BTR code for NBI Design and Optimization

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Abstract. BTR code (*Beam Transmission with Re-ionization*) is used for NBI beamlines design and studies since 2005. Initially tailored for beam re-ionized particles tracking in neutral beam ducts, BTR finally became a universal tool for 3D geometry optimization and thermal loads evaluation in injectors' beamlines. BTR simulations include all variety of neutral beam formation and transport conditions - from the ion beam extraction grid of the ion beam source. From the very beginning BTR is created for public usage, and it comes with a truly interactive User-friendly interface (Windows GUI). The beam tracing model is straight-forward and deterministic, it is replicable and easily cross-checked with other beam tracking codes, including analytical models. BTR standard beam is a regular array of beamlets; their spatial positions, focusing and inner angular distributions are reproduced with high resolution: up to 10^5 test particles per each beamlet. The particles are tracked in electromagnetic fields, with their transforming on gas and plasma targets, including neutralization, ionization in gas or plasma, etc. The accurate 6D (space + velocity) statistics allows a precise evaluation of beam direct losses; power deposition profiles are delivered with high resolution at the beamline components; the total amount of maps can reach several hundreds. BTR is parallel and able to trace up to 10^{10} macro-particles within few hours on average Windows machine, with the best performance achieved on 4-8-processor systems. Today BTR is a lively and evolving code, and free support is available to all the Users. Basic applications of BTR code are shown – with a focus on the conventional, Single-Run versions. The information on BTR upgrades and code manuals can be found online.

INTRODUCTION

Neutral Beam Injection (NBI) is generally used for plasma heating, rotation, current drive source and operation modes control in tokamaks; it can be also applied for plasma diagnostics. While NBI main purpose can vary through the target fusion designs, the engineering tasks which are to be solved during each NBI development have much in common between specific beamlines. Any NB system design, especially aimed at the high-power operation in long pulse devices, includes the accurate evaluation of the beam transmission losses and resulting power deposition at the injector components, which are applied next for thermal analysis and cooling requirements. And even for the final NBI design, these tasks are *regenerated* any time, when some component geometry or position is slightly modified, or physical conditions are updated (e.g. the magnetic field from the fusion device).

NBI principles can be found in [1] and briefly summarized as following. The source ions – hydrogen or deuterium – either positive or negative – are extracted from a beam source (BS) and accelerated to the required energy in a multi-grid multi-aperture electrostatic accelerator, the last grid is grounded (null-potential, GG). The beam energy is chosen with account of the penetration capability to target plasma, and for large plasma devices (R > 2m) only negative-based neutral beams can be efficiently produced. The extracted ion beam is next neutralized by charge exchanging process in a neutralization cell. If a neutralization on gas target is used, the Neutralizer typically has multi-channel structure, so that to minimize gas injection requirements. The negative beams neutralization efficiency on gas is limited by ~58%. The remaining charged fractions are removed from the beam in a Residual Ion Dump (RID), which can apply an electrostatic or magnetic deflection, depending on the ions species energy spectra.

Due to the neutralization and transmission losses, a total power injected to plasma will not exceed ~50% of the source power, and the value highly depends on the source beam divergence and deflections caused by various effects. In fact, the total beamline efficiency (i.e. the ratio between the injected power and the source power) is defined by the beam neutralization efficiency and beam transmission. The actual beam divergence is unknown so the ITER DDD [2] adopts three possible core divergences: 3 mrad, 5 mrad, and 7 mrad accompanied by a beam halo (~30 mrad), which contains 15% of the beam particles. The resulting transmission evaluated for this range of divergence is varied from 70% to 90%, leading to the total beamline efficiency range 35-50%.

Since a beamline design should be matched with the stringent space constraints imposed by the tokamak systems, the geometry optimization with account of heat removal demands lead to increasingly complex beamline geometries. In general, the optimization goal is to minimize the beam losses while reducing the local heat load in each component to a removable level. This requires multi-parametric study of power loads, conducted with helps of specialized numerical tools.

One of these tools is BTR code [3, 4], initially intended to simulate *Beam Transport with Re-ionization*. It is used to perform massive design studies of any NBI geometry, with the source beam structures consisting of beamlets (i.e. elementary beams). BTR delivers the heat load images and the beam footprints in any plane or surface defined, and evaluates the total beam losses due to the direct interception and beam interaction with gas. It can be also applied to match the beamlets directions with the beamline geometry, to fine-tune the components geometry, although these are not the main code applications. BTR specific scope of tasks includes magnetic field (MF) effects and electrostatic field analysis (RID), and the effects of beam conversions. And finally, the task of beam stopping in tokamak is added recently, hence BTR is currently used for preliminary optimization of beam penetration and capture in plasmas too. BTR models are simple and easily verified analytically (*Light models*); the code can be used for more sophisticated NBI models verification [5].

