Simulations of neutral beam injection in TJ-II stellarator using ASCOT5

S. Mulas[1], Á. Cappa[1], D. López-Bruna[1], J. Kontula[2],
I. Calvo[1], F. Parra[5], T. Kurki-Suonio[2], M.J. Mantsinen[3,4] and TJ-II team[1]

1 Laboratorio Nacional de Fusión
Ciemat

Infraestructuras Científicas y Técnicas Singulares

UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional

2 Aalto University

3 Barcelona Supercomputing Center
Centro Nacional de Supercomputación

4 ICREA

5 University of Oxford

Outline

- Motivation
- TJ-II stellarator and NBI heating system
- Plasma scenarios
- ASCOT5 simulations
- Conclusions

Outline

- **Motivation**
- TJ-II stellarator and NBI heating system
- Plasma scenarios
- ASCOT5 simulations
- Conclusions

Motivation

- Interpretation and modelling of NBI experiments using ASCOT5 (heating, neutral beam current drive, MHD instabilities, ...) in TJ-II.
- Historically, the Monte Carlo code FAFNER2 [1] (guiding center) has been used in TJ-II for this purpose.
- The use of cutting-edge tools is desirable to take advantage of new developments and keep a close contact with the community of fast-ion physics in magnetic confinement devices.
- ASCOT5 [2] (GC or FO) is becoming a widely spread code to model fast-ion physics in magnetic confinement devices (JET, ITER, AUG, W7-X, MAST-U, SPARC, TJ-II, ...).
- Experiments in TJ-II, in turn, can contribute to validate the code predictions in non-axisymmetric configurations.

[1] G. Lister, Max-Planck-Institut für Plasmaphysik Technical Report IPP 4/222 (1985)
[2] J. Varje et al., Submitted to Computer Physics Communications (2019) (arXiv:1908.02482v1)

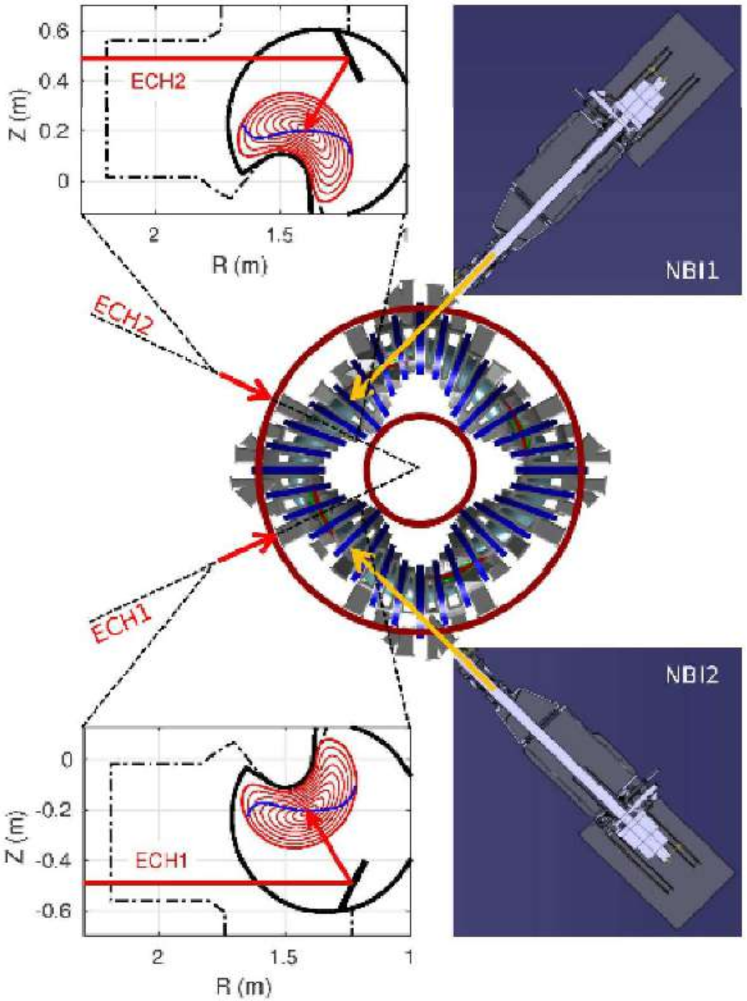
Outline

- Motivation
- **TJ-II stellarator and NBI heating system**
- Plasma scenarios
- ASCOT5 simulations
- Conclusions

TJ-II stellarator and NBI heating system

- TJ-II stellarator [1] is a flexible heliac (R=1.5m, a=0.2m, B=1T)
- Equipped with 2 NBIs [2]:
  - NBI1 (Co-injected)
  - NBI2 (Counter-injected)
- $E_{max} = 31.5$ keV

Energy [keV]	Fraction [%]
E_{max}	55
$E_{max}/2$	25
$E_{max}/3$	20



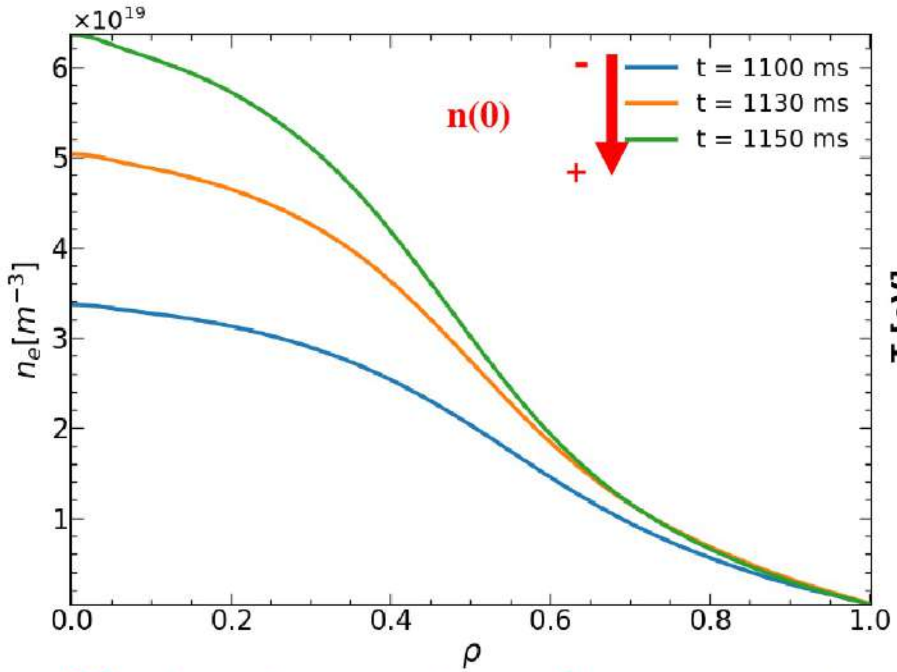
[1] C. Alejaldre et al., *Fusion Technology* **17** 131-139 (1990)
[2] M. Liniers et al., *Fusion Engineering and Design* **123** 259-262 (2017)

