Excitement at the Plasma Boundary

Rob Goldston
(with help from many)

PRINCETON UNIVERSITY
U.S. DEPARTMENT OF ENERGY | Office of Science
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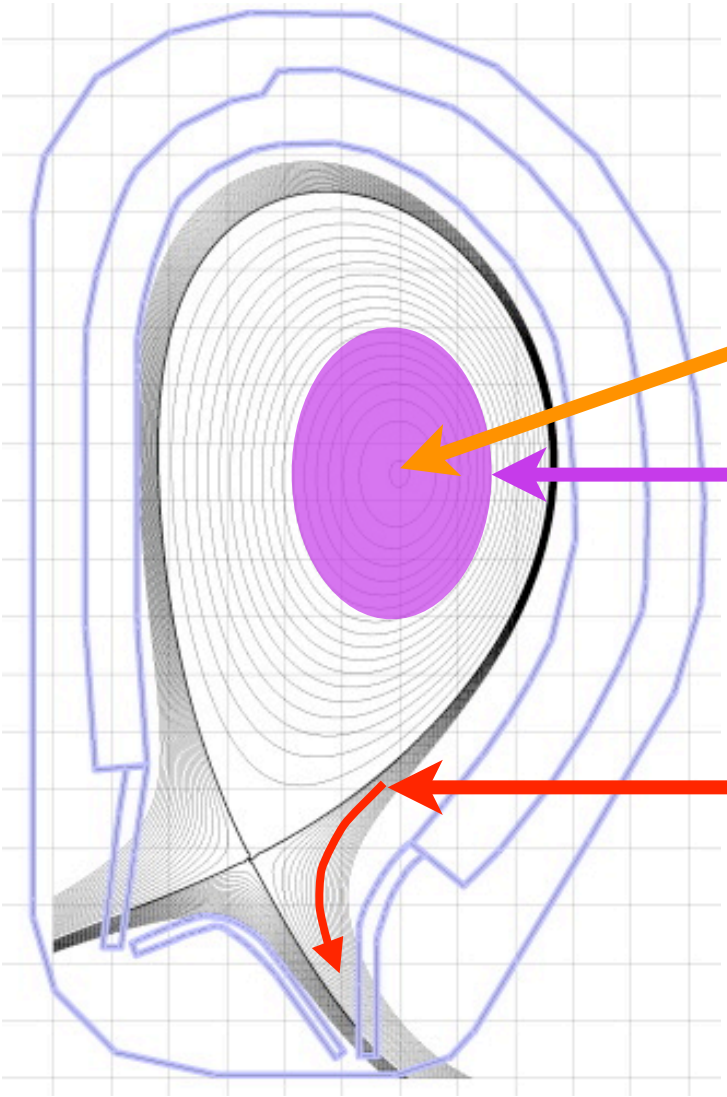
Fusion Plasma Physics is as Easy as 1-2-3



1) Inject heat into plasma

2) Hold onto the heat & amplify it by fusion

3) Manage the heat outflux

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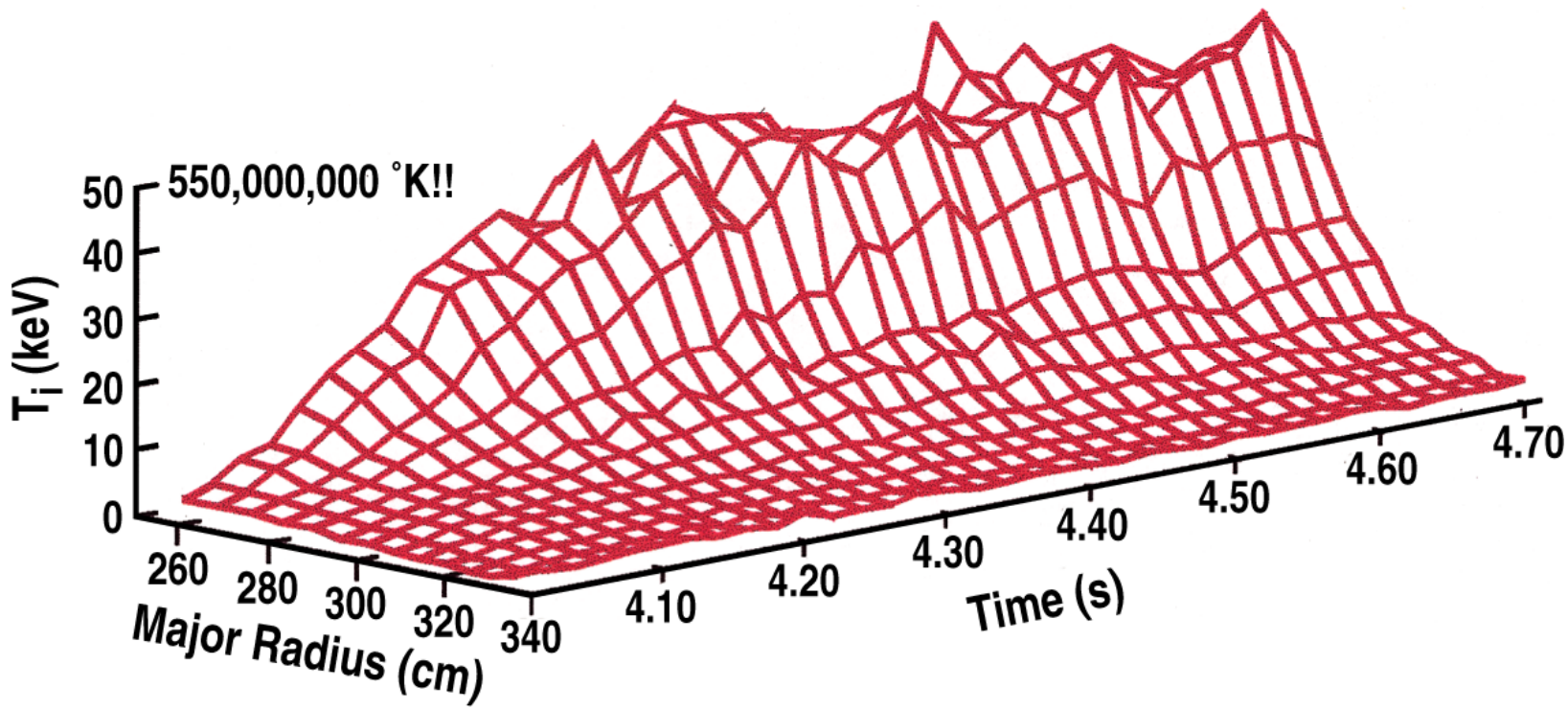
Inject Heat into Plasma

