Stochastic magnetic fields and plasma effects in fusion edge plasmas

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Content: resonant magnetic perturbations – comparison of measurement and model

- Vacuum approach:
  - Hamiltonian systems → magnetic topology
  - Heat flux in L-mode plasmas
  - Flux tubes
- H-mode plasmas
  - Heat & particle flux
- Drift effects → electric fields
- Plasma currents → ELM modeling
- Summary

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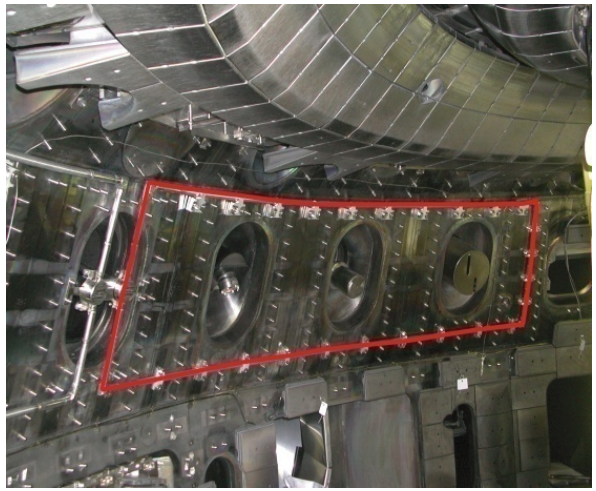
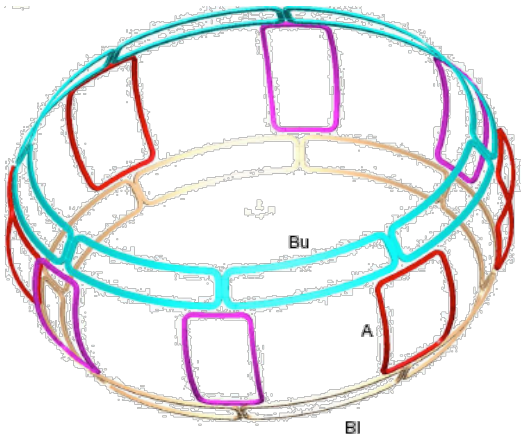
Stochastization by coil systems is a widely used method to affect edge plasma physics

TEXTOR - DED

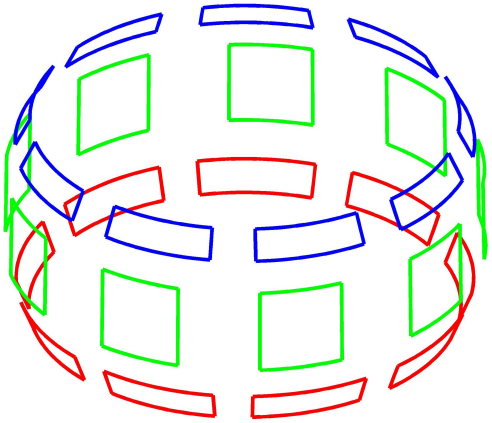


DIII-D I-coils

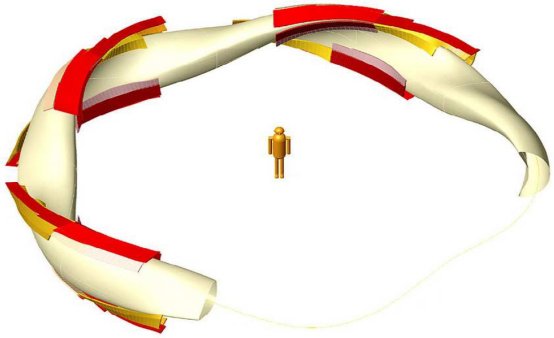


ASDEX- Upgrade

JET
EFCC-coils



ITER RMP coils



Wendelstein
7-X

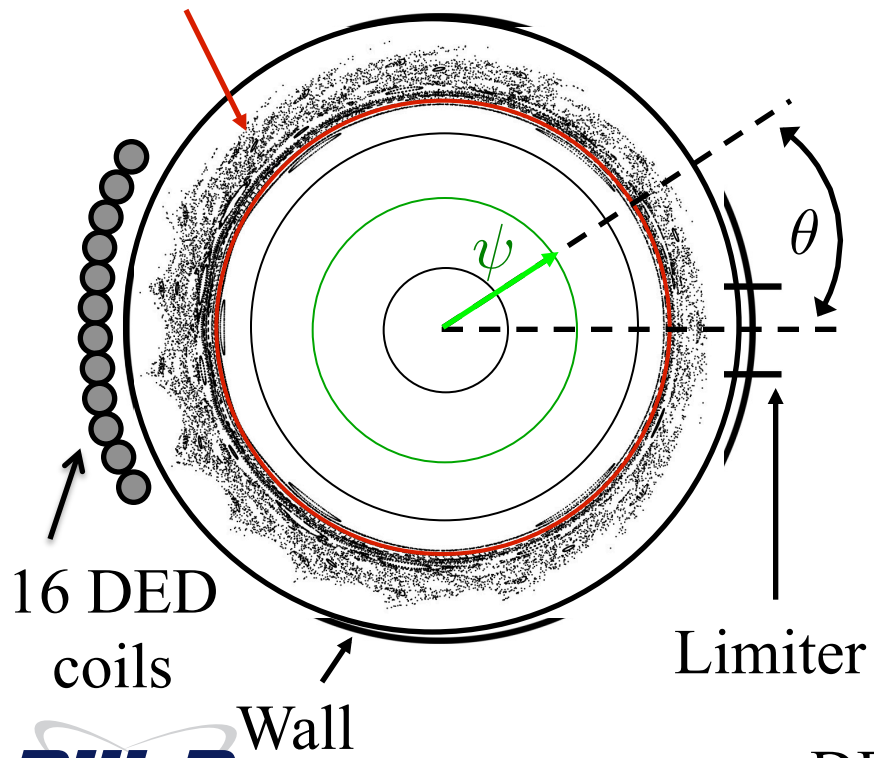
Edge stochastization using external perturbation coils

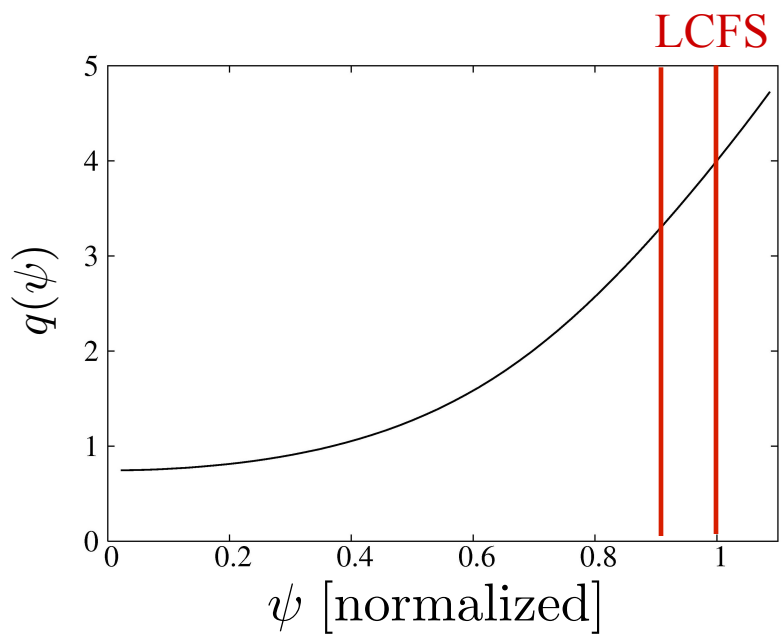
Limiter tokamak, e.g. TEXTOR with DED off

Field lines are organized on circular surfaces with constant flux ψ

last closed flux surface (KAM surface)

q-profile:
ratio of toroidal to poloidal mode number



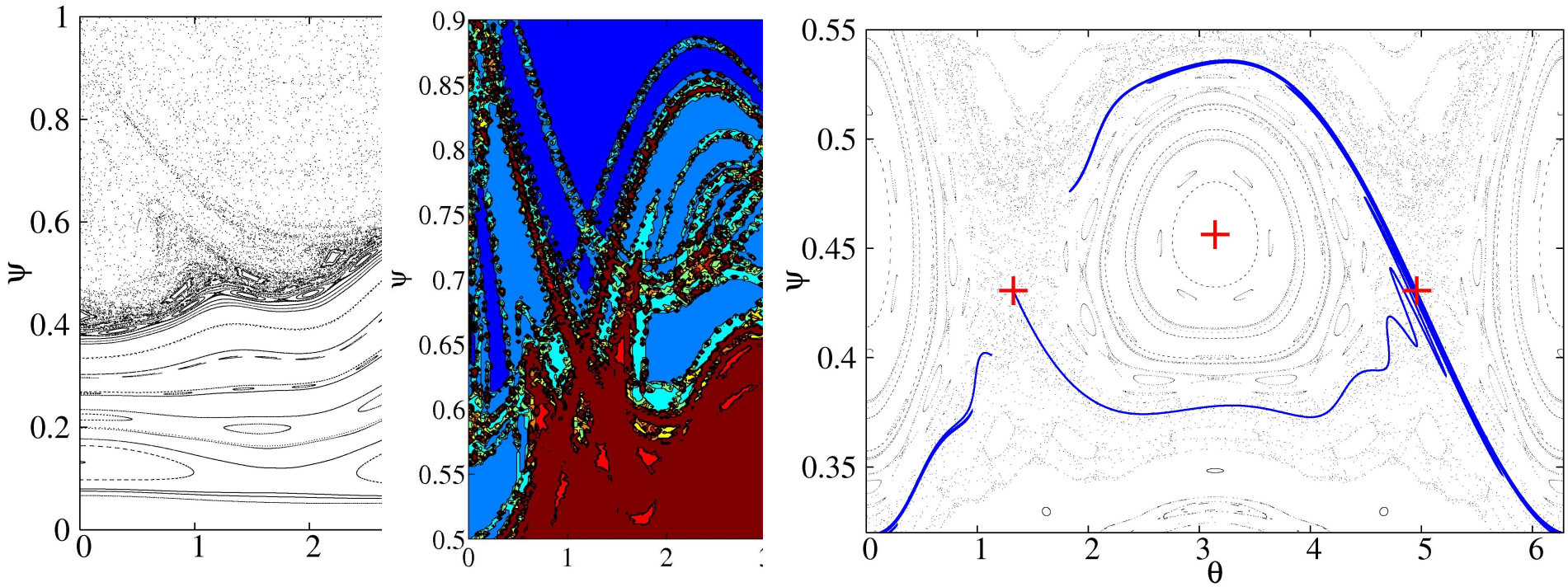


DED creates stochastic edge

Magnetic fields can be described as a Hamiltonian system: Hamilton theory applies

$$H(\psi,\theta,\varphi) = H_0(\psi) + \varepsilon H_1(\psi,\theta,\varphi)$$

Poincaré Section	Connection length	Manifolds
transport, resonances, escape rates, barriers	fractal, flux tubes, penetration depth	stochastic layer formation, boundaries, dynamics

