Recent results of ECRH/ECCD experiments on TCV

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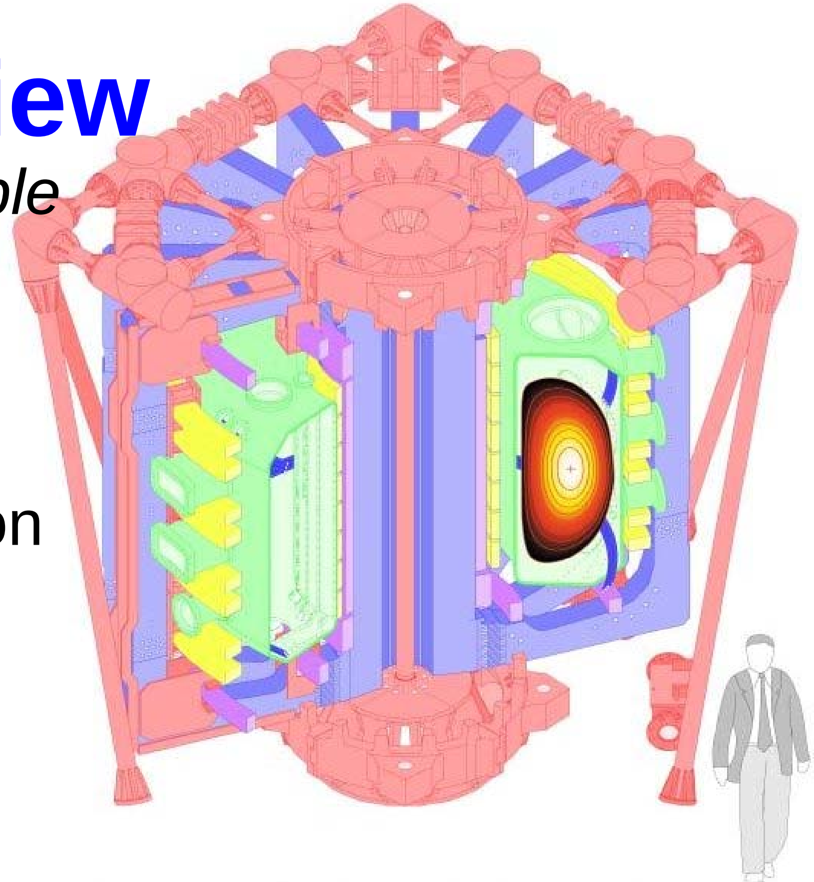
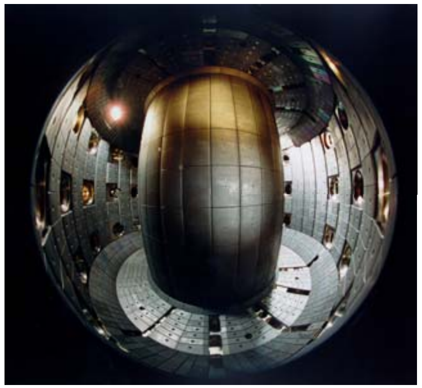
Talk outline

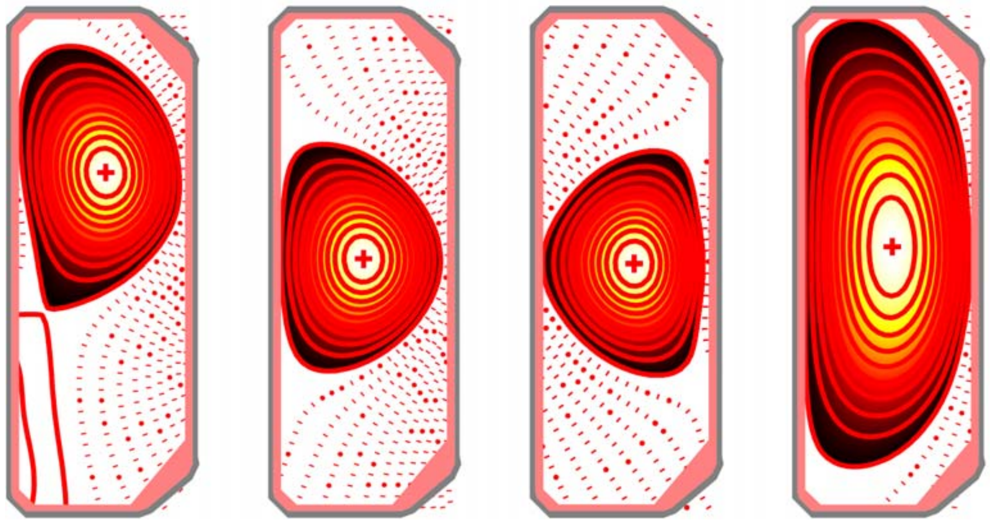
- TCV Tokamak overview and features
  - ECH/ECCD system
  - Real-time control
- Recent results of ECH/ECCD experiments
  - Real-time control of
    - Sawtooth period
    - Peak-in-profile
  - Plasmas with internal electron transport barriers (eITBs)
    - Creation and sustainment in steady-state
    - Steady-state 100% bootstrap current
    - Global oscillations, suppression using current density profile perturbations
  - Tearing mode studies
- Conclusions & Summary

TCV Overview



- TCV: *Tokamak à Configuration Variable*
- R/a = 0.88m/0.25m,
- $B_T < 1.45T$, $I_p < 1.2MA$
- High flexibility in plasma shape/position
- 0.9 < elongation < 2.8
- -0.6 < triangularity < 0.9
- $t_{pulse} < 4s$, $T_e < 10keV$
- Graphite inner wall





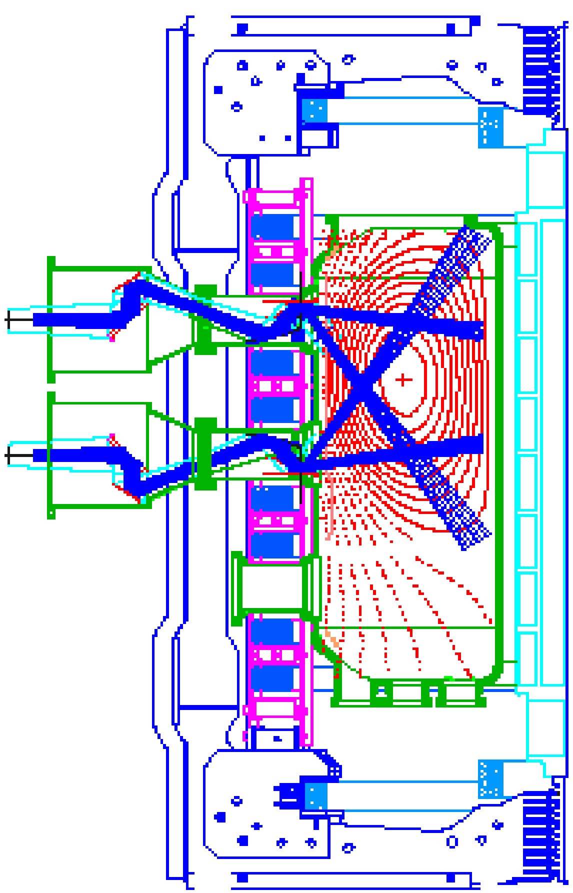
Flexible ECH/ECCD system

2nd harmonic X2 (82.7GHz)

