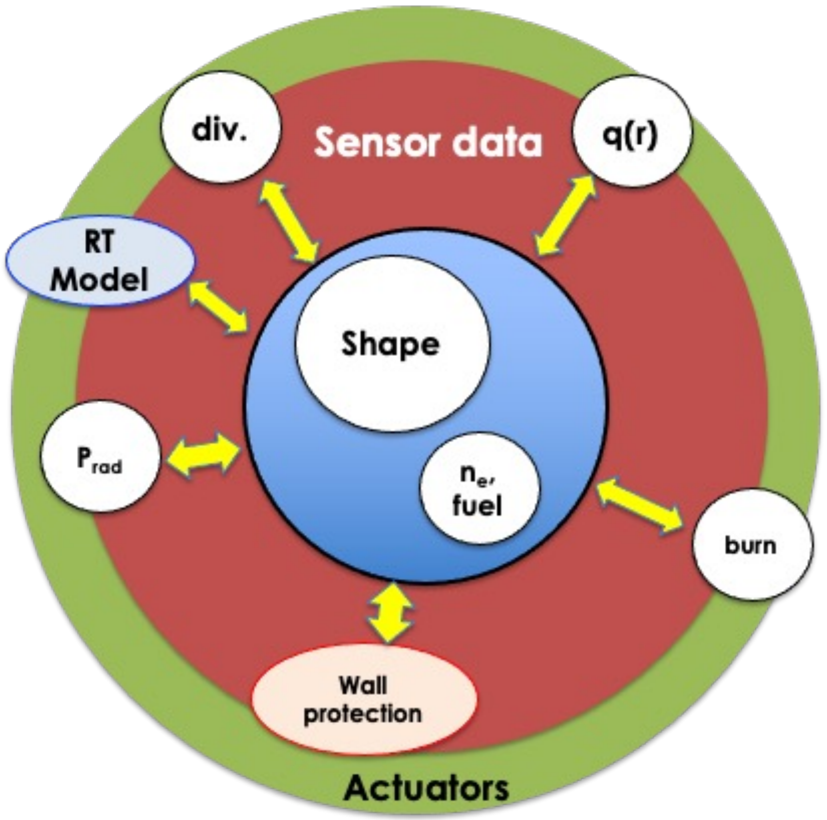
Actuators and Sensors for tokamak control

by
George Sips

ITER International Summer School
On Plasma Operation Scenarios and Control

UCSD, San Diego

July 28, 2022



Outline – Sensors and Actuators for Control

1. **Sensor** processing and RT networks
2. Magnetic sensors, reconstruction and control
3. PFC power loads and prevent overheating
4. Density and fuel control

25 mins

5. **Actuators**
   - ✓ PF coils, I_p, B_t, 3D-coils, gas/pellets, NBI, ECH, ICRH, RF
6. Current profile control?
7. Discharge phases (e.g. plasma formation)

20 mins

8. **Key** take aways…

1. Sensor processing and RT networks

RT systems for plasma control

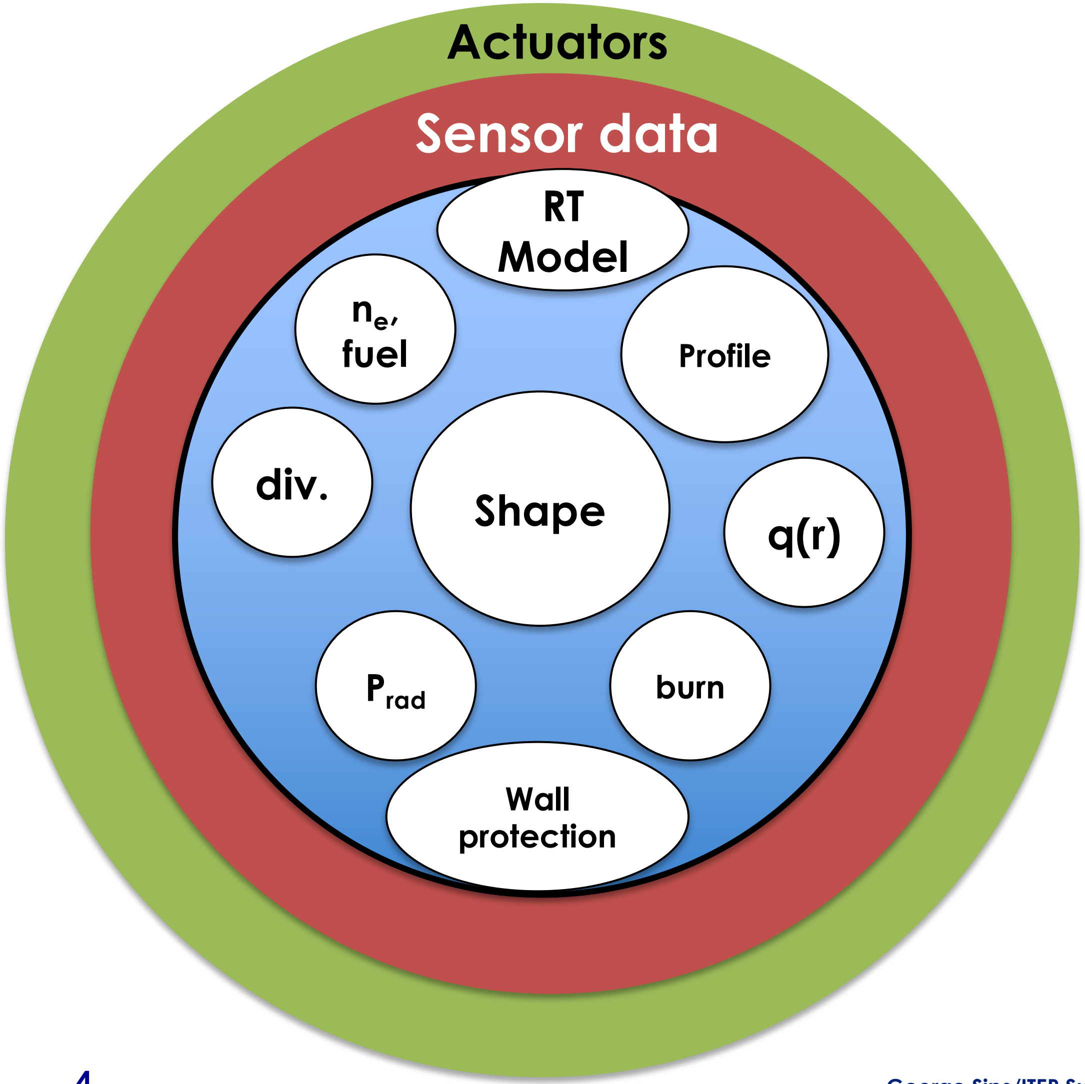
I. All sensors & diagnostic data go into <u>one</u> RT control/server system
   - ✓ Connection of sensors and actuators

II. Outsource processing → results going to RT server and core system
   - ✓ Expandable RT system, leave core intact
   - ✓ Dedicated (more secure) nodes for protection

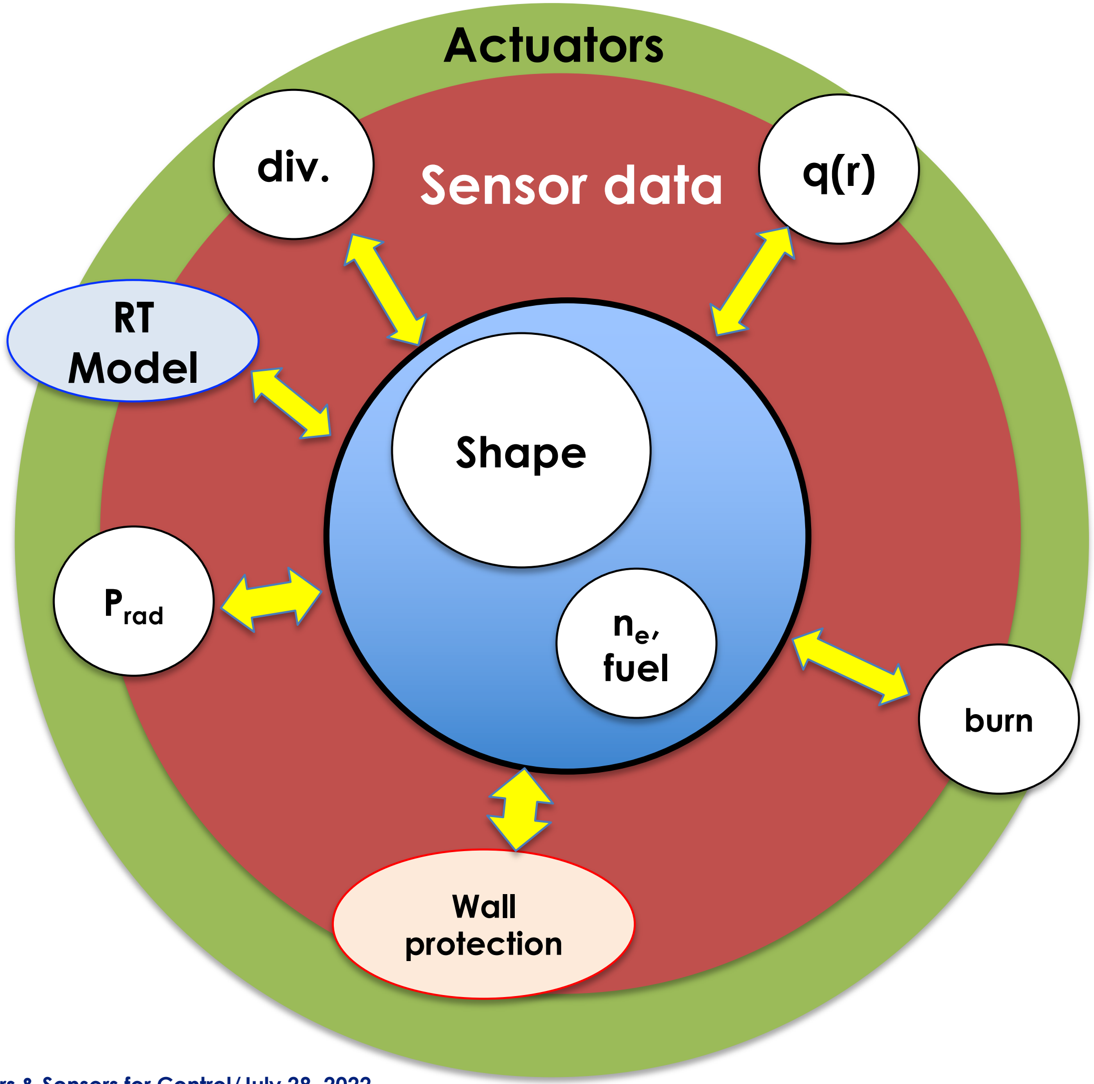
Both can include plasma models and simulation tools

RT Network Options - Central v. Distributed Processing

I - One integrated system



II- Dedicated outsourced nodes



2. Plasma equilibrium

Magnetic sensors, reconstruction and control

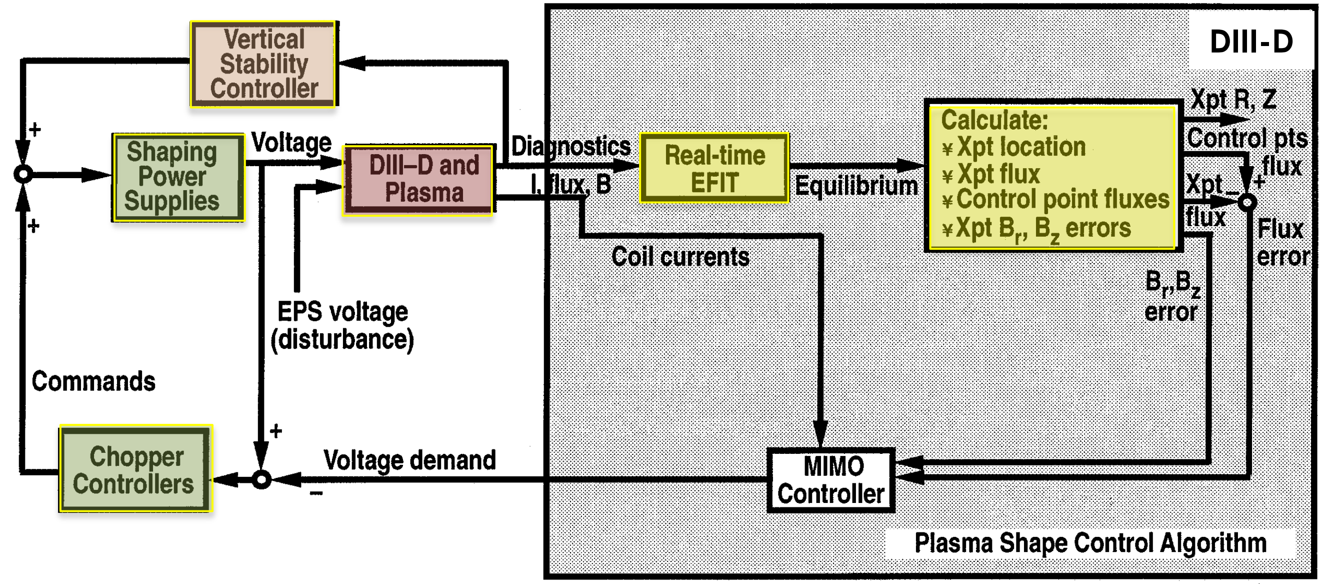
- Reconstruction challenges:
  1. DIII-D: RT EFIT
  2. JET: XLOC
  3. AUG: FP (training database)

- Assisting magnetic control (
  - ✓ RF coupling, strike point power locations, CCD cameras

Real time equilibrium reconstruction and control

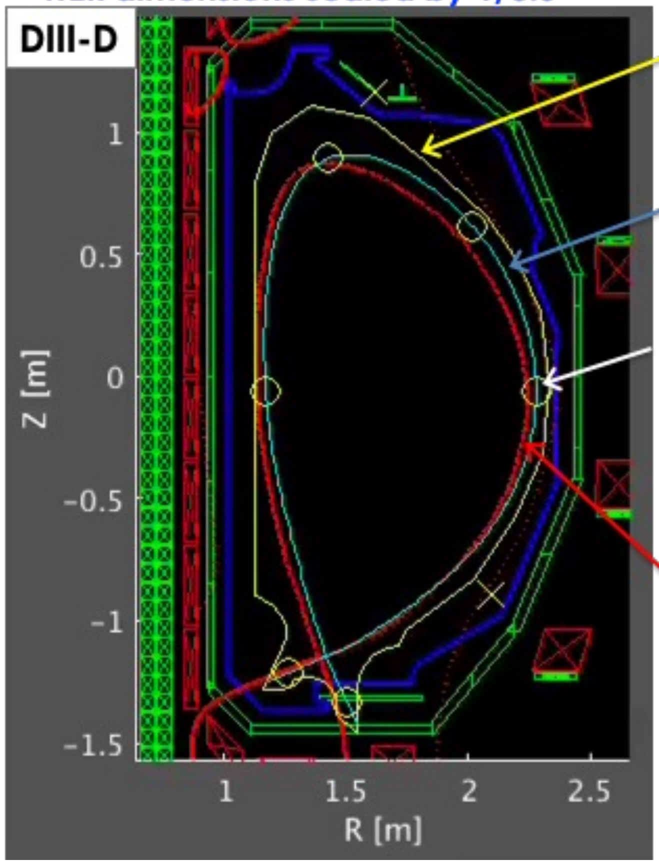
Magnetic sensors, reconstruction and control

- **DIII-D:** Overview of MIMO isoflux control scheme using RT-EFIT



M.L. Walker et al., Fusion Engineering and Design 56–57 (2001) 727–731

ITER dimensions scaled by 1/3.6



scaled ITER wall

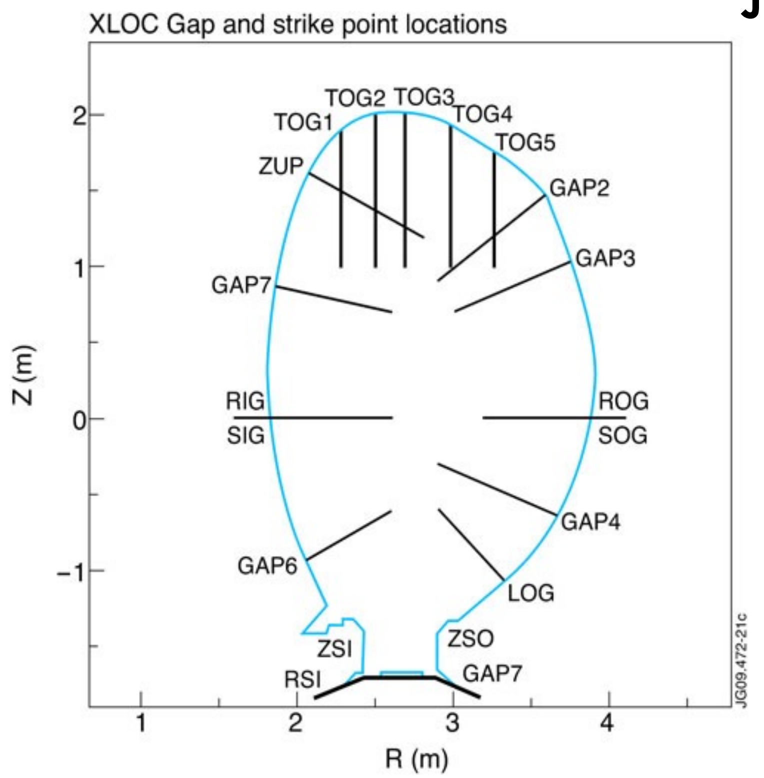
ITER control locations

DIII-D plasma (961014)

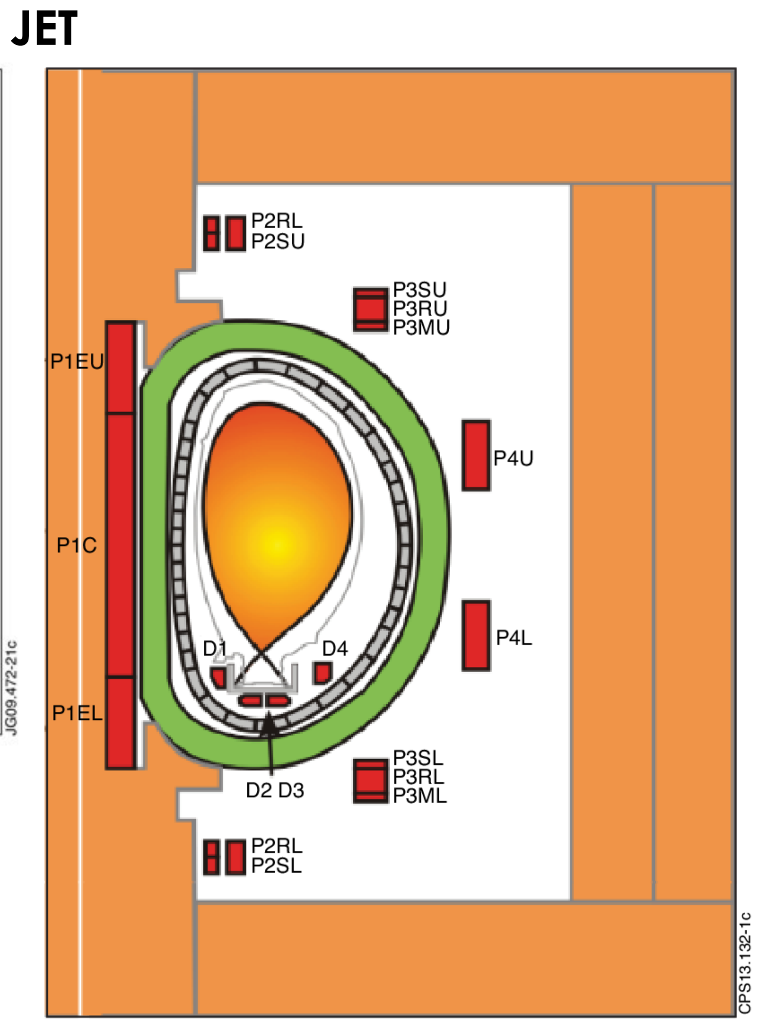
JET – Plasma Boundary → Control

Magnetic sensors, reconstruction and control

- JET has an "Iron core" transformer, making reconstruction more CPU consuming
- **JET: XLOC**
- Vacuum extrapolation of LCFS – XLOC
- 5-12 mm difference with offline EFIT
- Routines (S-integrals) for real-time β_N and l_i



O. Barana et al, 2004 Nucl. Fusion 44 335

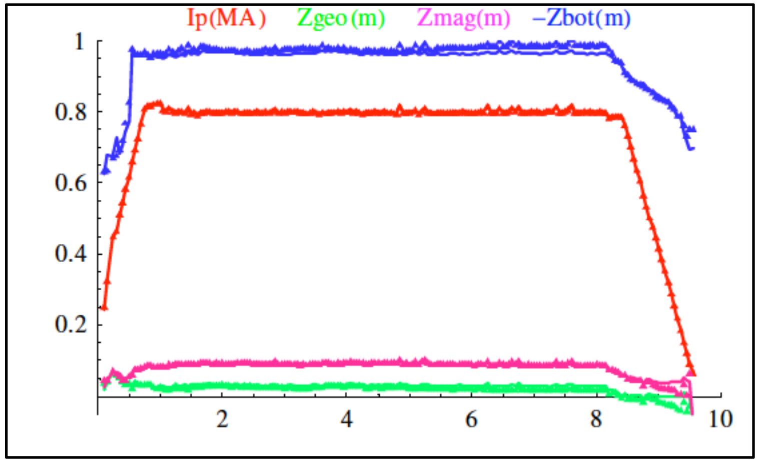


ASDEX Upgrade – Plasma Boundary and Control

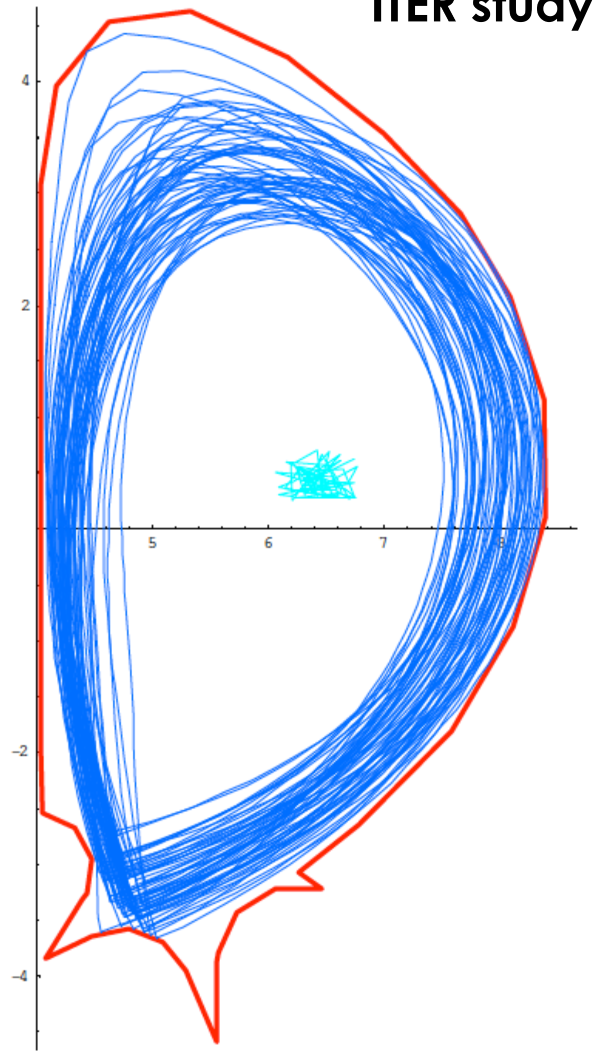
Magnetic sensors, reconstruction and control

