Performance of High Triangularity Plasmas as the Volume of the Secondary Divertor is Varied in DIII–D*

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ABSTRACT

- The design of any future tokamak begins with a decision on the shape of the core and divertor plasmas. The desire is to achieve the performance advantages of high triangularity (high–δ) operation with the core plasma volume maximized and the divertor volume minimized. At low δ in single-null divertor configurations, only the primary X–point is present inside the vacuum vessel. As δ is increased the location of the secondary X–point, which maps at the midplane to a flux surface radially outboard of the primary, can move from outside the vacuum vessel to inside and divertor physics (recycling, target heat flux etc.) becomes important in this secondary divertor

- This paper reports on a series of high–δ H–mode discharges in DIII–D in which the effect of variation in the secondary divertor volume on edge pedestal and divertor performance was examined. Since the secondary divertor takes up volume that could be used for the burning core plasma, the focus of the study was to determine the minimum secondary divertor volume consistent with good core, pedestal and divertor heat flux sharing, core fuelling, density at the H-L transition, and edge pedestal performance is presented

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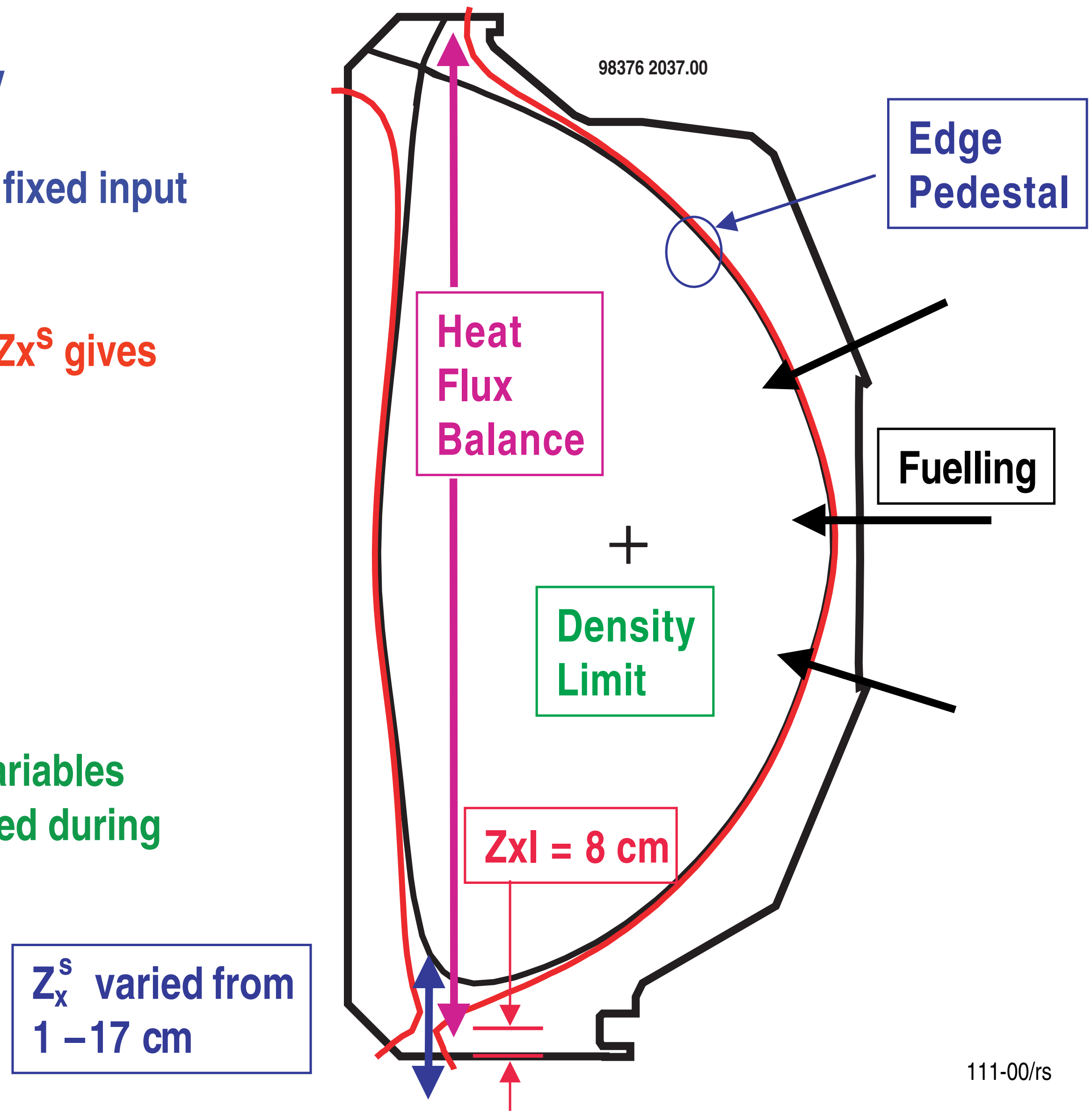
SECONDARY DIVERTOR VOLUME AFFECTS HEAT FLUX BALANCE, FUELLING, DENSITY LIMIT AND EVOLUTION OF EDGE PEDESTAL PARAMETERS

Experiment : Attempt to vary secondary divertor volume (lower X–point height, Zx^S) at fixed input plasma conditions

Goal : Determine if reduced Zx^S gives acceptable performance

- Heat flux balance
- Fuelling
- Density limit
- Edge pedestal evolution

Observation: Uncontrolled variables (eg. wall conditions) also varied during Zx^S scans



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REDUCTION OF SECONDARY DIVERTOR VOLUME PRODUCES BOTH POSITIVE AND NEGATIVE EFFECTS ON PERFORMANCE

As secondary divertor volume ($Z_X{}^S$) decreases:

- Secondary peak heat flux decreases — good; divertor design easier
- Effective fuelling rate at L–H transition increases — not good for low density AT scenarios using current drive for profile control
- Density at H–L back transition (at fixed q_{95}) decreases — not good for high density reactor scenarios
- Locations of boundaries in $T_e{}^{ped}$ versus $n_e{}^{ped}$ operating space (e.g. type I vs. type III ELMs) vary, especially for unpumped plasmas — There may be an optimum $Z_X{}^S$
- Optimized unbalanced DN (60% divertor volume in primary, 40% in secondary) shows improved performance versus single null with similar divertor volume
  - — Reduced fuelling at L–H
  - — Higher (maximum) $\beta_N H$
  - — Reduced peak outer leg heat flux
  - — Higher density at H–L back transition

