ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

CRPP

“Snowflake” H-mode in Tokamak Plasmas

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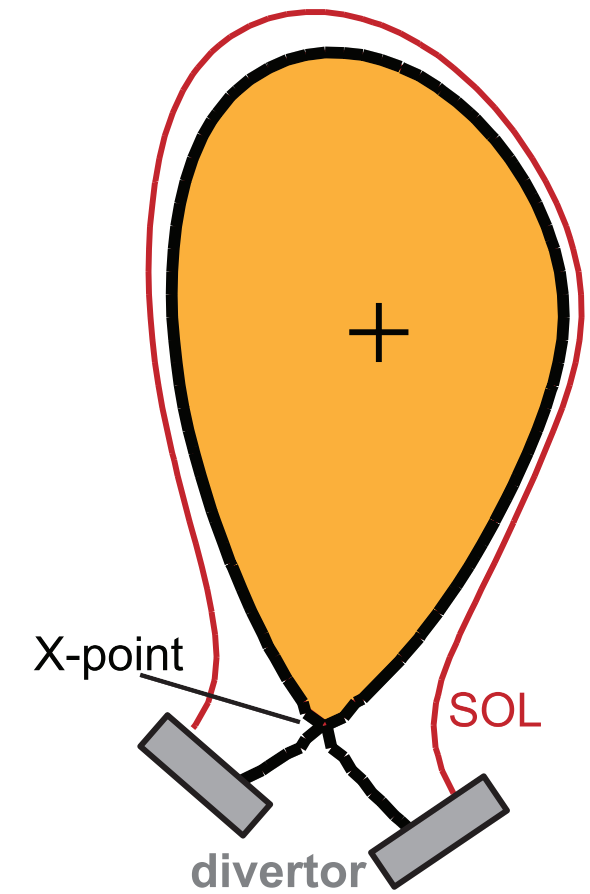
The Standard Divertor Configuration

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



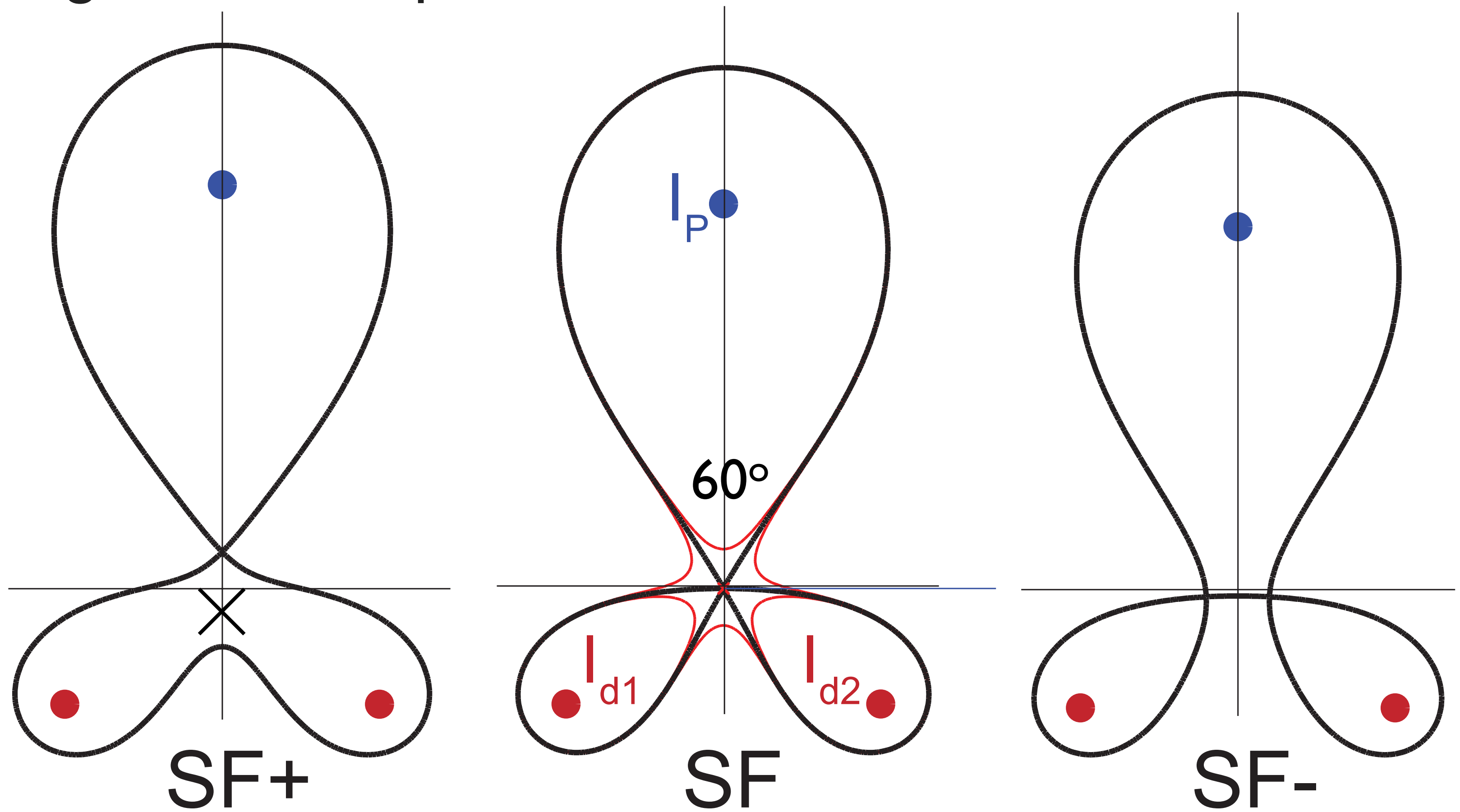
Divertor lifetime remains a crucial issue for tokamaks

- 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

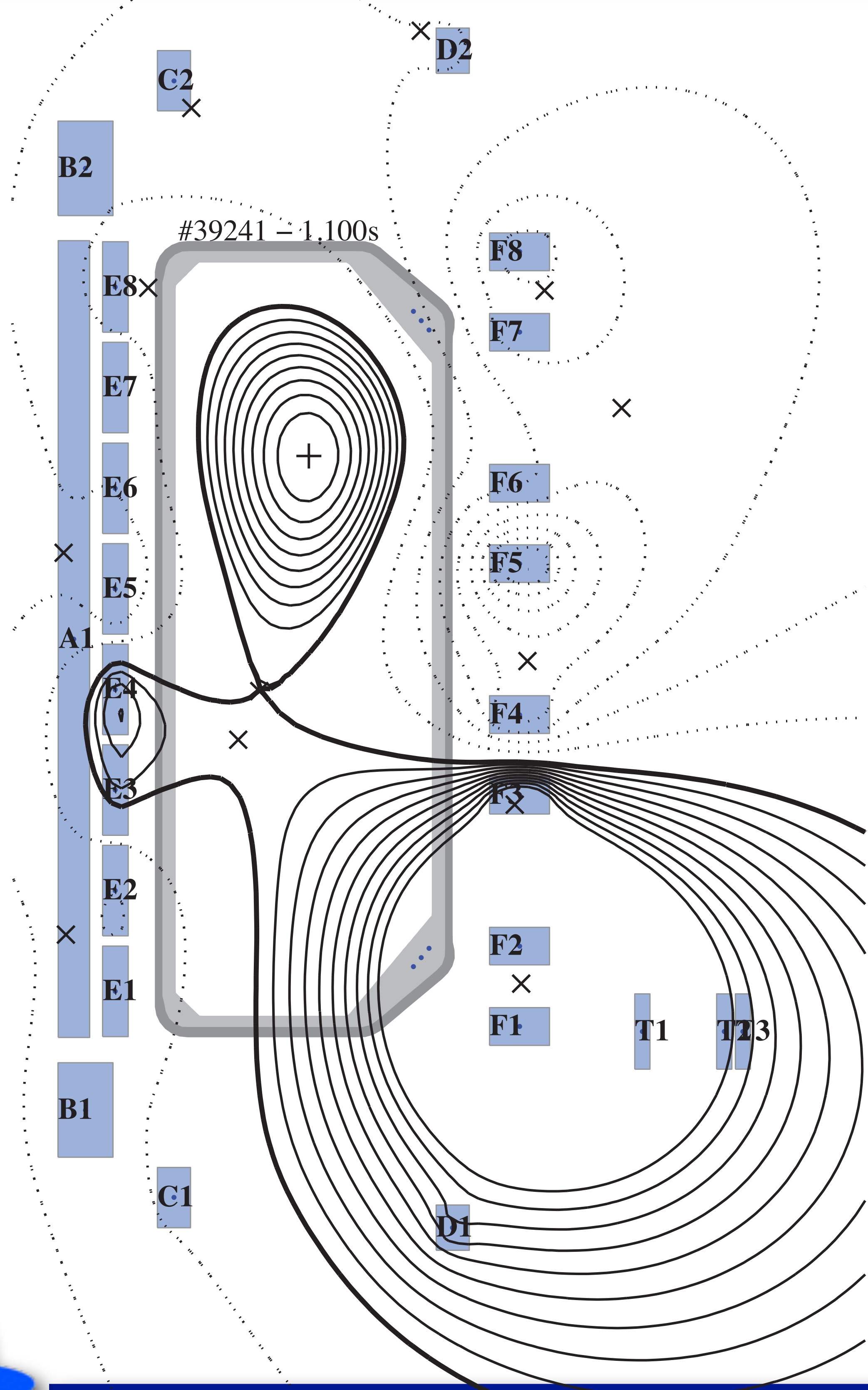
F.Piras, PPCF 2009
V.Soukhanovskii, APS 2010

Outline of the Talk

- Snowflake Divertor on TCV
- Magnetic properties of the TCV snowflake
- Snowflake divertor in the H-mode regime
  - Access to the ELMy H-mode
  - Properties of the Snowflake Divertor H-mode
  - Stability of the Snowflake Divertor H-mode pedestal