- **AUG: Function Parametrization** (training database)
  - Large equilibria data set with different shapes pressure and current profiles
  - Mapping magnetic sensors and PF coils
- Inversion matrix from magnetic sensors & PF coils to plasma boundary, pressure, q-profiles
  - Very fast (<< 1 ms)
  - Detect sensor failure
  - But inversion matrix unique
  - Poor core q(r) resolution

AUG



ITER study

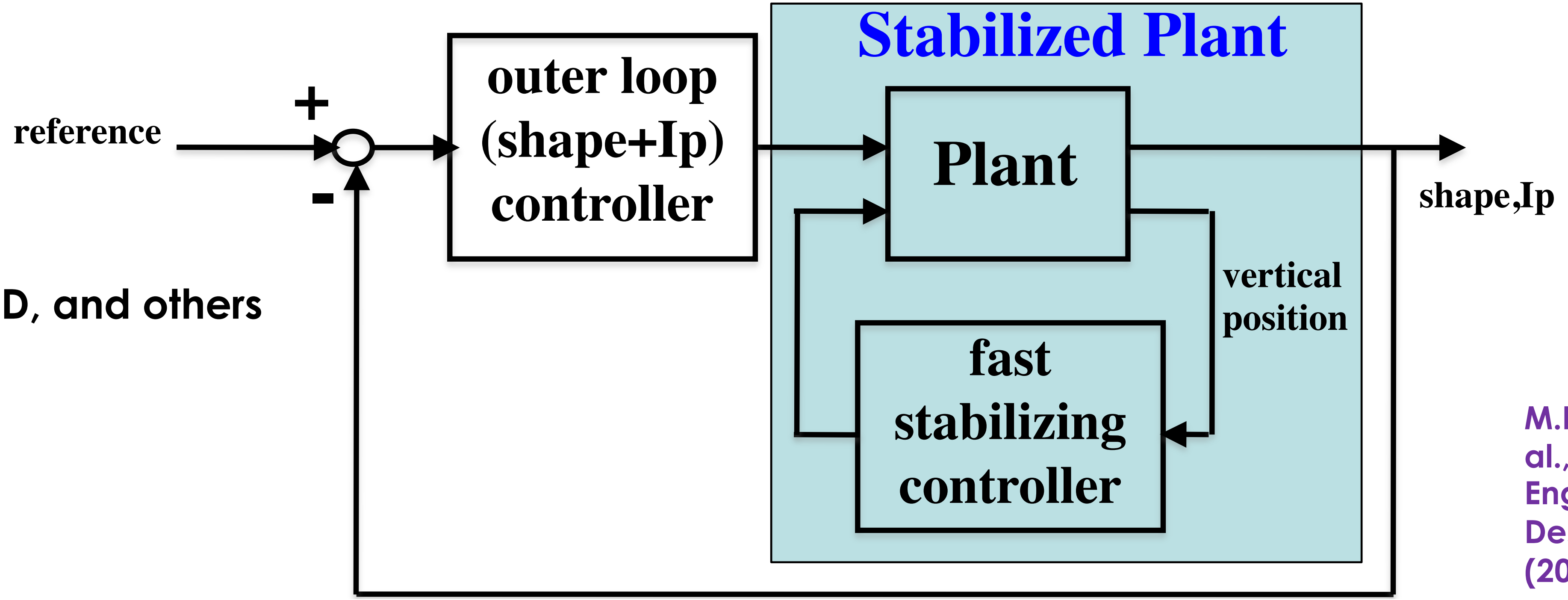


P.J. Mc Carthy et al, IAEA FEC (many years)

Decoupling of the control actions

Vertical stabilization control requires faster control

- Usually implemented as separate loop, with commands in higher spectral range ("spectral decoupling")
- Allows lower cost coils and power supplies for slower shape+I_p control



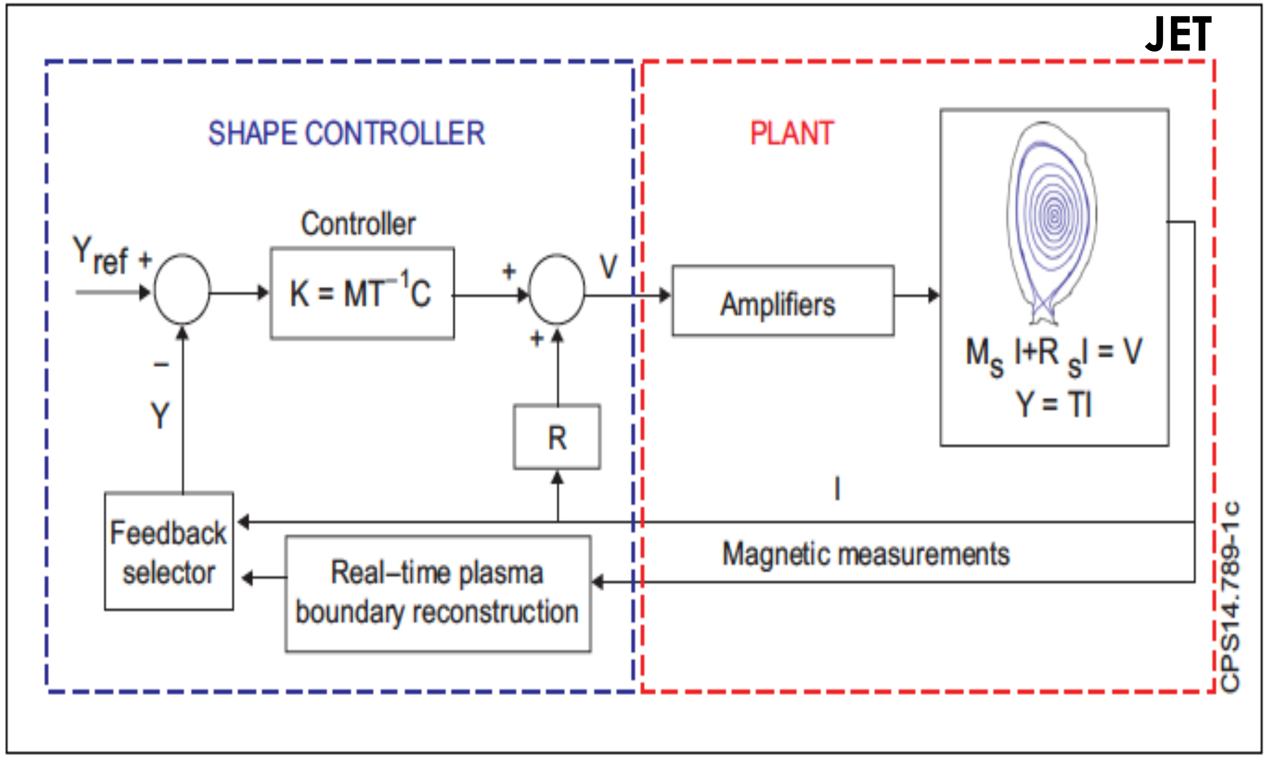
DIII-D, and others

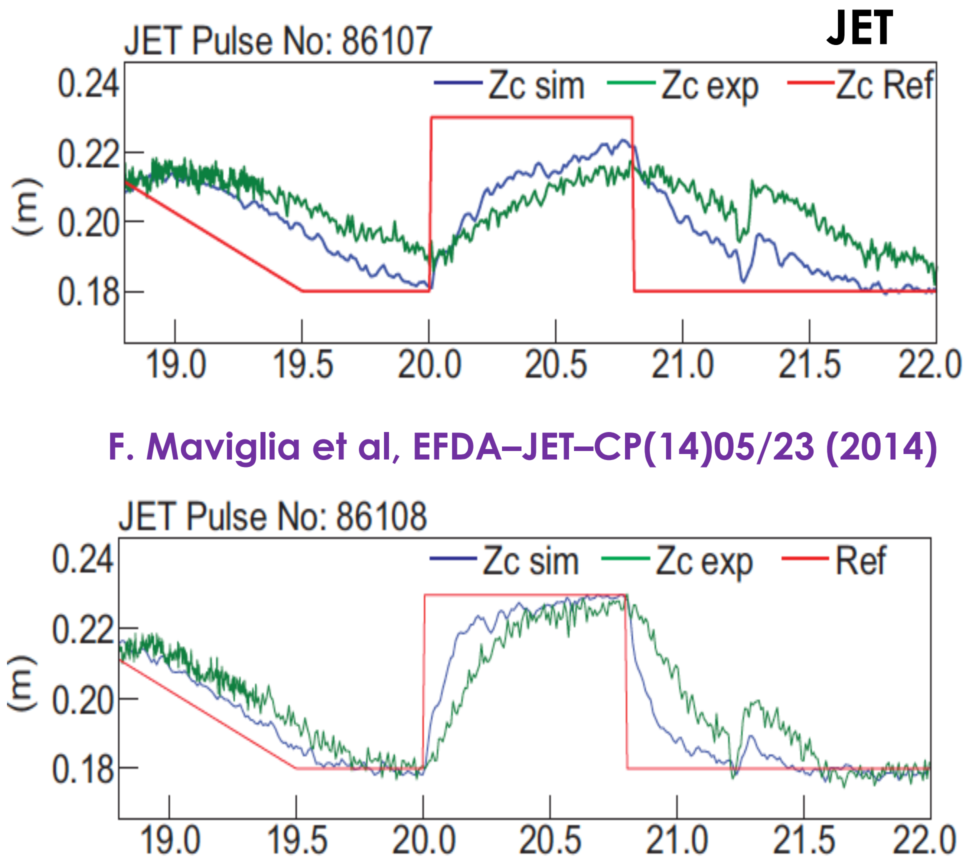
M.L. Walker et al., Fusion Engineering and Design 56–57 (2001) 727–731

Decoupling of the control actions

Mutual inductance of PF coils

- Provide a linear response to a control gap with effects on other gaps or coils compensated (decoupled)



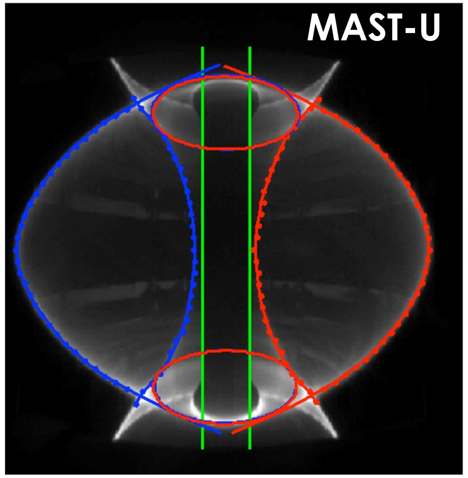


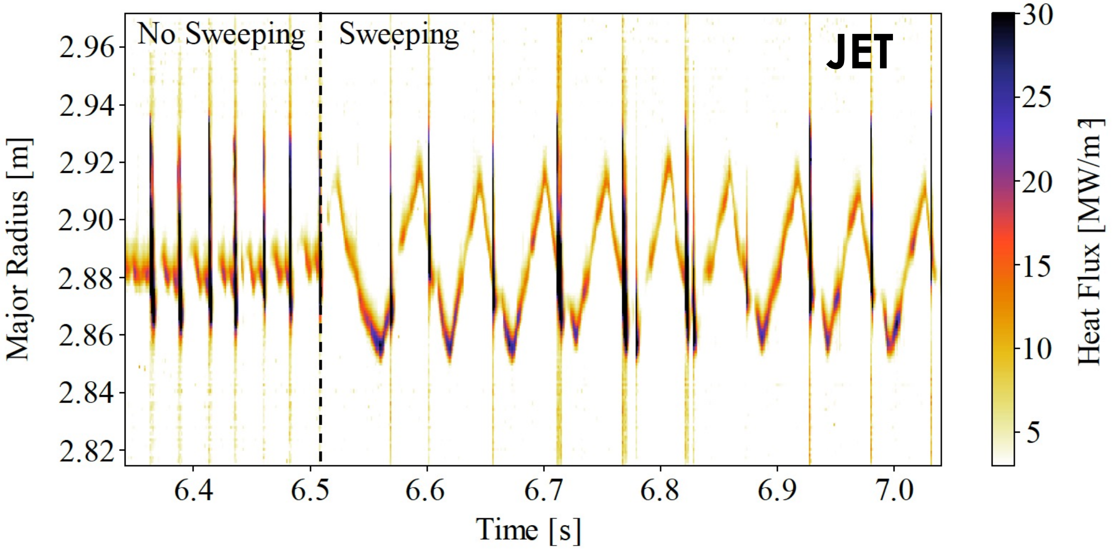
F. Maviglia et al, EFDA–JET–CP(14)05/23 (2014)

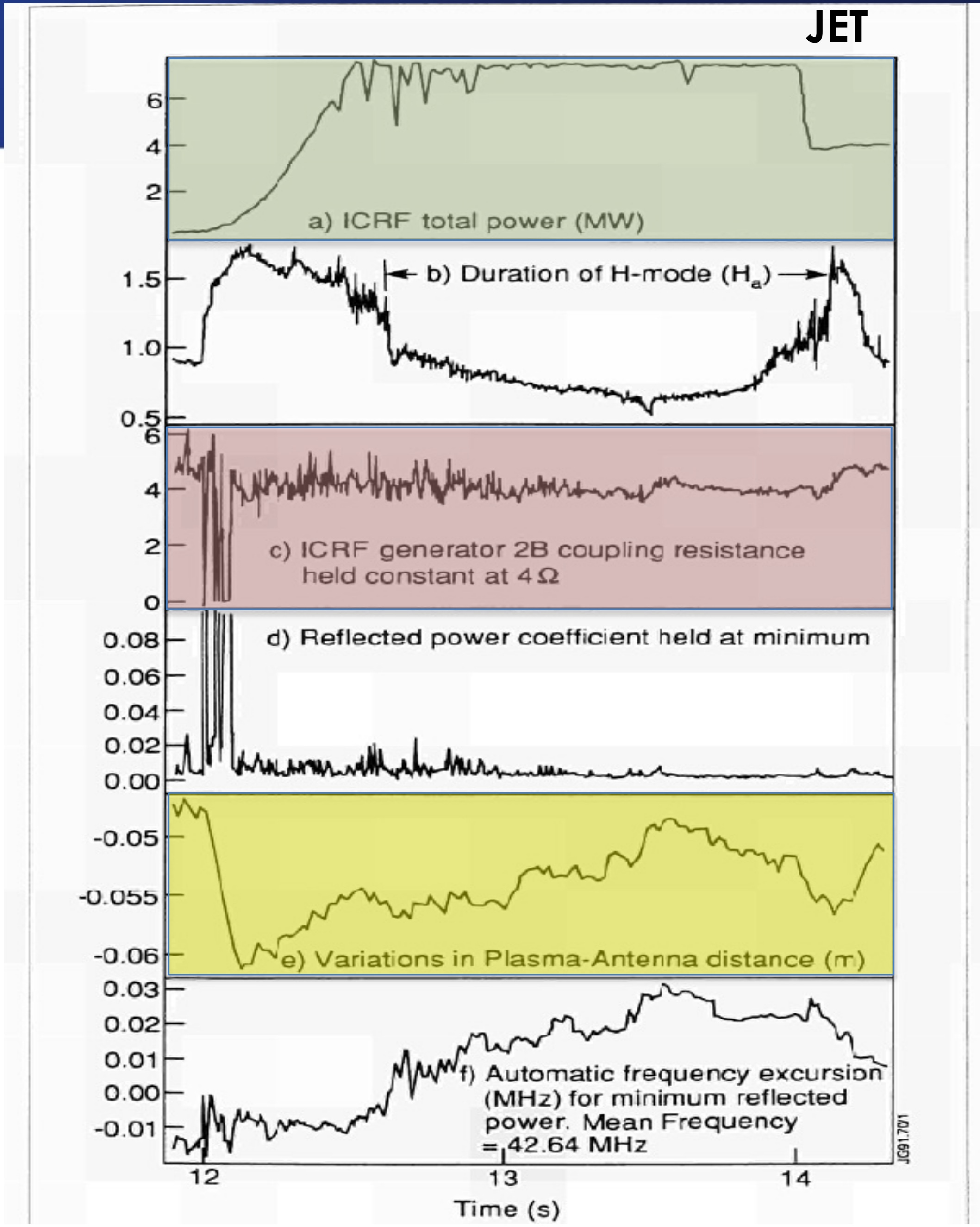
Other sensors for shape control

Assisting control

- CCD camera imaging
- RF coupling resistance
- Strike point power
- Reflectometry (see later)







3. Protecting the wall/divertor - Sensors

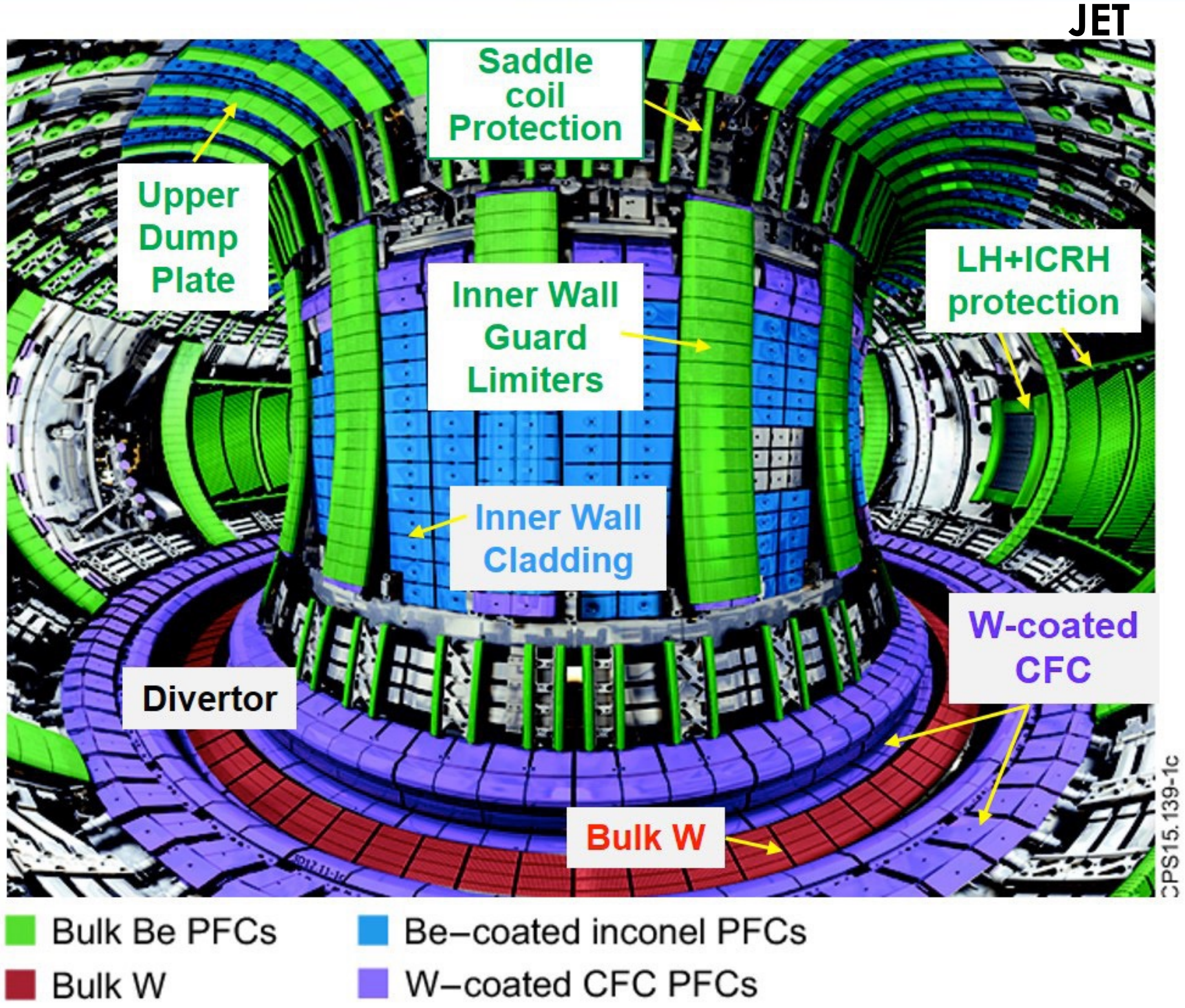
Be & W components of the "ITER-like" wall at JET require a reliable protection system to avoid damage - due to Be melting or cracking of W (thermal fatigue):

A. Huber et al, Nucl. Fusion 58 106021 (2018)

- **Imaging diagnostics in the Near Infra-Red (Sensors)**
  - ✓ Covering 2/3 of the main chamber and ½ of the divertor
  - ✓ RT processing to convert raw data

- **Dedicated & robust Real-time system (outside, but connected to the PCS)**
  - Protecting regions of interest (ROI's)
  - Hot spot validation (e.g. false hot spots)

Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems



The JET ITER-like wall

- Solid beryllium
- Beryllium-coated Inconel
- Solid (bulk) tungsten
- Tungsten-coated carbon fibre composite tiles.