BTR is written in MS Visual C++, first version was released in 2005. The main idea of the code is to be User-friendly, and it comes with interactive Windows graphical user interface (GUI). In fact, it is used not only for NB design studies, but also as NBI *flight simulator*. BTR execution is parallel, and it runs especially fast on multi-core Windows machines. The input configuration (BTR *Config*), comprising NBI geometry, physical environment, and beam tracing settings, is flexible and intuitive, it can be easily adjusted for any specific NB design.

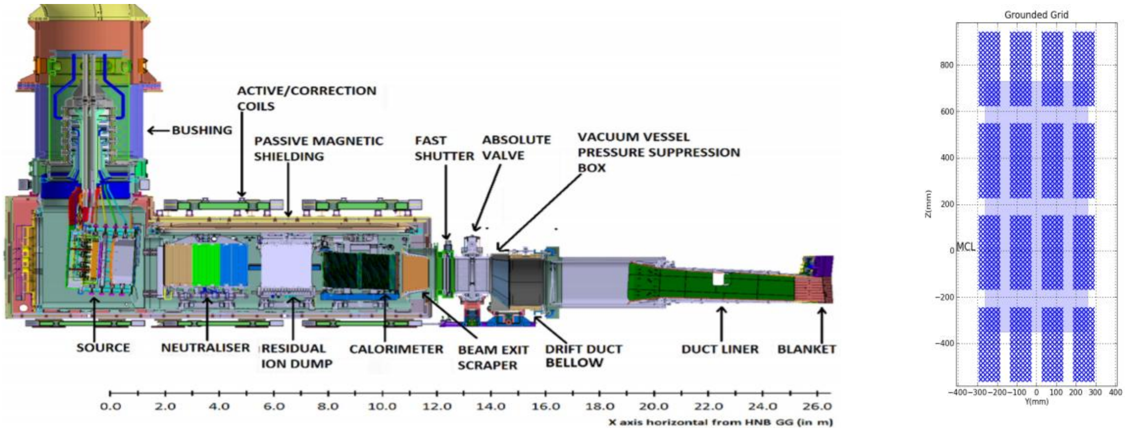
The information on all BTR upgrades during 2005-2020 can be found in BTR dedicated webpage [3]. In 2020 a new version BTR-5 (*Multi-Run*) is released, it allows easy multi-parametric NBI studies with flexible input. The upgrade to BTR-5 is described in other paper. This paper introduces the BTR code methods and features – with a focus on the code conventional applications before 2020 (versions 1-4, *Single-Run*). Note, all the images with BTR results mean to illustrate the code *capabilities*; they can refer to different designs and operation conditions. The plots in the Model section are given to demonstrate examples of BTR built-in charts (they serve for data control - during the code execution): their quality is not high, due to the paper size. The paper structure is as follows: the NBI geometry and the beam are described in the 1st section; the numerical approach is introduced in the 2nd section; BTR User Interface tools are briefly shown in the 3rd section; finally some examples of BTR applications are given.

NBI GEOMETRY

Figure 1 from [6] shows the layout of ITER heating neutral beam (HNB) injector. The beamline basic components used through all NBI designs (especially based on negative ions) are similar, with minor variations. The HNB vacuum vessel includes the beam source vessel (BSV), and the beam line vessel (BLV). Coupled to the BSV is the high voltage bushing (HVB) from the top flange in the case of HNB. The beamline components (BLCs) include an ion beam source (BS), a neutralizer (N), an electrostatic residual ion dump (ERID), and a calorimeter (C). The exit scraper (ES) is followed by a series of front end components (FEC) comprising a fast shutter (FS), absolute valve (AV), drift duct liner (DDL), vacuum vessel suppression system (VVPSS) box, connecting duct liner (CDL) with a liner and the duct liner (DL) made up of several modules. The end of the DL couples to the tokamak port.

