New Scaling for Detachment and Implications for Tokamak Power Plant Design

Burning Man
2010 (RG)

Rob Goldston,
Matt Reinke, Jacob Schwartz

NSTX-U Physics Meeting
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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

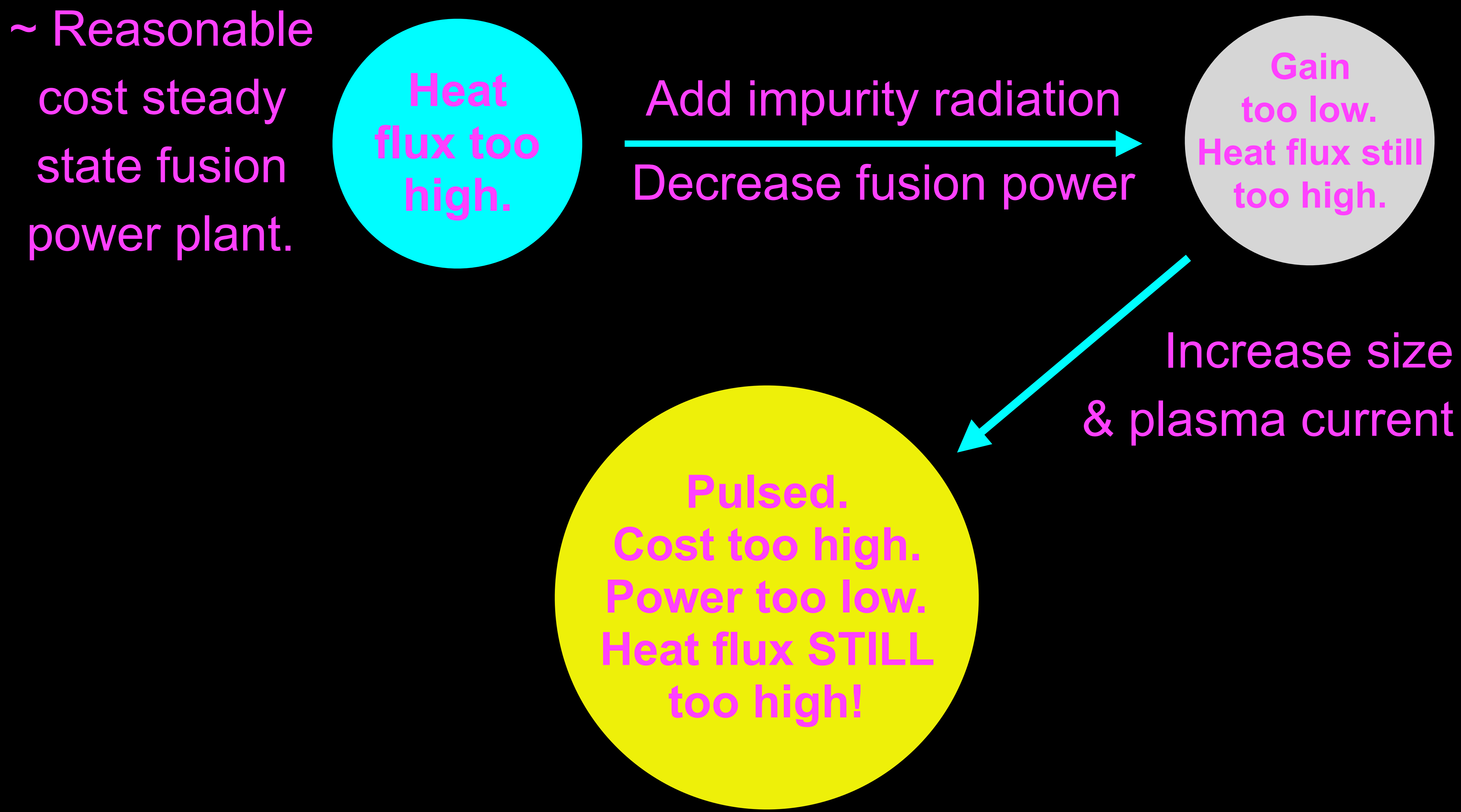
1. *Plasma Operation*
2. *Heat Exhaust*
3. ***Neutron resistant Materials***
4. ***Tritium-self sufficiency***
5. ***Safety***
6. ***Integrated DEMO Design***
7. ***Competitive Cost of Electricity***
8. *Stellarator*

DEMO

Wenninger et al.
EPS, 2015

- Demo must *point to* competitive COE
  - > 1.5^2 x price of ITER
  - 0.5 GWe, pulsed
  - Much more than fission $/GWe?
- How does this *point to* lower COE?

The Problem is Power Handling



We need to understand this problem.

Outline

- Parallel heat flux
  - Surface heat flux
- Simple detachment model
  - Magnetic geometry
- Lithium vapor box divertor

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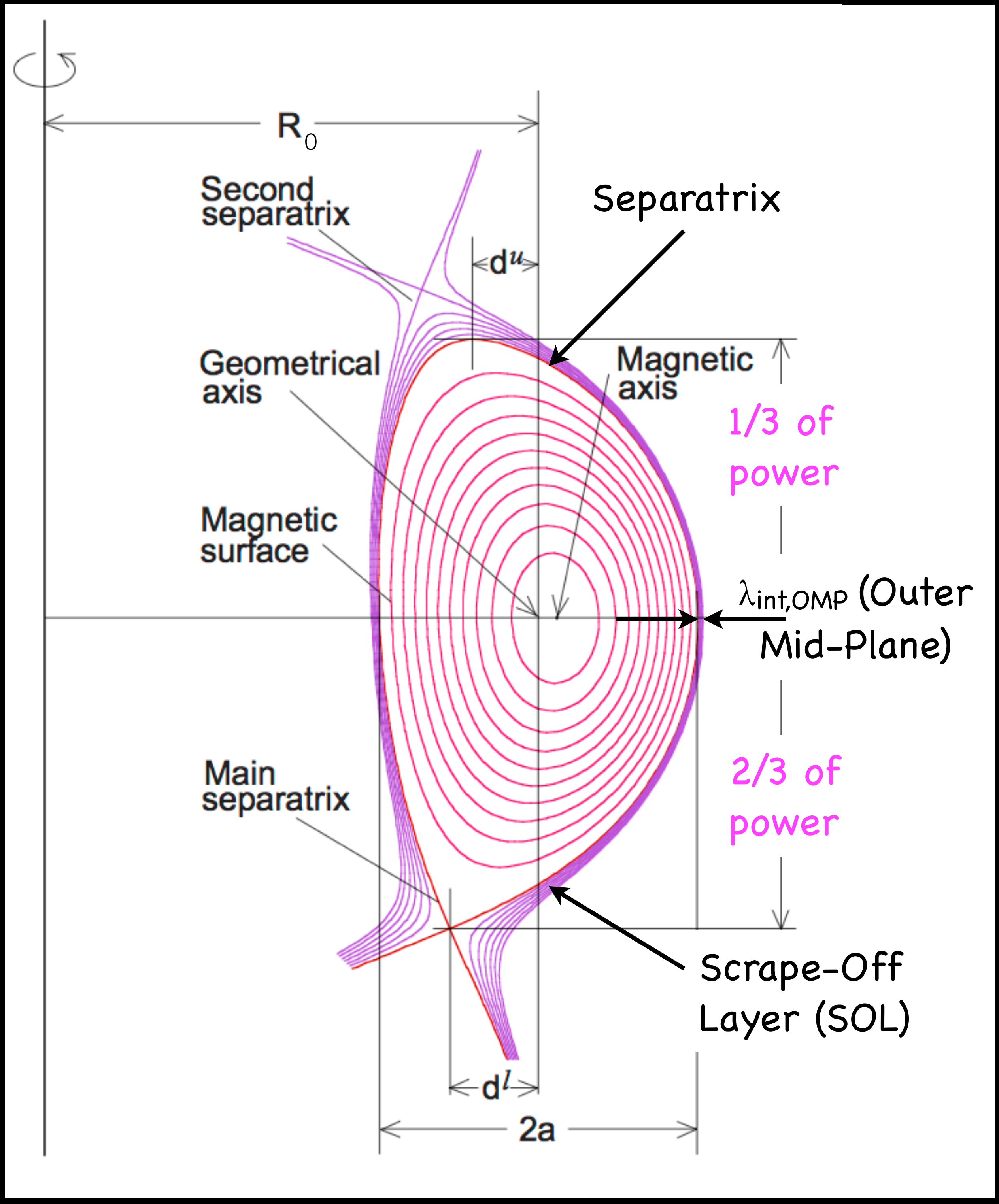
Parallel Heat Flux



$$\lambda_{int,OMP} \equiv \int q_{p,OMP}\, dR \Big/ \hat{q}_{p,OMP}$$

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

$$Assume\ \vec{q} = q_{\parallel}\hat{b} = q_{\parallel}\frac{\vec{B}}{B}\ \left(\Rightarrow no\ \vec{q}_{\perp}\right)$$

$$\hat{q}_{p,OMP} = \hat{q}_{\parallel,OMP}\frac{B_{p,OMP}}{B_{OMP}}$$

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

$$Assume\ \vec{\nabla}\cdot\vec{q} = 0\ \ \left(\Rightarrow no\ losses\right)$$

$$0 = \vec{\nabla}\cdot\frac{q_{\parallel}}{B}\vec{B} = \frac{q_{\parallel}}{B}\vec{\nabla}\cdot\vec{B} + \vec{B}\cdot\vec{\nabla}\frac{q_{\parallel}}{B}$$

$$\Rightarrow \hat{q}_{\parallel} = \hat{q}_{\parallel,OMP}\frac{B}{B_{OMP}}\ along\ \vec{B}$$

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

Conventional Calculation of λ

- Parallel confinement time

$$\tau_{\parallel} \approx (\pi q R)^2 / 2\chi_{\parallel}$$

- Cross-field diffusion during $\tau_{\parallel}$

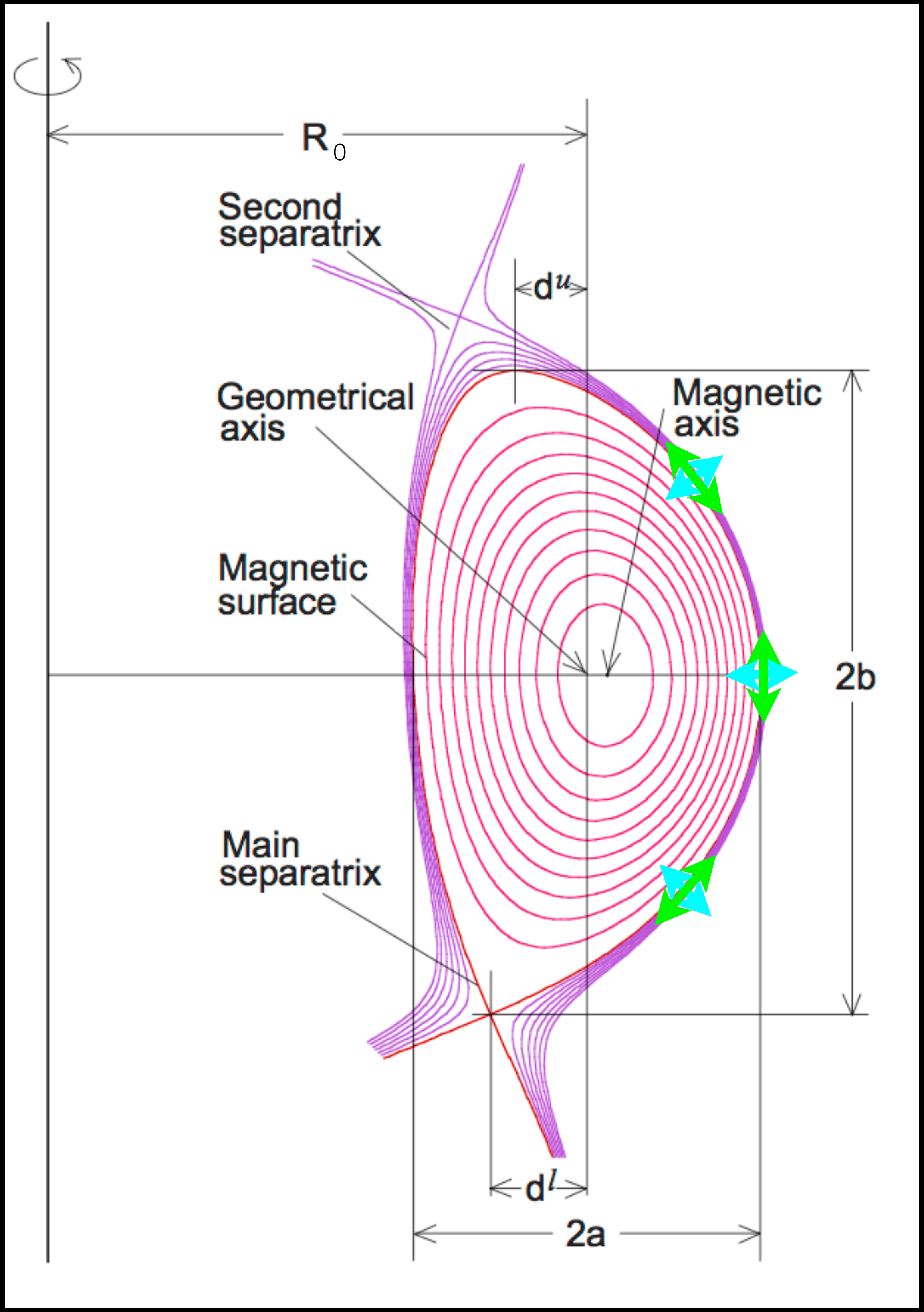
$$\lambda_{\perp}^2 = 2\chi_{\perp}\tau_{\parallel} = \frac{\chi_{\perp}}{\chi_{\parallel}}(\pi q R)^2$$

