PF1B for 2MA plasmas
- Heat-flux profile evolution time-scale ~1-few seconds
  - Likely acceptable from diagnostic and physics stand-point
- Physics/operational impacts of not having PF1B:
  - Maximum flux expansion reduced – especially for lower-κ
  - For lower-κ (and higher-κ + more negative I_{OH}) not possible to reduce θ_B down to 1º → factor of 1.5-2× increase in peak heat flux at strike-point
  - Increased radiation / partial detachment may be required at 2MA, 10MW
    - Increased risk of detachment front instability w/o strong flaring + control? (TBD)
  - And/or higher-κ SFD- / X operation must be made reliable
  - ➢ Overall, vertical and l_i control demands increased for SFD-/exhaust control