Based on this layout, the BTR *Standard NBI geometry*, i.e. default input configuration, includes the following NBI standard components: the beam source grounded grid (BS GG) position, a multi-channel Neutralizer (N), a Residual Ion Dump (RID, multi-channel), Calorimeter (neutral beam dump), and the beam transmission Duct, defined by multiple modules, including Scrapers, FEC, Liners, Blanket sections, etc. The channel structure of NBI components is optimal for gas supply and pumping conditions. Apart from Standard geometry input, BTR allows the option to specify the list of *Free* surfaces, which can describe the complex structure and details of the beamline components. Free surfaces can be created either directly by the interactive input tools (see BTR GUI section), or specified in text files, created by external tools (e.g. converted from CAD).

The *Standard Beam geometry* is defined by a regular array of beamlets which start from BS GG plane. Each beamlet represents an elementary beam current from a single GG aperture. The beamlets start positions are arranged in clusters (or *group)* according to GG apertures structure, as shown in **Fig. 1-b**. The standard beamlets optics is a combination of beam source groups' steering at the injected port center, and individual axes focusing within each group in horizontal plane - for optimal transmission through NBI channels. Finally, the entire beam envelope is inclined or tilted (as in ITER HNB, [7]) - to hit the specific tangential point in plasma and switch between on-axis and off-axis injection. The NBI geometry and the BS beam, as they appear in the BTR screen, are shown in **Fig. 2**.



(a) (b)

FIGURE 1. a - Sectional view of ITER HNB beam line, taken from [6], b – BS GG layout

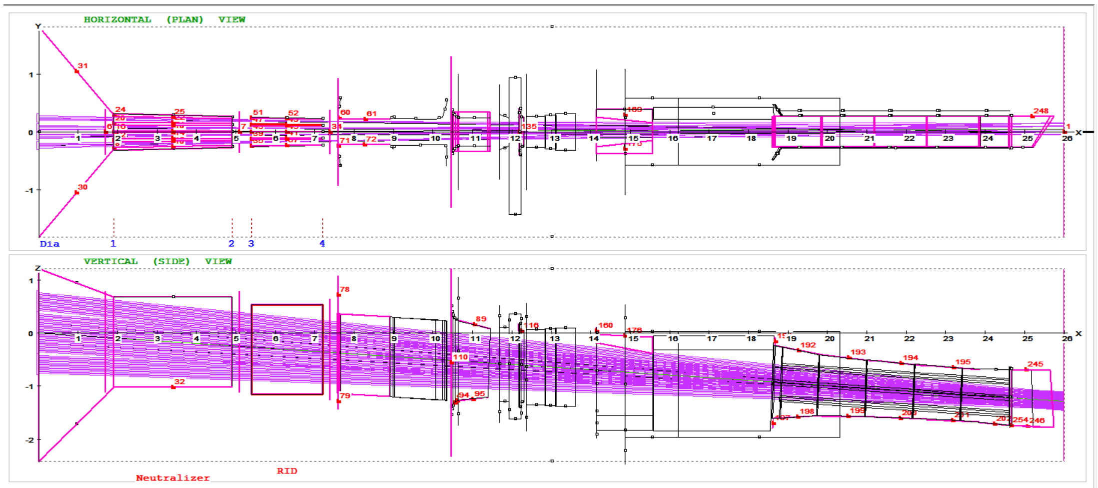


FIGURE 2. BTR Screen with ITER HNB geometry: horizontal and vertical plane views. *Standard* NBI geometry is combined with *Free* surfaces import. *Standard beam* model is defined by regular array. The beamlets' axes are shown in violet.

Note: the examples presented below refer to NBI design for a Fusion Neutron Source DEMO-FNS. Its layout is similar to ITER HNB and based on negative source ions, but with lower power (7.5 MW per injector).

BTR MODEL

Beamlet current. Each source beamlet (elementary cone) current profile is a sum of *core* (~85%) and *halo* (~15%) fractions with Gaussian profiles along polar angle

$$j(\theta) = \frac{1-H}{\pi\Delta_c^2} e^{-\theta^2/\Delta_c^2} + \frac{H}{\pi\Delta_h^2} e^{-\theta^2/\Delta_h^2} \tag{1}$$

Here θ is a polar angle, measured from beamlet axis, H is halo fraction of beam current, Δ_c and Δ_h - gauss divergence for core and halo fractions. The fractions ratio and divergence are taken from experiments and can be set like other input parameters in BTR. The beamlet current is represented by a finite number of particles (**Fig. 3-a,b)**, by splitting the total current cone to a regular number of discrete rays in polar and azimuth directions: 10^2 –10^5 rays per beamlet, each ray carrying a specific weight. The splitting numbers are set with direct input tools. With a typical beam of more than 1000 beamlets, the total amount of particles in the model can reach 10^9 or more.

