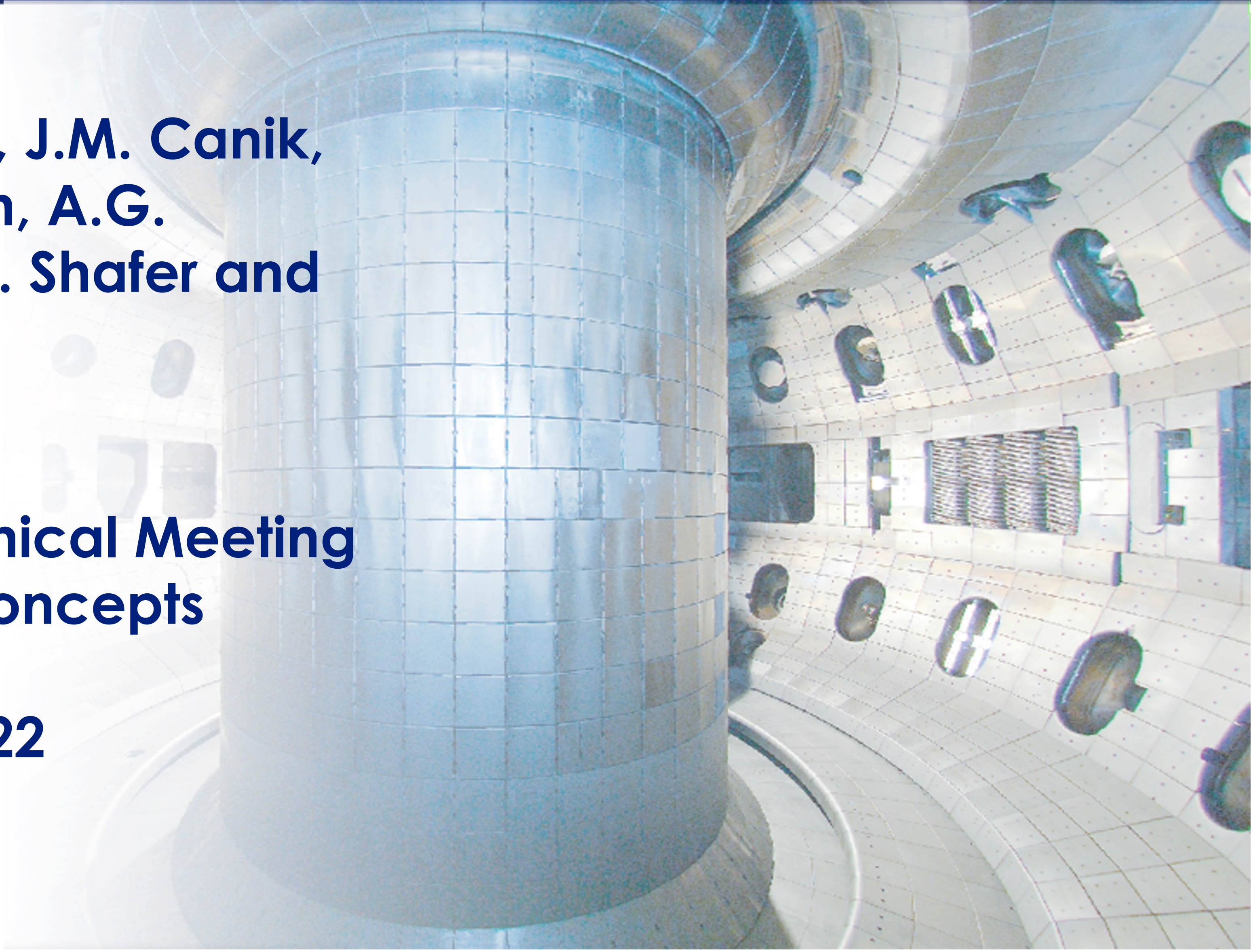
Minimum divertor leg length for a detached divertor and high performance core plasma



by
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Determine minimum divertor volume for core-compatible heat flux dissipation

- **A divertor solution should simultaneously:**
  - Provide full heat flux dissipation
  - Maintain hot X-point/pedestal plasma for high core performance

- **Divertor volume is expensive**
  - Larger toroidal field coils for long divertor legs
  - Complicated poloidal field coils for advanced, higher volume configurations; X-divertor, Snowflake, Super-X

- **Goal: Determine processes and scaling of radiative dissipation scale lengths from X-point to divertor target**

Convection dominates poloidal energy transport in divertor dissipative region

- **Conductive transport models predict small radiating volume and low levels of dissipation due to low-Z impurities**
  - Conduction dominated models at high power density exhibit small volumes with appropriate conditions for low-Z impurity radiation, $30e \geq T_e \geq 5eV$;

