USER MANUAL

NEMEC OUTPUT

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NEMEC EQUILIBRIUM OUTPUT

The program **readnemec.f90** reads the equilibrium output of the NEMEC code, which is stored in the output file **wout.**xxx. Both, ASCII and binary data files are possible. Please note, the equilibrium output is provided in double precision: real-size 64. Therefore, on a LINUX system the program has to be compiled with

ifort -real-size 64 or mpiifort -real-size 64

Please also read the comments in program **readnemec.f90**.

The NEMEC code [1, 2, 3] uses the left-handed flux coordinates (s, θ, ζ) with the radial coordinate s being the normalized toroidal flux, the poloidal coordinate, θ, $(0 \leq \theta < 2\pi)$, and the toroidal coordinate, ζ, $(0 \leq \zeta < 2\pi)$.

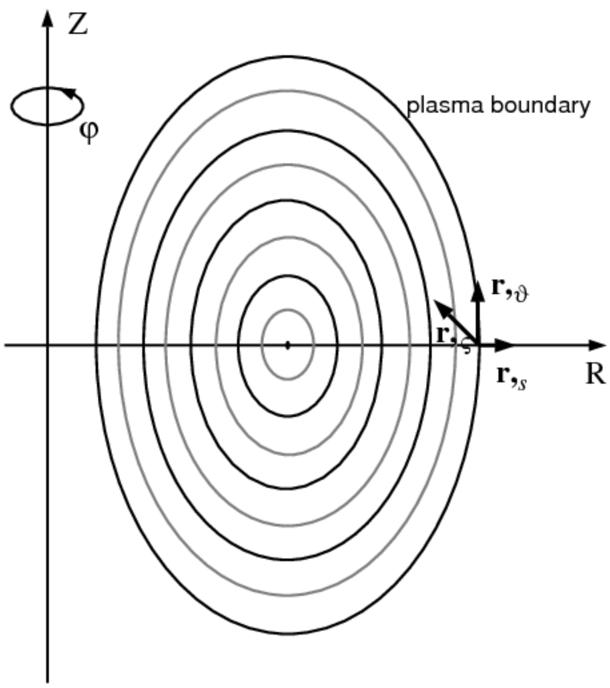

Fig. 1: Flux surfaces from the magnetic axis to the plasma boundary for a poloidal cross-section in the cylindrical coordinate system (R, φ, Z). The solid lines mark the flux surfaces (full mesh) on which the Fourier coefficients $\{\hat{r}^{\rm c}_{\rm m,n}(s_{\rm i}), \hat{r}^{\rm s}_{\rm m,n}(s_{\rm i}), \hat{z}^{\rm c}_{\rm m,n}(s_{\rm i}), \hat{z}^{\rm s}_{\rm m,n}(s_{\rm i})\}$ are given, while the dashed lines belong to surfaces (half mesh) on which the Fourier coefficients of the magnetic field are defined. The arrows represent the curvilinear basis vectors $(\mathbf{r},_s, \mathbf{r},_\theta, \mathbf{r},_\zeta)$ used in the NEMEC code.

The flux coordinates are related with the cylindrical coordinates (R, φ, Z):

$$R = \sum_{\rm m=0,n=-n_b}^{\rm m_b,n_b} \hat{r}^{\rm c}_{\rm m,n}(s)\cos({\rm m}\theta - {\rm n}\zeta{\rm N_p}) + \hat{r}^{\rm s}_{\rm m,n}(s)\sin({\rm m}\theta - {\rm n}\zeta{\rm N_p}),$$

$$\varphi = \zeta, \tag{1}$$

$$Z = \sum_{\rm m=0,n=-n_b}^{\rm m_b,n_b} \hat{z}^{\rm c}_{\rm m,n}(s)\cos({\rm m}\theta - {\rm n}\zeta{\rm N_p}) + \hat{z}^{\rm s}_{\rm m,n}(s)\sin({\rm m}\theta - {\rm n}\zeta{\rm N_p}),$$

with $\{\hat{r}^{\mathrm{c}}_{\mathrm{m,n}}(s), \hat{r}^{\mathrm{s}}_{\mathrm{m,n}}(s), \hat{z}^{\mathrm{c}}_{\mathrm{m,n}}(s), \hat{z}^{\mathrm{s}}_{\mathrm{m,n}}(s)\}$ being the Fourier coefficients of a flux surface with normalized toroidal flux s. $\mathrm{N_p}$ is the number of periods, $0 \le \mathrm{m} \le \mathrm{m_b}$ are the poloidal harmonics, and $-\mathrm{n_b} \le \mathrm{n} \le \mathrm{n_b}$ are the toroidal harmonics.