$$\lambda_{\perp} = \pi q R \sqrt{\frac{\chi_{\perp}}{\chi_{\parallel}}}$$

Turbulent ~ Bohm

Spitzer

- *λ⊥ scales linearly with R*



Heuristic Drift Calculation of λ

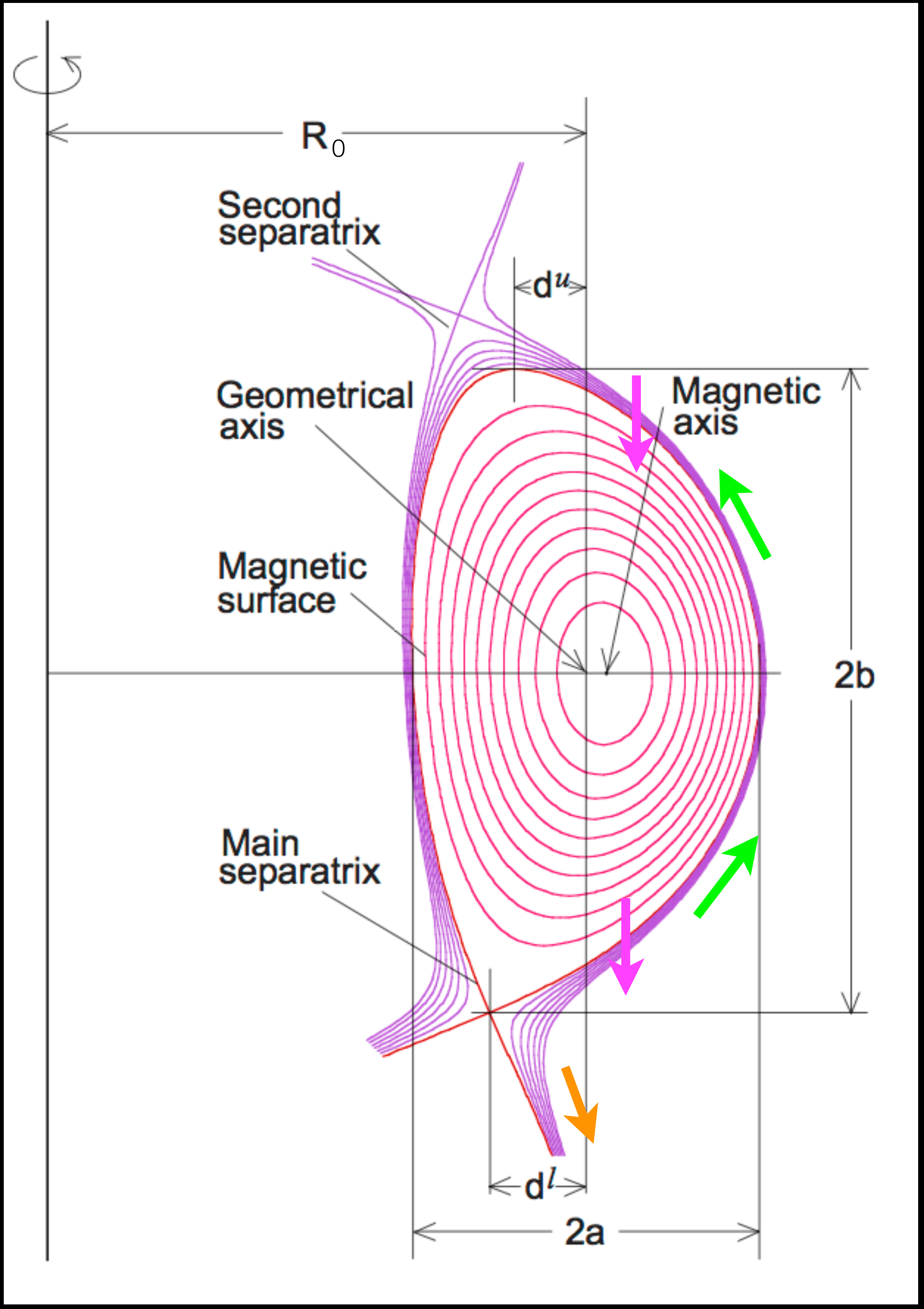
- Vertical Grad B and Curv B drifts cross plasma edge
- Parallel flows connect bottom to top like core Pfirsch-Schlüter flow
- But ~1/2 of flow goes to divertor. Time scale for parallel plasma loss (particles accelerate up to c_s):

$$\tau_{\|} = L_{\|}/(c_s/2) \qquad c_s \equiv \left[(T_e + T_i)/m_i\right]^{1/2}$$

Assume that cross-field drifts during this time set SOL width.

$$\lambda_{SOL} \approx v_{\nabla B + curvB}\tau_{\|} = 2(a/R_0) r_{L,p}$$

- Get closed form result using Spitzer parallel conduction to give $T_e = T_i$.
- *No explicit size scaling in $\lambda_{\perp}$*



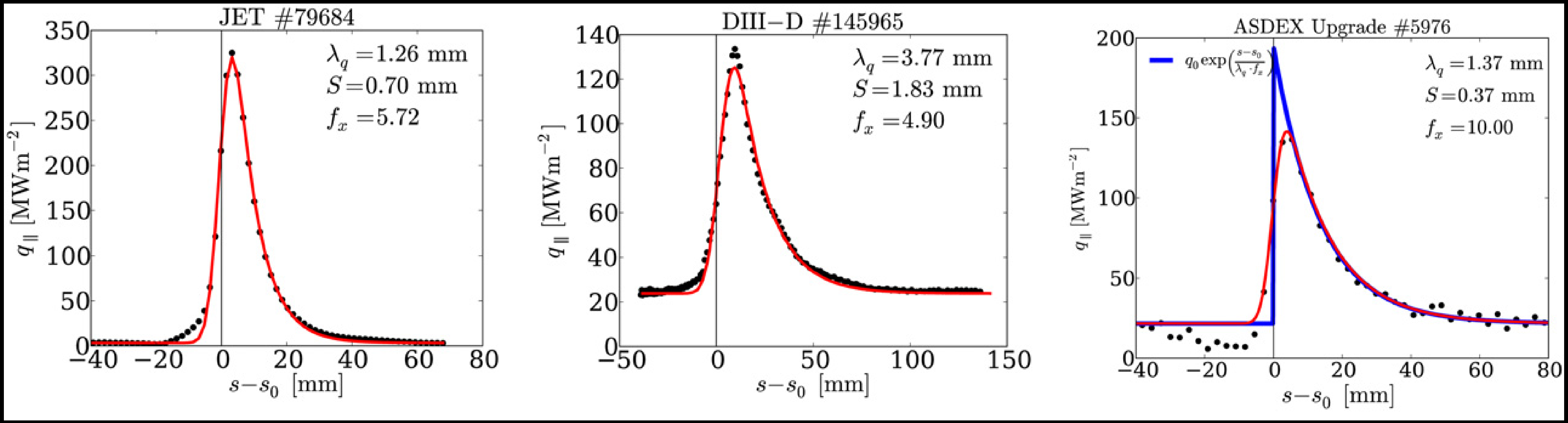
IR Data are Fit with "Eich Function"

- Convolve an exponential (λ_q) starting at the separatrix, representing the near SOL around the plasma, with a Gaussian (S) representing spreading along the divertor leg.

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

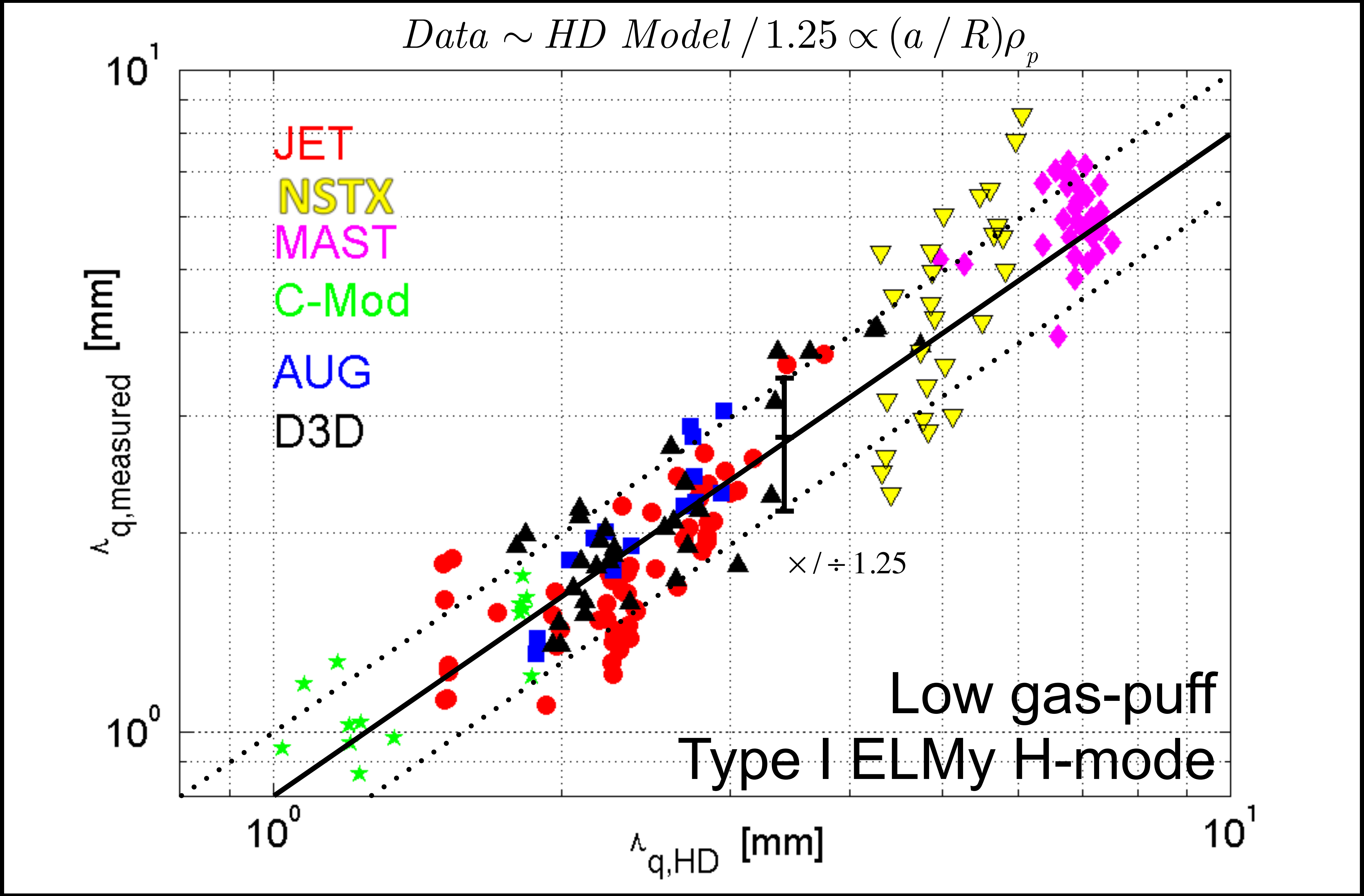
$$= \frac{q_{\parallel 0}}{2} \exp\left[\left(\frac{S}{2\lambda_q} \right)^2 - \frac{x}{\lambda_q} \right] \mathrm{erfc}\left(\frac{S}{2\lambda_q} - \frac{x}{S} \right)$$

