

# An automated approach to magnetic divertor configuration design

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The first fusion reactor ITER is currently under construction in Cadarache, France and fusion power plant conceptual design activities are intensified in Europe, US and Asia. Within this context the transition from advancements in more fundamental plasma physics research towards (computational) engineering and design is regarded as urgent in all ITER partner states. One important component that needs special attention is the so called "divertor". It is designed to modify the magnetic field configuration such that strong plasma flows develop towards particular high heat flux wall components of the reactor vessel. Even on the most powerful supercomputers available today, divertor design is extremely CPU demanding, not least due to the large number of design variables and the hybrid micro-macro character of the flows. Therefore, automated design methods based on optimization can greatly assist current reactor design studies. An approach is developed to optimize the magnetic field configuration, using a somewhat reduced model for the plasma edge. The design objective is to spread the target heat load as much as possible, while maintaining the full helium ash removal capabilities of the pumping system.

## Optimization problem

$$\begin{aligned} \min_{\phi \in \Phi_{ad}, q_1, q_2} \quad & I(\phi, q_1, q_2) \\ \text{s.t.} \quad & c_1(\phi, q_1) = 0, \\ & c_2(q_1, q_2) = 0, \\ & h(\phi, q_1) \geq 0, \end{aligned}$$

Or in reduced form:

$$\begin{aligned} \min_{\phi \in \Phi_{ad}} \quad & \hat{I}(\phi) \\ \text{s.t.} \quad & \hat{h}(\phi) \geq 0, \end{aligned}$$

With following constraints on core shape

$$\begin{aligned} h(1) &= \max_{\theta \in \theta_{core}} (R_{core}(\theta)) - R_{max} \leq 0 \\ h(2) &= \max_{\theta \in \theta_{core}} (Z_{core}(\theta)) - Z_{max} \leq 0 \\ h(3) &= R_{min} - \min_{\theta \in \theta_{core}} (R_{core}(\theta)) \leq 0 \\ h(4) &= Z_{min,x} - Z_x \leq 0 \\ h(5) &= R_{min,x} - R_x \leq 0 \\ h(6) &= R_x - R_{max,x} \leq 0 \end{aligned}$$

Control currents through shaping conductors

Controlled conductors

Core

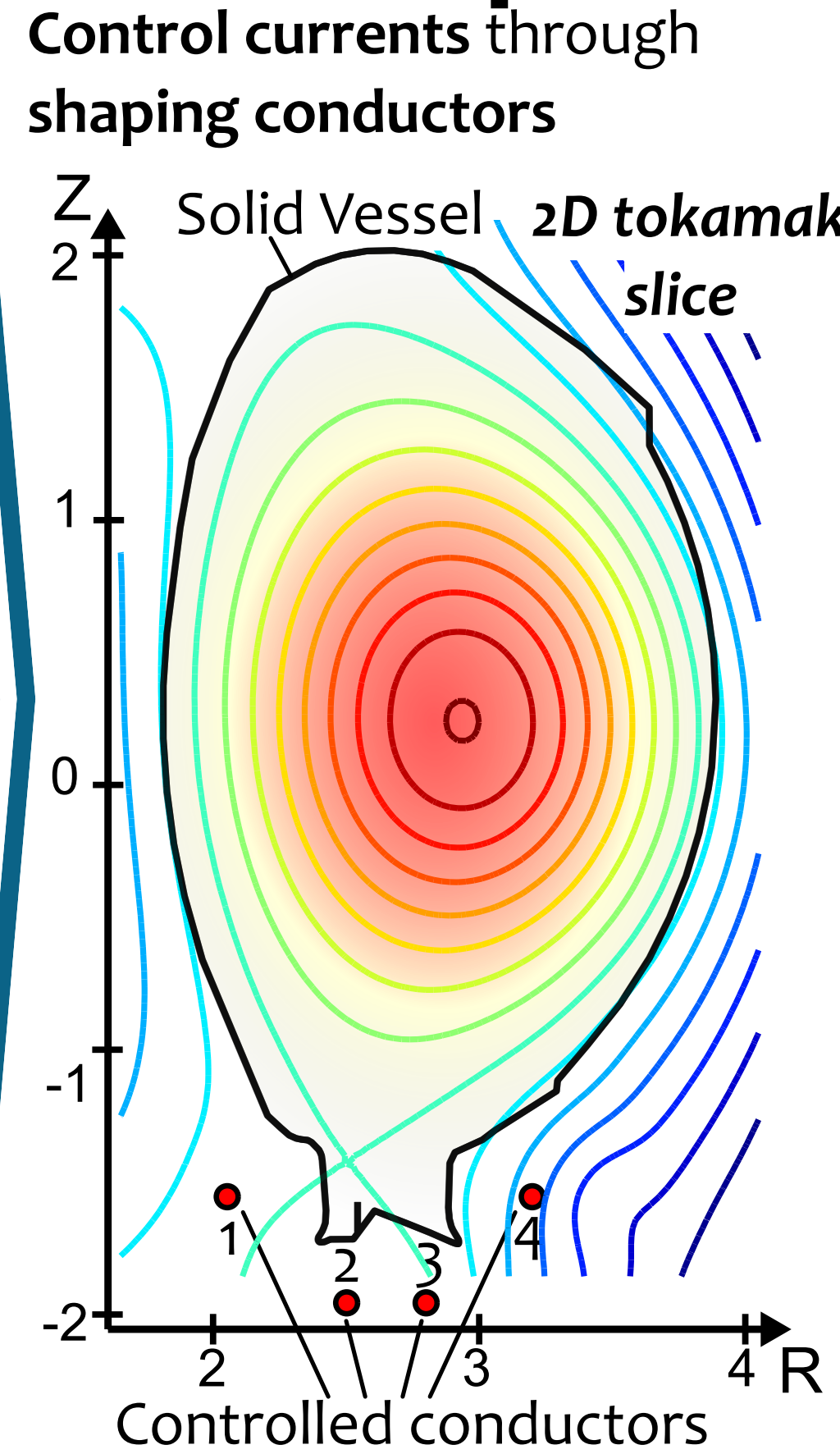
X-point

Constrains

Core

Controlled conductors

## Set-up



## Magnetic field computation

Use perturbation approach to avoid full MHD calculations

Starting from

$$\Delta^* \Psi_0 + \Delta^* \delta \Psi = -\mu_0 R (J_{\phi,0} + \delta J_{\phi,int} + \delta J_{\phi,ext})$$