Creating a Snowflake on TCV

Snowflake Divertor demonstrated for the first time in TCV

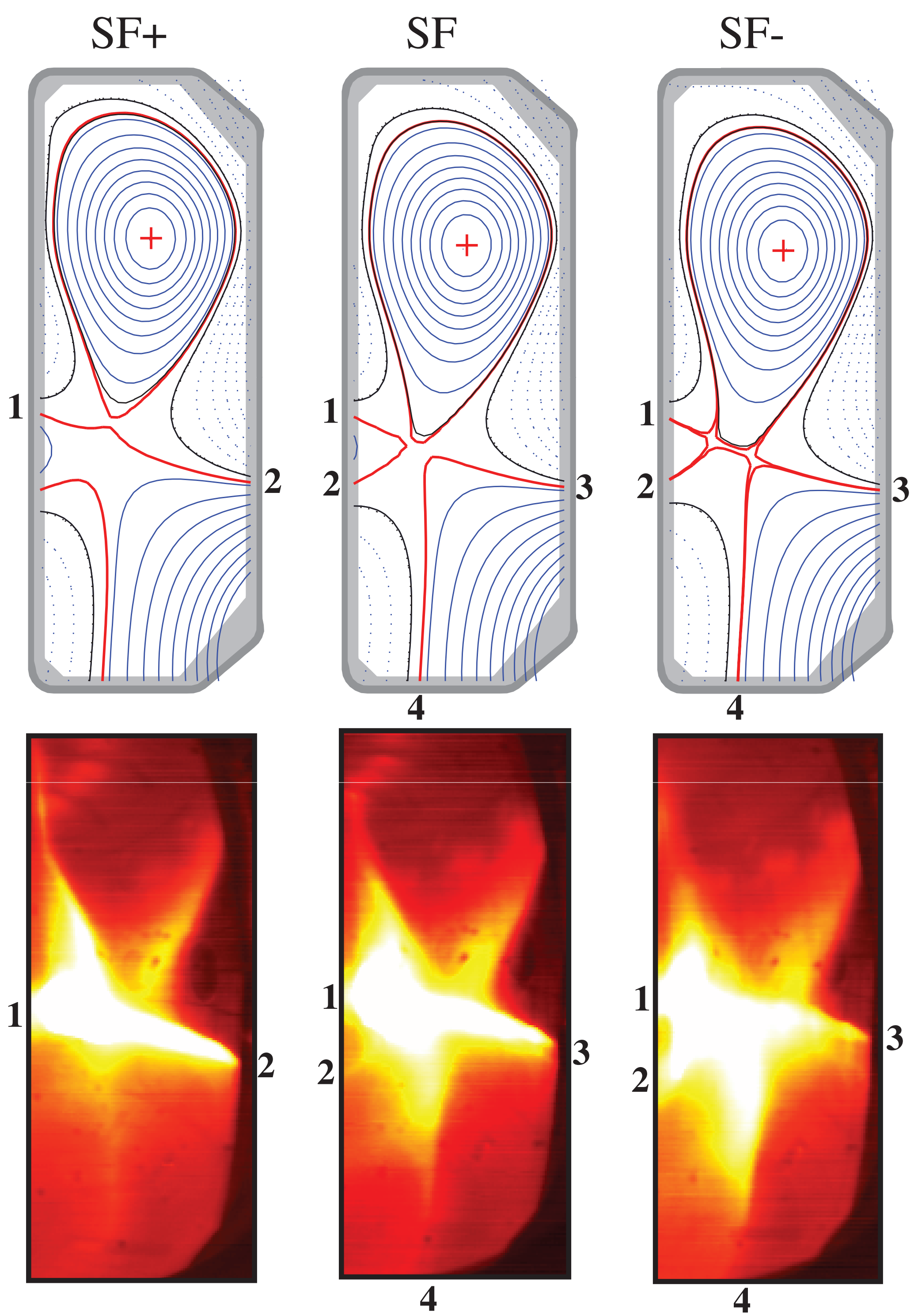


- Open divertor can be freely configured
  - 16 independently powered coils
  - Vessel covered with graphite tiles
- TCV Parameters
  - R = 0.88m; a = 0.25m
  - $B_T \leq 1.5T$; $I_P \leq 1MA$
  - $0.9 \leq \kappa \leq 2.8$
  - $-0.6 \leq \delta \leq 0.9$
  - Internal Fast n = 0 coils
- ECH System:
  - 2nd harmonic 6 x 0.5MW (Side launch)
  - 3rd harmonic 3 x 0.5MW (Top launch)
- Several PF coils used as SF divertor coils

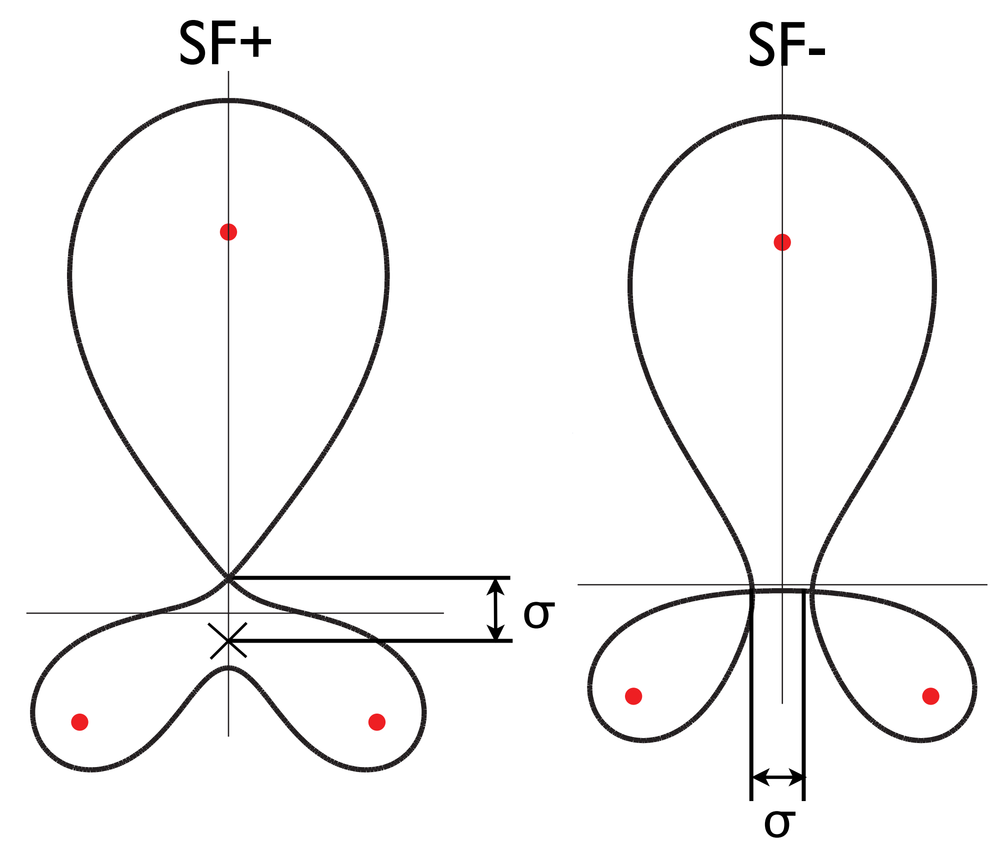
F.Piras, PPCF 2009

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)



