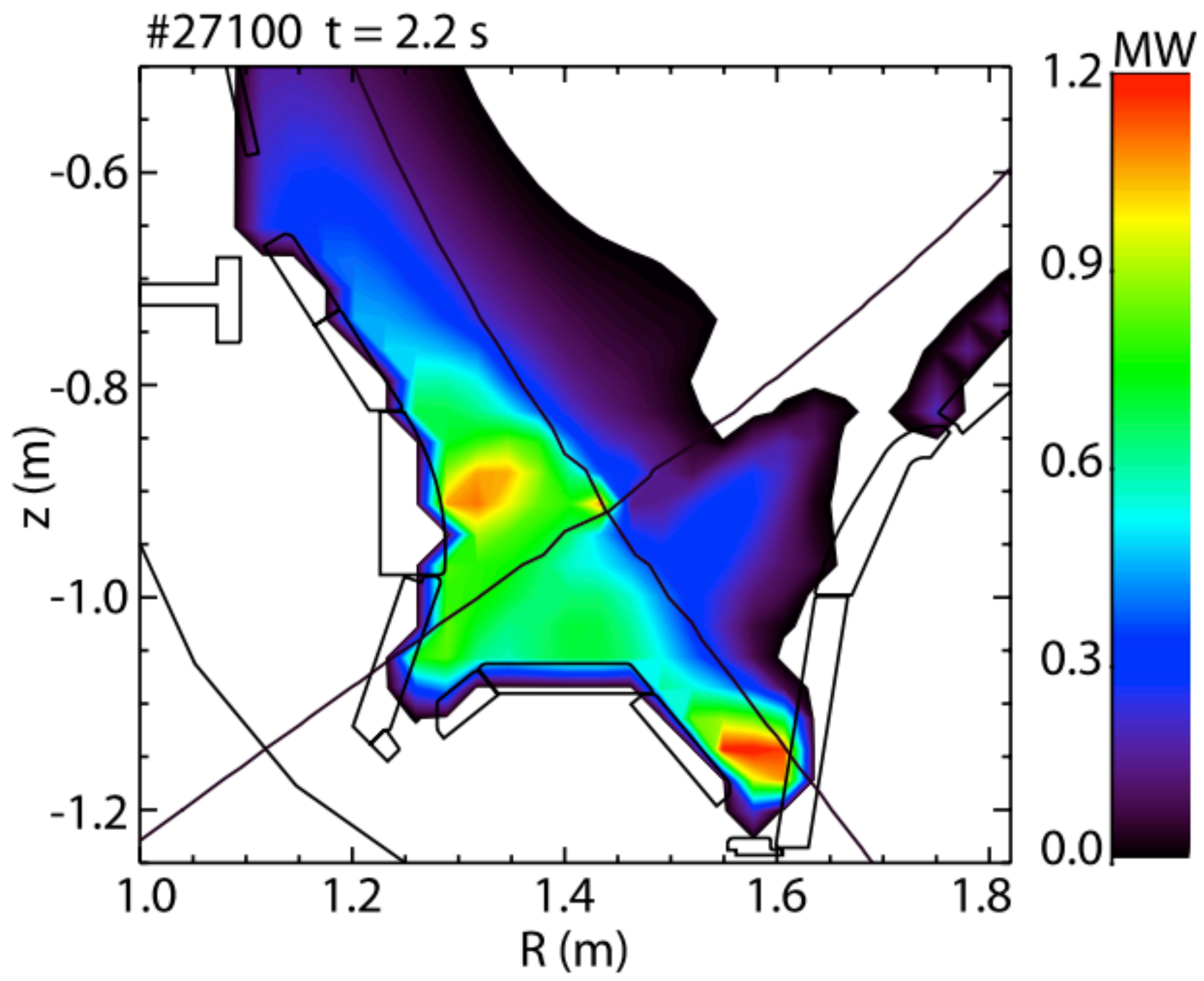
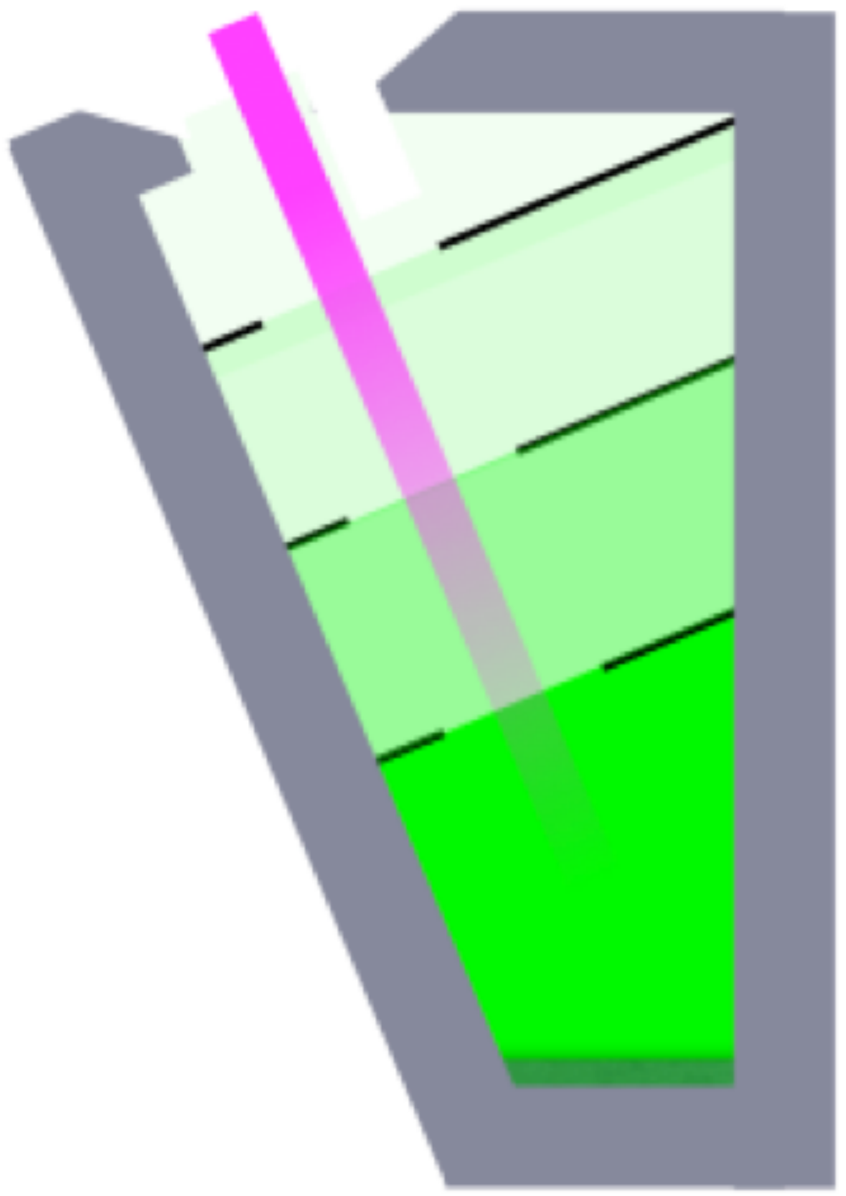
A New Scaling for Divertor Detachment