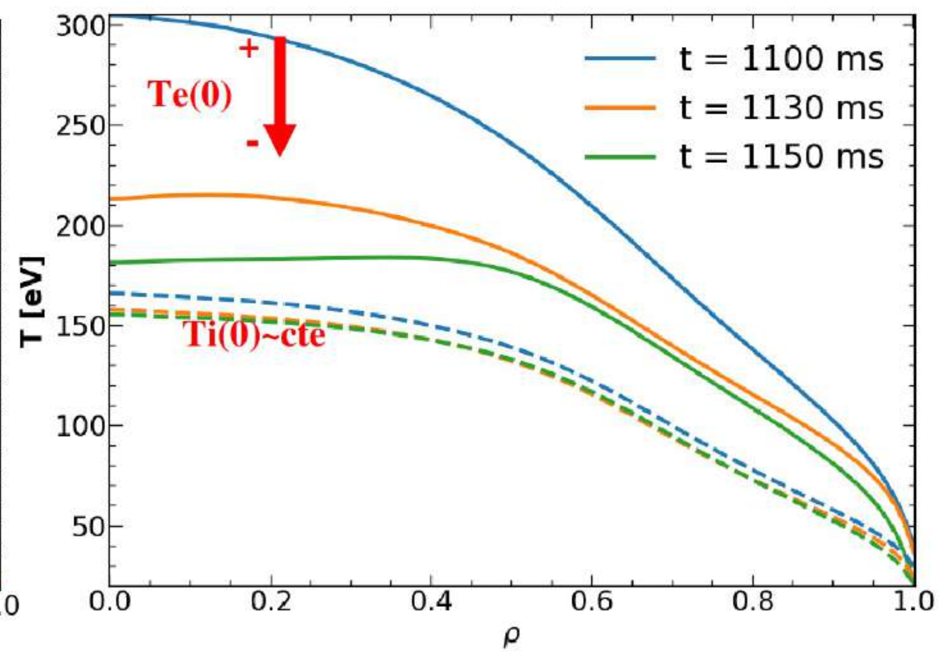
Outline

- Motivation
- TJ-II stellarator and NBI heating system
- **Plasma scenarios**
- ASCOT5 simulations
- Conclusions

Plasma scenarios

- This work has been focused on high-density NBI plasmas.
- Experimental discharge with increasing-density has been simulated with ASTRA, consistently with experimental measurements.
- A set of 3 plasma profiles at 3 different times of such discharge have been chosen.





- Electron temperatures decrease as density increases.
- Ion temperatures approximately constant.

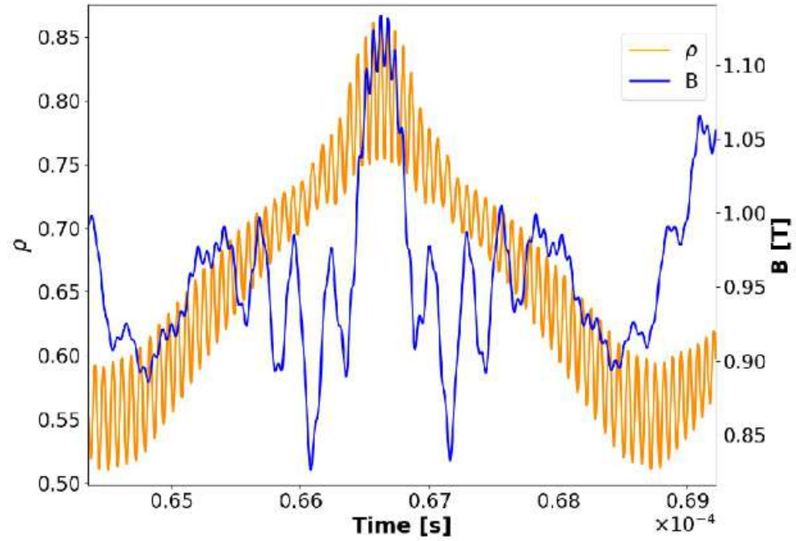
Outline

- Motivation
- TJ-II stellarator and NBI heating system
- Plasma scenarios
- **ASCOT5 simulations**
- Conclusions

ASCOT5 simulations: details

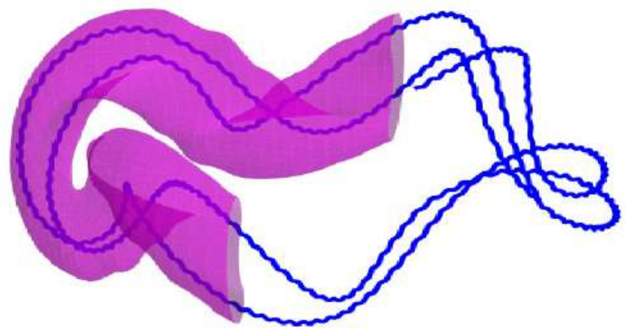
Simulation details

- Full-orbit collisional simulations with 200k markers
- NBI power = 500 kW
- Followed until they hit the wall or thermalised
- Thermalisation ocurrs at $E_f \leq 2T_i(\rho)$
- Equilibrium from VMEC+EXTENDER



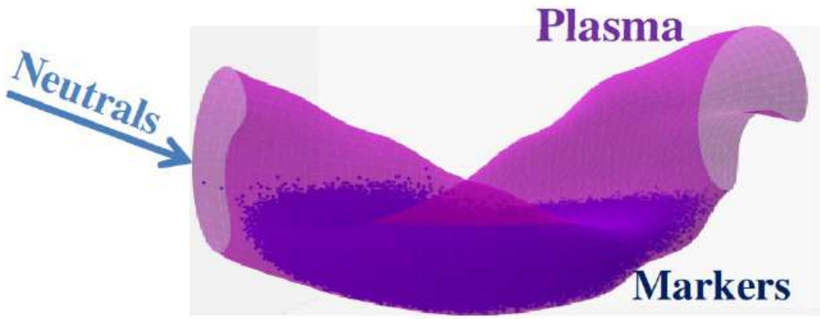
HPC resources

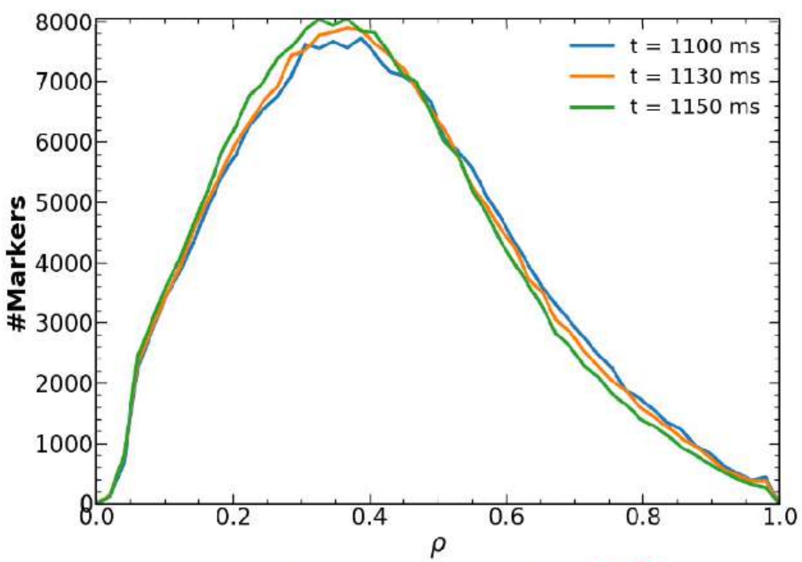
- Simulations performed in the HPC facility MARCONI
- Partition A3 (Intel Xeon Skylake processors)
- 4 nodes x (48cpus/node) x 2h/sim. = 384 cpu hours/sim.



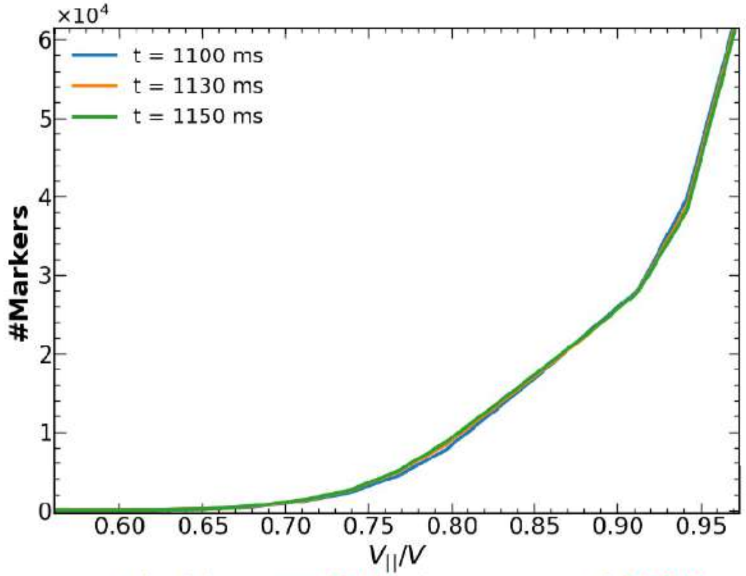
ASCOT5 simulations: initial markers

- BBNBI [1] simulates the flight of the fast neutrals from the last grounded grid towards the plasma until they either ionise or produce shine-through.





