W7-AS SOL and Divertor Plasma Characteristics: Report on Visit to IPP Oct 13

Max Fenstermacher

- Visit occurred during IPP International Workshop on Tokamak Pedestal Physics, MHD Stability and their Effect on the Divertor.
  - Limited time during breakout sessions
  - Did not know IPP closes at 3 pm on Fridays
  - Did not know Mike Zarnsdorff was giving NCSX seminar.
- Limited success in getting SOL information through discussions, however:
  - Many papers from McCormick, Sardei
  - Many IAEA papers from W7-AS
  - Talked briefly to McCormick (1 hr), Sardei (1/2 hr), Kisslinger (1/2 hr)
- SOL personnel and responsibilities
  - McCormick - Boundary plasma diagnostics Group Leader
  - Sardei - Equilibrium configurations
  - Kisslinger - Field line tracing etc.
  - Grigull - Experimental group leader for boundary physics
  - Feng - SOL/divertor modeling

This talk is report on discussions and results from boundary physics papers.

- Results from papers give some idea of SOL and target plasma parameters.
- Scaling from W7-AS (low shear, current free, high aspect ratio) to NCSX is not at all clear.
- Valuable input from W7-AS is their experience from multiple configurations of plasma facing components and recommendations for calculational tools to use.
- I would like to thank the authors of the following papers from which the results in this talk are taken:
  - K. McCormick:
    - PSI 2000 to be published in J. Nucl. Mater., (May 2001)
    - EPS 1999 Invited in PPCF, 451, (1999) B285-304
    - 12th Int. Stellarator Conf., Madison
  - F. Sardei:
    - PSI 1996 Invited, in J. Nucl. Mater., 241-243, (1997) 135-148.
  - E. Strumberger:
    - In Proc. 20th EPS Lisboa, v.17C, II, (1993) 791-794.

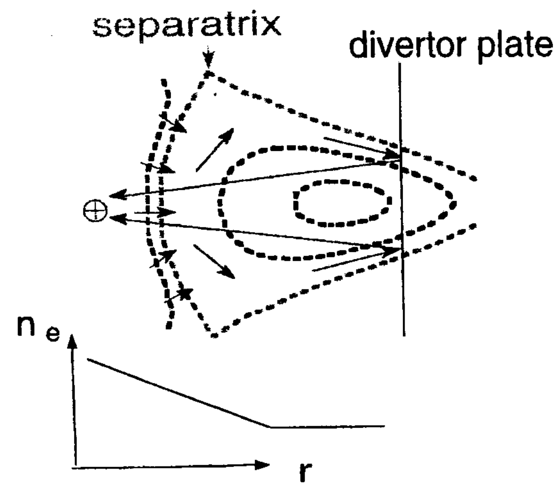
SOL and Divertor/Limiter operational considerations for stellarators.

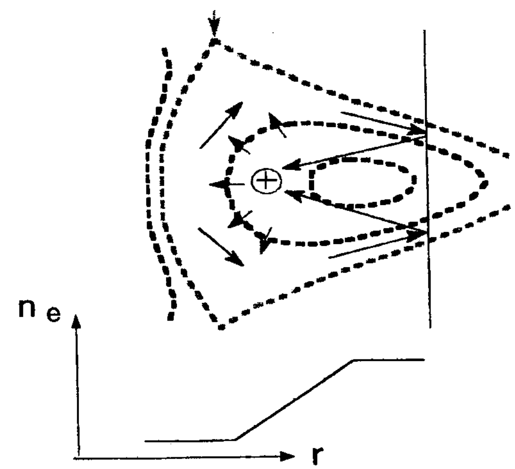
- As in tokamaks, need to establish high recycling conditions near target surfaces to keep impurities out of the core plasma.
- n_e^{lim},n_e^{sep} and n_e^{avg} are linked so high n_e^{lim} requirement tends to high n_e^{avg}.
  - Scalings are different than tokamaks
  - Techniques to modify scalings (gas puff, pumping, pellet injection, etc.) may work differently than tokamaks.
- UNLIKE tokamaks, get H-mode more easily for fixed P_{inj} at higher n_e^{avg}.
  - H-mode reduces n_e^{sep}/n_e^{avg} ratio
  - Gas injection increases n_e^{sep}/n_e^{avg} ratio
  - n_e^{avg} (density limit) ~ $[P_{inj} / V]^{0.48}$ $[B_T]^{0.54}$ (stellarator scaling Giannone, PPCF, 42, (2000) p.603)
- Therefore, high recycling requires high power - avoids H-mode and raises density limit.

Need to establish high recycling conditions in stellarator islands to keep impurities out of core plasma.

Sardei PSI96

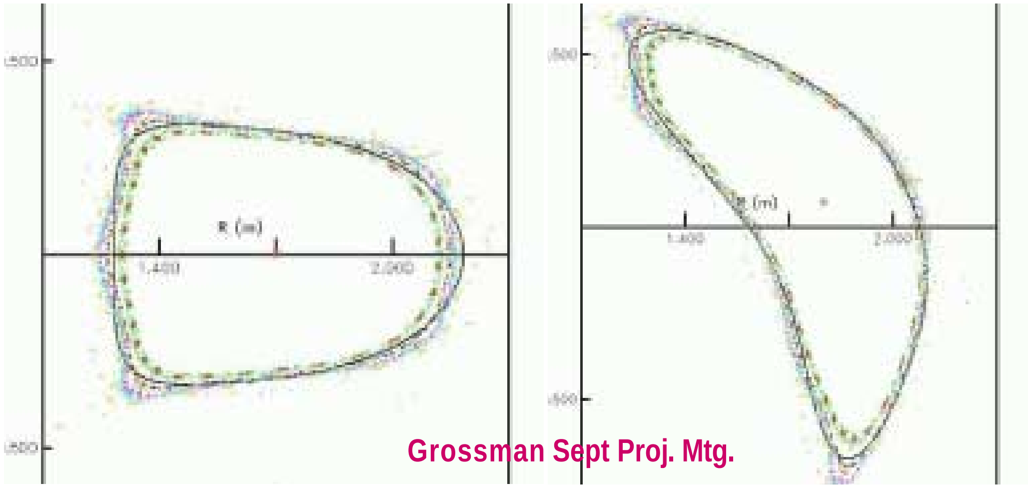
- High recycling operation requires that neutrals born on target surfaces be ionized in the island plasma, not inside the last closed flux surface.
- High density that builds up near the targets means low temperature there
  - Sputtering reduced
  - Target peak heat flux reduced due to efficient carbon radiation for high density when Te ~ 10 eV.
  - Short mean free path for impurities