$$\frac{dT_e}{ds} = \kappa_0^{-1} q_{\parallel} T_e^{-5/2} \kappa_0$$

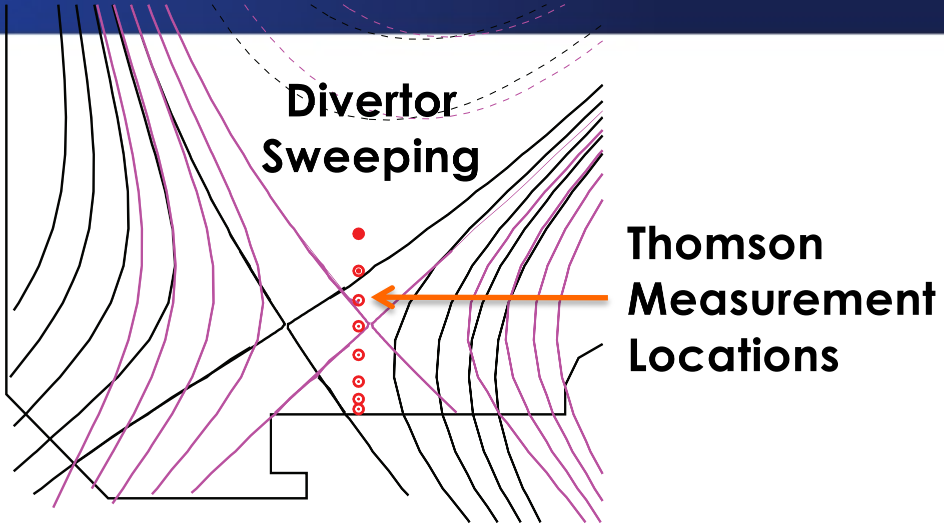
  - Lengyel-type scaling models exhibit weak dependence on divertor leg length; $n_{sep,detach} \propto L^{2/7}$, with small fraction of divertor volume providing dissipation

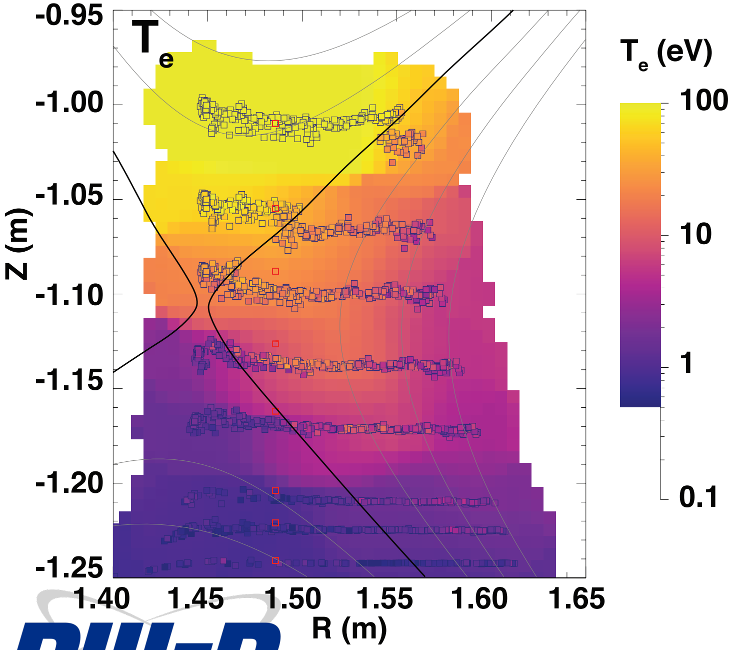
- **Experimental evidence, and modeling, find convection dominates and expands volume of dissipative region**
  - Motivates re-examination of dissipative divertor scaling
  - Transport dominated by parallel flow and ExB poloidal drifts

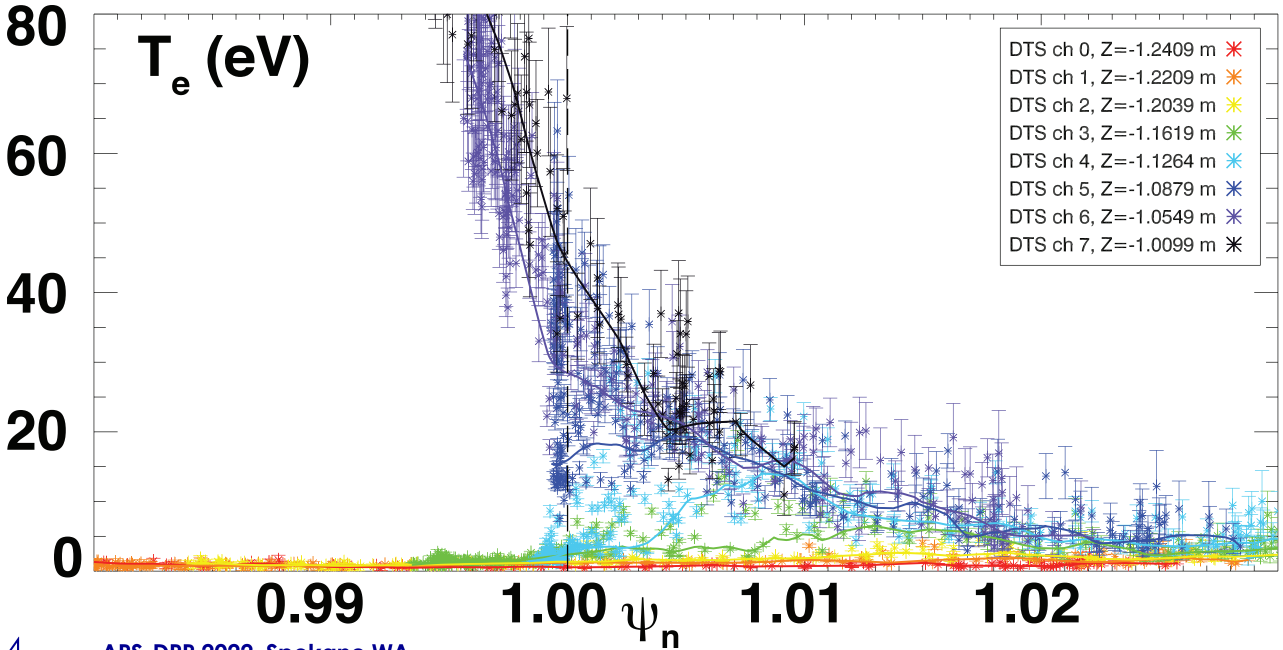
2D Profile of Divertor n_e and T_e Reconstructed from Divertor Thomson Scattering

