Stellarator Impurity STRAHL Code Development in NIFS

Yu. Igitkhanov*, P. Goncharov, S. Sudo, N.Tamura, D. Kalinina, H. Funaba, R. Dux*, M. Yokoyama, K. Kawahata, N. H. Yamada and O. Motojima.

National Institute for Fusion Science, Oroshi-cho 322-6, Toki 509-5292, Japan,
**Max-Planck Institut für Plasmaphysik, Germany*

Large Helical Device

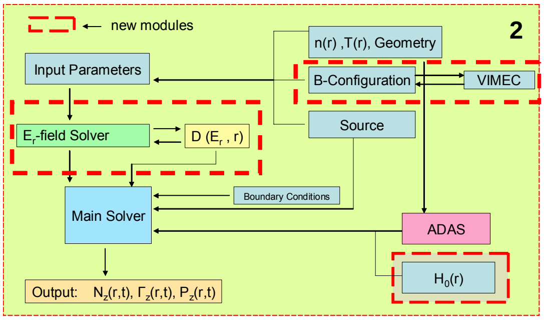
Goal: 1

- Modeling of impurity radiation signal in TESPEL experiments and assessment of the impurity transport in LHD plasma

this requires a new Impurity Code, which includes

- stellarator relevant neoclassical transport coefficients and LHD relevant B metrics
- equation for ambipolar Er field
- new solver for stiff impurity equations

CHART: Heliotron STRAHL Code



Impurity Transport Equations 3

The set of coupled time-dependent 1-D continuity equations for impurity density, n_j^I for each ionization stages, j of a given impurity species I, averaged over the magnetic surfaces ψ :

$$\frac{\partial n_j^I}{\partial t}+\frac{1}{\sqrt{g}}\frac{\partial}{\partial r}\left(\sqrt{g}\,\Gamma^{I,j}\right)=S_j^I, \qquad j=1,2 \ldots Z_I \qquad g=g(\psi)$$

$$\Gamma^{I,j}=\Gamma_{an}^{I,j}+\Gamma_{neo}^{I,j} \qquad \Gamma_{an}^{I,j}=-D_{an}^{I,j}\nabla n_j^I+n_j^I V_{an}^{I,j}$$

$$\Gamma_{neo}^{I,j}=-D_1^{I,j}\nabla n_j^I+n_j^I V_{neo}^{I,j}$$

$$V_{neo}^{I,j}=\frac{D_1^{I,j}}{T}\left\{Z_j E_r-\left(\frac{D_2^{I,j}}{D_1^{I,j}}-\frac{3}{2}\right)\nabla T\right\} \qquad T_i=T_I=T$$

Solver: method of line; stiff ode -Rosenbrocks (Z<10) or semi implicit extrapol. (Z>10) methods

Stellarator Neoclassical Transport

input output

$$\begin{pmatrix} B(\vec{x}) \\ f_0(\vec{x}) \end{pmatrix} \rightarrow \boxed{\text{VMEC}} \begin{Bmatrix} \Psi(\vec{x}) \\ g_{ik}(\vec{x}) \\ \iota(\vec{x}) \end{Bmatrix} \rightarrow \boxed{\text{DKES}} \; \{D_n(V,E,n)\} \text{--} \boxed{\text{Aver. over V space}} \rightarrow D_n(n,T,E) \qquad 4$$

Transport Code

and the monoenergetic diffusion coefficients D^{imp} can be given by the analytical expressions:

$$D^{imp}=D_a^{imp}+D_h^{imp} \qquad \frac{1}{D_h^{imp}}=\frac{1}{D_{1/\nu}^{imp}}+\frac{1}{D_{\sqrt{\nu}}^{imp}}+\frac{1}{D_\nu^{imp}} \qquad D_a^{imp}=\left\{\left(D_{PS}^{imp}\right)^{2/3}+\left(D_{bp}^{imp}\right)^{2/3}\right\}^{3/2}$$

