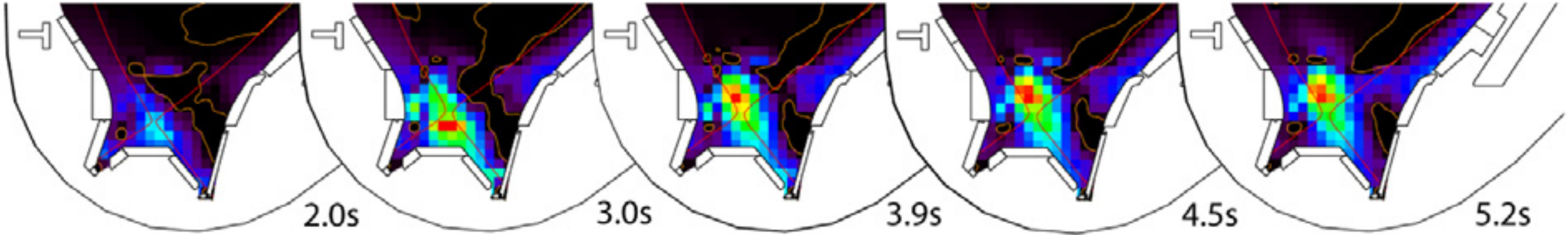
A New Scaling for Divertor Detachment

Rob Goldston, APS-DPP 2017

M. Bernert, NME 2016



R. Goldston,
M. Reinke,
J. Schwartz
PPCF 2017

M. Reinke
NF 2017

PPPL

EU Demo1 is Large & Low Power

	EU DEMO1 2015
$R[m]$	9.1
A	3.1
B_T [T]	5.7
I_P [MA]	20
H (rad. cor.)	1.1
$\beta_{N,tot}[\%]$	2.6
$f_{bs}[\%]$	35
$P_{sep}/R[MW/m]$	17
$\tau_{burn}[h]$	2
$P_{el,net}[MW]$	500

1. *Plasma Operation*
2. *Heat Exhaust*
3. ***Neutron resistant Materials***
4. ***Tritium-self sufficiency***
5. ***Safety***
6. ***Integrated DEMO Design***
7. ***Competitive Cost of Electricity***
8. *Stellarator*

Demo Goals (items 3–7)

R. Wenninger et al., EPS 2015

How can this even *point to* a reasonable COE?

The Problem is Power Handling

Reasonable cost steady-state fusion power plant.

Heat flux too high.

Add impurity seeding.

Decreases DT fuel density.

Gain too low. Heat flux still too high.

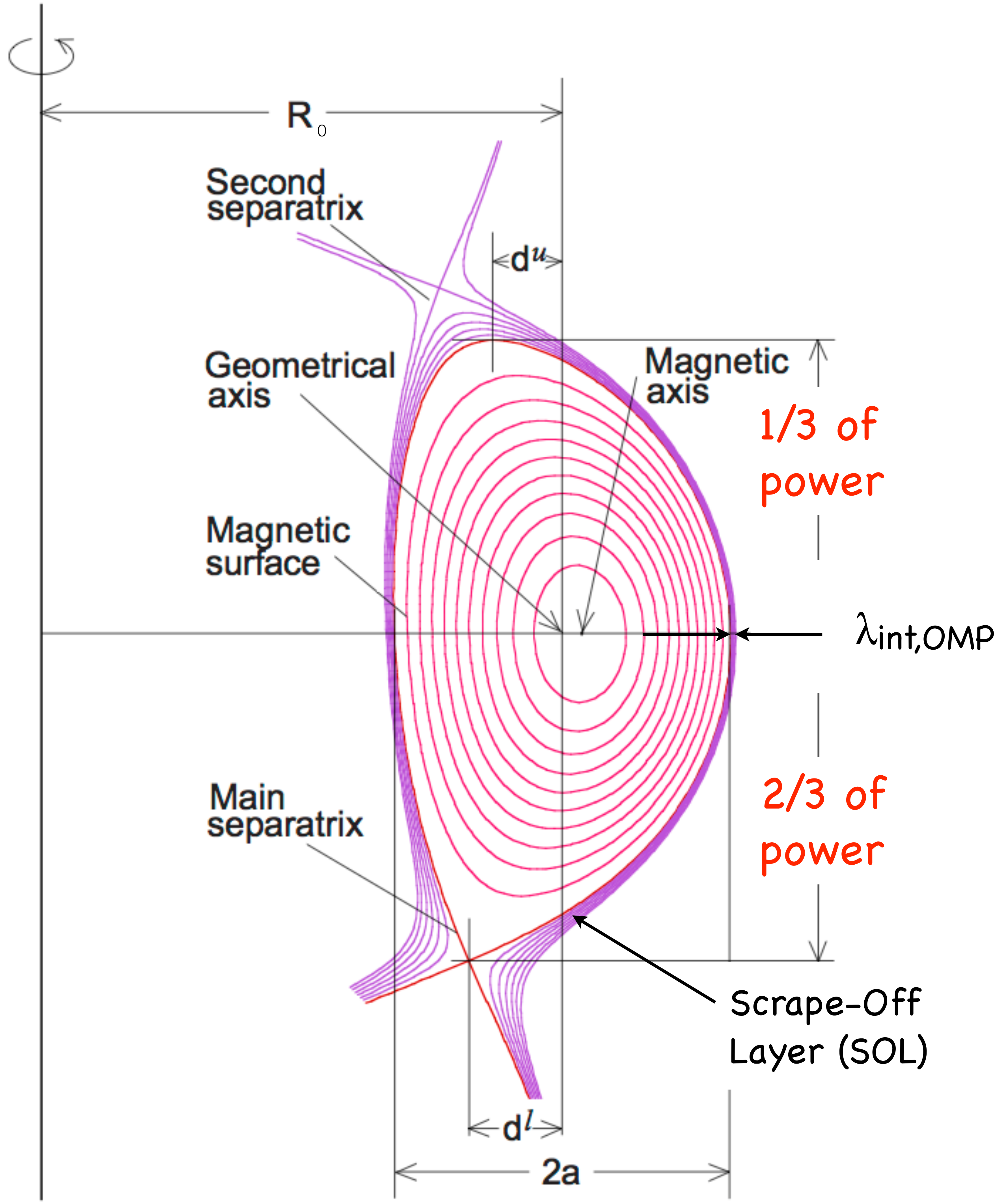
Increase size & I_p for gain.