- **Divertor swept across DTS during constant conditions**

- **Data selection for $n_e(L_{||})$, $T_e(L_{||})$**
  - Within λ_q of separatrix, ψ=1.004
  - Only data points between ELMs





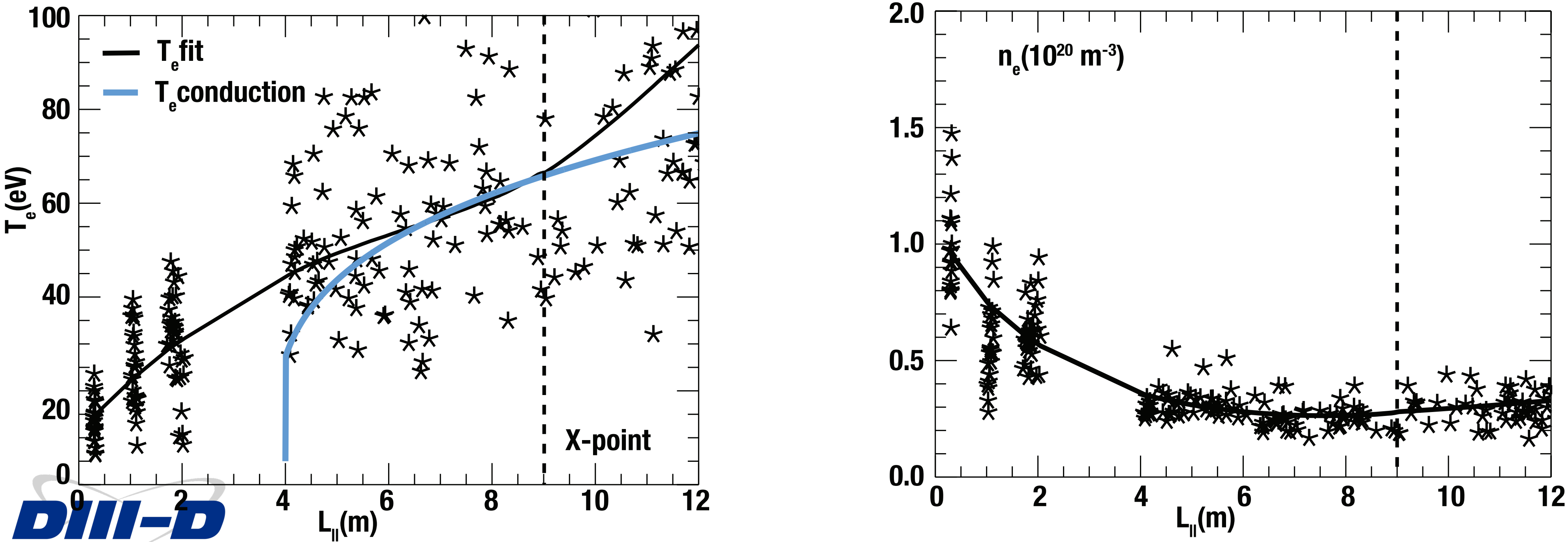


DIII-D
NATIONAL FUSION FACILITY

Parallel temperature gradient, ∇T_e, inadequate to support conductive heat flux

- **For conductive transport, T_e gradient very steep for $T_e \leq 30$ eV**
- **Poloidal heat flux carried by parallel and ExB plasma flow**
  - H-mode attached, $q_{\parallel} \sim 700\ MW/m^2$

