Nonlinear approaches in Tokamak plasmas control: an overview of some results

Luca Zaccarian

University of Rome, Tor Vergata (Italy)

With FTU plasma control team, CREATE group

EFDA Task Force D Meeting – September 17, 2009

Advantages of nonlinear control solutions

- May overcome **intrinsic limitations** of linear control (e.g., overshoots, disturbance rejection, etc)

- Can handle **soft and hard constraints** more efficiently

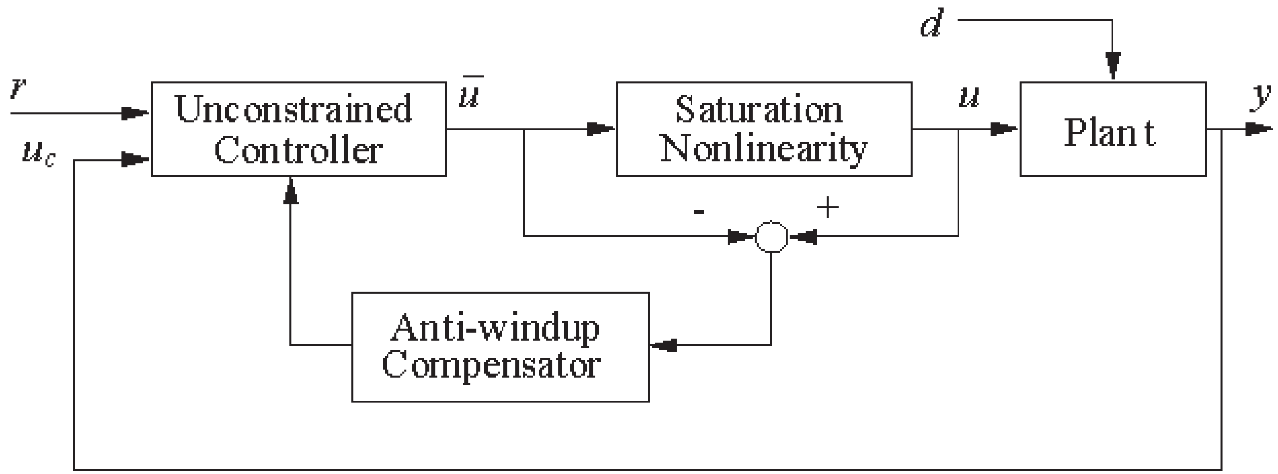
- Can directly address **nonlinearities** in a plant (saturations, quantization, general nonlinearities)

- Allows bumpless **switching** between different controllers

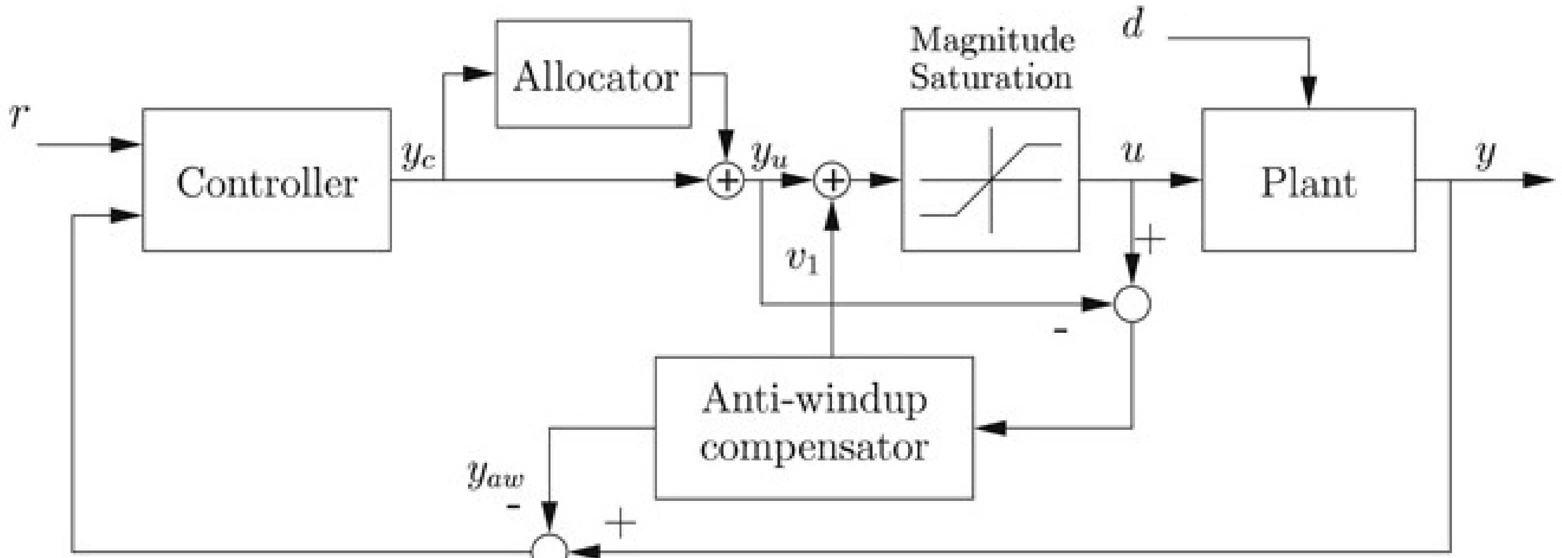
- Often **small extensions** and modifications of substantially linear control schemes lead to **large** stability and performance improvement

Handling input nonlinearities

- Anti-windup: address plant input distortion during transients



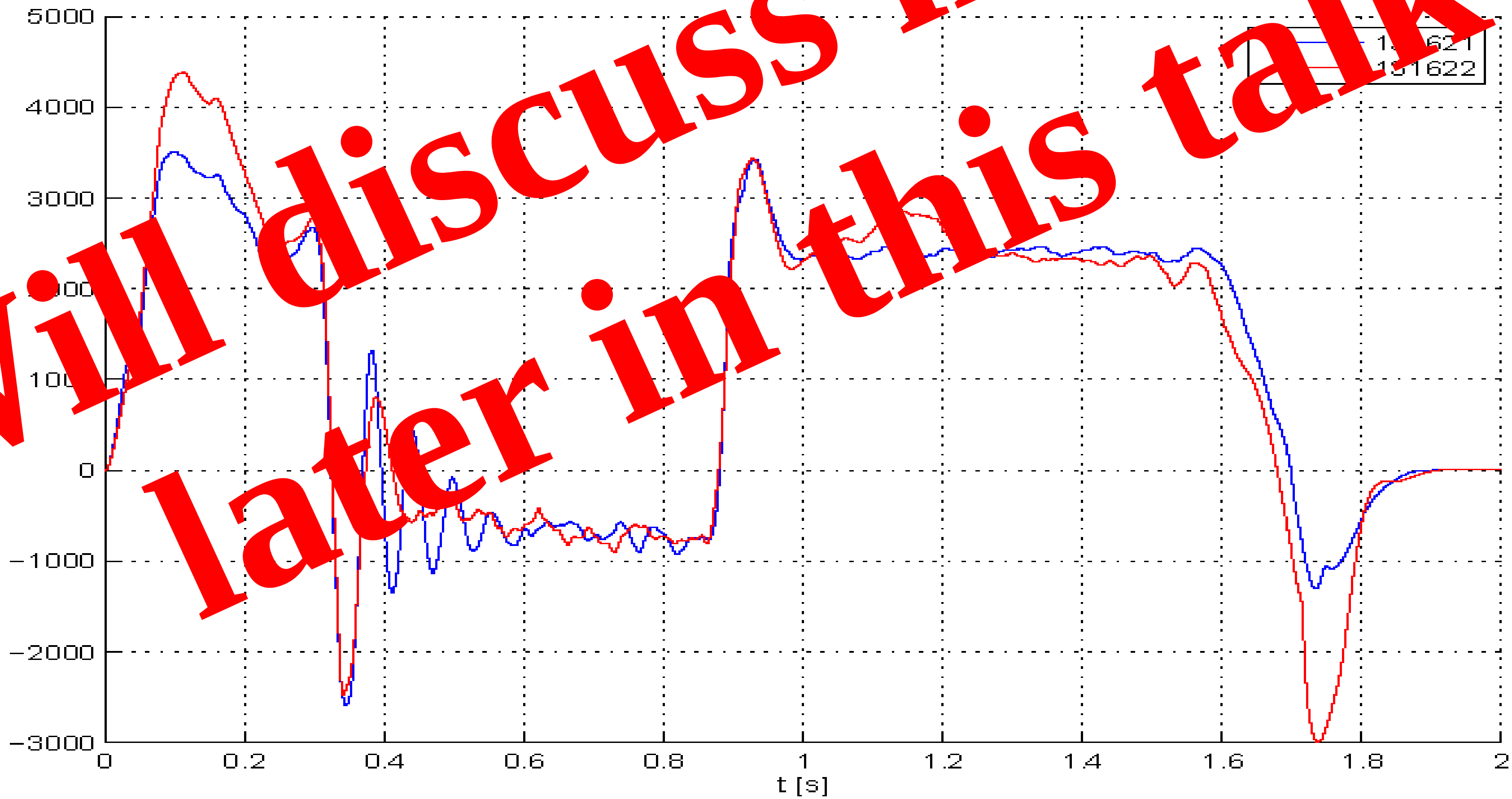
- Dynamic allocation: address steady-state input specs