6 x 0.5MW, 2s gyrotrons

3rd harmonic X3 (118GHz)

3 x 0.5MW, 2s gyrotrons



Side launch ECH, ECCD

$n_{cut\text{-}off} \approx 4\times10^{19}\ m^{-3}$

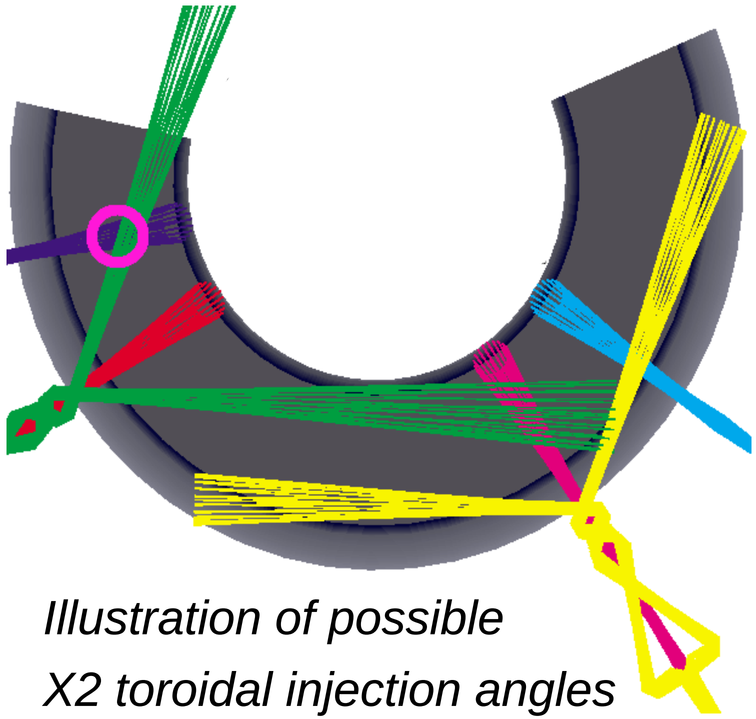
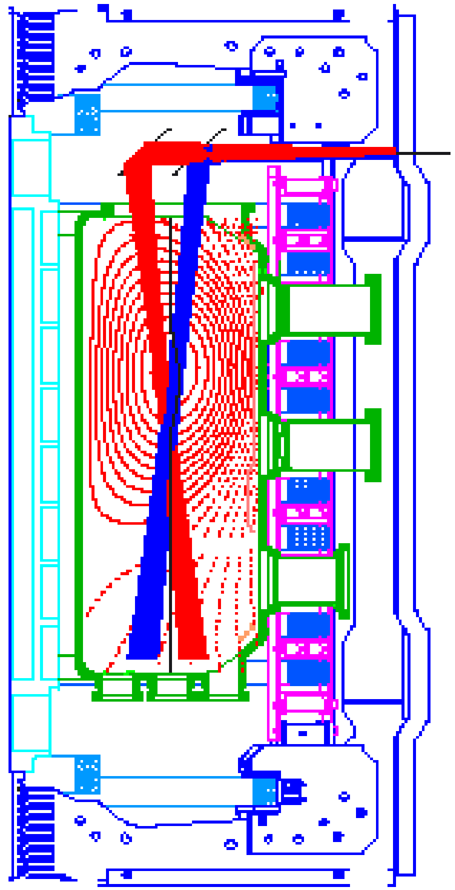