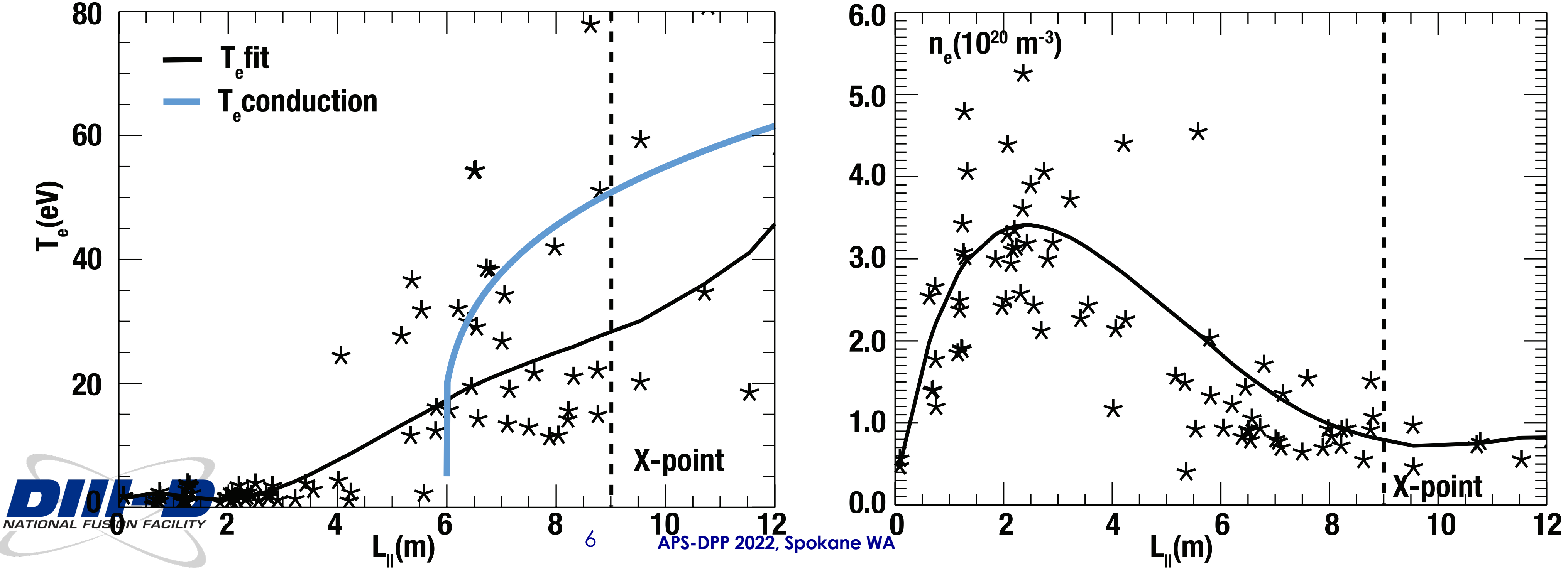
Thomson Scattering near SOL T_e profile (ψ_n=1.0005-1.004)



Convective transport also indicated in detached divertor plasmas

- **Large region of low T_e in detached plasmas**
- **Poloidal heat flux carried by parallel and ExB plasma flow**
  - H-mode detached, $q_{\|} \sim 500\ MW/m^2$

Thomson Scattering near SOL T_e profile (ψ_n=1.0005-1.004)

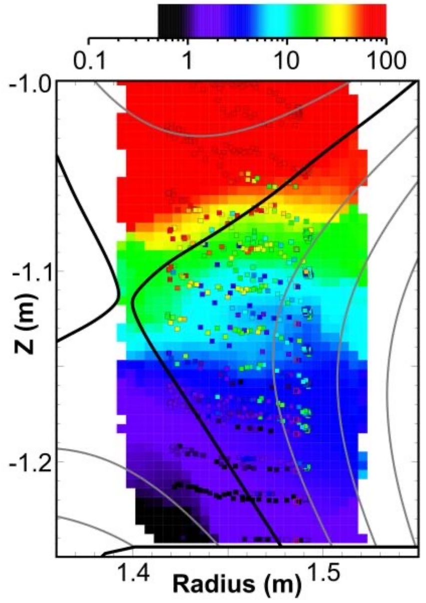


DIII-D observes a maximum poloidal ∇T_e

- **Shots with a detached OSP, and a stable high T_e gradient and radiation front mid-way up the outer leg show maximum gradient of ~200 eV/m**
  - *Open lower divertor cases only, inter ELM*

- **This still presents a control challenge as many shots pushed into deep detachment to the point of X-point radiation**
  - *Goal to 'hold' radiation front near the target surface, but still with $T_{e,OSP}$<2 eV*

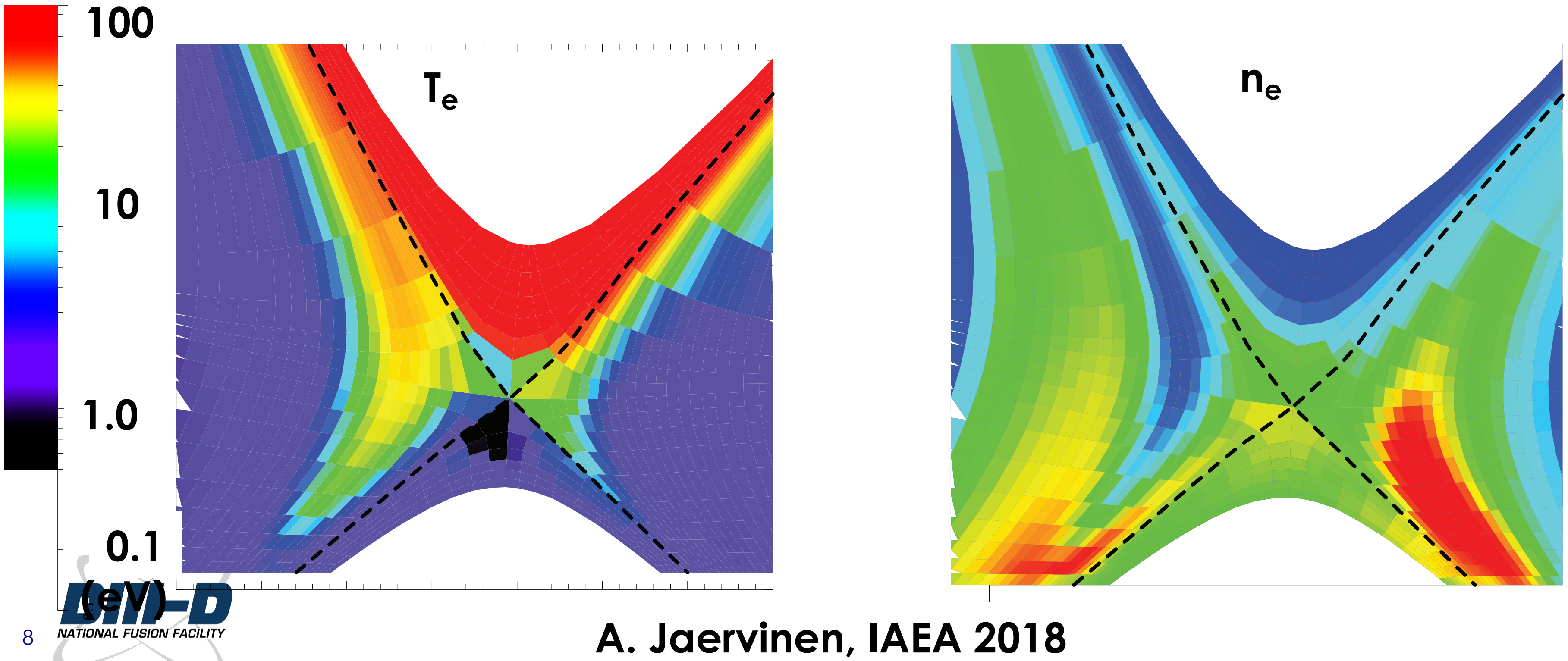
Shot	P_{inj} (MW)	$\nabla T_{e,\ avg}$ (eV/m)
174310	**13 MW**	**188.3**
183557	Ohmic	154.5
185819	3.3 MW	38.3
185822	3.3 MW	110.8
185825	3.3 MW	146.3
185836	3.3 MW	131.6
186802	**9 MW**	**205.1**