$$D_{PS}^I(E_r,V,r)\approx D_{PS}^I\left[\frac{1}{1+\left(\frac{3\nu_I\Omega_E R_0^2}{\iota^2 V^2}\right)^2}+\left(\frac{\varepsilon_t}{b_{1,0}}\right)^2\right], \qquad D_{PS}^I=\frac{4}{3}\frac{V_I^2 R_0}{\Omega_I}\left(\frac{b_{1,0}}{\varepsilon_t}\right)^2\nu_I$$

$$D_{bp}^{imp}=\left(\frac{\sqrt{b_{1,0}}}{\varepsilon_t^2}\right)\frac{V_d R_0}{\Omega\iota^2}\nu \qquad D_{1/\nu}^{imp}=\frac{4}{9\pi}\left(2\varepsilon_{eff}\right)^{3/2}\frac{V_d^2}{\nu}$$

$$D_\nu^{imp}=A_\nu\left(\frac{b_{1,0}}{\varepsilon_t}\frac{V_d}{\Omega_E}\right)^2\nu \qquad D_{\sqrt{\nu}}^{imp}=A_{\sqrt{\nu}}\left(\frac{b_{1,0}}{\varepsilon_t}V_d\right)^2\sqrt{\frac{\nu}{\Omega_E^2}}$$

where $\Omega_E=E_r/aB_0$, $\Omega_I=ZeB_0/m_Z$, a and R_0 are the average minor and major radii, $\nu=\nu_I(x,r)$ is the collisional frequency for impurity ions, $V_d=xT/ZeR_0B_0$, $x=m_Z V^2/2T$, $\Omega=eZB_0/m_Z$. Expressions for ε_{eff}, A_ν, $A_{\sqrt{\nu}}$, $b_{1,0}$, ι, ε_t are functions of the radial coordinate, determined numerically with the DKES code and monoenergetic Monte Carlo simulations (C. D. Beidler) .

Radial Electric Field 5

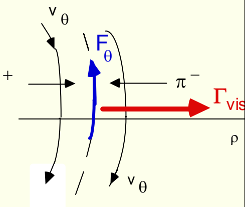
- flux surface average of the radial component of Ampere,s law [Shaing 1984, Wobig 2001].

$$\varepsilon_\perp\frac{\partial E_r}{\partial t}=4\pi e\left(z_i\Gamma_i-\Gamma_e\right) \qquad \varepsilon_\perp\approx(c/v_A)^2(1+2/\iota^2)$$

$$\Gamma_i=\Gamma_i^{dif}+\Gamma_i^{vis}$$

$$F_\theta\approx-\frac{\partial}{\partial r}\left(\eta\frac{\partial v_\theta}{\partial r}\right) \qquad v_\theta\propto\frac{E_r}{B}$$

$$\Gamma_i^{vis}\approx nV_{F\times B}=nF_\theta/B=-\frac{n}{B^2}\frac{\partial}{\partial r}\left(\eta\frac{\partial E_r}{\partial r}\right)$$



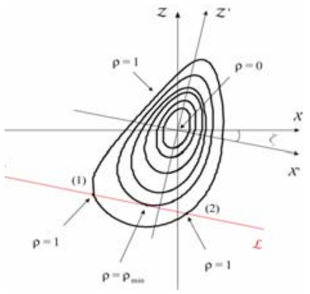
[Hastings, 1985; Maassberg, 1993].

$$\boxed{\varepsilon_\perp\frac{\partial E_r}{\partial t}-\frac{2}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\eta\tilde{E}_r}{B^2}\right)+\left(\frac{\tilde{E}_r}{B}\right)^2\left(\frac{\partial\eta}{\partial E_r}\right)=e\left(z_i\Gamma^{dif}(E_r)-\Gamma_e(E_r)\right)} \qquad \tilde{E}_r\equiv E_r'-E_r/r$$

$\eta(E_r)$: $\eta\approx const.$ for $E_r\le E_{res}\equiv\iota v_{Te}Br/R$; $\eta\propto E_r^{-\beta}$ for $E_r\ge E_{res}$. $\beta\approx4$

- Boundary conditions: r = 0 $E_r=0$; and at the edge either $E_r=0$ for limiter, otherwise $\Gamma_{vis}\approx0$ (no transition at the edge!)

