Scoping for PCS heat flux control

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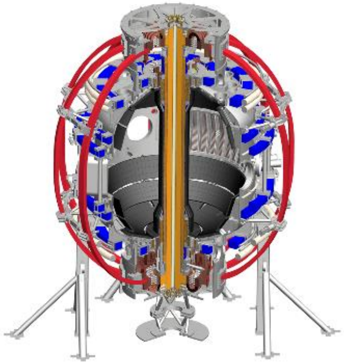


Control of heat flux to PFCs expected to be important part of commissioning/operating NSTX-U at high power

- Other activities will define **engineering limits of PFCs** and **monitoring requirements**
- **Validated models** are expected to become available for use in **real-time prediction of heat flux**
  - Likely to feed into existing **‘shutdown handler’** system to avoid exceeding pre-determined thresholds
- It is expected that, at least over some operational range, **active control of the heat flux will be used to avoid exceeding thresholds for as long as possible**, e.g., to achieve 5s 10MW discharges
  - Operations guidance from PFC working group will determine final requirements for active control, but we can begin scoping

Goals of present scoping activity

- Develop **mechanism for simulating control** for arbitrary plasma equilibria from EFIT or TRANSP
- **Control algorithm** for simultaneous control of heat flux related quantities defined in PFCR-MEMO-017-01
- **Mechanism for generating GEQDSK files from output** of simulations for further heat load analysis
- Feasibility study for two cases and **assessment of impact on control of other shape parameters**

