EUROfusion

TRANSP physics and application to JET plasmas

I. Voitsekhovitch

Acknowledgements:
D. McCune, R. Andre, R. Budny, J. Conboy, M. Gorelenkova, S. Kay

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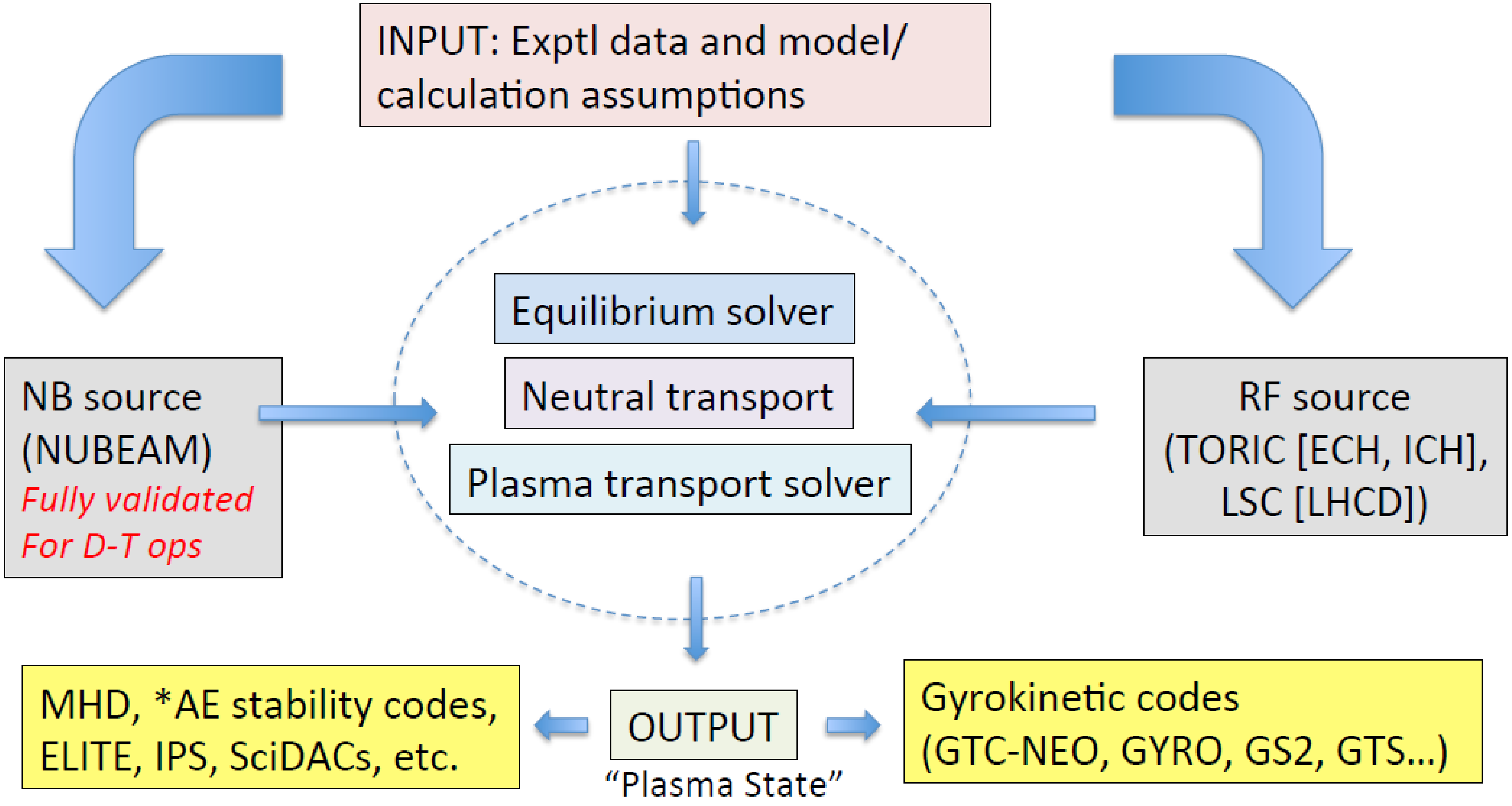
TRANSP is a time-dependent, 1 ½ D tool for interpretive and predictive analysis of tokamak, ST and RFP plasmas



INPUT: Exptl data and model/ calculation assumptions

Equilibrium solver

Neutral transport

Plasma transport solver

NB source (NUBEAM)
Fully validated For D-T ops

RF source (TORIC [ECH, ICH], LSC [LHCD])

MHD, *AE stability codes, ELITE, IPS, SciDACs, etc.

OUTPUT
"Plasma State"

Gyrokinetic codes (GTC-NEO, GYRO, GS2, GTS…)

Output of TRANSP (Plasma State File) is standardized for simplifying input to other computationally intensive codes

TRANSP documentation

- User guide to select the physics modules and options is available, but no manual describing physics
- Information on TRANSP physics presented here comes from publications and discussions with TRANSP team during last 10 years
- This talk includes physics description when available and the options for physics modules in TRANSP
- Ref. to TRANSP: R. J. Goldston et al., J. Comput. Phys. **43,** 61 (1981). Refs. to TRANSP modules on JET/TRANSP and NTCC pages

Outline

- Equilibrium (see also talk by Hyun-Tae Kim)
- Diagnostics simulations and data consistency: will be addressed later on
- Poloidal field diffusion
- Auxiliary heating
- Edge particle source
- MHD: sawtooth model
- Predictive TRANSP

Grad-Shafranov equation

$$\Delta^* \psi = r^2 \mathrm{div} \frac{\nabla \psi}{r^2} = -4\pi^2 \left(\mu_0 r^2 \frac{\partial p}{\partial \psi} + I \frac{\partial I}{\partial \psi} \right) .$$

or

$$\begin{aligned} \Delta^* \psi &= \frac{2\pi \mu_0 R_0 J}{\langle B^2 / B_0^2 \rangle} j_{\|} + \frac{2\pi \mu_0 R_0^2}{B_0 \rho \mu} \left(\frac{J^2}{\langle B^2 / B_0^2 \rangle} - \frac{r^2}{R_0^2} \right) \frac{\partial p}{\partial \rho} \\ &= 2\pi \mu_0 R_0 \left[\frac{J}{\langle B^2 / B_0^2 \rangle} \left(j_{\|} + \frac{R_0 J}{B_0 \rho \mu} \frac{\partial p}{\partial \rho} \right) - \frac{r^2}{B_0 R_0 \rho \mu} \frac{\partial p}{\partial \rho} \right] \end{aligned}$$

- No explicit time dependence: plasma is always in equilibrium, fast relaxation process with respect to transport

- Coupled to time-dependent transport equations in predictive part of code

Equilibrium modules: VMEC

VMEC = Variational Moments Equilibrium Code (S. Hirshman, ORNL)

- the full 3D MHD equilibrium equations for arbitrary geometry
- truncated to a 2D code suitable for modeling tokamak geometries of arbitrary moment and adapted it to TRANSP:

1. fixed boundary: the plasma boundary prescribed by a set of Fourier coefficients in R and Z

2. other input parameters:

a) enclosed toroidal flux
b) pressure profile
c) profile $\mu = \partial\psi/\partial\Phi$

3. can handle pressure anisotropies IN PRINCIPLE. The version currently in TRANSP, however, is purely isotropic

4. Φ_{tot} is used as an initial guess in arriving at a solution that conserves Ip, by varying Φ_{tot}

References:

S.P.Hirshman and J.C.Whitson, PHYS.FLUIDS 26, 3553 (1983).
S.P.Hirshman and H.K.Meier, PHYS.FLUIDS 28, 1387 (1985).
S.P.Hirshman and D.K.Lee, COMP.PHYS.COMM. 39, 161 (1986).

Equilibrium modules: TEQ

- MHD equilibrium code used in the Corsica transport code (LLNL)

- Fixed boundary solution using the pressure and q profiles as input

- The vacuum R*Btor is used as a boundary condition

- After the initial startup, TEQ is called in a loop which adjusts the q profile near the edge region in order to match to the total plasma current

- Radial grid: uniform or stretched near the axis or the edge

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Options for current profile evolution

- Prescribed q-profile, q(time, r)

- Evolve the q profile using input data: Bpol/Btor vs (R,t) or θ vs (R,t) where $\tan(\theta)$=Bpol/Btor

Poloidal field diffusion equation (PFDE) can be used to estimate the resistivity profile in these two cases, but non-physical negative values of resistivity can come out (it depends on the quality of the q profile data, dq/dt, etc)

- Solve poloidal field diffusion equation

It is possible to switch back and forth amongst these options in the course of a run.

