Snowflake Divertor Experiments on TCV

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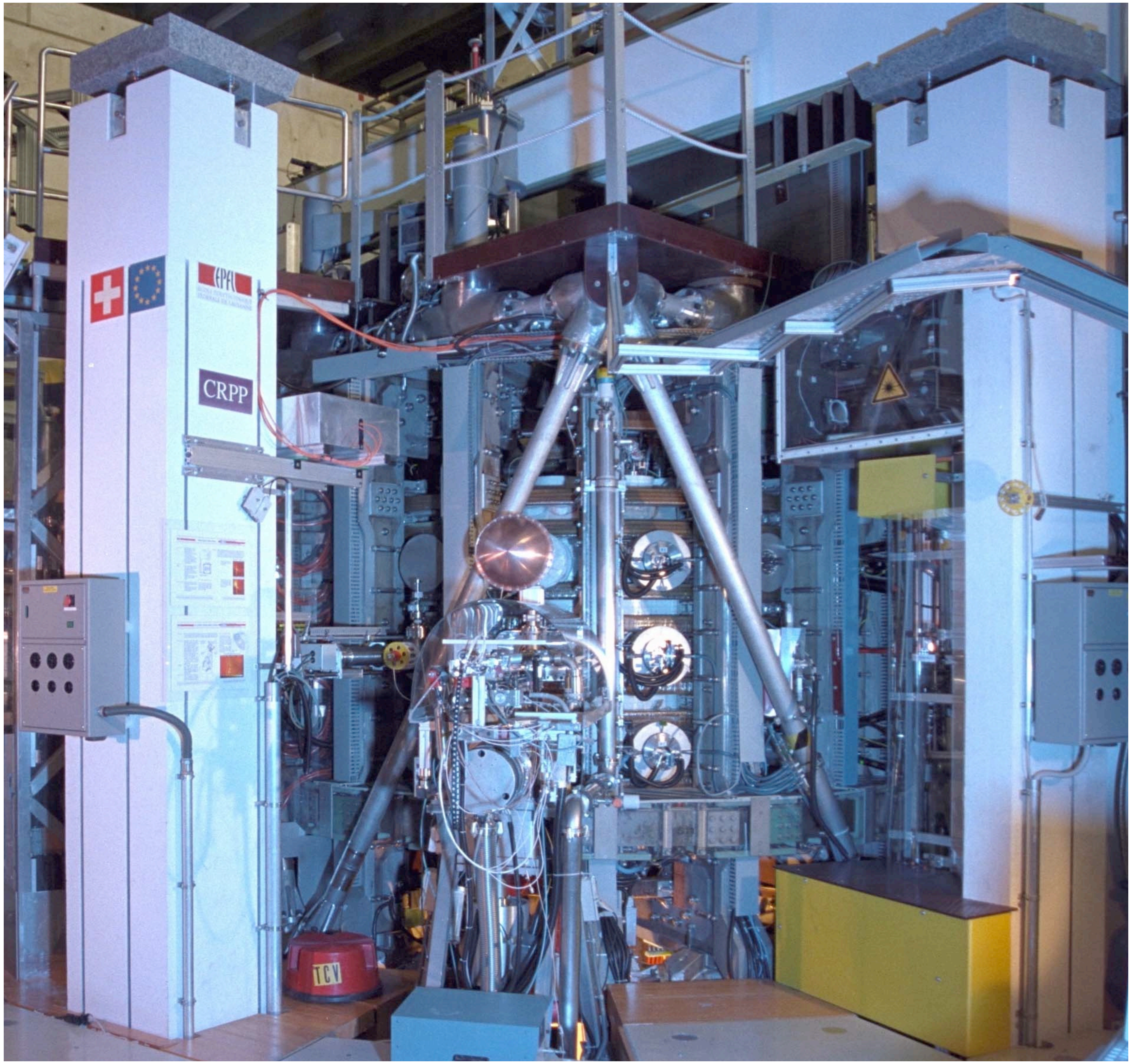
Outline of the Talk

- The TCV Tokamak
- Magnetic in-situ Calibration
- Ohmic and Assisted Plasma Start-up
- Doublet Shaped Plasmas
- Snowflake Divertor
  - Snowflake divertor on TCV
  - Magnetic properties of the TCV snowflake
  - Snowflake divertor in the H-mode regime

The TCV Tokamak

TCV - Tokamak à Configuration Variable

Mission

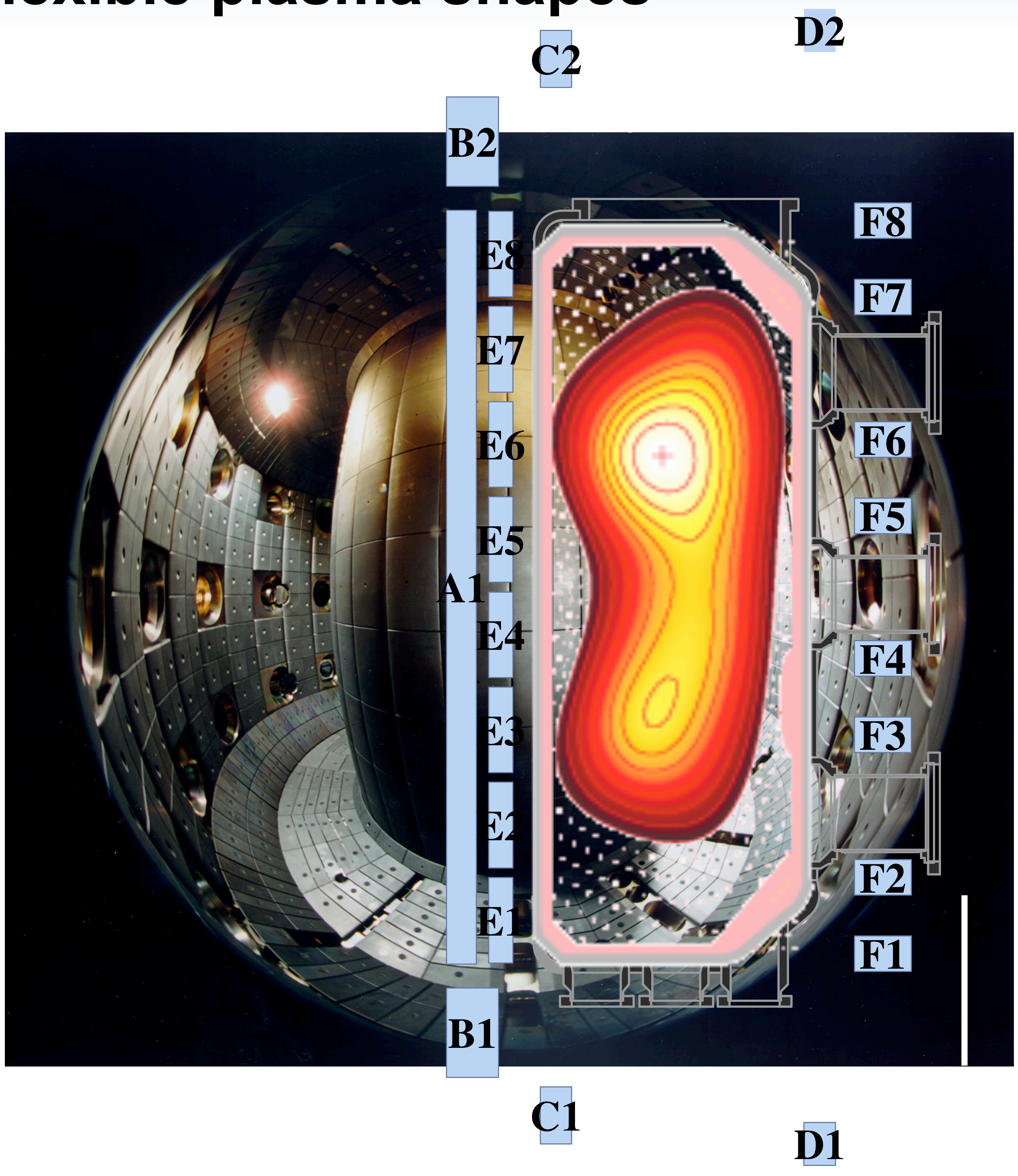


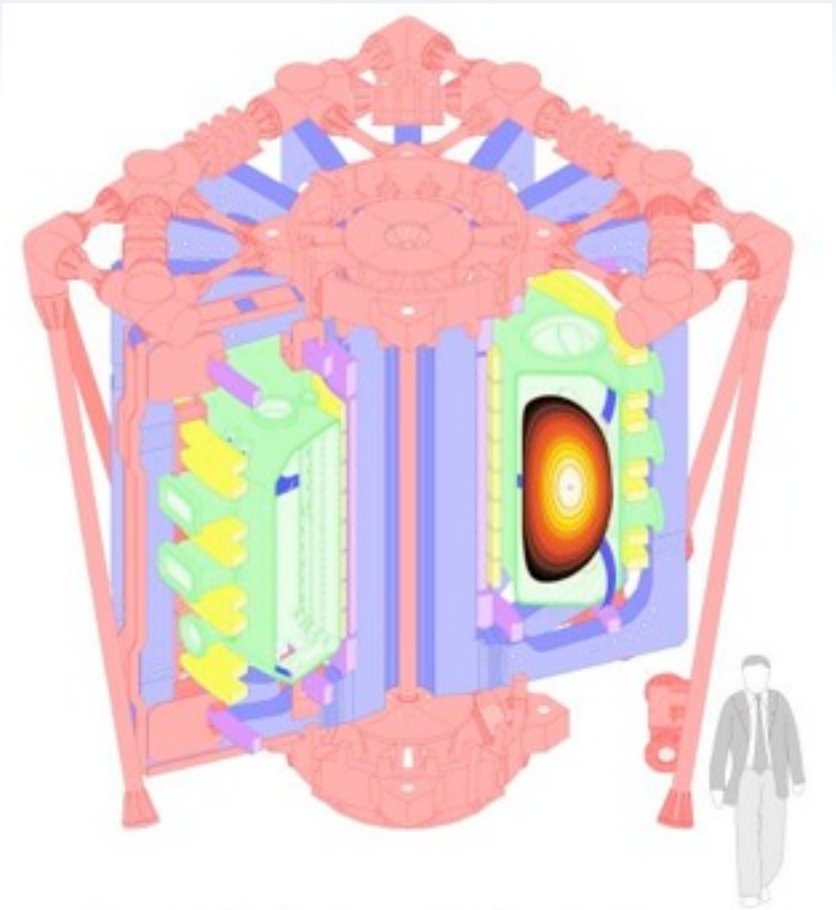
Contribute to physics basis for

- ITER scenarios
- DEMO design
- Tokamak concept improvement

Unique TCV Features

Flexible plasma shapes

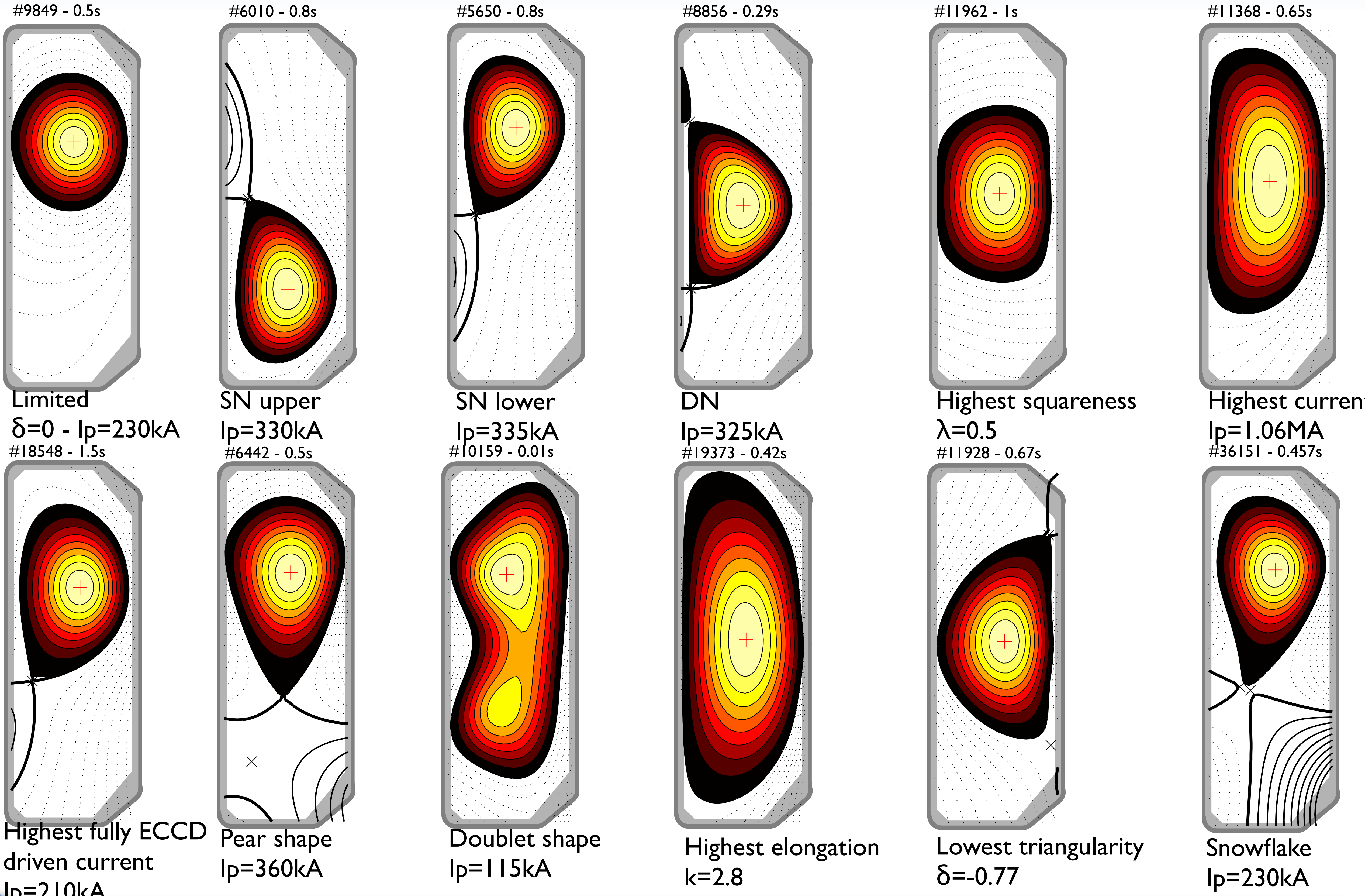




- **TCV Parameters**
  - R = 0.88m; a = 0.25m
  - $B_T \leq 1.5T$; $I_P \leq 1.2MA$
  - $0.9 \leq$ elongation $\kappa \leq 2.8$
  - $-0.8 \leq$ triangularity $\delta \leq 0.9$
  - Internal fast n=0 coils (as in ITER)

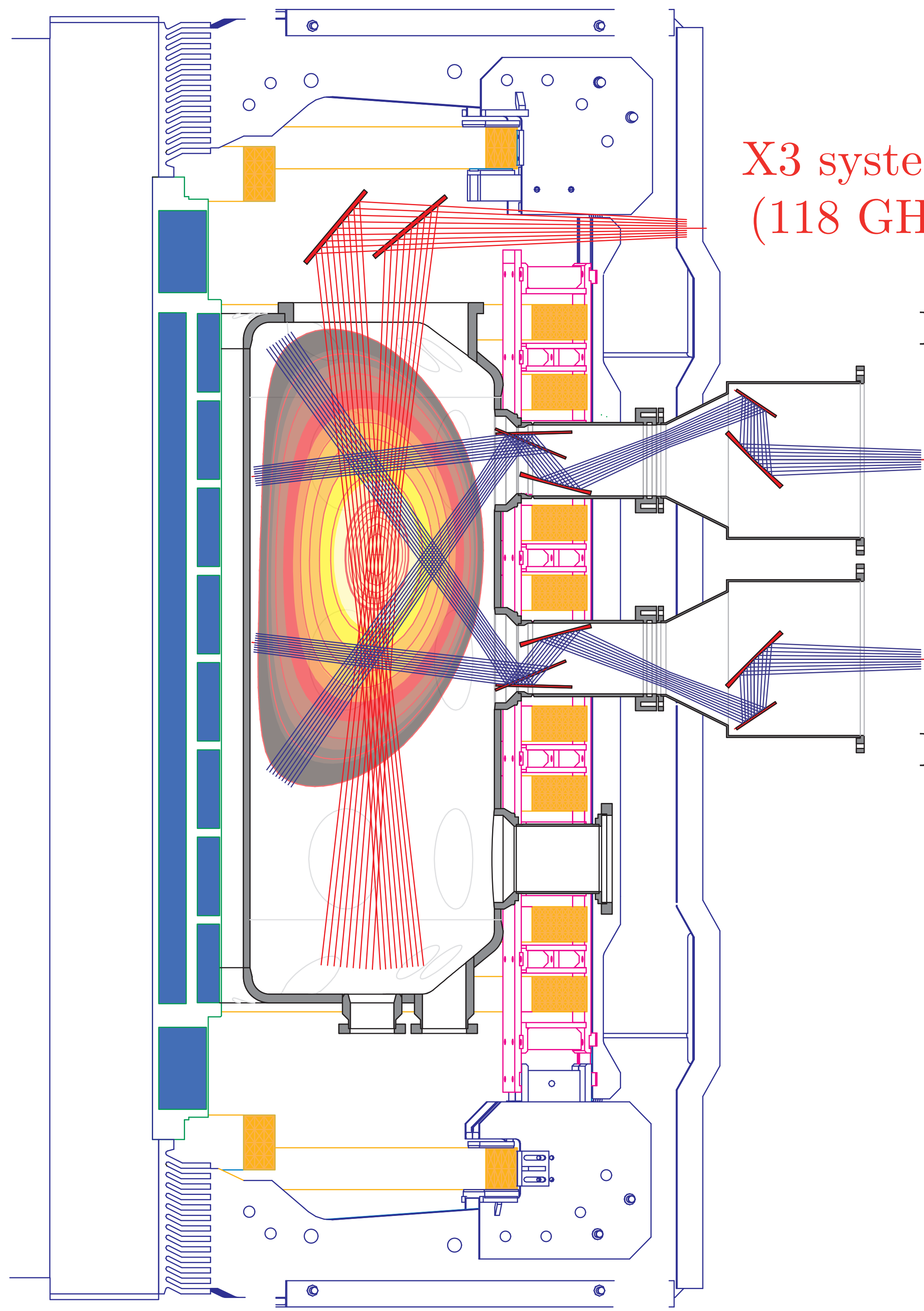
Unique TCV Features

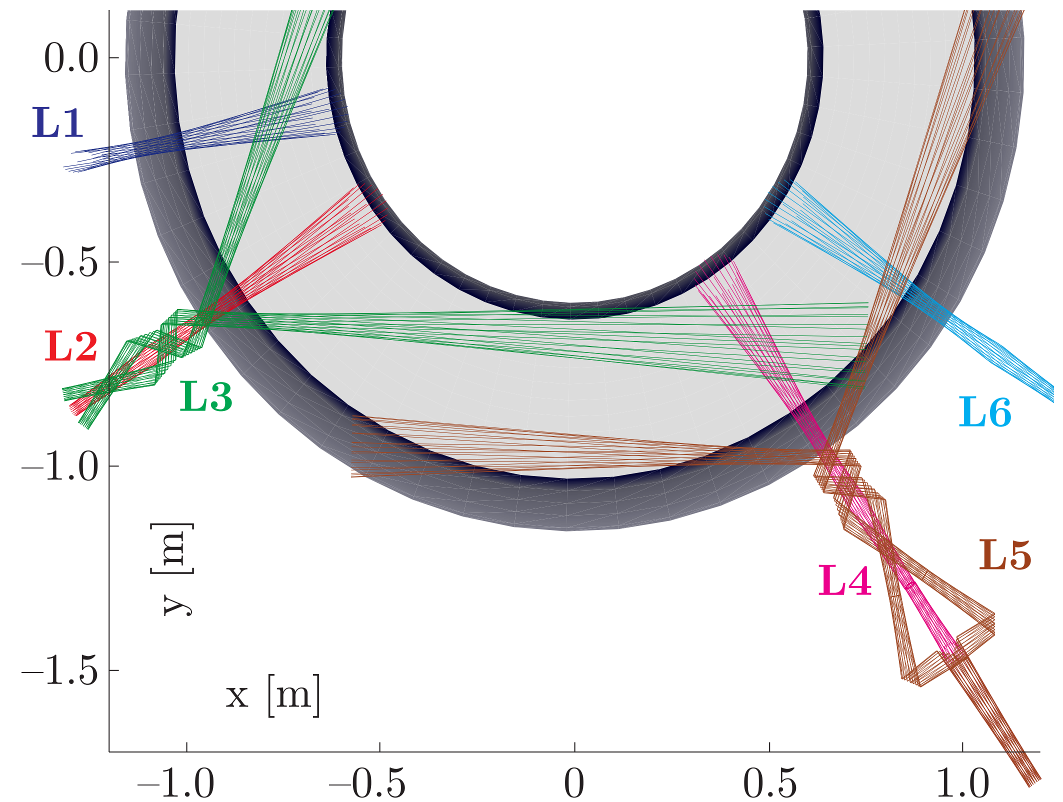
Flexible plasma shapes



Unique TCV Features

Electron Cyclotron Systems





- **2nd harmonic X2 (82.7GHz)**
  6 × 0.5MW - 2s
  Side launch ECH, ECCD
  $n_{cut\text{-}off} = 4\times10^{19} m^{-3}$
- **3rd harmonic X3 (118GHz)**
  3 × 0.5MW - 2s
  Top launch ECH
  $n_{cut\text{-}off} \approx 10^{20} m^{-3}$

