Systematic study of turbulence properties through reflectometry spectra

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INTRODUCTION

- Objective: Systematic study of turbulence properties from fluctuation reflectometer [1] data
- Motivation: discovery of general trend or global pattern
- Methodology: Decomposition of spectrum ➔ parameter reduction ➔ database

Parametrization of frequency spectra

Nonlinear curve fitting (or constrained optimization): $S_{fit} = C_{DC} + C_{LF} + C_{BB} + C_N$

- Decomposition of frequency spectrum
  - The direct current (DC) component
  - The low-frequency (LF) fluctuations
    - ← MHD, ZFs, …
  - The broadband (BB) fluctuations
    - ← **turbulence**
  - The noise (N) level: constant

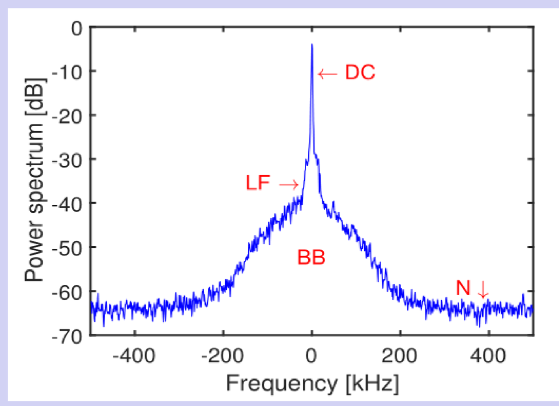

Figure 1. Typical spectrum with different components.

- Fitting functions:
  - DC & LF components: Gaussian functions
  - The BB turbulence: 2 options
    - ✓ The Generalized Gaussian (GG) function

$$C_{BB}{}^{GG} = A_{BB}\exp\left[-\left(\frac{|f-\mu_{BB}|}{\alpha_{BB}}\right)^{\beta_{BB}}\right]$$

    - ✓ FFT of the **Taylor function** [5]

$$C_{BB}{}^{Taylor} = A_{BB} \times FFT\{\exp[-\Delta_{BB}(t-\tau_{BB}+e^{-t/\tau_{BB}})] \times \exp(\mu_{BB})\}$$

- Cost function (S: normalized spectrum, S_{fit}: fitting model, $lg = 10 \times log10$)

$$F_{cost} = 0.5 \times \frac{|lg(S_{fit}) - lg(S)|^2}{A_{lg}} + 0.5 \times |S_{fit} - S|^2,$$

$$A_{lg} = \int_{f_{min}}^{f_{max}} [\lg(S)]^2 df, S = S_0 / \int_{f_{min}}^{f_{max}} S_0(f)\, df$$