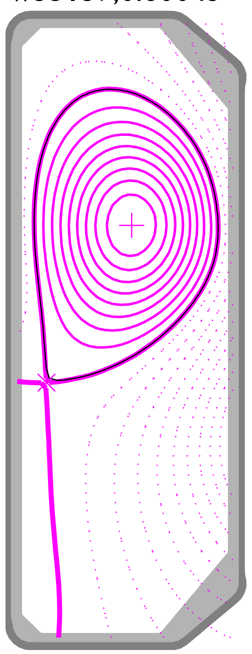
F.Piras, PPCF 2009

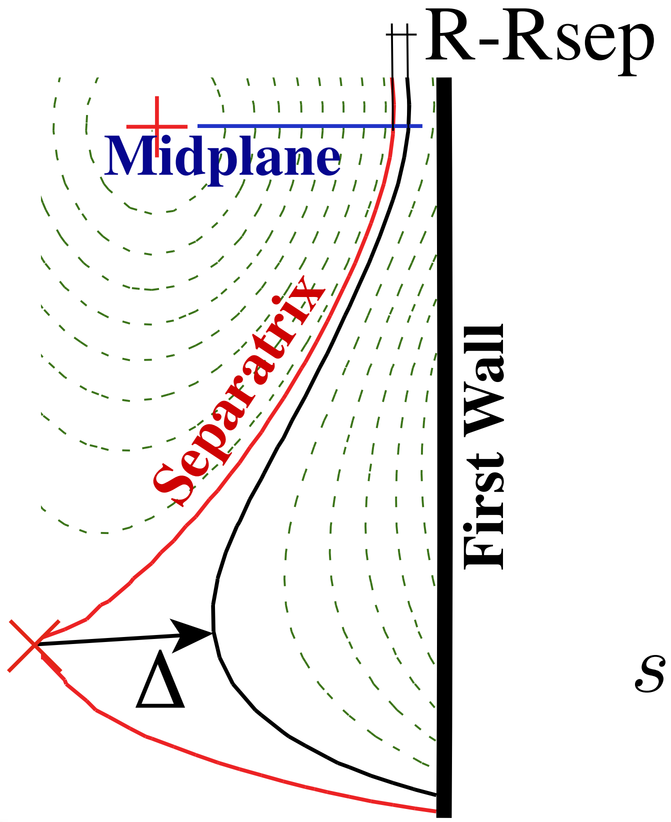
Magnetic Structure of TCV Snowflake

I_P = 230kA, B_T=1.4T

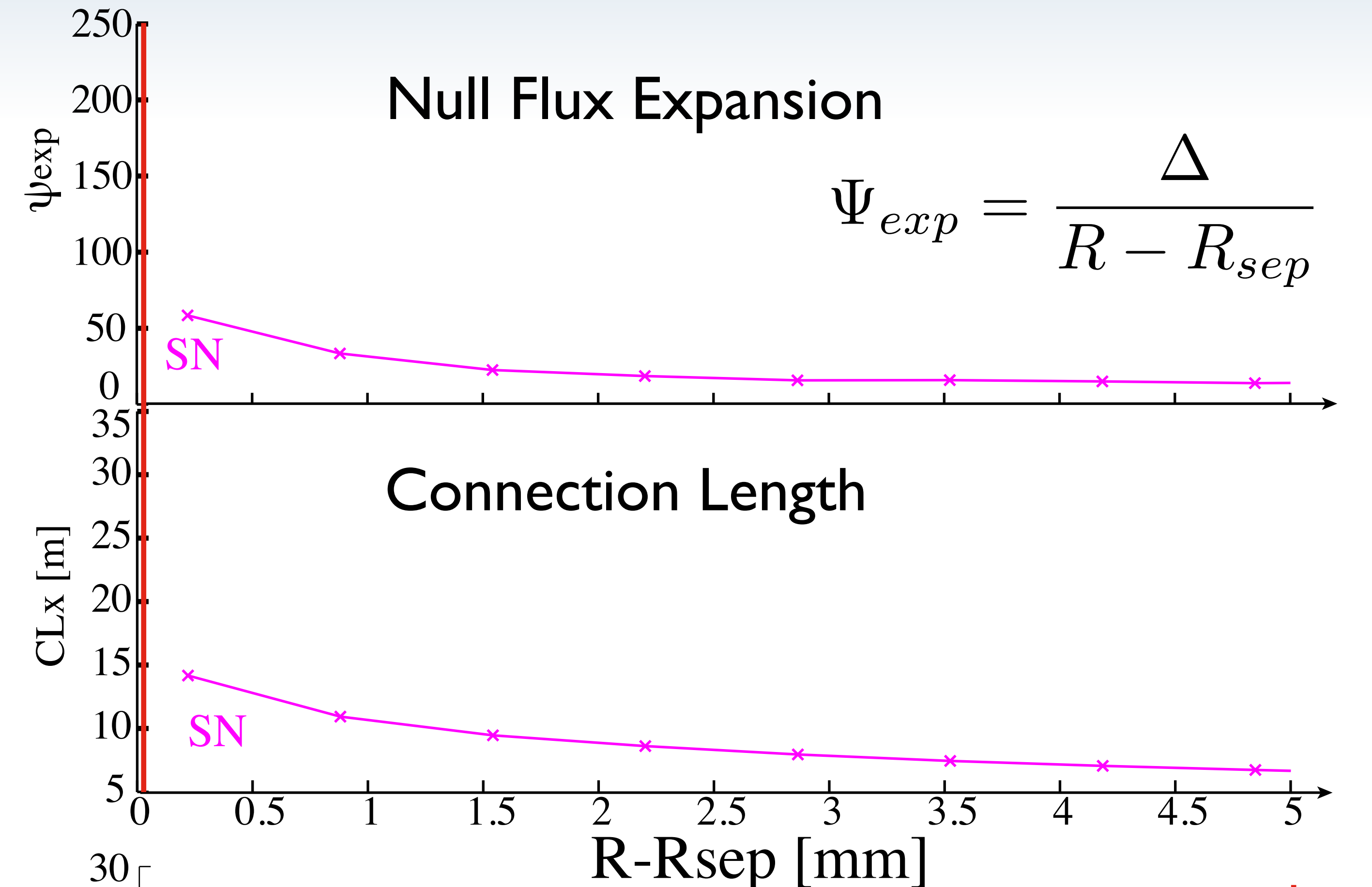
SN

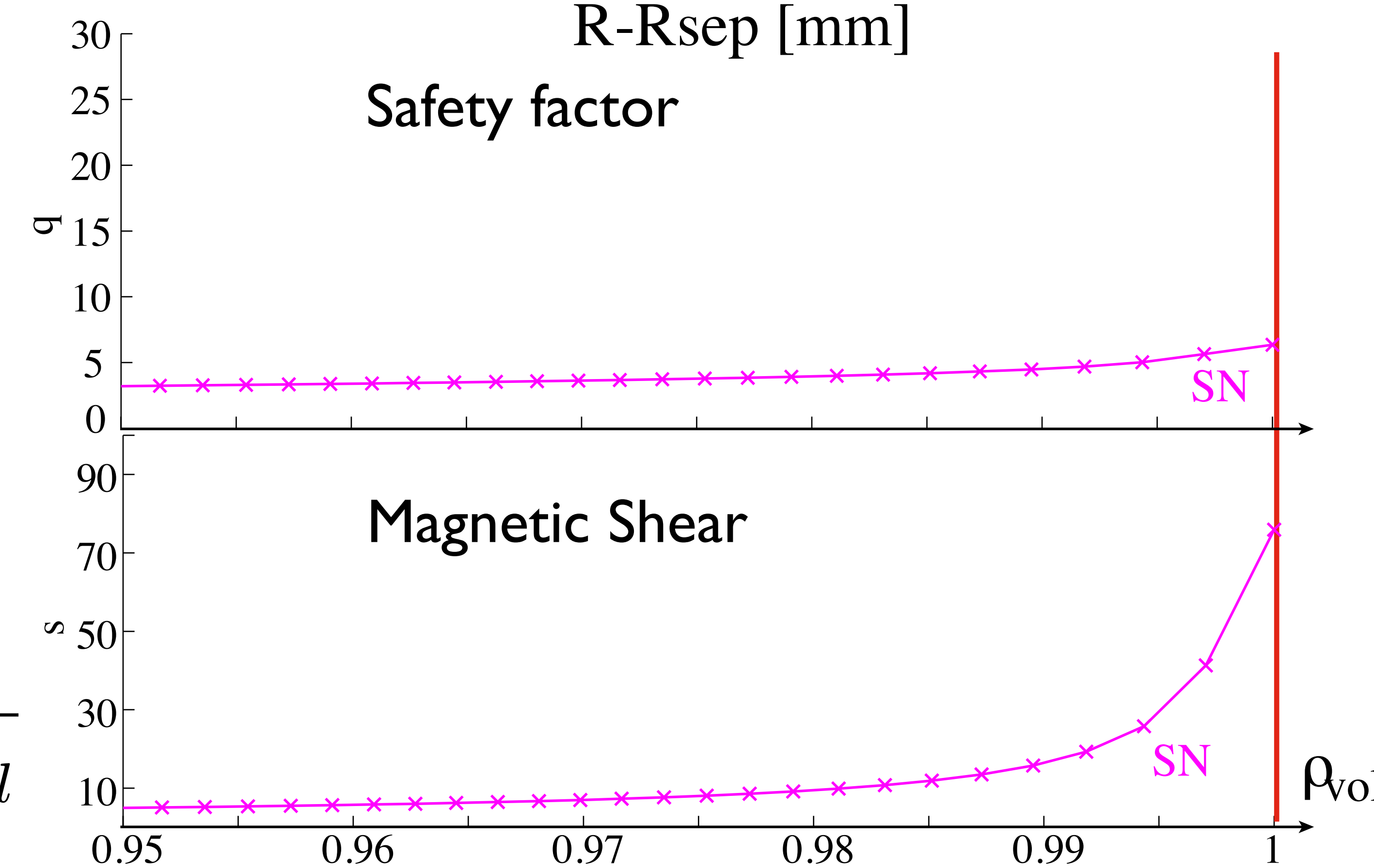
#35137,0.6004s





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





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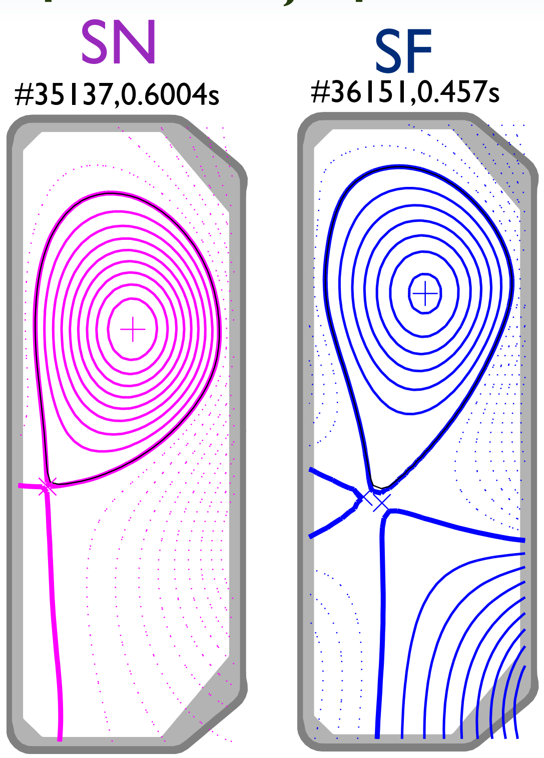
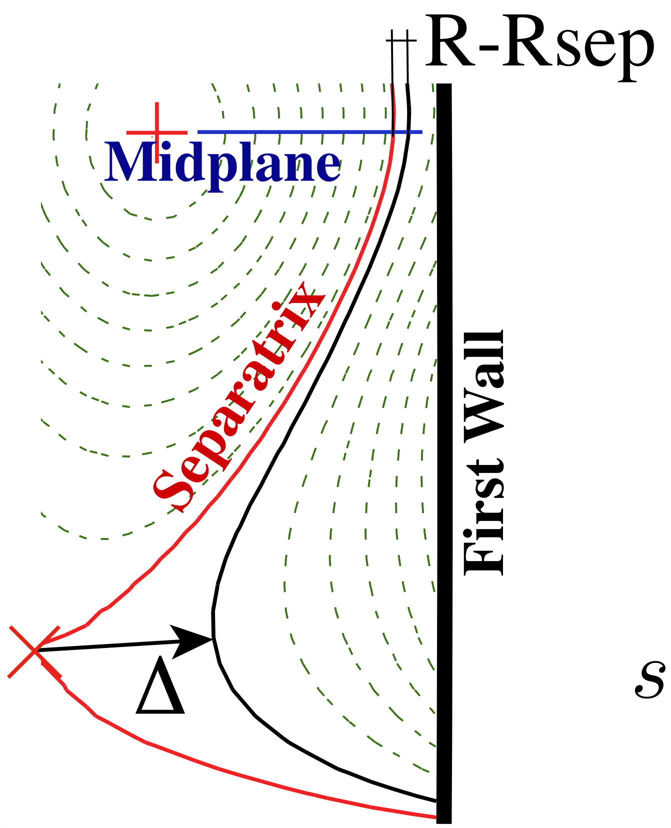


σ=15%



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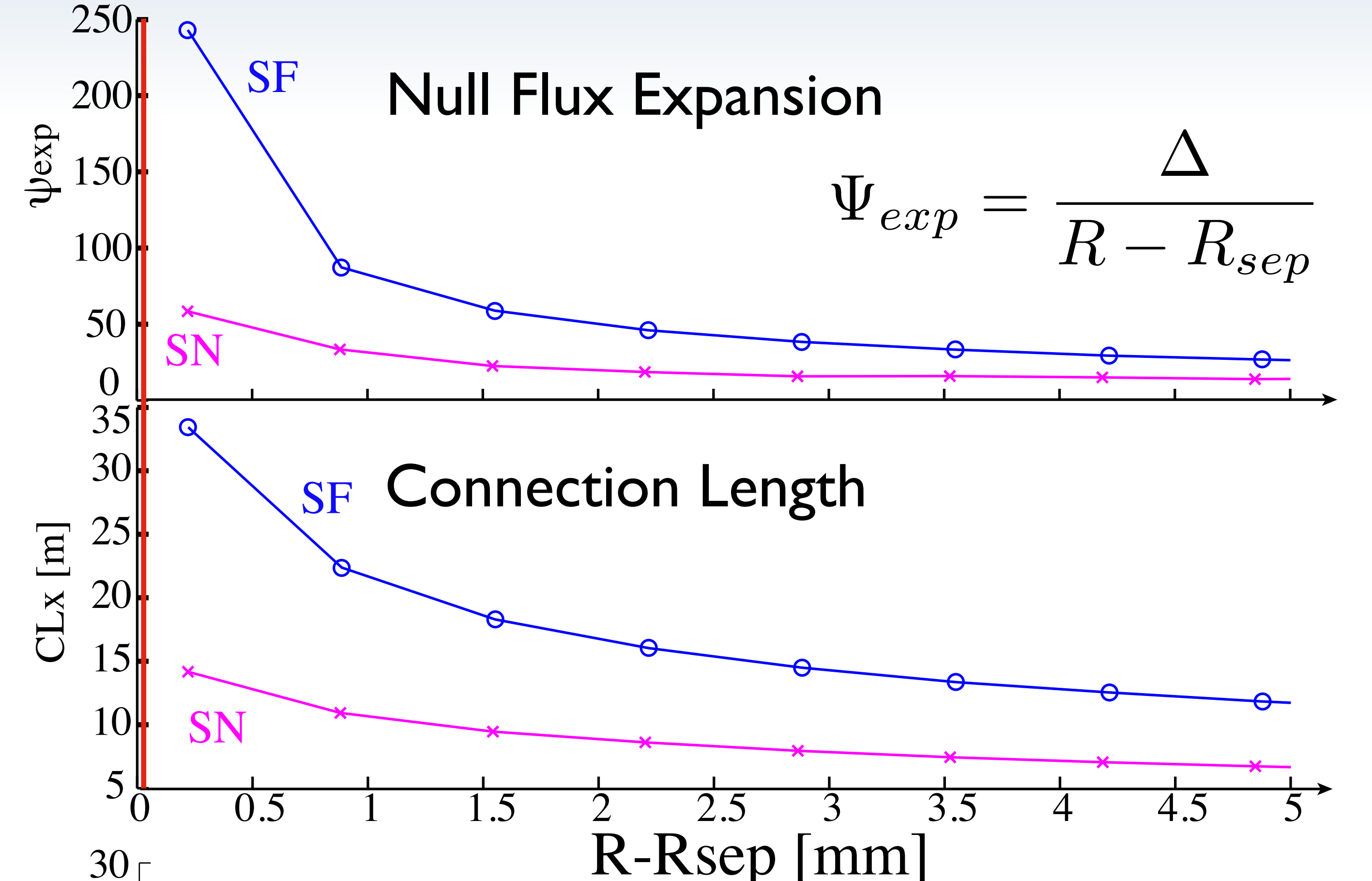