Poloidal field diffusion equation (PFDE)

$$\sigma_{||}\left(\frac{\partial\psi}{\partial t} - \frac{\rho\dot{B}_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right) = \frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}\left(j_{BS} + j_{CD}\right)$$

$$G_2 \overset{\text{def}}{=} \frac{V'}{4\pi^2}\left\langle\left(\frac{\nabla\rho}{r}\right)^2\right\rangle \qquad J \overset{\text{def}}{=} \frac{I}{R_0B_0}. \qquad \rho \overset{\text{def}}{=} \sqrt{\frac{\Phi}{\pi B_0}}. \qquad V' = \frac{\partial V}{\partial\rho},$$

$$I_{\text{pl}} \overset{\text{def}}{=} \int\limits_{\mathrm{S}_\zeta} \mathbf{j}\cdot d\mathbf{S}_\zeta = \frac{1}{2\pi}\int\limits_{\mathrm{V}} (\mathbf{j}\cdot\nabla\zeta)\, d^3x = \frac{1}{2\pi R_0}\int\limits_0^\rho V' j_{\text{tor}}\, d\rho = \frac{J}{2\pi R_0}\int\limits_0^\rho \frac{V'}{J^2} j_{||}\, d\rho$$

$$= \frac{G_2}{\mu_0}\frac{\partial\psi}{\partial\rho} = \frac{2\pi B_0}{\mu_0}\rho G_2\mu = \frac{2\pi R_0}{\mu_0}G_2B_{\text{p}}$$

$$j_{\text{tor}} = 2\pi R_0\frac{\partial I_{\text{pl}}}{\partial V}, \qquad j_{||} = 2\pi R_0J^2\frac{\partial}{\partial V}\left(\frac{I_{\text{pl}}}{J}\right) = J^2\frac{\partial}{\partial V}\int\limits_0^V \frac{j_{\text{tor}}}{J}dV.$$

$$j_{||} = \sigma_{||}E_{||} + j_{\text{BS}} + j_{\text{CD}}$$

Initial condition for PFDE

$$\psi(\rho,t)\big|_{t=0} = \psi_0(\rho)$$ *not measured*

Measured /reconstructed variables are

$$q \overset{\text{def}}{=} \frac{1}{\mu} = \frac{\partial\Phi}{\partial\psi}.$$

$$j_{\|} \overset{\text{def}}{=} \frac{\langle \mathbf{j}\cdot\mathbf{B}\rangle}{B_0} = \frac{2\pi R_0}{\mu_0 V'} J^2 \frac{\partial}{\partial\rho}\left(G_2 J^{-1} \frac{\partial\psi}{\partial\rho}\right)$$

but they involve 1st or 2nd derivative of $\psi(\rho)$ and equilibrium (V', G_2)

Two types of initial conditions:

$$\mu(\rho,t)\big|_{t=0} = \frac{\bar{\mu}(\rho)}{\bar{\mu}(\rho_B)} \frac{\mu_0 I_{\text{pl}}}{2\pi B_0 \rho_B G_2(\rho_B)}$$

Prescribed q(r)

Ipl is matched by applying some adjustment procedure

Ipl is not matched

$$j_{//}(\rho,t=0) = j_0(\rho)$$

Prescribed j(r). Current density is re-normalised to be consistent with Ipl

$j_{//}(\rho)$ is given, $E_{//}(\rho)$ is calculated using resistivity model

$E_{//}(\rho)$ is flat (SS), $j_{//}(\rho)$ is calculated using resistivity model

Boundary conditions for PFDE

$$\left.\frac{\partial \psi}{\partial \rho}\right|_{\rho=0} = 0. \text{ ??}$$

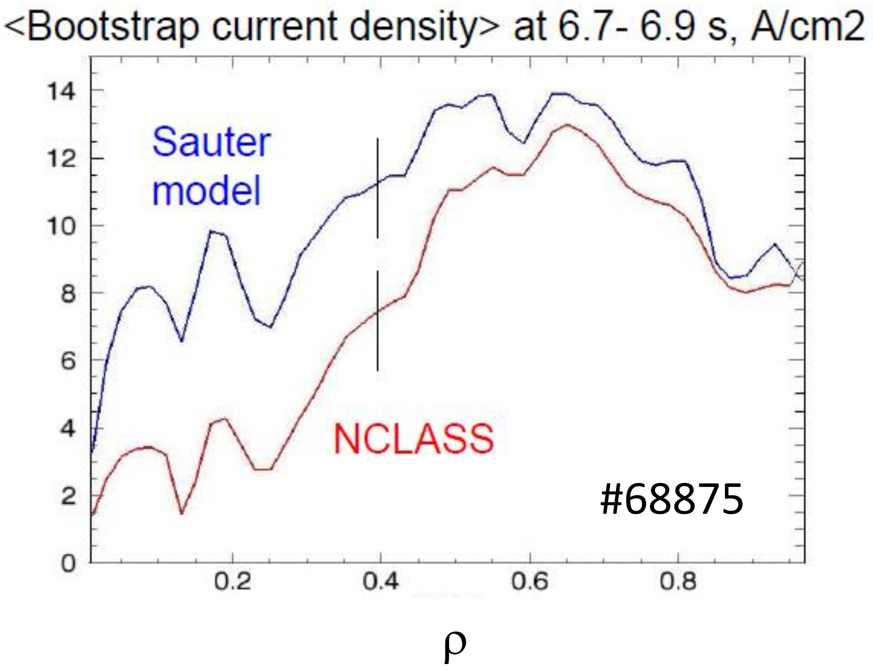
a) Prescribed total plasma current:

$$\boxed{\left.\frac{\partial \psi}{\partial \rho}\right|_{\rho=\rho_B} = \frac{\mu_0}{G_2(\rho_B)} I_{\mathrm{pl}}(t)}$$

b) Prescribed loop voltage: may be inconsistent with total plasma current

Modules for resistivity and bootstrap current

- Spitzer resistivity
- Analytical neoclassical models (S. P. Hirshman, et al Nucl. Fusion 1977; TSC model)
- NCLASS (*full multi-species representation of plasma profiles, valid for arbitrary geometry and collisionality regimes*) [W. A. Houlberg et al, Phys. Plasmas 1997]
- Sauter model (*analytical expressions fitting the code simulations: Fokker–Planck equation with full collision operator, arbitrary equilibrium and collisionality regimes*) [O. Sauter and C. Angioni, PoP 1999]



Ibs, simulated *q*, NCLASS	0.36 MA
Ibs, simulated *q*, Sauter model	0.43 MA
Ibs, EFIT/q, NCLASS	0.4 MA
Ibs, EFIT/q, Sauter model	0.5 MA

Current diffusion studies for JET: OH current ramp up

- *Simulations of current diffusion with measured T_e and line averaged Z_{eff}*
- *EFIT/Q is initial profile*
- *First sawtooth crash (i.e. $q_0 > 0.8$) at 6.9 s*

$$\sigma \sim T_e^{3/2} / Z_{eff}$$

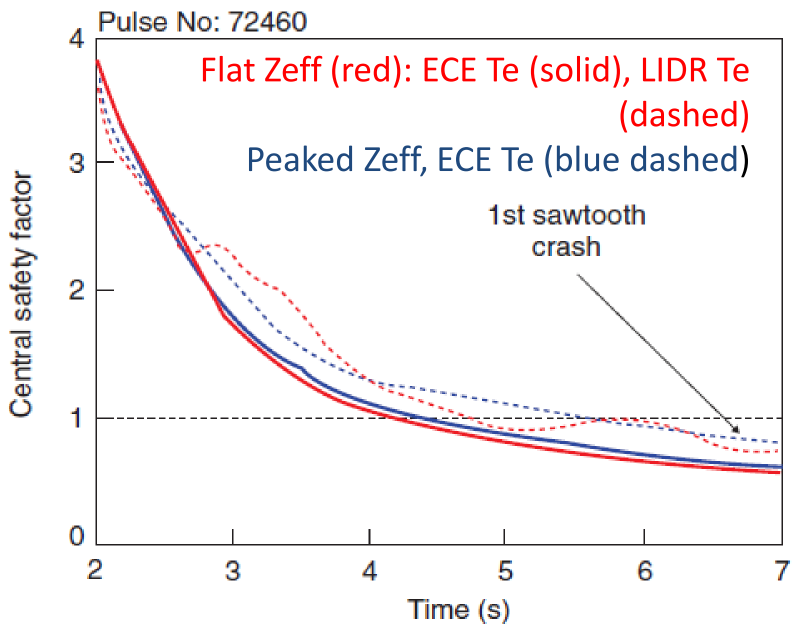
Sensitivity to Z_{eff} profile:

