УДК 621.039.616

BTR CODE FOR NBI DESIGN AND STUDY

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BTR code (Beam Transmission with Re-ionization) has been applied to neutral beam injection (NBI) design and studies for many years. BTR was conceived in 1995, initially implemented in Turbo Pascal, and finally was released in 2005 («Born To Run»), using MS Visual C^{++}. From the very beginning the code is intended for public usage. BTR is speed-optimized, user-friendly and fully interactive. Thanks to extensive visualization capabilities it looks and feels like a real NB flight simulator, and even can be used for NBI training purposes. BTR supports parallel computing, thus the best performance is achieved on multiprocessor systems. But even on relatively aged and humble Windows PCs it still allows to trace up to 10^{10} particles in a matter of hours. BTR numerical methods are «light» and straightforward, easily reproducible and analytically verifiable. They can serve as benchmarks for other numerical tools simulating beam propagation. The simulation capacity, mesh resolution and the amount of output data can be flexibly fit for specific tasks during NBI project engineering. Today, BTR is still live and evolving code, and its users may reckon on free support and assistance from the code author. BTR traditional applications include the detailed analysis of beam propagation and beam power losses along the beamlines, magnetic field effect studies and setting magnetic field limits, beam interactions with gas and plasma targets, tracking of different beam species, generation of beam power footprints and density maps, data visualization, image processing, and many other. The paper describes several typical applications of BTR code through many years of user experience, and with a focus on the conventional, «Single-Run» code versions. Information on BTR major upgrades as well as the BTR Code User Manuals are available online.

Key words: BTR code, NBI, neutral beam, transmission, beamline, beam power losses, power loads, injected power, simulator.

DOI: 10.21517/0202-3822-2021-44-1-68-79

КОД BTR ДЛЯ ПРОЕКТИРОВАНИЯ И ИССЛЕДОВАНИЯ СИСТЕМ НЕЙТРАЛЬНОЙ ИНЖЕКЦИИ

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Код BTR (Beam Transmission with Re-ionization) много лет используется для проектирования и исследования систем нейтральной инжекции. Работа над кодом началась в 1995 г., первые версии созданы на Turbo Pascal, а первый официальный релиз состоялся в 2005 г. («Born To Run»), разработанный уже в MS Visual C^{++} for Windows. BTR изначально создавался для публичного использования. Его отличают высокая скорость расчётов, дружественный и интуитивно понятный интерфейс пользователя, благодаря обширным визуальным возможностям он похож на «авиасимулятор» реальной установки и может быть полезен для обучения новых специалистов в области нейтральной инжекции. Поскольку BTR поддерживает параллельные расчёты, наилучшая производительность наблюдается на многопроцессорных Windows ПК (менее часа для самых массивных прогонов), но даже на относительно старых и скромных ПК код позволяет выполнять серьёзные расчёты (до миллиардов частиц) всего за несколько часов. Методы расчёта, используемые BTR, относятся к классу так называемых «лёгких моделей», они быстрые, легко воспроизводятся и верифицируются аналитически. Их можно применять для проверки других моделей трассировки пучков. Ёмкость модели, объёмы выводимых данных и их разрешение легко настраиваются на конкретные задачи в процессе инженерной проработки конструкции инжекторов. Сегодня BTR — живой и развивающийся код, его пользователям всегда доступна бесплатная помощь и поддержка автора. Традиционные приложения BTR включают детальный анализ транспортировки пучков и потерь мощности на элементах пучковых линий, изучение влияния магнитных полей и постановку ограничений, моделирование взаимодействия пучков с газовыми и плазменными мишенями, отслеживание потоков частиц различного сорта, получение пучковых отпечатков и карт нагрузки, визуализацию и обработку изображений и многое другое. В данной работе описаны некоторые типичные применения BTR — с учётом многолетней практики его использования и с акцентом на версиях кода «Single-Run» (однократный запуск). Вся информация об обновлениях кода, а также Руководства пользователя доступны в интернете.

Ключевые слова: нейтральный пучок, транспортировка пучков, пучковая линия, потери пучков, тепловые нагрузки, инжектируемая мощность, NBI, BTR, симулятор СНИ.