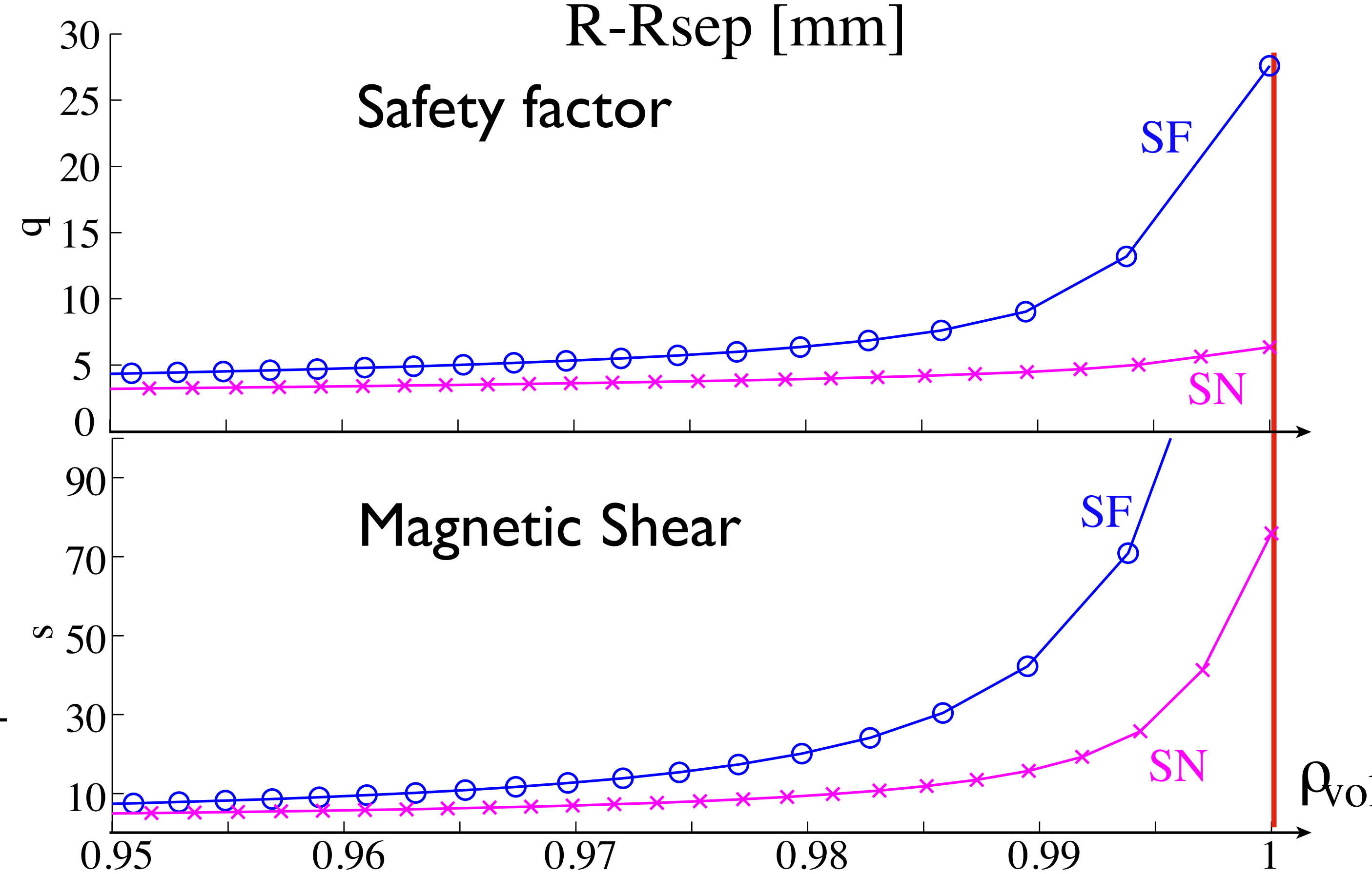

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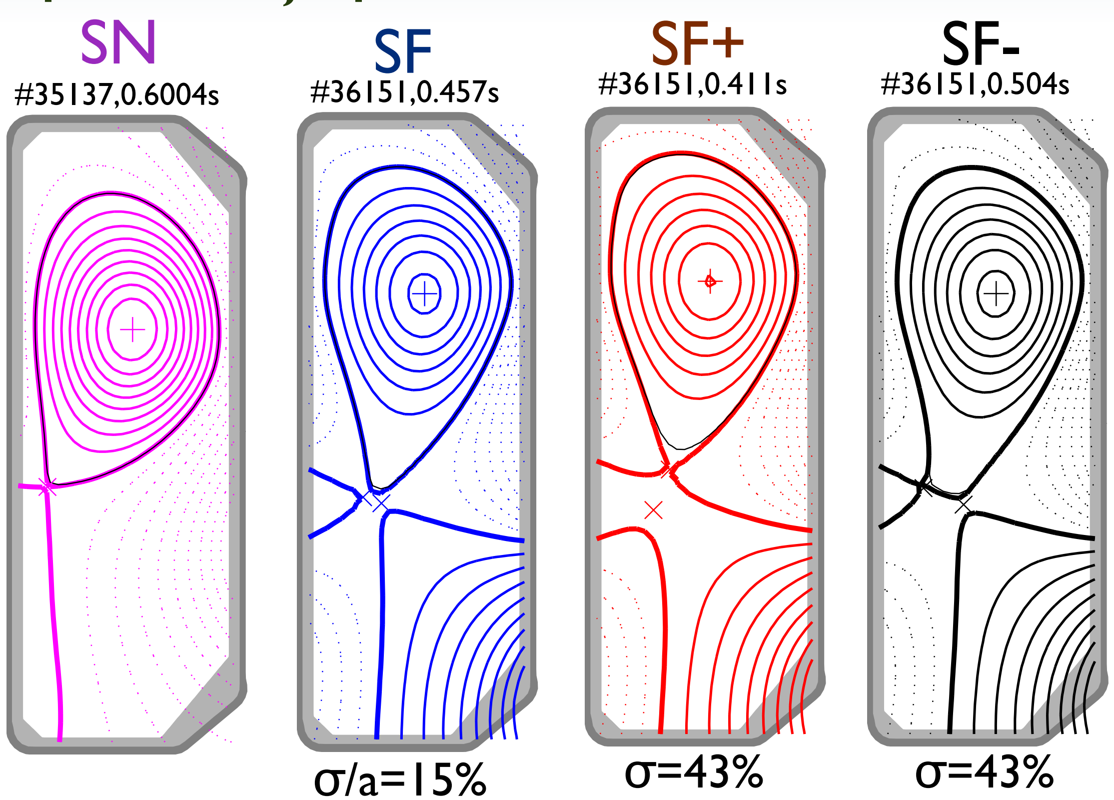

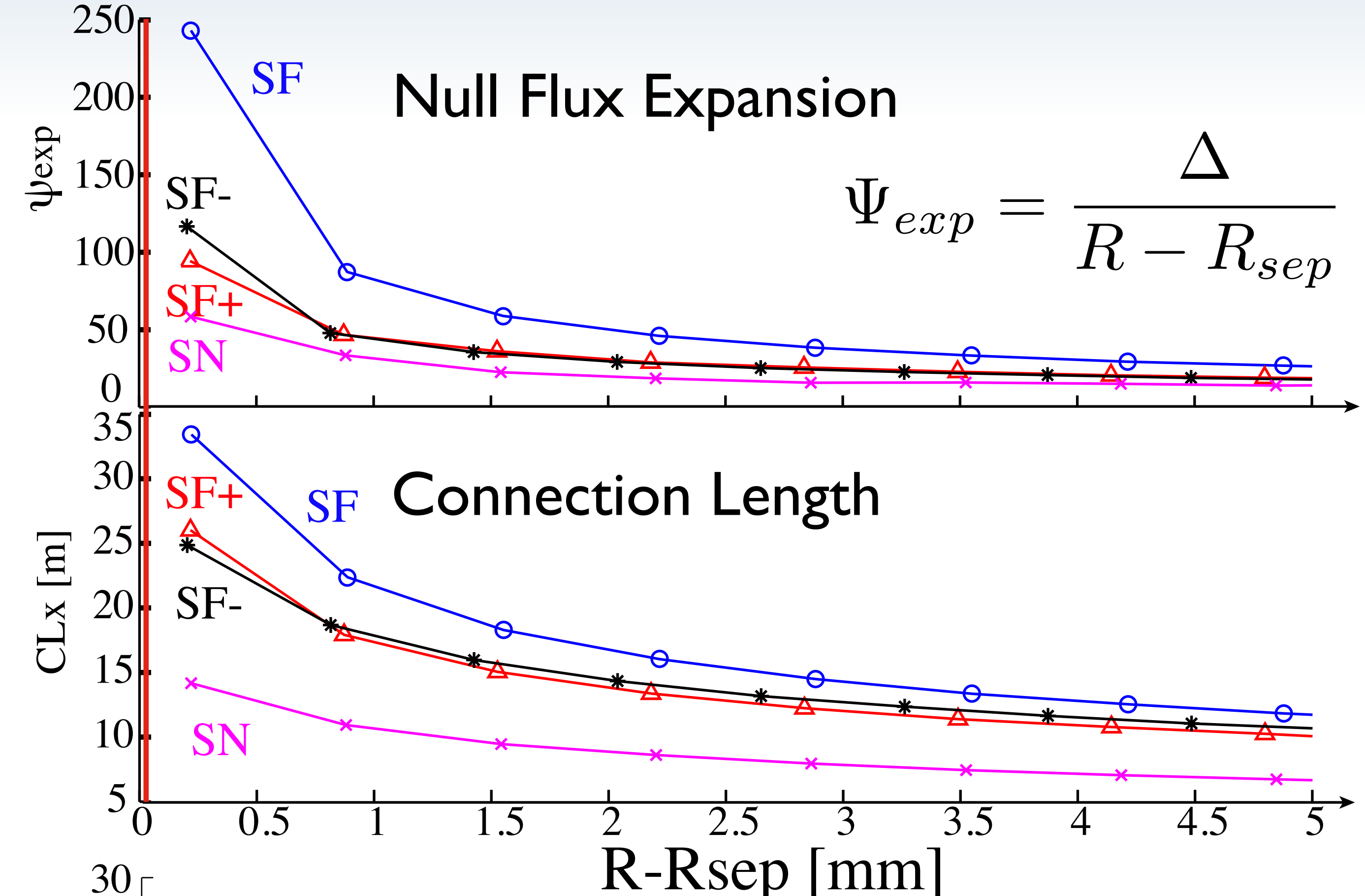

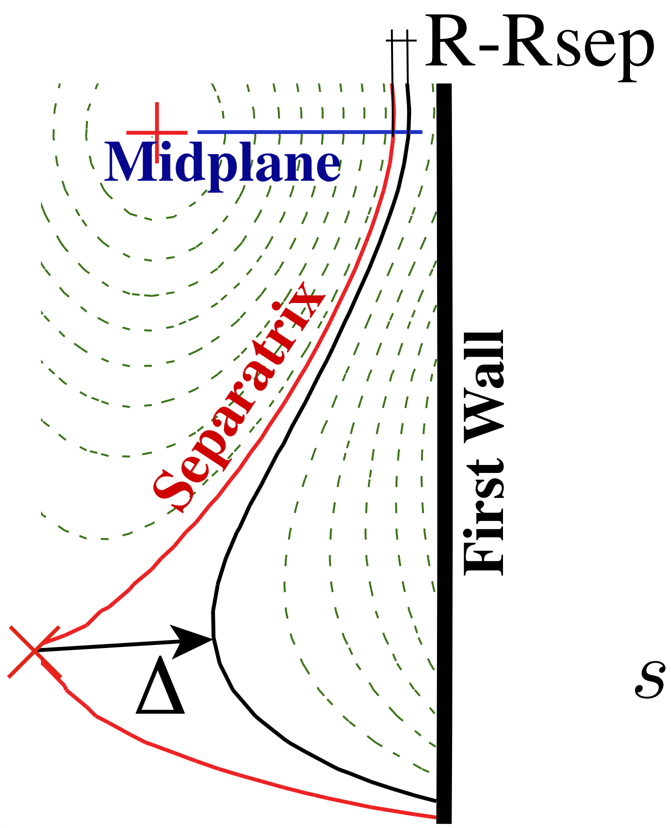

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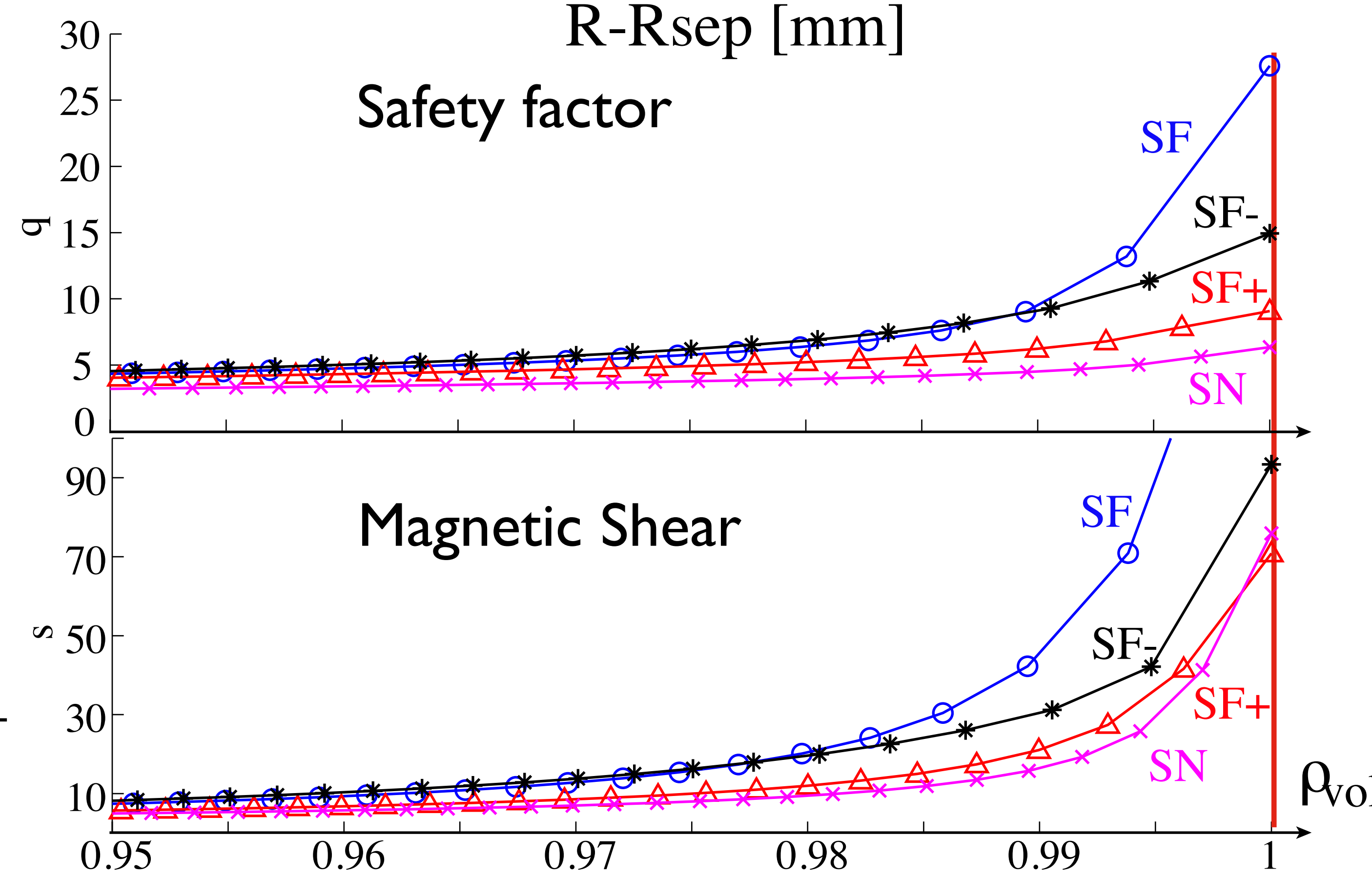