The beam test-particles are traced straight-forward. Atoms are ray-tracked (*light* NB model), while charged species are traced with regular local steps, defined for different regions (via direct input). The conversions of primary beam particles caused by the interactions with gas or plasma are applied with cross-sections (*σ - approach*).

Neutralization. The source ions (negative or positive) are converted to atoms via collisions with D_2 gas in the Neutralizer with relevant atomic cross-sections: 4 *sigmas* are involved for negative ions: σ_{-10} *(electron stripping),* σ_{-11} *(double electron stripping),* σ_{10} *(positive ion neutralization),* and σ_{01} *(atom ionization);* only 2 *sigmas* are working in positive source ions case (σ_{10}, σ_{01}). There are two options available in BTR for beam neutralization – *thick* and *thin* models. Thin model is less accurate: the total gas volume is *pushed* to a single step at the Neutralizer exit, leading to higher beam deflection after the Neutralizer. However, the model is a great deal faster and is used more often, than thick model, which accounts for the real gas target distribution and leads to smaller beam deflection with wider velocities spectra. The *thick* model (**Fig. 3-c,d**) solves the balance equations solved for beam species:

$$\frac{d\Gamma^-}{dx} = -\Gamma^-(\sigma_{-10} + \sigma_{-11})n \tag{2}$$

$$\frac{d\Gamma^0}{dx} = \Gamma^-\sigma_{-10}n + \Gamma^+\sigma_{10}n - \Gamma^0\sigma_{01}n \tag{3}$$

$$\frac{d\Gamma^+}{dx} = \Gamma^-\sigma_{-11}n + \Gamma^0\sigma_{01}n - \Gamma^+\sigma_{10}n \tag{4}$$

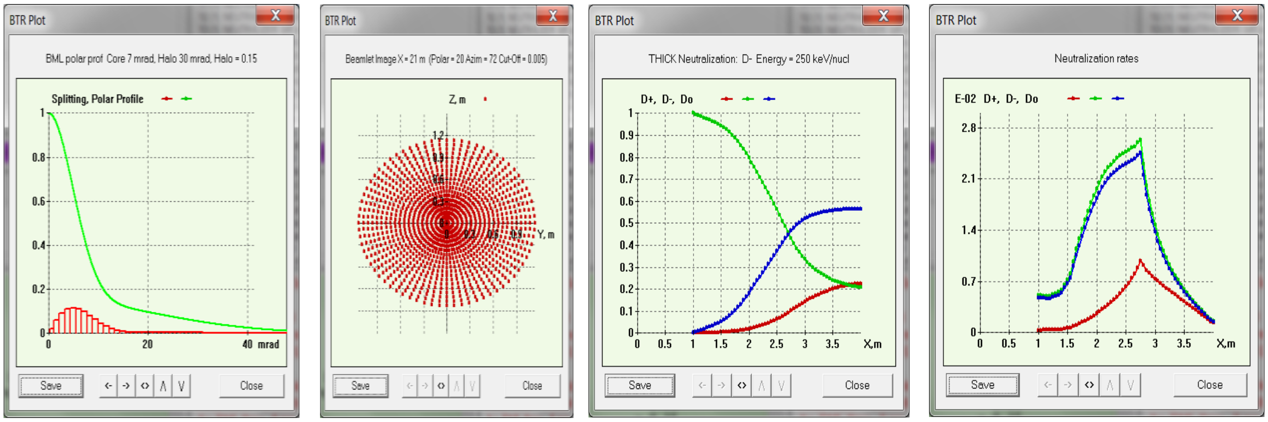
Here Γ^k is the k-th specie flux, n – the background gas density.

The model of the neutral beam *Re-ionization* along Duct regions is very similar to thick neutralization: it accounts the actual gas target distribution; it is relatively fast, implementing but the atoms ionization (σ_{01}).

Beam stopping in plasma. The neutral beam ionization in plasma is very similar to Re-ionization (thick) model. Each injected atom current is decayed, the decay rate is equal to fast ions birth rate. The main expression used for the neutral current decay and fast ions instant deposition along injected ray (see **Fig. 4-a,b**) is