Detachment onset in ASDEX-U
Potzel et al., Nuc. Fusion 2014



Lithium Vapor Box Divertor
R. Goldston et al., NME, 2017

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

M. Reinke
NF 2017

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

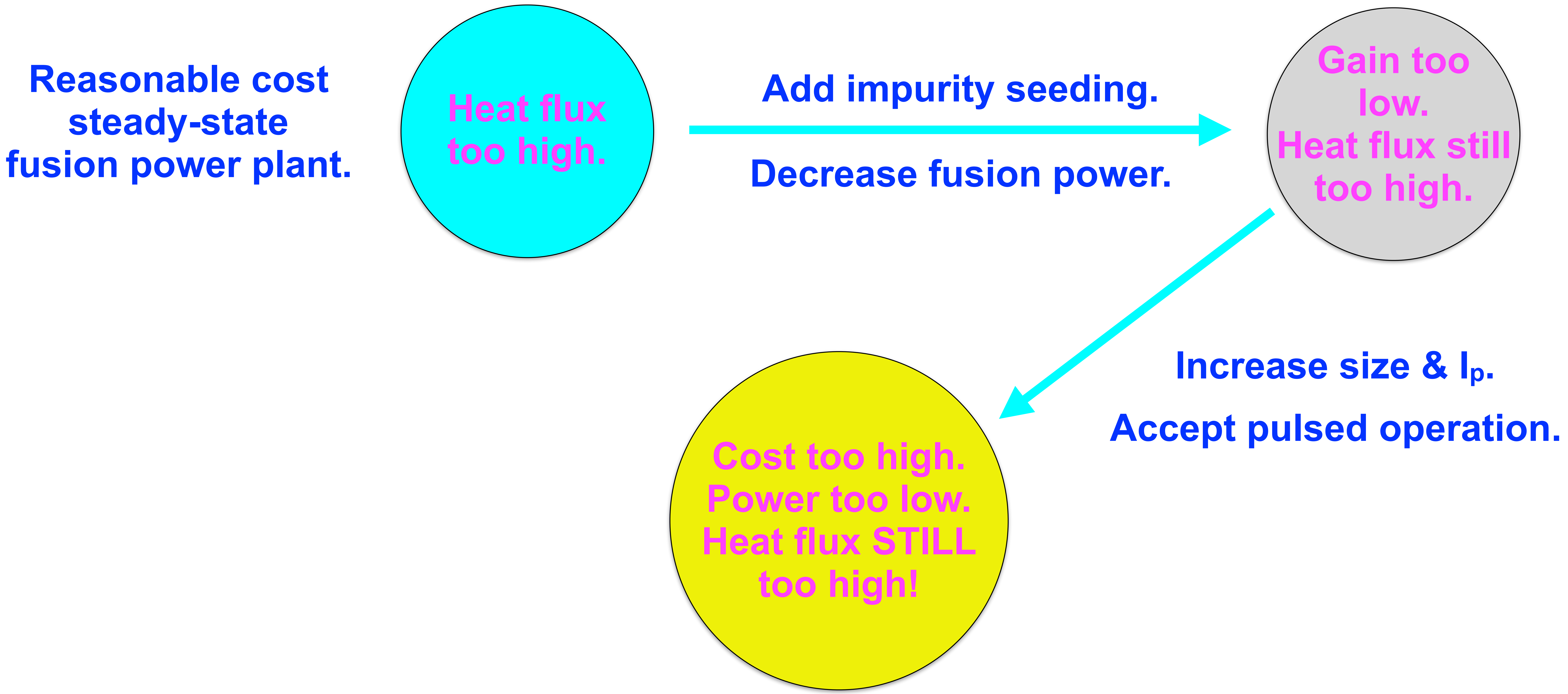
1. *Plasma Operation*
2. *Heat Exhaust*
3. ***Neutron resistant Materials***
4. ***Tritium-self sufficiency***
5. ***Safety***
6. ***Integrated DEMO Design***
7. ***Competitive Cost of Electricity***
8. *Stellarator*

Demo Goals (items 3–7)

R. Wenninger et al., EPS 2015

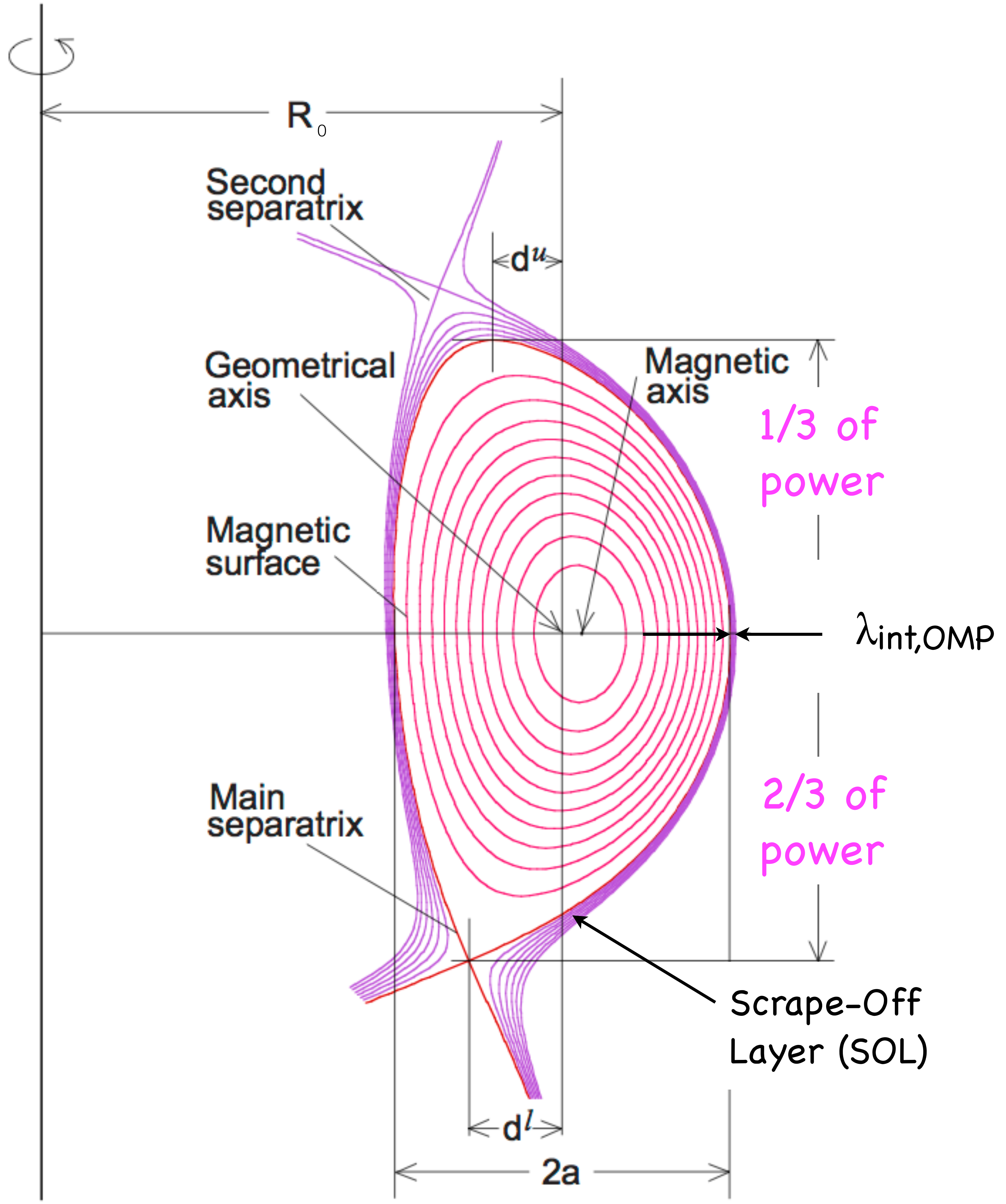
How can this even *point to* a reasonable COE?