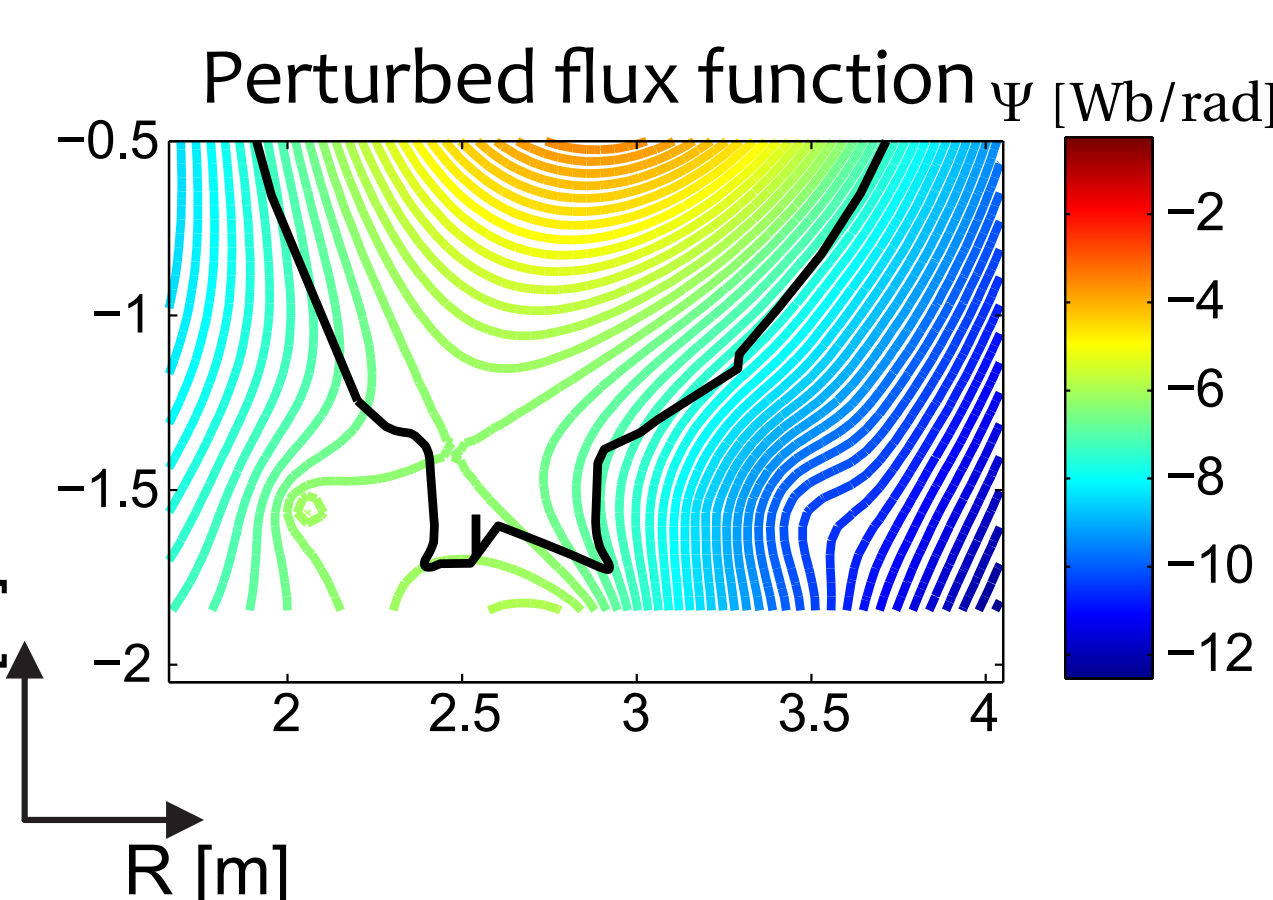
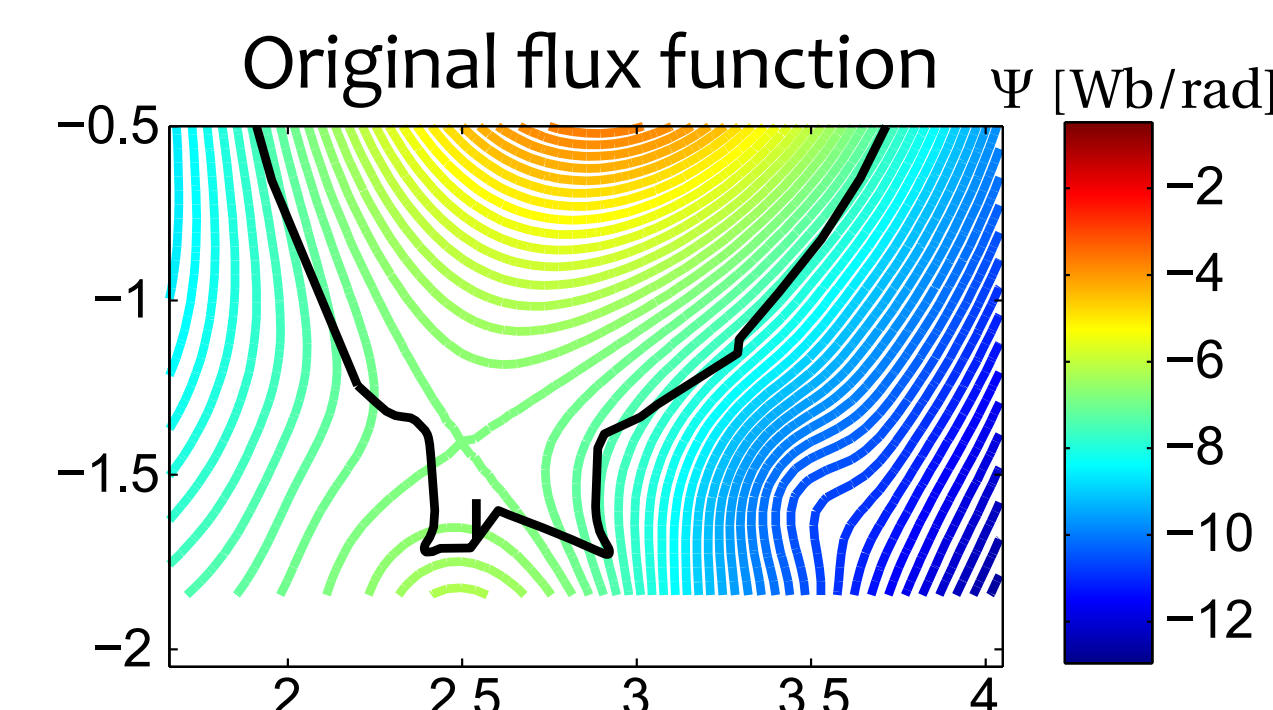
