

Cross-validation of control-oriented plasma magnetic models with EDICAM

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34th Symposium on Fusion Technology (SOFT 2026) | Sep 21–25, 2026 | Aix-en-Provence, France



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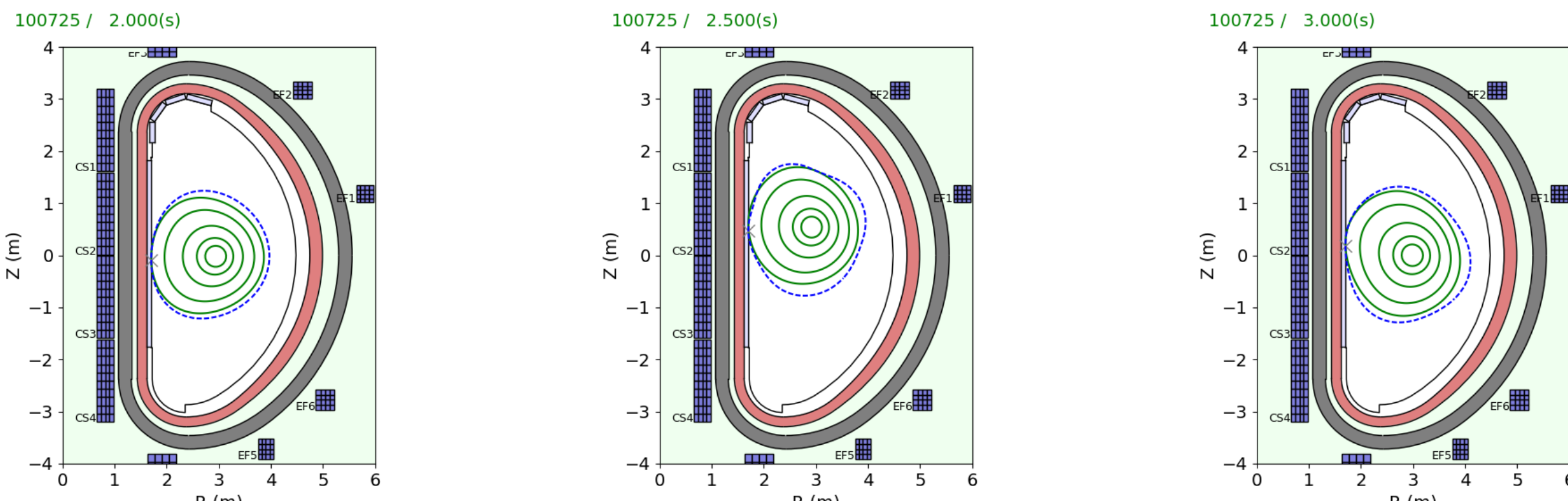


Key result: Cross-validation of the CREATE control-oriented linear model over a wide variation corresponding to a vertical displacement of the JT-60SA plasma of approximately 0.5 m.

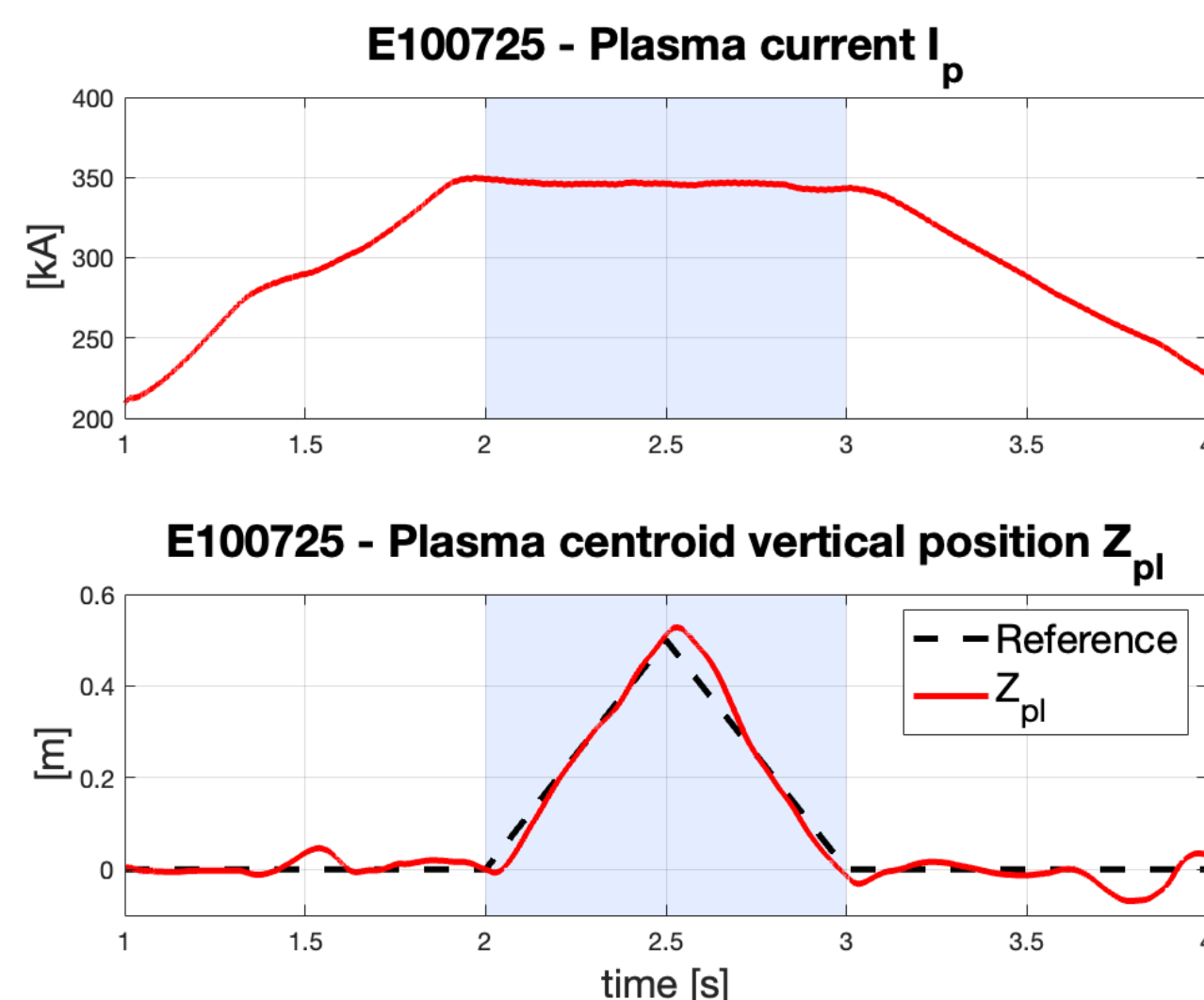
- The model output is compared with both model-based (CCS) and data-driven (CARONTE) real-time plasma boundary reconstruction codes, as well as with measurements acquired by the EDICAM during OP1.
- Despite the large variation considered and the challenging equilibrium, the linear model approximation proved to be accurate and reliable enough for control design purposes.