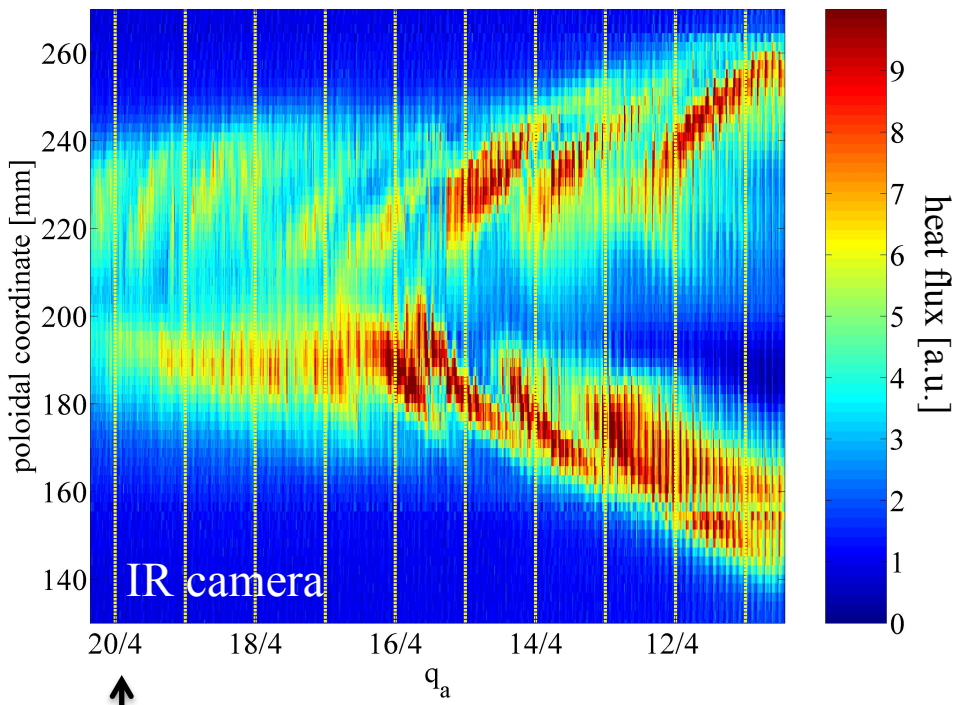


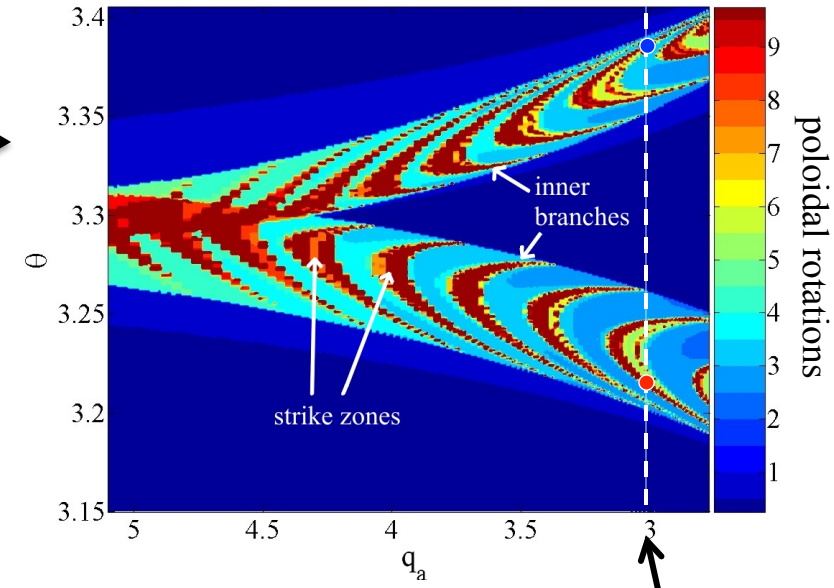
A. Wingen *et al.*, Contrib. Plasma Phys. **45,** 500 (2005)

Vacuum approach: Connection length footprints relate to heat flux in L – mode

TEXTOR (L-mode):

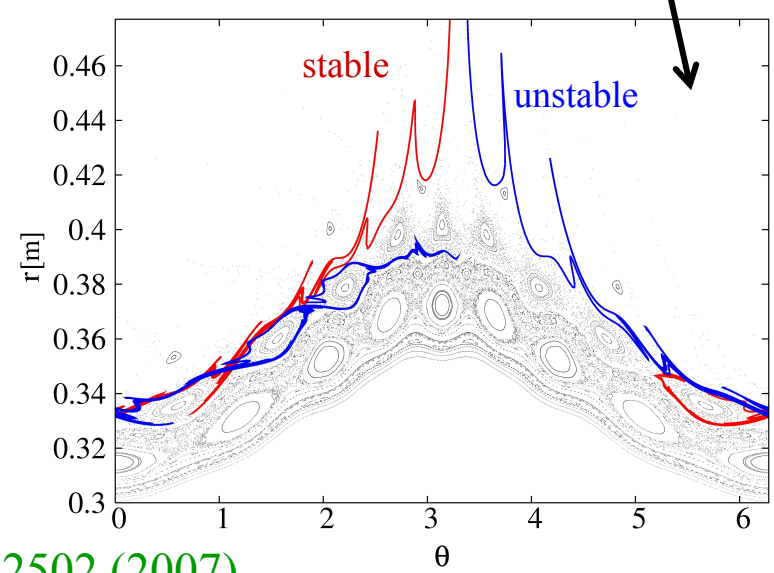
Connection length





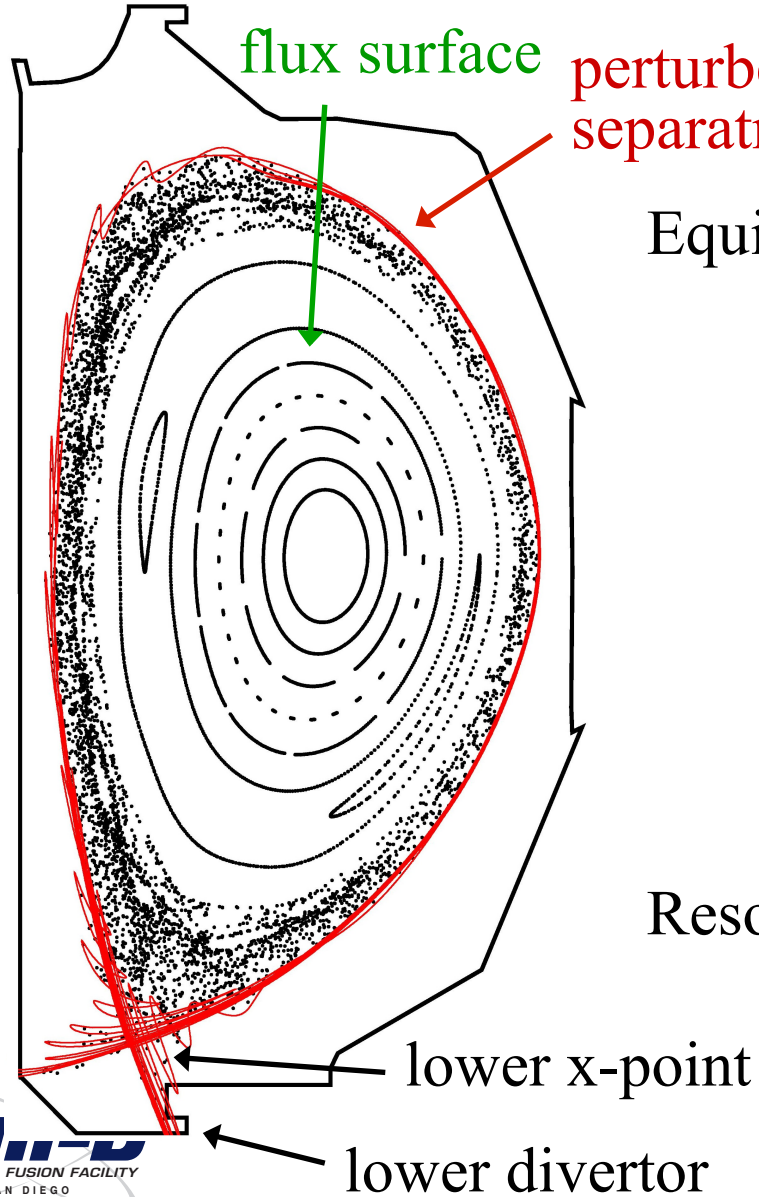
+ Manifolds

= Heat flux pattern in L-mode



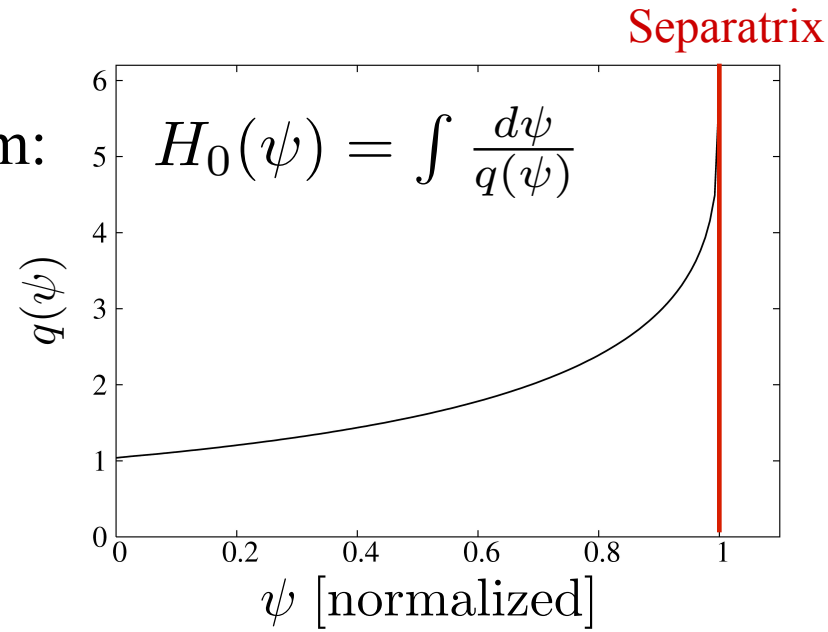
A. Wingen *et al.*, Phys. Plasmas **14**, 042502 (2007)