- Global convergence
  - ➔ **multiple initial guesses**

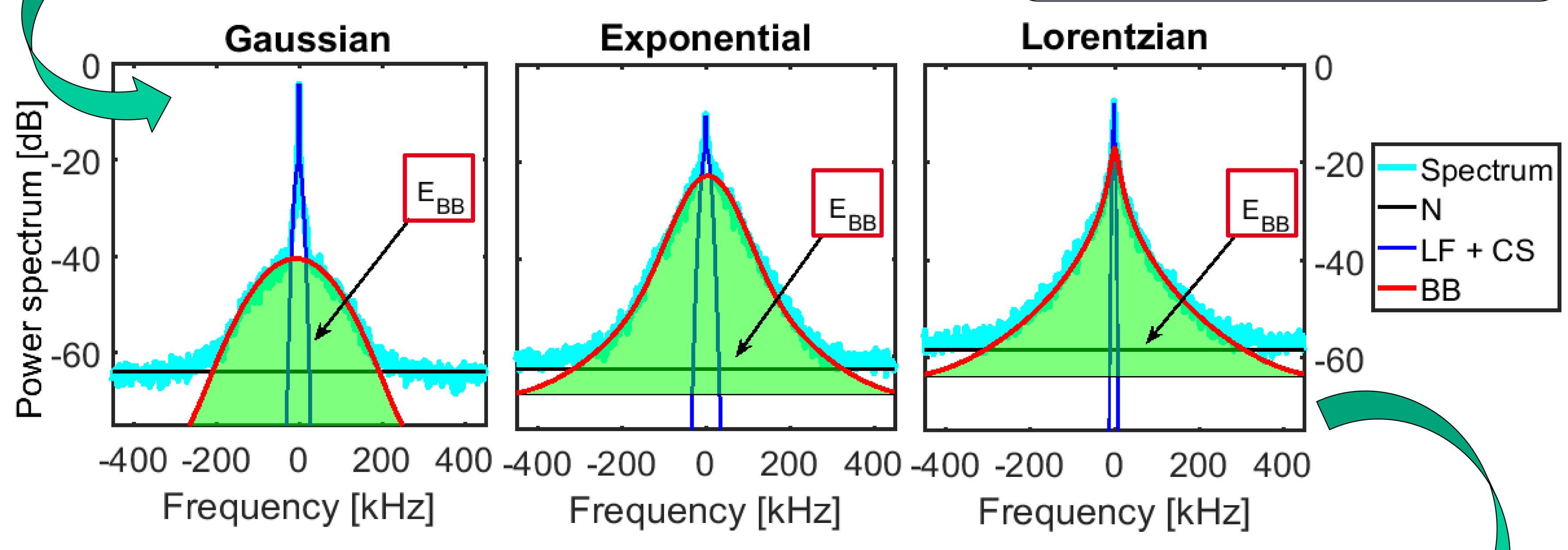

Figure 1. Typical spectra fits (Taylor function for the BB). FFT calculated over 1025 points and 50% overlap.

Database
- Includes **350,000** acquisitions from **6,000** Tore Supra discharges
- Contains Ohmic, ICRH, LH, limited ECRH plasmas
- Global ($B_t, I_p, \ldots$), local ($n_e, T_e, \ldots$) & diag. ($F, \rho_c \ldots$) parameters
- Turbulence properties ($\boldsymbol{E_{BB}}, W_{BB}, \ldots$)

Ohmic plasmas: broadband contribution drops in the core

- Drop from E_{BB}>30% outside $\rho_{q=1}$ to E_{BB}<10% in the core (Fig. 2).
- The E_{BB} basin location (Fig. 2) and width (Fig. 3) linked to the q=1 surface.