Anti-windup application: FTU

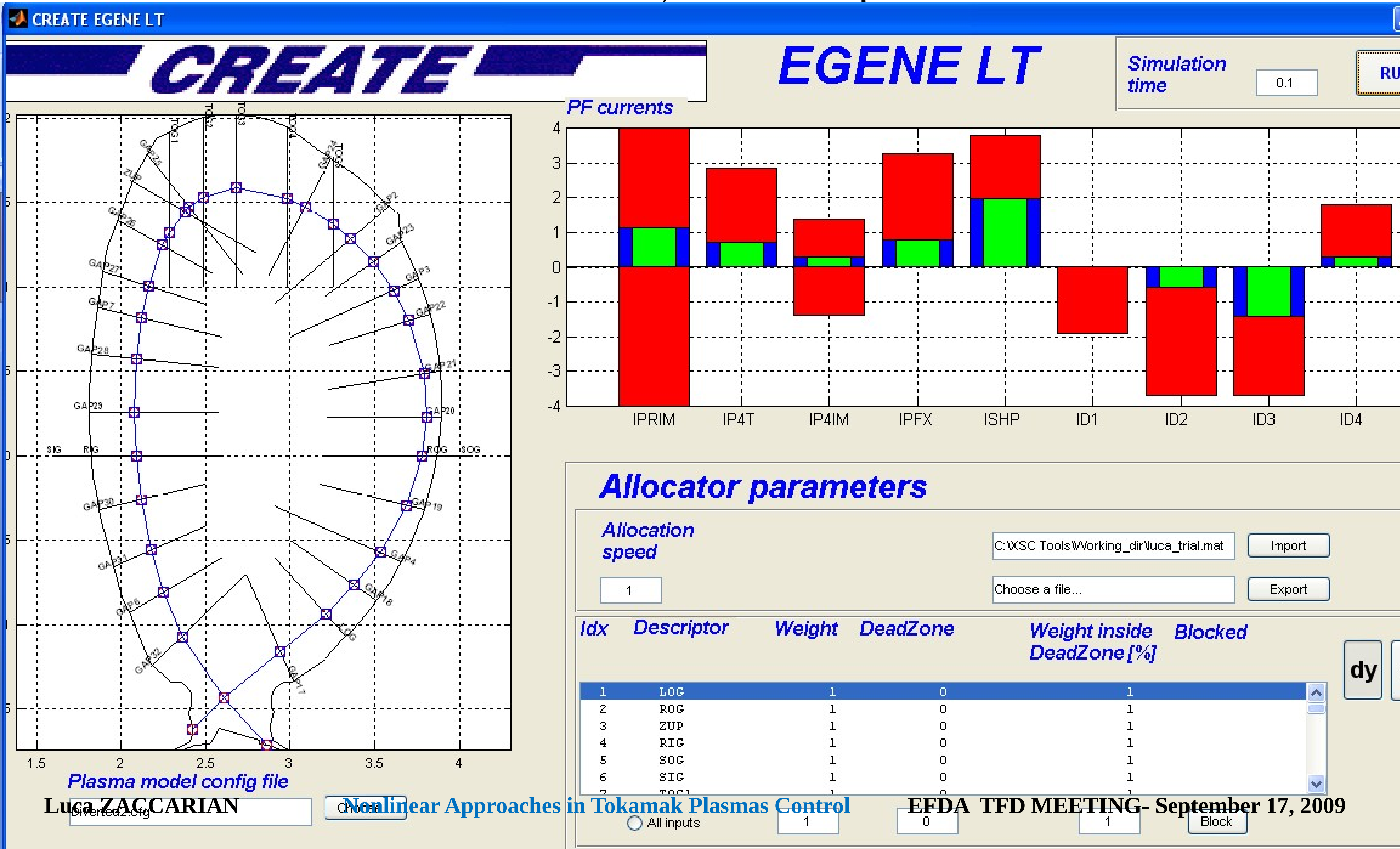
- Small signal nonlinearity in current control of F coils
- Circulating current in thyristor bridges causes nonlinear response and destabilizes the closed-loop
- Anti-windup solution recovers closed-loop stability