INTRODUCTION

Neutral beam injection (NBI) is used for plasma heating, current drive, rotation, plasma operation control, and plasma diagnostics. While NBI purposes vary through target fusion designs, the engineering tasks performed during any NBI development process have much in common for different beamlines. R&D studies of any neutral beamline, especially those addressing long pulse high-power operation, typically include the accurate evaluation of beam transmission and power deposition on injector components, which are applied next to thermal analysis and cooling requirements. And even at the final stage of the NBI design, when the geometry is almost «frozen», the same tasks emerge and have to be done every time the geometry or element position is slightly modified or physical conditions are updated (e.g. after recalculating the magnetic field of a fusion device).

NBI principles [1] can be summarized as following. Positively or negatively charged hydrogen or deuterium ions are extracted from a beam source (BS) and accelerated to required energy in a multi-grid multi-aperture electrostatic accelerator, in which the last grid is kept at ground potential (the so-called grounded grid, GG). Basic beam energy is chosen with account of the capacity to penetrate a plasma target, and for large plasma devices (with R > 2 m) only negative-based neutral beams can be efficiently produced. The accelerated ion beam is next neutralized by charge exchange process in a neutralization cell. A neutralizer employed in charge neutralization experiments with gas targets typically has several channels, designed to minimize gas flows required. Positive ions neutralization efficiency falls with energy and becomes low at E > 140 keV, while the negative beams neutralization efficiency on gas is almost stable and close to ~60%. Beam fractions that remain charged (not converted to neutrals) are removed from the beam by a residual ion dump (RID) either electrostatically or magnetically, depending on the energy spectra of ion fractions.

Factors such as the source current limited density, neutralization and beam transmission losses, prevent total power injected to plasma from being better than ~40—45% of the source power, and this value highly depends on the source beam divergence and deflections caused by various effects. In fact, the total beamline efficiency (i.e. the ratio of injected power to source power) is roughly defined by the beam neutralization efficiency and beam transmission. The actual beam divergence in many cases is unknown, so the ITER DDD [2] adopts three possible values of core divergence: 3, 5, and 7 mrad accompanied by a beam «halo» (~30 mrad), which contains 15% of beam current. The resulting transmission evaluated for this range of divergence varies from 70 to 90%, leading to the total beamline efficiency range of 35—50%.

Since a beamline design should be carefully fit into the tight space constraints of the tokamak configuration, the NBI geometry permanent optimization with account of cooling demands results in increasingly complex beamline specifications. The optimization procedure is needed to minimize the beam losses and reduce the local heat loads at each component to at least a removable level. The problem is generally solved through a multi-parametric study of power losses and thermal loads, typically with the help of specialized numerical tools.

One of these tools is BTR [3, 4]. The BTR code is initially intended to simulate Beam Transport with Reionization. It allows the user to perform massive design studies of any NBI geometry, with source beam structures based on «beamlets» (elementary cone shaped beams). The code delivers the heat load images and the beam power footprints for any plane or surface defined by the user, and evaluates total beam losses due to direct interception and beam-gas interaction. It can also be applied to match the «beamlets» directions to beamline geometry, fine-tune the components geometry, although these are not conventional BTR applications. The code is more relevant for beam neutralization and transmission in electro-magnetic fields, ion fractions deflection in electrostatic or magnetic ion dumps, and neutral beam losses. Also, with the recently added in-plasma beam stopping capability, BTR can now be used for the preliminary optimization of beam penetration and capture in plasma. All numerical models generated with BTR are simple and easily verified analytically («Light models»); the code itself can be used for verification of more sophisticated NBI models, such as the Monte-Carlo simulation [5].

BTR source code was transferred to MS Visual C^{++} and released for public usage 2005; the code versions numeration starts from this date, although there are few earlier versions in Turbo Pascal and TPW. Designed to be user-friendly, the code comes with a powerful interactive Windows graphical user interface (GUI). In fact, BTR is used not only for NB design studies, but also for training purposes, as an NBI simulation stand. Because BTR supports parallel execution, it performs best when used on multi-core Windows PCs. The standard input configuration («BTR Config» data list) which includes parameters of NBI geometry, physical environment, and beam tracing settings, is flexible and intuitive, and can be easily adjusted for any specific beamline design. Information on the code upgrades (2005—2020) can be found on BTR webpage [3]. In 2020, a new, BTR-5 («Multi-Run»), version was released, which allows users to easily perform multi-parametric NBI studies using a flexible scenario input procedure.

This paper introduces the BTR code numerical methods and interface tools, a focus is made on the code conventional applications and user experience before 2020, i.e. through versions 1—4 («Single-Run»).