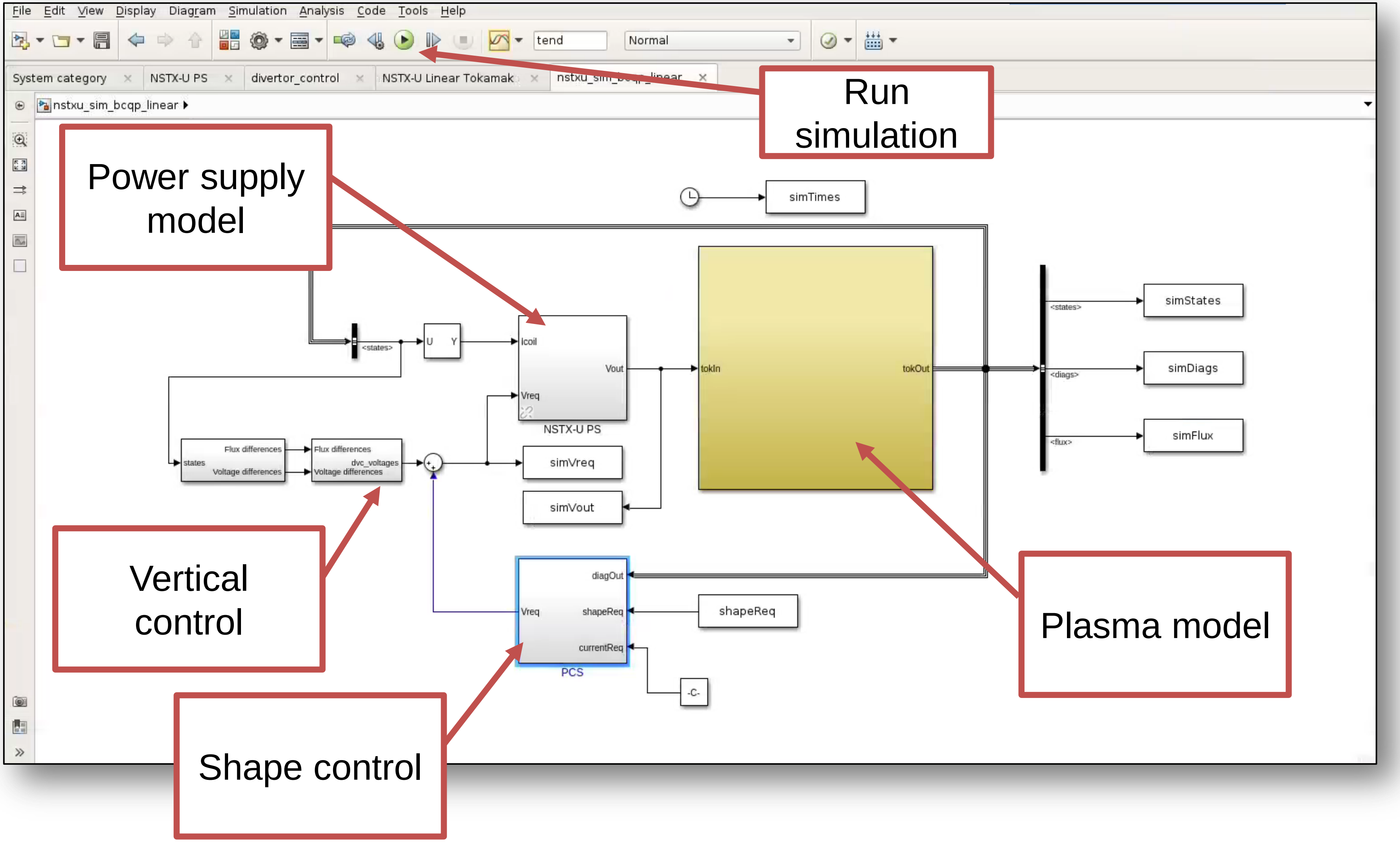
Mechanism for simulating control

- NSTX-U TOKSYS tools being developed by Pat Vail
  - EFIT description of conducting structures, magnetics
  - Linear and nonlinear models of shape evolution in response to coil voltage changes
  - Modeling approaches
    - **Fixed plasma:** Vacuum response with fixed current distribution from reference equilibrium
    - **Rigid plasma:** Linearized response assuming equilibrium current distribution
    - **Non-rigid plasma:** Linearization formed from perturbed solutions of G.S. equation
    - **Time-varying linear:** Update linearization at points during simulation (e.g., ramp-up studies)
    - **Nonlinear simulation:** Solve G.S. equation at each step, or linearize at many points during simulation

Setting up simulation

- Reading in reference equilibrium
  - Assuming non-inductive, $I_{vv,eq}=0$, $I_{OH,eq}=0$ for now, will add OH swing in later iterations
  - Can read in **EFIT** GEQDSK and AEQDSK data
  - **TRANSP** can generate GEQDSK – need to make AEQDSK files or mimic the data
- Matlab script for generating model linearized around reference
- Model implemented in Simulink along with necessary control algorithms
- Matlab script for setting up control parameters