- flat Z_{eff} → slower current diffusion towards the centre, higher q_0 at the beginning of the ramp up
- peaked Z_{eff} → broader stationary j, higher q_0

Sensitivity to T_e profile:

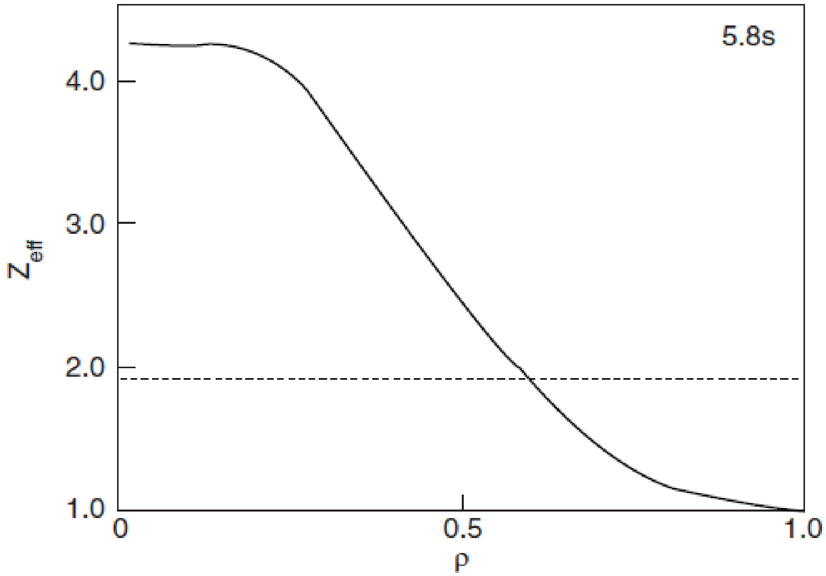
- peaked T_e →slower current diffusion towards the centre, higher q_0 at the beginning of the ramp up
- flat T_e → broader stationary j, higher q_0

Voitsekhovitch et al, PPCF 2010



Flat Zeff (red): ECE Te (solid), LIDR Te (dashed)

Peaked Zeff, ECE Te (blue dashed)



Current diffusion studies for JET: high β_N scenario

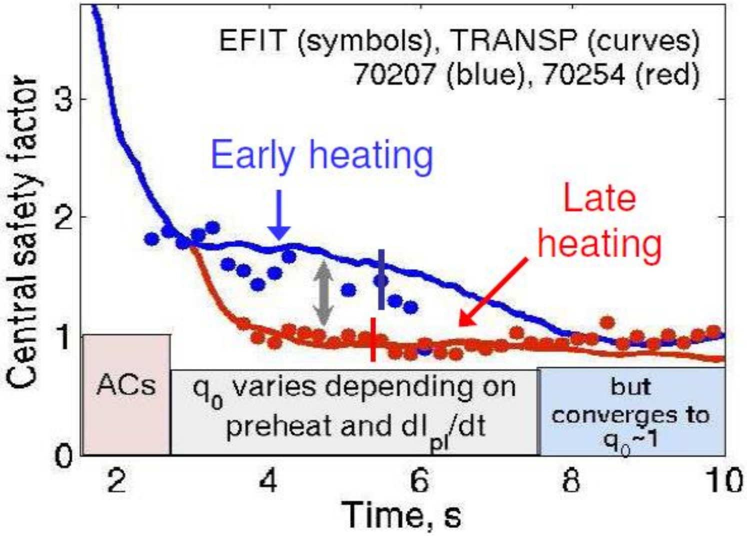
- Current diffusion simulations with measured Te, Zeff. NCLASS is used

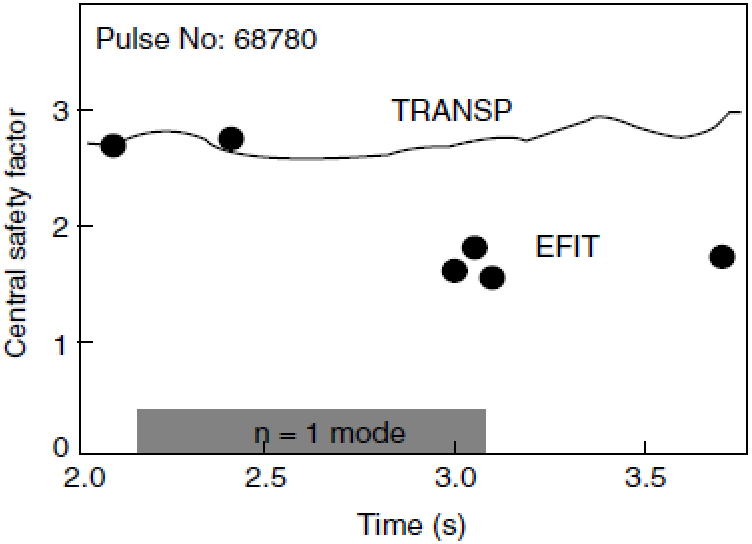
- EFIT/Q is initial profile taken 0.5 s before the NBI start

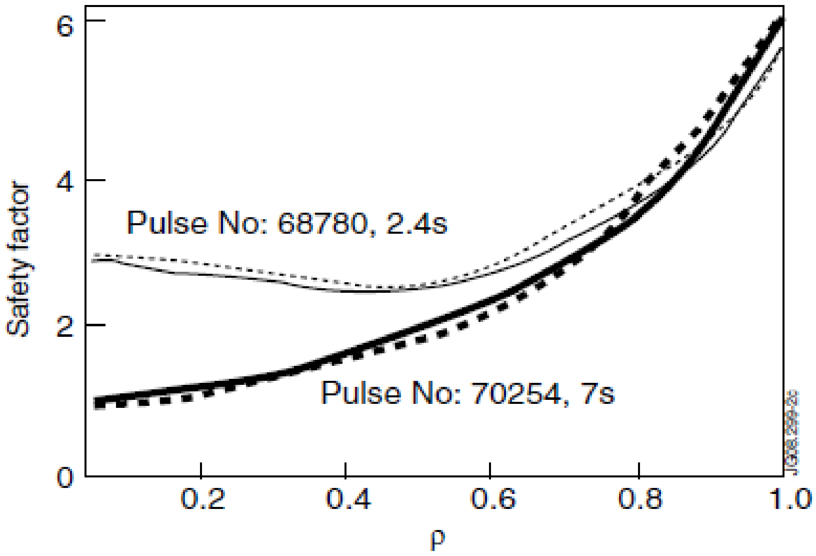
- Good agreement with EFIT for discharges with early and late NBI start

- Over-estimated central q in discharge with strong n=1 mode

Voitsekhovitch et al, Nucl. Fusion 2009







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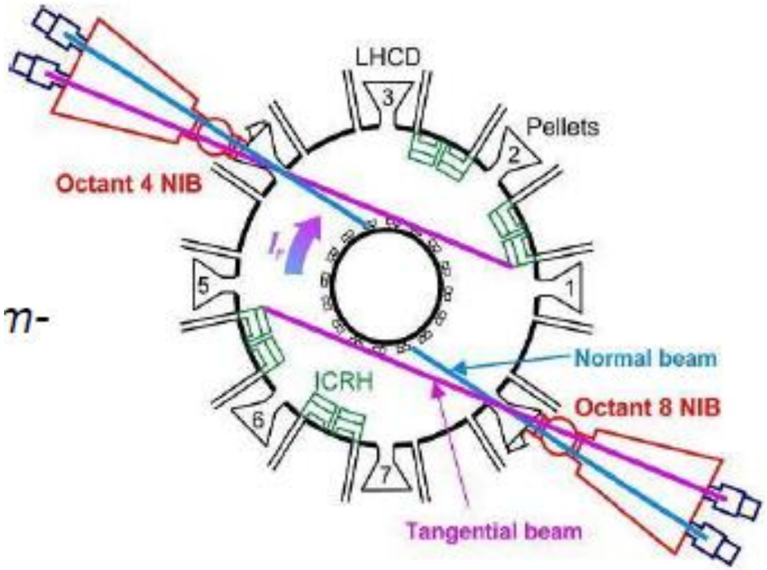
Neutral beam injection: NUBEAM [A.Pankin, CPC]