Reference scenario: the JT-60SA pulse E100725

- JT-60SA pulse **E100725**.
- **Limiter plasma** from the JT-60SA OP1 campaign.
- **A vertical movement of about 0.5 m** was performed during the 350 kA flattop.
- A relatively **challenging scenario for equilibrium and reconstruction codes**



FAME equilibria and CCS boundary reconstructions from eSurf



The CREATE control-oriented plasma model

Around a given plasma equilibrium, specified by means of **nominal/experimental values** I_{p0} , I_{PF0} , β_{p0} and i_{i0} , the behavior of the JT-60SA plasma can be described by the state space model [1]

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{A} \cdot \mathbf{x}(t) + \mathbf{B} \cdot \mathbf{u}(t) + \mathbf{E} \cdot \dot{\mathbf{w}}(t) \\ \mathbf{y}(t) &= \mathbf{C} \cdot \mathbf{x}(t) + \mathbf{F} \cdot \mathbf{w}(t),\end{aligned}\quad \begin{aligned}(1a) \\ (1b)\end{aligned}$$

where

- $\mathbf{x} = (\delta I_{PF}^T, \delta I_p^T, \delta I_p)^T$ holds the variations of the currents in the CS/EF coils δI_{PF} , of the eddy currents in the passive structures δI_e , and of the plasma current δI_p ;
- $\mathbf{u}$ is the vector of the voltages applied to the CS/EF coils;
- $\mathbf{w} = (\delta \beta_p, \delta i_i)^T$ is the disturbance vector, i.e. the variations of β_p and i_i ;
- $\mathbf{y}$ is the output vector that contains all the **quantities of interest** → in our case, **flux map** and plasma position descriptors such as **plasma centroid position**.