Operation started in 2011

All components are inertially cooled → power handling determined by heat capacity and incident power levels ($T_{surface}$)

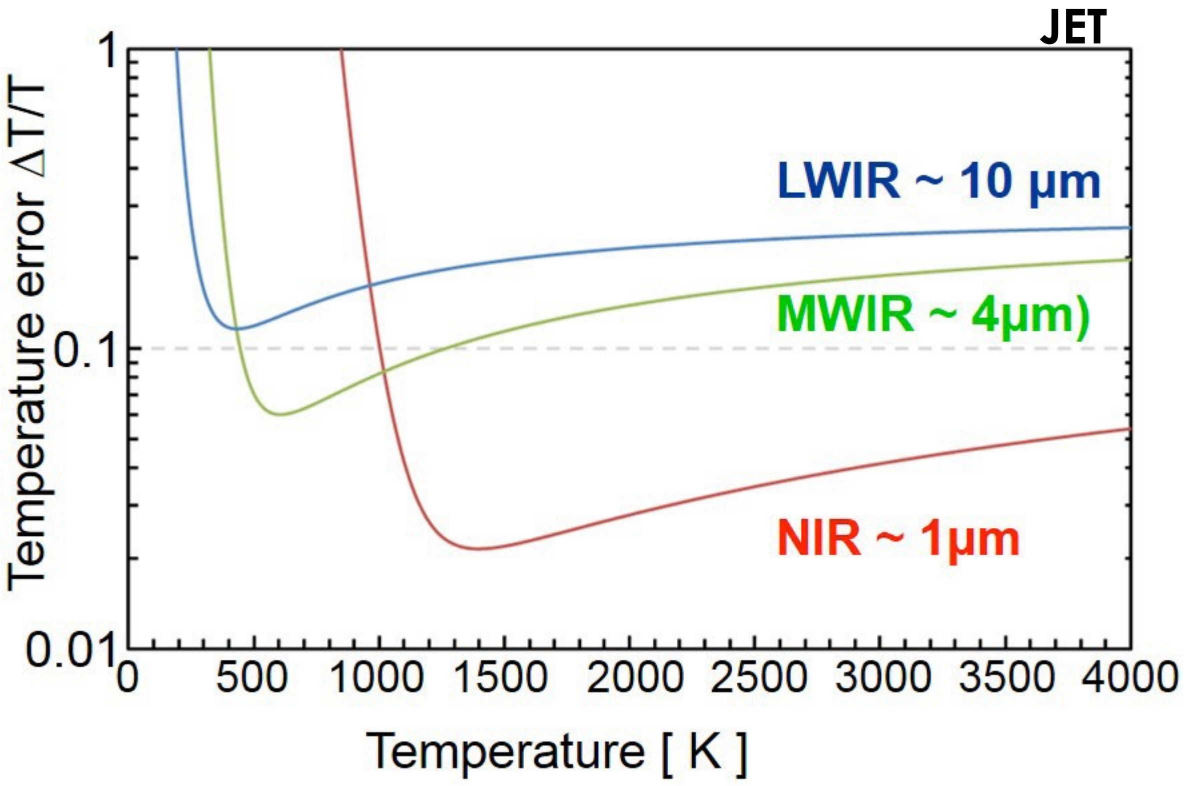
Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems

A. Huber et al, Nucl. Fusion 58 106021 (2018)

Surface temperature limits

- Avoid melting of beryllium (1287 °C) with a protection level at ~950°C
- Avoid delamination of W-coated tiles above 1200°C
- Keep bulk-W below re-crystallization threshold - < 1200°C

Accuracy required: +/- 50 °C
→ near infrared (NIR), which has
an error as low as 2%
in these temperature ranges



Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems

A. Huber et al, Nucl. Fusion 58 106021 (2018)

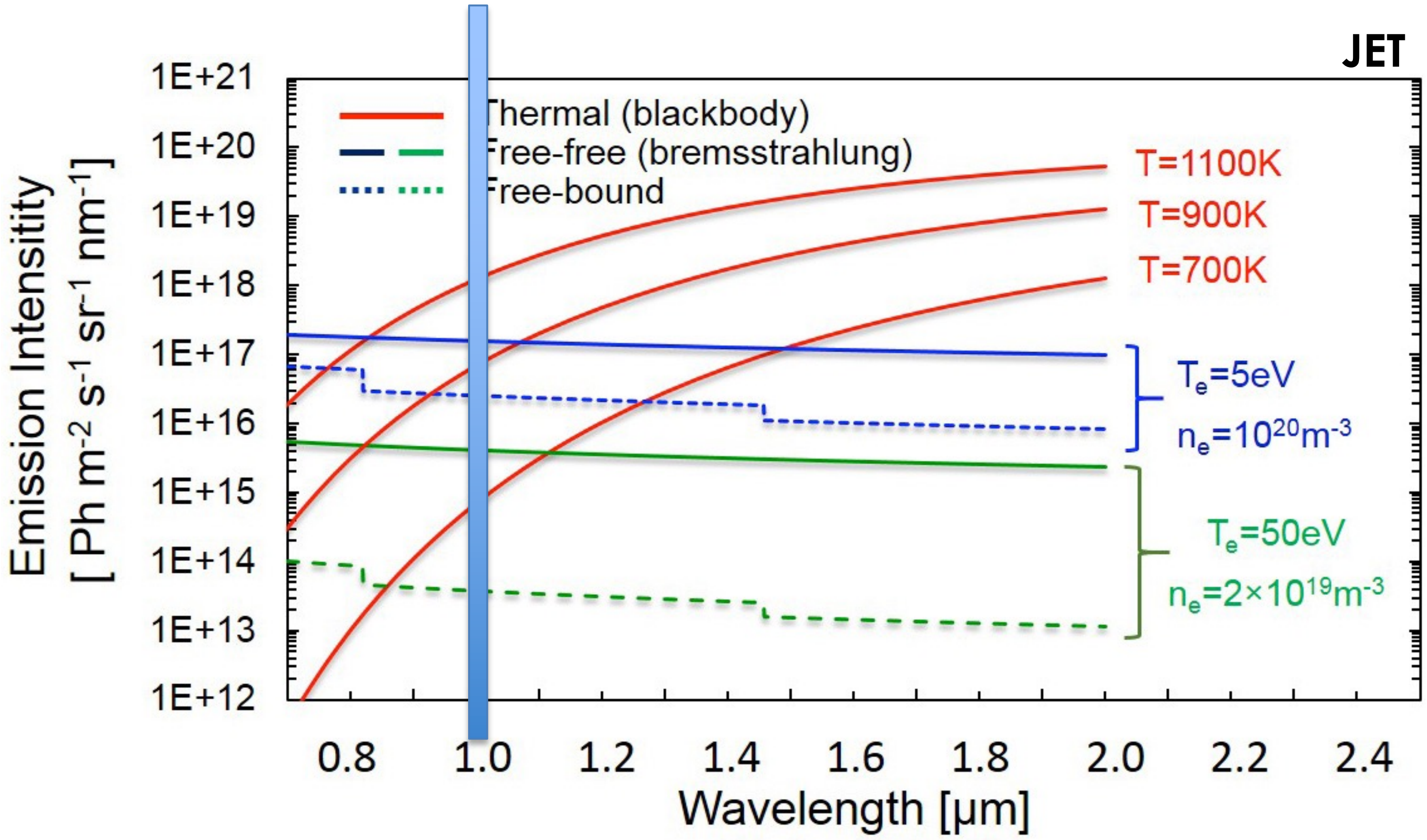
Near Infrared (NIR) measurements

Reliable measurements of $T_{surface}$ are only possible when the background is low:

- Thermal emissions

>> Plasma bremsstrahlung & free-bound emissions

Conventional optics around 1000 nm (1µm)



Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems

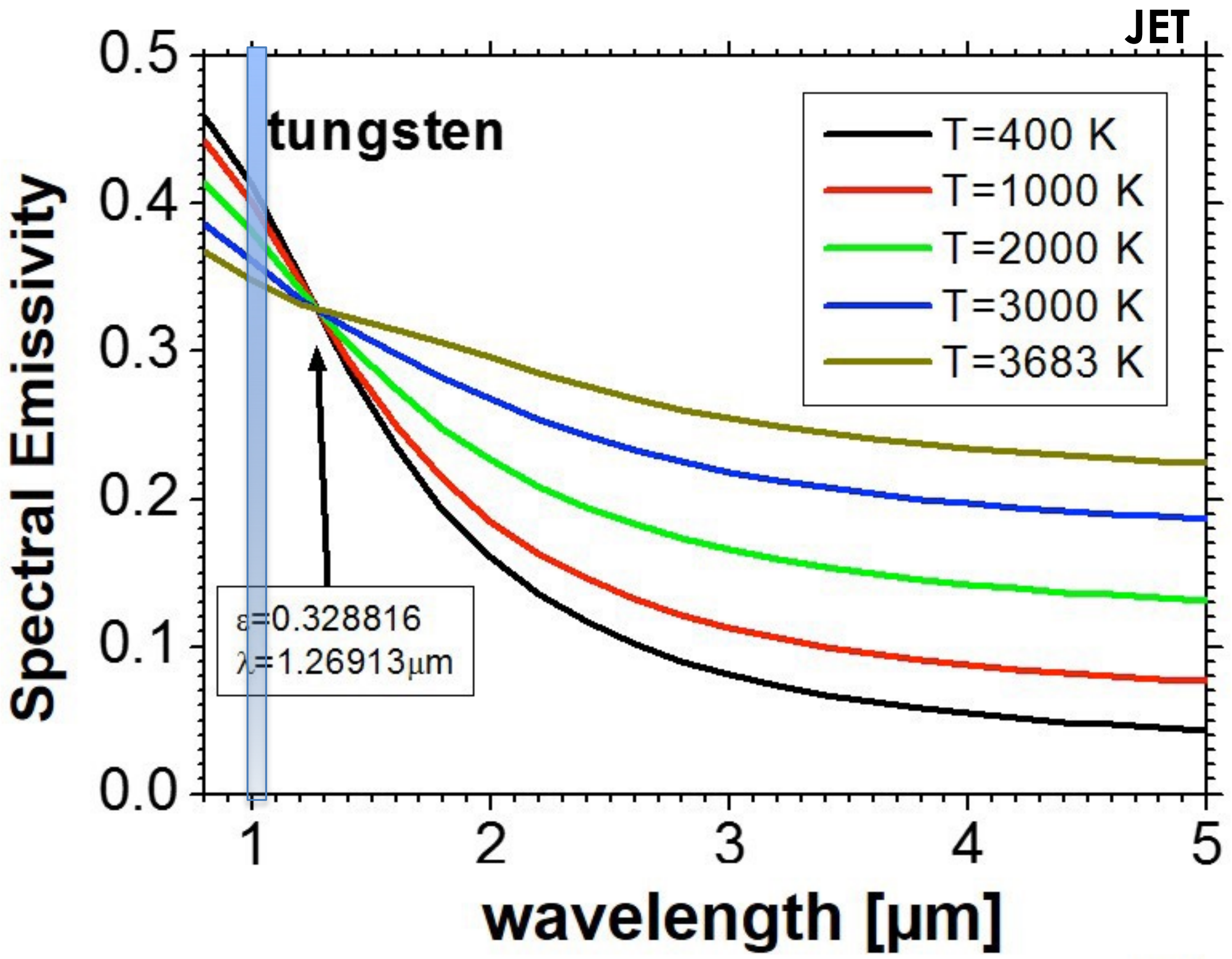
A. Huber et al, Nucl. Fusion 58 106021 (2018)

Spectral emissivity (ε) of W and Be

Perfect black body has $\varepsilon = 1$

Better to have small change in ε with temperature:

- otherwise emission intensity becomes non-linear with $T_{surface}$



NBI testbed data of ε at $1\mu m$:

- Beryllium: ε=0.25
- W-coatings: ε=0.6

Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems

A. Huber et al, Nucl. Fusion 58 106021 (2018)

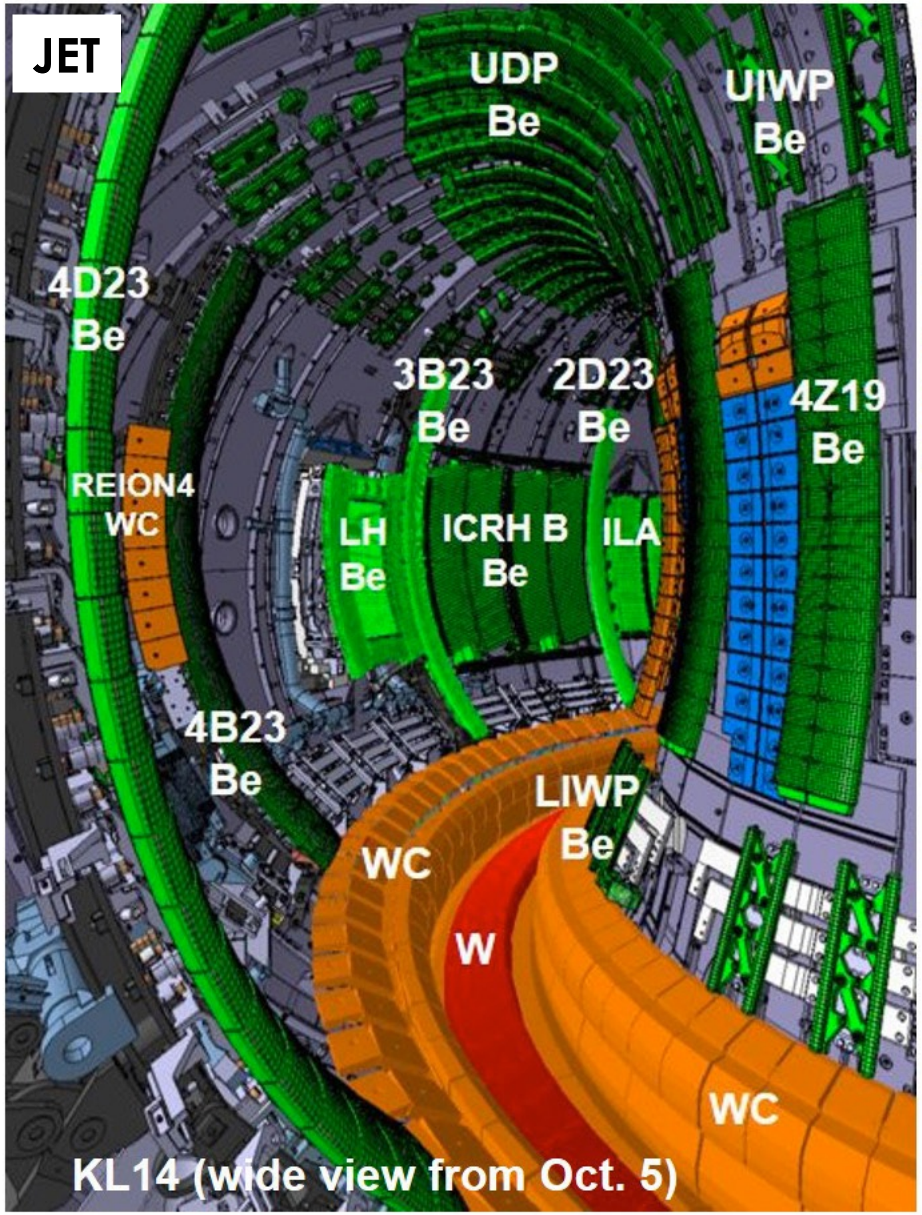
NIR digital cameras

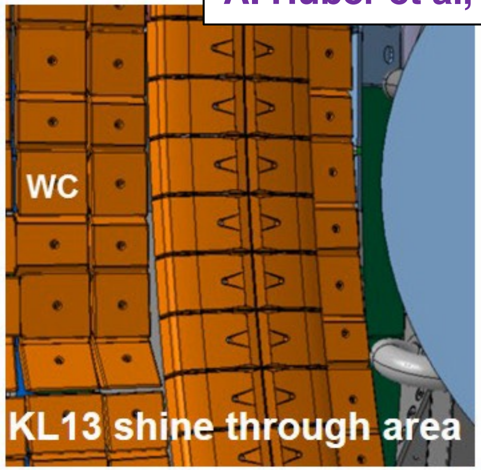
- Every 20ms

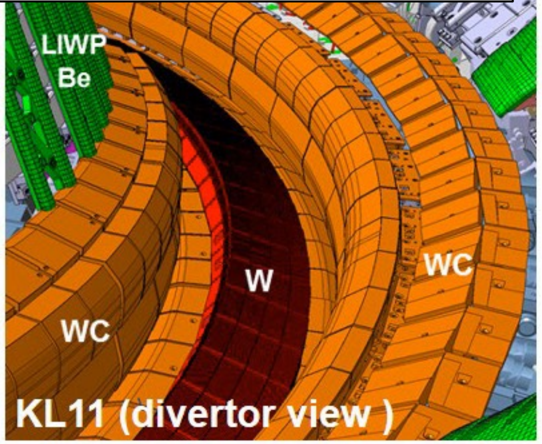
Coverage:

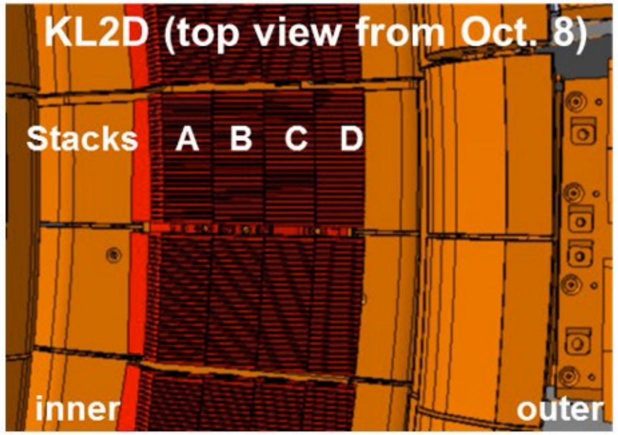
- 66% of main chamber
- 43% of divertor

Relay and endoscope systems









Main materials used
In the JET machine

- Beryllium
- W-coated CFC
- Inconel+8µm Be
- Bulk W

Alarm temperature thresholds:

Beryllium: 925°C for Be to avoid the Be melting

W-coated CFC: 1105°C to avoid the damage of the coatings

Bulk W: 975°C to avoid recrystallization (recrystallization temperature for tungsten of ~1200°C)

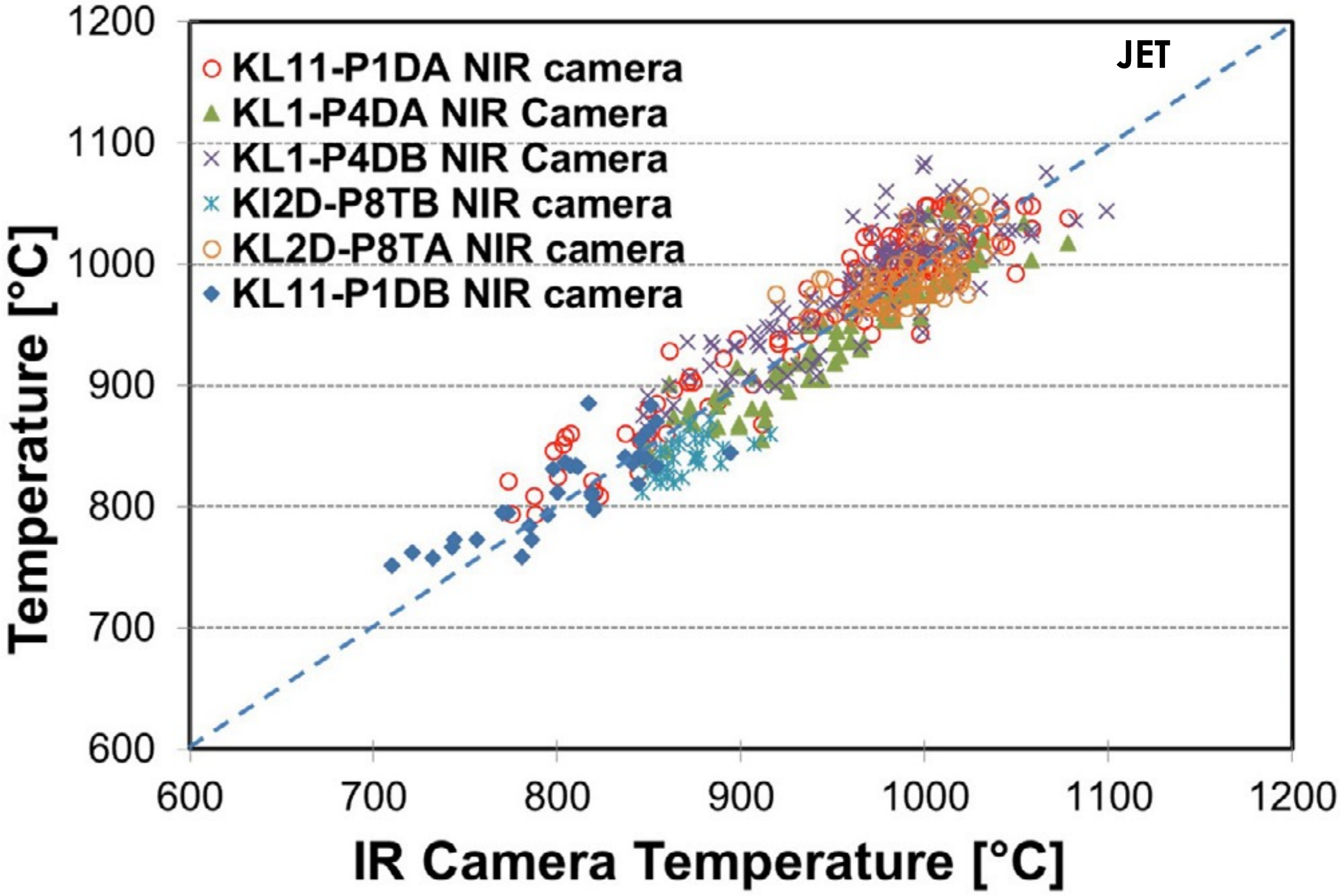
Inconel+8µm Be: 900°C to avoid formation of intermetallic phases

Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems

A. Huber et al, Nucl. Fusion 58 106021 (2018)

In-vessel calibration using a source at 1μm

Deployed with the JET in-vessel remote-handling arm

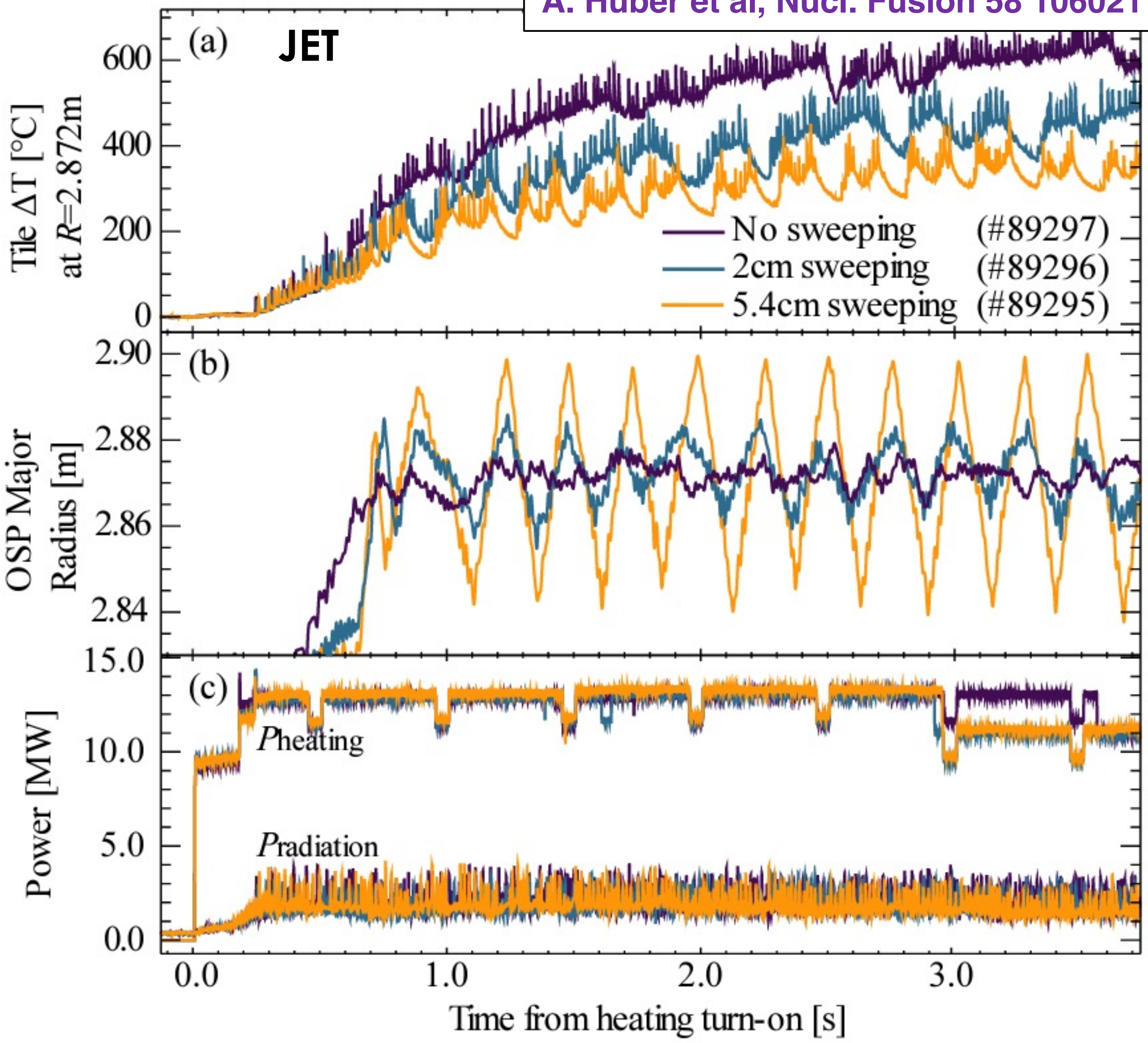


Example of using IR data in the Divertor

A. Huber et al, Nucl. Fusion 58 106021 (2018)

Divertor IR data (JET)

- Effect of strike point sweep
- Reduces surface temperature
- Can start sweeping when surface temperature goes above certain threshold level
  - ✓ Or move strike to different location (within preset limits)



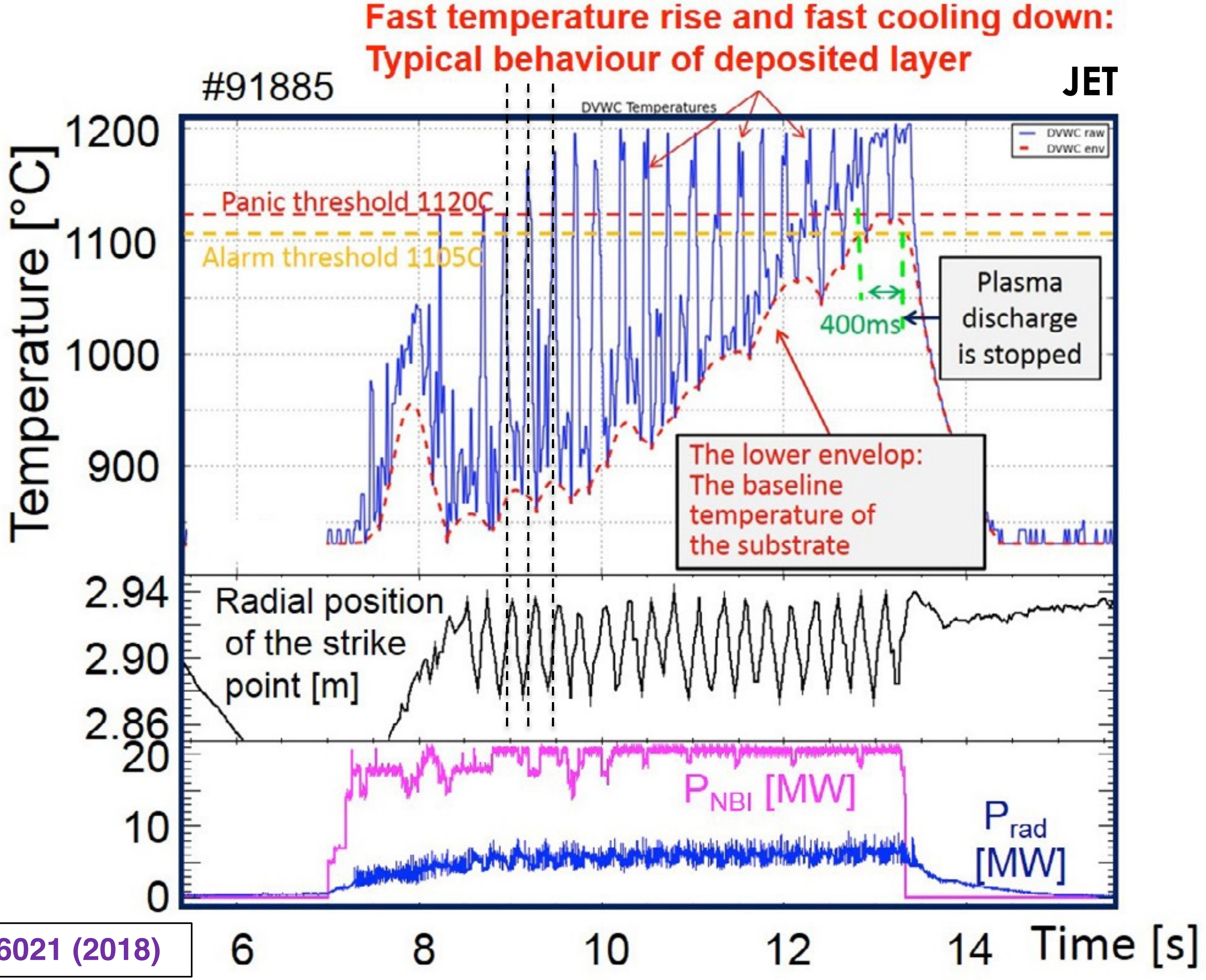
Real-time protection of the JET ITER-like wall based on near infrared imaging diagnostic systems

Divertor IR data (JET)

Measured surface temperature of the W-coated outer divertor target

Strike point on a "deposition layer" that has poor thermal contact → rapid T_{suface} rise at the same strike position

Baseline temperature reaches alarm level @ 1100 °C for > 400ms – heating is stopped



A. Huber et al, Nucl. Fusion 58 106021 (2018)

4. Density and fuel control - Sensors

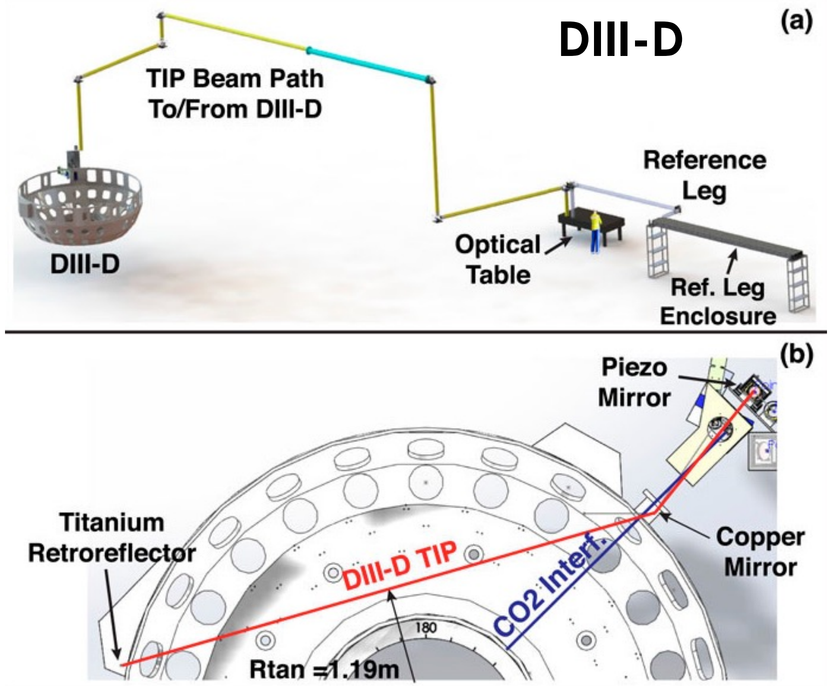
Density and fuel control

- Simple and robust interferometry (also protection)
- Fuel ratio (D-T)
- More advanced (Thomson scattering profile, edge density, peaking)
- Model for fueling actuators

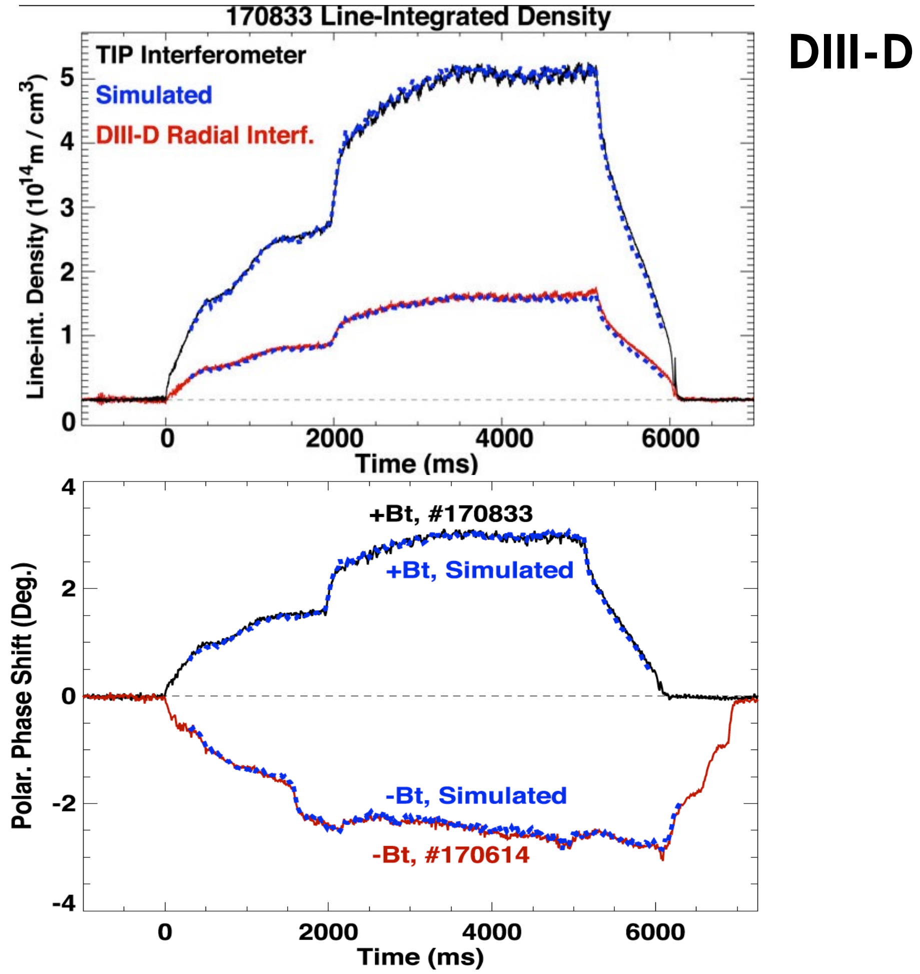
Density and fuel control - Sensors

Real-time density measurements

- Simple and robust measurements



M.A. van Zeeland, Rev. Sci. Instrum. 89, 10B102 (2018)

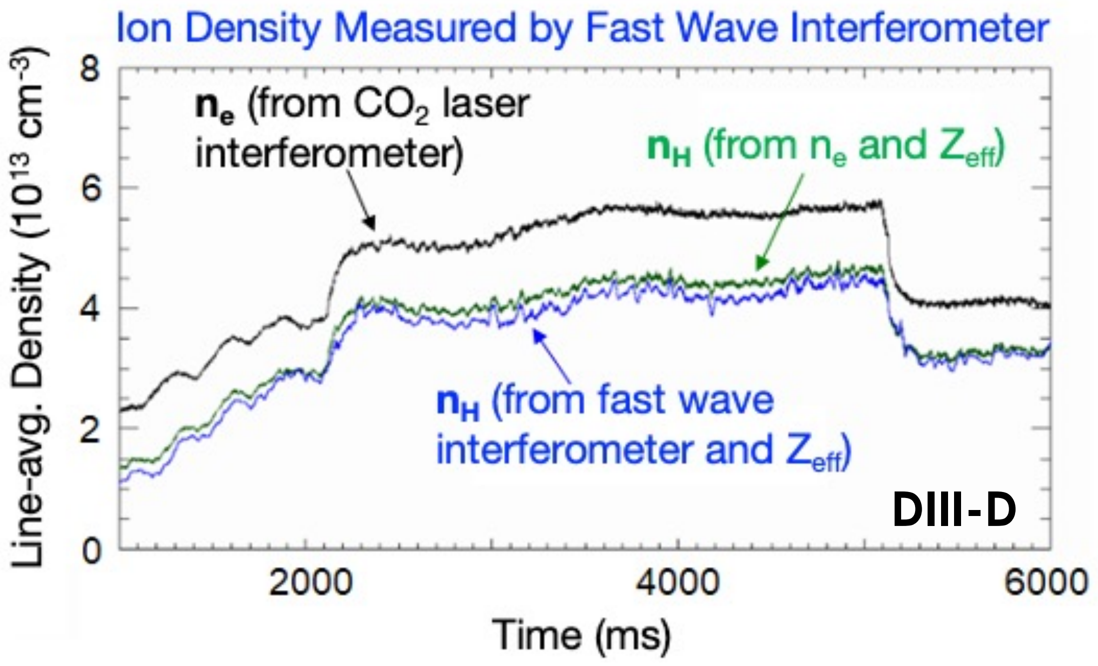


ITER prototype interferometry measurements for $n_e dl$ demonstrated. Also provides Faraday rotation angle → j(r)

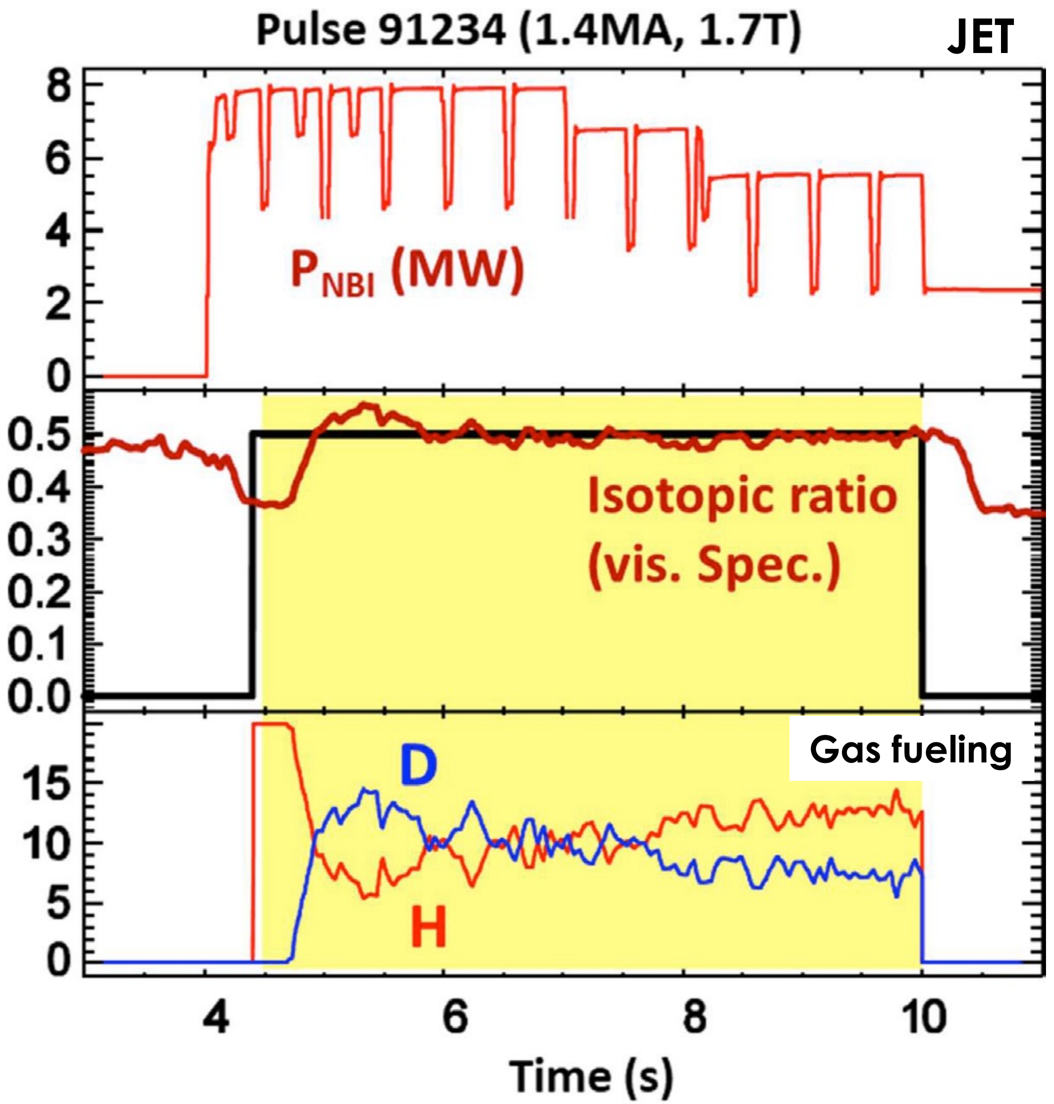
Density and fuel control - sensors and actuators

Fuel content Measurements

- Edge visible spectroscopy (H_α, D_α, T_α)
- Neutron diagnostics (core)
- Novel: Fast wave interferometry



M.A. van Zeeland, Rev. Sci. Instrum. 89, 10B102 (2018)

