Semi-empirical ELM models

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in collaboration with

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Why semi-empirical ELM models?

- the start of ITER start raises the importance of the helium balance, and thus of pedestal particle confinement (τ_p^{ped})

- ELM effect on τ_p^{ped} is not well quantified

- ELMs are 26 years old, but fundamental ELM models are still dealing with this problem

- ideal topic for integrated core/edge modeling, in close comparison with experiment

Present examples of the status and use of core and SOL semi-empirical ELM models for (mostly) DIII-D, and JET

ITER is the first experiment in which He transport and exhaust are fundamentally important

this makes it important for JET

Global replacement time (Reiter et al NF 1992)

$\tau_\alpha^* \equiv \tau_\alpha^1 + \tau_\alpha^2 R_\alpha / (1-R_\alpha) = \tau_\alpha^1 + \tau_\alpha^{2\,*}$

N.B. $R_\alpha \sim 1$

τ_α^1 'First pass' confinement

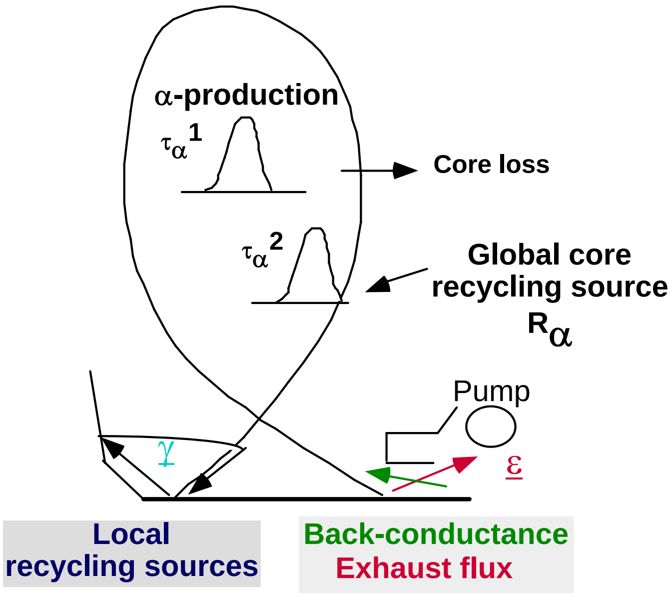
τ_α^2 Confinement of recycled helium

Global recycling coefficient, R_α

$R_\alpha \sim \gamma / (\varepsilon + \gamma)$

$\gamma \equiv$ boundary screening of recycled He

$\varepsilon \equiv$ exhaust efficiency of helium at pump



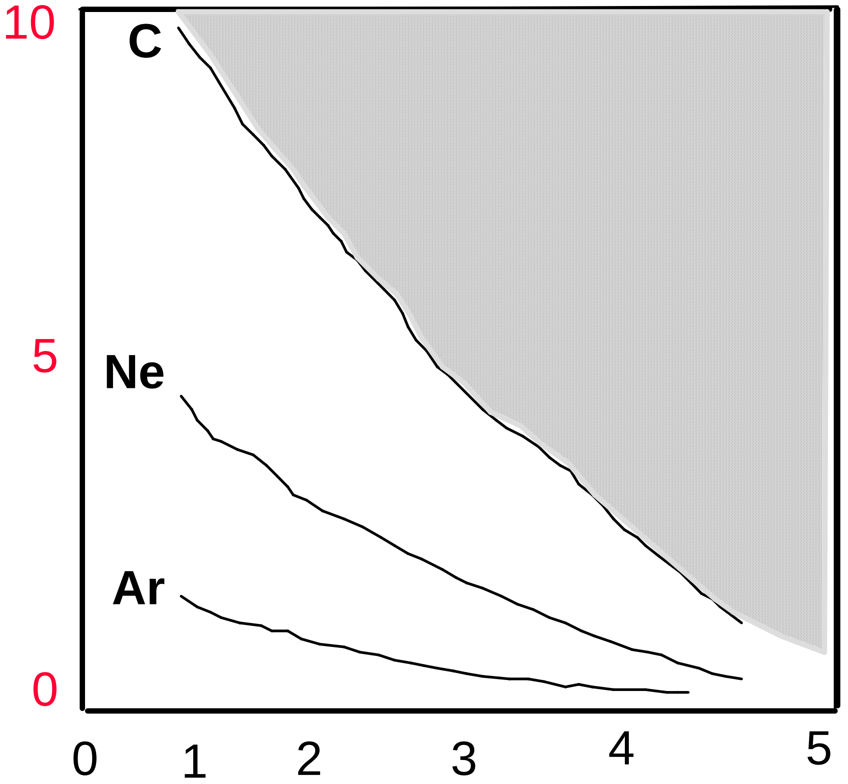
Confinement parameter: $\rho_\alpha \equiv \tau_{\alpha*} / \tau_E$

Pedestal <u>particle</u> confinement τ_α^2 determines ρ_{He}

We need a validated model for pedestal confinement, τ_α^2

Required pedestal particle confinement strongly depends on type and level of intrinsic and extrinsic impurities