Accept pulsed operation for gain & higher density.

Cost too high. Power too low. Heat flux STILL too high!

We need to understand this problem!

Parallel Heat Flux is too High



$$\hat{q}_{\parallel,OMP}\lambda_{int,OMP} \equiv \int q_{\parallel,OMP}\, dR$$

$$2\pi\left(R_0 + a\right)\hat{q}_{\parallel,OMP}\lambda_{int,OMP}\frac{B_{p,OMP}}{B_{OMP}} = \frac{2P_{sep}}{3}$$

$$\hat{q}_{\parallel} = \frac{2P_{sep}/3}{2\pi\left(R_0 + a\right)\lambda_{int,OMP}}\frac{B}{B_{p,OMP}}$$

… because $\lambda_{int,OMP}$ is too low.

IR Data are Well Fit with "Eich Function"

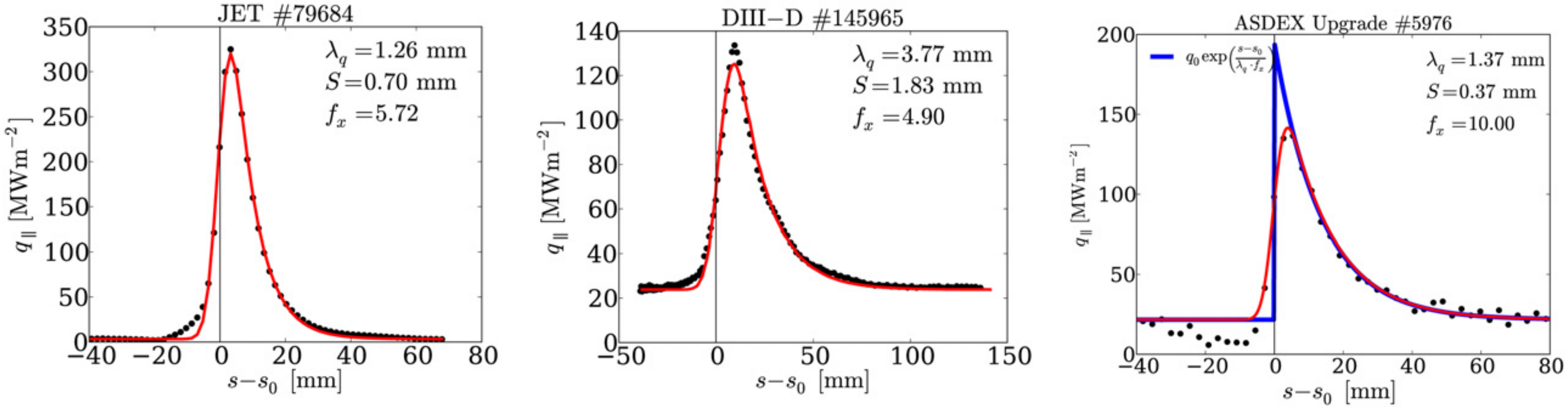
Convolve an exponential representing the near SOL, $\exp(-x/\lambda_q)$, with a Gaussian representing diffusive spreading below the X-point, $\exp(-x^2/S^2)$.

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

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

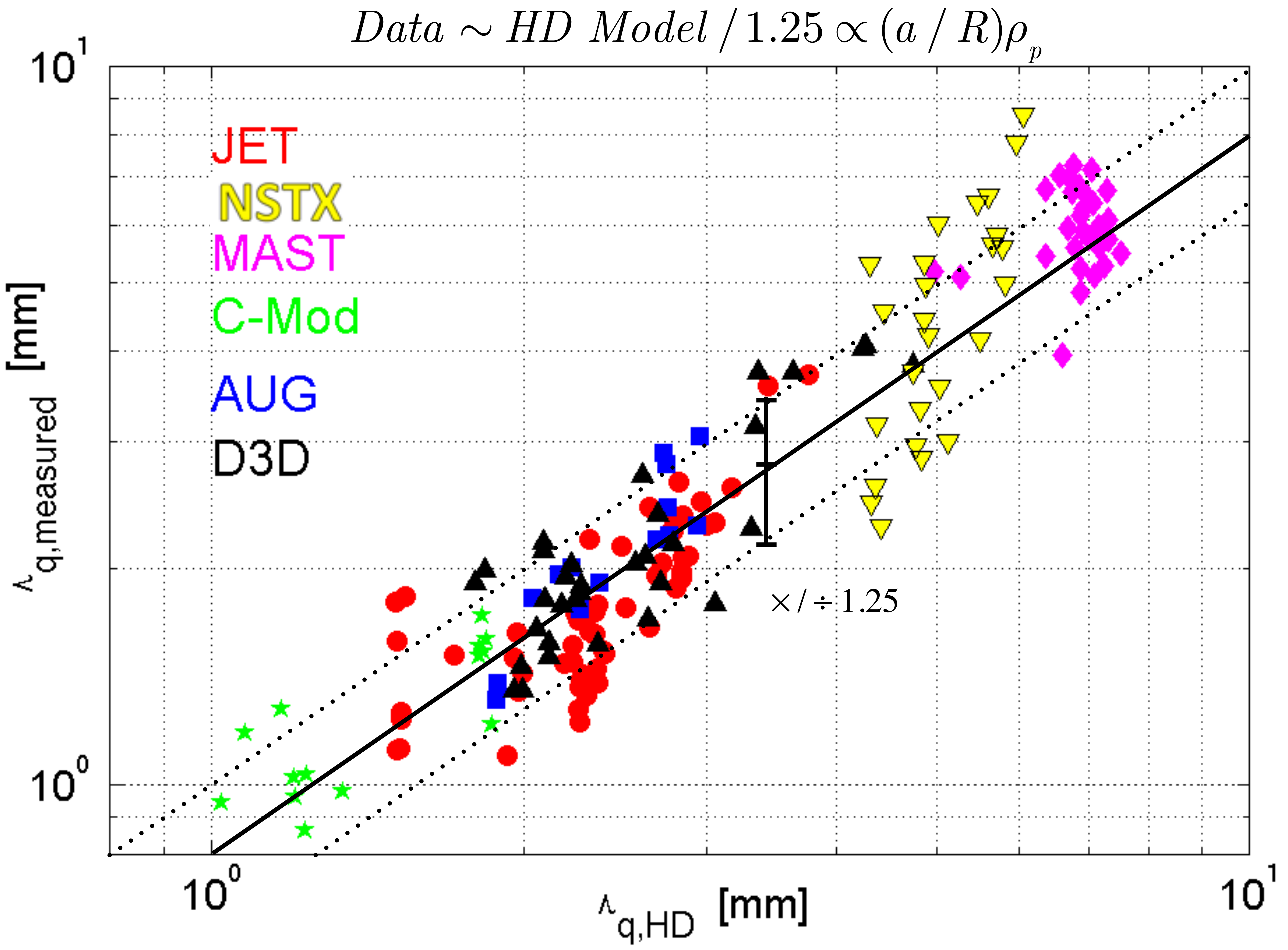
$$\Rightarrow \lambda_{int} \approx \lambda_q + 1.64 S$$