Simulink model



Run simulation

Power supply model

Vertical control

Plasma model

Shape control

Simulation mechanism on-going work

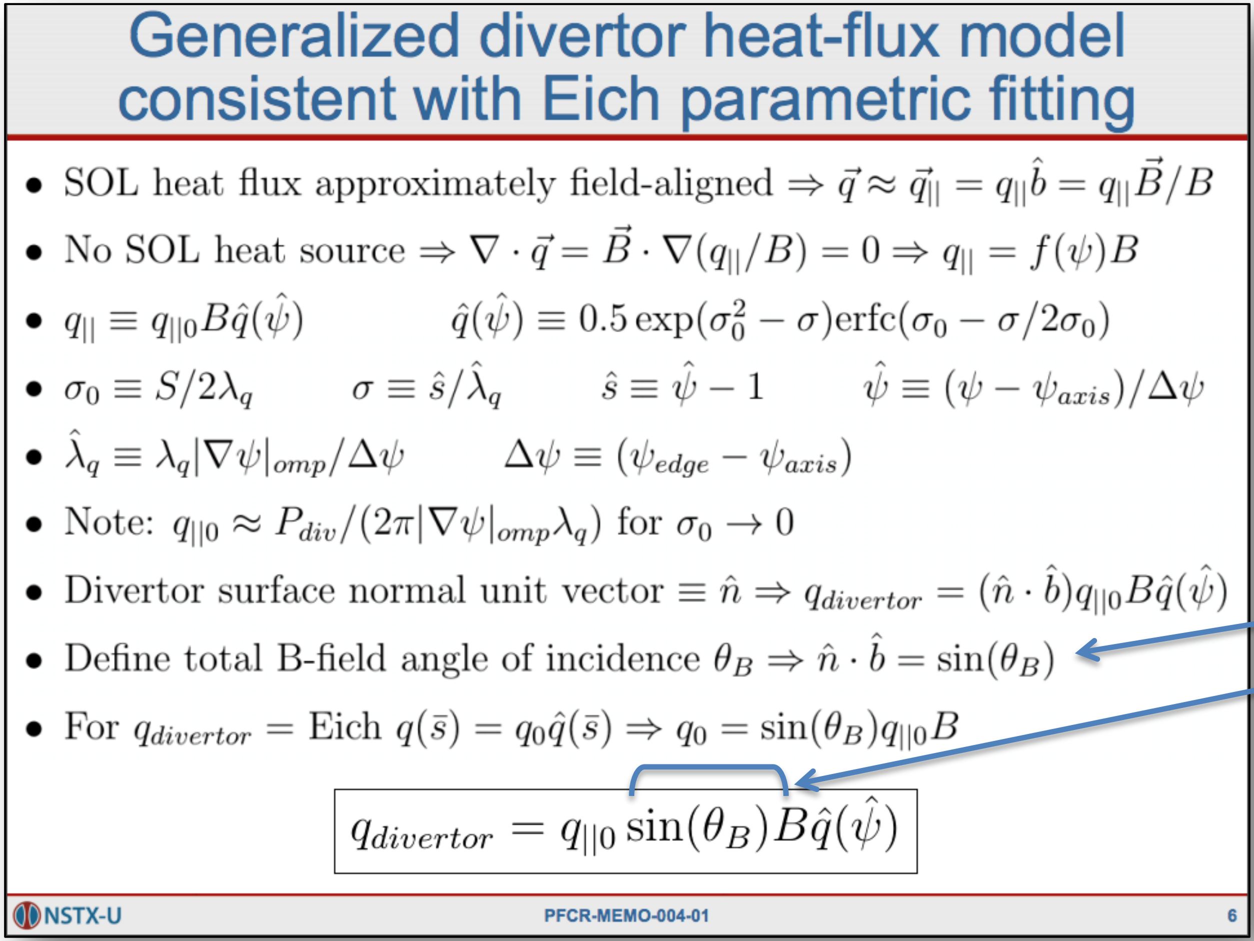
- Validate plasma models, begin using non-rigid model
- Include more sophisticated power supply model (only using a delay at the moment)
- Read in equilibria from TRANSP, write out GEQDSK
  - Related functions exist but need to put them together and debug
- Include option for OH swing in simulations
- Once control prototyping is complete, can connect models to PCS for PCS-in-the-loop simulations

Control system goals

- New algorithm needed to simultaneously control:
  - **dr_{sep}/λ_q:** Assuming λ_q is not a function of shaping parameters, this is equivalent to controlling dr_{sep}
  - **Inner and outer strike point locations:** NSTX-U commissioned X-point RZ control and X-point Z + outer strike point R control. Need to enable sweeping (triangle wave)
    - **Up for discussion –** Other waveform shapes for sweeping, how to select sweep amplitude, frequency, inner/outer phasing
  - **Average angle of incidence or normal field between strike point and a nearby point:** I think the latter can be achieved by controlling flux difference between nearby point and strike point. Angle of incidence most important in toroidal direction, may be best to control with small toroidal field changes.
    - **Up for discussion –** how should targets be defined? Maximize wetted area, constrained by tile edge limitations? Does this quantity need to stay fixed during strike point sweeps or just within some limits? Could we just sweep faster through points that have higher normal field?
  - **Outer boundary:** midplane outer gap, upper/lower outer gaps
  - **Inner gap:** Previously indirectly controlled through variation of X-point location, upper/lower outer gaps

Angle of incidence, normal field, or flux difference?