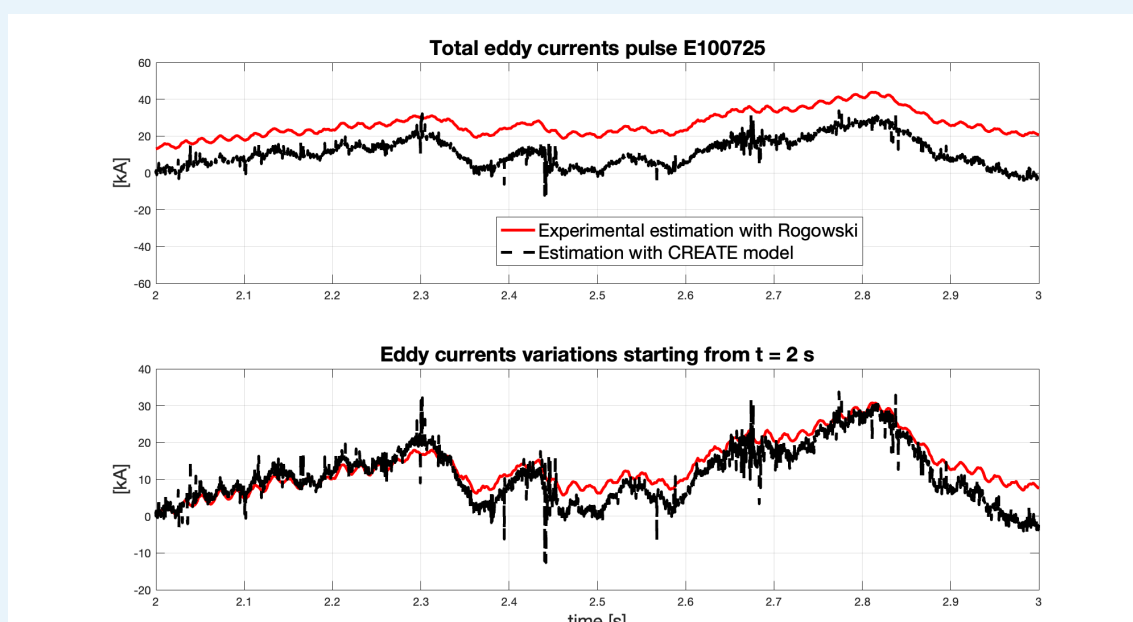
The model validation is performed by

- **feeding the experimental CS/EF currents** $I_{PF}^T(t)$ and $I_p(t)$ in (1b);
- **neglecting the variations** $\delta \beta_p, \delta i_i$, **since no real-time estimates are available for OP1**;

Because the eddy currents cannot be neglected in (1b), **they need to be estimated** → To this end, an approximated linear model is used (it also requires the experimental currents $(I_{PF}^T(t), I_p(t))^T$ as input)

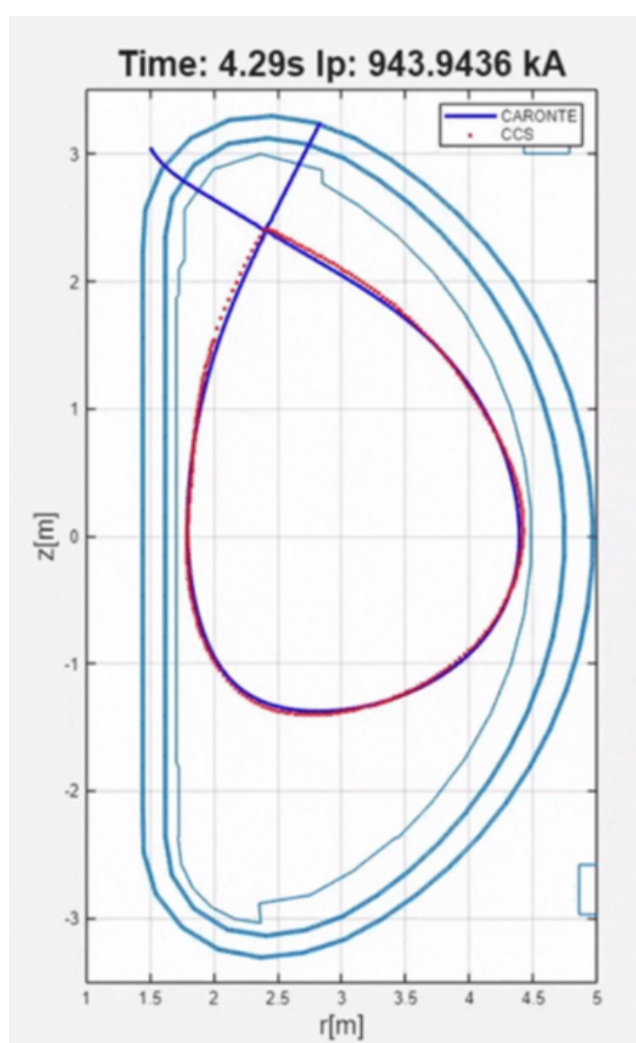
$$\dot{\Psi}(t) = -\mathbf{R}_{eddy} \mathbf{L}_{eddy}^{-1} \cdot \Psi(t) + \mathbf{R}_{eddy} \mathbf{L}_{eddy}^{-1} \mathbf{M}_{eddy,active} \cdot (I_{PF}^T(t), I_p(t))^T \quad (2a)$$

$$\mathbf{I}_e(t) = \mathbf{L}_{eddy}^{-1} \cdot \Psi(t) - \mathbf{L}_{eddy}^{-1} \mathbf{M}_{eddy,active} \cdot (I_{PF}^T(t), I_p(t))^T \quad (2b)$$



When dealing with linear models, the variations matter!

Real-time plasma boundary reconstruction codes



Cauchy Condition Surface code (CCS, [2])

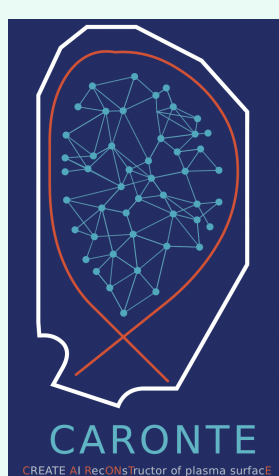
[Physics-based Algorithm]

- CCS solves the Grad-Shafranov equation in the vacuum by assigning the Cauchy conditions on a pre-determined surface, whose boundary is an ellipse.
- CCS is used at JT-60SA for real-time plasma boundary control.