M. Makowski et al.
PoP 2012



T. Eich et al.
NF 2013

Heuristic Drift (HD) Model Fits λ_q Data Well



$$\lambda = 5671 \cdot P_{\mathrm{SOL}}^{1/8} \frac{(1+\kappa^2)^{5/8} a^{17/8} B^{1/4}}{I_{\mathrm{p}}^{9/8} R} \left(\frac{2\bar{A}}{(1+\bar{Z})}\right)^{7/16} \times \left(\frac{Z_{\mathrm{eff}}+4}{5}\right)^{1/8} \quad \text{all units SI}$$

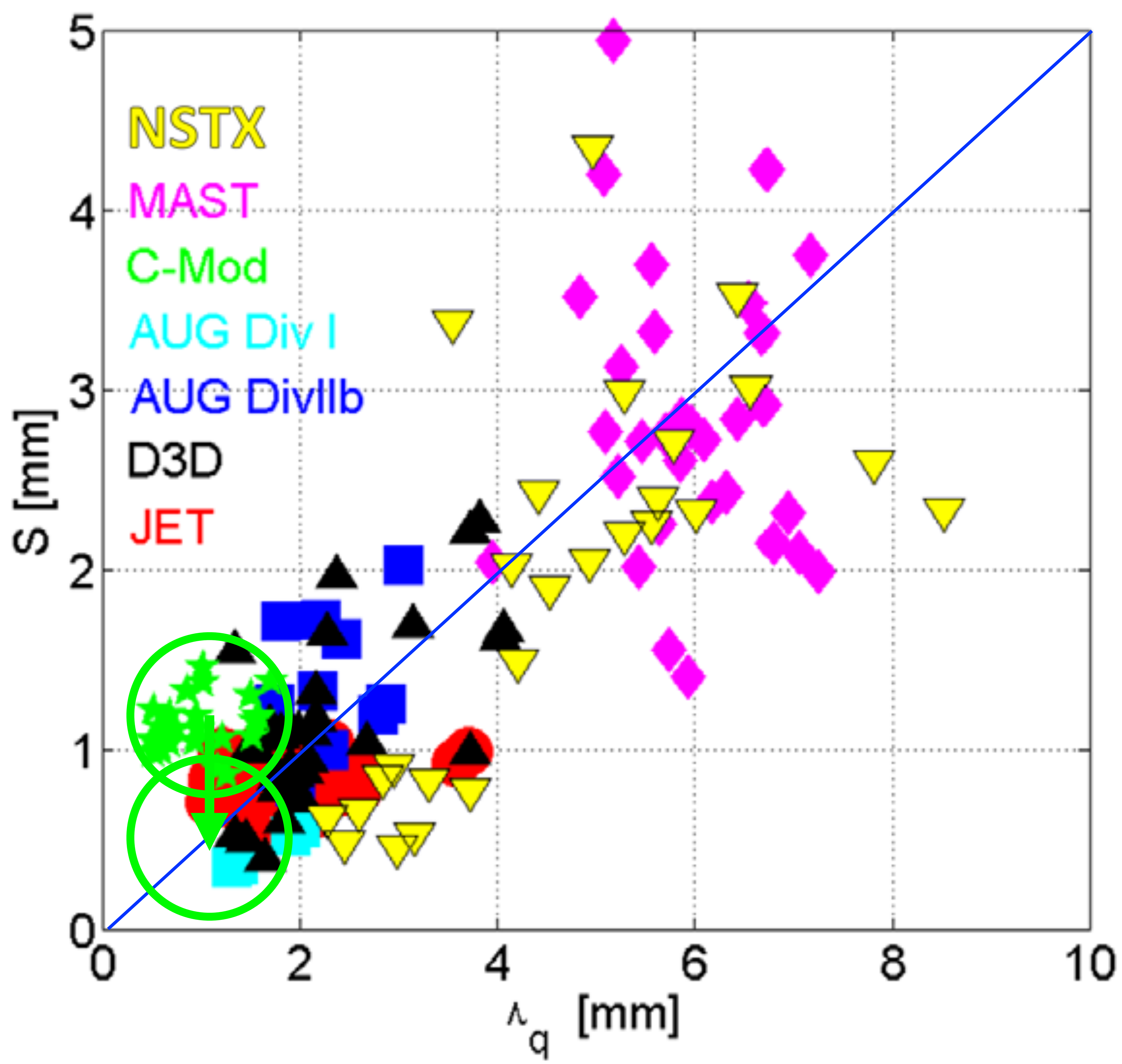
R. Goldston
JNM 2015

λ_q scales with intensive variables *T*, *B*, *a/R*, *not with system size!*

Ignoring dependence on $T^{1/2}$, $\lambda_q \propto (a/R)/B_p$

Projects to ITER, Demo λ_q ~ 1 mm!