From
PFCR-MEMO-004-01



Generalized divertor heat-flux model consistent with Eich parametric fitting

- SOL heat flux approximately field-aligned ⇒ $\vec{q} \approx \vec{q}_{||} = q_{||}\hat{b} = q_{||}\vec{B}/B$
- No SOL heat source ⇒ $\nabla \cdot \vec{q} = \vec{B} \cdot \nabla(q_{||}/B) = 0 \Rightarrow q_{||} = f(\psi)B$
- $q_{||} \equiv q_{||0}B\hat{q}(\hat{\psi})$ $\quad \hat{q}(\hat{\psi}) \equiv 0.5\exp(\sigma_0^2 - \sigma)\mathrm{erfc}(\sigma_0 - \sigma/2\sigma_0)$
- $\sigma_0 \equiv S/2\lambda_q \quad \sigma \equiv \hat{s}/\hat{\lambda}_q \quad \hat{s} \equiv \hat{\psi} - 1 \quad \hat{\psi} \equiv (\psi - \psi_{axis})/\Delta\psi$
- $\hat{\lambda}_q \equiv \lambda_q|\nabla\psi|_{omp}/\Delta\psi \quad \Delta\psi \equiv (\psi_{edge} - \psi_{axis})$
- Note: $q_{||0} \approx P_{div}/(2\pi|\nabla\psi|_{omp}\lambda_q)$ for $\sigma_0 \rightarrow 0$
- Divertor surface normal unit vector $\equiv \hat{n} \Rightarrow q_{divertor} = (\hat{n} \cdot \hat{b})q_{||0}B\hat{q}(\hat{\psi})$
- Define total B-field angle of incidence $\theta_B \Rightarrow \hat{n} \cdot \hat{b} = \sin(\theta_B)$
- For $q_{divertor} =$ Eich $q(\bar{s}) = q_0\hat{q}(\bar{s}) \Rightarrow q_0 = \sin(\theta_B)q_{||0}B$

$$\boxed{q_{divertor} = q_{||0}\overbrace{\sin(\theta_B)}B\hat{q}(\hat{\psi})}$$

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Angle of incidence

Normal field

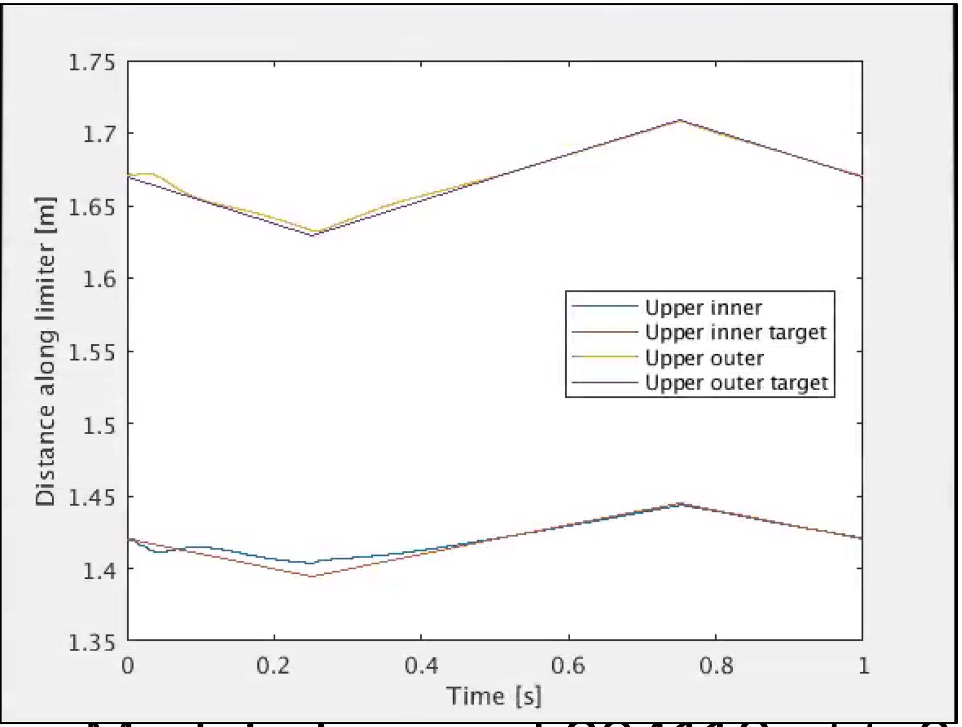
Integrating normal field over divertor just outside S.P. -> flux difference.