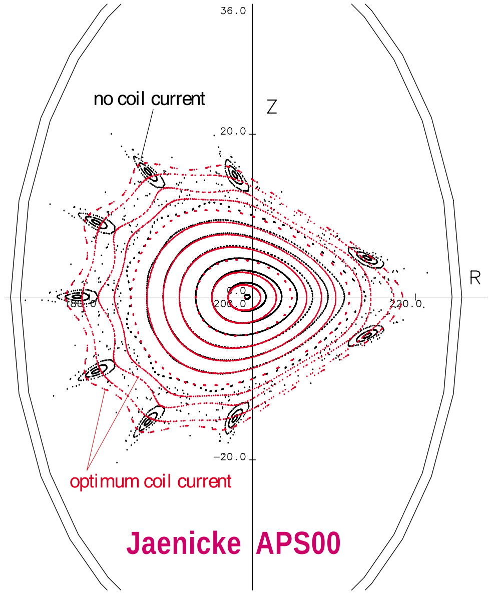


High power will be required in NCSX to match W7-AS power density.

- W7-AS needs P_{inj} = 1.2 MW to avoid H-mode with low n_e^{sep}, low recycling near targets and impurity influx.
- NCSX volume factor of ~ 7 higher than W7-AS
  - NCSX: R ~ 1.7 m, a_{eff} ~ 0.45 m
  - W7-AS: R ~ 2.0 m, a_{eff} ~ 0.15 m
- Implies 8 - 10 MW needed to avoid H-mode in NCSX if same scalings.
- Scalings may certainly be different in high shear, low aspect ratio QAS device with finite current compared with W7-AS at low shear, high aspect ratio, current free.



Grossman Sept Proj. Mtg.

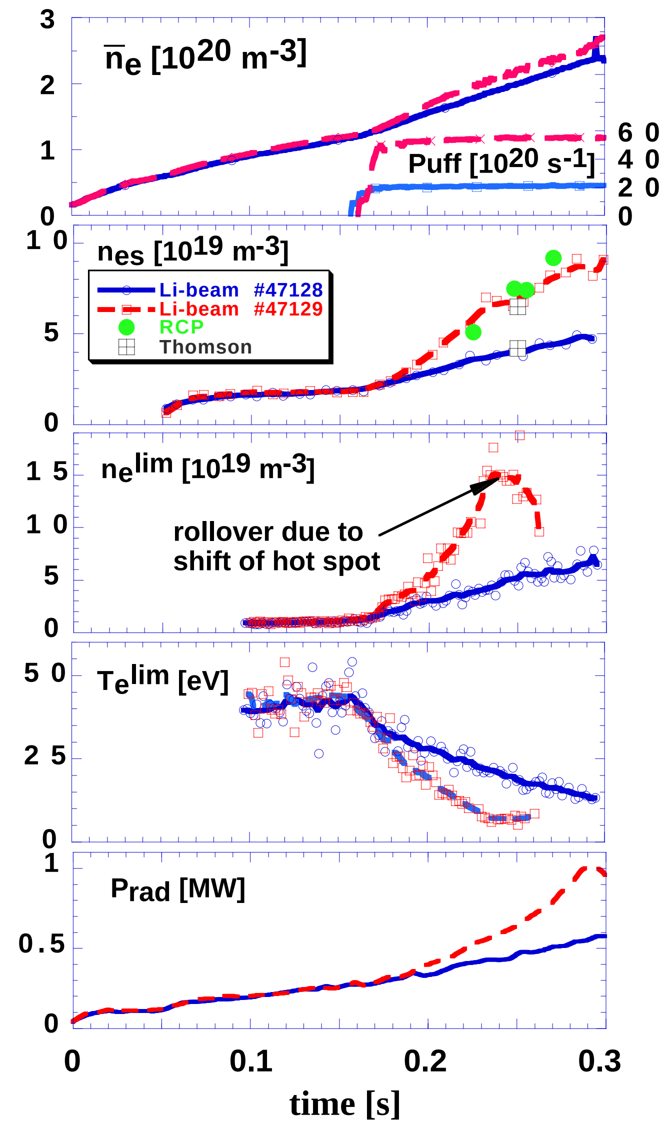


Jaenicke APS00

Increase in gas injection can produce increased limiter density without large increase in line averaged density.