Magnetics in-situ Calibration

Magnetics in-situ Calibration

Motivation

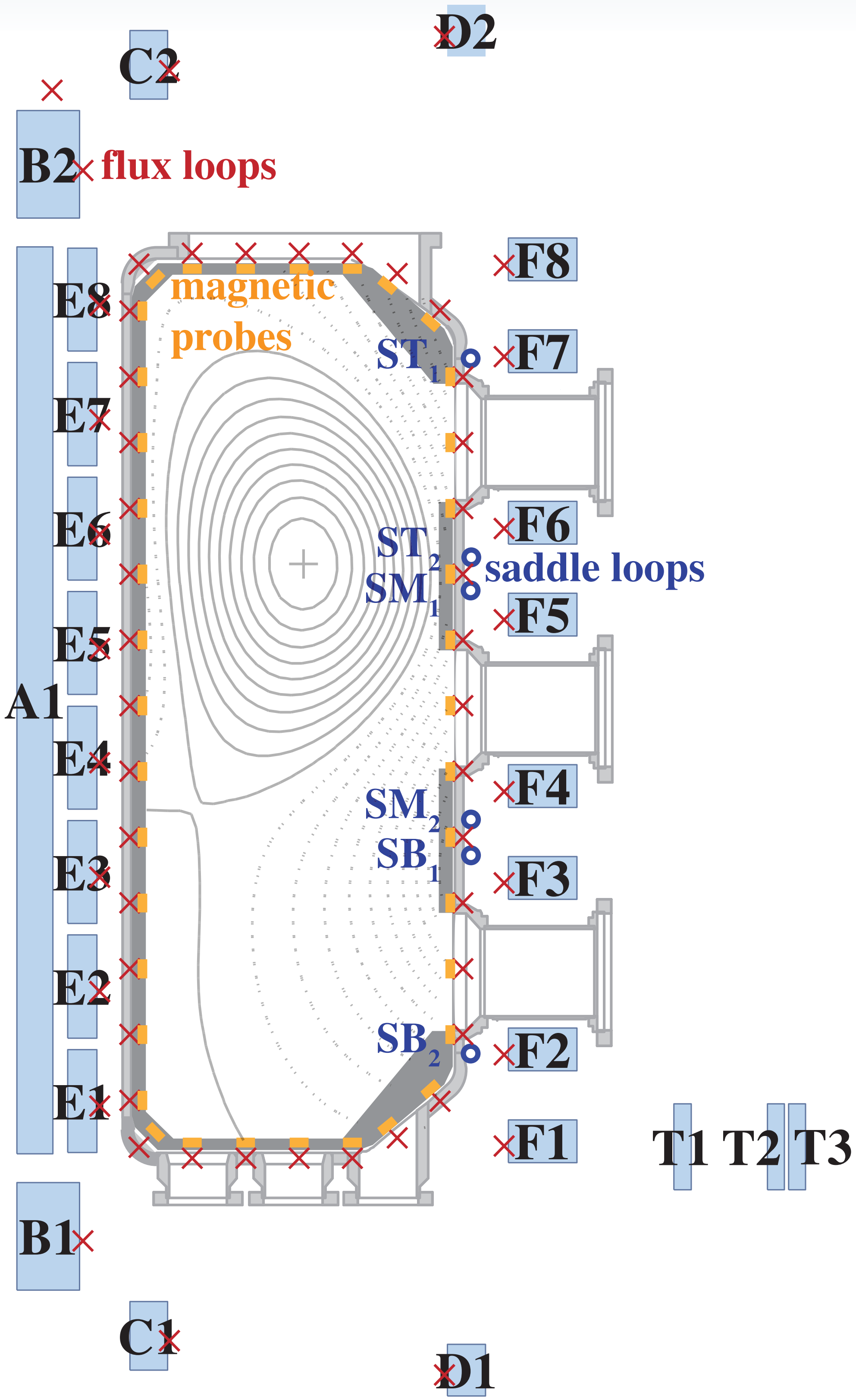
- Axisymmetric errors (n = 0):
  - Plasma shape deformation
  - Wrong plasma position/strike points location
  - Caused by:
    - -Errors in the radius and vertical position of the PF coils
    - -Errors in the measured PF coil currents

- Asymmetric errors (n > 0):
  - Creation of magnetic islands
  - Locked modes
  - Caused by:
    - -Misalignment/deformation of the PF coils

Goal of the calibration

- Find the real positions and gains of the TCV magnetic system

The TCV Magnetic System



- 16 PF Coils (E and F)
- 7 ohmic coils (A, B, C and D)
- 3 toroidal field connections (T)
- 4 x 38 magnetic field probes
- 61 flux loops
- 24 saddle loops

The Calibration Technique

- Each coil is separately powered
- All magnetic signals are acquired and compared to expected values

$$\begin{aligned}
\boldsymbol{\Delta\Psi}_f &= \boldsymbol{\Psi}_f - \underline{\underline{\mathbf{M}}}_{fc}\mathbf{I_c} \\
\boldsymbol{\Delta}\mathbf{b}_m &= \mathbf{b}_m - \underline{\underline{\mathbf{B}}}_{mc}\mathbf{I_c} \\
\boldsymbol{\Delta\Psi}_s &= \boldsymbol{\Psi}_s - \underline{\underline{\mathbf{M}}}_{sc}\mathbf{I_c}
\end{aligned}$$

- The discrepancies are associated to calibration errors (660 parameters)

- The correction parameters are determined by minimizing a cost function

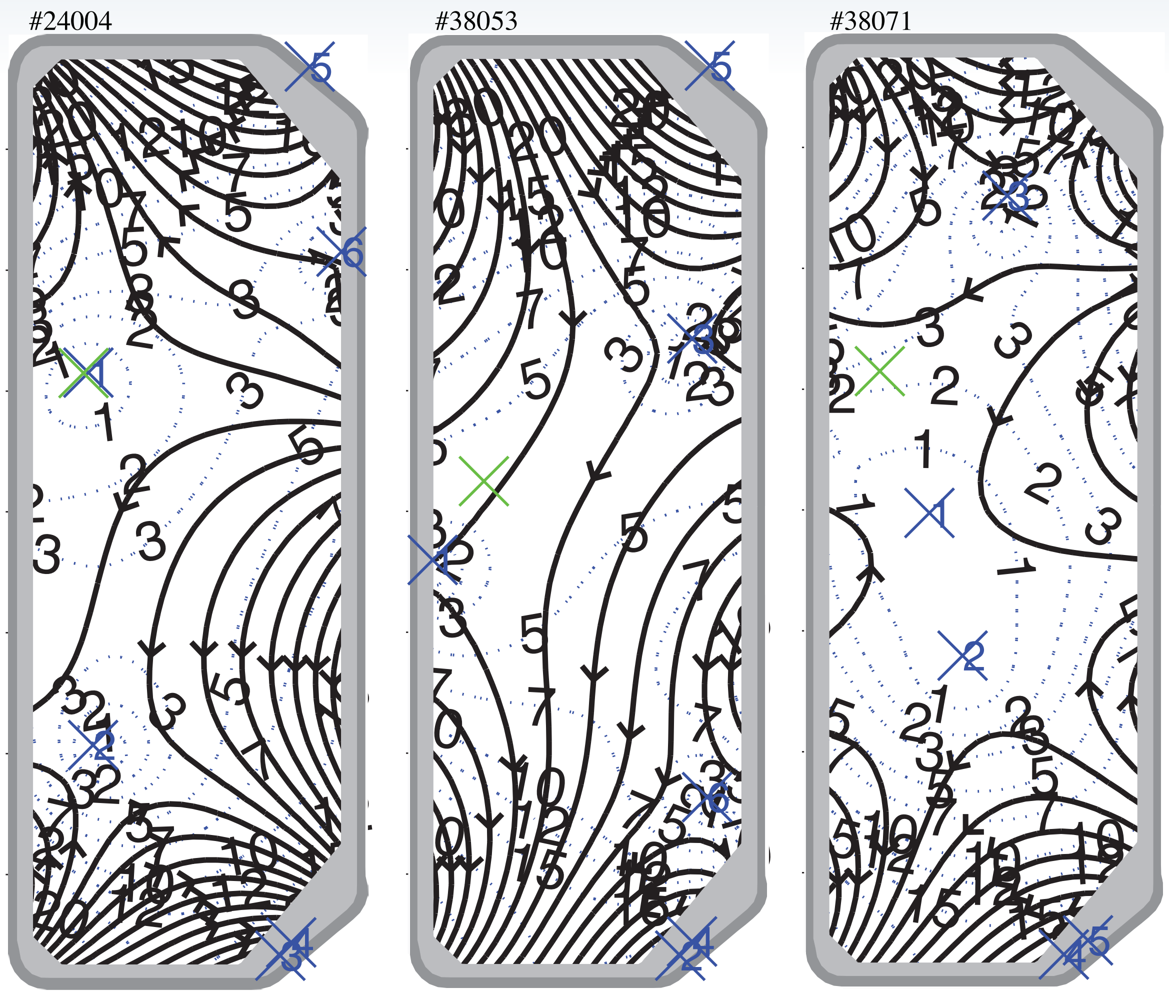
- The error on the PF coils position is of the order of ~1 mm
- The error on the n = 0 poloidal field is ~1 mT
- The n = 1 error field is of ~0.1 mT

F.Piras, Fusion Eng. Des. 2010

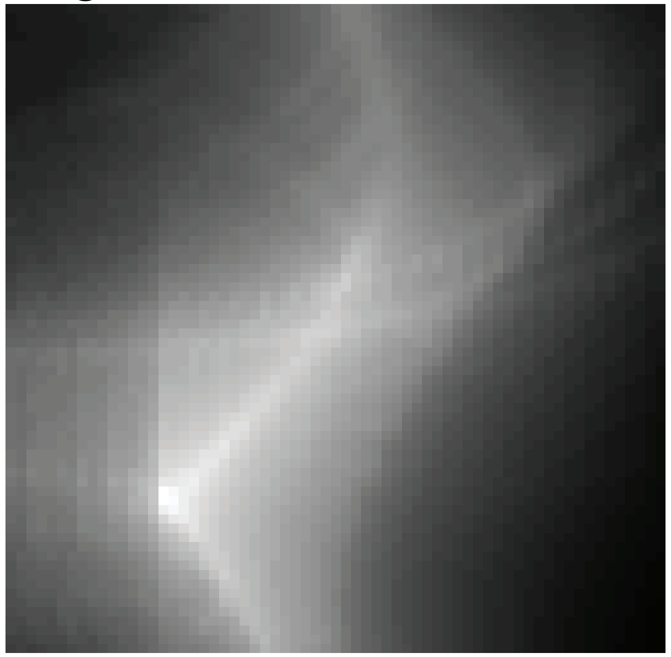
Ohmic and Assisted Plasma Start-up

Ohmic Plasma Start-up

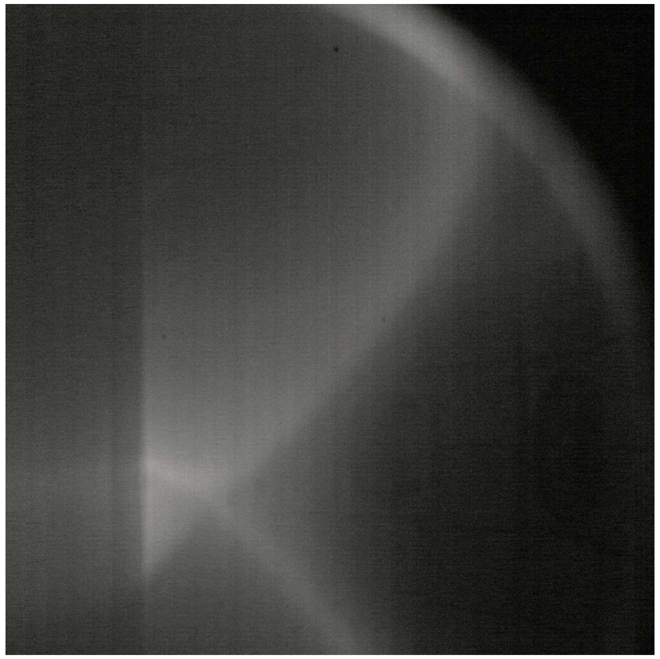
- Start-up magnetic field reconstruction
- Plasma evolution during early ramp-up phase
- Statistical analysis of breakdown
- Modeling of the ohmic start-up



mag. rec.



camera

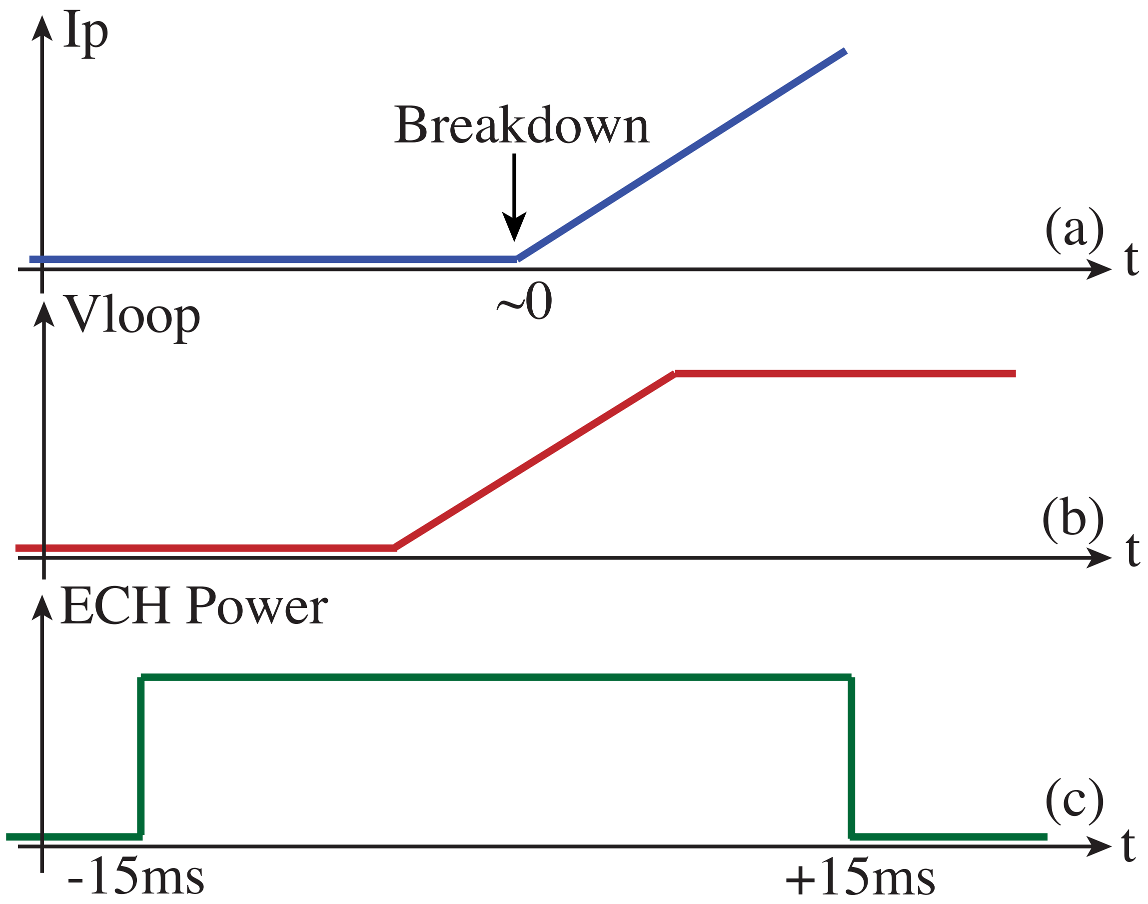


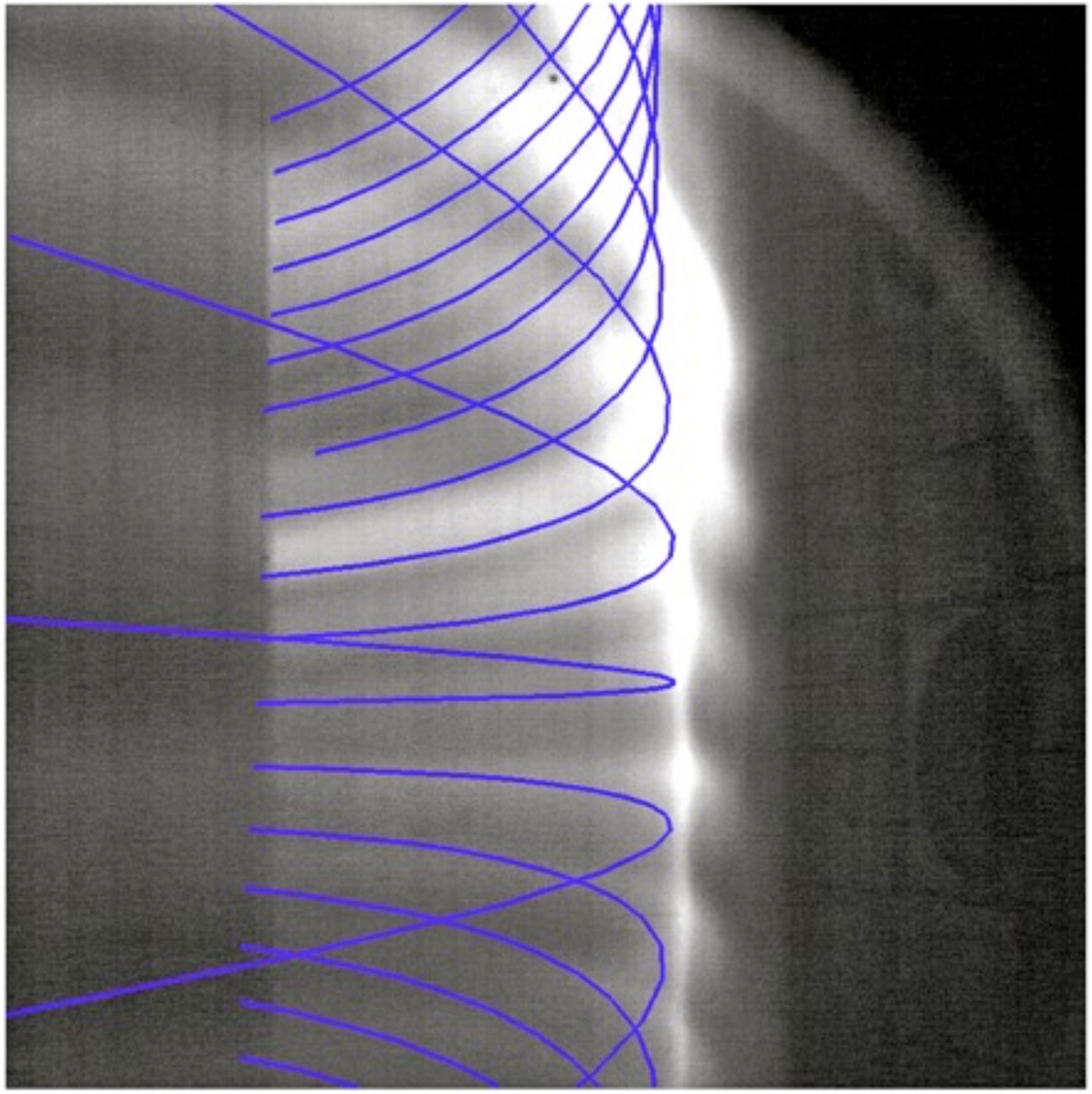
$$P_{i,j} = \int 1(R_{i,j}(t), Z_{i,j}(t))\, \mathrm{d}t$$

F.Piras, to be published

Assisted ECH-X2 Plasma Start-up

- Assisted plasma start-up scenario





- Power injected from the LFS (central port)