Magnetic structure in a diverted H – mode tokamak, here DIII-D



Divertor tokamak **RMP on**

Equilibrium:



+

q infinite at separatrix

→ always thin stochastic layer

Resonant Magnetic Perturbation (RMP):

$$\varepsilon H_1(\psi, \theta, \varphi)$$

→ large stochastic layer

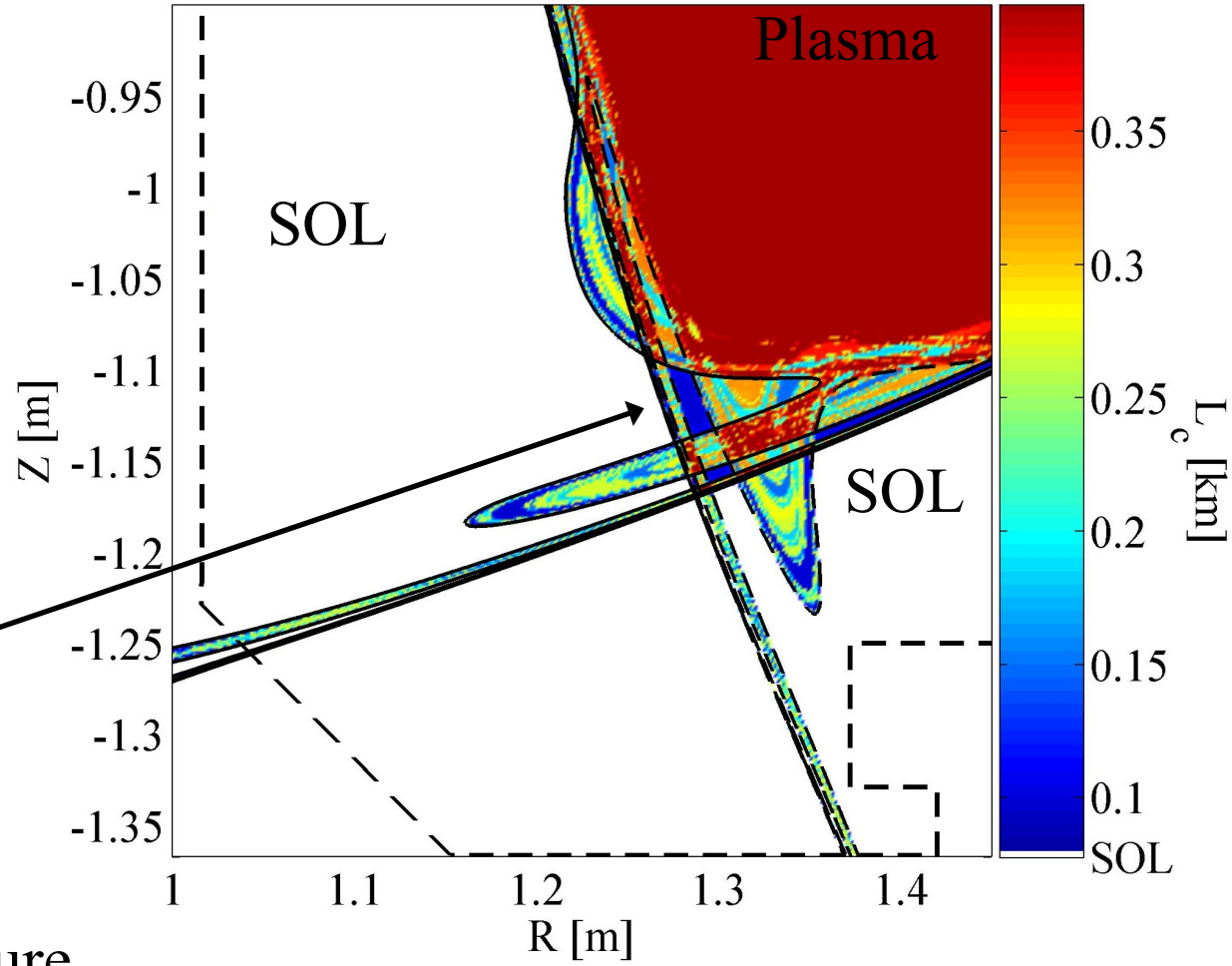
Flux tubes: a helical nonstochastic structure perforating the edge

Perturbation splits separatrix:

unstable separatrix manifold

stable separatrix manifold

Intersections form **flux tubes**

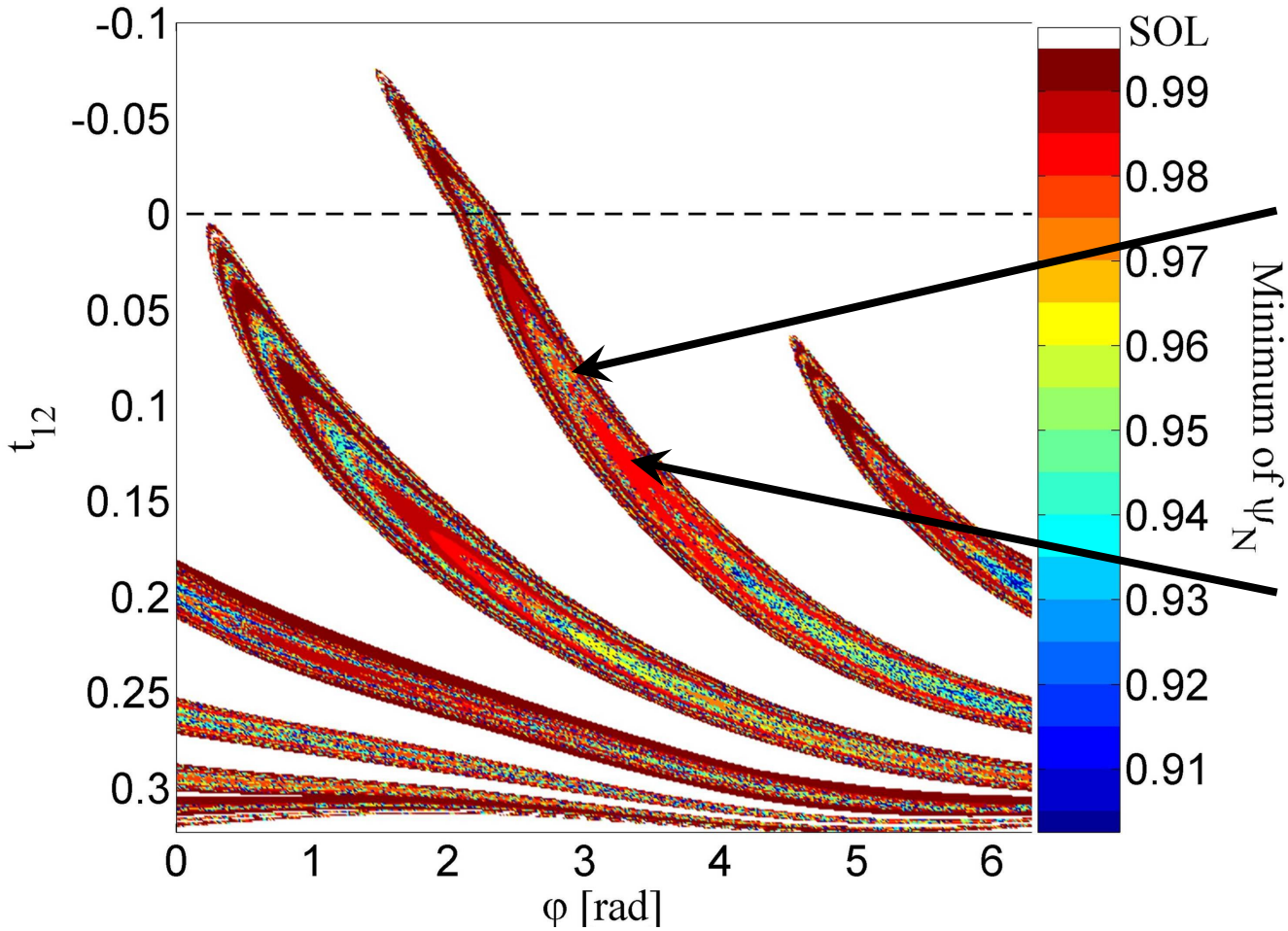


- perforate plasma edge
  → particle sink?
- compact helical structure
- winding around the plasma → tubes get deformed, but area preserved

A. Wingen *et al.*, Nucl. Fusion **49**, 055027 (2009)

Flux tubes are short connections between the targets though the plasma edge

Penetration depth by minimum of normalized flux



Substructures

Fractal bands:

- deep penetration down to $\psi_N = 0.77$ in all bands
- stochastic areas

Flux Tubes:

- field lines penetrate hardly the edge
- areas are uniform
- ordering of penetration

A. Wingen *et al.*, PoP **16**, 042504 (2009)

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Does the vacuum aproach hold in H-mode?