F. Wagner, NF 1985



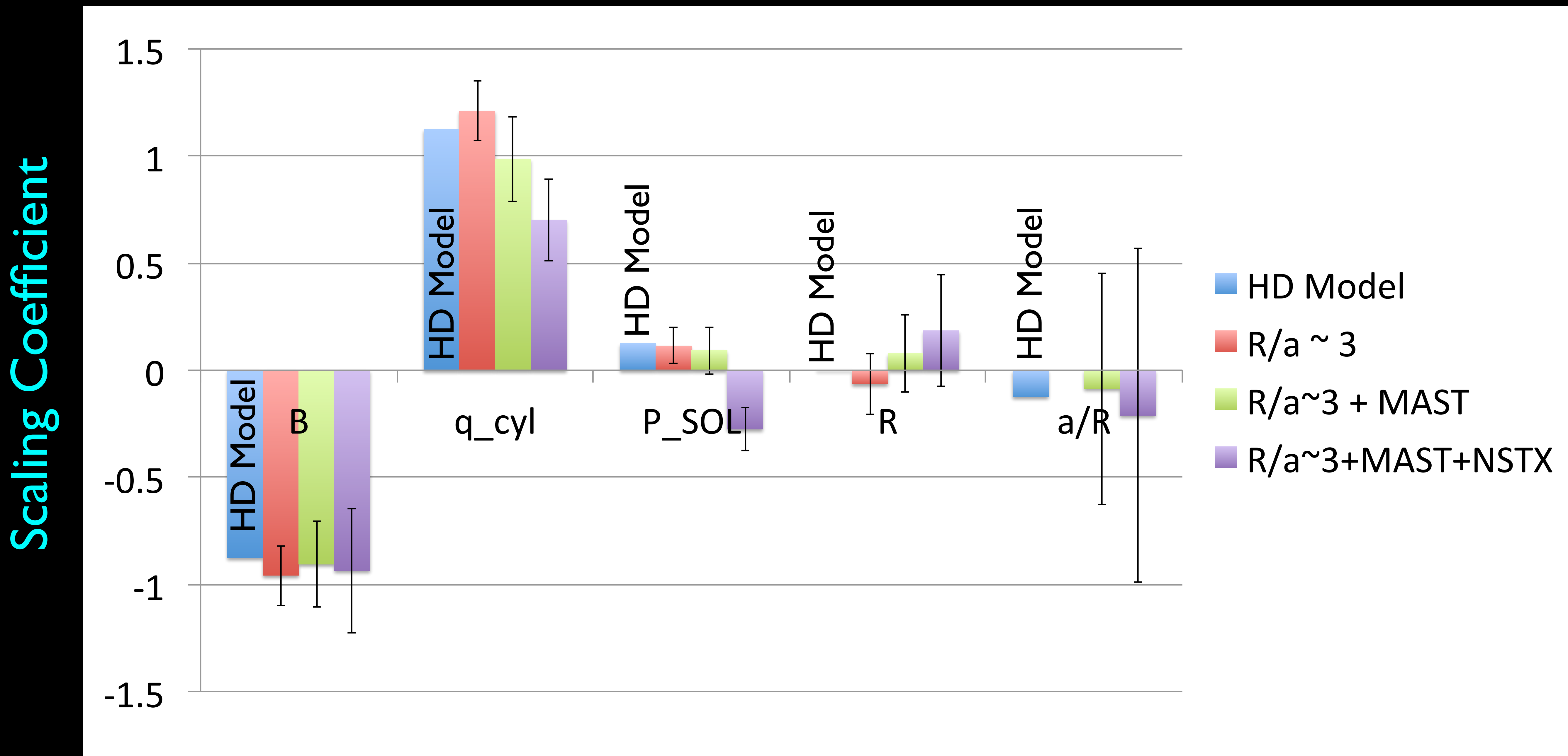
T. Eich, NF 2013

λ_q Data fit HD Model / 1.25 Well

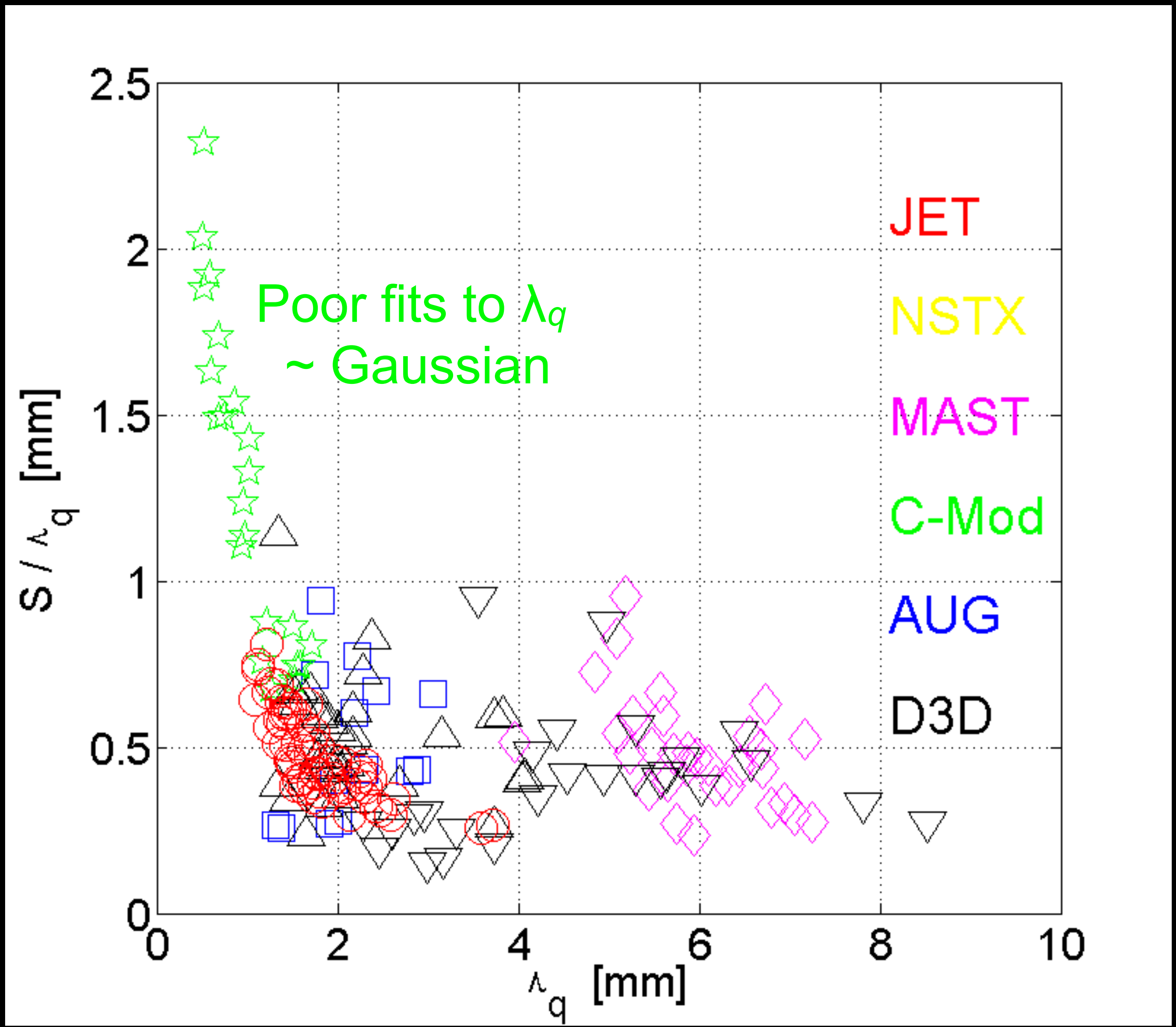


Scales with intensive variables, not system size.
Projections for ITER and Demo ~ 1 mm (!)

Individual Scalings fit HD Model



S/λ_q Relatively Constant @ ~ 0.5



T. Eich, 2014

- $\lambda_{int,OMP} \equiv \int q\, dR \Big/ \hat{q}$
- λ_{int}/λ_q varies with S/λ_q in Eich fct.
- For $S/\lambda_q = 0.5$, $\lambda_{int}/\lambda_q = 1.79$
- $\lambda_{int} \sim 1.79\lambda_q$

- It is possible that turbulence will cause λ_q or S to scale with size from JET upwards… but much less than linearly, since JET fits HD model & S/λ_q.

Let's Evaluate $q_{||}$ for Demo1

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

- Gives poloidal average width, $\langle\lambda_{q,HD}\rangle$
- Map to OMP along flux surfaces, by fixing $\lambda \nabla\psi_p = \lambda_{HD} (R_0 \langle B_p \rangle)$

$$\lambda_{int,HD,OMP} = \frac{1.79}{1.25} \frac{\langle\lambda_{q,HD}\rangle R_0 \langle B_p \rangle}{(R_0+a) B_{p,OMP}}$$

- Demo1 assumes P_{sep} = 154 MW = 0.33 (P_α + P_{aux})
  - Requires Z_{eff} ~ 2.6, H = 1.0
- 1.2 x H-mode threshold power.

R. Wenninger
ICFRM 2015

$$q_{\|,R_0} \approx \frac{2P_{sep}/3}{2\pi(R_0+a)\lambda_{int,OMP}} \frac{B_{OMP}}{B_{p,OMP}} \frac{B_{t,0}}{B_{OMP}}$$

$$= \frac{1.25 P_{sep} B_{t,0}}{3\pi \cdot 1.79 \langle\lambda_{q,HD}\rangle R_0 \langle B_p \rangle} \approx 3.6\,GW/m^2$$

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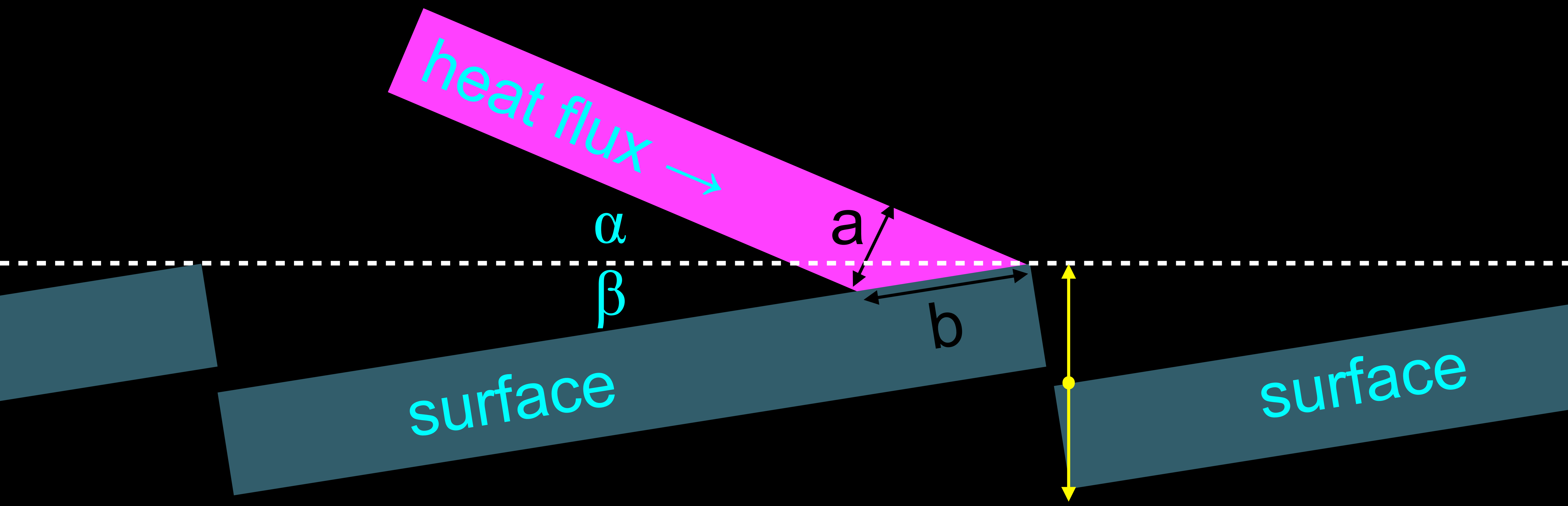
Fish-scaling Hides Leading Edges



Misalignments are inevitable

$a/b = \sin(\alpha+\beta)$; $q_\perp b = q_{||} a$

$$q_\perp = q_{||} a/b = q_{||} \sin(\alpha+\beta)$$

There are limits to both α and α_0

- To reduce α requires
  - reducing poloidal field at target and/or
  - inclining target plate nearly tangential to B
- To reduce β requires
  - very high-precision alignment and
  - very little degradation of alignment over time
- $\alpha + \beta = 2^o$ would constitute major success
- $3.6\ GW/m^2 \times \sin 2^o = 126\ MW/m^2$

  A factor of 12.5 – 25 too high!

