Neutral Beam Injector (NBI)

Introduction

Neutral Beam Injection (NBI) is a key technique used in tokamak fusion devices to heat the plasma and drive current. In NBI systems, neutral atoms—typically hydrogen or deuterium—are accelerated to high energies and injected into the plasma. Because charged particles would be deflected by the magnetic fields in the tokamak, the ions are first neutralized before injection. Once inside the plasma, these fast neutrals transfer their energy to the plasma particles through collisions, increasing the plasma temperature and contributing to the overall performance of the fusion experiment. NBI is valued for its ability to deliver precise and controllable heating, making it an essential tool in plasma physics research and fusion reactor development.

Neutral Beam Injectors on TCV

Parameter	NBI-1	NBI-2	DNBI	Comment
Beam				
NB power range in TCV	50…1100 kW	250…1100 kW	70…90 kW	14% of losses in the beam duct excluded for NBI-1
NB energy range	7…28 keV (1)	29…51 keV	48…50 keV	DNBI with lower (up to 25-30 keV) possible
NB energy stability	±100 eV	±100 eV	±600 eV	
Power losses in beam duct	15-20 %	2-5 %	< 2 %	NBI-1 size in horizontal direction mismatch specification
Beam main species	DO (2)	DO	HO (3)	
Max. NB energy per shot	1.1 MJ (4)	2 MJ	50 kJ (5)	

Parameter	NBI-1	NBI-2	DNBI	Comment
Max. NB pulse duration	0.8…2.0 s (4)	2 sec	1.4 s (5,6)	
Neutral beam energy fraction (in % of power)	73:22:05 %	59:33:8 %	78.5:8.5:13.0 %	at [1:1/2:1/3] of NB energy for nominal beam energy: 25/47/49 keV for NBI-1(D)/NBI-2(D)/DNBI(H)
Low energy fraction (in % of power)	<0.1 %	<0.4%	<0.3%	with 1/(12..16) of NB energy
Modulation				
Power sweep during TCV shot	full power range	full power range	not available	few sweeps for NBIs possible
Power sweep response dP/dt	25/40 MW/s	25/40 MW/s	not available	slope limit of NBI power (up/down)
Full power modulation on-time	2.5 ms … 2 s	3.5 ms … 2 s	6…30 ms	Min. DNBI modulation on-time is limited by current rise time
Minimal modulation off-time	5 ms	4.5 ms	8 ms	limited by delay between suppression grid modulation and beam current
Modulation rise/fall time	1…3 ms	1.5…3.5 ms	1.5…2.5 ms/250 mks	shorter DNBI time planned after upgrade of power supply
Fast modulation	100…300 Hz	100 Hz	50 Hz	NBIs at reduced power and higher divergence
Geometry before/from August 2019				
Grids (IOS) aperture	ø250 mm	ø250 mm	ø87.2 mm	area of grids with beamlet apertures
Beam divergence, mrad (deg.)	36x8 (2.06x0.46) / 23.6x9.9 (1.35x0.57)	13.8x5.1 (0.79x0.30)	9.25 (0.53)/9.20(0.53)	NBIs (horizontal) x (vertical) according to measurement

Parameter	NBI-1	NBI-2	DNBI	Comment
Focal length	3.20 m (7) / 3.76(h)/3.98(v) m	4.20(h)/4.25(v) m	4.00 / 1.80 m	according to measurement
Distance from IOS to port exit in TCV	4.05 m	4.28 m	3.81 m	along beam axis
TCV port size (horizontal x vertical)	220x170 mm^2	210x160 mm	ø160 mm	NBIs: rectangular, DNBI: circular
NB tangency radius	736.0 mm	736.0 mm	235.3 mm	distance from NB axis to TCV machine vertical axis
Beam diameter in TCV (hor. x vert.)	24.37x10.22 cm / 21.6x9.4 cm	13.2x5.2 cm	8.02 / 12.1 cm	(1/e) level, NBIs in horizontal cutted by port size

$$\mathrm{DCD}_{\text{NBI-2}} = (r_d, Z_d, \phi_d, \theta_d, tv_d) = (5.2123, -0.0025, 212, 6947 \cdot \pi/180, 0, -8.4896 \cdot \pi/180)$$