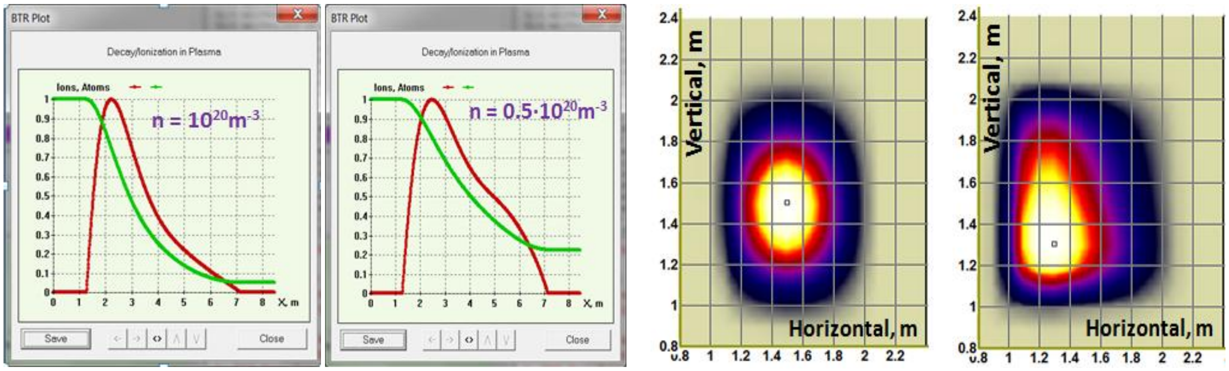
$$P(x) = -\frac{\partial I}{\partial x} = \sigma\, n(x)\, I(x) \tag{5}$$

Here *P(x)* – fast ions birth rate, *I* – the neutral beam current, $\sigma = \sigma_s$ – effective ionization cross-section (CS);
$n = n_e$ – local plasma density. The mean free path (λ) for atom can be introduced as $<\lambda> = (n\sigma)^{-1}$. The neutral current expression is also used to calculate the shine-through (lost) power left from all the rays (see **Fig. 4-c,d**).



(a) (b) (c) (d)

FIGURE 3. BTR models: a – beamlet current density profile (green), and polar group currents (red); b – single beamlet particles imprint at a normal cross-plane; c – the beam species current in *thick* neutralization (green – negative, red – positive, blue - atoms); d – neutralization rates (similar colors)



(a) (b) (c) (d)

FIGURE 4. BTR beam stopping in plasma: a, b – the beam species currents along beam axis (green – atoms, red – fast D+) - for two values of plasma density; shine-through power: c – gauss beam, d – rectangular beam

Power maps. Power load to any Surface comes from the primary beam direct interception and from secondary fluxes. All the target surfaces, including the beamline *solid* components and virtual *transparent* planes, are covered by rectangular mesh, defined by individual cell steps. The meshing approach differs through BTR versions, but in all cases it is possible to adjust the mesh resolution: either after the beam trace – in the Single-Run versions (BTR1-4), or before each beam start - in the new Multi-Run BTR-5. With the amount of particles in the model being reduced only by the User's time (in fact, it is limited by RAM), a detailed beam geometry and statistics allow for high maps refinement (~1mm cell size). The surfaces amount for power maps calculation can be several hundreds.

Resume. All BTR models are *light*, i.e. fast and easy to verify. Basic BTR beam includes an accurate beamlet based 6D representation (space + velocity components). The beam tracing is deterministic, the particles tracks and conversions are simulated in realistic fields and gas environment. The power map resolution can be adjusted; the result maps are applied for thermal cooling analysis of the NB-line components. BTR beam model is extended to tokamak plasma, it also performs a detailed 6D analysis of beam stopping and ions generation, brings beam power footprints and shine-through maps on plasma facing components.