  Requires essentially full detachment

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Simple Detachment Model

- Parallel heat flux is reduced by impurity cooling

$$q_{\|} = \kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial z} \qquad \frac{\partial q_{\|}}{\partial z} = n_e n_z L_z = n_e^2 c_z L_z; \quad c_z \equiv \frac{n_z}{n_e}$$

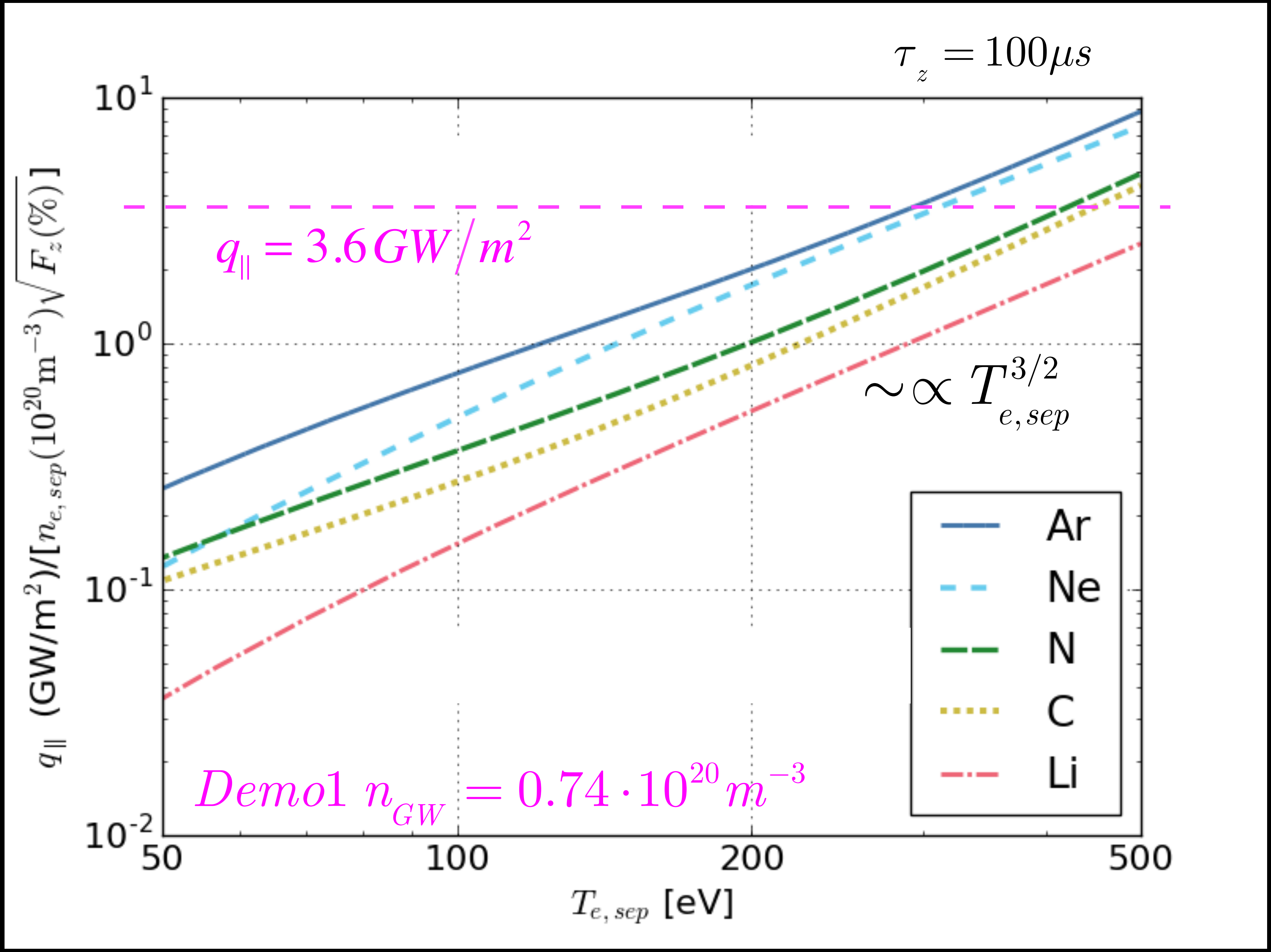
- Multiply these: $$\frac{1}{2}\frac{\partial q_{\|}^2}{\partial z} = n_e^2 c_z L_z \kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial z}$$

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

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

Lengyel, 1981

$q_{||}$ / ($n_{e,sep,20}\sqrt{f_{z\%}}$) using ADAS

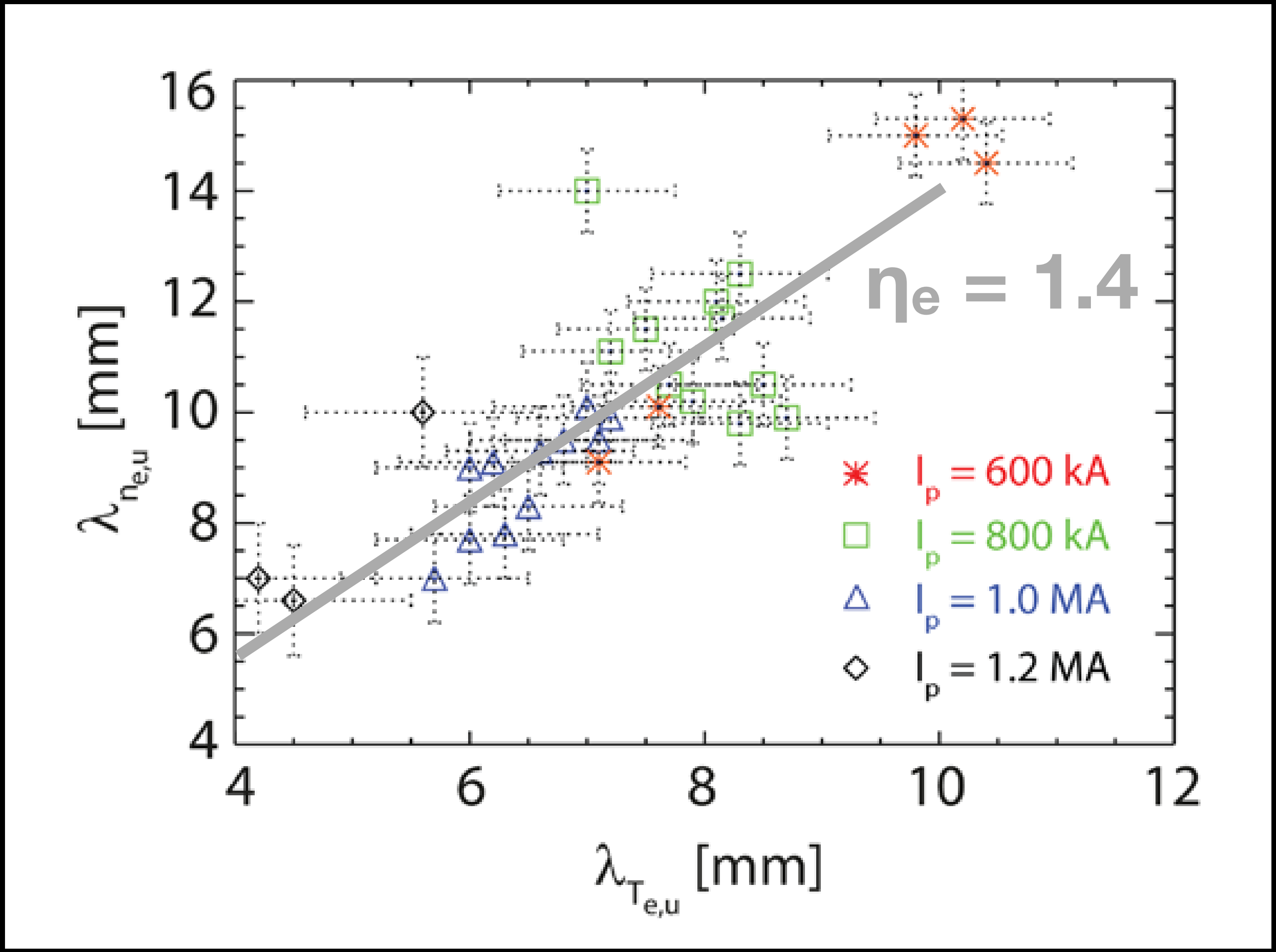


J. Schwartz

$q_{||}$ that can be detached $\propto$ ~$n_{sep}\sqrt{c_z}\,T_{sep}^{3/2}$

Can we Increase n_{sep}/n_{GW}?

- Experiments run with $n_{sep} \sim \bar{n}/3$
- HD model consistent with ballooning limit in SOL at $n_{sep} \sim \bar{n}_{GW}/3$



H.J. Sun, PPCF 2015

- Strong pedestal ∇T_e with low ∇n_e impossible?

Bring in Spitzer $T_{e,sep}$ & GW Density

$$q_{\parallel,det} = n_{e,sep} T_{e,sep} \sqrt{2 \int_{T_{det}}^{T_{sep}} c_z L_z \kappa_0 T_e^{1/2}\, dT_e} \sim\propto n_{e,sep} T_{e,,sep}^{3/2} c_z^{1/2}$$

- Assume Spitzer $\chi_{\|e}$, Greenwald density scaling

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

- Plug these into equation on the right, above

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

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

← No size scaling!

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

$$q_{\parallel}R_0 \propto P_{sep}^{7/8} B_{t,0}^{3/4} \left\langle B_p \right\rangle^{1/8} \frac{R_0}{a} \left(1+\kappa^2\right)^{-1/16} \left(\frac{\bar{A}}{1+\bar{Z}}\right)^{-7/16} \left(\ell_{\parallel}^{*}\right)^{-1/8}$$

- Substitute this into result from last slide

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

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

OMG!

NO SIZE SCALING !

We Should not be Surprised

- Look at the simplest model possible

$$q_{\parallel} \propto P_{sep} B / a \quad from \ \lambda_{int} \propto (a/R_0)\rho_p \sim\propto a/(R_0 B_p)$$

$$p_{rad} \propto c_z n_e^2 \propto c_z f_{GW}^2 \langle B_p \rangle^2 a^2 (1+\kappa^2) / a^4$$

$$q_{\parallel} \propto p_{rad} L_{\parallel} \propto c_z f_{GW}^2 \langle B_p \rangle^2 a^{-2} (1+\kappa^2) q_{cyl} R_0 \ell_{\parallel}^*$$

$$q_{cyl} \propto a B_0 (1+\kappa^2)^{1/2} / R_0 \langle B_p \rangle$$

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

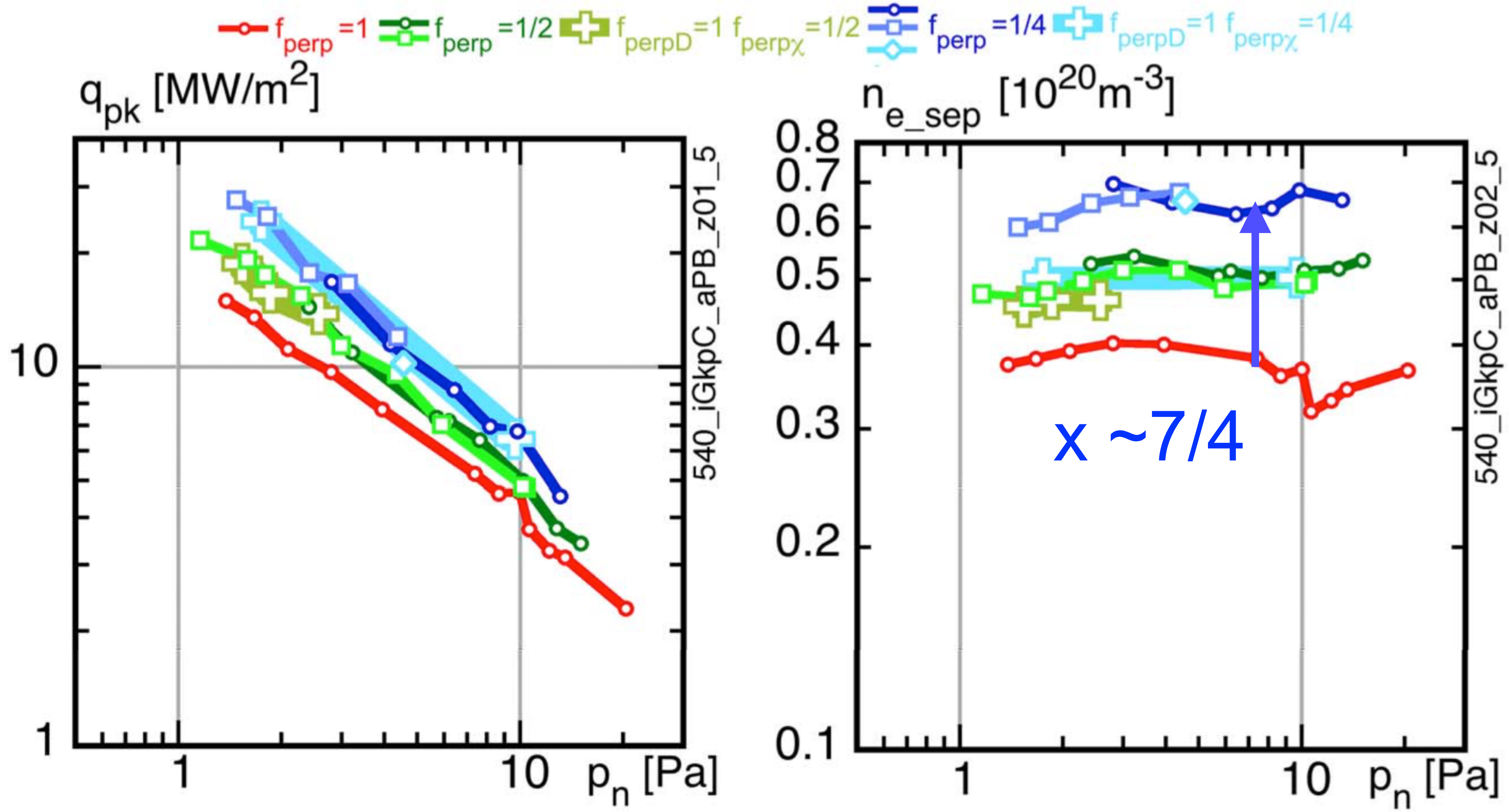
SAME RESULT:
NO SIZE SCALING !