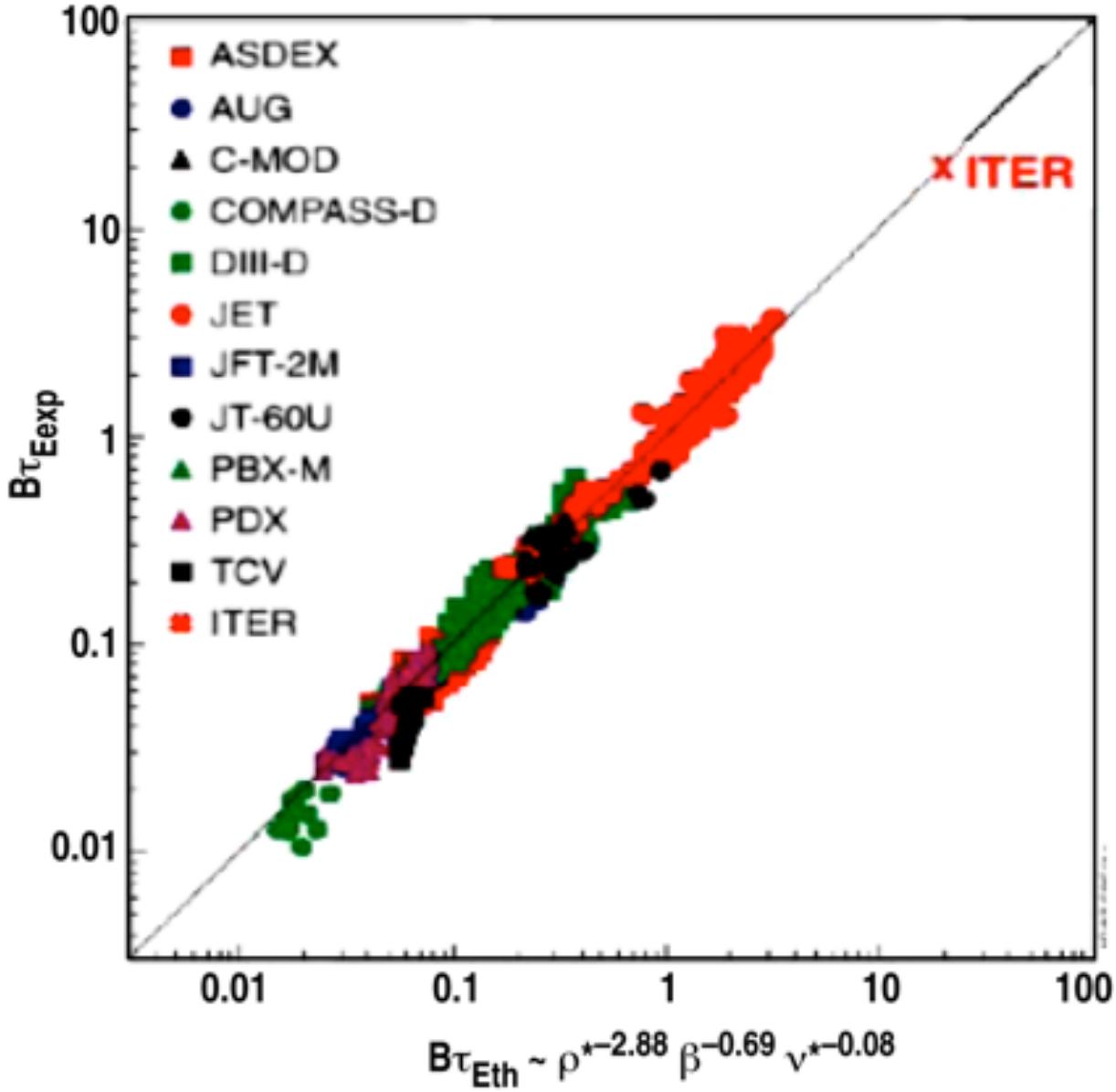
Mike Williams



We put 40 MW of neutral beams into TFTR.
Heating was ~ classical, with some *AE's, fishbones, etc.
ITER needs ~ 2x more heating. Projections pretty reliable with multiple types of heating systems planned.

Hold onto the heat…

Stan Kaye

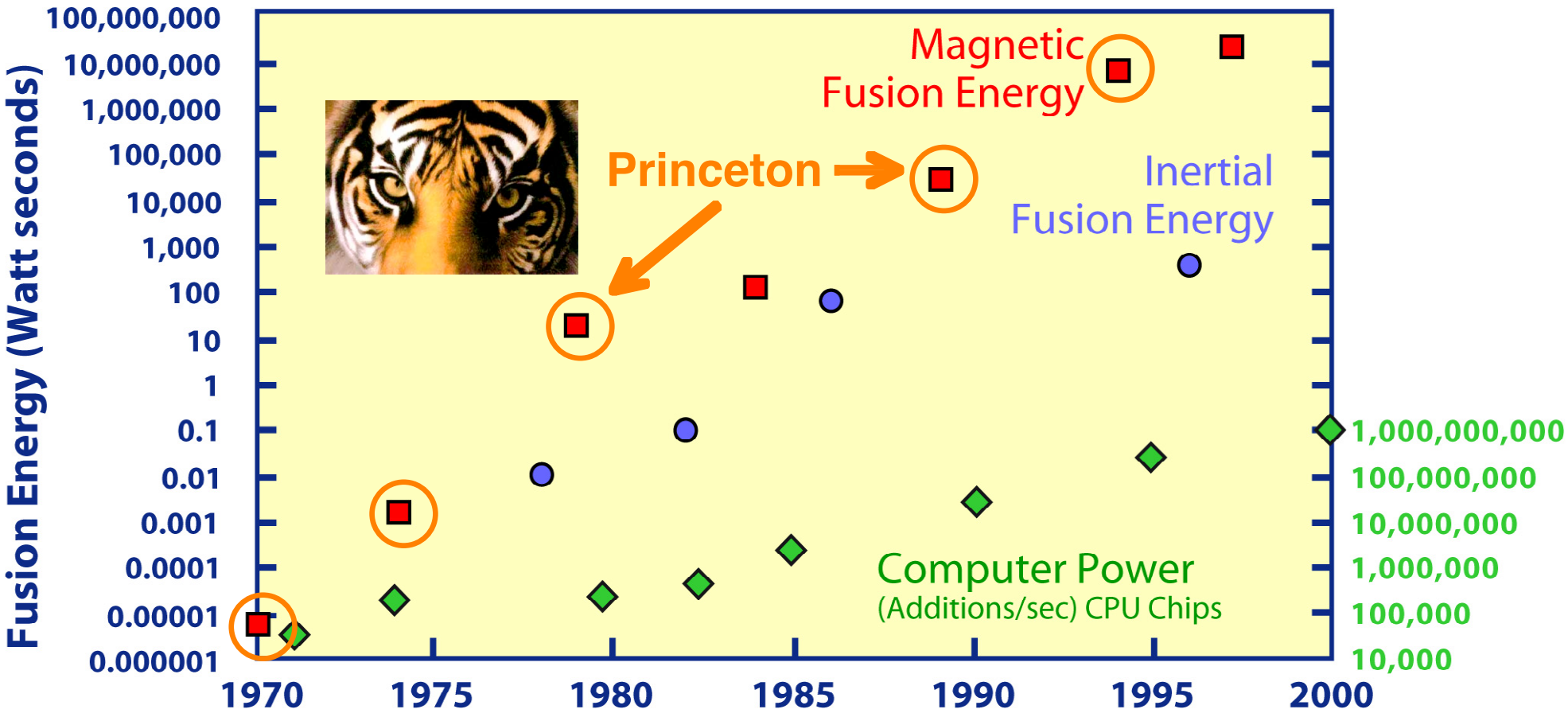


Empirical scaling relations are consistent with basic nonlinear ideas about turbulence, with some surprises: H-modes, Super-shots, etc.

ITER needs ~5x higher $B\tau_E$. Projections pretty reliable for ~5x higher current.

...and Amplify it by Fusion

Harold Furth



Fusion gain projection pretty reliable for 5x higher current.

But full-performance ITER needs to handle 2000x more energy. Projection ??

Topics

- **The Magnitude of the Challenge**
- **Scientific Understanding**
- **Possible Solutions**

First Q=10 Attempt on ITER

New Year's Eve 2027

The Poseidon Adventure, 1972

How much Rougher will Transient Events be in the Future?

	JET	ITER	ARIES-AT
Stored Energy, W (MJ)	12	350	560
Surface Area A (m^2)	160	710	460
W/A (MJ/m^2)	0.075	0.49	1.2
Ratio	1	6.6	16

Long-pulse Plasma Facing Components are more fragile, not less.