Exploring H-mode Snowflakes

Motivation:

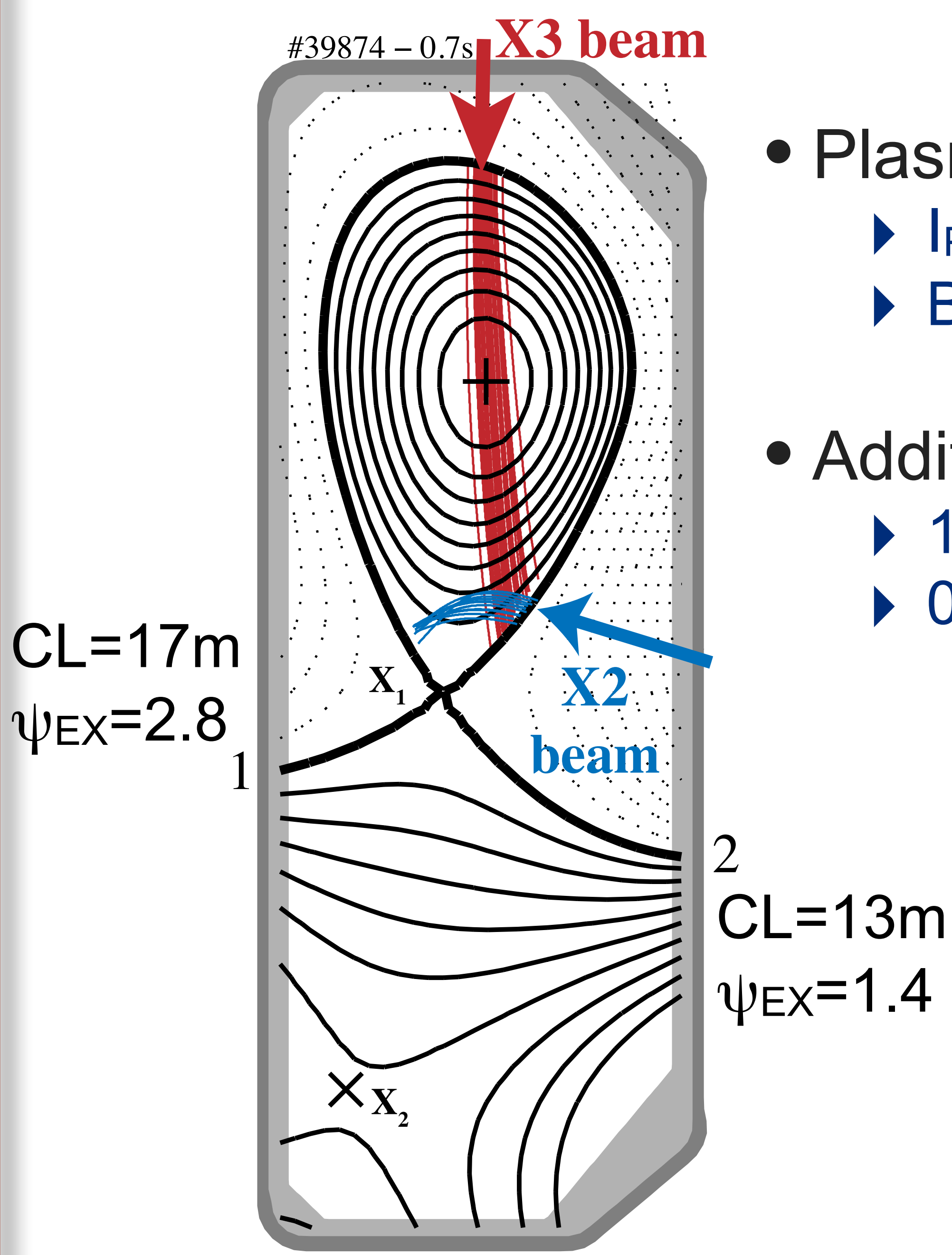
- The H-mode and ELMs are important in present and future tokamaks
- Do the different SF magnetic properties affect the H-mode?

Experiments:

- Can a SF divertor reach an ELMy H-mode?
- How do the ELM dynamics compare with a SN H-mode?

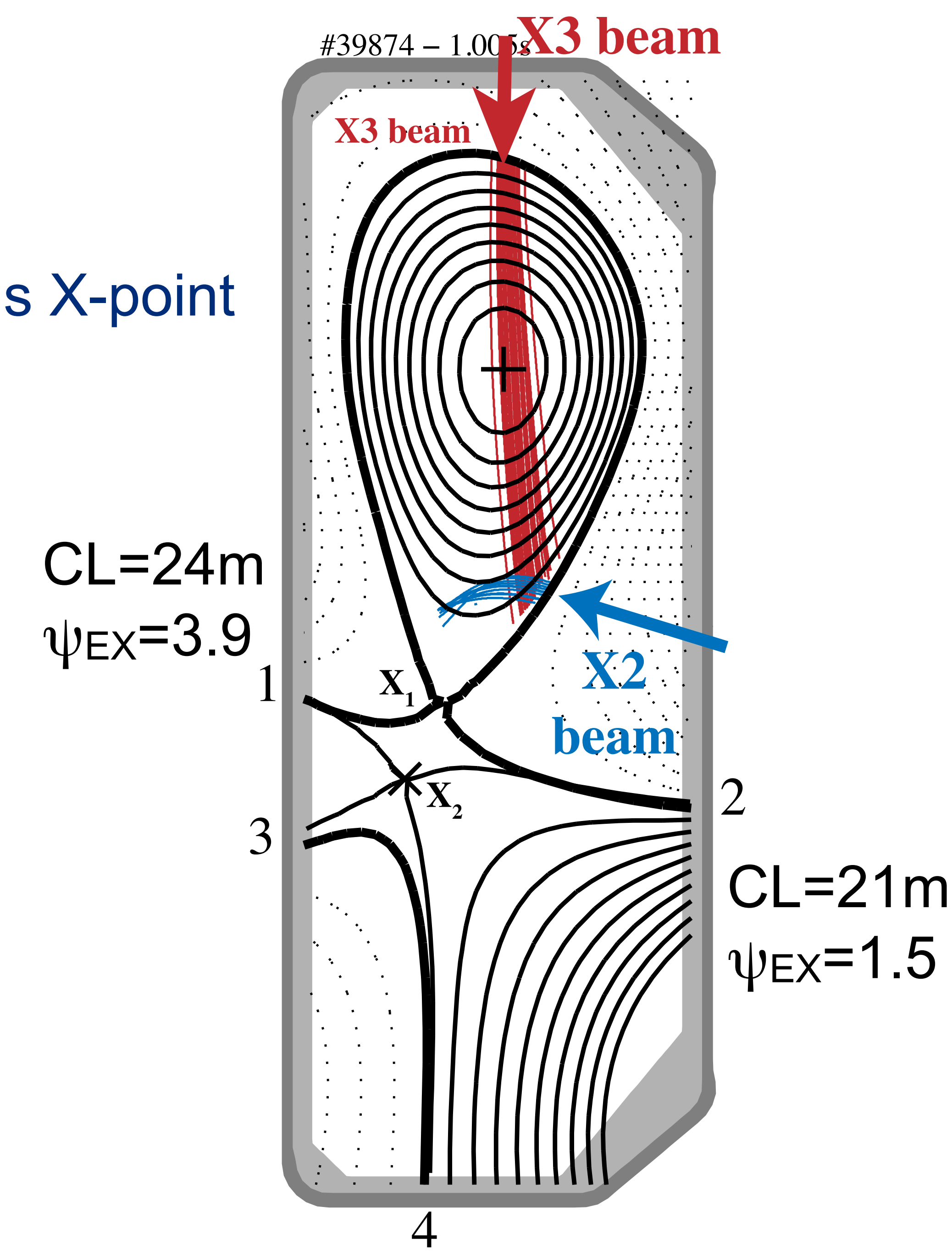
Tuning the Configurations

Comparison between SN and SF+ with similar plasma shape



SN σ=270%

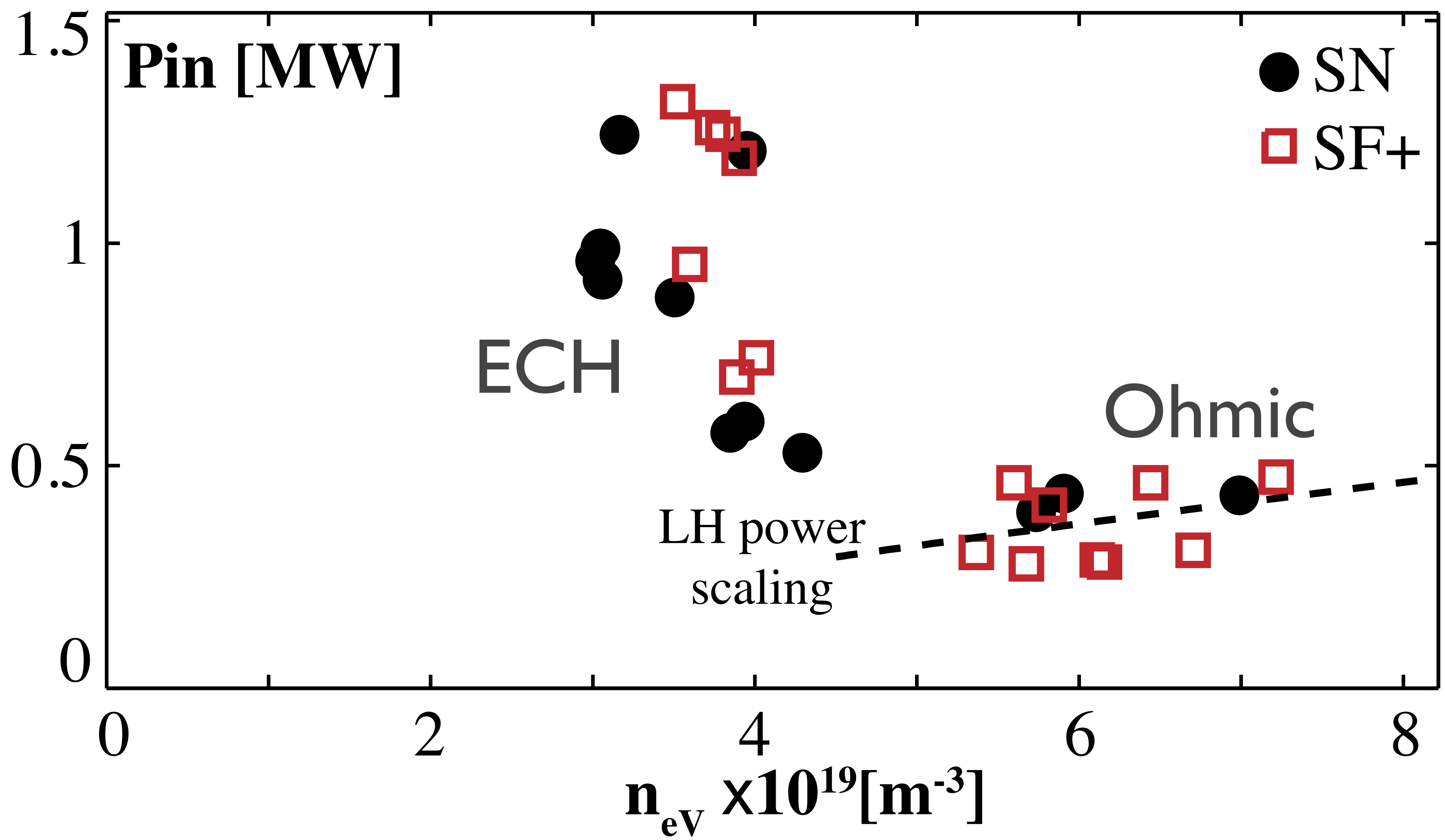
- Plasma properties
  - I_P = 300kA
  - Bx∇B ion-drift towards X-point
- Additional heating
  - 1MW ECH-X3
  - 0.5-1MW ECH-X2



