The science program of the TCV tokamak: exploring fusion reactor and power plant concepts

S. Coda for the TCV team*

*including collaborating institutions:

CEA, France
CNRS/AMU, France
LPP Palaiseau, France
LCIS, Grenoble INP, France
U. Grenoble, France
F-Z Jülich, Germany
IPP Garching, Germany
IPNP, Hungary
Consorzio CREATE, Italy
ENEA-CNR Milan, Italy
TUe, The Netherlands
DIFFER, The Netherlands
IST, Portugal
RRC Kurchatov, RF
NRNU MEPhI, RF
EHU, Spain
U. York, UK
Lehigh U., US
UCSD, US
U. Tennessee, US
Princeton U., US

Outline

- Scientific mission of the TCV program
- Present and future capabilities of TCV
- Scientific results
  - Heat exhaust: conventional and advanced concepts
  - H-mode threshold
  - MHD and integrated instability control
  - Turbulence and zonal flows
  - Turbulence-driven spontaneous rotation
  - New insights into confinement and a new I-mode
- Summary and outlook

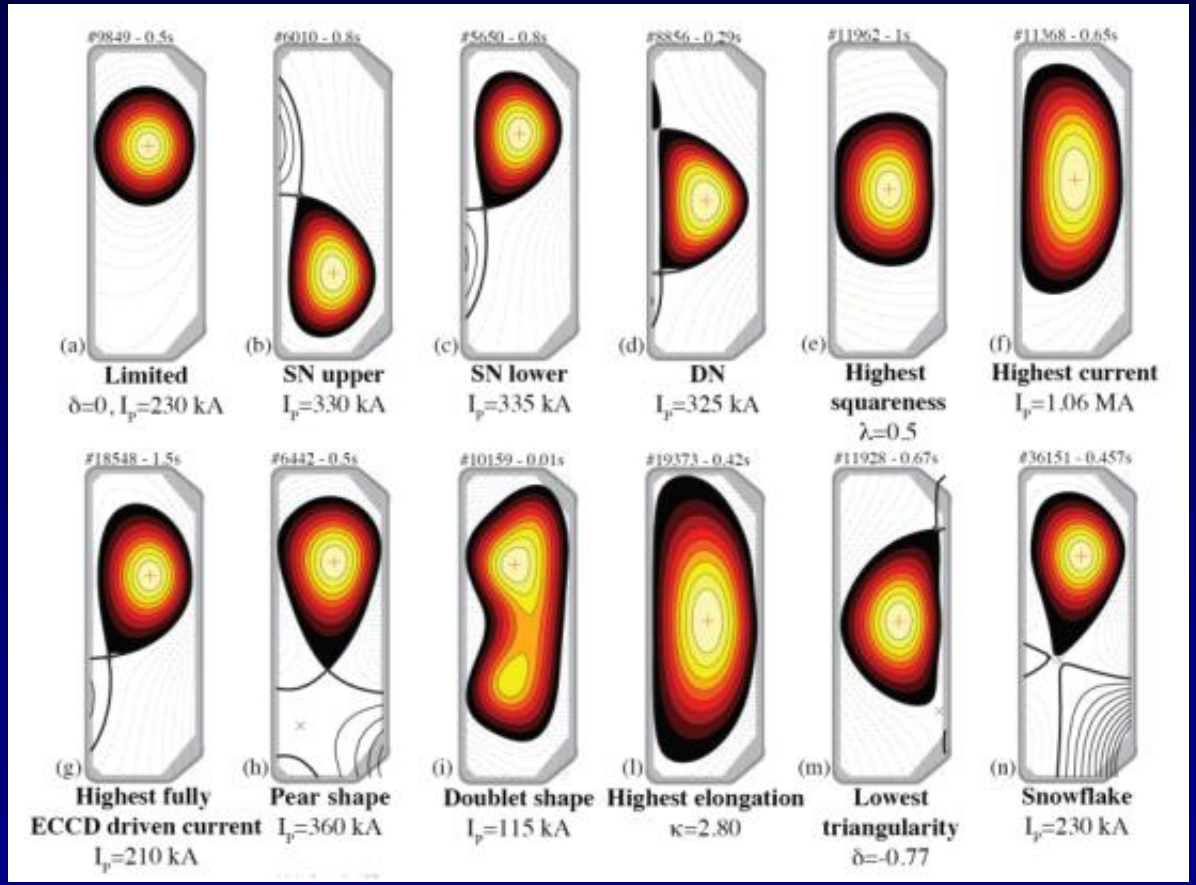
TCV mission

- Investigating fusion science and control techniques for reactor and power plant
  - versatile control tools
  - wide range of scenarios and parameters
- Furthering high-temperature plasma science
  - agile program to respond to new ideas and theoretical challenges

Run from 2015 partly as a European facility within Medium-Size Tokamak (MST) Task Force in EUROfusion program

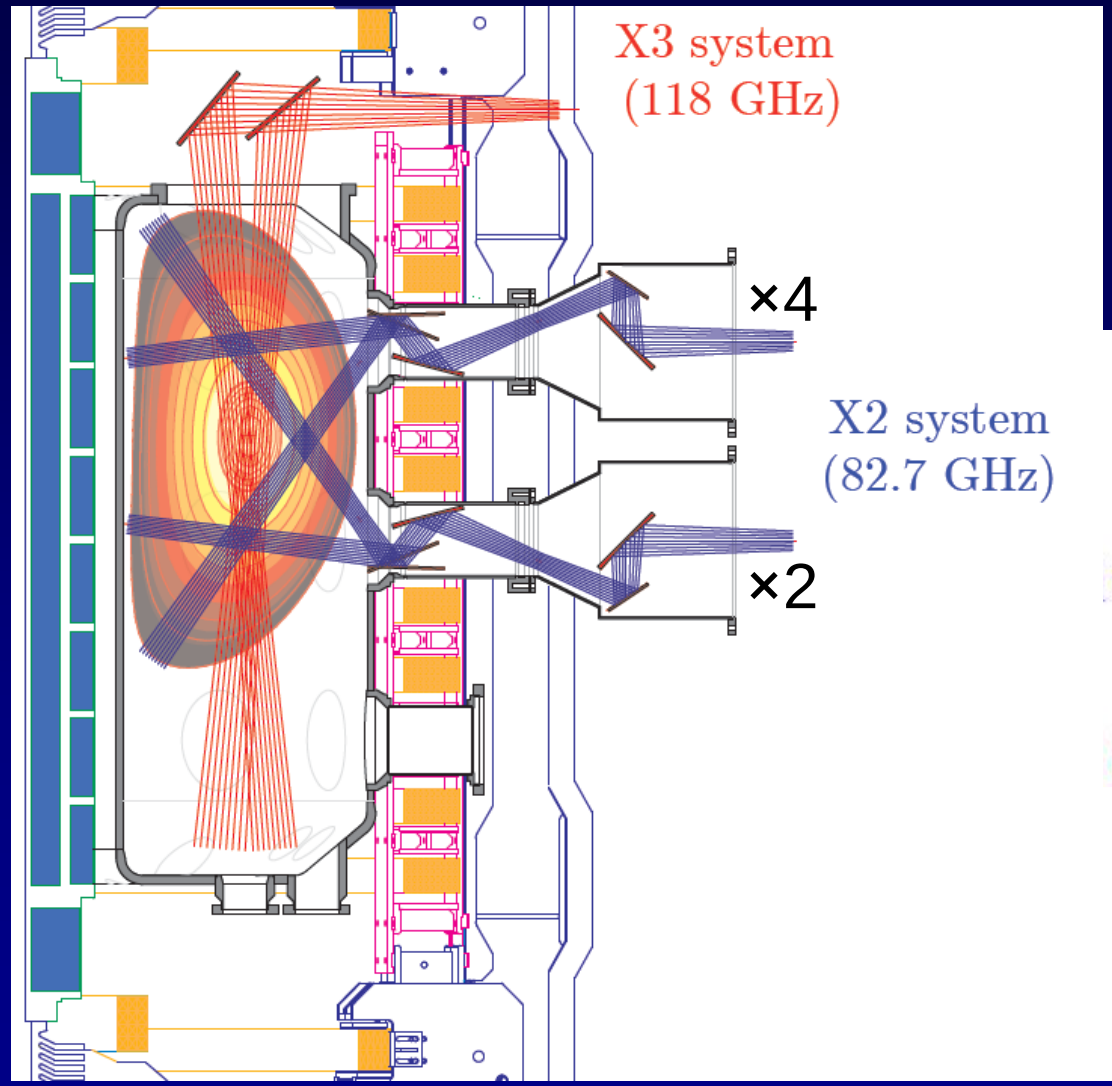
TCV

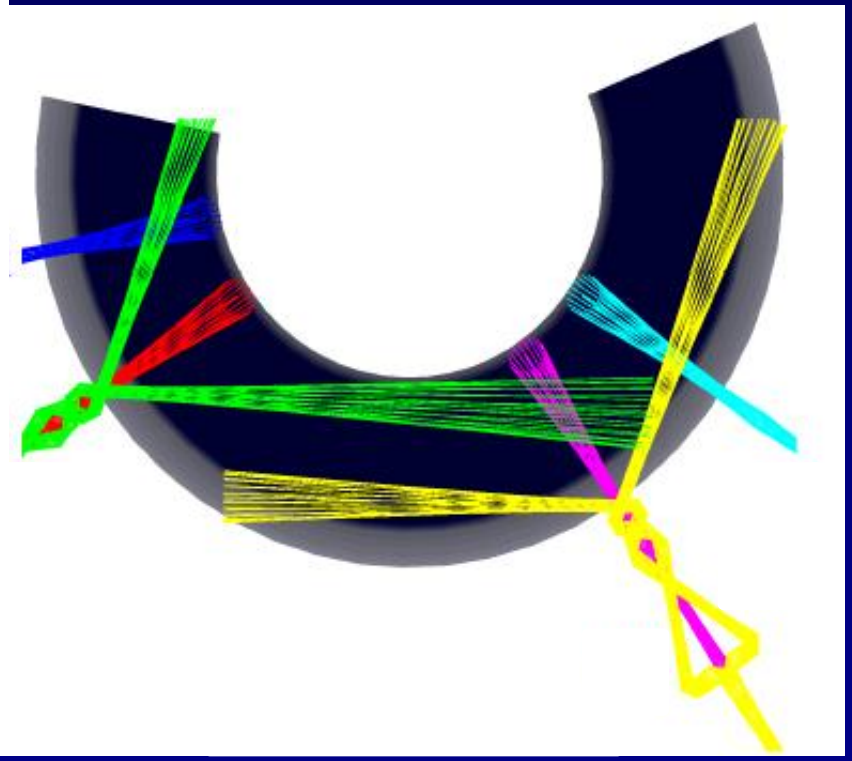
- R/a = 0.88/0.25 m
- I_p < 1 MA
- B_T < 1.54 T
- n_e = 1-20×10^{19} m^{-3}
- κ < 2.8
- -0.6 < δ < 0.9
- graphite wall



TCV

2014: 2.5 MW ECRH power, 6 steerable launchers





TCV

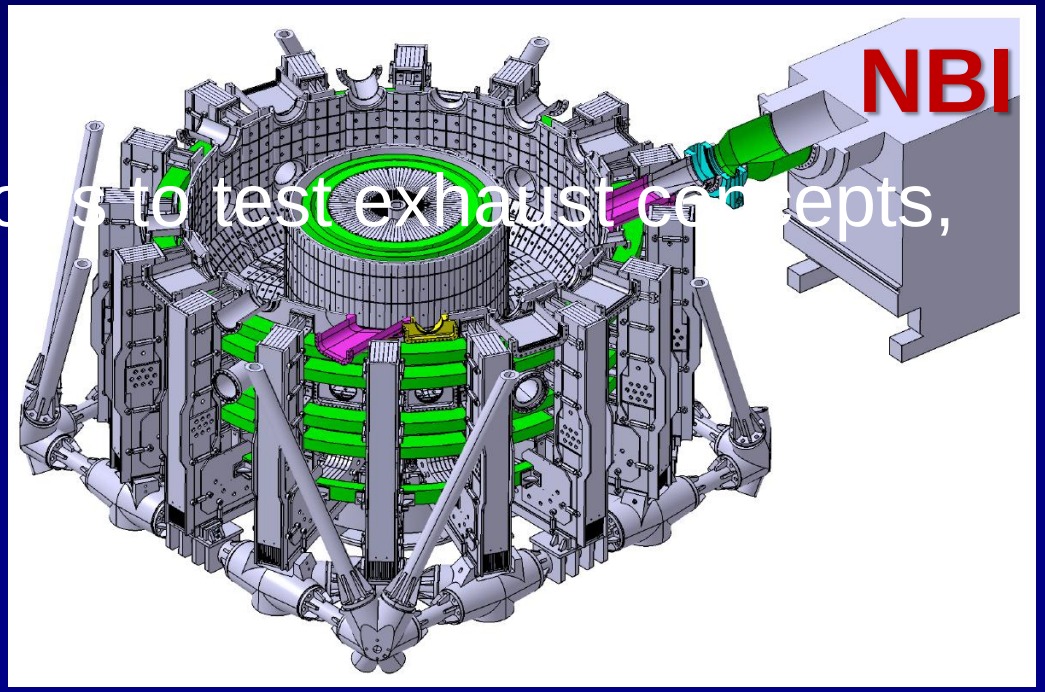
2014: 2.5 MW ECRH

2015: + 1 MW NBI ⇨ β_N=2.4, $T_e \sim T_i$=2.5 keV
+ diagnostic upgrades

2016: 4 MW ECRH

2018: 5 MW ECRH ⇨ β_N=2.8

20??: additional NBI,
vessel modifications to test exhaust concepts,
?



see also A. Fasoli et al, FIP/P7-7 (Friday morning)