The covariant form of the magnetic field reads

$$\mathbf{B} = B^{\theta}\mathbf{r}_{,\theta} + B^{\zeta}\mathbf{r}_{,\zeta}\,, \tag{2}$$

with the contravariant components

$$B^s = 0,$$

$$B^{\theta} = \sum_{\mathrm{m}=0,\mathrm{n}=-\mathrm{n_b}}^{\mathrm{m_b},\mathrm{n_b}} \hat{b}^{\theta,\mathrm{c}}_{\mathrm{m,n}}(s)\cos(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) + \hat{b}^{\theta,\mathrm{s}}_{\mathrm{m,n}}(s)\sin(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}), \tag{3}$$

$$B^{\zeta} = \sum_{\mathrm{m}=0,\mathrm{n}=-\mathrm{n_b}}^{\mathrm{m_b},\mathrm{n_b}} \hat{b}^{\zeta,\mathrm{c}}_{\mathrm{m,n}}(s)\cos(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) + \hat{b}^{\zeta,\mathrm{s}}_{\mathrm{m,n}}(s)\sin(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}),$$

and the Fourier coefficients $\{\hat{b}^{\theta,\mathrm{c}}_{\mathrm{m,n}}(s), \hat{b}^{\theta,\mathrm{s}}_{\mathrm{m,n}}(s), \hat{b}^{\zeta,\mathrm{c}}_{\mathrm{m,n}}(s), \hat{b}^{\zeta,\mathrm{s}}_{\mathrm{m,n}}(s)\}$.

Its contravariant form is given by

$$\mathbf{B} = B_s\nabla s + B_{\theta}\nabla\theta + B_{\zeta}\nabla\zeta \tag{4}$$

with the covariant components

$$B_s = \sum_{\mathrm{m}=0,\mathrm{n}=-\mathrm{n_b}}^{\mathrm{m_b},\mathrm{n_b}} \hat{b}^{\mathrm{m,n}}_{s,\mathrm{c}}(s)\cos(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) + \hat{b}^{\mathrm{m,n}}_{s,\mathrm{s}}(s)\sin(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p})$$

$$B_{\theta} = \sum_{\mathrm{m}=0,\mathrm{n}=-\mathrm{n_b}}^{\mathrm{m_b},\mathrm{n_b}} \hat{b}^{\mathrm{m,n}}_{\theta,\mathrm{c}}(s)\cos(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) + \hat{b}^{\mathrm{m,n}}_{\theta,\mathrm{s}}(s)\sin(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) \tag{5}$$

$$B_{\zeta} = \sum_{\mathrm{m}=0,\mathrm{n}=-\mathrm{n_b}}^{\mathrm{m_b},\mathrm{n_b}} \hat{b}^{\mathrm{m,n}}_{\zeta,\mathrm{c}}(s)\cos(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) + \hat{b}^{\mathrm{m,n}}_{\zeta,\mathrm{s}}(s)\sin(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p})$$

and the Fourier coefficients $\{\hat{b}^{\mathrm{m,n}}_{s,\mathrm{c}}(s), \hat{b}^{\mathrm{m,n}}_{s,\mathrm{s}}(s), \hat{b}^{\mathrm{m,n}}_{\theta,\mathrm{c}}(s), \hat{b}^{\mathrm{m,n}}_{\theta,\mathrm{s}}(s), \hat{b}^{\mathrm{m,n}}_{\zeta,\mathrm{c}}(s), \hat{b}^{\mathrm{m,n}}_{\zeta,\mathrm{s}}(s)\}$.

Furthermore, the NEMEC code uses the following Fourier representation of the single-valued function λ

$$\lambda = \sum_{\mathrm{m}=0,\mathrm{n}=-\mathrm{n_b}}^{\mathrm{m_b},\mathrm{n_b}} \hat{\lambda}^{\mathrm{c}}_{\mathrm{m,n}}(s)\cos(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) + \hat{\lambda}^{\mathrm{s}}_{\mathrm{m,n}}(s)\sin(\mathrm{m}\theta - \mathrm{n}\zeta\mathrm{N_p}) \tag{6}$$

with the Fourier coefficients $\{\hat{\lambda}^{\rm c}_{\rm m,n}(s), \hat{\lambda}^{\rm s}_{\rm m,n}(s)\}$.

