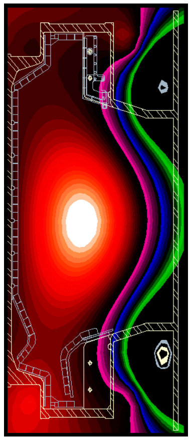
DENSITY LIMITS IN TOROIDAL PLASMAS



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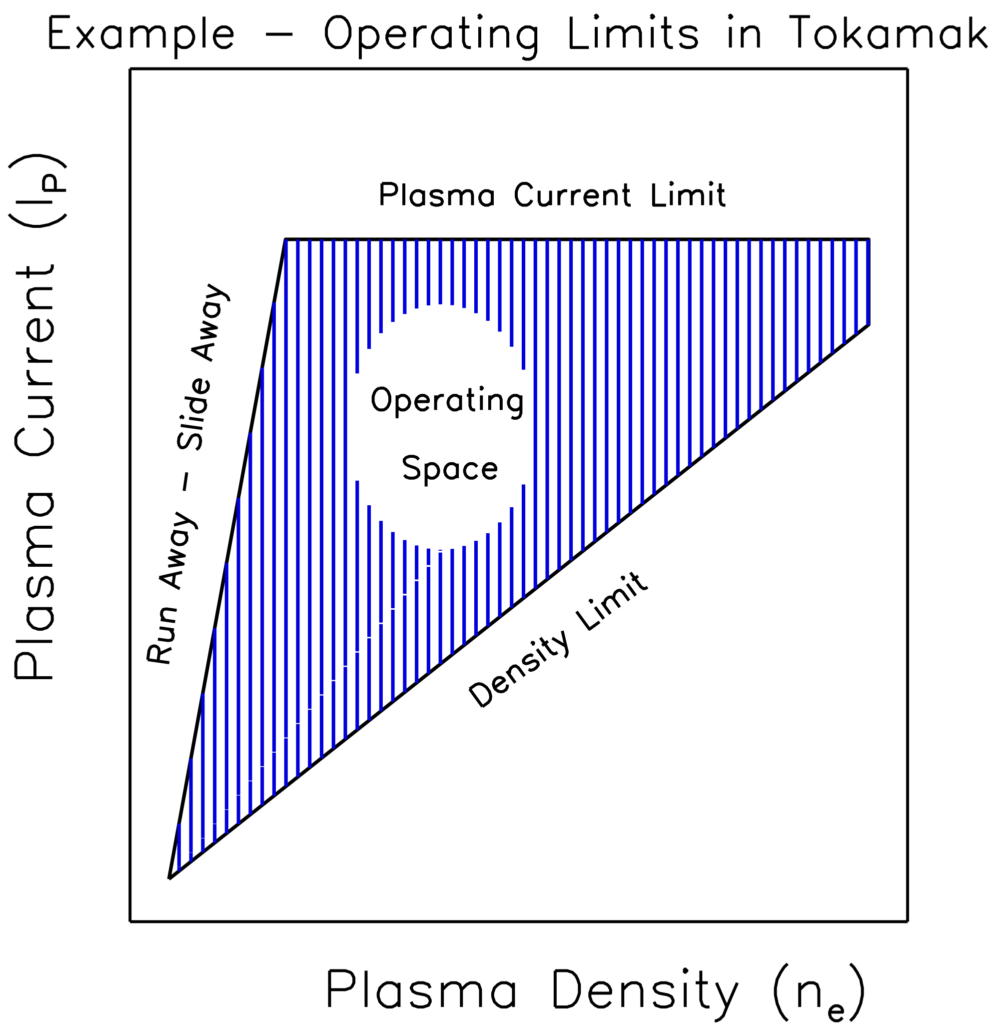
S. Kaye	T. Osborne	A. Staebler	

- Not enough time to show all deserving work
- Mistakes in interpretation are my own

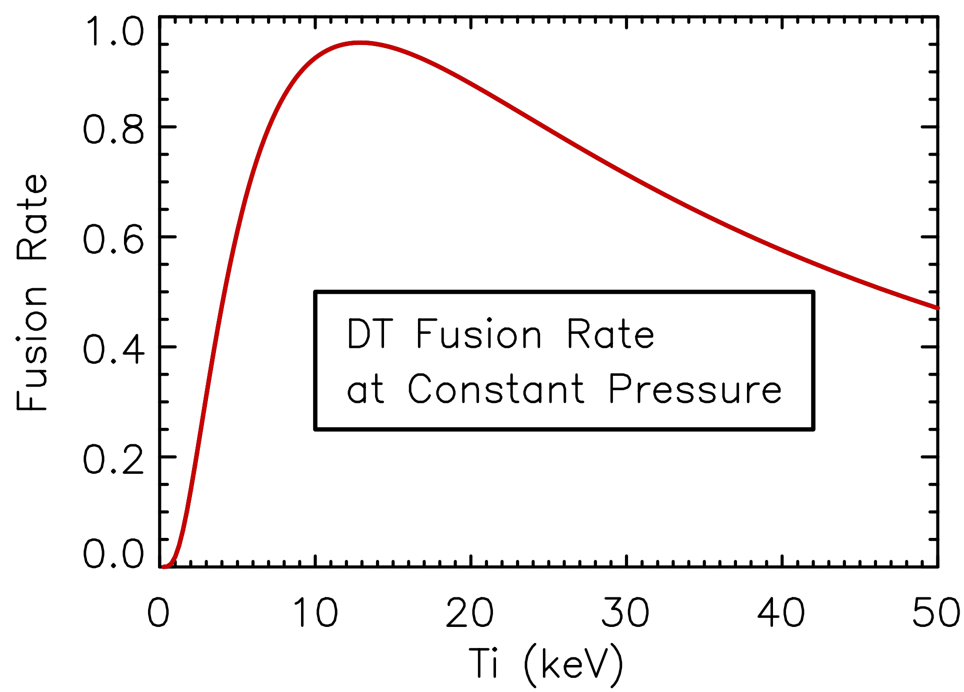
OPERATIONAL LIMITS

- Magnetic confinement devices don't operate at arbitrary plasma parameters
- There are well established, **distinct** limits on plasma **pressure, current, and density**
- Understanding these limits and their implications has always been an active area of research



DENSITY LIMITS - AN IMPORTANT ISSUE FOR MAGNETIC FUSION

- $R_{DT} \propto n^2 \langle \sigma v \rangle$
- Plasma pressure limited by MHD stability
- At fixed pressure, there is an optimum temperature ➔ optimum density
- **No guarantee that this density is achievable in any given device**
- Critical issue for conventional tokamak reactor

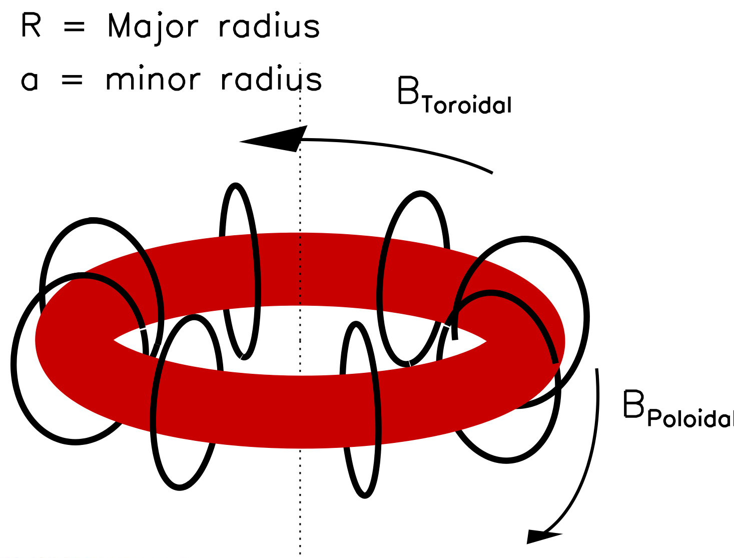


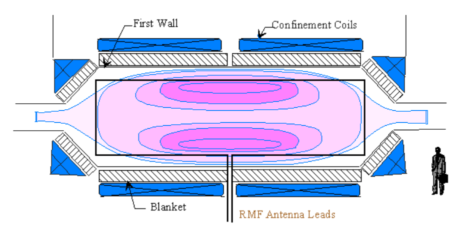
DENSITY LIMITS - THE PHYSICS PROBLEM

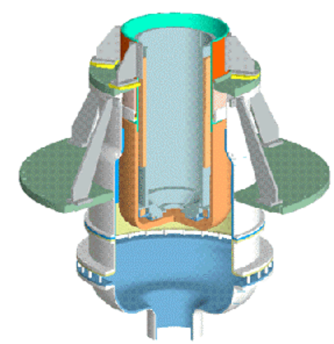
- What physics can limit the density?
  - Ideal MHD only cares about pressure (and current) not density
    - ✷ Temperature profile influences current profile
    - ✷ (Resistive MHD could be a factor at low temperatures)
  - Radiation cooling $P_{RAD} \propto n_e^2 f_Z R(T_e)$
  - Neutral shielding: fueling limits
  - Density or collisionality dependent transport → edge cooling
- **No widely accepted first principles theory available**
- **Not even agreement on critical physics**

OUTLINE OF TALK

- Experimental observations including
  - Tokamak
  - Stellarators
  - Reversed Field Pinches (RFP)
  - Spheromaks and FRCs
- Physics basis for density limit
  - Neutrals
  - Radiation models
  - Role of transport physics
- Summary and Discussion