S Appears to Scale with λ_q, not Device Size

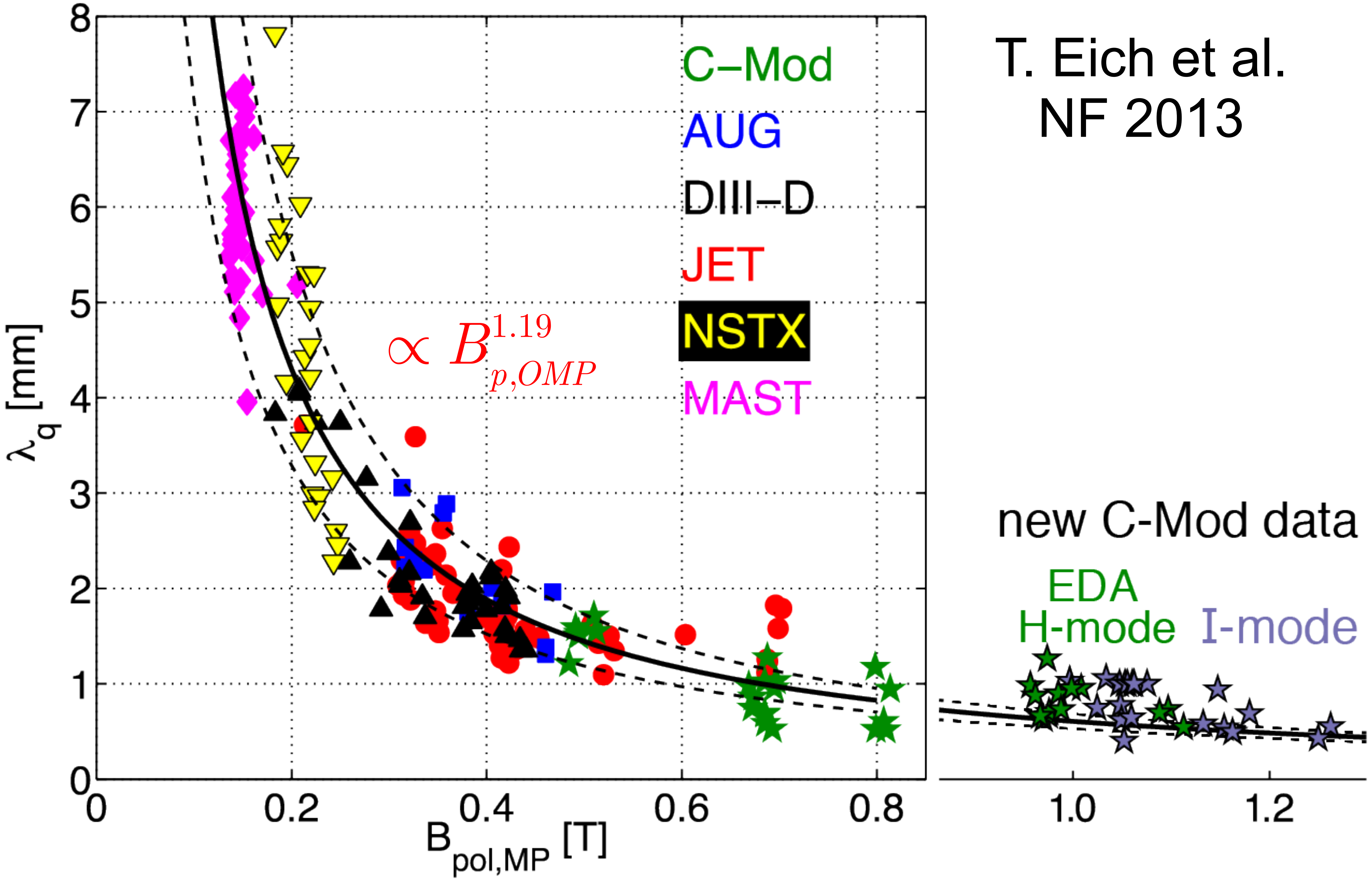


T. Eich et al.
NF 2013

$S \approx 0.5\ \lambda_q \quad \Rightarrow \quad \lambda_{int,OMP} \approx 1.8\ \lambda_q$

***S* provides no relief, unless trends change dramatically.**

The ***Problem*** can be Expressed Simply



T. Eich et al.
NF 2013

$$\hat{q}_{\parallel} = \frac{2P_{SOL}/3}{2\pi(R_0 + a)\lambda_{int,OMP}} \frac{B}{B_{p,OMP}}$$

D. Brunner
CO4: 00002

If $\lambda_{int,OMP}$ scales ~ $\propto$ *1/B_p* the $q_{||}$ problem scales ~ $\propto$ *PB/R*.

So reactor designers constrain *PB/R* or *P/R*.

But we need to take into account how the solution scales too!

Lengyel Model for Cooling due to Impurities

- **Assume local impurity cooling and Spitzer electron thermal conduction.**

$$\frac{dq_\parallel}{dz} = n_e n_z L_z = n_e^2 c_z L_z; \quad c_z \equiv \frac{n_z}{n_e} \qquad q_\parallel = \kappa_0 T_e^{5/2} \frac{dT_e}{dz}$$

- **Multiply these two equations together.** $\frac{1}{2}\frac{dq_\parallel^2}{dz} = n_e^2 c_z L_z \kappa_0 T_e^{5/2} \frac{dT_e}{dz}$