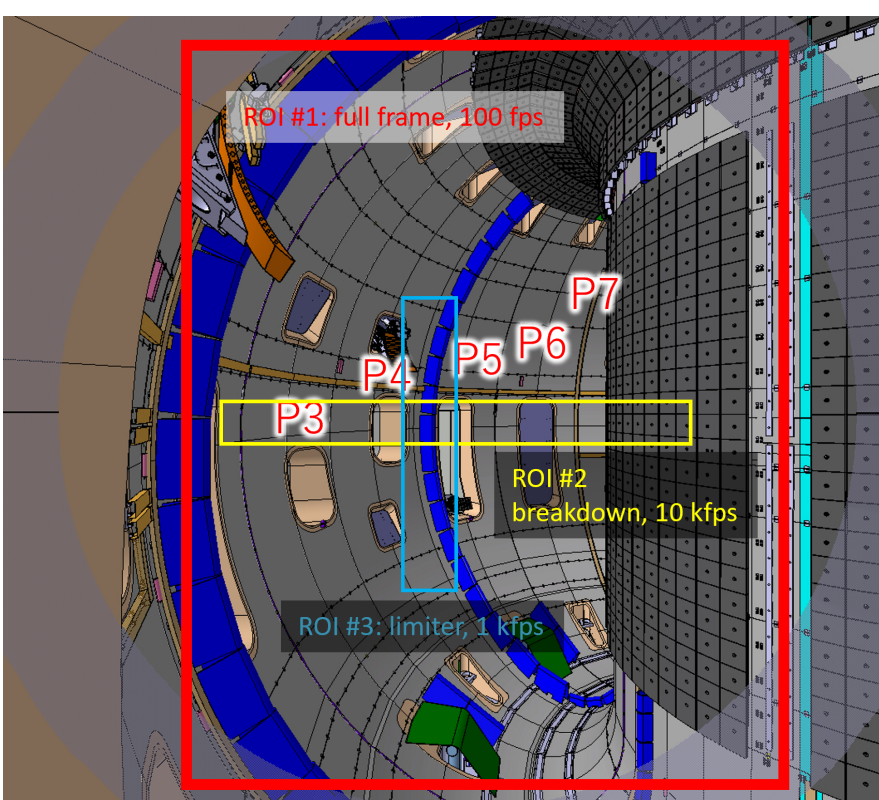
CREATE AI ReConstrucTor of plasma surfaceE (CARONTE, [3] and POSTER S1-045)

[Physics-Informed Neural Network]

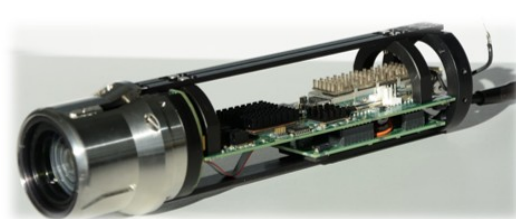
- It uses a single Extreme Learning Machine Neural Network to reconstruct the plasma boundary.
- The Grad-Shafranov equation is enforced as a hard constraint.
- The neural network can be trained in real time.