Value of $\rho_{\alpha} \equiv \tau_{He*} / \tau_E$ required to attain $n_e \tau_E T_e = 10^{22}$ keV s / m^3



Single impurity concentrations $f_{i,max}$ (%)

Adapted from U. Samm et al, Proc. 22nd EPS, Bournemouth

A prototype for semi-empirical core ELM model

Semi-empirical MHD ELM model for MIST*

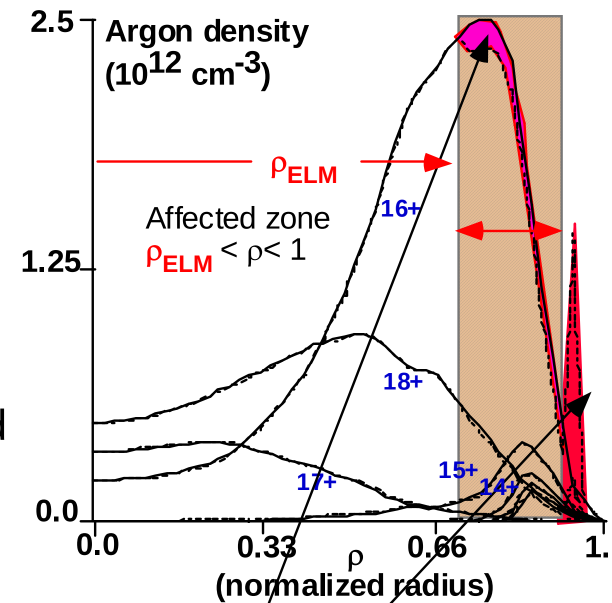
Treat ELM as *instantaneous* *MHD event on transport timescale*

Separates MHD from both transport and exhaust physics, but introduces new free parameters (ρ_{ELM}, A_{ELM}, Ω_{ELM})

- for radius $\rho > \rho_{ELM}$ a fraction A_{ELM} of the impurity density is instantaneously transferred to the SOL
- ELM frequency (Ω_{ELM}) = experimental D_α

All subsequent evolution (after ELM) with D_A, V_A, and recycling models

In principle ... the new fitting parameters can be determined
- experimentally, CXRS before/after
- through MHD simulation, e.g., JOREK



$A_{ELM} = \Delta N^{16+} / N^{16+}$

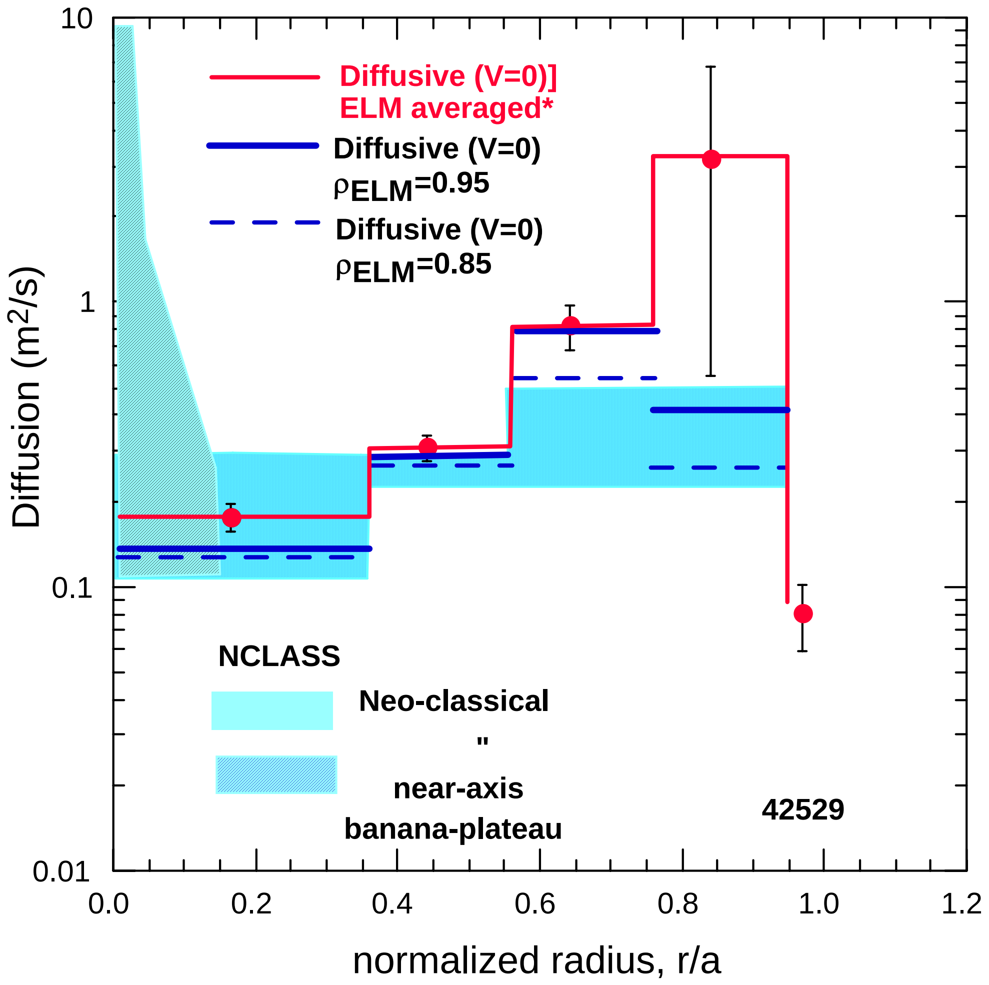
Ar 16+ density
- removed from core
- deposited in SOL