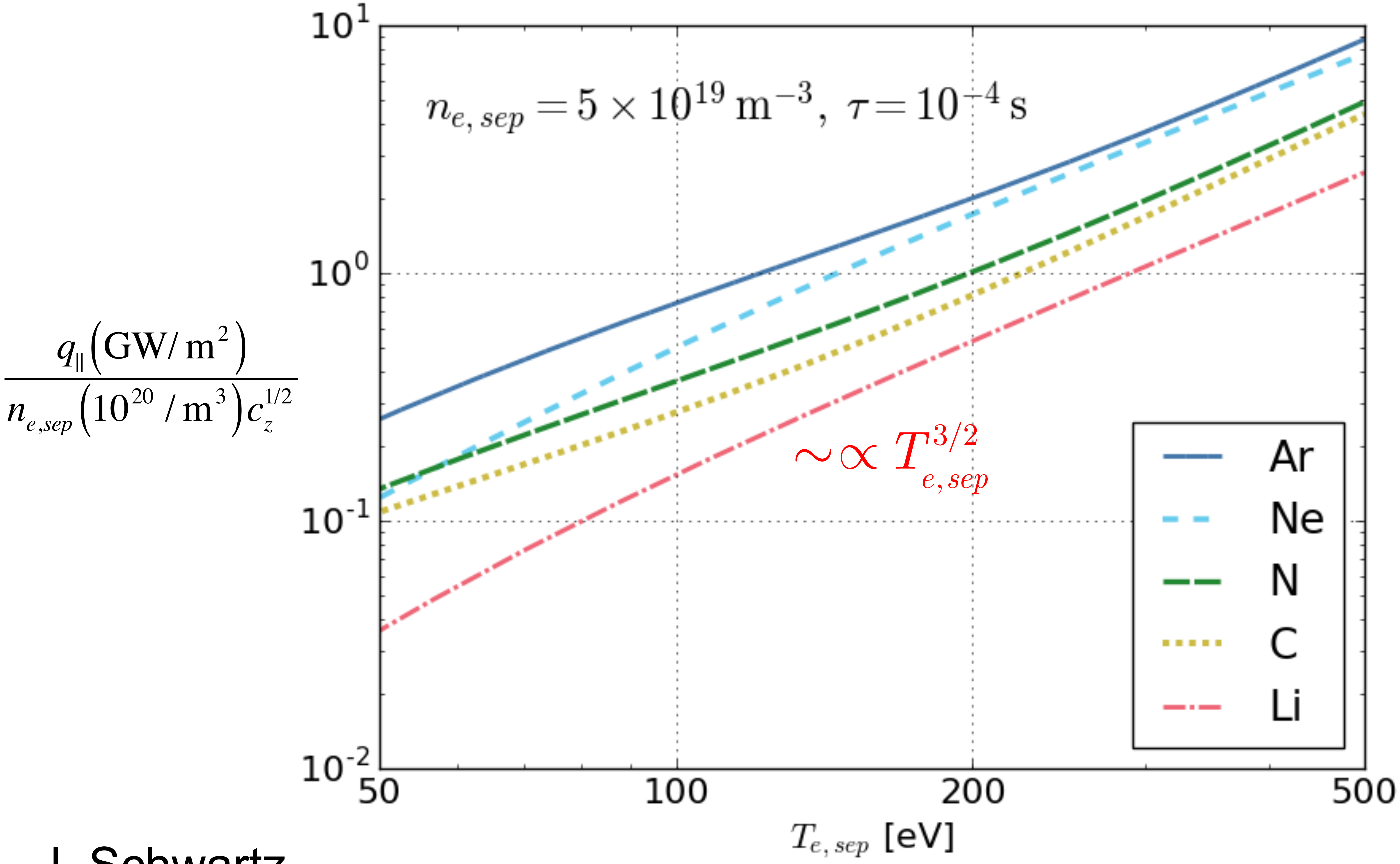
- **Integrate *dz* and assume $p_e = n_e T_e = const.$ along *B* (*down to the detachment region*).**

$$\Delta q_\parallel^2 = \int_{T_{det}}^{T_{sep}} 2 n_e^2 c_z L_z \kappa_0 T_e^{5/2}\, dT_e = 2\left(n_{e,sep} T_{e,sep}\right)^2 \int_{T_{det}}^{T_{sep}} c_z L_z \kappa_0 T_e^{1/2}\, dT_e$$

- **Assume $c_z = const.$** $\frac{\sqrt{\Delta q_\parallel^2}}{n_{e,sep} c_z^{1/2}} = \left(2\kappa_0 T_{e,sep} \int_{T_{det}}^{T_{sep}} L_z T_e^{1/2}\, dT_e\right)^{1/2}$ **(R.H.S. depends only on T_e.)**

L. Lengyel, IPP 1981

Use ADAS to Evaluate Lengyel Integral



J. Schwartz

- **Assume nearly all of P_{sep} must be dissipated to achieve detachment at a few eV. (Not always true in present expt's.)**
- **Include finite-lifetime non-coronal radiation in evaluating R.H.S.**
- **$q_{||}$ that can be detached scales as $n_{e,sep}\, c_z^{1/2} T_{sep}^{3/2}$**
- **Note that per electron, lithium is comparable to nitrogen.**

Bring in Greenwald Density & Spitzer T_{sep}

- **So far we have something very simple:** $q_{\|,det} \sim\propto n_{e,sep} T_{e,sep}^{3/2} c_z^{1/2}$

- **Assume Greenwald density scaling & Spitzer electron thermal conduction:**

$$n_{e,sep} \propto f_{GW,sep} \frac{\langle B_p \rangle}{a} \left(1+\kappa^2\right)^{1/2} \qquad T_{e,sep} \propto \left(R_0 q_\| \ell_\|^* q_{cyl}\right)^{2/7} \qquad \ell_\|^* \equiv L_\| / \left(\pi q_{cyl} R_0\right)$$

- **Multiply top equation by R_0 and substitute for $n_{e,sep}$ and $T_{e,sep}$.**

$$R_0 q_\| \propto f_{GW,sep} \frac{R_0}{a} \langle B_p \rangle \left(1+\kappa^2\right)^{1/2} \left(R_0 q_\| \ell_\|^* q_{cyl}\right)^{3/7} c_z^{1/2} \quad \Rightarrow \quad c_z \propto \frac{\left(R_0 q_\|\right)^{8/7}}{f_{GW,sep}^2 \left(\ell_\|^* q_{cyl}\right)^{6/7} \left(\frac{R_0}{a}\right)^2 \langle B_p \rangle^2 \left(1+\kappa^2\right)}$$

- **OOPS, we had before, *$q_\| \sim\propto PB/R \Rightarrow$ Strong P & B scalings, no size scaling!***

Now Use HD λ_q to Evaluate $R_0 q_{||}$

- **Using HD model for λ_q, with its Spitzer model for $T_{e,sep}$:**

$$q_{\|}R_0 \propto \frac{P_{sep}}{\lambda_{q,HD}}\frac{B_t}{B_p} \propto P_{sep}^{7/8} B_t^{3/4} \left\langle B_p \right\rangle^{1/8} \frac{R_0}{a}\left(1+\kappa^2\right)^{-1/16}\left(\frac{\bar{A}}{1+\bar{Z}}\right)^{-7/16}\left(\ell_{\|}^{*}\right)^{-1/8}$$

- **Substitute this into the result from the last slide:**

$$c_z \propto \frac{P_{sep} B_{t,0}^{6/7}\left(\frac{\bar{A}}{1+\bar{Z}}\right)^{-1/2}}{f_{GW,sep}^2\left(\frac{R_0 q_{cyl}}{a}\right)^{6/7}\left\langle B_p\right\rangle^{13/7}\left(1+\kappa^2\right)^{15/14}\ell_{\|}^{*}}$$

- **Lots of terms cancel:**

$$c_z \propto \frac{P_{sep}}{\left\langle B_p\right\rangle \ell_{\|}^{*}\left(1+\kappa^2\right)^{3/2} f_{GW,sep}^2}\left(\frac{1+\bar{Z}}{\bar{A}}\right)^{1/2}$$

- If you take into account the *solution* as well as the *problem*, the difficulty of detachment scales as *P/B_p* not as *PB/R*.
- No wonder making the machine larger doesn't help.
- Surprisingly, you want higher B_p, higher $\ell_{\|}$, and higher κ, not larger size.