The Problem is Power Handling



We need to understand this problem!

Parallel Heat Flux is too High



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

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

IR Data are Well Fit with "Eich Function"

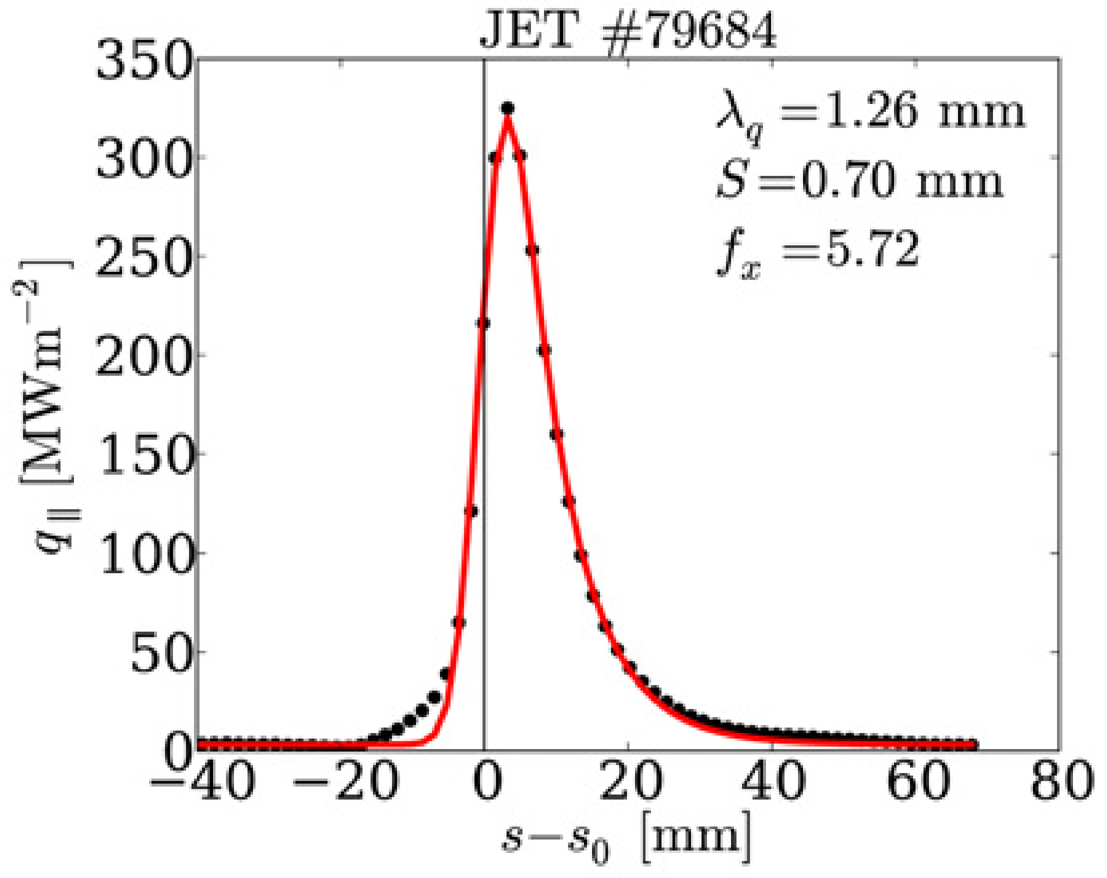
Convolve an exponential representing the near SOL, $\exp(-x/\lambda_q)$, with a Gaussian representing diffusive spreading as the plasma travels down the divertor leg, $\exp(-x^2/S^2)$.

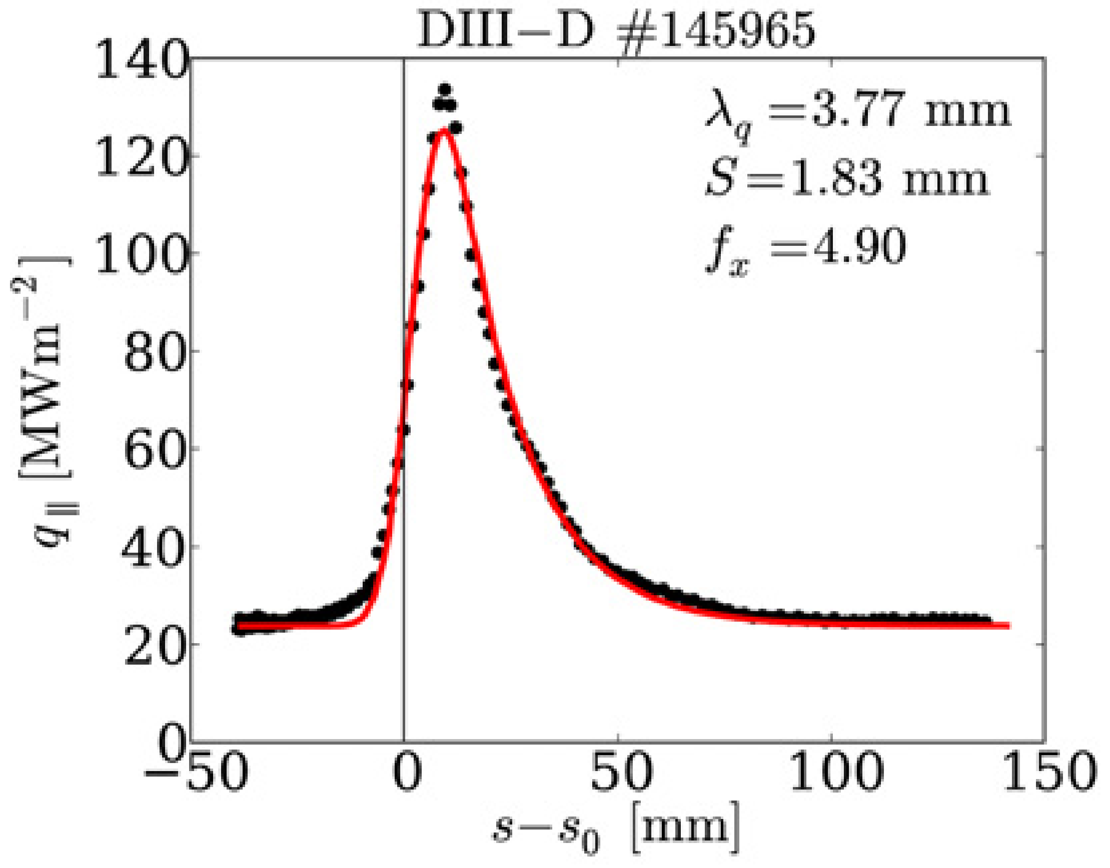
$$q_{\|}(x) = q_{\|0} \int_0^{\infty} \left[\exp\left(\frac{-x'}{\lambda_q} \right) \right] \left\{ \frac{1}{\sqrt{\pi} S} \exp\left[\frac{-(x-x')^2}{S^2} \right] \right\} dx'$$