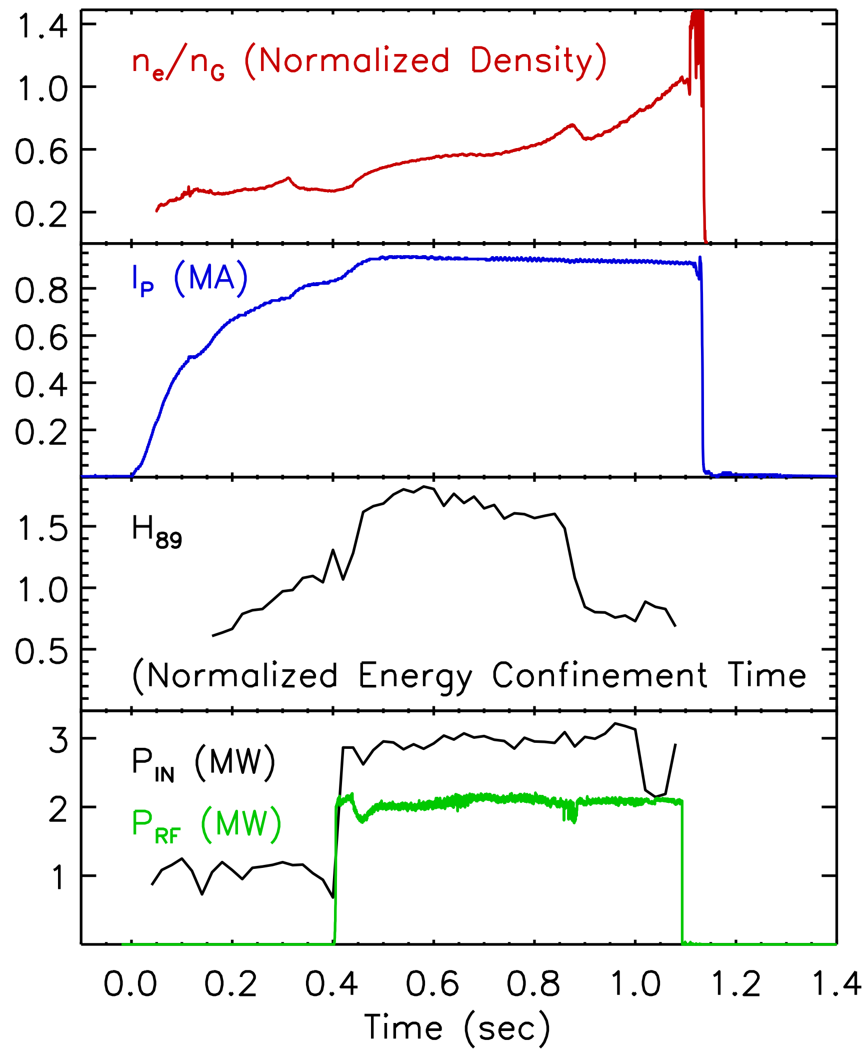






IN TOKAMAKS, LIMIT ULTIMATELY MANIFESTS ITSELF AS DISRUPTION

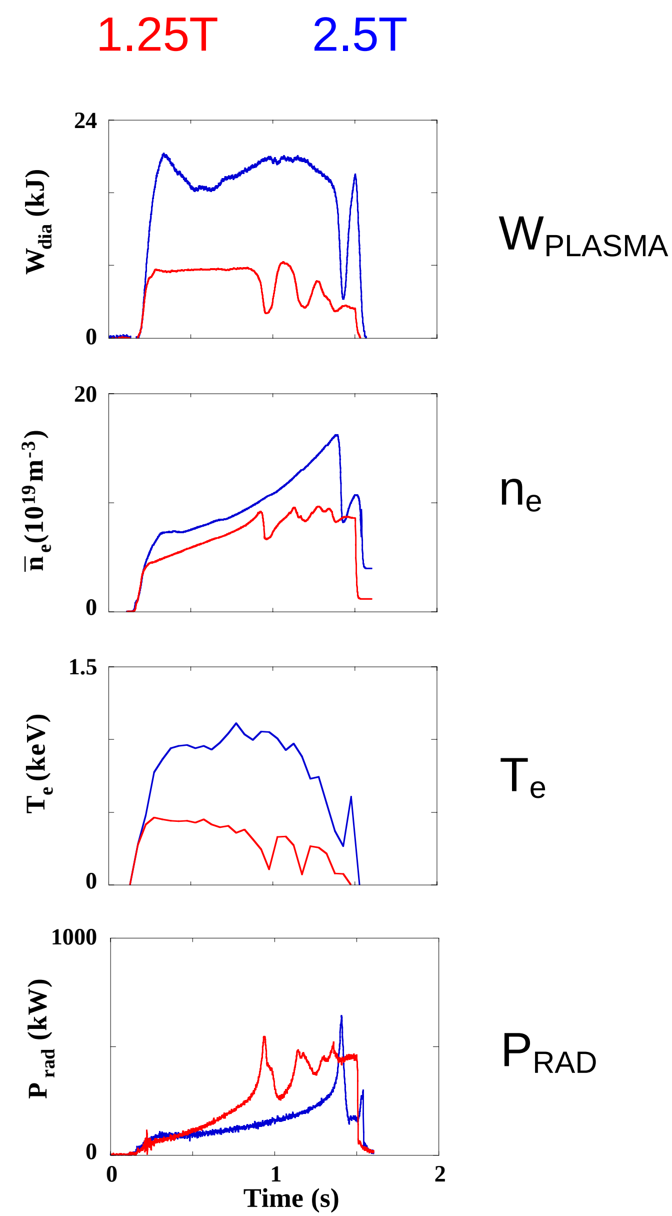
- General agreement on final scenario
- Current profile shrinkage → MHD instability → disruption
- Critical questions involve the evolution to the point where the current profile collapses
- What is the essential physics of the bifurcation or catastrophe
- "Hard" terminations also seen at times in reversed field pinches



"SOFT LIMITS" SEEN IN OTHER DEVICES

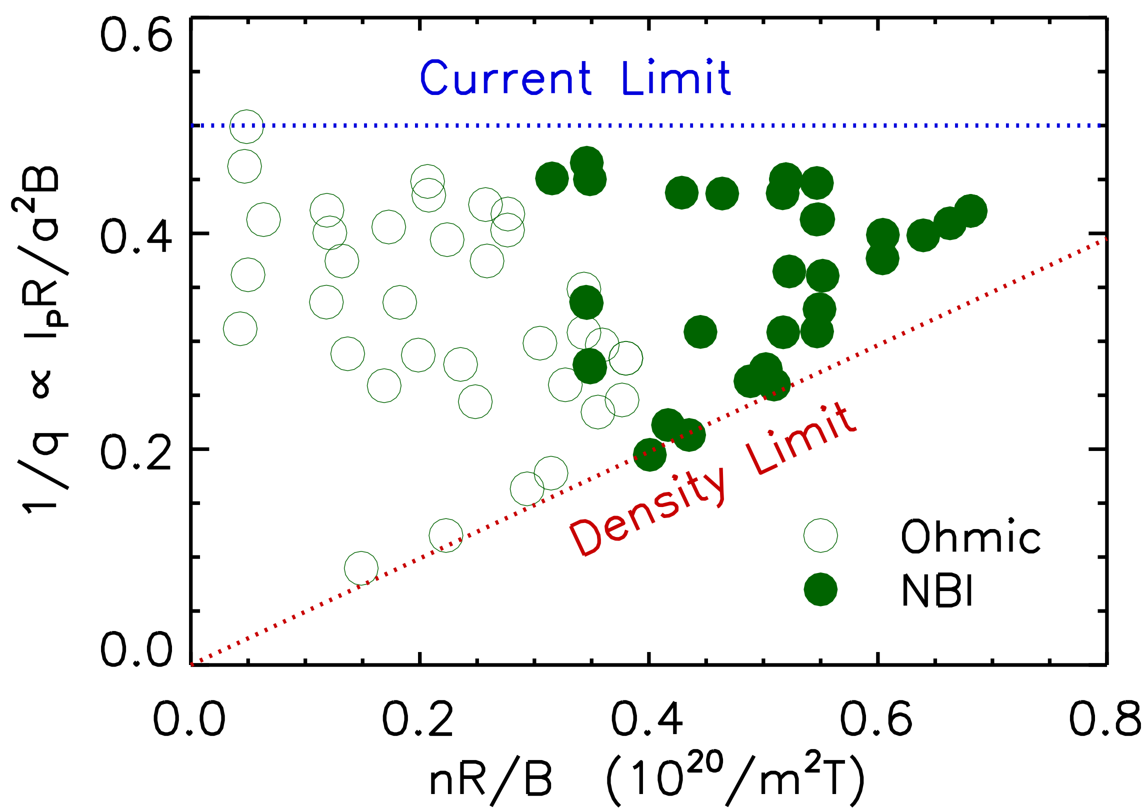
- In Stellarator, clear evidence of thermal collapse - plasma can recover if density is lowered
- No coupling from Te profile through resistivity and current profile to MHD stability
- Physics is not so clearly confined to edge
- RFPs have quenches as well as fast terminations
- Spheromak and FRC don't have density limit data operation at "optimized" density.
- **Doesn't preclude (or require) a common cause**

(Giannone 2000)



DENSITY LIMIT FIRST CHARACTERIZED BY EMPIRICAL SCALING

- First motivated by observation that impure plasmas disrupted at lower densities
- Murakami limit (1976)
  $B_T / R \propto j_0 \approx P_{Ohmic}$
- Hugill plot ~ 1978
- Leading dependence is with plasma current density



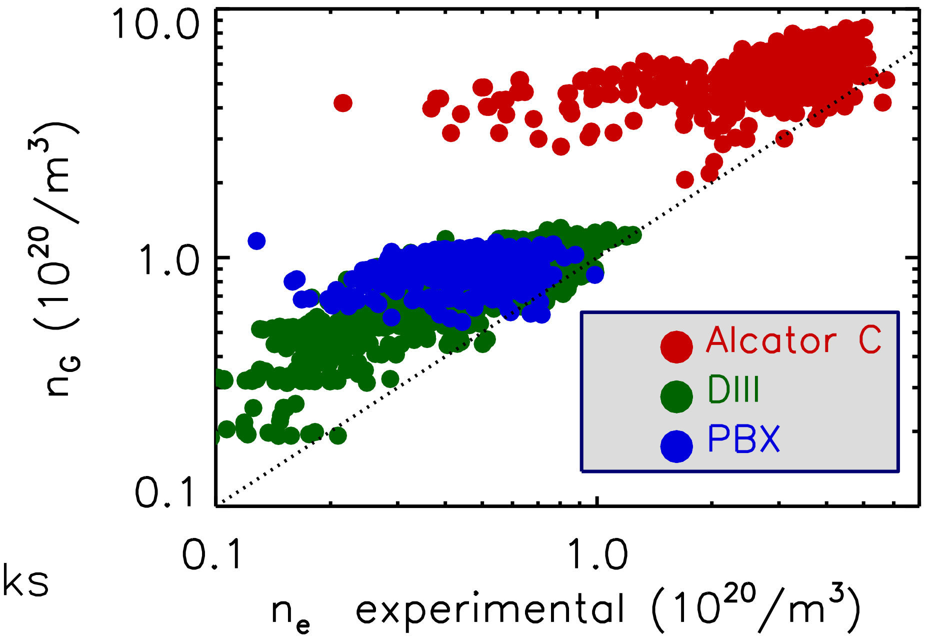
(Axon 1980)

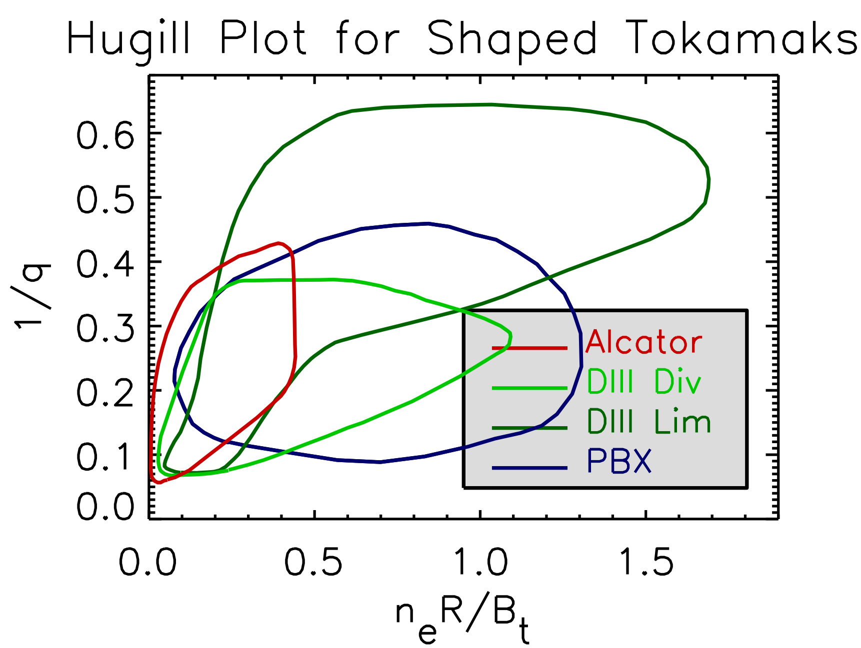
- $n_{LIM} \propto \frac{B}{qR} \approx \frac{I_P}{a^2}$ (Note absence of significant power scaling)

SCALING REFINED BY INCLUSION OF DATA FROM SHAPED TOKAMAKS

- Greenwald limit: $n_G = \frac{I_P}{\pi a^2}$

  (with n: $10^{20}/m^3$, I_P: MA, a: m)

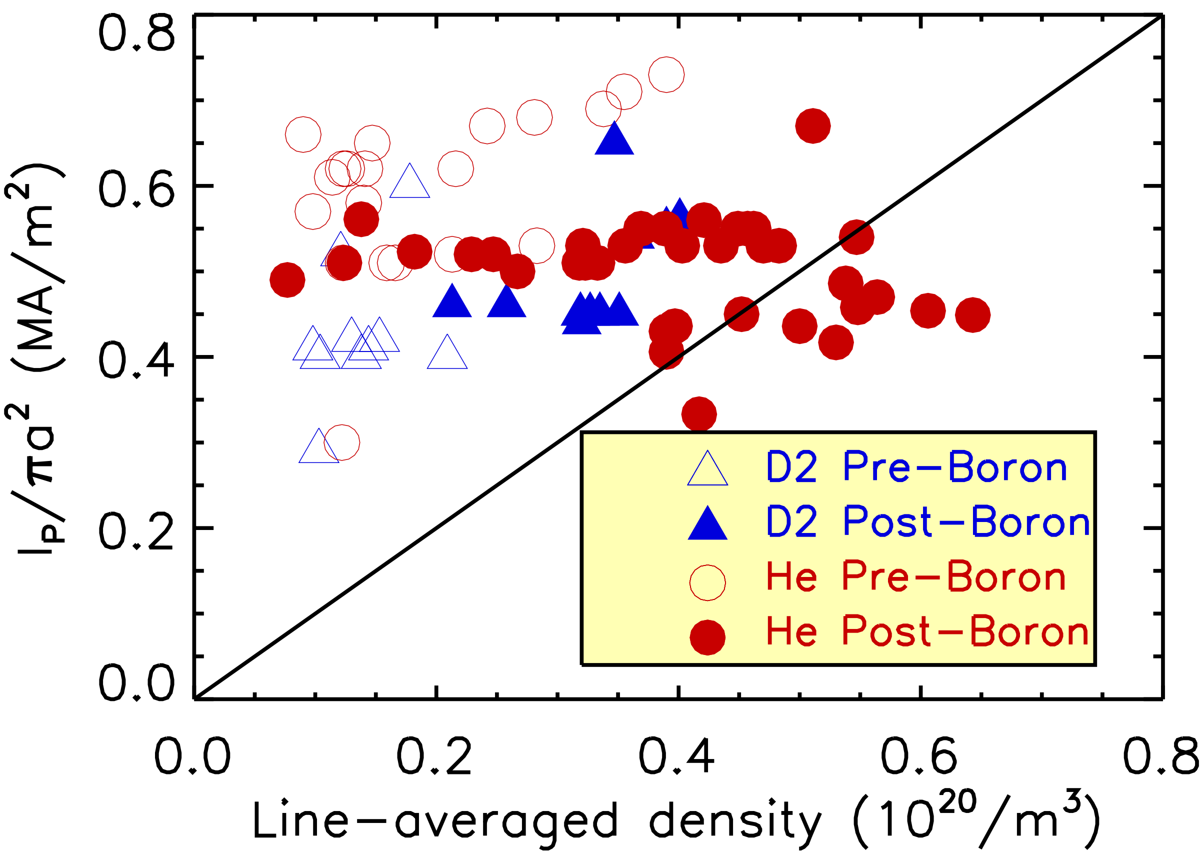




- Identical to Hugill for circular plasmas
- Differs significantly for shaped plasmas