For 80-100 eV X-point consistent with a high-performance core, implies a 40-50cm poloidal leg

UEDGE Modeling For Examining Role of Plasma Drifts in Divertor Transport

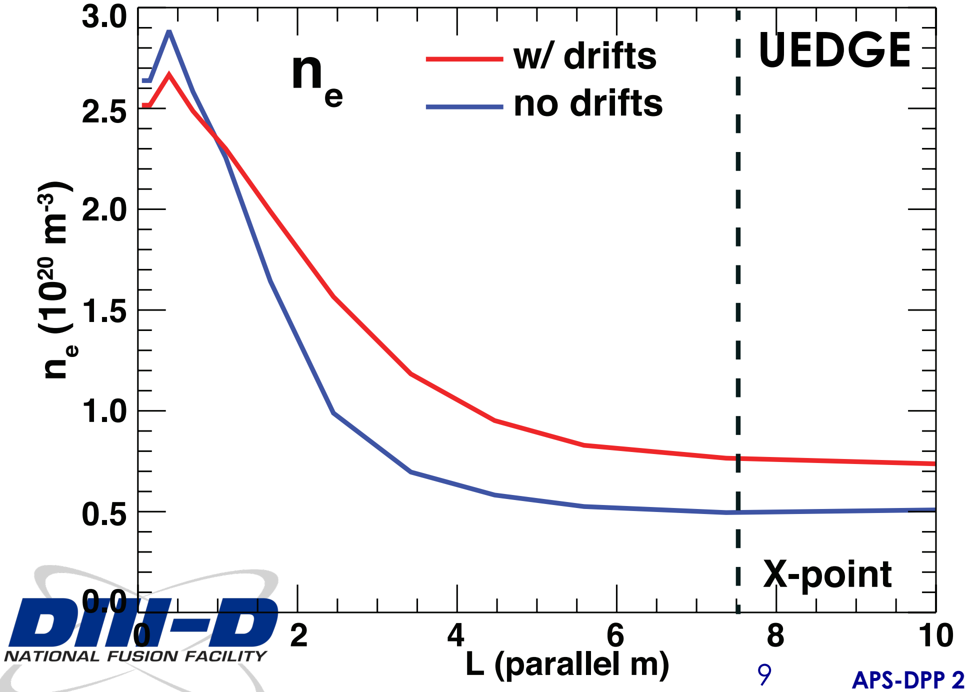
- **UEDGE: 2D fluid modeling with realistic geometry**
  - Includes convective transport driven by ionization, and drifts
- **UEDGE constraints for 3 MW case**
  - Radial transport set to match upstream profiles
  - Carbon source from standard physical and chemical sputtering yields
  - Increase upstream density for detached target conditions, $T_{e,Div} \leq 5$ eV