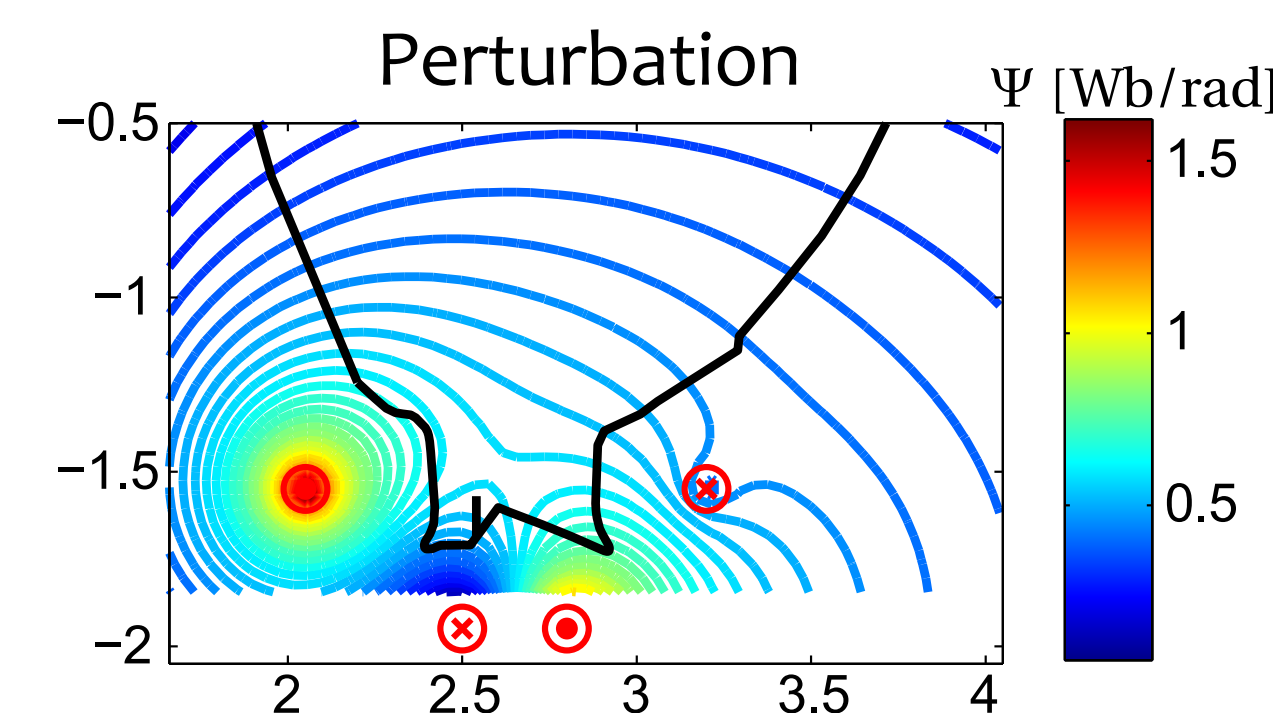
Original Perturbation