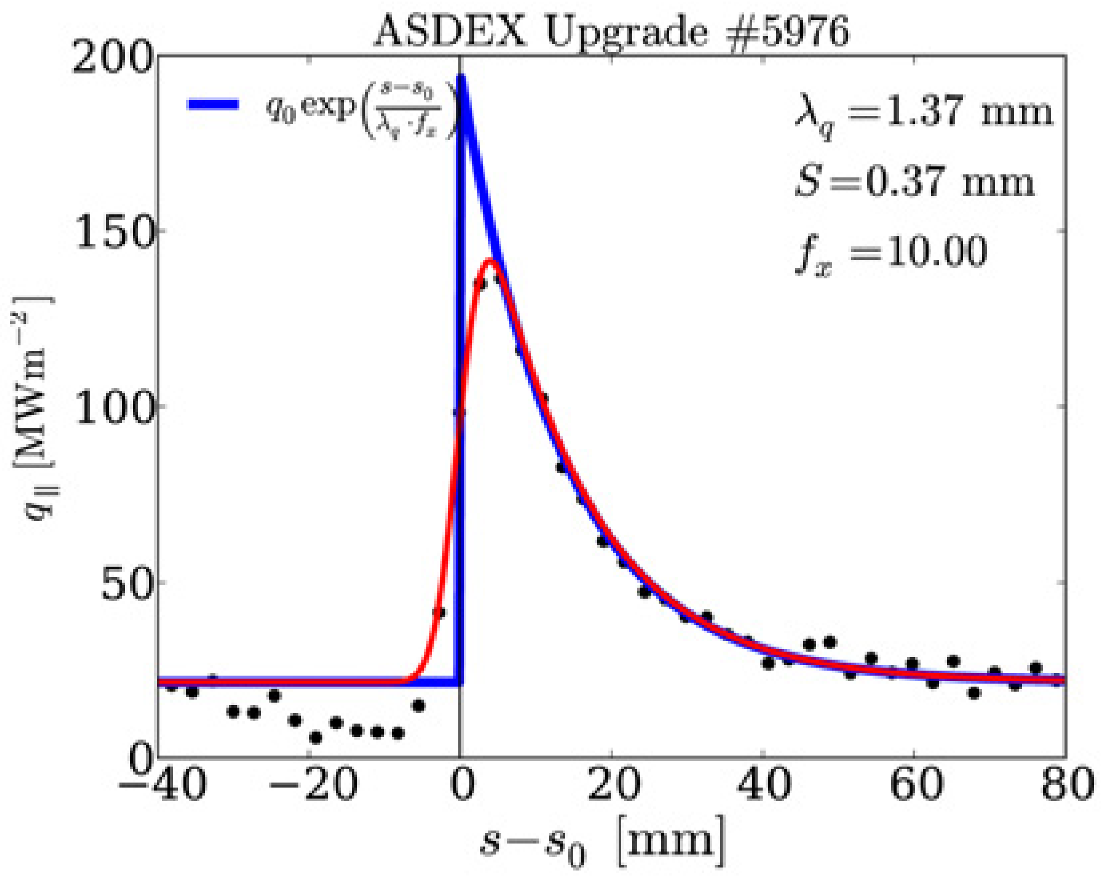
$$= \frac{q_{\|0}}{2} \exp\left[\left(\frac{S}{2\lambda_q} \right)^2 - \frac{x}{\lambda_q} \right] \operatorname{erfc}\left(\frac{S}{2\lambda_q} - \frac{x}{S} \right)$$