- ρ distribution peaked at 0.35
- No difference between plasmas

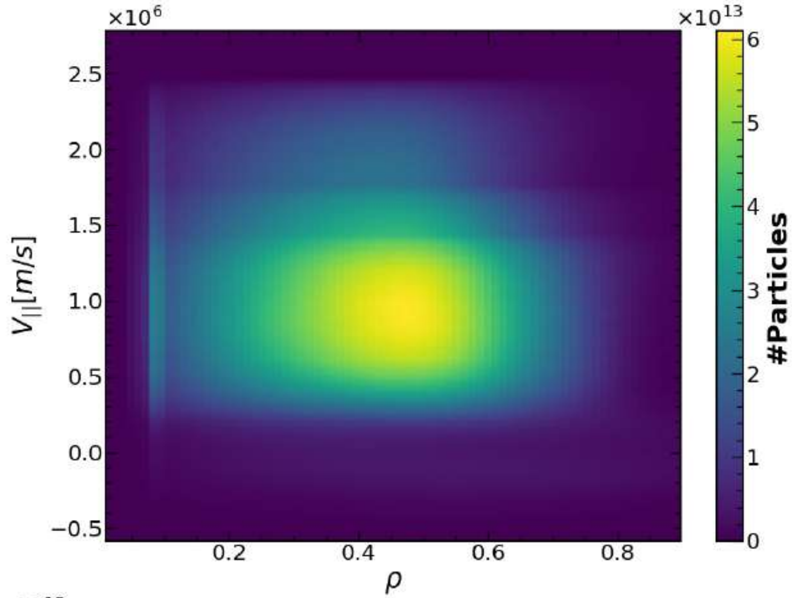


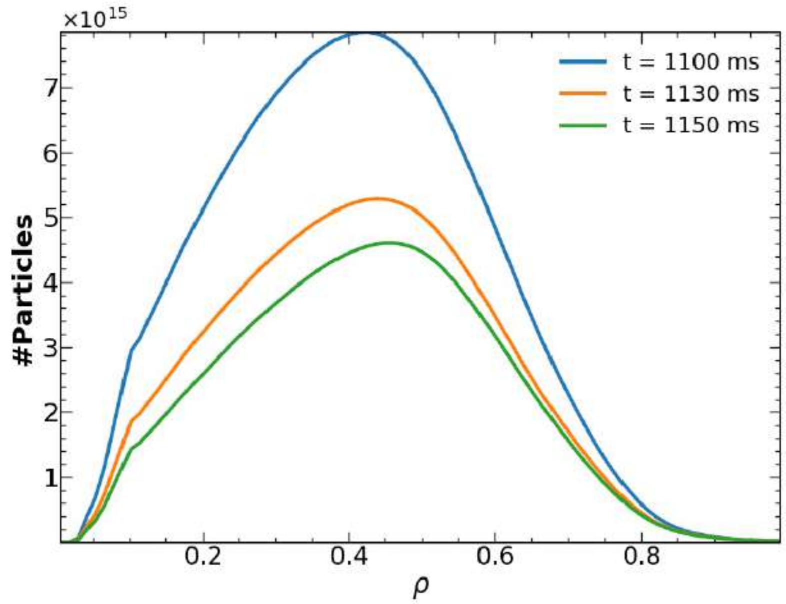
- Highly parallel character of NBI
- All particles are born passing

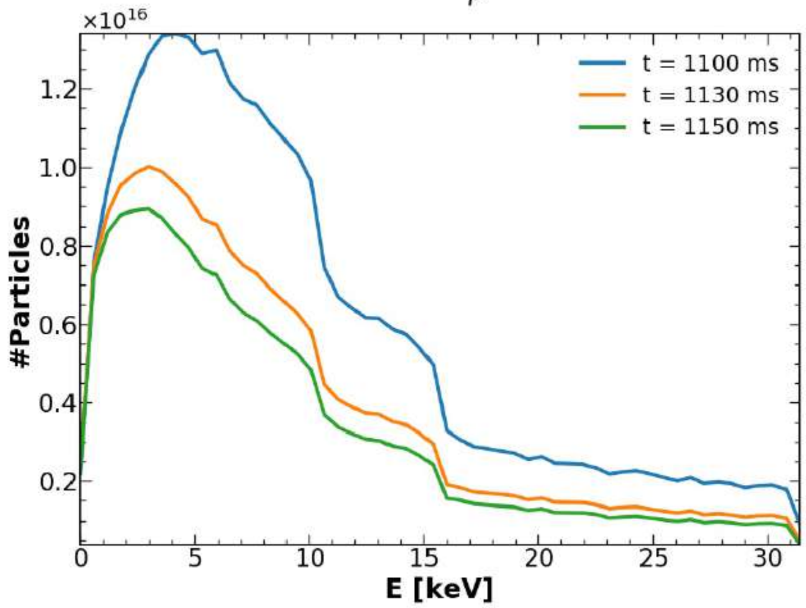
[1] O. Asunta et al., Computer Physics Communications 18833-46 (2015)

ASCOT5 simulations: distribution function

- Reduction of the fast-ion density as plasma density increases (temperature decreases) due to higher collisionality ($\nu \propto n/T^{3/2}$).
- Energy distribution with 3 steps at the operational energies.
- 2D distribution function ($V_{\|}$, ρ) used as input for NBCD model.