Calculate effect of additional conductors in vacuum

$$\Delta^* \delta \Psi = -\mu_0 R \left( \delta J_{\phi,int} + \delta J_{\phi,ext} \right)$$

Add perturbation flux function to reference

$$\Psi = \Psi_0 + \delta \Psi$$



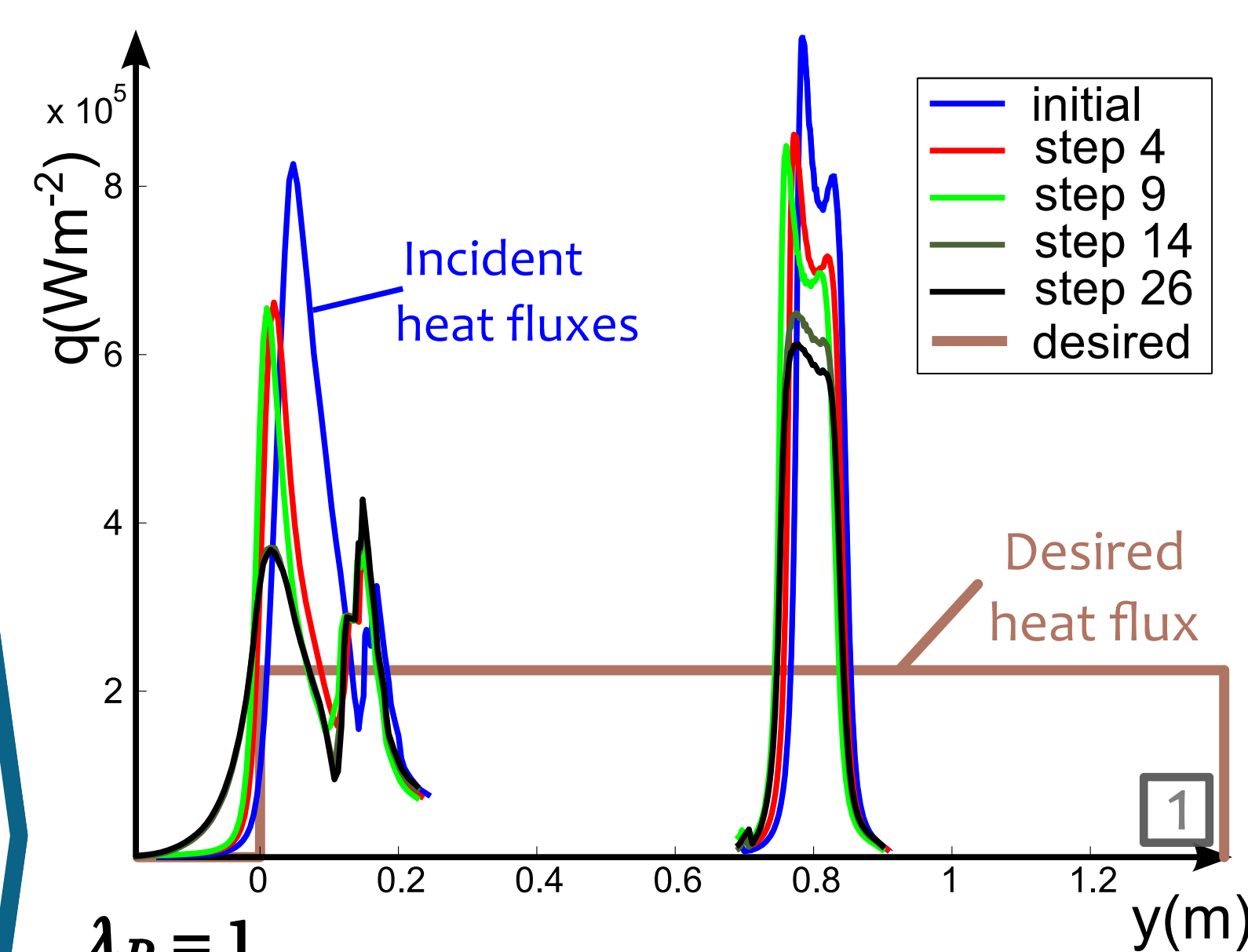
## Next iteration

## Optimization

Solution through:

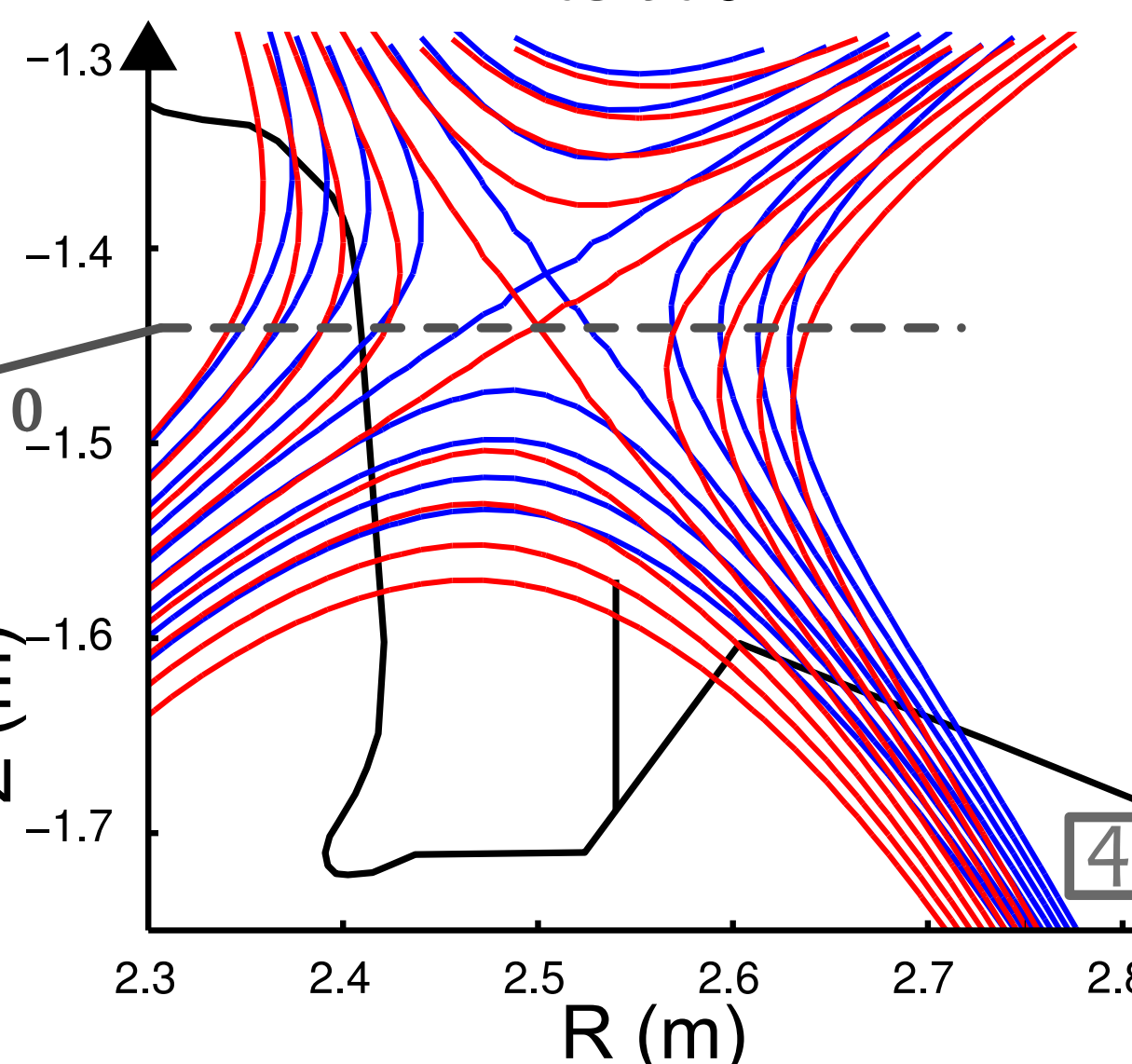
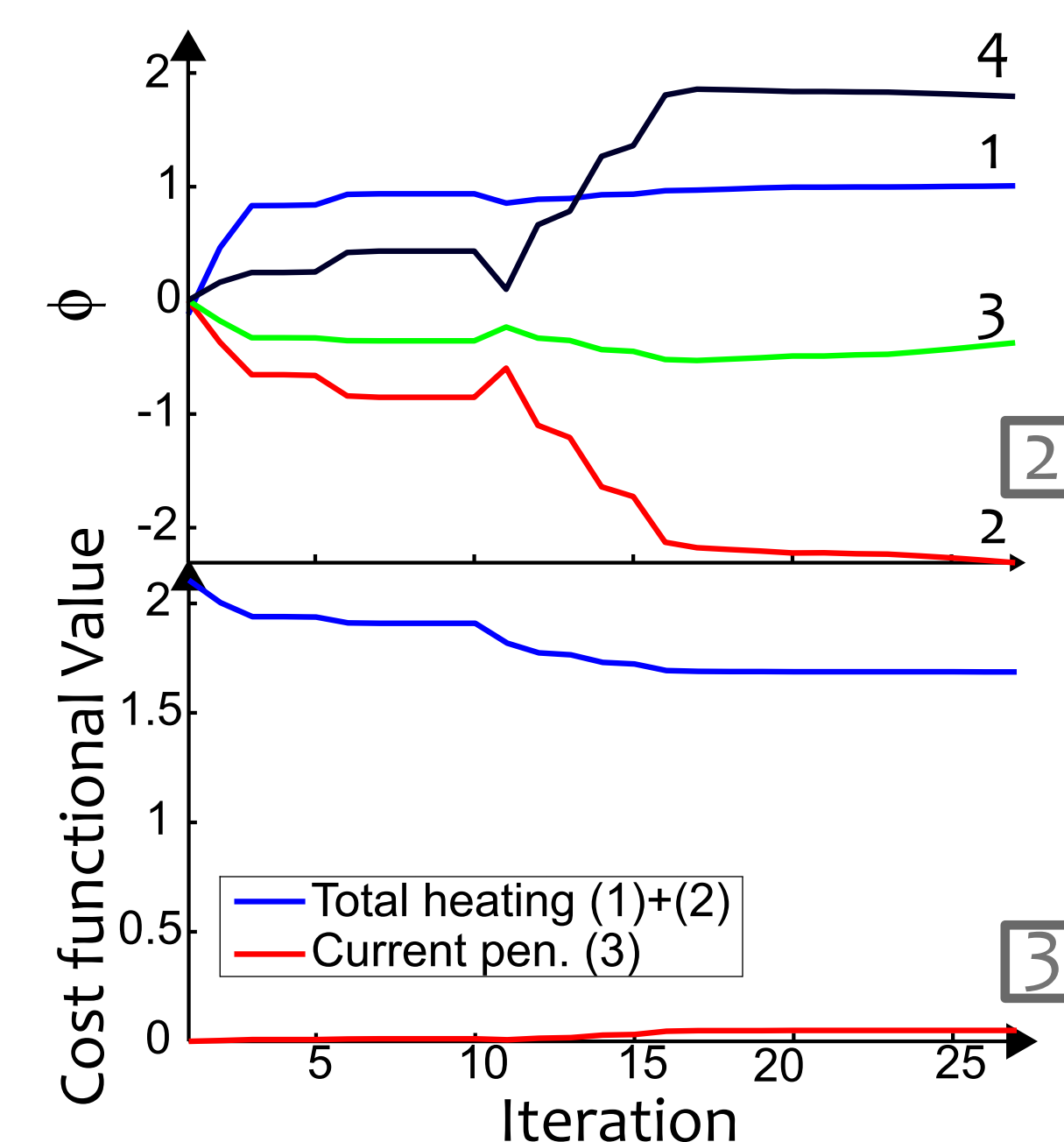
- SQP Optimization
- FD gradient computation
- Bracketing line search with Wolfe conditions
- Gradient projection optimization subproblem