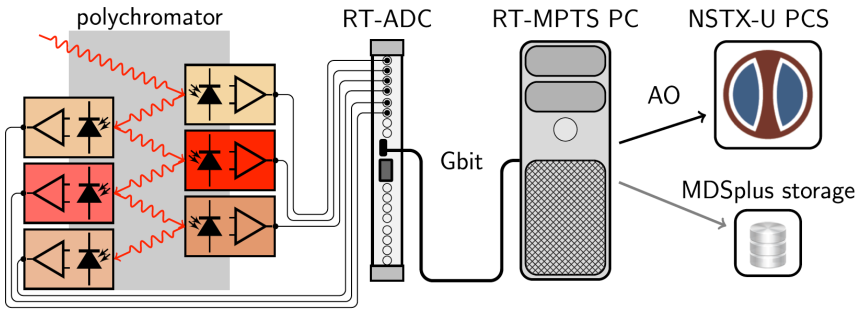


E. Joffrin et al, Nucl. Fusion 59 (2019) 112021

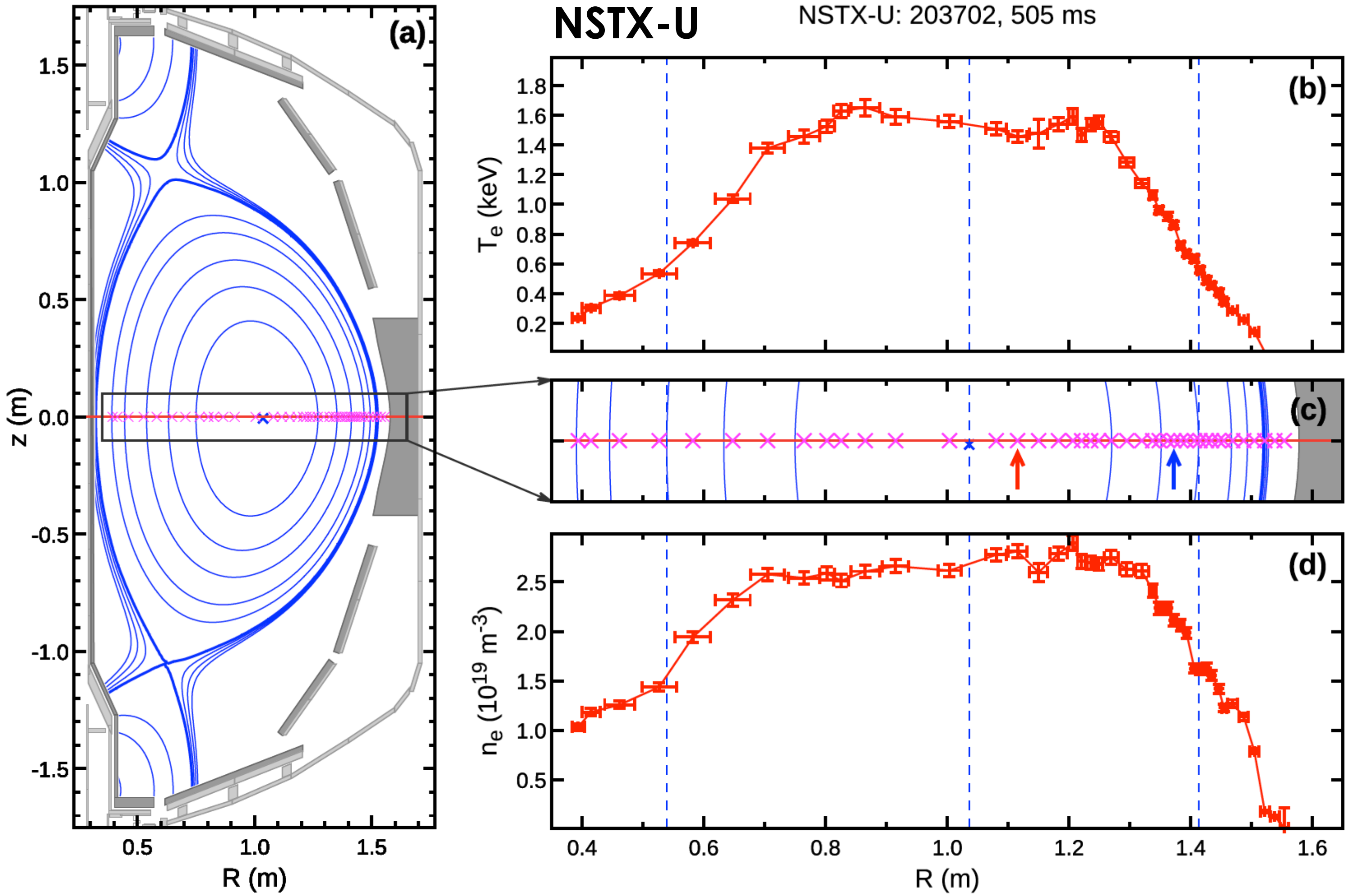
Density and fuel control - Sensors

RT density/temperature

- Thomson scattering data at 60Hz
- Analyses independent of the PCS



- Derivative parameters:
  - ✓ Edge n_e, n_e peaking



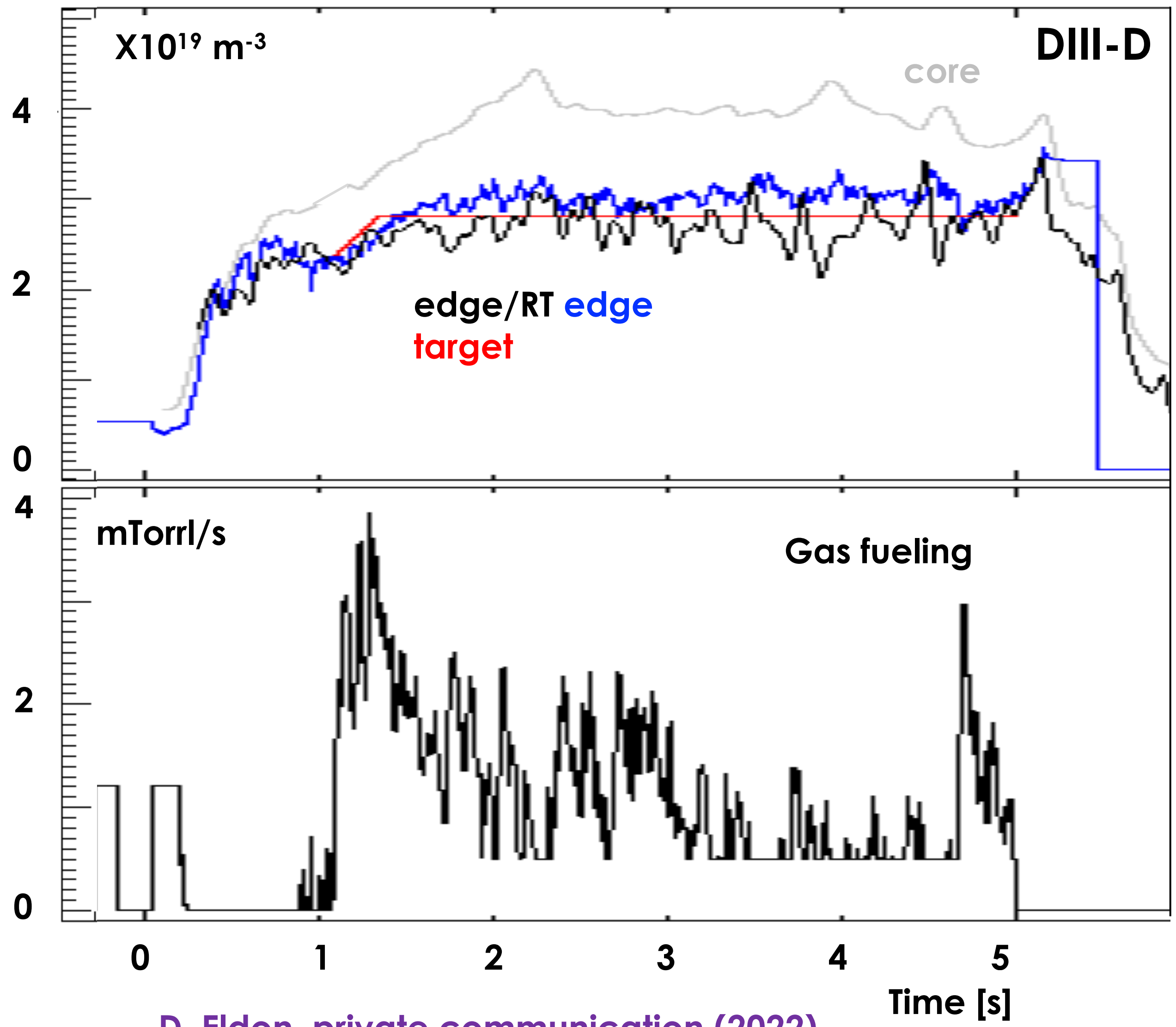
F. M. Laggner, Rev. Sci. Instrum. 90, 043501 (2019)

Density and fuel control - Edge density

Control of the edge density

- A few TS channels near the expected pedestal location are averaged to get an estimate for pedestal density → density feedback loop

- Used for high-β_p scenario, which has an internal transport barrier

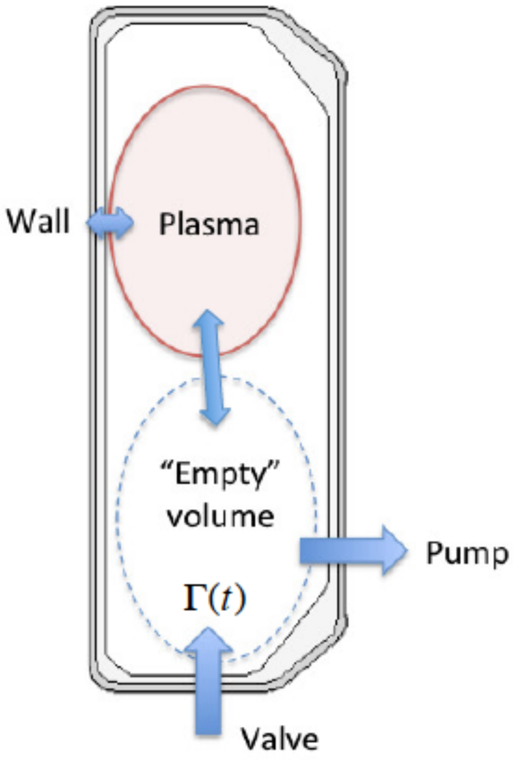


D. Eldon, private communication (2022)

Density control - Model for actuators

Non-linear digital real-time density control in the TCV tokamak

TCV

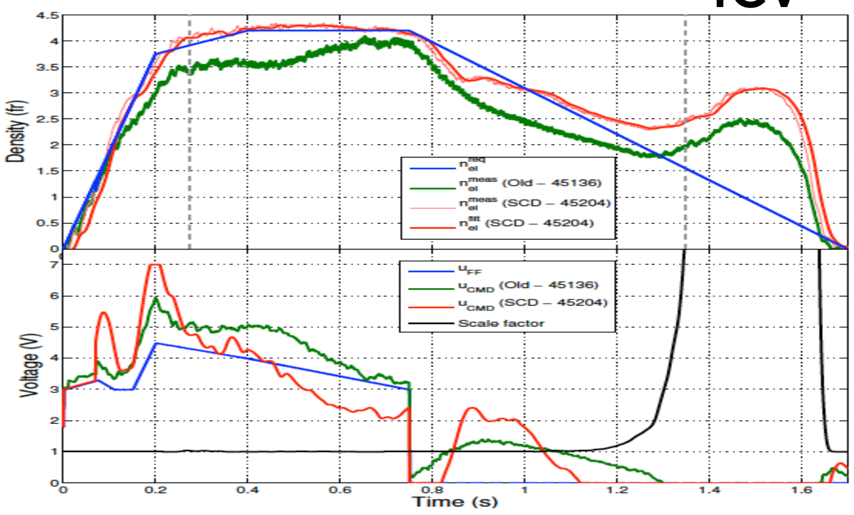


$$\frac{dN_p}{dt} = -N_p\left(\frac{1}{\tau_p} + \frac{1}{\tau_{retention}}\right) + \frac{N_w}{\tau_{release}} + 2\frac{N_v}{\tau_{ion}}$$

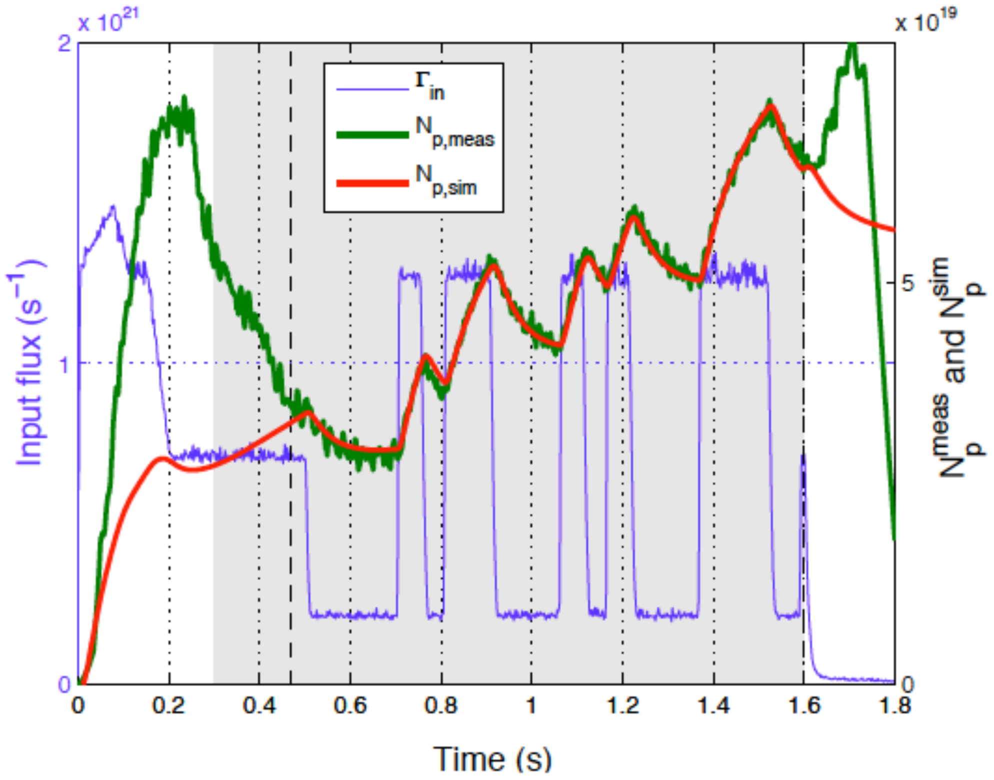
$$\frac{dN_w}{dt} = -\frac{N_w}{\tau_{release}} + \frac{N_p}{\tau_{retention}}$$

$$\frac{dN_v}{dt} = \Gamma(t) - N_v\left(\frac{1}{\tau_{pump}} + \frac{1}{\tau_{ion}}\right) + \frac{1}{2}\frac{N_p}{\tau_p}$$

TCV



TCV



W.A.J. Vijvers et al, 39th EPS conference (2012)

5. Actuators

Main actuators used

- PF coils, I_p
- TF coils, TF ripple
- Non-axisymmetric, 3D coils (RMP)
- Gas & pellets (fueling, pacing, DMS)

- Heating systems:
  - ✓ NBI - power, torque
  - ✓ ECRH - heating, CD, MHD, pre-ionization (later in this talk)
  - ✓ RF - Heating (ions, electrons), CD (ICRH, Helicon, LHCD)

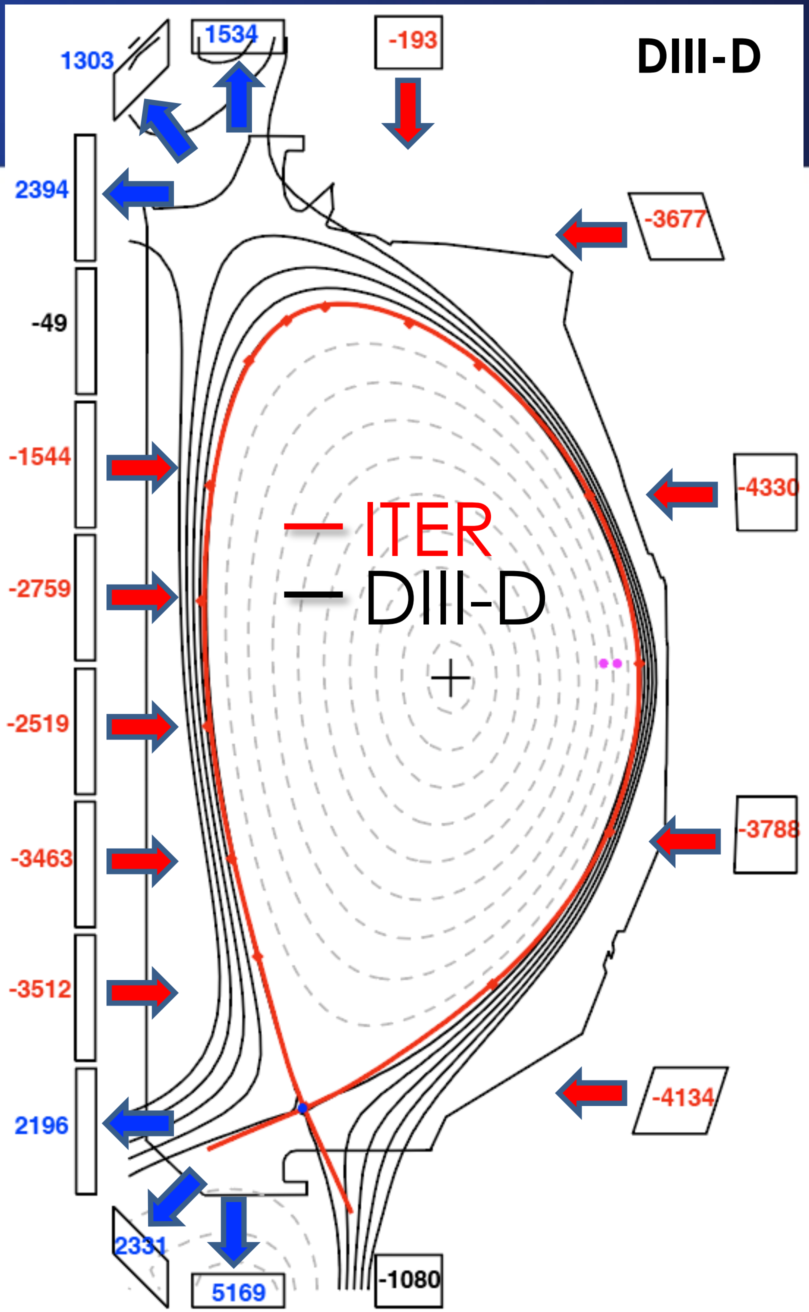
Actuators – PF coils

PF coils for plasma shape, position

DIII-D demonstrated passively stable scenario meeting ITER goals:

- **<u>Plasma shape</u>**
- G=0.4
- T_e/T_i~0.8
- f_{GW}~0.6
- ν^*_{ped}~0.6
- Duration: $3\tau_R$
- q_{95}=3.2-3.8
- β_N=1.9-2.3
- Torque: T=-0.5-4 Nm

F. Turco et al, Nucl. Fusion 58 106043 (2018)



Match also obtained for upper SN shape in DIII-D

Actuators – Plasma current (I_p)

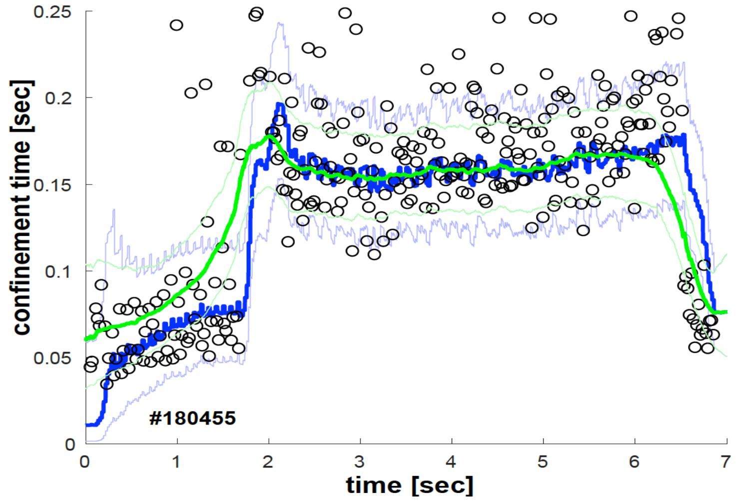
May seem trivial – but I_p is an actuator

- Current ramp up/down rate (→j(r))
- Changes to edge current
- Changing q_{95} (constant B_t & shape)

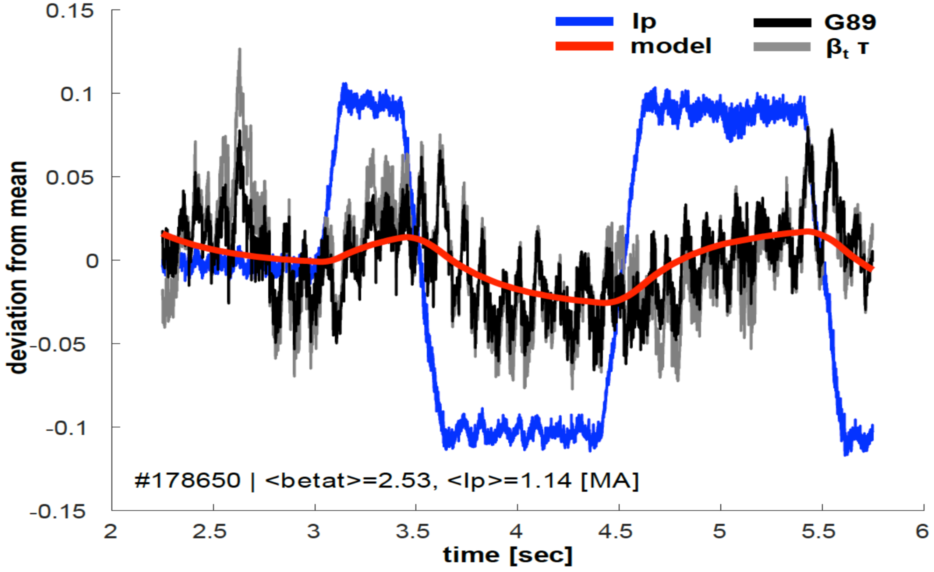
- **More advanced:**
  In a reactor at constant I_p there is no explicit control of the fusion power gain: → Fusion power gain (G_{89}) is explicitly regulated using I_p

$$G_{89} = \beta_N H_{89} / q_{95}^2$$

DIII-D



DIII-D

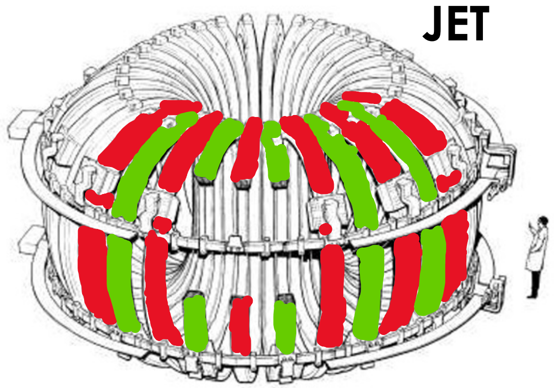


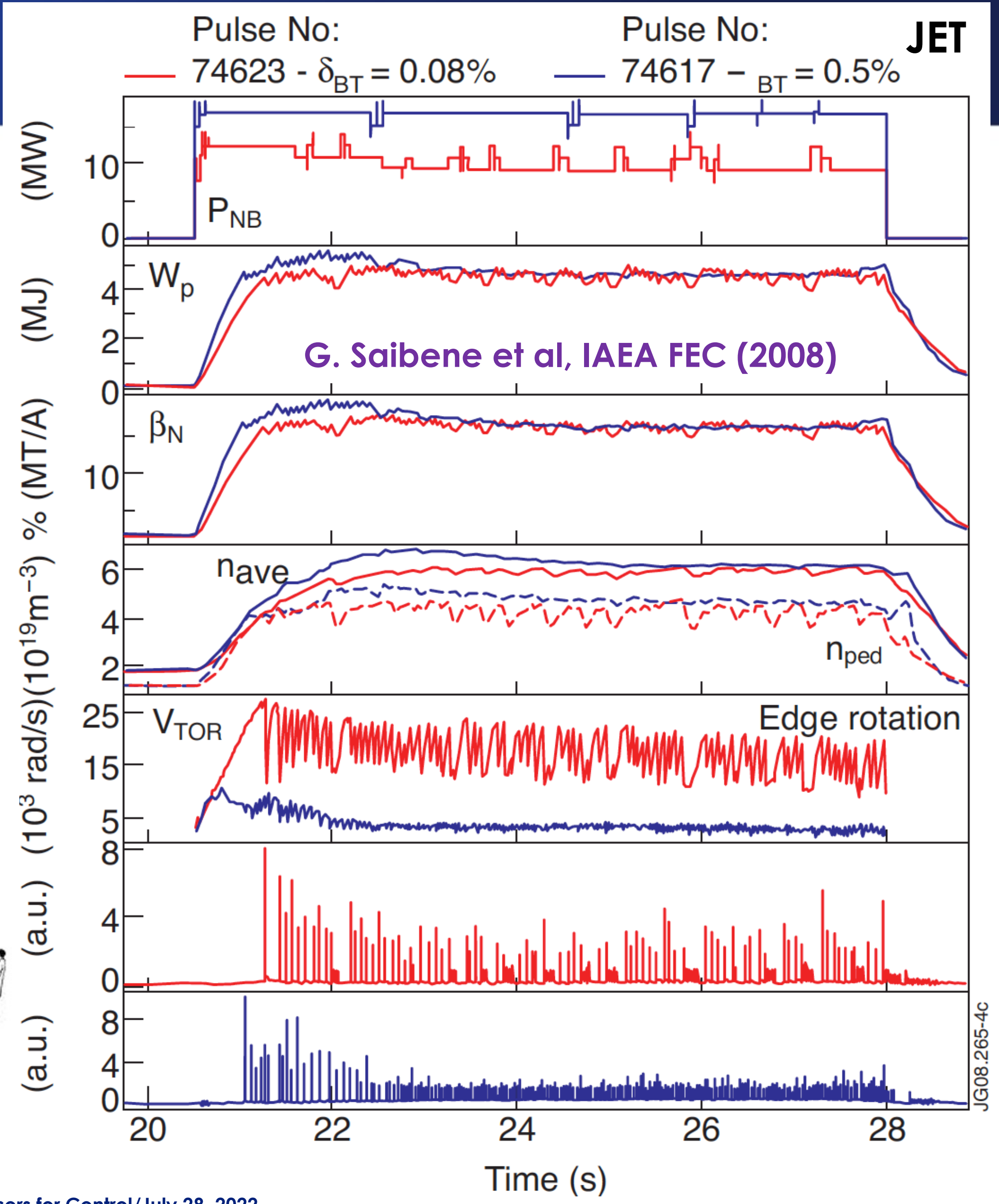
K.E.J. Olofsson, IEEE Conference on Control Technology and Applications (CCTA) (2020)

