Experiments in LHD of large importance for the W7-X program (EF Mission 8) --**What is left to do?**

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Motivation and purpose of this presentation

- LHD is a mature stellarator, comparable to W7-X in size and parameters, that might be approaching its shut-down.
- The accumulated **body of knowledge from LHD** is of enormous value for a young project like W7-X.
- The following question appears timely and necessary:
  - *Are there blanks in that body of knowledge of particular importance for the WPW7X that we could fill in the coming years?*
- In these slides we point out some of the areas of particular importance where additional experiments could be proposed.
  - Disclaimer: an exhaustive revision of the scientific literature needs to be conducted to assess the degree of completion of each area.

Access to high beta low collisionality regimes at reduced field.

Description	According to the energy confinement scalings, it should be possible to achieve FFHR2m2 beta/nu values in LHD at 1T with P=22MW and ne=5e19. The experiment should target those values and examine confinement degradation and or MHD activity that prevents from achieving the expected values.
Relevance for M8	One the of milestones of M8 in FP9 is the high-beta, low-collisionality W7-X operation. With the foreseeable increase of heating power this appears mots likely at reduced field (1.7T). LHD has operated at 1T with ~4% beta but only high-nu. The identification of obstacles to achieve high-beta/low-nu and whether or not they are Heliotron-specific is important.
Ref.	https://doi.org/10.1088/1741-4326/aa65aa

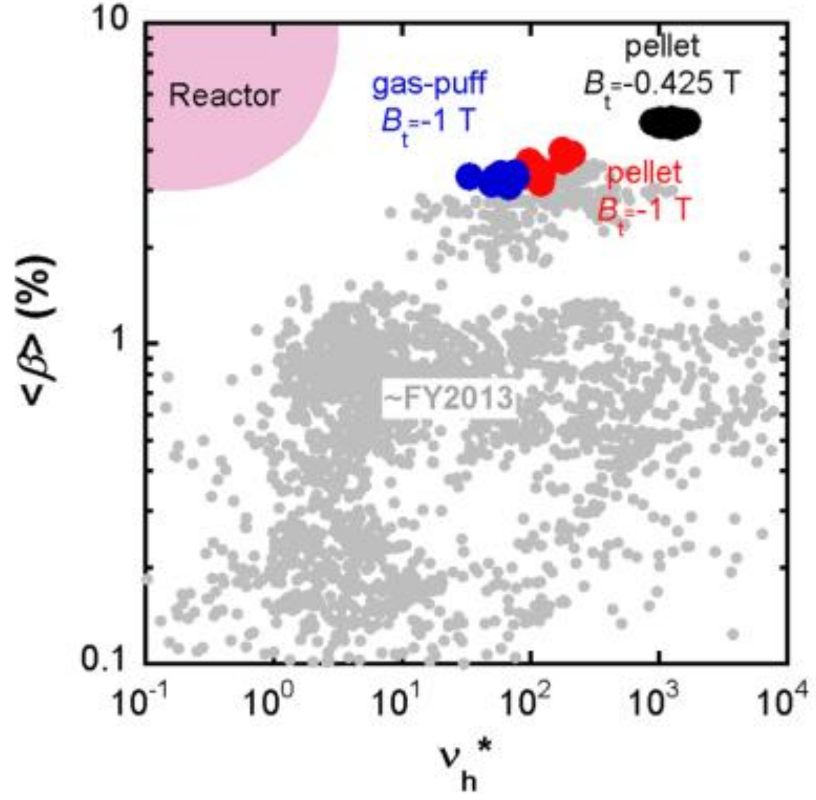


Figure 1. Operational regime of averaged beta as a function of normalized collisionality.

Start-up and plasma sustainment at reduced field

Description	Produce and characterise a plasma with ICRH, aiming at values that could provide a adequate plasma for subsequent NBI and/or ECRH X3 plasma sustainment.
Relevance for M8	See previous slide.
Ref.	

Characterisation and physics description of operational limits

Description	Identify the causes of the several operational boundaries in LHD (radiation, currents/MHD, heating...) and its implication for the W7-X. (Also the absences of limits otherwise expected on theoretical grounds!).
Relevance for M8	In today's devices, the most limiting operational boundary is the density or "Sudo" limit, which is related to the radiative power balance with low-Z (C, O) impurities with peripheral radiation. This limit is however or lesser importance in a burning plasmas with strong self-heating and different wall elements. A more profound physics understanding is required for extrapolation. The relevance of MHD boundaries (saw-teeth, core density collapse) for W7-X needs to be elucidated.
Ref.	https://doi.org/10.1109/TPS.2017.2784380