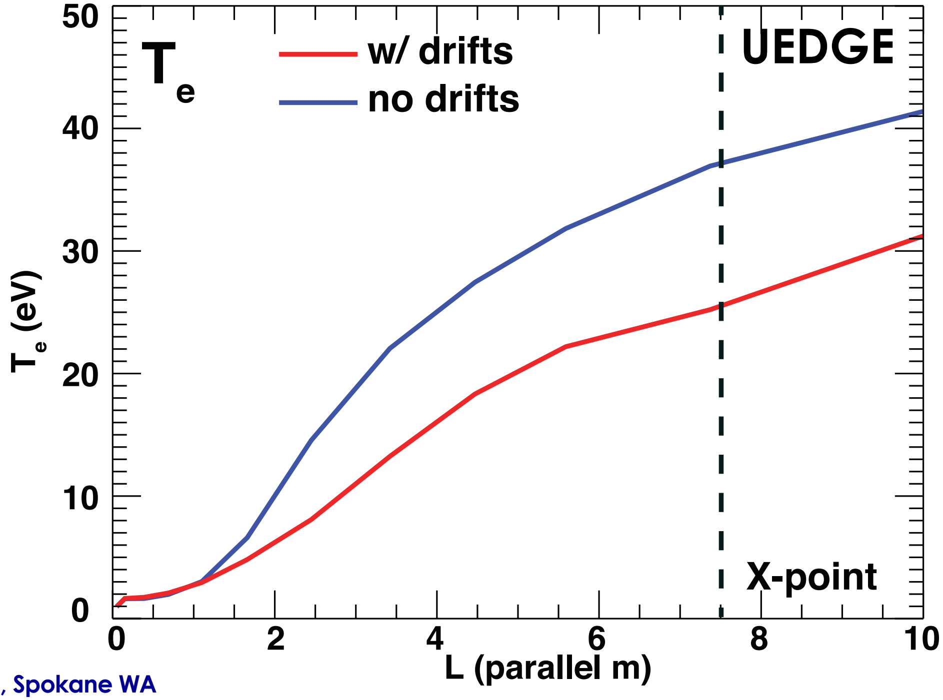


A. Jaervinen, IAEA 2018

UEDGE Highlights Importance of Drifts in Detached Divertor Plasmas

- **Inclusion of drifts adds to poloidal transport, flattening parallel T_e and n_e gradients**
- **Upstream input power and transport coefficients adjusted to match experiment upstream profiles and divertor entrance $q_{||}$**
  - Same power and transport coefficients for cases w/ drifts and no drifts
- **Upstream density increases until target T_e < 3eV**





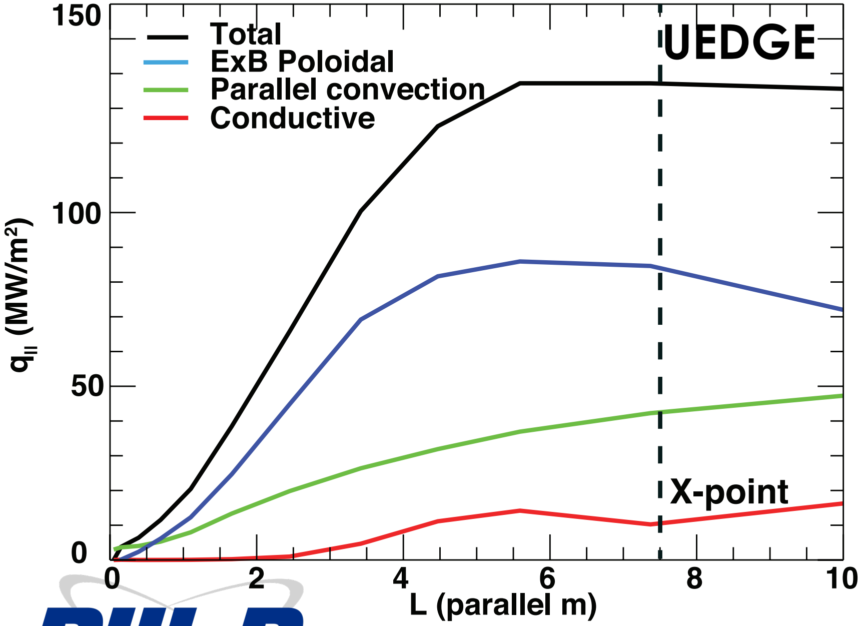
Poloidal ExB Drift Dominates Divertor Heat Flux Transport

- **UEDGE achieves near complete dissipation of heat flux**
- **Parallel convection carries only 1/3 of heat flux, consistent with experimental measurements**
- **ExB poloidal drift effective**

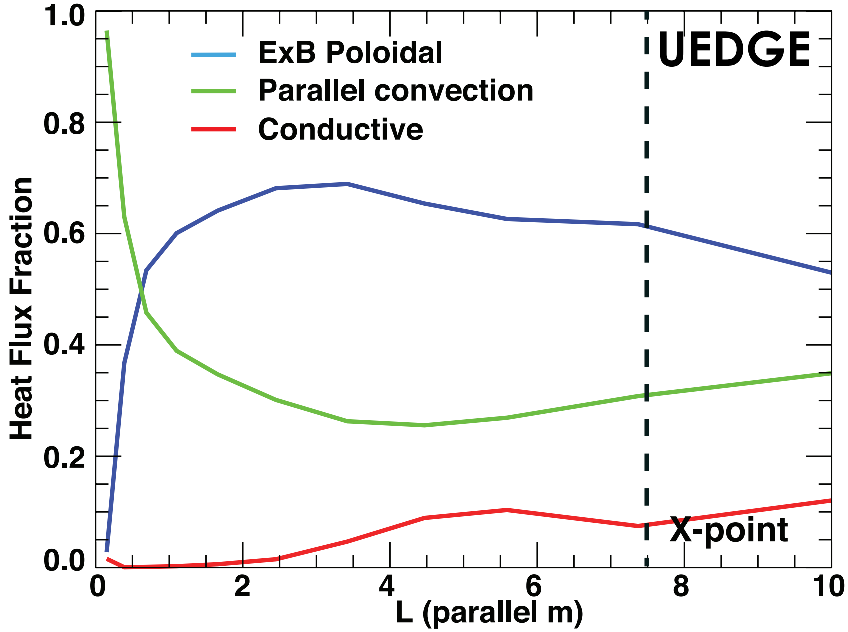
$$q_{\parallel,ExB} = q_{pol,ExB}\frac{|B|}{B_p}$$