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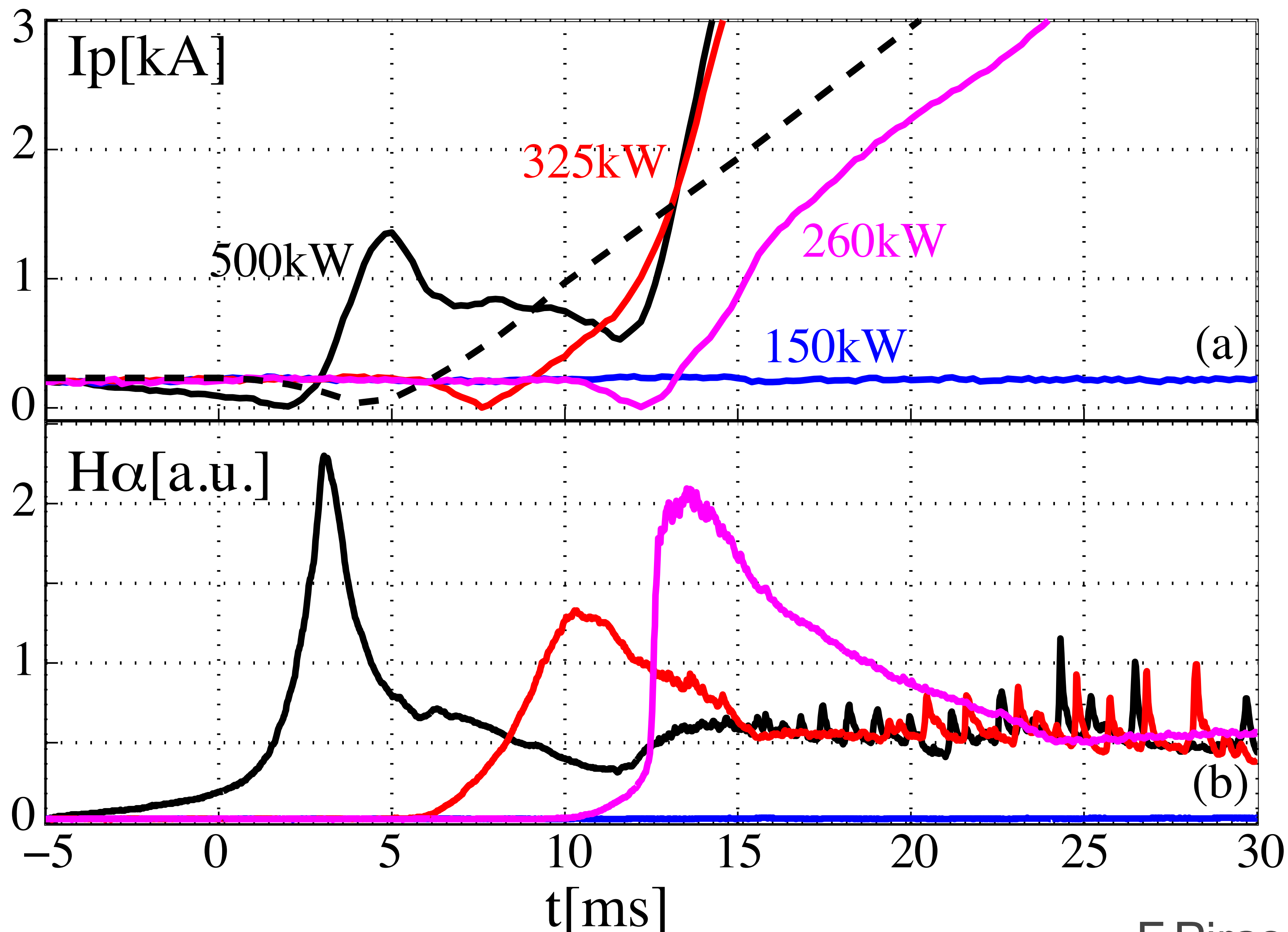
Assisted ECH-X2 Plasma Start-up

Scan of the main ECH parameters

- ECH power scan (better high power)



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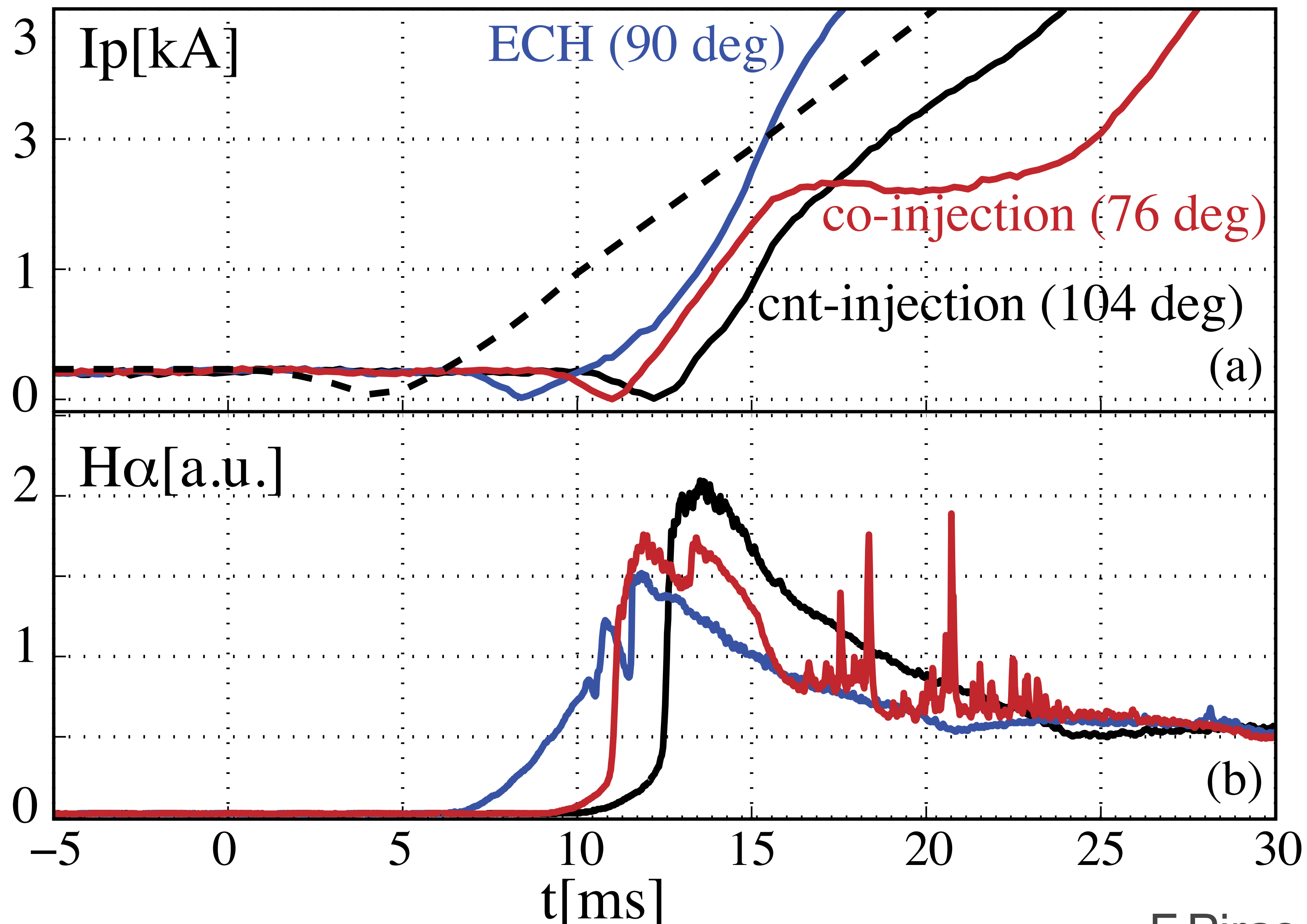
Assisted ECH-X2 Plasma Start-up

Scan of the main ECH parameters

- ECH toroidal angle scan (best 90 deg)



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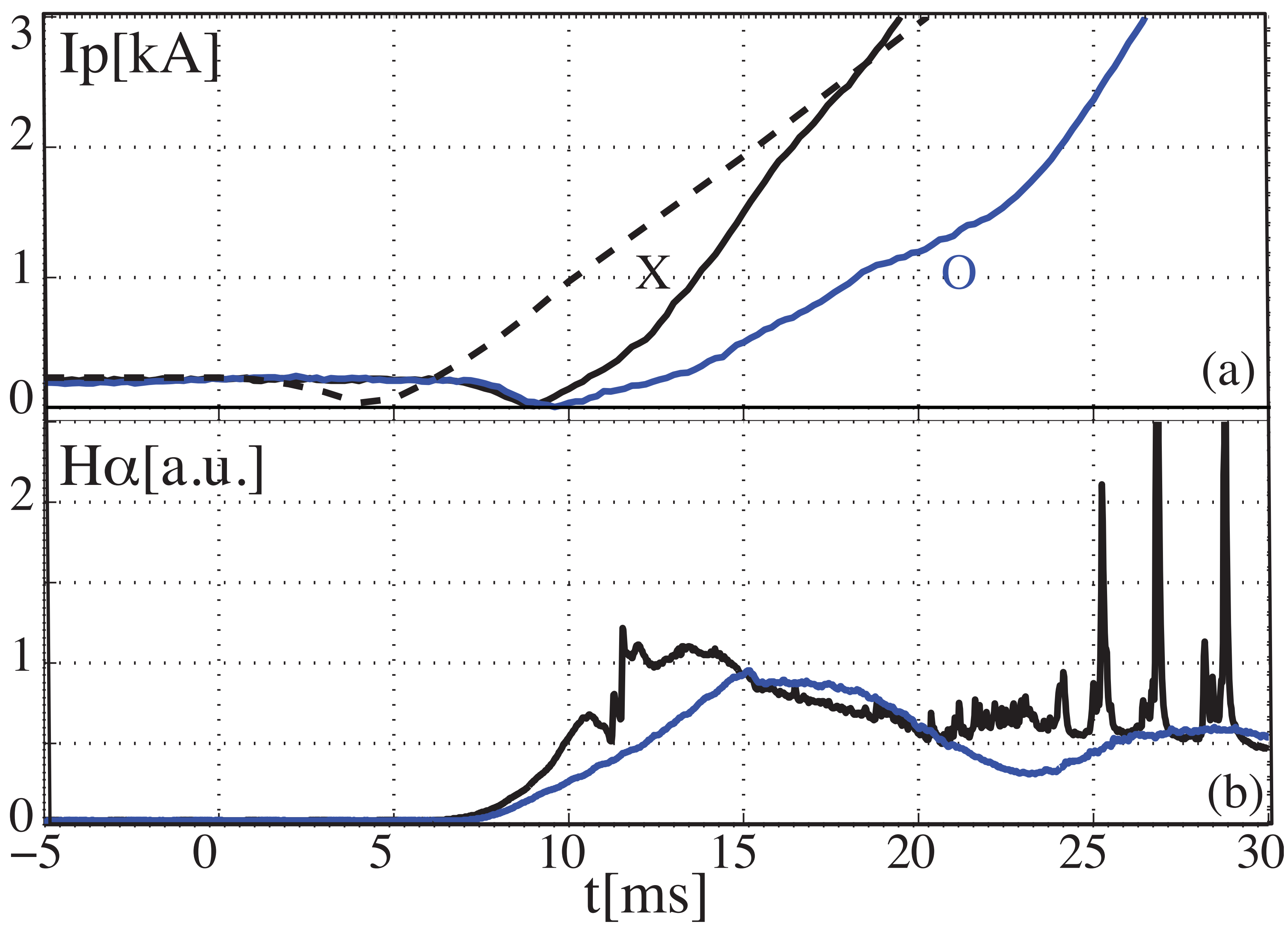
Assisted ECH-X2 Plasma Start-up

Scan of the main ECH parameters

- ECH polarization scan (better X pol.)



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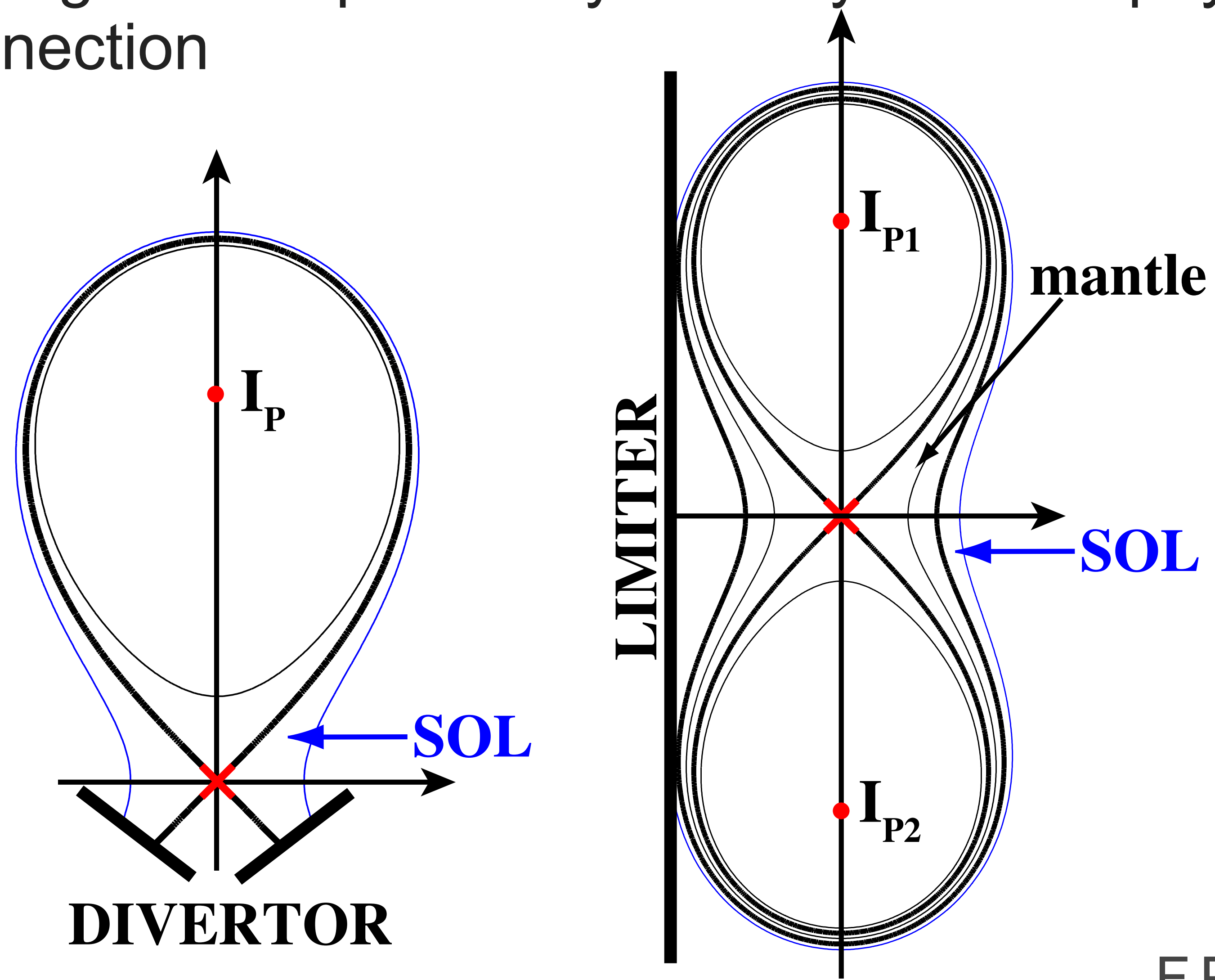
Doublet Shaped Plasmas

Doublet Shaped Plasma Concept

Why doublets

- Intrinsic zone of negative magnetic shear
- Lower vertical instability growth rate
- Possible advantages related to radioactive mantle
- Net current present at the plasma pedestal

- Doublet plasmas gives the possibility to study H-mode physics and magnetic reconnection



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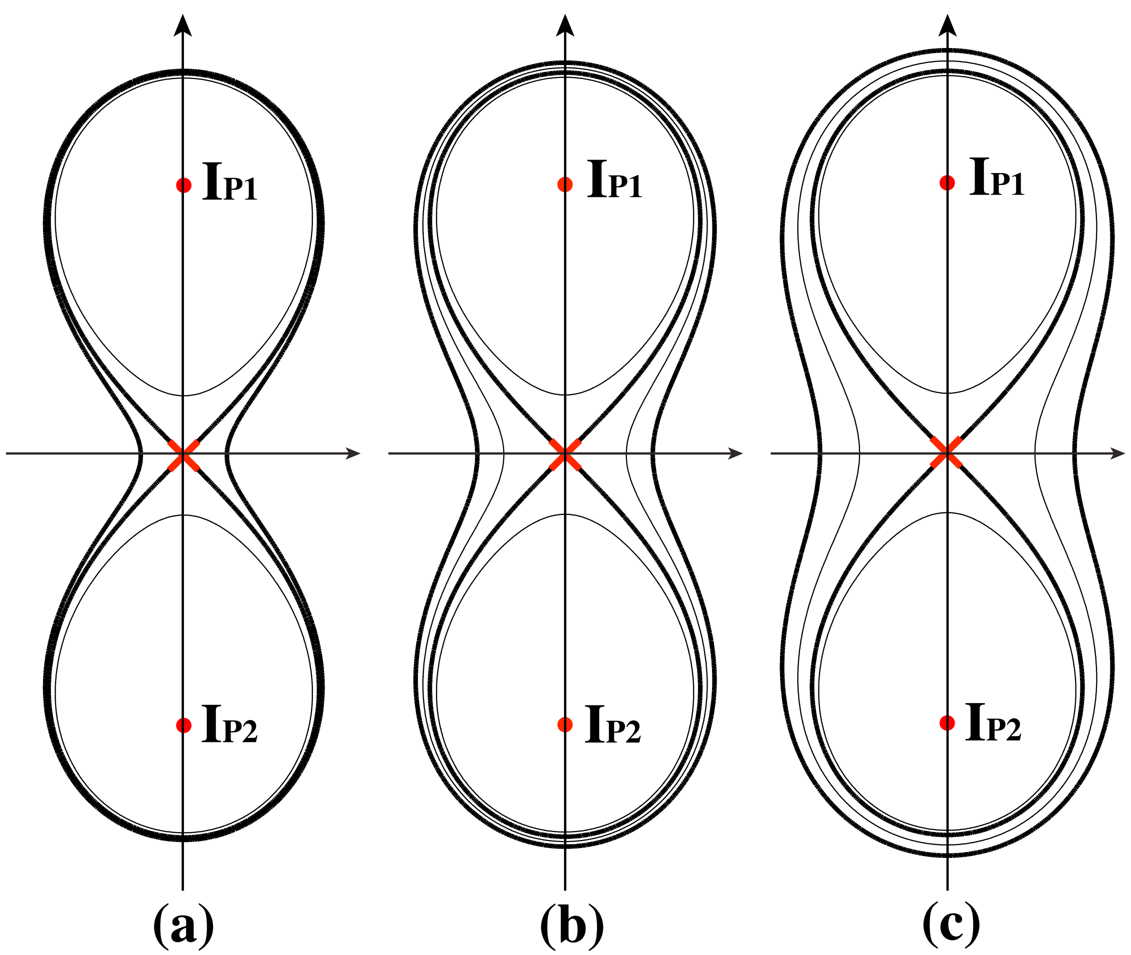
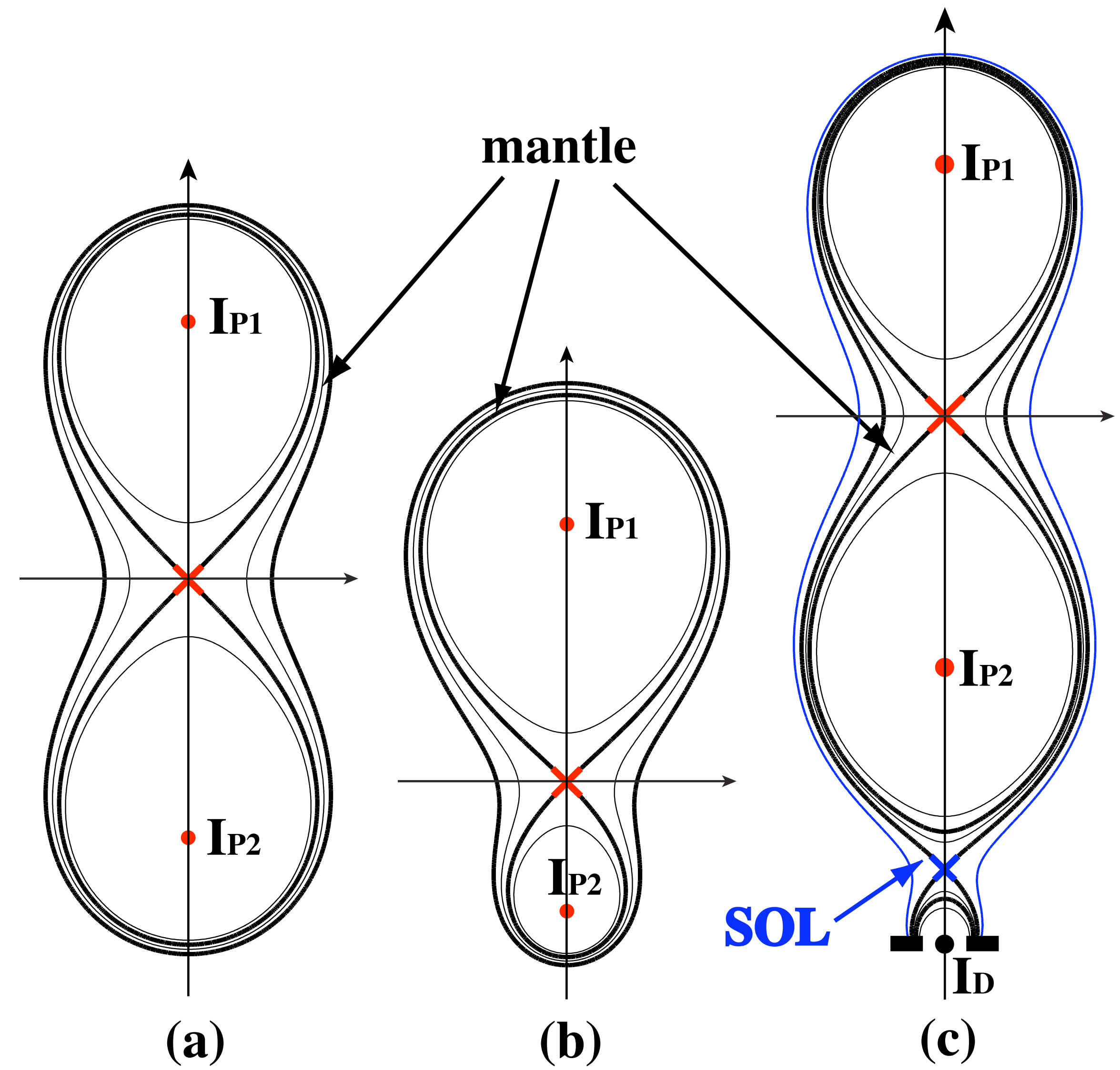
Possible Doublet Configurations