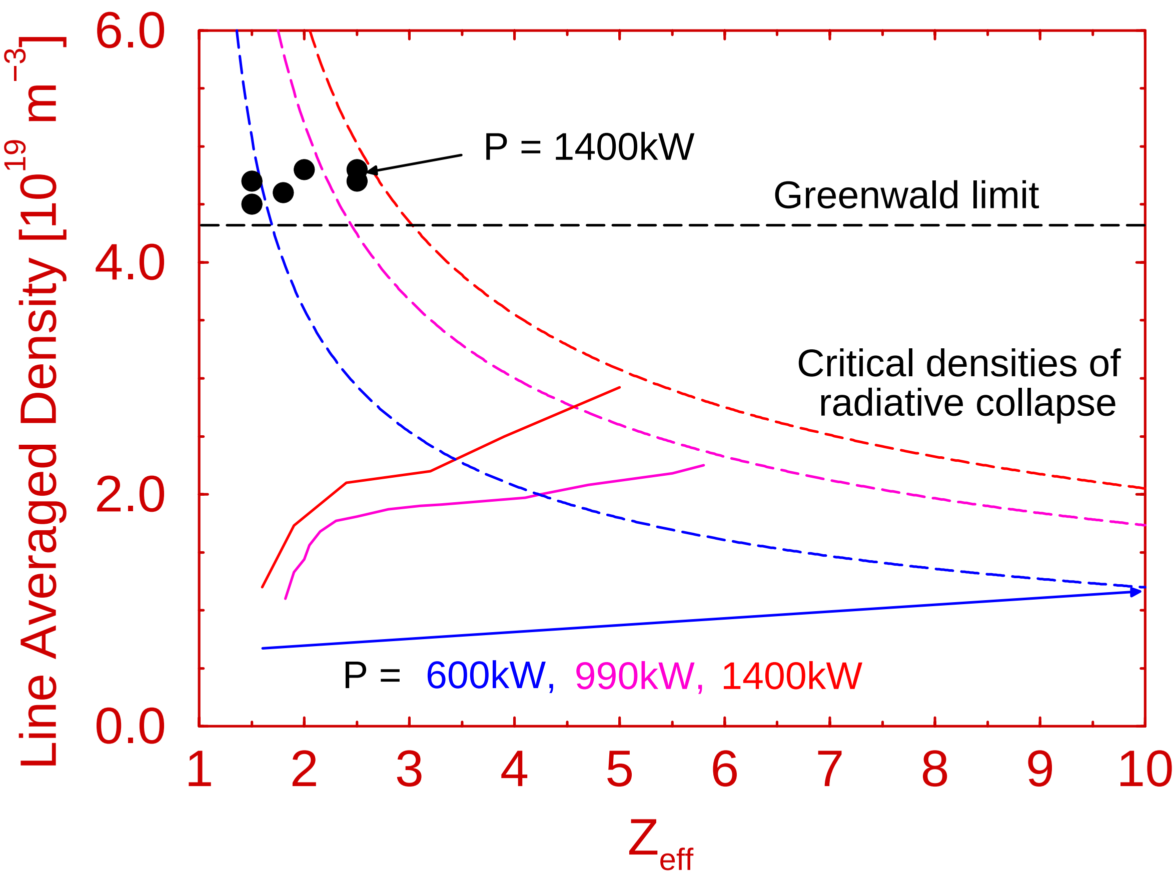
RECENT DATA WITH VERY DIFFERENT PLASMA SHAPE IS ROUGHLY FIT BY EMPIRICAL LAW

- Original data had wide range in B_T, I_P, P_{IN}
- Aspect ratio only 3-5
- Elongation only up to 1.5
- Spherical tokamaks aspect ratio ~ 1.5 elongation ~ 2



(Kaye 2001)

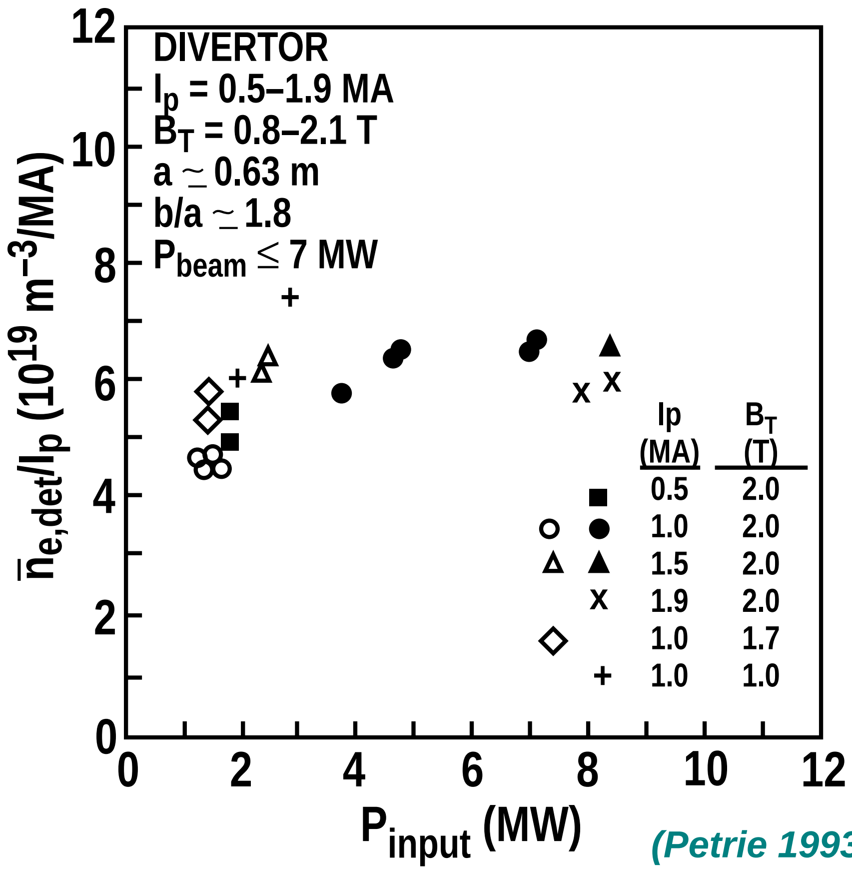
IMPURITIES ARE IMPORTANT …. BUT ONLY UP TO A POINT



(Rapp et al, 2000)

- Below around Z_{EFF} ~ 2.5, drops out $\left(Z_{EFF} \equiv \frac{\sum n_i Z_i^2}{n_e}\right)$

DENSITY LIMIT IN TOKAMAKS DOES NOT DEPEND STRONGLY ON INPUT POWER



(Petrie 1993)

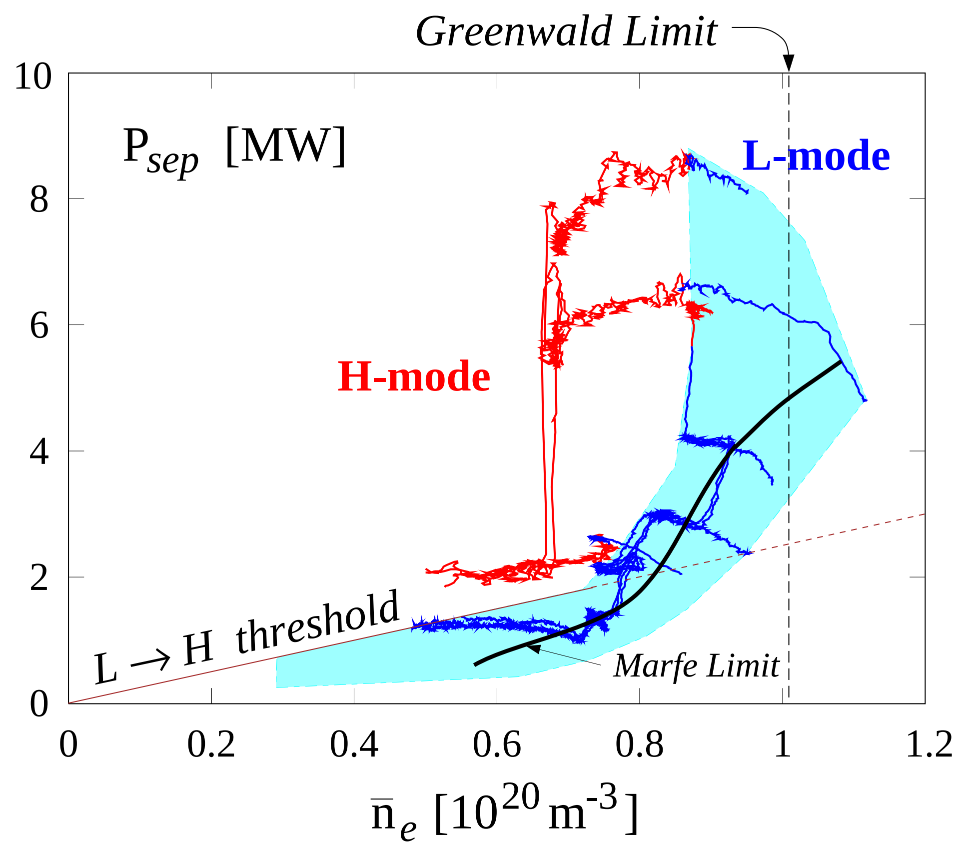
- Power dependence in low confinement mode (L-mode) varies from P^0 - $P^{0.25}$
- Role of neutral beam fueling in power dependence is uncertain

AT HIGH DENSITIES, HIGH CONFINEMENT (H-MODE) DISCHARGES DEGRADE THEN REVERT TO L-MODE

- H-mode plasmas have edge "transport barrier"

→ Pedestal in T_e, n_e profile

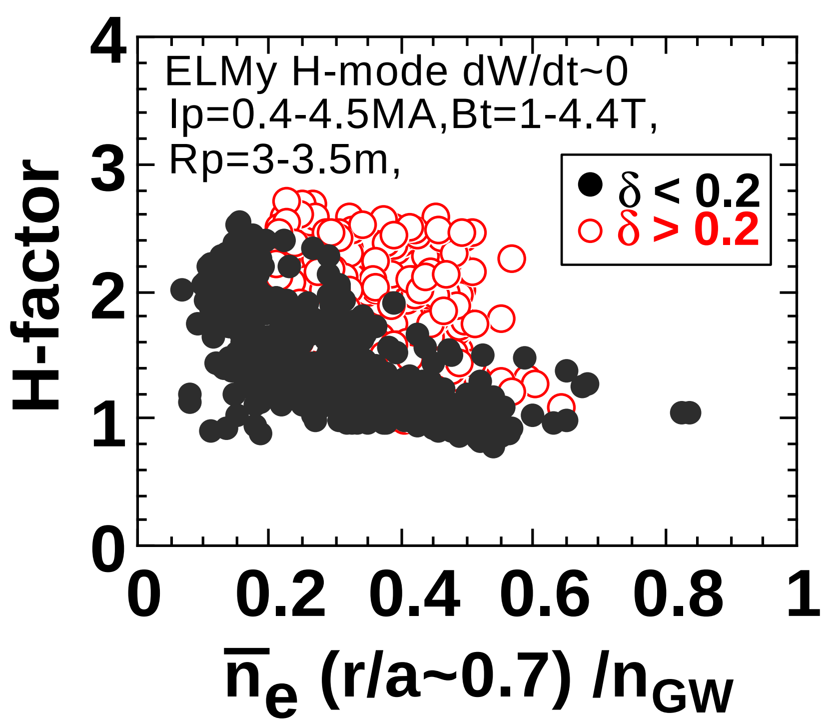
- **Confinement degradation** can set in as low as $0.3n_G$
- **Threshold power diverges** as the limit is approached
- H/L transition at $0.8\text{-}1.0n_G$