All Positive Effects

MANY DESIRABLE CHARACTERISTICS OF TOKAMAK OPERATION MAY BE ENHANCED BY PLASMA SHAPING

- High core plasma confinement — at low n_e from high $\delta \Rightarrow$ favors unbalanced DN
- High core plasma beta limit — from high $\delta \Rightarrow$ favors unbalanced DN
- Minimum sensitivity of core and divertor behavior to magnetic balance
  - Heat flux shared nearly equally between the divertors — favors unbalanced DN — Petrie poster P-3.45
  - Efficient particle control by pumping - favors SN
  - High H$\Rightarrow$L back transition density limit - either DN or SN with ∇B into divertor
- Rapid small ELMs at high density — Leonard poster P-3.54, Lasnier poster P-3.56
- Efficient fueling to high density with good confinement — Osborne oral O-7.3
- Minimize core impurities and fuel dilution
- Minimum divertor volume needed within the TF coils

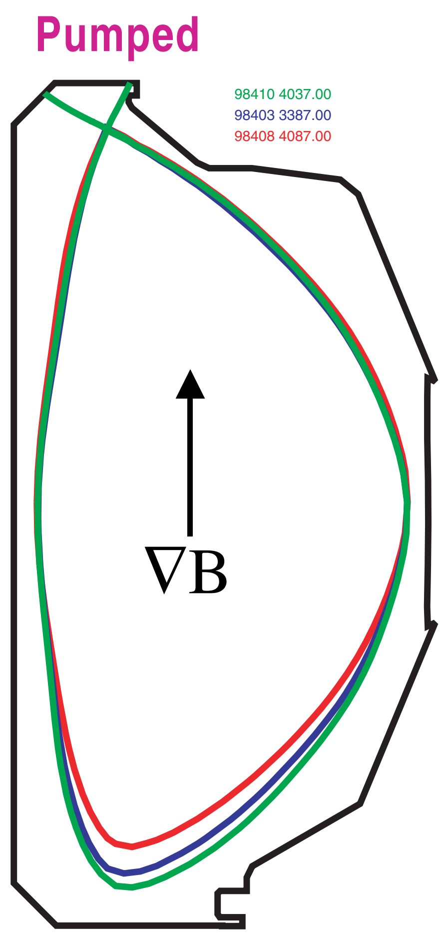
THESE EXPERIMENTS HAVE SYSTEMATICALLY VARIED THE VOLUME OF THE SECONDARY DIVERTOR IN UNBALANCED HIGH-δ DN PLASMAS

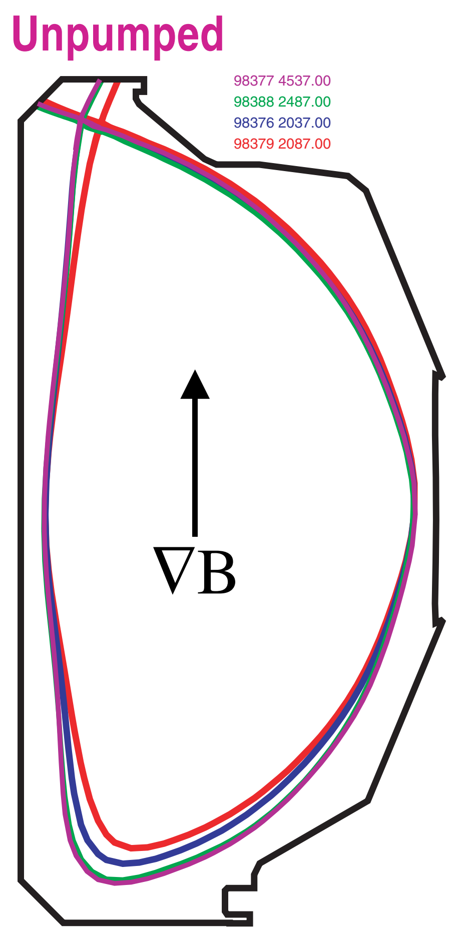
- Since future designs tend to high δ for confinement and β, how much secondary divertor effect can be tolerated?

- Constant parameters:
  - $I_p = 1.37$ MA, $P_{inj} = 4.6$ MW, $R_0 = 1.75$ m, $a = 0.6$ m, $B_T = 2.0$ T, ∇B toward upper divertor, δ (unpumped) = 0.75, δ (pumped) = 0.6

- Small variations:
  - $q_{95} = 4.6$–5.4, $\kappa = 1.88$–2.15

- Shapes with Z_x^S = 16, 8, 3, 1 cm at Z_x^S = 16 cm, both pumped and unpumped were studied



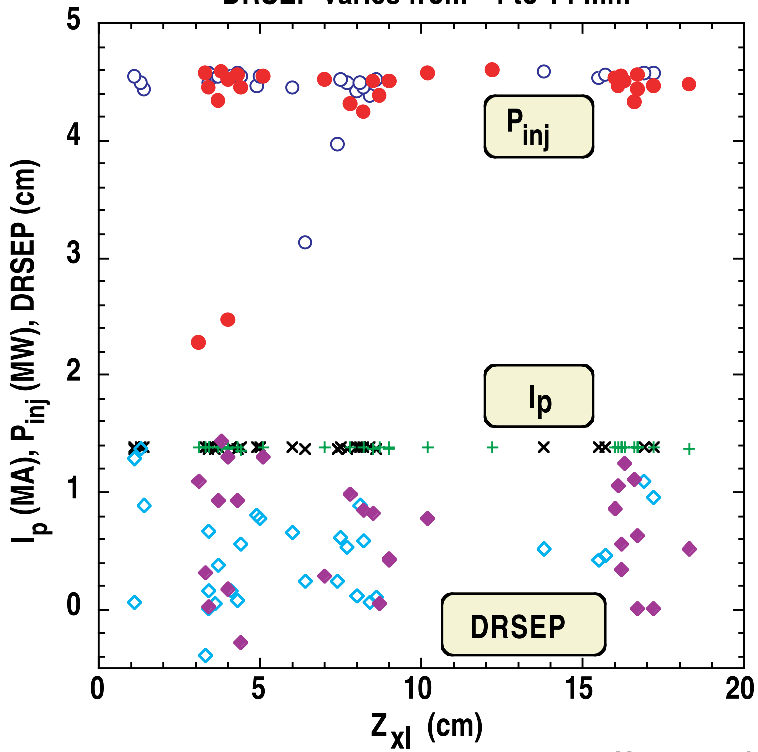


EXPERIMENTS KEPT I_P, P_{INJ}, κ, δ CONSTANT WHILE VARYING $Z_X{}^S$; Q_{95} VARIED 20% AND DRSEP VARIED IN THE RANGE –4 TO 14 mm