Radiation observation sight-line geometry 6



$$Q^-(\rho,\zeta)=\frac{dX'}{d\rho} \qquad Q^+(\rho,\zeta)=\frac{dX'}{d\rho}$$

$$\Gamma(\zeta)=\int_{\rho_{min}}^{1}\tilde{g}(\rho)\left(Q^+(\rho,\zeta)-Q^-(\rho,\zeta)\right)d\rho$$

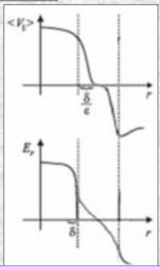
Radial E-field in the vicinity of a magnetic island (anomalous viscosity) 7

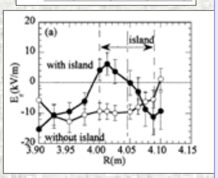
Rozhanski,2004

$$E_r\approx T_i\left(\frac{\partial\ln n}{h\partial r}+k\frac{\partial\ln T_i}{h\partial r}\right)+\left\langle V_\theta B_{//}\right\rangle$$

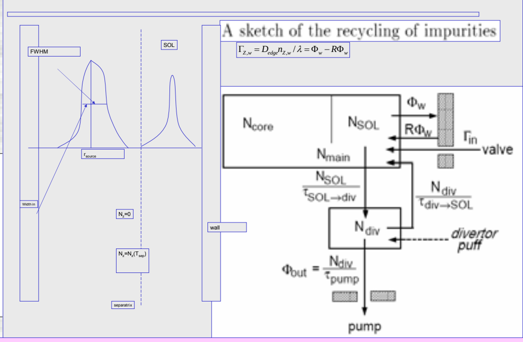
$$E_r=E_r^{neo}\left\{\frac{1-e^{[r-r_{sep}]}}{\sqrt{2\delta}}\right\}-\frac{\langle B\rangle\omega r}{m}$$

$$\delta=\left(\frac{2}{3}\frac{\eta_{an}r^2}{\eta_0 B_p/B}\right)^{1/2}$$





Boundary conditions 8



Output Parameters 9

- Density & Temperature Distribution of main plasma
- Fractional Abundance
- Density Distribution in Corona Approx.
- Concentration of impurities in non-coronal case
- Mean Charge, Zeff profile
- Radial E-field
- Diffusion Coefficient
- Drift Velocity
- Drift Velocity/Diffusion Coefficient
- Neoclassical Drift-Coefficients
- Collisionality Regime
- Ionisation Source
- Recombination Source
- Line Rdiation from Diagnostic Lines
- Total Radiation
- Total Radiation in soft X-ray range
- Spectral Bremsstrahlung
- Electron/Main Ion Density

Conclusions

- A new **Stellarator Impurity Transport Code (SIT)** has been developed aiming to describe impurity behaviour in the frame of stellarator-relevant neoclassical transport theory.
- An analytical description of the neoclassical transport coefficient for background plasmas (based on numerical results from the DKES code and monoenergetic Monte Carlo simulations) have been generalized to the impurity ions of arbitrary mass and charge number.

- Modeling with the interpretative code SIT (STRAHL) of impurity radiation signal in TESPEL experiments and assessments of the impurity transport coefficients have been started (see Poster P13-07, 08)
- The SIT (STRAHL) Code is an important part (subroutine) of general integrated Code TASK, which is currently under development in NIFS.
- The Impurity Transport Code ST STRAHL will be operating on the NEC SX-8 vector supercomputer

Further plans

- benchmarking with MIST and STRAHL
- SOL and stochastic edge: new boundary conditions
- link with ADAS, atomic data for heavy impurity ions (Mo, W, Ti) will be needed
- ultimate goal: Incorporation into TASK Code