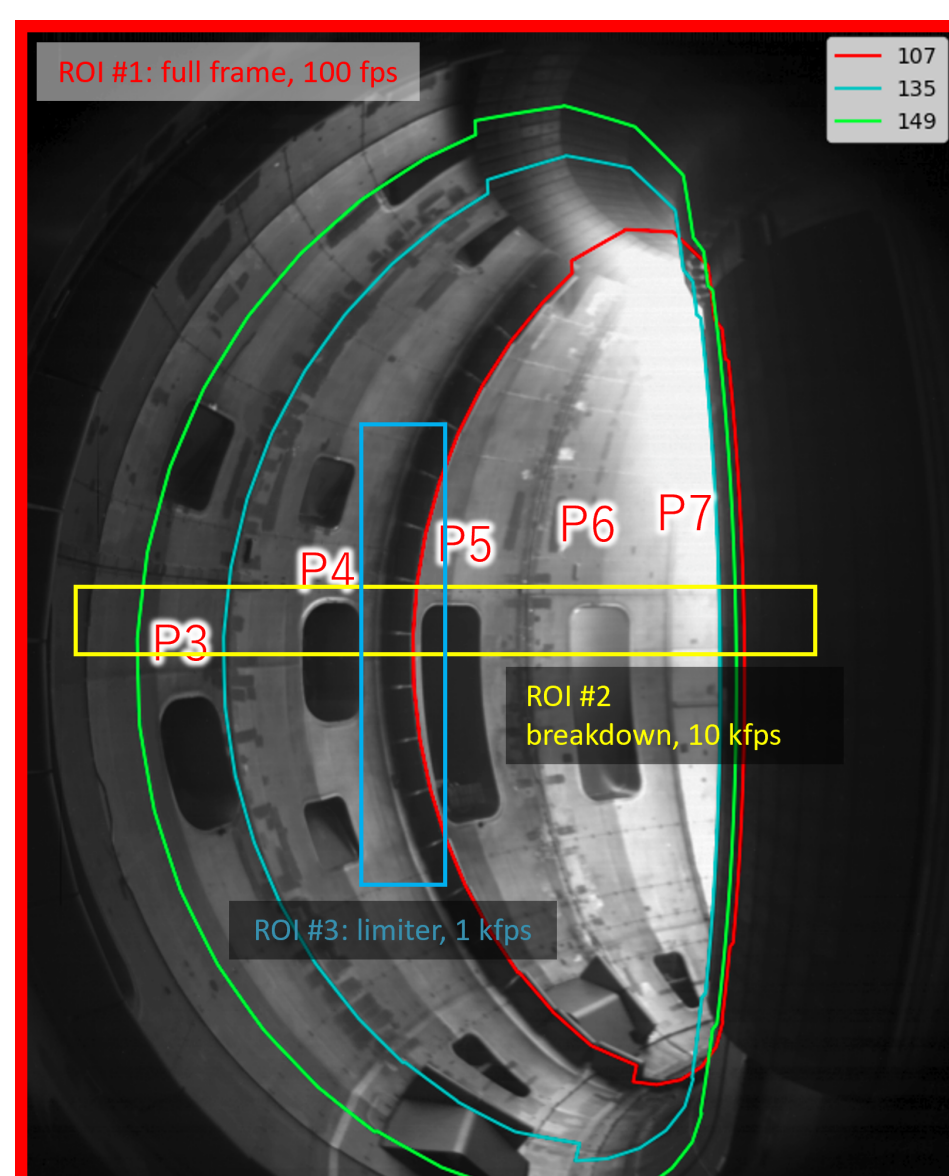
The JT-60SA EDICAM



Event Detection Intelligent Camera (EDICAM)



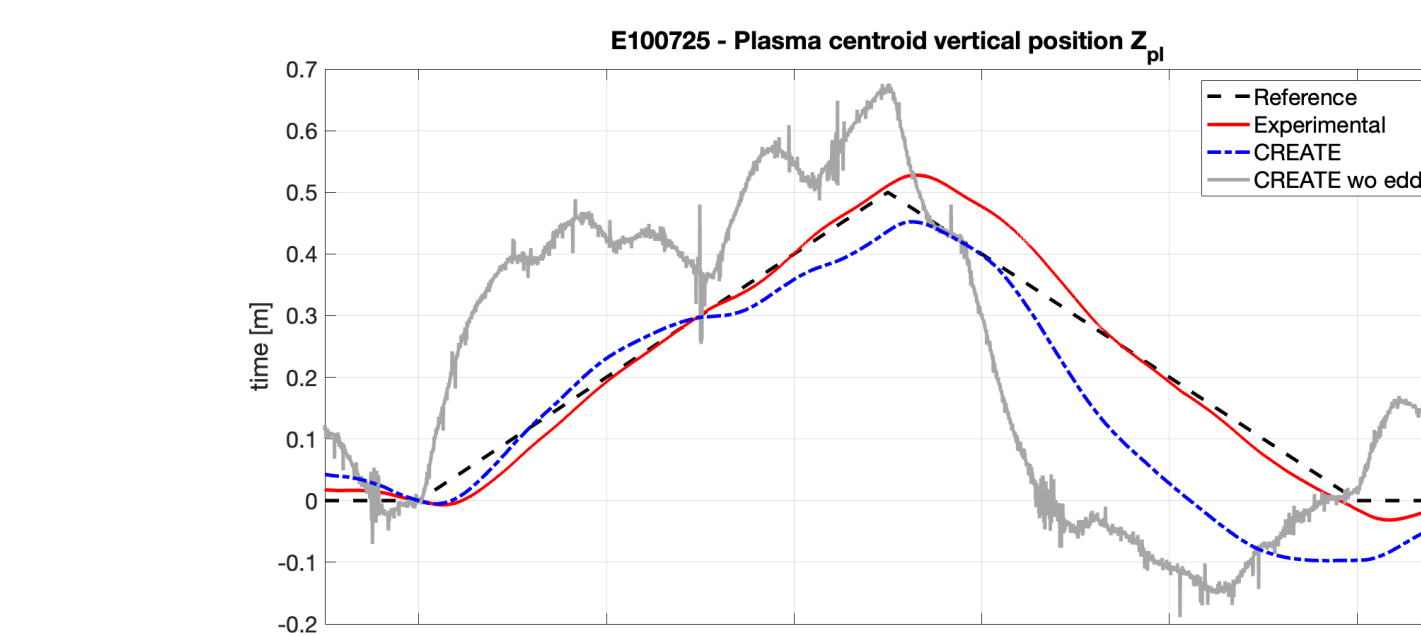
- CMOS sensor: 400 fps @ 1280×1024 pixel
⇒ a 32×32 Region-of-Interest (ROI) @ 60,000 fps.
- real-time ROI handling (up to 6 ROIs);
- real-time event detection & actions.