Illustration of possible X2 toroidal injection angles

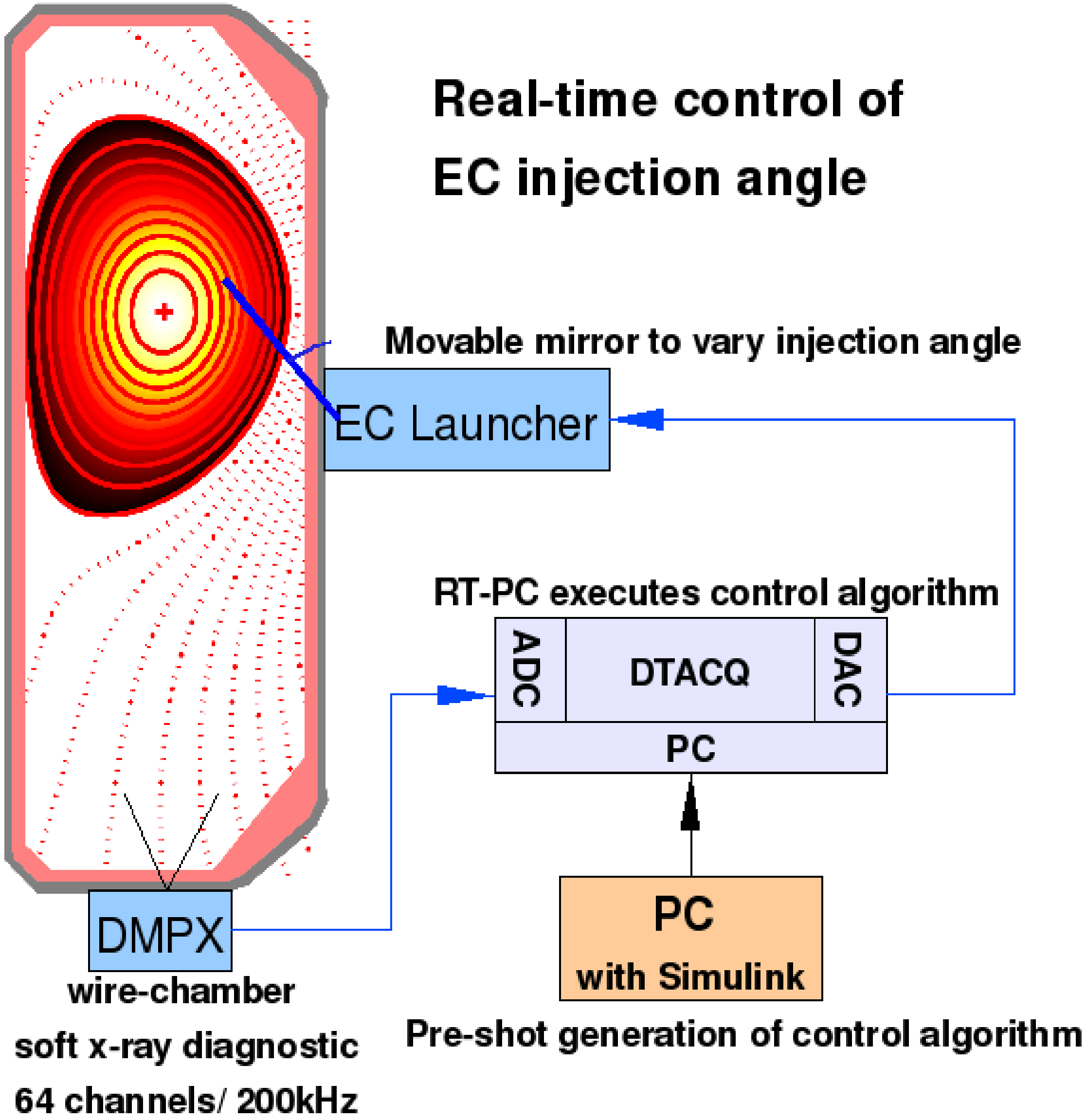


Top launch ECH

$n_{cut\text{-}off} \approx 10^{20}\ m^{-3}$

CRPP

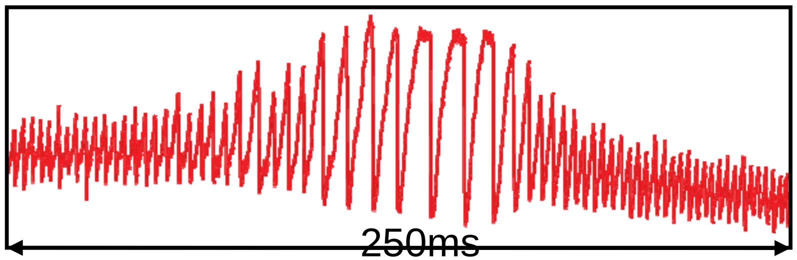
Real-time control of EC system



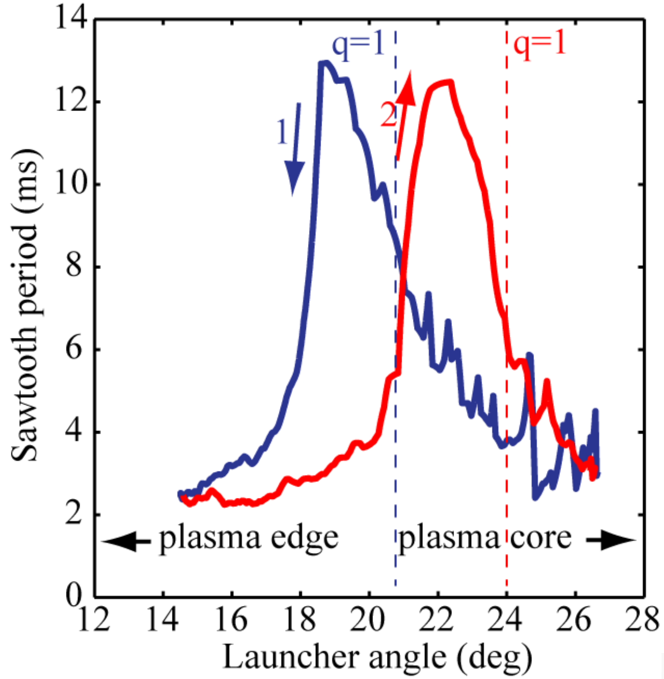
- Digital real-time feedback control of EC system
- EC power/mirror angles can be controlled in Real-time. [Paley, PPCF2007]
- Recently, injection angle was regulated to control
  - Sawtooth period
  - Peak-in-profile

Control of sawtooth period

- Sawtooth crashes – periodic core pressure and temperature drop inside *q=1* surface.
  - Control is important as sawteeth can trigger NTMs -> confinement loss
- Period can be controlled by localized EC deposition near *q=1*
  - Causes local changes in the magnetic shear.
  - Sweep of the EC deposition shows a clear peak
    - Hysteresis due to change in *q=1* surface location, caused by global current profile changes.
    - Nonlinear response, system gain changes



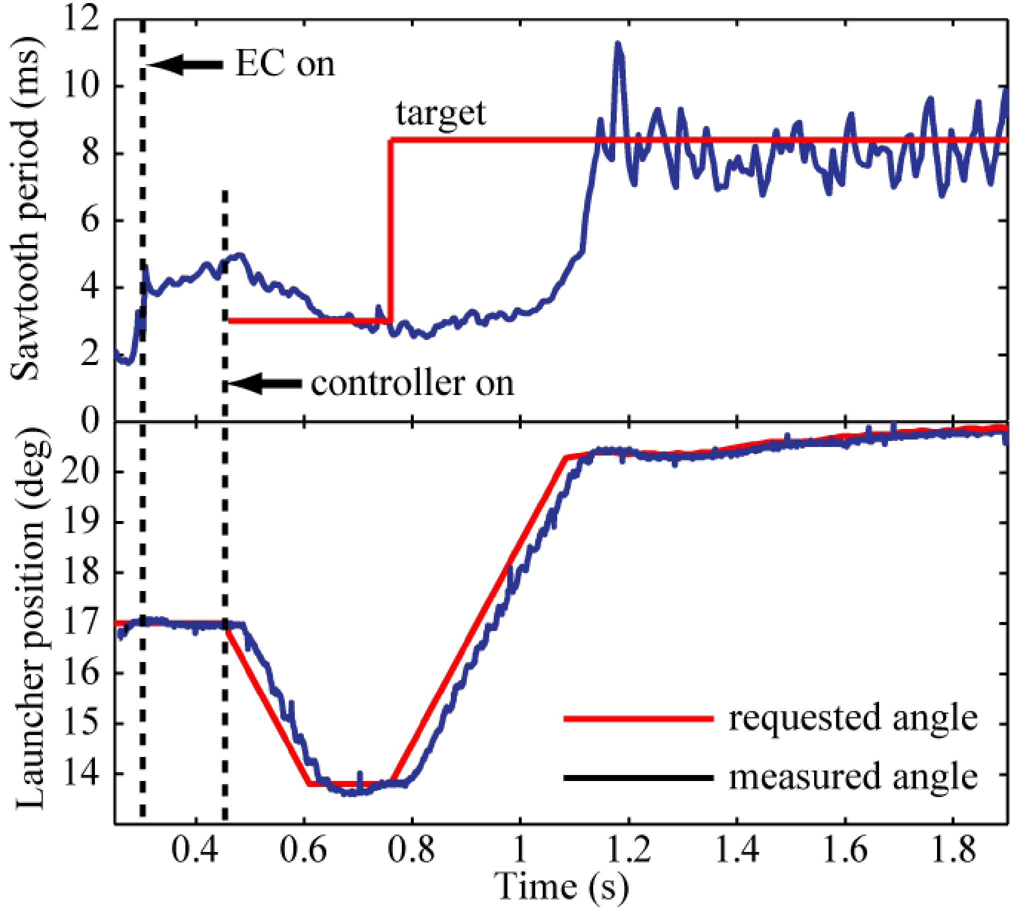
Typical signal of central X-rays with sawteeth



[J.Paley, Submitted to PPCF]

Control of sawtooth period

- Linear controller use is limited due to increasing system gain.
- Loop can be either unstable or too slow.
- Solution: nonlinear, gain scheduling controller.
  - Two possible movement speeds depending on requested period.
  - Result: successful tracking of reference signal.

