BTR APPLICATION for BEAM SLOWING-DOWN ANALYSIS

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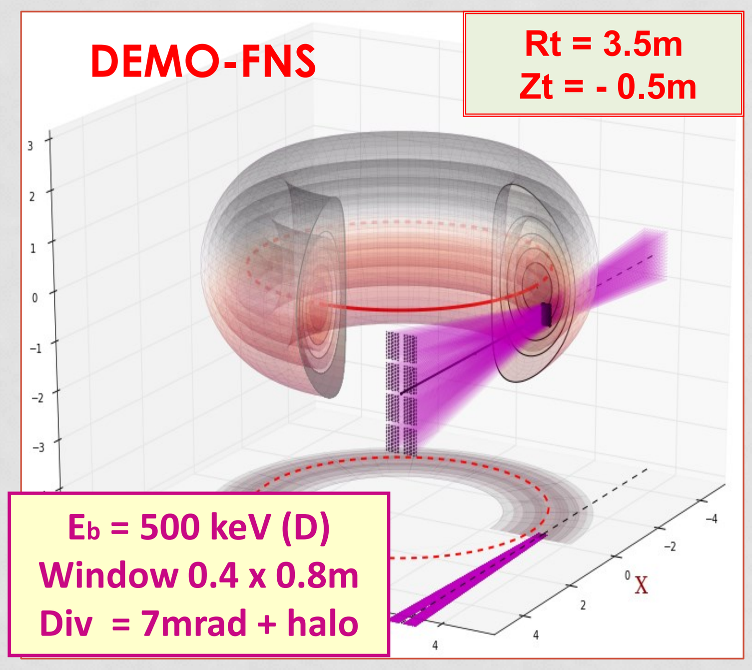
DEMO-FNS Parameters	
Aspect ratio R/a, m	3.2/1
Toroidal magnetic field, T	5
Electron/ion Temperature, keV	10-15
Av. plasma Density, 10^{20}, m^{-3}	0.5-1
Beta normalized β_N	2.1
Plasma current I_p, MA	5
6 NB injectors (tangential)	
Neutral injection power P_b, MW	30
D atoms Energy, keV	500
Ion source current, A	40
Pulse length, s	1000
Consumed / generated power, MW	200

NBI TASKS

- ❑ Particles fueling for fusion
- ❑ Plasma heating (steady-state)
- ❑ Current drive
- ❑ Radial profiles control
- ❑ Plasma toroidal rotation



NBI CD CHALLENGES

- ❑ beam power capture by plasma core
- ❑ shine-through losses, power loads at FW
- ❑ non-confined fast ion orbits
- ❑ Fast ions energy, pitch angle distributions
- ❑ NBCD overall efficiency
- ❑ Momentum source from NB

DEMO-FNS neutron yield is mainly caused by D-T fusion on beam; High density of NB power >> specific **operation scenarios**: high fraction of fast particles, high rotation velocity, low collisions.

Effective neutral beam penetration, fast ions generation and energy transfer to plasma components need optimization >> **high accuracy 3D calculations:**
+ tune NB energy;
+ optimum injection geometry,
+ analysis of plasma scenario influence on : NB deposition profile, NB losses, and NB driven current (NBCD)