Important note: all the images with BTR output just illustrate the code GUI capabilities; the plots are obtained for different designs and operation cases. In particular, the plots in the section «BTR Model» show the sample charts which are built-in in BTR GUI and serve for data control during the code execution. The paper is structured so that the NBI geometry and the beam are described in the 1st section, the numerical models are introduced in the 2nd section, the overview of BTR GUI tools is given in the 3rd section, and finally some examples of the code applications are shown in the end.

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 are very similar, with variations associated with NB production scheme. In Fig. 1 the HNB vacuum vessel includes the beam source vessel (BSV), and the beam line vessel (BLV).

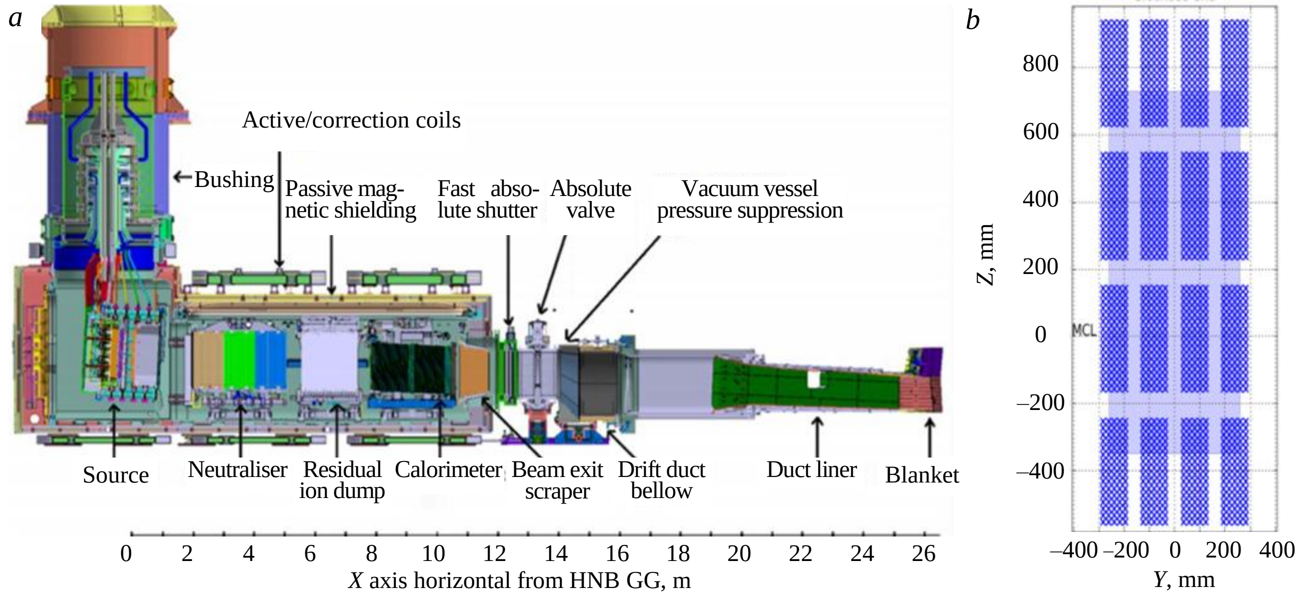


Fig. 1. Sectional view of ITER HNB beam line (*a*), taken from [6], BS GG layout (*b*)

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 gas neutralizer (N), an electrostatic residual ion dump, and a neutral beam dump — 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. The channel structure of NBI components (neutralizer and RID) is optimal for gas supply and pumping.

Based on this typical layout, the BTR Standard geometry, or the default input configuration, includes the following NBI standard components: the beam source grounded grid (GG) position, a multi-channel (or single-channel) neutralizer, a residual ion dump (multi- or single channel), calorimeter, and the beam transmission duct, consisting of multiple modules, including scrapers, FEC, liners, blanket sections, etc. Apart from the 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 elements. «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 GG plane. Each beamlet represents an elementary beam current cone from a single GG aperture (or slot). If the NBI scheme is based on positive ion source (PIS), the source beam has different divergence in horizontal and vertical planes, due to horizontally elongated multi-slot structure of acceleration grids. Typical horizontal and vertical divergence values for PIS are 7—10 and 15—20 mrad respectively. The beamlet internal structure is more complicated and less defined [7] for the injectors based on negative ion source (NIS). It is found experimentally, the accelerated D^- «beamlets» to have a «halo», i.e. a certain beam fraction (at least ≈15% of current) with a divergence much higher than the beamlet «core» part, estimated to be about 30 mrad. This fraction is supposed to be released at the plasma grid surface (due to cesium migration downstream the ion source). Such particles are then accelerated and transmitted with high divergence through the accelerator, but many of them are intercepted on the downstream grids. The actual characteristics of the beam from the negative ion source are not known, therefore for design purposes they have to be assumed, with the assumptions based on experimental data from existing high energy negative ion beam systems. Therefore, the general requirements for ITER beamlines design include a maximum beam duration 1 h, beamlet divergence of 3, 5 or 7 mrad with 15% of the power in each beamlet carried by a halo fraction with a divergence of 30 mrad.