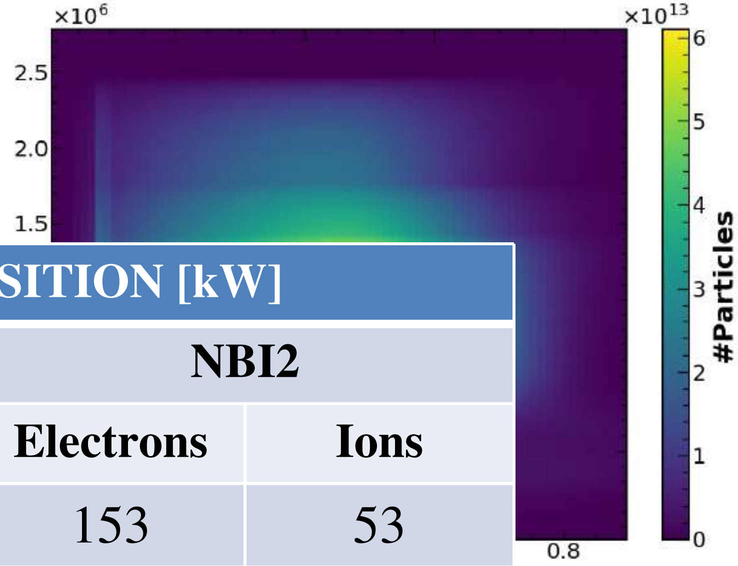




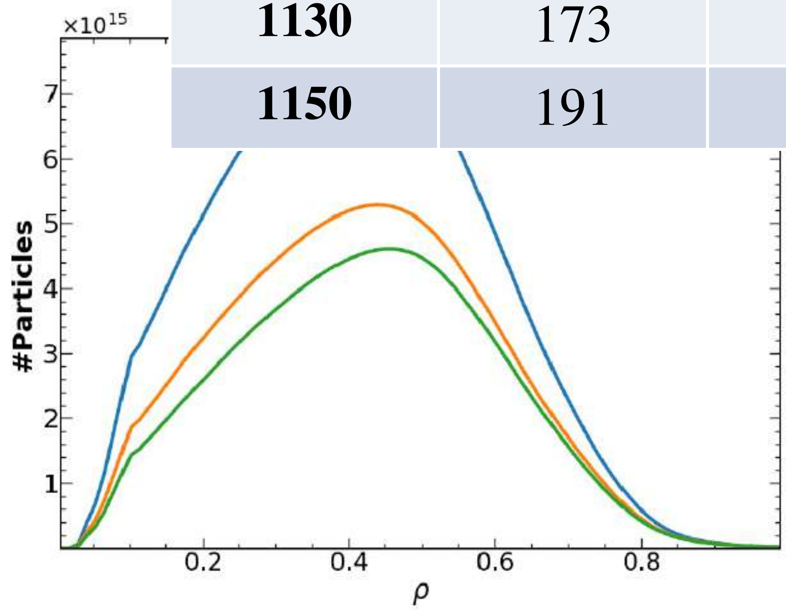


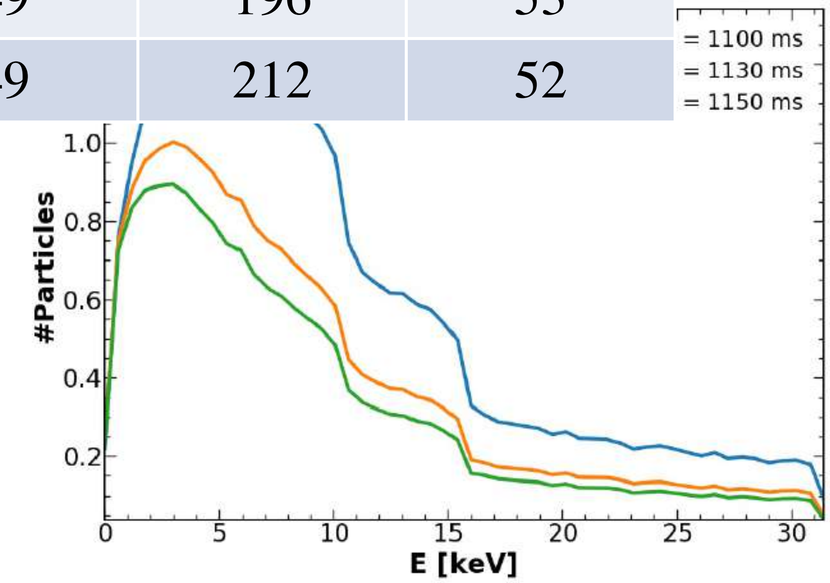
ASCOT5 simulations: distribution function

- Reduction of the fast-ion density as plasma density increases (temperature decreases) due to higher collisionality ($\nu \propto n/T^{3/2}$).
- Energy operati
- 2D dist for NB



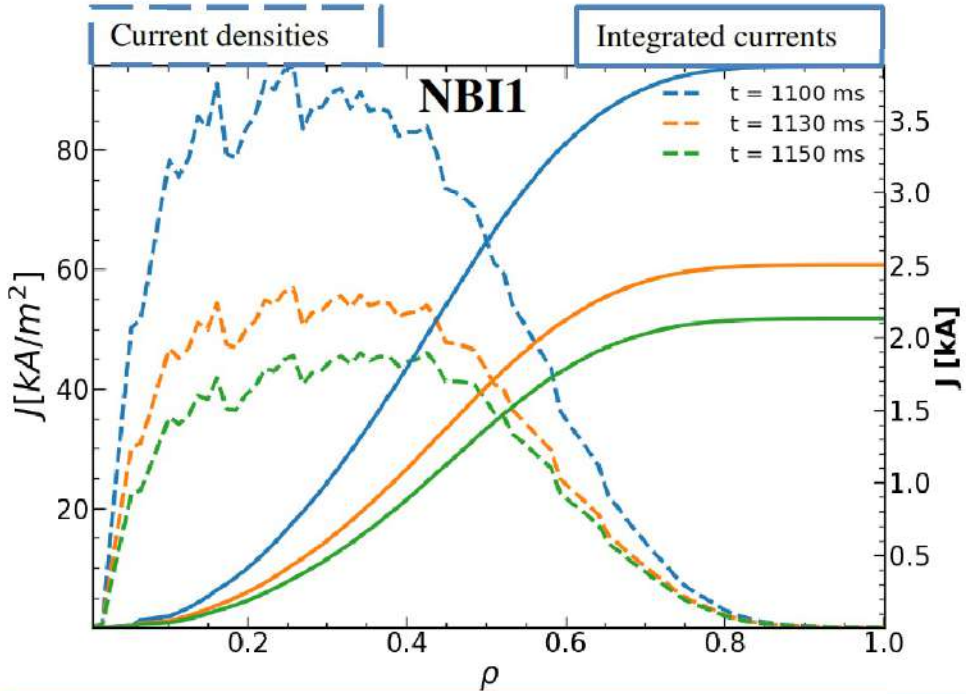
	POWER DEPOSITION [kW]			
	NBI1		NBI2	
	Electrons	Ions	Electrons	Ions
1100	135	50	153	53
1130	173	49	196	53
1150	191	49	212	52

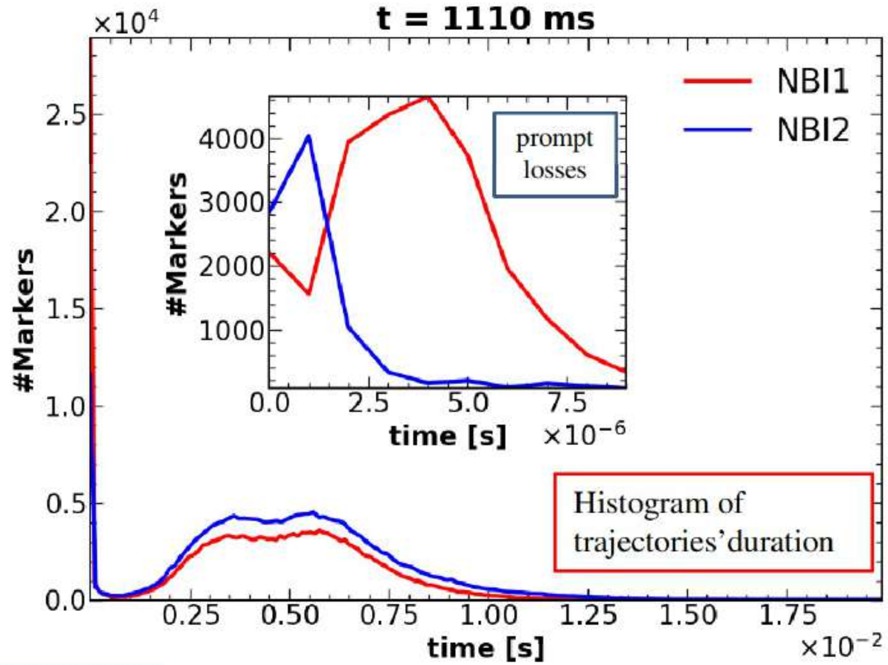




ASCOT5 simulations: neutral beam current drive

$$J_{||} = e\left(Z_b n_b V_{b||} - \int v_{||} g_e \mathrm{d}^3 v\right) \Rightarrow J_{||} = J_b(1 - A)$$





Integrated NBCD (kA)				
Time [ms]	n(0)[$10^{19} m^{-3}$]	NBI1	NBI2	Total
1100	3.4	4.03	-4.6	-0.57
1130	5	2.54	-3.02	-0.48
1150	6.3	2.16	-2.59	-0.43

- Non-balanced current due to different prompt losses.