Will discuss in detail later in this talk



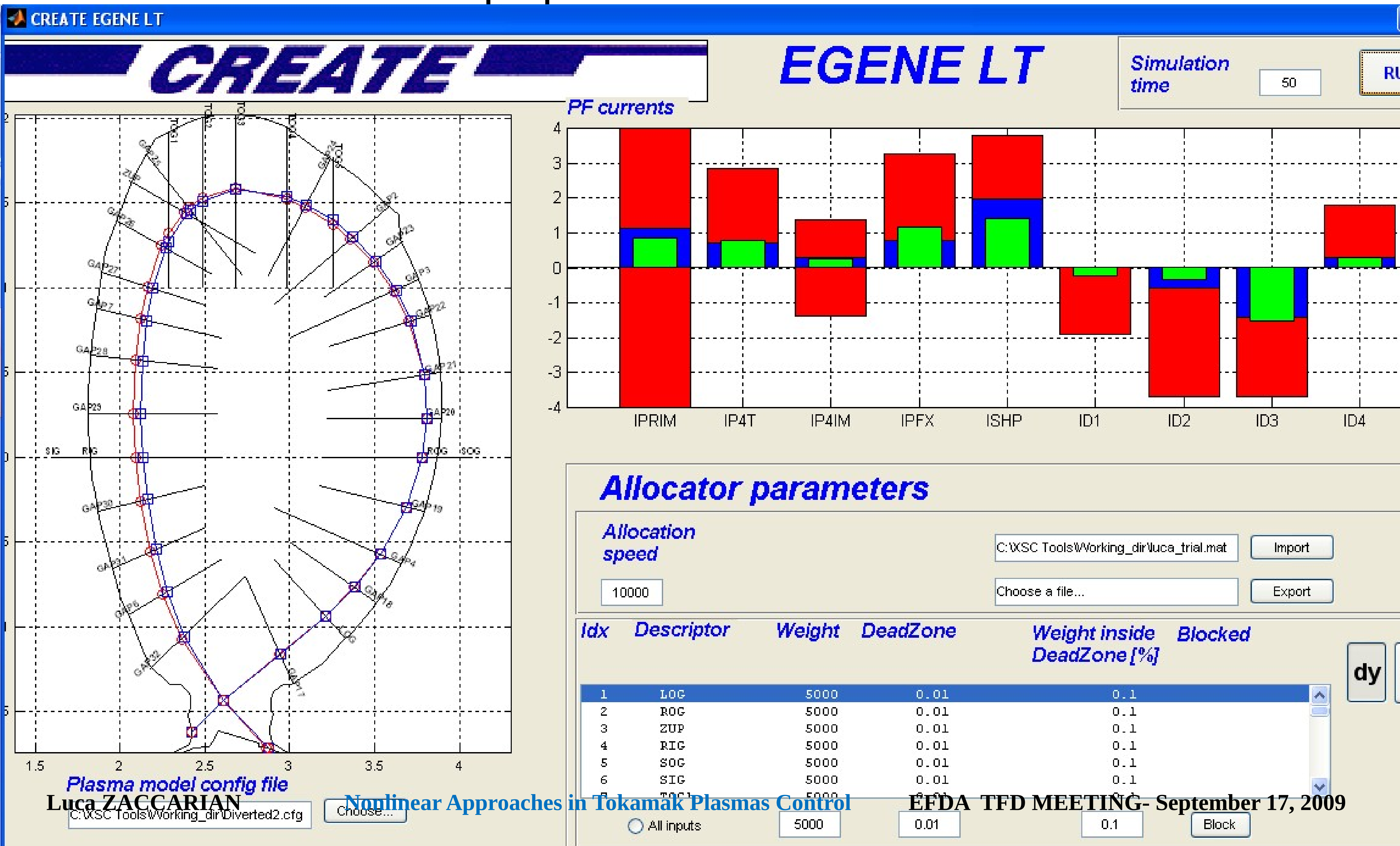
Dynamic allocation application: JET

- Coil current saturation may cause experiment loss



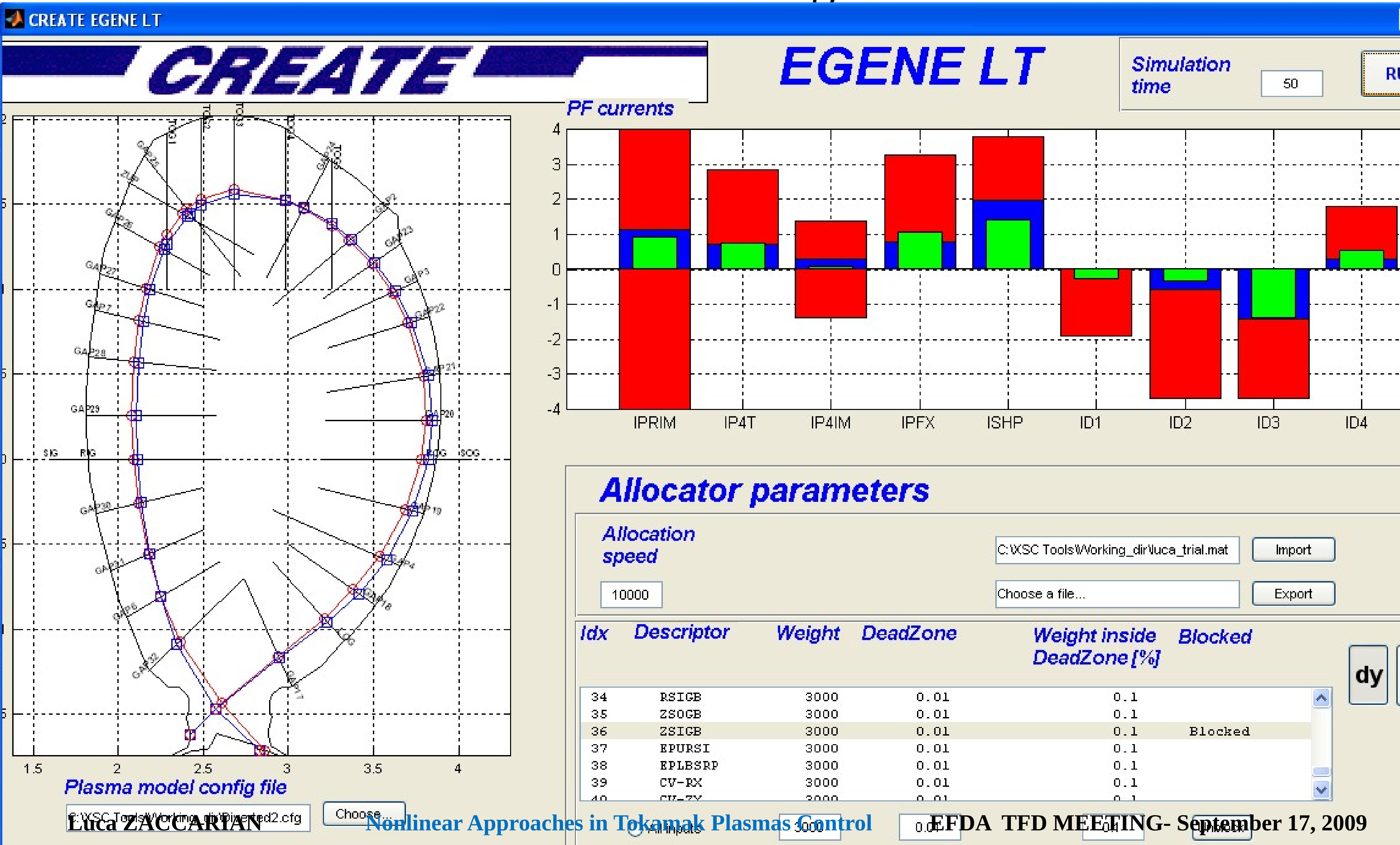
Dynamic allocation application: JET

- Trade in some shape performance to move coils out of sat



Dynamic allocation application: JET

- Similar tools allow to achieve elongation control at FTU



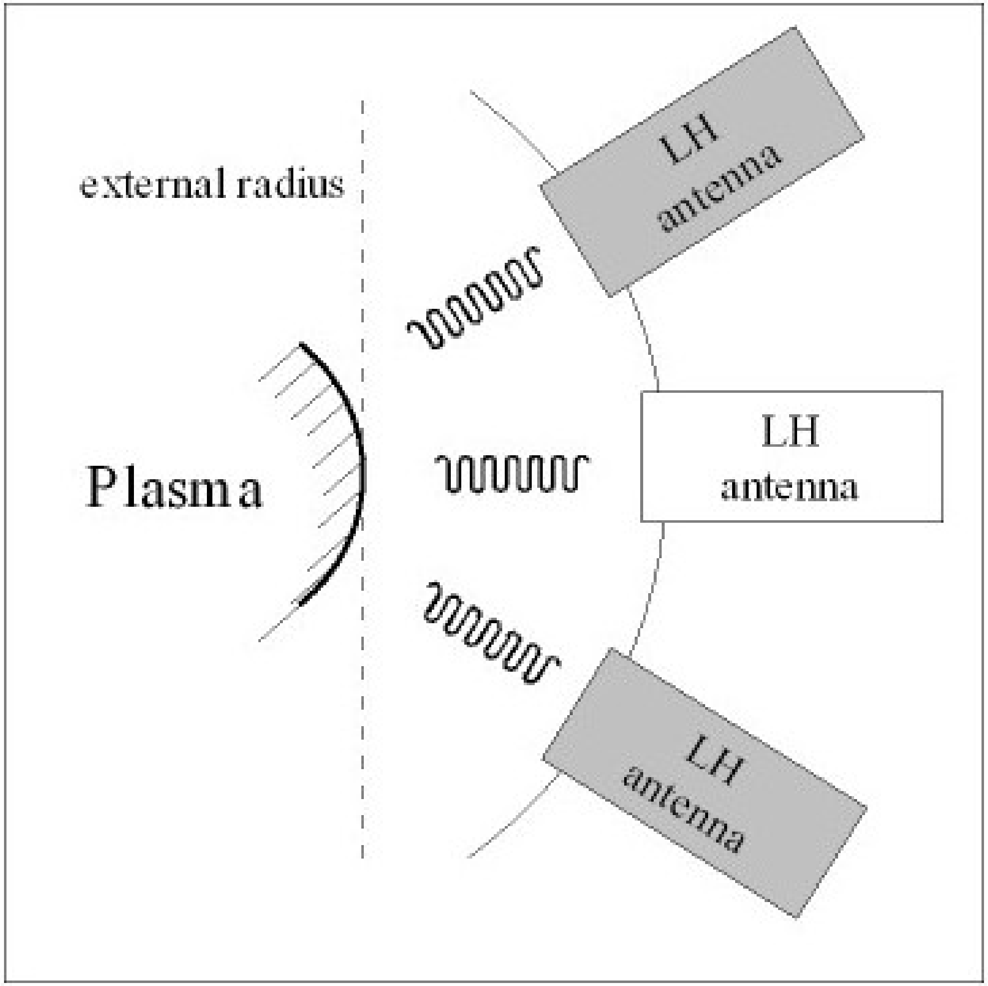
FTU: NL extremum seeking application

Framework:

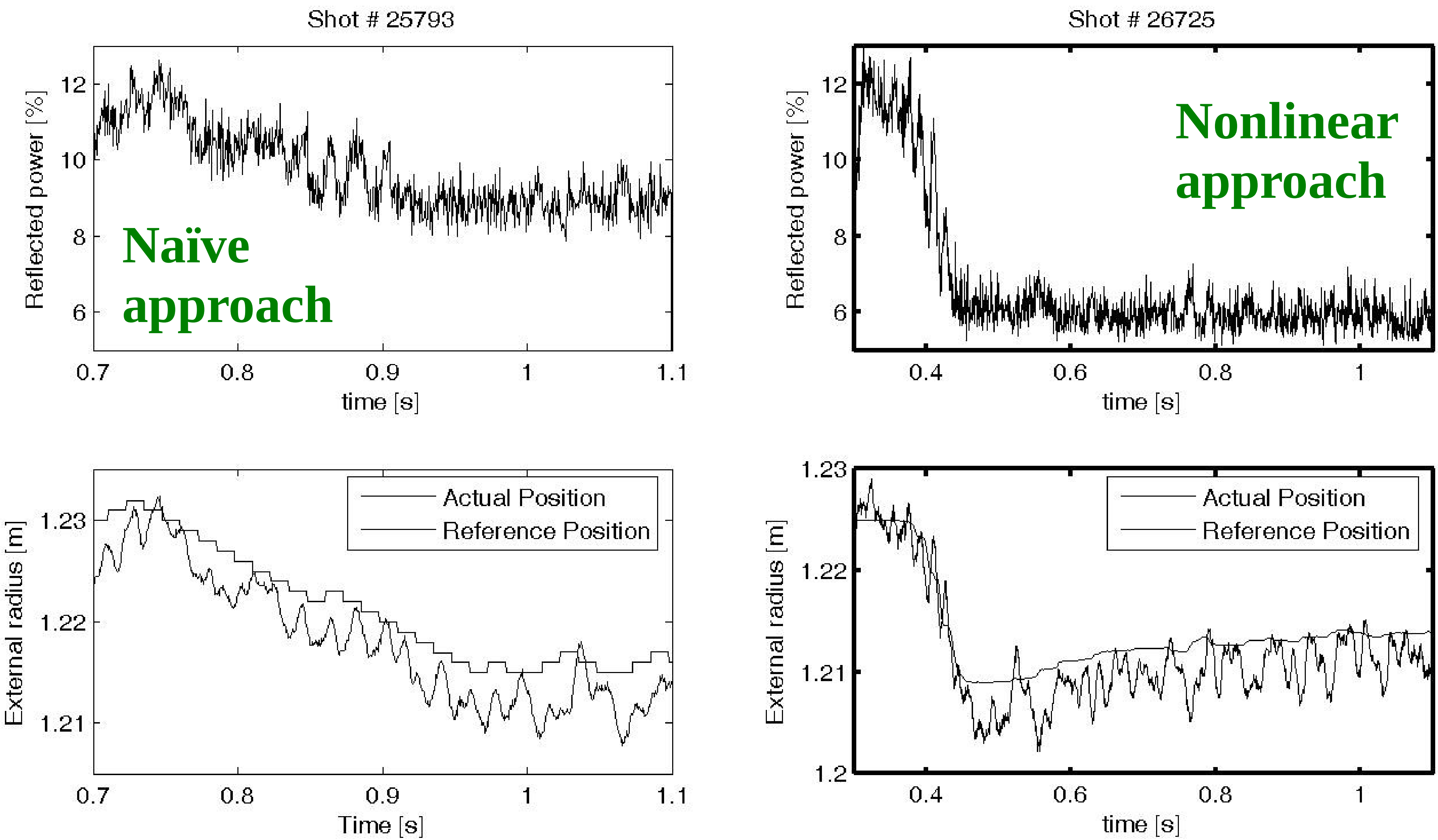
Additional RadioFrequency heating injected in the plasma by way of Lower Hybrid (LH) antennas: plasma reflects some power

Goal:

Optimize coupling between the Lower Hybrid antenna and tha plasma, during the LH pulse



Nonlinear extremum seeking for RF heating

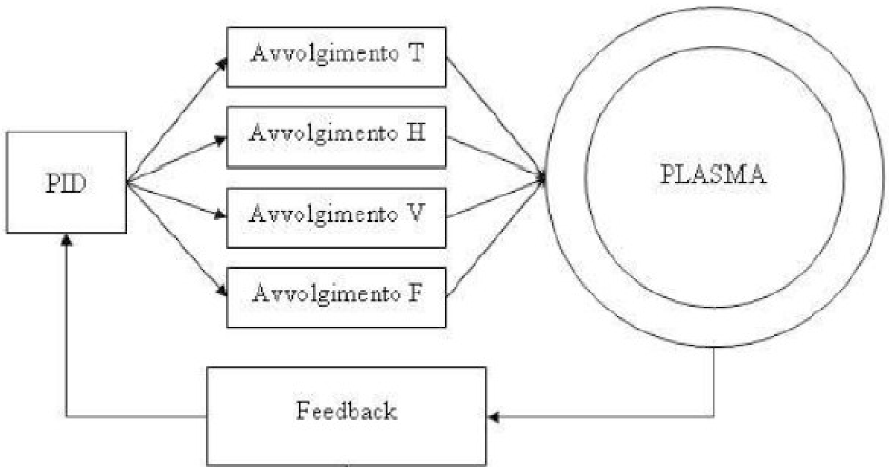


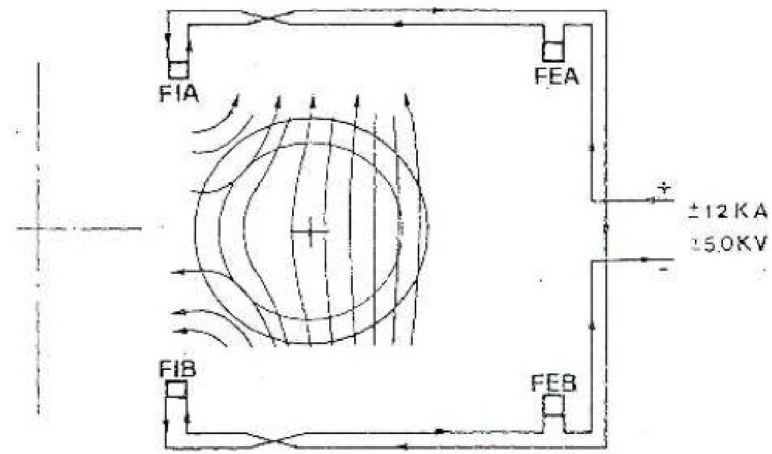
Summary of overview

- Nonlinear control solutions have been illustrated on **examples**
  - with input nonlinearities causing **transient** problems
  - with input nonlinearities causing **steady-state** problems
  - in the **extremum seeking** context maximizing RFH efficiency
- More generally **several tools are available** and can be used to improve upon what is achieved by linear tools
- Typically, **interaction** between control theorists and applied control people uncovers directions where **nonlinear control can help**
- An example of such a situation is given next