Actuators – TF coils

TF coils for main B_t value & TF ripple

- Change B_t value during the shot – Physics studies & RF resonance location
  - ✓ Not an option for ITER
- TF ripple value (JET): 2 sets of 16 TF coils – interleaved → Change TF ripple (δ)
- **ITER:**
  - ✓ δ~0.4% @ 2.65T, 5.3T
  - ✓ δ~1.2% @ 1.8T

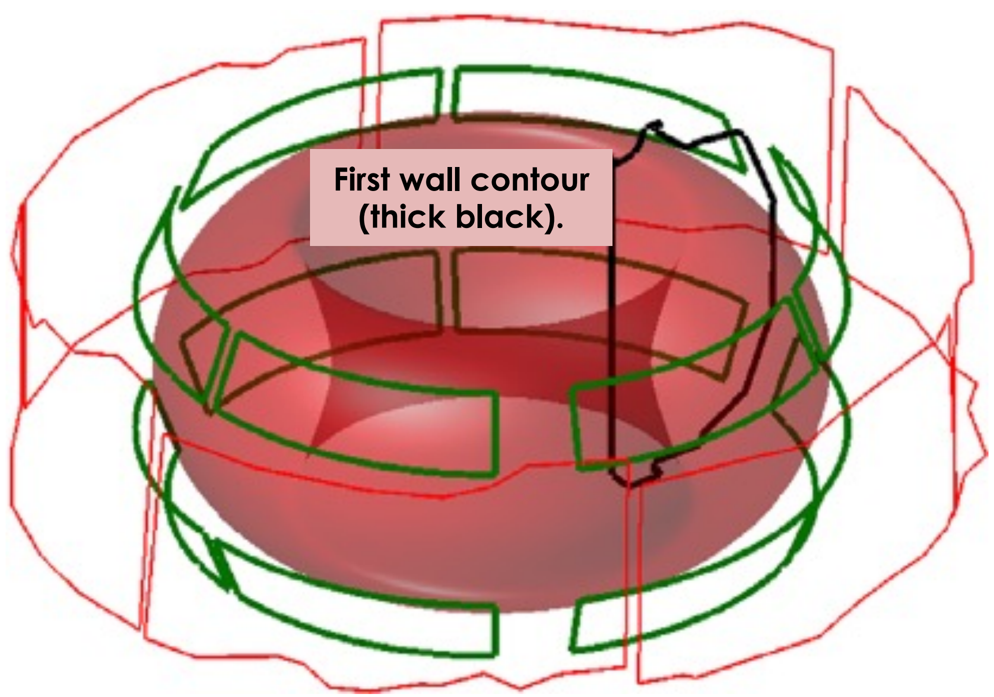


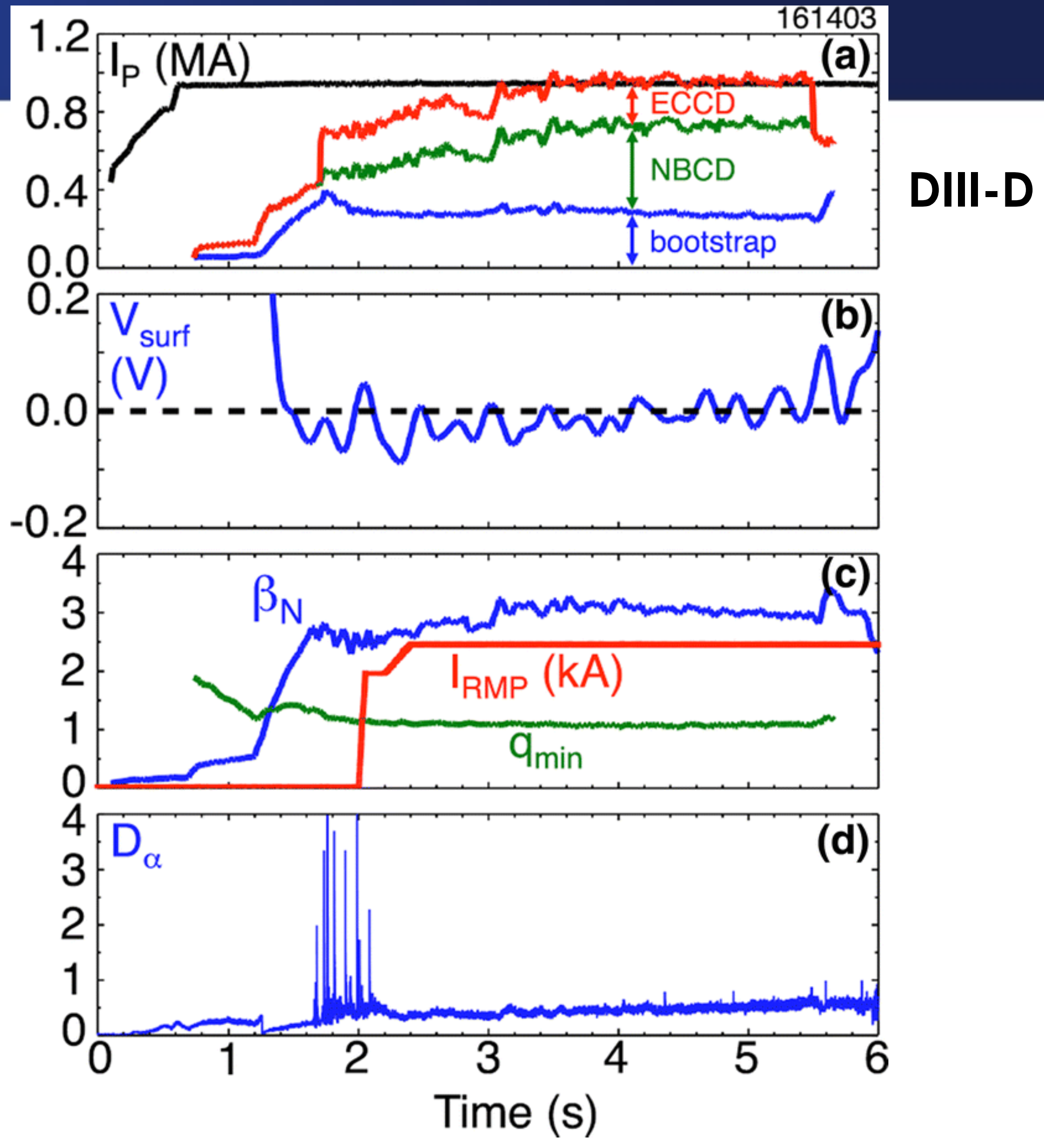


Non-axis symmetric, 3D coils

DIII-D non-axis symmetric coil-set

- RMP coils (I-coil, thick green)
- Error field correction coils (C-coil, thin red)





R.J. Buttery, Journal of Fusion Energy volume 38, pages 72–111 (2018)

D-T Pellet Injection for ITER Plasma Fueling

ITER Fueling Requirements are a Significant Challenge

- ITER plasma volume is 840m^3
- Plasma density > 1x10^{20} m^{-3}
- D-T mixture control
- Gas fueling will be limited by poor neutral penetration
- Pellet injection from HFS
- 1 hour duration
- At high reliability

AUG pellet injection

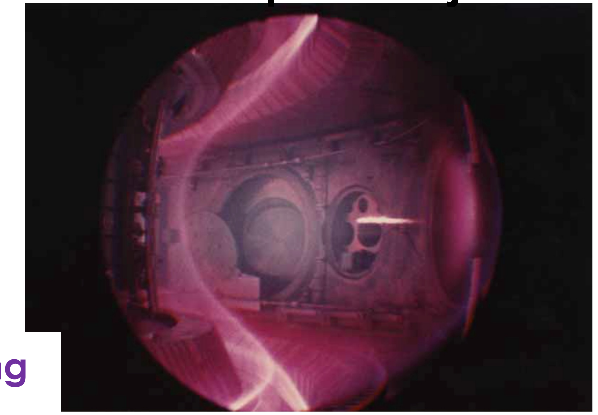
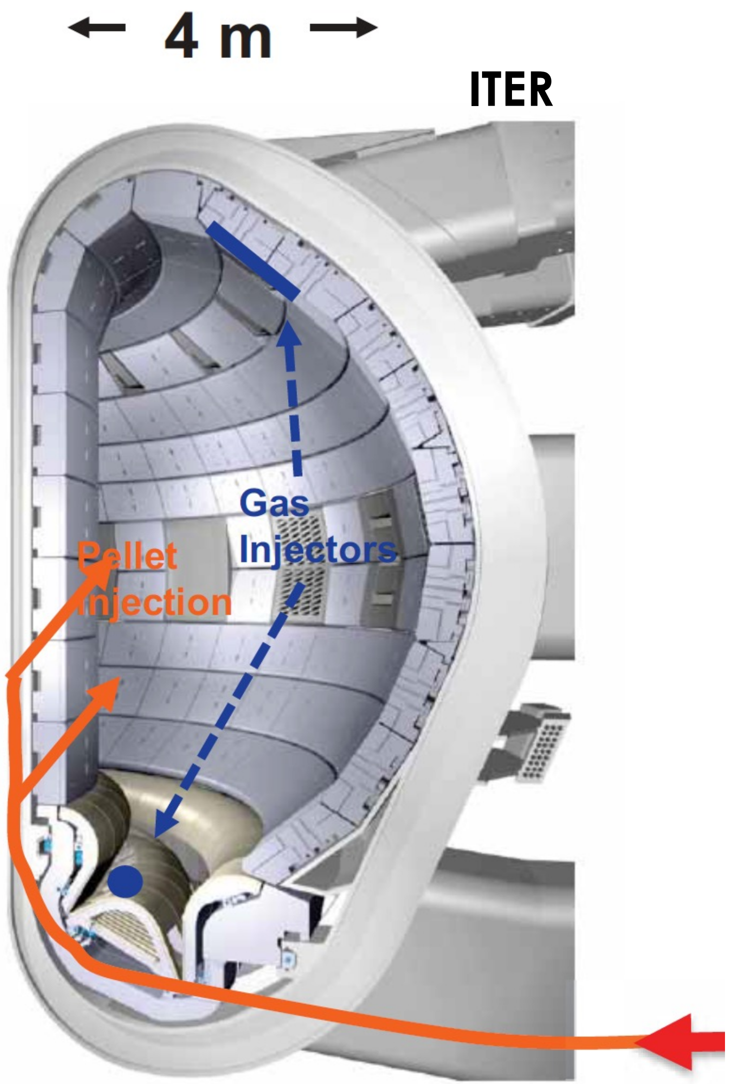


Photo provided by P.T. Lang and K. Büchl (AUG)

D. Rasmussen, Tritium Working Group (2018)

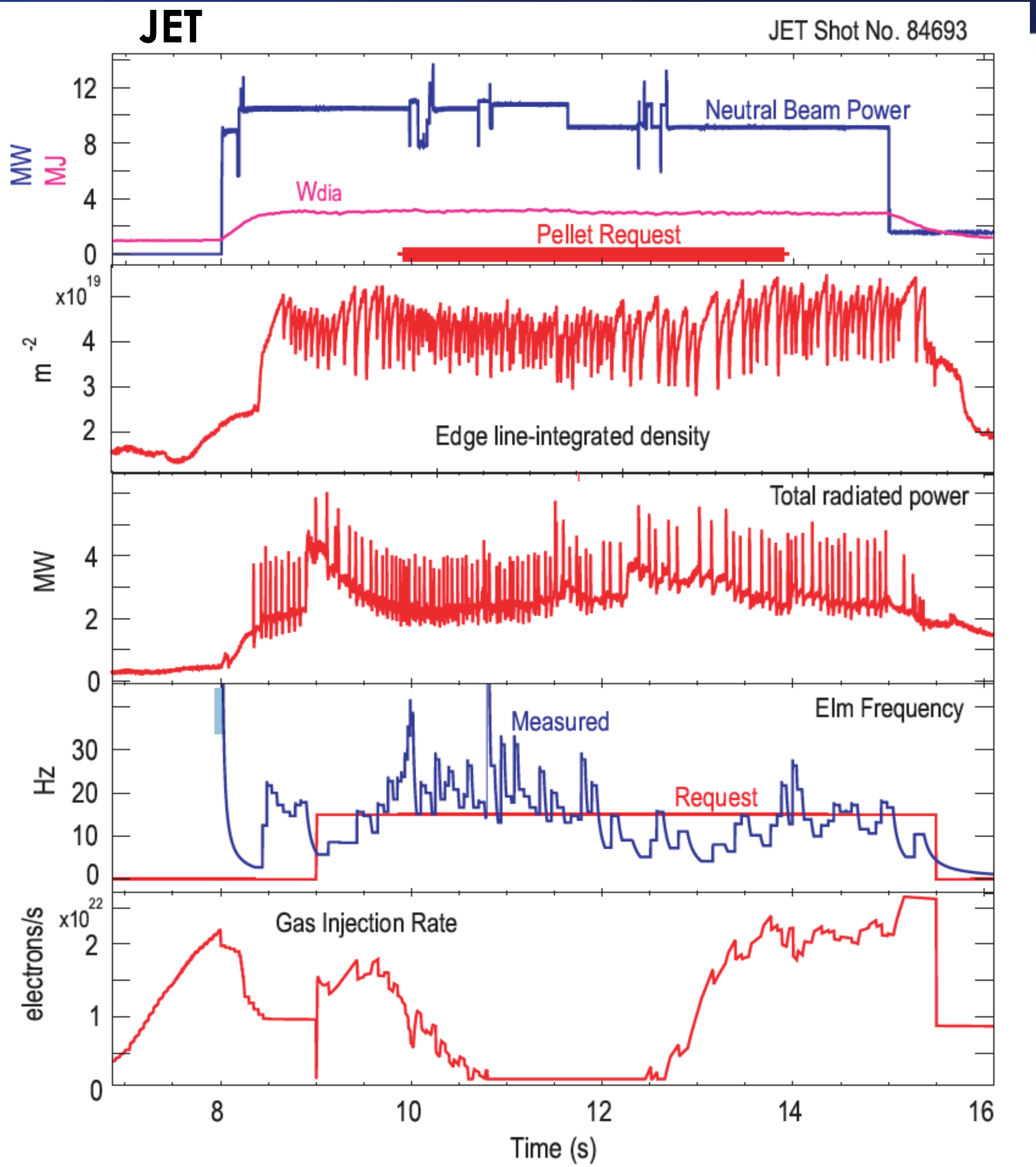


Density and fuel control - sensors and actuators

Gas & pellets → ELM control

- Compute ELM frequency in real time
- Set requested ELM frequency and control ELMs using
  - ✓ Pellet pacing
  - ✓ Gas injection rate

  Or combination
- For 1.5s the pellets successfully trigger the ELMs and so the injected gas is reduced to zero

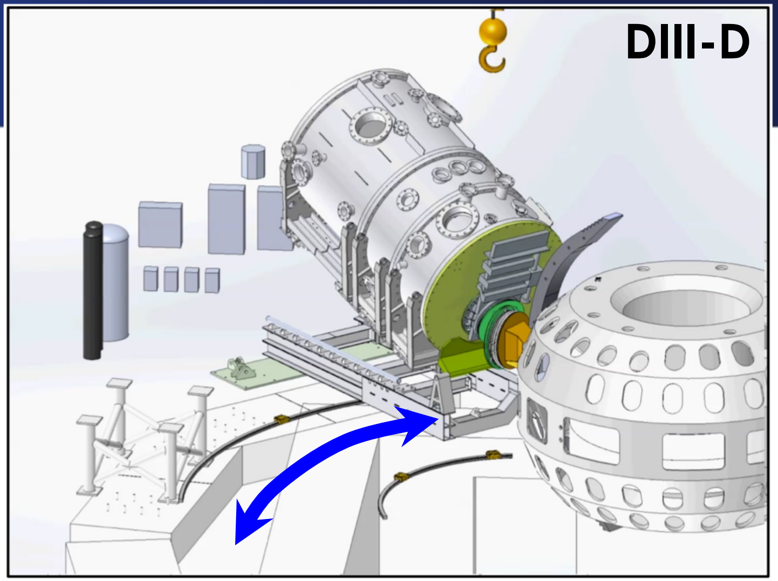


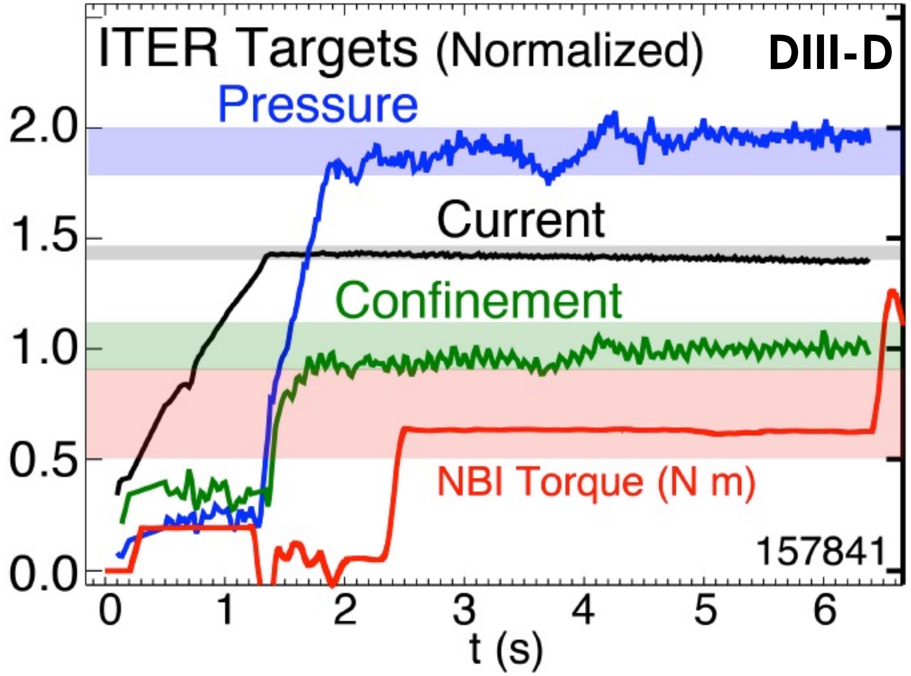
I.T. Chapman et al, Plasma Phys. Control. Fusion 58 014017 (2016)

NBI as actuator

At DIII-D, NBI system can control

- **Power (8 sources at 2.2MW each):**
  - ✓ EFIT_W, EFIT_β_T, EFIT_β_N, EFIT_β_p
  - ✓ T_e/T_i, Ti, neutrons
- **Current profile (4 off-axis NBI):**
  - ✓ EFIT_q_0, EFIT_q_{min}, q_0-q_{min}, ECE position
- **Rotation (2 counter NBI in co-counter mix):**
  - ✓ Torque input, CER rotation
- **Stability (power and q-profile):**
  - ✓ β_N/l_i, active MHD Spectroscopy amplitude





F. Turco, IAEA-TM (2015)

Electron Cyclotron Resonance Heating

DIII-D

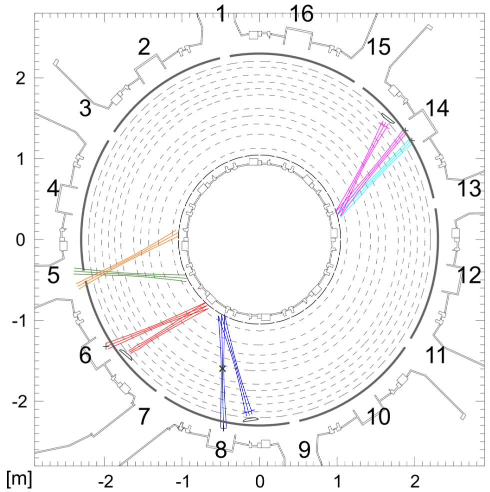
ECRH – Main heating system at ITER (24MW)

DIII-D: 7 (1MW) gyrotrons in 2023 – 10+ gyrotrons in 2025+

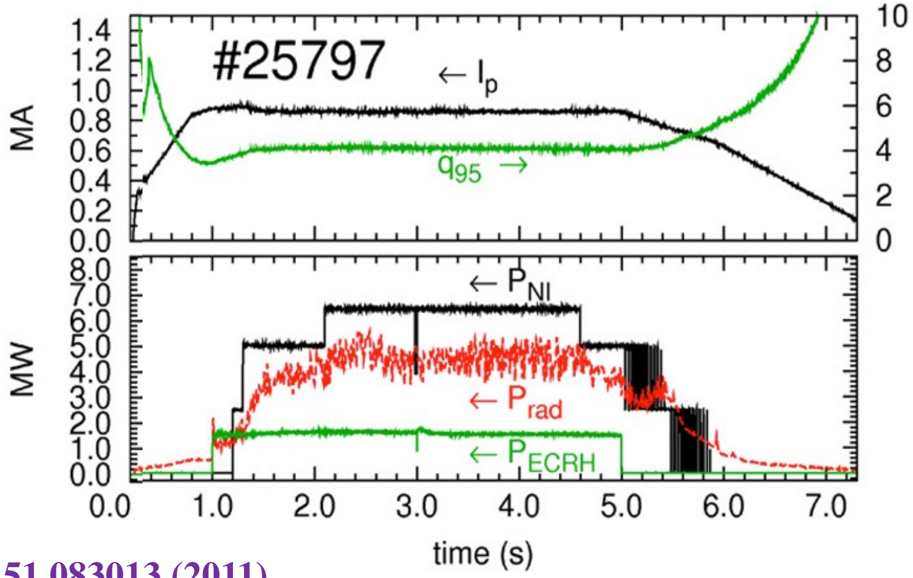
AUG: 8 gyrotrons in 2022 (maximize O2, X3 absorption)