- Vacuum approach:
  - Hamiltonian systems → magnetic topology
  - Heat flux in L-mode plasmas
  - Flux tubes
- H-mode plasmas
  - Heat & particle flux
- Drift effects → electric fields
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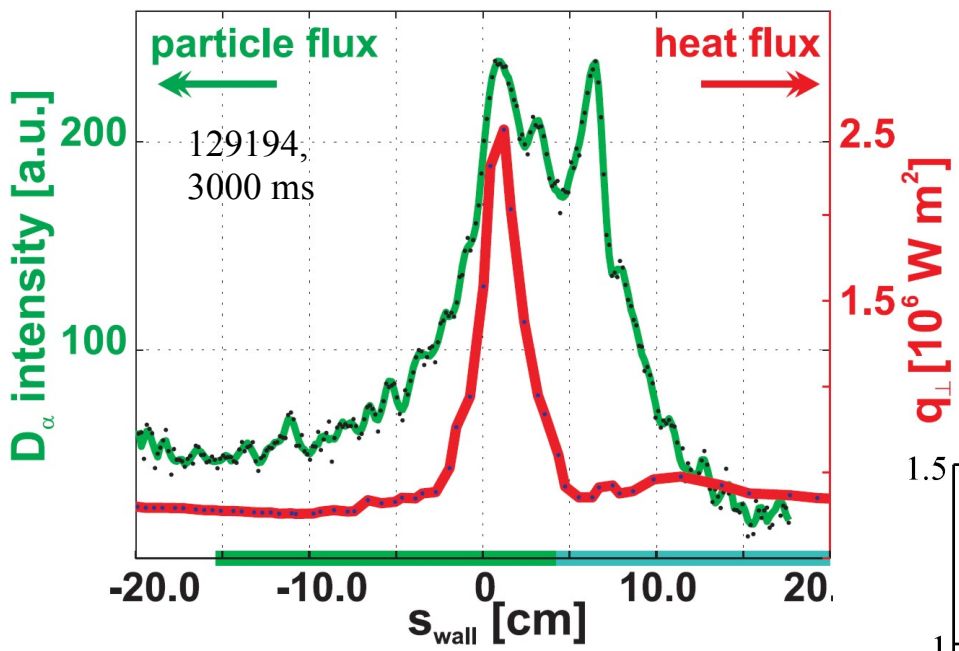
In DIII-D H-mode, heat and particel flux differ, while vacuum approach fits neither of them



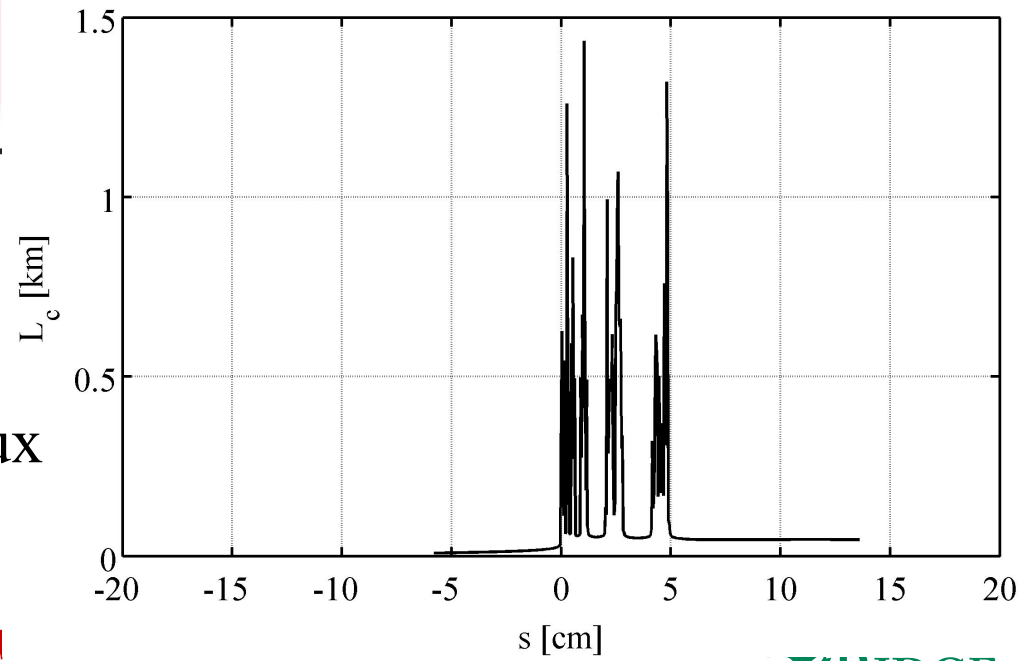
Particle flux:

striation, pattern width ≈ 8 cm

Heat flux:

no striation, only one peak

(here: low collisionallity case)



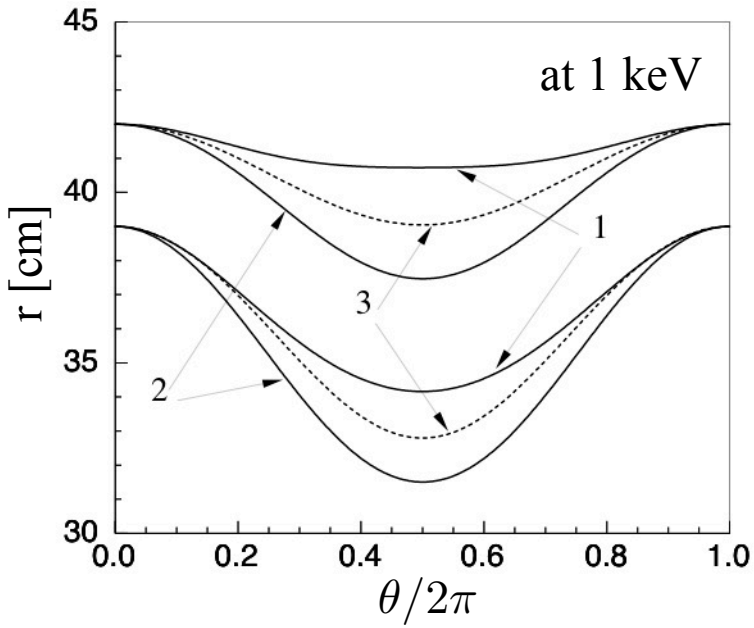
Field lines: connection length

- pattern is too small, ≈ 5 cm
- striation similar to particle flux
- no similarity to heat flux

Unsolved problem!

Include plasma effect: Ion drift orbits deviate from field lines, while electrons stick to them

drift depends on kinetic energy



1: passing ions
2: counter-passing ions
3: electrons $\approx$ field lines

Calculate heat flux:

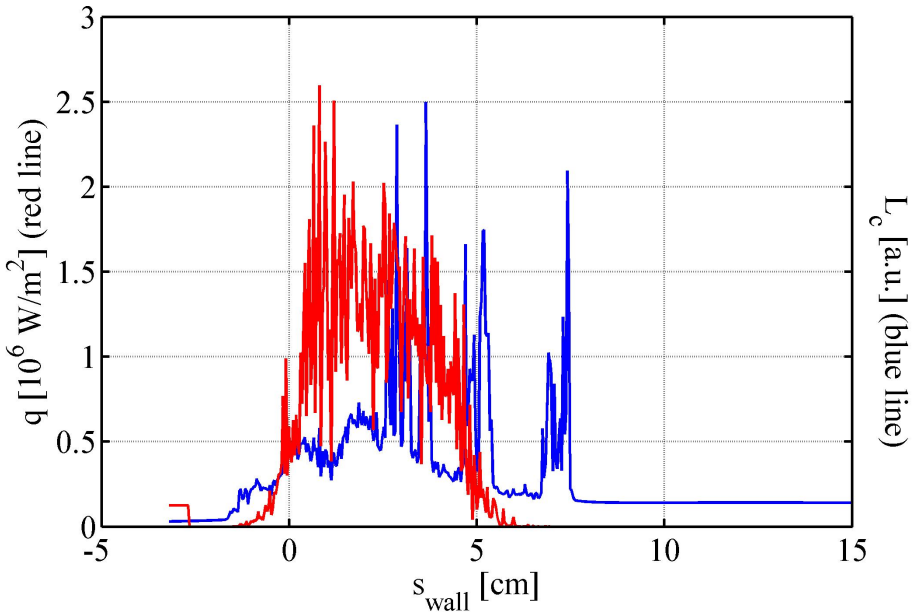
- assume Maxwellian energy distribution at T_i = 1 keV
- ion footprints for various energies
- average over all footprints
  - relate penetration depth to T_i profile, take only respective part
  - selected ions have fixed energy
  - weigh with contribution to Maxwellian