Scaling to ITER & Demo1

	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%

Demo1 needs ~ 5x AUG's c_N ??

No Problem in ITER?



A.S. Kukushkin et al., PSI-20, Aachen, May 2012. ITER_D_7M93AL

No Problem for 8.25m Demo?

- Fix target conditions including $q_\perp$ & λ_q
- Integrate along B up to OMP $\Rightarrow$ $P \sim\!\propto R$
- But… B_p is fixed, so f_{GW} goes up x ~3 even though n_e falls a bit.

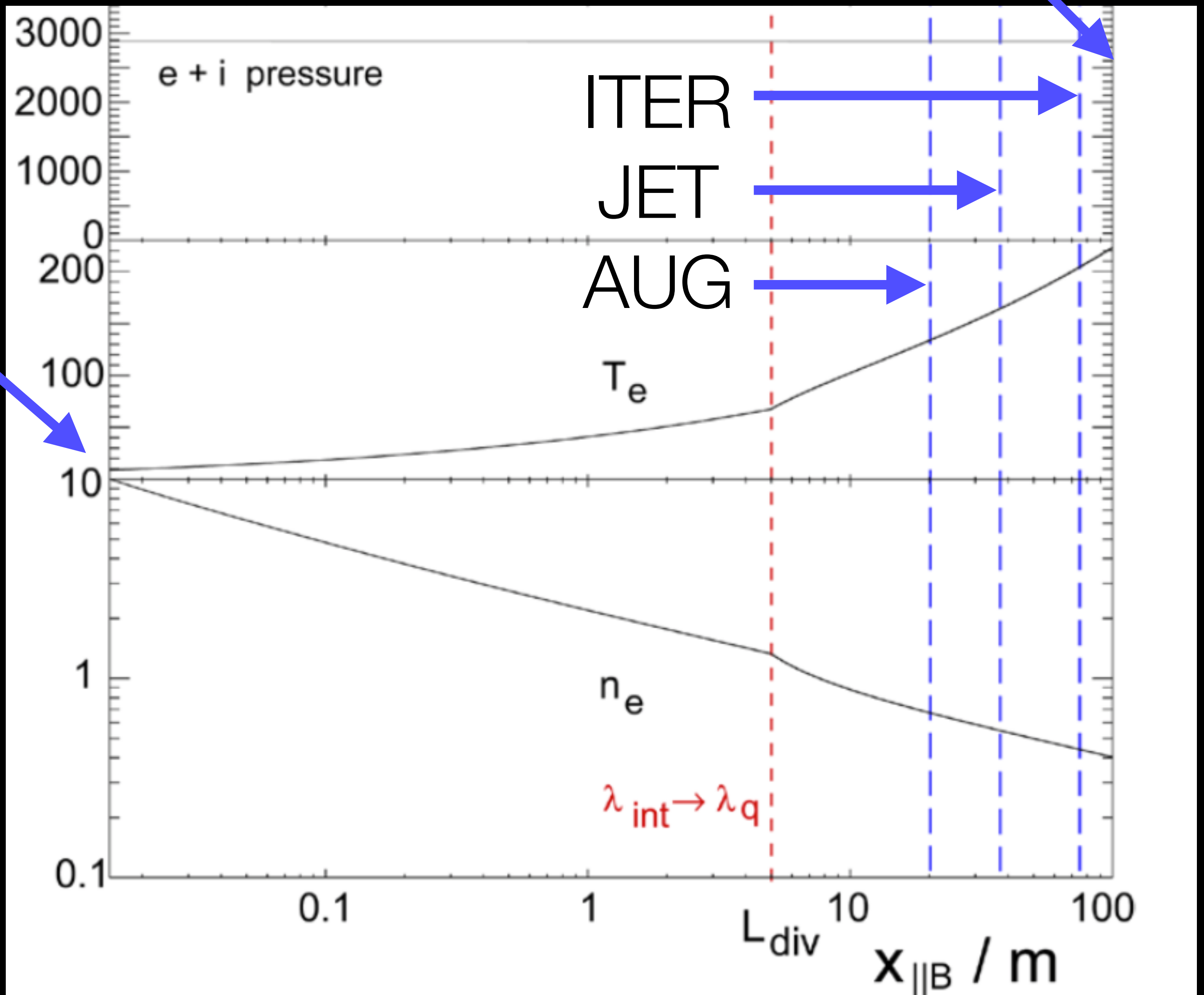


Figure 4. (a) Plasma parameters and radiative losses according to the 1D model close to the target and (b) along the flux tube up to the midplane. The parameters correspond to semi-detached divertor conditions: divertor nitrogen concentration $c_N = 0.04$, $T_{e,tar} = 2.3$ eV, power load of 2.3 MW m^{-2}, $f_{mom} = 0.5$, neutral pressure $p_0 = 4.9$ Pa. The power width λ is reduced from 5 mm to 2 mm at the divertor entrance L_{div}. Dashed vertical lines indicate the midplane for devices of different size. P_{up} is 4.7 MW for the AUG size ($R = 1.65$ m, $L = 20$ m) and 27 MW for the case with $R = 8.25$ m, $L = 100$ m. Corresponding values of the separatrix power, P_{sep}, are 10.8 and 62 MW, respectively.

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Magnetic Geometry Can Help 3 Ways

- Reduce $q_\perp \propto B_{p\perp}$ at the target plate: (XD)
  - Limited by α + β
- Reduce $q_{||} \propto |B|$ at the target plate: (SXD)
  - Requires access to high R
  - May also help with stability of detachment
- Increase $L_{||}$ to the target by reducing $\langle B_p \rangle$: (SFD)
  - *This directly decreases* $c_z \propto L_{||} / \pi q R$

Significant Effects May be Available

H. Reimerdes

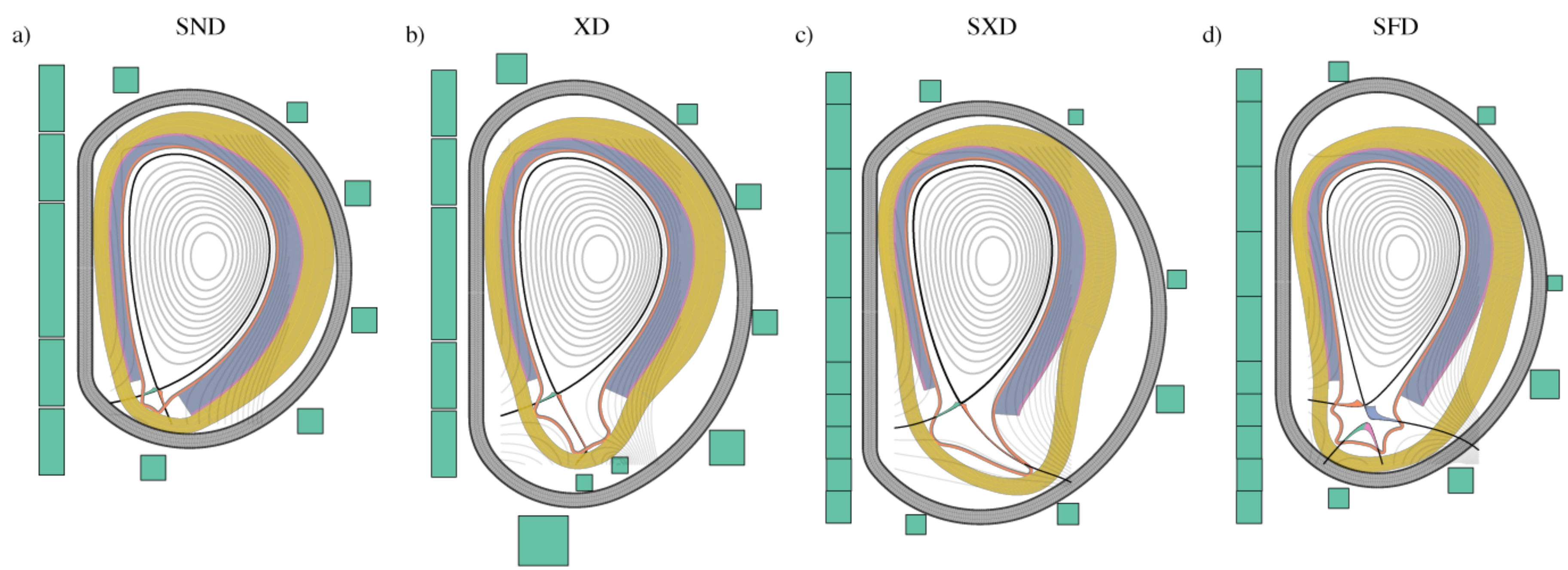

Fig. 6: (a) Reference configuration and alternative configurations including (b) an X divertor, (c) a Super-X divertor and (d) a snowflake divertor.

		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

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Three Modalities for Liquid Metals

Heat Conduction to Substrate	Liquid protects surface
Heat Convection by Liquid Metal	Liquid carries away heat
Evaporation & Radiative Cooling	Steady vapor shielding