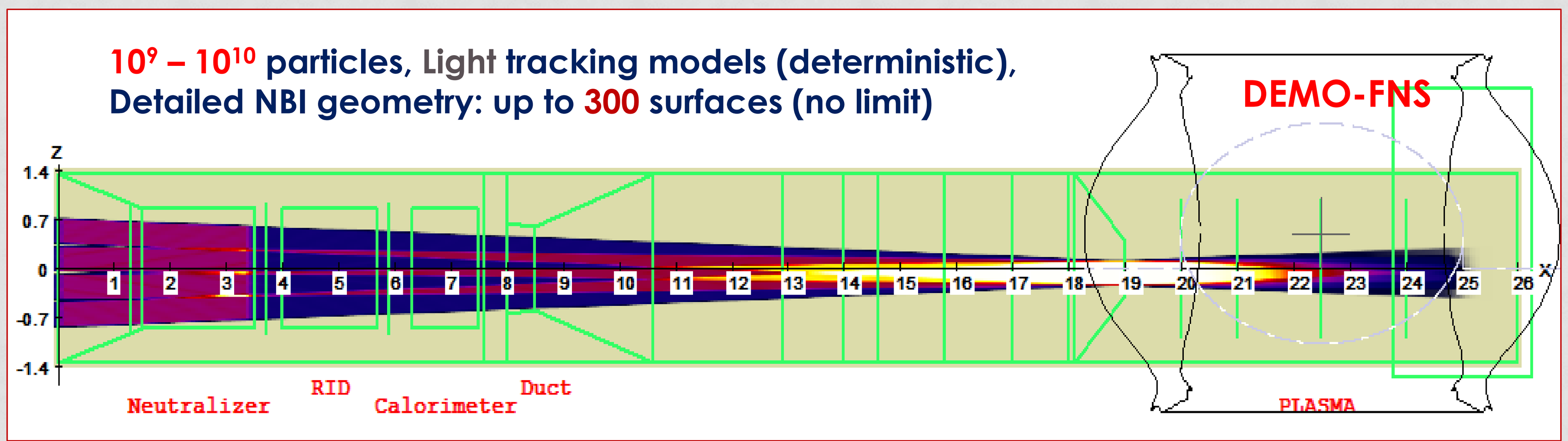
BTR OVERVIEW

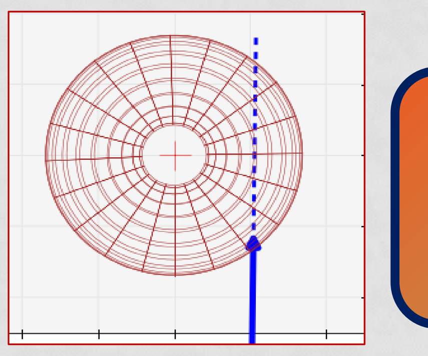
BTR for PLASMA

- ➢ Detailed NB 6D geometry at plasma entrance: $10^5 - 10^9$ macro-particles population (no limit)
- ➢ Plasma magnetic geometry, $n_e/T_e/Z_{eff}$ are taken from experiment or plasma equilibrium codes (no need to be toroidal!)
- ➢ Neutral Beam stopping/ ionization 3D profiles in plasma
- ➢ Shine-Through Power maps at FW
- ➢ NB instant axial and radial deposition profiles
- ➢ Fast NB ions (~10^{12}) slowing-down to thermal state
- ➢ Fast Ion ψ/ρ = const
- ➢ Fast ions Energy / Velocity / Pitch angle distributions
- ➢ Fast ions parallel current profile, integral NBCD
- ➢ Plasma heating (power to ions, electrons)
- ➢ Plasma toroidal rotation (NB momentum source)
- ➢ Beam-plasma Fusion rate and power (NB-fusion source)
- ➢ Neutron yield (NB source)
- ➢ Fast ions Larmor center orbits can be traced (with BTR!)
- ➢ Permanent development
- ➢ Full lifespan support for Users

BTR code for BEAM STOPPING

$10^9 - 10^{10}$ particles, Light tracking models (deterministic),
Detailed NBI geometry: up to 300 surfaces (no limit)