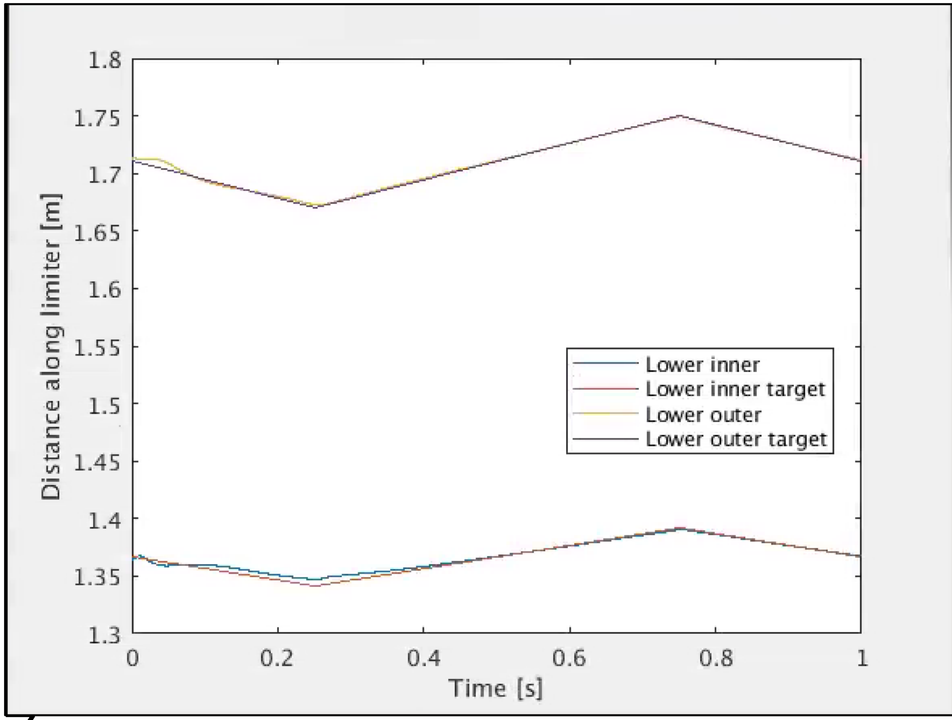
Control flux difference and monitor predicted angle of incidence?
Optimal control scheme could minimize normal field or heat flux and enforce constraints on angle of incidence.

Feedback control approach

- **Outer boundary:** SISO ISOFLUX control
- **dr$_{sep}$:** Adjust upper/lower outer boundary target points to achieve target dr$_{sep}$
- **Strike points and ‘flux expansion’ points:** Constrained model-based optimization of divertor coil currents (constrained by current limits for now, planning to eventually include limits on outputs, coil forces)
  - Optimization weights flux errors at target points, could include weights on X-point errors, or affect on inner gap, triangularity, etc.
  - Constraints on outputs could include limits on angle of incidence, avoiding introducing rogue X-points
- **Inner gap control:**
  - Not sure yet – may need to optimize sweep to minimize impact on inner gap

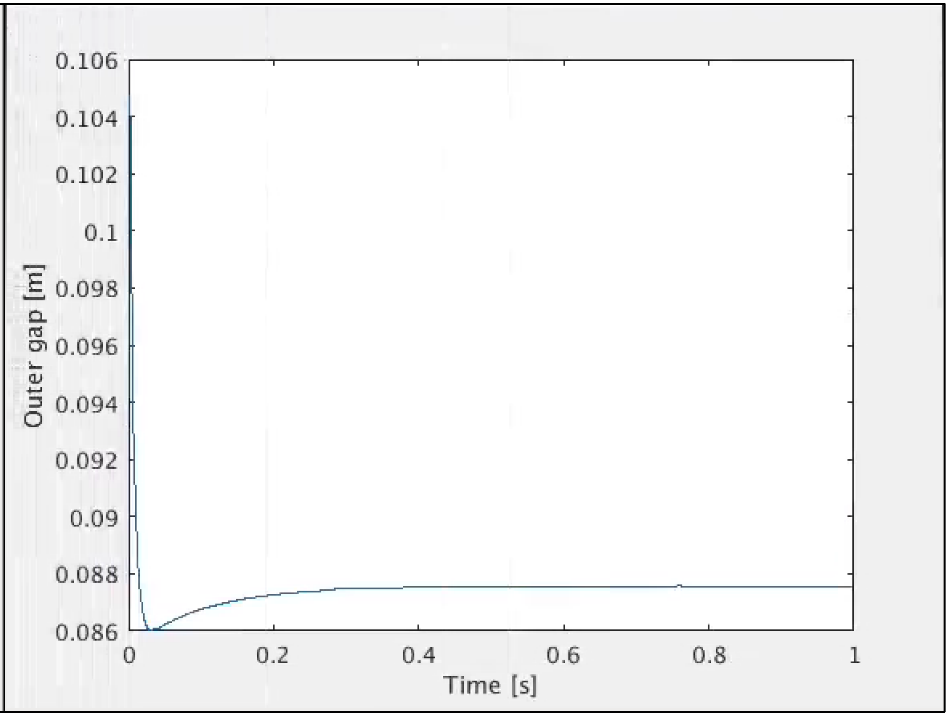
Initial test: strike point location tracking