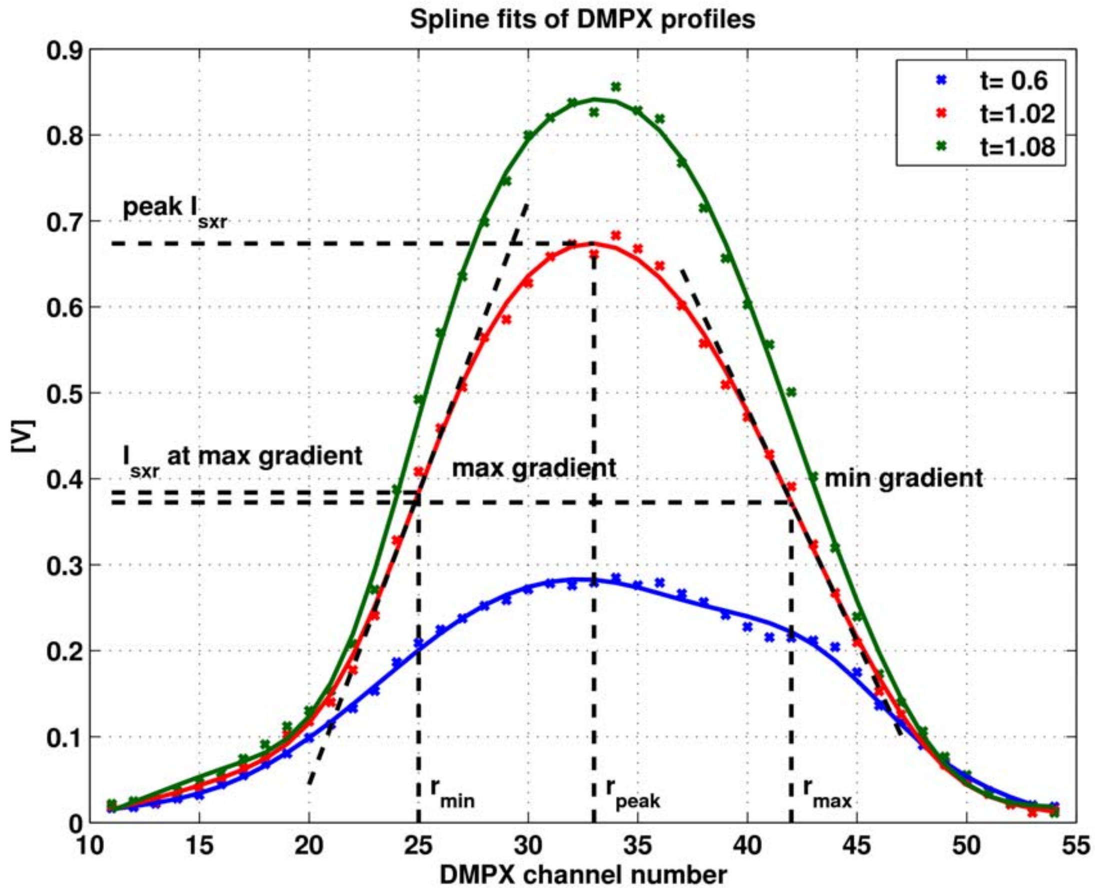


Profile control

- Acquire all 64 DMPX chords, filter, spline fit in real-time
  - Gives soft x-ray emission profile maximum value, peakedness, width, ...

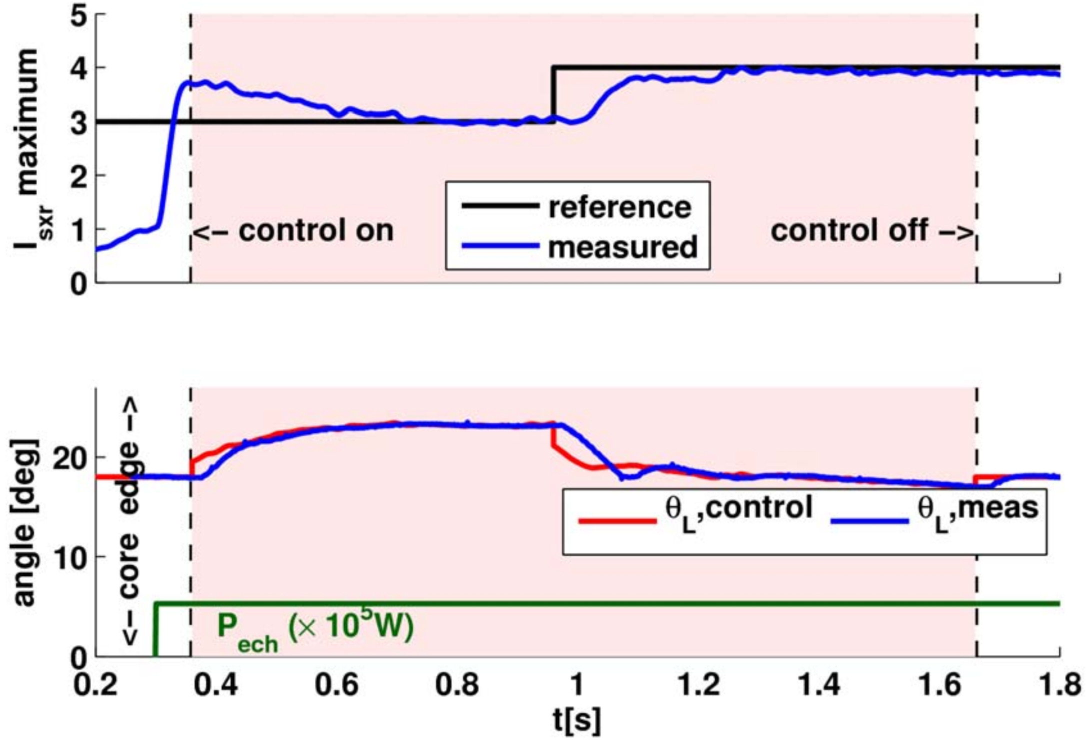
- Objective: control multiple parameters of the profiles using multiple launchers.

- First experiment: control the maximum value (peak) of the line-integrated SXR emission profile by moving one launcher



Peak-in-profile control

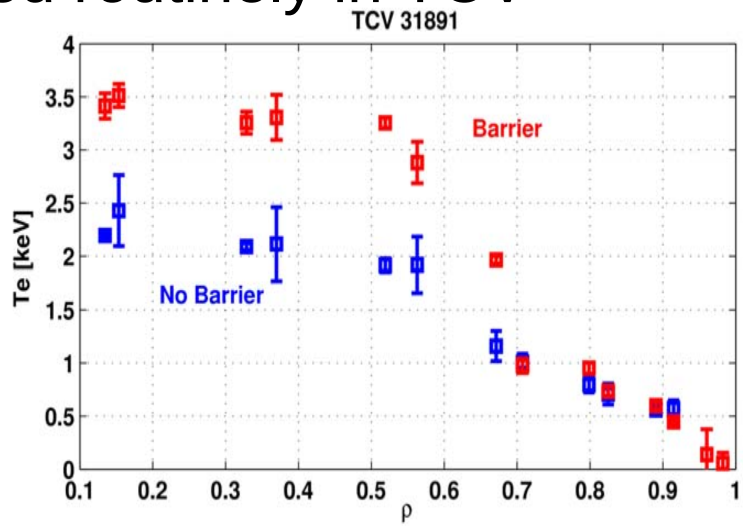
- Control the maximum value (peak) of the spline fitted profile
- Reference tracking experiment
  - Subtract measured maximum from given reference
  - Feed error to PI controller
  - Controller adjusts mirror angle