SF+ σ=55%

Accessing the H-mode

Comparison SN and SF+



LH power threshold scaling

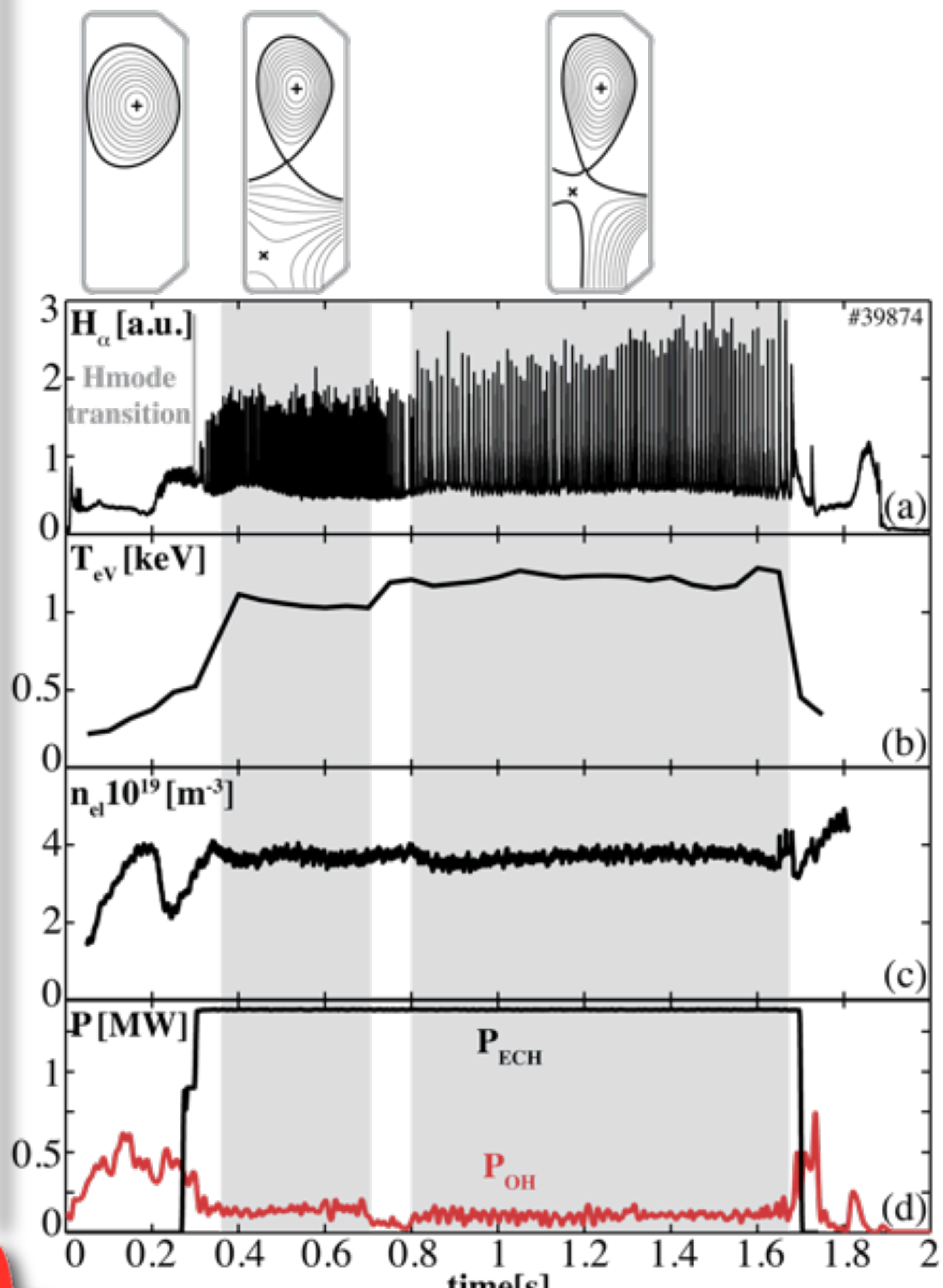
- Scan P_{in} to identify H-mode power threshold
  - Low density: a fraction of Pin from ECH
  - High density: only ohmic power (ECH cut-off)

Unchanged power threshold for Ohmic and ECH H-modes

F.Piras, PRL 2010

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%

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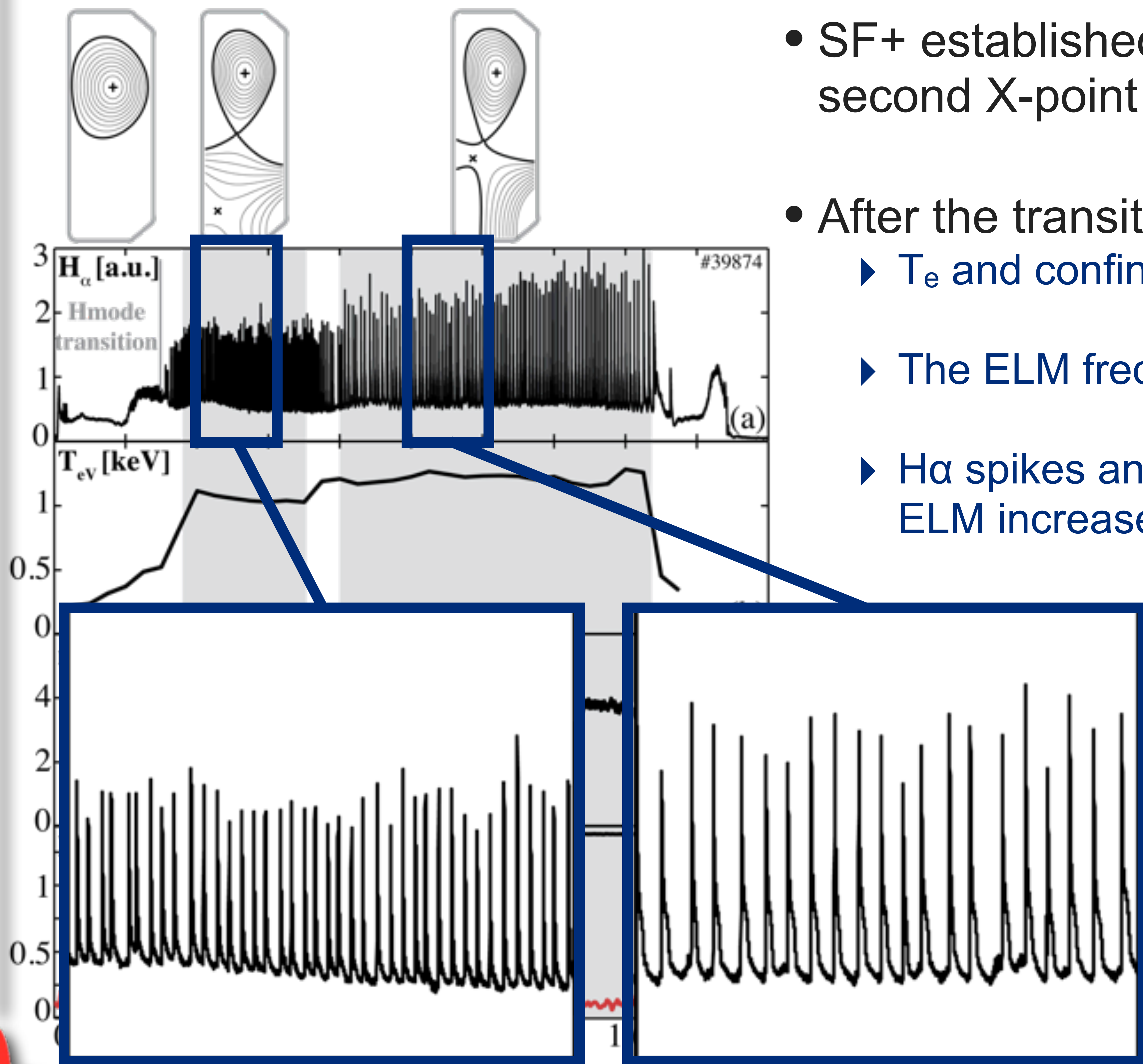

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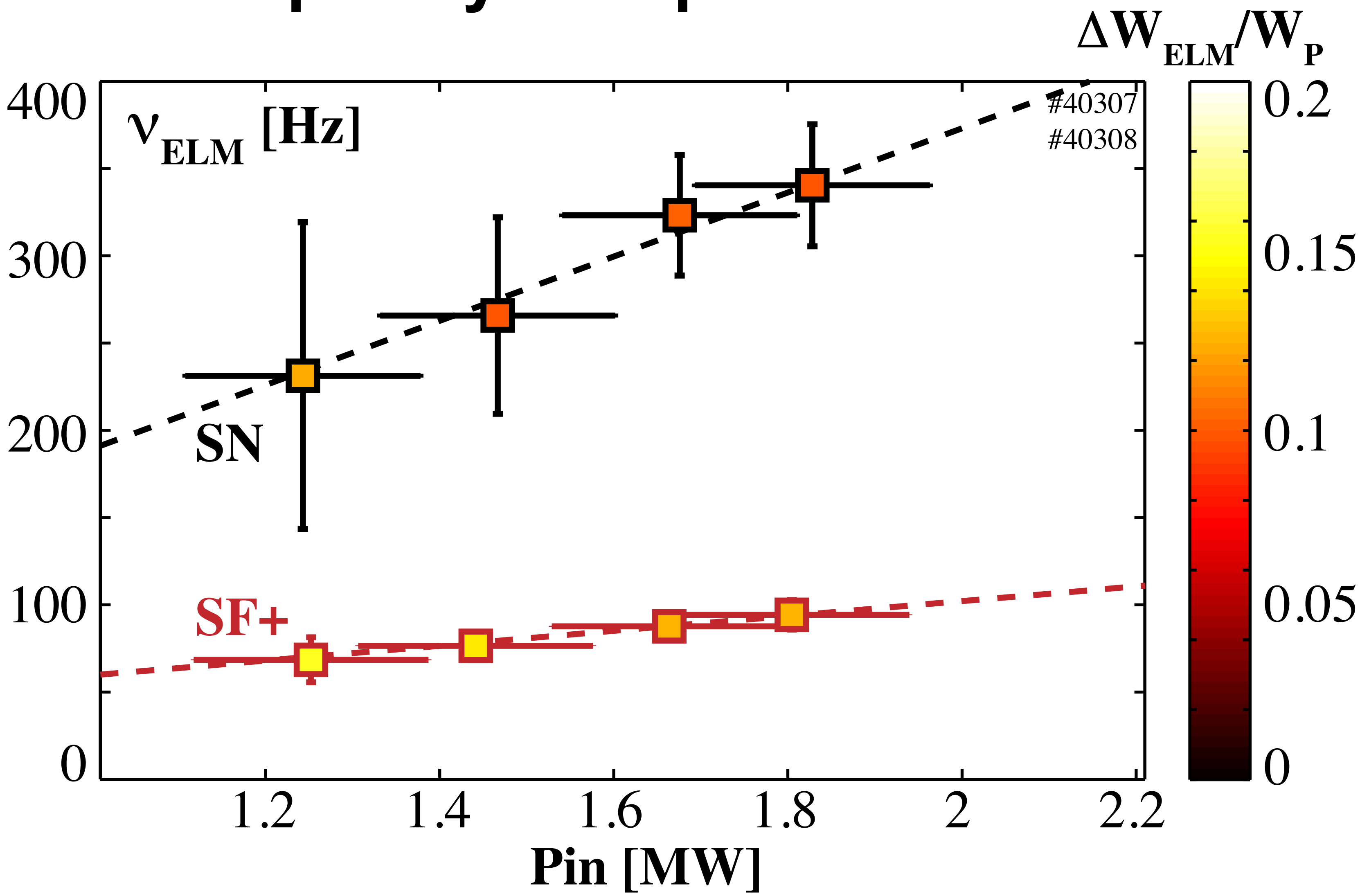
Snowflake Reduces ELM Frequency