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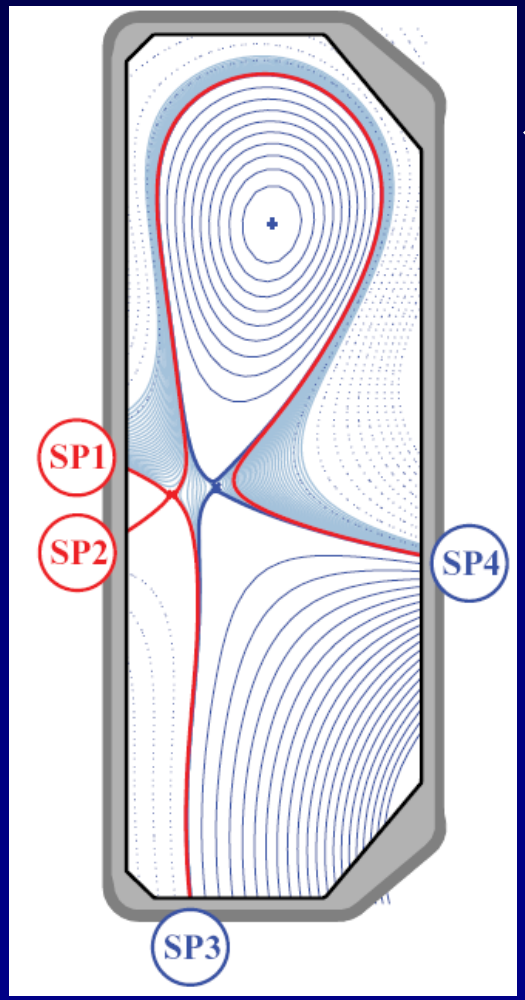
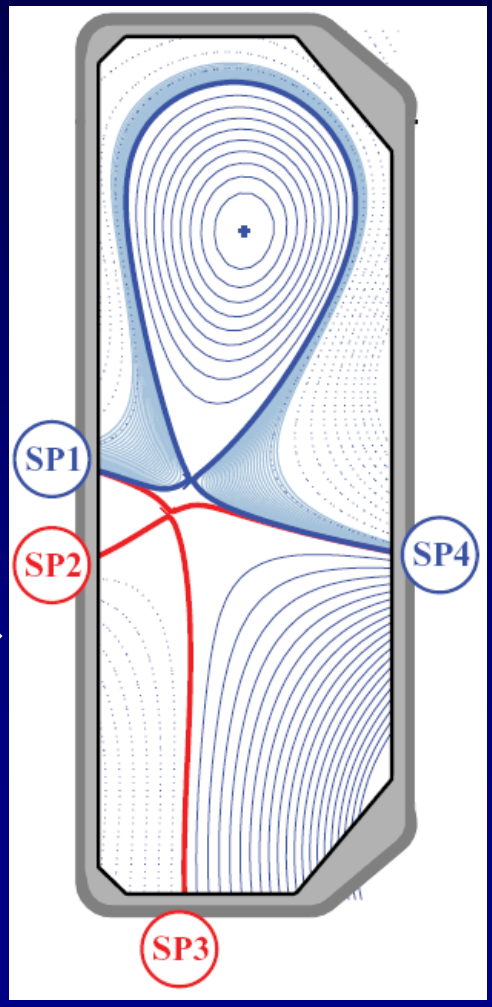
Snowflake vs conventional divertor: reduced peak heat flux, enhanced transport into private region

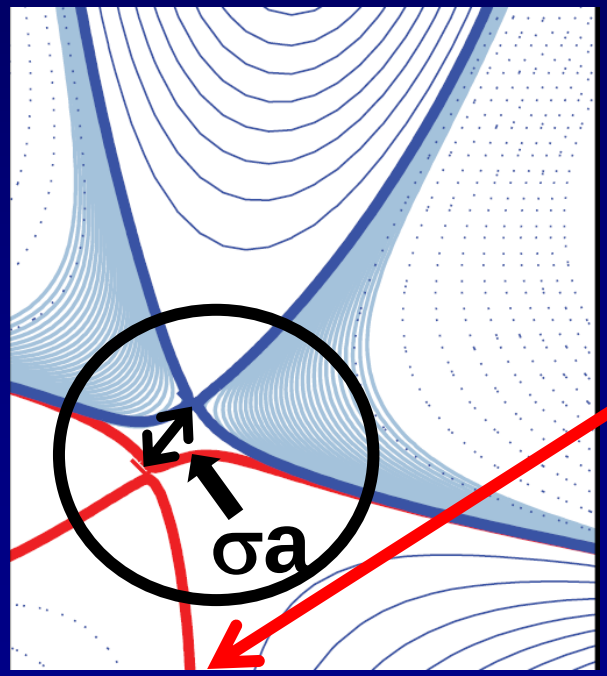


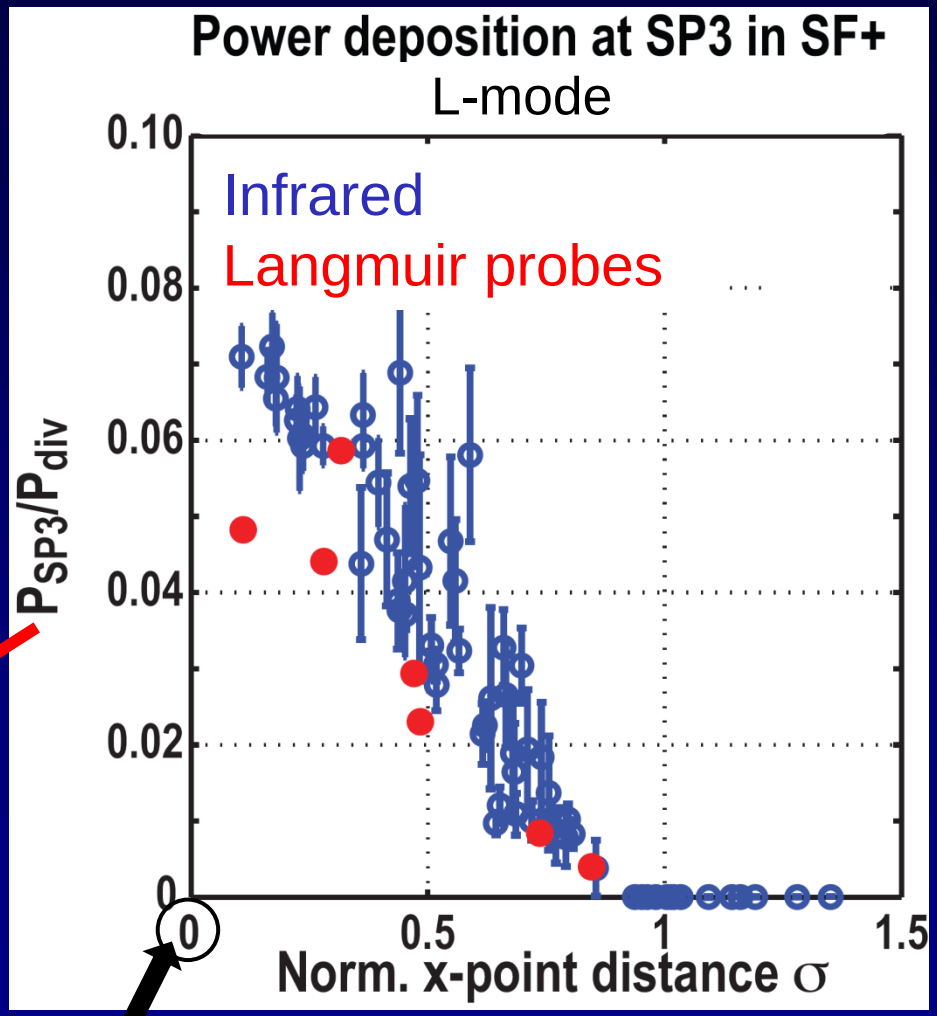
SF-

SF+



Power channeled to extra strike points is substantial even for "imperfect" SF

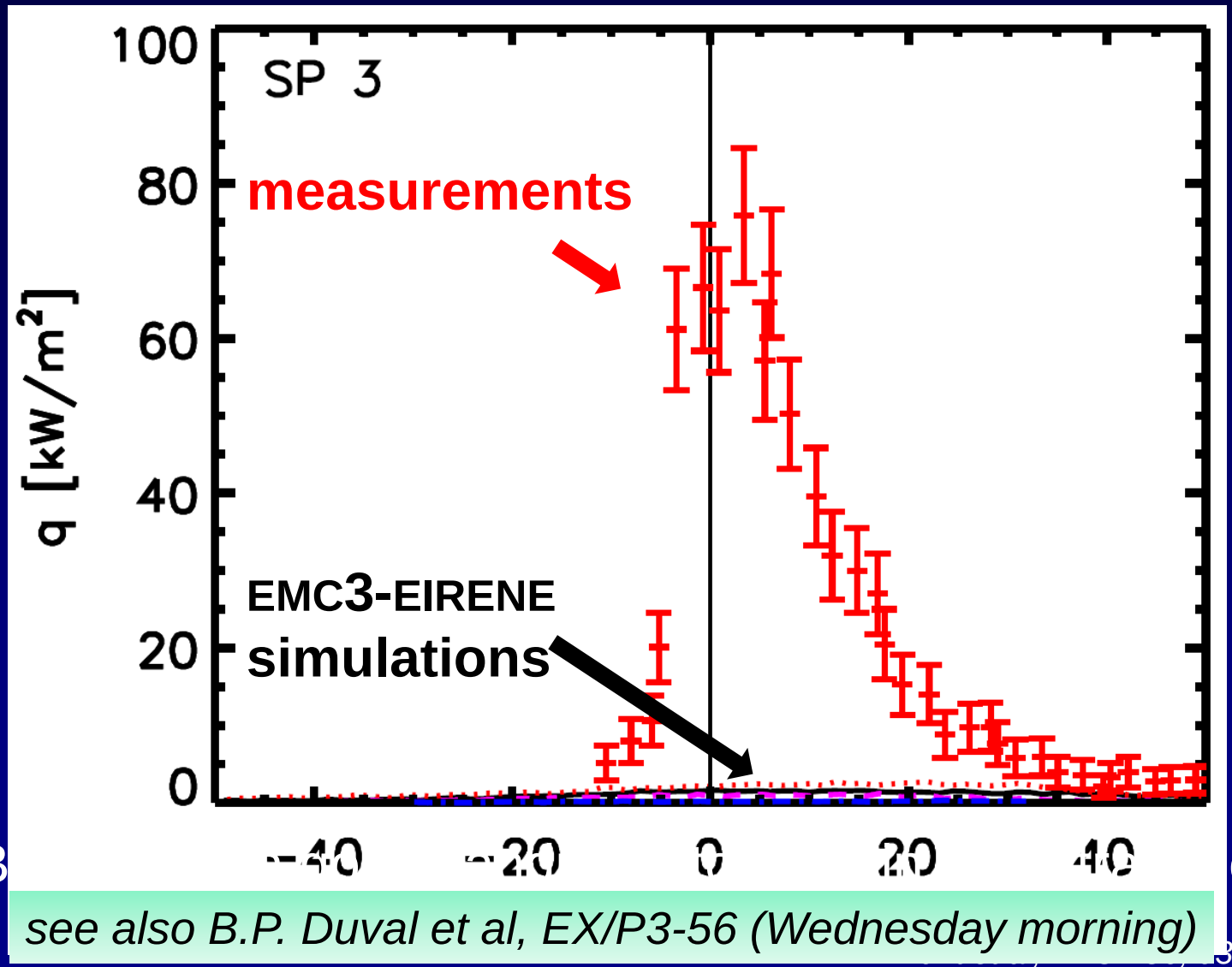




perfect SF

*H. Reimerdes et al, PPCF **55**, 124027 (2013)*

Simulations greatly underestimate transport into private SF region



ExB

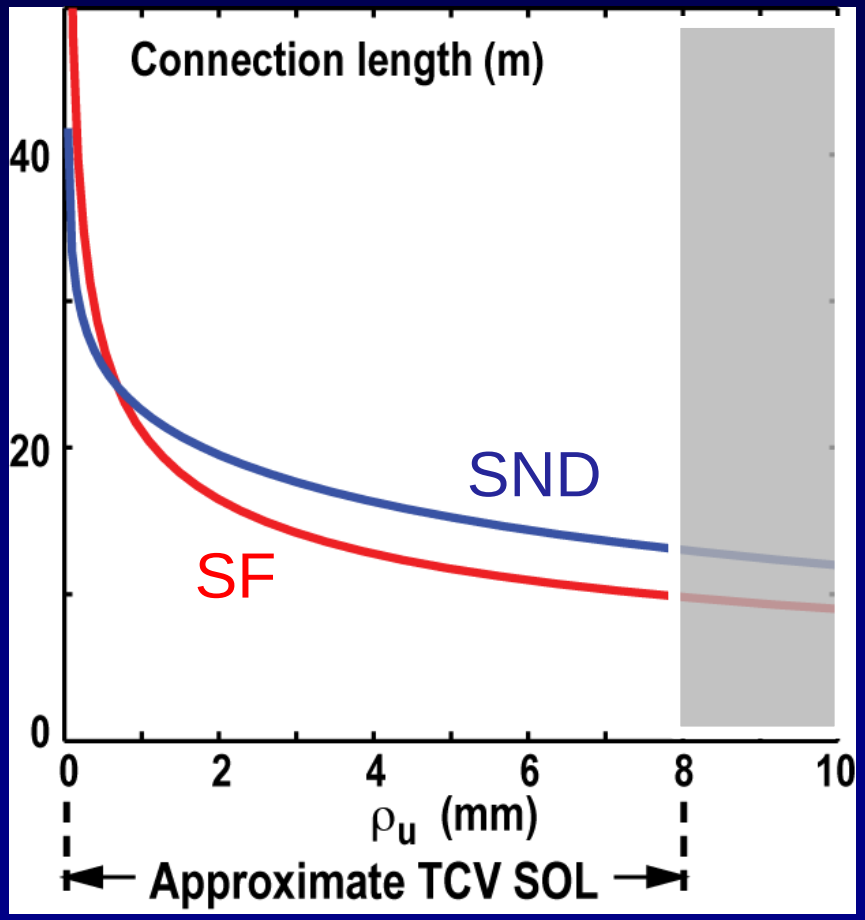
ort

see also B.P. Duval et al, EX/P3-56 (Wednesday morning)