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Disruptions on ITER

Richard Pitts

W melts at "e" ~ 50

I_p (MA)	Mode	P_{IN} (MW)	Stored energy (MJ)	$E_{transient}$ (MJ)	$l_{q\|\|omp}$ (m)	q_{target} (MJ m^{-2})	e (MJ $m^{-2}s^{-1/2}$)
7.5	L	20	26	13 → 26	0.02	0.22 → 2.86	4.1 → **74.3**
7.5	L	30	30	15 → 30	0.02	0.25 → 3.30	4.5 → **84.9**
7.5	H	40	75	25 → 38	0.01	0.83 → 8.3	15.2 → **213**
15	L	8	35	16 → 35	0.01	0.52 → 7.69	9.4 → **199**
15	L	18	52	26 → 52	0.01	0.86 → 3.43	15.7 → **295**
15	L	28	73	37 → 73	0.01	1.21 → 11.4	22.2 → **406**
15	L	40	85	43 → 85	0.01	1.39 → 18.7	25.5 → **483**
15	H	50	350	88 → 175	0.005	5.78 → 76.9	**105 → 1984**

Non-active phases

DT

Unmitigated major disruptions in ITER will melt W divertors.

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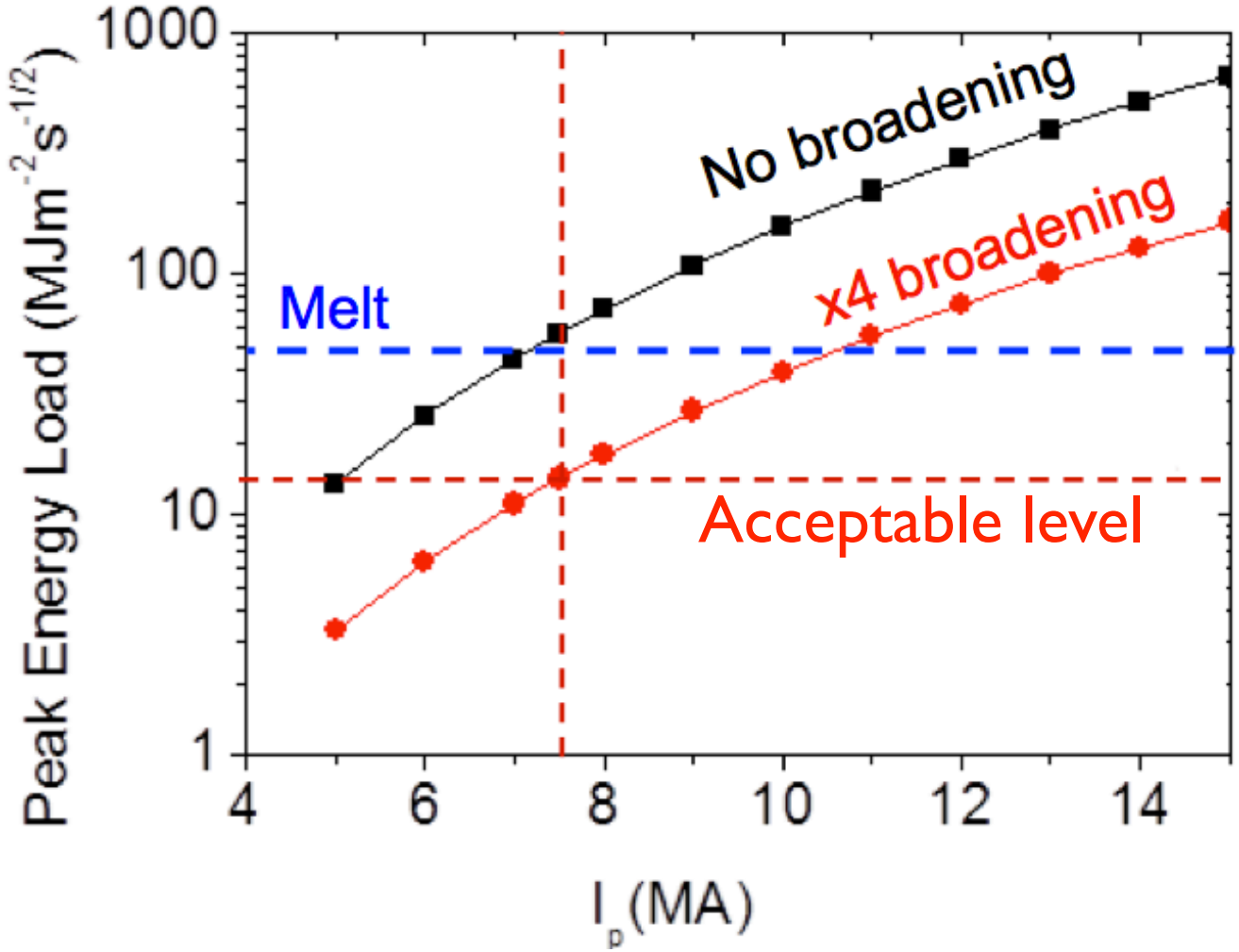
Type I ELMs on ITER

Richard Pitts



Unmitigated ELMs in ITER will cause unacceptable heat loads.

How much Rougher will Steady Loading be in the Future?

	JET	ITER	ARIES-AT
Heating Power P (MW)	24	150	390
Major Radius R (m)	3	6.2	5.2
Toroidal Field B (T)	3	5.3	5.9
PB/R (MW T/m)	24	128	443
Ratio	1	5.3	18

Long-pulse Plasma Facing Components are more easily burned out, not less.

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Topics

- **The Magnitude of the Challenge**
- **Scientific Understanding**
  (focus here on steady heat loads)
- **Possible Solutions**

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There are Some Scientific Disagreements

Gene Hackman *vs*. Ernest Borgnine

What Sets the SOL Width?
Standard Analysis

Parallel Confinement:

$$\tau_{\parallel} = (qR)^2 / \chi_{\parallel}$$

or

$$\tau_{\parallel} = qR / c_s$$

+ Cross-field Diffusion:

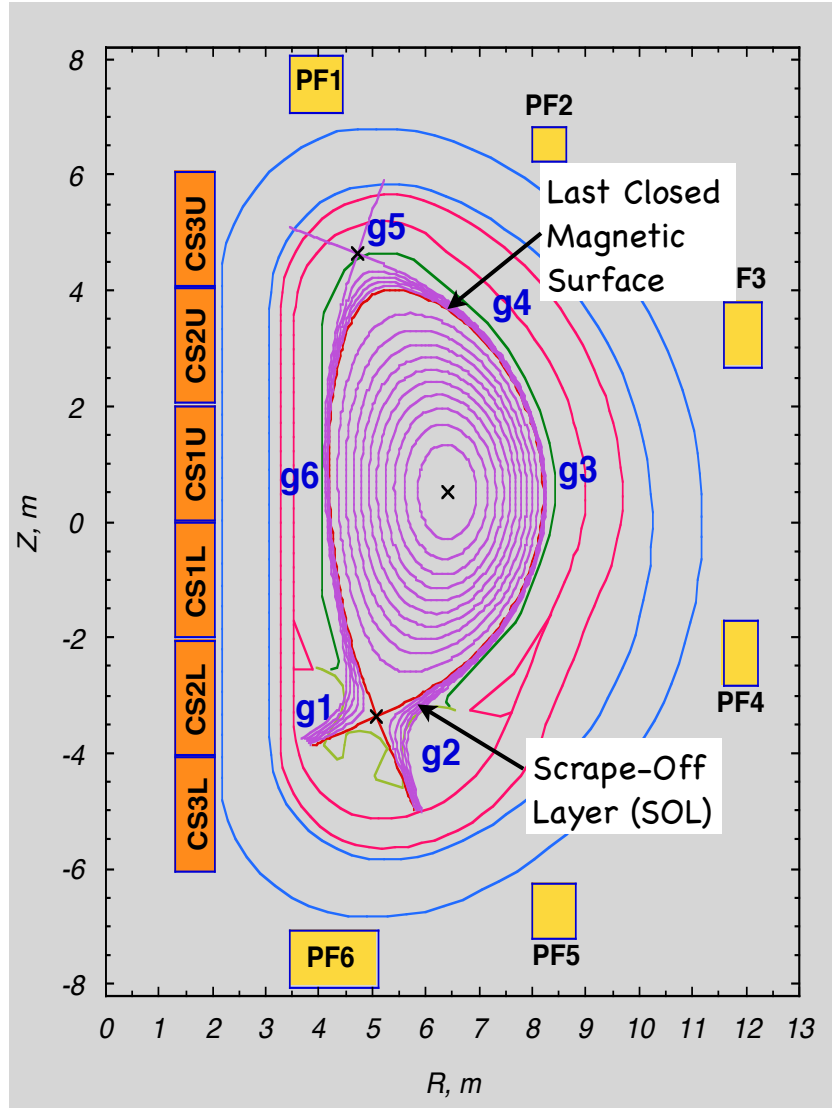
$$\lambda^2 = \chi_{\perp} \tau_{\parallel}$$