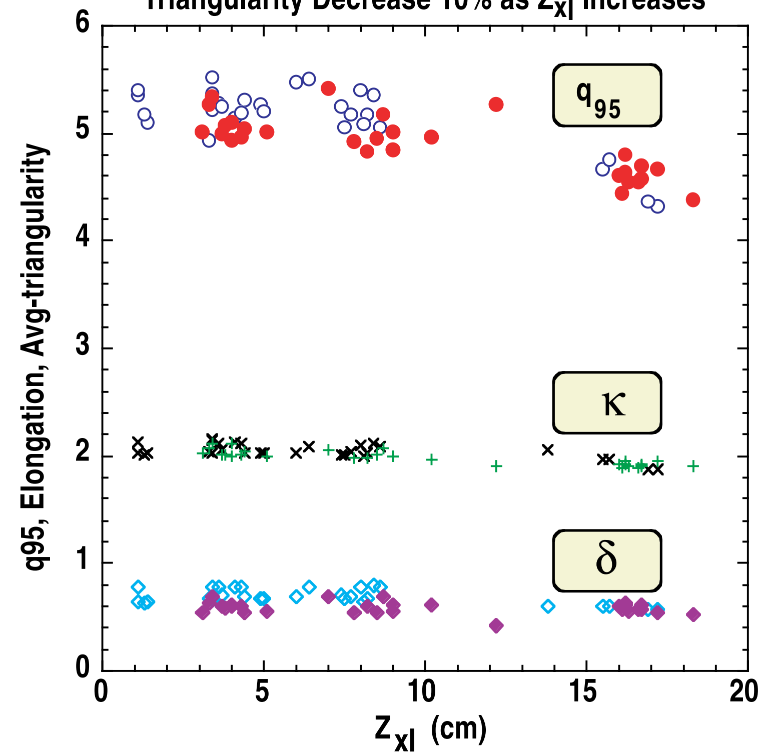
- DRSEP variation must be taken into account in analysis of divertor heat flux sharing, power SOL width and density at H$\Rightarrow$ L back transition

- Points taken during ELM-free, ELMing H–mode and at high density near H–L back transition

I_p Constant, P_{inj} Constant within 10%
DRSEP Varies from –4 to 14 mm



I_{95} Decreases 20%, Elongation and Average Triangularity Decrease 10% as Z_{xl} Increases



Unpumped (Open), Pumped (Solid)

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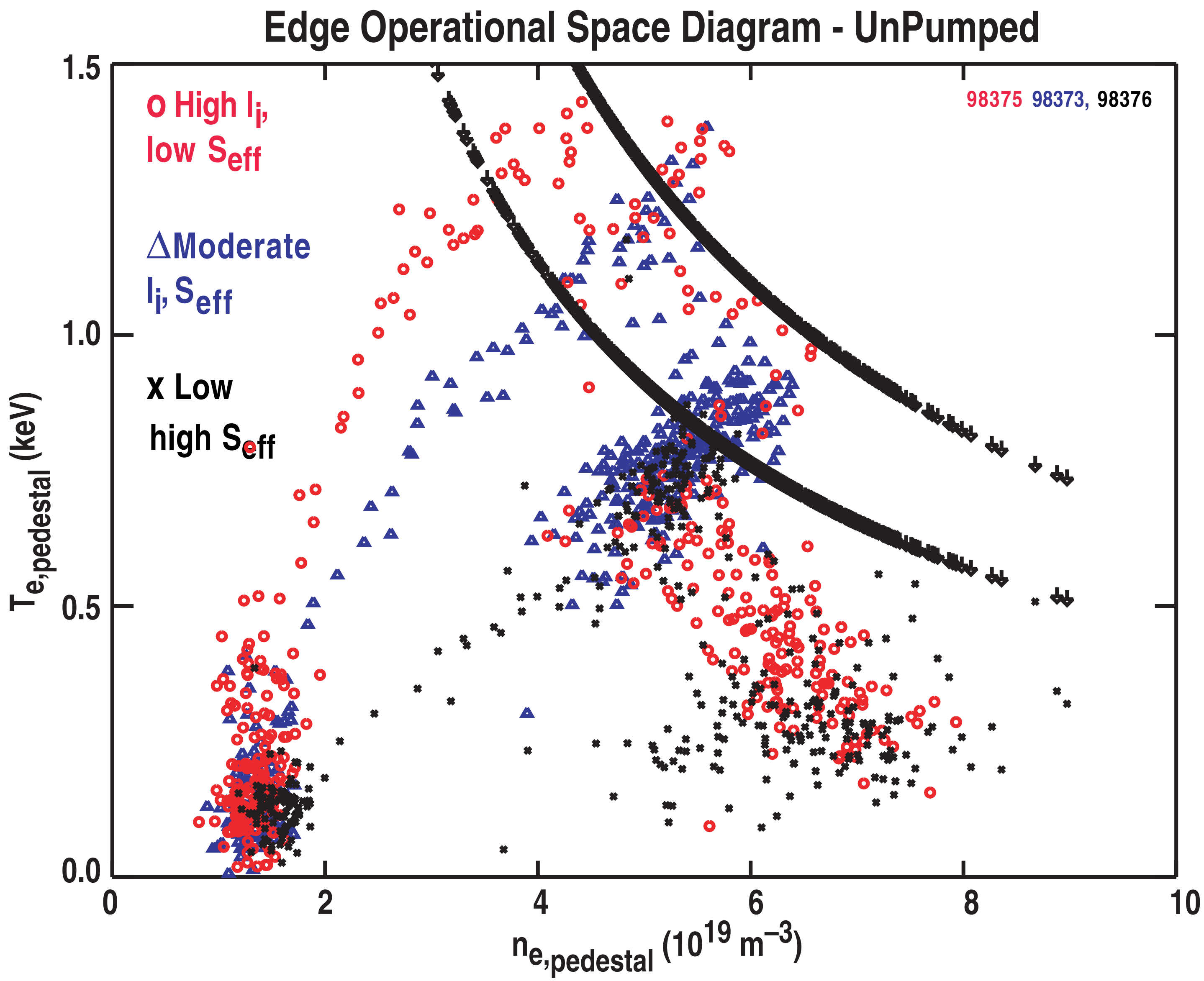
TRAJECTORIES IN EDGE PEDESTAL OPERATING SPACE FOR SHOTS WITH THE SAME Z_X^S = 8 CM SHOW DIFFERENCES DURING THE ELM-FREE PHASE