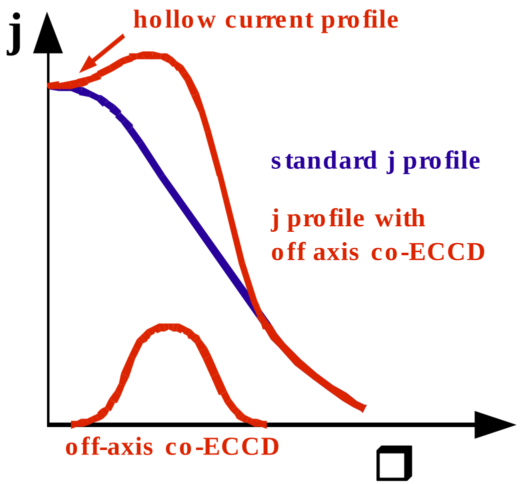
- Future objectives:
  - Invert line-integrated signals to obtain true profile.
  - Control temperature profile instead of SXR emissions
  - Use multiple launchers

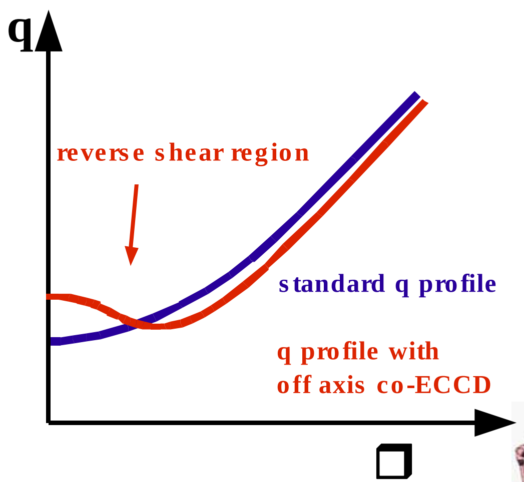
Scenarios with eITBs

- Electron internal transport barriers created routinely in TCV
  - High pressure gradients in off-axis region
  - confinement improvement 3-6 times TCV L-mode scaling



- Created in reversed shear conditions: hollow *j profile, reverse shear q* profile
- In TCV: steady-state eITB plasmas, lasting several current redistribution times.
  - Low current and density
  - Non-inductive:
    - Off-axis ECCD.
    - High bootstrap fraction (>50%)

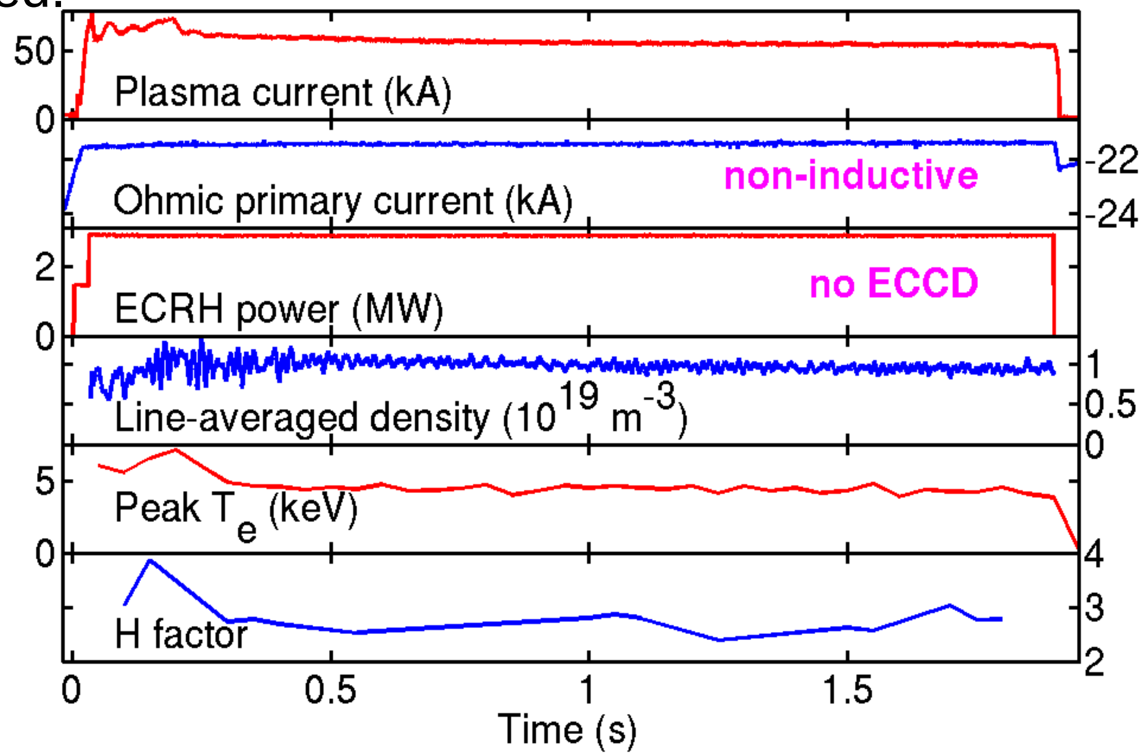




[Sauter, PRL 2005]

Steady-state 100% bootstrap current

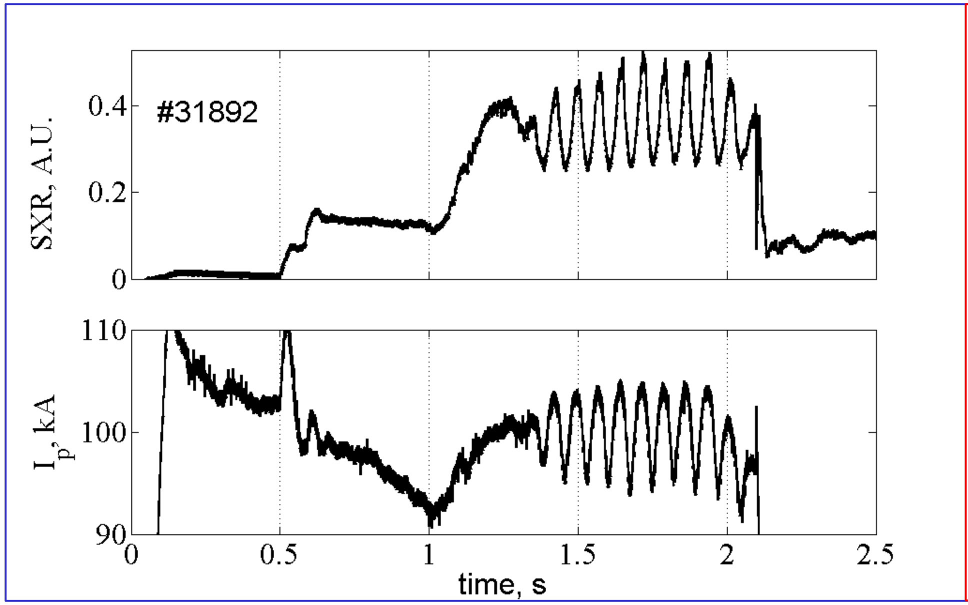
- eITB generates bootstrap current in high pressure gradient region. The bootstrap current profile must then itself generate the barrier.
  - Need for high-pressure gradient region and bootstrap current profile to be *precisely* and *stably* aligned.
- Experimental results
  - Heating during I_p ramp-up
  - Only EC Heating (perp. to B field)
  - Quiescent period lasting several current redistribution times (~0.2s)