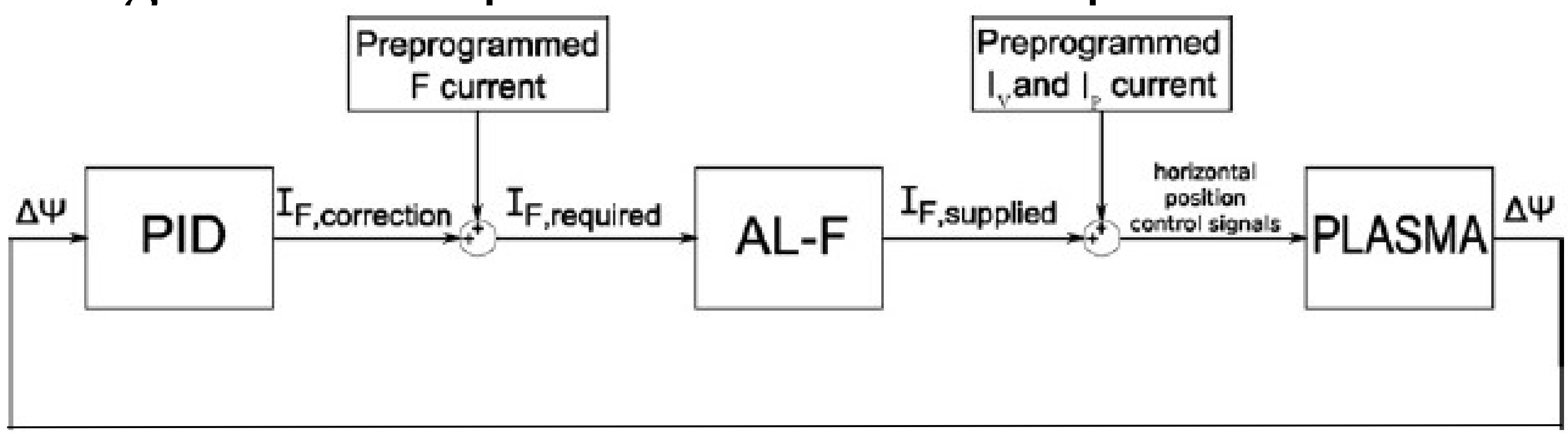
Horizontal position controller at FTU

- At FTU the horizontal plasma position hinges upon the F coil



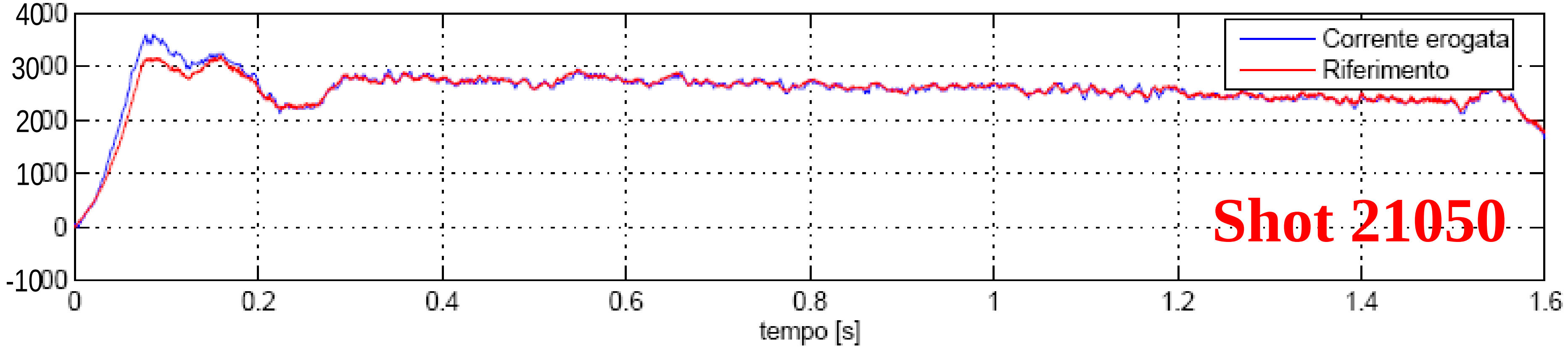


- The coil is controlled in feedback by a PID controller driving a circulating current 4 quadrants current amplifier

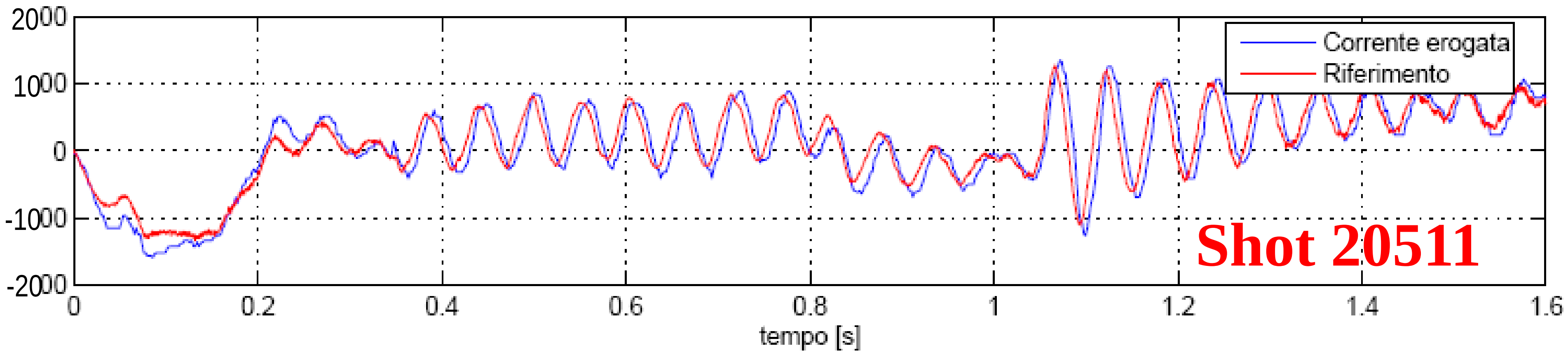


Problem description

- During experiments, feedback performs well with large currents



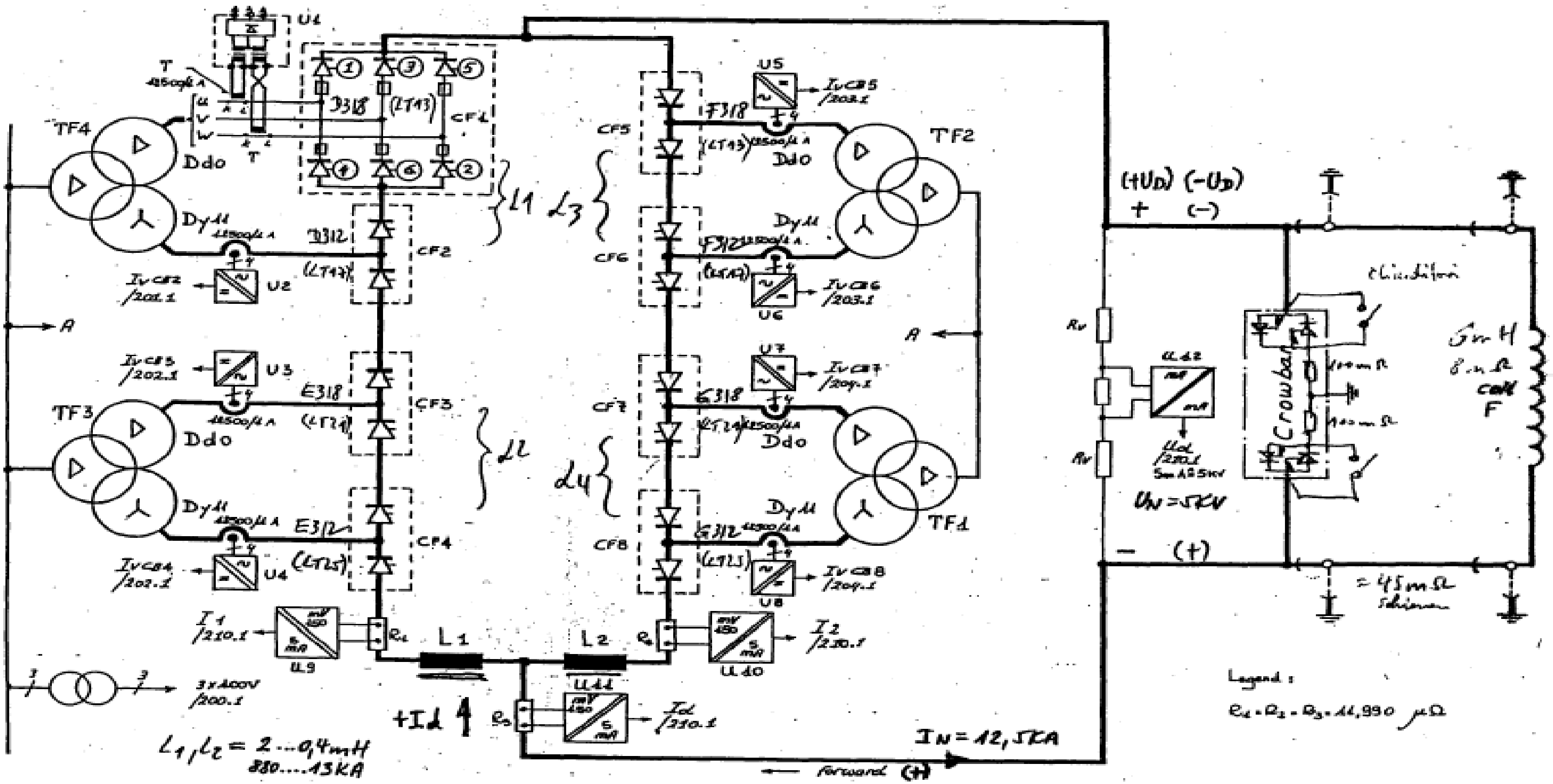
- When the current request is close to zero, instability occurs