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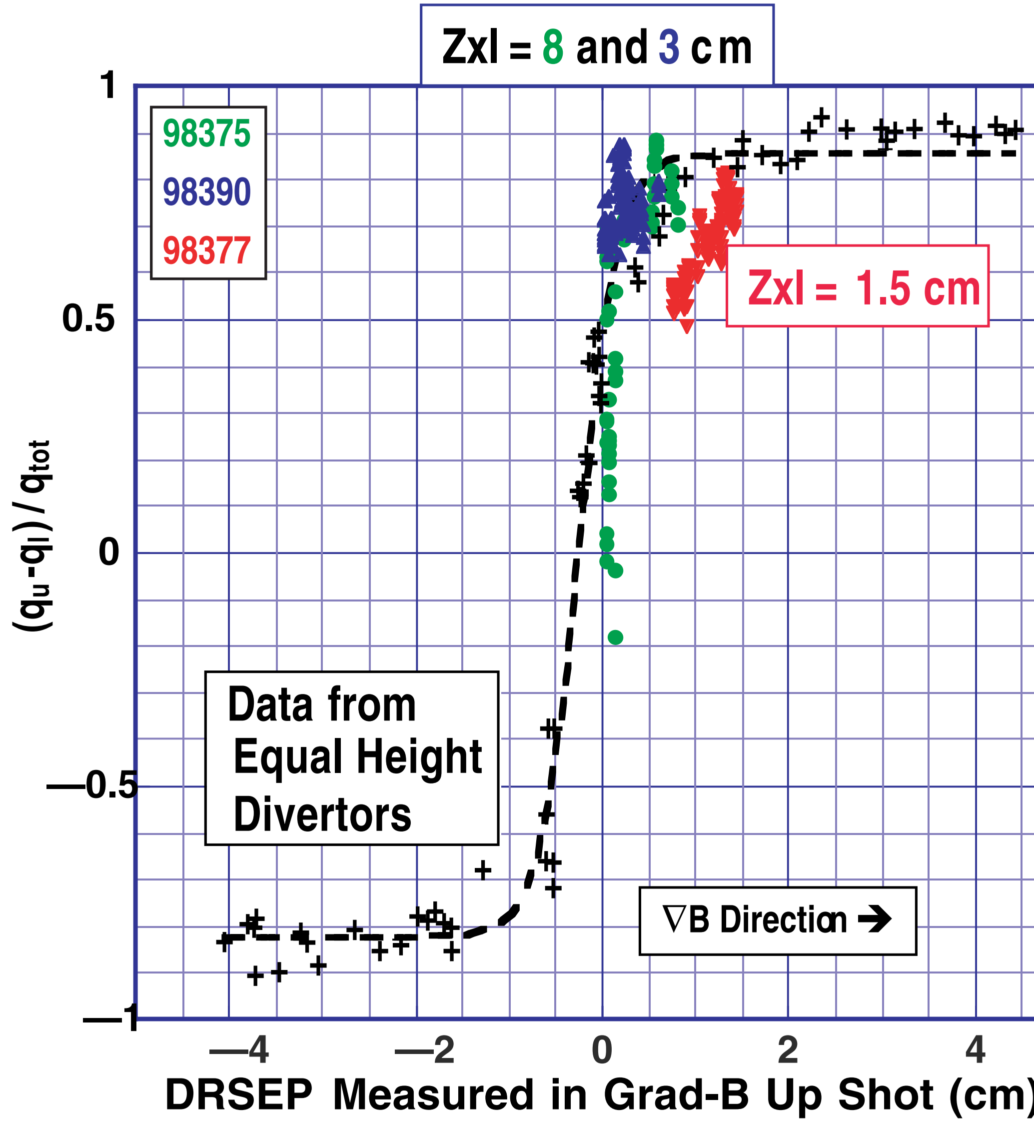
HEAT FLUX SHARING RATIO IN SHOTS WITH Z_X^S < 3 CM IS LOWER THAN FOR CONFIGURATIONS WITH EQUAL DIVERTORS

- Heat flux sharing when Z_X^S >~ 3 cm similar to result from equal divertors

- Effect of reduced secondary volume (for Z_X^S < 3 cm) is to increase lower peak heat flux
  - Outer divertor leg length in secondary divertor becomes negligible
  - High recycling divertor converted to limiter



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RESULTS FROM DRSEP VARIATION IN CONFIGURATIONS WITH EQUAL DIVERTOR VOLUME ARE USED TO REMOVE DRSEP EFFECTS FROM $Z_X{}^S$ SCAN SHOTS

- Assume that upper peak heat flux is nearly constant as $Z_X{}^S$ varies
- Expected variation in lower peak heat flux is calculated from TanH fit to DRSEP scan data with equal divertors
- Assume measured lower peak heat flux is product of component due to DRSEP variation and component from $Z_X{}^S$ variation
- Calculate ratio $F_{Z_X^S}$ of measured secondary peak heat flux to expected value from DRSEP variation alone

$$R_{DRSEP}^{FIT} \equiv \frac{q_u - q_l}{q_{tot}} = B + A \tanh\left[\left(\frac{d_r - d_r^{sym}}{d_r^{wid}}\right)\right]$$

where: d_r = DRSEP, d_r^{sym} = 0.26 cm, d_r^{wid} = 0.42 cm, A = 0.84, B = –0.07

$\therefore$ Expected Lower Peak Heat Flux is:

$$q_l^{DRSEP} = q_u^{measured} \frac{\left(R_{DRSEP}^{FIT} + 1\right)}{\left(1 - R_{DRSEP}^{FIT}\right)}$$

$$q_l^{measured} = F_{Z_x^s} \, q_l^{DRSEP}$$

or

$$F_{Z_x^s} = \frac{q_l^{measured}}{q_u^{measured}} \left.\frac{\left(1 - R_{DRSEP}^{FIT}\right)}{\left(R_{DRSEP}^{FIT} + 1\right)}\right]_{\substack{measured\\DRSEP}}$$

$\therefore F_{Z_x^s} > 1 \Rightarrow$ Greater peak heat flux in secondary than expected from DRSEP variation alone