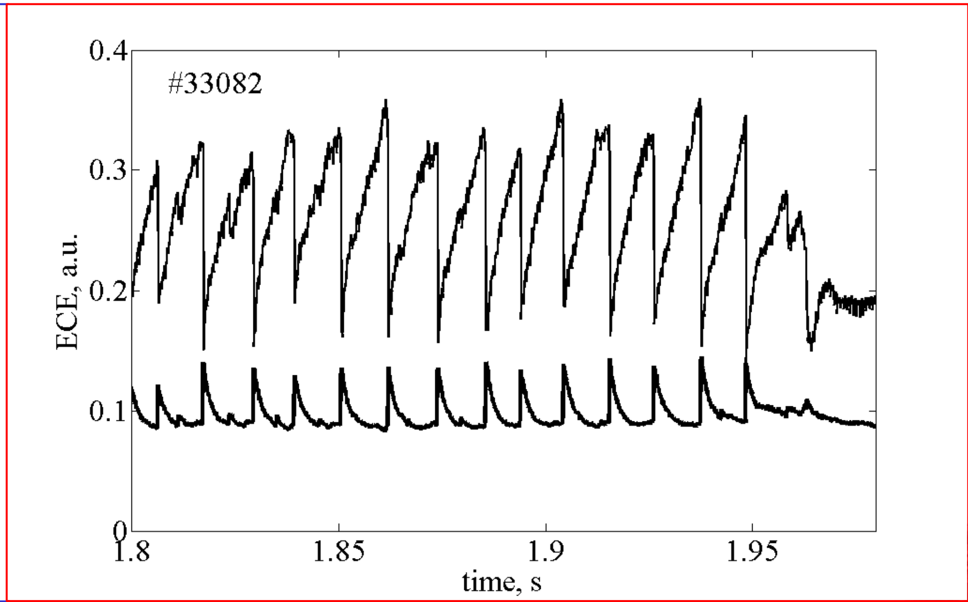


[S.Coda, IAEA2008]

Global oscillations during eITB plasmas

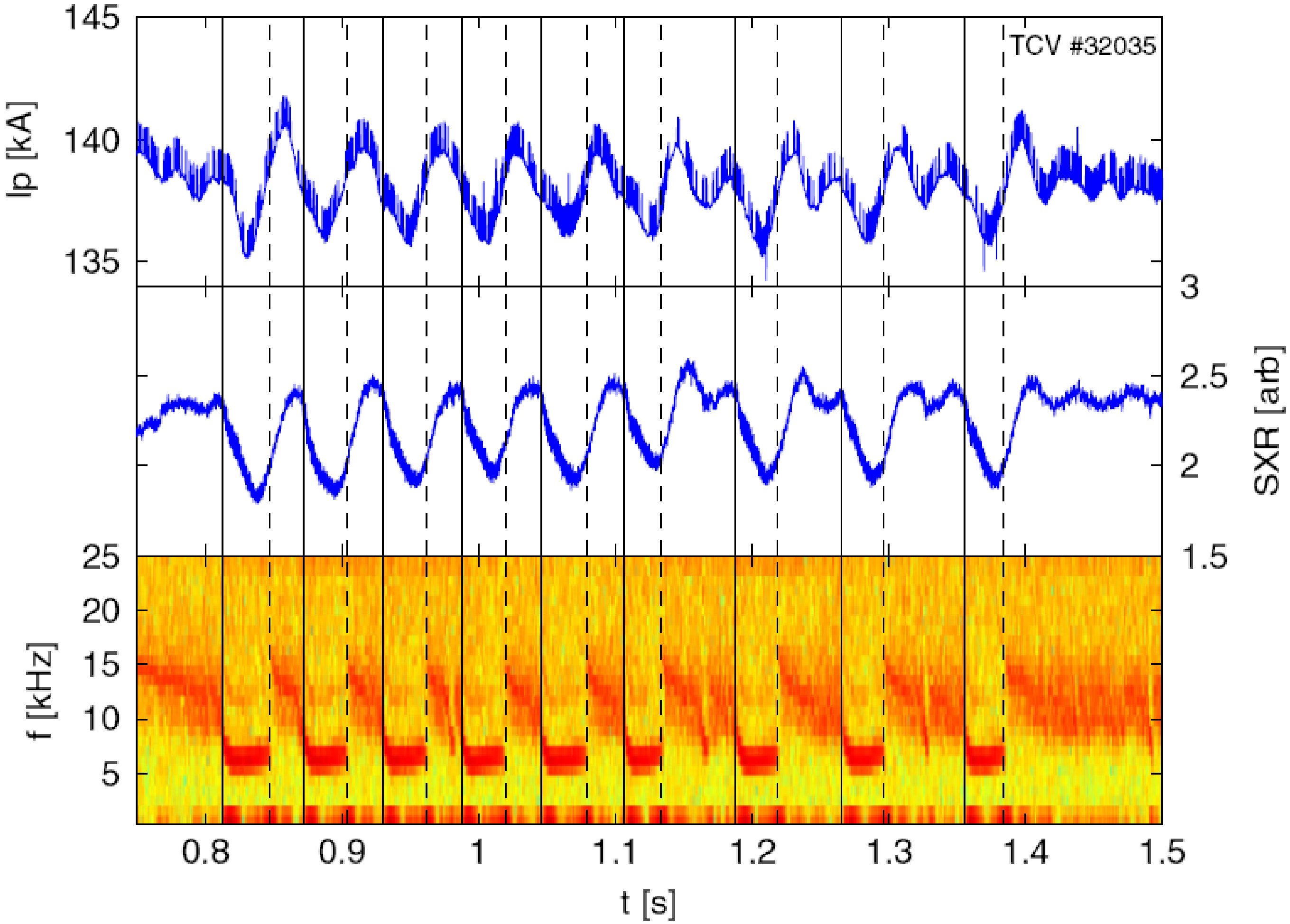
- Global oscillations of several plasma quantities (n, I_p, ...) have been observed on several Tokamaks [Giruzzi PRL2003, Hanada ICPP2004].
  - These oscillations are present when approaching the ideal limit *infernal modes* [Ozeki, 1993]. Inherent to high-performance eITB scenarios.
  - In TCV, these can be either sinusoidal (triggered by resistive MHD) or crash-like (triggered by ideal MHD). [G. Turri, PPCF2008, V. Udintsev, PPCF2008]