- Find a nonlinear compensation preserving 21050 and fixing 20511

System model

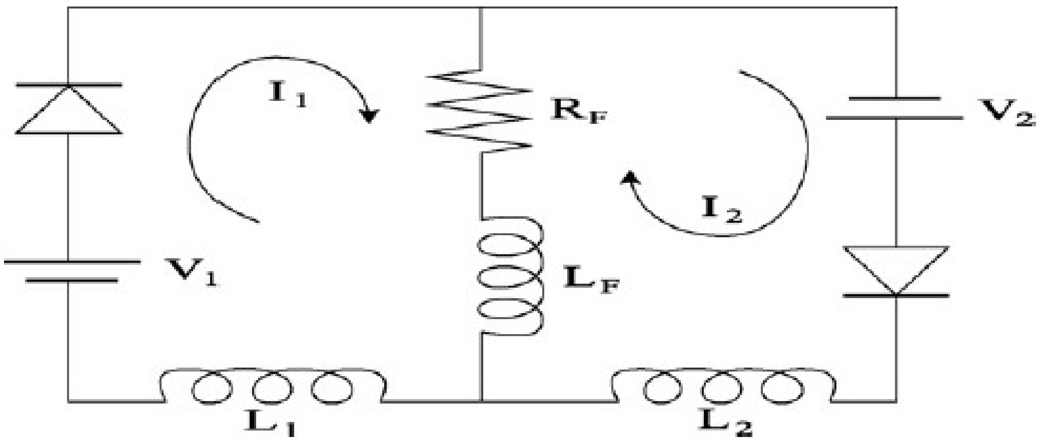
- Actuator is nonlinear close to the origin:
  - high current demands → current flows only in one branch
  - low current demands → current flows in both branches



System model (cont'd)

- Simplified electrical scheme:

$$V_1 = L_1 \frac{\mathrm{d}I_1}{\mathrm{d}t} + L_F \frac{d(I_1 - I_2)}{\mathrm{d}t} + R_F(I_1 - I_2) + 8V_T$$
$$V_2 = L_2 \frac{\mathrm{d}I_2}{\mathrm{d}t} - L_F \frac{d(I_1 - I_2)}{\mathrm{d}t} - R_F(I_1 - I_2) + 8V_T,$$



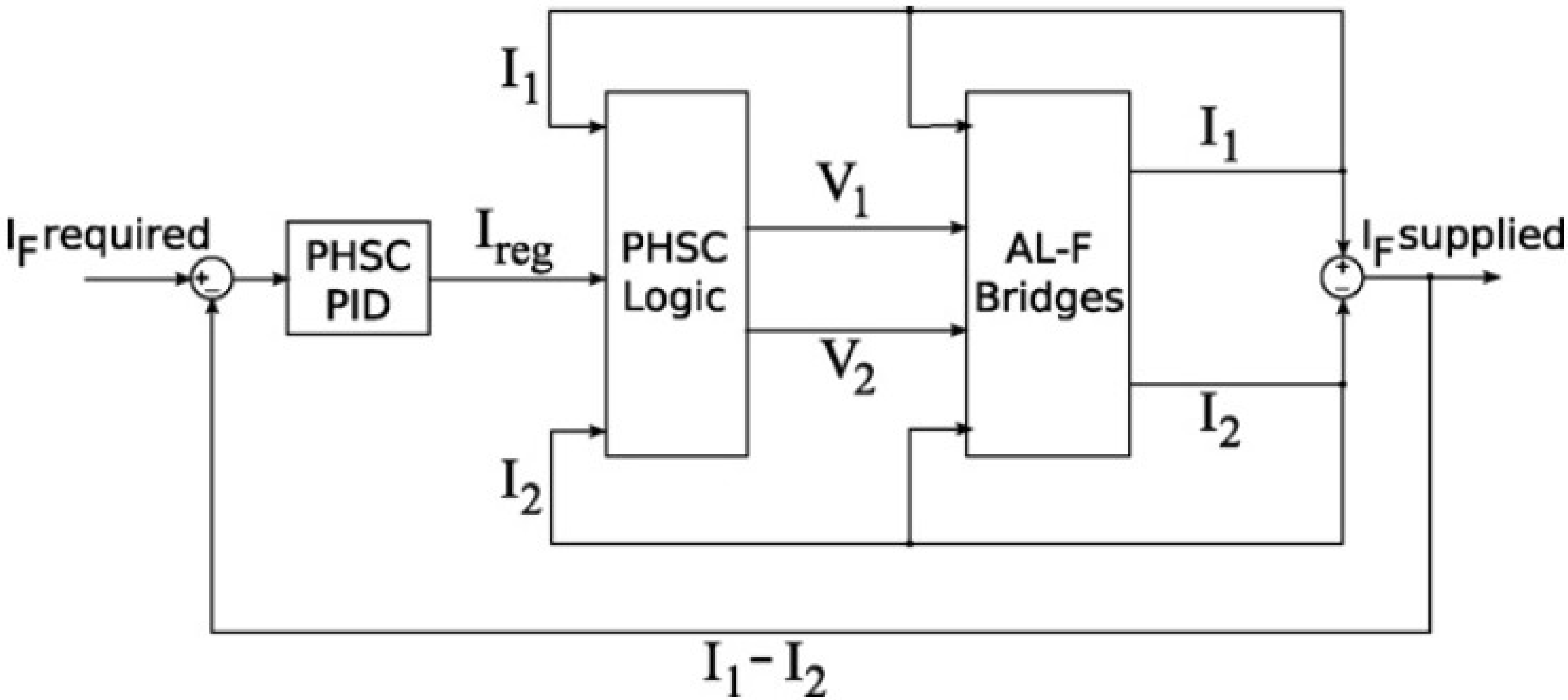
- When incorporating the diodes in the equations (nonlinear):

$$\frac{\mathrm{d}I_1(t)}{\mathrm{d}t} = \begin{cases} \max\left\{0, \frac{(L_2+L_F)V_1(t)+L_FV_2(t)+L_2R_F(I_2(t)-I_1(t))-8(2L_F+L_2)V_T}{L_1L_2+L_F(L_1+L_2)}\right\}, & \text{if } I_1(t)\leq 0, \\ \frac{(L_2+L_F)V_1(t)+L_FV_2(t)+L_2R_F(I_2(t)-I_1(t))-8(2L_F+L_2)V_T}{L_1L_2+L_F(L_1+L_2)}, & \text{otherwise,} \end{cases}$$

$$\frac{\mathrm{d}I_2(t)}{\mathrm{d}t} = \begin{cases} \max\left\{0, \frac{(L_1+L_F)V_2(t)+L_FV_1(t)+L_1R_F(I_1(t)-I_2(t))-8(2L_F+L_1)V_T}{L_1L_2+L_F(L_1+L_2)}\right\}, & \text{if } I_2(t)\leq 0, \\ \frac{(L_1+L_F)V_2(t)+L_FV_1(t)+L_1R_F(I_1(t)-I_2(t))-8(2L_F+L_1)V_T}{L_1L_2+L_F(L_1+L_2)}, & \text{otherwise,} \end{cases}$$

System model (cont'd)