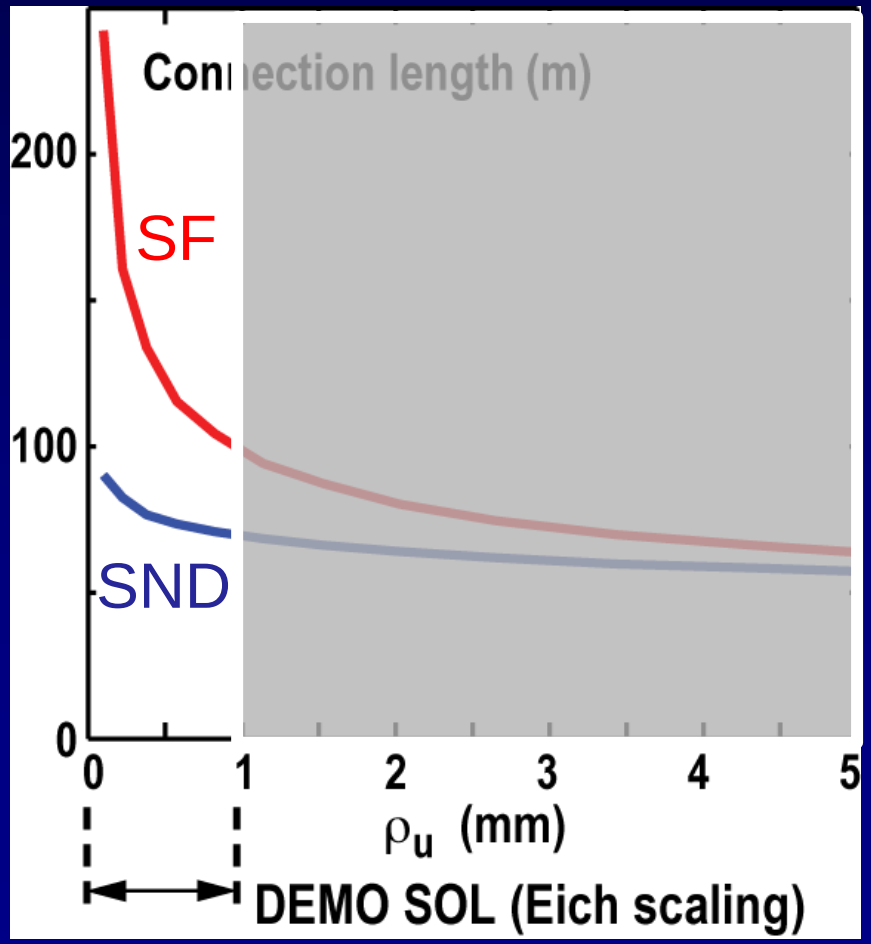
35009 (2014)

SOL not broadened in today's devices but could broaden in DEMO-sized SF

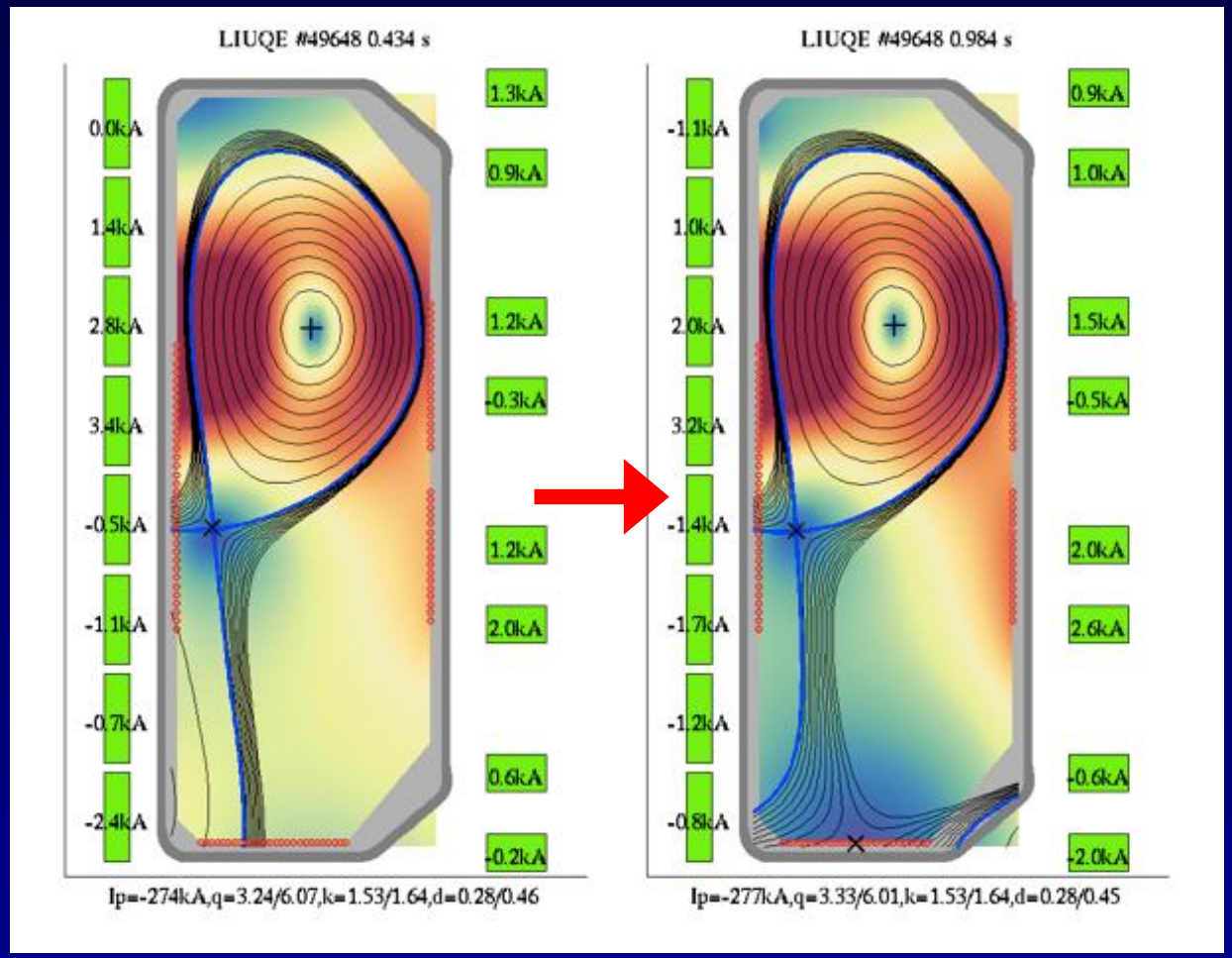
TCV L-mode



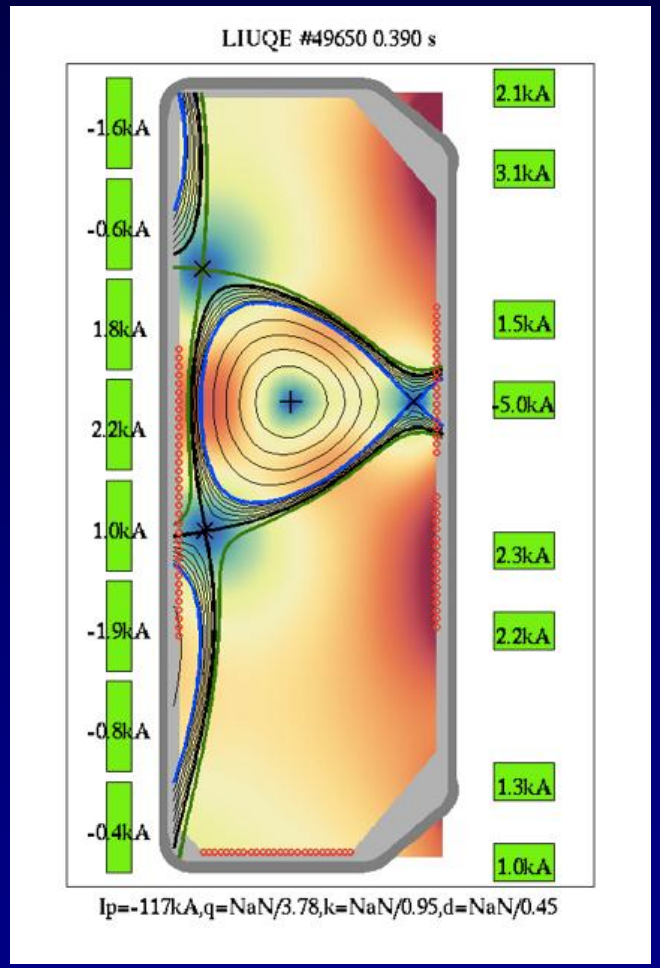
DEMO H-mode



Further exotic shapes prototyped in TCV for future studies



X-divertor (high flux expansion)



Triple-null

W. Vijvers et al, 55th APS, PP8.00047 (2013)

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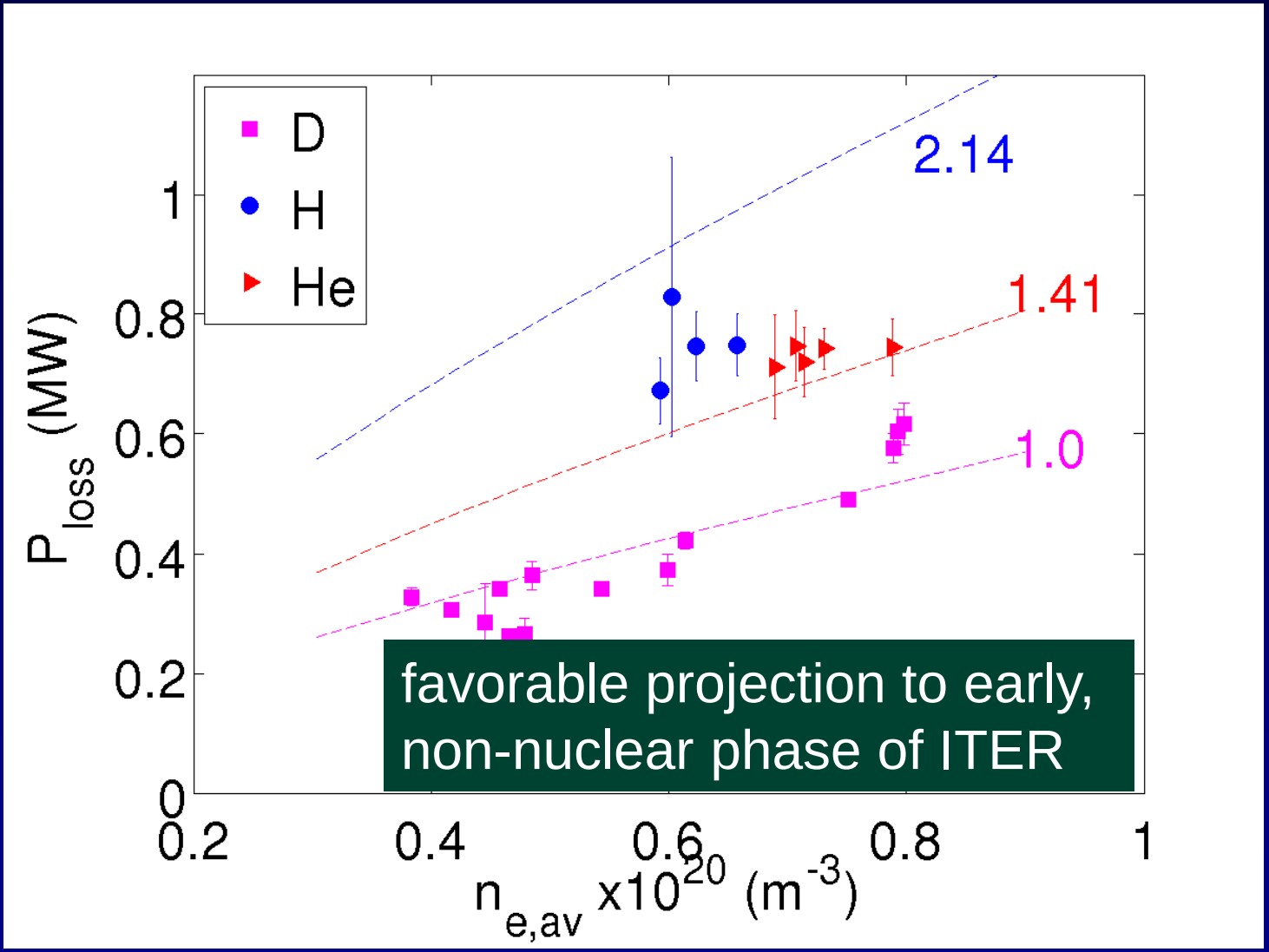
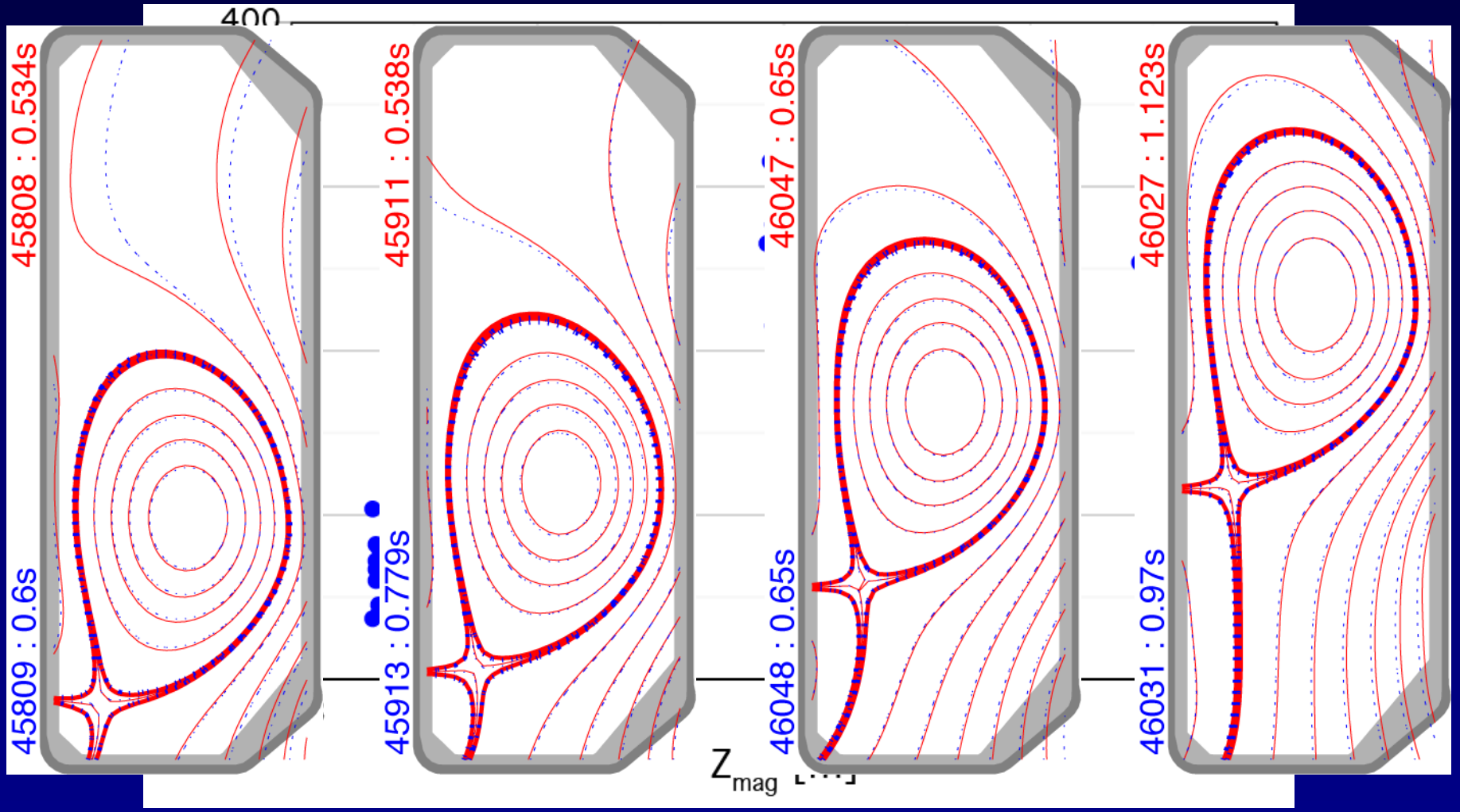
Ohmic H-mode power threshold in hydrogen is lower than expected