Changing the mantle thickness, symmetry and edge properties





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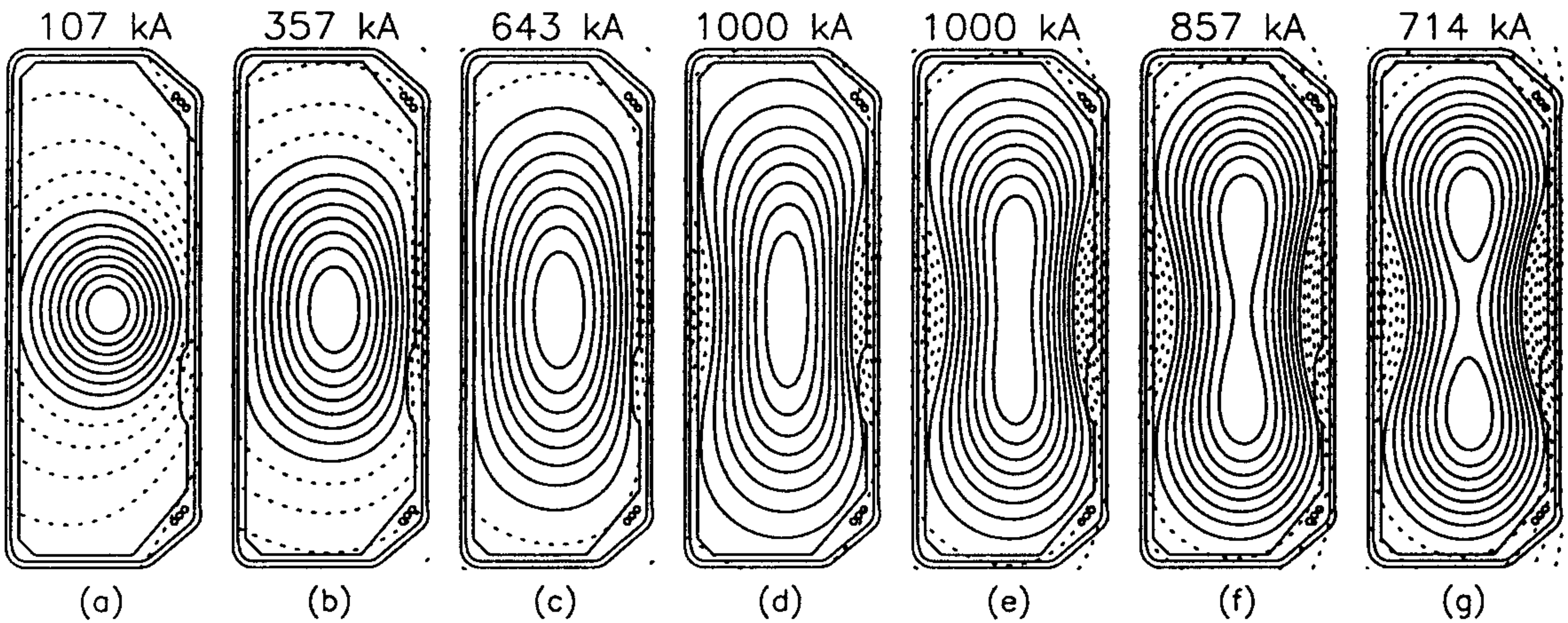
Doublet Shaped Plasma Scenario

- Lateral constriction of highly elongated plasma



- Predicted maximum growth rate beyond ideal stability limit

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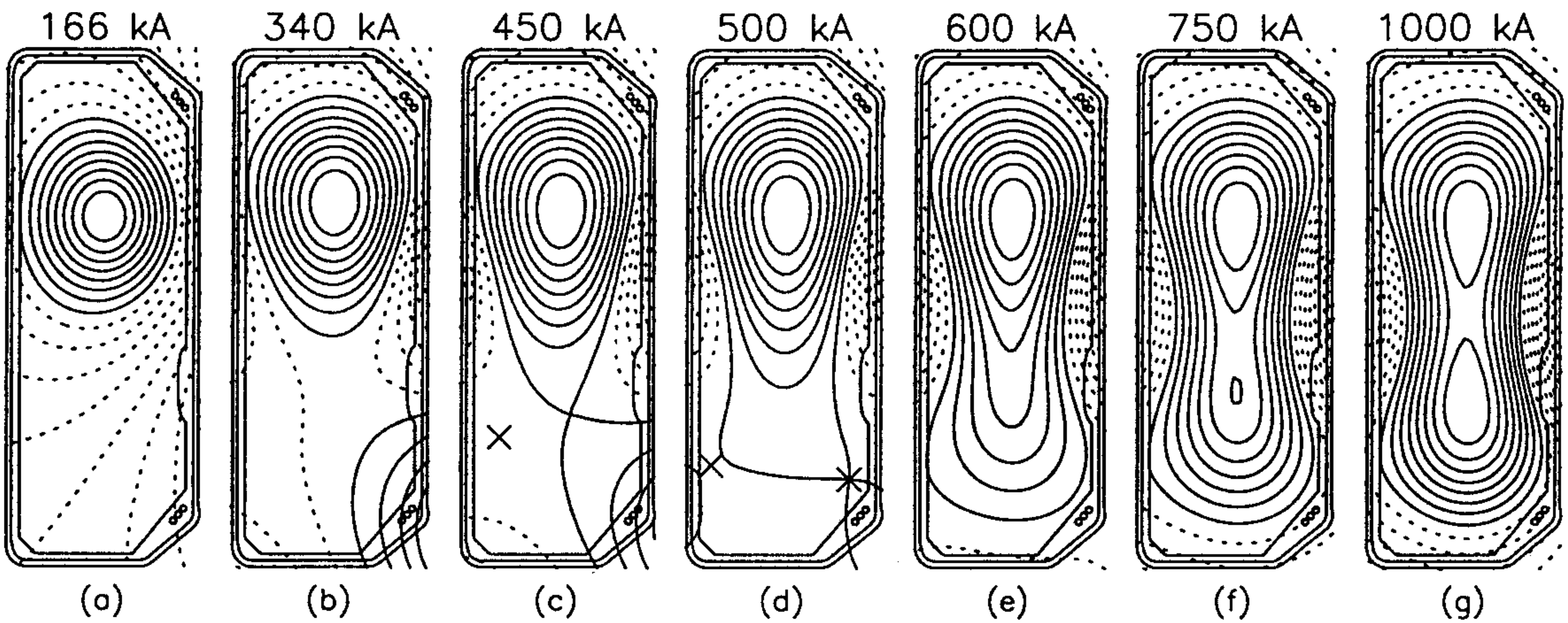
Doublet Shaped Plasma Scenario

- Hour-glass scenario



- For peaked profiles the highly asymmetric doublets (e) does not exist
- Low MHD stability

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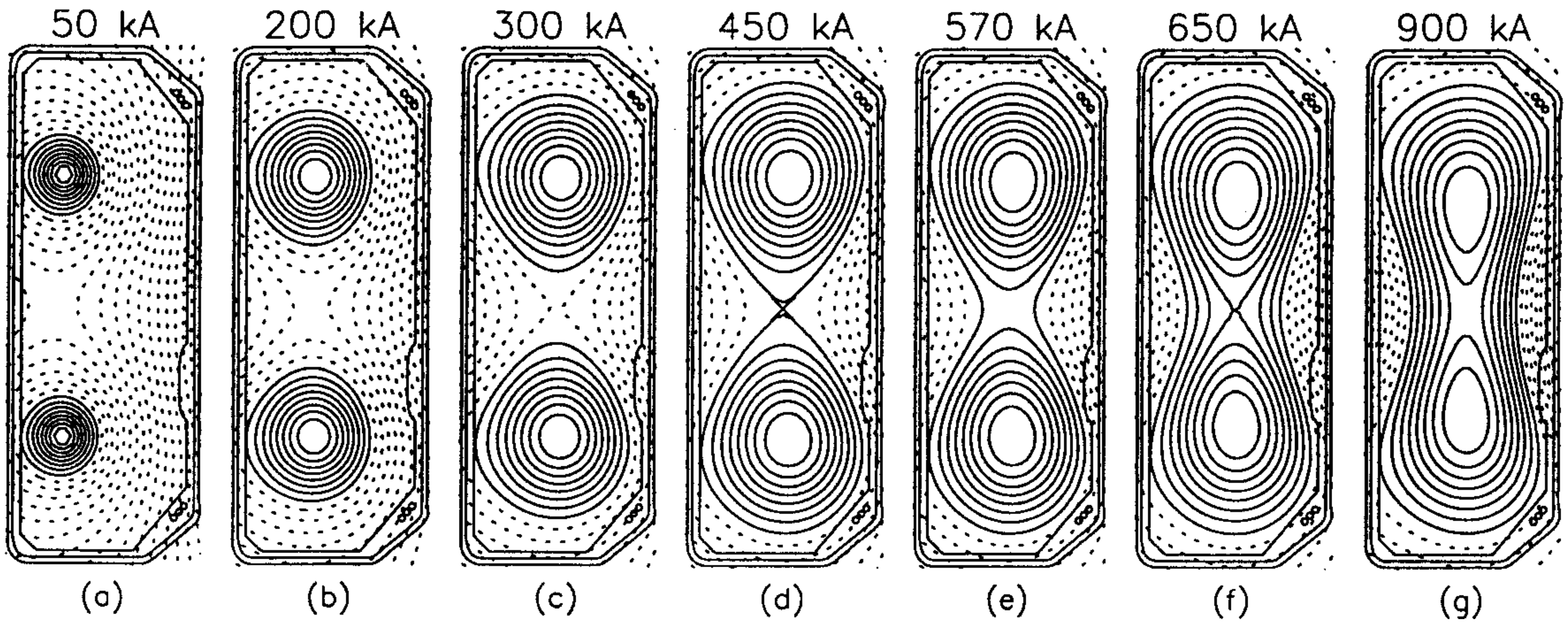
Doublet Shaped Plasma Scenario

- Merging of two droplet-shaped plasmas



- The two breakdowns have to be simultaneous

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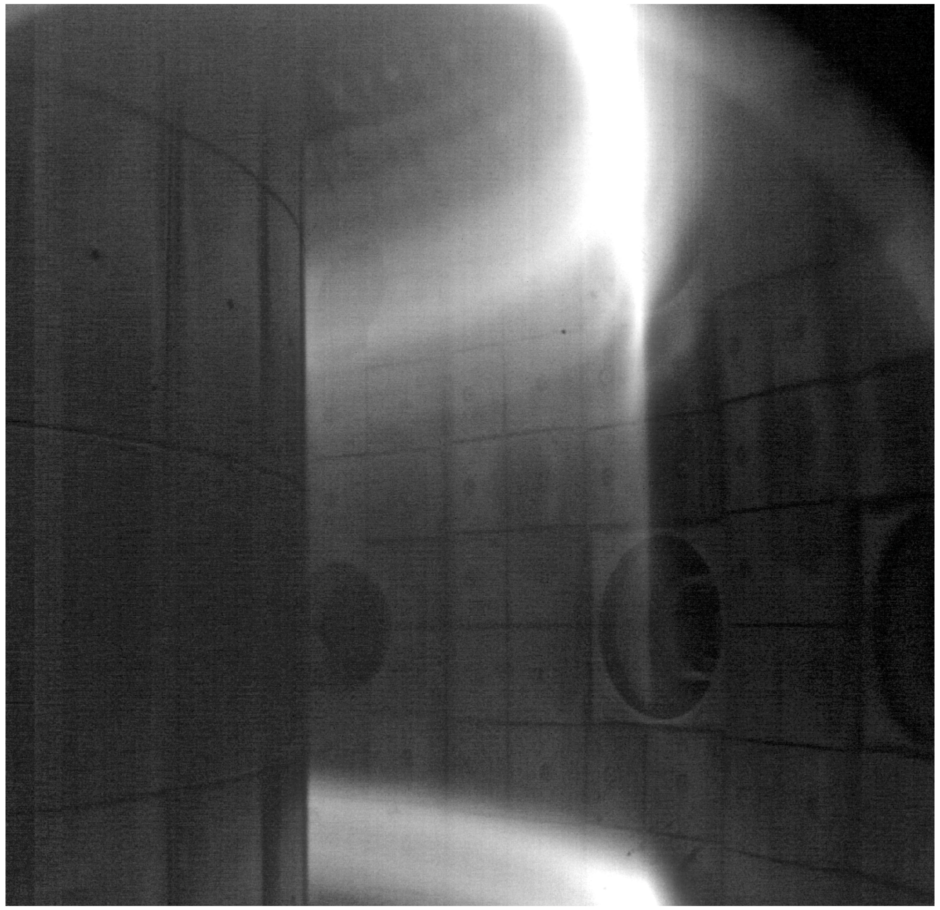
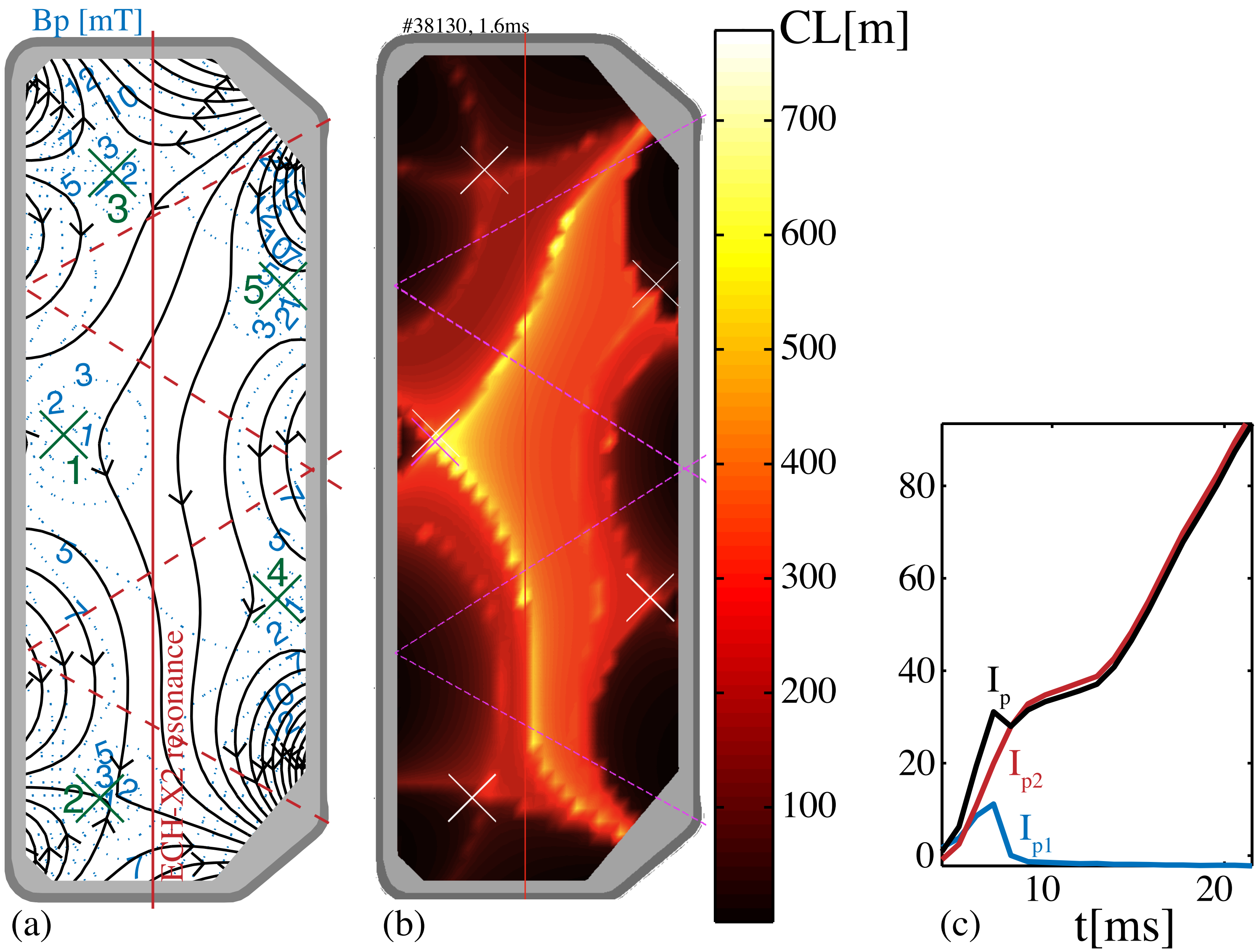
The Double Breakdown Problem

- Low chance to have a double ohmic breakdown
- Double breakdown assisted with ECH-X2





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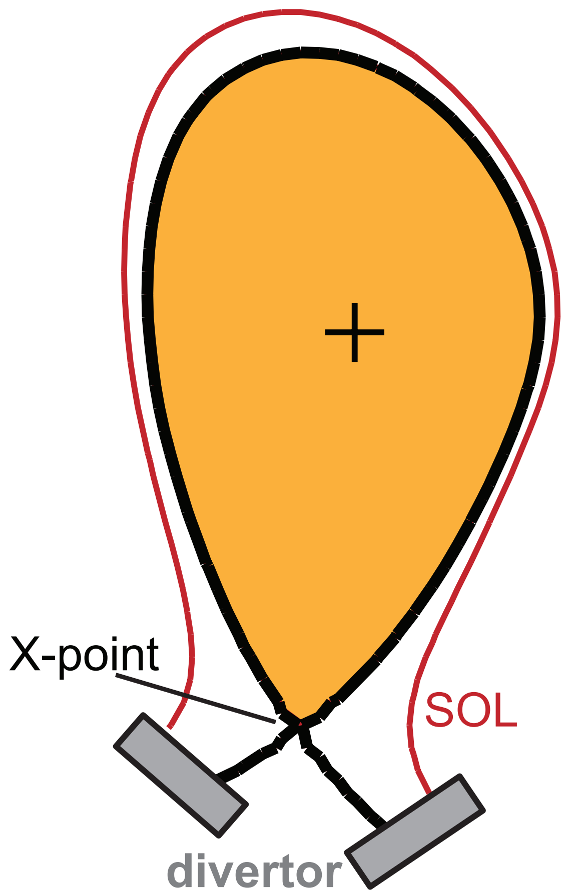
Snowflake Divertor

The Standard Divertor Configuration

Heat flux on the tokamak PFCs is a primary challenge of magnetic fusion research

- In diverted plasmas:
  - Magnetic X-point present ($B_P = 0$)
- Several strategies reduce the divertor heat loads:
  - Tile tilting
  - High flux expansion at strike points
  - Large radiated power fraction