McCormick PSI00

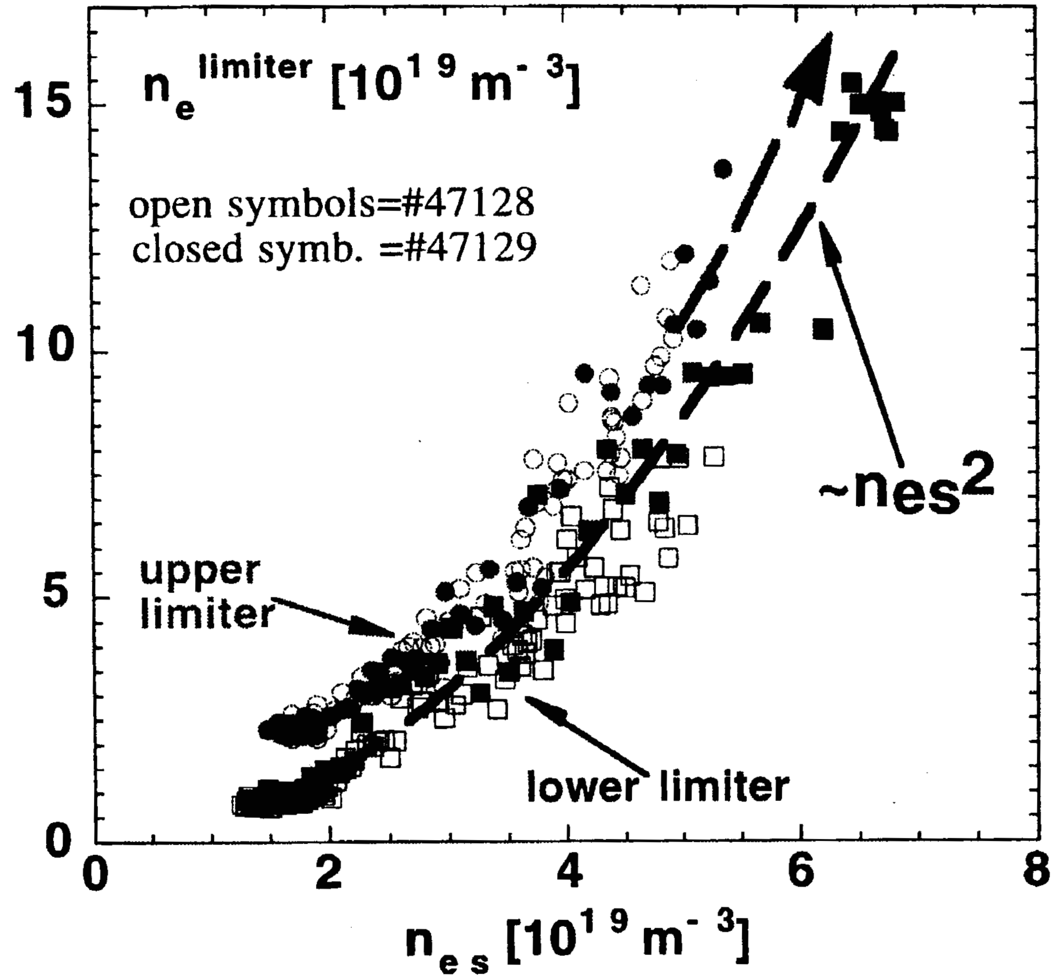
- Gas puff scan done at high power Pinj = 2 MW to avoid H* (quiescent H-mode) transition.
- Both separatrix and limiter densities higher in high gas injection (red) shot
- Rollover of n_e^{lim} is not indication of detachment (plasma moves instead)
- $P_{lim} / (P_{inj} - P_{rad}) \sim 0.5$ indicates that a lot of power is going somewhere besides on the limiters.



W7-AS data suggests that limiter density scales as separatrix density squared.

McCormick EPS99

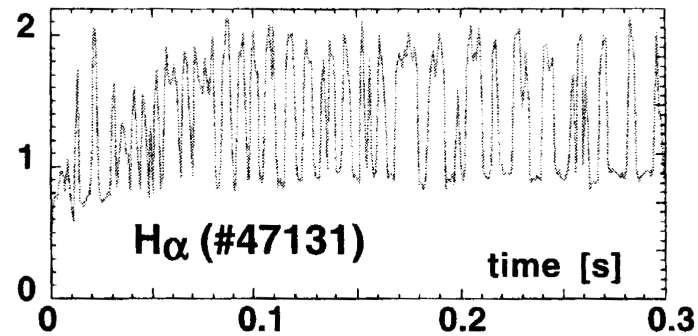
- Data from discharges with Pinj = 2.0 MW
  - High power for W7-AS
  - Sufficient to avoid H* regime
  - 4 Co-, 1-Counter beam
  - Fresh boronization
- Heavy puffing to increase n_e^{sep}
  - Core profiles also broaden
  - Highest values are transient
- Dependence is weaker than 2-point model
  - Data shows $n_e^{lim} \sim (n_e^{sep})^2$
  - 2-point model predicts $n_e^{lim} \sim (n_e^{sep})^3$ - Seen in tokamaks