R. Behn et al, submitted PPCF (2014)

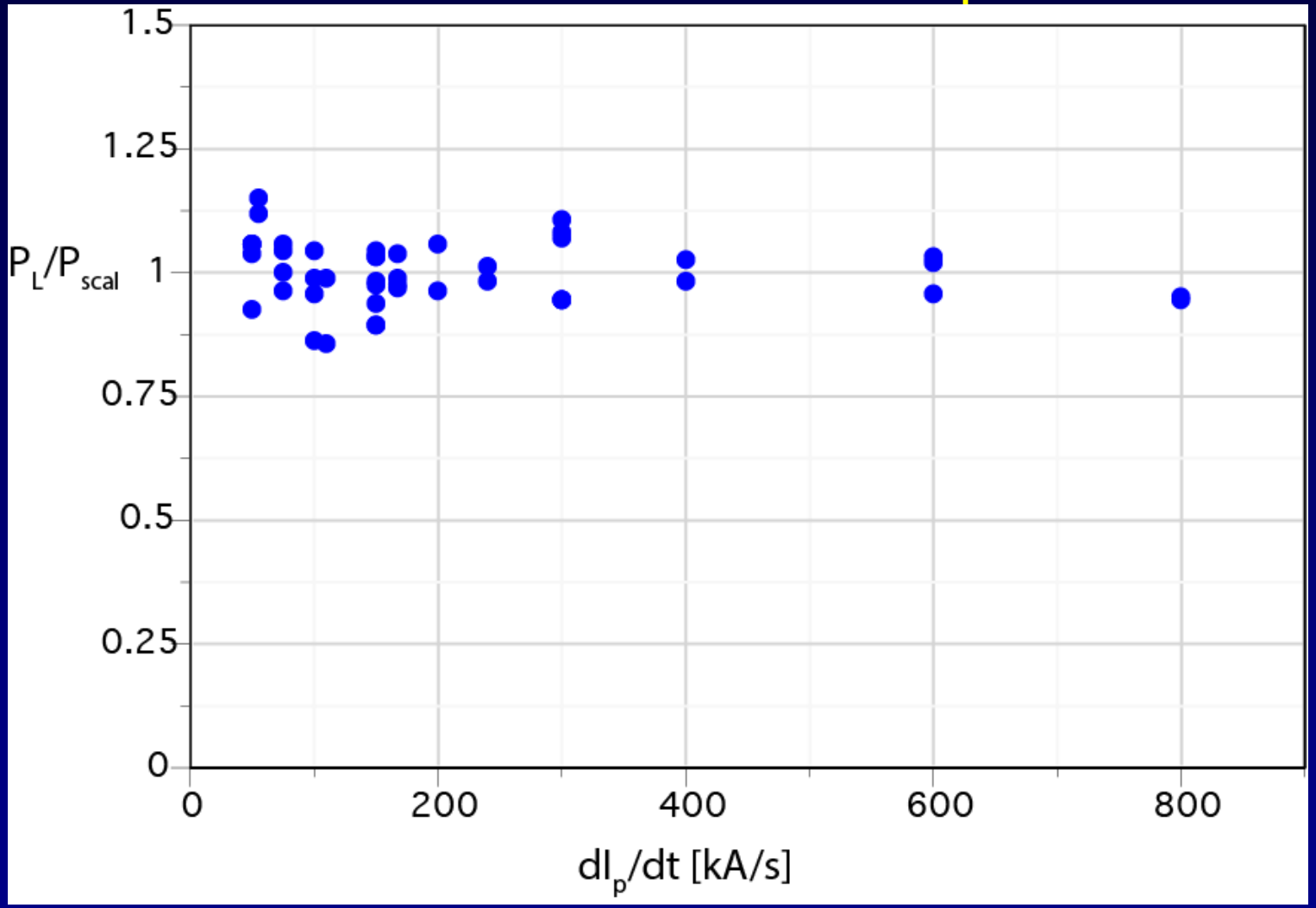
Ohmic H-mode threshold increases with divertor leg length



Scaling refinements required by ITER

Y. Martin et al, H-mode workshop (2013), to be published in NF (2014)

Ohmic H-mode threshold is independent of dI_p/dt



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Integrated control

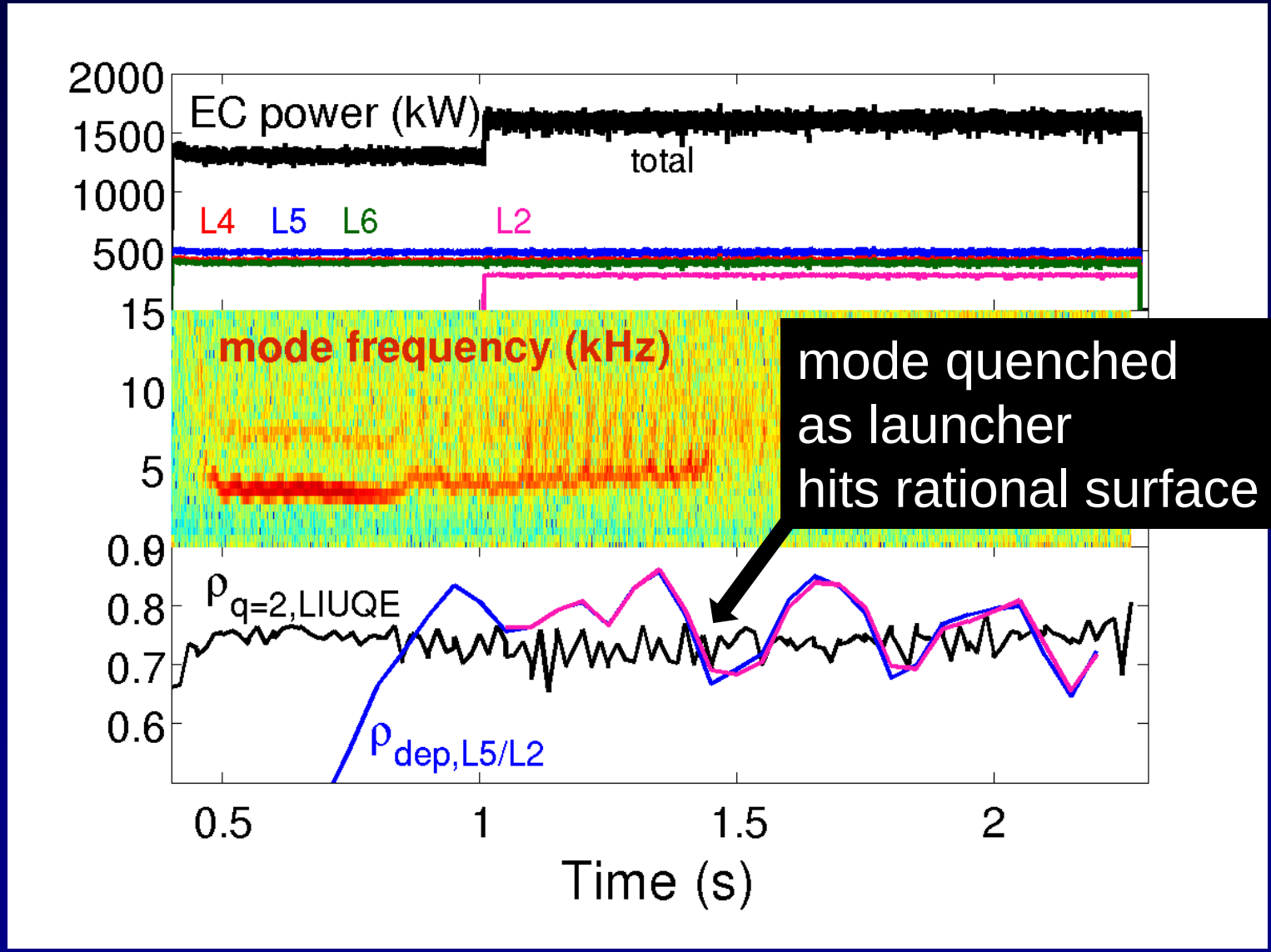
- New r/t version of equilibrium reconstruction code LIUQE runs in 200 μs

⇨ used for new generalized shape/position controller

⇨ used to improve NTM control by ECRH through r/t knowledge of rational surface location

J.-M. Moret et al, accepted Fus. Eng. Design (2014)

Sinusoidal dither improves reliability of NTM control, in both pre-emption and stabilization schemes



T.P. Goodman et al, EC-18 (2014)

MHD and integrated control: additional work

- Study of neoclassical toroidal viscosity and interplay with sawtoothless NTM excitation and spontaneous rotation

see also S. Nowak et al, EX/P2-54 (Tuesday afternoon)