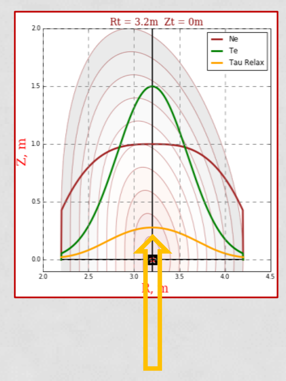




FAST IONS SLOWING-DOWN and NB CURRENT DRIVE

BASIC ASSUMPTIONS

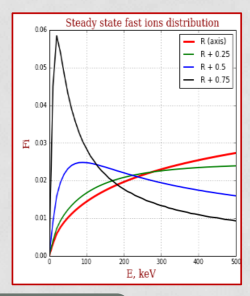
- ▪ Fast Ion (FI) slows-down within the MagSurf layer ρ + Δ ρ (i.e. ρ = const)
- ▪ Fast Ion charge-exchange losses, velocity diffusion, pitch angle scattering, electron screening, trapped orbits are ignored, $I_{NBCD} = I_{NBFI}$
- ▪ Toroidal Fast Ion current is defined by parallel velocity
- ▪ Ions are "Fast" until thermal velocity: V / V0 = 0.2



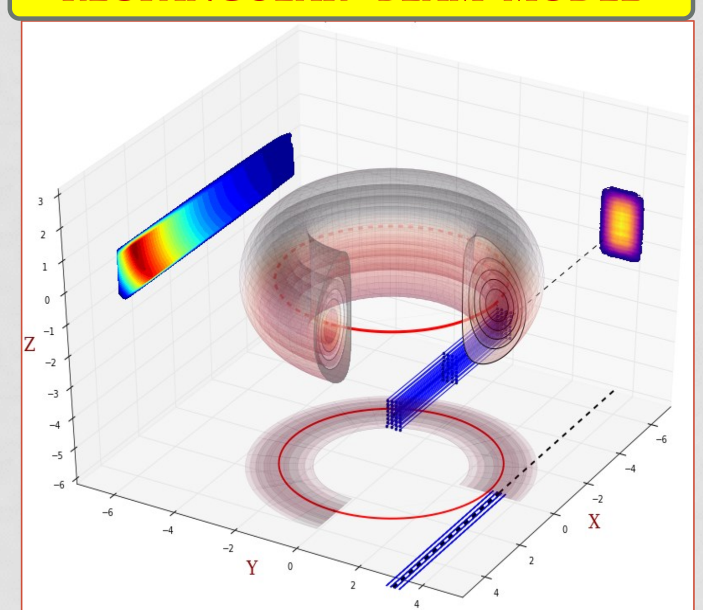
[5] $\tau_s = \tau_{se}$ / 3 · ln(1+ $(E_b / E_c)^{2/3}$) Ion slowing down on plasma electrons and ions

τ_{se} = Coeff · $T_e^{3/2} / n_e$ Slowing down on electrons (Spitser time)

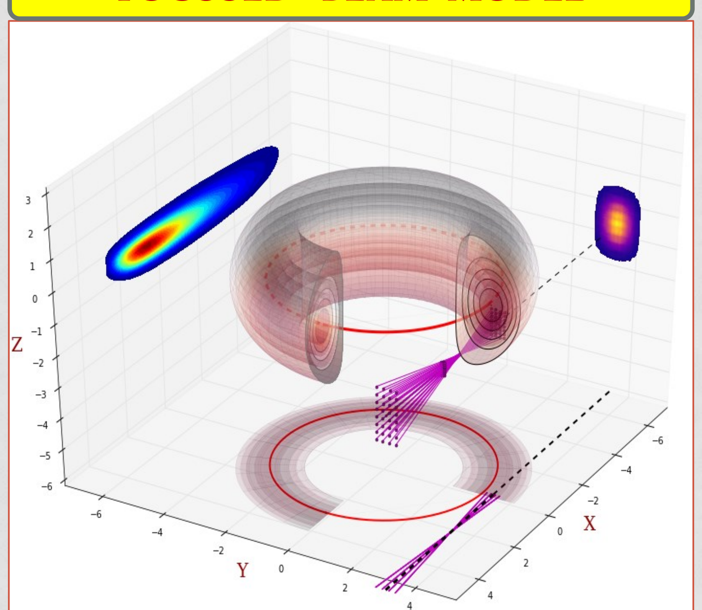
E_c = 14.8 · A_b / $A_i^{3/2}$ ·T_e Critical energy