N. Nakajima and M. Okamoto,Journal of the Physical Society of Japan. ***59*** *3595-3601 (1990)*

Outline

- Motivation
- TJ-II stellarator and NBI heating system
- Plasma scenarios
- ASCOT5 simulations
- **Conclusions**

Conclusions

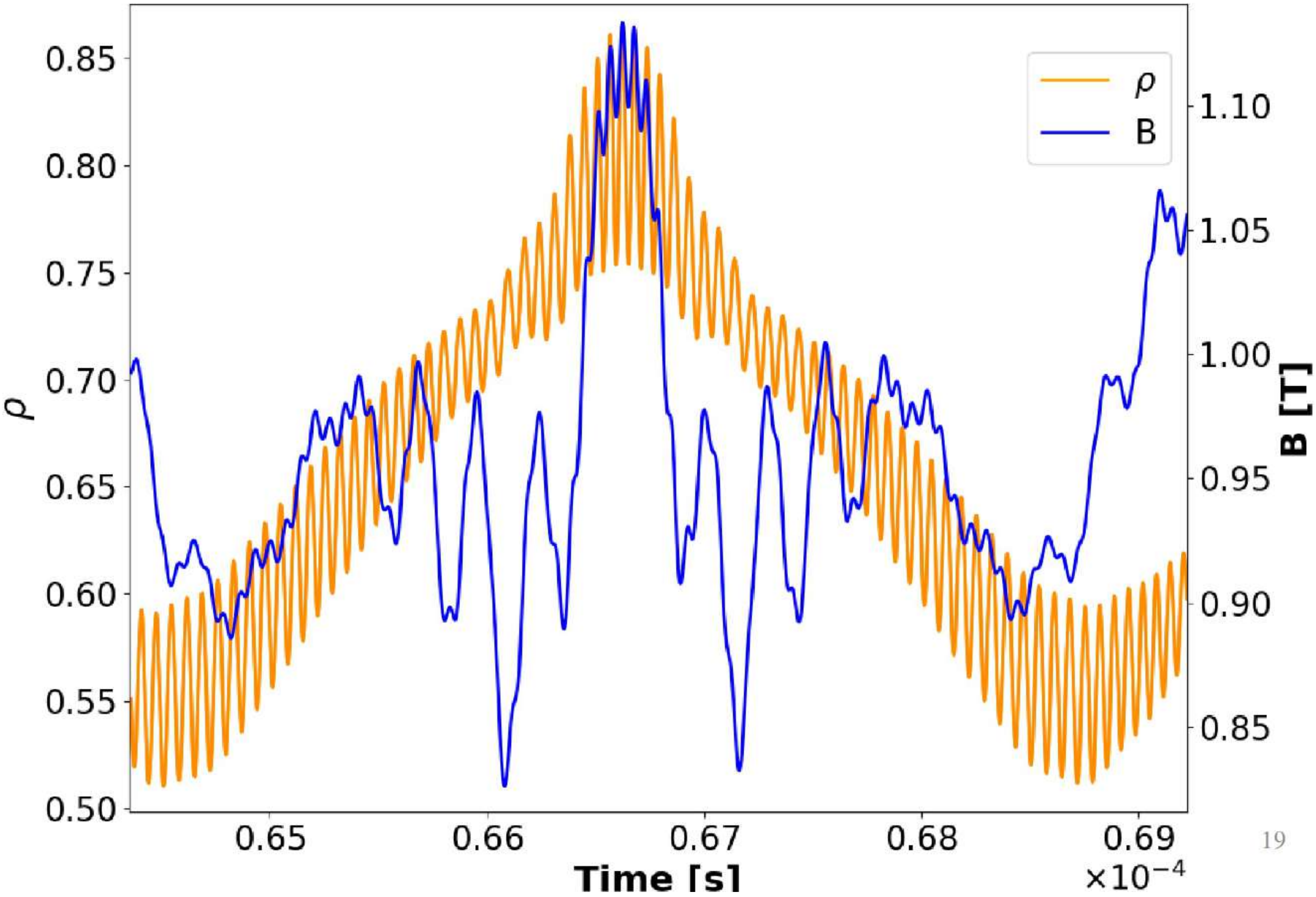
- TJ-II has been implemented in ASCOT5.
- CX, already implemented in ASCOT5, will be used in future studies.
- Validation of the NBCD model in TJ-II, taking into account, bootstrap and ECCD (ongoing work)

BACK UP

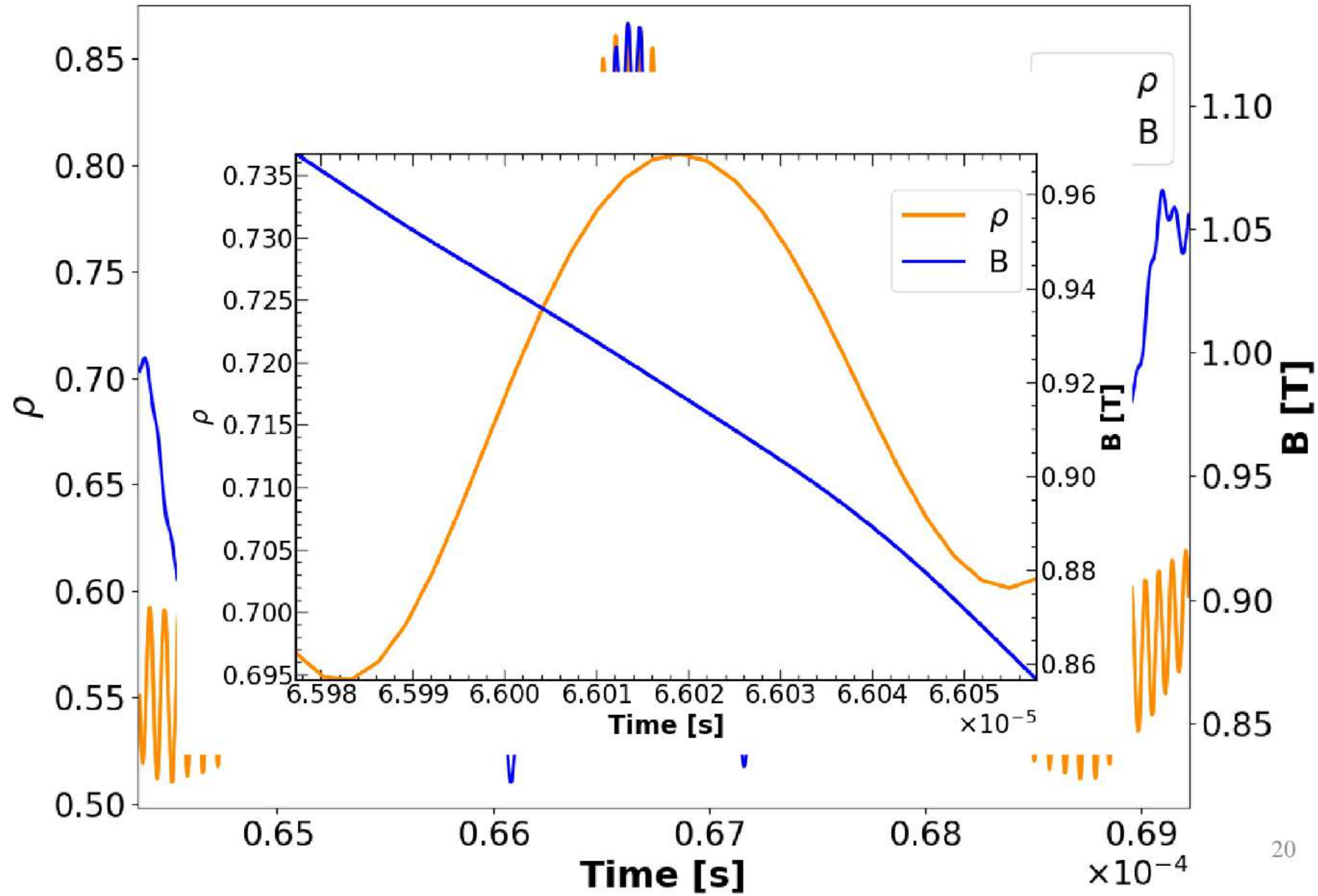
Back up: losses to wall by neutrals

Shine-Through + scraper power losses [%]			
Time [ms]	**n(0)[$10^{19} m^{-3}$]**	**NBI1**	**NBI2**
1100	3.4	52	52
1130	5	44	45
1150	6.3	41	42