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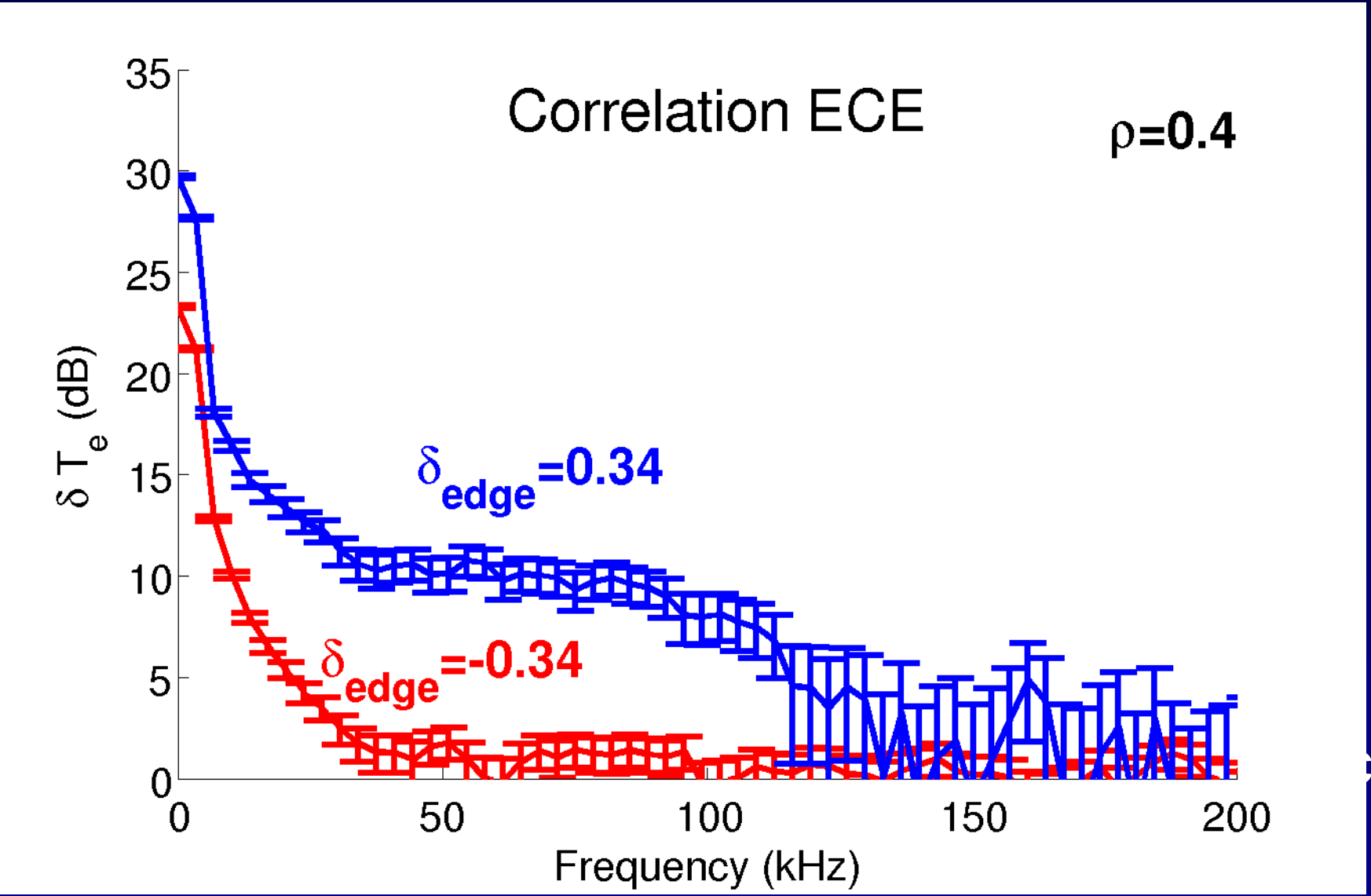
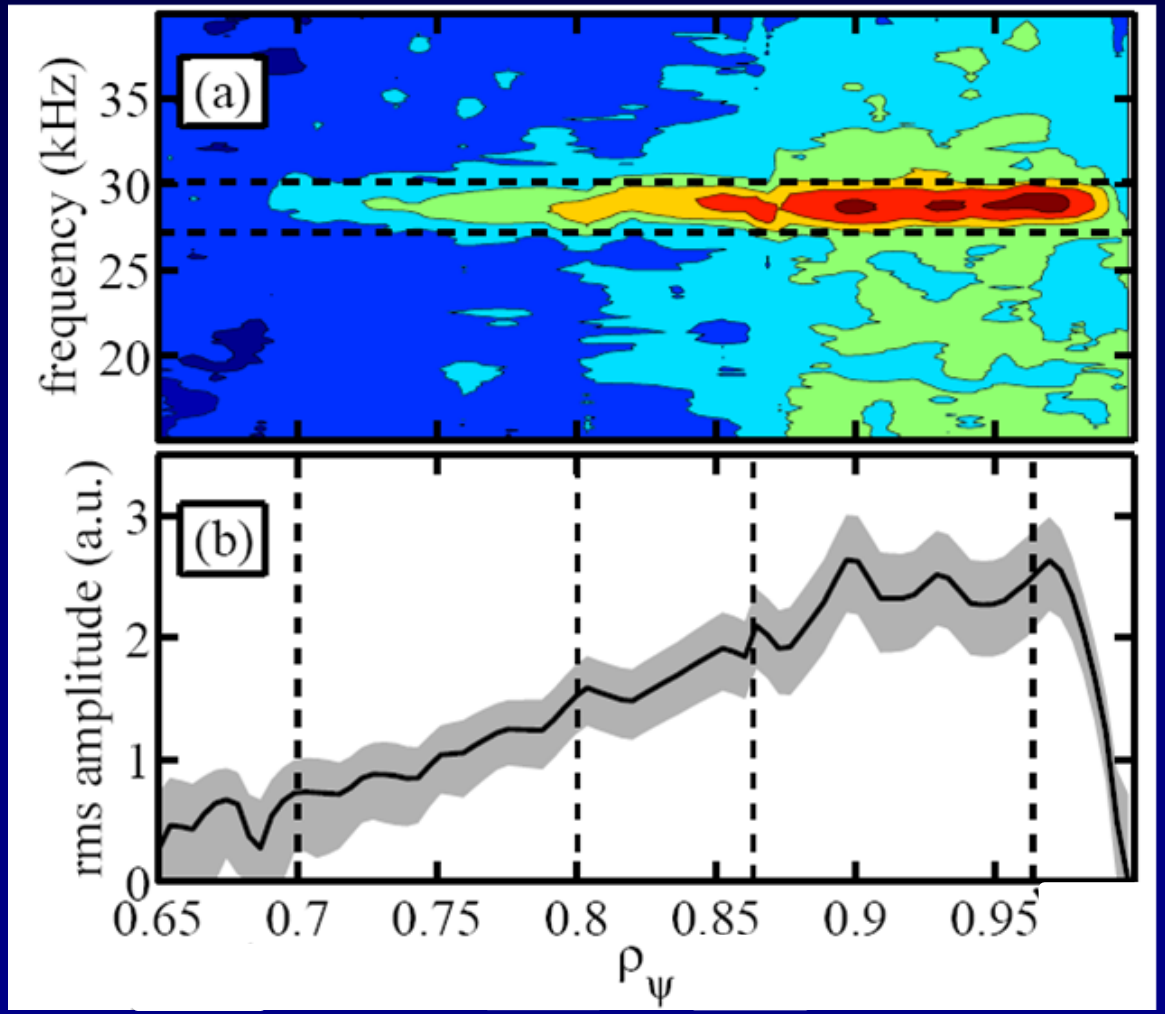
Edge triangularity (which affects global τ_E) also influences core turbulence



Geodesic acoustic mode observed at low *q* as a global eigenmode

δn_e by phase contrast imaging



C.A. de Meijere et al, PPCF ***56****, 072001 (2014)*

GAM seen simultaneously by four diagnostics

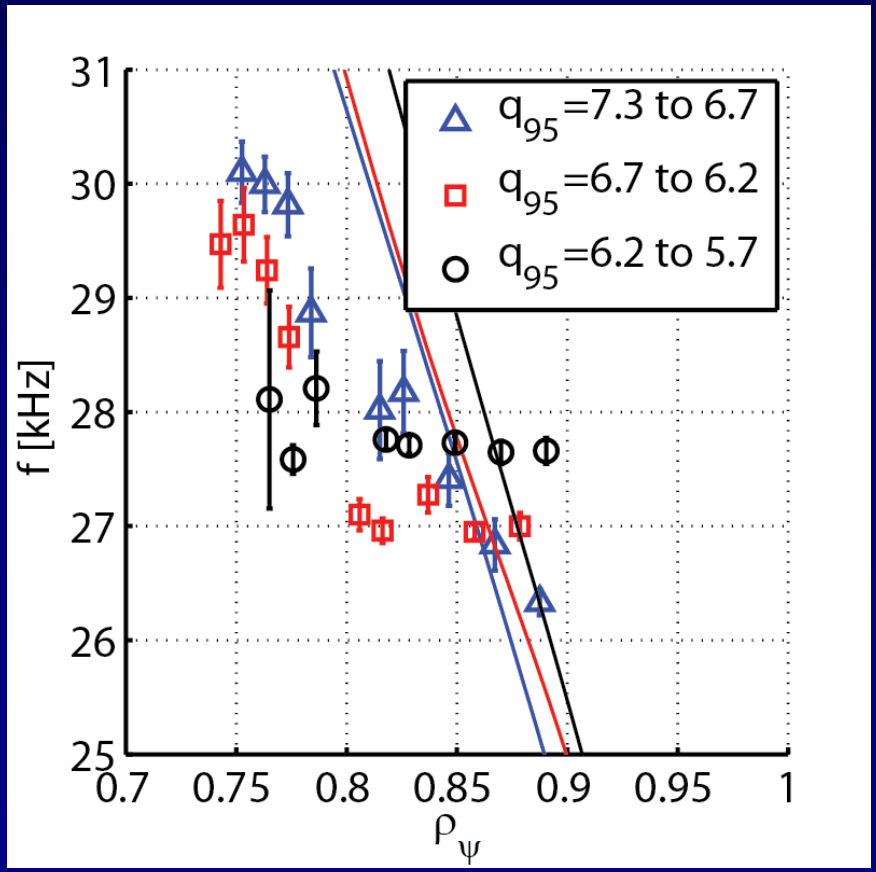
- Phase contrast imaging (δn_e), correlation ECE (δT_e), Doppler backscattering (flow), magnetics (δB)
- All quantities (ω, k, location, etc.) derived through multi-diagnostic coverage

see also L. Porte et al, EX/P3-57 (Wednesday morning)

*C.A. de Meijere et al, PPCF **56**, 072001 (2014)*

GAM structure

- Magnetics confirm axisymmetry and find predicted *m*=2 structure
- Spatially extended eigenmode or dispersive mode depending on parameters (esp. safety factor)



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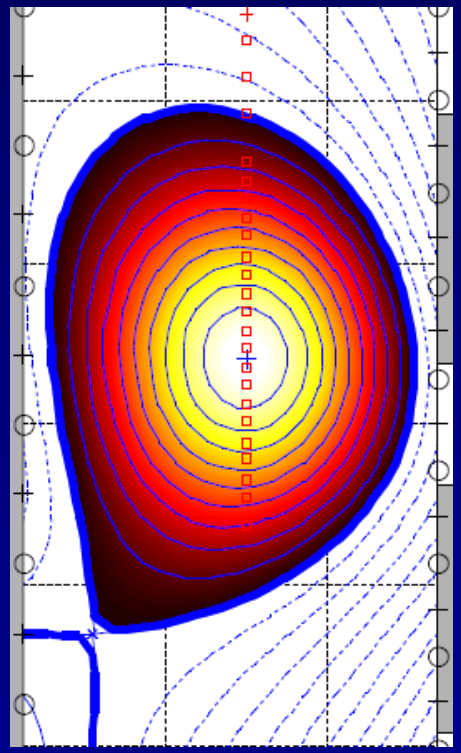
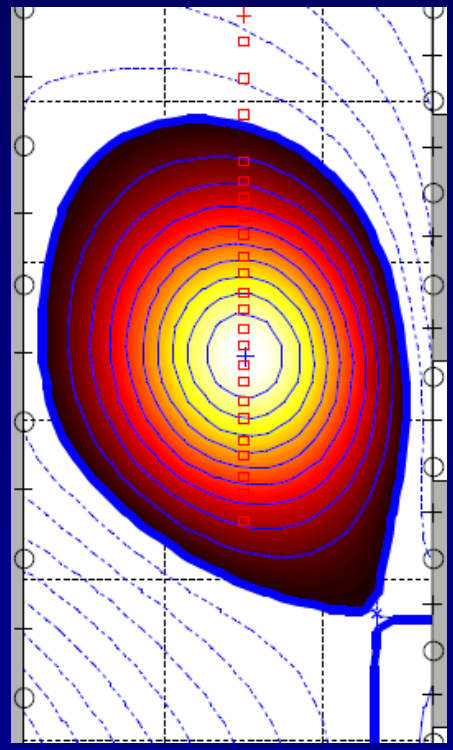
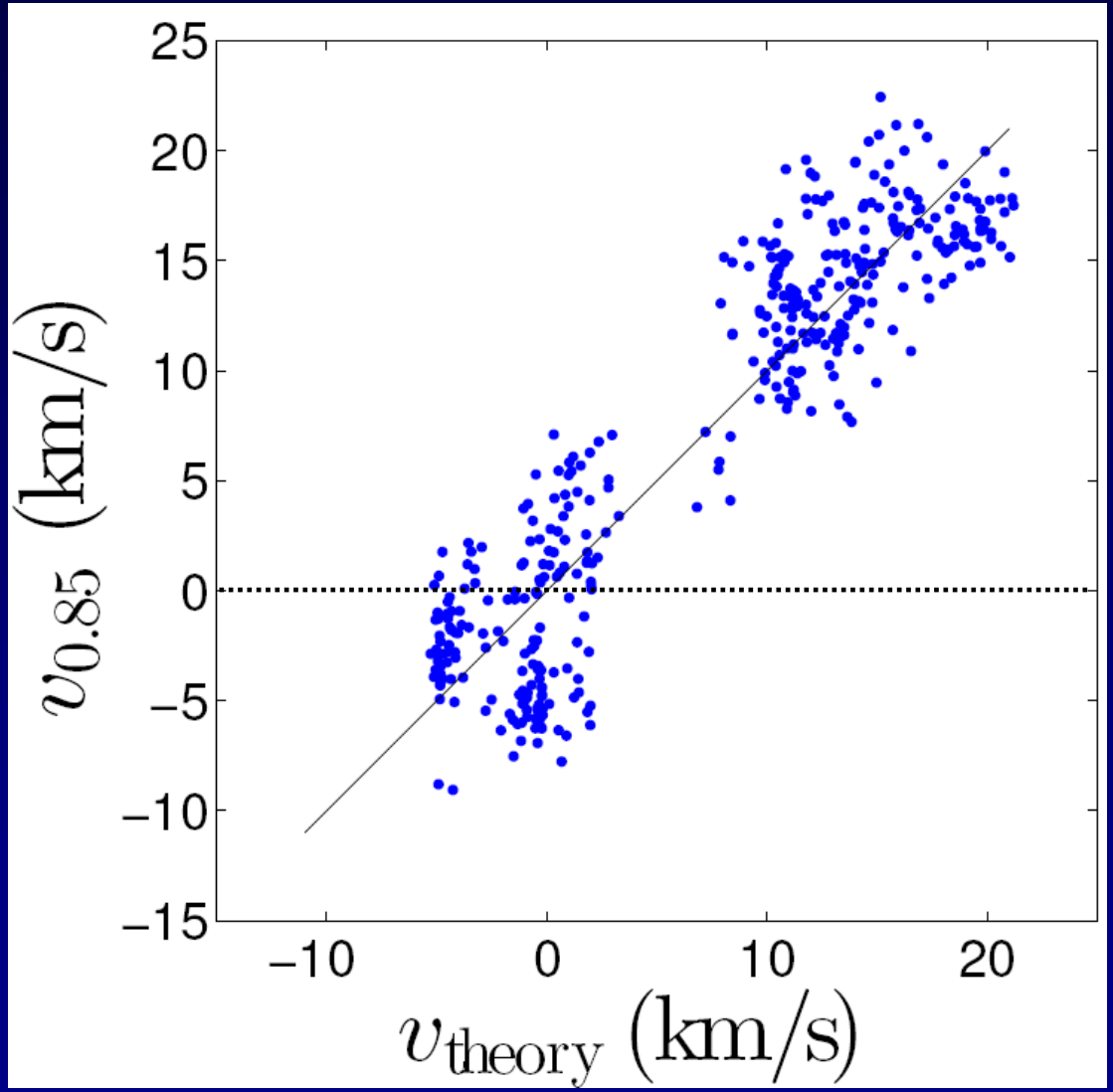
Edge rotation driven by turbulence and co/counter-ion orbit asymmetry