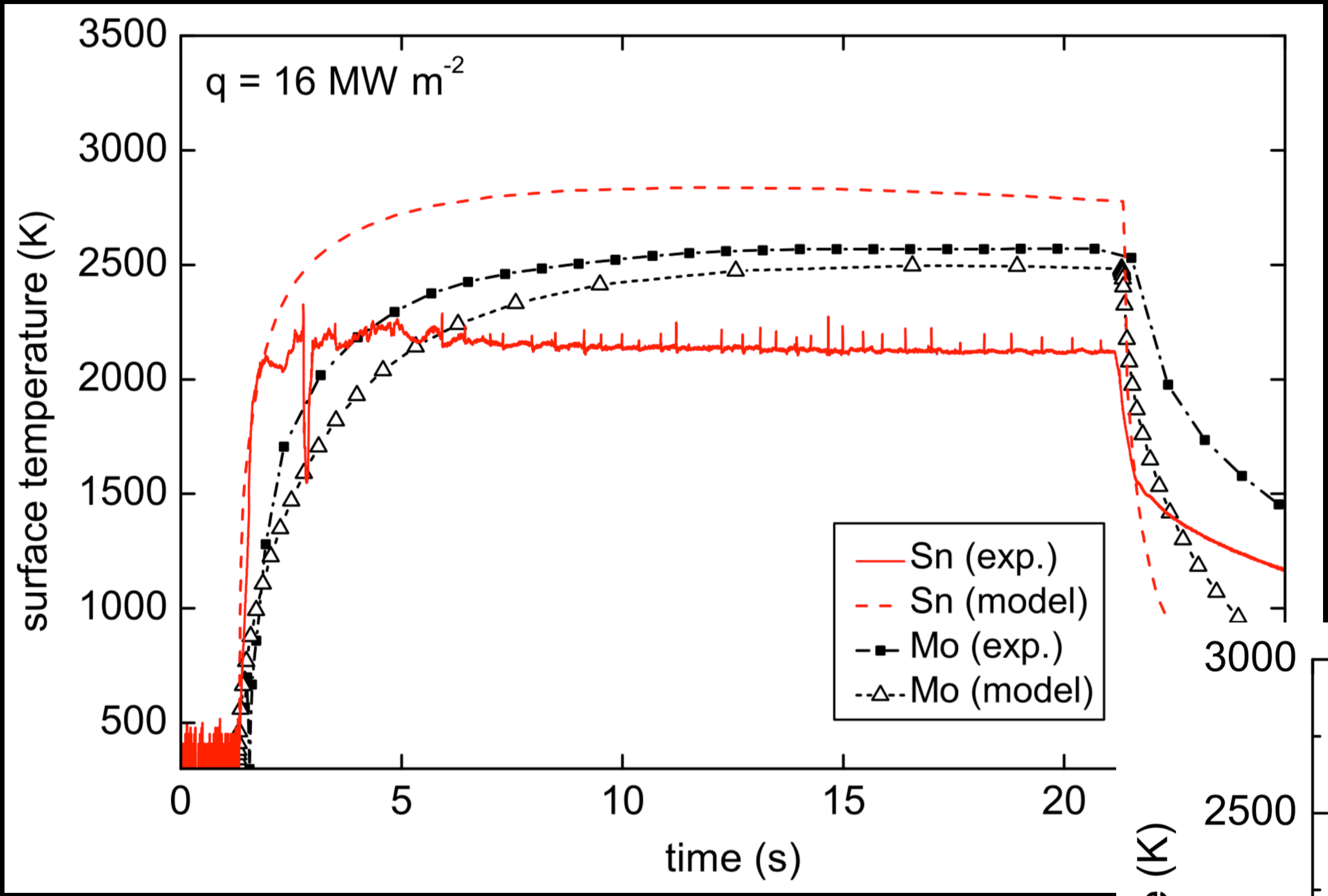
M.A. Jaworski
FED 2016

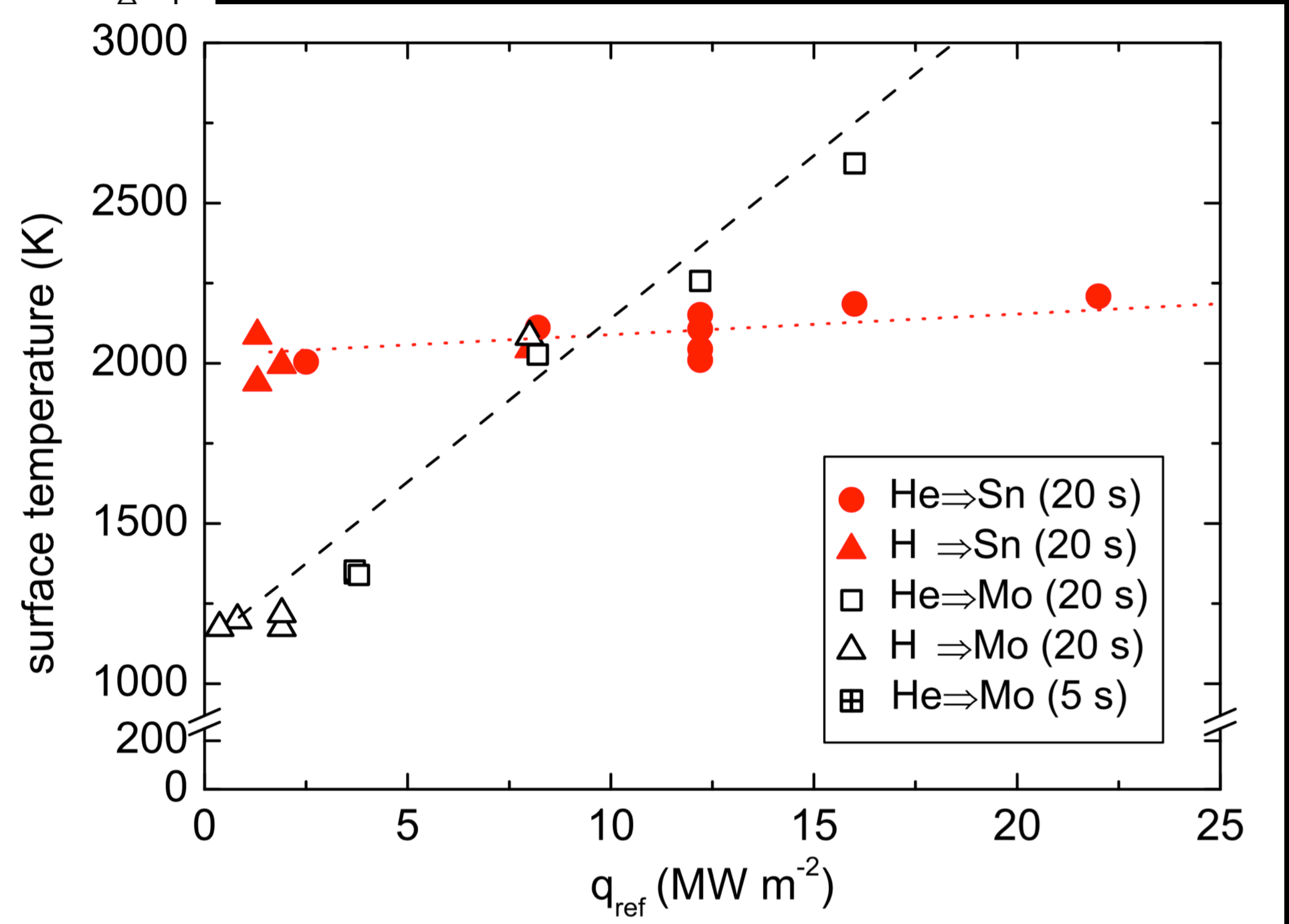
Slow Flow Covering Substrate for FW

- Capillary Porous Systems (Red Star)
- Gravity feed (Zakharov)

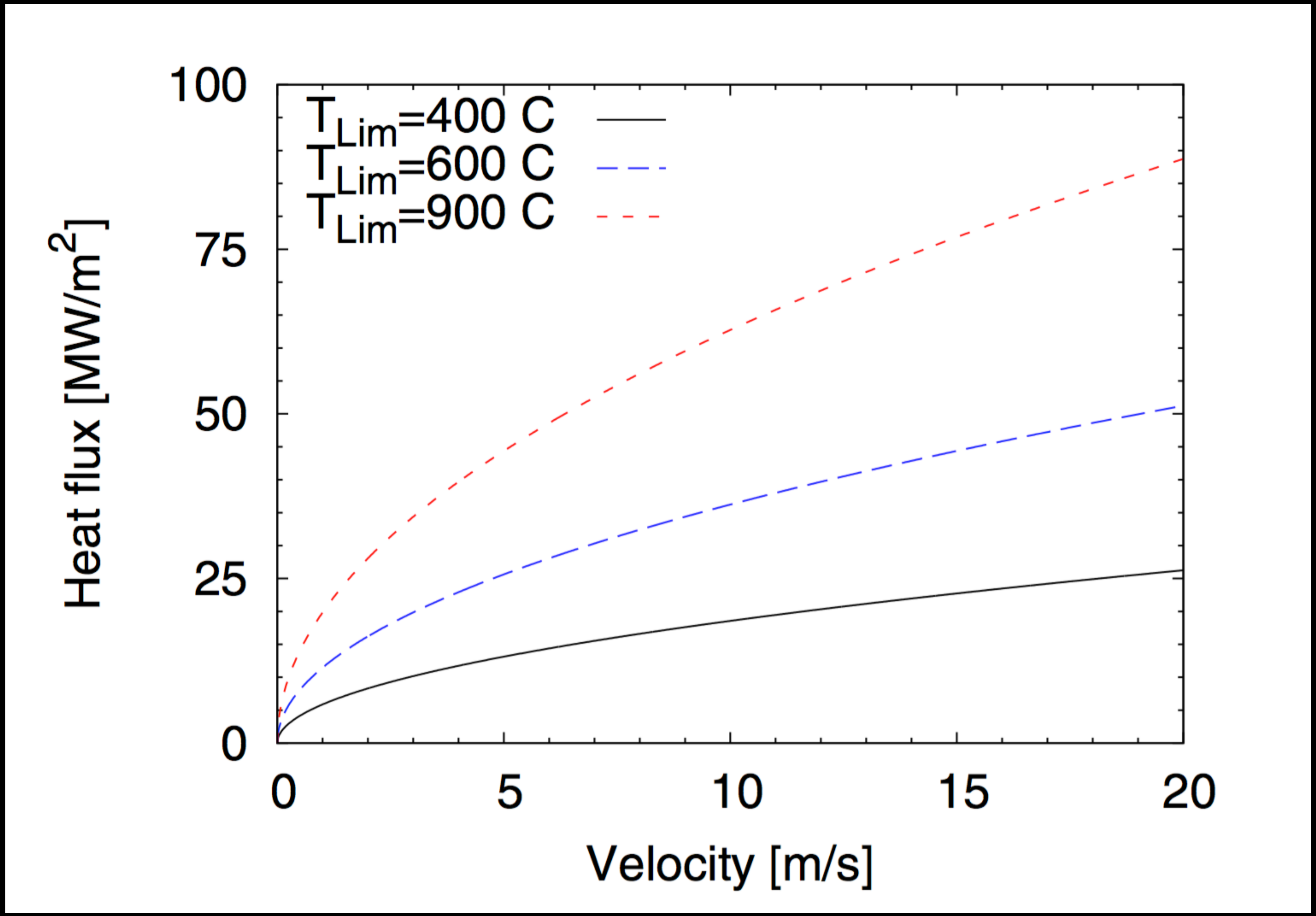
- CPS protects surface from transient events (but not from runaway electrons)
- First wall temperature ~ 500 ^{o}C may be too high for pure lithium application.
- Possible Sn or LiSn application at first wall.
- ISTTOK results:
  - low T retention with Sn and LiSn
- Pilot PSI result: good Sn power handling

Impressive Power Handling with CPS Sn





Lithium Carrying Away Heat @ Divertor



$$q_0 = \frac{\left(\Delta T\right) k \sqrt{\pi v}}{2\sqrt{\alpha L}}$$

M.A. Jaworski
FED 2016

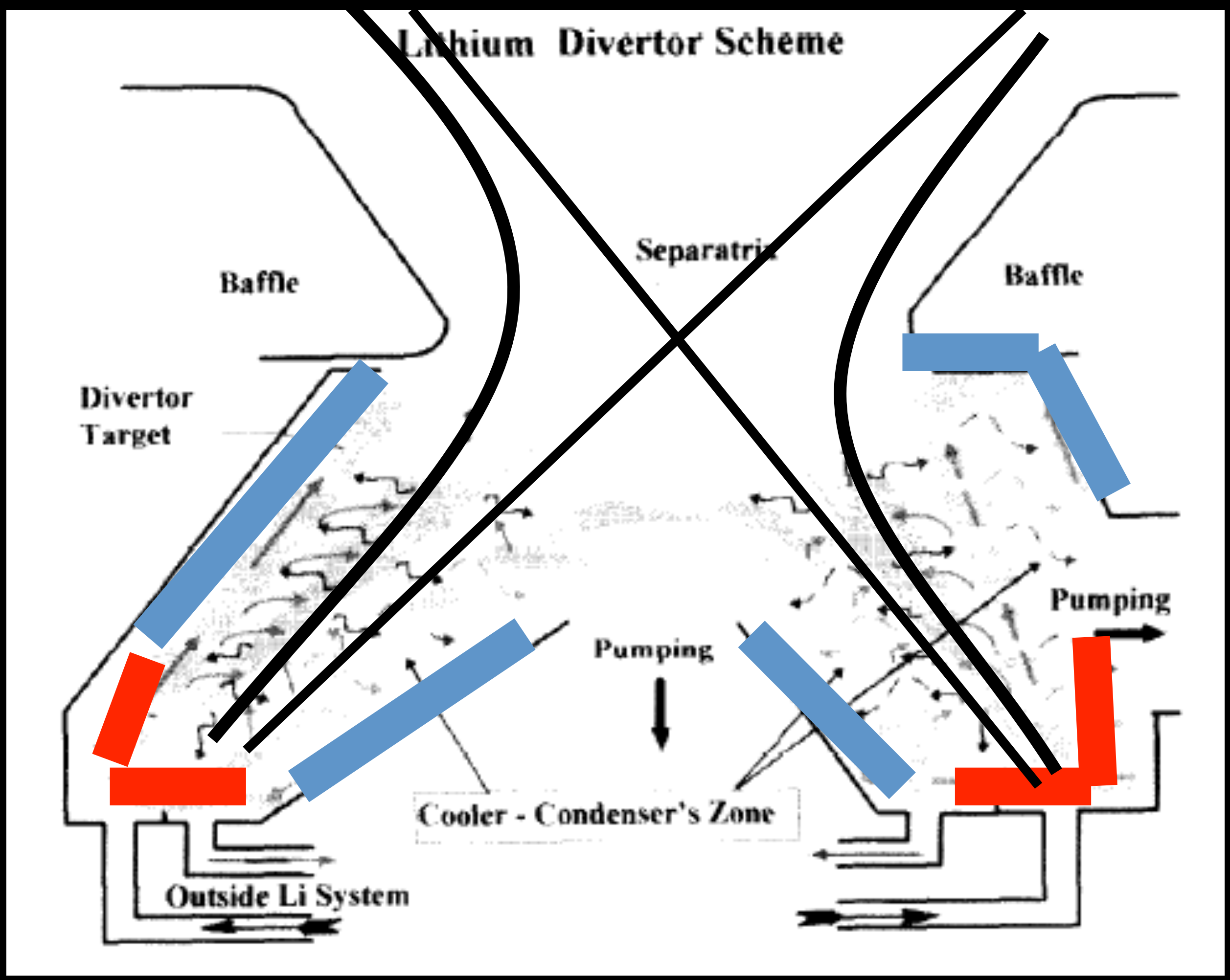
- Assumes L = 10cm hot spot, T_0 = 190 °C
- Heat depth ~ 1mm $(L/10\text{cm})^{1/2}$ / $(v/10\text{m/s})^{1/2}$