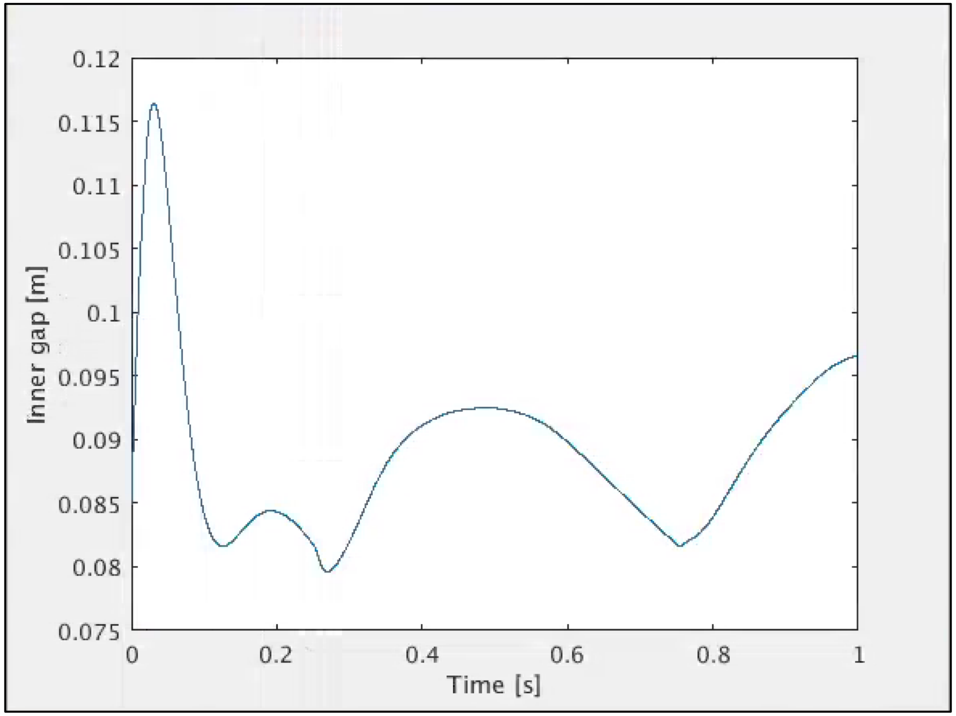




- Modeled around 204118 at t=0.7s
  - – Controller designed with same model – not a good test of robustness to uncertainties
- Sweep frequency defined in memo from Matt, magnitude and phase adjusted to reduce impact on shape
- Tracking improves on second oscillation