The beamlets start positions are arranged in clusters (or BS segments, or groups) according to GG structure shown in Fig. 1, *b*. Standard beamlet optics is a combination of beam source groups' steering at the injected port center, and individual beamlet axes focusing within each group in horizontal plane — for the sake of optimal transmission through vertically elongated NBI channels. Finally, the entire beam envelope can be inclined or tilted (as in ITER HNB, [7]) — to hit the specific tangential point in plasma and to switch between on-axis and off-axis injection. Finally, for ITER design purposes it is assumed that the beam may be horizontally and vertically misaligned by ±2 mrad and ±4 mrad respectively, and additionally tilted by ±10 mrad from the nominal downward inclination of 49.2 mrad.

The NBI geometry and the source beam, as they appear on BTR screen, are shown in Fig. 2.

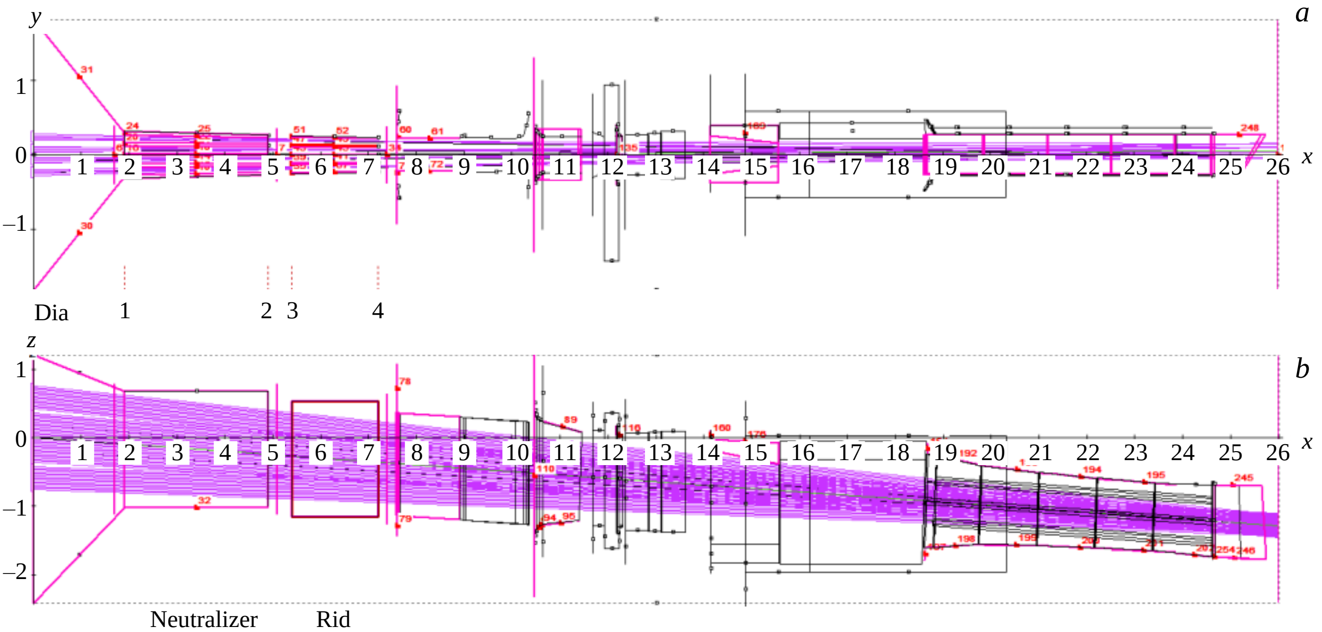


Fig. 2. BTR screen with ITER HNB geometry: horizontal (*a*) and vertical plane views (*b*). Standard NBI geometry is combined with «Free Surfaces» import. Standard beam model is defined by regular array. The beamlets' axes are shown in violet.