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

M. Makowski et al.
PoP 2012



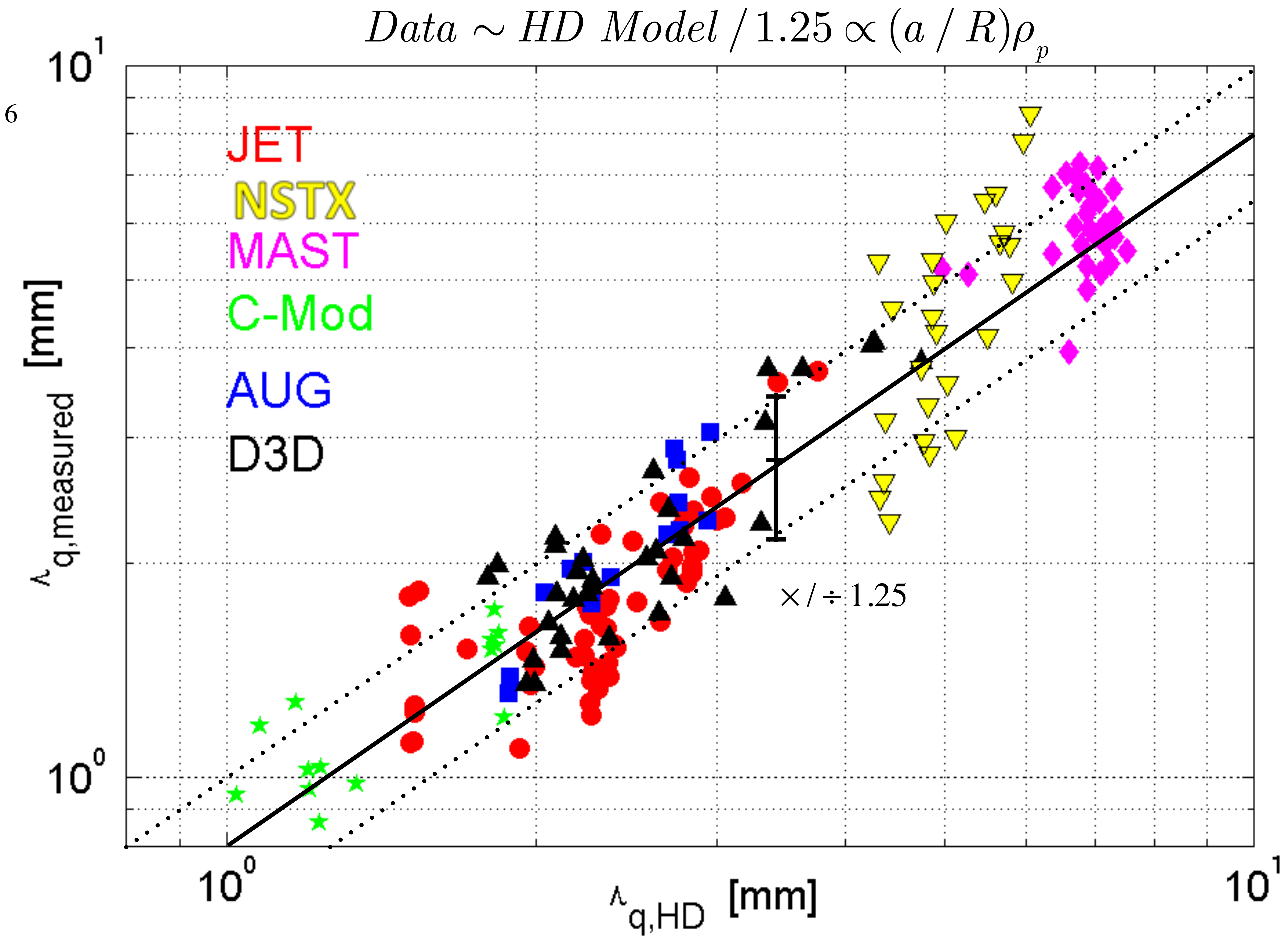




T. Eich et al.,
NF 2013

Heuristic Drift (HD) Model Fits λ_q Data Well

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



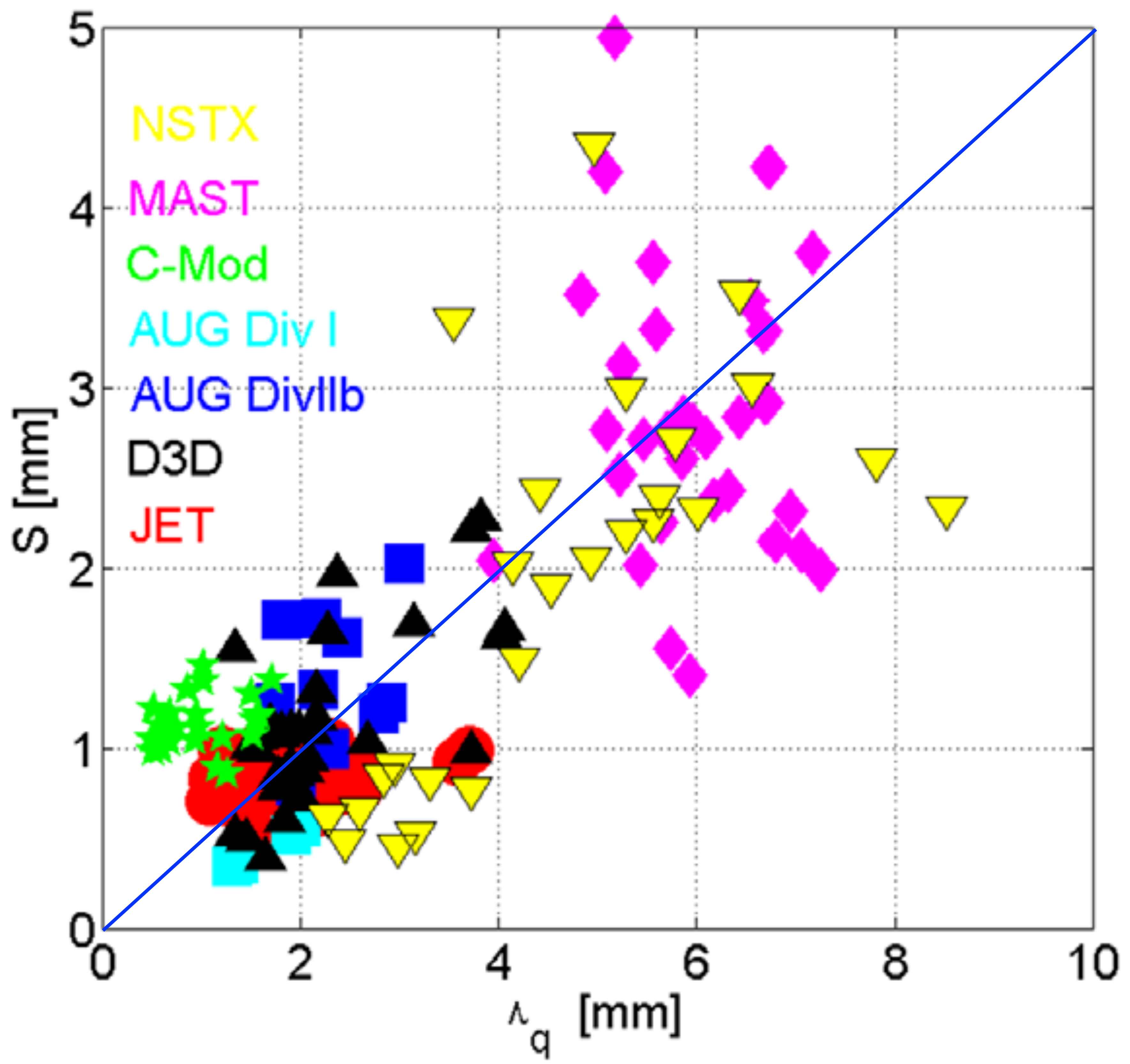
R. Goldston
JNM 2015

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



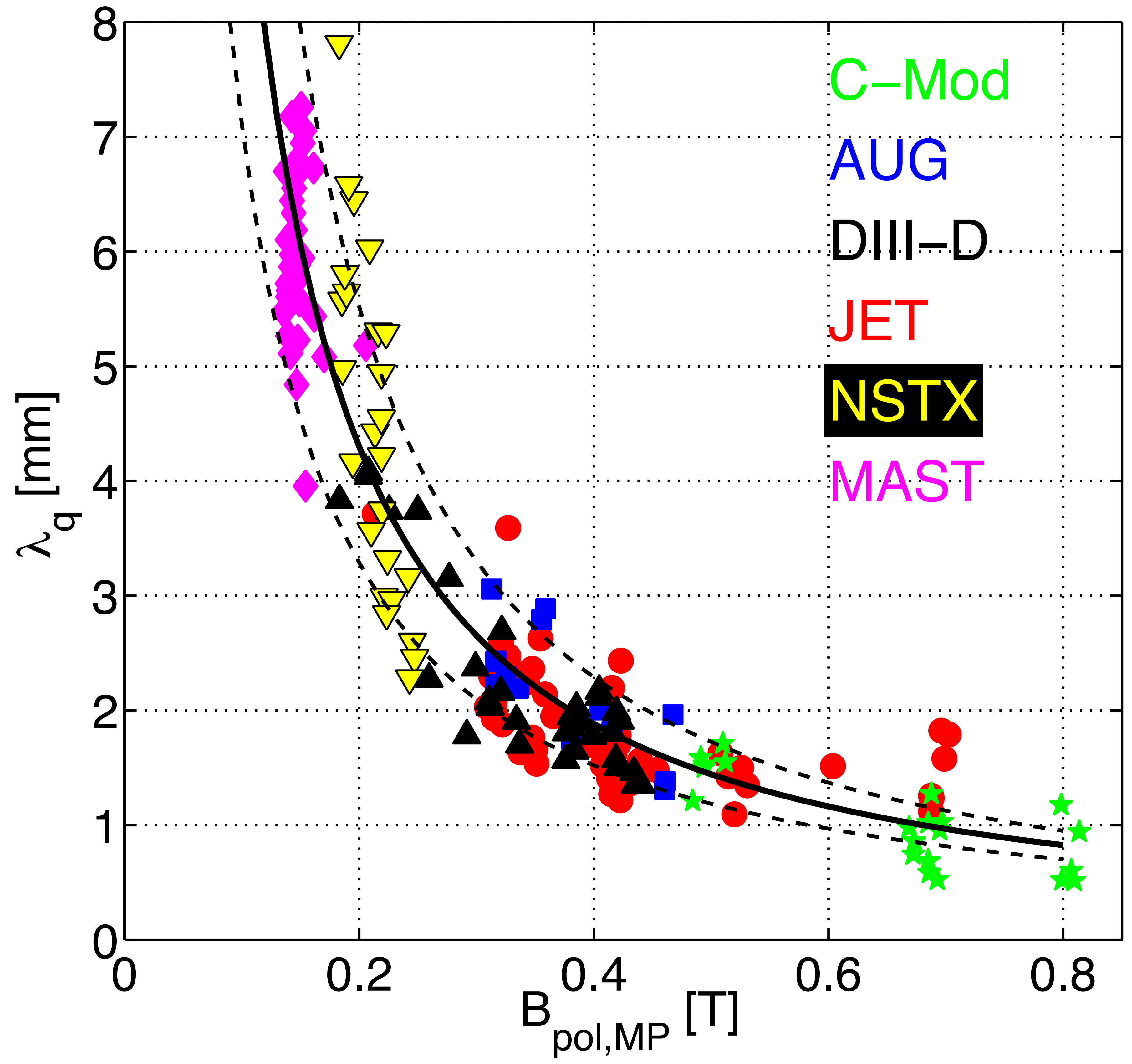
T. Eich et al.
NF 2013

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

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

The Problem can be Expressed Simply

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



T. Eich et al.
NF 2013

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

But we also need to know how the solution scales!