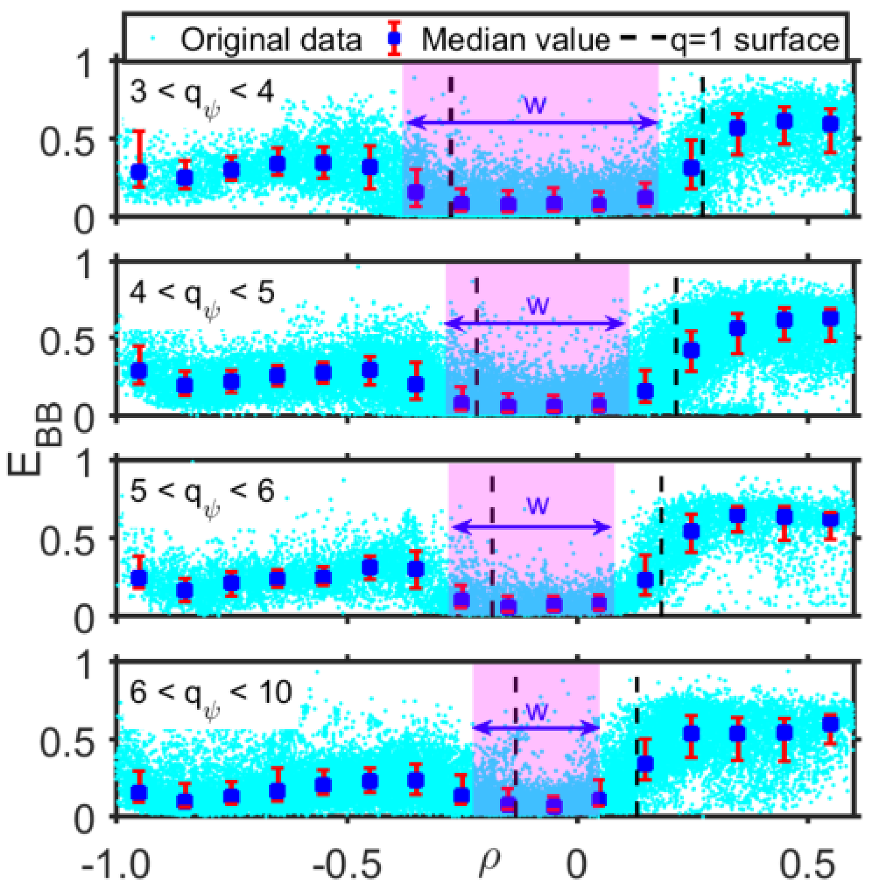

Figure 2. Radial profiles of E_{BB} for different q_ψ. The median value is calculated from a small radial interval. The BB basin is indicated by the shaded area with basin width indicated by w.

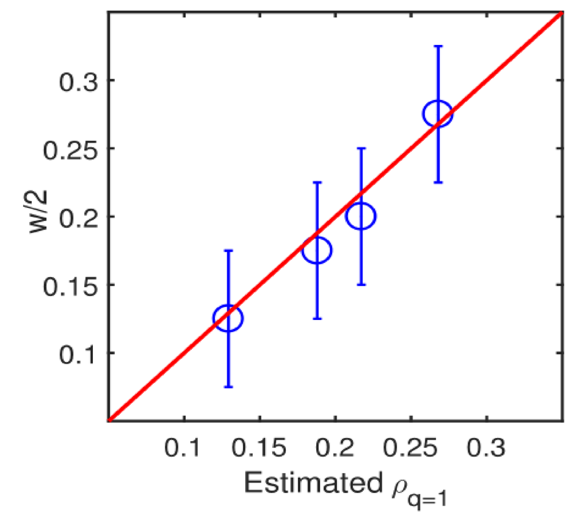

Figure 3. Half-width of E_{BB} basin vs q=1 position

- The systematic radial shift toward the HFS w.r.t $\rho_{q=1}$ may be due to an underestimation of the core density profile measured by interferometry (Fig. 4).

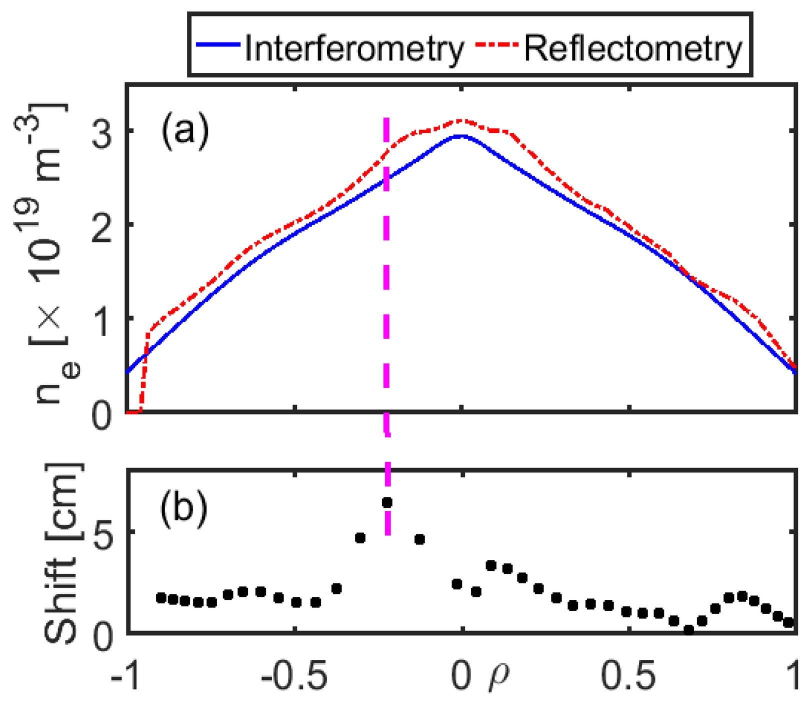

Figure 4. (a) Density profiles and (b) Difference of the cutoff positions from interferometry w.r.t. reflectometry at different radial positions.

Higher broadband contribution in SOC than LOC

- The global trend of E_{BB} remains in LOC and SOC regimes.
- In all radial positions, $E_{BB}{}^{SOC} > E_{BB}{}^{LOC}$.