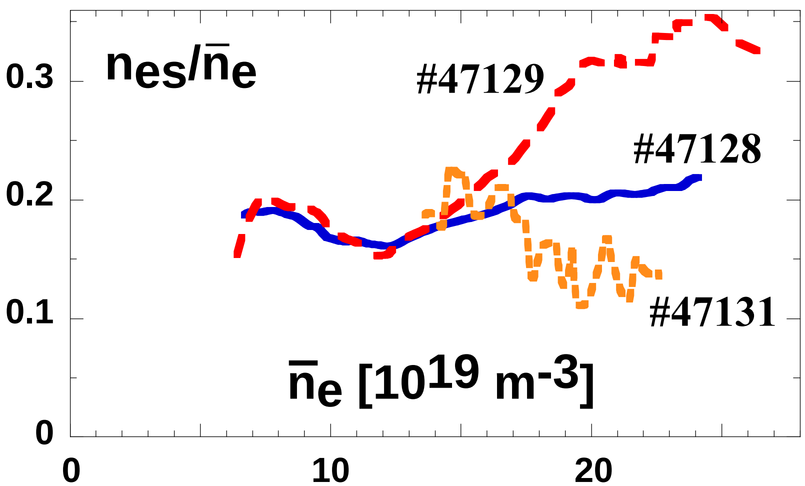


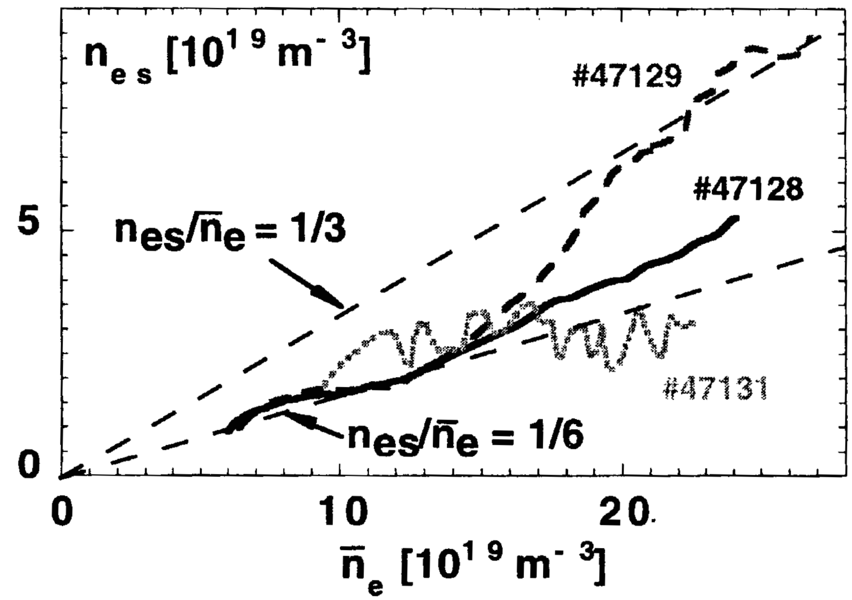
Dithering H-mode (H_alpha trace in Shot 47131) causes saturation in separatrix density during core density ramp.

McCormick EPS99

- High power P_{inj} = 2 MW used.
- Stronger gas puff in Shot 47131 produces dithering in/out of H-mode
- Suggests build-up of n_e^{sep} is sensitive to power balance in the SOL.



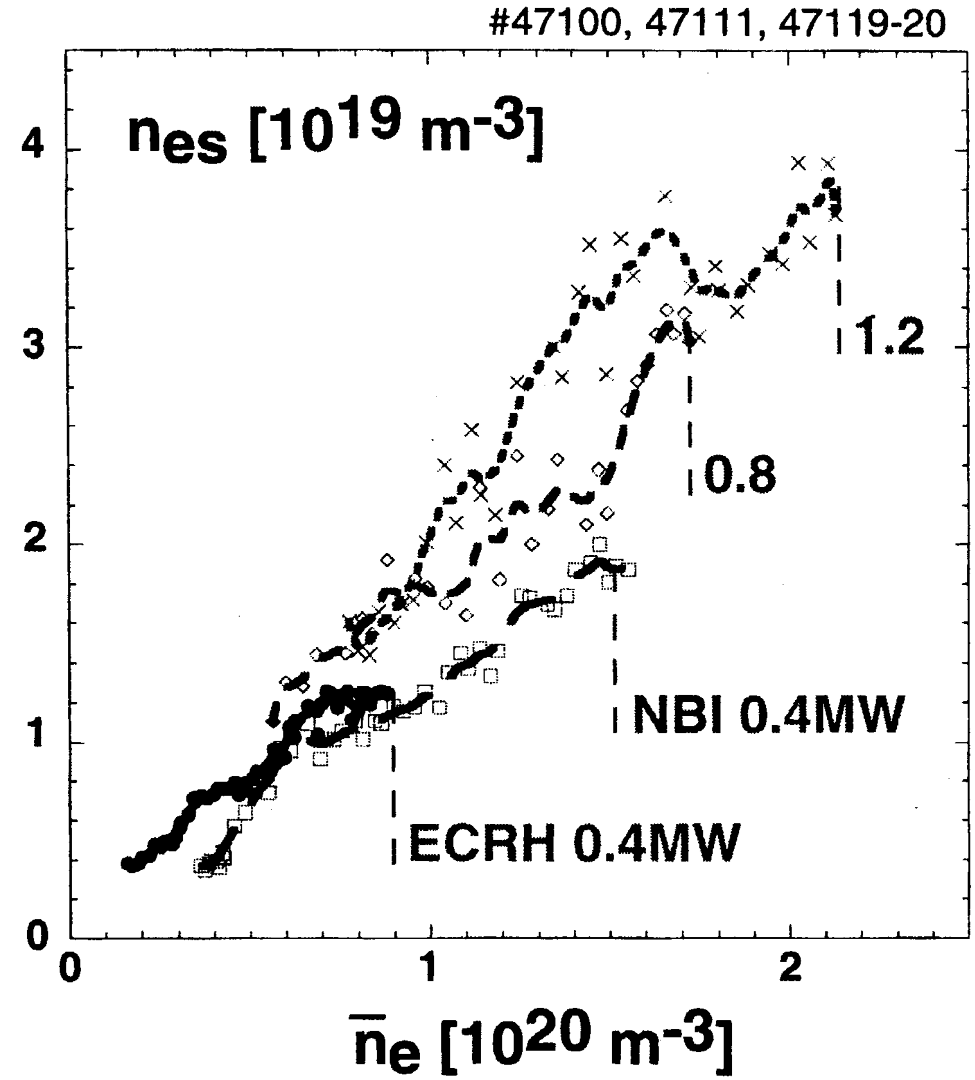




Separatrix density in W7-AS nearly linear with core line averaged density.