We Really Should Not Have Been Surprised

- **Ignore temperature variation and use ultra-simple radiation scaling.**

$$P_{rad} \propto n_e n_z V = c_z n_e^2 V \quad \Rightarrow \quad c_z \propto \frac{P_{sep}}{n_{sep}^2 \lambda_{HD} R a \ell_\parallel^* \left(1+\kappa^2\right)^{1/2}}$$

- **The HD model (at fixed *T*) and the Greenwald density are**

$$\lambda_{HD} \propto \frac{a}{RB_p}\left(\frac{1+\bar{Z}}{\bar{A}}\right)^{1/2} \qquad n_{sep}^2 \propto f_{GW}^2 \frac{B_p^2}{a^2}\left(1+\kappa^2\right)$$

- **This gives the *exact same result* we had from the Lengyel calculation.**

$$c_z \propto \frac{P_{sep}}{B_p \ell_\parallel^* \left(1+\kappa^2\right)^{3/2} f_{GW}^2}\left(\frac{1+\bar{Z}}{\bar{A}}\right)^{1/2}$$

λ_q Gets You Coming & Going

The same narrow λ_{int} that made $q_{||}$ *very* high also takes away the scrape-off layer volume needed to radiate away that high $q_{||}$.

Credit where Credit is Due Dept.

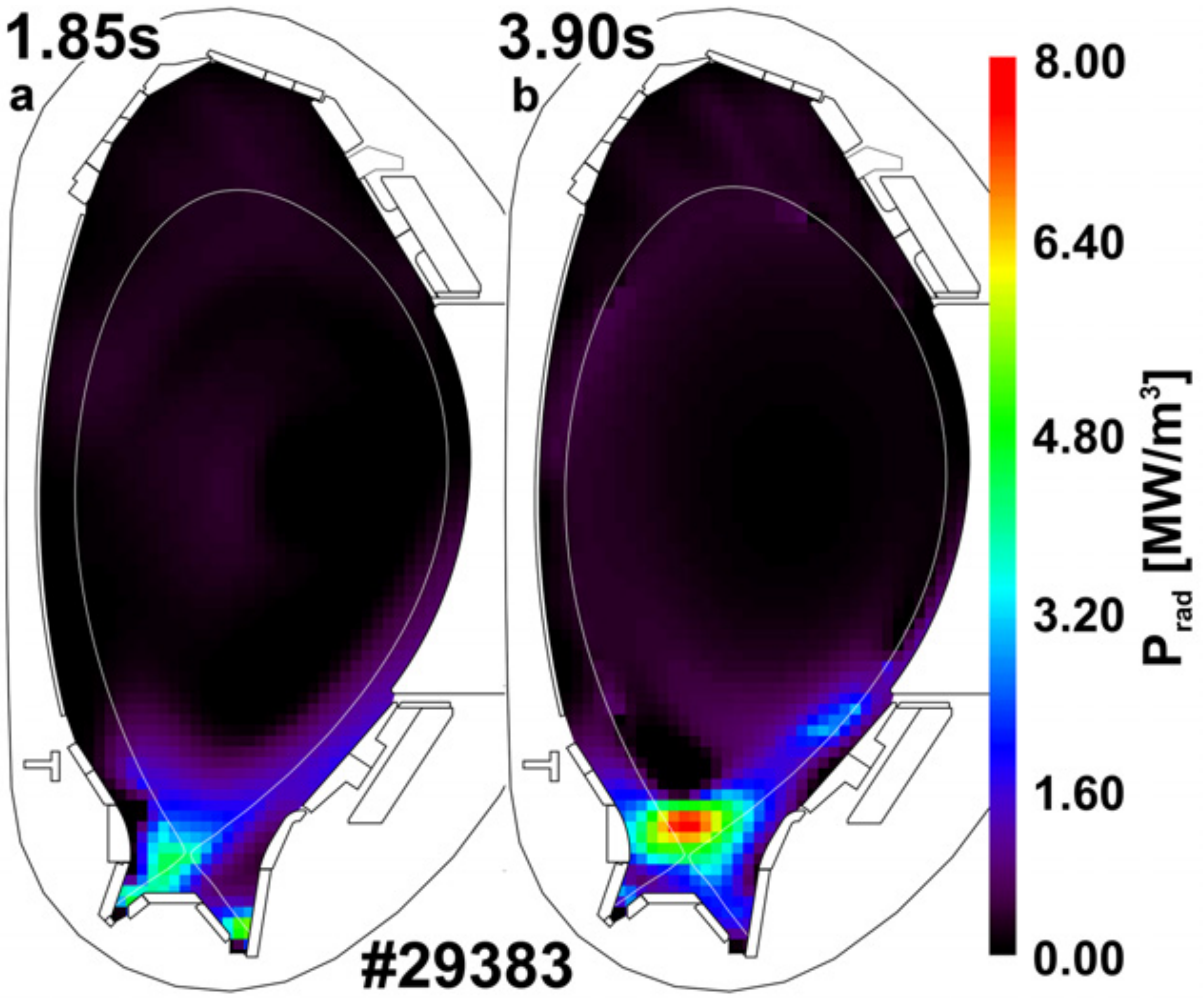
Matt Reinke & I arrived at the "Taming the Flame" Lorentz Workshop in Sept. 2016, already looking into these ideas. We worked together and improved each other's thinking.
See also Matt's paper: NF, 2017.

How Serious is This Problem?

	C-Mod	ASDEX-U	JET	ITER	FNSF (A=4)	EU Demo1
P_{sep}	3.83	10.7	14	100	96	154.7
B_t	5.47	2.5	2.5	5.3	7.0	5.7
R_0	0.7	1.6	2.9	6.2	4.5	9.1
P_{sep}/R	5.5	6.7	4.8	16.1	21.3	17.0
$P_{sep}B_t/R$	29.9	16.7	12.1	85.5	149.3	96.9
I_p	0.82	1.2	2.5	15	7.5	20
a	0.22	0.52	0.90	2.00	1.13	2.94
κ_{95}	1.51	1.63	1.73	1.80	2.10	1.70
$\langle B_p \rangle$	0.58	0.34	0.39	1.03	0.81	0.98
q_{cyl}	3.78	3.16	2.79	2.42	3.55	2.62
n_{GW}	5.39E+20	1.44E+20	9.82E+19	1.19E+20	1.89E+20	7.39E+19
Projected c_N for detachment from AUG	1.0%	4.0%	4.1%	10.1%	8.6%	18.8%

Pretty serious.