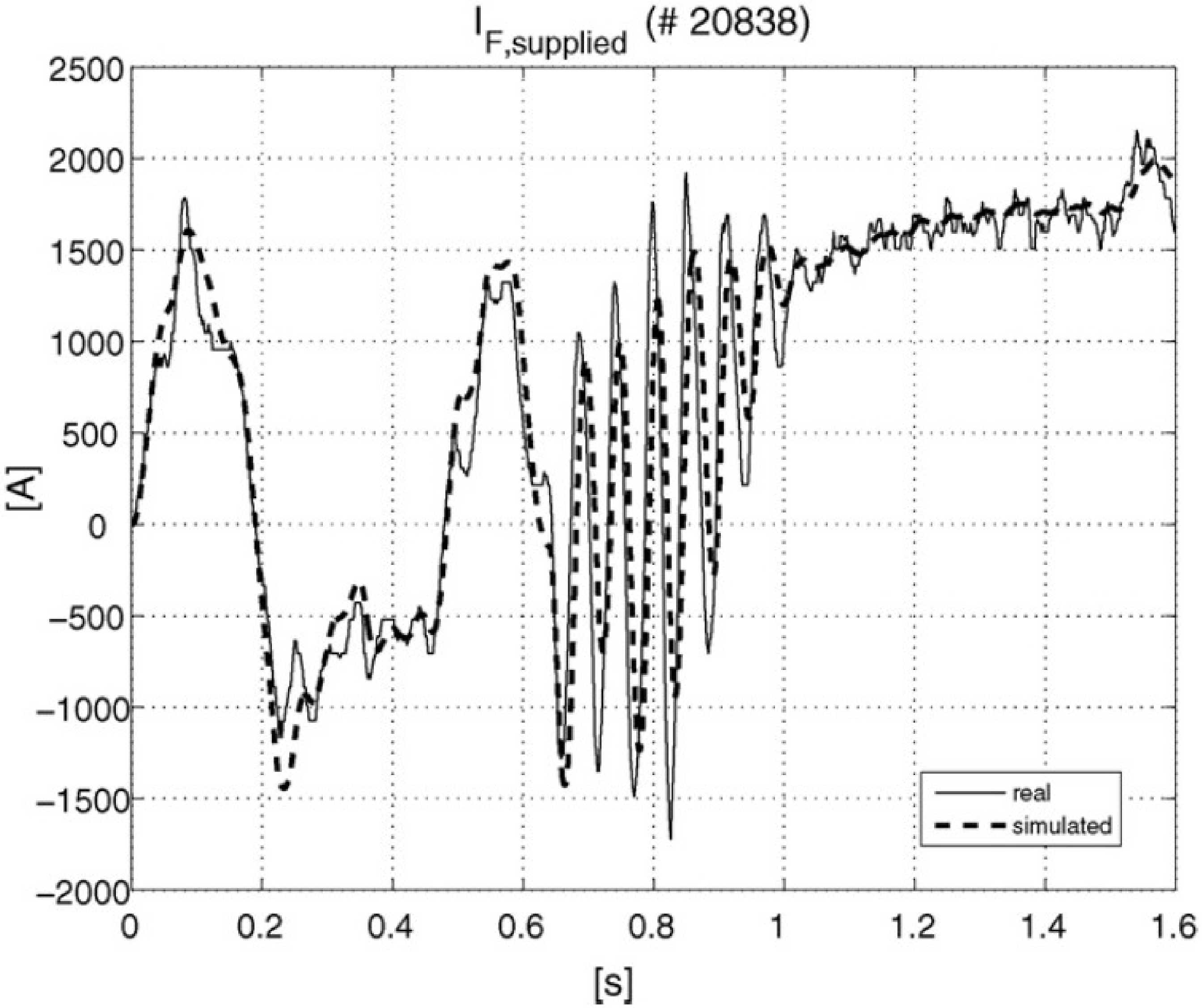
- Hardware controller enforces a further nonlinear behaviour:



- PHSC Logic is a nonlinear block ensuring that the bridges provide currents *I1*, *I2* both above the lower conduction limits of the thyristors (*1200 A*)

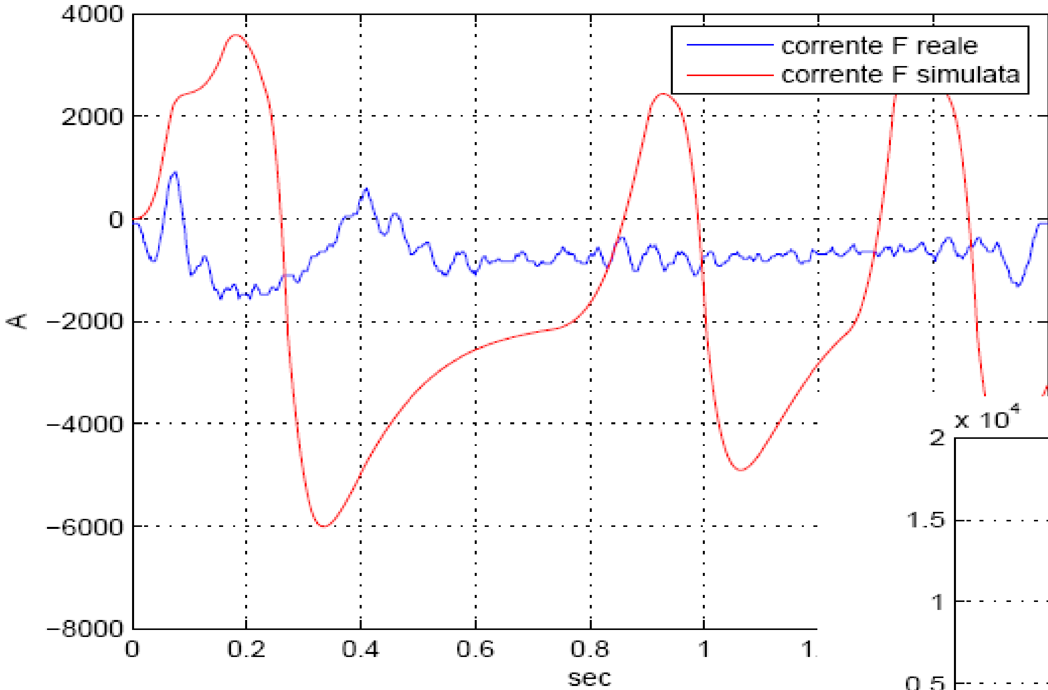
Simulations show matching responses

- Open-loop simulations show good matching of the model:

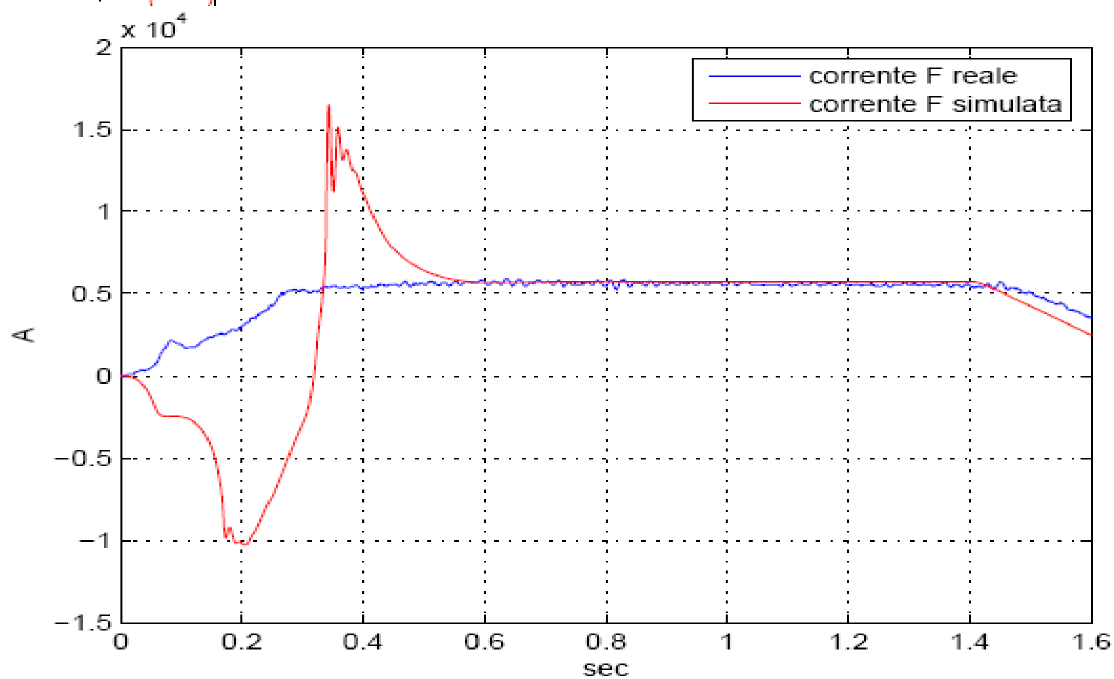


Simulations show matching responses

- Closed-loop simulations reproduce the experimental instability:



