Improved Real-time Equilibrium Reconstruction with Kinetic Constraints on DIII-D and NSTX-U

Mechanical & Aerospace Engineering

Princeton Plasma Control
control.princeton.edu

R. Shousha, J.R. Ferron, Z.A. Xing, A.O. Nelson, K.G. Erickson and E. Kolemen (rshousha@Princeton.edu)

Department of Mechanical & Aerospace Engineering, Princeton University

Princeton Plasma Control
control.princeton.edu

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Motivation and Background

(Kinetic) RT-equilibrium reconstruction is crucial because many quantities of interest are not measured directly

Many Discharge relevant parameters **can not by measured directly** ...
However,

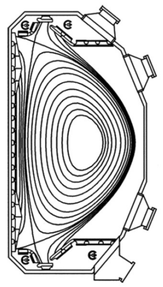
- They can be evaluated indirectly from available diagnostic data
- Least squares solution of diagnostic data to the Grad-Shafranov model allows evaluation

Grad-Shafranov model

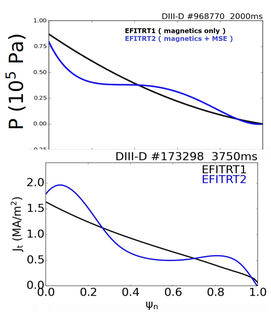
- **Describes force balance of tokamak equilibrium (axisymmetric)**
- **Allows for distributed current source**
- **Determines distribution of poloidal flux ψ and toroidal current density J_ϕ in R, Z-plane**

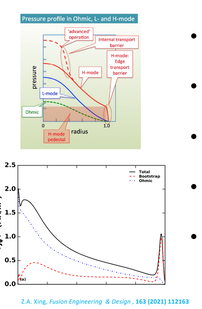
$$\boldsymbol{J}\times\boldsymbol{B} = \nabla p \qquad \nabla\times\boldsymbol{B} = \mu_0\boldsymbol{J} \qquad \nabla\cdot\boldsymbol{B} = 0$$

$$\frac{\partial^2\psi}{\partial z^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial r^2} = -\mu_0 R\left(RP'(\psi) + \frac{FF'(\psi)}{\mu_0 R}\right) = -\mu_0 R J_\phi$$

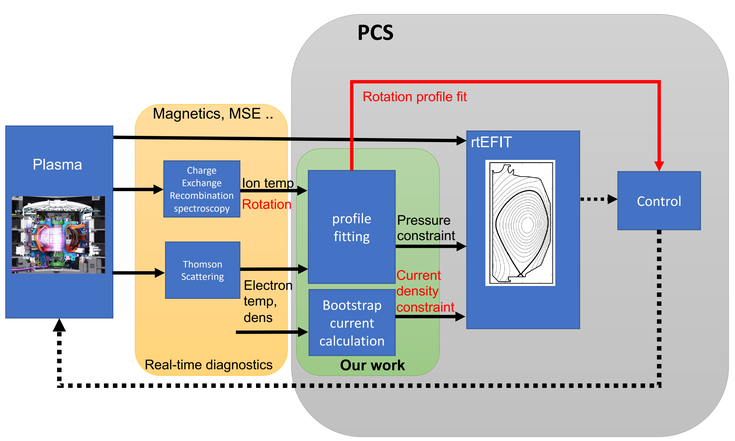


Reconstructed pressure and current density profile for H-mode:





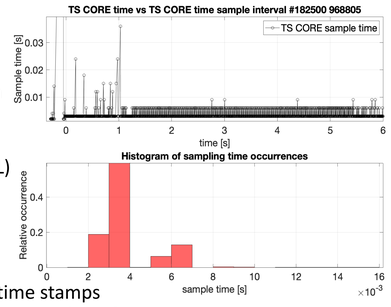
- Typical "H-mode pedestal" completely absent
- Without kinetic data, only 3 global parameters constrained
- Need real-time pressure profile estimation
- Typical "H-mode bootstrap peak" completely absent
- Need real-time current density profile constraints!



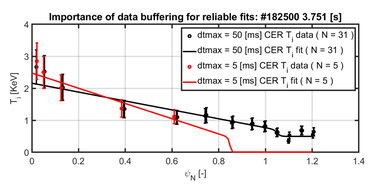
Method

Data buffering required to robustly handle variable data availability in real-time application:

- TS outputs **CORE**, DIVERTOR and TANGENTIAL measurements (not in parallel), limiting data refresh rate
- CER outputs **CORE** and **EDGE** measurements (not in parallel, no ML)
- Need enough data points in core and pedestal for fit, using data that is not 'too old'



→ Buffer TS and CER data & associated time stamps
→ Check if enough data in core and edge to perform fit



If we assume that the data is 'correct':

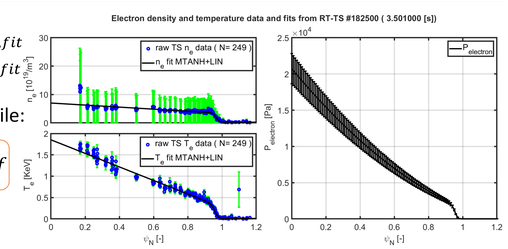
- Red profile (few data points, none in pedestal region) takes form of model function but completely wrong in pedestal compared to same case but with added data from the EDGE CER, stressing importance of buffering.