$$= (\chi_{\perp} / \chi_{\parallel})(qR)^2$$

or

$$\lambda^2 = \chi_{\perp} qR / c_s$$

$\chi_{\perp}$ *anomalous!*

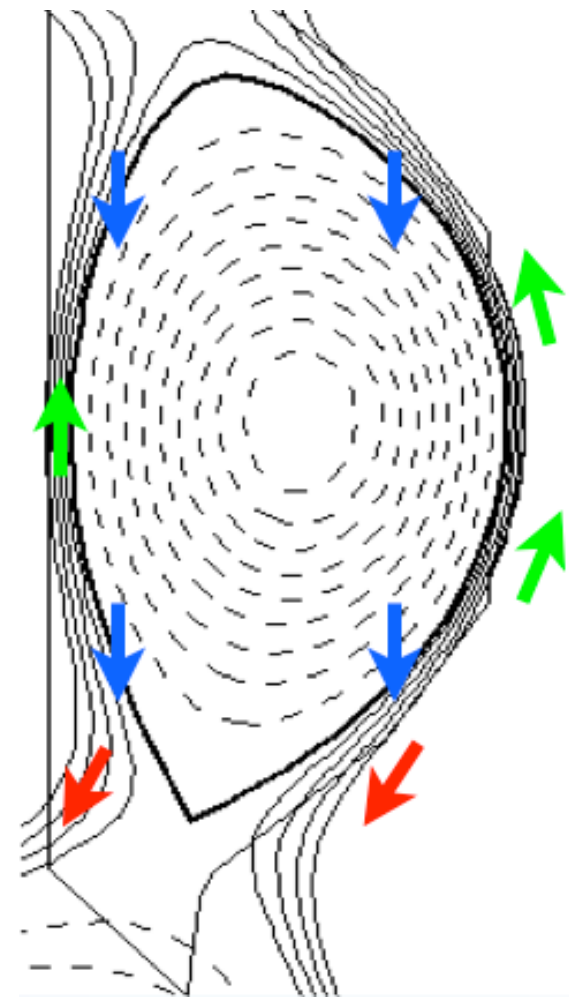


What about Cross-Field Drifts?

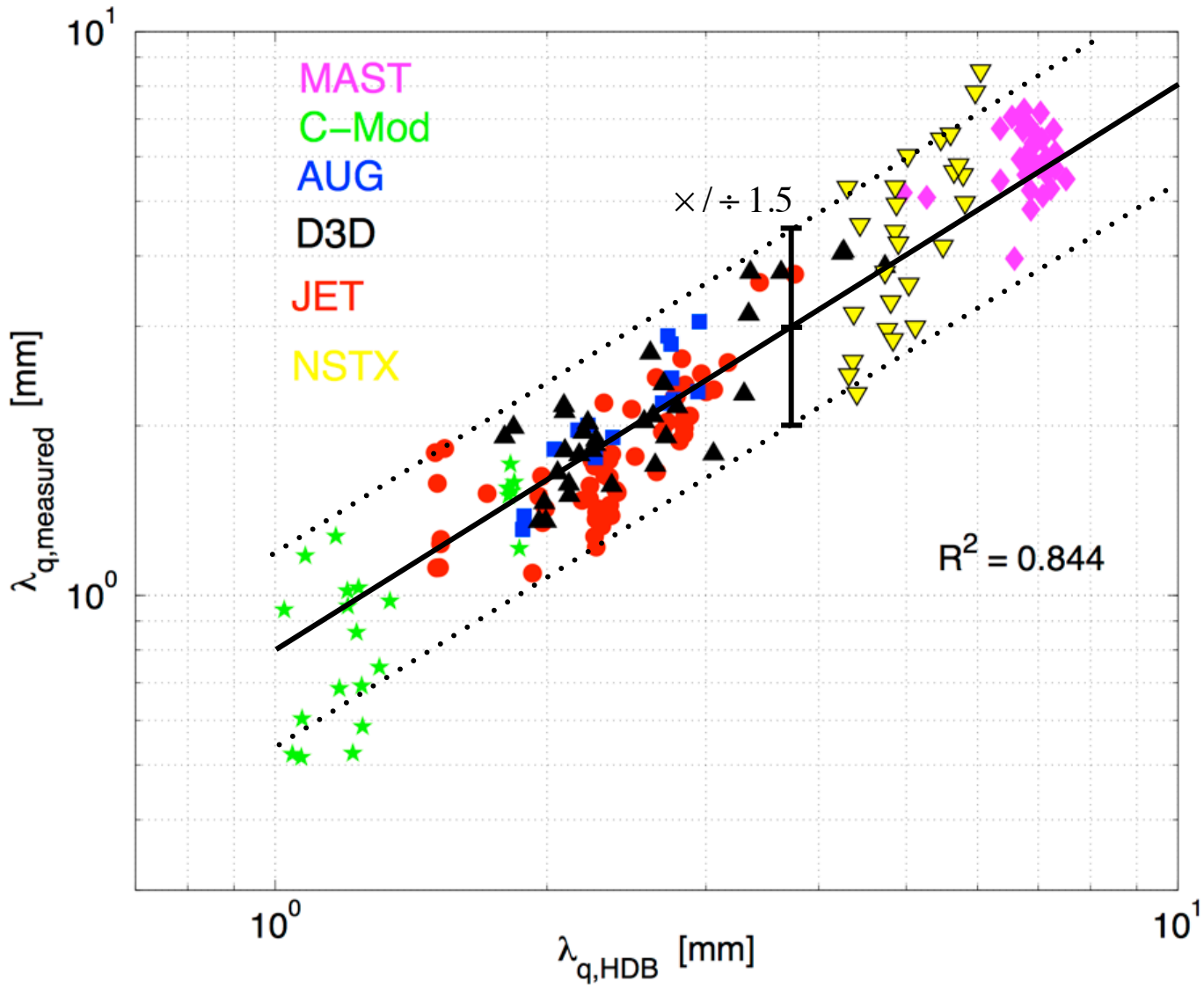
Non-Standard Analysis

- Vertical drifts cross scrape-off layer (SOL)
- Parallel flows connect SOL to divertor and SOL bottom to SOL top at ~ $c_s/2$, consistent with simple model, experiments.
- $\lambda_n \approx v_{\nabla B+curvB}\tau_{\|} \approx 2v_{\nabla B+curvB}L_{\|}/c_s \approx 2(a/R)\rho_p$
- Edge temperature determined by anomalous cross-field electron thermal conduction balanced against Spitzer parallel electron thermal conduction, within λ_n.
- Gives a closed-form, absolute prediction:

$$\lambda_q \simeq 5671 \cdot P_{SOL}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left(\frac{2\bar{A}}{1+\bar{Z}}\right)^{7/16} \left(\frac{Z_{eff}+4}{5}\right)^{1/8}$$



Fits the Data Surprisingly Well!



$$1.6(a/R)\rho_p$$

The explanation may well be wrong, but the SOL width is certainly ~ ion poloidal gyro-radius over a wide range of parameters.