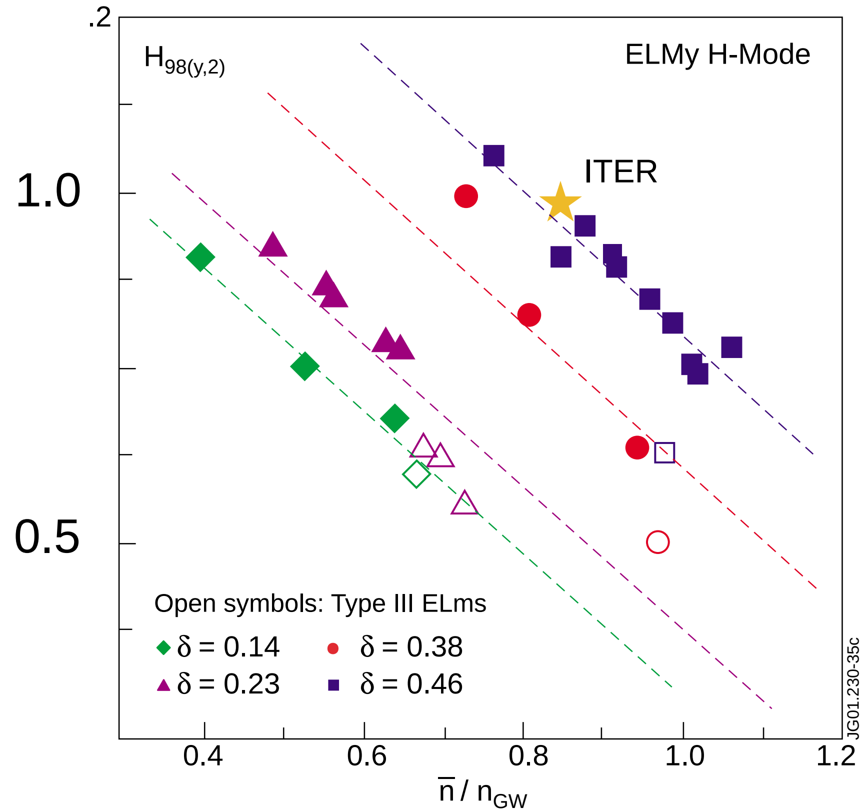
(Mertens 1997)

STRONG SHAPING DOES ALLOW FOR BETTER CONFINEMENT IN H-MODE AS THE DENSITY IS RAISED TOWARD THE LIMIT.

- Increase in confinement at high triangularity attributed to improved pedestal stability



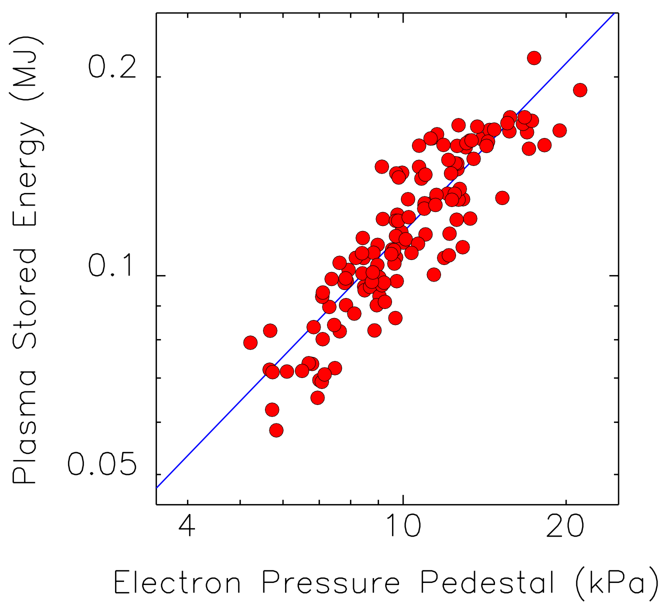
(Kamada 1996)



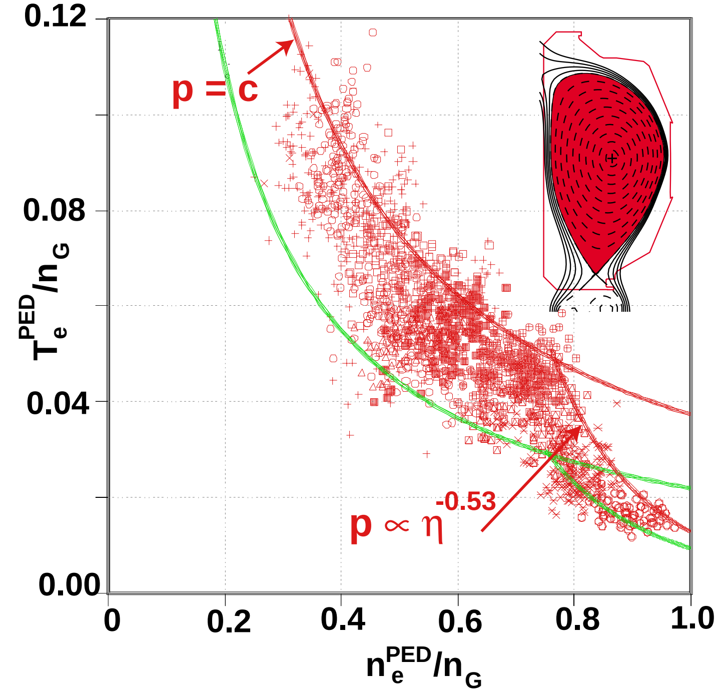
(Ongena 2001)

DETERIORATION IN H-MODE CONFINEMENT IS CORRELATED WITH DROP IN EDGE TEMPERATURE

- $H \text{ and } \nabla T_{CORE} \propto T_{EDGE}$
- Constant edge pressure implies τ_E independent of density



(Hughes 1997)

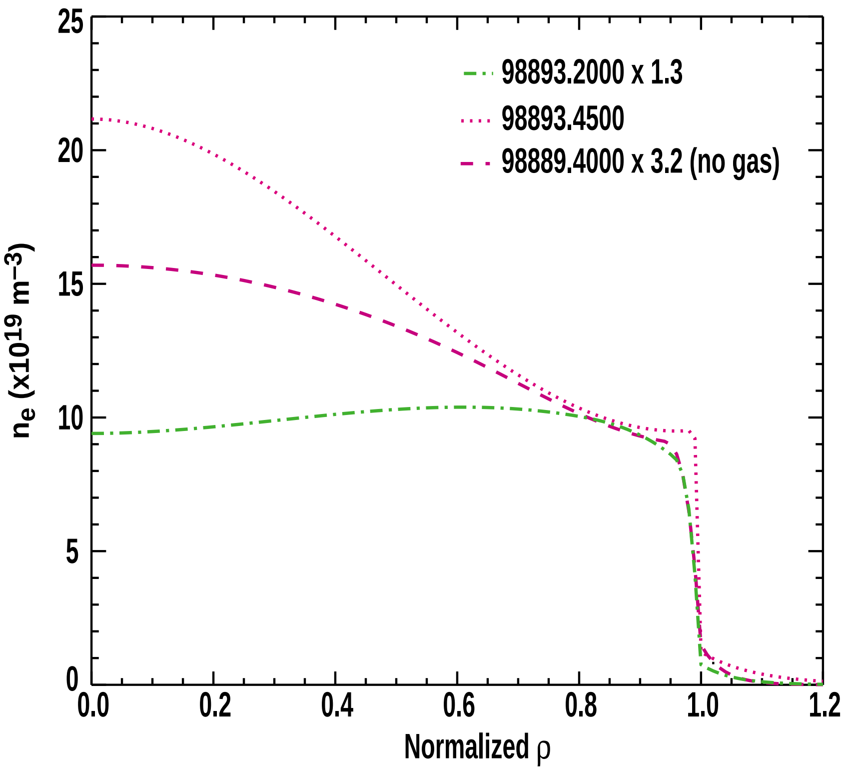


(Osborne 2000)

- Deterioration in edge confinement can be offset by internal transport barrier

SO…THE TRICK FOR EXCEEDING THE EMPIRICAL LIMIT - PEAKED DENSITY PROFILES

- All indications are that limit is due to edge
- Particles in core apparently don't drive density limit

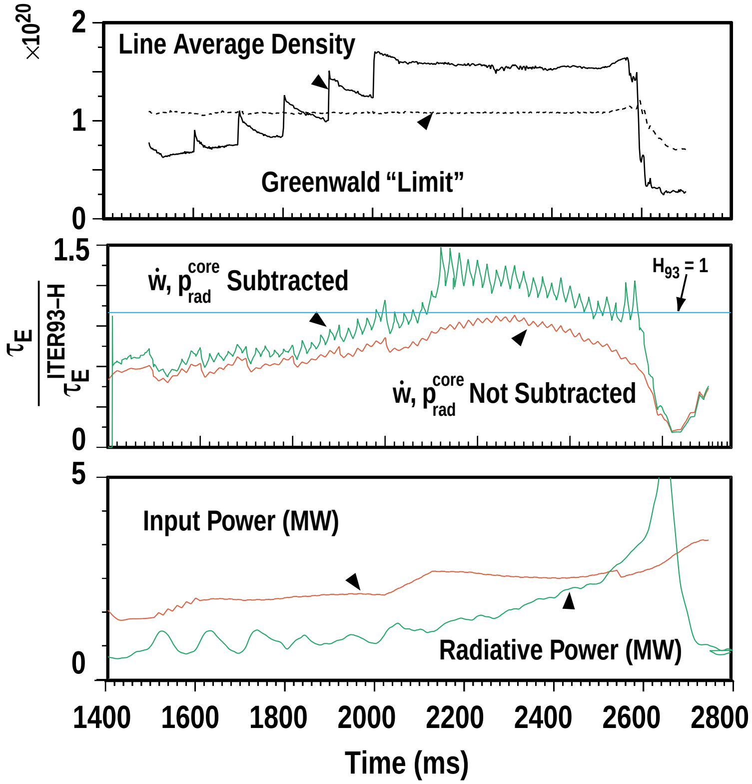


(Mahdavi 1997)

- Density profiles not stiff
- Peaked by core fueling, edge pumping, transport modification

GOOD CONFINEMENT WITH DENSITY IN EXCESS OF n_G IS CORRELATED TO PEAKED DENSITY PROFILE

- Widely seen (Alcator C, TFTR, DIII-D, JET, ASDEX, ASDEX-Upgrade, TEXTOR…)
- Also seen in stellarators (Heliotron E, LHD)
- Edge density apparently never exceeds empirical limit
- Combination of density peaking and strong plasma shaping open window for high density operation



(Mahdavi 1997)