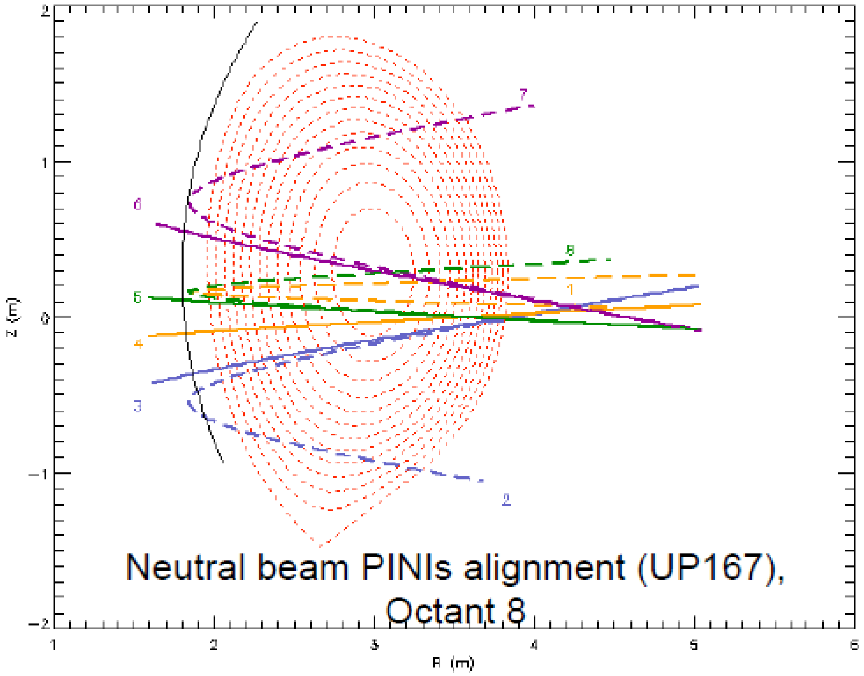
- 2D code, realistic geometry
- Monte-Carlo technique for beam ions and fusion products
- FLR effects included
- Deposition, secondary CX, slowing down
- Orbit losses, collisional and anomalous diffusion
- Sawtooth mixing of fast ions
- Built into JET database
- Frequently used output:

\- *heat, particle and momentum source*

\- *Fast particle distribution function f(ρ, pol.angle, E, pitch angle)*

η-

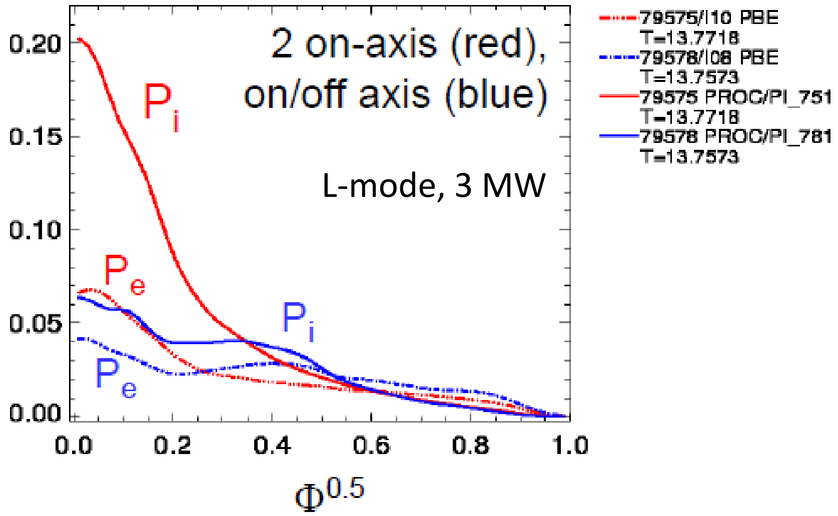


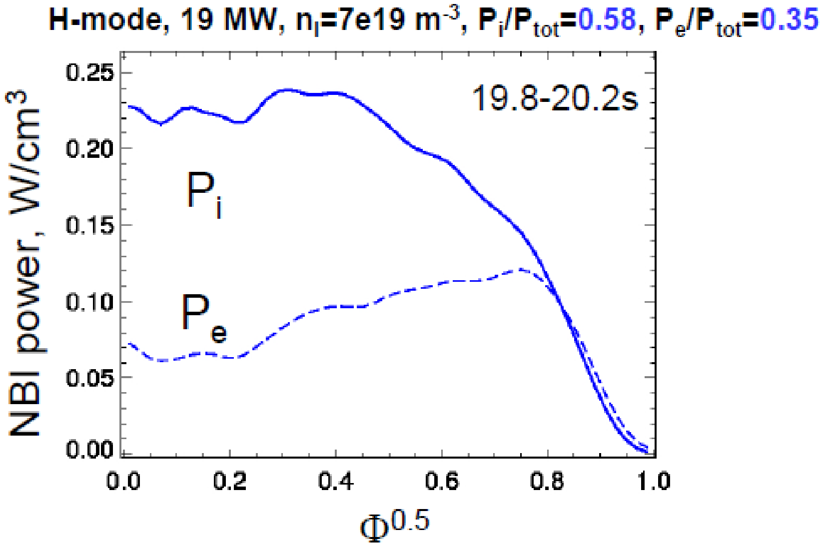


Neutral beam PINIs alignment (UP167), Octant 8

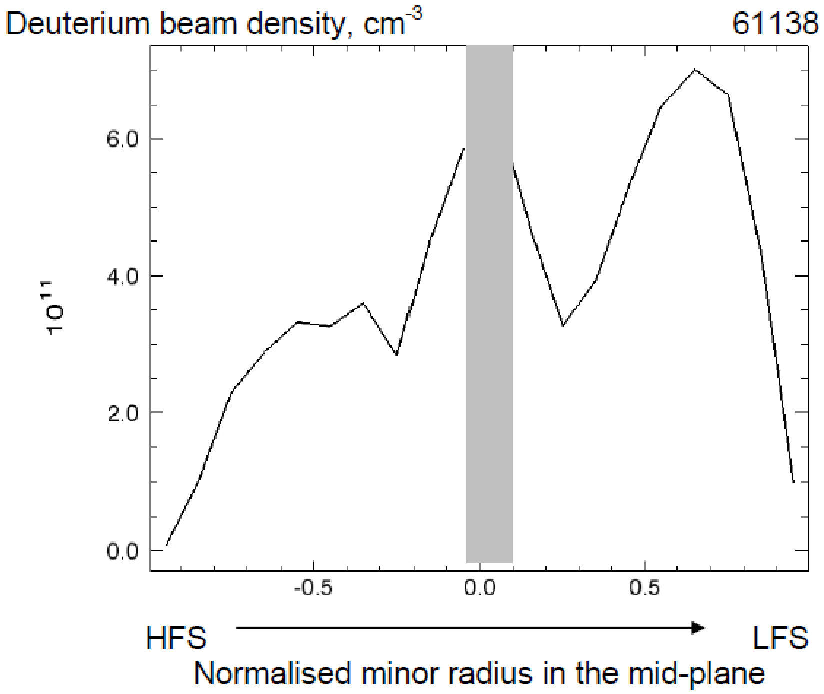
Examples of NUBEAM simulations for JET

NBI heating profile obtained with different beam configuration and plasma density