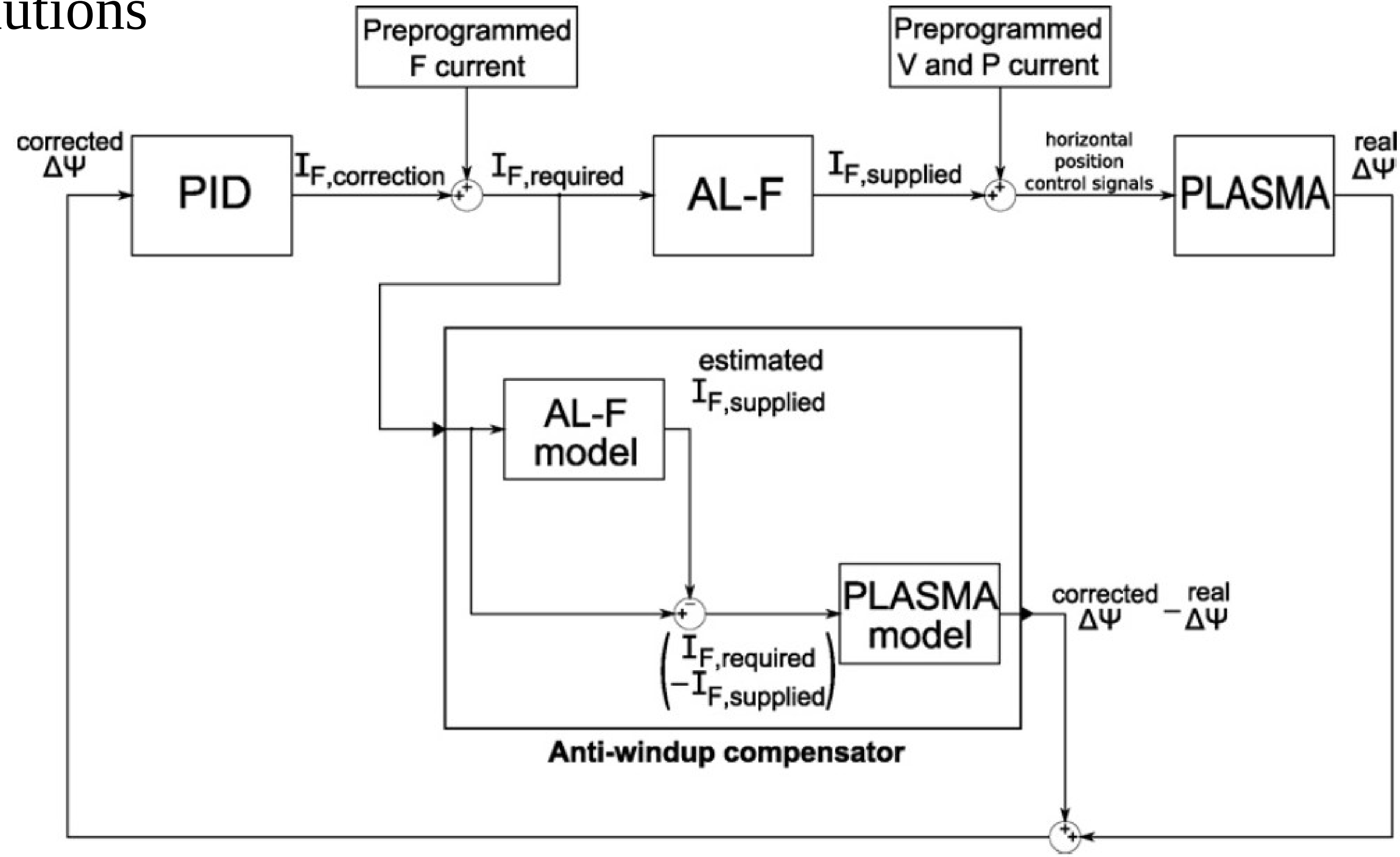
- Model provides further insight into the instability mechanism



- Note the uncertainty of the initial conditions

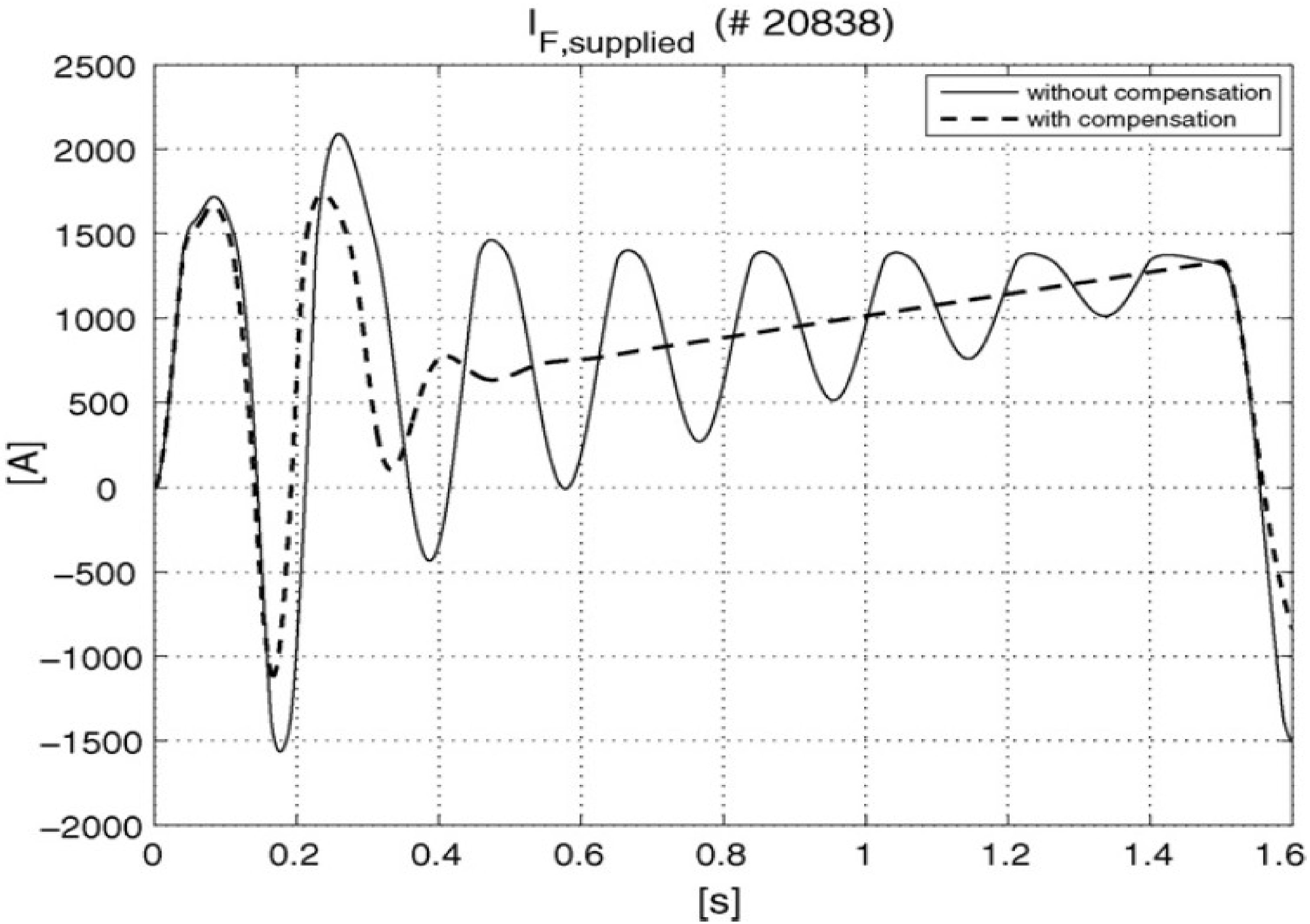
Nonlinear compensation

- Solution along the lines of consolidated nonlinear anti-windup solutions



Simulation results

- Anti-windup successfully recovers the closed-loop stability



Experimental results

- Preliminary experiments confirm the effectiveness of the solution