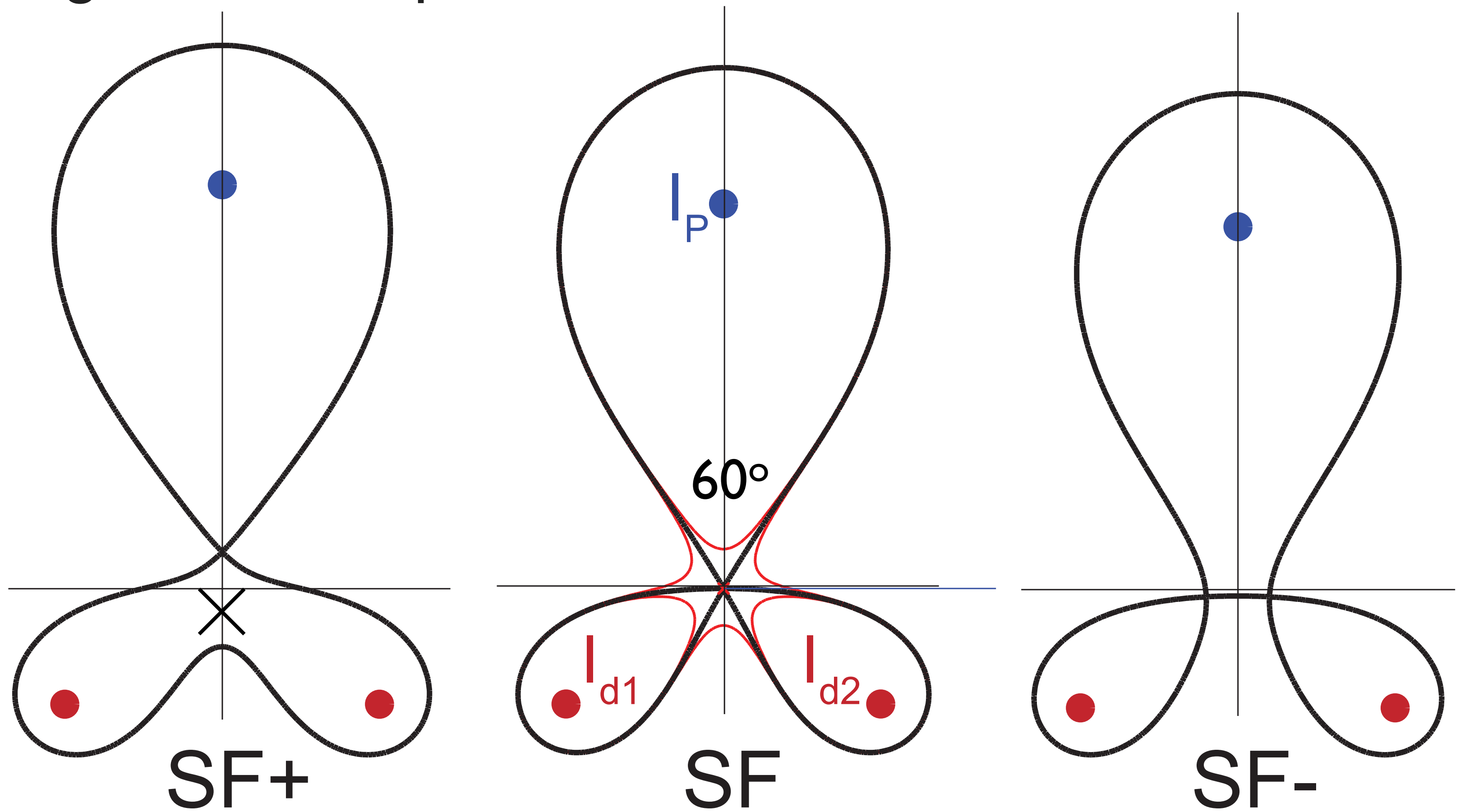
Divertor lifetime remains a crucial issue for tokamaks

- New solutions proposed to reduce the power heat loads:
  - The Snowflake Divertor [D.D.Ryutov, 2007]
  - The Super-X Divertor [P.M.Valanju, 2009]

The Snowflake Divertor Concept

X-point replaced by second order null

- $B_P = 0$ AND $\nabla B_P = 0$
- 4 divertor legs
- Minimum two divertor coils necessary
- Separatrix angle at the X-point of 60° instead of 90°

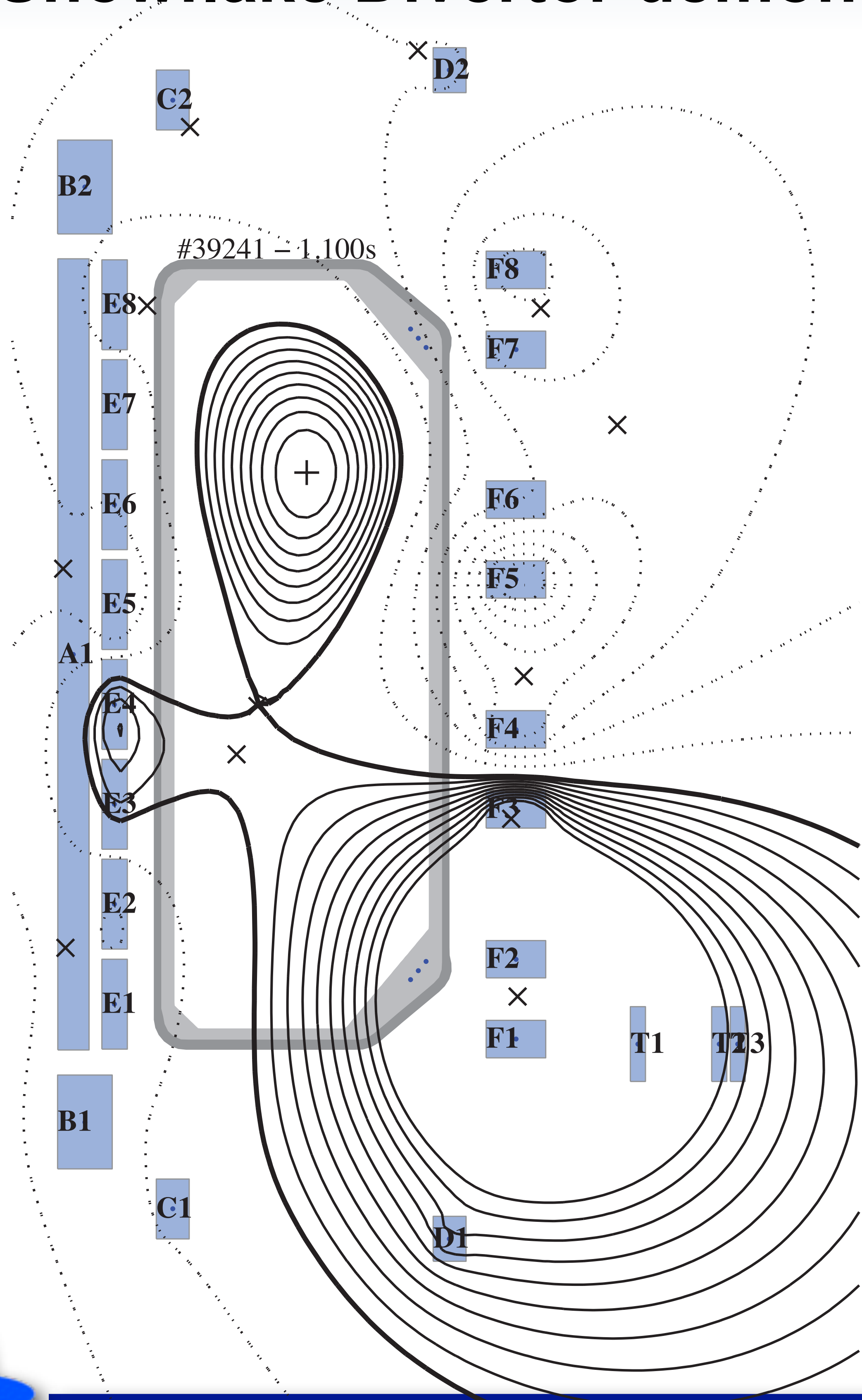


- The SF features:
  - Larger flux expansion in the X-point region
  - Longer connection length in the SOL
  - Higher magnetic shear close to the separatrix

F.Piras, PPCF 2010
V.Soukhanovskii, APS 2010

Creating a Snowflake on TCV

Snowflake Divertor demonstrated for the first time in TCV

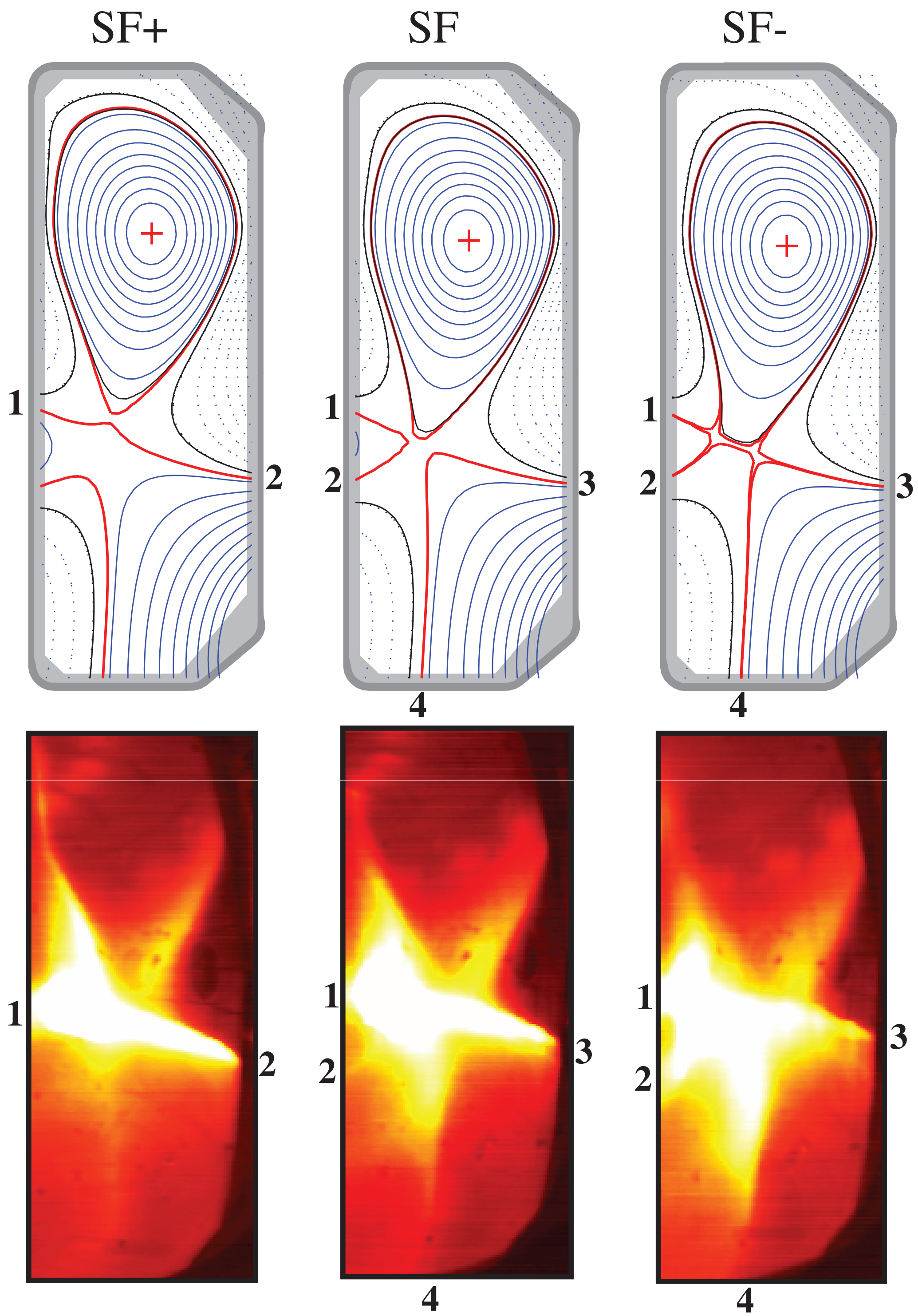


- Open divertor can be freely configured
  - 16 independently powered coils
  - Vessel covered with graphite tiles
- Several PF coils used as SF divertor coils

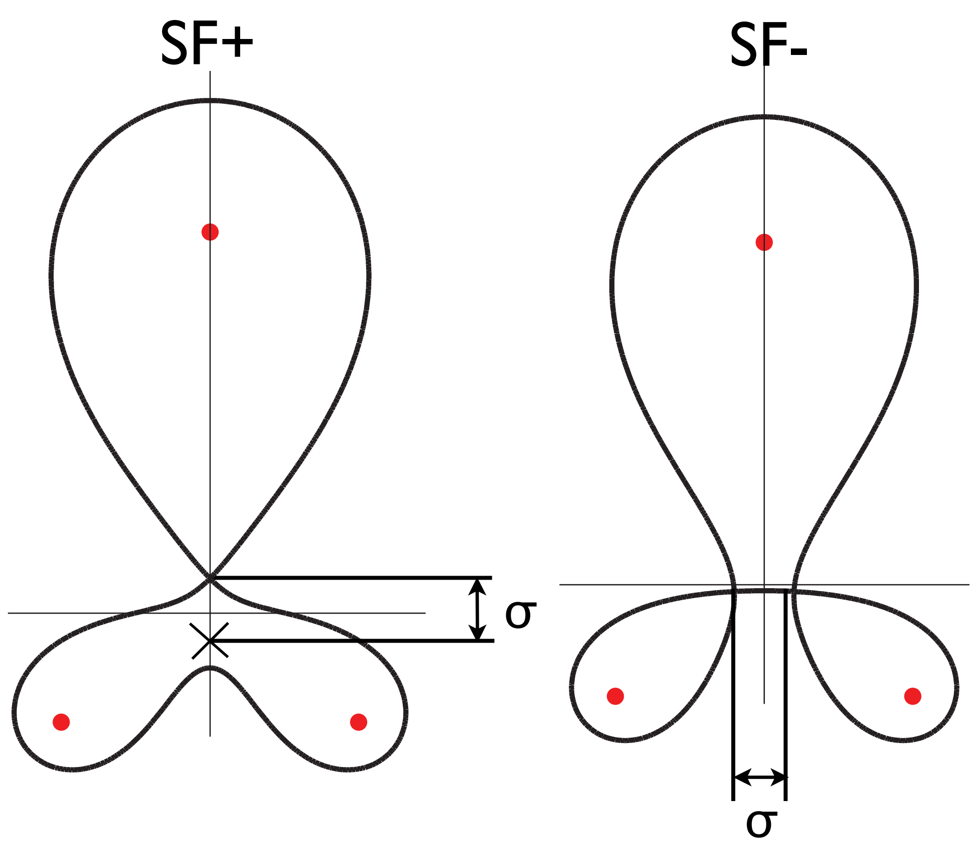
F.Piras, PPCF 2009

Viewing a Snowflake on TCV

All three SF configurations have been successfully established and controlled



- The tangential visible camera confirms the magnetic configurations
- σ parametrizes the proximity to an ideal snowflake configuration (SF)