Individual Scalings Fit Also

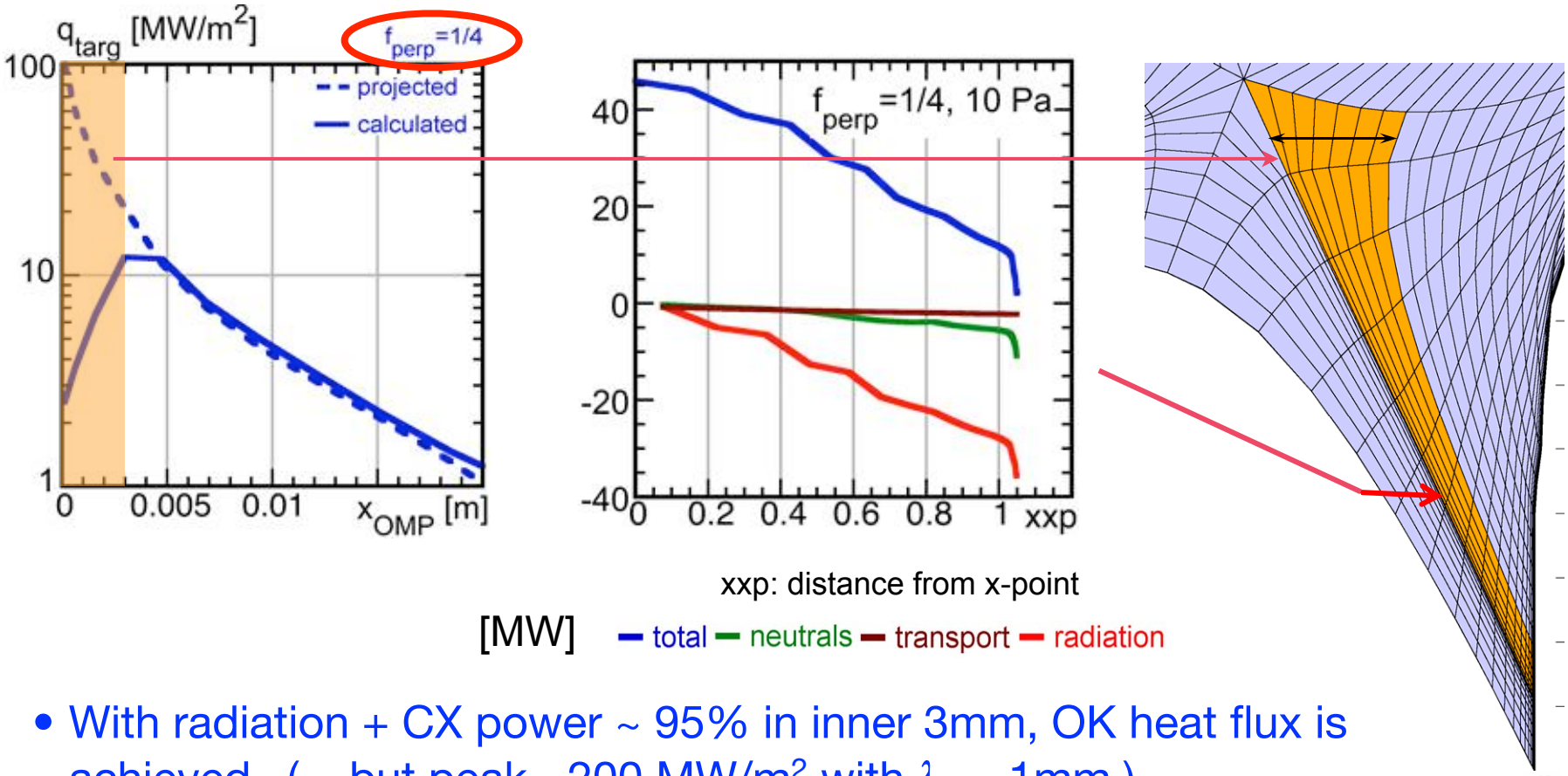
HD MODEL SCALING AND EXPERIMENTAL REGRESSION COEFFICIENTS

	B	q_{cyl}	P_{SOL}	R	a/R	R^2	RMS Deviation
HD Model	– 0.875	1.125	0.125	0	– 0.125		
AUG, C-Mod, DIII-D, JET	– 0.958 +/– 0.14	1.21 +/– 0.14	0.114 +/– 0.084	– 0.0655 +/– 0.14		0.784	0.489
AUG, C-Mod, DIII-D, JET, MAST	– 0.905 +/– 0.2	0.985 +/– 0.2	0.0918 +/– 0.11	0.0783 +/– 0.18	– 0.0864 +/– 0.54	0.908	0.393
AUG, C-Mod, DIII-D, JET, NSTX	– 0.875 +/– 0.21	1.27 +/– 0.18	– 0.071 +/– 0.11	0.2 +/– 0.19	– 0.0917 +/– 0.58	0.853	0.993
AUG, C-Mod, DIII-D, JET, MAST, NSTX	– 0.935 +/– 0.29	0.701 +/– 0.19	– 0.276 +/– 0.1	0.185 +/– 0.26	– 0.211 +/– 0.78	0.838	2.08

Net ~ 1/B scaling in SOL width.

Modeling can Get Radiated Power Needed for ITER, but…

André Kukushkin



- With radiation + CX power ~ 95% in inner 3mm, OK heat flux is achieved. (… but peak ~200 MW/m^2 with λ_q = 1mm.)
- Requires 7x higher gas pressure than standard case, substantially limiting operating space w/o full detachment.
- Requires upstream <u>separatrix</u> n = 6 10^{19}/m^3 = 0.6 $\overline{n}$ = 0.5 n_{GW}

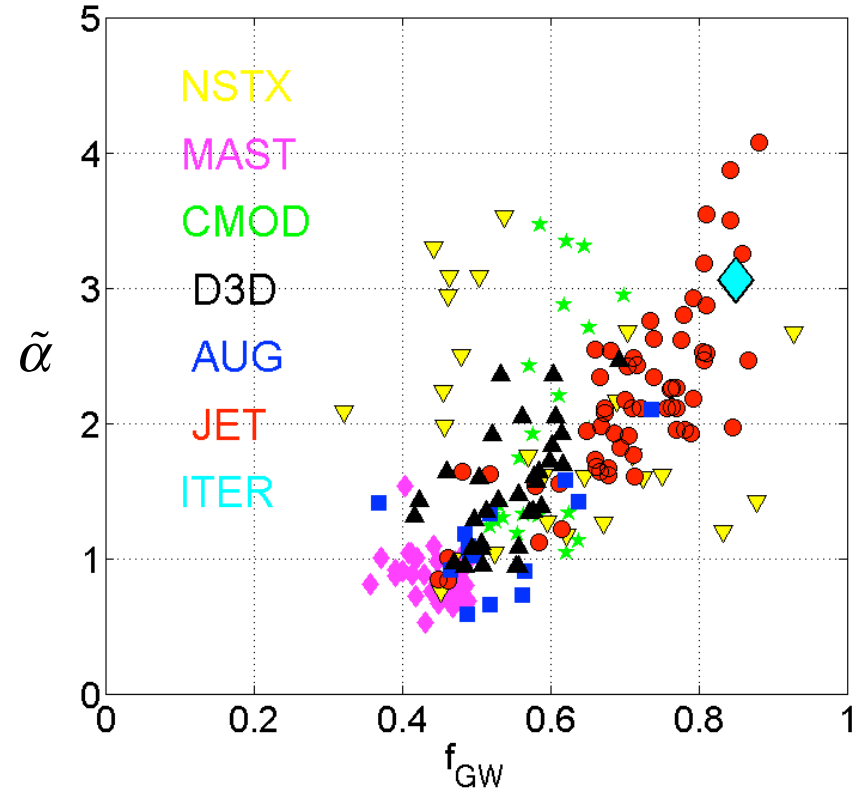
Is the Greenwald Limit tied to SOL MHD Stability?

$$n_{sep} = \bar{n} / 3$$

$$T_{sep}(eV) = \left(P_{SOL} \frac{B}{B_p} \frac{q_{cyl}}{(4/7)\kappa_{0e} 4\pi\lambda_{q,\exp}} \right)^{2/7}$$

$$\tilde{\alpha} \equiv R q_{cyl}^2 \beta / \lambda_{q,\exp} \approx 1.5\alpha$$

$$\tilde{\alpha}_{crit} \sim 1.5\alpha_{crit} \sim s\kappa \sim 2\kappa \sim 3.5$$