DENSITY LIMITS IN REVERSED FIELD PINCH

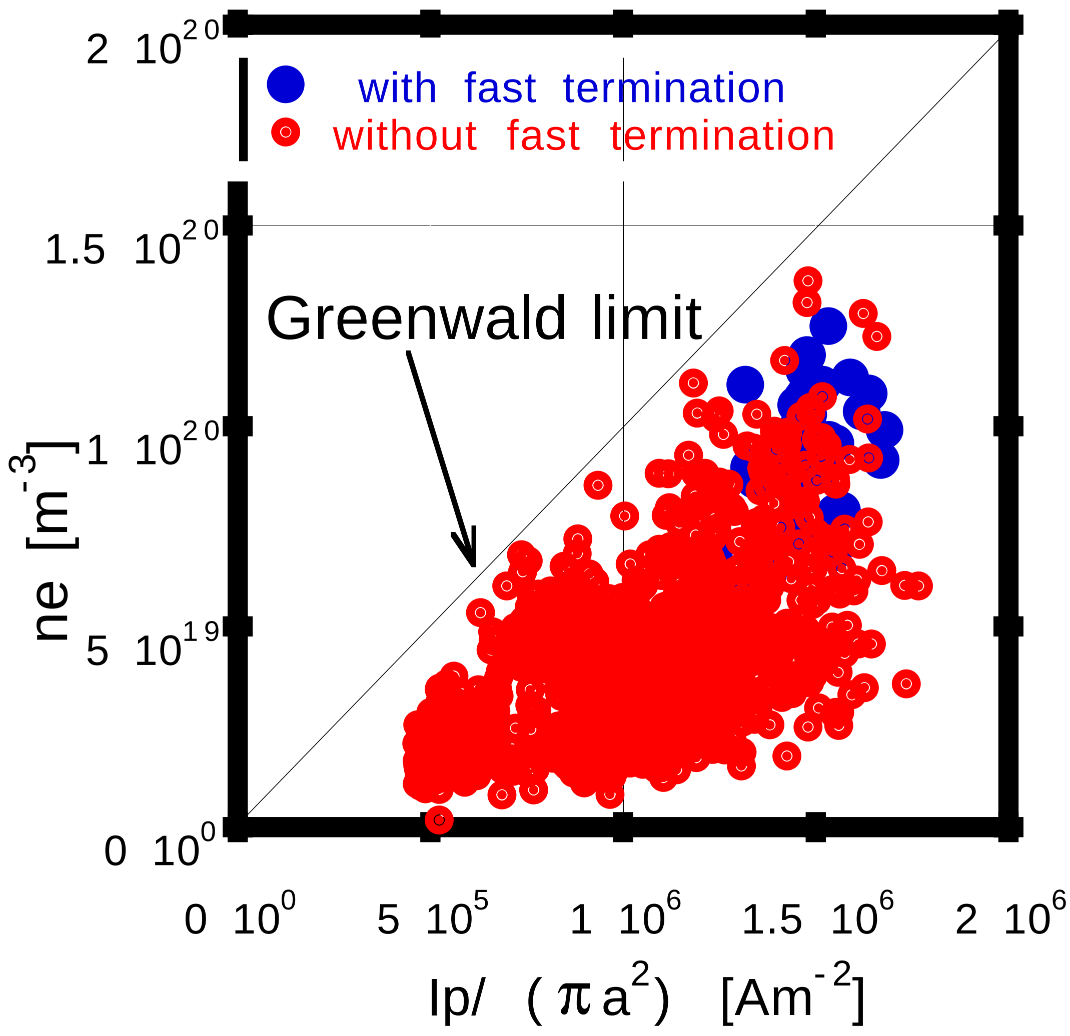
- RFP operating space characterized historically by I/N

- $\frac{I}{N} \propto \frac{n_G}{n}$

- Same scaling !

- Limit is quantitatively identical (!!)

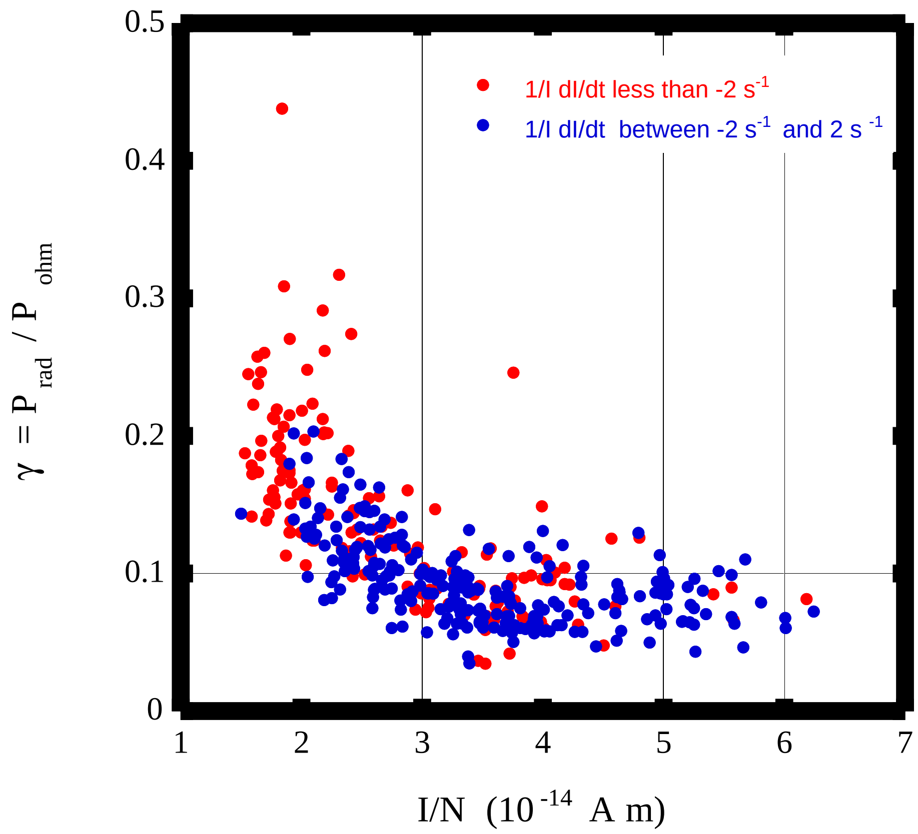
(Bartiromo 2000)



RADIATED POWER PROBABLY NOT CRUCIAL FOR RFP LIMIT

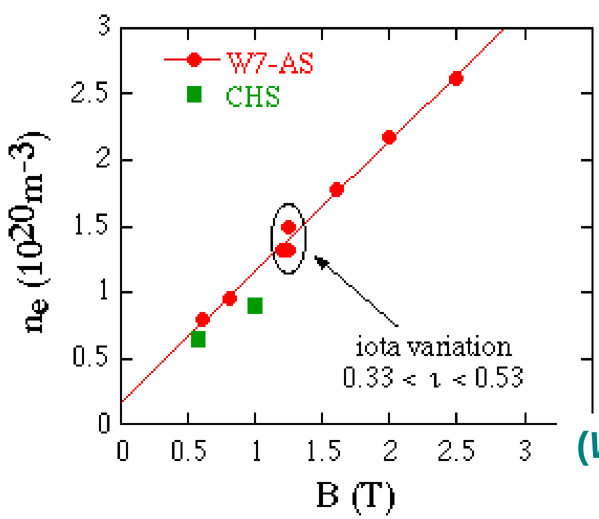
(Marrelli 1998)

- RFP has both soft (quench-like) and hard (disruption-like) density limits
- Radiated power increases at high density (low I/N), but
- **Radiated fraction is never very high**



STELLARATORS REACH SIMILAR DENSITIES BUT SHOW DIFFERENT DEPENDENCES

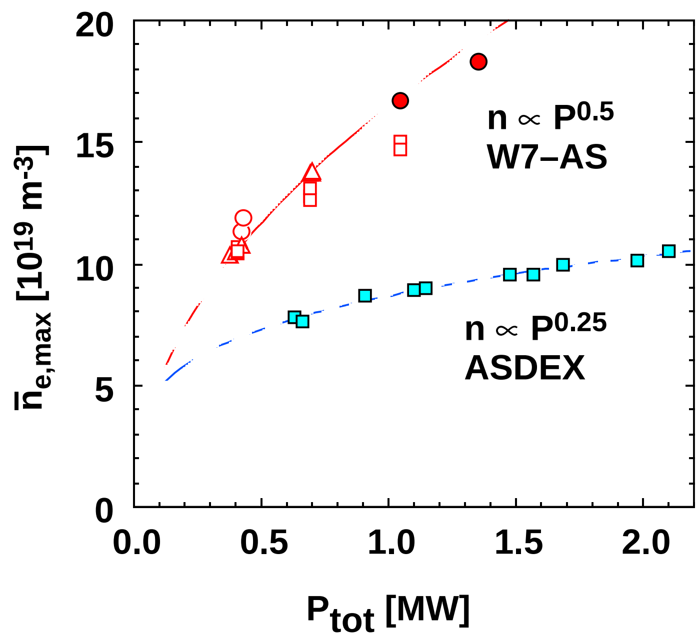
- Different scaling with power, size
- Shaping: B/qR vs I/a^2 scaling
- Scaling with $\iota = 1/q$
- For machines with similar size and fields, stellarator will reach about twice the density of a tokamak



(Wagner 1997)

Power dependence of density limit

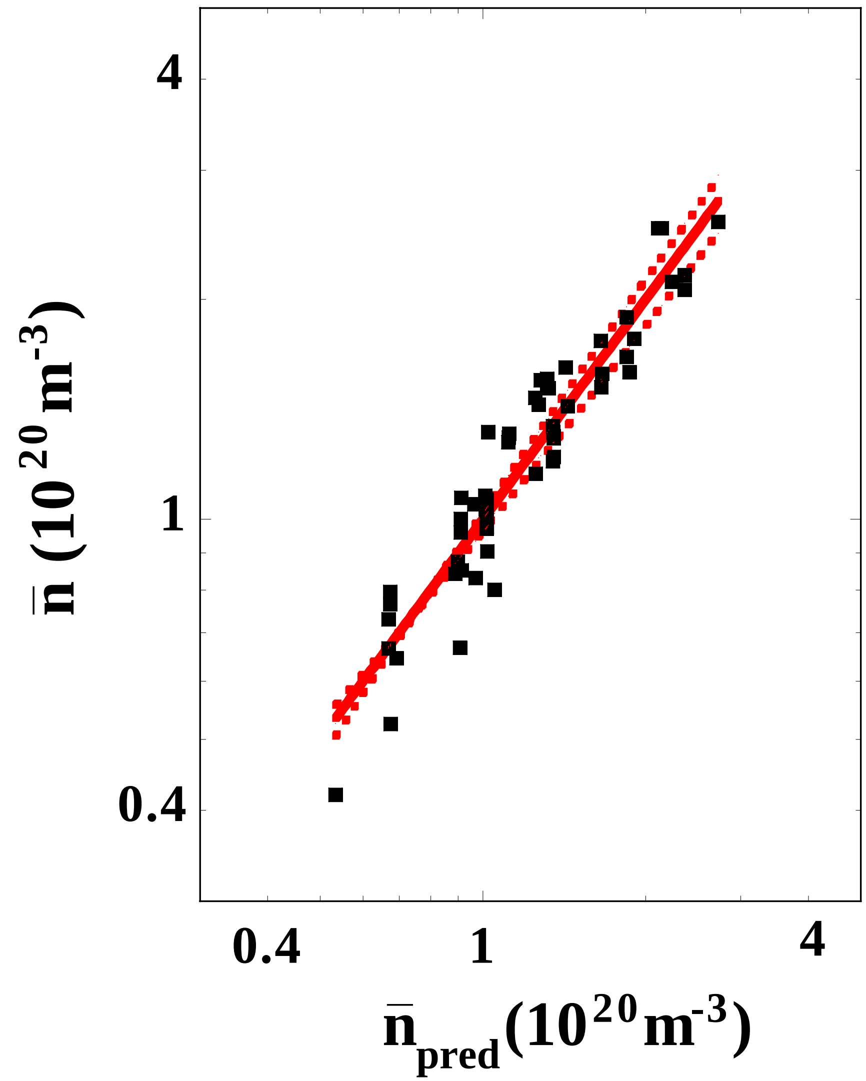
(Staebler 1992)



ASDEX: B_t = 2.1 T, $1/q_a$ = 0.34
W7-AS: B_t = 1.28 T, $\iota(a)$ = 0.33
both with boronized walls