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

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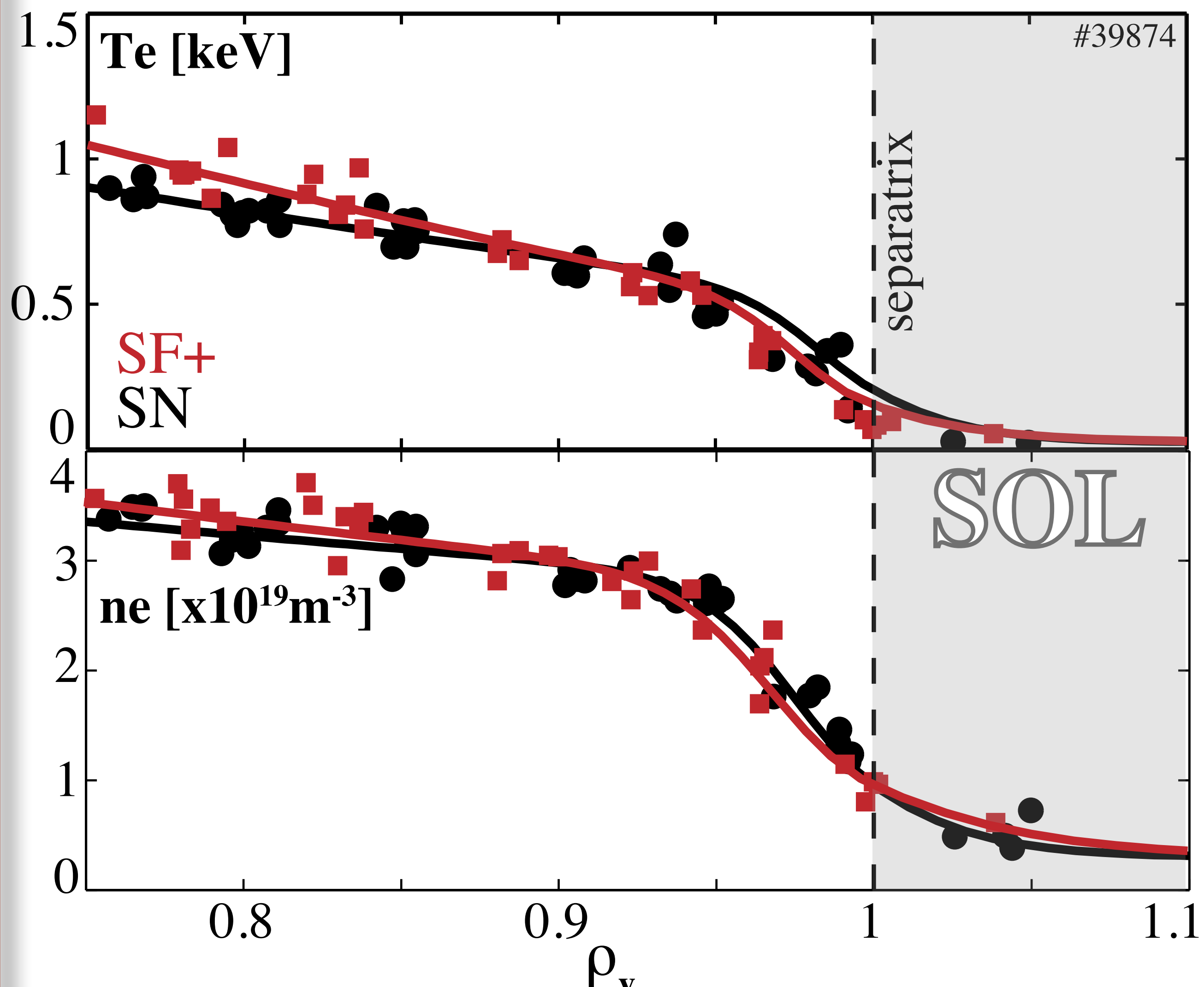
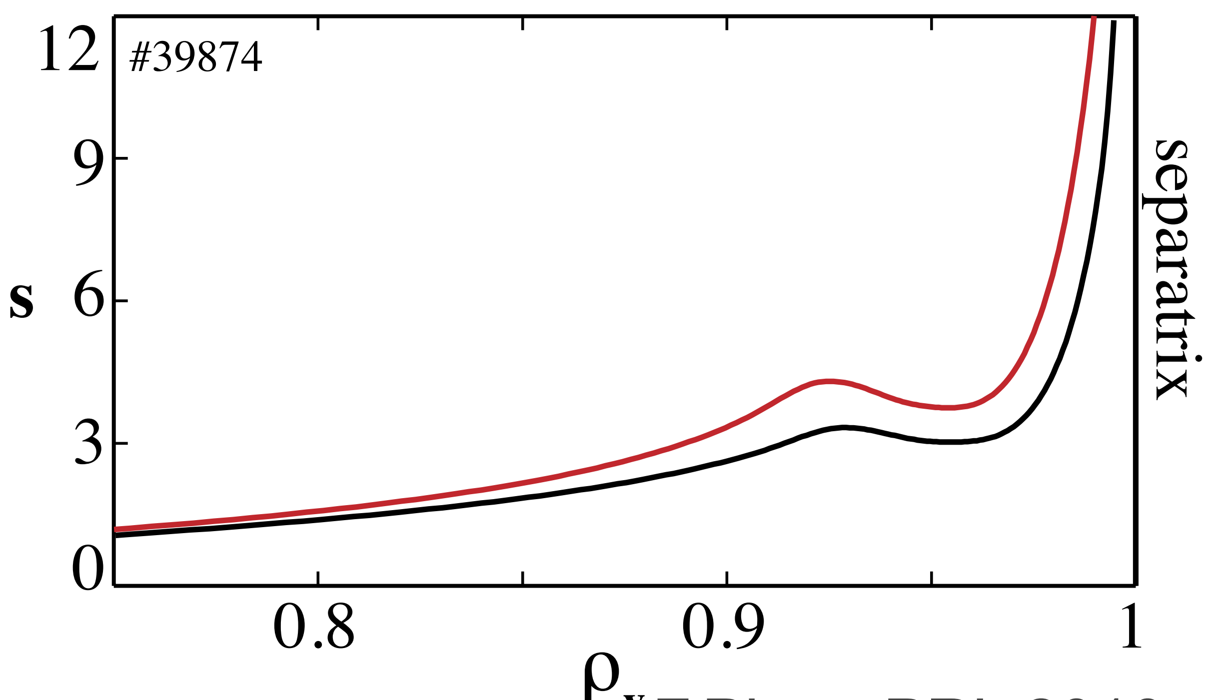
Similar Pedestal Profiles

Temperature and density profiles



- Similar T_e and n_e profiles from Thomson scattering



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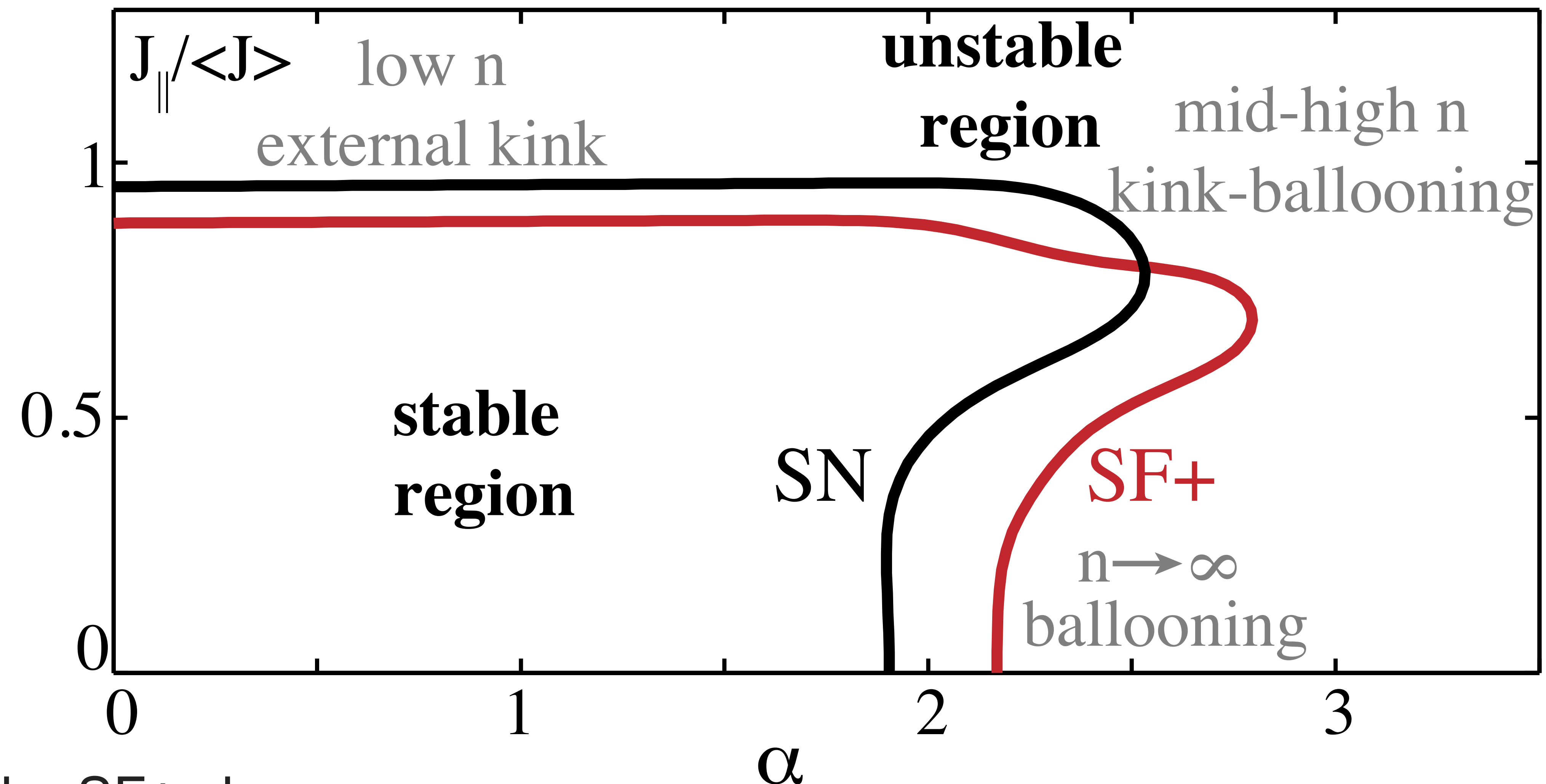
- Magnetic shear includes the bootstrap current
- SF+ has higher magnetic shear