3 MW case

Effective $q_{\parallel}$

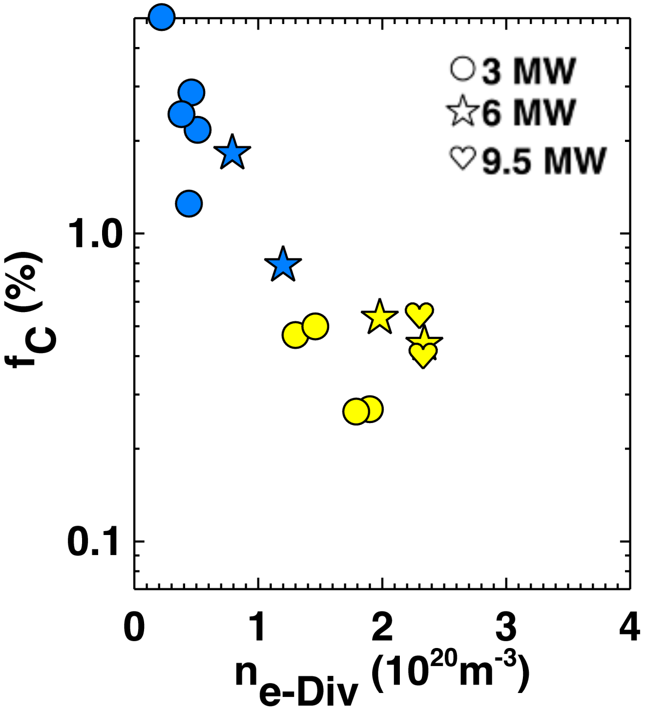


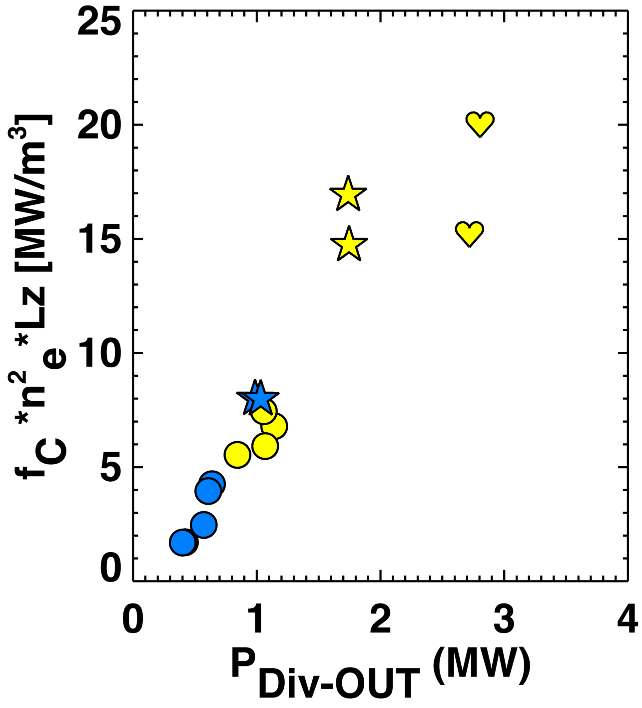
Heat Flux Fraction



Impurity density and radiation are directly measured with VUV spectroscopy

- **Local impurity density and radiation measured with VUV spectroscopy**
- **Local T_e and n_e measured with Thomson scattering**
- **For typical detached H-mode plasma at 10 MW**
  - $\mathcal{E} = 10\, MW/m^3$ in carbon radiation
  - $T_e = 10eV$
  - $n_e = 10^{20} m^{-3}$





Convective transport reduces ∇T_e and expands radiating volume

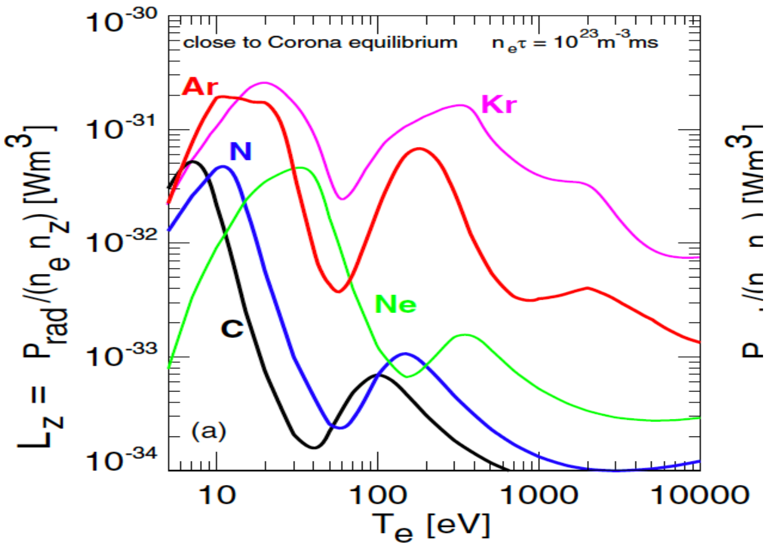
- **For a convecting plasma**

$$\frac{dT_e}{ds} = \frac{P_{rad}}{\mathcal{E}_{th} v_{\parallel}}$$

  - With measured P_{rad}= 10 MW/$m^{3,}$

    n_e= $10^{20}m^3$, T_e = 10 and sonic flow

    implies; $\frac{dT_e}{ds} \sim 2\ eV/m_{\parallel}$ or $\frac{dT_e}{ds} \sim 100\ eV/m_{pol}$
  - Poloidal drift may increase ∇T_e consistent with measured $200\ eV/m_{pol}$

