INTRA-SHOT TOOLS FOR PLASMA SCENARIO OPTIMIZATION AND MAGNETIC CONTROL

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ABSTRACT

- Scenario design tools will be very important in view of the start-up and operation of future large tokamaks.
- Model based intra-shot optimization tools have been proved to be useful for the magnetic design of plasma initiation and early ramp-up scenarios with experiments on TCV [1] and MAST-U [2].
- The main objective here is to describe how the algorithms used in TCV and MAST-U are modified to account for the beneficial contribution of closed loop control.
- Numerical examples on the design of a ramp-up for large superconducting coils tokamaks like JT-60SA and ITER are presented for the first time.

CHALLENGES / METHODS / IMPLEMENTATION

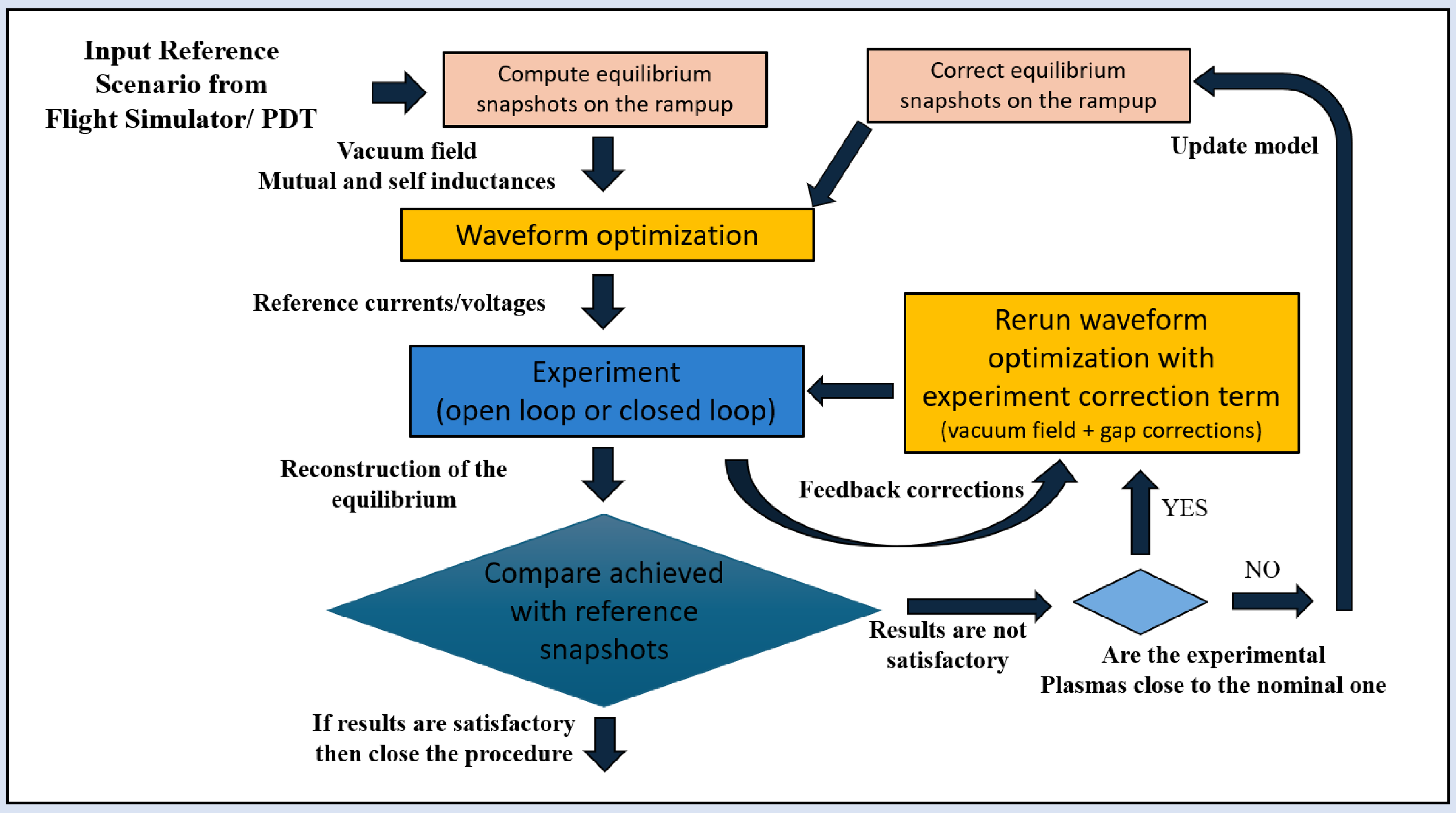
CHALLENGE: Provide a model based intra-shot tool to correct the scenario nominal currents/voltages on the basis of the experimental results, taking advantage of the feedback control action generated in real time.