McCormick EPS99

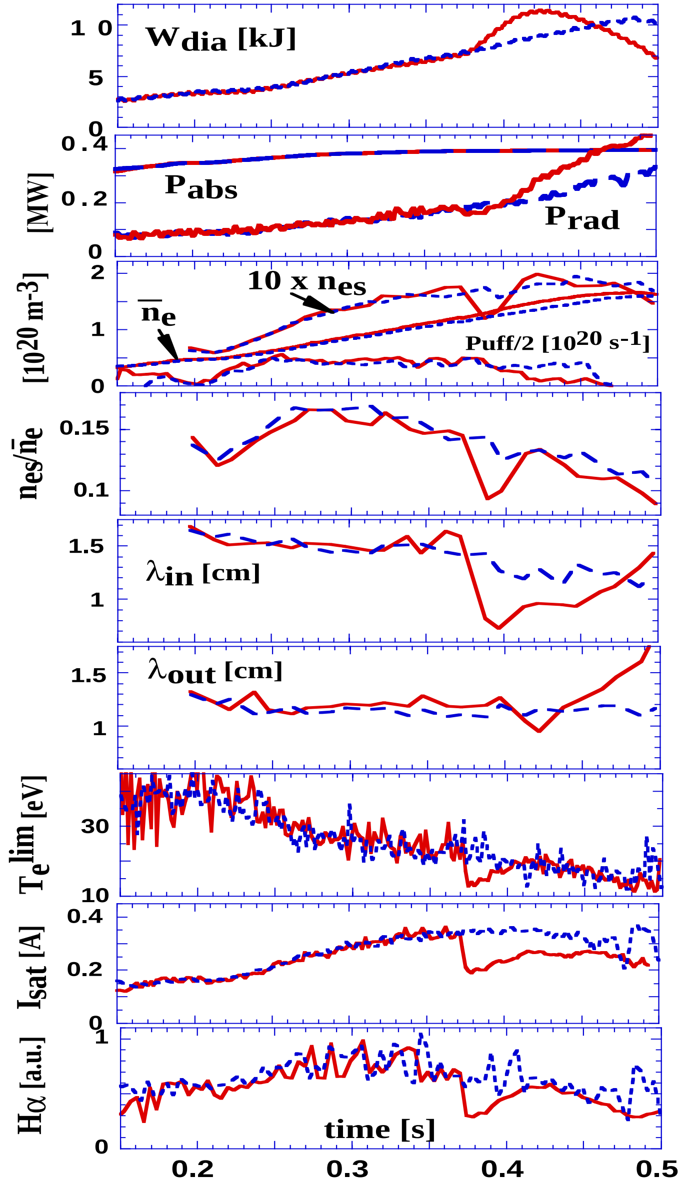
- P_{inj} = 1.2 MW just high enough to avoid H* at highest density shown.
- Slope increases with higher NBI heating power
- H* density threshhold lower with ECH than NBI
- Limiter density should scale as line averaged density squared, $n_e^{lim} \sim (n_e^{avg})^2$.



Very small change in iota in W7-AS produces large change in plasma evolution

McCormick PSI00

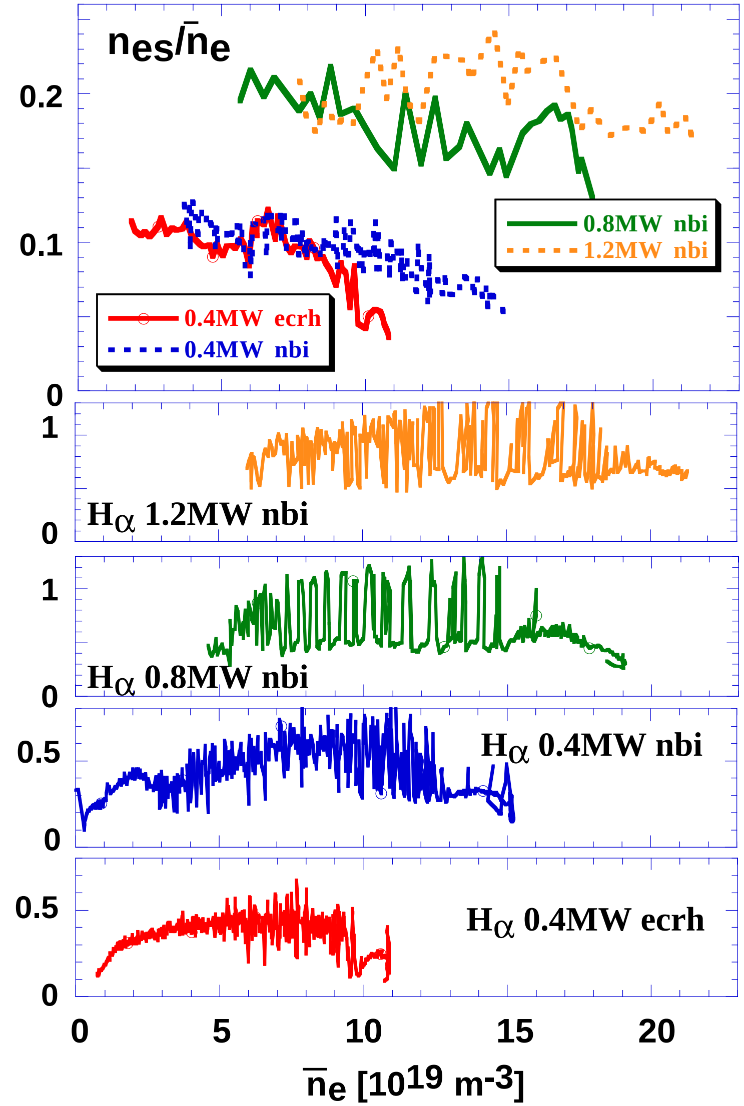
- Red and blue shots differ only by delta_iota = 0.005
- H-mode transition (370 ms) for shot with iota = 0.558, no transition at iota = 0.553 (note 5/9 = 0.556)
  - Jump in W_{dia} and P_{rad}
  - Drop in n_e^{sep} / n_e^{avg}, I_{sat} and H_alpha
  - Density profile e-fold length reduced inside LCFS
- N_e^{sep} far lower than needed for high recycling divertor in this P_{inj} = 0.4 MW case.



Separatrix to line averaged density ratio increases and H-mode transition at higher density for higher injected power