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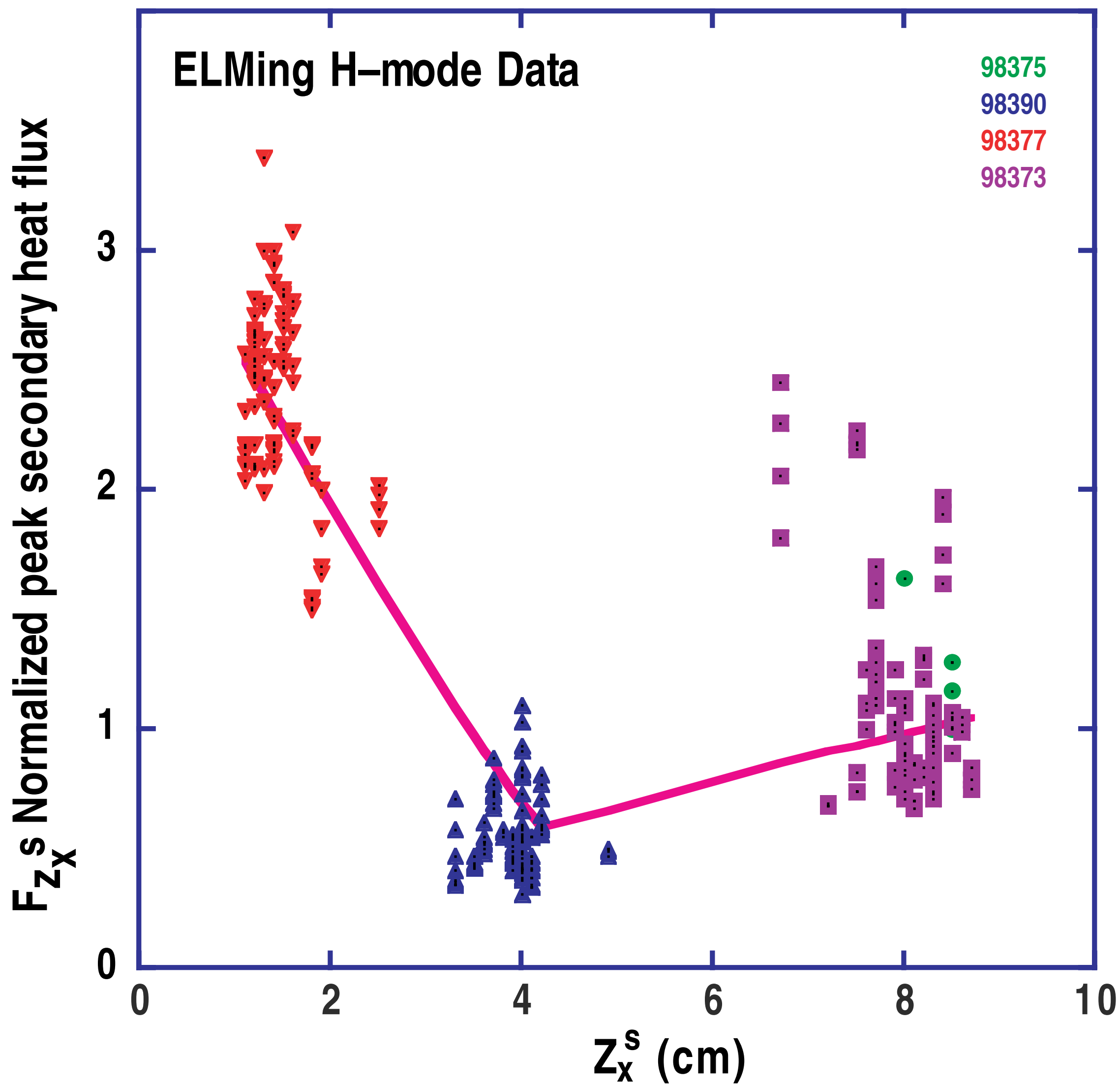
NORMALIZED SECONDARY PEAK HEAT FLUX IN H–MODE, CORRECTED FOR DRSEP VARIATION, SHOWS MINIMUM VERSUS $Z_X{}^S$ IN UNPUMPED DISCHARGES

- Peak secondary heat flux normalized to $Z_x{}^s$ = 16 cm case
- For $Z_x{}^s$ > 8 cm peak secondary heat flux similar to 16 cm case
- Effect of $Z_x{}^s$ reduction to 4 cm is to reduce secondary peak heat flux due to flux expansion
- For $Z_x{}^s$ < 3 cm secondary divertor outer leg length negligible and secondary acts like limiter with high peak heat flux



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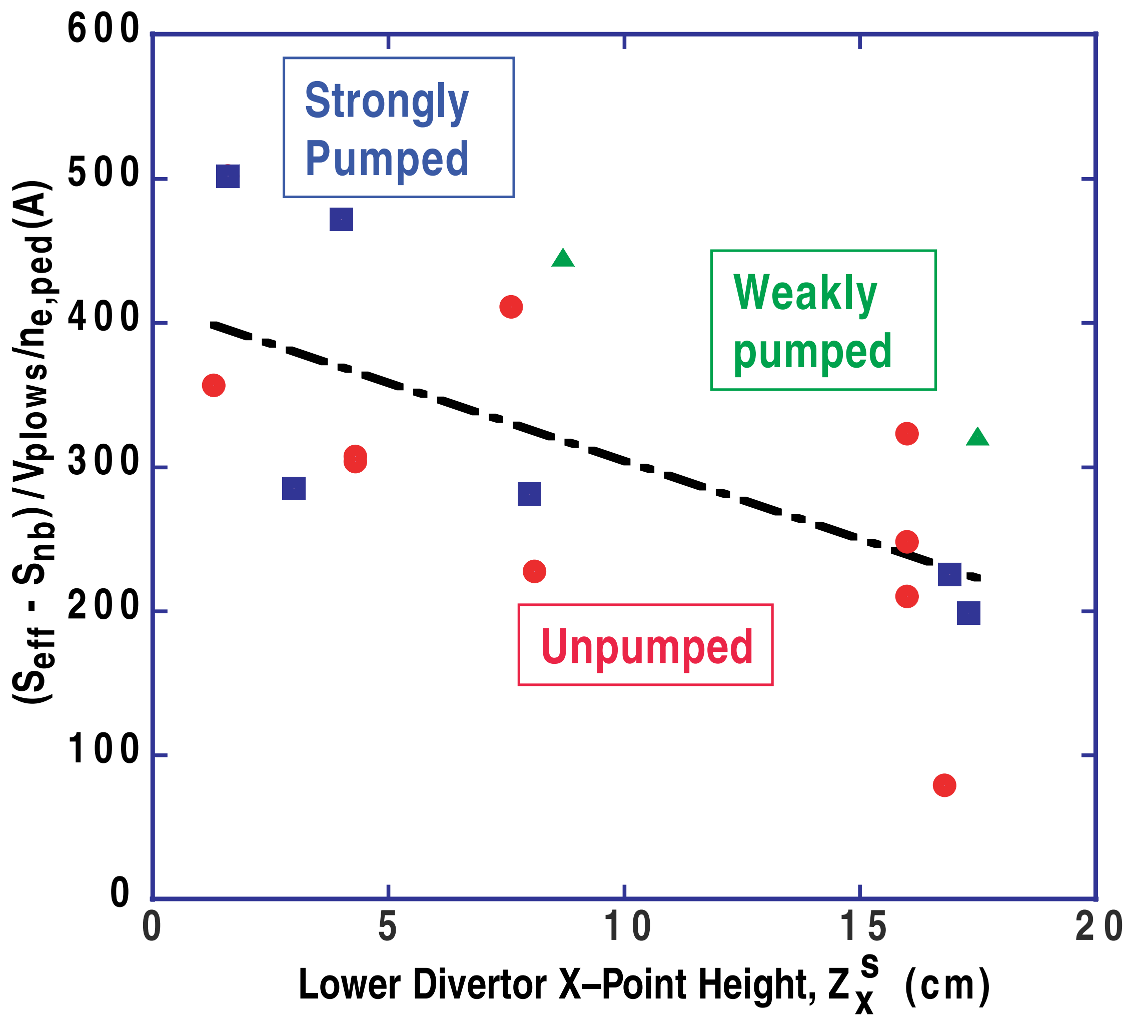
EFFECTIVE CORE FUELLING RATE AT L–H TRANSITION INCREASES WITH DECREASING SECONDARY DIVERTOR VOLUME.