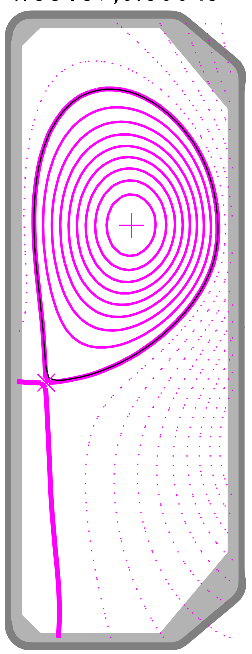
F.Piras, PPCF 2009

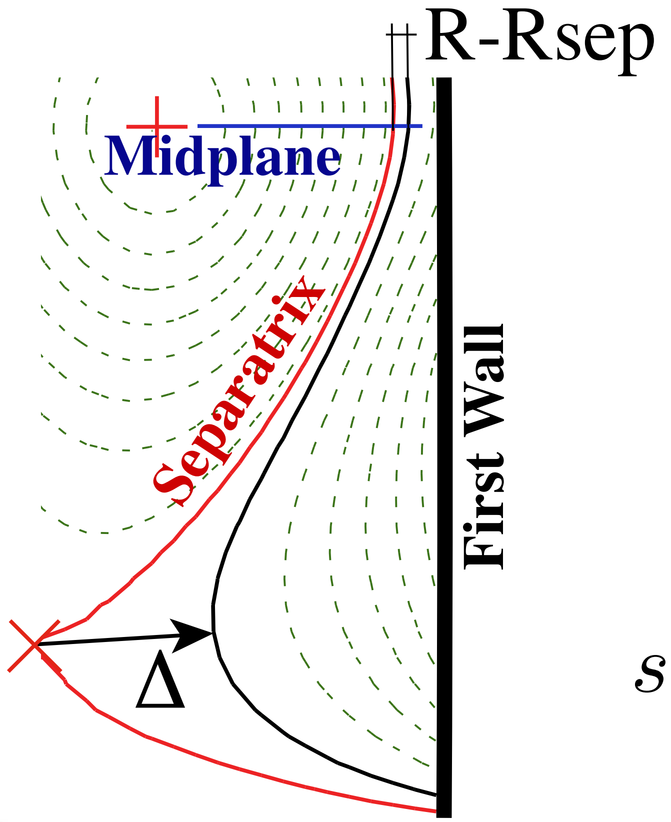
Magnetic Structure of TCV Snowflake

I_P = 230kA, B_T=1.4T

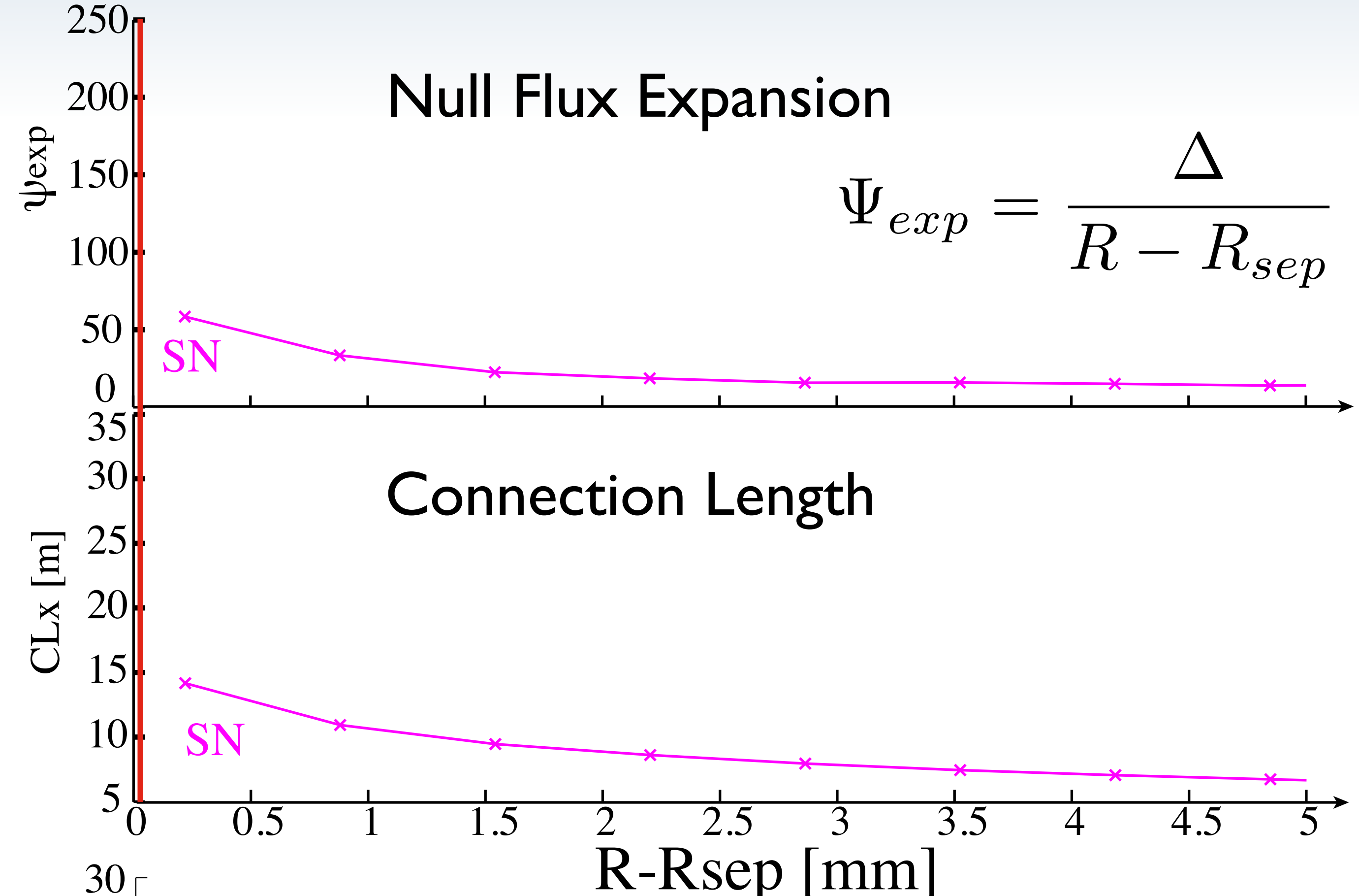
SN

#35137,0.6004s

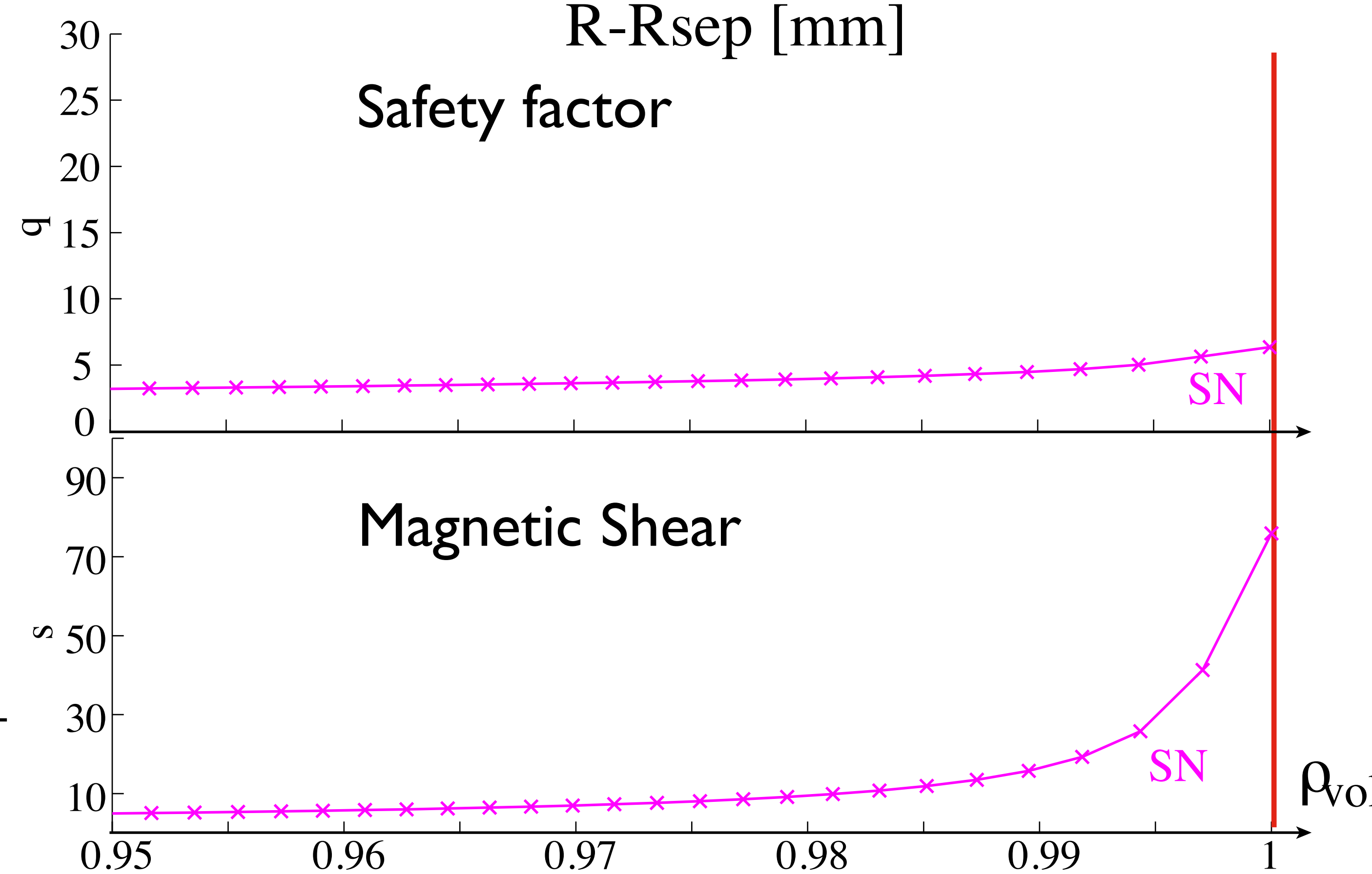




$$s = \frac{\rho_{vol}}{q}\frac{dq}{d\rho_{vol}}$$



$$\Psi_{exp} = \frac{\Delta}{R - R_{sep}}$$



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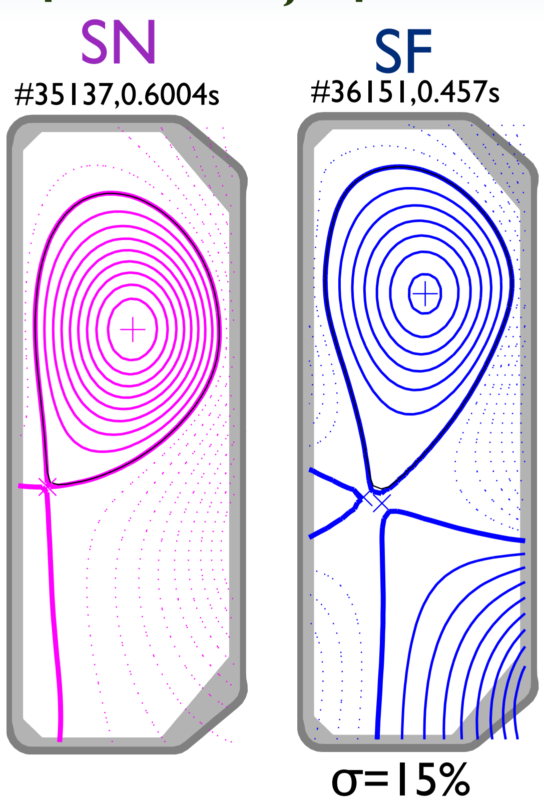

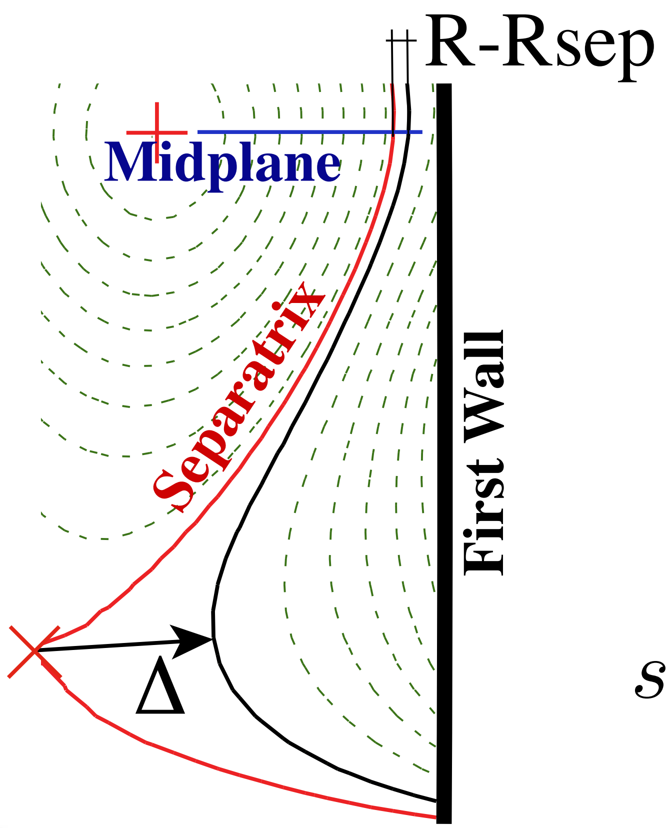

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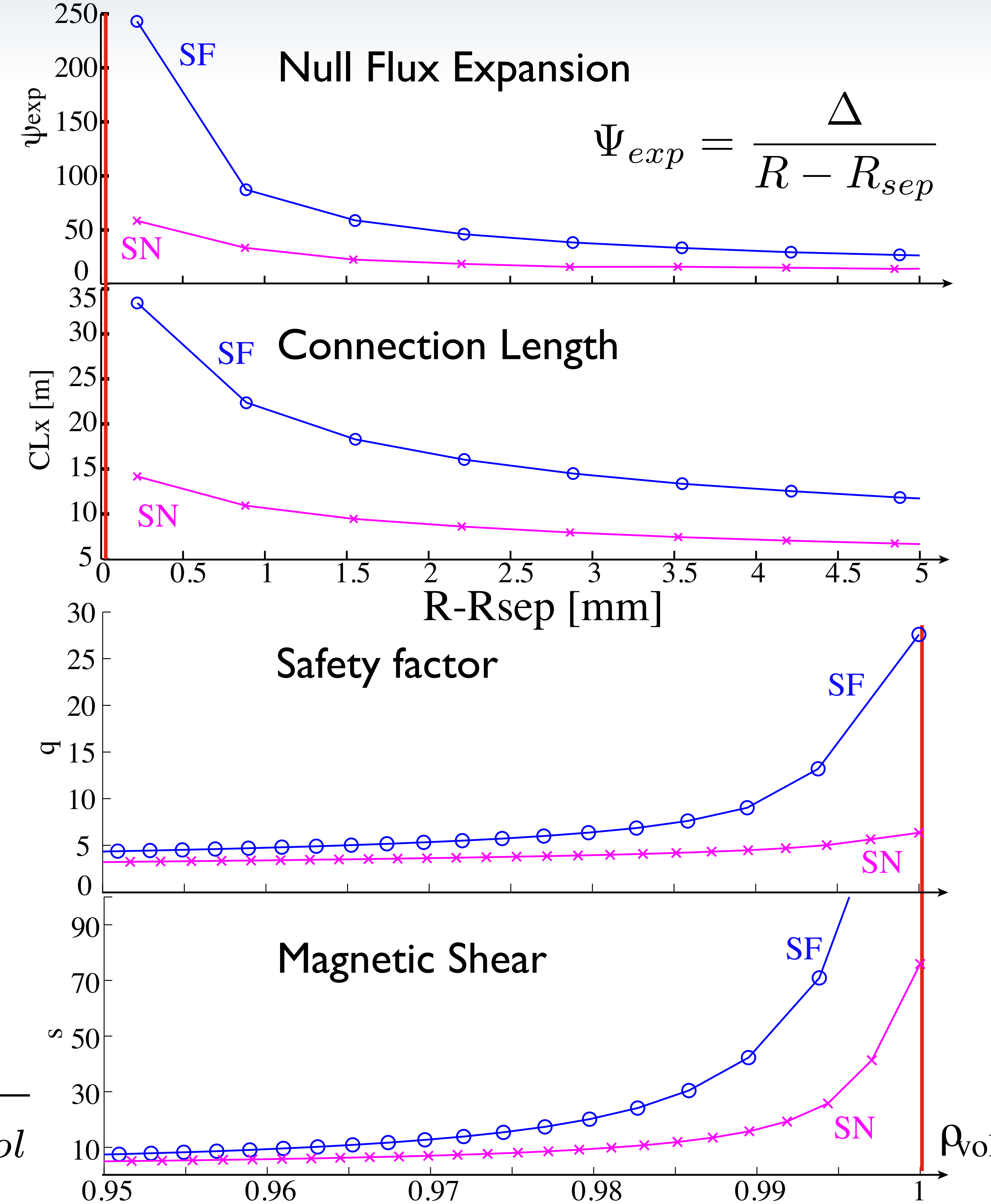

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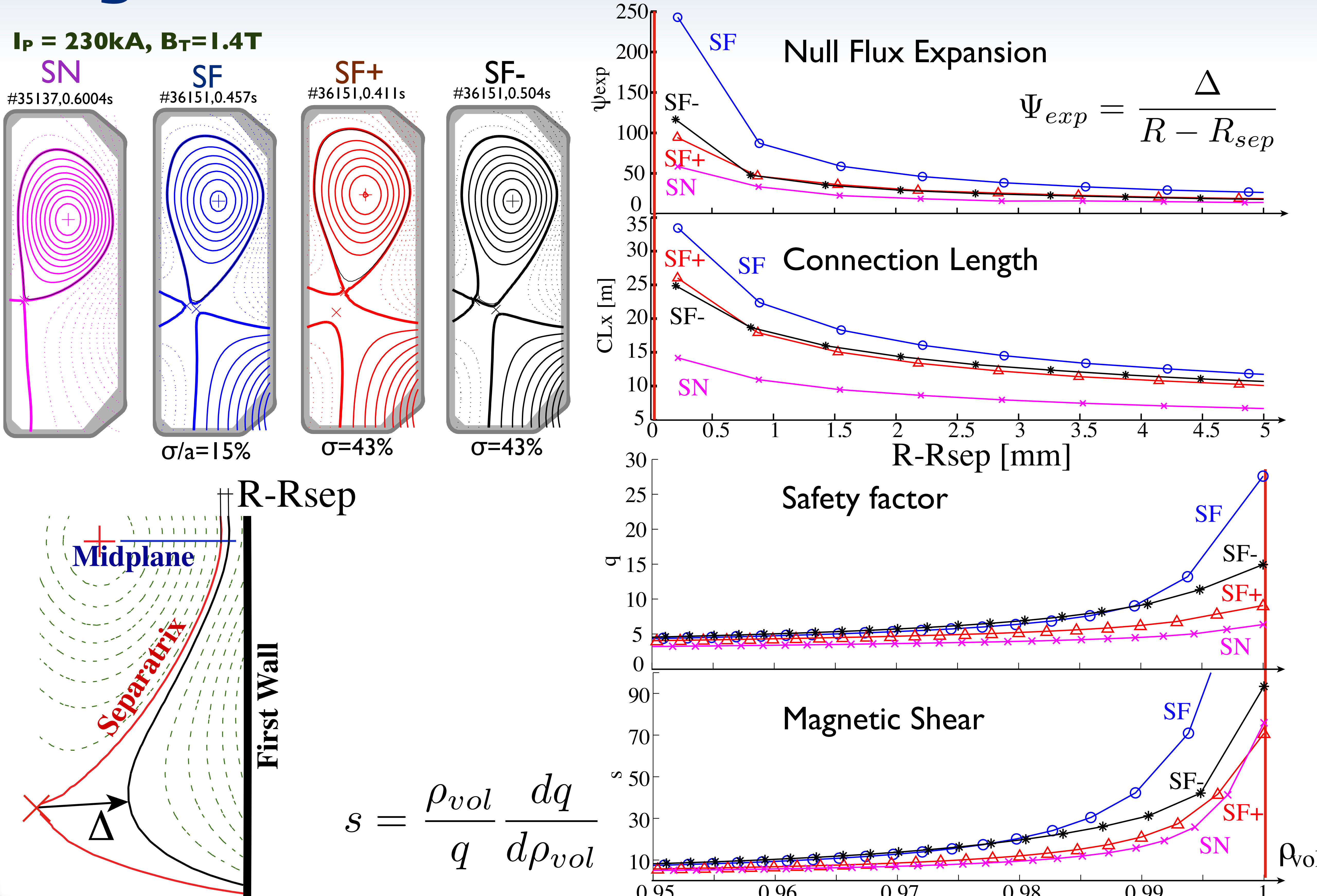


Exploring H-mode Snowflakes

Motivation:

- The H-mode and ELMs are important in present and future tokamaks
- Do the different SF magnetic properties affect the H-mode?

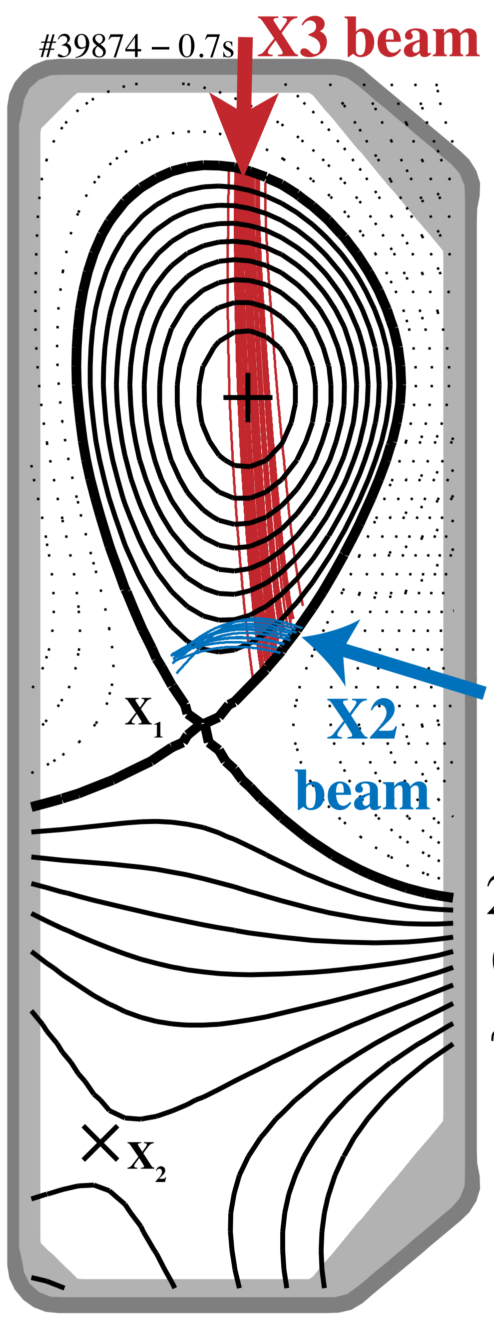
Experiments:

- Can a SF divertor reach an ELMy H-mode?
- How do the ELM dynamics compare with a SN H-mode?
- Can we channel ELM power onto the additional strike points?

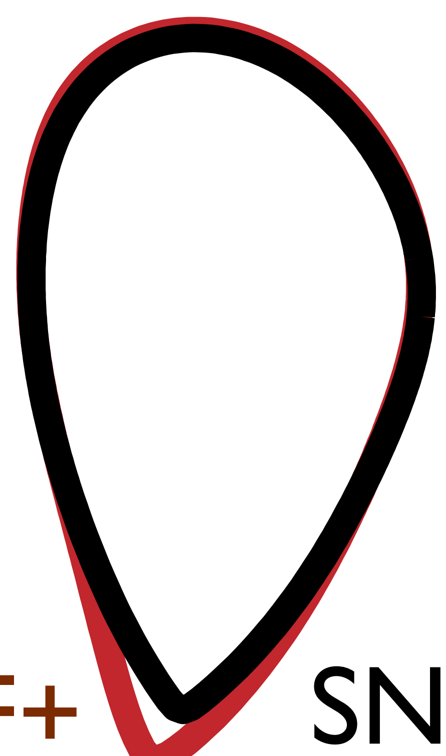
Tuning the Configurations

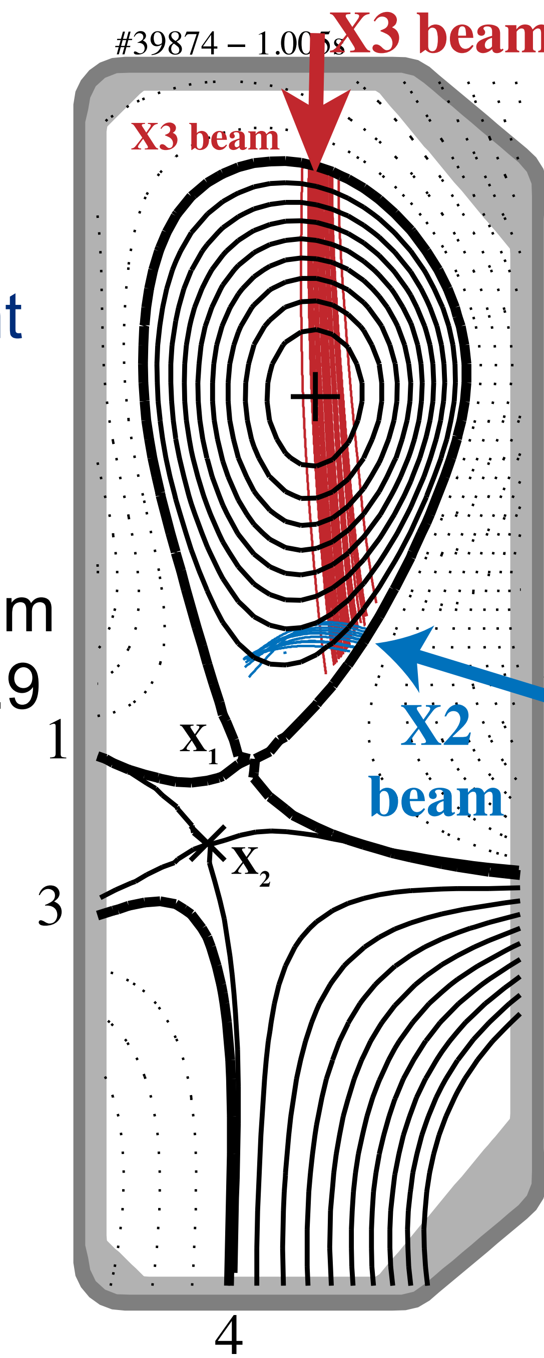
Comparison between SN and SF+ with similar plasma shape