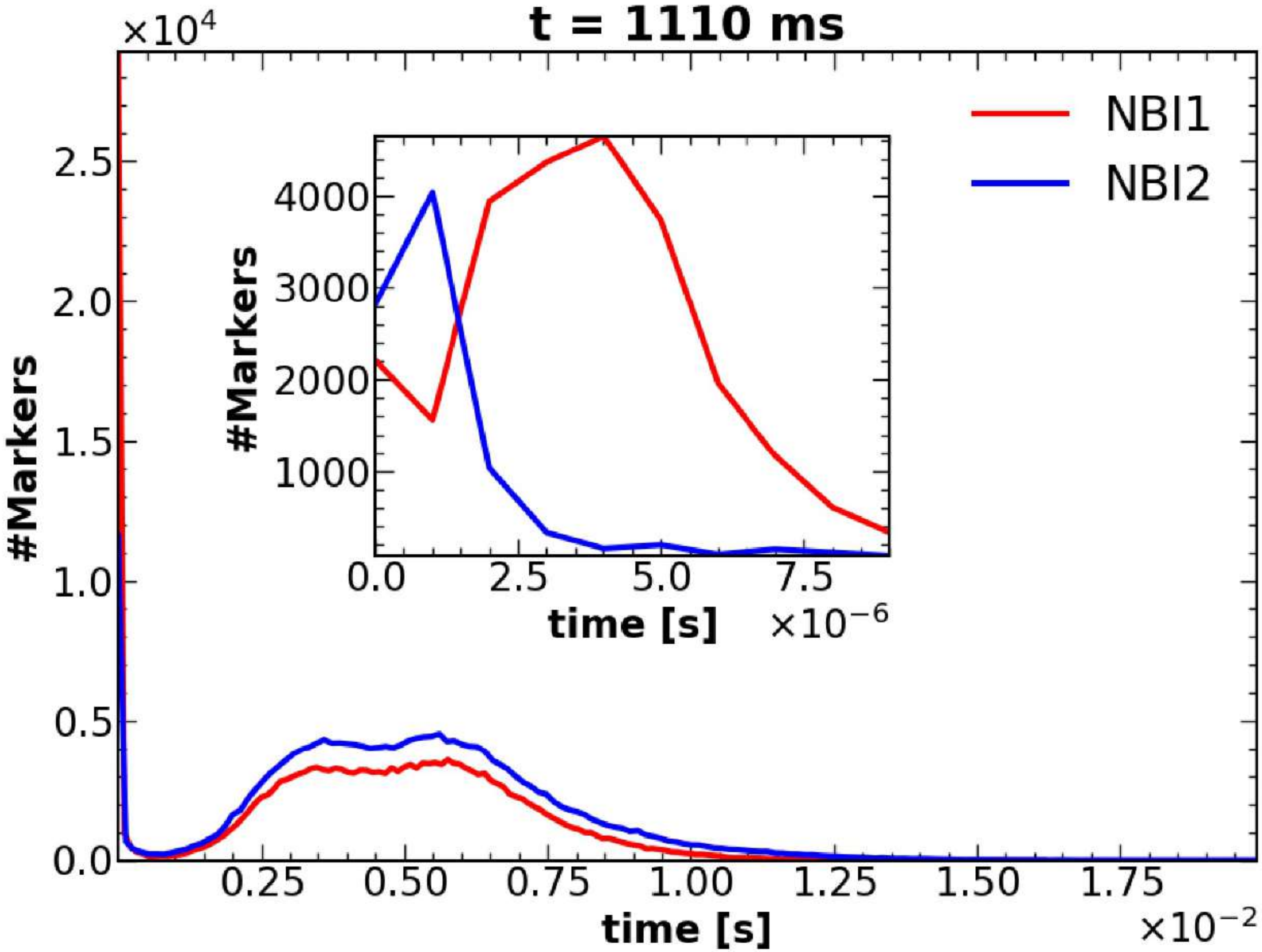
Back up: orbit



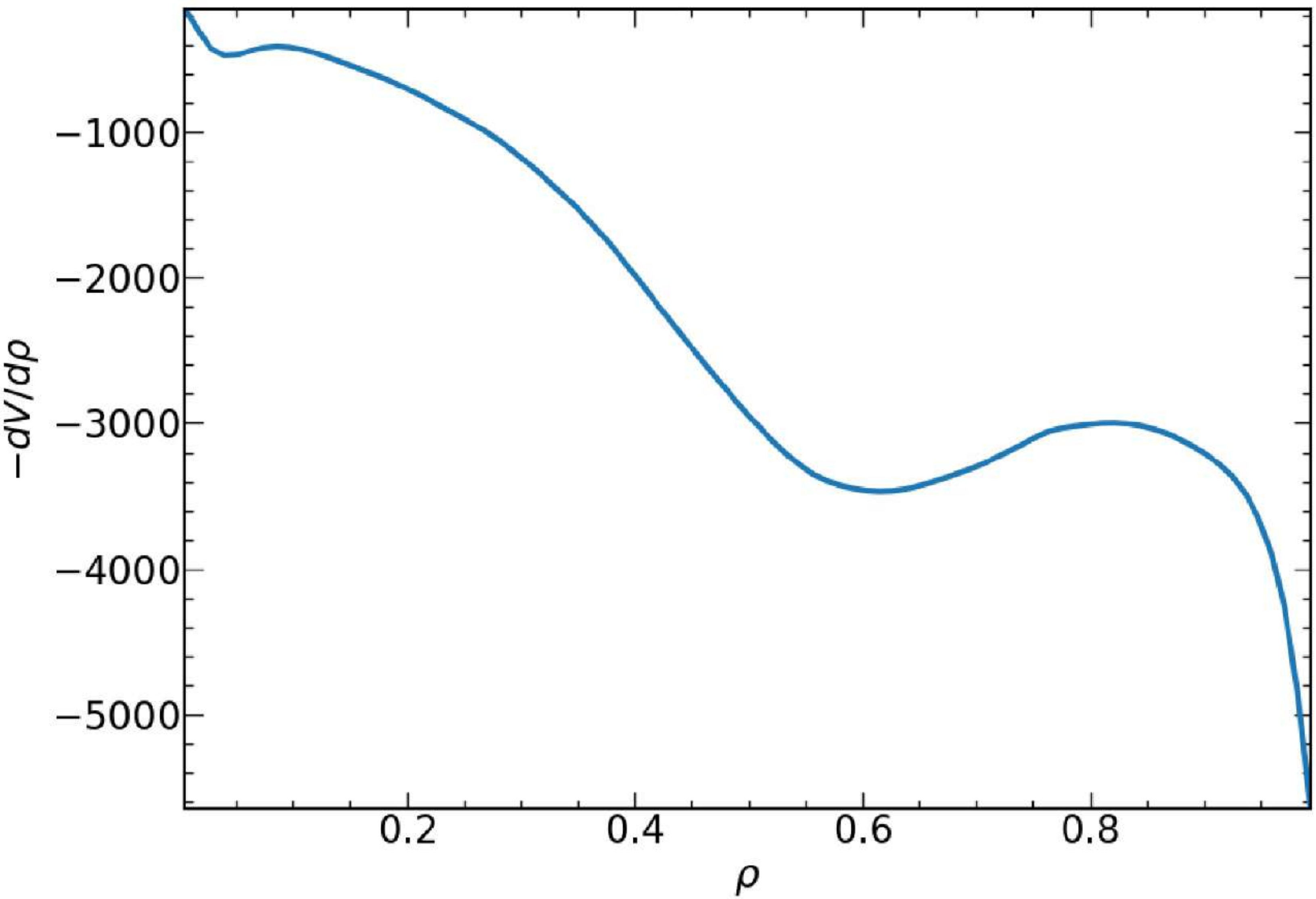
Back up: orbit



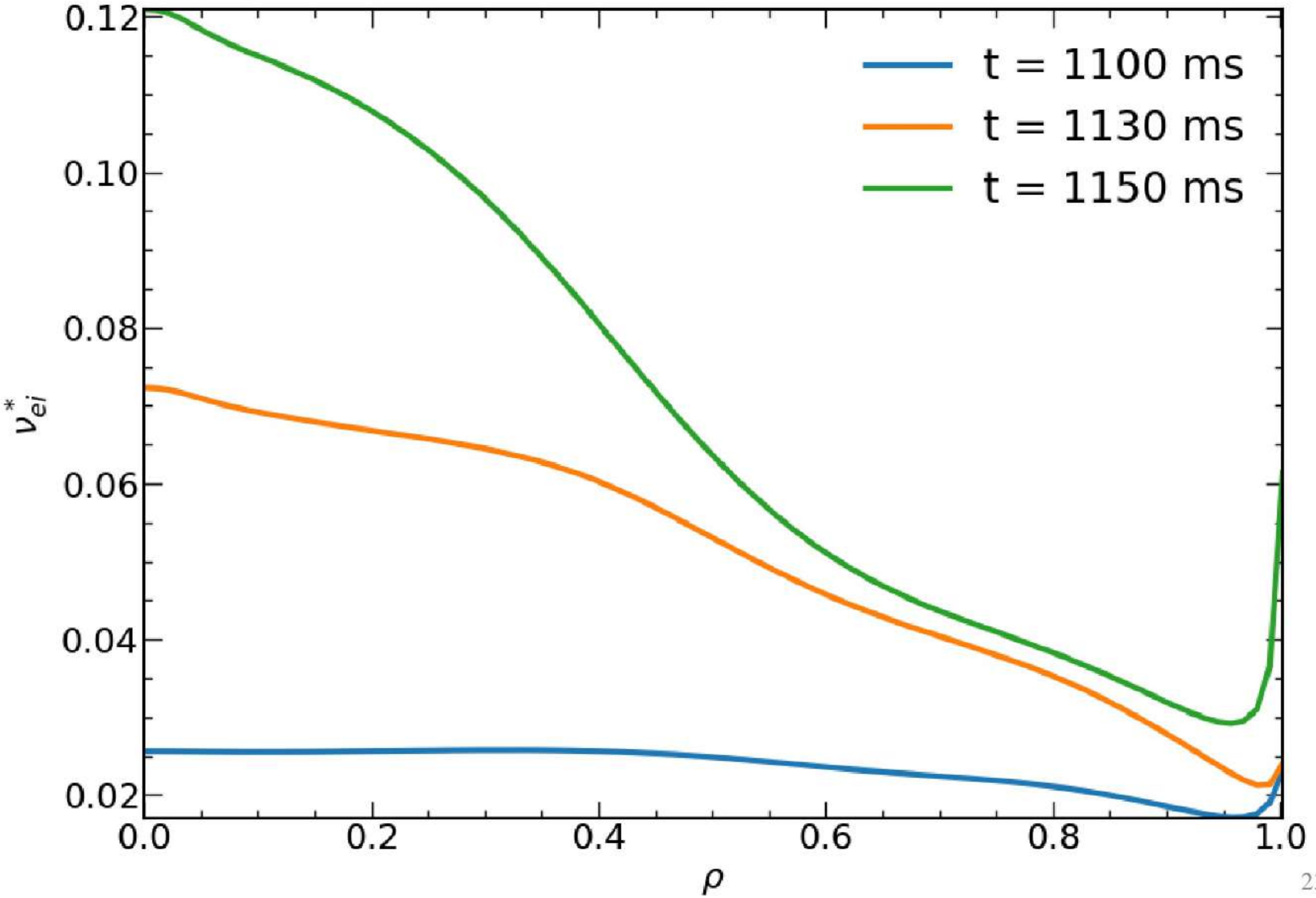
Back up: endtimes



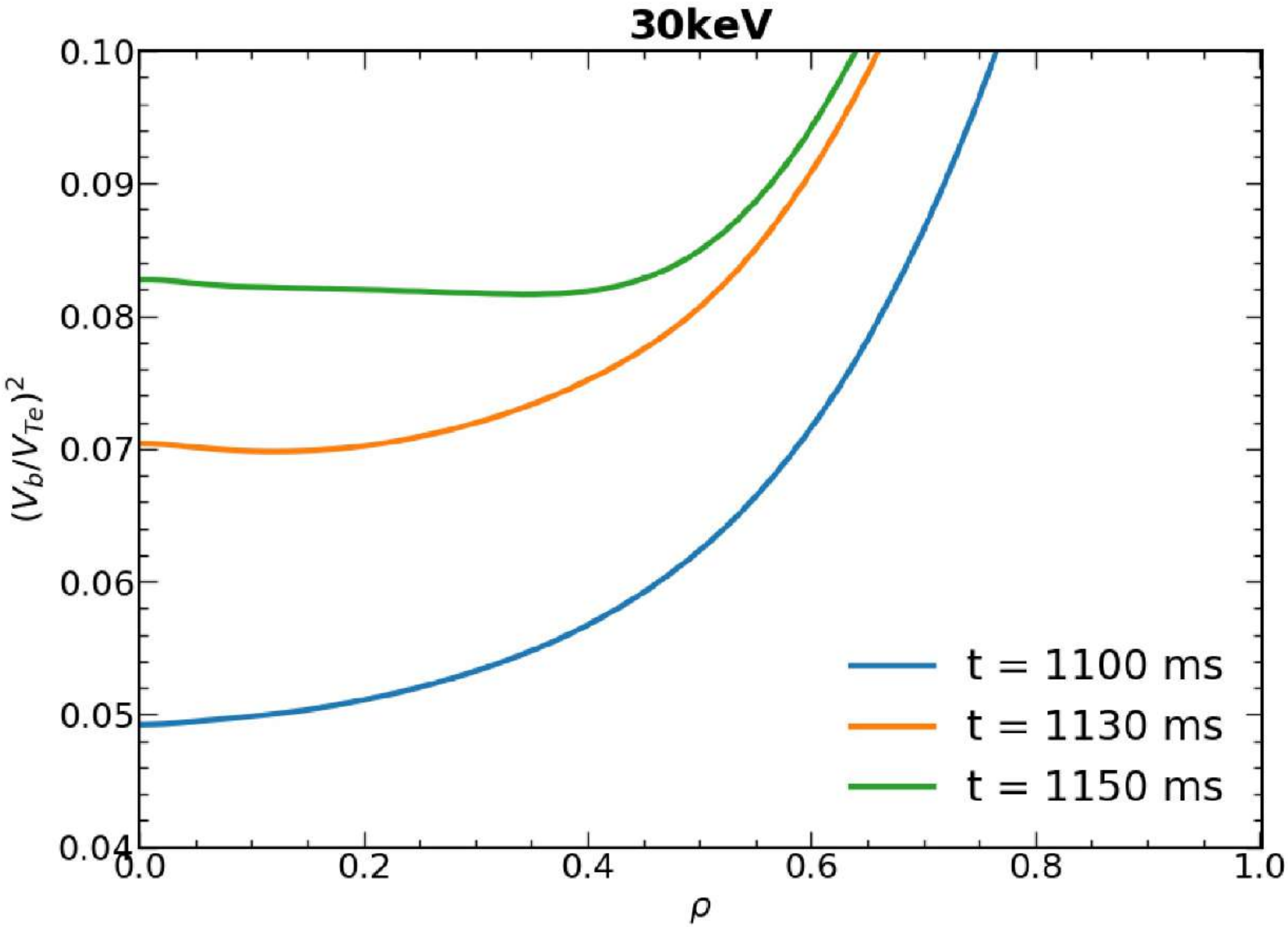
Back up: electric field



Back up: collisionality



Back up: V_b/V_{Te}



Back up: collision operators

$$C_{eI}^{(\ell)}\left[g_e\right] \simeq \nu_{eI}\left(\mathcal{L}\left[g_e\right] + \frac{m_e v_\parallel V_{I\parallel}}{T_e} f_{Me}\right)$$

$$\nu_{eI}(v) = \frac{2n_I}{m_e^2 v^3}\frac{2\pi Z_I^2 e^4 \ln\Lambda_{eI}}{\left(4\pi\epsilon_0\right)^2}$$

$$C_{ee}^{(\ell)}\left[g_e\right] = \nu_{ee}\left(\mathcal{L}\left[g_e\right] + \frac{m_e v_\parallel u_e}{T_e} f_{Me}\right)$$

$$\mathcal{L}\left[g_e\right] = \frac{2v_\parallel}{v^2 B}\partial_\lambda\left(v_\parallel \lambda \partial_\lambda g_e\right) \qquad \nu_{ee}(v) = \frac{3\sqrt{\pi}}{4\tau_{ee}}\frac{\phi(v\sqrt{m_e/\left(2T_e\right)}) - G(v\sqrt{m_e/\left(2T_e\right)})}{(v\sqrt{m_e/\left(2T_e\right)})^3}$$

$$u_e = \frac{\int \nu_{ee} v_\parallel g_e \mathrm{d}^3 v}{\int \nu_{ee}\left(m_e v_\parallel^2/T_e\right) f_{Me}\mathrm{d}^3 v}$$