- Effective source normalized to pedestal electron density and midplane gas pressure

- Effective core fuelling increases 80% for reduction in Z_X^S from 17 cm to 1 cm

- Large scatter in the data implies shot-to-shot variation in other parameters affecting fuelling efficiency, eg.
  - Wall conditions
  - Pedestal temperature



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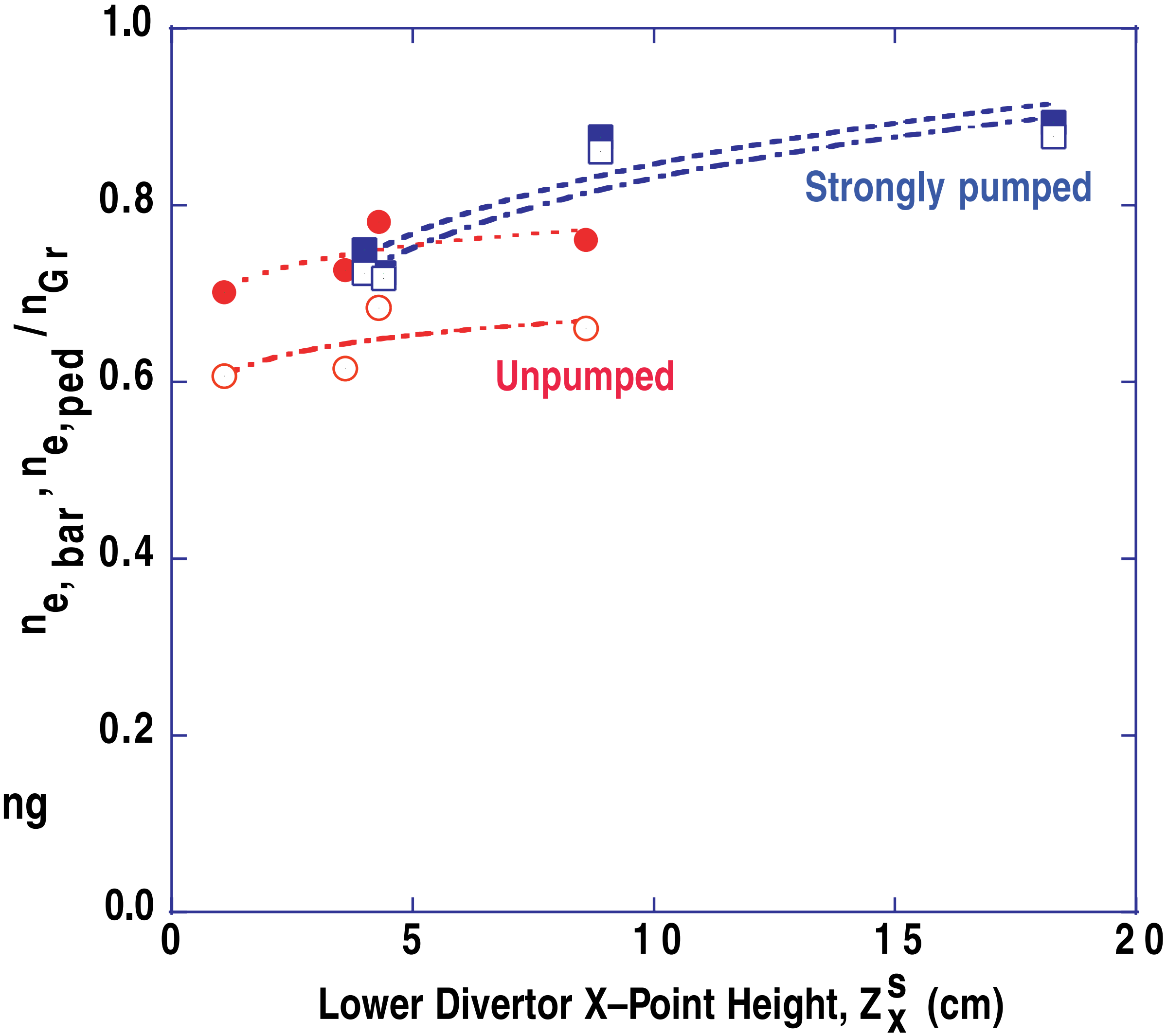
LINE AVERAGED AND PEDESTAL DENSITIES AT THE H–L BACK TRANSITION DECREASE AS Z_X^S DECREASES

- Line averaged density at H--L transition decreases in both pumped and unpumped discharges
- For high Z_X^S the transition density is higher with pumping
- Contributing physics as Z_X^S decreases:
  - — Increased neutral penetration from secondary divertor recycling
  - — Higher pedestal temperature with pumping



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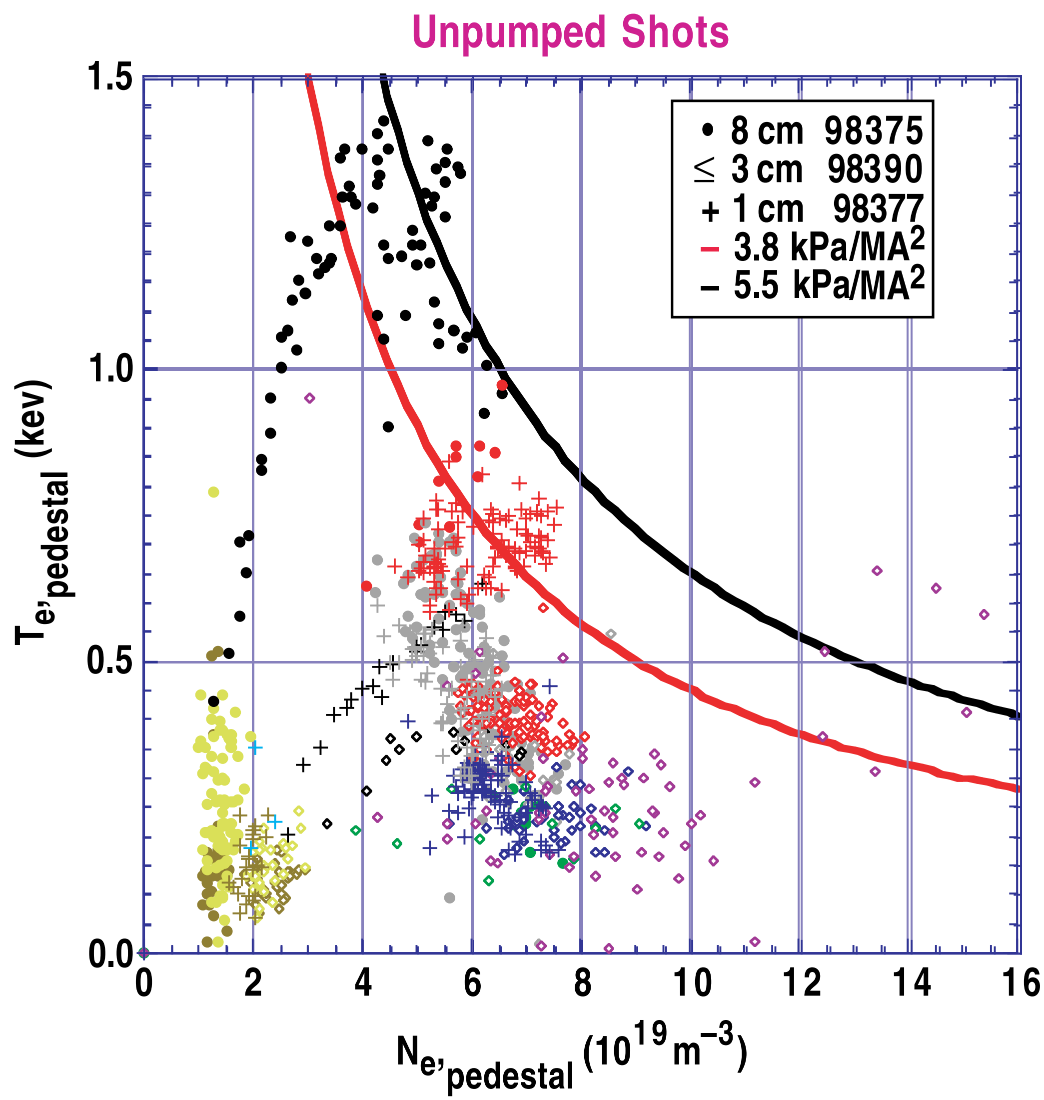
TRAJECTORIES IN PEDESTAL OPERATIONAL SPACE SHOW DEPENDENCE ON $Z_X{}^S$ IN UNPUMPED DISCHARGES