Detachment Tends to Run up to the X-Point

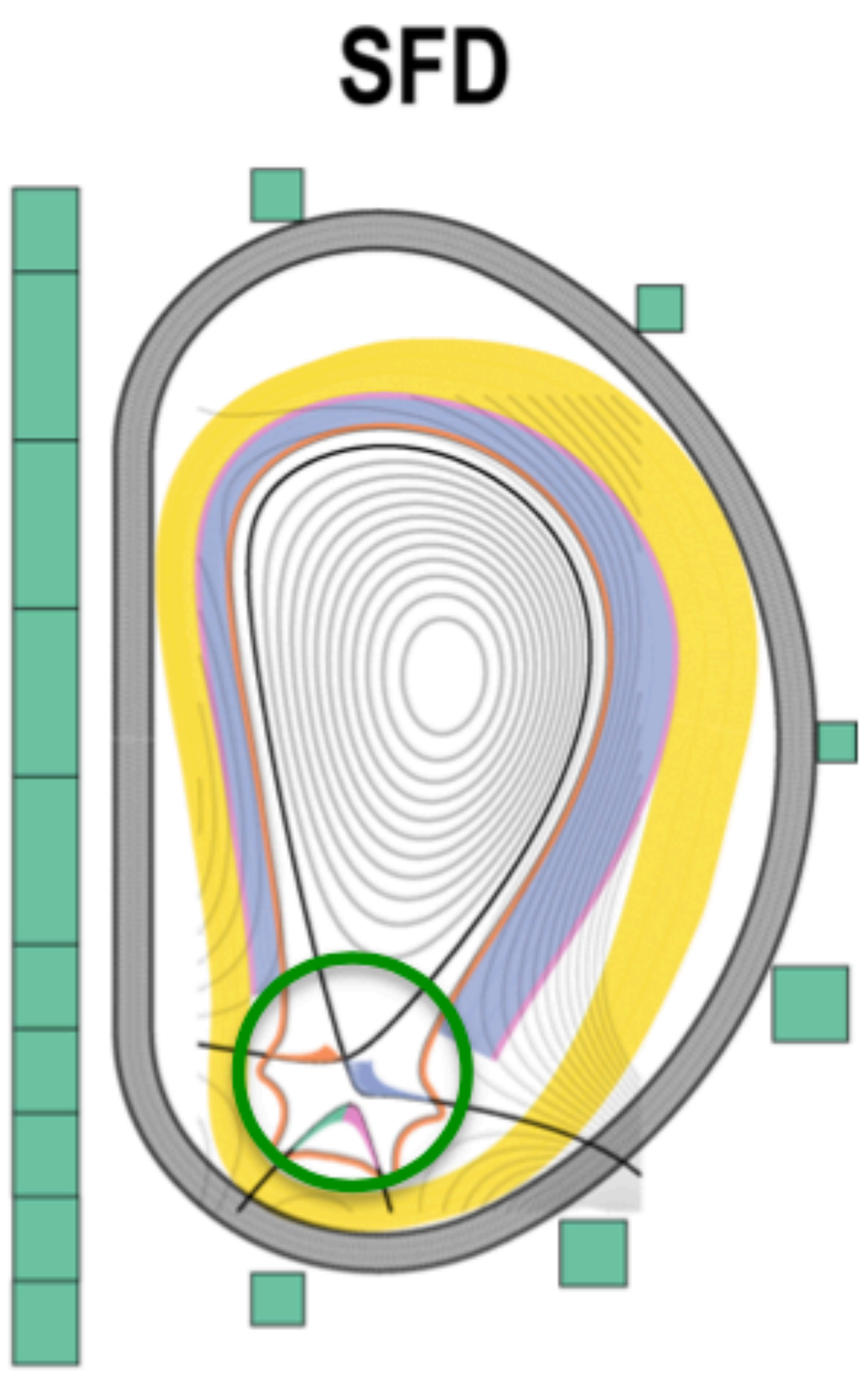


- Exposes core plasma to impurity influx.
- Degrades pedestal pressure.
- Reduces helium compression for pumping.

F. Reimold et al.
NF 2015

$\ell_{\parallel}^{*}$ May be a Useful Knob

		SND	SFD+/-	Limit
Constraints	Max. force on single coil $F_{z,PF}$ (MN)	145	439	< 450
	Max. vertical force on CS $F_{z,PCS}$ (MN)	130	28	<300
	Max. CS separation force $F_{z,CS}$ (MN)	130	329	< 350
Costs	Max. Σ $\|I_{PF}\|$ (MA·turns)	160	174	
	Total $I_{PF,internal}$ (MA·turns)	-	-	
	Flux swing for current drive (V · S)	330	**215**	
	V_{TF}/V_{plasma}	2.9	3.8	**+ 31%**
Benefits	$L_{\|\|,outer}$ (ρ_u=3mm) (m)	110 →	**232/234**	
	$f_{x,t}/f_{x,min}$	1	1	
	R_t/R_x	1.04	1.19	