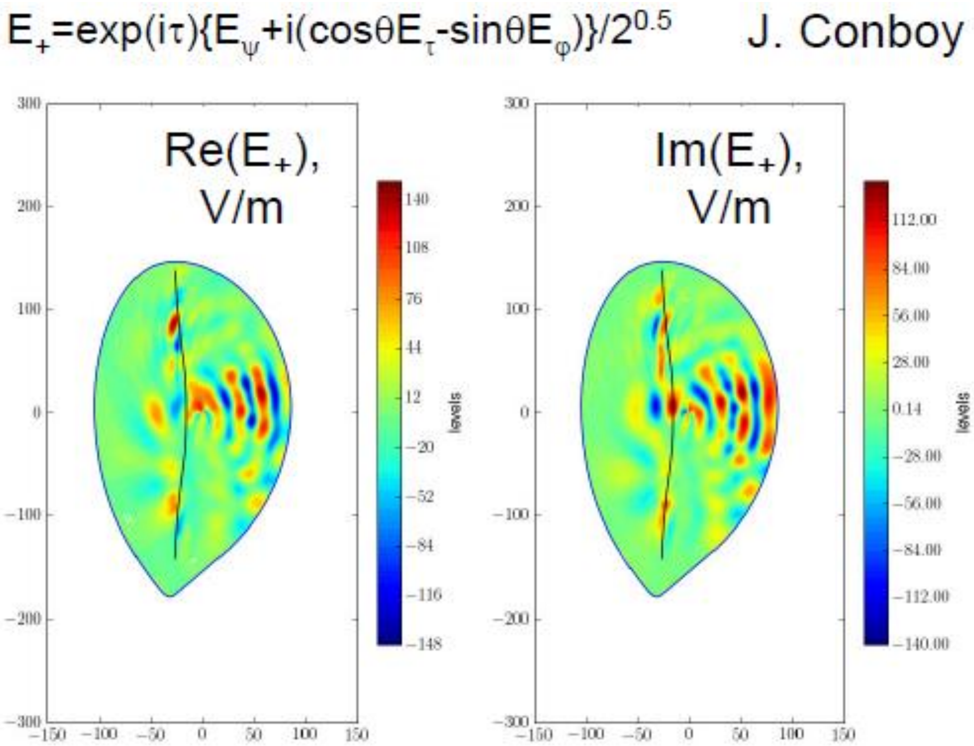
Voitsekhovitch et al, Nucl. Fusion 2007



Deuterium beam density profile in high density H-mode plasmas, obtained by integrating the 4D distribution function

Ion Cyclotron Heating: TORIC

- *FLR full wave code*
- *Solves Maxwell's equations in presence of plasma and wave antenna*
- *Retains the 2nd harmonic wave frequency*
- *specify both the damping power density on minority fast ions, and the 2D wave field (E+, polarization,* $k_{\perp}$*,* $k_{||}$*)*
- *Combined with FP module FPPMOD: re-normalises the original QL operator zone by zone while keeping the total power constant*



$E_+ = \exp(i\tau)\{E_\psi + i(\cos\theta E_\tau - \sin\theta E_\varphi)\}/2^{0.5}$ J. Conboy

Application for:

(1) minority heating (H and He3)
(2) fundamental D heating
(3) mode conversion

Refs: M. Brambilla, PPCF 41, 1, (1999) & M. Brambilla and T. Krucken, NF 28, 1813 (1988); D. G. Swanson, Phys. Fluids 24, 2035 (1981); P. T. Colestock and R. J. Kashuba, NF 23 763 (1983); J. C. Wright et al, PoP 11, 2473 (2004)

Lower hybrid heating and current drive

LSC (D.W.Ignat, E.J.Valeo):

- multiple ray tracing in general non-circular axisymmetric plasmas specified by a numerical equilibrium
- solve at each of several flux surfaces a simple one-dimensional (in velocity) Fokker Planck equation for the quasilinear evolution of the electron distribution function
- provide the RF power and RF-driven current electric field

Refs: D. W. Ignat, Phys. Fluids, 1981; E. J. Valeo and D. C. Eder, J. Comp. Physics, 1987. C. F. F. Karney and N. J. Fisch, Phys. Fluids 1986

GENRAY (work in progress):

- ray tracing code
- can be used for modeling electron cyclotron and lower hybrid heating and current drive in tokamaks

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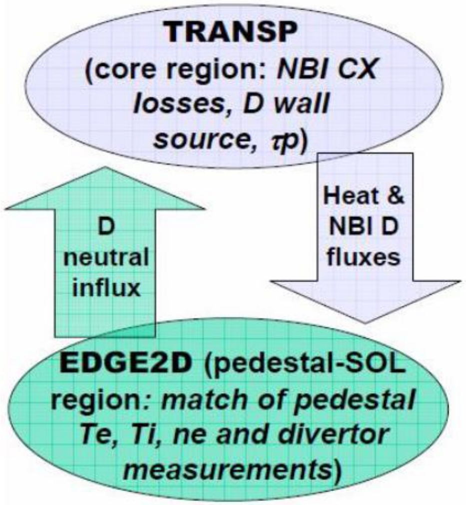
FRANTIC [Korotkov A.A., Zinove'v A.N, Sov. J. Plasma Phys. 1989]

- Fluid 1.5D model, no poloidal variation of the source
- Simplified geometry: nested cylinders of shifted centers given by flux surfaces
- Multiple ion and neutral species
- Charge exchange, impact ionization
- Input: neutral flux and energy of incoming neutrals (multiple energy species)
- For JET simulations: gas puff and re-normalised Dα signal, Γneut = Γpuff + const*$\Gamma\alpha$
- Wall particle source Γneut is ad hoc, should not be used for estimation of global particle confinement
- TRANSP-EDGE2D estimation of wall particle source for JET plasmas started under ITM/ISM (collaboration with Paula Belo)

TRANS-EDGE2D iterations (more detailed description in Voitsekhovitch et al NF 2013)

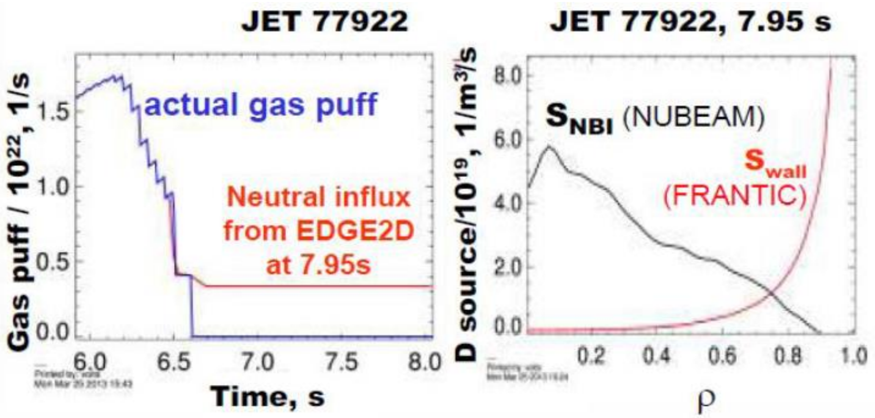


TRANSP (core region: *NBI CX losses, D wall source, τp*)