- **ELM-free performance**
  - Highest pedestal Te for $Z_X{}^s$ = 8 cm
  - Trend not monotonic with $Z_X{}^s$
- **Maximum pedestal pressure**
  - Shot with $Z_X{}^s$ = 8 cm exceeds pressure limit estimate from previous studies
  - Peak pressure lower at lower $Z_X{}^s$
- **Discharge at $Z_X{}^s$ = 3 cm** gives indication of MARFE boundary



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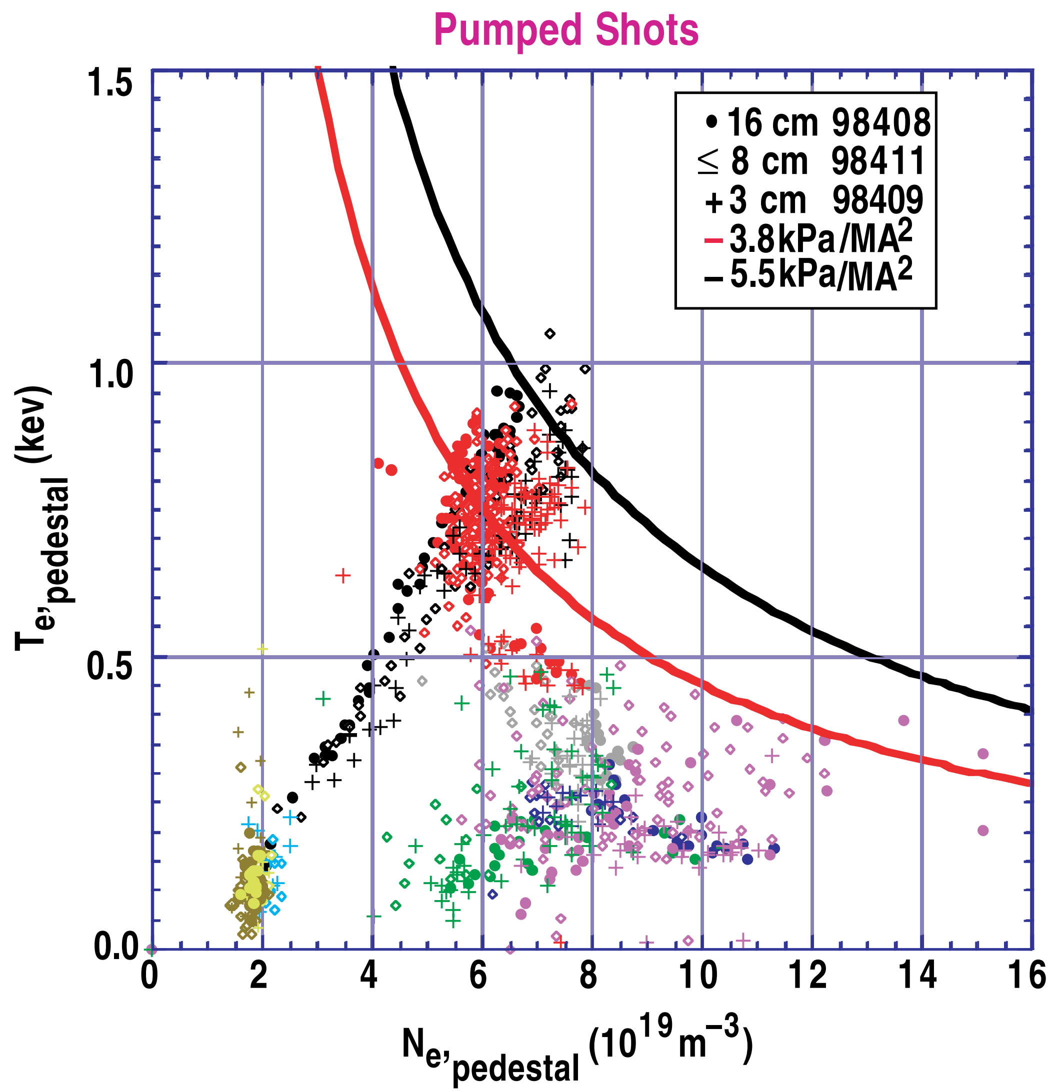
Ohmic, L–mode, Dithering, ELM-free, T I, Compound, T III, after H⇒L, MARFE

TRAJECTORIES IN PEDESTAL OPERATIONAL SPACE SHOW LITTLE DEPENDENCE ON $Z_X{}^S$ IN PUMPED DISCHARGES

- ELM-free performance and maximum pressure are very similar for $Z_X{}^S$ = 16, 8, and 3 cm
- MARFE boundary is also similar for all three shapes