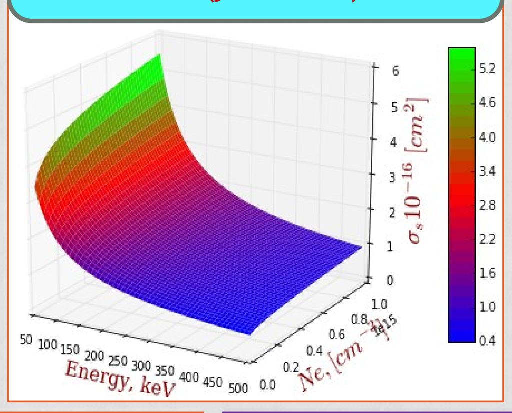
RECTANGULAR BEAM MODEL



FOCUSED BEAM MODEL



BEAM IONIZATION σ (JANEV)

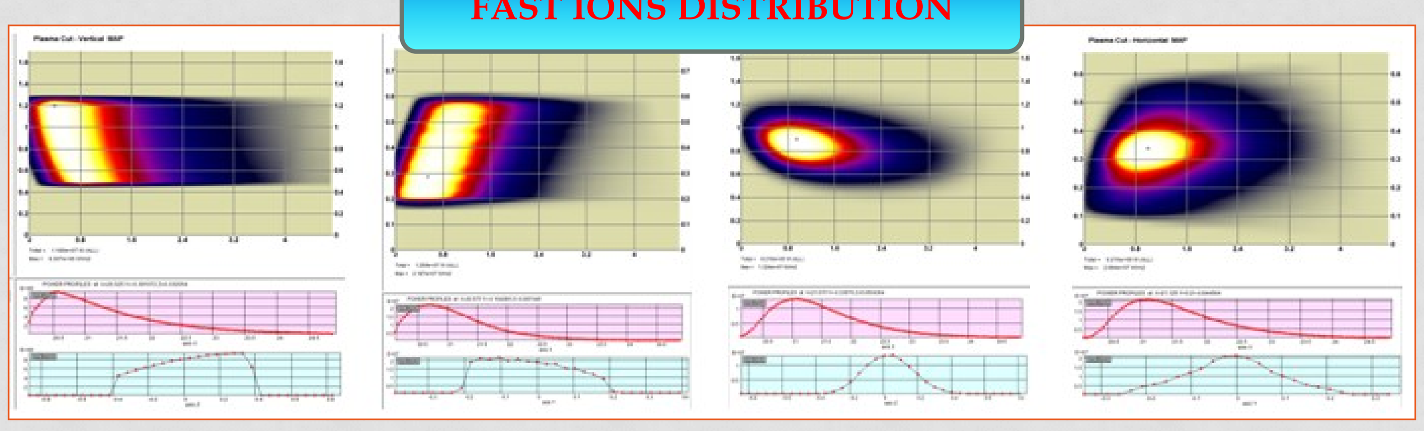


$\frac{dI}{dx} = -\sigma_s n_e I$

DEMO-FNS : σ_s = 0.9 - 1.2*10^{-20} m^2