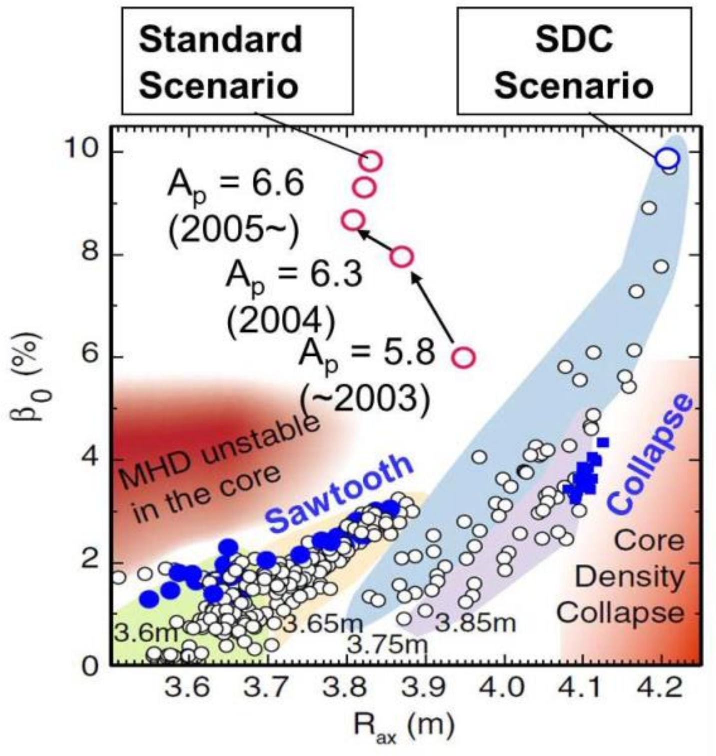


Fig. 4. Operation regime of high-β plasmas in the hydrogen experiment phase in LHD, on the plane of central β value (β_0), and the magnetic axis position (R_{ax}). Legends are as follows. Black open symbol: no event, blue circle: sawtooth event, blue square: core density collapse, red open circle: history of raising β_0 values in standard scenario, and blue open circle: the highest β_0 value achieved in SDC scenario.

Pellet Fuelling and Particle transport in high-n, high-T regimes

Description	Characterise and model (NC + turbulent) the pellet fueling and particle transport in LHD.
Relevance for M8	Considerable uncertainty exist about the extrapolation of density profiles to reactor scenarios. It is generally considered necessary to have central pellet fuelling, but the particle deposition and transport are not well understood. The LHD offers the diagnostic and modelling capabilities to characterise particle transport.
Ref.	https://doi.org/10.13182/FST10-A10795

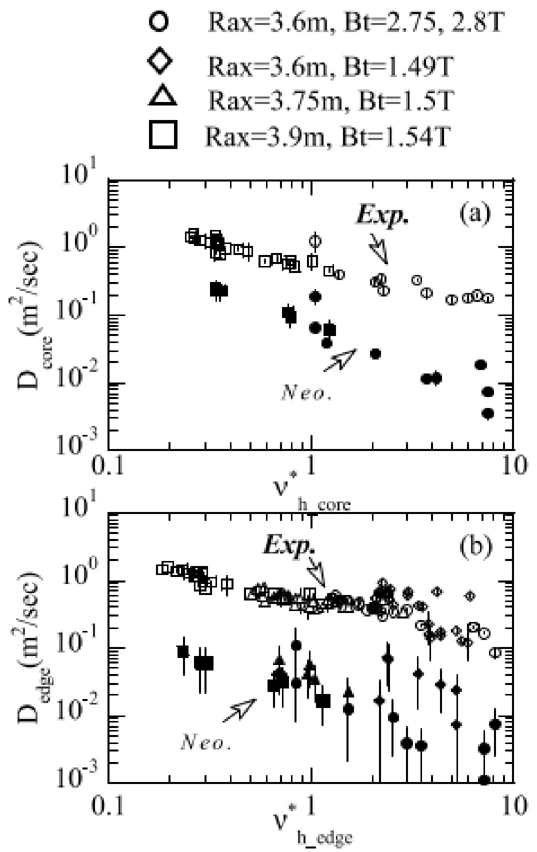


Fig. 7. The ν_h^* dependence and comparison with neoclassical value: (a) D_{core} and (b) D_{edge}. The definitions of D_{core} and D_{edge} are shown in Figs. 1a and 1b. Open and solid symbols indicate experimental and neoclassical values, respectively. Neoclassical values are calculated by GSRAKE and DCOM. The bar of the neoclassical values indicates standard deviation at $\rho = 0.4$ to 0.7 and 0.7 to 1.0 for core and edge values, respectively.

EMC3/ERIENE modeling of LHD edge-SOL-divertor and detachment.