The NEMEC code provides the Fourier coefficients

$$\{\hat{r}^{\rm c}_{\rm m,n}(s_{\rm i}), \hat{r}^{\rm s}_{\rm m,n}(s_{\rm i}), \hat{z}^{\rm c}_{\rm m,n}(s_{\rm i}), \hat{z}^{\rm s}_{\rm m,n}(s_{\rm i}), \hat{\lambda}^{\rm c}_{\rm m,n}(s_{\rm i}), \hat{\lambda}^{\rm s}_{\rm m,n}(s_{\rm i})\},$$

for a discrete number, N_s of nested flux surfaces i with $0 \le {\rm i} \le {\rm N}_s - 1$ (full mesh), while the Fourier coefficients

$$\{\hat{b}^{s,{\rm c}}_{\rm m,n}(s_{\rm j}), \hat{b}^{s,{\rm c}}_{\rm m,n}(s_{\rm j}), \hat{b}^{\theta,{\rm c}}_{\rm m,n}(s_{\rm j}), \hat{b}^{\theta,{\rm s}}_{\rm m,n}(s_{\rm j}), \hat{b}^{\phi,{\rm c}}_{\rm m,n}(s_{\rm j}), \hat{b}^{\phi,{\rm s}}_{\rm m,n}(s_{\rm j}), \hat{b}^{\rm m,n}_{\theta,{\rm c}}(s_{\rm j}), \hat{b}^{\rm m,n}_{\theta,{\rm s}}, \hat{b}^{\rm m,n}_{\phi,{\rm c}}(s_{\rm j}), \hat{b}^{\rm m,n}_{\phi,{\rm s}}(s_{\rm j})\}$$

are defined on flux surfaces in between (half mesh), that is, $s_{\rm j} = (s_{\rm i} + s_{\rm i+1})/2$ (for details see Fig. 1).

The equilibrium output (file **wout.xxx**) of the NEMEC code, which is written in subroutine **wrout.f90**, has the following form:

List of variables:

Dimensions of the fields

gamma	real	adiabatic constant
enfp	real	N_p = number of periods
enrho	real	N_S = number of flux surfaces $(0 \le {\rm i} \le {\rm N_s} - 1)$
empol	real	$m_b + 1$ = number of poloidal harmonics $(0 \le m \le m_b)$
entor	real	n_b = maximum toroidal harmonic $(-{\rm n_b} \le {\rm n} \le {\rm n_b})$
empmnt	real	total number of harmonics $m_b(2n_b + 1) + (n_b + 1)$
eiasym	real	symmetry of the equilibrium
	= 0	stellarator-symmetric equilibrium
	= 1	asymmetric equilibrium
phiedge	real	total toroidal flux

Please note, these variables are transformed into integers after reading.

Fourier coefficients of R, Z, B^θ, B^ζ, λ, B_θ, B_ζ, and B_s

frmnc(m,n,i)	real	$\hat{r}^{\rm c}_{\rm m,n}(s_{\rm i})$
fzmns(m,n,i)	real	$\hat{z}^{\rm s}_{\rm m,n}(s_{\rm i})$
frmns(m,n,i)	real	$\hat{r}^{\rm s}_{\rm m,n}(s_{\rm i})$
fzmnc(m,n,i)	real	$\hat{z}^{\rm c}_{\rm m,n}(s_{\rm i})$
hbumnc_up(m,n,j)	real	$\hat{b}^{\theta,{\rm c}}_{\rm m,n}(s_{\rm j})$
hbvmnc_up(m,n,j)	real	$\hat{b}^{\zeta,{\rm c}}_{\rm m,n}(s_{\rm j})$
hbumns_up(m,n,j)	real	$\hat{b}^{\theta,{\rm s}}_{\rm m,n}(s_{\rm j})$
hbvmns_up(m,n,j)	real	$\hat{b}^{\zeta,{\rm s}}_{\rm m,n}(s_{\rm j})$

flmns(m,n,i)	real	$\hat{\lambda}^{\mathrm{s}}_{\mathrm{m,n}}(s_{\mathrm{i}})$
flmnc(m,n,i)	real	$\hat{\lambda}^{\mathrm{c}}_{\mathrm{m,n}}(s_{\mathrm{i}})$
hbumnc_dw(m,n,j)	real	$\hat{b}^{\mathrm{m,n}}_{\theta,\mathrm{c}}(s_{\mathrm{j}})$
hbvmnc_dw(m,n,j)	real	$\hat{b}^{\mathrm{m,n}}_{\zeta,\mathrm{c}}(s_{\mathrm{j}})$
hbsmns_dw(m,n,j)	real	$\hat{b}^{\mathrm{m,n}}_{s,\mathrm{s}}(s_{\mathrm{j}})$
hbumns_dw(m,n,j)	real	$\hat{b}^{\mathrm{m,n}}_{\theta,\mathrm{s}}(s_{\mathrm{j}})$
hbvmns_dw(m,n,j)	real	$\hat{b}^{\mathrm{m,n}}_{\zeta,\mathrm{s}}(s_{\mathrm{j}})$
hbsmnc_dw(m,n,j)	real	$\hat{b}^{\mathrm{m,n}}_{s,\mathrm{c}}(s_{\mathrm{j}})$