$\tilde{\alpha}_{crit}$

$$\left(\frac{\bar{n}}{\bar{n}_{GW}} \right)_{crit} = 9.78 \left(\frac{\bar{n}}{n_{sep}} \right) \left(\frac{a/R}{q_{cyl} P_{SOL} B_t} \right)^{1/8} \left[\frac{\kappa}{(1+\kappa^2)^{3/2}} \right] \left[\frac{2\bar{A}}{(1+\bar{Z})} \right]^{9/16} \left(\frac{Z_{eff}+4}{5} \right)^{-1/8} \sim 1$$

Topics

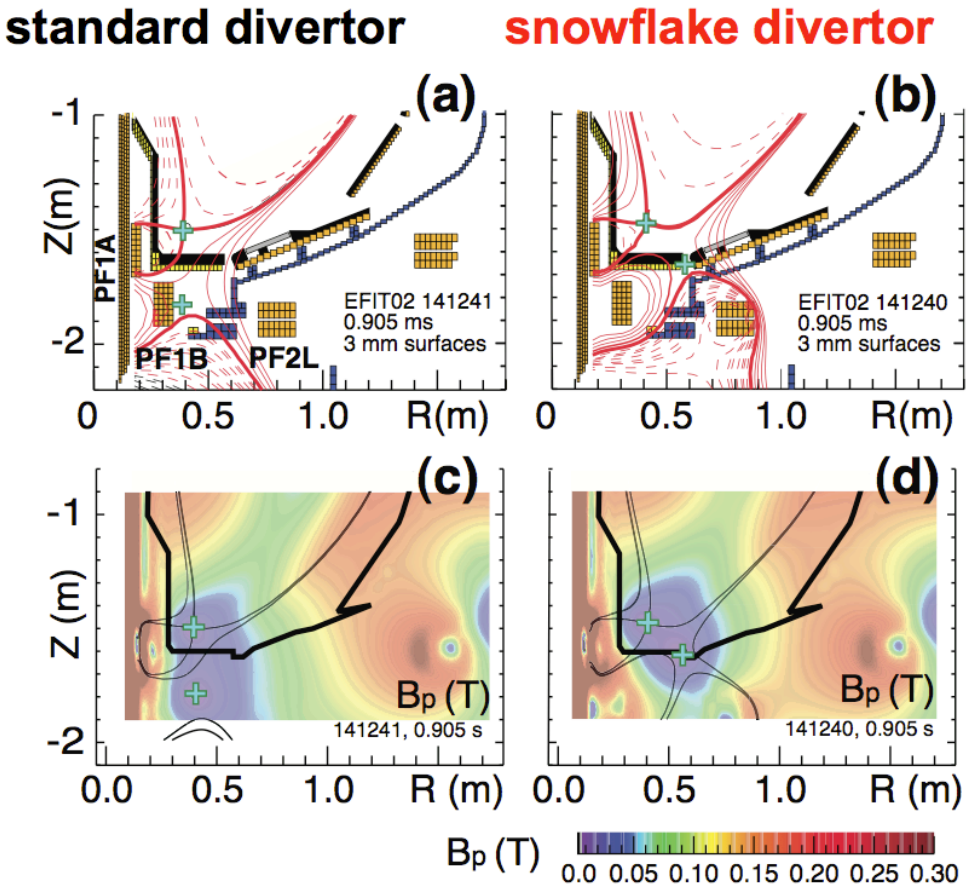
- The Magnitude of the Challenge
- Scientific Understanding
- Possible Solutions

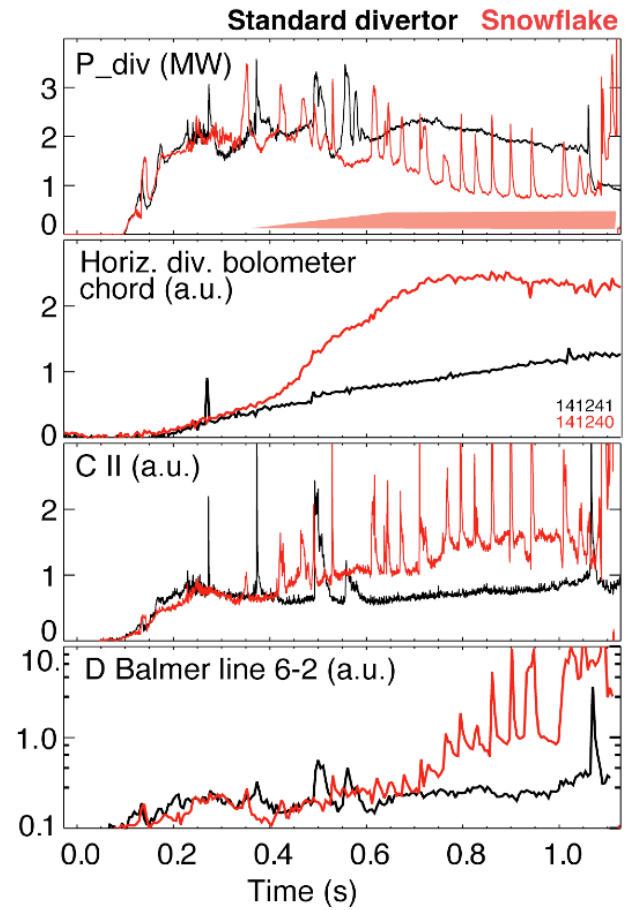
There are Some Possible Ways Out

Safely, Safely, Safely

Snowflake Increases Parallel Length to Divertor Target

Vlad Soukhanovskii





It works: Reduced heat flux, higher radiated power, signatures of detachment at divertor target.

But… big forces due to powerful divertor coils, very tangential field lines problem at divertor plate.

Why are Long Field Lines Good?

- **Doug Post showed that the integral of P_{rad} along B can be turned into an integral along T, assuming Spitzer thermal conduction and fixed impurity fraction. All that matters then *seems to be $q_{||} \sim PB/R$.***

$$\Delta q_{||}^2 = 2\kappa_{0e}\left(n_{e,up}T_{up}\right)^2\left(1+1/\bar{Z}_u\right)^2 f_{e,Li}$$
$$\times\int_{T_{div}}^{T_u}\left[\left(0.308+0.767Z_{eff}-0.075Z_{eff}^2\right)/Z_{eff}\right]\frac{T^{0.5}}{\left(1+1/\bar{Z}\right)^2}\frac{L_{Li}\left(n_e,T\right)}{\bar{Z}_{Li}}dT$$

- **But T_{div} depends on $q_{||}$ $L_{||}$ – an advantage for large $L_{||}$.**

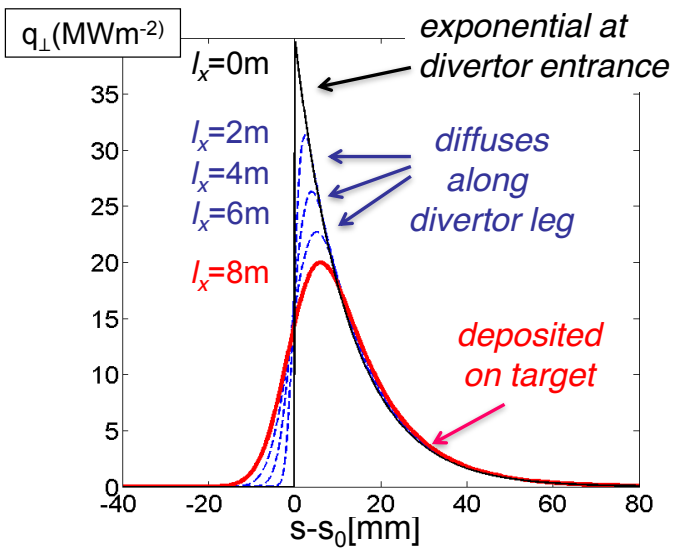
$$T_{div,eV}^{7/2} = T_{up,eV}^{7/2} - \frac{7}{2}\frac{q_{||,up}L_{||}}{\kappa_{0e}}$$

- **To take advantage of long field lines, need to use low T zone for radiative detachment. *Seen w/Snowflake.***

Another Use for Long Field Lines

Thomas Eich

- **Heat flux to divertor plate is well fit by exponential convolved with Gaussian (Eich fct.)**



$$q_{\|}(x) = \int_0^{\infty} \left[q_{\|0} \exp\left(\frac{-x'}{\lambda_q} \right) \right] \left[\frac{1}{\sqrt{\pi} S} \exp\left(\frac{-(x-x')^2}{S^2} \right) \right] dx'$$

$$= \frac{q_{\|0}}{2} \exp\left[\left(\frac{S}{2\lambda_q} \right)^2 - \frac{x}{\lambda_q} \right] \operatorname{erfc}\left(\frac{S}{2\lambda_q} - \frac{x}{S} \right)$$

λ_q is compared with model

- **ASDEX closed divertor has more Gaussian spreading, *S*, than JET.**
  Raw FWHM gives inverse size scaling!