- Plasma properties
  - I_P = 300kA
  - Bx∇B ion-drift towards X-point
- Additional heating
  - 1MW ECH-X3
  - 0.5-1MW ECH-X2



SN σ=270%

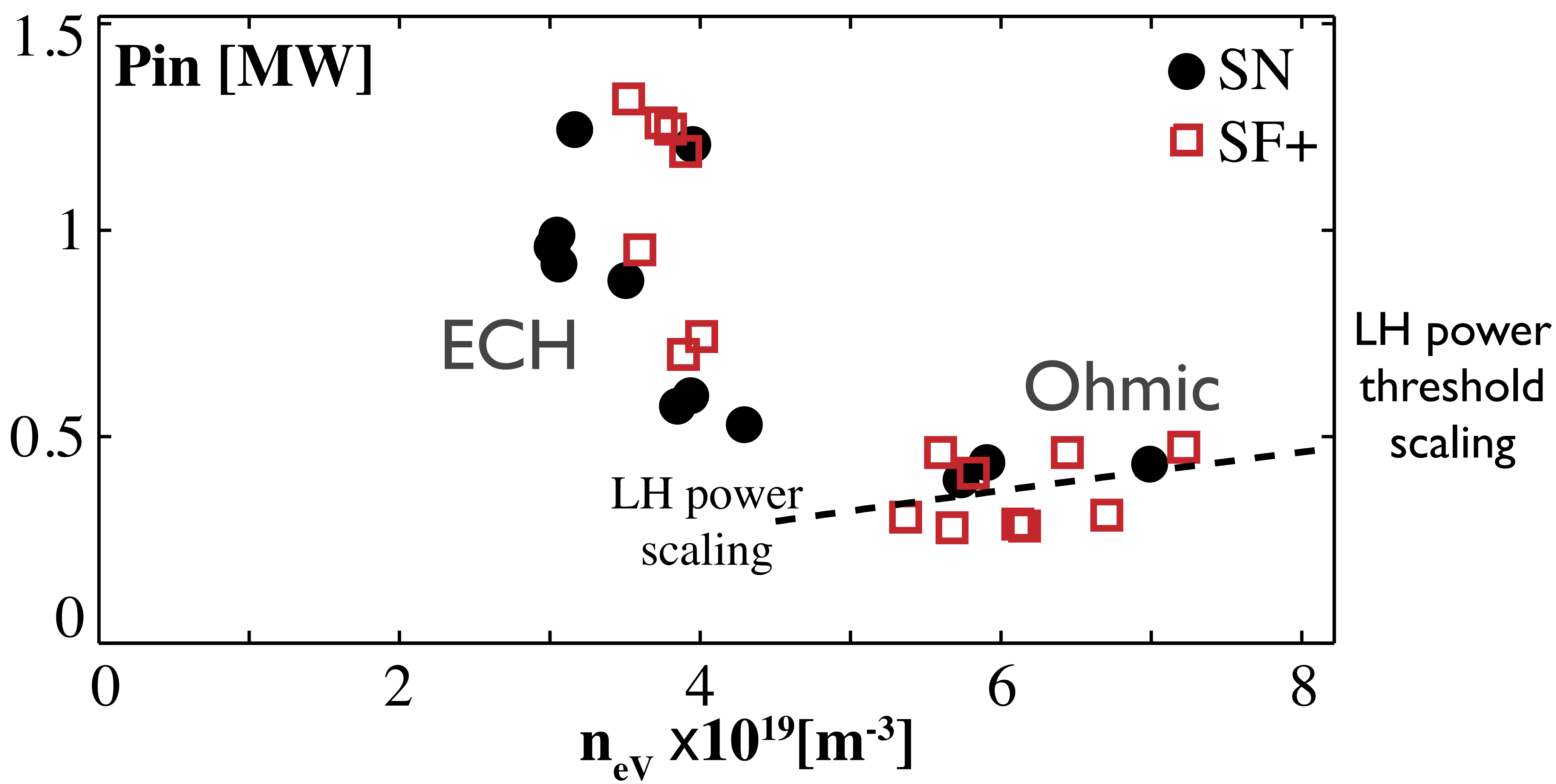




SF+ σ=55%

Accessing the H-mode

Comparison SN and SF+

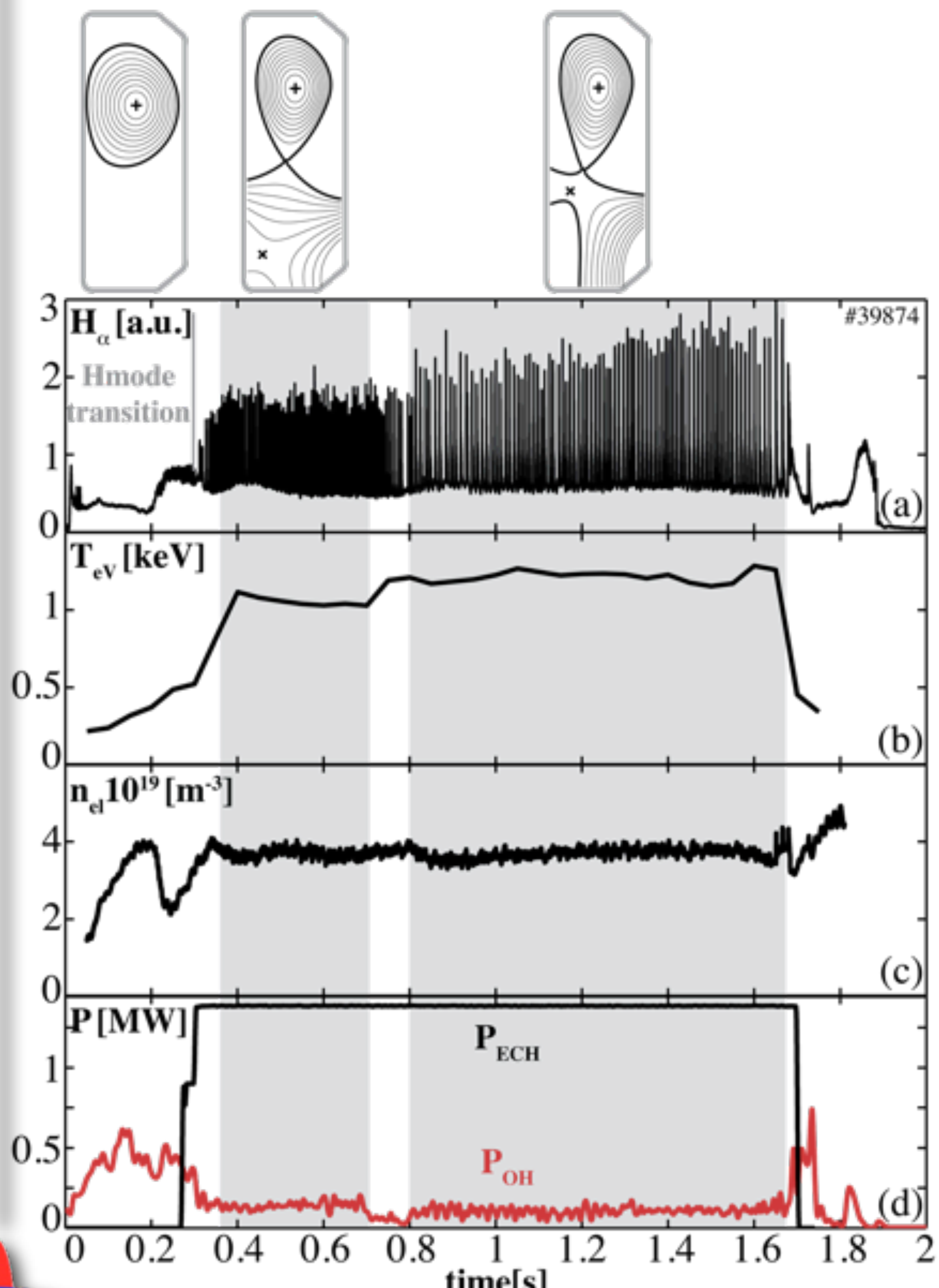


- Scan P_{in} to identify H-mode power threshold
  - Low density: a fraction of Pin from ECH
  - High density: only ohmic power (ECH cut-off)

Unchanged power threshold for Ohmic and ECH H-modes

Type I ELMy H-mode

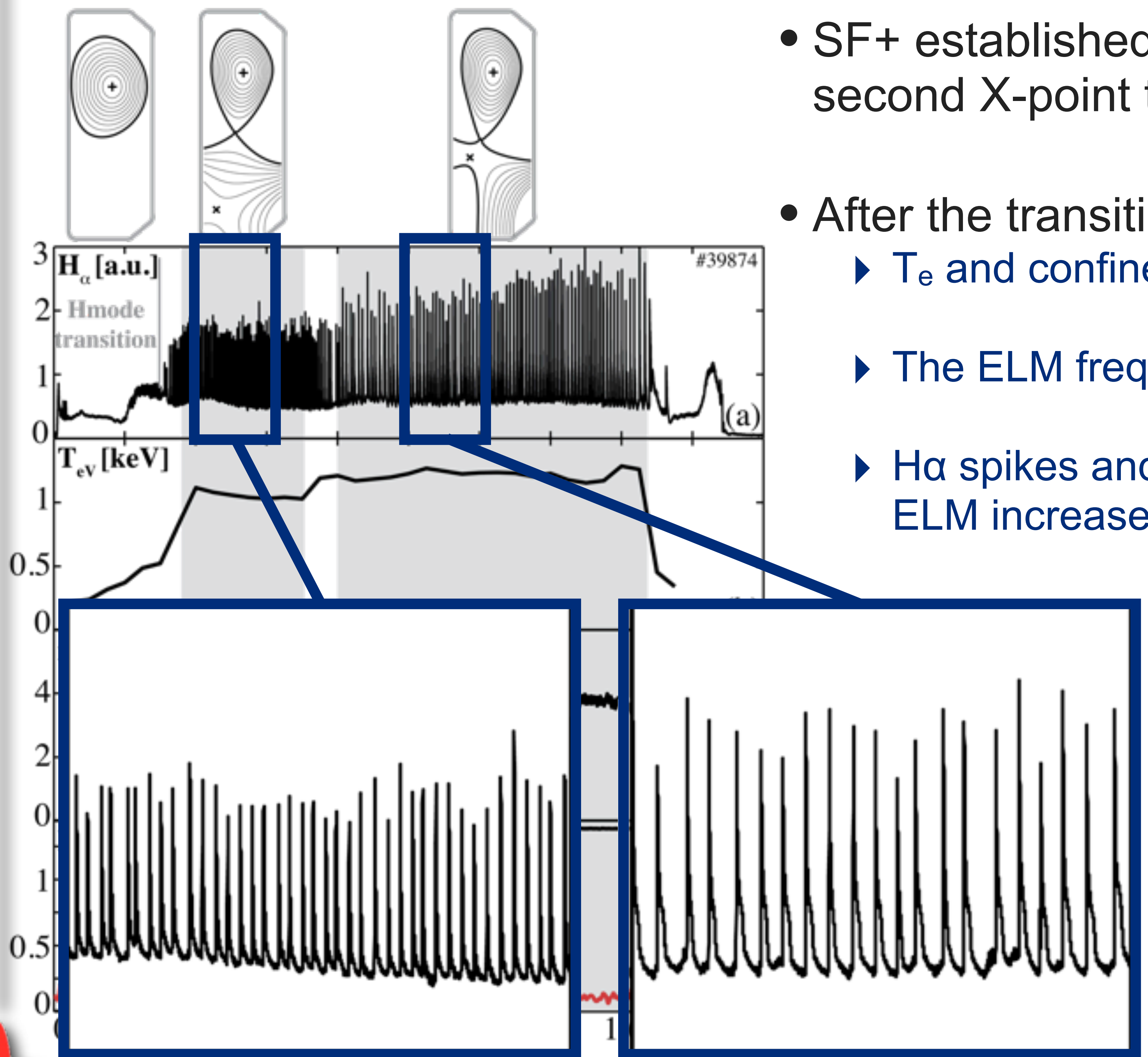
ELMy H-mode for SN and SF+ within the same discharge



- SF+ established from SN moving the second X-point toward the SN X-point
- After the transition:
  - T_e and confinement increase by ~15%
  - The ELM frequency is lower
  - Hα spikes and integrated Hα across each ELM increase by ~30%

Type I ELMy H-mode

ELMy H-mode for SN and SF+ within the same discharge



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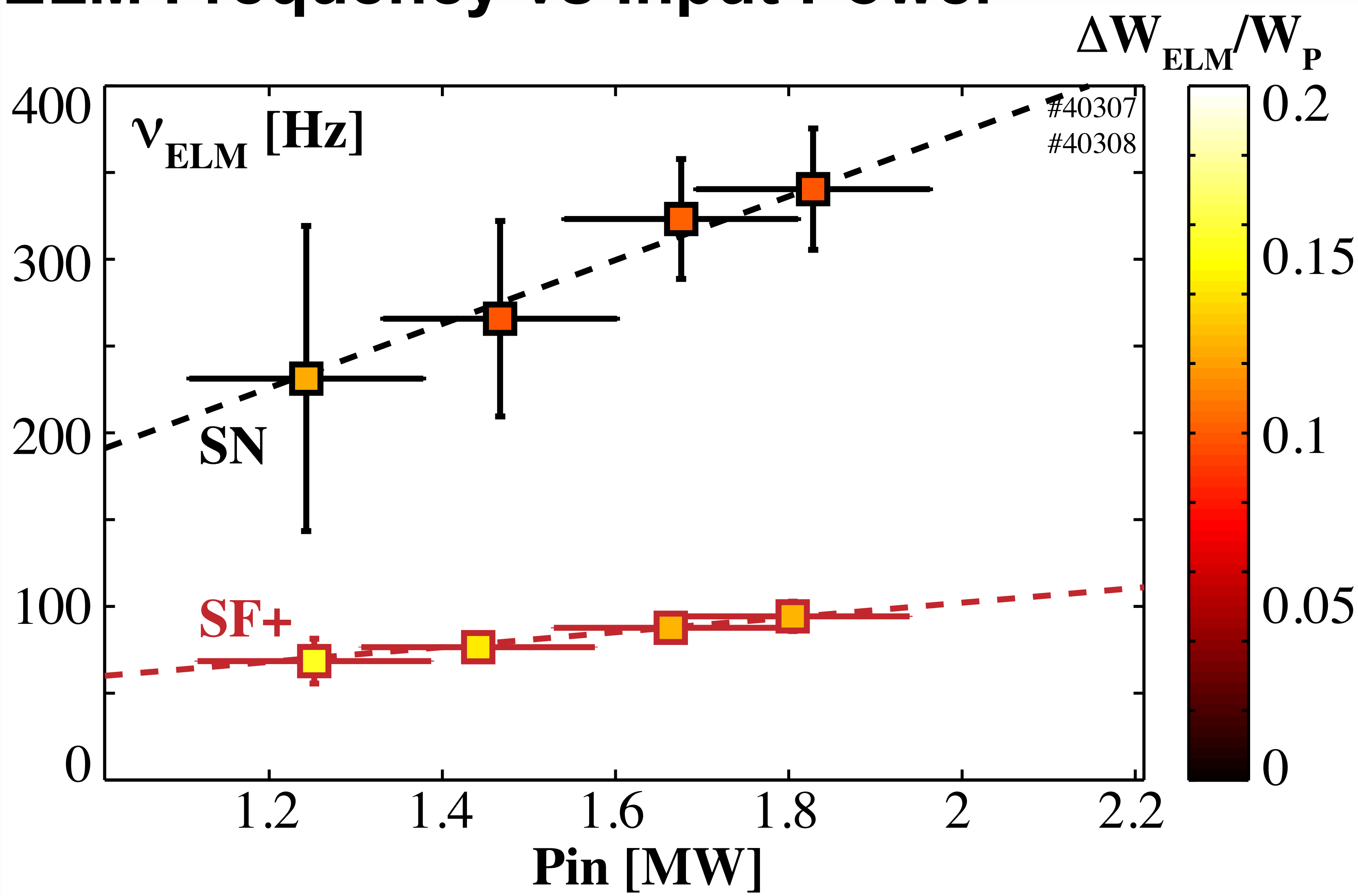
Snowflake Reduces ELM Frequency

ELM Frequency vs Input Power

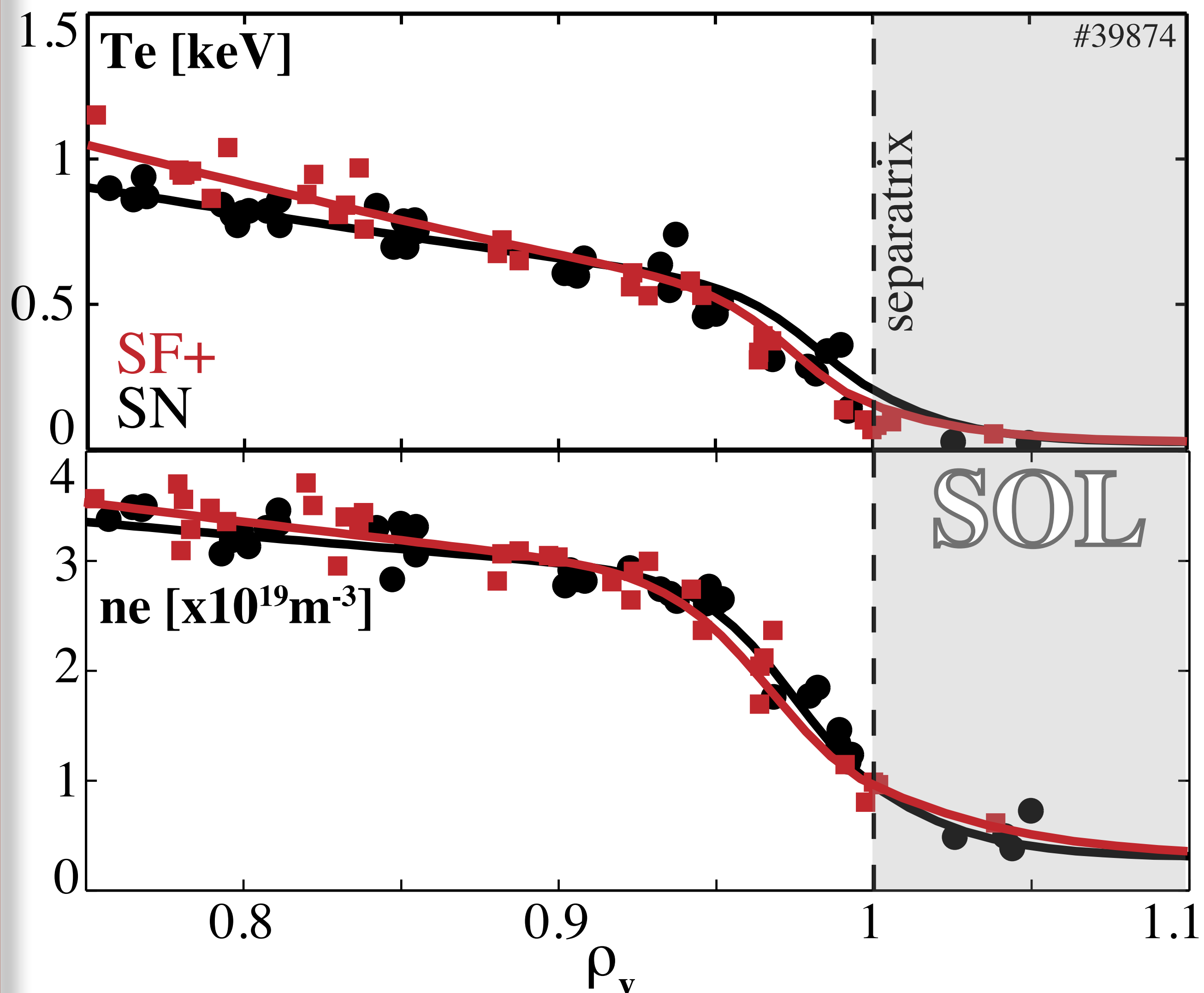


	SN	SF
ΔW_{ELM}	1.6kJ	2.3kJ
$\Delta W_{ELM}/W_p$	10.6%	13.7%
$\nu_{ELM} \times \Delta W_{ELM}/P_{in}$	30%	12.4%