METHODS

- implement suitable models to be used in the optimization procedure;
- convert the design problem into a QP optimization problem that can be solved in short time;
- Use Iterative learning control to adapt active current/voltage waveforms to correct the vacuum field and plasma current on the basis of the experimental results;
- Include shape descriptors in the procedure to account for plasma evolution uncertainties;
- Include the action of feedback control in the algorithm.

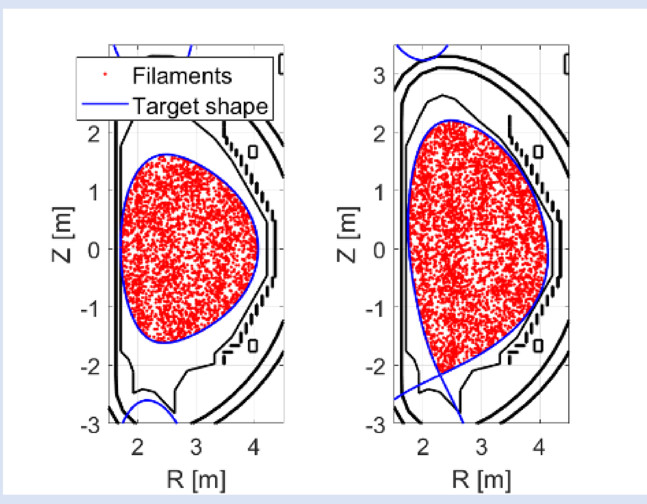
IMPLEMENTATION

- Filamentary models generated with the use of Green Functions
- Finite element models (CREATE-NL+) to produce the nominal equilibria
- Linearized models (CREATE-NL+ [5]) to account for shape variations
- Design optimization procedure implemented in the CREATE-BD [3-4]
- ILC procedures implemented in the CREATE-ILC
- Tested on TCV [1] and MAST-U [2] for the BD and early phase of ramp-up
- Tested on MAST-U for the entire ramp-up



$$L_{aa}(t)\dot{I}_a(t) + L_{au}(t)\dot{I}_u(t) + L_{ap}(t)\dot{I}_p(t) + (R_a(t) + R_{SN}(t))\, I_a(t) = V_a(t)$$
$$L_{ua}(t)\dot{I}_a(t) + L_{uu}(t)\dot{I}_u(t) + L_{up}(t)\dot{I}_p(t) + L_{uu}(t)I_u(t) = 0$$
$$\left(L_{pa}(t)\dot{I}_a(t) + L_{pu}(t)\dot{I}_u(t)\right)\cdot 1(t - t_{BD}) + L_{pp}(t)\dot{I}_p(t) + R_p(t)I_p(t) = 0$$
$$y = C_a I_a + C_u I_u + C_p I_p$$
$$y_v = C_{av} I_a + C_{uv} I_u$$
$$I_a(t_0) = I_{a0}, I_u(t_0) = I_{u0}, I_p(t_0) = 0$$

Structure of the filamentary model used for the design



Filaments representing plasma for two configurations

MAIN REFERENCES

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SCENARIO DESIGN PROBLEM

Breakdown and early ramp-up phase

The BD region is where plasma is expected to born (a circular massive conductor with assigned resistance, simulating plasma, is located here).

Control Points (CPs) are points where the value of the magnetic field and/or of the electric field is optimized (e.g. a uniform rectangular grid in the vacuum chamber).

At BD time t_{BD} the requested poloidal field map is a quadrupolar field. Before t_{BD}, a purely vertical field that fades linearly over time is superimposed to the quadrupolar field to avoid unwanted breakdowns.

Transition to the ramp-up

The Equilibrium Field Map in Vacuum is the map guaranteeing plasma equilibrium for $t > t_{BD}$: this starts as a Shafranov field and then turns into an equilibrium vacuum field compute via CREATE-NL+. With well formed plasma, a direct shape correction term based on gaps is implemented.

$$\min_{W,z_0} (Y_{B_r} - Y_{B_r,d})^T Q_{B_r} (Y_{B_r} - Y_{B_r,d}) + (Y_{B_z} - Y_{B_z,d})^T Q_{B_z} (Y_{B_z} - Y_{B_z,d}) +$$
$$+(Y_I - Y_{I,d})^T Q_I (Y_I - Y_{I,d}) + (Y_{I_p} - Y_{I_p,d})^T Q_{I_p} (Y_{I_p} - Y_{I_p,d}) +$$
$$+(W - W_d)^T R_w (W - W_d) + (z_0 - z_{0,d})^T R_{z_0} (z_0 - z_{0,d})$$