*R. Hulse, PPPL FusTechnol 1980

Second example : T particle transport

Effect of semi-empirical parameter variation on inferred τ_p^{ped}

JET tritium injection, DTE1

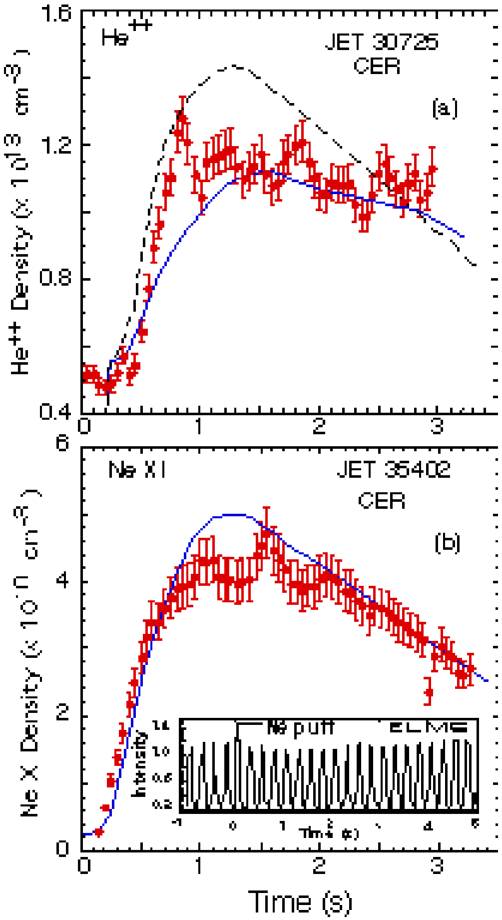


Inferred
ELM-averaged transport
is ~ 10x higher
(too optimistic)

* K-D. Zastrow et al
EPS 1998, Prague

D Hillis, J Hogan et al
Physics of Plasmas, 1999

τ_p^{ped} with/without ELMs



JET He / Ne transport

compare MIST evolution for He and Ne

- with (solid line) $D_A = 1.2\ m^2/s$
- without ELM model (dashed line) $D_A = 3.6\ m^2/s$

He injection, JET pulse 30725, no Ar frost

MIST ELM model (solid line) for neon injection in JET pulse 35402 with 4 Hz giant ELMs

$D_A = 1.2\ m^2/s$ for the solid curve

insert : ELM activity

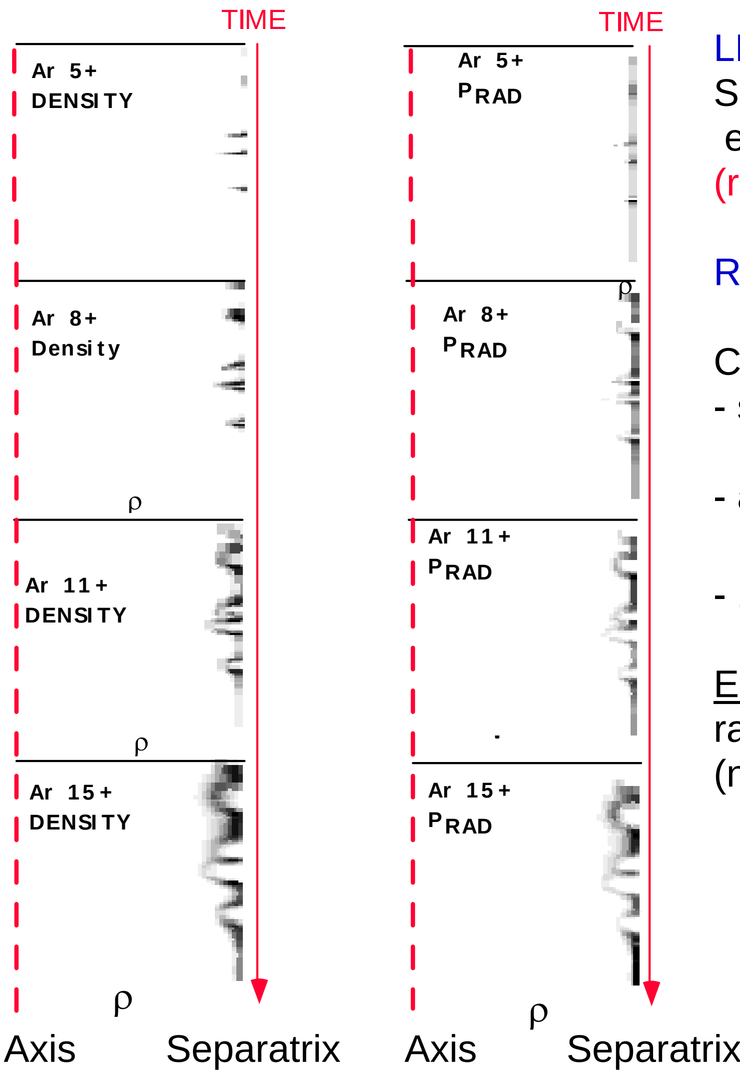
D Hillis, J Hogan et al
J Nucl Mater 1999