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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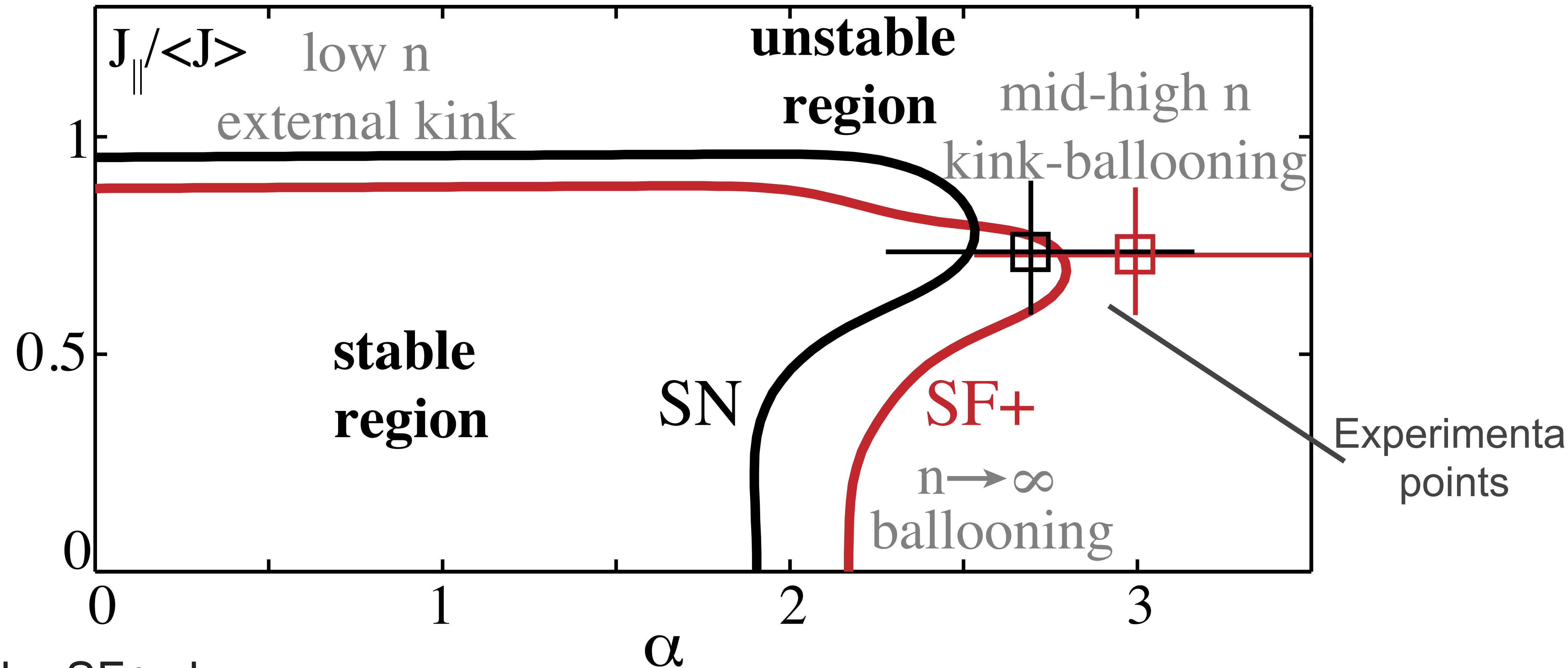

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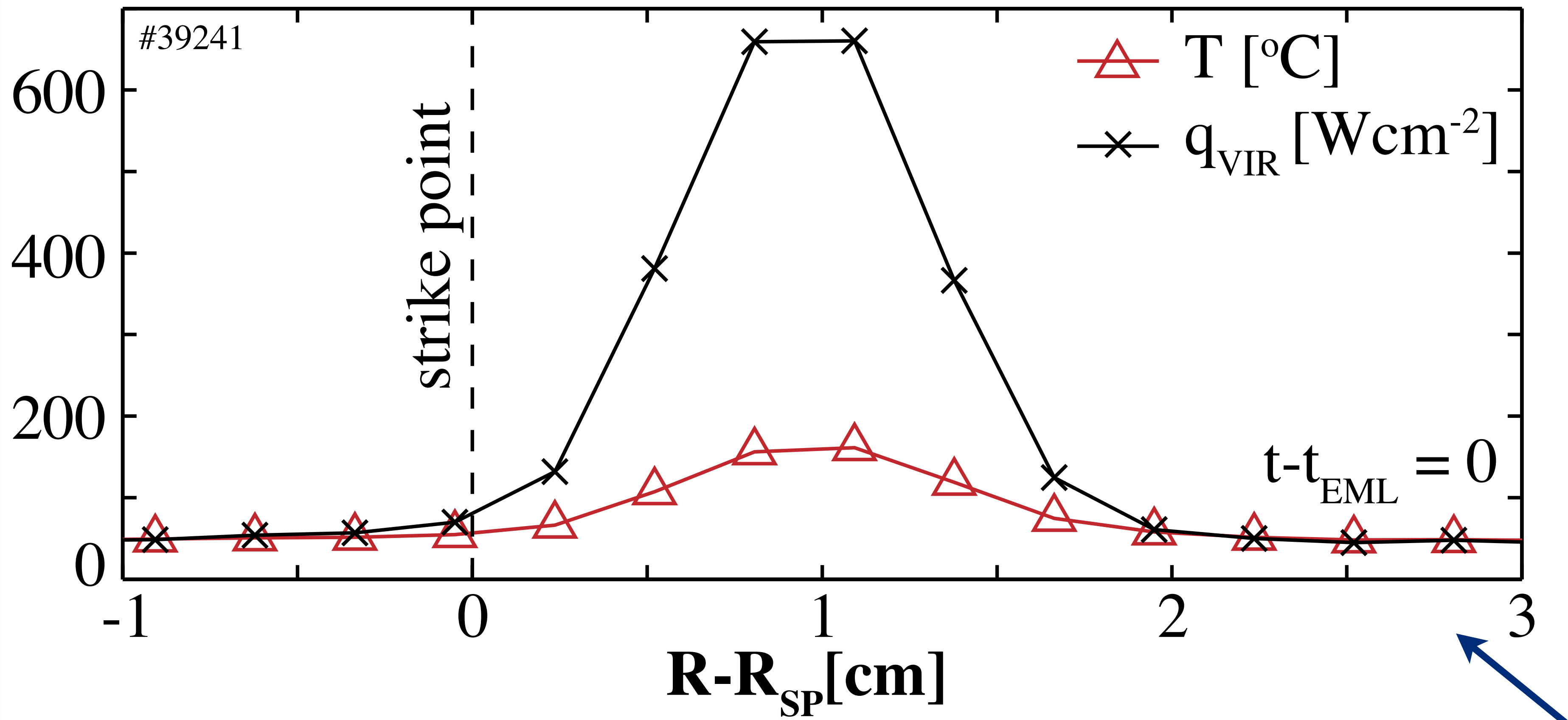
Conclusions

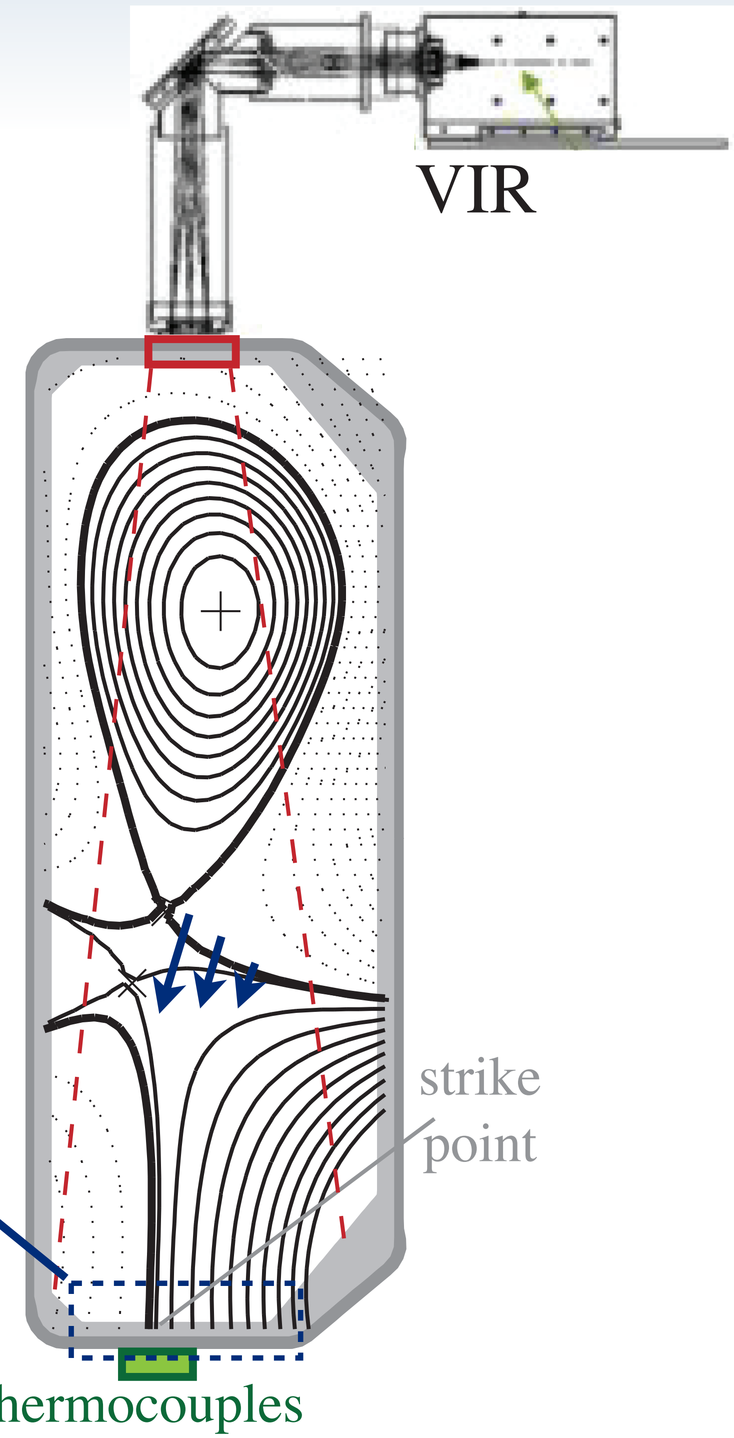
- The snowflake divertor has been established and controlled on TCV with:
  - Higher flux expansion, connection length and magnetic shear
- An ELMy Type I H-mode was established, showing:
  - Similar H-mode power threshold to single-null plasmas
  - ELM frequency reduced by 2-3, while energy lost per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

Strike Point Power Sharing

Vertical infrared camera profiles

- Coherently averaged ELM profiles

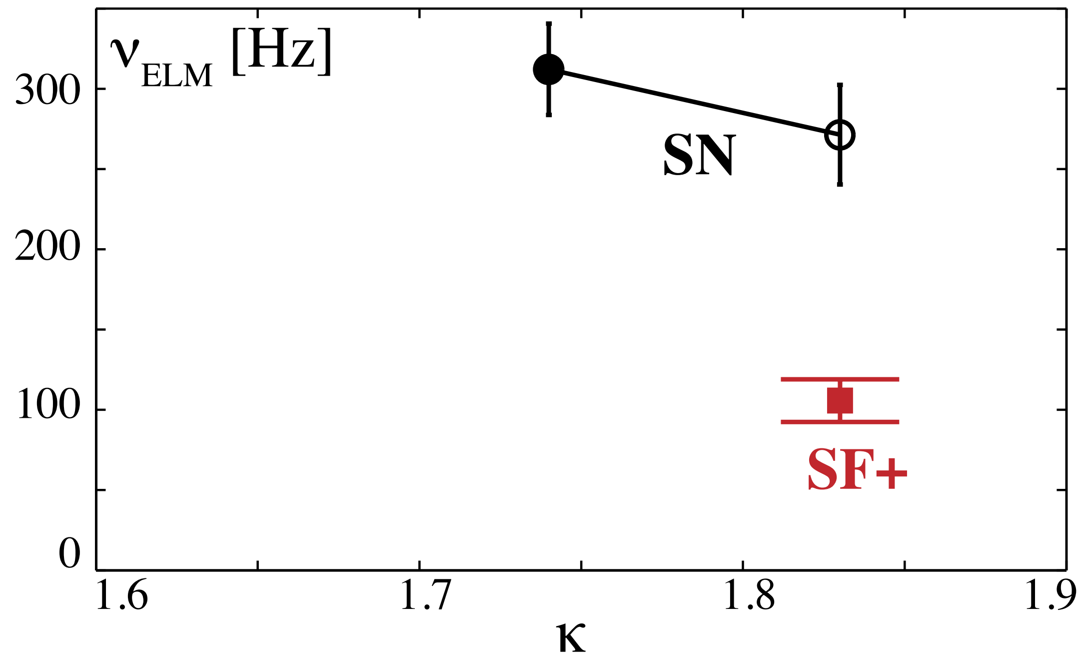




- 15% of ΔW_{ELM} reaches the bottom strike point
  - confirmed with thermocouples on divertor tiles
- Cross-field transport from the null region explains the measured profiles
- No significant profile broadening during ELMs

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