- **Perhaps long field lines inside closed divertors enhance spreading? Not seen by Kukushkin**

Lithium is an Attractive Target Material

FTU, Italy
Capillary Porous System (CPS)
$T_{max} \leq 600C$
> 10 MW/m^2 in T-11

- Successful tests of lithium limiters in TFTR, T-11, FTU, CDX-U
- Reduces recycling, improves confinement
- E-beam test to 25 MW/m^2 for 5 - 10 minutes, 50 MW/m^2 for 15s.
- Plasma focus test to 60 MJ/m^2 transient load
- No dust, no damage due to transients, tritium removal by outflow of lithium?

NSTX Divertor Results Very Encouraging

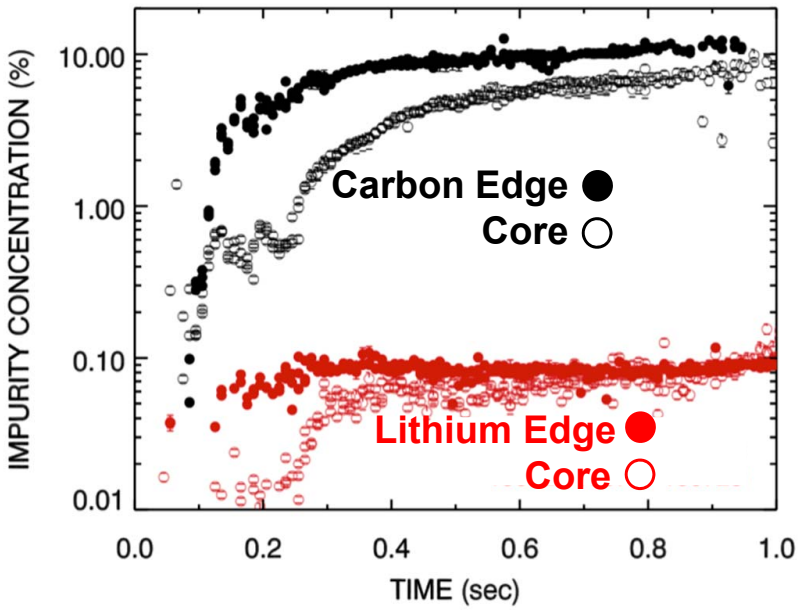
Lots of lithium, everywhere.

Capillary-Porous Molybdenum surface, evaporatively coated

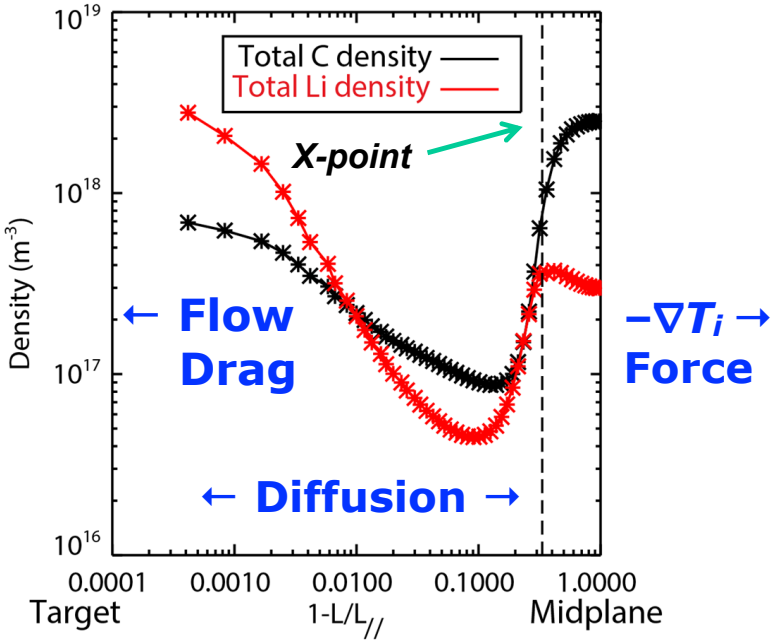
- **Reduced recycling, improved confinement**
- **No damage with strike-point directly on Li-coated Moly surface**
- **No evidence of Moly influx**
- **Reduced peak heat flux and increased radiated power**

Lithium Does not Accumulate

Ron Bell, Filippo Scotti



Very low Li in plasma.

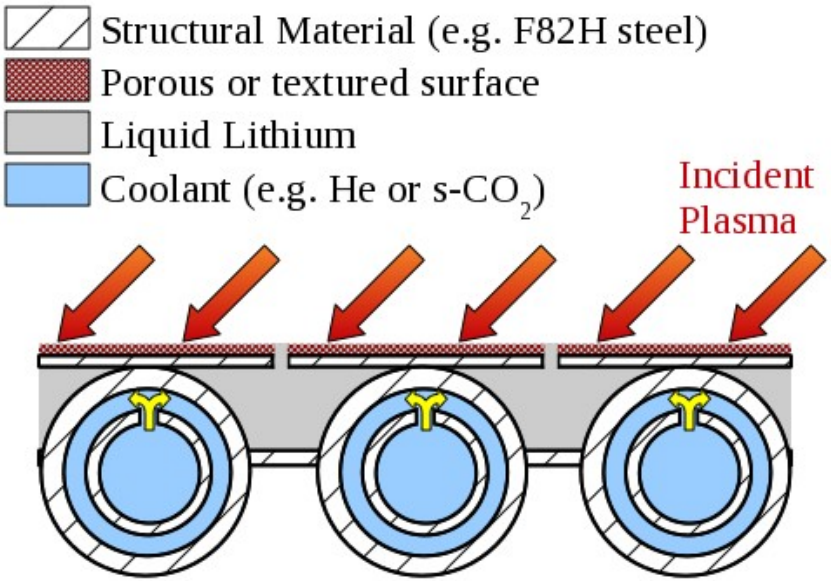


Strong divertor retention for very low-Z impurity.

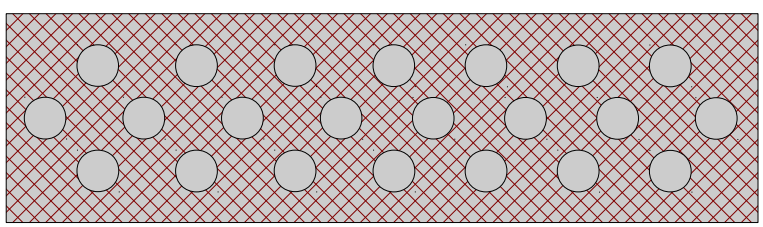
Diamagnetic friction in the SOL plasma and neoclassical parallel friction in the bulk plasma cause only weak *V/D*.