Transport and ELM physics scale differently to ITER

Since $\tau_{ELM} << \tau_{re\text{-}heat} << \tau_j$ from Mukhovatov-Shafranov*, as q is frozen, ‘flux-conserving’ evolution produces edge current and
<u>ELM-averaged transport gives the wrong scaling</u>

*Nucl. Fusion **11**, 605 (1971)

Potential for local profile modification

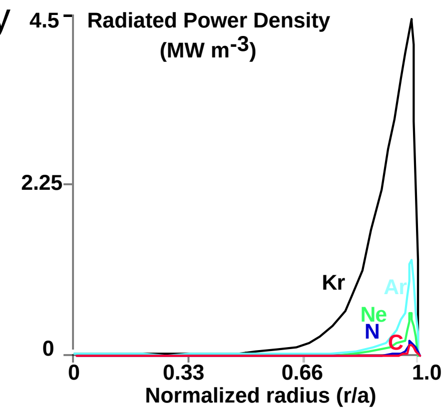


LEFT:
Simulated Ar density and radiation evolution (vs. ρ, t) for 56107
(radiated power is localized)

RIGHT:

Comparison for
- same Te, ne profiles (based on 56107)
- all cases with impurity $\Delta Z_{eff} = 0.5$
- 10Hz ELMS

<u>ELM-averaged</u>
radiated power density (normalized)



Injected impurities can tailor the radial pressure profile preferentially in a narrow, near-separatrix region

Variation with A_{ELM}

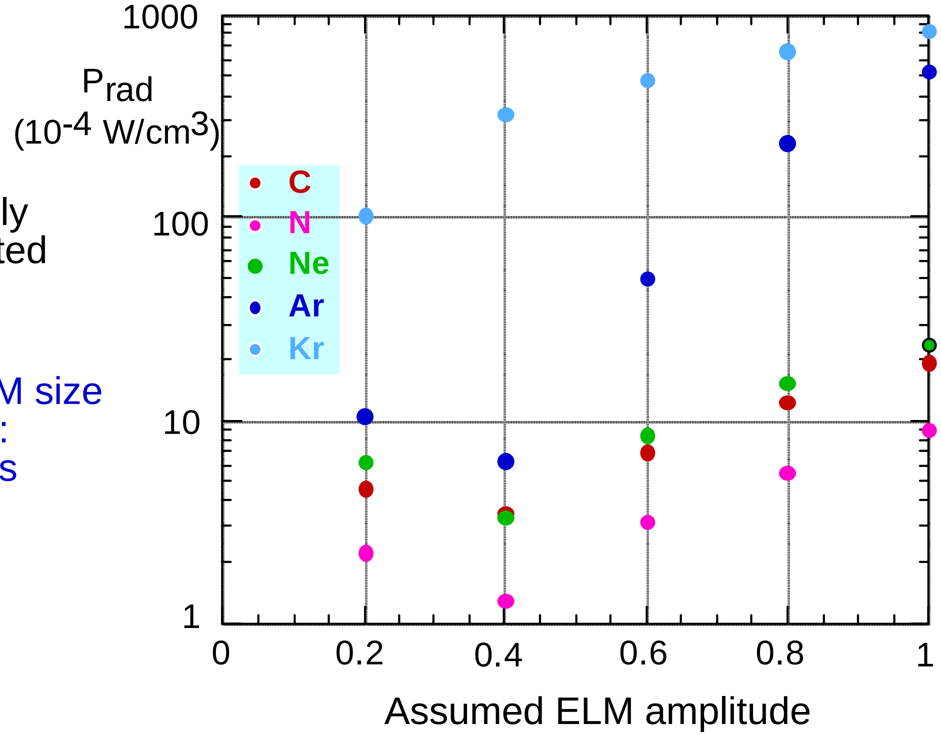
ELM-averaged radiation density increases with ELM size
(e.g., Type II-> Type I)

"ELM size" ≡ assumed impurity fraction expelled from ELM-affected region ($\rho > \rho_{ELM}$)

Impurities assumed instantaneously expelled into SOL from ELM-affected region ($\rho > \rho_{ELM}$)

Radiative power increases with ELM size due to non-coronal atomic physics: increased expulsion efficiency leads to higher recycling flux

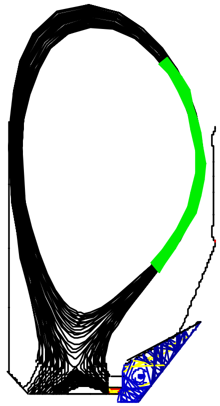
ELM-averaged radiation density (radial max. value)
vs
model ELM size