SCALING FOR STELLARATOR DENSITY LIMIT

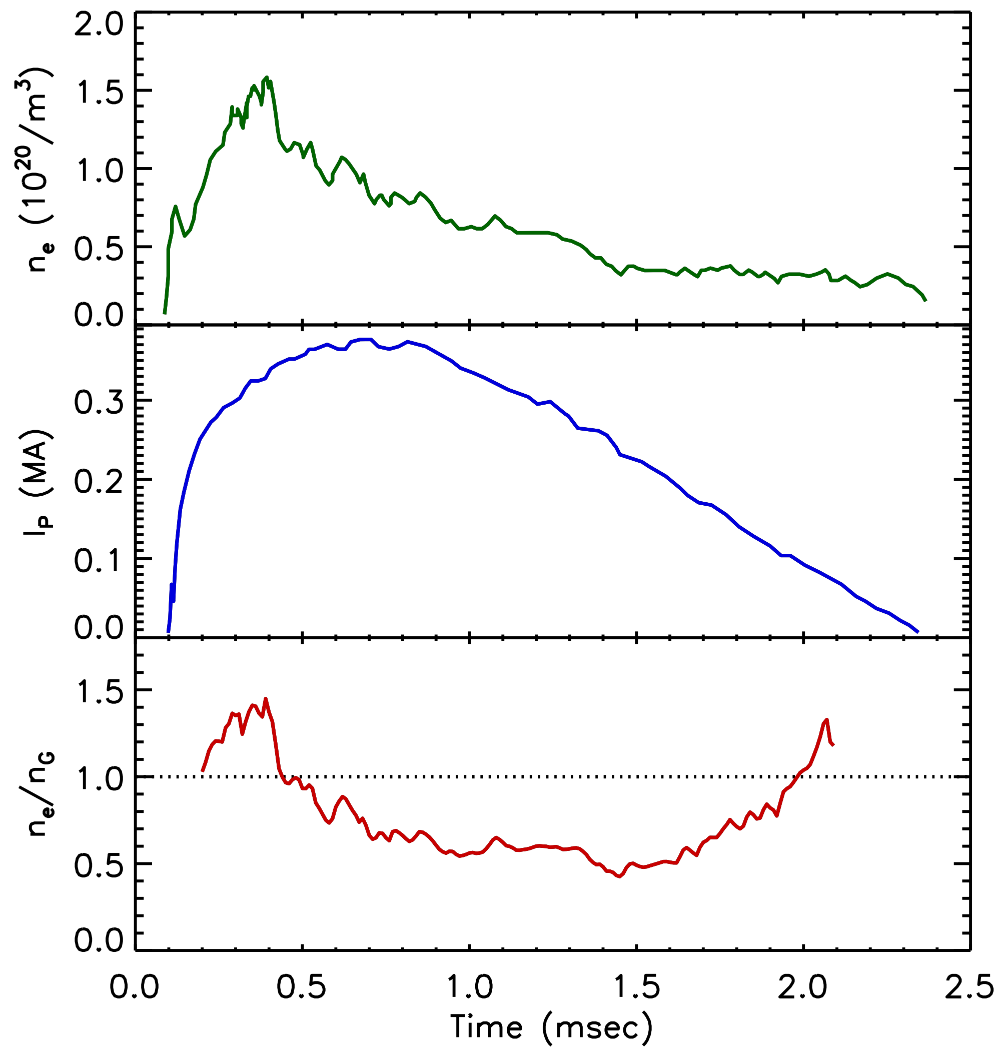
- Variation in results
- Consensus: $n_{CRIT} \propto (BP/V)^{0.5}$ *(Sudo 1990, Giannone 2000)*
- But note evidence for stronger B and weaker size scaling
- Preliminary results from LHD (Large Helical device) support scaling
- Results generally consistent with radiation/power balance models



(Giannone 2000)

"DENSITY LIMIT" IN SPHEROMAK AND FIELD REVERSED CONFIGURATION (FRC)

- Spheromak and FRC don't have density limit data
- "Optimized" discharges obtained by scanning fill pressure
- Turns out to be quite close to empirical scaling.
- Significant?



(Jarboe 1985)

PHYSICS MODELS FOR THE DENSITY LIMIT

- **NEUTRALS - FUELING AND POWER BALANCE**
- **RADIATION MODELS - POWER BALANCE**
- **ROLE OF TRANSPORT PHYSICS**

GLOBAL SCALING BY ITSELF IS AN INSUFFICIENT FOUNDATION FOR PREDICTING THE PERFORMANCE OF FUTURE MACHINES

- Scaling does an OK job, may need small corrections for aspect ratio, power, etc,

  but

- Covariance in data, may hide dependences (I_P and P_{IN} for example)
- Misses important local physics - **density profiles**

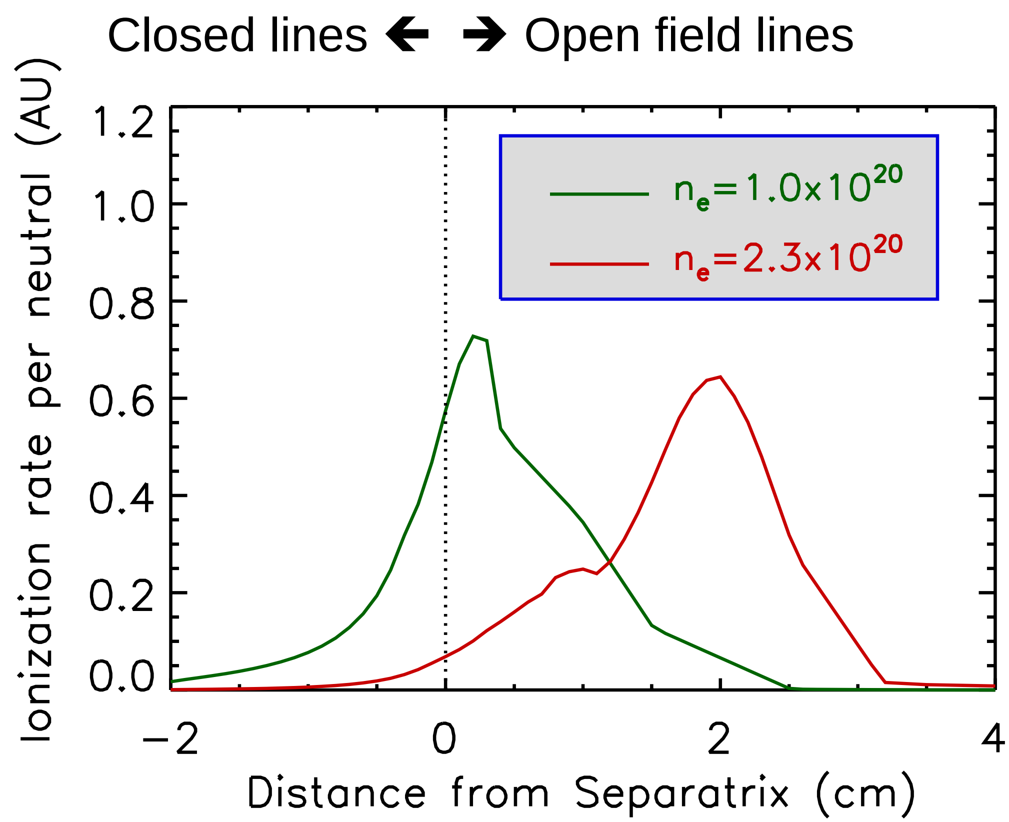
- **Need verified, first principles model**

Big questions

- Where does the catastrophe come from?
- How do we compute the density limit?

ROLE OF NEUTRALS IN THE DENSITY LIMIT

- Self shielding - limits gas fueling
- Energy loss via ionization and charge exchange
- Sets edge gradient length cause unstable pressure profile
- Despite this - n_G is not describing a fueling limit - obviated by core fueling

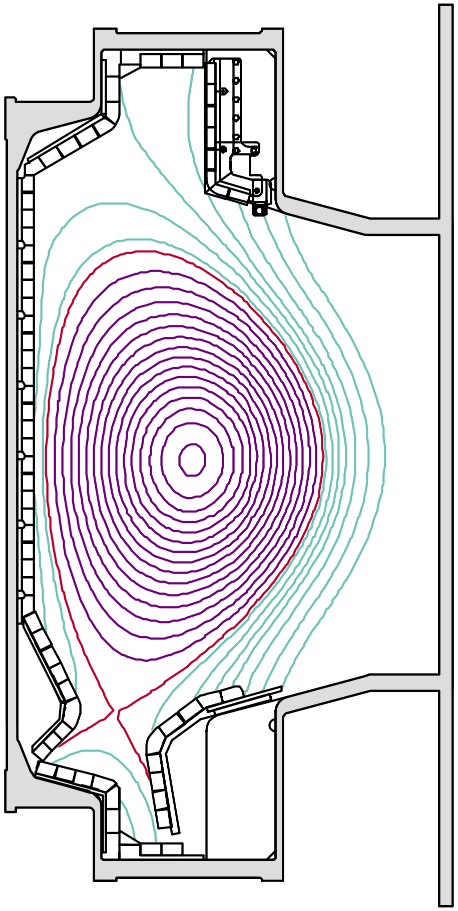


(LaBombard)

Relatively small increase in density leads to large reduction in ionization inside last closed flux surface

RADIATION POWER BALANCE - EDGE OR SCRAPE-OFF LAYER (SOL)

- **Motivation**
  – Very dirty plasmas don't reach high density
  – $P_{RAD} \propto n_e^2 f_Z R(T_e)$ - edge cooling
- **Choose physical phenomenon to model**
  – Global thermal collapse
  – Radiation condensation
  – Poloidal detachment
  – Divertor detachment
  – Radiation dominated transport → MHD unstable pressure profiles

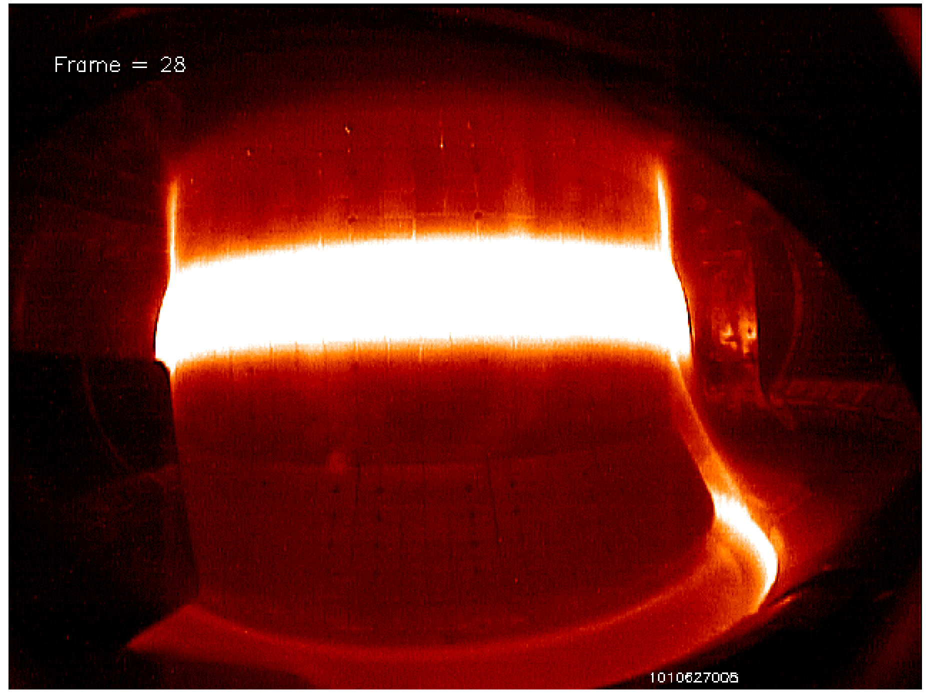


- **Solve coupled equations for energy, momentum, particle balance**

(+ Ad hoc assumption to relate "edge" density to core density)

RADIATIVE CONDENSATION - MARFE THRESHOLD

- MARFE = MARmar wolFE
- At low temperatures $\frac{dR(T)}{dT} < 0$
- With insufficient conducted power, radiative collapse occurs
- At constant pressure T↓ n↑ further increases $n_e^2 R(T_e)$
- In some machines, MARFEs appear just before the density limit



(Boswell)

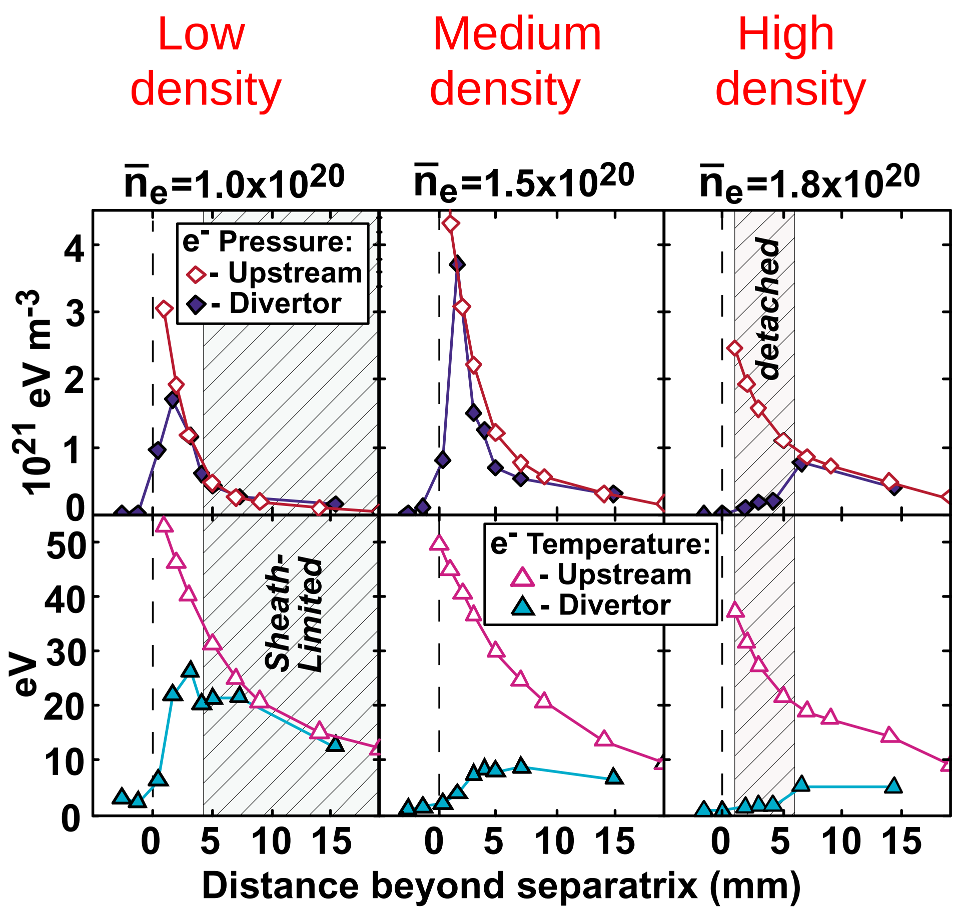
- So… compute density limit by calculating MARFE threshold
- **However - MARFEs observed from 0.4 -1.0 n_G**