Physical origins of the oscillations

- Nonlinear coupling between barrier, current profile and MHD



(1)Barrier forms

(2)Mode is destabilized

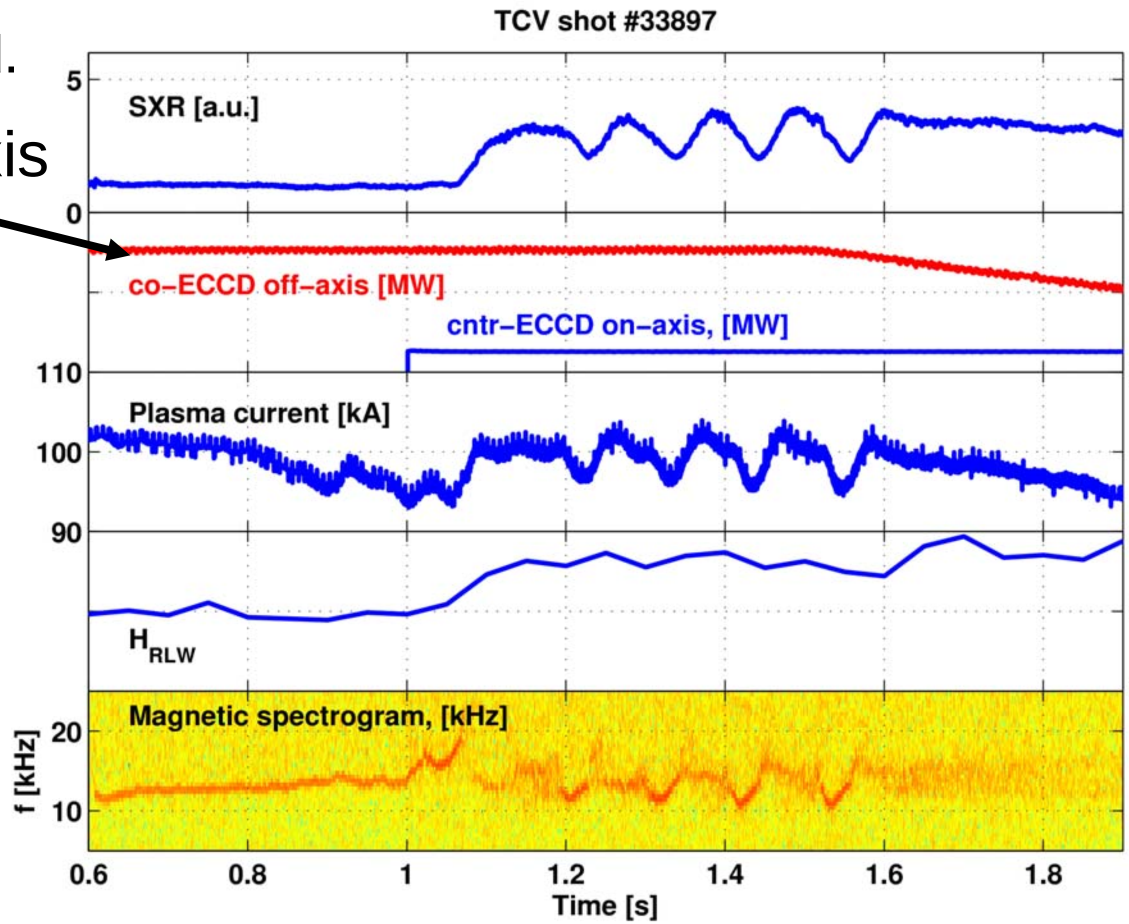
(3)Barrier degrades

(4)Mode disappears

[G. Turri, PPCF2008]

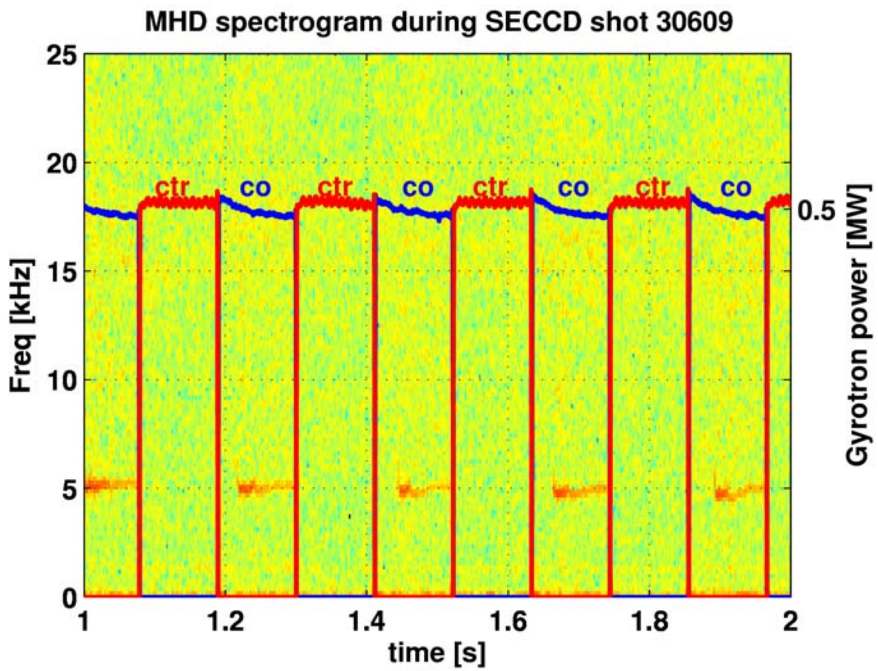
Current density perturbations - effects on the oscillatory regime

- Make current density profile less hollow
  - Move away from ideal MHD limit
  - Barrier strength reduces but oscillations are suppressed.
- Experiment: reduce off-axis co-ECCD
  - current profile becomes less hollow,
  - oscillations stop
  - barrier remains