We Will Need Active Cooling & Wetting

Mike Jaworski



Top view



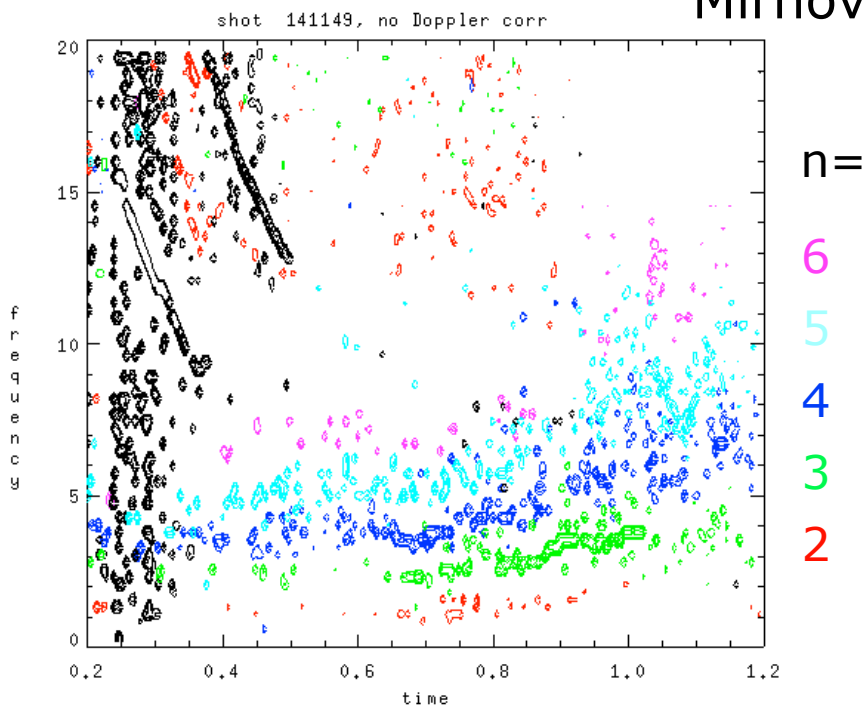
- **Local $q_{||}$ is removed by**
  - **Radiation**
  - **Evaporation**
  - **Conduction to coolant**
- **Li in surface is replenished from below**
  - **Li flow is slow**
- **To avoid too-high *T* inventory**
  - **Need hot walls to avoid accumulation**
  - **Need to recollect liquid**

Need modeling of plasma response to high Li influx and practical experience with this technology!

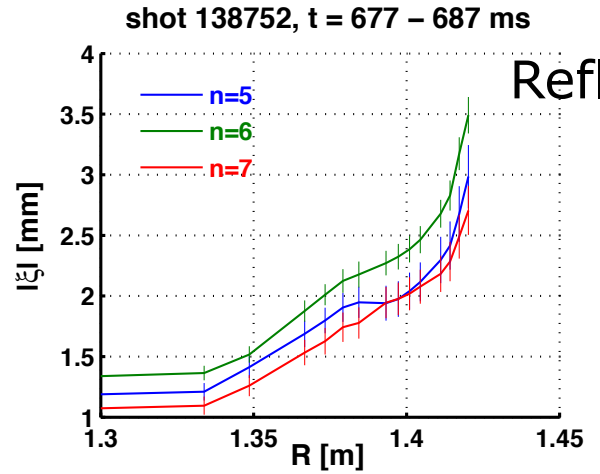
Edge Harmonic Oscillations

Eric Fredrickson, Neal Crocker, Mike Jaworski

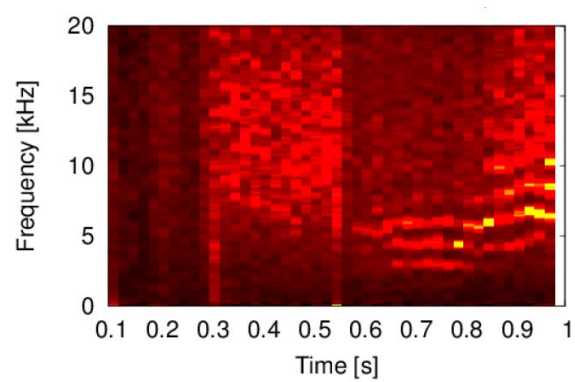
Mirnov



Reflectometry



Langmuir Probes



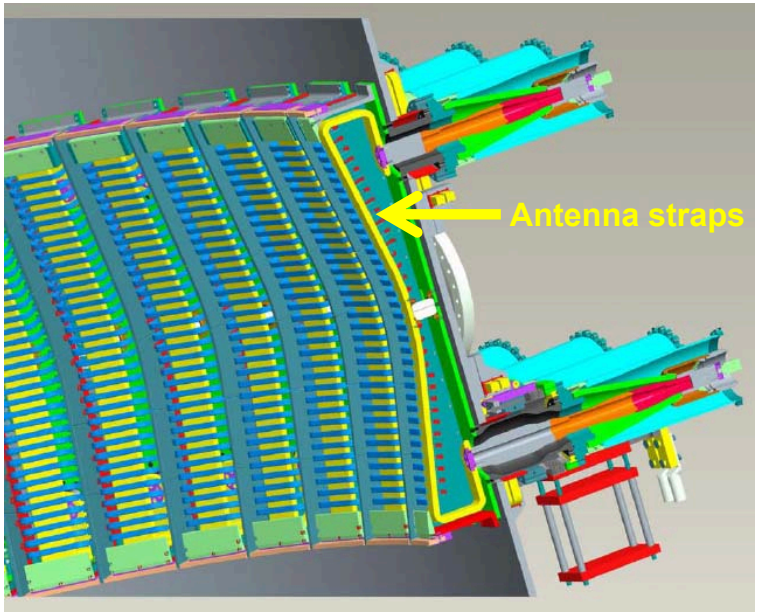
EHO's limit density rise in QH modes on DIII-D. They are observed on NSTX with Li, but don't seem to limit density.

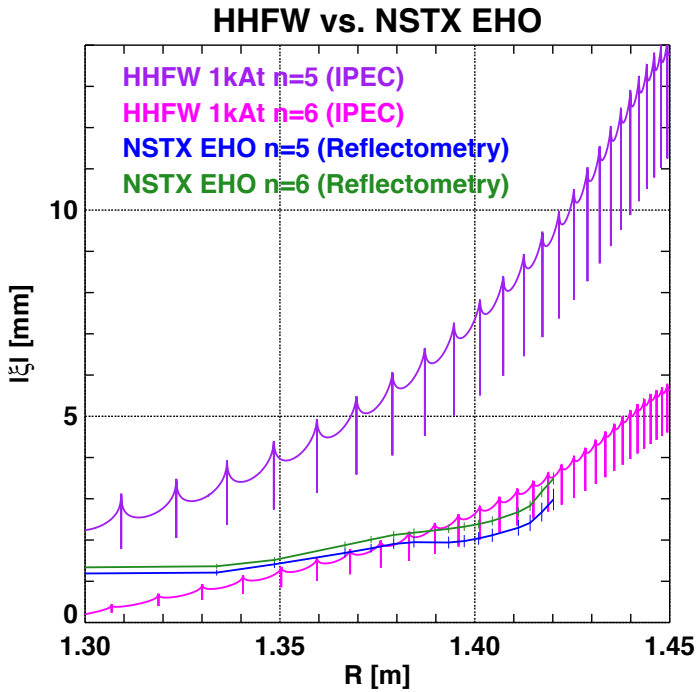
However EHOs do affect the edge and SOL strongly.

Driving Edge Harmonic Oscillations

Key to Edge Control?

Jong-Kyu Park





MHD calculations indicate we can amplify edge kinks by driving HHFW antenna straps at audio frequencies.

Can this give us external control over edge pressure gradient (and so ELMs) and/or the SOL width?

Topics

- **The Magnitude of the Challenge**
- **Scientific Understanding**
- **Possible Solutions**

The plasma boundary is a rich frontier for both scientific understanding and creative innovation.

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The Most Interesting Creatures are at the Boundaries between Habitats

Shore

Interesting creature

Sea

Land