References

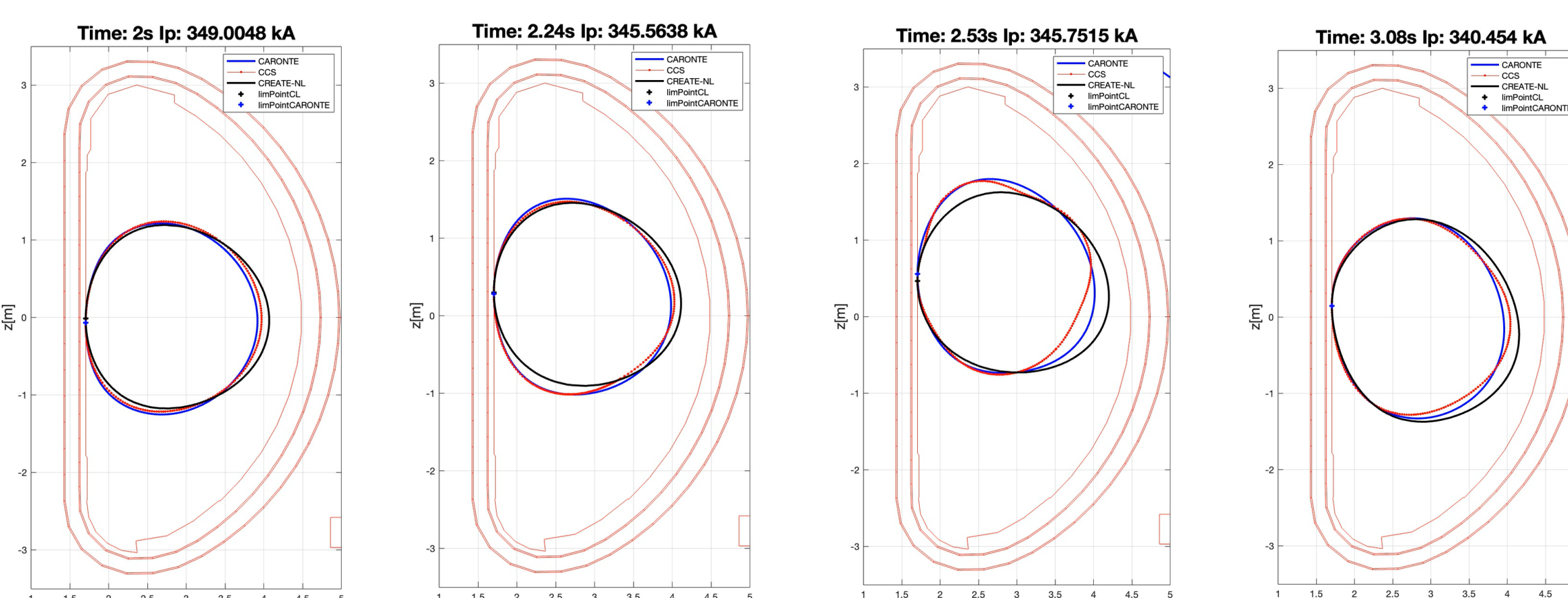
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Plasma centroid vertical position



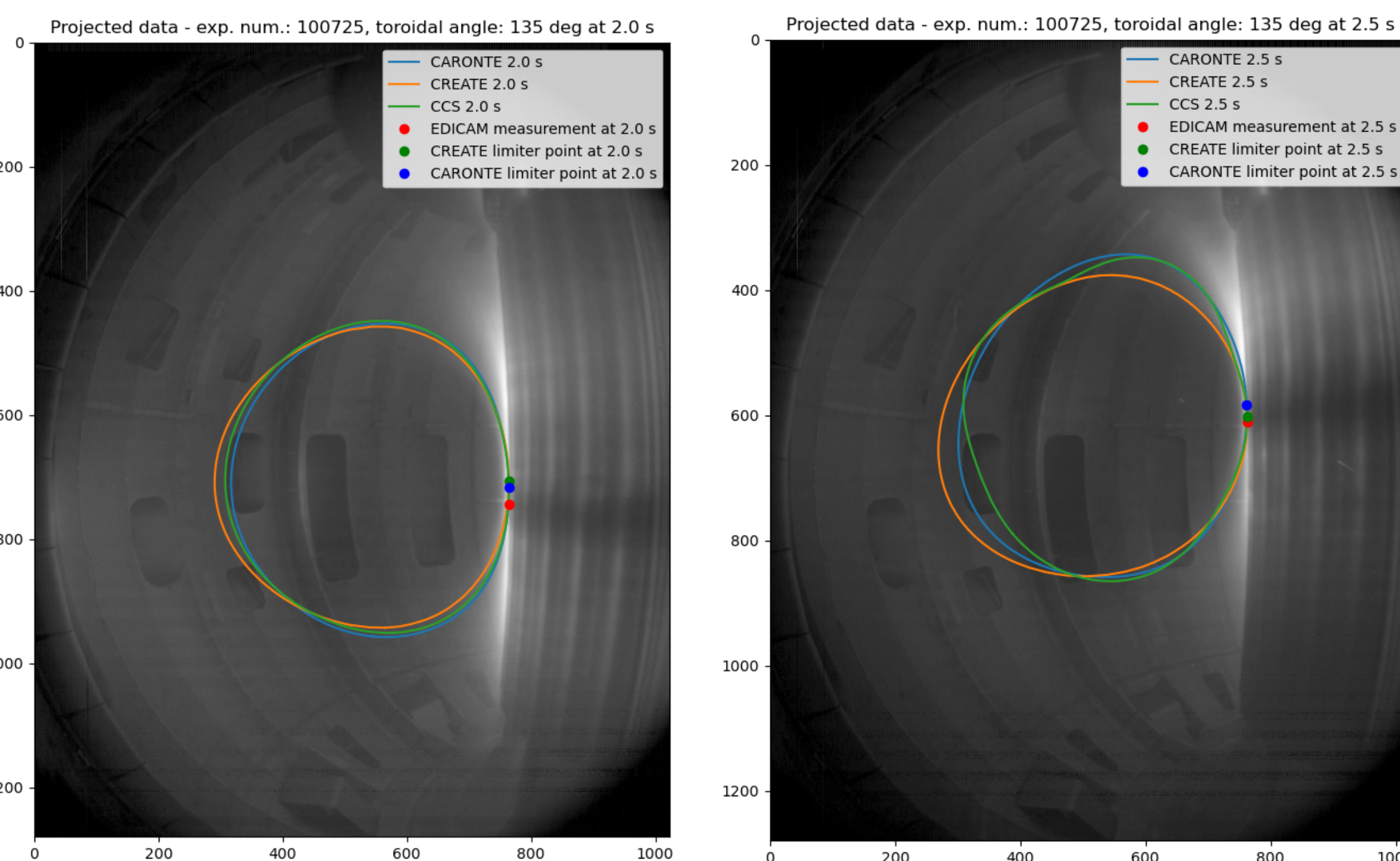
- Although the plasma current is at flattop, the eddy currents cannot be neglected.
- The linear approximation is sufficient to capture the eddy currents dynamics.
- **The linearized model is sufficiently accurate for control-design purposes [5,6].**