Tearing modes during current profile modulation

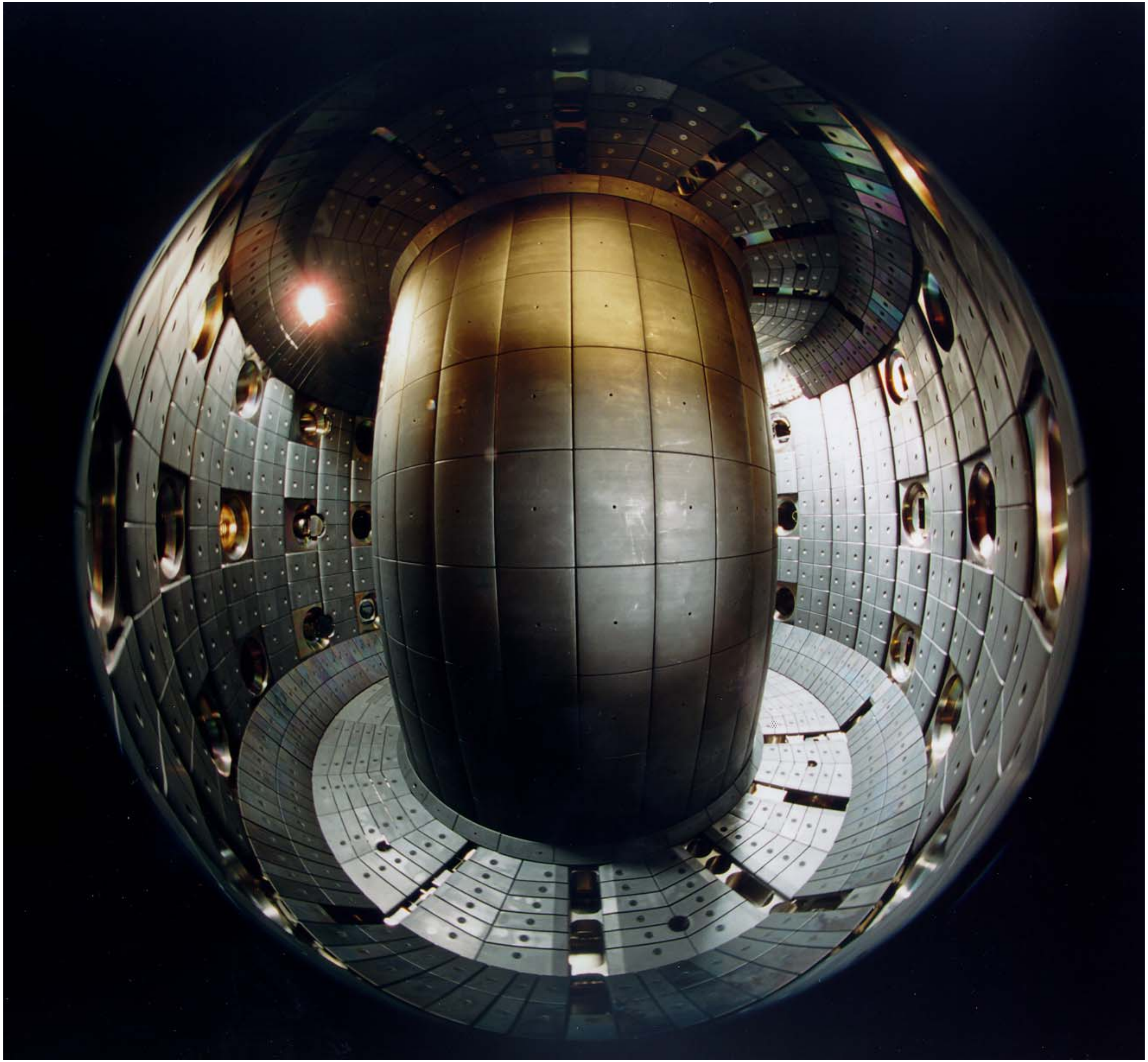
- Current profile modulation experiments [Cirant NF2006]
  - Experimental set up
    - One set of gyrotrons aimed for off-axis co-current drive
    - Another set of gyrotrons aimed for off-axis counter current drive
    - Switch gyrotron powers repeatedly
  - Tearing modes are regularly destabilized by current profile changes.
    - Classical destabilization: $\Delta'>0$.
      [Pletzer POP1999]
  - Goals
    - demonstrate precise control
      of j profile, important for adv. scenarios
    - Aid predictions of NTM stability limits
      for ITER.
  - This will be studied in detail during the coming campaign



Summary & Conclusions

- Recent TCV experiments with ECRH/ECCD
  - Real-time control
    - Demonstration of feedback control of sawtooth period by local EC deposition using non-linear controller.
    - Demonstrate of peak-in-profile control by changing EC deposition location.
  - Scenarios with internal electron transport barriers
    - Steady-state sustainment using off-axis ECCD.
    - 100% bootstrap current in steady-state achieved, no external current drive.
    - Global oscillations, inherent to high performance steady-state scenarios
      - Caused by proximity to the infernal mode limit, interplay between barrier and MHD.
      - Stabilization by current profile perturbations rendering profile less hollow.
  - Localized ECCD deposition effects on tearing stability, aiming at precise control of j profile and NTM stability predictions for ITER.

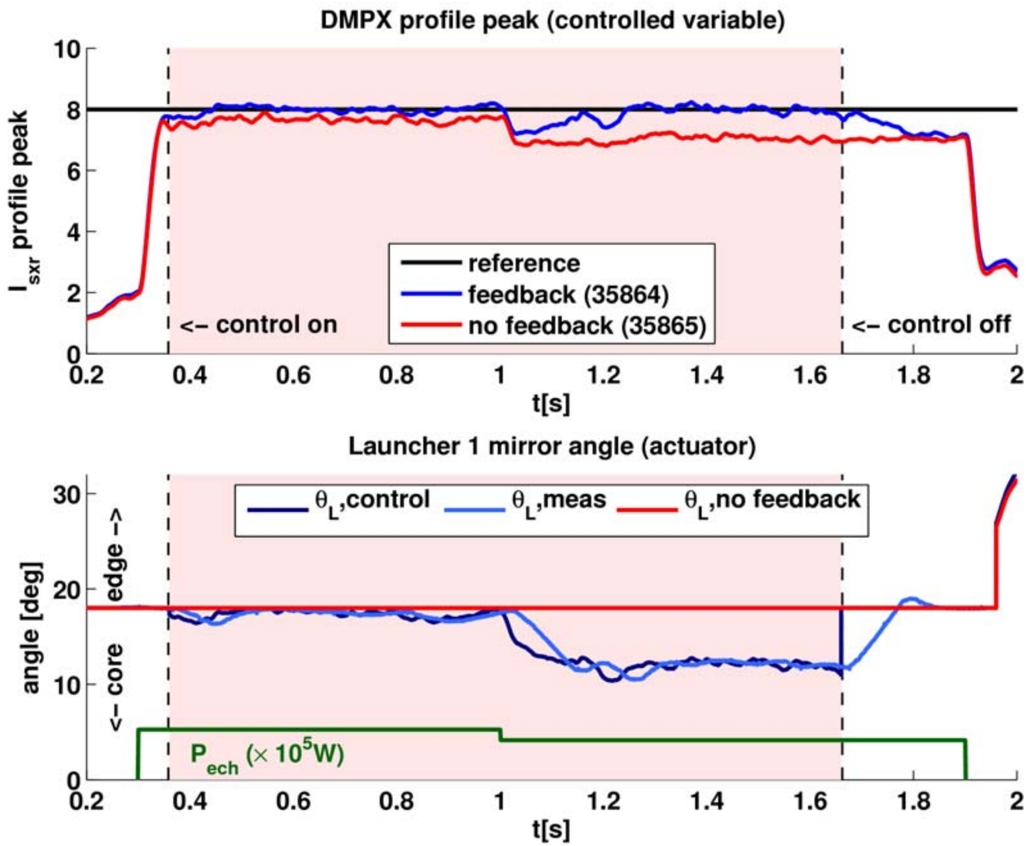
CRPP



Reserve slides

Peak-in-profile control (2)

- Gyrotron power decrease during the shot
- Shot with feedback control recovers maximum by moving deposition off-axis
- Shot with no feedback does not recover.



Stabilization of the oscillatory regime

- Example 2: Apply co-current ohmic perturbation
  - Negligible increase in injected power
  - The perturbation will be peaked on-axis due to better conductivity.
  - current profile becomes less hollow
  - oscillations stop
  - barrier is maintained