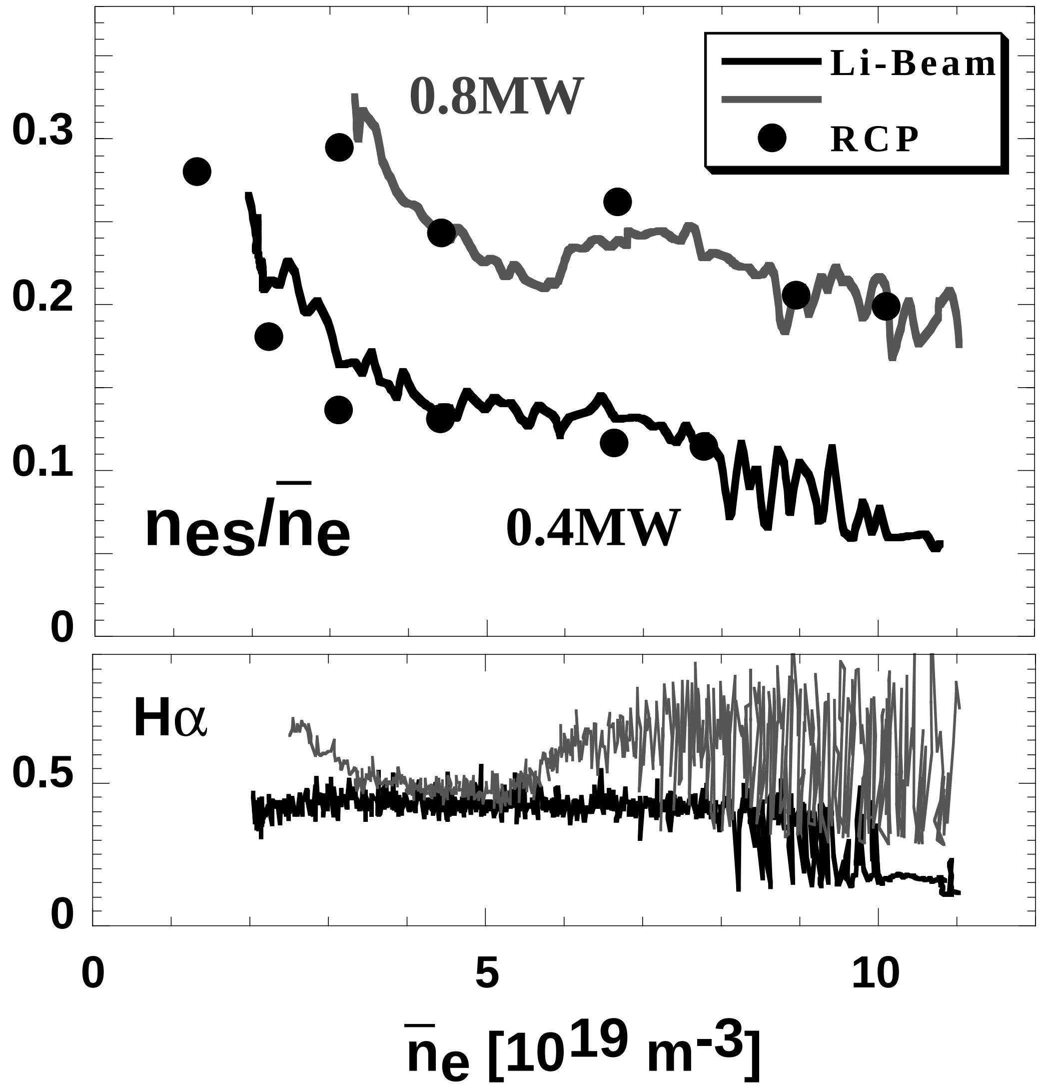
McCormick PSI00

- Density ramp shots with gas injection.
- Iota = 0.558 (H-mode easier than iota = 0.553)
- At P_{inj} = 0.4 MW H-mode transition at lower density with ECH vs. NBI
- Power scan with NBI shows H-mode transition density increases with power.
- N_e^{sep}/n_e^{avg} ratio
  - increases with power,
  - decreases with density as H-mode transition approached



Separatrix to line averaged density ratio higher in higher power ECRH discharges.

- Trend similar to NBI power scan results.
- Again n_e^{sep}/n_e^{avg} decreases with density as H-mode transition approached.

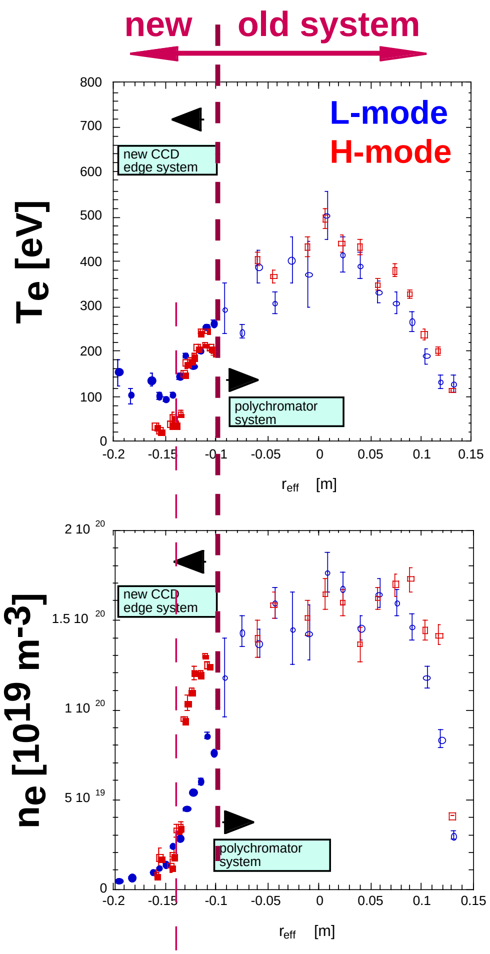


Density and temperature profiles in L-mode ("somewhat ELMy"), H-mode (quiescent) and high edge density operation

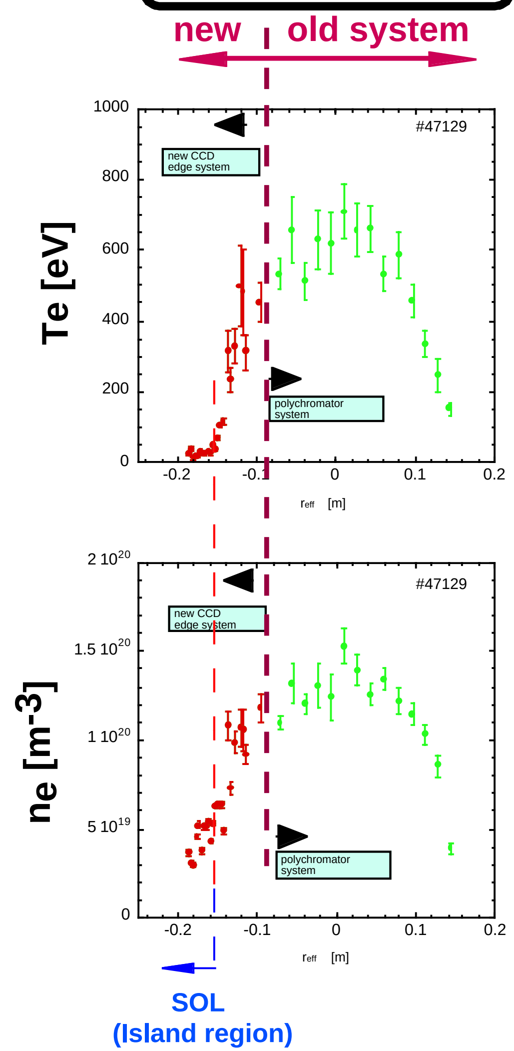
McCormick 12th Stellarator Conf.