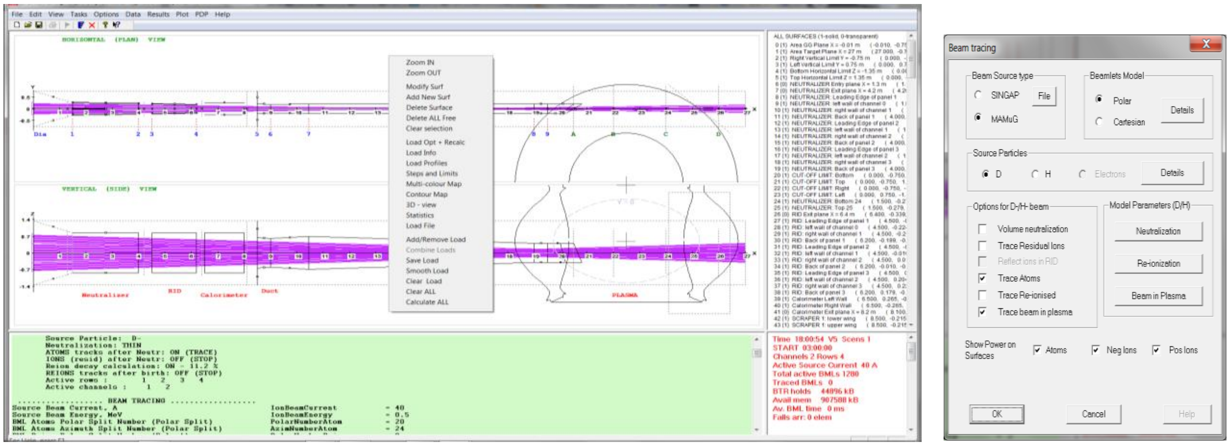
BTR code performance and benchmarks. At present the total run of $1.5{\cdot}10^6$ beam atoms with $25{\cdot}10^6$ of re-ionized particles takes ~3-5 minutes on old 2-core Windows-machine. Comparing with analytical models, which run typically in a few seconds, BTR is slow enough. However, the analytical NBI codes do not apply any electromagnetic effects, and not trace secondary particles – so the models can be cross-verified for ideal conditions. The results for secondary particles are cross-checked with SAMANTHA code [5] which is intended to study additional phenomena in the beamlines, such as the production and dynamics of secondary particles in realistic electromagnetic fields. Although the numerical methods in the codes are different (in general, BTR methods are fast and less accurate than SAMANTHA's), the agreement in the power load profiles is found to be very close (<1%).

BTR USER INTERFACE

The main BTR screen is shown in **Fig. 5-a**. BTR window is divided into 4 sections:

1. Input Configuration View with NBI geometry and Beam layout;
2. The Green Panel tool (BTR Input Data Container);
3. Loads Summary or Map Image view;
4. Running Status or Profiles view.

The Green Panel – is the basic interface engine of the code, its input processor, used for interactive data control and revision. When the User modifies any data field in the Green Panel, the input Config (data set) is updated, and all the views are refreshed accordingly. The data can be stored in the Output file with same format as Input Config.



```
        Source Particle:  D-
        Neutralization: THIN
        ATOMS tracks after Neutr: ON (TRACE)
        IONS (resid) after Neutr: OFF (STOP)
        Reion decay calculation: ON - 11.2 %
        REIONS tracks after birth: OFF (STOP)
        Active rows :        1   2   3   4
        Active channels :     1   2

 .................. BEAM TRACING ..................
Source Beam Current, A                          IonBeamCurrent          = 40
Source Beam Energy, MeV                         IonBeamEnergy           = 0.5
BML Atoms Polar Split Number (Polar Split)      PolarNumberAtom         = 20
BML Atoms Azimuth Split Number (Polar Split)    AzimNumberAtom          = 24
```

```
Time 18:00:54 V5 Scens 1
START 03:00:00
Channels 2 Rows 4
Active Source Current 40 A
Total active BMLs 1280
Traced BMLs 0
BTR holds    44896 kB
Avail mem    907588 kB
Av. BML time  0 ms
Falls arr: 0 elem
```

Beam Source type: ○ SINGAP ● MAMuG
Beamlets Model: ● Polar ○ Cartesian
Source Particles: ● D ○ H ○ Electrons
Options for D-/H- beam:
☐ Volume neutralization
☐ Trace Residual Ions
☐ Reflect ions in RID
☑ Trace Atoms
☐ Trace Re-ionised
☑ Trace beam in plasma
Show Power on Surfaces: ☑ Atoms ☑ Neg Ions ☑ Pos Ions

(a) (b)

FIGURE 5. a - BTR Screen with the Windows: NBI geometry with Beam (Standard BTR Config-file), the Green Panel (bottom-left), Results Summary (top-right), Run Status (bottom-right); b – Beam Model input dialog.

The main screen is supplied with the *Main menu*. The main Menu commands can be called to set input data by categories (alternative method for BTR direct input), to manage the Tasks and output options, to edit the input profiles, to show the images, and many other. Apart from the Main menu, there is a *Pop-up menu* (see **Fig. 5-a**), which is invoked by right mouse click. This menu is used for results zooming, scrolling and post-processing.

One example of multiple BTR input dialog-boxes, which are called from the Main menu, is shown in **Fig. 5-b**: this is *Beam Tracing* dialog, which can be optionally used to set the parameters and options for beam tracing model – the source particle species, beamlet splitting, tracking options and steps, specific conditions, etc.