## Results

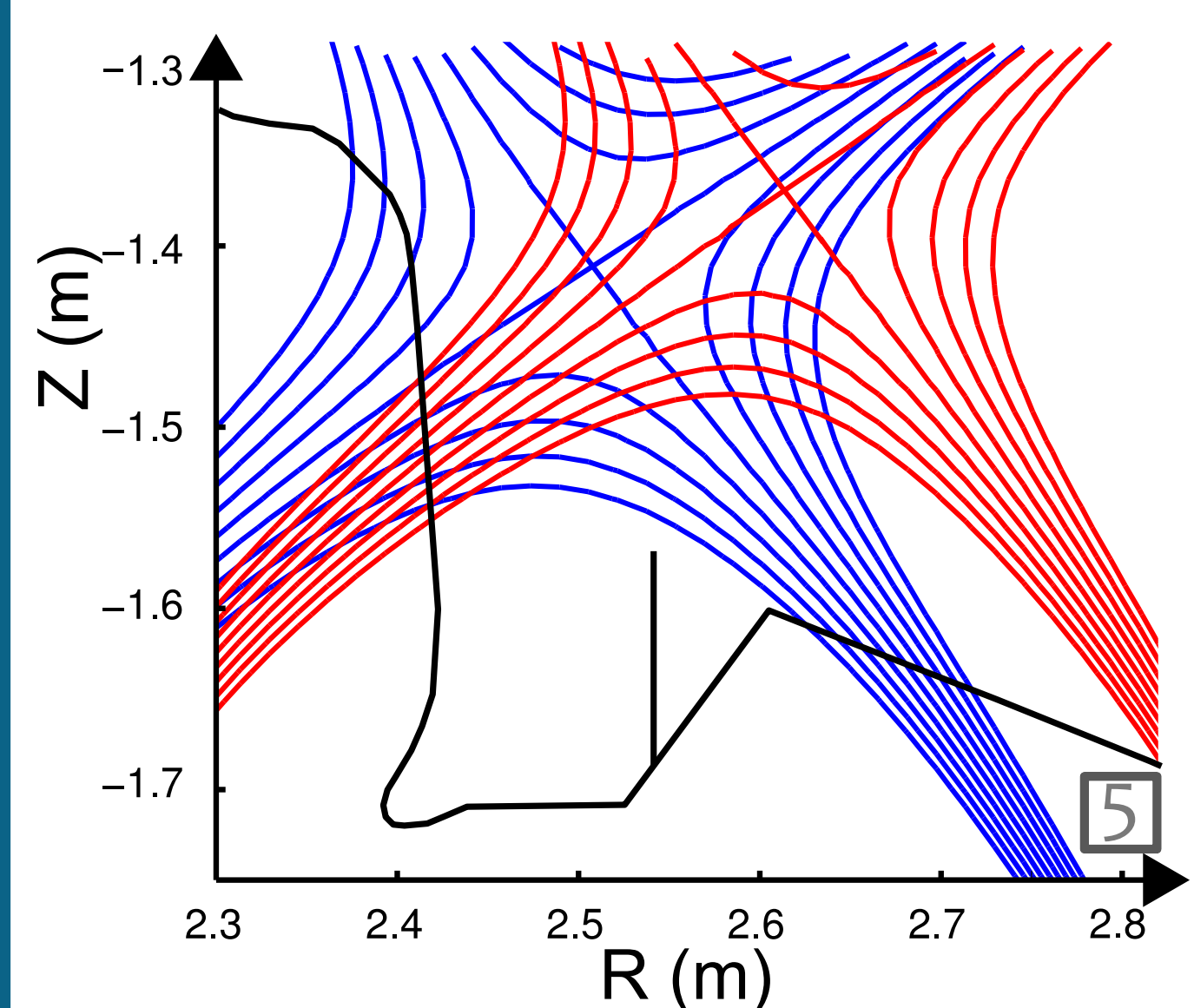
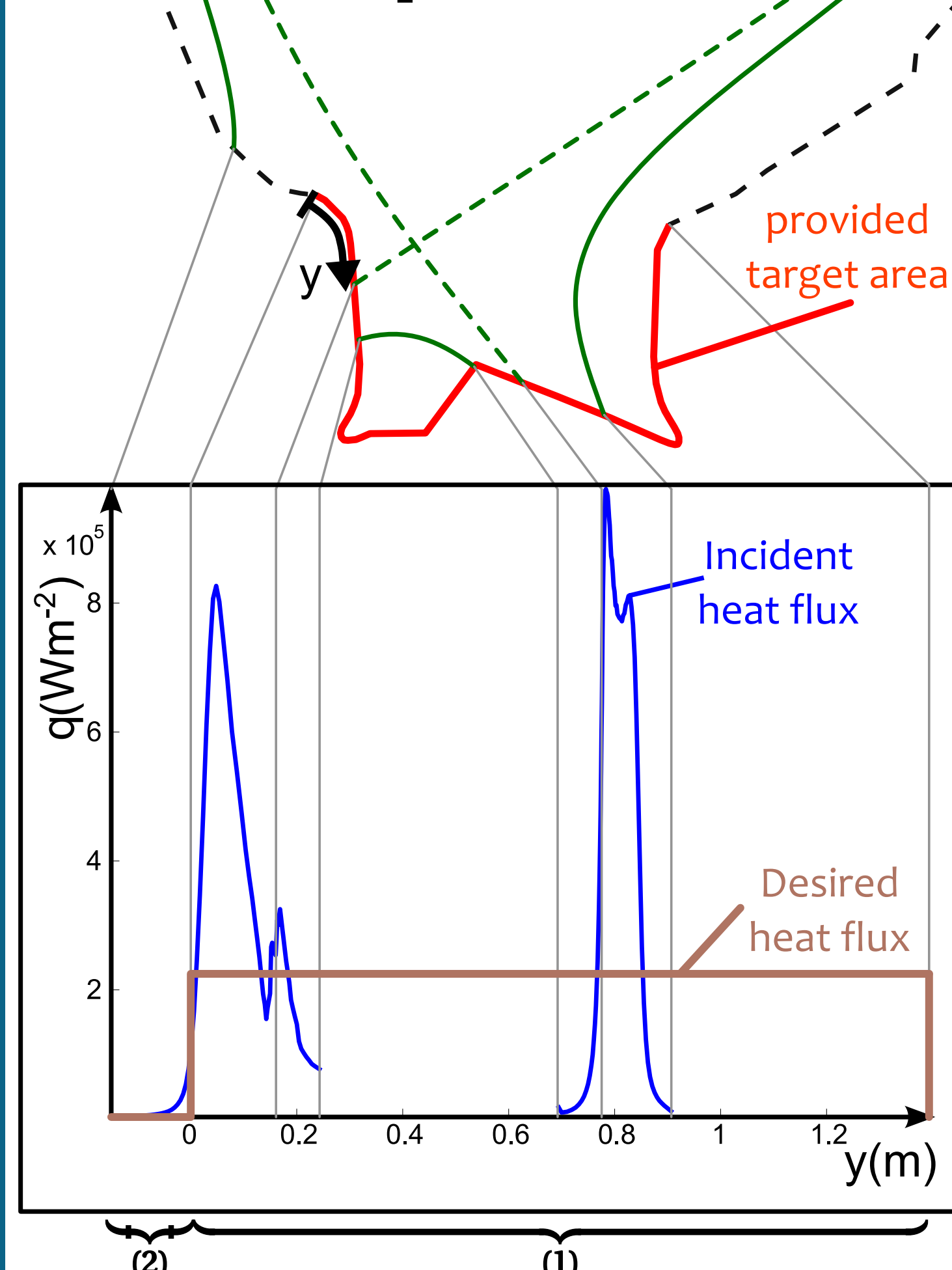