- Spatial resolution is 4 mm
- Transition from L-mode to quiescent H*-mode produces:
  - Large change in edge density profile
  - No significant change in edge Te profile
- High density achieved in SOL island region with gas injection.

Low edge density without gas injection



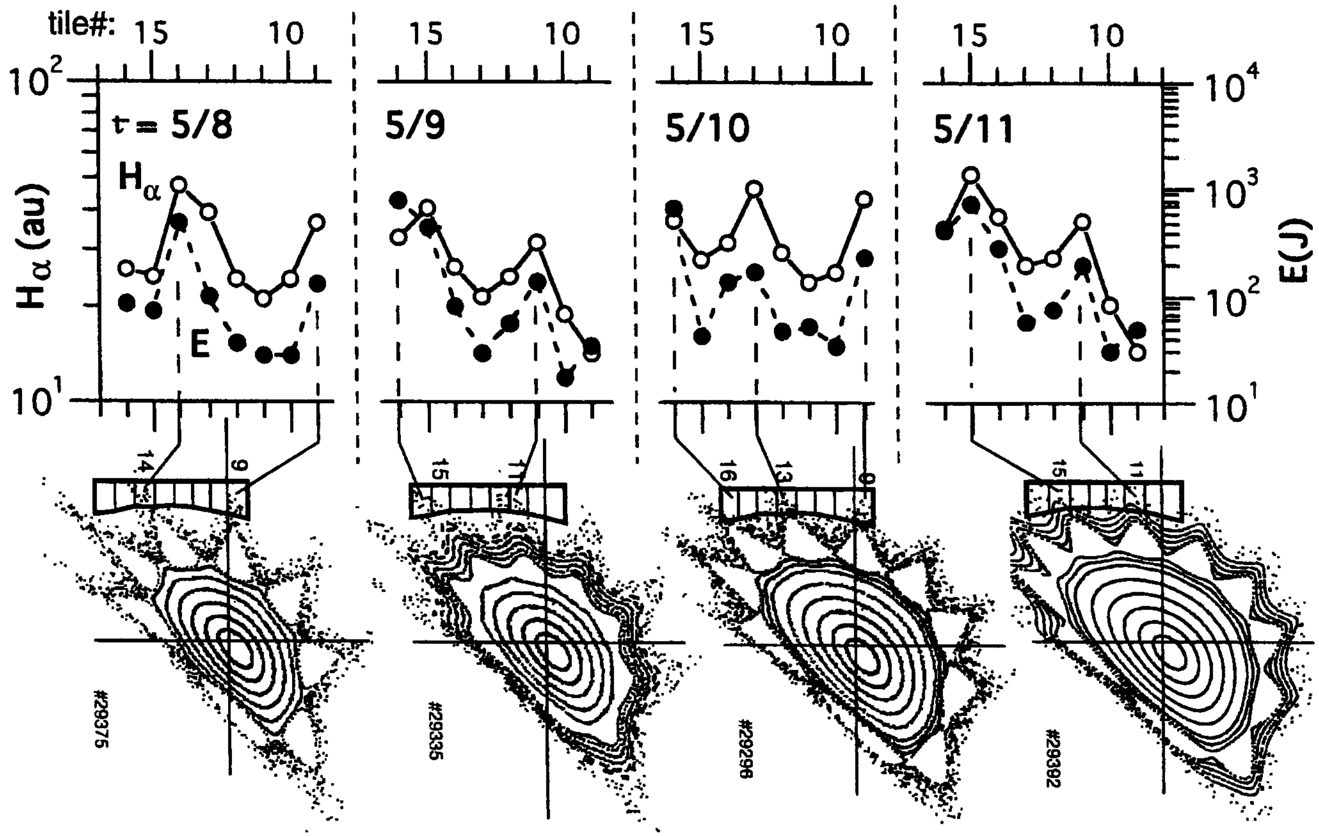
High edge density with gas injection



Particle and heat flux follows island footprints on target plates in W7-AS.

Sardei PSI96

- Good alignment of H_alpha and energy peaks with field line tracing of island footprints.
- Peaking factor ~ 2.5 : 1 for both H_alpha and energy at island footprints.



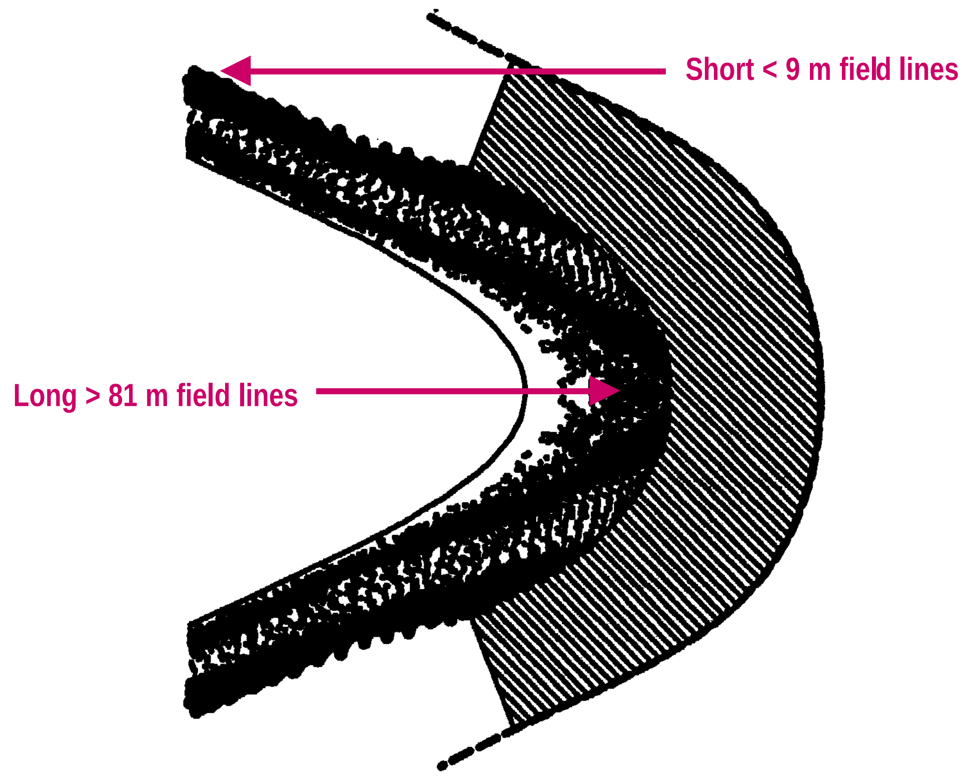
Where does the power and particle flux hit the wall? First step: field line tracing with diffusion added.