Semi-empirical divertor models for ELM transport enhancement

Green: ELM-affected region in the model

C neutrals, ions
D neutrals, ions



pedestal + SOL
low-field side only

pedestal only,
low-field side only

SOL only
low-field side only

CIII T_e

CIII T_e

CIII T_e

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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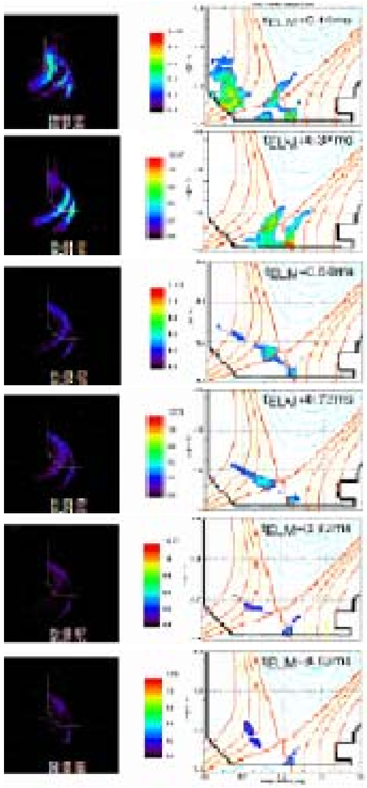
divertor impurity profile
(CID camera)



Comparison with fast camera data (C^{2+})

Divertor C^{2+} evolution:

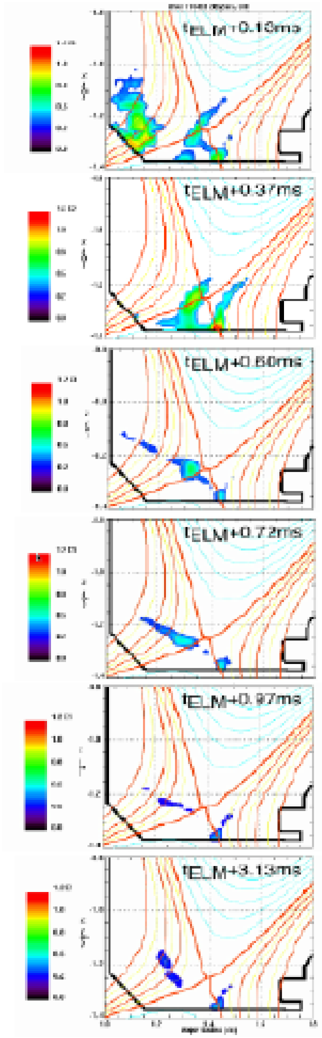
ELM sequence reconstructed
from fast camera snapshots

M Groth et al, J Nucl Mater 2003

left: camera view

right: 2-D reconstruction

CIII - ELMs generate divertor carbon



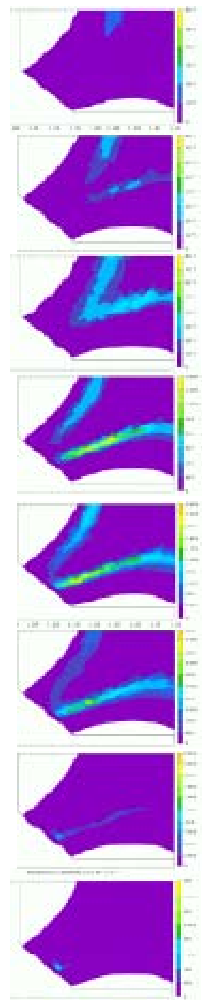
Sequence
before ELM - detached

attached

re-detaching

detached

CIII evolution: reconstructed from
CID camera snapshots
(M Groth et al, J Nucl Mater 2003)



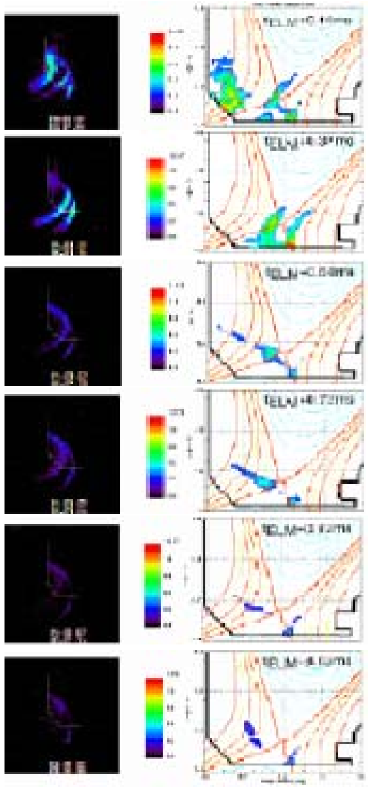
CIII 4650.1 evolution
solps 'standard' model

Semi-empirical model matches some qualitative features.