Plasma boundary



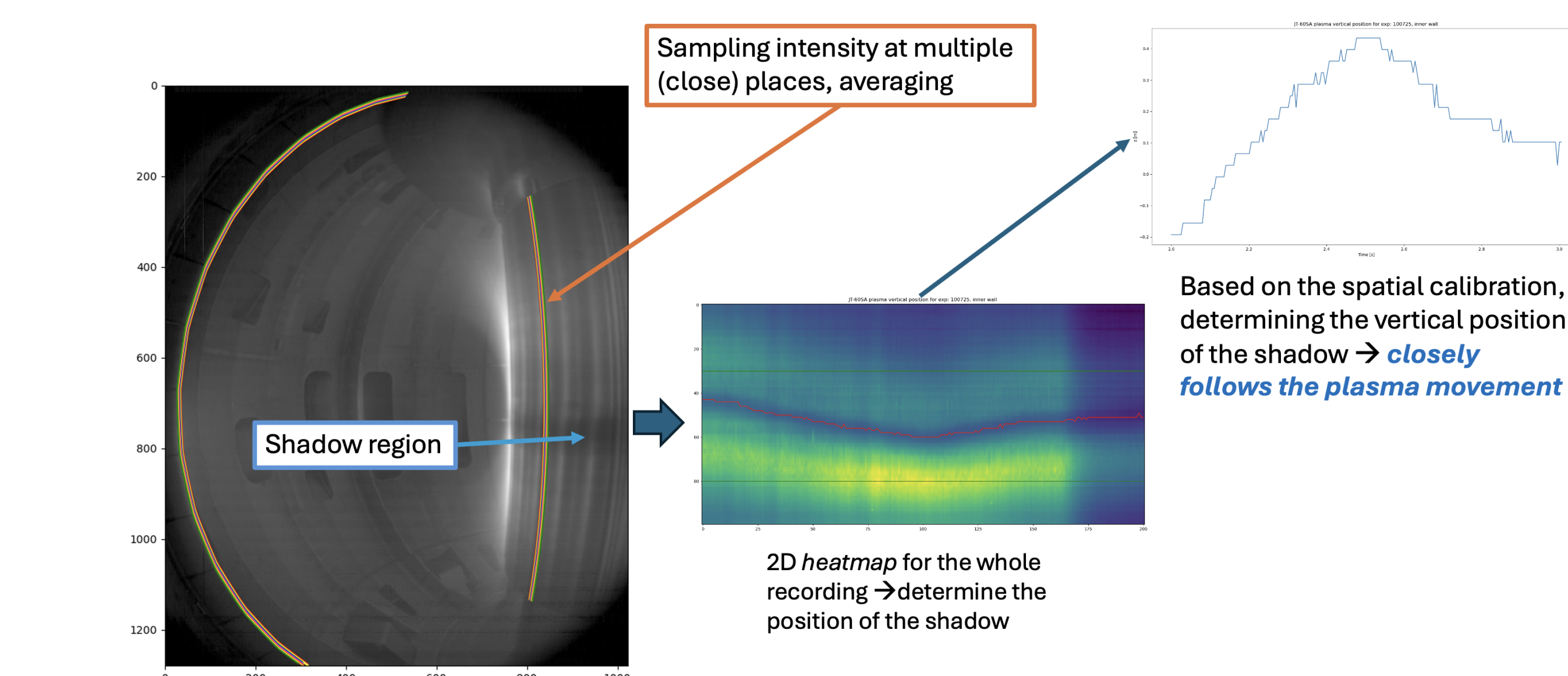
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EDICAM cross-validation