- Unanimous recommendation of W7-AS group interviewed was to start with Strumberger's field line tracing code and add diffusion (code by Kisslinger).
  - Reference - E. Strumberger, 20th EPS Conf., Lisboa, 1993, V. 17C, Part II, 791.
  - Standard field line tracing neglects energy and particle transport across field lines
    - Gives narrow deposition profiles on target plates
    - Probably overestimates peak to average heat and particle fluxes
    - May underestimate the required toroidal and poloidal coverage of target plates
  - To simulate transport, add random displacements of field lines at characteristic mean free path lengths during the tracing calculation
  - Subroutine adding diffusion has been written by Kisslinger as part of Gourdon code package in his version of MFBE.
- Art Grossman, Strumberger, Kisslinger and I will work to get this capability in Grossman's implementation of MFBE for NCSX.

Long length field lines which pass close to last closed flux surface concentrate in narrow strip of W7-X divertor trough.

Strumberger EPS 93

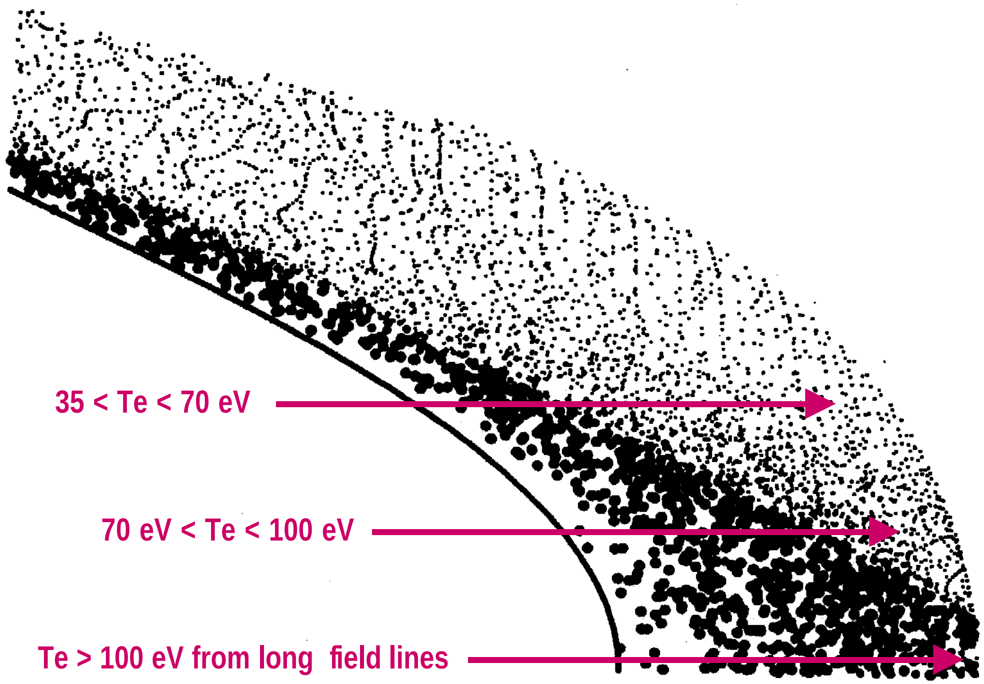
- Plot shows characteristics of the field line map between the divertor troughs in W7-X example.
- Long field lines pass near separatrix of the core plasma
- High heat flux expected to be deposited at strike points of long field lines.
- Narrow strike region of long field lines calculated without field line diffusion technique broadens with diffusion.



Field line diffusion technique used to obtain an initial profile of Te on W7-X divertor trough.

Strumberger EPS 93

- To get initial estimates of SOL plasma properties, field line tracing and one dimensional fluid solutions along field lines can be combined as done early on for W7-X
- Field line tracing then gives first cut estimate of Te profile on target surface.
- Example shown here includes field line diffusion.
- 2D solutions using B2-Eirene done by Feng for W7-AS.
- Full 3D solutions in the SOL will be done with BoRiS code (under development at IPP Greifswald).



Summary

- Good SOL and high recycling plasma/ target performance in the W7-AS stellarator requires high input power
  - Avoid H-mode to keep n_e^{sep}/n_e^{avg} high
  - Keep core density limit high
- Not clear how low shear, high aspect ratio, current free W7-AS results scale to NCSX
- Experience of W7-AS personnel produced several recommendations for NCSX:
  - Start with toroidally discrete limiters rather than toroidally continuous rails or shaped divertor baffles.
  - Use Strumberger code with field line diffusion and 1D fluid models to determine where thermal power and particles strike the wall
  - Try to determine also where fast particles hit the wall.
  - Plan for stochastic boundary operation to reduce peaking factors on wall.
  - Recommended limiter locations:
    - At the banana tips for best neutral trapping in the SOL, or
    - At the outer midplane of the bullet section for best flexibility.