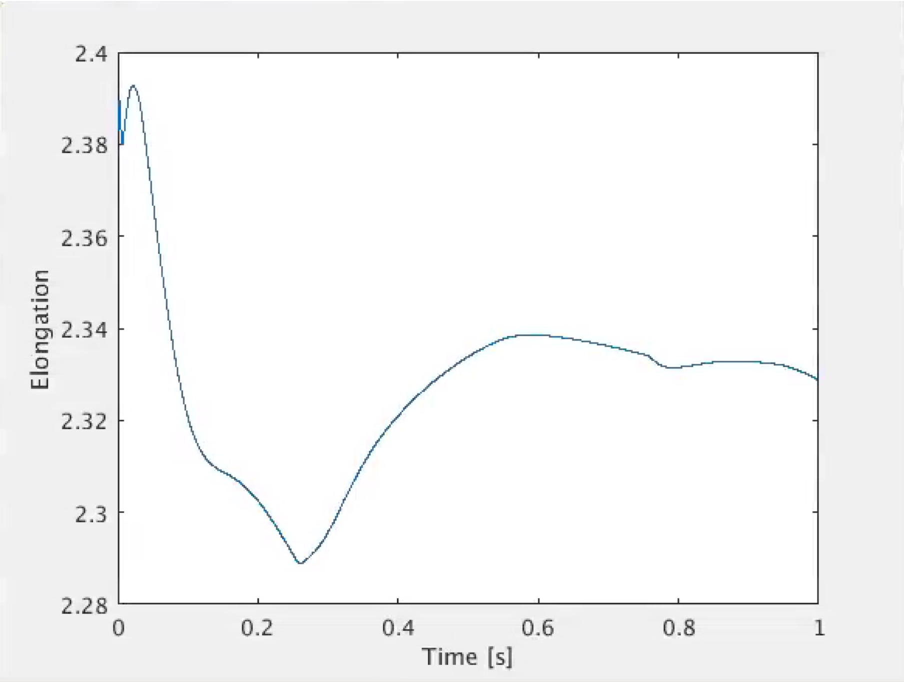
Initial test: impact on outer/inner gap

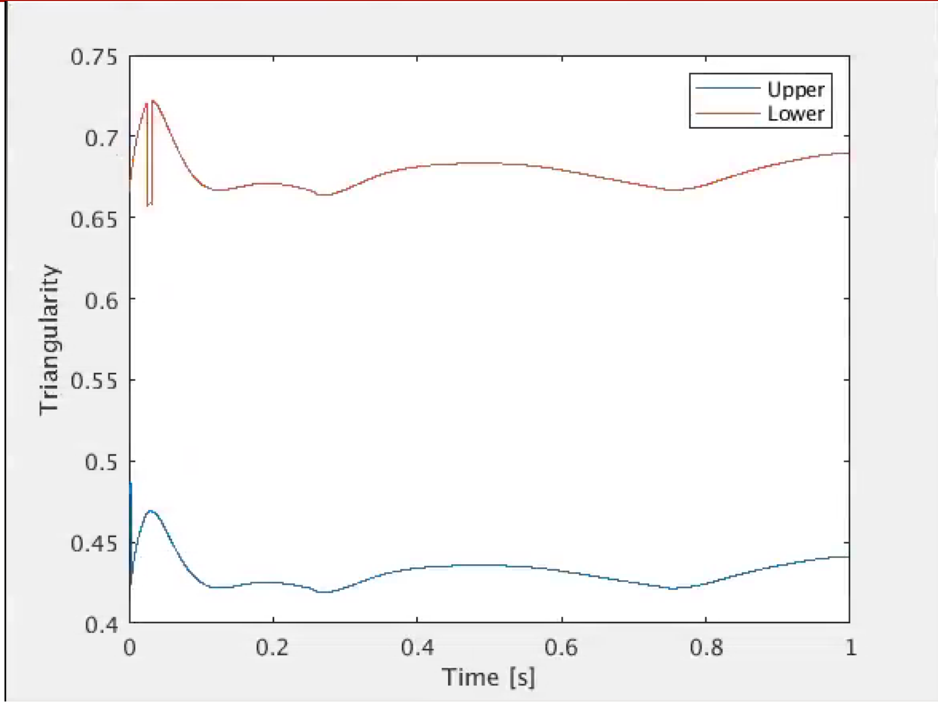




- Outer gap not really impacted at all
- Inner gap was changing by ~10cm with initial phasing of sweep. Switching phase and adjusting magnitude helped but could be optimized further.
  - Will need to avoid control inducing phase shift to avoid introducing large inner gap changes during sweeps

Initial test: Impact on elongation and triangularity





- On second oscillation, not much impact on elongation
- Fairly small oscillations in triangularity
  - Sweep design tool should minimize this impact and control should avoid introducing phase shifts

Possible deliverable: Offline (+real-time) sweep design tool

- **Input:** equilibrium and heating power
- **Model:** Linearized shape response model, Eich heat-flux model, tile temperature rise model -> options for this?
- **Process:** Optimize sweep magnitude, frequency, phasing
  - minimize weighted combination of
    - Shape parameters
    - Possible shot length – target shot length
    - Tile temperature
  - Constrained within
    - Current limits, voltage limits
    - Angle of incidence limits, temperature/heat flux limits
- **Output:** GEQDSK for further analysis,
  - Targets, current and voltage feedforward waveforms for PCS

Next steps for control design

- Increase sweep frequency
  - Optimize gains and control approach to achieve good tracking without extreme gains (reduce noise sensitivity)
- Add constraints on angle of incidence, decide how to choose targets for flux expansion (just rely on offline sweep design tool?)
- Scope real-time version of sweep design tool
  - Real-time tile temperature prediction
  - Adjust target sweeping based on changes to the shot
  - Predict time remaining – suggest changes to heating, etc.
- Add option to run feedback test to sweep design tool