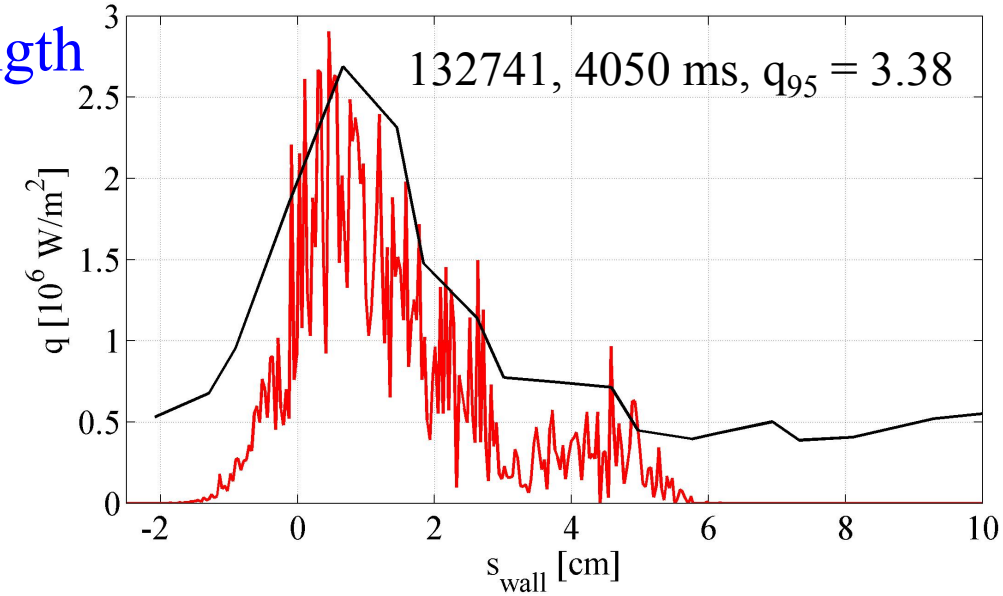
→ footprint of average energy per ion

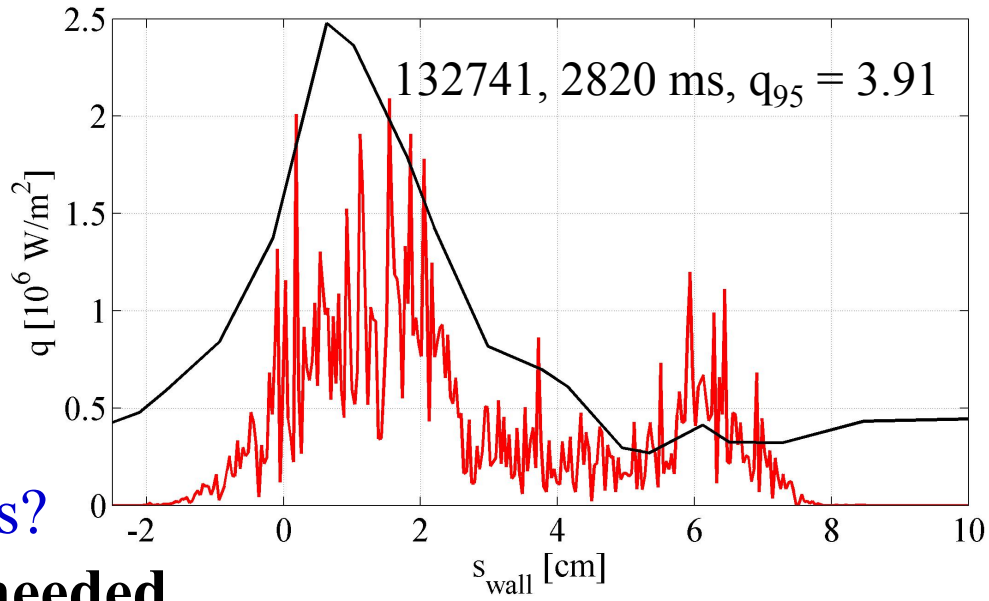
heat flux = density x v_{th} x energy per particle

Calculated heat flux agrees qualitatively and quantitativly with measurements

- Electron and ion connection length
- Calculated heat flux from drifting ions
- Measured heat flux with RMP







Role of electrons?

Ambipolar electric fields?

Further investigation needed

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Vacuum + self consistent electric fields

- Vacuum approach:
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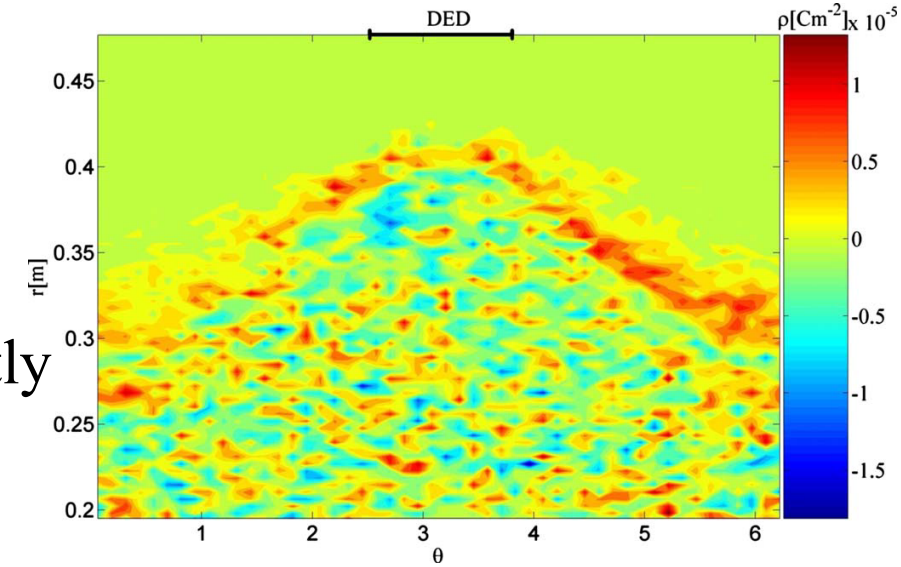
Electrical fields generated by charge separation due to drifts

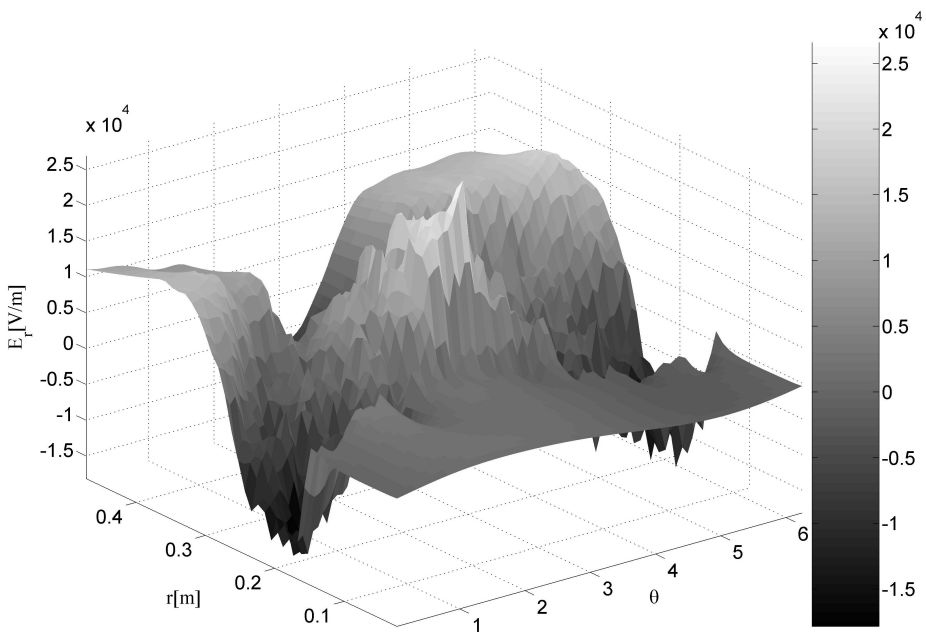
Drift orbits of electrons and ions deviate

→ local area charge density

→ radial electric field

→ add as perturbation, self-consistently





$\vec{E} \times \vec{B}$ drift

causes plasma rotation

Effective poloidal rotation:

average drift velocity over one poloidal turn along flux surface

A. Wingen *et al.*, PoP **15**, 052305 (2008)

Poloidal plasma rotation changes with increasing perturbation current

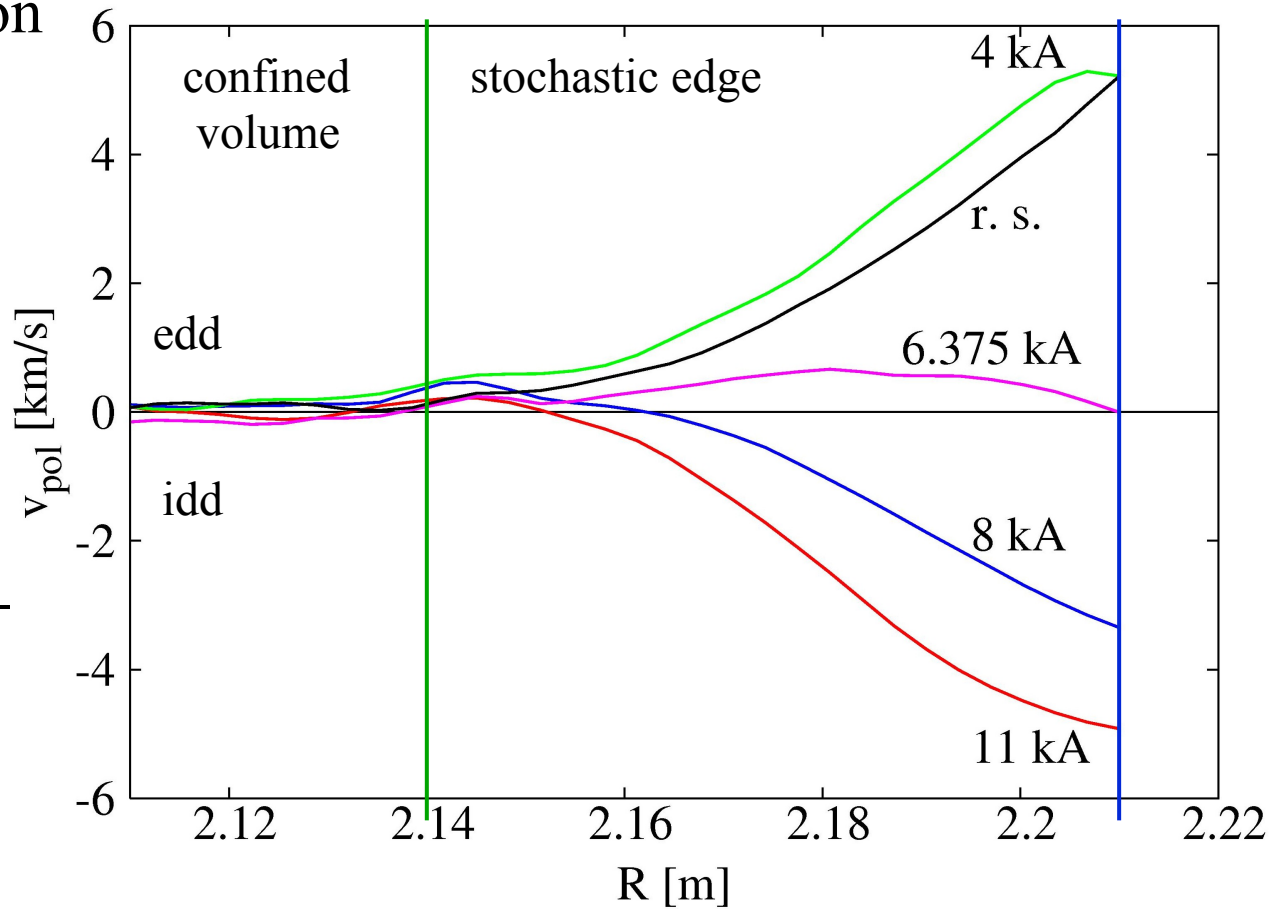
I_0 = 0 kA (r. s.) → 4 kA → 6.375 kA → 8 kA → 11 kA

spin up in idd - direction for large perturbation
→ rotation reverses

All profiles are alike up to 1 cm inside the stochastic zone

Low perturbations cause spin up in edd – direction

Rotation drops to zero for 6.375 kA at LCFS



A. Wingen *et al.*, PRL **102**, 185002 (2009)

Increasing perturbation breaks particle surfaces differently

Consider N_0 test particles below the last closed particle surface

Escape rate: $N(t) = N_0(N_1 + e^{-\lambda t})$

Scaling: $\lambda \sim (I_0 - I_c)^2$ and $\lambda = 0$ for $I_0 < I_c$

Extrapolate critical perturbation for break up:

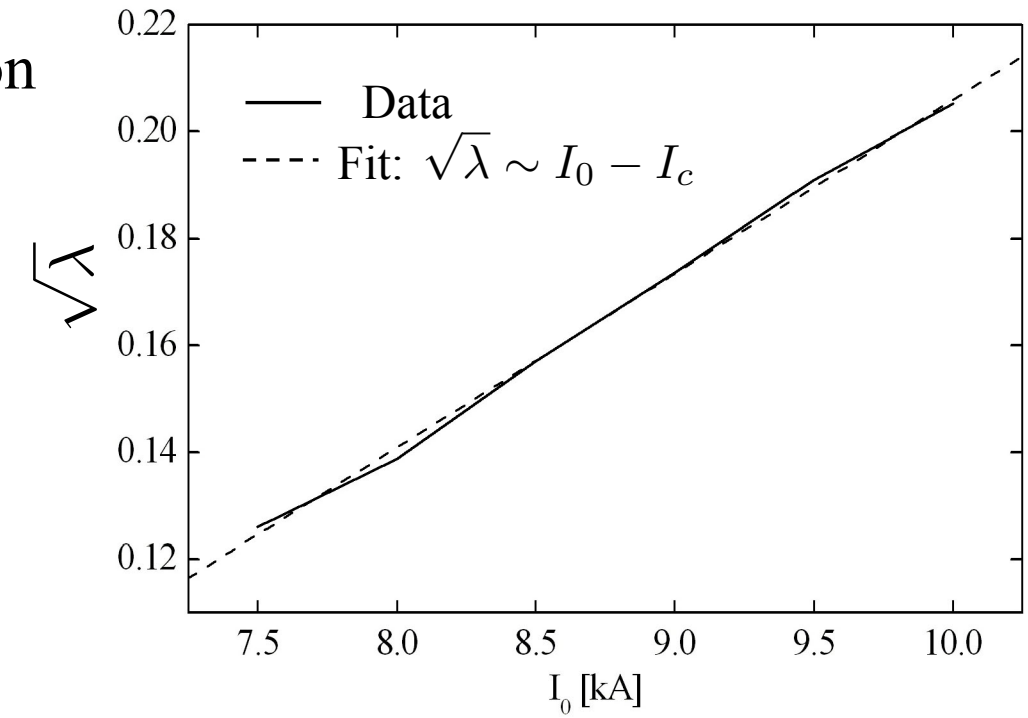
$I_{ce} \approx 3.7\,\mathrm{kA}$ $I_{ci} \approx 2.2\,\mathrm{kA}$

LCIS breaks much earlier than LCES

→ spin up in edd first

Electrons faster

→ spin up in idd later



Vacuum + plasma currents

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Special plasma currents create a self – amplifying edge instability ←→ ELM model

Onset of Edge Localized Mode:

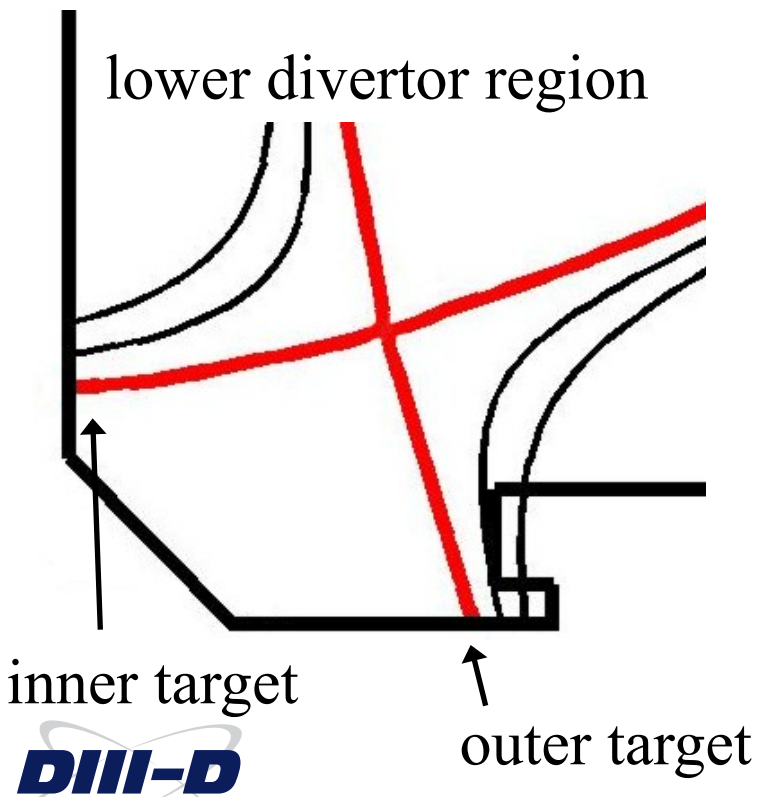
T.E. Evans *et al.*, J. Nucl. Mater. **390-391**, 789 (2009)

Pressure gradient exceeds stability limit

→ instability occurs → Heat pulse

→ Heat pulse transported to targets, but outer target first

→ Temperature difference between inner and outer target



Temperature difference drives thermoelectric currents from outer to inner target

Vacuum Model + perturbation field from currents

→ Model of initial ELM phase

Pathway of the current?

→ Short connection length flux tubes!

Initial flux tubes can carry a small current in a typical lower single null H-mode discharge in DIII-D

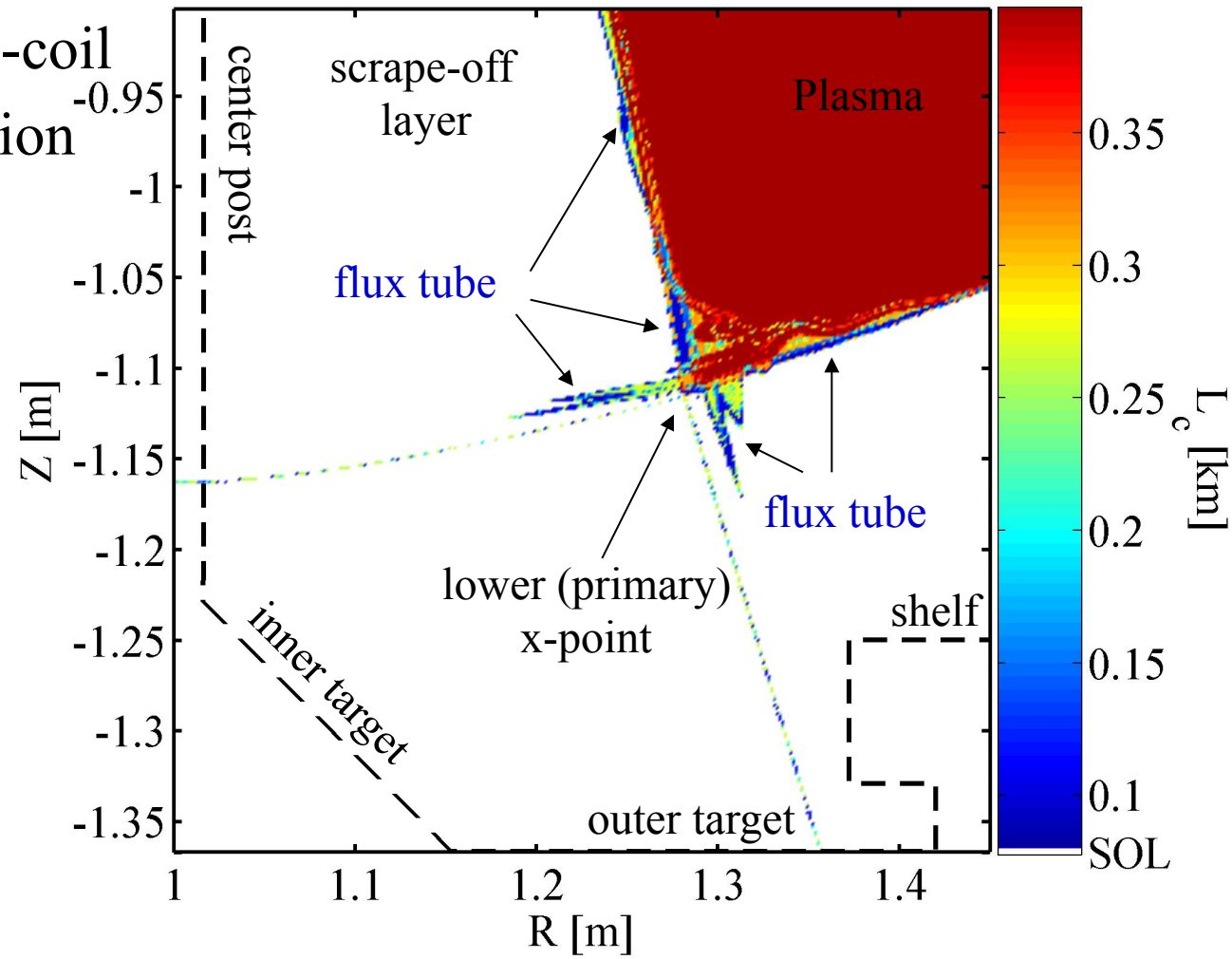
Only error fields and I-coil

- very small perturbation at x-point
- sharp strike point
- one small finger
- regions of short connection length