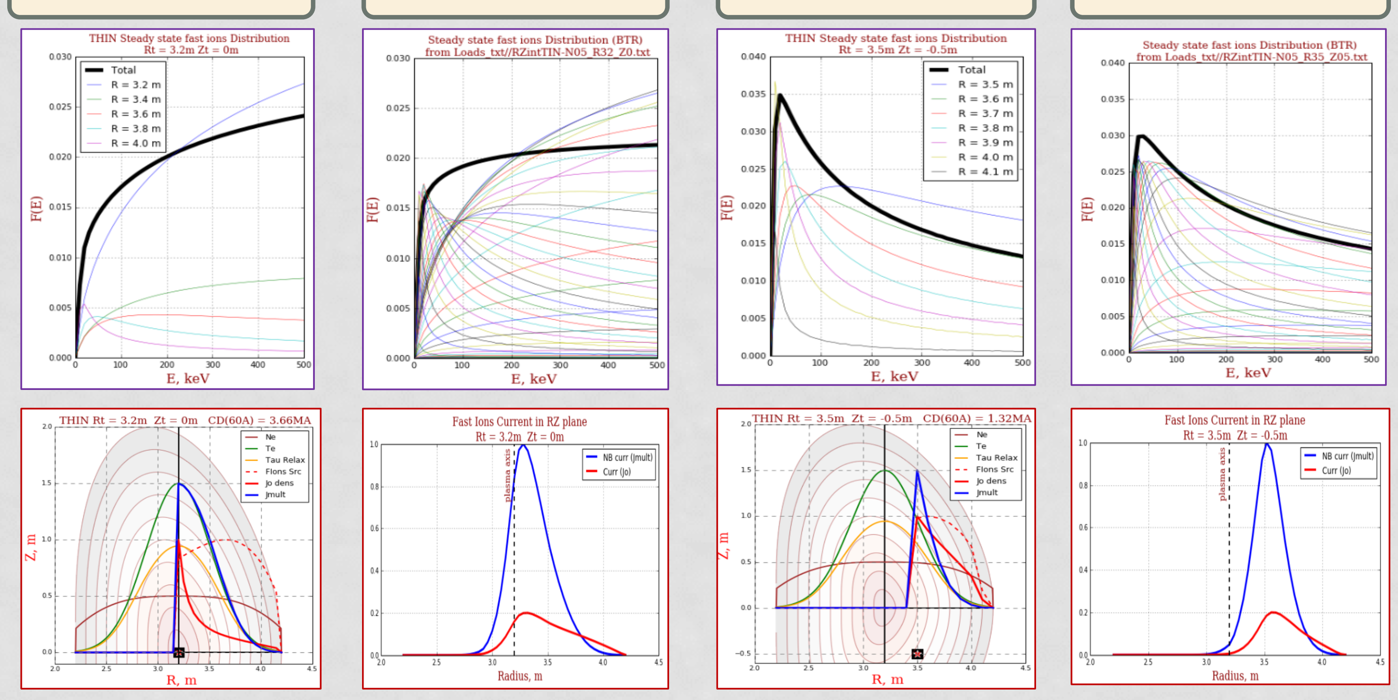
$\sigma_s = f(E,\ \ln(n_e),\ \ln(T_e),\ Z_{eff})$

FAST IONS DISTRIBUTION



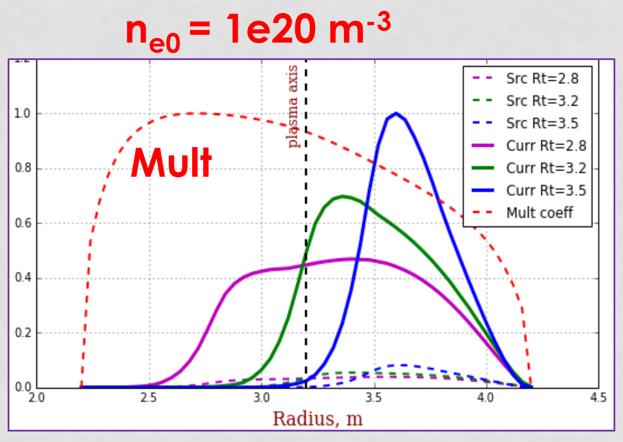
FAST IONS ENERGY DISTRIBUTION

ON-AXIS NB injection		OFF-AXIS NB injection	
THIN BEAM	BTR BEAM	THIN BEAM	BTR BEAM