Description	Validate the EMC3/EIRENE code in LHD with dedicated PWI studies. Study the importance of drifts, particularly in detached conditions with an without seeding. The validation of the div-sol model is required for the posterior validation of erosion-depositinon-migration tools like EROV2.
Relevance for M8	The SOL regions of LHD and W7-X are quite different as are their divertors. The differences are such that they preclude any direct comparison without a sofiticated edge/sol modeling. The differences, on the other hand, offer good conditions for the validation of the Eruopean code EMC3/EIRENE. Detachment access conditions, physics (e.g. volumetric recombination not observed in W7-X, required diffusivity coefficients) should be a primary focus of the validation.
Ref.	http://dx.doi.org/10.1088/0029-5515/55/10/104021

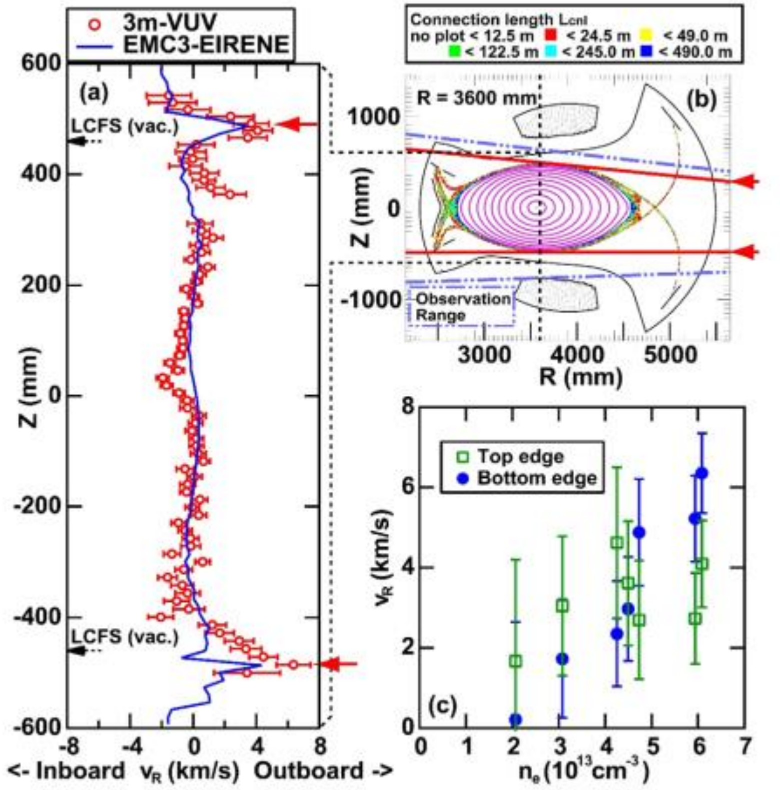


Figure 5. (*a*) Vertical profile of C^{3+} impurity flow evaluated from Doppler shift of the second order of CIV line emission (2 × 1548.20 Å) measured by VUV spectroscopy. The synthetic profile of C^{3+} flow simulated with EMC3-EIRENE code is also plotted with a solid line. (*b*) Observation range of the VUV spectroscopy. Two solid arrows in (*a*) correspond to each observation chord depicted with two solid arrows in (*b*). (*c*) Observed C^{3+} flow at the top and bottom edges of the stochastic layer as a function of density.

Characterisation and modeling of the operation conditions of benign impurity transport and source control (screening).

Description	Diagnose the relevant edge and core plasma parameters in regimes of edge screening and high NBI power to pursue validation of the edge (EMC3) and core (NC+Turbulent) impurity dynamics and transport. Investigate the importance of asymmtries in the impurity transport for its potential instrumentalisation.
Relevance for M8	Impurity accumulation is often regarded as the Achiles heel of stellarators. LHD has meticulously explored the parameter space and the accumulation properties on the plasmas (see reference). Regions of core and edge screening have been identified. Recently, the combination of NBI torque and Ti gradients has been claimed to strongly suppress accumualtion. The understanding of the strategies to avoid accumulation and their extrapolation to reactor conditions should be pursued.
Ref.	https://doi.org/10.1088/1741-4326/aa6187