Proposals for Driving Flow

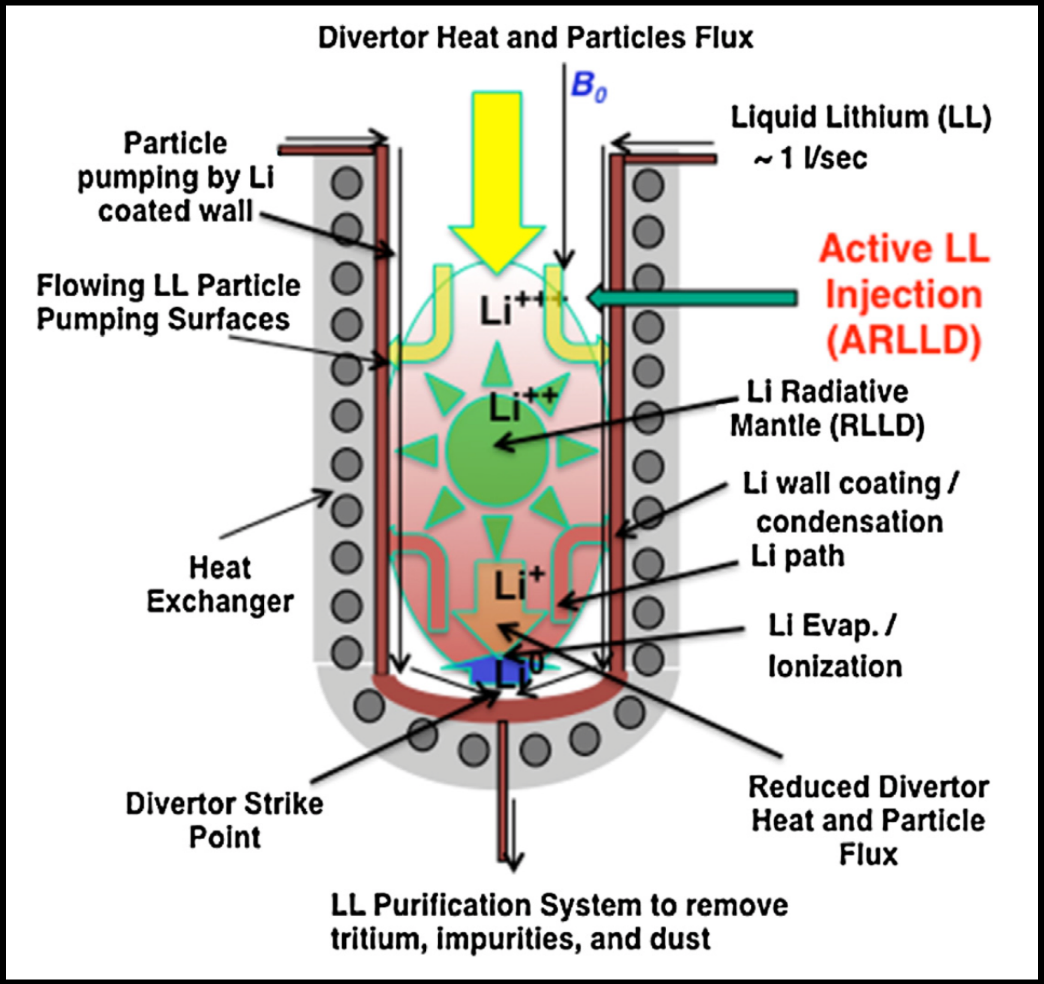
- Slot Nozzle + JxB propulsion (Majeski & Kolemen)
- Thermo-Electric effect (Ruzic)
- JxB Stirring (Shimada)
- Free surface jets (Ulrickson)
- JxB propulsion (Zakharov)

- Assume 10m/s, 2.5mm depth, $2\pi R$ = 40m width
- Flow is ~ $1 m^3/s$ ~ 500 kg/s
- How is heat extracted (in-torus, out of torus)?
- What is Li residence time in torus?
- Safety issues associated with tonnes of Li?

Steady Lithium Vapor Shielding

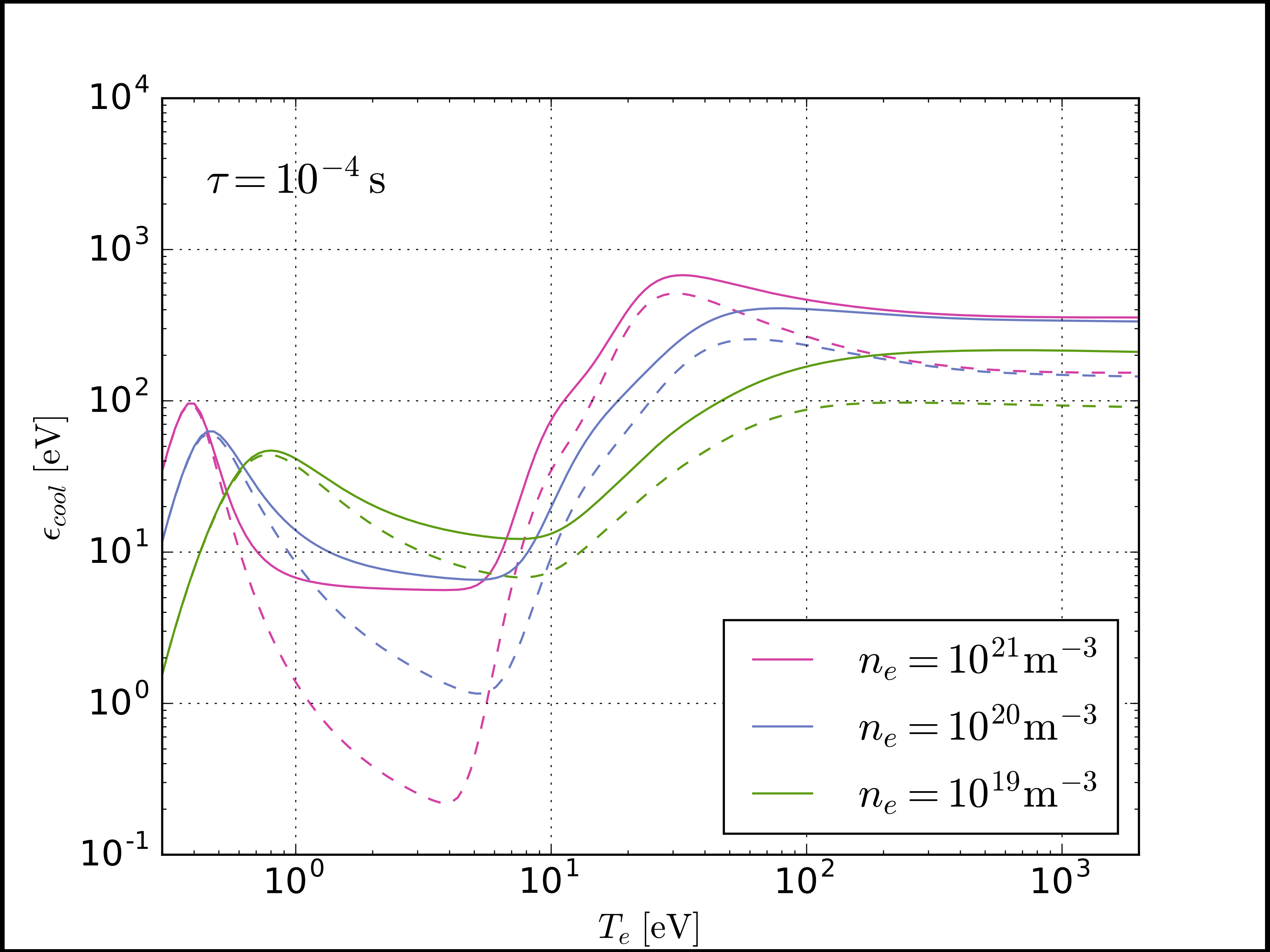


Golubchikov
1996



Ono
2013, 2014

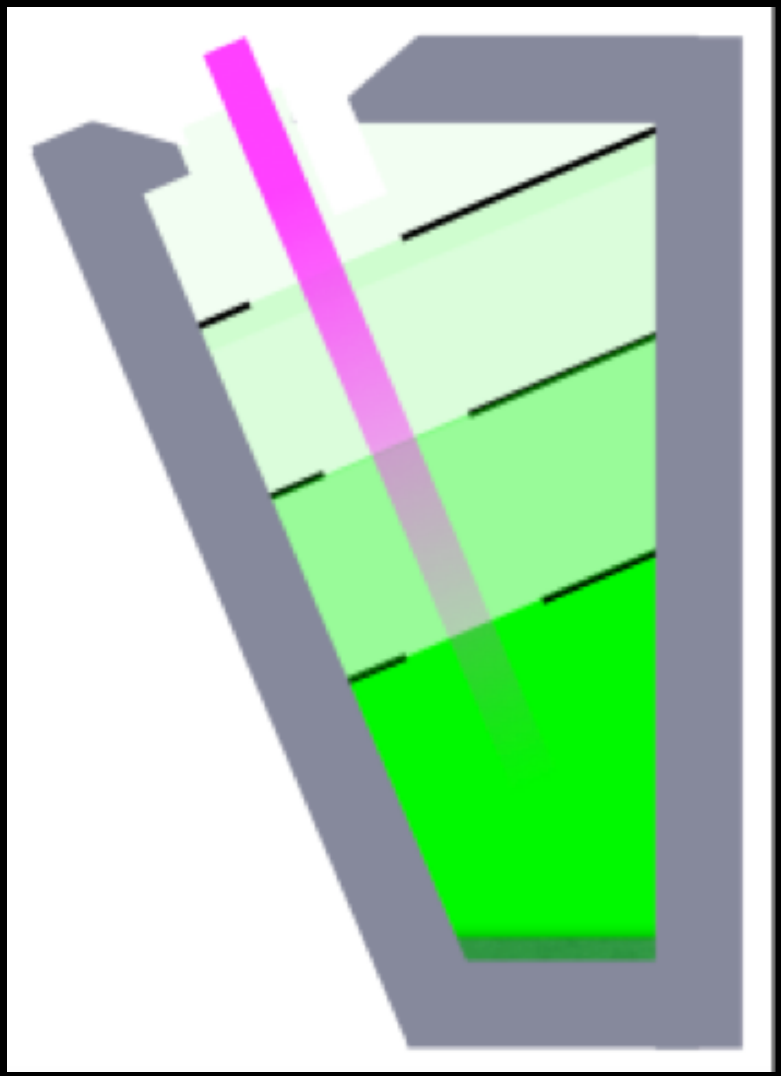
Lithium Vapor Shielding Promising



J. Schwartz

Estimate ~ 250 eV/particle e⁻ cooling.