Others: WEST, KSTAR, EAST, …

ASDEX-Upgrade

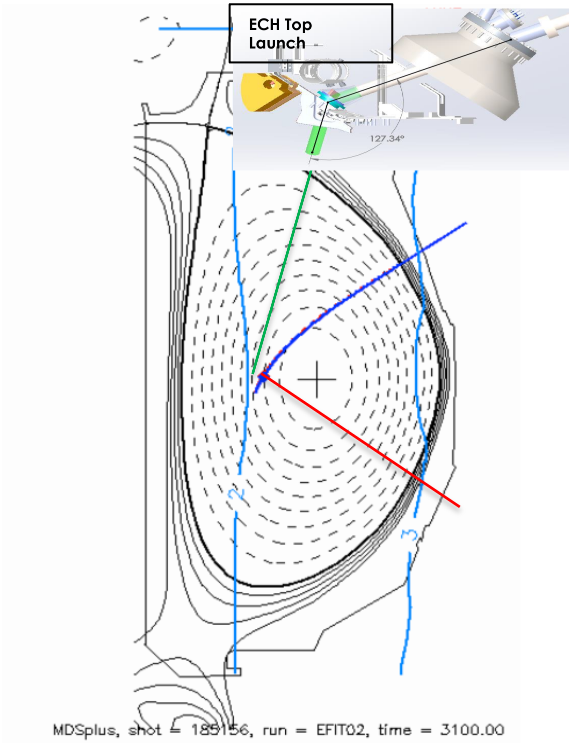


AUG: Test of X3 scheme (ITER PFPO, 1.8T)



H. Höhnle, Nucl. Fusion 51 083013 (2011)

DIII-D launch angles



NTMs and ECCD

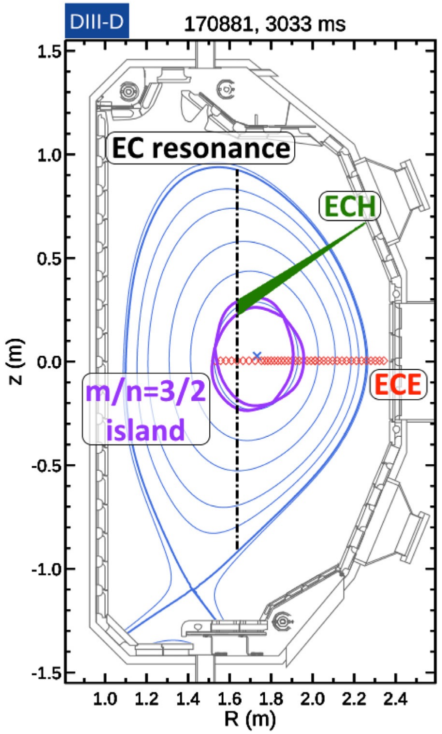
For NTM control

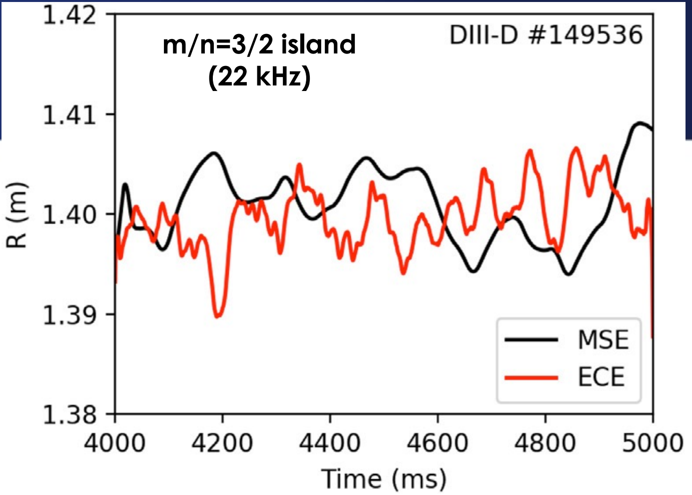
RT measurements of magnetic island and ECRH/ECCD locations:

- MSE constrained RT equilibria
- RT Thomson Scattering data used by TORBEAM
- Or, ECE radiometer for both island location and ECRH/ECCD deposition

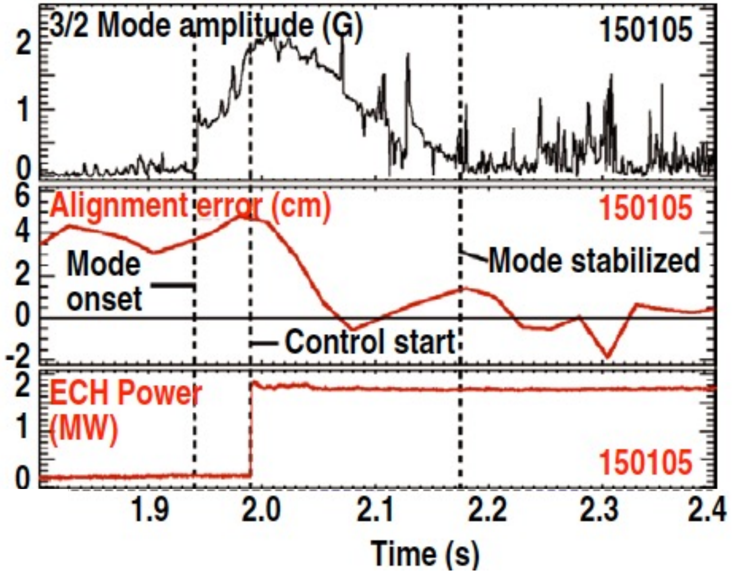
→ RT steering of ECH mirror and deposition location

A.O. Nelson, Fus. Eng. And Des. 141 25-29 (2019)





DIII-D



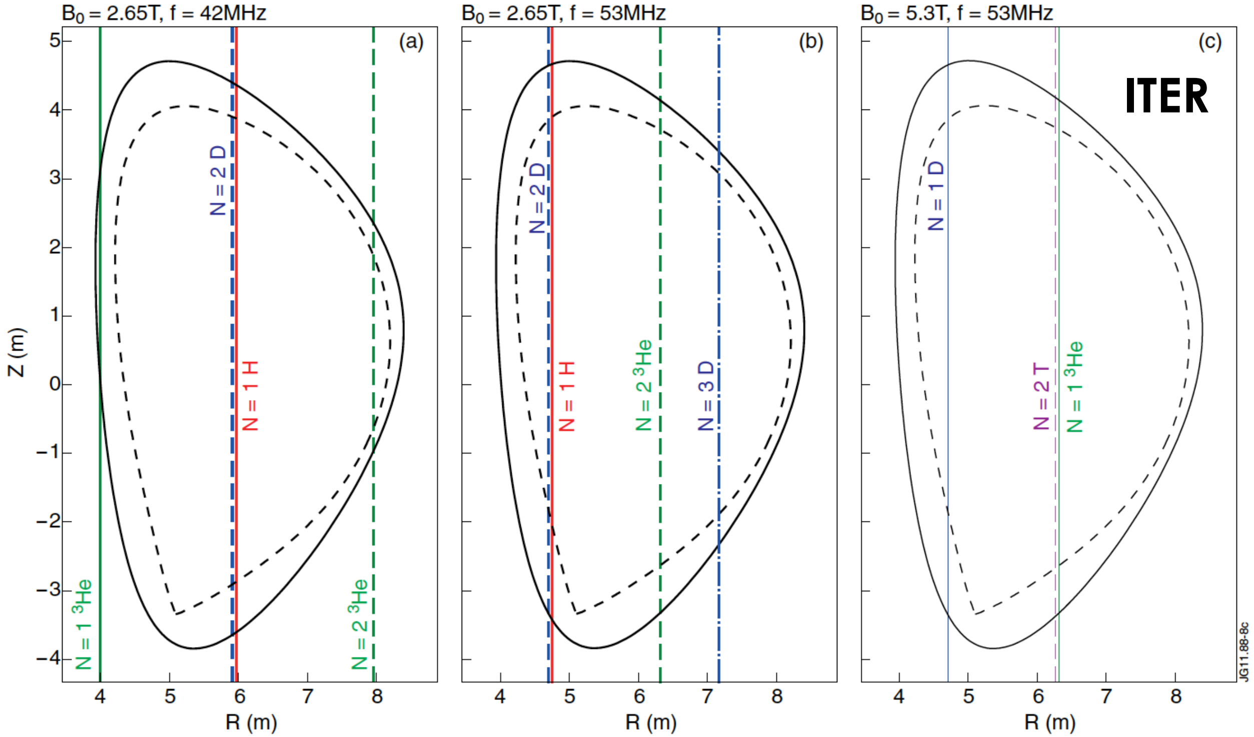
E. Kolemen, Nucl. Fusion 54 073020 (2014)

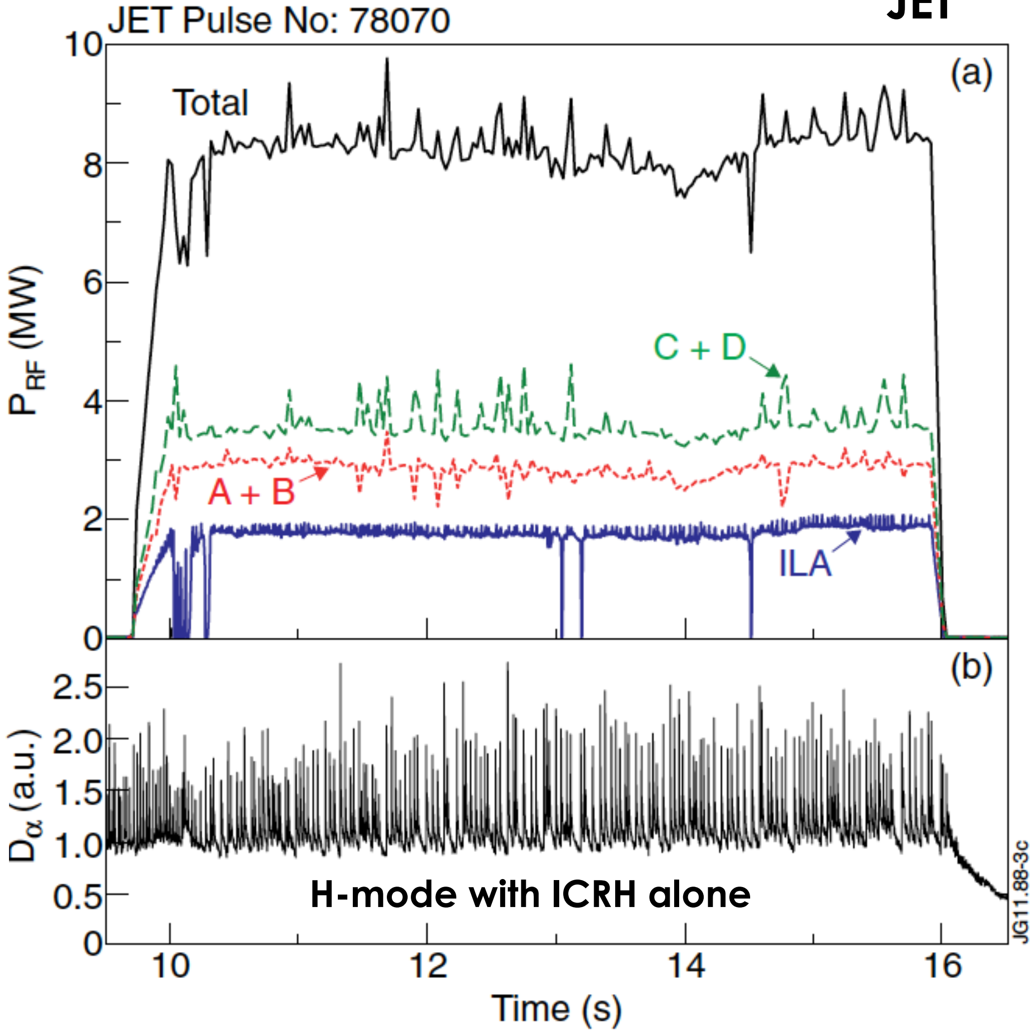
RF - Ion Cyclotron Resonance Heating

ITER: Ion Cyclotron Resonance Heating @ 20MW

(~60% e-heating, and ~40% ion-heating)

E. Lerche et al, EFDA-JET-CP(11)04/04 (2011)





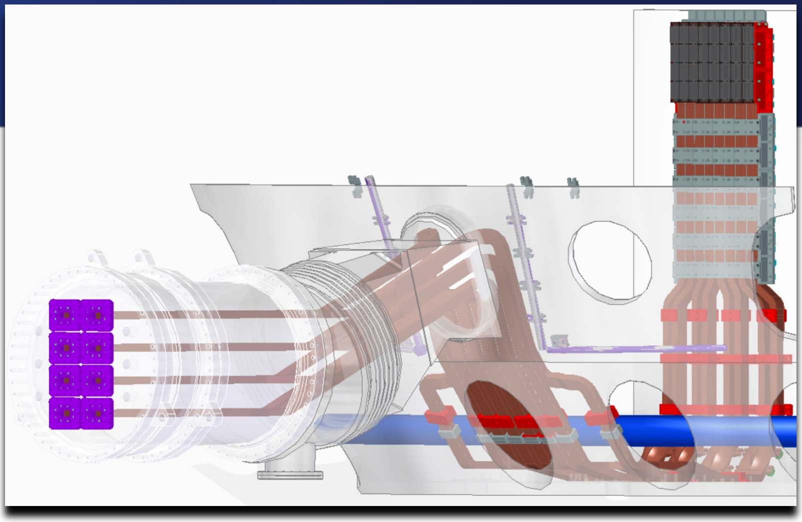
Main fundamental (solid), 2nd harmonic (dashed) and 3rd harmonic (dash-dot) ion cyclotron resonances: (a) B_0=2.65T and f=42MHz; (b) B_0=2.65T and f=53MHz; (c) DT operation at B_0=5.3T and f=53MHz.

RF Current Drive – Lower Hybrid

HFS LHCD being installed at DIII-D

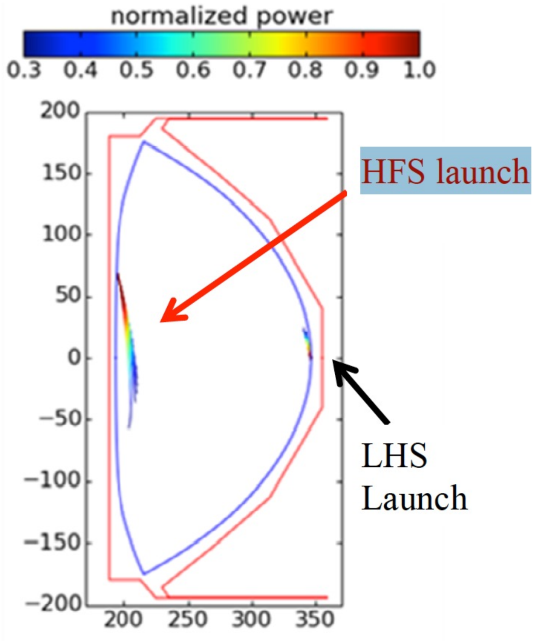
- HFS-LHCD: → 1MW (coupled)
  - Ready early 2024 (MIT)
  - 2MW klystron power

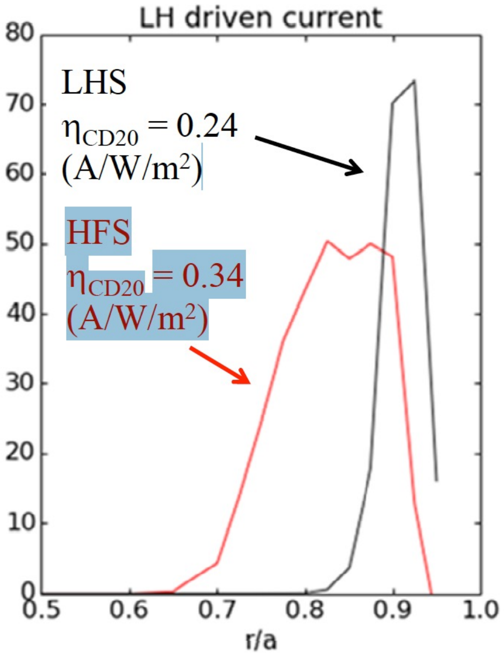
DIII-D & MIT

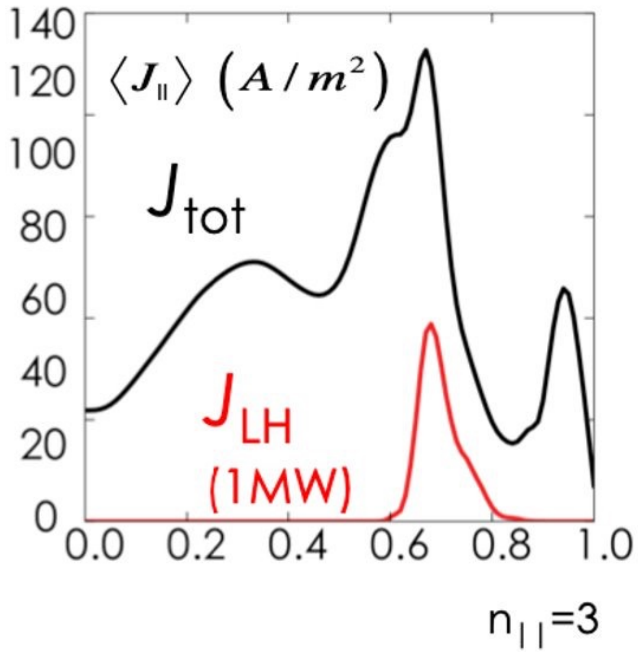


Simulation

S. Wukitch, FESAC TEC 2017





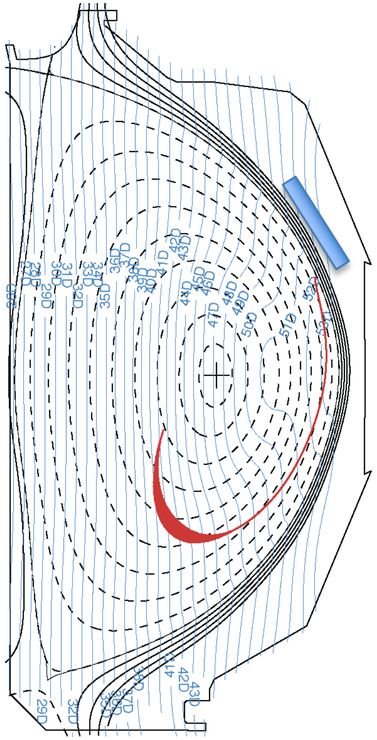


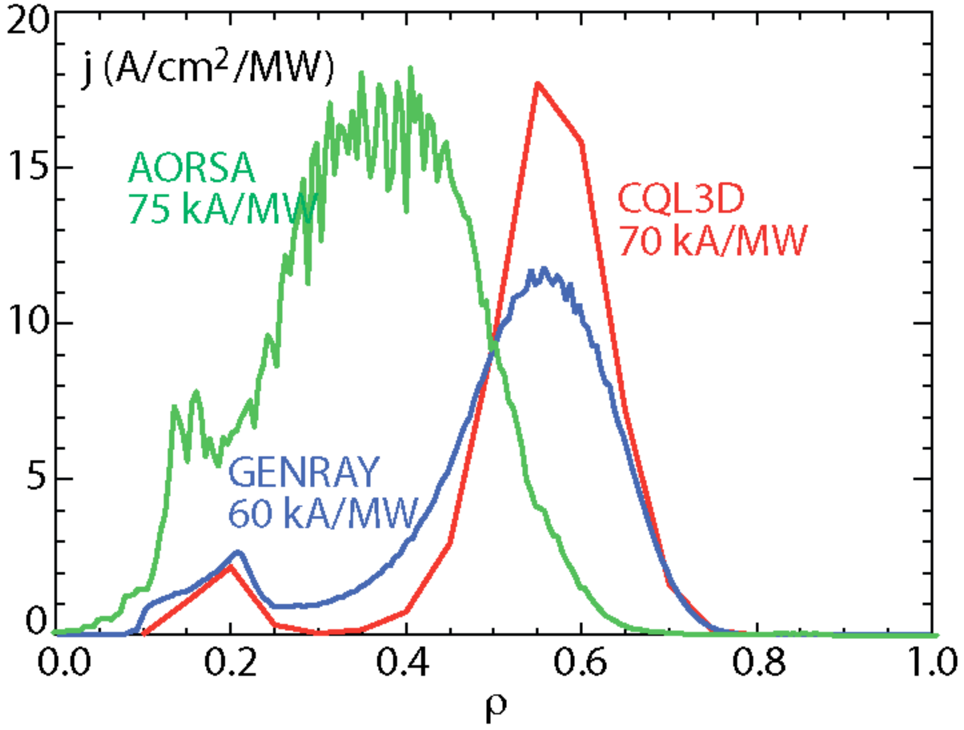
RF Current drive – Helicon

Helicon at 475 MHz, using a travelling wave antenna to provide off-axis current drive capabilities

DIII-D

- Being developed both at KSTAR and DIII-D
  - ✓ DIII-D, 1.2MW source → 0.5-0.8MW coupled ? (2022/23)
  - ✓ Verify technology and current drive predictions



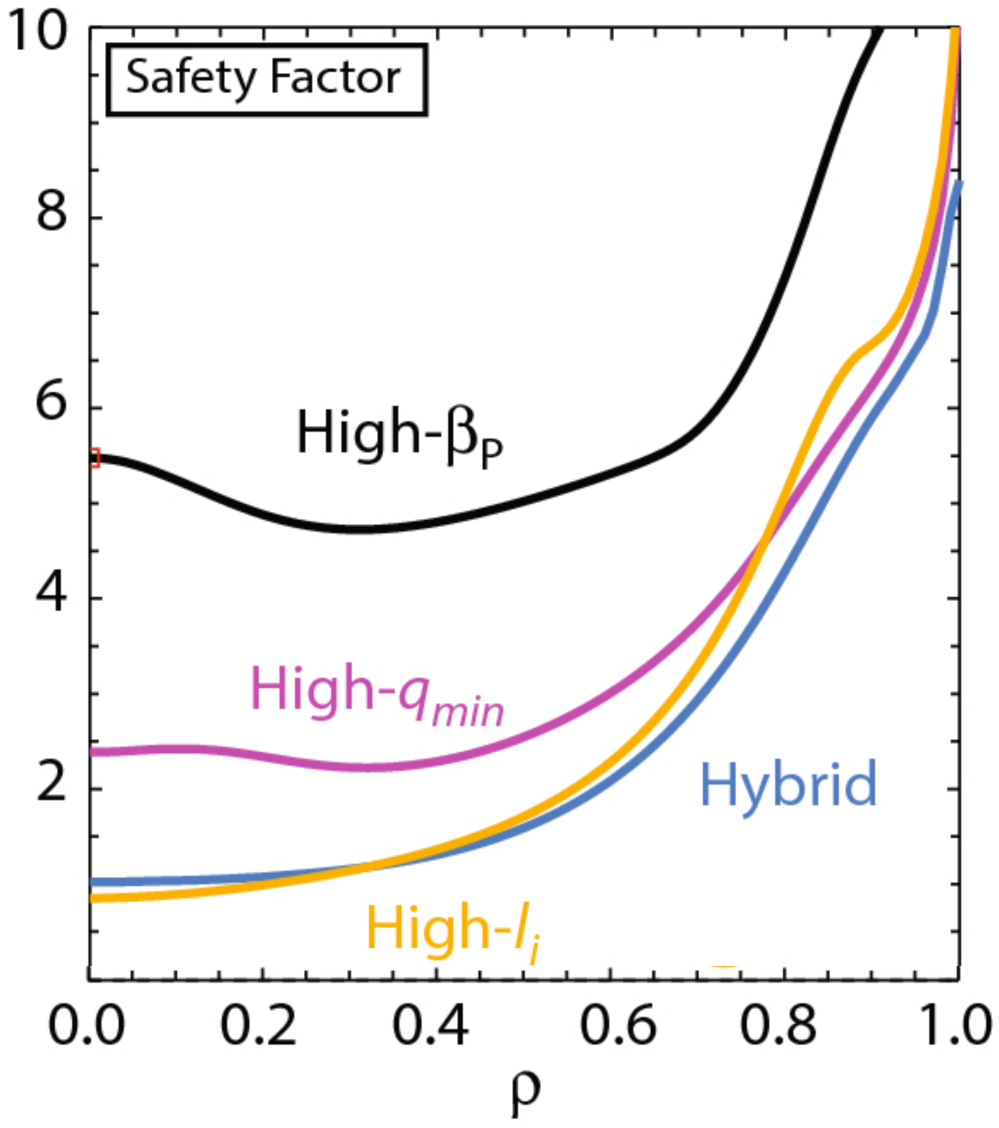


R. Prater at al, GA-A27841 (2014)

6. q-profile control ?