- A new theoretical proposal
- Testable on TCV: predicts linear dependence of toroidal rotation on X-point major radius, with sign inversion for sufficiently outward location





Predicted turbulence-driven edge rotation confirmed in TCV



T. Stoltzfus-Dueck, 56th APS invited (2014)

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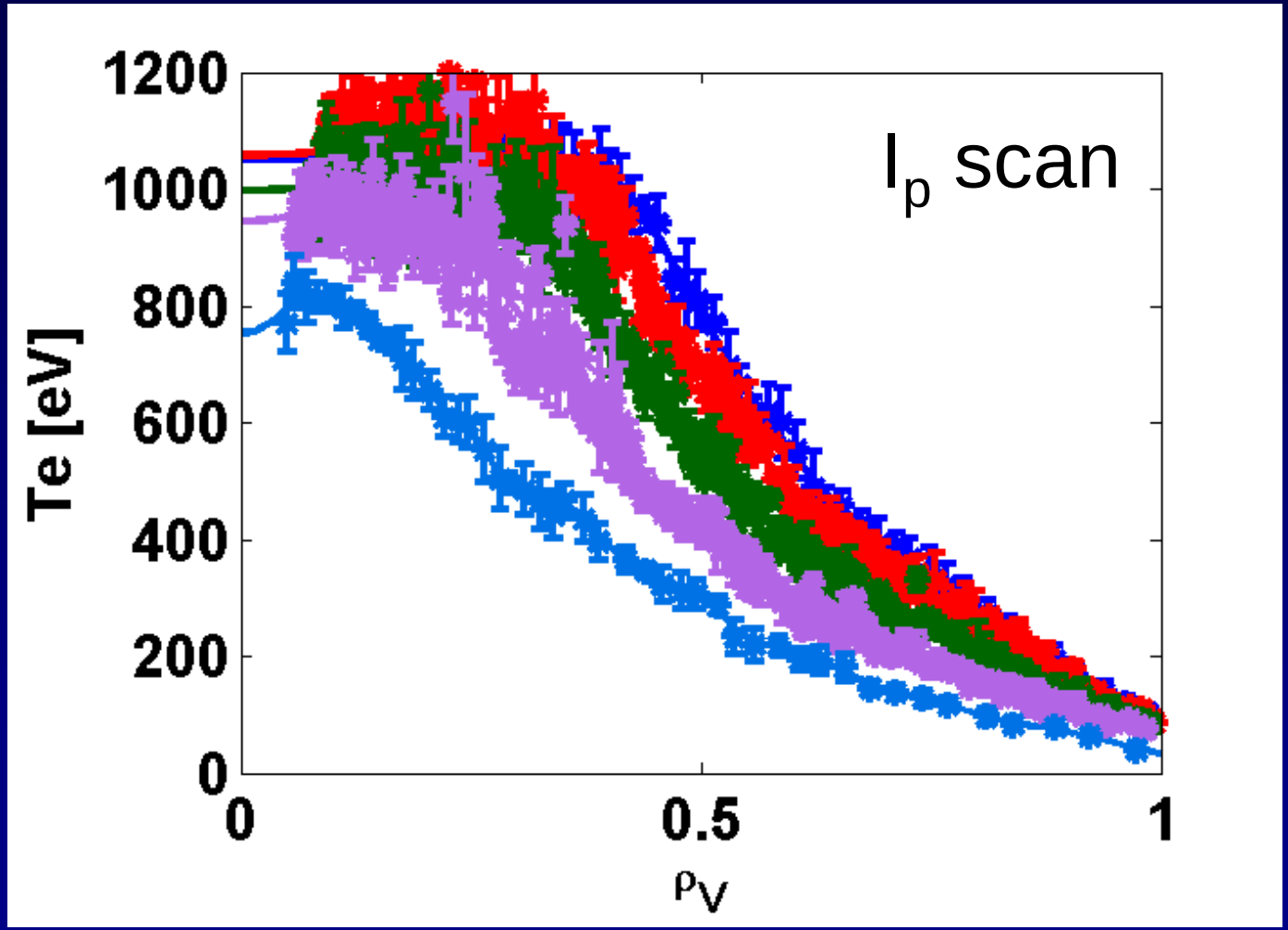
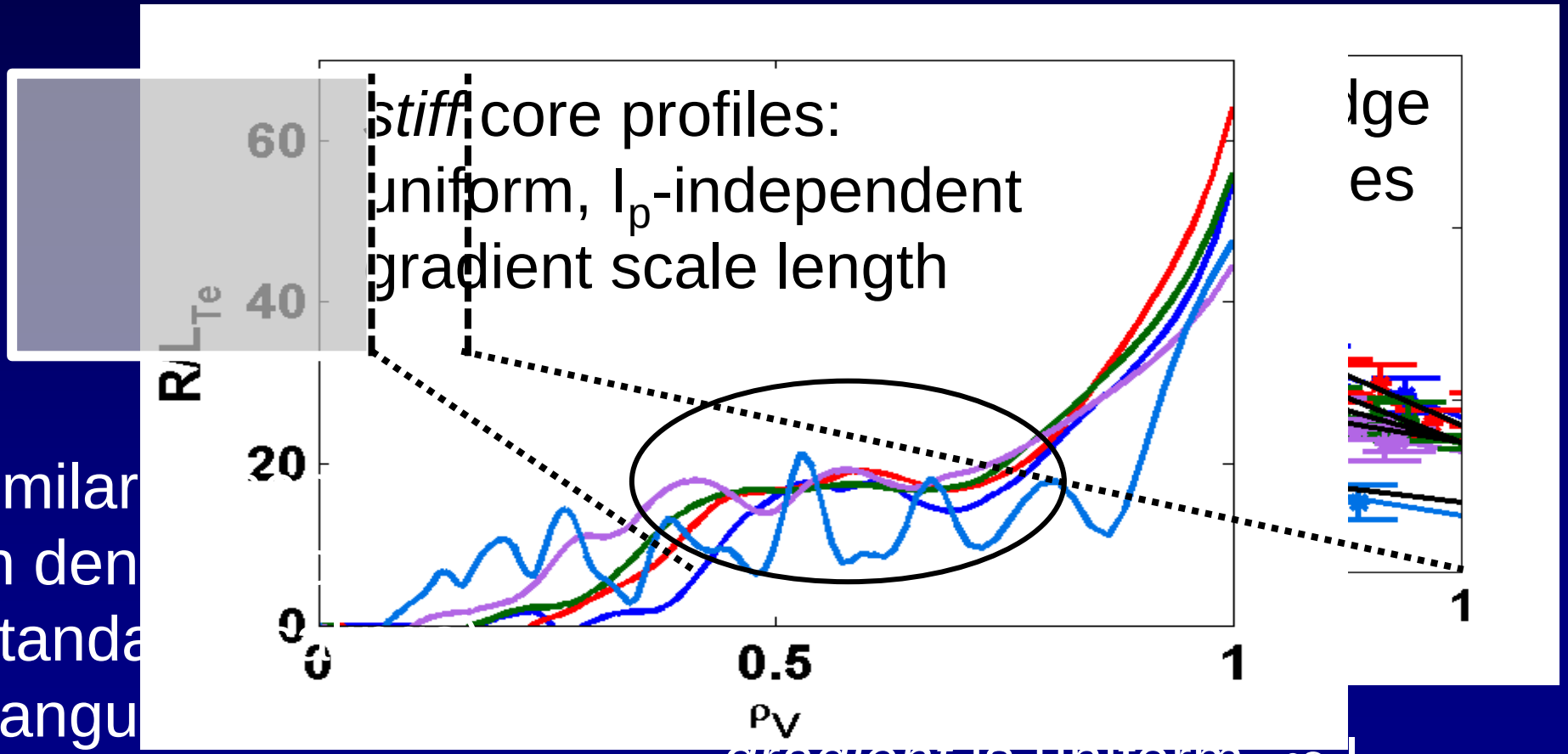
Study of edge role in global confinement: e.g. I_p scan with high-resolution measurements



Global confinement scalings largely regulated by extended edge region (ρ~0.8-1), *not* by plasma boundary



Similar
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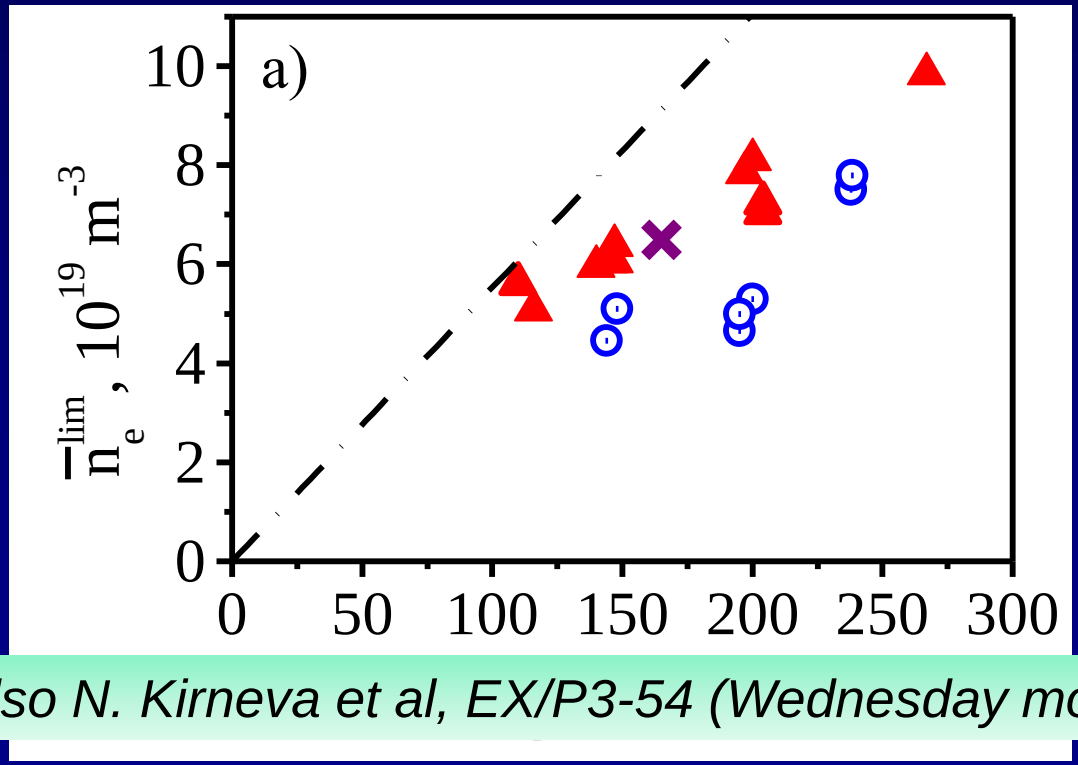
gradient is uniform, $\propto I_p$

see also A. Merle et al, EX/P3-55 (Wednesday morning)

uter et al, PoP **21**, 055906 (2014)