D neutral influx

Heat & NBI D fluxes

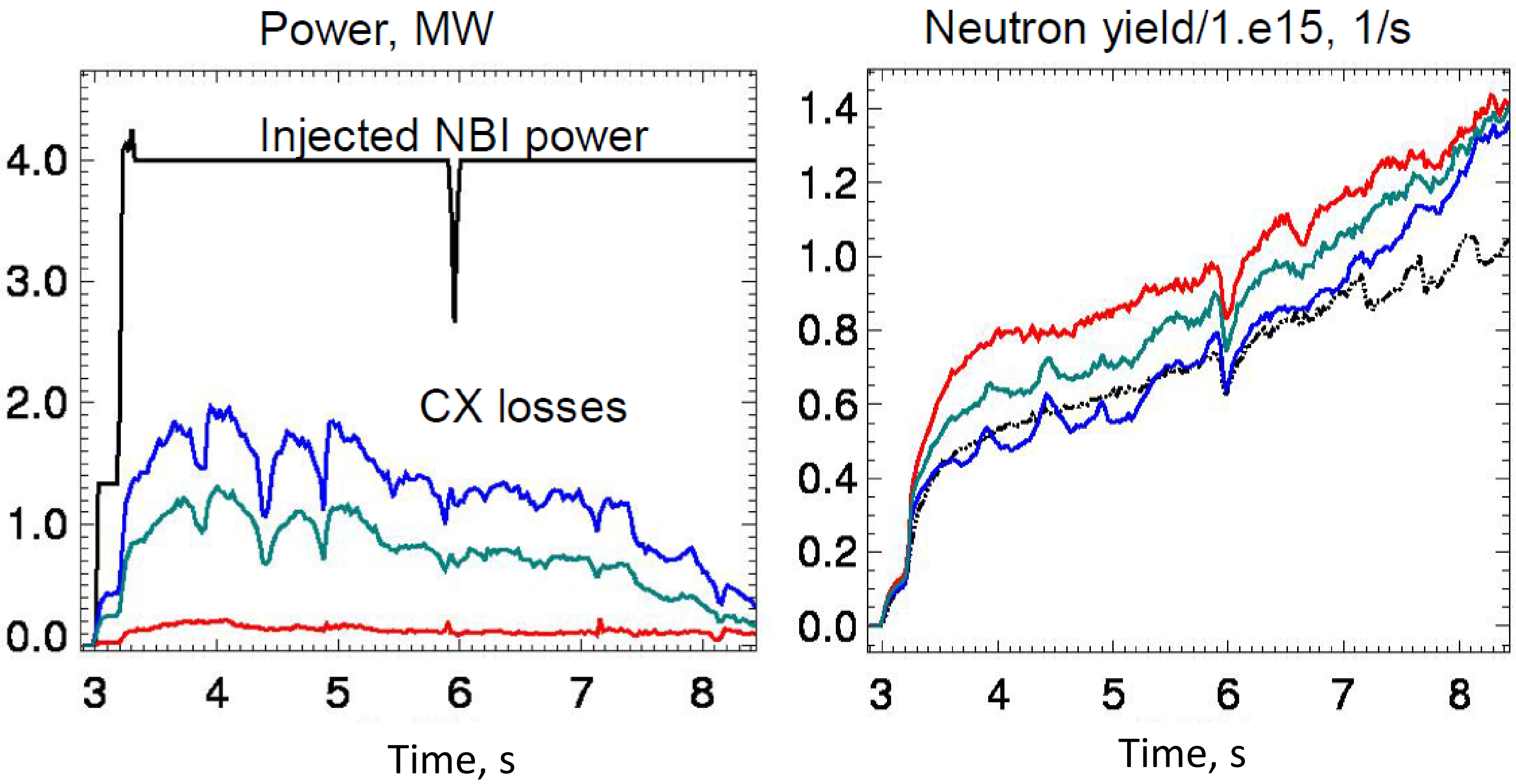
EDGE2D (pedestal-SOL region*: match of pedestal Te, Ti, ne and divertor measurements*)



Estimation of particle confinement time and $\Gamma\alpha$ normalisation [Voitsekhovitch et al EPS 2012:
79635 (low power HS): τp=0.4 s, τE=0.16 s, const=17.5
77922 (high power HS): τp=0.54 s, τE=0.25 s, const=16.8

Effect of gas puff (CX losses) on neutron yield during current ramp up

Γpuff = C*GASM, C=1, 20, 50



- sensitivity to CX losses is tested by varying gas puff
- good agreement with measured neutron yield with C ~ 40, but the CX losses are high

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Kadomtsev reconnection model [Sov. J. Plasma Phys., 1975]

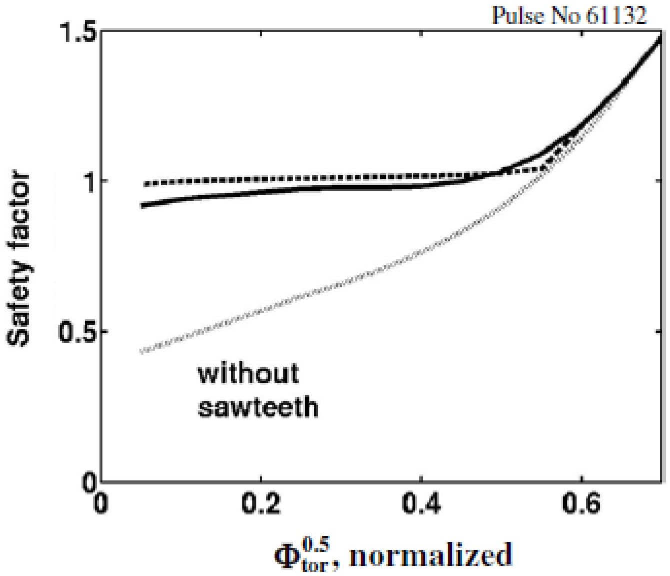
TRANSP sawtooth models:

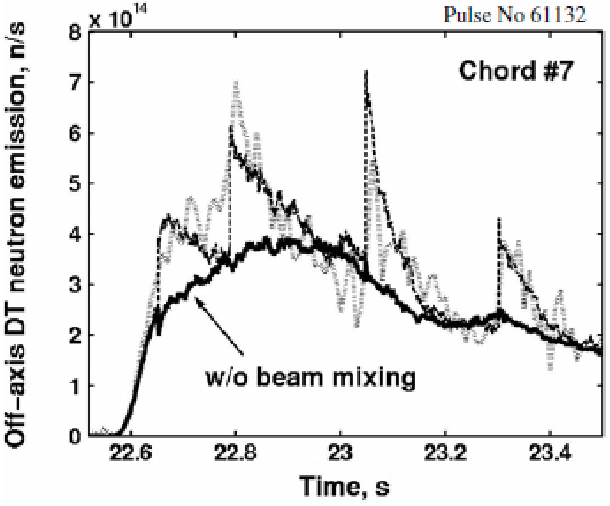
- crash times taken from data (ECE, soft X-ray)
- radius with q=1 is extended to provide the helical flux conservation
- q, Te, Ti, thermal and fast ion (NBI & RF) densities are mixed following the reconnection of magnetic flux surfaces:

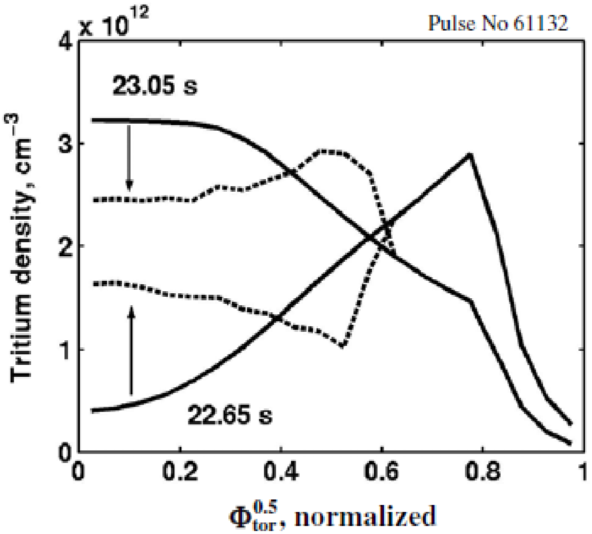
  → centrally peaked profiles flatten

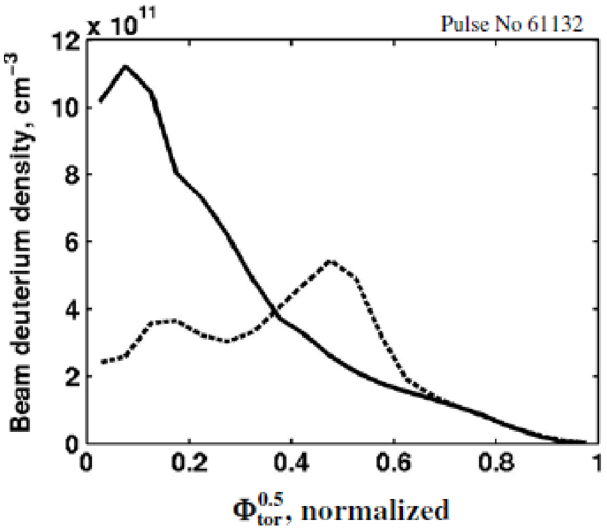
  → off-axis particles go towards the center

Voitsekhovitch et al, PPCF 2005









Porcelli reconnection model [PPCF, 1996]

Kadomtsev mixing yields q>=1 everywhere; Porcelli mixing generally leaves a region with q<1 near the axis

Options in Porcelli model:

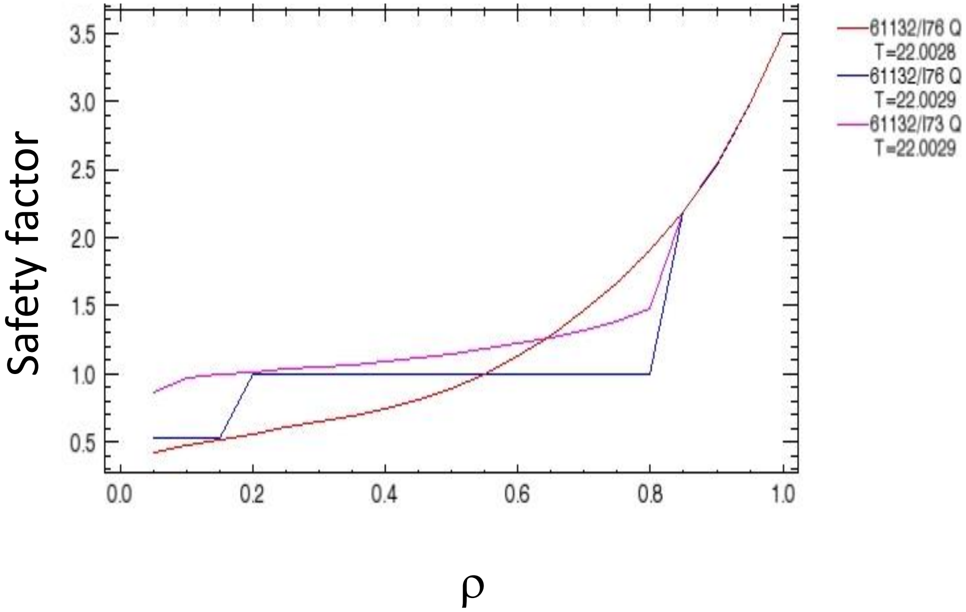
- two mixing regions: "island" around q=1 and axial region inside the island annulus

- single mixing region for predicted plasma species, covering both the q=1 island and the axial region

- island width controlled by user

- fraction of mixed fast ions controlled by user

Evolution of q-profile during the first sawtooth crash in Kadomtsev (red and pink) and Porcelli (red and blue) models (same initial conditions)



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Predictive TRANSP:

- thermal ion and electron temperature equations

- transport modules for temperature and density

- momentum equation

- modelling of density of trace species

Particle and energy balance equations

Particle: $$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rnV) + S_{gas} + S_{beam} - L_{c-x,recomb,etc}$$

Energy (e$^-$): $$\frac{\partial nT}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(rn\chi\frac{\partial}{\partial r}T\right) - nTV_r + P_{OH} + P_{beam} - P_{ie} - P_{rad}$$

S. Kay, JET-PPPL remote meeting 20/09/2013

- *Whole plasma region or shifted boundary*
- *Source computed with NUBEAM, TORIC, LSC, FRANTIC*
- *Radiative power taken from measurements or computed assuming coronal equilibrium*
- *Transport models: GLF23, Multi-Mode Model, TGLF (not in production version yet)*

Transport modules: Gyro-Landau-Fluid (GLF23)

[*R E Waltz et al Phys. Fluids B 1992*]

- 3D non-linear GLF code (fluctuating n_i, $P_{i//}$, $P_{i\perp}$, $V_{i//}$, trapped n_e and P_e, passing n_e, $A_{//}$, etc., quasineutrality condition + 3D ballooning GKS code

- mixing length estimation of transport coefficients:

$$\chi \approx 1.5(\gamma_{net} / k_{xM}^2) \times \gamma_d\gamma / (\gamma^2 + \omega^2)$$

- ITG, TEM and ETG turbulence, 10 modes in *k*-spectrum

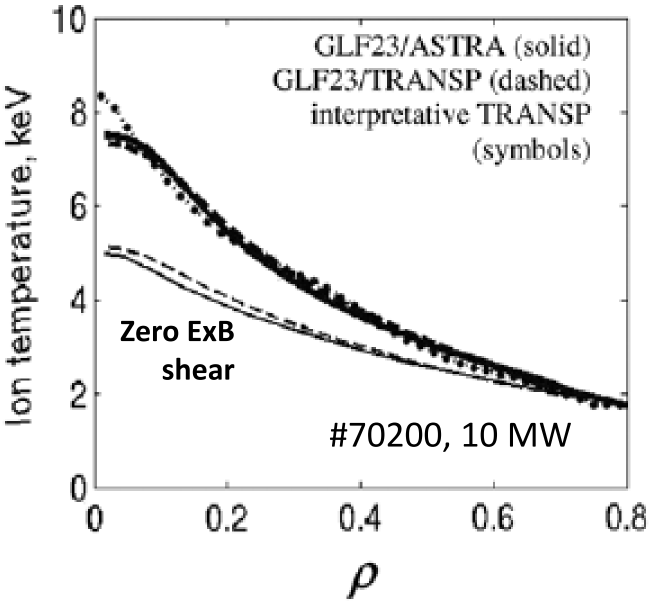
- dependencies: critical gradient, T_i/T_e, L_{Ti}, L_{Te}, L_n, q

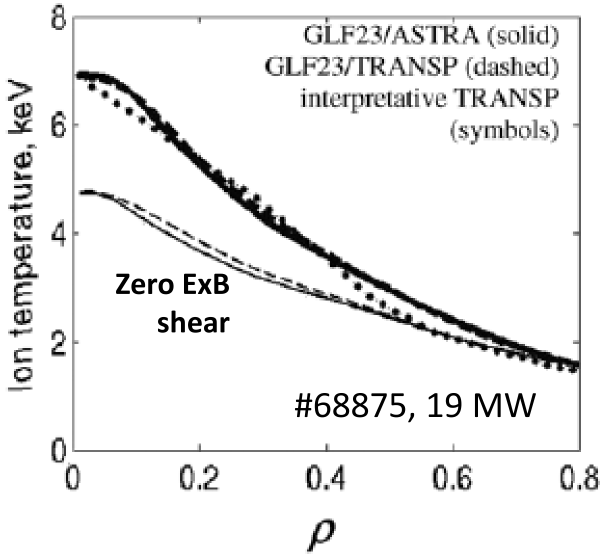
- implementation: GLF23 coefficients computed self-consistently with Braginskii equations for averaged quantities in time dependent simulations

- computes χ_e, χ_i, D_i, χ_φ

- available in NTCC module library: http://w3.pppl.gov/rib/repositories/NTCC/catalog/

Voitsekhovitch et al NF 2009





Transport modules: Multi-Mode Model

[G Bateman et al Phys. Plasmas 1998]

$$\chi = \chi(centre) + \chi(gradient\ region) + \chi(edge) + \chi_{\text{neocl.}}$$

Kinetic Ballooning Model

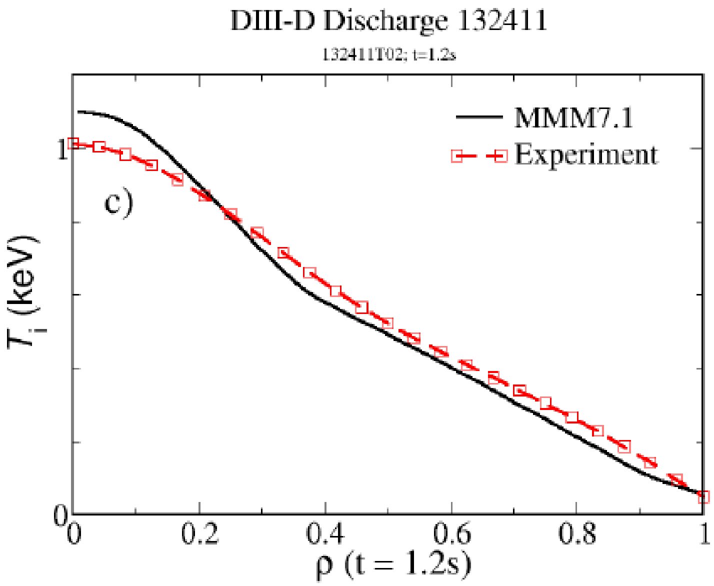
Weiland model
Horton ETG model

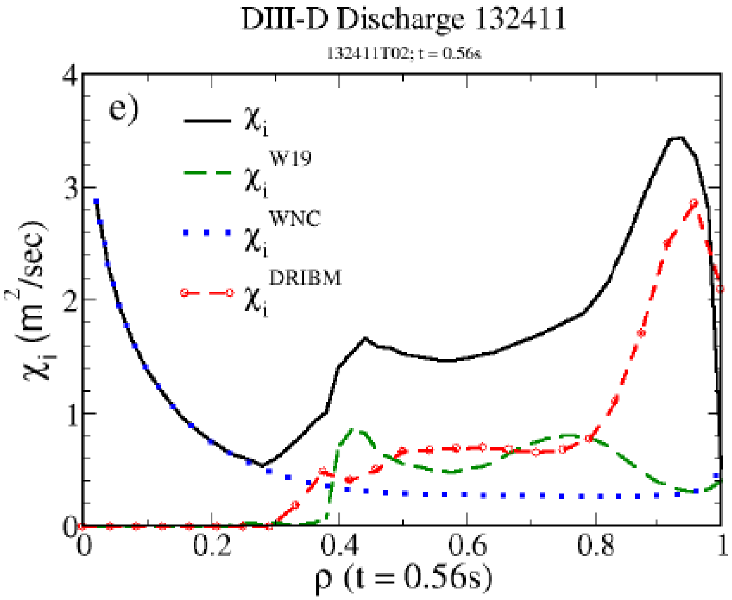
RBM, DRIBM
by T. Rafiq
(L-mode)