RADIAL STABILITY - POLOIDAL DETACHMENT

- **Assumes** limit associated with **$P_{RAD} = P_{IN}$ (Seen in some machines)**
- Plasma is no longer coupled thermally to wall
- Compute radial stability from perturbation analysis for radiating layer at $r = a_p$
- **Stability criteria** $-\frac{a_P}{n}\frac{dn}{da_P} > \frac{3}{2}$ (Assumes density profile fixed)
- Can get result for scaling law assuming ohmic heating and $\tau_E \propto na^2$
- **Transport assumption probably not correct**
- With other assumptions - don't get result much like experiments
- **(Not universal - P_{RAD}/P_{IN} = 0.3 - 1.0 at limit)**

DIVERTOR DETACHMENT - SCRAPEOFF LAYER MODEL

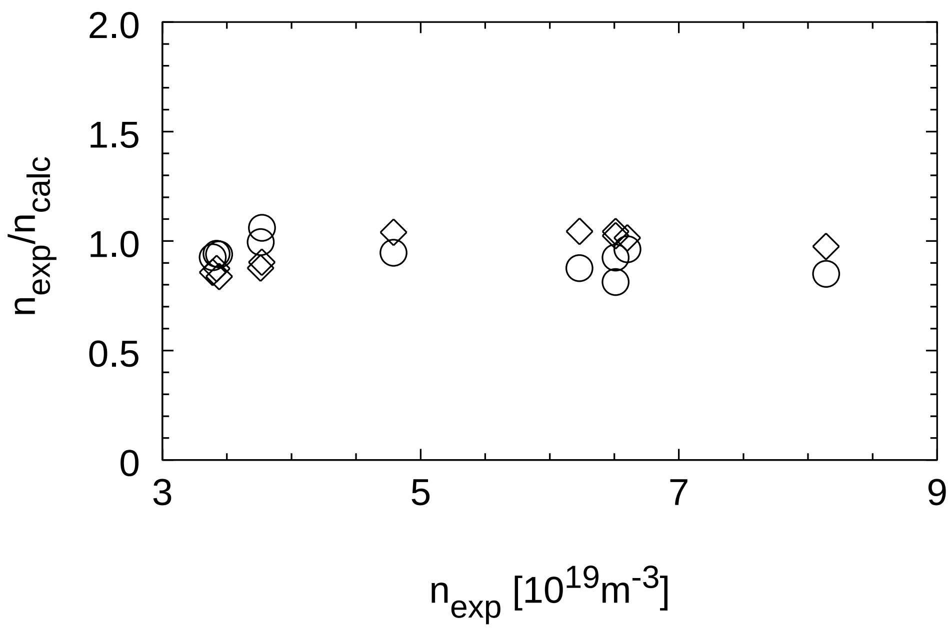
- As density ↑, Te↓ allows Te gradient along open field lines "divertor marfe"
- At sufficiently low temperatures, **neutral collisions dominate momentum transport**
- Leads to drop in plasma pressure at divertor plate
- Radiation zone moves up to x-point (x-point marfe)



- Theory uses detachment threshold as criteria for density limit *(LaBombard 1994)*
- **In experiment, detachment occurs from 0.4-1.0 n_G**

SCRAPE-OFF LAYER/DETACHMENT THEORY

- Analytic theory - divertor two point model - forced into power law form
- Finds critical separatrix density $n_{SEP} \propto \frac{q_{\perp}^{x} B^{5/16}}{(qR)^{11/16-x}}$ *where* $x = \frac{10-\beta}{16(1+\beta)}$
- Requires assumption - Bohm transport
- Reasonable agreement with JET, ASDEX-Upgrade data
- Numerical simulations find limit diverges for ZEFF → 1



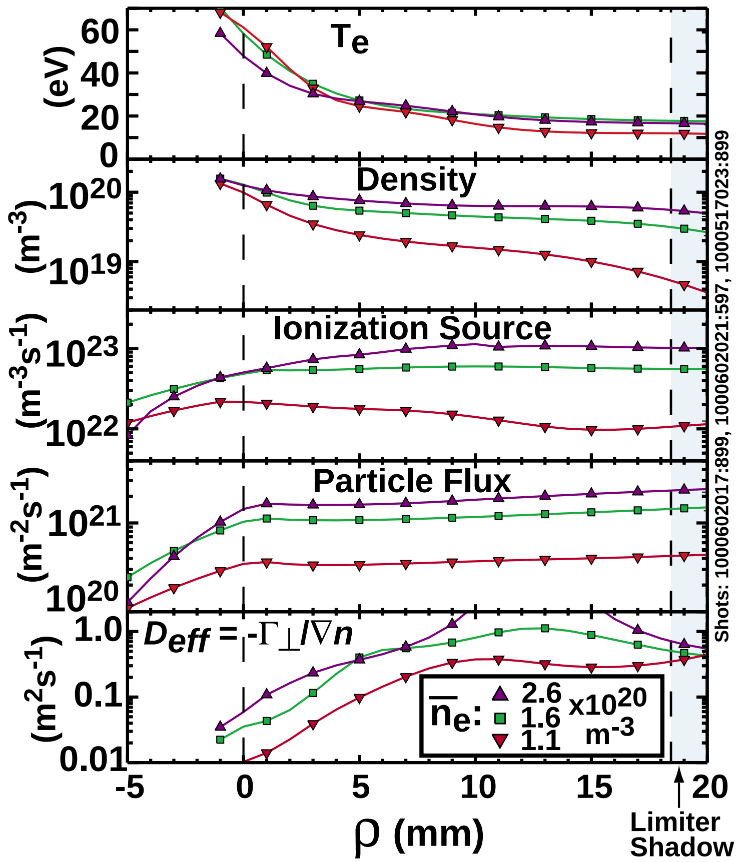
(Borrass 1997)

IS THERE MORE PHYSICS INVOLVED?

- **Problem with radiation models**
  - Power and impurity dependence too strong → $n_{LIM} \propto \sqrt{P_{IN} / (Z_{EFF} - 1)}$
  - Threshold mechanisms show up well below density limit
  - Transport assumptions: theories are incomplete at best
- **Evidence for increased transport as cause of edge cooling**
  - Transient transport experiments (Greenwald 1988, Marinak 1993)
  - Fluctuation measurements (Brower 1991)
  - Detailed probe measurements in edge (LaBombard 2001)
- **General observations of edge turbulence at high densities**
  - Universal result?

TURBULENT TRANSPORT IN EDGE INCREASES WITH COLLISIONALITY

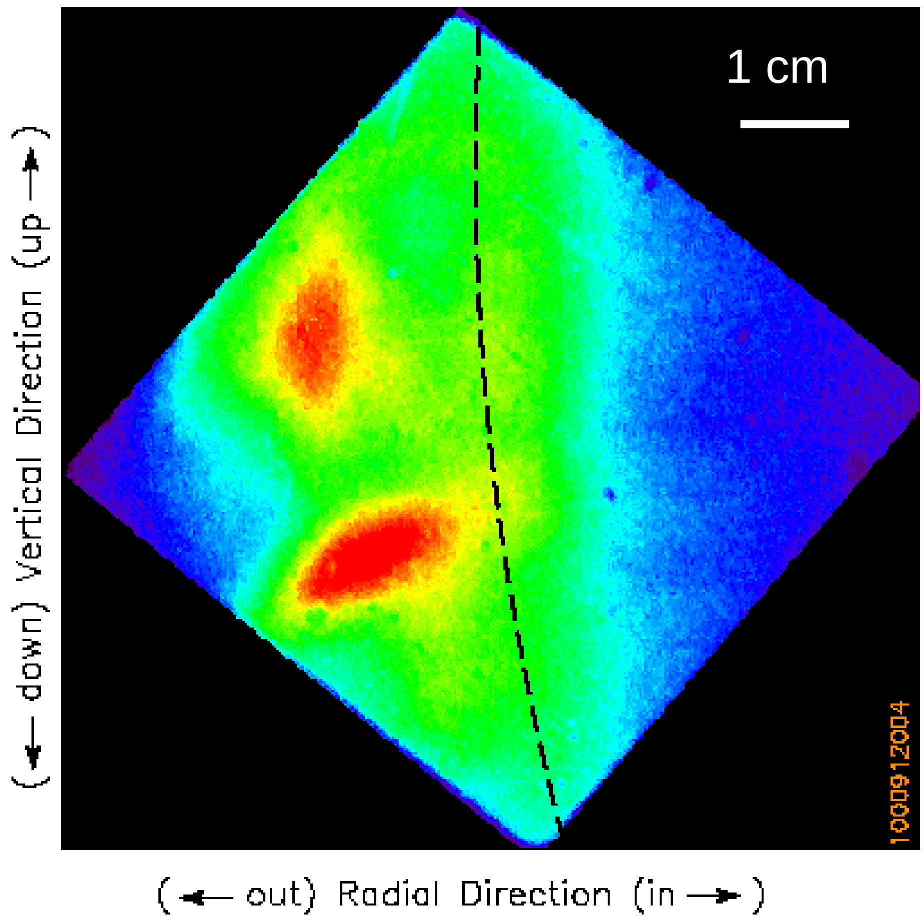
- **Two regimes observed in scrape-off layer (SOL)**
  - Near-SOL: steep gradients
  - Far-SOL: flat profiles
- **Particle flux and transport**
  - Near-SOL: cross-field transport low
  - Far-SOL: cross-field transport high
- **Fluctuation changes character**
  - Near-SOL: low amplitude, short correlation times and lengths
  - Far-SOL: large amplitude, bursty, long correlation times



(LaBombard 2000)

WE CAN VISUALIZE THE FAR-SOL FLUCTUATIONS

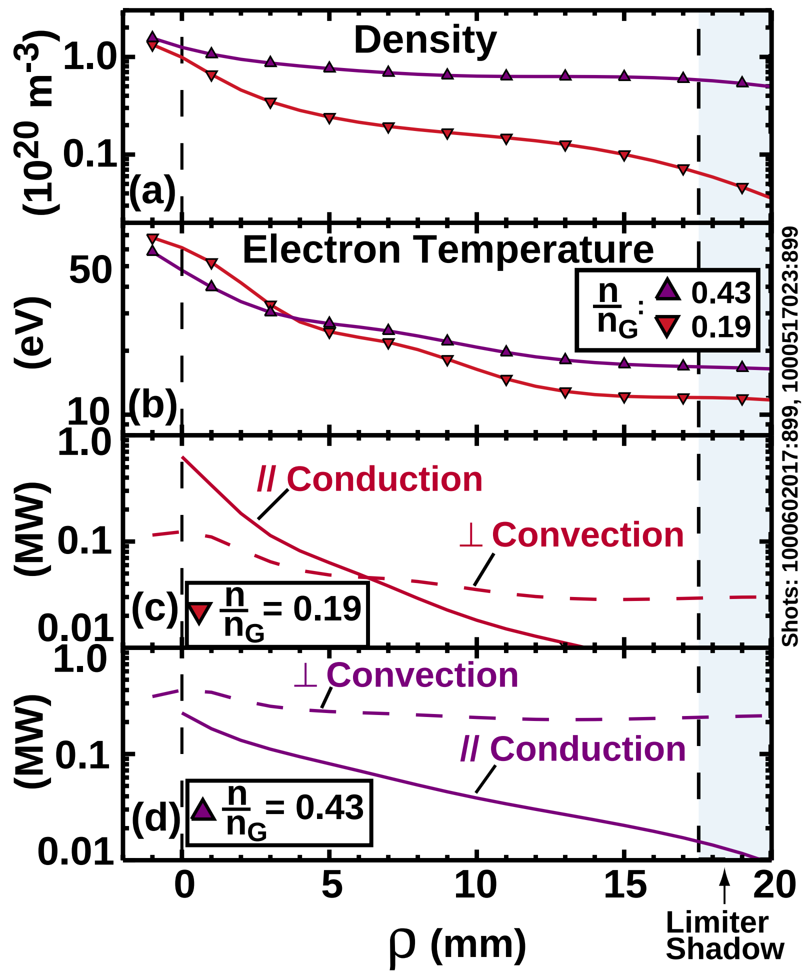
- Images taken with fast CCD camera
- 4 μsec framing time
- D_2 gas puff: image Hα
- Large "blobs" dominate far SOL
- Seen to move poloidally and radially
- Correlation length, correlation time, propagation velocity consistent with probe measurements