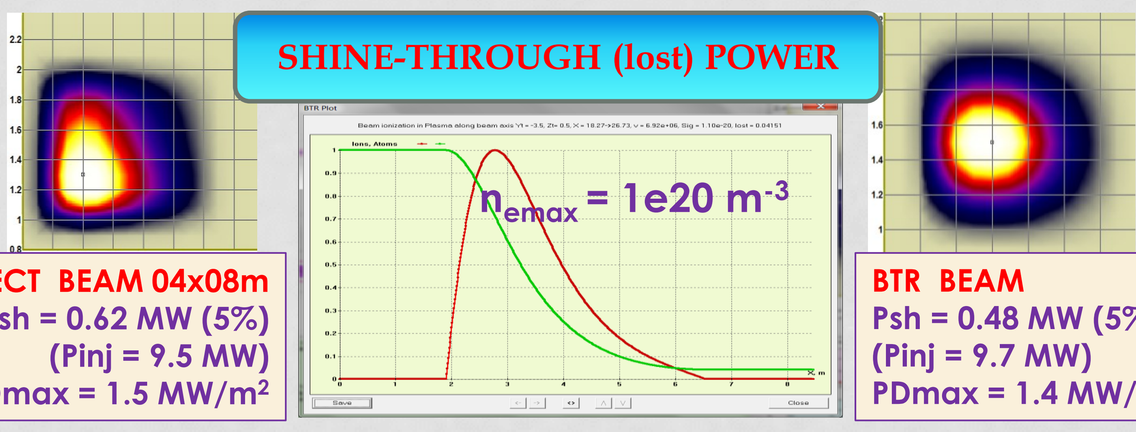
JNB = 3.7MA	JNB = 4.1MA	JNB = 1.3MA	JNB = 2.7MA

n_{e0} = 1e20 m^{-3}



Multiplication coefficient for ion instant current
Mult = <V> x Nturns
and total *stacked* Current
JNBCD - for different NB axis targeting

SHINE-THROUGH (lost) POWER



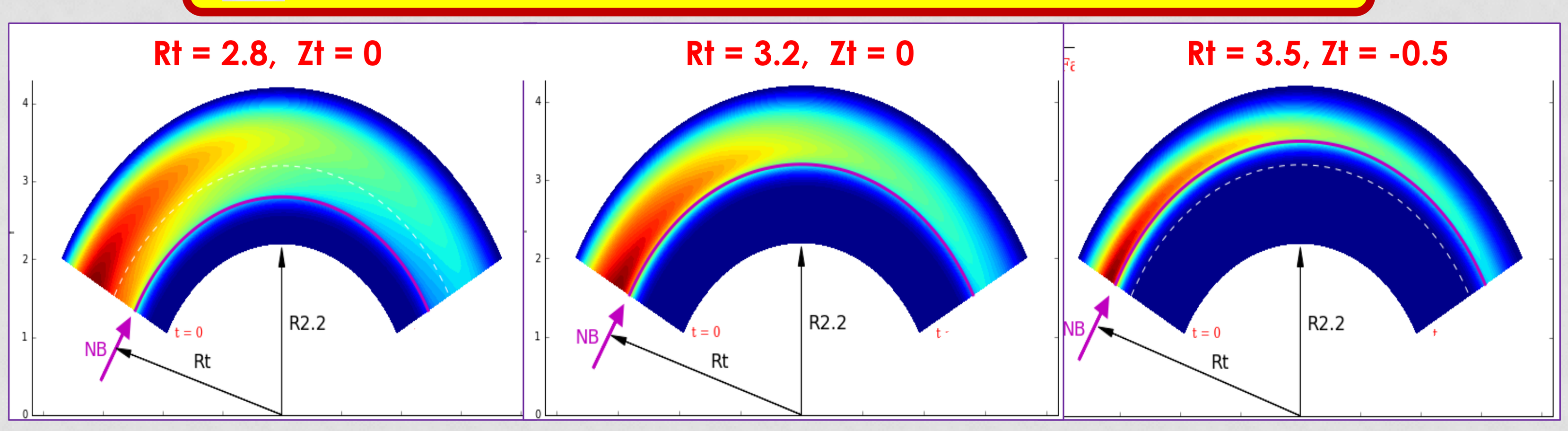
RECT BEAM 04x08m
Psh = 0.62 MW (5%)
(Pinj = 9.5 MW)
PDmax = 1.5 MW/m^2

BTR BEAM
Psh = 0.48 MW (5%)
(Pinj = 9.7 MW)
PDmax = 1.4 MW/m^2

For DEMO-FNS nominal conditions and OFF-AXIS injection generates lower average Energy and CD of fast ions: 2-3 times lower than ON-AXIS; THIN beam produces less CD than Real (BTR) beam under similar conditions.