NCLASS
paleoclassical

- *Flexible implementation: various components can be switched on/off*
- *Detailed output: χi, χe, $\chi\varphi$, D for all models, growth rates for Weiland and DRIBM)*

T. Rafiq et al, submitted to PoP


DIII-D Discharge 132411
132411T02; t=1.2s


DIII-D Discharge 132411
132411T02; t = 0.56s

Momentum transport

TRANSPP variables and equations relevant to momentum transport:

angular velocity:

$\omega(\sqrt{\Phi}) = V\varphi/R$ (all thermal species are assumed to have the same angular velocity)

angular momentum density (in analysis mode inferred from density, Z_{eff} and toroidal rotation measurements):

$m = \langle R^2 \rangle \omega \Sigma_j n_j{}^* M_j$ (sum over thermal species, electron momentum is ignored)

input torques:

$S\varphi_{total} = S_{nbi,coll}$(including $S_{nbi,i}$ & $S_{nbi,e}$) + $S_{nbi,therm}$ +

S_{JxB}(radial movement of fast ions) + S_{ripple} + S_{anom}(prescribed)

CX losses:

$S_{CX\_losses} = S_1$(beam CX momentum loss (NUBEAM)) - S_2(partly recaptured by neutral gas model (FRANTIC))

Momentum transport

Momentum balance equation:

$$dm/dt = S\varphi_{total} - S_{CX\_losses} - (1/r)(d/dr)(\chi_\varphi \nabla m) - \langle R^2 \rangle \omega \Sigma_j \Gamma_j M_j$$

χ_φ is the momentum diffusivity calculated in analysis mode

Momentum confinement time :

$$dL/dt = \int (S\varphi_{total} - S_{CX\_losses} - \langle R^2 \rangle \omega \Sigma_j \Gamma_j M_j) dv - L/\tau_\varphi \qquad L = \int (\langle R^2 \rangle \omega \Sigma_j n_j{}^* M_j) dv$$

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* Description of toroidal momentum transport in TRANSP: R. J. Goldston in "*Basic Physical Processes of Toroidal Fusion Plasmas*", Varenna, 1985
ftp://ftp.pppl.gov:/pub/dmccune/transp/Goldston_Rotation.pdf

Modelling of trace species

$$\frac{dn}{dt} = \mathrm{S} - \mathrm{div}(\Gamma)$$

Here S includes beam fuelling, gas flow and recycling

$$\Gamma = \mathrm{V} * (- \mathrm{Lf} * \mathrm{grad}(n) + n) \qquad (1)$$

or

$$\Gamma = -\mathrm{D} * \mathrm{grad}(n) + \mathrm{V} * n \qquad (2)$$

V is the non diffusive radial velocity, Lf is the diffusive flow scale length, D is the specie diffusivity (Ufile input).

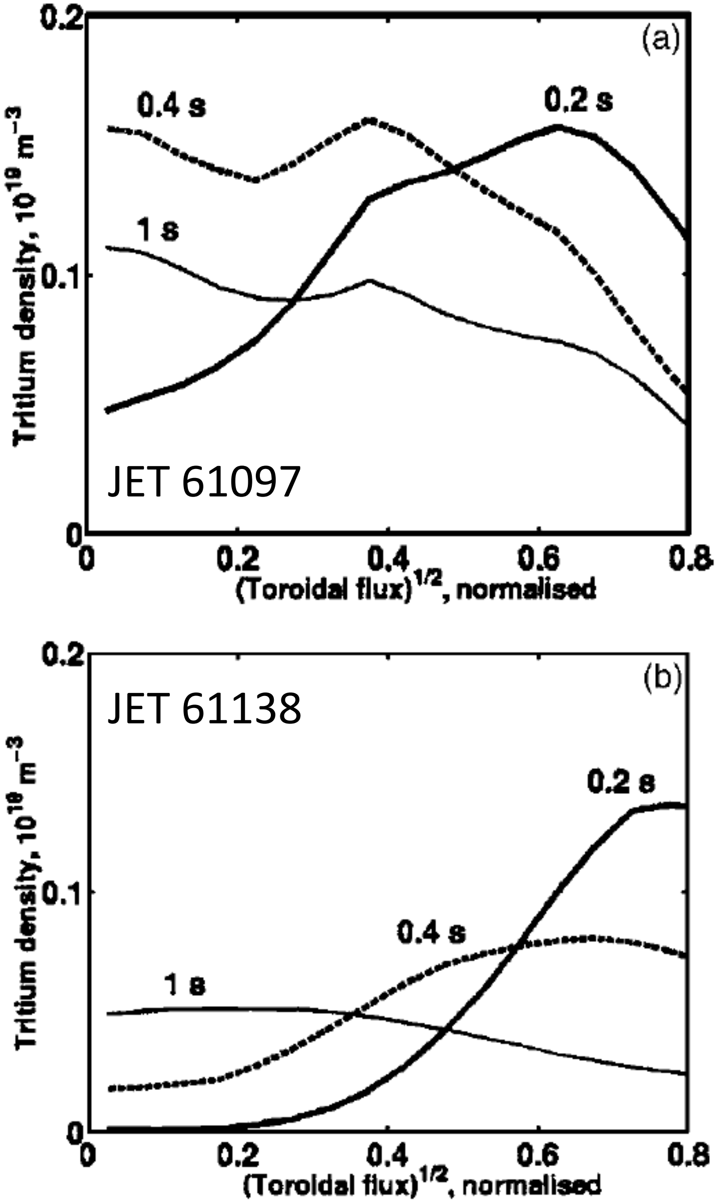
The following combinations are allowed:

V only -- formula (2), assuming D=0.0

D only -- formula (2), assuming V=0.0

D and V -- formula (2)

Lf and V -- formula (1)



Evolution of trace tritium density after the short tritium gas puff [Voitsekhovitch et al, PoP 2005]

Summary

- TRANSP has incorporated state-of-the-art source and transport models for use as either an interpretive or predictive analysis tool
  - Driven by community input and needs

- Treatments and solvers are becoming increasingly sophisticated and comprehensive

- Provide links to other computationally intensive codes (macro-, micro-fast ion stability, RF full wave, etc.)

- Extensive use of TRANSP capabilities (presently and planned) by a large number of institutions around the world

- Running TRANSP on FusionGrid allows for timely support and quick debug turnaround by PPPL Computational Plasma Physics Group

Areas of developments

- Continued PT_SOLVER development
  - Momentum, density predictions, benchmark with TGYRO
- Free boundary equilibrium
  - Shape control algorithms, more flexible current control
- NUBEAM and RF
  - TF ripple, coupling to RF, assess GPU for speedup, upgrade RF modules
- Regression testing for code upgrades
- Parallel architecture
  - NUBEAM/TORIC simultaneous execution, solver speedups
- Output pipeline
  - More flexible and state-of-the-art outputs and graphics
- Update tools for preparing and launching runs, assess UFILE structure
- Additional physics
  - Improved (2D) neutral transport model, physics-based AE-driven fast ion diffusion model, long term (edge-core, stability, turbulence code interfaces)

S. Kay, JET-PPPL remote meeting 20/09/2013