Finally, the result *power maps* and *profiles* are represented by images in color, available after the beam tracing: they appear at mouse clicks on the surfaces in the main View. The beam footprints and profiles are shown the same way - by clicking on the virtual cross-planes (*transparent* surfaces). All the maps and profiles are *interactive* too: when the User moves the mouse within a map, the local power density value is shown; when a point is clicked – the local cell value is *printed* over the map or profile.

BTR APPLICATIONS

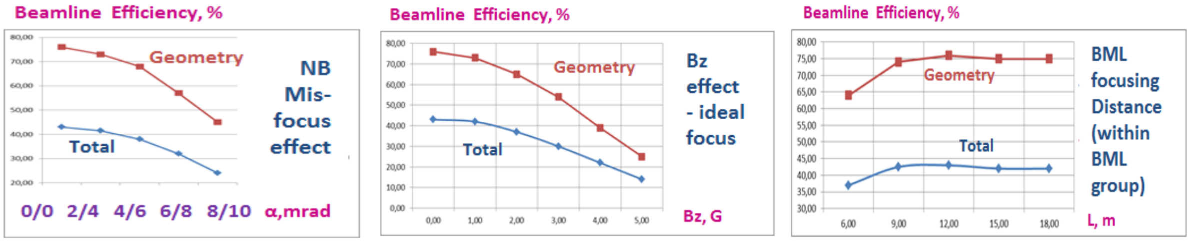
BTR can be helpful through different stages of NBI design:

1. To choose NBI scheme and to make the geometry optimization;
2. When a specific NB design is ready and more or less frozen, the code can be used to provide thermal loads study, sensitivity analysis, and to define the operational constraints of parameters (NBI operation window).

BTR main applications include: *realistic* beam transmission, beam direct losses/power, beam formation in the Neutralizer, magnetic field effects and tolerance, residual ions deflection and power in RID, Re-ionized beam losses/power, beam stopping and ionization in plasma, shine-through losses/power, and many other.

NBI performance

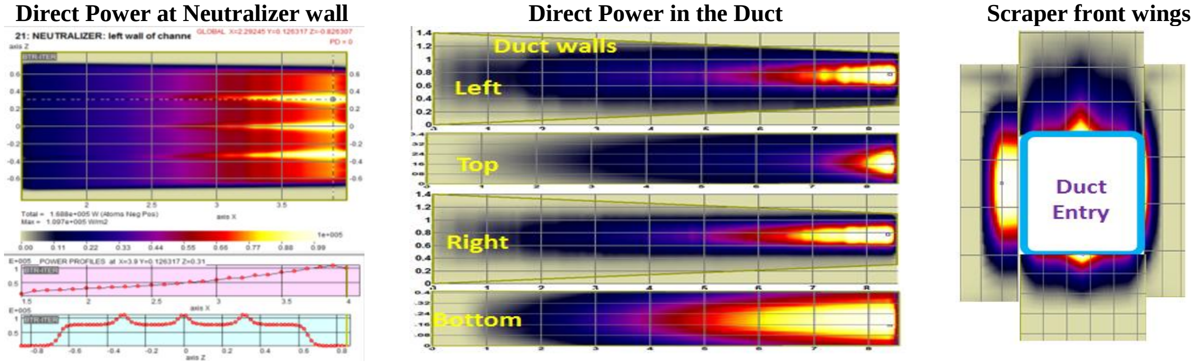
The plots in **Fig. 6** illustrate three examples of NBI performance studies and optimization (for DEMO-FNS). Their general purpose is to set the range of nominal parameters for NBI operation, as well as the main design requirements (maximum beam misalignment, magnetic shield, etc). The NBI total efficiency is proportional to the beamline geometry transmission. The studies proved the source beam horizontal misalignment (most critical value) shall not exceed 2mrad, while vertical focusing is not as stringent and can be ~4-5mrad. Vertical component of magnetic field should be limited to ~1G, MF effect is added to the deflection and scattering to the source beam. Finally, for the best transmission the beamlets within each group (or cluster) should be focused at 12m from GG along the group axis, and this is possible by tuning the grids geometry in the ion source accelerator.



(a) (b) (c)

FIGURE 6. Examples of NBI efficiency: geometry transmission (P_{inj} / P_{Neutr}) – in red, total efficiency (P_{inj} / P_0) – in blue

To set the heat removal demands, BTR delivers power maps and profiles on each surface (as shown in **Fig. 7**). They give all information needed for thermal load analysis – the total power deposition at each component, the peak power density and the expected peak position (with possible variations). The examples in **Fig. 7** refer to a Neutralizer wall (a), the Duct walls (b), with the Duct represented by a 4-sides cone, and the Scraper front (c), used to cut the beam tails at the Duct entrance.