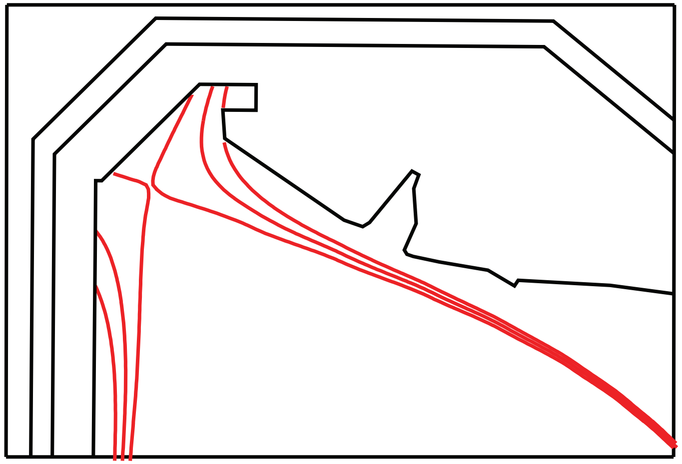


[1] Kallenbach PPCF 2013

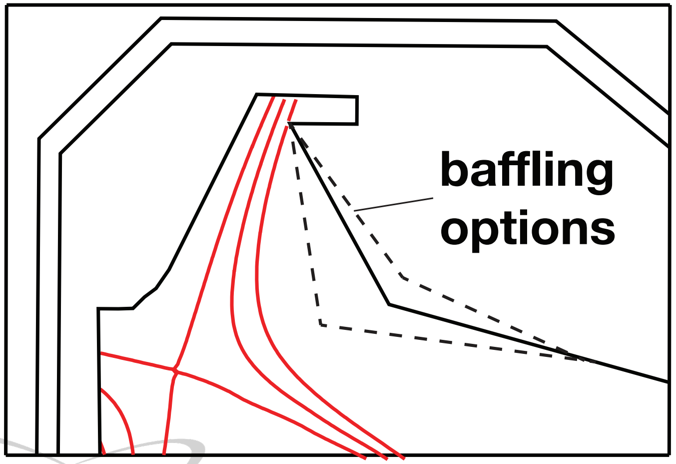
- **For DIII-D Phase II divertor a 50 cm divertor leg would allow for 100 eV at X-point plasma and 1 eV at the target**

DIII-D will take a staged approach to address the exhaust challenge

Stage 1: Shape & Volume Rise



Stage 2 Concept: Longer Leg

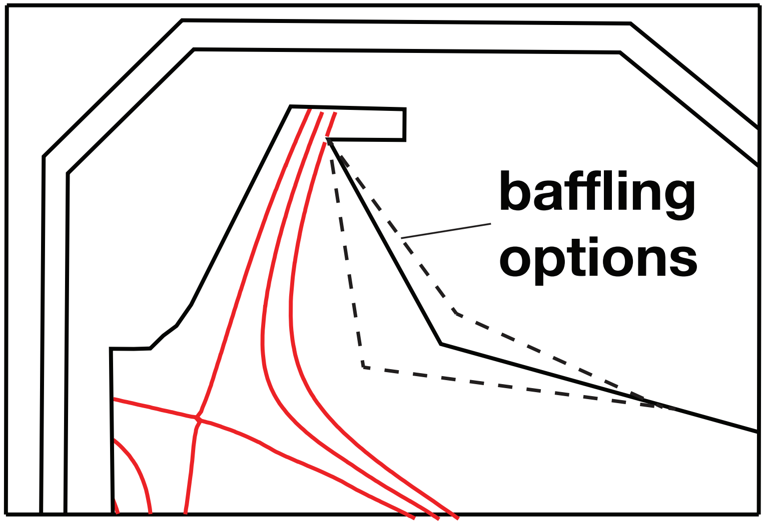


- **Stage I**
  - Higher field and power to access more reactor relevant plasma parameters
- **Stage II**
  - A divertor geometry to determine minimum divertor leg length and optimal baffle structure
- **Stage III**
  - Divertor geometry to test optimization of highest performance integrated core-edge solution

Stage 2 will explore divertor leg length as well as baffle optimization

- **Divertor performance examined**
  - Full detachment and dissipation
  - Hot X-point plasma
  - Detachment front stability
  - Dependence on operational scenario, B_t, I_p, Power, etc
- **Divertor performance may improved by baffle options due to**
  - Recycling ionization and recombination profiles
  - Neutral transport
  - Plasma drifts

Stage 2 Concept: Longer Leg



Implications of convection dominated transport

- **Conduction dominated Lengyel-type models do not accurately describe divertor dissipation**
  - While radiative dissipation scales as, $\mathcal{E} \propto f_z n_e^2$ in a device,
  - Such models not appropriate for prediction of total radiation in different configurations, detachment front stability, etc.
- **Projecting ∇T_e (radiating volume) requires detailed modeling of particle balance**
  - Ionization, recombination, baffling control of neutral transport, pumping, etc.
  - $E \times B$ drifts
- **Other effects may also expand radiating volume**
  - Radial diffusion
  - Turbulence