Current profile control

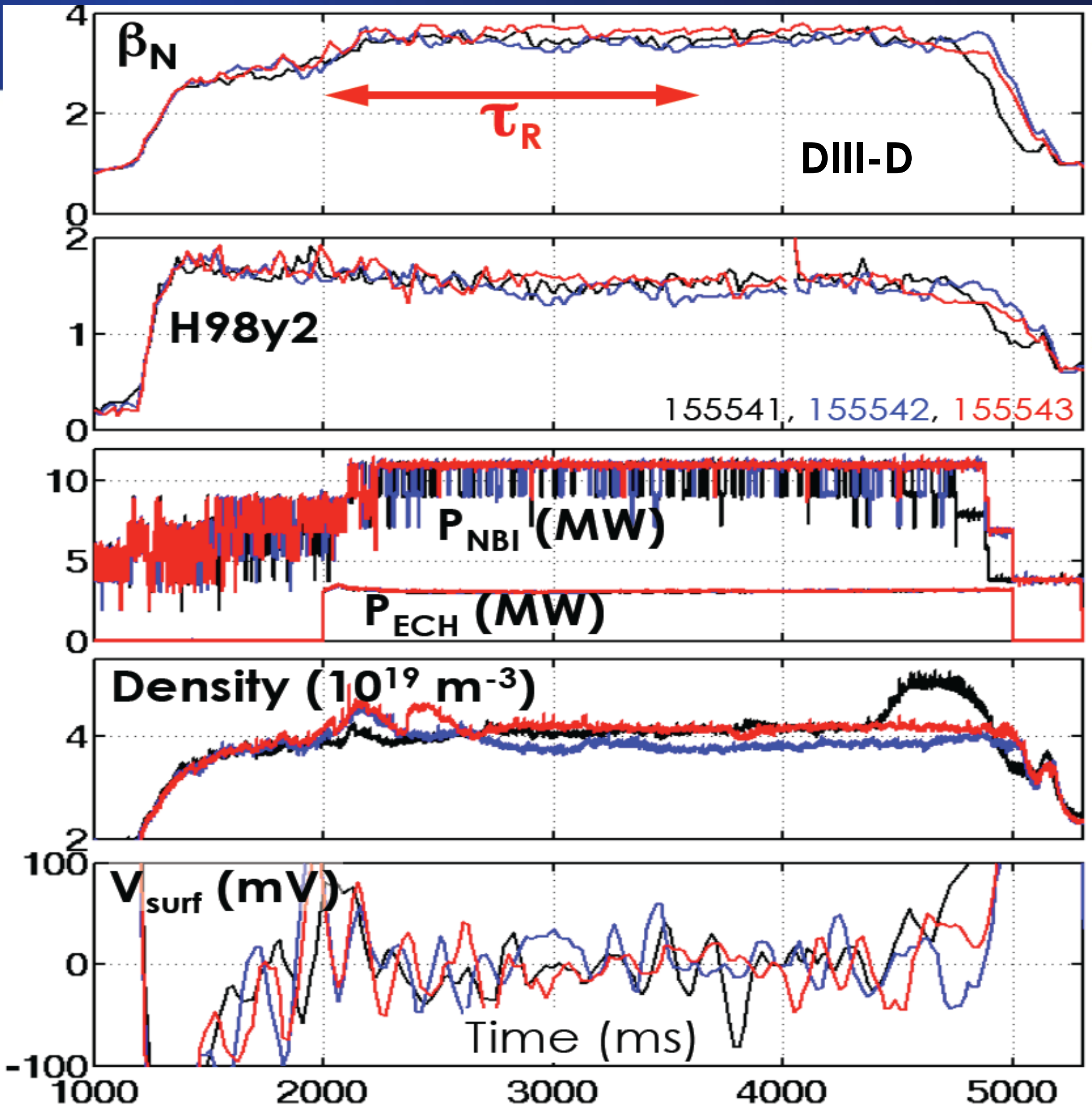
- Forming the q-profile (Ramp-up)
- Self organization
  - ✓ Hybrid Steady state scenario
  - ✓ Standard AT (high-$q_{min} \gtrsim 2$)

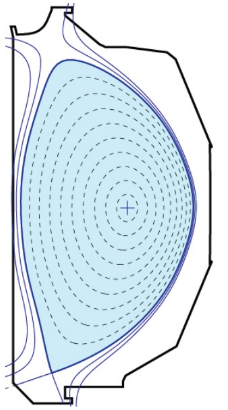


Non-inductive scenarios

DIII-D advanced the two extrema of the steady-state scenario options for ITER

- Standard AT (high-q_{min}≳2)
- Low q_{min}, steady-state hybrid
  - ✓ β_N~3.6, Vloop ~0 for ~2 τ_R
  - ✓ Limited by NBI duration
  - ✓ Particularly attractive using core current drive → fully NI
  - ✓ **No q-profile control required**





F. Turco, IAEA-TM (2015)

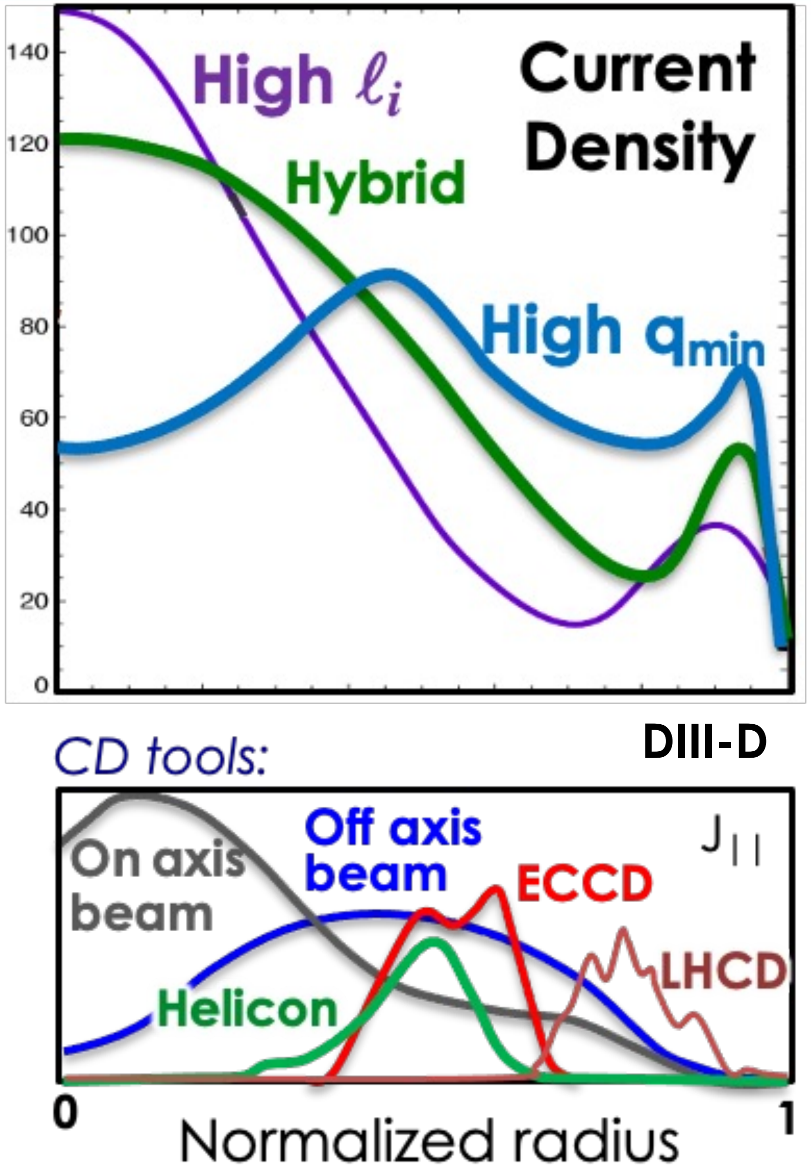
q-profile control ?

Steady-state core

High q_{min} ($q_{min} \gtrsim 2$) operation can be achieved with off-axis CD tools

- Fully NI conditions have been achieved at DIII-D in this regime
  - ✓ using preheating during the current rise
  - ✓ Off-axis ECCD

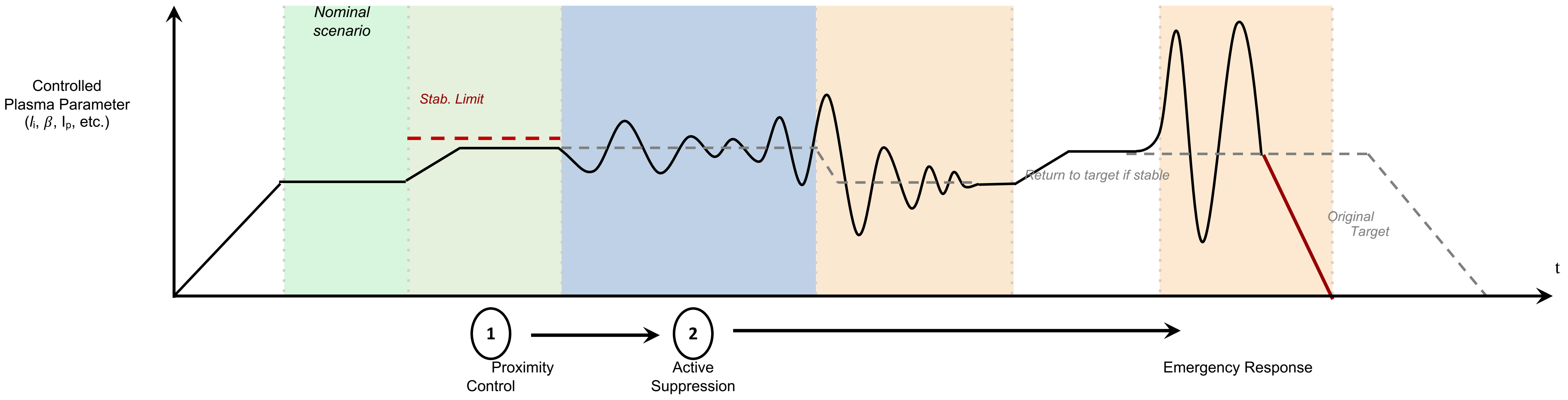
- With new CD tools (Helicon and HFS-LHCD) at DIII-D further optimization is possible
  - ✓ No q-profile control required ?



7. Different discharge phase require different controls

When ? – Discharge phases

- Sensor and actuator requirements depend on plasma phase
- Several control phases



Real time recognition of confinement phases → Control

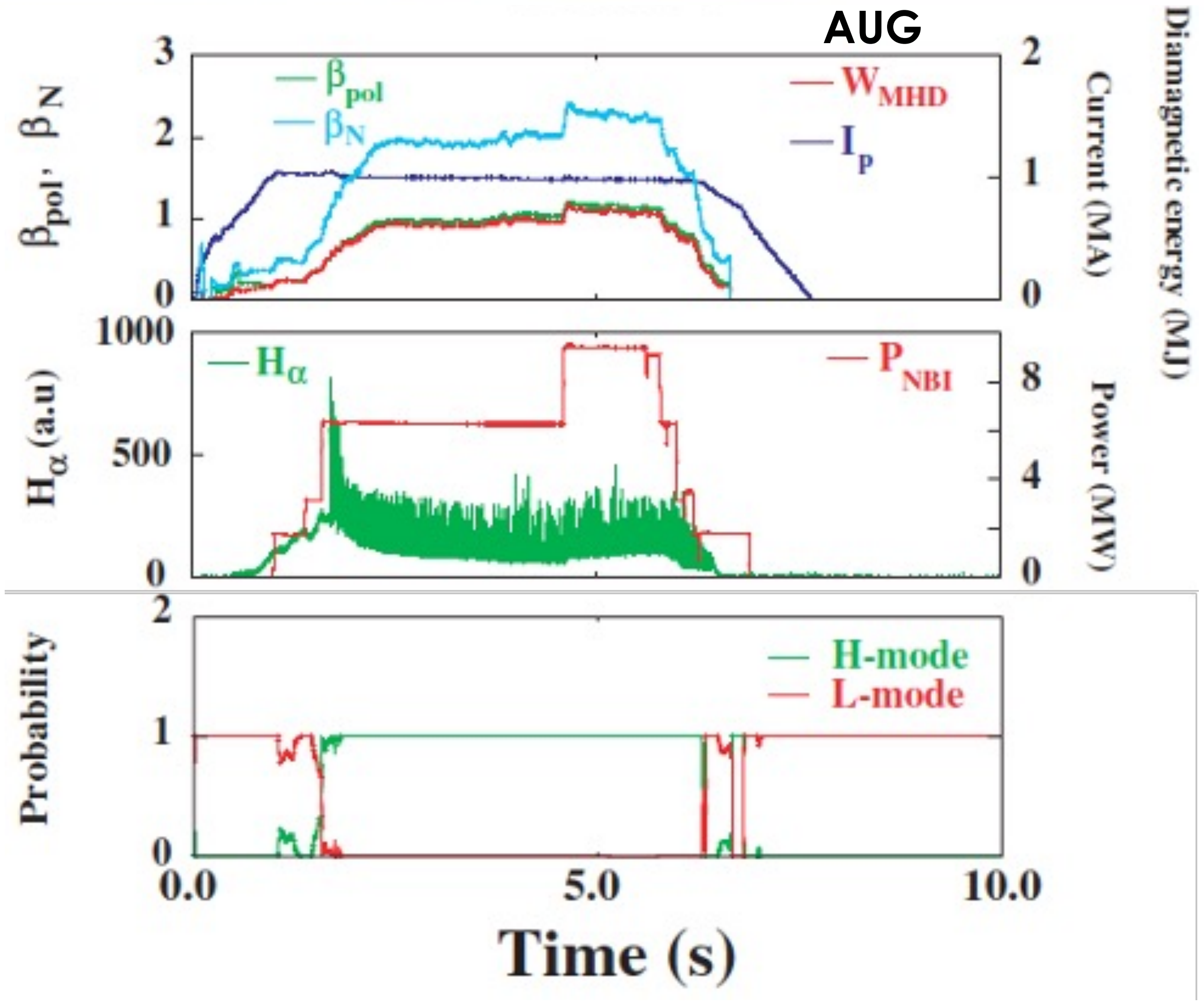
ASDEX: H-mode & L-mode (others)

- Using a training data set
- Discriminant Analyses
  → Assigns probability to L-mode or H-mode
- Global variables, <u>not</u> P_L/P_{LH} !

Prediction error

Number	Variables
2	P_{Ohm}, l_i
3	$P_{\mathrm{Ohm}}, I_p, \beta_N$
4	$P_{\mathrm{Ohm}}, P_L, I_p, \beta_N$
5	$P_L, I_p, \beta_p, q_{95}, U_{\mathrm{loop}}$

More than 5 variables → no improvement



L. Giannone, A.C.C, Sips et al, Plasma Phys. Control. Fusion 46 835–856 (2004)

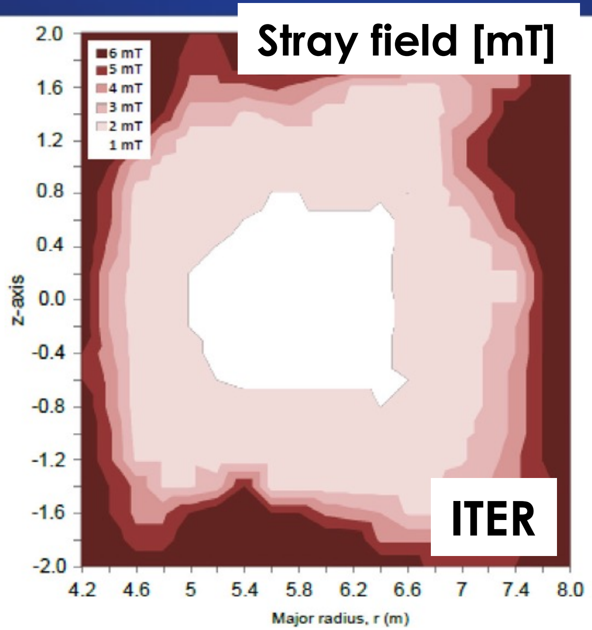
ITER- plasma formation (FF)

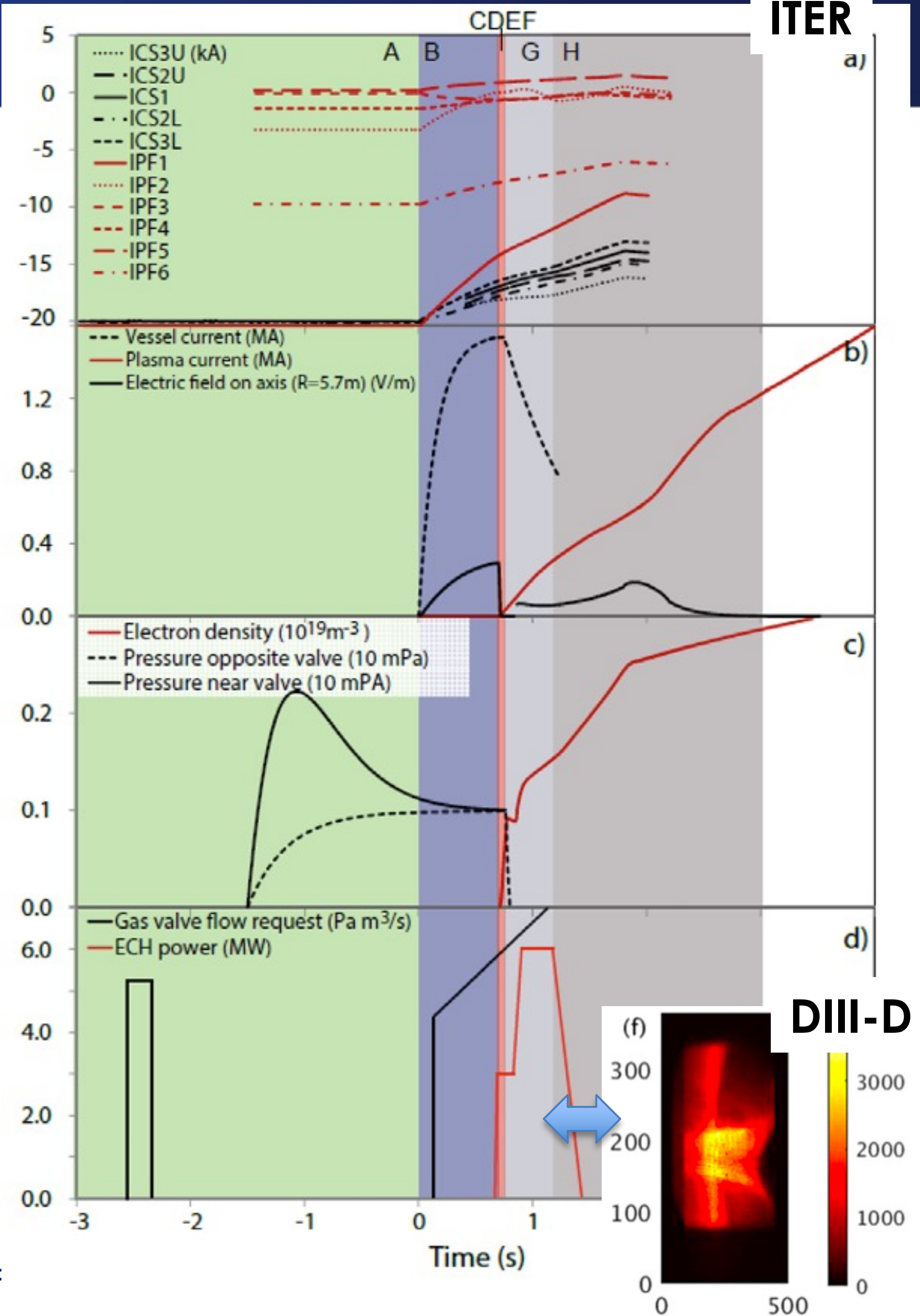
ITER breakdown

- Feedforward (FF) PF currents, loop voltage
- Gas pressure, evolution or control
- ECH pre-ionization & burn-through assist
- **After plasma formation:**
    - Flux control of plasma position

    → ***Transition to control phases***

    → ***Protection circuits*** (RE, no plasma)





P.C. de Vries, Nucl. Fusion 59 (2019) 096043

8. What have we “learned” on Sensors and Actuators

1. Sensor processing is key to using diagnostic information in real-time systems
   - ✓ Examples given for magnetic sensors, IR data, density information

2. Various techniques for sensor processing are used

3. High computation and data reduction can be outsourced
   - ✓ In some cases be “ringfenced” such as the protection of the ITER-like wall at JET

4. Actuators are varied - sometimes their use can be optimized using model calculations in the control system (gas fueling, ECRH deposition)

5. Do not underestimate feedforward use of actuators & keep it simple
   - ✓ Use control only when needed (shape, density, wall protection beta,..)