Back up: NBCD @ low collisionality

The Neutral Beam Current Drive (NBCD) is the current created by NBI beam in the plasma. However, the effect of the return (shielding) current carried by electrons must be taken into account. Here, the subscripts $b,\ i,\ e$ stand for beam ions, bulk ions and electrons and z_k for impurities.

$$J_{||} = J_{b||} + J_{e||}$$

Assuming that $f_e = f_{M,e} + g_e$ the DKE for electrons becomes:

$$v_{||}\hat{\mathbf{b}} \cdot \nabla g_e = C_e^{(\ell)}\left[g_e\right]$$

where $C_e^{(\ell)}\left[g_e\right] = C_{ee}^{(\ell)}\left[g_e\right] + C_{ei}^{(\ell)}\left[g_e\right] + \sum_k C_{ez_k}^{(\ell)}\left[g_e\right] + C_{eb}^{(\ell)}\left[g_e\right]$

In the low-collisionality regime we can expand in g_e $\quad \nu_{es*} = \nu_{es} R_0 / v_{te}$

$$g_e = g_e^{(0)} + g_e^{(1)} + \ldots$$

N. Nakajima and M. Okamoto, *Journal of the Physical Society of Japan* **59** 3595-3601 (1990)

Back up: NBCD @ low collisionality

$$v_{\|}\hat{\mathbf{b}}\cdot\nabla g_e = C_e^{(\ell)}\left[g_e\right]$$

$$g_e = g_e^{(0)} + g_e^{(1)} + \dots$$

where, whithout loss of generality, we assume $g_e^{(2k+1)}$ to be odd and $g_e^{(2k)}$ even.

The 0th order equation is $v_{\|}\hat{\mathbf{b}}\cdot\nabla g_e^{(0)} = 0 \Longrightarrow g_e^{(0)} = cte$

Along the orbit (trapped) or in the flux surface (passing)

Back up: NBCD @ low collisionality

To obtain the solution, we must go to the 1st order equation, which reads for:

- Trapped particles

$$\overline{\frac{v_\|}{B}\partial_\lambda\left(v_\|\lambda\partial_\lambda g_e^{(0)}\right)} = 0 \quad \Longrightarrow \quad g_e^{(0)} = 0$$

$$\lambda = B^{-1}\left(1 - v_\|^2/v^2\right)$$

- Passing particles

$$\left\langle \frac{B}{v_\|}\mathcal{L}\left[g_e^{(0)}\right]\right\rangle = -\frac{m_e}{\nu_e T_e}\left(\left\langle \nu_{eb} B V_{b\|}\right\rangle + \nu_{ee}\left\langle B u_e\right\rangle\right) f_{Me}$$

$$g_e^{(0)} = -\frac{(v/v_{Te})^2}{\nu_{ee}+\nu_{eZ}}\left(\nu_{ee}\left\langle Bu_e\right\rangle + \nu_{eb}\left\langle BV_{b||}\right\rangle\right) f_{Me}\int_{B_{max}^{-1}}^{\lambda}\langle v_{||}\rangle^{-1} d\lambda$$

Back up: NBCD @ low collisionality

The current is then:

$$J_{||} = e\left(Z_b n_b V_{b||} - \int v_{||} g_e \mathrm{d}^3 v\right)$$

and we can define the factor F as:

$$F = \frac{J_{||}}{J_b} = \frac{J_b + J_{e||}}{J_b} = 1 - A$$

so that $J_{||} = J_b(1 - A)$

with $$A = \frac{Z_b}{Z_{eff}} \frac{B\langle B\rangle}{\langle B^2\rangle}\left[1 - \frac{8}{3\sqrt{\pi}} \frac{I_1}{1 + Z_{eff}\frac{I_2}{I_3}\frac{f_c}{f_t}}\right] f_c.$$

$I_1 = \int_0^\infty \frac{x^4 h(x) e^{-x^2}}{h(x)+Z_{eff}} dx$

$I_2 = \int_0^\infty \frac{x h(x) e^{-x^2}}{h(x)+Z_{eff}} dx$

$I_3 = \int_0^\infty x h(x) e^{-x^2} dx$

$$f_c = \frac{3}{4}\langle B^2\rangle \int_0^{B_{max}^{-1}} \frac{\lambda}{\langle\sqrt{1-\lambda B}\rangle} d\lambda$$

$f_t = 1 - f_c$

Back up: NBCD models

Nakajima:

$$\frac{J_{\|}}{J_b} = 1 - \frac{Z_b}{Z_{eff}}\left[1+\frac{6}{5}\left(\frac{v_b}{v_{Te}}\right)^2\right]\frac{<B>^2}{<B^2>} f_c \left\{1 - \frac{4}{3\sqrt{\pi}}\frac{I_1(Z_{eff})}{1 - Z_{eff}\frac{f_c}{f_t}\frac{I_2(Z_{eff})}{I_3}}\right\}$$

Hirshman:

$$\frac{J_{\|}}{J_b} = 1 - \frac{Z_b}{Z_{eff}}\frac{[1+(6/5)(\overline{v}_b^2/n)]^n}{[1+(\overline{v}_b/\alpha)^m]^{(3+2n)/m}}$$

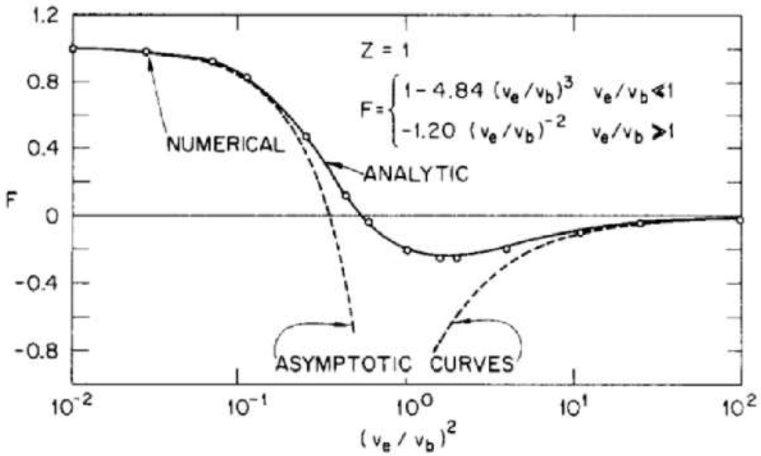


FIG. 1. Graph of beam current ratio F as a function of $\overline{v}_b$ from Eq. (24c) for $\overline{Z} = Z_b = 1$ (solid curve). Open points are numerical results from Ref. 1. Dashed curves are asymptotic curves from Eqs. (15b) and (15c).

ASCOT:

$$\frac{J_{\|}}{J_b} = 1 - \frac{Z_b}{Z_{eff}}\frac{[1+(6/5)(\overline{v}_b^2/n)]^n}{[1+(\overline{v}_b/\alpha)^m]^{(3+2n)/m}}\frac{<B>^2}{<B^2>} f_c \left\{1 - \frac{4}{3\sqrt{\pi}}\frac{I_1(Z_{eff})}{1+Z_{eff}\frac{f_c}{f_t}\frac{I_2(Z_{eff})}{I_3}}\right\}$$