(Radial field error) (Vertical field error) (Circuit currents error) (Plasma current error) (Input penalization term) (Initial conditions term)

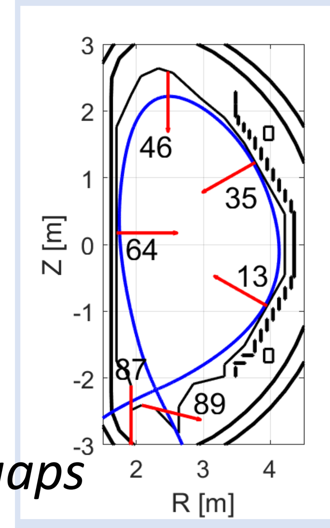
s.t.

Model

$$Y = \Phi_Y z_0 + H_Y W$$
$$W = [w(t_0)^T w(t_1)^T w(t_2)^T \dots w(t_k)^T]^T$$
$$Y(t_k) = [y_V(t_0)^T \dots y_V(t_k)^T]^T$$

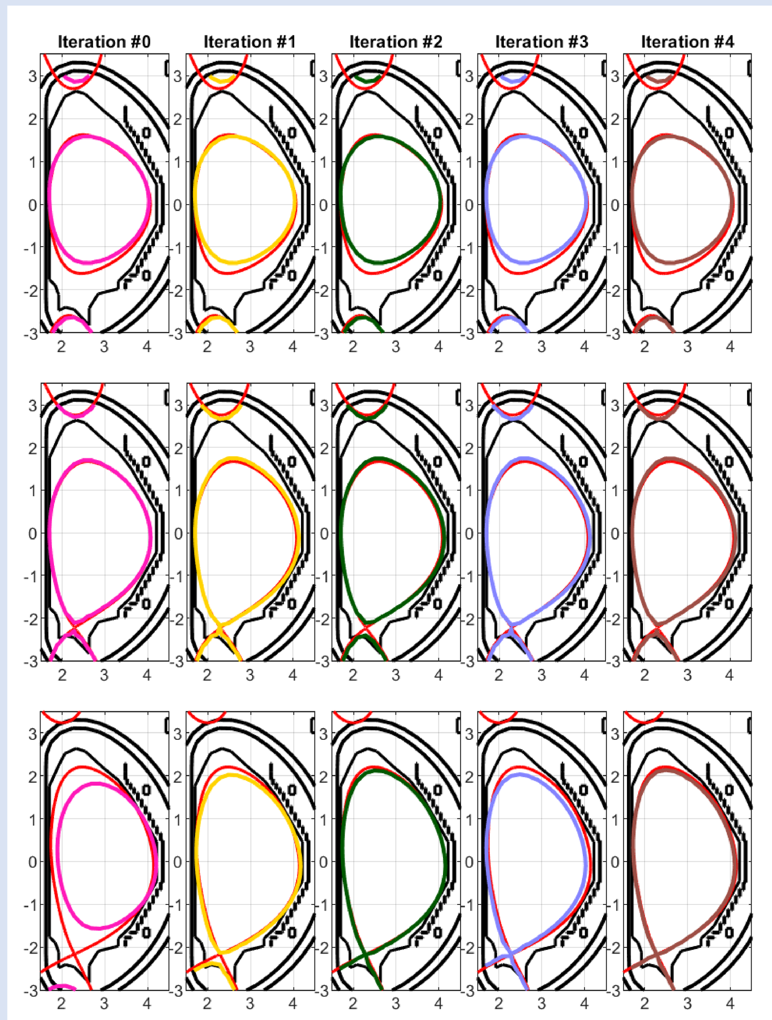
$$Y_{csm} \le Y_{cs} \le Y_{csM};$$ (input constraints)
$$W_m \le W \le W_M;$$ (output constraints)
$$z_{0m} \le z_0 \le z_{0M};$$ (initial conditions constraints)
$$I_u(t_0) = 0, I_p(t_0) = 0$$