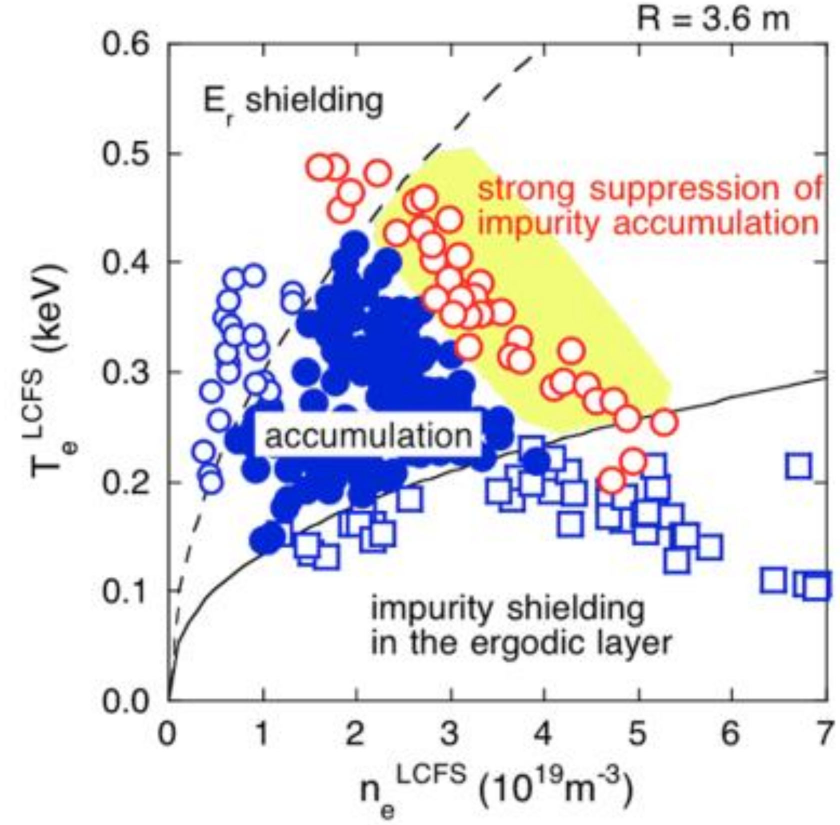
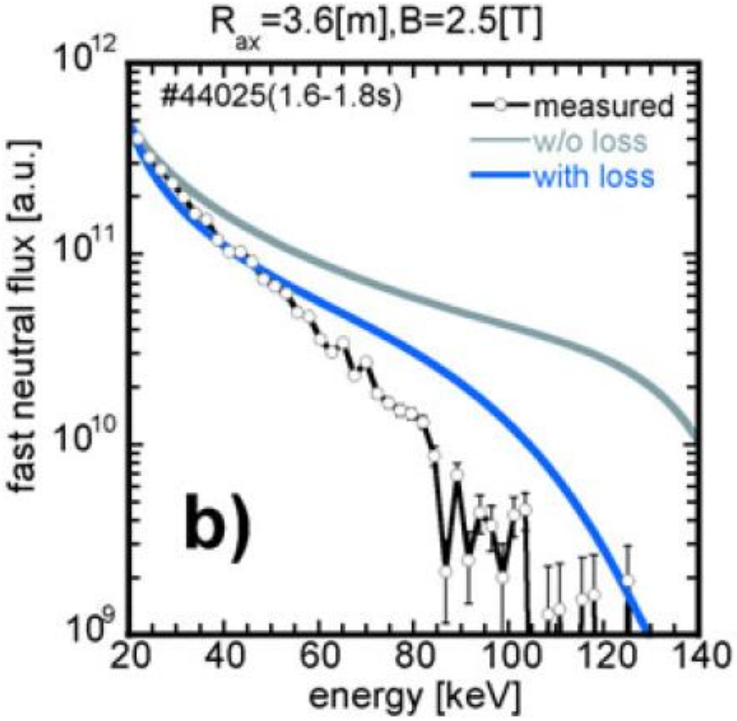


Figure 4. *n–T* diagram at the LCFS for impurity behavior. Closed and open blue symbols indicate low power discharges ($P_{NBI} < 10$ MW) with and without impurity accumulation, respectively. Open red points represent high power discharges ($P_{NBI} = 13$ MW) with the strong suppression of impurity accumulation.

ASCOT validation against LHD ICHR and NBI generated fast ions.

Description	Application of similar diagnostic and simualtion tools in LHD and W7-X aimed at the validation of ASCOT.
Relevance for M8	LHD has illustrated a general agreement between experiments and expectations of the effect of the magnetic configuration on fast particle confinement. Detailed analysis of the FI loss pattern, Alfvén wave interactions are scarce. Is LHD fast ion confinement regareded sufficient in FFHR2m2 high and low density scenarios?
Ref.	https://doi.org/10.13182/FST10-A10800



LHD call for proposals now open

22nd Experimental Campaign Schedule
June 12 start submission of experiment proposal
June 30 deadline of submission of experiment proposal
Oct. 15 start experiment
Feb. 18 end experiment

For more information, please contact your counter person
or Dr. Yasuhiro Suzuki (e-mail: suzuki.yasuhiro@nifs.ac.jp).