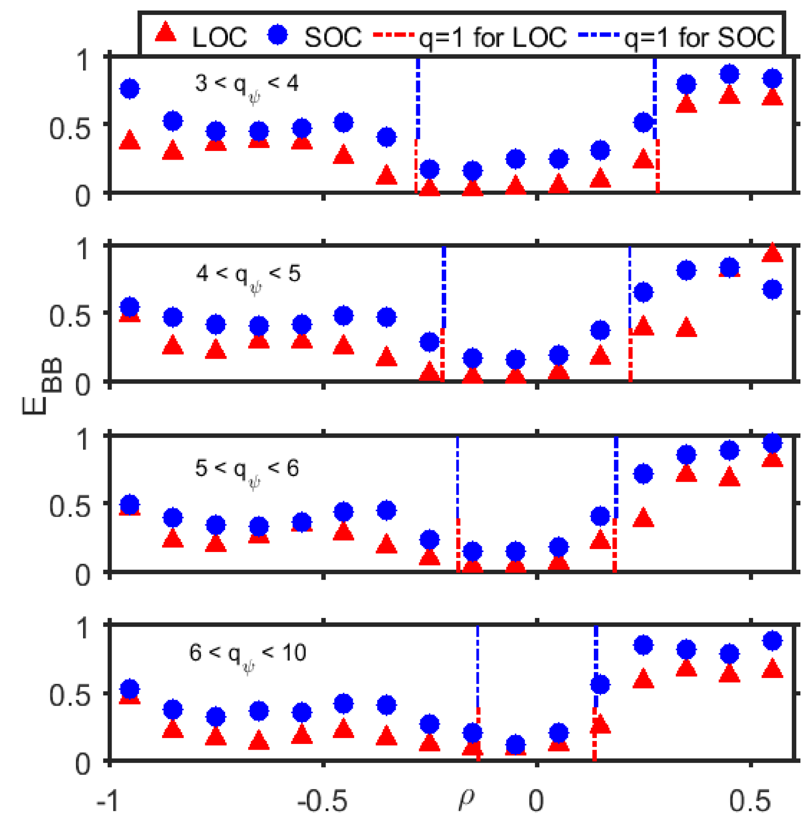

Figure 5. Radial profiles of E_{BB} for different q_ψ in LOC & SOC.

- Within the E_{BB} basin
  - LOC: E_{BB} ↗ with q_ψ ↗
  - SOC: E_{BB} ↘ with q_ψ ↗

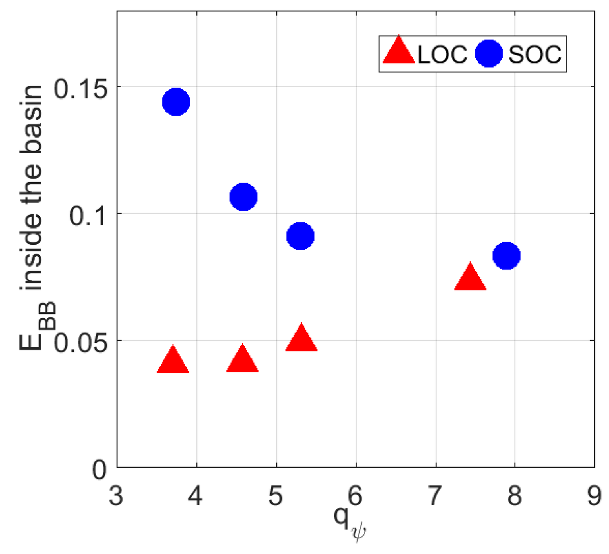

Figure 6. Evolution of E_{BB} within the E_{BB} basin w.r.t. q_ψ.

Evolution of the E_{BB} basin with increasing P_{ICRH} & P_{LH}

- Within the basin, E_{BB} ↗ with P_{ICRH} ↗ (Fig. 7a).
- The basin disappears at high P_{ICRH} (very weak basin above 2.5 MW in Fig. 7a).
- The E_{BB} basin remains even for $P_{LH} > 3$ MW (Fig. 7b).
- Large scatter of E_{BB} might be linked to the turbulence evolution during the sawteeth activity, which needs further study.