$$L_c \approx 100 \text{ m}$$

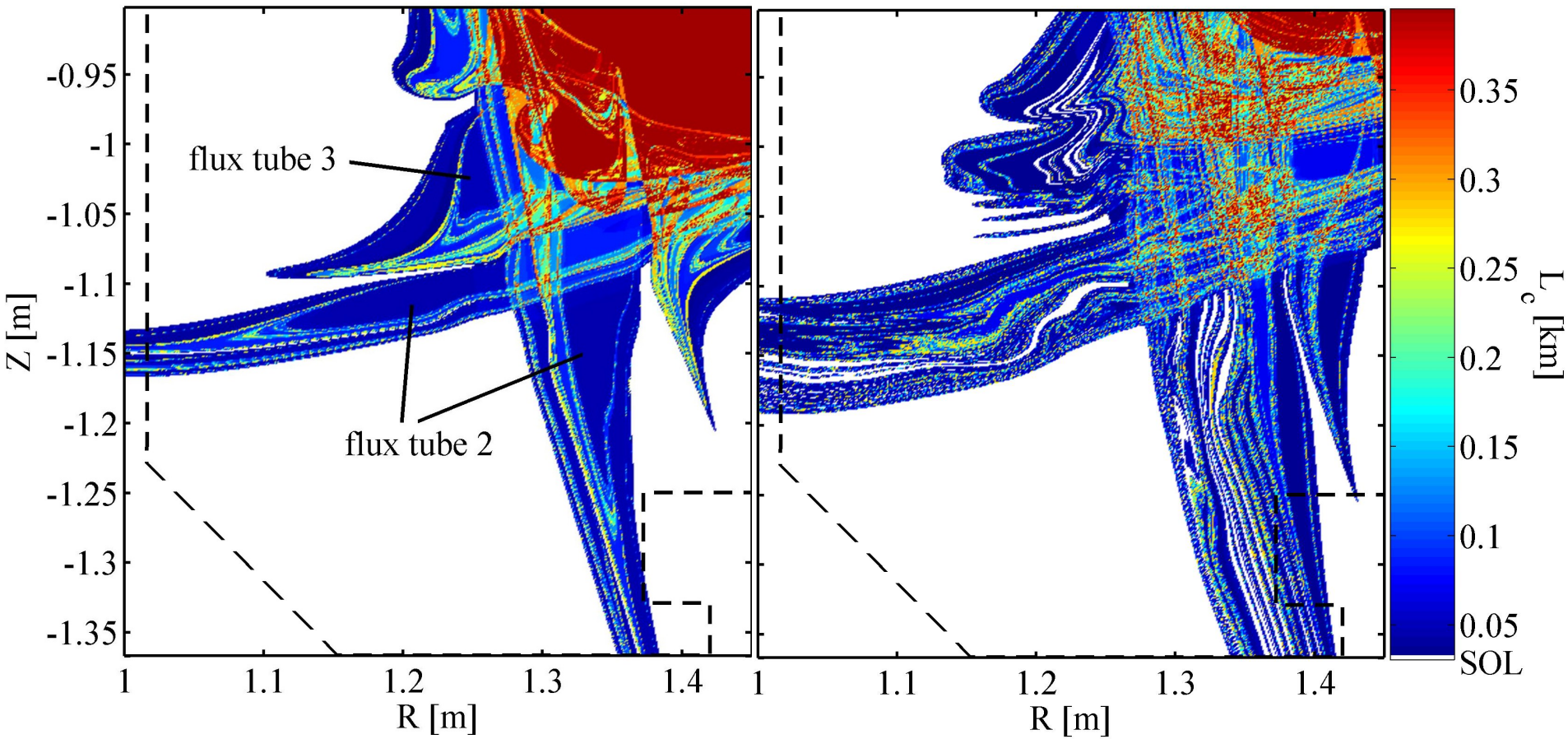
= 2 poloidal turns

One flux tube



Run initial small current, here 300 A, through flux tube

A small initial current generates a self – amplifying change in magnetic structure

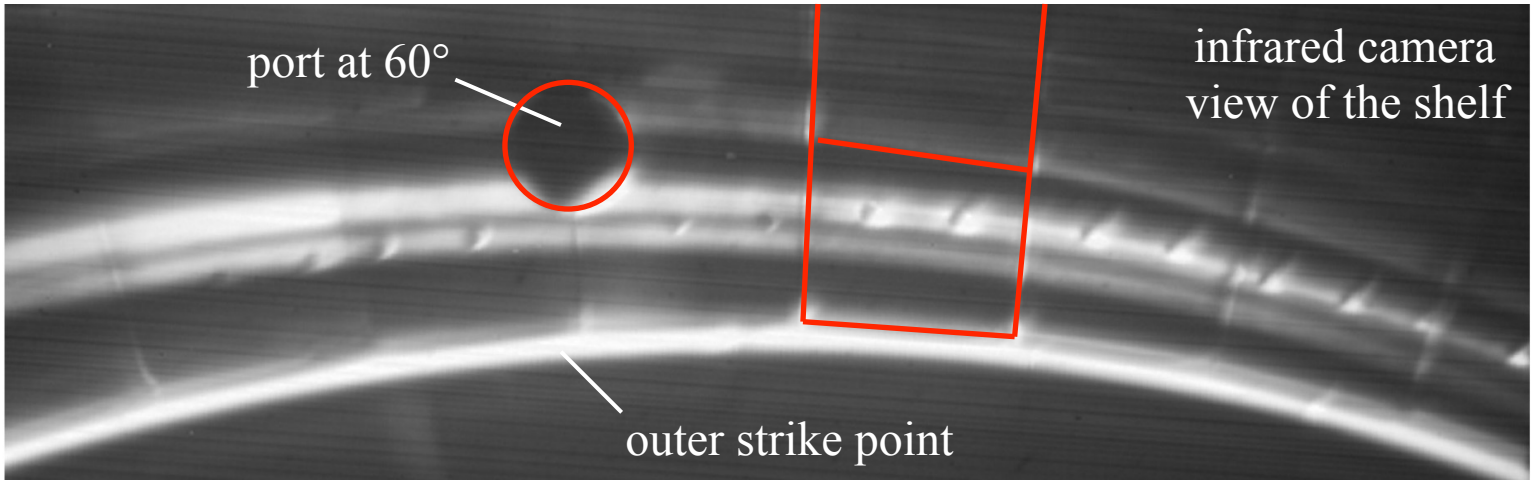


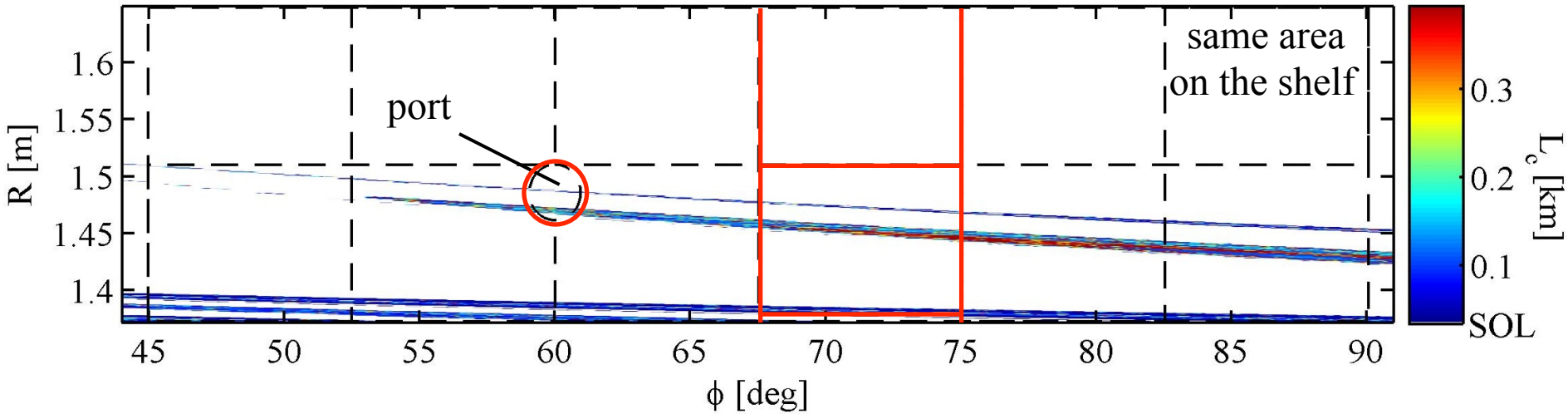
Step 1: new large flux tubes → more current

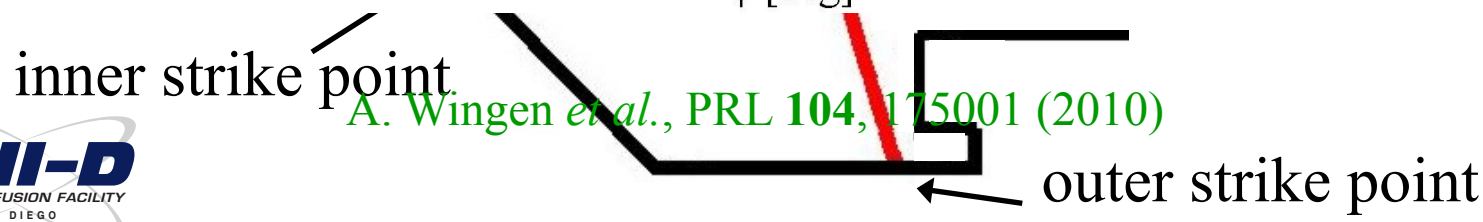
Step 2: 4.6 kA total current → highly perturbed structure