- Heat peaks are lowered (fig 1) during optimization to lower cost functional value (fig 3)
- Current couples with opposing currents are formed, widening the flux tubes towards target area (fig 2,4)
- The optimum is found to be at the boundary of the h(4) constraint (fig 4)

$$h(4) = Z_{min,x} - Z_x \leq 0$$



## Cost functional computation



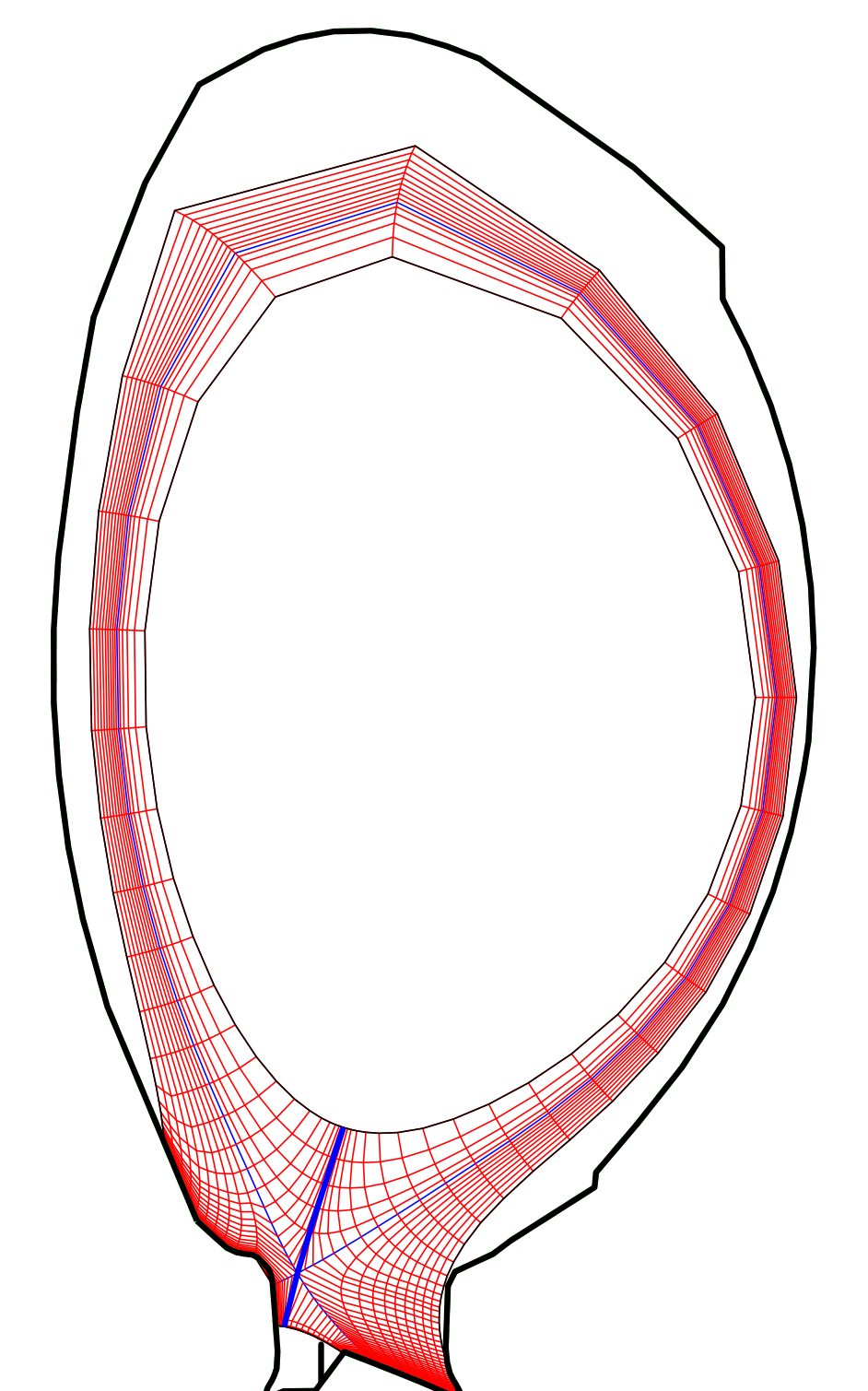
$$I(q, \phi) = \frac{1}{2} \lambda_Q \left( \int_{\Gamma_t} [Q_{\perp} - Q_{a,t}]^2 d\sigma + \int_{\Gamma_p} [\lambda_P (Q_{\perp} - Q_{a,p})]^2 d\sigma \right) + \frac{1}{2} \lambda_{\phi} \sum_i \phi_i^2$$