Direct Power at Neutralizer wall **Direct Power in the Duct** **Scraper front wings**

(a) (b) (c)

FIGURE 7. BTR power maps and profiles used for thermal analysis: a – Neutralizer wall; b – Duct walls; c – Scraper front

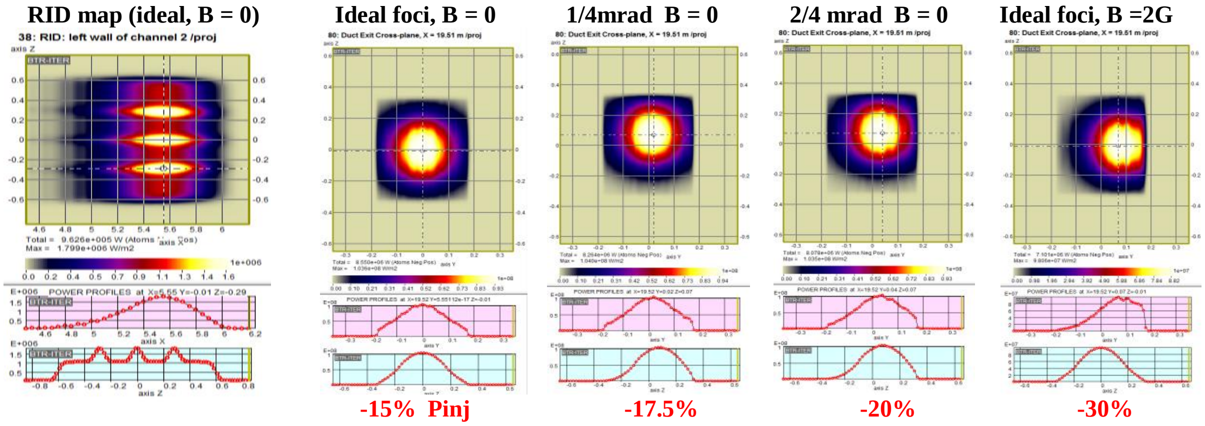
RID and Re-ionized power loads

The Residual ions fraction is the unwanted charged part of the beam after neutralization, it is next removed and dumped in RID. The deflection mechanism is either magnetic or electrostatic. To ensure the ions proper deflection and full interception by the RID dumping surfaces, the beam ions are tracked by BTR in the NBI channels within the nominal range - with scanned neutralization yield, beam tilting/focusing, divergence, and magnetic field. When the deflecting field (e.g. electrostatic potential) is chosen, the power maps/profiles are calculated (**Fig. 8-a**).

Re-ionized particles form a lost fraction, which appear due to beam atoms interactions with background gas in the Duct regions. The analysis is similar to Residuals study in RID. The major difference is that magnetic field in the long Duct region with shield is many orders higher than in RID, and the gas flow from tokamak cannot be efficiently pumped, therefore the ionization rates can grow and potentially produce high fluxes of ions. Therefore the main purpose is to define the expected peak power densities at the Duct surfaces caused by re-ionized fluxes. The results are used to set the heat removal requirements in the Duct region, given a reduced space available for cooling.

NB port optimization

The injection port size issue is to be addressed almost in any NBI design. Typically a tokamak has a reduced space available for tangential injection, so the injected beam footprint need to be minimized. The source beam internal divergence and the beamline transmission put the lower bounds on the port size, and even small deviations from nominal operation only increase it. BTR is used for the injected power sensitivity study, which helps to choose the port size. **Figure 8-b** illustrates the efforts for DEMO-FNS tokamak. It shows the injected power decrease from nominal value, when the port nominal size is reduced by 5cm. The effects of beam misfocusing and MF are shown.



(a) (b)

FIGURE 8. BTR power maps and profiles: a – at RID wall; b – at the Duct exit plane (injected beam footprints).

CONCLUSIONS

BTR was conceived in 1995, and released in 2005 (Born-To-Run). It provides a set of numerical tools for NBI accurate 3D studies. From the very beginning it is open and intended for public usage. BTR is fast and fully interactive, it looks and feels like a real NB flight simulator, and can be used for training purposes. BTR is parallel, traces up to 10^{10} beam particles within few hours on moderate Windows machines, with the best performance achieved on multi-core systems. BTR models are light, easily reproduced and analytically verified, the results resolution is flexibly adjusted to the tasks. BTR is still evolving code, and full support is available to its Users.

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