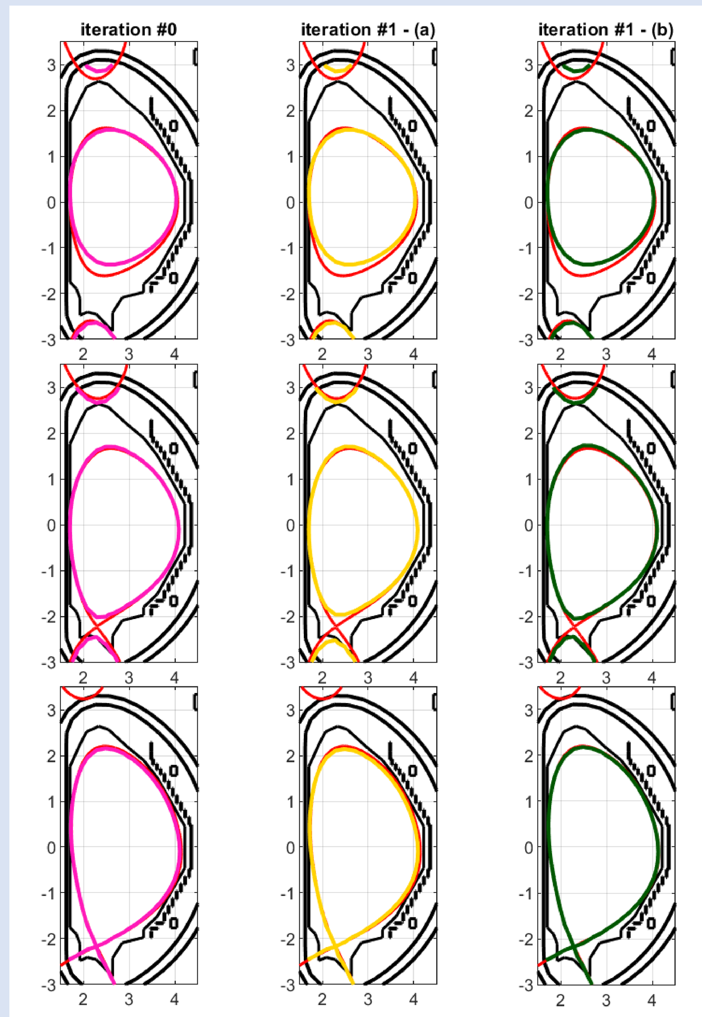
$$Y_{ct} = \left[Y_{B_r}^T, Y_{B_z}^T, Y_I^T, Y_{I_p}^T\right]^T, Y_{cs} = \left[Y_{V_{Loop}}^T, Y_{I_a}^T, Y_{V_a}^T\right]^T$$

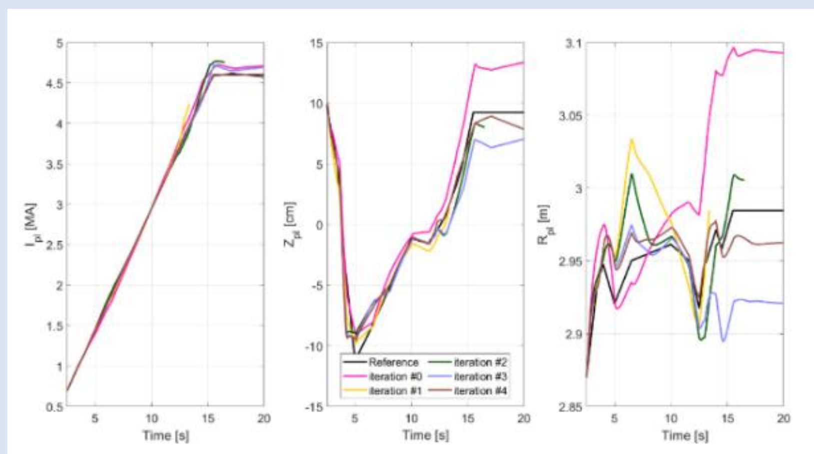


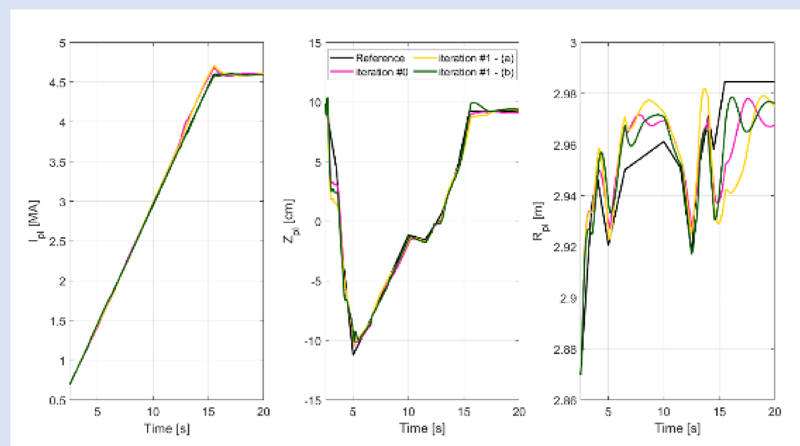
Controlled gaps

SIMULATION RESULTS ON JT-60SA









ILC without Feedback corrections

ILC with feedback correction with the old (a) and new (b) formulation

SIMULATION RESULTS ON A 2 MA ITER SCENARIO