New structures on formerly untouched wall regions

ELM structures on the shelf reproduced numerically by flux tube currents

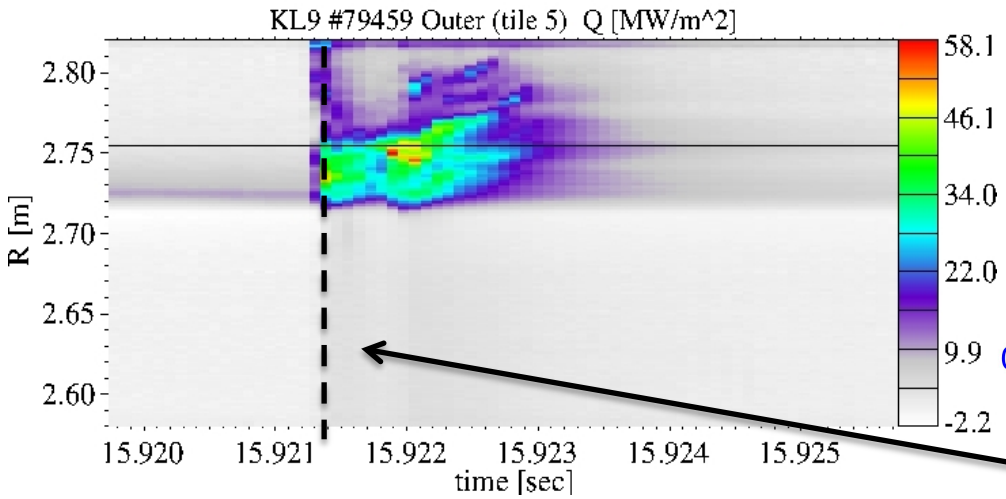




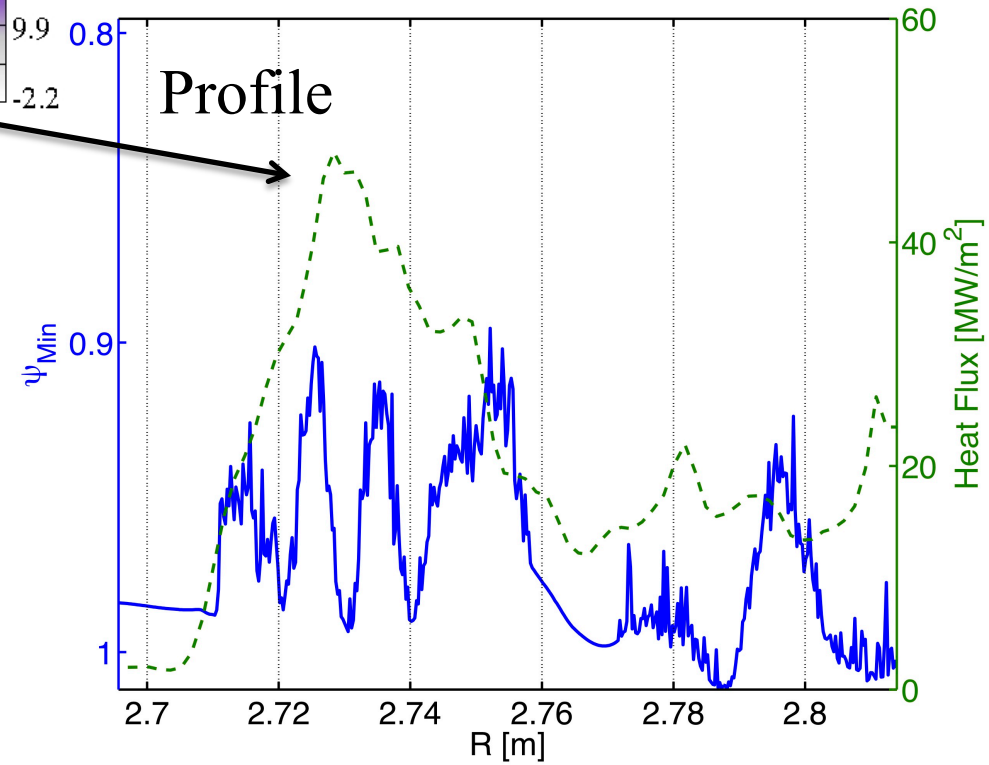


A. Wingen *et al.*, PRL **104**, 175001 (2010)

ELM model shows good qualtiative agreement with initial onset of ELM in JET



Observation of an ELM in JET with infrared camera



Use the ELM model:

- run current in flux tubes
- include magnetic perturbation

→ initial nonlinear growth phase

Penetration depth of field lines:
very good qualitative agreement

M. Rack, A. Wingen, *et al.*, Nucl. Fusion **52**, 074012 (2012)

Many interesting and challenging problems have to be solved to understand fusion plasmas

Like:

- Drift effects
  → heat & particle flux patterns on divertor

- Plasma response
  → ambipolar electric fields
    - $\vec{E} \times \vec{B}$ drift, plasma rotation
  → plasma currents
    - instabilities
    - screening currents, field penetration

- Tokamak: ELM control, ELM modelling

- Measurement and vizualization of plasma edge structures by e.g. soft X-ray diagnostic, ...

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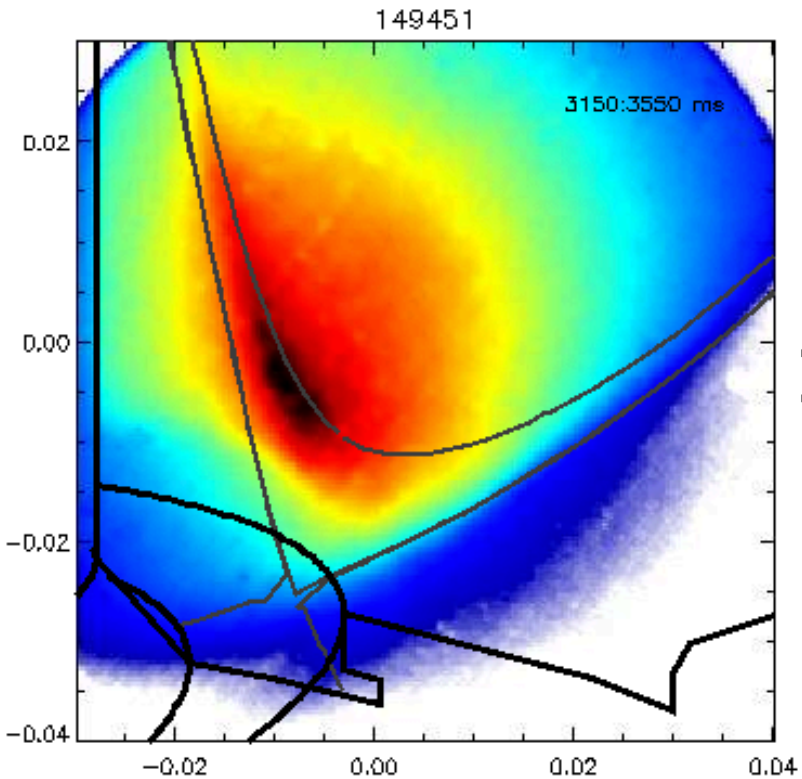
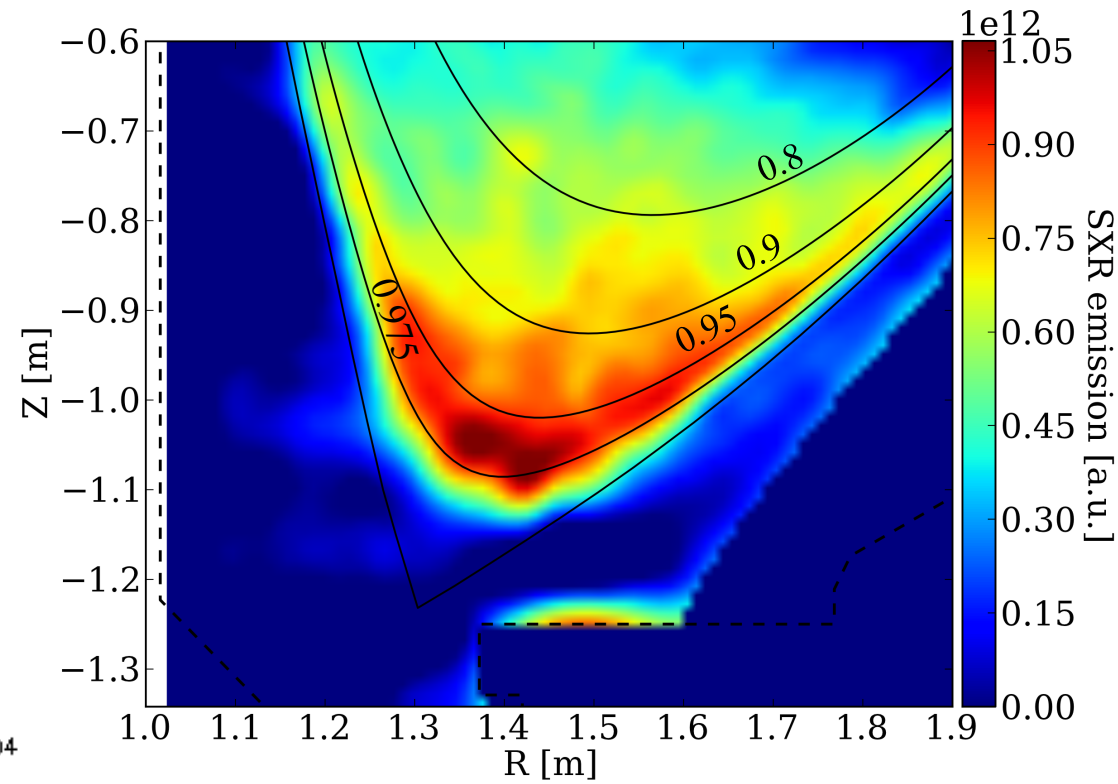
Preliminary, first result from SXR data inversion

line integrated camera data



inversion



Summary

- First principle studies on Hamiltonian systems
  → numeric tools like mapping, footprints, manifolds, etc.
  → Visualization of magnetic topology in existing devices

- Heat flux pattens in L-mode plasmas
  → good agreement with vacuum predictions

- Heat & particle flux patterns in H-mode
  → Plasma effects no longer negligible
  → Ion drifts seem to be important

Summary

- Particle drift effects
  - → Different electron and ion drifts generate electric fields
  - → Ambipolar electric field adds $\vec{E} \times \vec{B}$ drift
  - → Poloidal rotation; changes due to RMP in TEXTOR
- Plasma currents
  - → ELM modeling shows good agreement in DIII-D and JET