Matching 2D reconstructions introduces the problem of image artefacts

Comparison with fast camera data (C^{2+})

divertor impurity profile (CID camera)



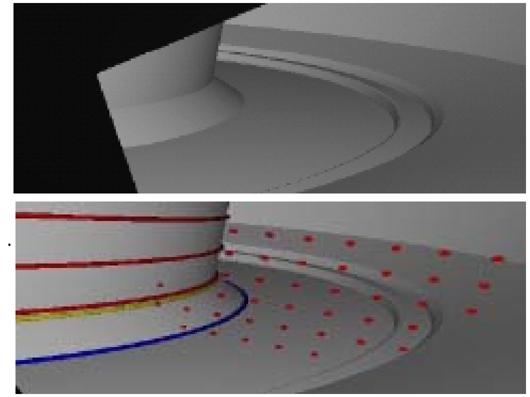
Divertor C^{2+} evolution:

ELM sequence reconstructed from fast camera snapshots

M Groth et al, J Nucl Mater 2003

POVRAY camera view for lower divertor (W Meyer, LLNL)

240parIa



QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Direct comparison of semi-empirical models is now becoming possible

DIII-D Fast CER

Time resolution

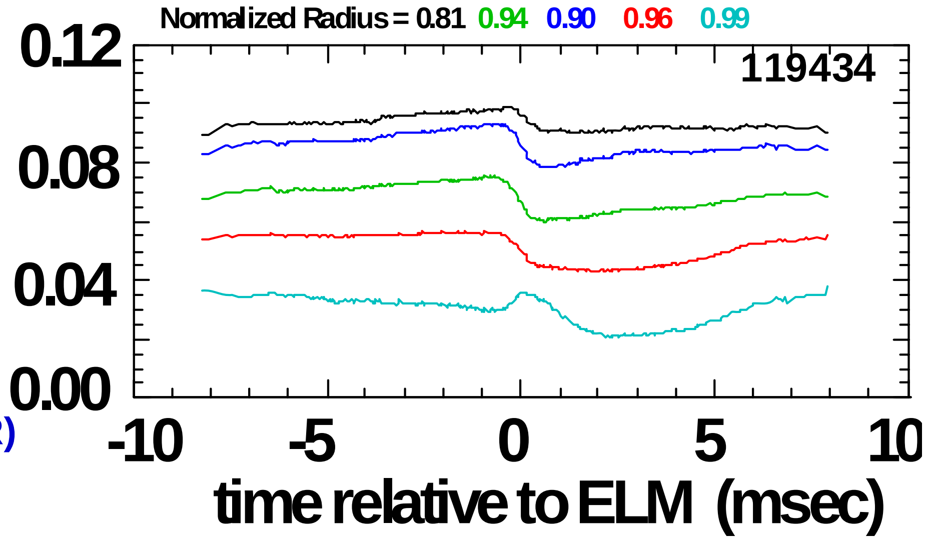
>274 μsec

Spatial resolution

3mm n_{C6+}, T_i

6 mm $V_{\theta,\ \phi}$

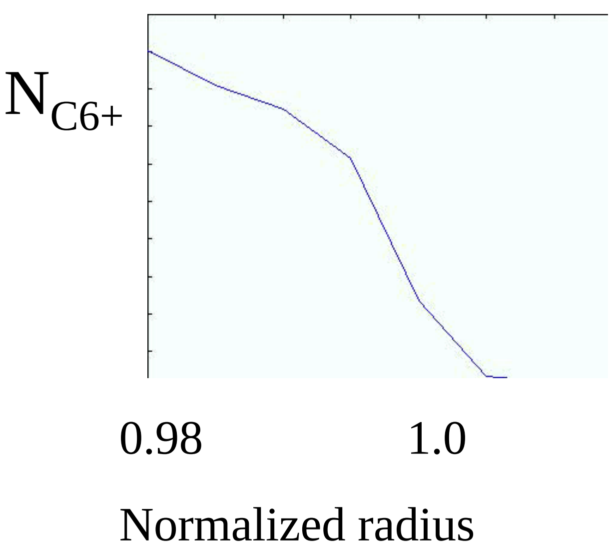
Impurity Density

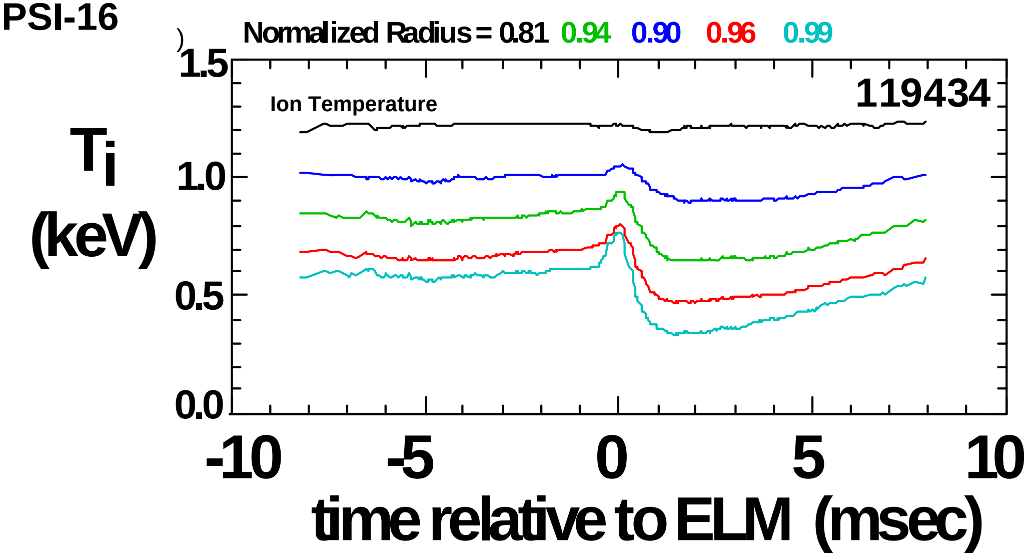


pedestal C^{6+} density profile (CER)

ELM sequence reconstructed from fast CER profiles