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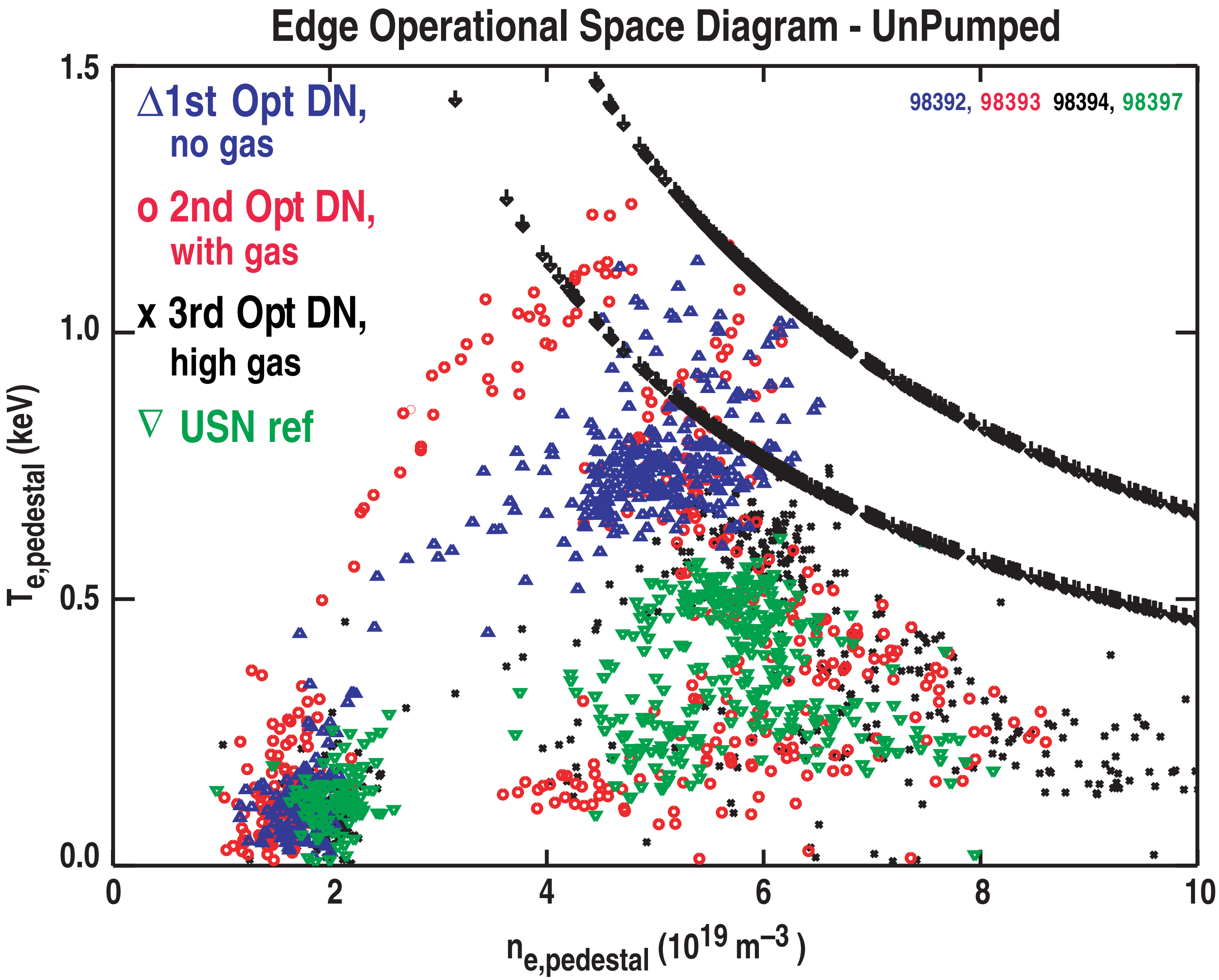
Ohmic, L–mode, Dithering, ELM-free, T I, Compound, T III, after H⇒L, MARFE

EDGE OPERATIONAL SPACE DIAGRAM SHOWS BETTER ELM-FREE PERFORMANCE IN "OPTIMIZED DN" COMPARED WITH USN

- Highest pedestal temperature achieved in Optimized DN with pumping walls
- Peak edge T_e is factor of 2 lower in SN with comparable divertor volume



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COMPARISON OF "OPTIMIZED DN" WITH SN HAVING SIMILAR TOTAL DIVERTOR VOLUME

Parameter	SN Reference Shot 98397	Optimized DN Shot 98392	Optimized DN Shot 98393	Optimized DN Shot 98394
Seff at L—H Transition (Normalized)	289	25 - 80	40	126
Maximum $\beta_N H$	3.77	9.14	7.16	4.83
Maximum Outer Leg Heat Flux / P_{inj}	332	178	N/A	125
Line-avg. Density at H—L Transition	8.83	N/A	9.0	11.0

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REDUCTION OF SECONDARY DIVERTOR VOLUME PRODUCES POSITIVE (+) AND NEGATIVE (-) EFFECTS ON PERFORMANCE

(+) Heat Flux Sharing

- Normalized secondary peak heat flux in unpumped plasmas reduced as $Z_x{}^s$ reduced until secondary acts as limiter

(-) Fueling at L–H Transition

- Seff increases 80% as $Z_x{}^s$ reduced from 17 to 1 cm
- Large scatter even with corrections for I_{nb}, n_e, $p_{midplane}$ $\Rightarrow$ other variables may be important

(-) Density Limit at H–L Back Transition (fixed q_{95})

- n_e/n_{Gw} decreases as ZxI reduced in pumped and unpumped plasmas
- Increased neutral penetration contributes to density limit reduction

REDUCTION OF SECONDARY DIVERTOR VOLUME PRODUCES POSITIVE (+) AND NEGATIVE (-) EFFECTS ON PERFORMANCE (cont.)

(+) Optimized Unbalanced DN (60% primary, 40% secondary)

- Limited comparison shows some advantages of "optimized" DN versus SN with comparable divertor volume
  - ★ Fueling at L–H reduced by factor of 2 –10
  - ★ Maximum β_NH achieved was factor of 1.3 – 2.5 higher
  - ★ Peak outer leg heat flux was factor of 1.9 – 2.7 lower
  - ★ n_e/n_{Gr} at H–L was up to 25% higher

(+-) Edge Pedestal Performance

- Higher pedestal temperature and pressure obtained with higher Z_X^S in unpumped plasmas
  - ★ Some variation in performance at constant $Z_X^S \Rightarrow$ other variables (eg. Wall conditions)
- Performance of pumped discharges insensitive to Z_X^S

QUANTITATIVE UNDERSTANDING FROM THIS STUDY PROVIDES GUIDANCE ON THE EFFECT OF SHAPE VARIATIONS ON PERFORMANCE

- When using high δ for good core performance, the minimum secondary divertor volume requirement for favorable performance is predictable
  - Secondary X–point must be high enough so that flux surface one midplane power SOL length from primary separatrix has finite outer divertor leg length
- Optimum secondary X–point height is trade-off between reduced core volume versus increased density control and H–L transition density limit
- Performance is less sensitive to secondary divertor volume when outer SOL is pumped