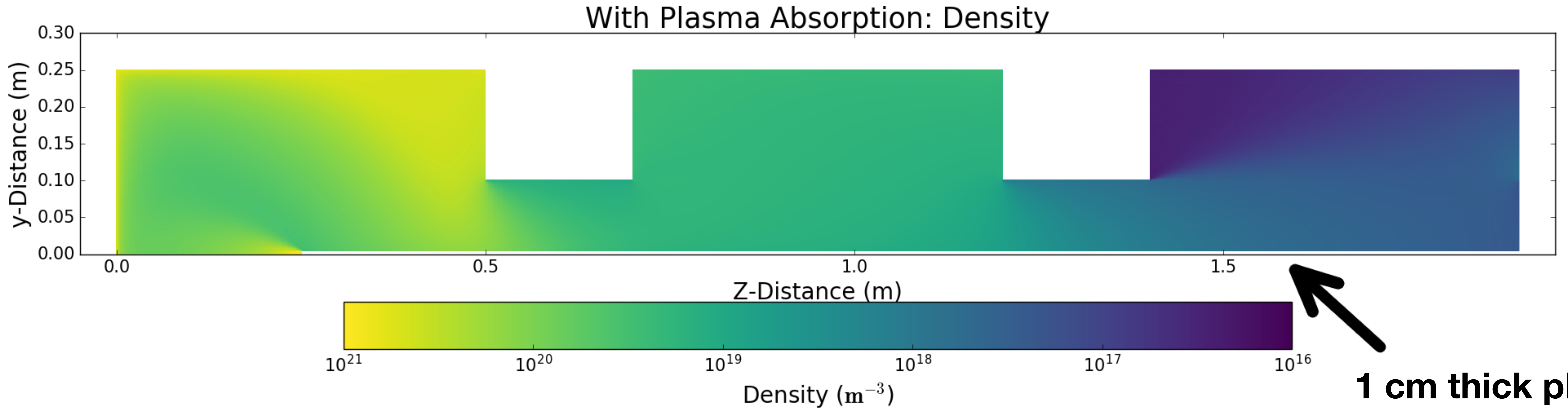
$$c_z \propto \frac{P_{sep}}{B_p \ell_{\parallel}^{*} \left(1+\kappa^2\right)^{3/2} f_{GW}^2}$$

- **If you have plenty of $\ell_{\parallel}^{*}$ you gain stability against variations in P_{sep} and n_{sep}.**

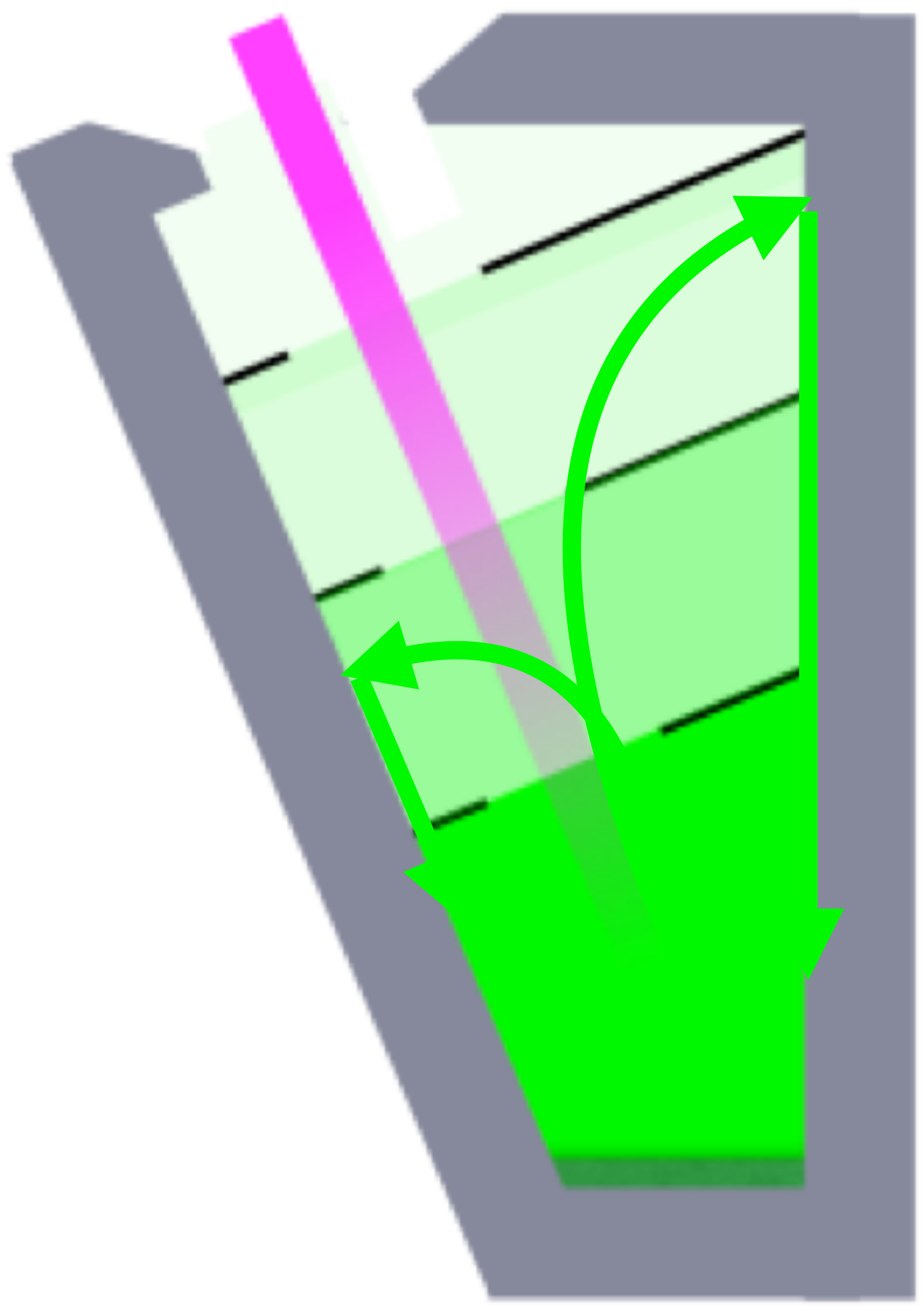
H. Reimerdes, 2016
4th IAEA Demo Programme Workshop

Lithium Vapor Box Provides Stable Detachment

- Multiple boxes are used to provide strong differential pumping of Li.
- Lithium recirculates via capillary action (like in a heat pipe).
- Reduced Li thermal force along *B*, and reduced neoclassical pinch across *B* should reduce core impurity level.
- Bottom box provides enough lithium vapor to detach 200 MW.
  - Higher boxes are cooler, less dense.
  - Efflux to main chamber, 20 mg/s
- **Plasma detachment cannot move to the X-point.**



1 cm thick plasma



E. Emdee et al., Poster PP11.00094… NOW!

Conclusions

- **Difficulty of detachment is better characterized by P/B_p than PB/R.**
  - **We should perform numerical studies and laboratory experiments to confirm this hypothesis.**
- **This adds motivation for more compact, higher *B* reactor designs.**
  - **A Divertor Test Tokamak should have relevant P/B_p.**
- **Enhancing the divertor leg parallel length should reduce the impurity content required for detachment, and improve its stability.**
- **Detachment location can be assured by localizing the impurity influx, as in a Lithium Vapor Box Divertor.**