Lengyel Model for Cooling due to Impurities

- Parallel heat flux is reduced by impurity cooling:

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

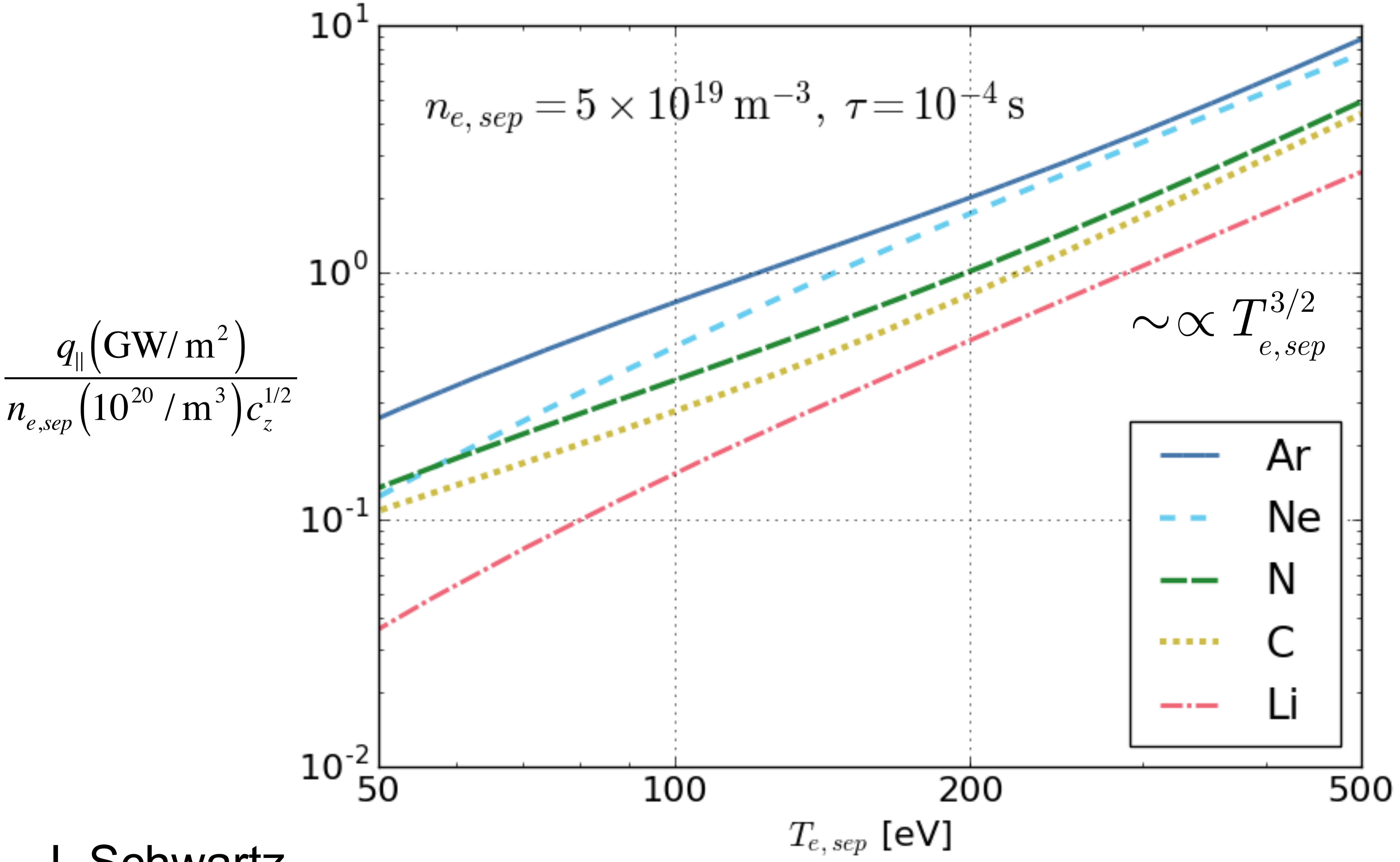
- Multiply these two equations together: $\frac{1}{2}\frac{dq_{\parallel}^2}{dz} = n_e^2 c_z L_z \kappa_0 T_e^{5/2} \frac{dT_e}{dz}$

- Integrate *dz* and assume $p_e = n_e T_e = const.$ along *B*.

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

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

Use ADAS to Evaluate Lengyel Integral



J. Schwartz

- Includes finite lifetime non-coronal radiation
- Assume nearly all of P_{sep} must be dissipated to achieve detachment at a few eV.
- $q_{\parallel}$ 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.

NEW: 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:

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

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

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

- OOPS, we had before, very roughly, *$q_{\|} \propto PB/R \Rightarrow$ Strong P scaling, no size scaling!*

Now Bring in HD λ_q to get $R_0 q_{||}$

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

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

- 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 scales as P/B_p not as PB_t/R.
- No wonder making the machine larger doesn't help.
- Surprisingly, you want higher field, not larger size.