- (1) Maximal target heat load spreading
- (2) Wall heating penalty
- (3) Current penalty, regularization term

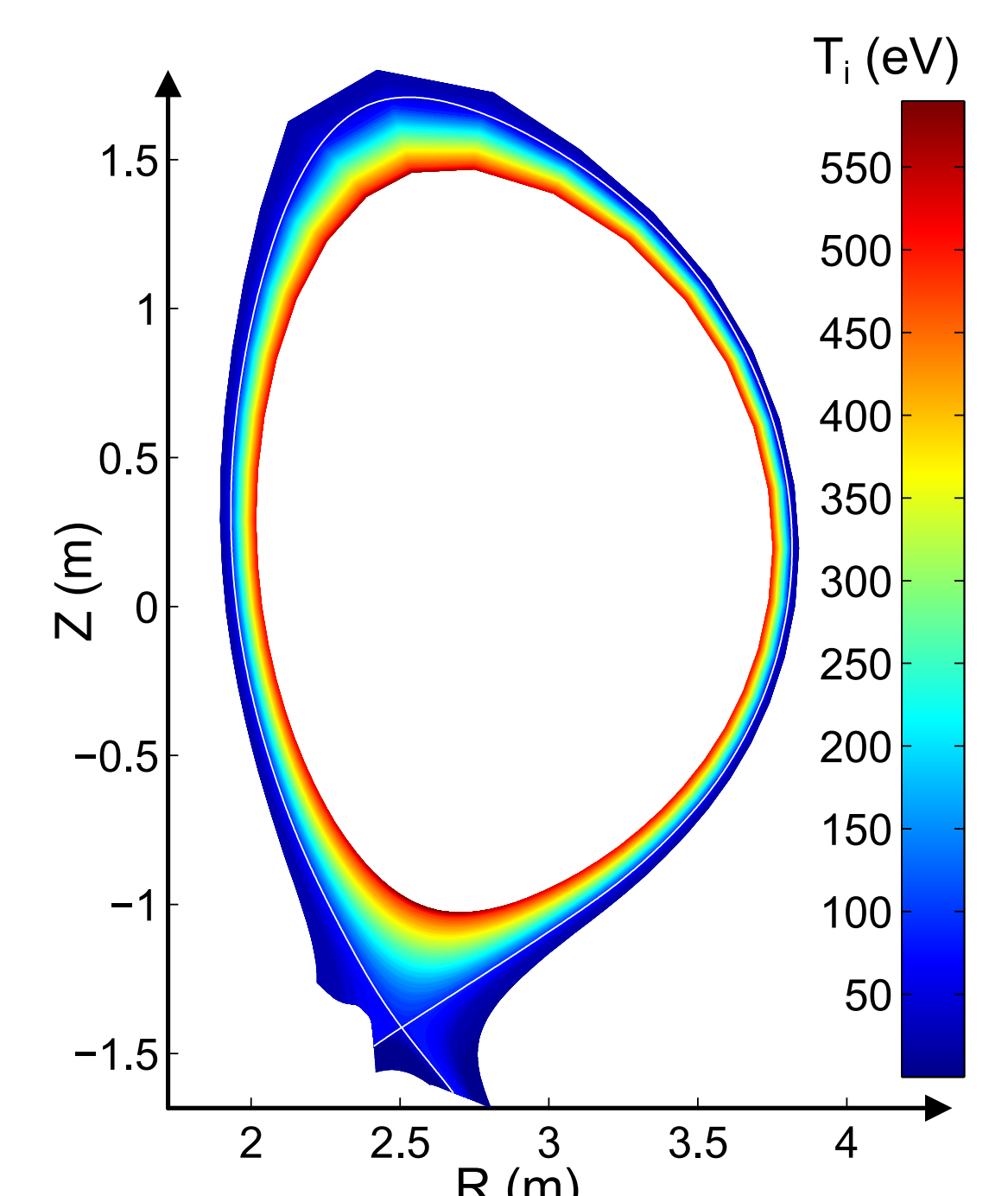
## Grid generation

Strong anisotropic transport in physics

→ Create grid aligned with magnetic field



## Plasma flow simulation



Solve plasma edge conservation equations

- Ion continuity equation
- Ion parallel momentum equation
- Internal energy equation
  - Sum of ion, electron and neutral internal energy equations
  - $T = T_i = T_e = T_n$
- Neutral continuity equation
  - Pressure diffusion equation

State variables:  $n_i, n_n, u_{//}, T$

## Conclusions

- Optimization framework with FD gradient calculation successfully adjusts the magnetic field design to reduce the heat peak at the target area
- When increasing the relative importance of the heat flux outside the target area, the optimization avoids using all non-target material as desired
- Plasma edge simulation are computationally extremely expensive, even for this reduced model and limited set of control variables

## Future work

- Use adjoint gradient calculation to allow for more control variables and reduce computational costs
- Extend magnetic model to allow larger changes to the magnetic configuration
- Incorporate more MHD-stability criteria, to account for unstable configurations in the optimization results