Raw kinetic measurements from TS fitted to MTANH+LIN with 50 ms buffer

- MTANH+LIN profile fit $n_{e,fit}$
- MTANH+LIN profile fit $T_{e,fit}$

→ Compute $P_{electron}$ - profile:

$$P_{electron} = n_{e,fit} \quad T_{e,fit} \quad f$$



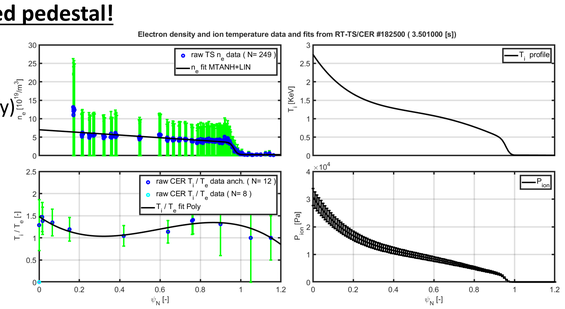
MTANH+LIN fit generated based on CER and TS separately not robust against misaligned pedestal!

Solution inspired by CAKE:

- Fit ratio Ti/Te (poly)
  - Anchor points with large uncertainty
- Multiply by Te fit
- Aligned pedestal

Real-time specific:

- Chebyshev polynomials
- Regularized weighted LS



(Impurity contribution to pressure not accounted for yet)

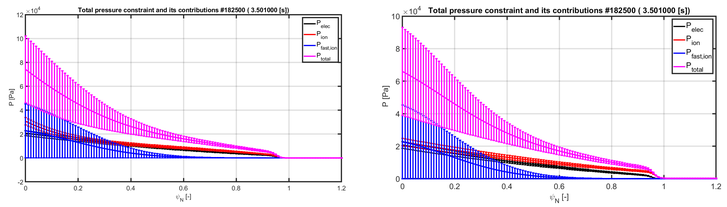
→ **Same quality fit, able to reduce condition number by factor > 400 !**

Method

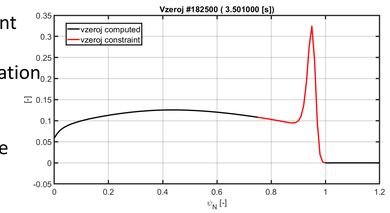
The total pressure profile resulting from the Ti/Te method is similar to the one generated using MTANH+LIN

Total pressure constraint and subcomponents:

Ti/Te **MTANH+LIN**



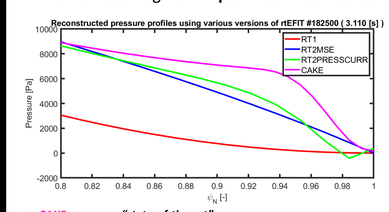
- Lack of measurements to constrain current density in H-mode pedestal
  →Motivates use of Sauter model for estimation bootstrap current
  →Constraints on the flux surface average toroidal current density normalized to the average plasma density (same type of constraint as in **EFIT**):
- Only data between $0.7 \le \psi_N \le 1$ are sent to rtEFIT as constraints (red)

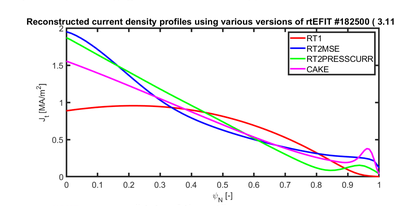


$$\mathrm{vzeroj} = [\langle J_t/R\rangle/\langle 1/R\rangle]/(I_p/A_C) = \frac{A_C}{I_p\langle 1/R\rangle}\left[P' + \langle 1/R^2\rangle\frac{\mu_0 F F'}{4\pi^2}\right]$$

Result

- Profiles resulting from **equilibrium reconstruction** (rtEFIT, CAKE), given different types of constraints





- **CAKE:** "state-of-the-art"
- **RT1:** magnetics only → pedestal absent
- **RT2MSE:** magnetics+MSE → Pedestal presence inconsistent
- **RT2PRESSCURR:** +Pressure+ Bootstr. →Pedestal presence consistent

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NOTE: CAKE corrects for profile misalignment (3D effects, TS); RTEFIT does NOT (YET)

Conclusions

- Data buffering successfully implemented and tested during experiments. → Enables more robust profile fitting
- Inclusion of bootstrap model improves shape of reconstructed current density
- Ti/Te fitting in combination with RT-profile realignment is way to go forward
  - Prevent potential double pedestal when Ti is fit to MTANH+LIN
  - Correct RT-profiles from being shifted inward

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