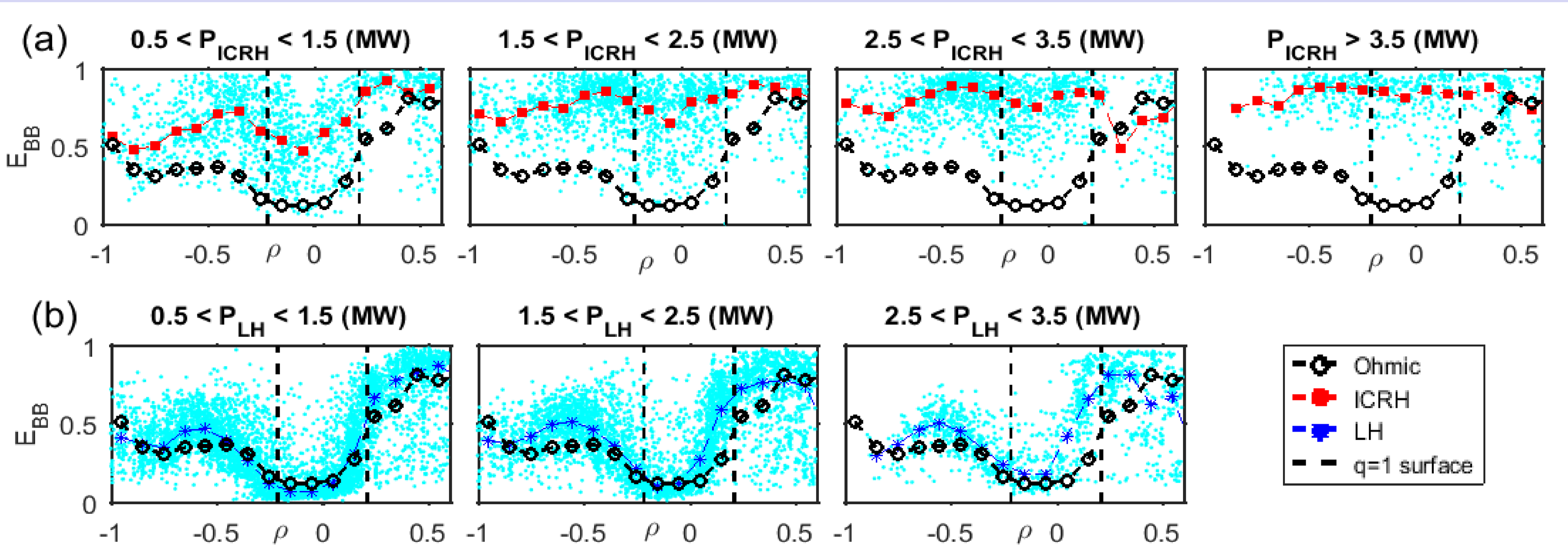

Figure 7. Radial profiles of E_{BB} with increasing ICRH and LH power under the condition $4 < q_\psi < 5$.

- The radial profiles of E_{BB} recover in a systematic study (Fig. 8) the observations as in the Ohmic, ICRH & LH dedicated shots (Fig. 9).