Hereafter, most examples presented refer to the NBI design for a fusion neutron source DEMO-FNS [8]. The NBI layout is similar to ITER HNB and based on negative source ions, but with power reduced to 7.5 MW per injector.

BTR MODEL

Beamlet current. Each source beamlet current profile is a sum of the «core» (~85%) and «halo» (~15%) fractions with Gaussian profiles, which can be generally expressed as

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

Here θ is a polar angle, measured from the beamlet axis direction, H is «halo» fraction of the beam current, Δ_c and Δ_h — the gaussian divergence of «core» and «halo» beam fractions. The fractions shares and their divergence are generally taken (or extrapolated) from experiments and can be specified directly like any other BTR input parameter.

In case of beamlet divergence asymmetry (for the PIS scheme, discussed above), the 1st term in expression (1) is modified to a product of horizontal and vertical gauss profiles, and the *halo* part is set equal to zero (for PIS).

The beamlet current is represented by a finite number of particles (Fig. 3, *a*, *b*), generated by splitting the total current cone to a regular number of discrete rays in polar and azimuthal directions, so that each beamlet is represented by 10^2—10^5 rays, with each ray carrying a specific part of source aperture current. The splitting numbers are set by direct input too. With a typical beam of more than 1000 beamlets, the total amount of particles in the model can reach 10^9 or even more (no hard limit).