We Should not Have Been Surprised

- Ignoring temperature variation

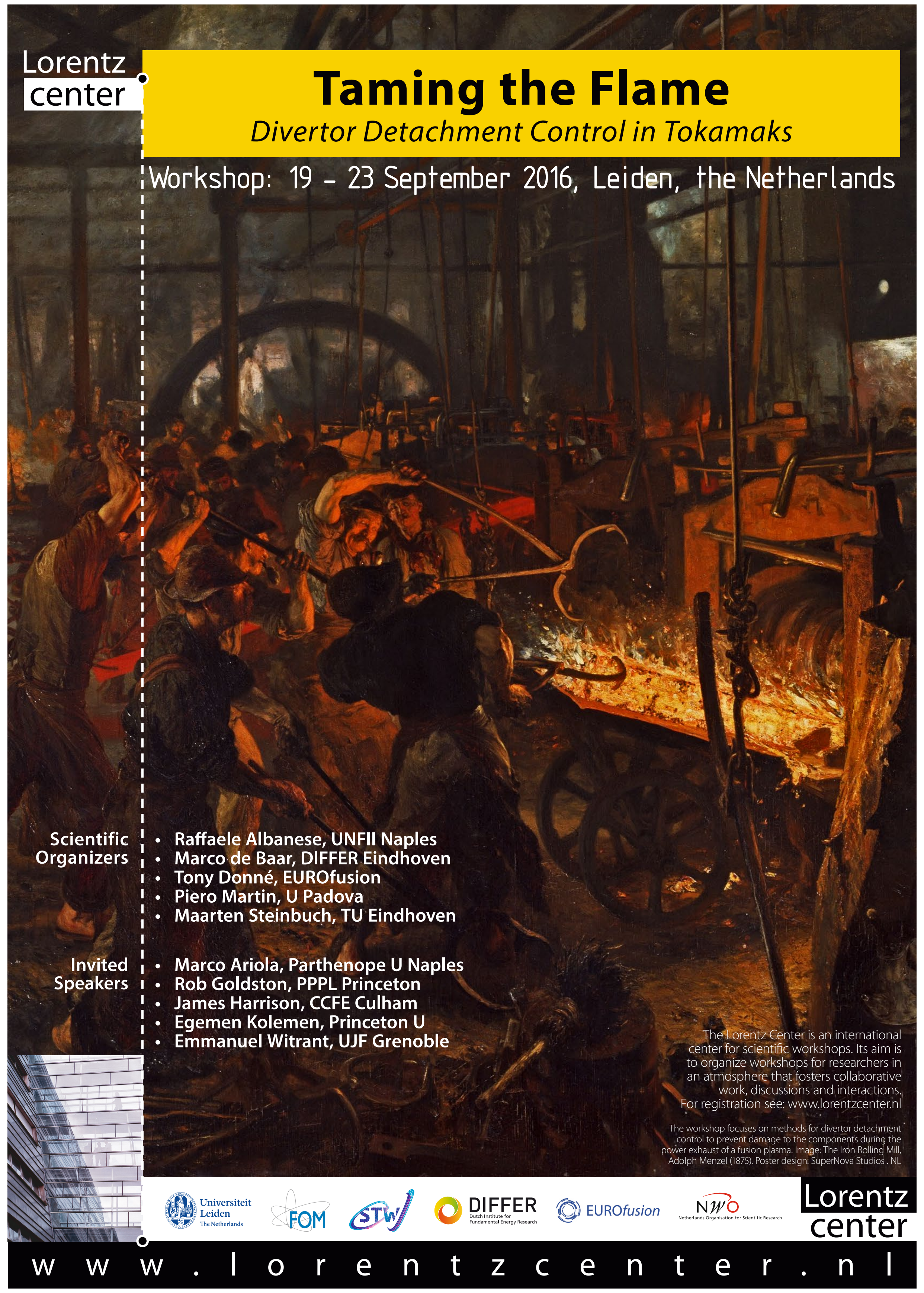
$$P_{rad} \propto c_z n_e^2 V \quad \Rightarrow \quad c_z \propto \frac{P_{sep}}{n_{sep}^2 \lambda_{HD} R a \ell_{\parallel}^* \left(1+\kappa^2\right)^{1/2}}$$

- The HD model and the Greenwald density are

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

- Giving the familiar result:

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



<u>Credit Where Credit is Due Dept.</u>

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 his paper in 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.

Parallel Connection Length May be a Useful Knob

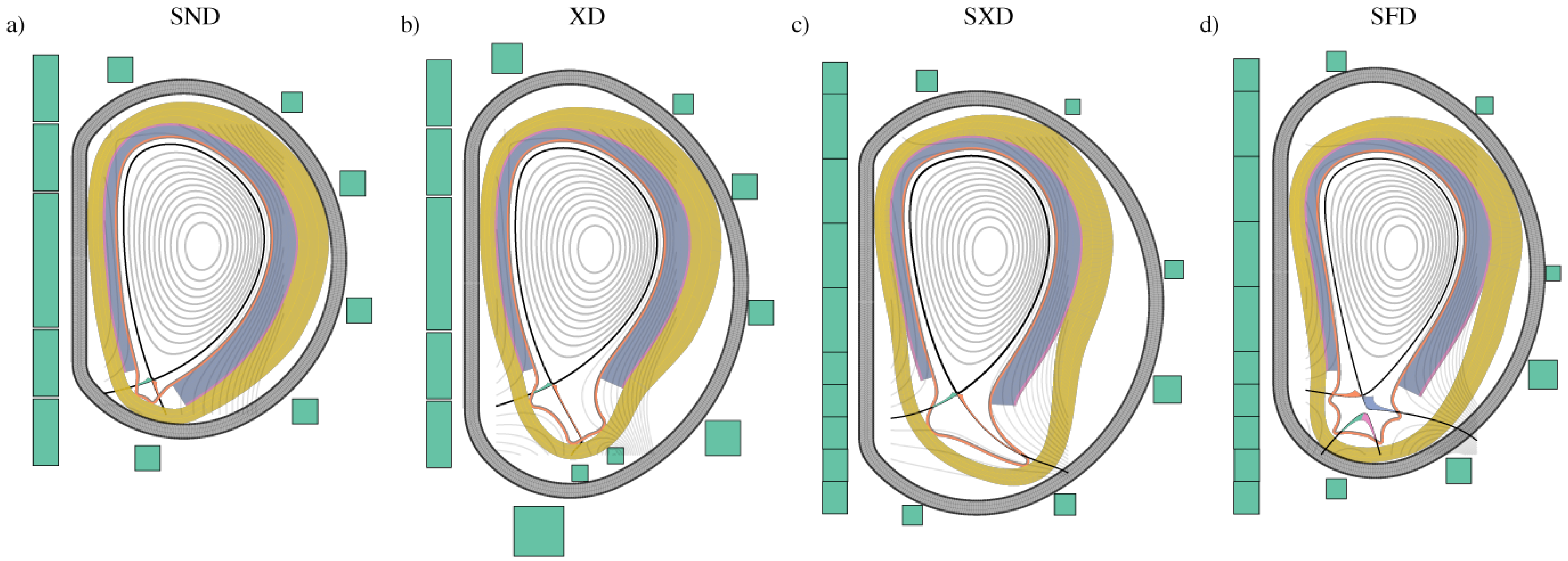


Fig. 6: (a) Reference configuration and alternative configurations including (b) an X divertor, (c) a Super-X divertor and (d) a snowflake divertor.