Radial profiles: The definitions below relate the NEMEC output quantities to the corresponding ASDEX Upgrade quantities in SI units.

hiota(j)	real	rotational transform ι
hmass(j)	real	mass function
hpres(j)	real	$\mu_0 p$ with p = pressure in [Pa]
hphip(j)	real	$\frac{1}{2\pi}\frac{\partial\Phi(s)}{\partial s}$ with Φ = toroidal flux in [Tm^2]
hbuco(j)	real	$-\frac{\mu_0}{2\pi}I$ with I = toroidal current in [A]
hbvco(j)	real	$-\frac{\mu_0}{2\pi N_p}J$ with J = poloidal current in [A]
hphi(j)	real	$\Phi(s)$ = toroidal flux in [Tm^2]
hvp(j)	real	$\frac{1}{4\pi^2 N_p}\frac{\partial V(s)}{\partial s}$ with $V(s)$ = volume in [m^3]
hoverr(j)	real	overr(j) in NEMEC
fjcuru(i)	real	-$\frac{1}{2\pi N_p}\frac{\partial J}{\partial s}$
fjcurv(i)	real	$\frac{1}{2\pi}\frac{\partial I}{\partial s}$
hspecw(j)	real	specw(j) in NEMEC

The prefixes **f** and **h** denote full mesh and half mesh quantities, respectively. The suffix **up** markes the contravariant vector components, while **dw** denotes the covariant ones.

Below ASDEX Upgrade and NEMEC algebraic signs of the toroidal current, I, the poloidal current, J, the toroidal magnetic field, B_{tor}, the poloidal magnetic field, B_{pol}, the toroidal flux, Φ, and its radial derivative, Φ', the poloidal flux, Ψ, and its radial derivative, Ψ', and the safety factor $q = \Phi'/\Psi'$ are defined.

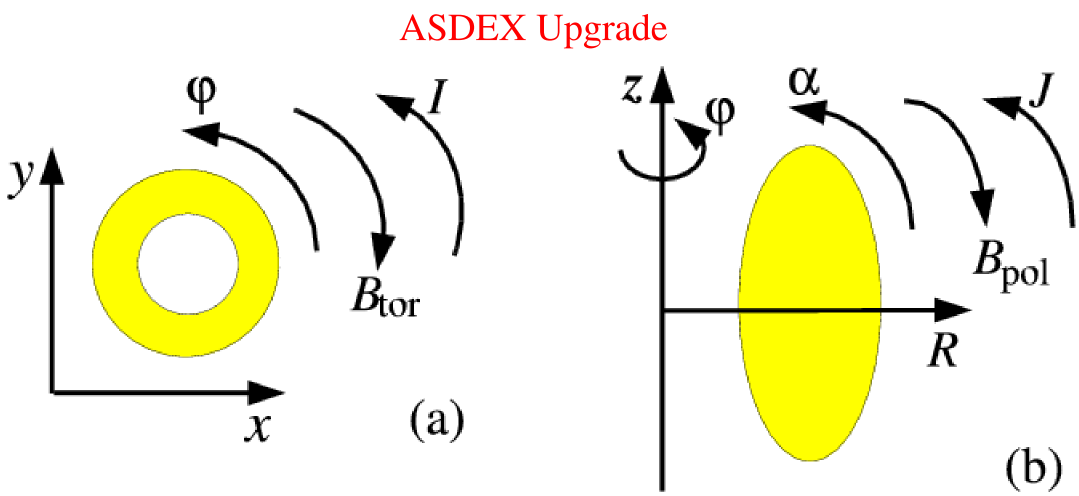

Fig. 2: (a) Toroidal and (b) poloidal field and current directions of ASDEX Upgrade.

Algebraic signs of AUG and NEMEC quantities

	I	J	B_{tor}	B_{pol}	Φ	Φ'	Ψ	Ψ'	q
AUG	+	+	-	-	-	-	+	-	+
NEMEC	+	+	-	-	-	-	-	-	+

Please note, $\Psi_{NEMEC}(s) = \Psi_{AUG}(s) - \Psi_{AUG}(s = 0)$

References

[1] Hirshman S P and Whitson J C 1983 'Steepest-decent moment method for three-dimensional magnetohydrodynamic equilibria.' *Phys. Fluids* **26** 3553. doi:10.1063/1.864116.

[2] Hirshman S P and Lee D K 1986 'MOMCON: a spectral code for obtaining three-dimensional magnetohydrodynamic equilibria.' *Comput. Phys. Commun.* **39** 161.

[3] Hirshman S P, van Rij W I, and Merkel P 1986 'Three-dimensional free boundary calculations using a spectral Greens's function method.' *Comput. Phys. Commun.* **43** 143.