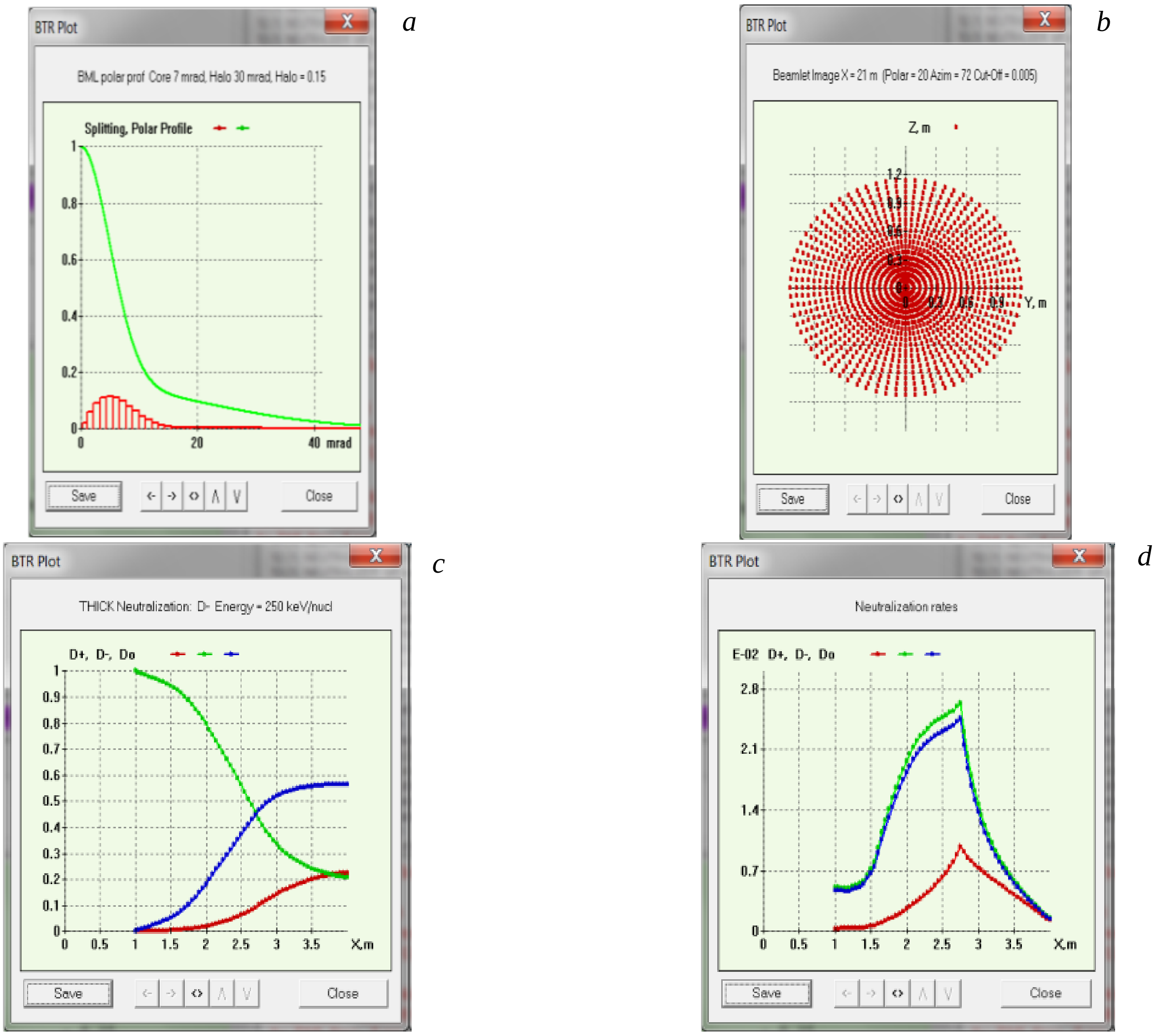


Fig. 3. BTR models: beamlet current density profile (——), and polar group currents (——) (*a*); single beamlet particles imprint at a normal cross-plane (*b*); the beam species current in «thick» neutralization (—— — negative, —— — positive, —— — atoms) (*c*); neutralization rates (similar colors) (*d*)

All the test particles are traced in a straightforward manner. Atoms are ray-tracked (the truly «light» NB model), while charged species are traced with the regular local steps, that may differ across the tracked regions. The conversions of primary beam particles through the interactions with gas or plasma are applied with cross-section model («σ-approach»).

Neutralization. The source ions, which are either 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). A positive ion neutralization process is defined by the ratio σ_{10}/σ_{01}. There are two options (models) available in BTR for beam neutralization — «thick» and «thin». «Thin» model is less accurate: the total gas volume is «pushed» to a thin layer at the neutralizer exit, causing an overestimated beam deflection at the device output. However, it is by many orders of magnitude faster and finds much wider use, than «thick» model, which takes the real gas target distribution and produces a reduced beam deflection, and in fact to a wider test-particles divergence. The «thick» model (Fig. 3, *c*, *d*) solves balance equations for beam species:

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

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

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

Here Γ^k is the kth species flux, n is background gas density.

The model of the neutral beam re-ionization along duct regions works quite similar to «thick» neutralization: it applies actual gas target distribution downstream the neutralizer. It runs relatively fast, as due to atom ionization only one secondary particle (positive ion) is produced and traced.

Beam stopping in plasma. The neutral beam ionization in plasma, in fact, uses the same re-ionization routine — with gas target replaced by plasma. The rate of decay of injected test atoms is equal to fast ions birth rate. The main expression used for the neutral current decay calculation and fast ions instant deposition along the ray (see Fig. 4, *a*, *b*) is