M Wade, K Burrell et al, PSI-16

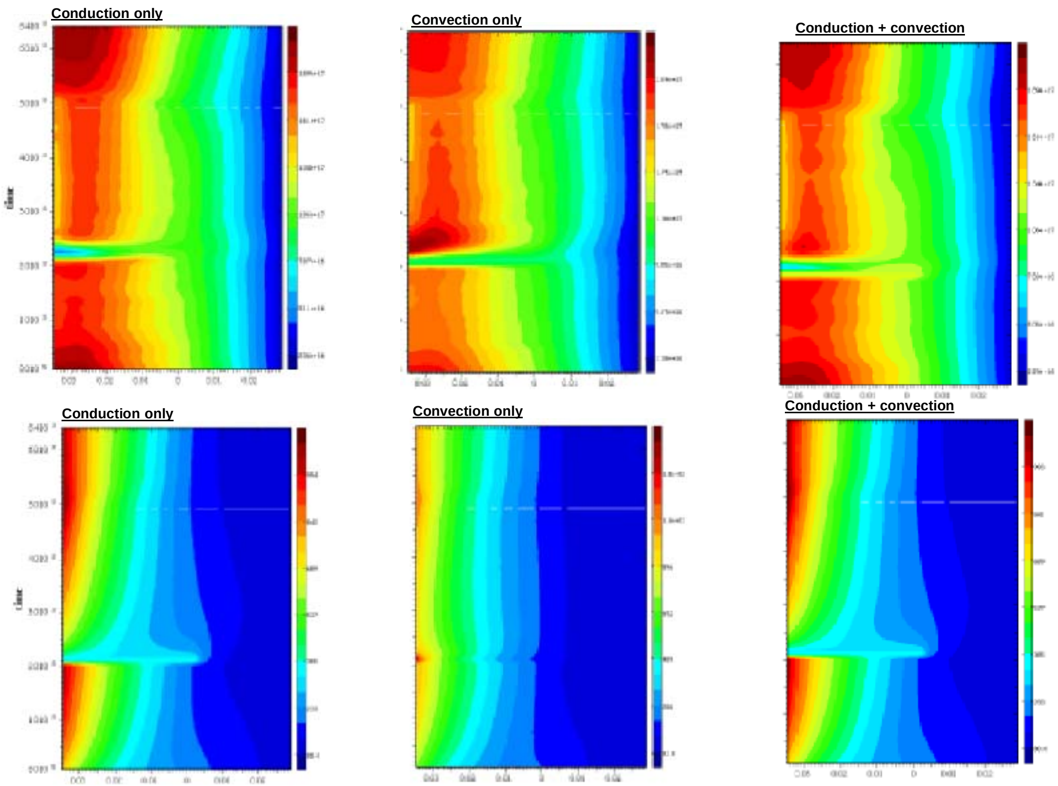




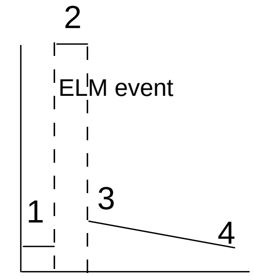
Fast CER comparison: pedestal ELM transport model

- intra-ELM radial transport transport enhanced for 100 μsec ("ELM")
  then $\chi_{e, I}$ increased 2x above intra-ELM value (E_r well destroyed)
- this factor reduced to unity intra-ELM, as E_e well is re-established
- Spatially, “ELM” transport is enhanced only in core region (not SOL)

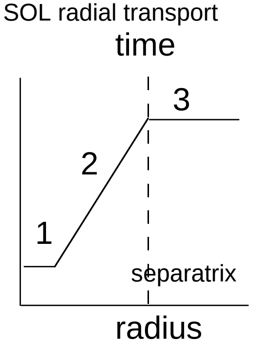
convective enhance only D	conductive enhance only $\chi_{e, i}$	standard' enhance both D, $\chi_{e, i}$



Transport time dependence
(*schematic*)
1. Pre-ELM (barrier)
2. Strong enhancement (100 μsec) ELM
3. Loss of barrier, 2 x pre-ELM value
4. reducing to pre-ELM value as barrier is re-established