Shine-through power calculated for DEMO-FNS nominal conditions and Real (BTR) beam geometry (Div = 7mrad) can be 2-3 times higher, than THIN beam evaluation for similar conditions.

FAST IONS CURRENT GENERATION



Trelax ≈ 0.1 … 2.3 s , Nturns ~ (1 … 26) · 10^4

Rt: Trelax ≈ 0.85s
~ 170 000 turns
1A NB >> 0.07 MA

Rt: Trelax ≈ 1.5s ~ 260 000 turns
1A NB >> 0.07 MA

Rt: Trelax ≈ 0.76 s
~ 120 000 turns
1A NB >> 0.045 MA

OFF-AXIS beam CD profile is more peaked, but CD efficiency (i.e. NB current per 1A NB) is 1.5-2 times lower due to Te profile slope; Real (BTR) CD is shown for 3 target points .

SUMMARY

✓BTR CAN BE USED FOR 3D CALCULATIONS OF NEUTRAL BEAM DEPOSITION IN PLASMA, FAST IONS ENERGY AND NB CURRENT DRIVE ANALYSIS

✓FAST IONS ENERGY AND CURRENT RADIAL PROFILES (OBTAINED WITH BTR BEAM MODEL) DEPEND ON INSTANT IONS DEPOSITION (NB IONIZATION RATE) IN PLASMA

✓NB IONIZATION PROFILE IN A GIVEN PLASMA TARGET (T/N) IS DEFINED NOT ONLY BY NB ENERGY AND AXIS AIMING, BUT IT IS HIGHLY SENSITIVE TO THE REAL BEAM SHAPE AND INNER BEAMLETS STRUCTURE (6D), ESPECIALLY FOR OFF-AXIS INJECTION

✓SHINE-THROUGH POWER LOSSES AND FW POWER MAPS ALSO DEPEND ESSENTIALLY ON THE BEAM TARGETING AND 6D BEAM GEOMETRY

➢FOR DEMO-FNS OFF-AXIS INJECTION AT TE≈10KEV THE OPTIMUM VALUES OF PLASMA DENSITY ARE DEFINED BY EFFICIENT BEAM CAPTURE BY PLASMA AND CURRENT DRIVE (NB DEPOSITION: NE (≥) ≈ 1E20 M^{-3}

➢FOR DEMO-FNS: TO ACHIEVE OPTIMAL NB DRIVEN CURRENT VALUES (~ 4MA) THE NB AXIS SHOULD BE AIMED BETWEEN R_T = 2.8 AND 3.3 M (WITH PLASMA AXIS AT R_0 = 3.2M). IN FACT, THE SHAFRANOV SHIFT ACCOUNT AND MORE DETAILED MAGNETIC GEOMETRY CAN SLIGHTLY CHANGE THESE VALUES (ADD ~ 0.1M)

[1] BTR-webpage https://sites.google.com/site/btrcode/
[2] BTR Source https://github.com/EDlougach/BTR
[3] Kuteev et al., Nuclear Fusion, vol. 57, p. 076039, 2017
[4] R.K. Janev *et al*, Penetration of energetic neutral beams into fusion plasmas, 1989 *Nucl. Fusion* 29 p2125.
[5] S.Suzuki et al 1998 Plasma Phys. Control. Fusion 1998 40 2097-2111
[6] J.Wesson, Tokamaks, 4th Edition 2011, Oxford: Oxford University Press