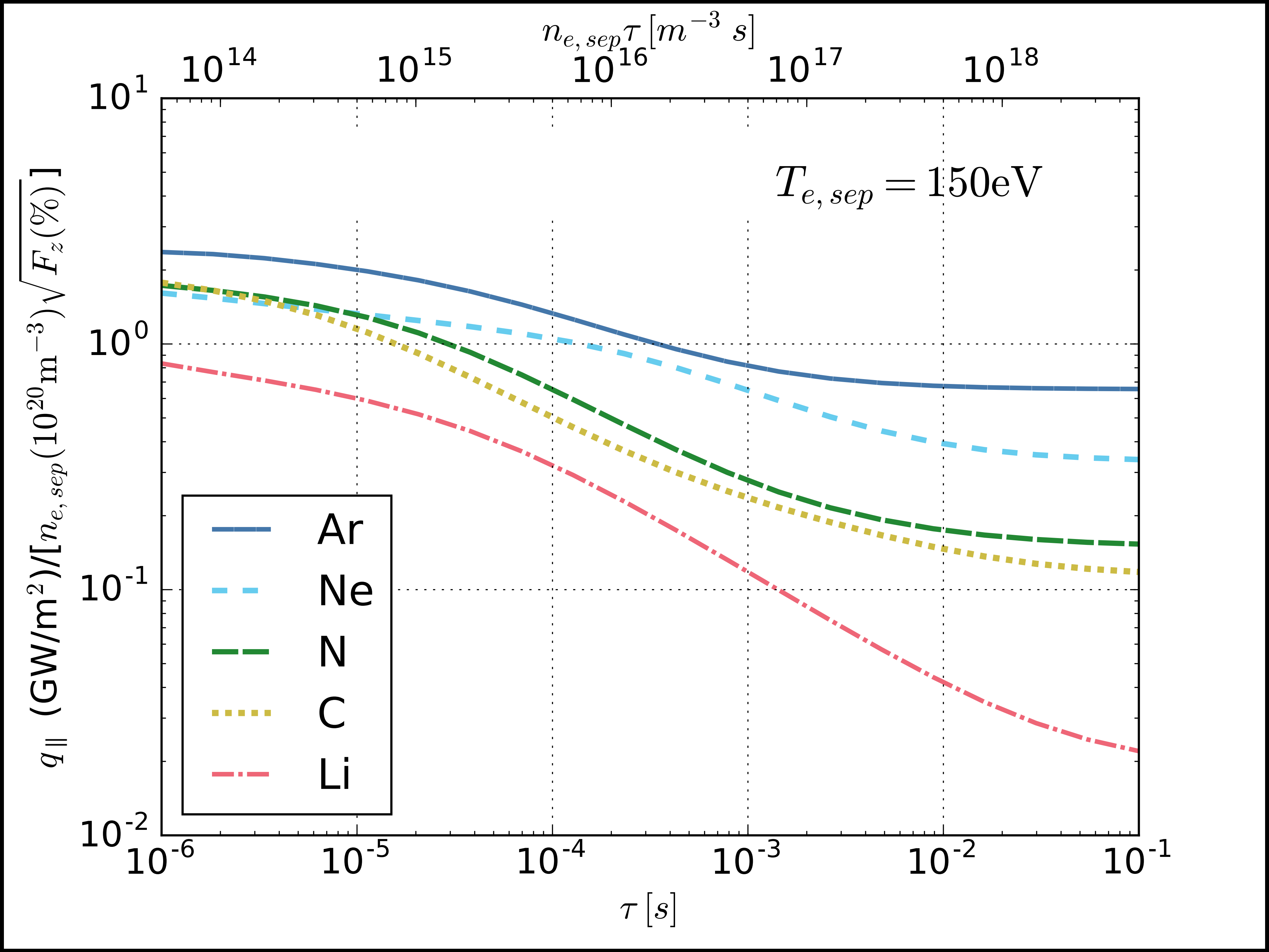
Lithium Vapor Box Divertor



Goldston
2015

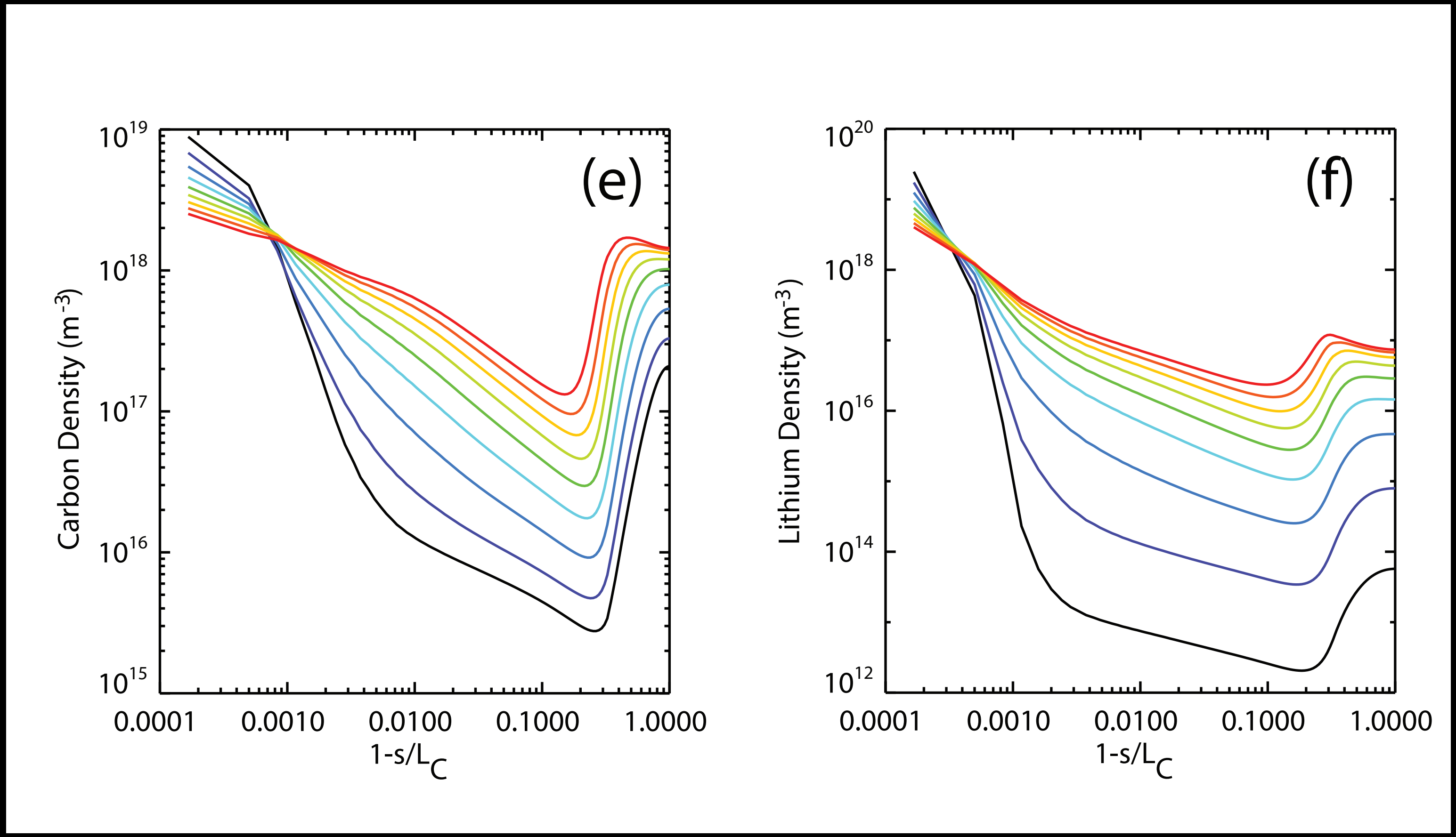
- Lithium injected into plasma as vapor
- Multiple boxes to localize Li cloud
  - Lined with Li CPS
  - Cooler towards the top, less vapor
  - Heat-pipe-like Li recycling
- Bottom box for 2.5 GW ITER, 580 ^oC
  - Depth 50 cm, aperture 20 cm
- Efflux from bottom box
  - 18 g/s, ~ 1/10 reduction per box
- Lithium inventory:
  - $2\pi R$ x 2m x 0.25mm = 10 kg Li

Lithium Radiation ~ 1/2 N

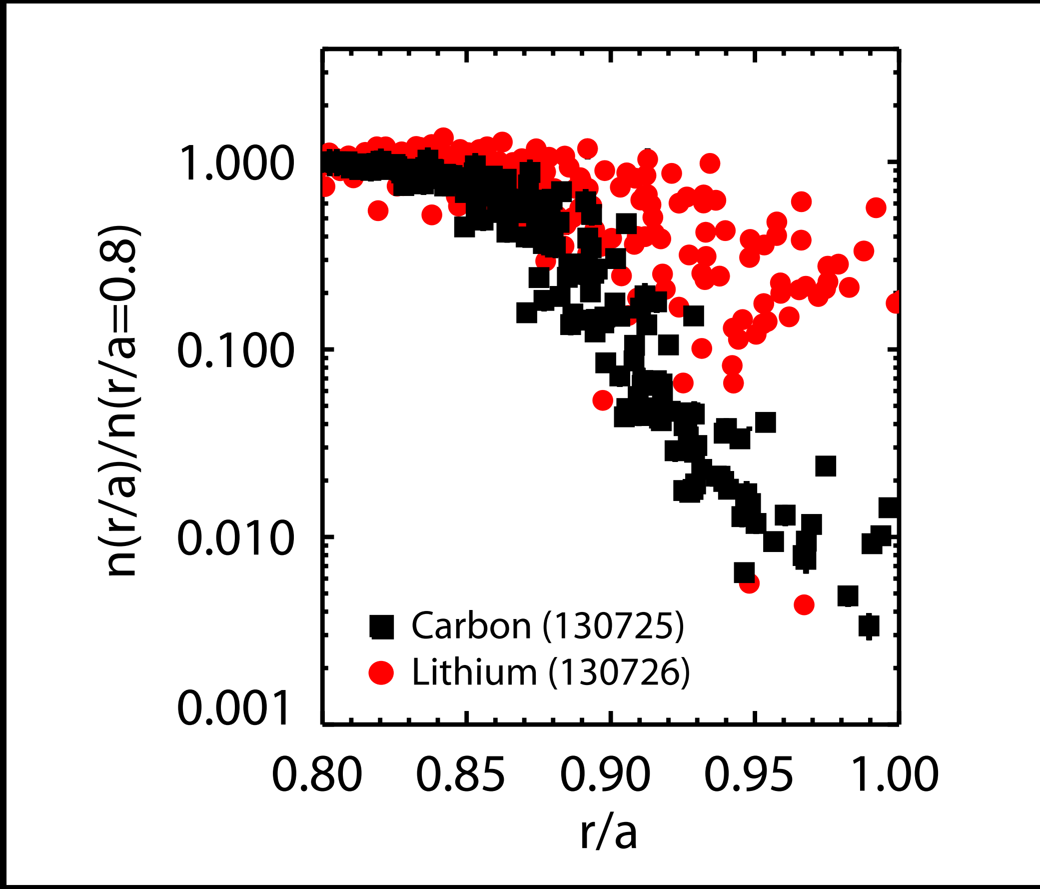


Lithium Concentrated Downstream

Recycling Variation in UEDGE



Edge CHERS



F. Scotti
Ph.D. Thesis

In NSTX, L pulled relatively weakly

upstream & into plasma core.

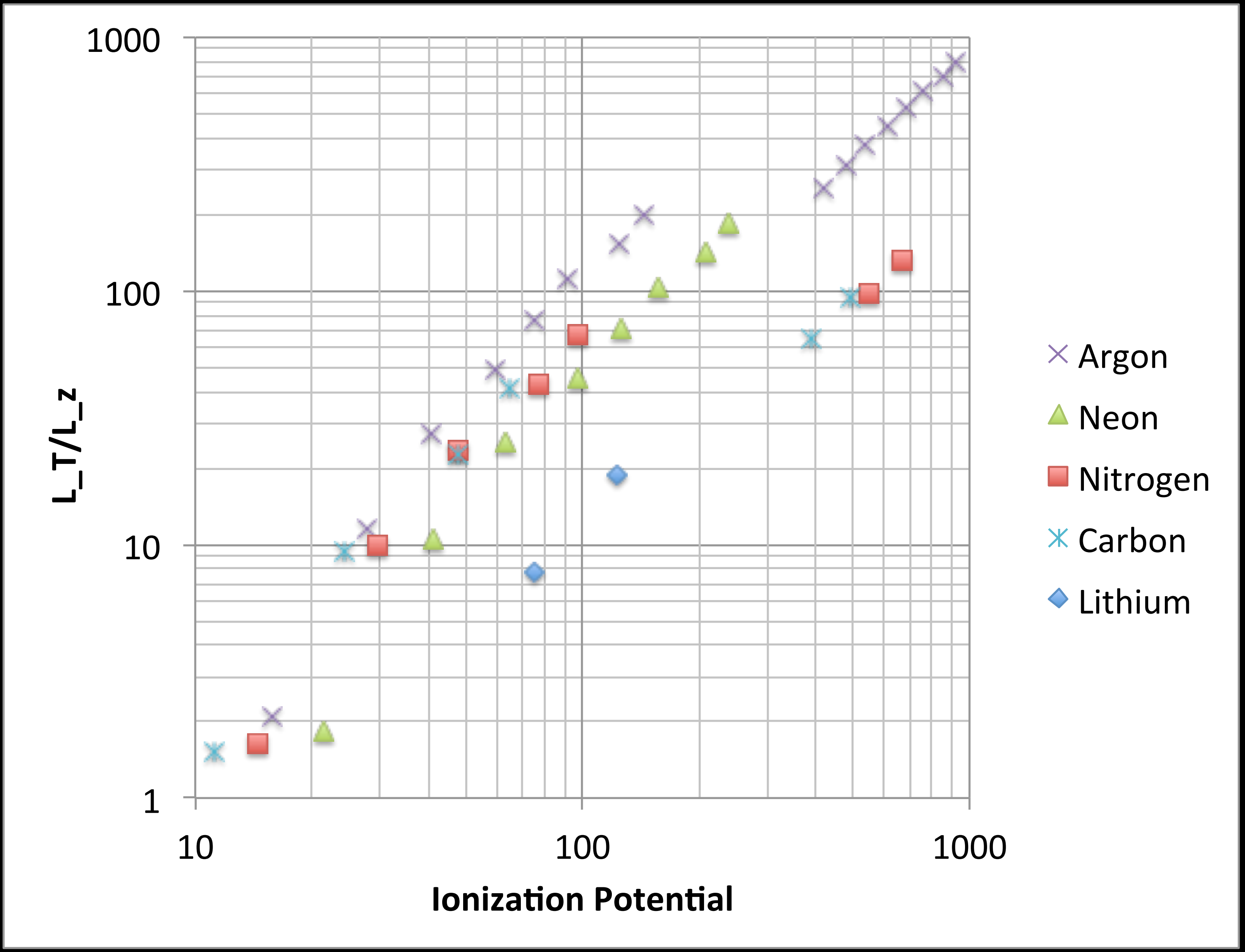
Thermal Force Much Weaker on Lithium

Simple balance between

∇p_z and thermal force:

$$\frac{T_z}{n_z}\frac{dn_z}{ds} + \frac{dT_z}{ds} = \alpha_e \frac{dT_e}{ds} + \beta_i \frac{dT_i}{ds}$$

$$\frac{L_T}{L_z} = \alpha_e + \beta_i - 1$$



Stangeby 2001

$$\alpha_e = 0.71Z^2$$

$$\beta_i = \frac{3(\mu + 5\sqrt{2}Z^2(1.1\mu^{5/2} - 0.35\mu^{3/2}) - 1)}{2.6 - 2\mu + 5.4\mu^2}$$

$$\mu \equiv m_z/(m_z + m_i).$$

Conclusions - 1

- A very large, low power Demo does not even *point to* cost-effective fusion power.
  - *Due to the problem of power handling.*
  - Even with 2/3 core radiated power and 500 MWe @ R = 9.1m, still must detach.
- The measure for difficulty in detachment is more likely P/B_p than P/R – *no size scaling!*
  - Should validate with 2-d codes & experiments – *but it makes simple sense.*

Conclusions - 2

- Steady lithium vapor shielding is attractive
  - Substantial dissipation per atom
  - Lithium vapor can be localized
  - Thermal force << than for N, Ne, Ar
  - Neoclassical inward pinch $\propto Z$
- Demo designs should study increasing B_p and $\ell_{||}^{*}$, rather than R, to foster detachment.
- The community should develop self-consistent scenario(s) for liquid metals in Demo.