Intra-ELM transport radial dependence
(*schematic*)
1. barrier
2. enhancement toward SOL
3. SOL radial transport



Proposed edge CXRS upgrade for JET-EP2

Spectrometer hardware proposed for JET edge CER upgrade

ORNL EDGE CXRS Upgrade for JET-EP2 Experiments

Reproduce recently completed ORNL core CXRS CXRS upgrade for a new JET-EP2 edge upgrade

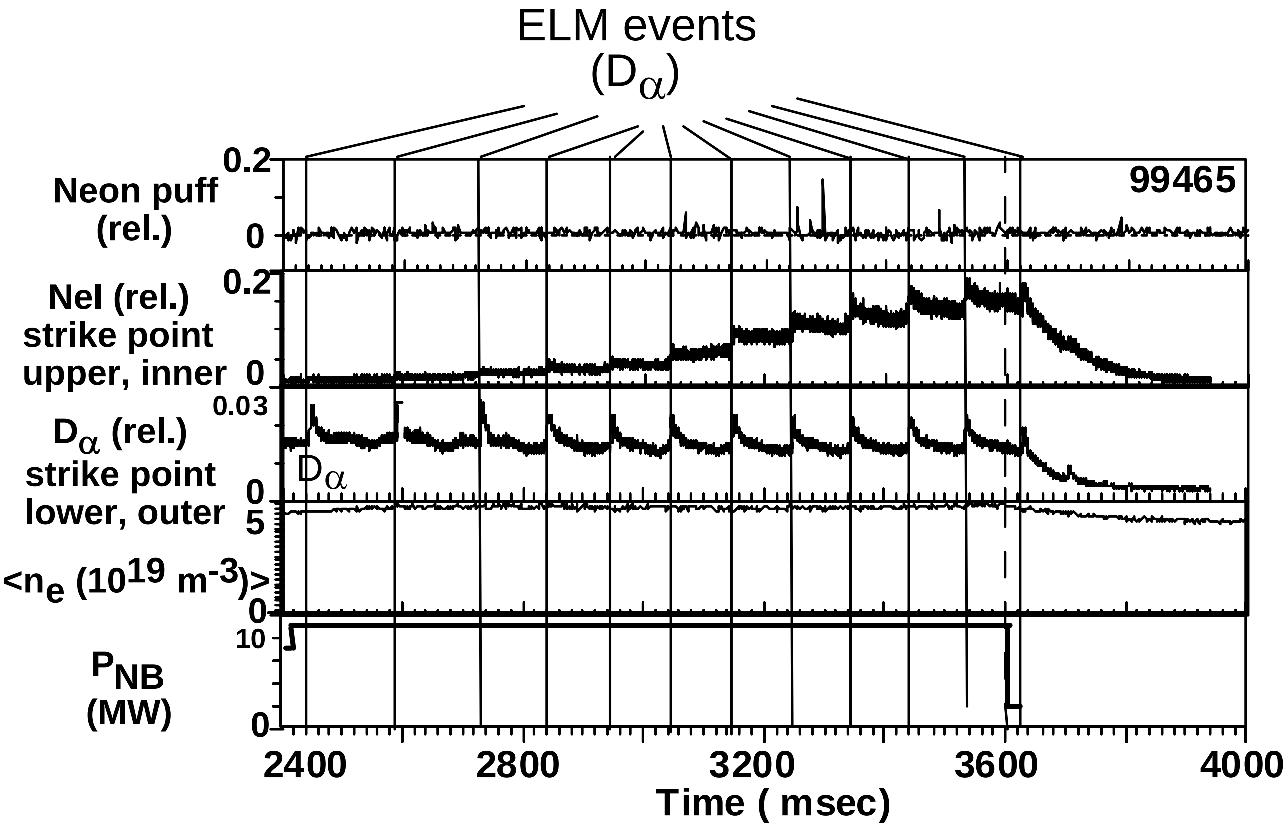
- increased profile sensitivity for T_i density, poloidal rotation, and E_r
- increased spatial resolution for pedestal,ELM pellet pacing studies (55 radial chords)
- improved time resolution (5 ms)
- real time data acquisition

Joint project by ORNL / PPPL

Interaction of ELMs and recycling

DIII-D during RI-mode experiments

- one of the first discharges of the day with NBI, but no Ne puff
- no Ne puff any preceding discharge that day.
- on the preceding day of operations, however, strong Ne puffing in 25 out of 34 discharges.



a) Ne injection rate (~0),

b) Ne I emission, upper inner strike point

c) D_a emission, lower, outer strike point

d) average electron density

e) NB power.

Adequate helium removal in ITER requires preferentially lower pedestal particle confinement, since recycled He is the largest He source.

Control of pedestal parameters through impurity radiation also requires better ELM characterization and control

The trade-off between ELM amplitude and particle removal efficiency has not yet been established

Experimental capability for validation of semi-empirical models is advancing rapidly.

Development of semi-empirical ELM models, coupled with detailed experimental comparison, offers a potentially attractive and feasible route to developing the required particle control solutions in the pedestal region.