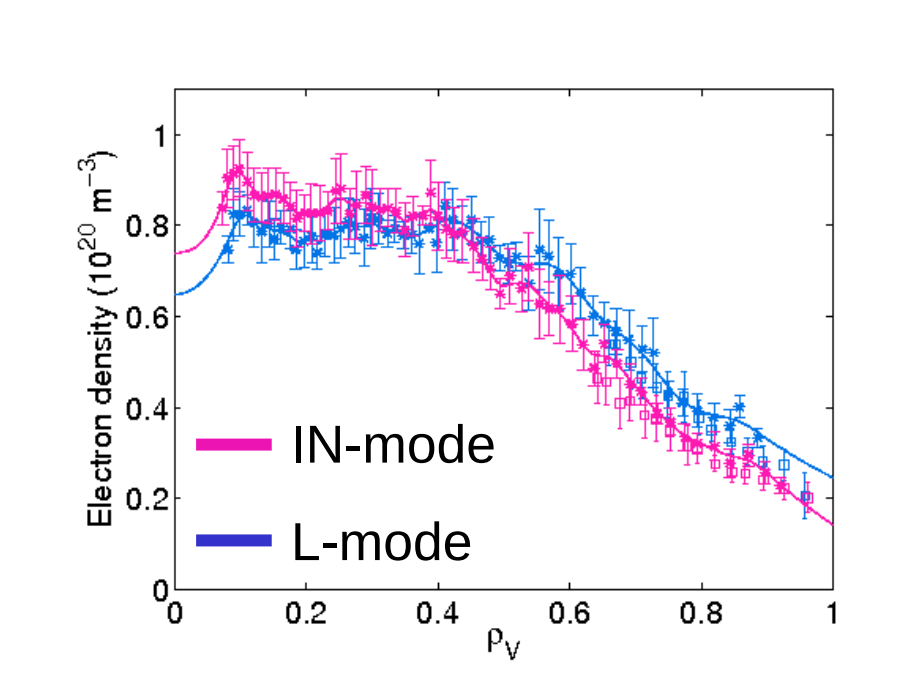
Density limit

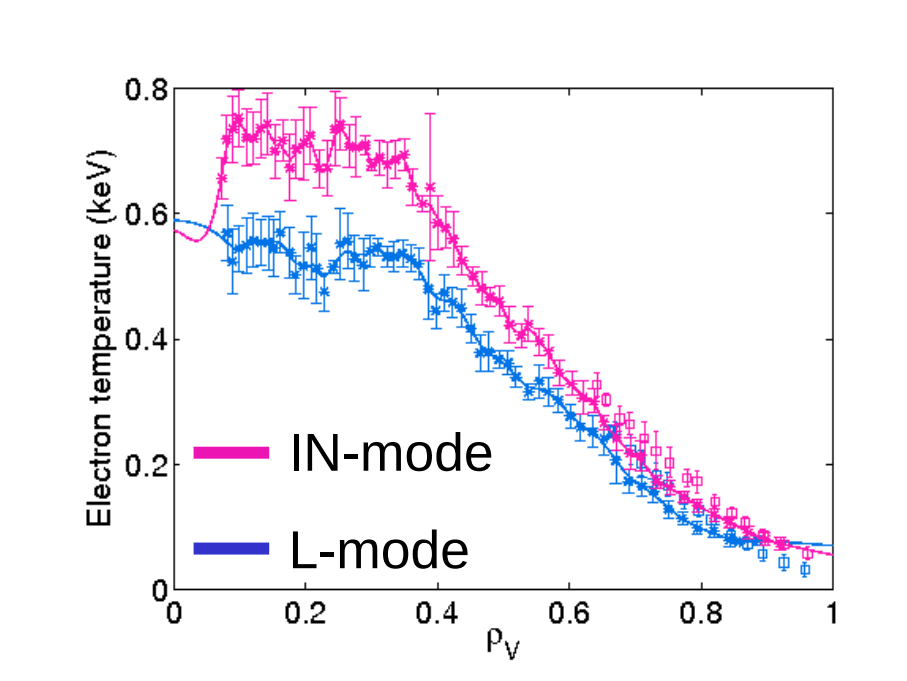
- Density rise causes positive feedback loop: density peaking, core cooling, sawtooth stabilization ⇨ ultimately 2/1 mode and disruption
- n_{max} is close to Greenwald density at low current, well below at higher current



see also N. Kirneva et al, EX/P3-54 (Wednesday morning)

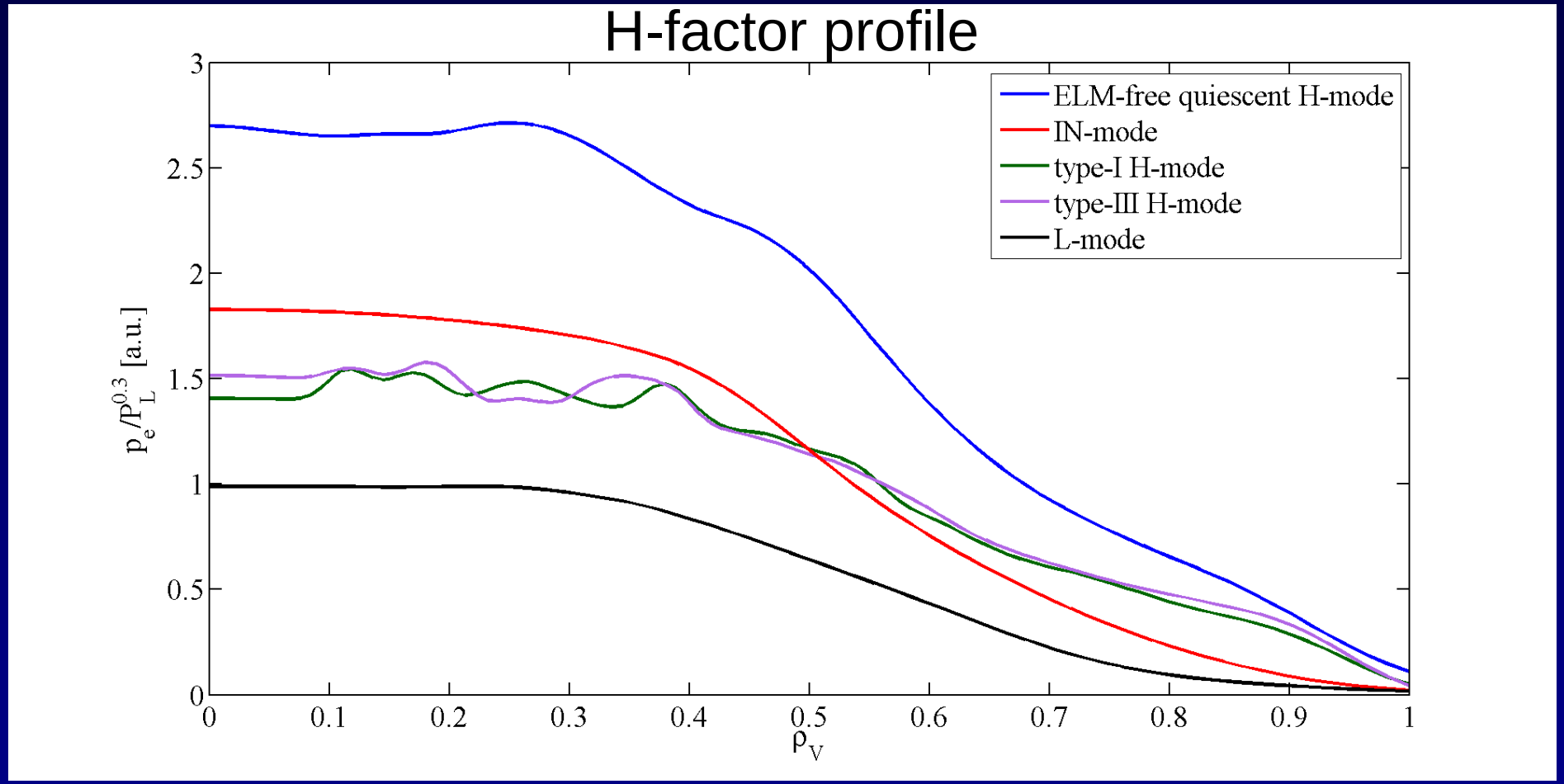
IN-mode: raised edge density gradient, L-mode-like edge temperature





Obtained by early gas puffing
or by marginal entry into H-mode followed by H-L transition
(low internal-inductance trajectories)

IN-mode: H-mode-like confinement



see also A. Merle et al, EX/P3-55 (Wednesday morning)

Summary of highlights

- Enhanced transport to private region in snowflake greatly underestimated by modeling thus far
- Lower than expected H-mode threshold in hydrogen
- Improved MHD control through real-time equilibrium reconstruction
- Complete multi-diagnostic characterization of GAM
- Confirmation of new theory of turbulence-driven edge rotation
- Determination of regulatory role of edge plasma in global confinement
- New high-particle-confinement regime (IN-mode) discovered

The immediate future

Europe-wide call for proposals in November
for TCV and ASDEX Upgrade in 2015

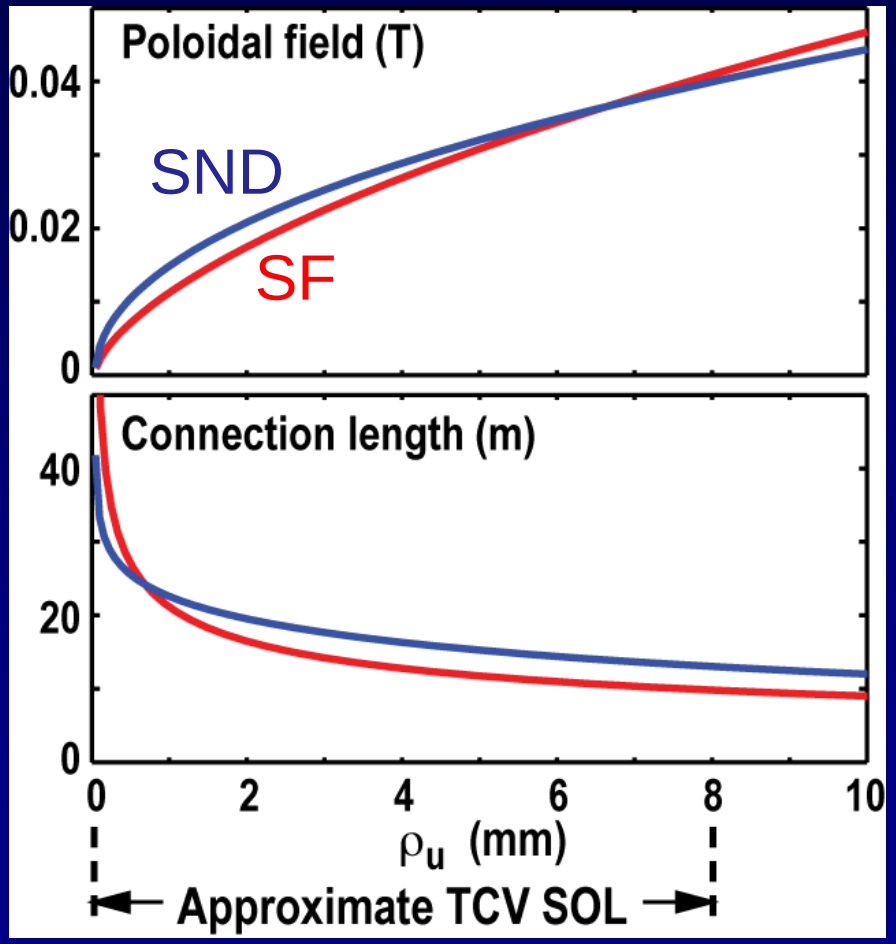
International collaborations always welcome

CRPP contributions

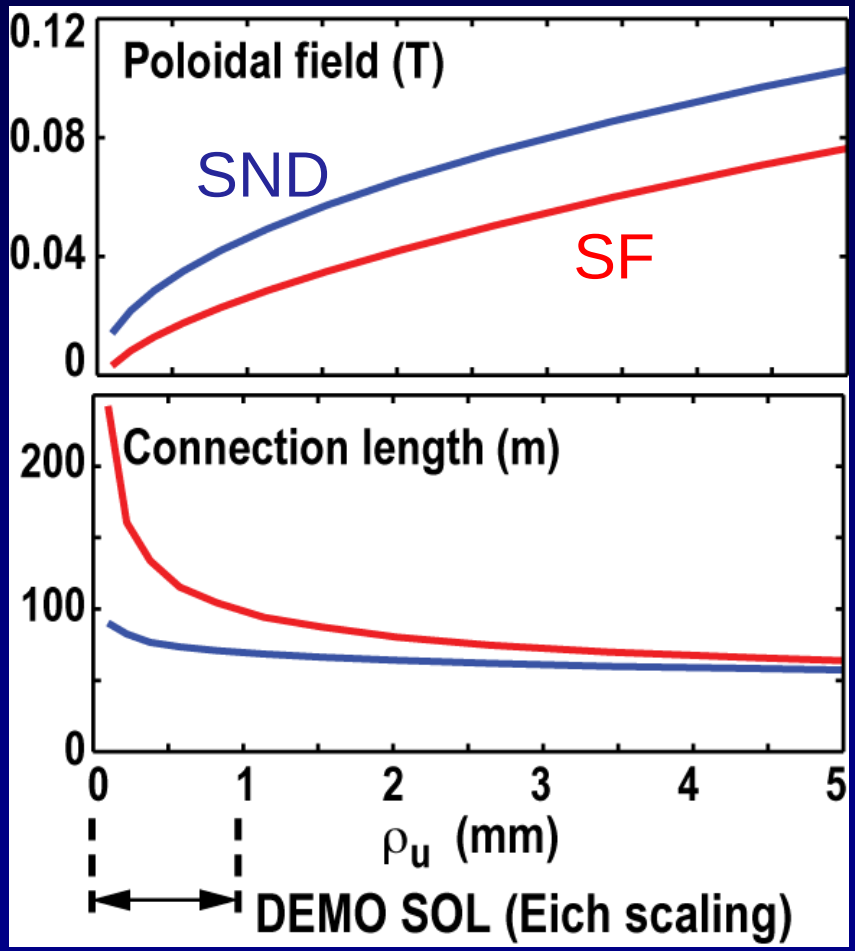
- TCV
  - EX/P2-54: S. Nowak, “(N)TM onset by central EC power deposition in FTU and TCV tokamaks”, Tue pm
  - EX/P3-54: N. Kirneva, “High density regime in Ohmic TCV discharges with positive and negative triangularity”, Wed am
  - EX/P3-55: A. Merle, “From edge non-stiffness to improved IN-mode: a new perspective on global tokamak radial transport”, Wed am
  - EX/P3-56: B.P. Duval, “Progress in snowflake divertor studies in TCV”, Wed am
  - EX/P3-57: L. Porte, “Multi-diagnostic study of core turbulence and geodesic acoustic modes in the TCV tokamak”, Wed am
  - FIP/P7-7: A. Fasoli, “TCV heating and in-vessel upgrades for addressing DEMO physics issues”, Fri am
- Fusion technology
  - FIP/1-4Ra: B. Stepanov, “Summary of the test results of ITER conductors in SULTAN”, Mon pm
- Basic plasma physics
  - EX/P3-59: I. Furno, “Basic investigations of turbulence and interactions with plasma and suprathermal ions in the TORPEX device with open and closed field lines”, Wed am
- Theory
  - TH/3-2: P. Ricci, “First-principle theory-based scaling of the SOL width in limited tokamak plasmas, experimental validation, and implications for the ITER start-up”, Wed pm
  - TH/P7-13: W. Cooper, “Equilibrium and fast particle confinement in 3D tokamaks with toroidal rotation”, Fri am