H. Reimerdes
???

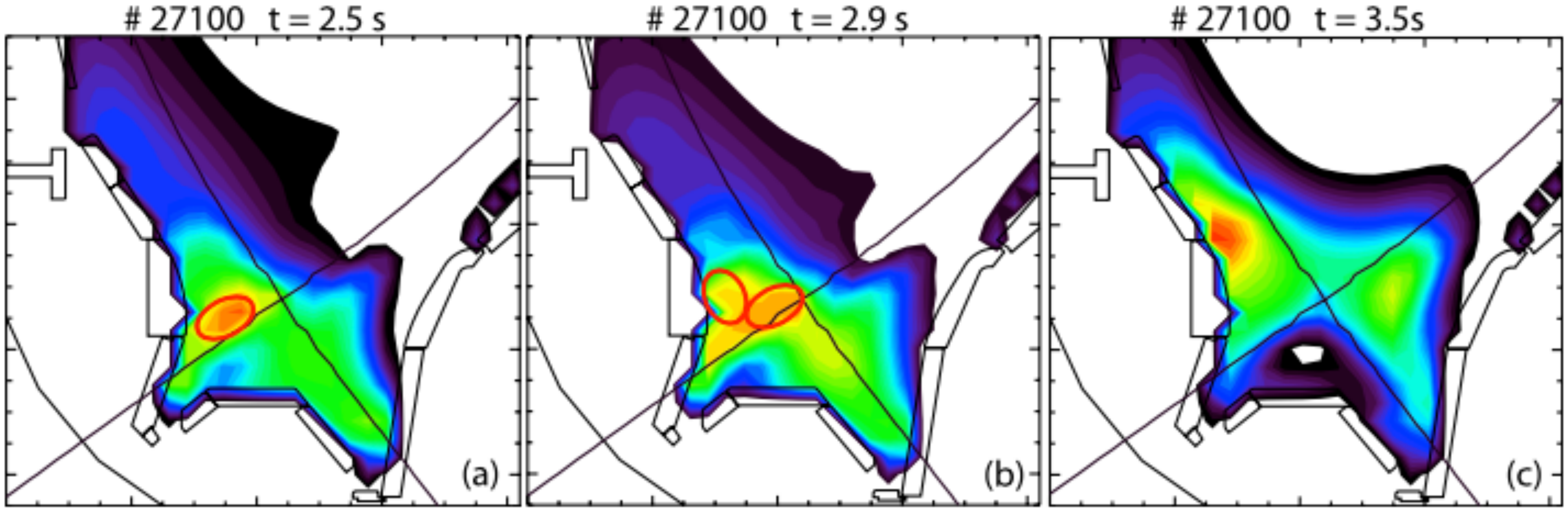
$$c_z \propto \frac{P_{sep}}{B_p \ell_\parallel^* \left(1+\kappa^2\right)^{3/2} f_{GW}^2}$$

		SND	XD	SXD	SFD	Limit
Costs	Max $\Sigma\|I_{PF}\|$ (Ma turns)	160	194	164	174	
	Total $I_{PF,internal}$ (MA turns)	-	10	-	-	
	Max. force on single coil $F_{z,PF}$ (MN)	145	301	451	439	<450
	Max. CS separation force $F_{z,CS}$ (MN)	130	244	284	329	<350
	Flux swing (Vs)	330	340	297	215	
	Norm. TF coil volume V_{TF}/V_{plasma}	2.9	3.6	4.2	3.8	
Benefits	$L_{\|\|,outer}$ (r_u=3mm) (m)	114	146	158	245	
	$f_{x,t}/f_{x,min}$	1	1.43	1	1	
	R_t/R_x	1.04	1.14	1.34	1.19	

c_z down x2

Detachment Tends to Run up to the X-Point

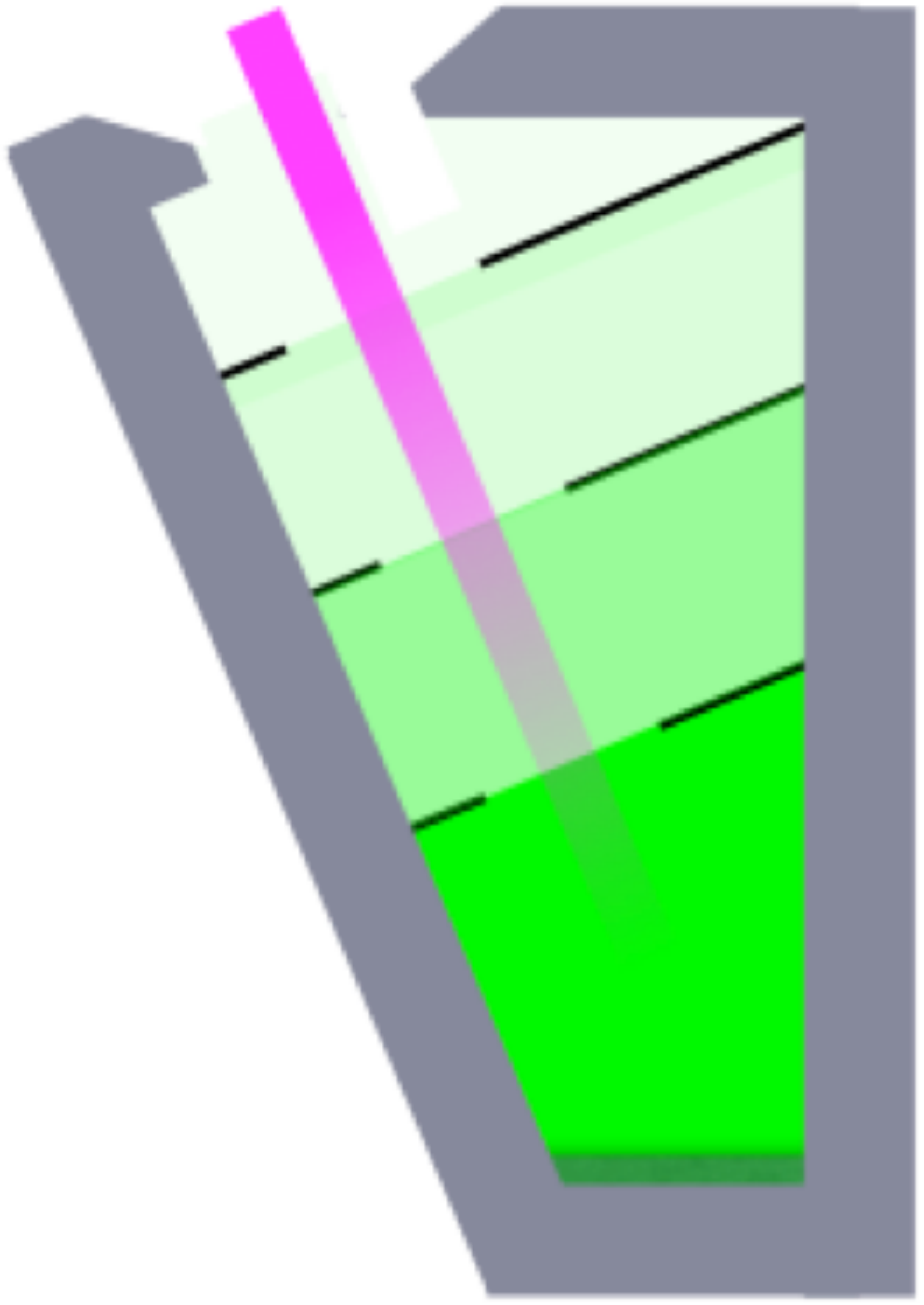
S. Potzel et al.
NF 2014



This exposes the core to impurity influx.

Lithium Vapor Box Should Provide Stable Detachment

- Multiple boxes are used to provide differential pumping.
- Lithium recirculates via capillary action (like a heat pipe)
- Bottom box provides enough lithium to detach.
  - Higher boxes are cooler, less dense.
- Plasma detachment should be very stable.



Picture of vapor calculation with efflux calculation from Eric.

E. Emdee et al. APS Poster NOW!

Conclusions

- Attempting to achieve ITER-like $q_{||} \propto PB/R$ drives Demo designs to large size and low power.

- The difficulty-of-detachment parameter is more likely P/B_p
  - We should perform numerical and laboratory experiments to test this hypothesis.
  - This is further motivation for compact high-field designs.

- Enhancing the divertor leg length should reduce the impurity content required for detachment.

- Detachment stability can be assured by localizing the impurity influx, as in a Vapor Box Divertor.