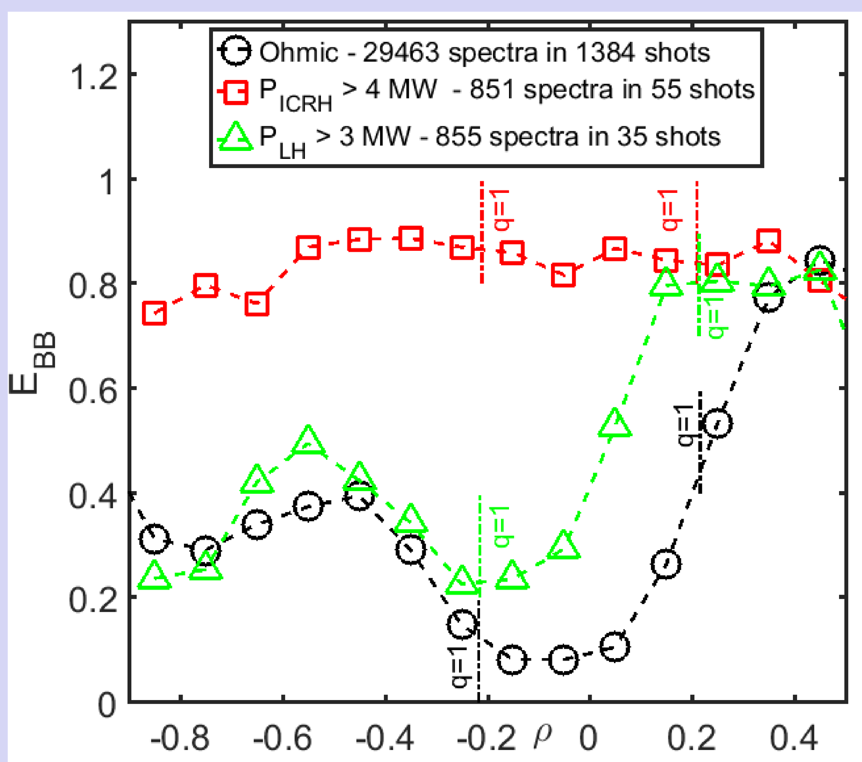

Figure 8. Radial profiles of E_{BB} in Ohmic, ICRH and LH plasmas.

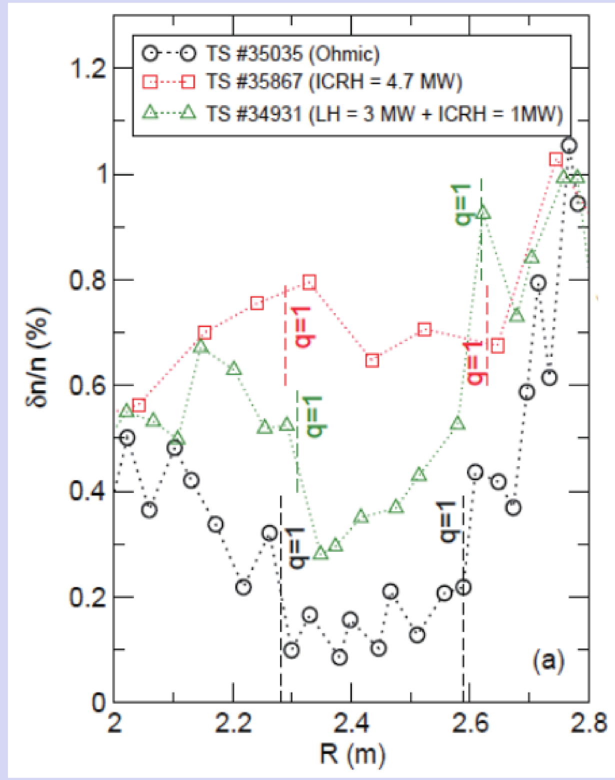

Figure 9. Fluctuation level calculated from typical discharges. In Ohmic, ICRH and LH plasmas. Reprinted from [6].

- The evaluation of $\delta n/n$ from the decomposition components is underway.

CONCLUSION

- ❖ The broadband contribution (E_{BB}) from the decomposition of turbulence spectrum drops in the core and its location and width are linked to the q=1 surface in Tore Supra database.
- ❖ In Ohmic plasmas, E_{BB} is higher in SOC regime than in LOC regime.
- ❖ Inside the basin, E_{BB} trend w.r.t. q_ψ is opposite for LOC (↗) and SOC (↘).
- ❖ The E_{BB} increases much faster with P_{ICRH} than with P_{LH}.
- ❖ The basin disappears for moderate P_{ICRH} while it remains at higher P_{LH}.

References

[1] R. Sabot, A. Sirinelli, J.-M. Chareau, and J.-C. Giacalone, Nucl. Fusion **46**, S685 (2006)
[2] V. A. Vershkov *et al*., Nuclear Fusion **51**, 094019 (2011)
[3] A. Krämer-Flecken *et al*., New Journal of Physics **17**, 073007 (2015)
[4] Y. Sun, R. Sabot, G. Hornung, S. Heuraux, S. Hacquin, and G. Verdoolaege, "Parametrization of reflectometry fluctuation frequency spectra for systematic study of fusion plasma turbulence," (submitted RSI)
[5] P. Hennequin *et al*., in 26th EPS Conf. on Contr. Fusion and Plasma, Vol. 23J (1999) pp. 977 – 980
[6] A. Sirinelli, PhD Thesis (2006)