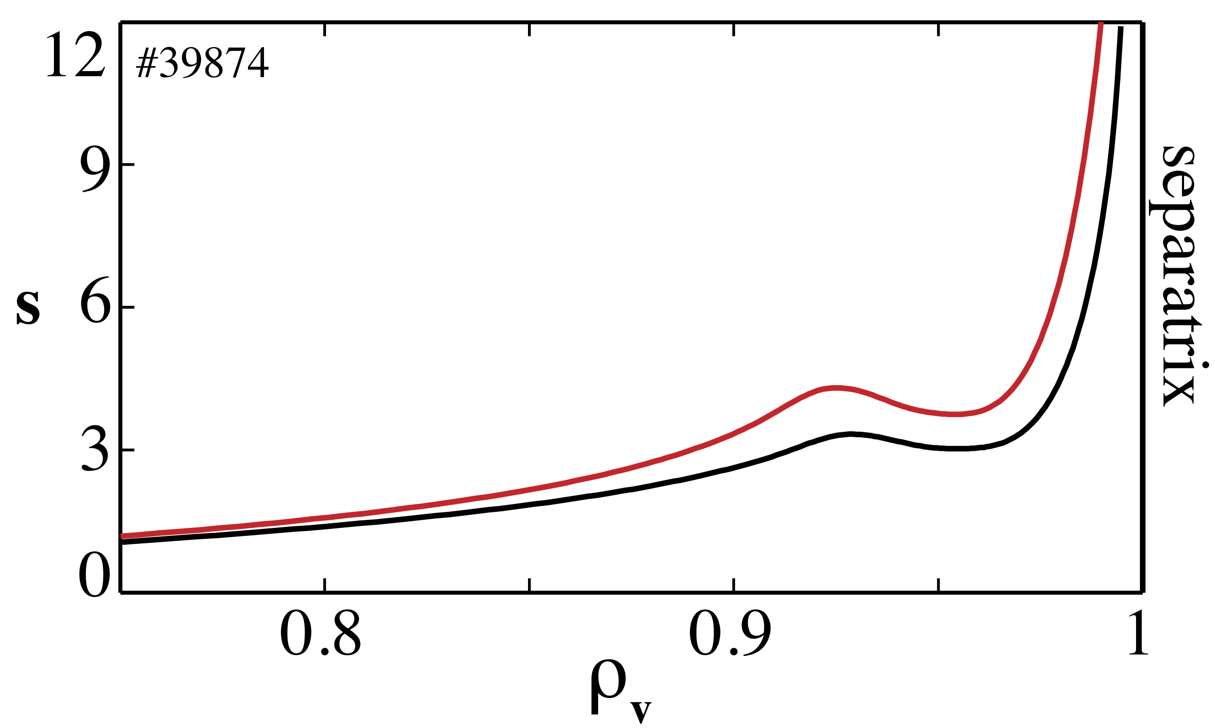
- Scan ECH-X2 input power keeping ECH-X3 constant
- $d\nu_{ELM}/dPin > 0$ for both configurations → type I ELMs
- SF+ has 2-3 times lower ν_{ELM}
- $\Delta W_{ELM}/W_P$ only 20-30% higher in SF+
- ν_{ELM} does not change with X2/X3 deposition, κ, SF+→SN

Similar Pedestal Profiles

Temperature and density profiles



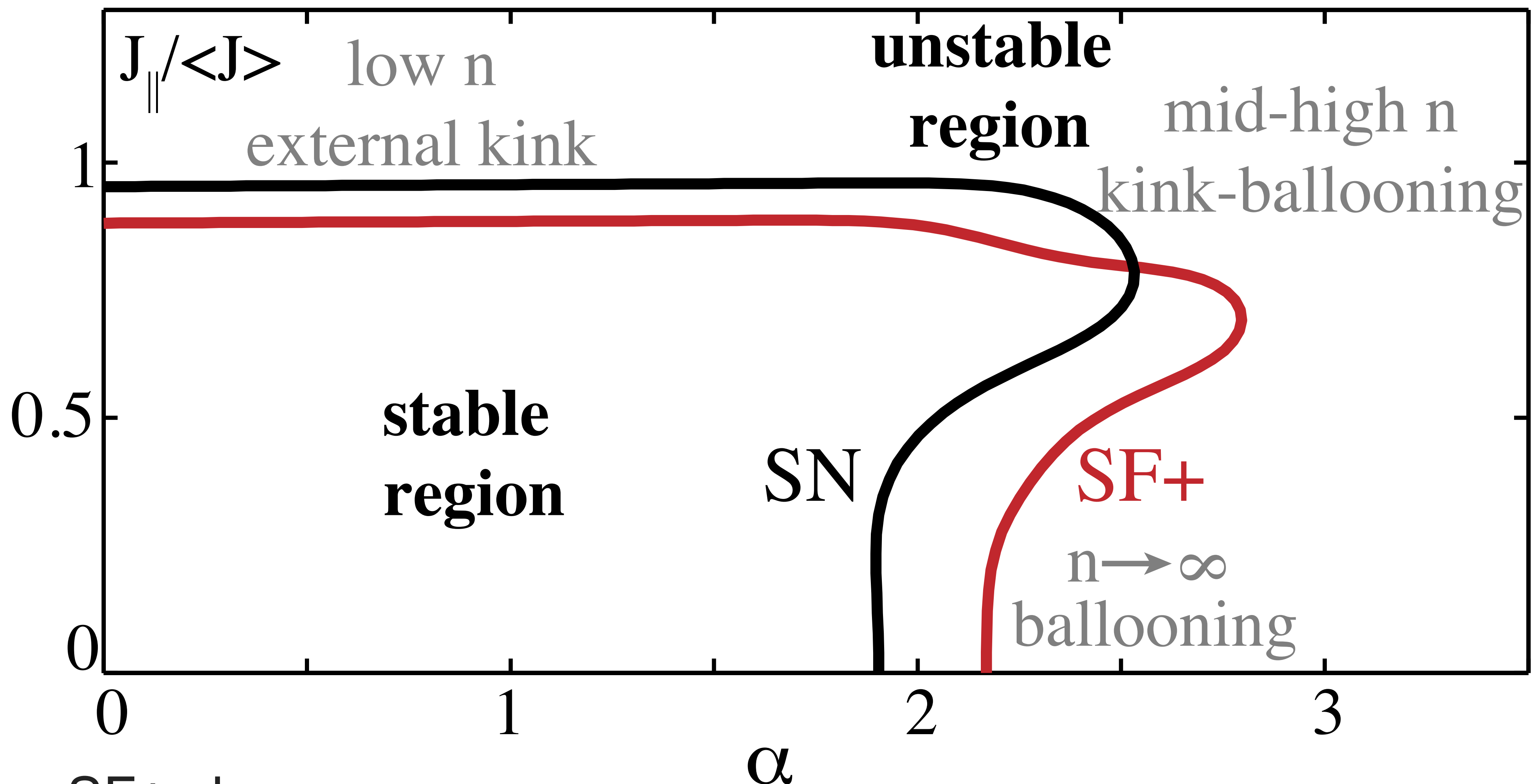
- Similar T_e and n_e profiles from Thomson scattering



- Magnetic shear includes the bootstrap current
- SF+ has higher magnetic shear

Enhanced Pedestal Stability

Ideal MHD pedestal stability computed with the KINX code



- The SF+ shows:
  - Larger second stability region, i.e. enhanced kink-ballooning stability
  - Better stability of ideal ballooning modes (n→∞)
  - Lower low n (external kink) stability limits

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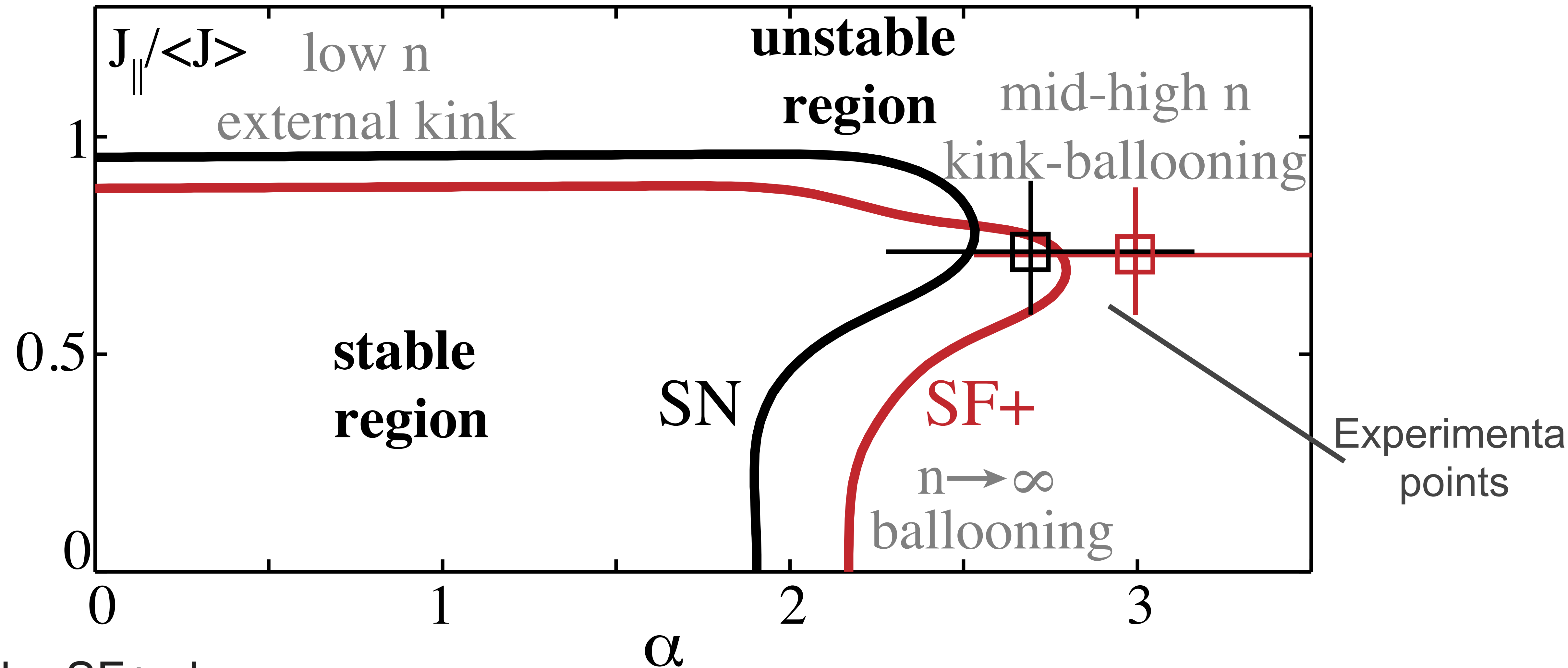

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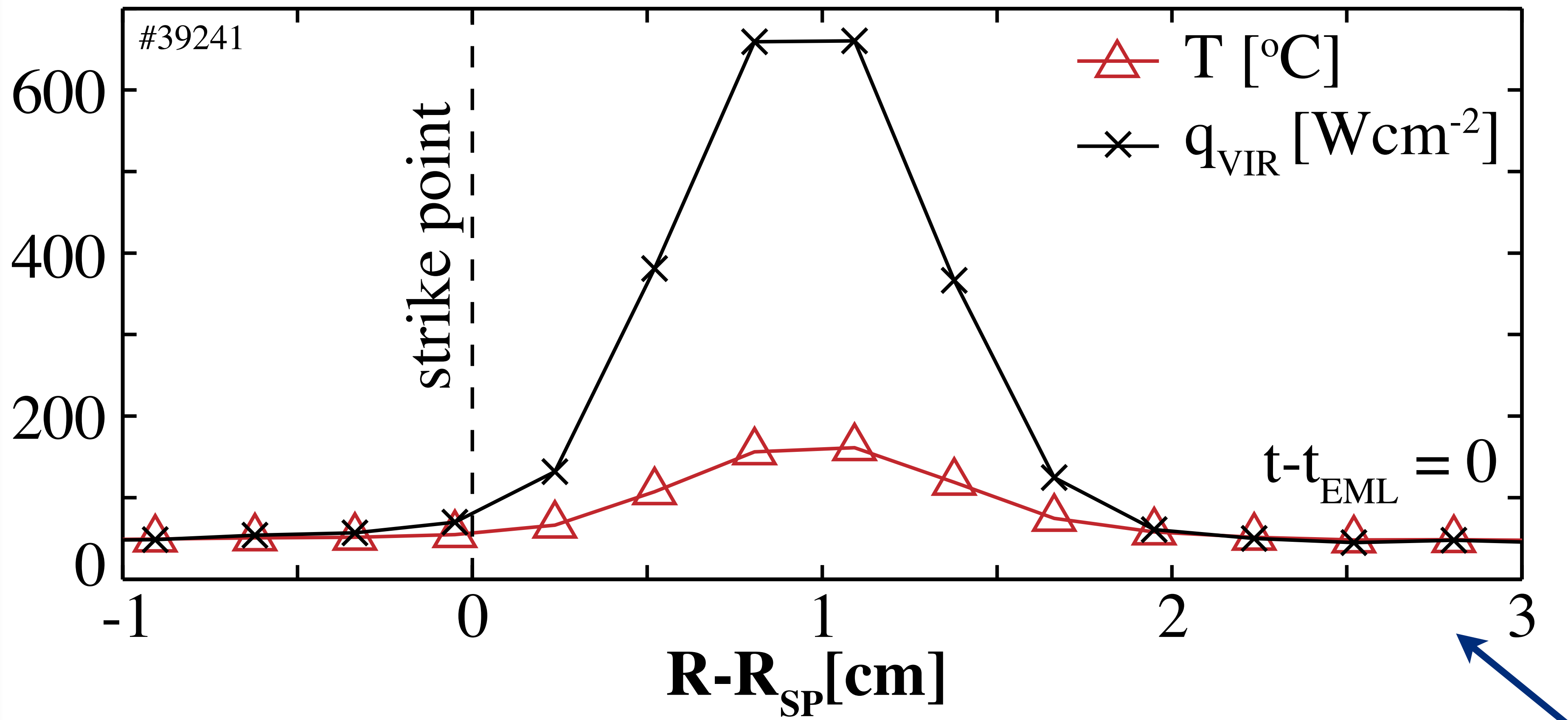
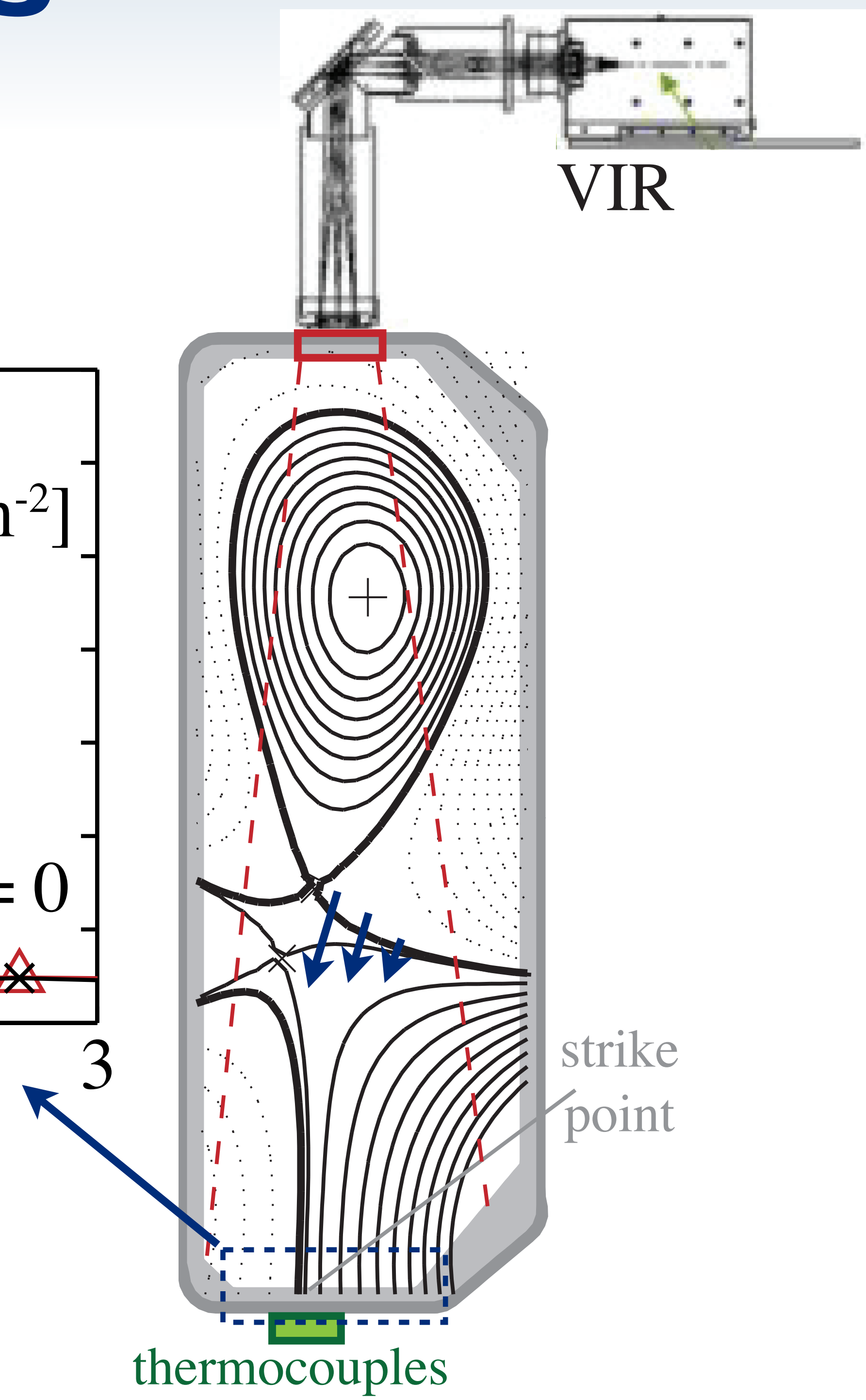
S.Medvedev P4.145

Strike Point Power Sharing

Vertical infrared camera profiles

- Coherently averaged ELM profiles





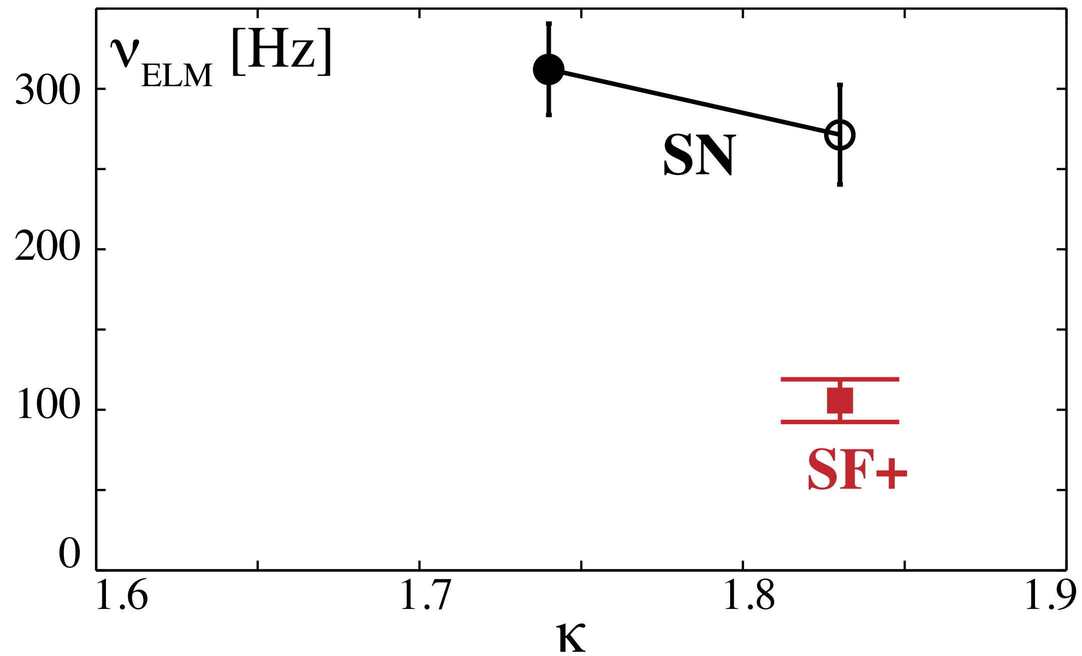
- 15% of ΔW_{ELM} reaches the bottom strike point
  - confirmed with thermocouples on divertor tiles
- Cross-field transport from the null region explains the measured profiles
- No significant profile broadening during ELMs

Conclusions (Snowflake Divertor)

- The snowflake divertor has been established and controlled on TCV with:
  - Higher flux expansion, connection length and magnetic shear
- An ELMy Type I H-mode was established, showing:
  - Similar H-mode power threshold to single-null plasmas
  - ELM frequency reduced by 2-3, while energy lost per ELM increased by 20-30%
  - Higher plasma temperature and better confinement (~15%)
  - Similar pedestal profiles
- 15% of the ELM energy reaches one of the additional strike points
- The pedestal stability analysis suggests enhanced kink-ballooning stability
- Future work will focus on the strike point power sharing

ν_{ELM} vs X2/X3 absorption, κ

- υ_{ELM} does not change with X3 deposition location
- Relatively small variation of υ_{ELM} with κ



- υ_{ELM} does not change with X2 deposition location