(Zweben, Terry 2001)

TURBULENCE DRIVEN CONVECTION CAN COMPETE WITH PARALLEL TRANSPORT

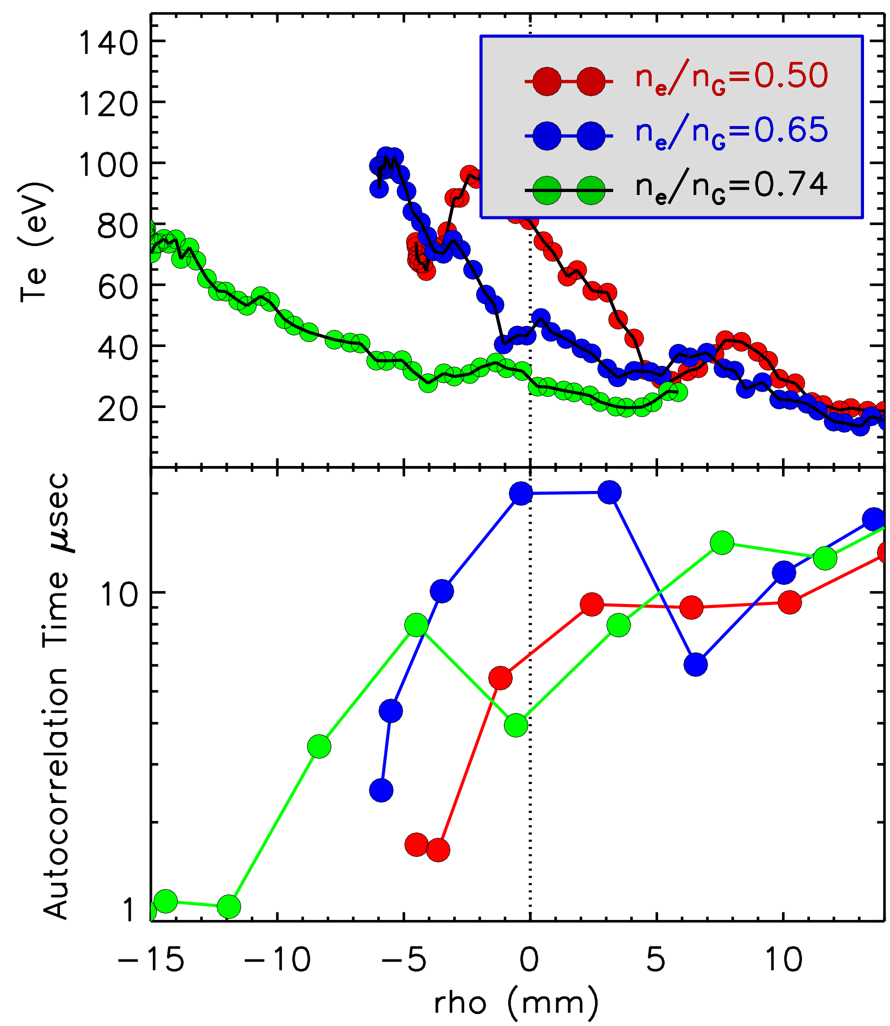
- In far SOL, cross-field transport overwhelms parallel transport
- As density is increased, region of large fluctuations and transport move inward toward separatrix
- Parallel transport ~$T_e^{7/2}$ is stable with respect to temperature perturbations
- Collisionality driven cross-field transport is unstable



(LaBombard 2000)

AS THE DENSITY LIMIT IS APPROACHED, HIGH TRANSPORT REGIME CROSSES SEPARATRIX AND MOVES INTO MAIN PLASMA

- Has the potential to explain range of density limit phenomena
- Once perpendicular transport dominates, stabilizing influence is lost
- Threshold condition not known
- Requires that complex transport physics have the "correct" form
- Where does I_P (or B_P) dependence come from?



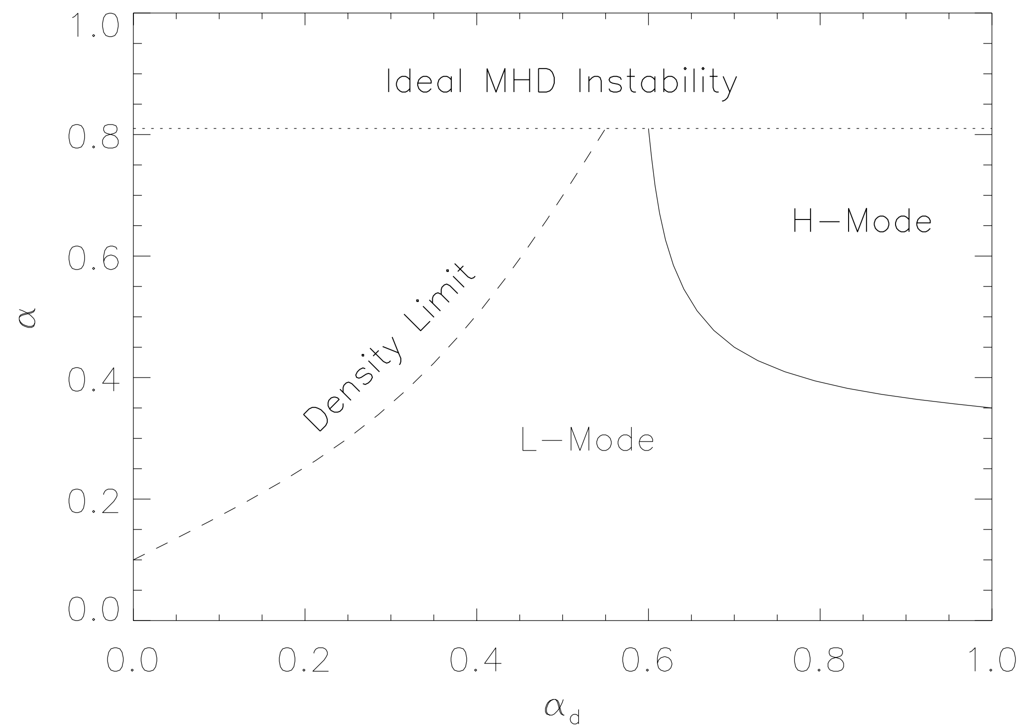
(LaBombard 2001)

NEED IMPROVED MODELS FOR EDGE TURBULENCE

- Unfortunately, theory and models for edge turbulence are not understood well enough yet
- 3D gyro-fluid simulations have found regime of extremely high transport
- $\alpha = -Rq^2 d\beta / dr$
- $\alpha_D = \rho_s c_s t_0 / L_n L_0$

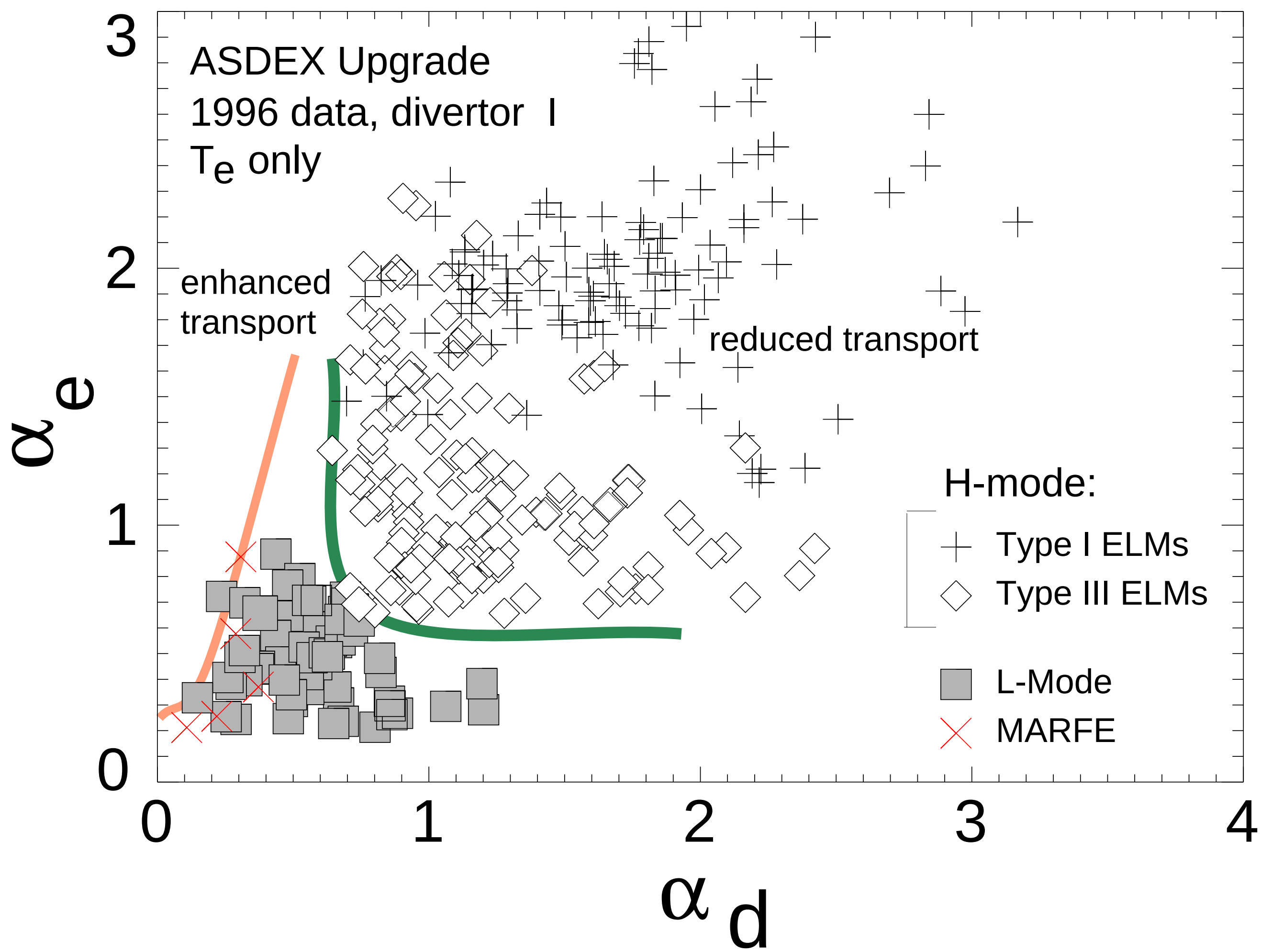
$$\propto \left(\frac{T^2}{nL_n} \right) \rightarrow \frac{\lambda}{L_n}$$

- Region of high transport consistent with high density, low temperature
- No quantitative predictions yet



(Rogers, Drake 1998)

EXPERIMENTAL SUPPORT FOR TURBULENCE MODEL



(Suttrop 1999)

DISCUSSION - MECHANISMS

- Various models proposed - progress has been made but none are entirely satisfactory
- Physics strongly coupled - cause and effects hard to untangle
- May need combination of turbulent transport and atomic mechanisms
- Lead to investigation of very different physics
- Need to use self-consistent profiles, transport, power balance etc. for all models

SUMMARY

- Substantial progress has been made in understanding this interesting and important problem
- It is remarkable that simple empirical laws can capture such complex physics
- The similarity of the limit across a wide range of confinement devices is remarkable as well
- By peaking the density profile, it is possible to obviate what is essentially and edge limit.
- Still, it remains a significant challenge to understand the underlying physics