SOL not broadened in today's devices but could broaden in DEMO-sized SF

TCV L-mode

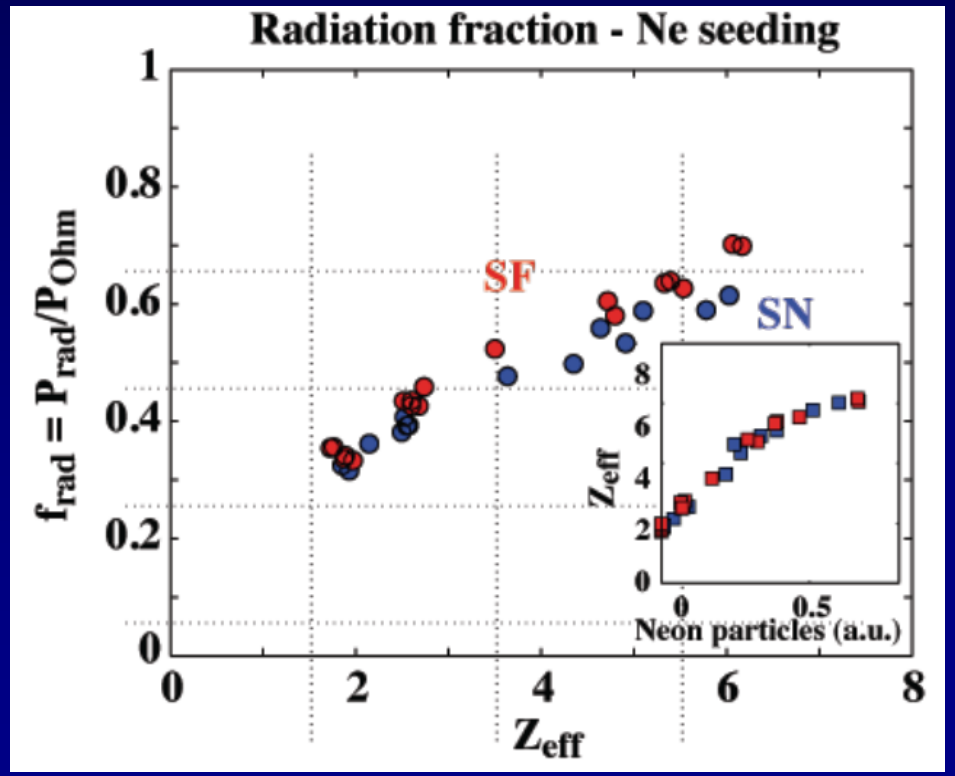


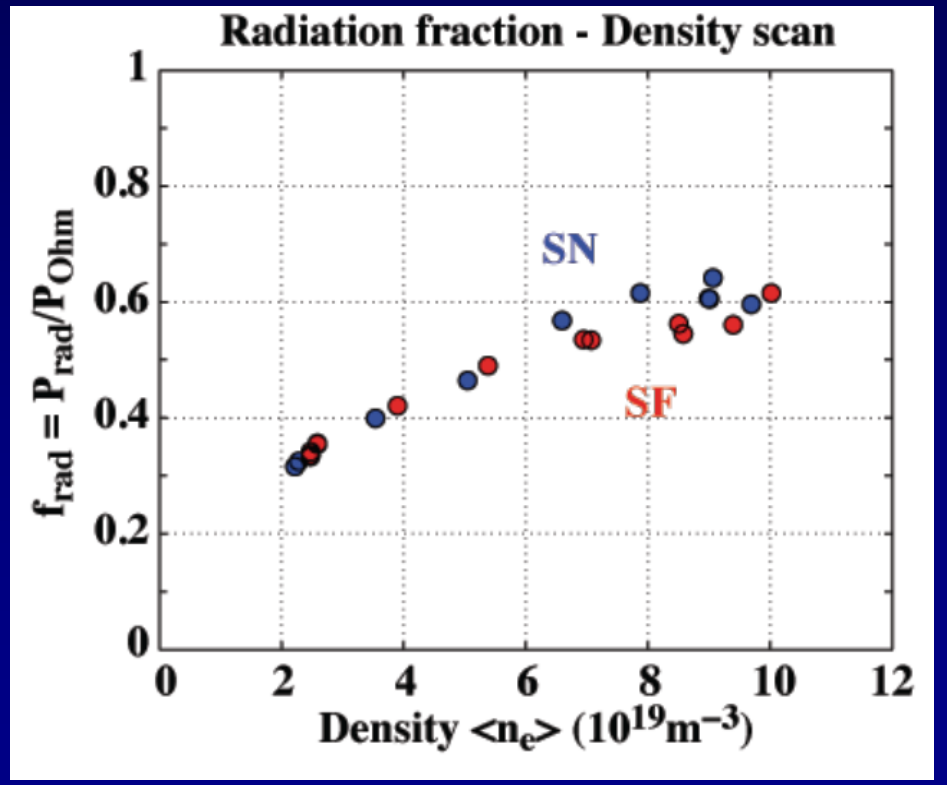
DEMO H-mode



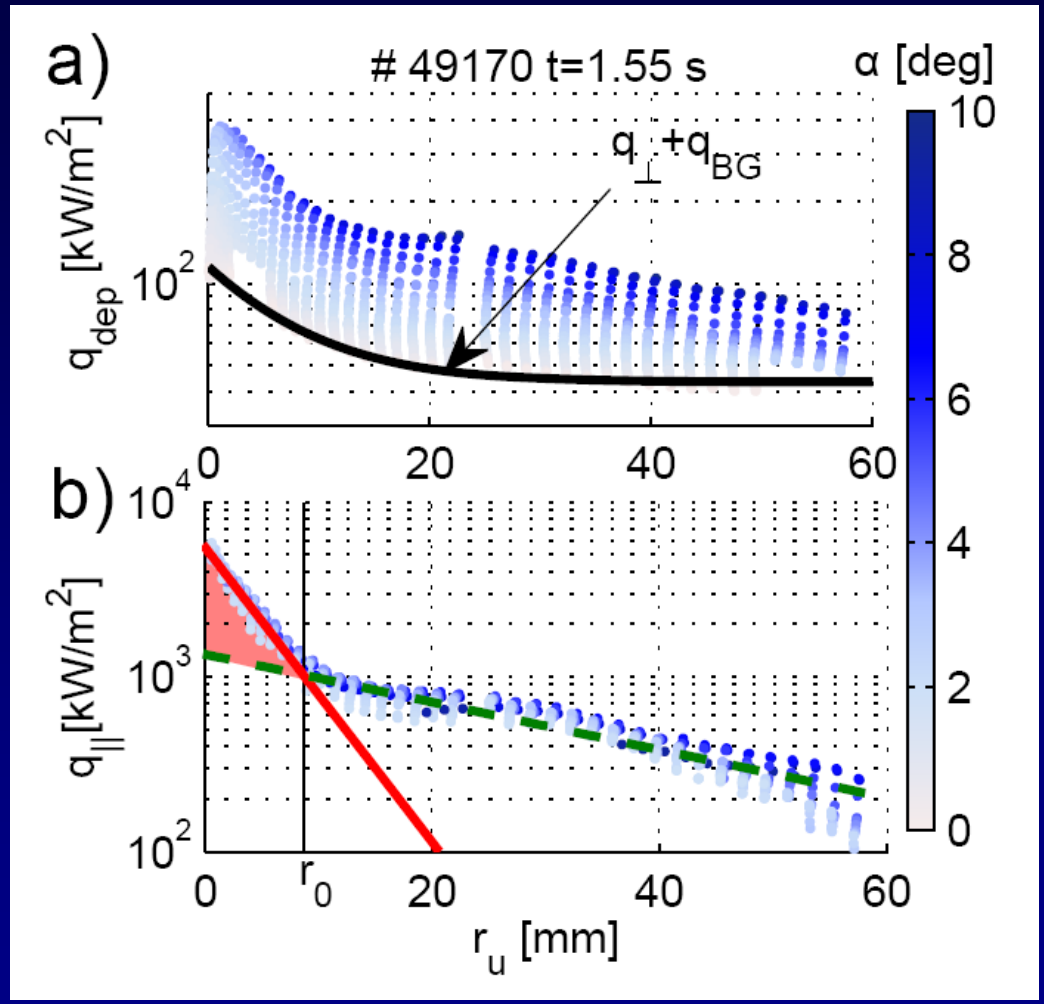
Neon radiates more in SF, carbon radiates more in SND

Likely due to different radiative properties of species, appears consistent with relevant divertor volume ratios



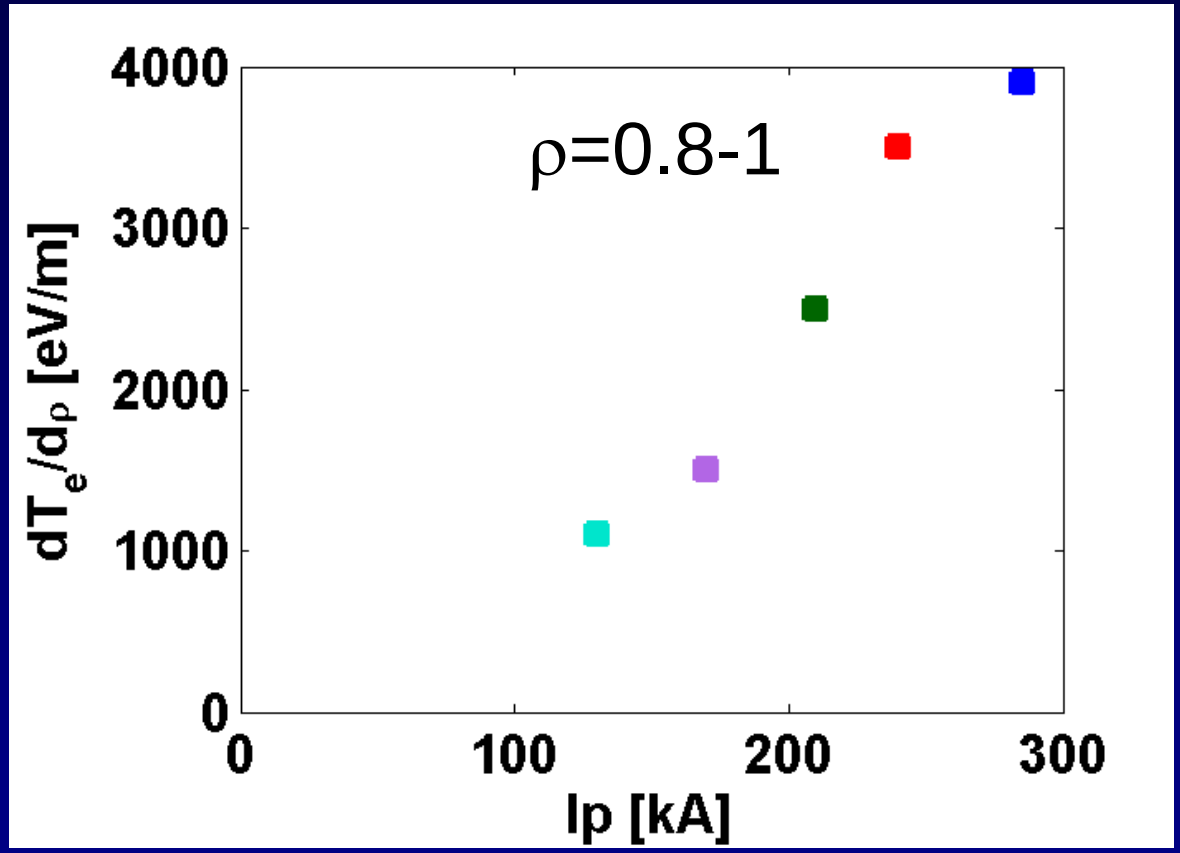


L-mode limiter: double decay length for parallel heat flux



Up to ~10% extra power from narrow feature

Global confinement scalings largely regulated by extended edge region (ρ~0.8-1), *not* by plasma boundary



Similar dependence on density, power (Standard scalings), triangularity

see also A. Merle et al, EX/P3-55 (Wednesday morning)

Edge physics and exhaust concepts: additional results

- Characterization of limiter heat flux in L-mode
- Comparison of radiation properties of SF and SND
- Study of blobs in SF and SND
- Control optimization to increase maximum SF current

see overview paper and references therein

H-mode and ELMs: additional results

- Study of magnetic structure of type-I ELMs: nonlinear phase dominated by *n*=1 component

see overview paper and references therein

MHD and integrated control: additional work

- Study of neoclassical toroidal viscosity and interplay with sawtoothless NTM excitation and spontaneous rotation
- Study of effect of MHD on suprathermal electrons
- Possible 3D helical equilibrium state found
- Position control through visible boundary images
- Improved vertical stability of high-κ plasmas by bang-bang control
- Exact sawtooth period control used for diagnostic purposes (coherent averaging over s.t.)
- Iterative Learning Control helped to improve internal inductance control over several shots

see overview paper and references therein

Spontaneous rotation: additional results

- 2D poloidal map of carbon density, temperature, flow; poloidal asymmetries under analysis

see overview paper and references therein