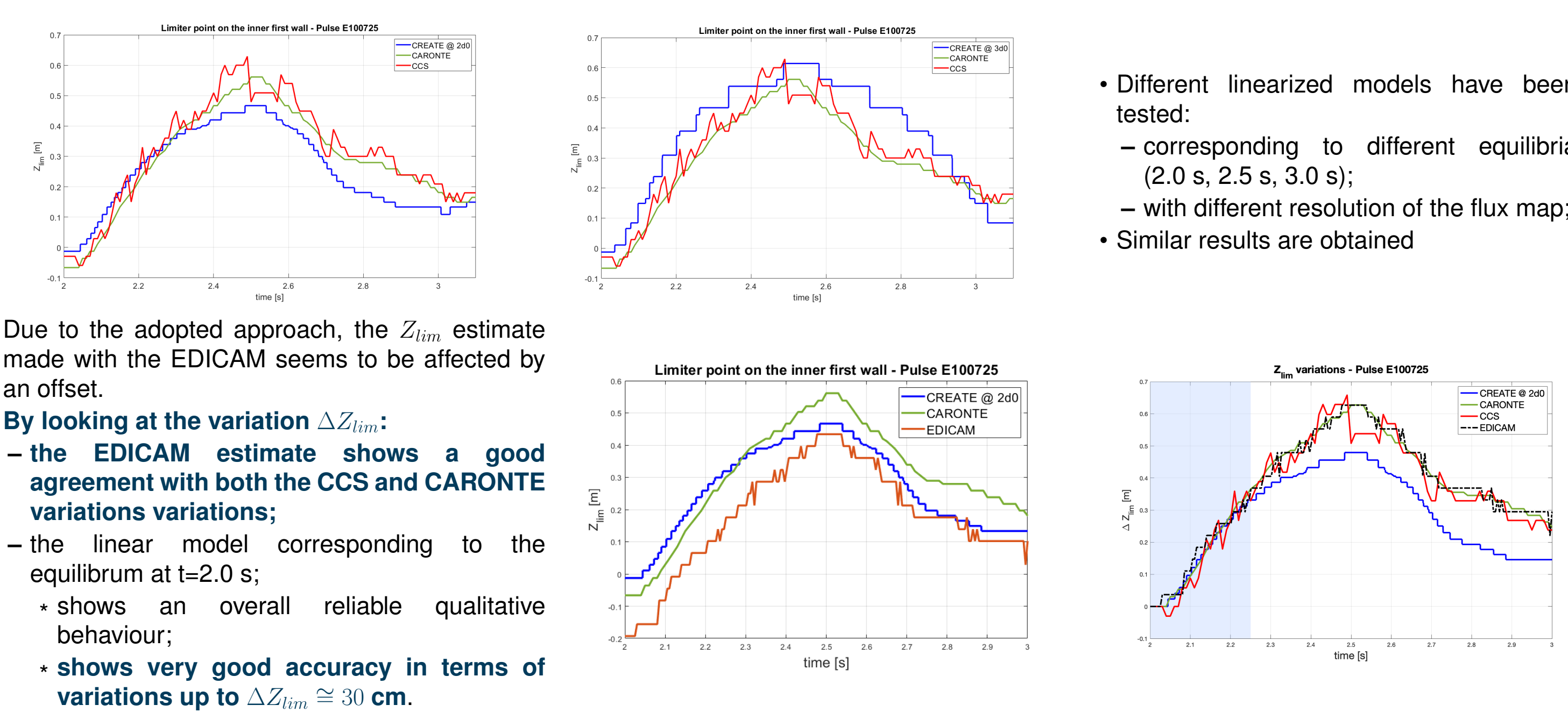


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EDICAM estimate of the limiter point



Vertical position of the limiter point



- Different linearized models have been tested:
 - corresponding to different equilibria (2.0 s, 2.5 s, 3.0 s);
 - with different resolution of the flux map;
- Similar results are obtained

- Due to the adopted approach, the Z_{lim} estimate made with the EDICAM seems to be affected by an offset.
- **By looking at the variation ΔZ_{lim} :**
 - the EDICAM estimate shows a good agreement with both the CCS and CARONTE variations variations;
 - the linear model corresponding to the equilibrium at $t=2.0$ s;
 - shows an overall reliable qualitative behaviour;
 - shows very good accuracy in terms of variations up to $\Delta Z_{lim} \approx 30$ cm.

Conclusions

- **Linearized models of the plasma response proved to be sufficiently accurate for control purposes, even for challenging scenarios.**
 - at relatively **low** plasma current;
 - with relatively **small** plasmas;
 - when relatively **large** variations are considered (0.5 m for JT-60SA).
- **Very good agreement, in terms of variations, between plasma boundary reconstruction codes and EDICAM estimate.**
 - Provided a suitable HW, the EDICAM estimate can be deployed in real-time.
- A control architecture for OP1 has been designed exploiting the CREATE linear model [5] and successfully validated using the MECS simulator [6,7].
- A proposal to test control algorithms on JT-60SA is under consideration.

Acknowledgments

- JT-60SA was jointly constructed and is jointly funded and exploited under the Broader Approach Agreement between Japan and EURATOM.
- These results were partially funded by the TRAINER project "Tokamak plasmas data-driven identification and magnetic control." CUP E53D23014670001, funded by the European Union under the NextGenerationEU plan through the Italian PRIN call, D.D. 1409 of 14 September 2022, issued by Italian University and Research Ministry (MUR).
- This research has been partially carried out within the ITER Scientist Fellow Agreement.