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

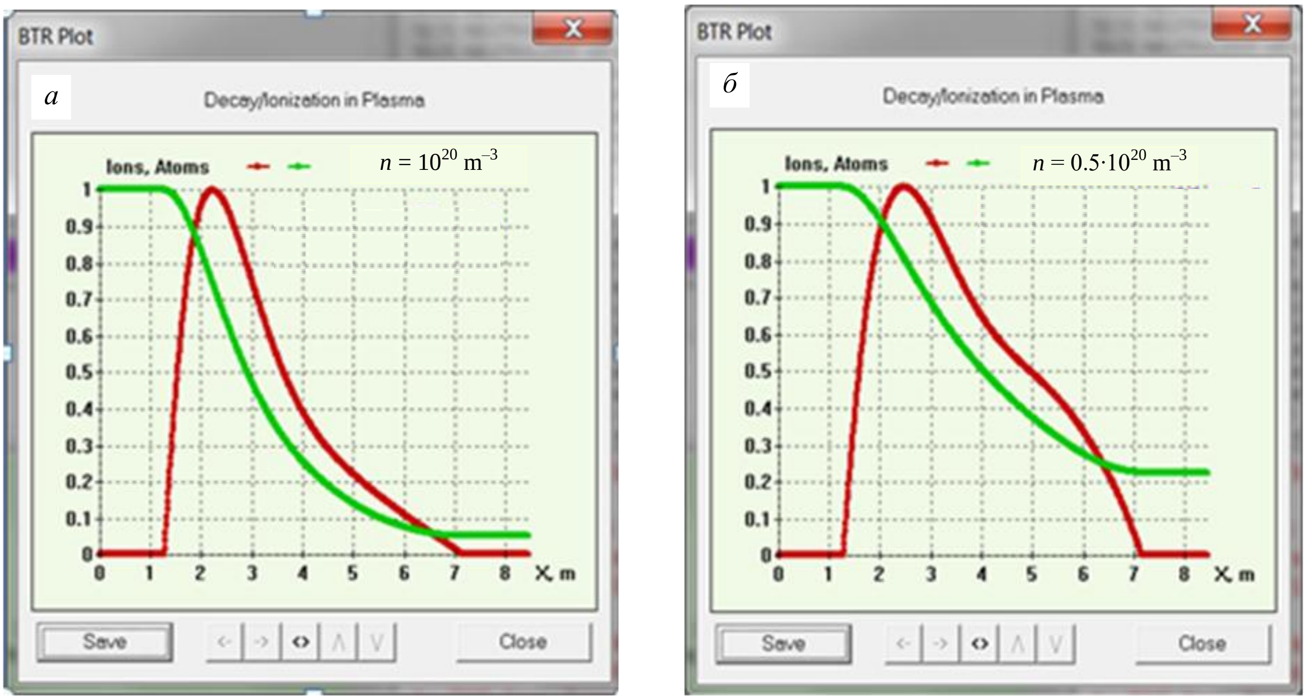


Fig. 4. BTR beam stopping in plasma: *a*, *b* — the beam species currents along beam axis (—— — atoms, —— — fast D^+) — for two values of plasma density

Here $P(x)$ is the fast ions birth rate, I is the neutral beam current, $\sigma = \sigma_s$ is the effective ionization cross-section (CS); $n = n_e$ is the local plasma density. In this approach («σ-approach») the mean free path (λ) for atom can be introduced as $\langle\lambda\rangle = (n\sigma)^{-1}$. The neutral current decay allows the calculation of the shine-through power (lost fraction) from all the rays.

Plasma magnetic configuration can be taken from the EQDSK database files or defined analytically using the «Green Panel» (see the BTR User Interface section below) with the magnetic surfaces assumed to be elliptic by default. The kinetic profiles can be read from input files or defined directly in the form $V_{max}(1 - \rho^\gamma)$, where V_{max} is the value at magnetic axis, ρ is the normalized minor radius, and **γ** is the power degree (γ = 2 corresponds to parabola). Both approaches are available in BTR, and the resultant sensitivity can be easily checked. However, for large-sized facilities, such as ITER the effect of detailed magnetic shape is hardly noticed for on-axis NB targeting or within one-third of the minor radius, or in the case of a relatively large beam cross-section («thick» beam). Indeed, the effect of realistic plasma geometry including the plasma triangularity and Shafranov's shift

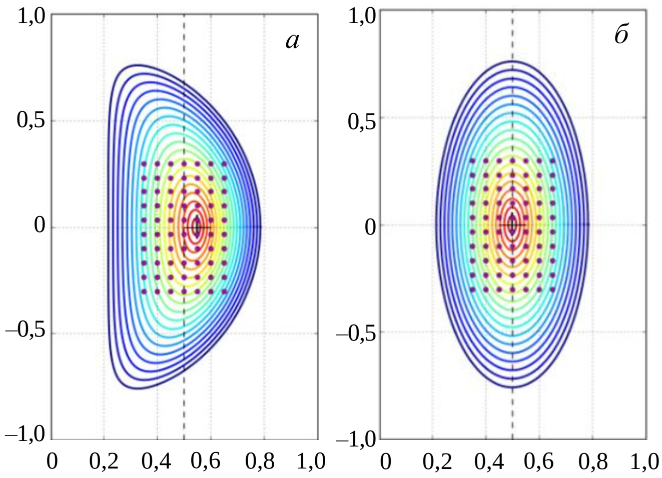


Fig. 5. Two models of plasma magnetic configuration available in BTR: *a* — realistic geometry (with triangularity and Shafranov's shift), *b* — elliptic (simplified analytical model). The beam is shown by violet points

has shown to be essential for compact tokamaks and «thick» beams, and for these cases the simplified approach is not accurate enough. Some illustration of this is given in Fig. 5, *a*, *b* — for a spherical tokamak cross-section.

Power maps. Power loads on any injector element (or surface) result from the direct interception of the primary beam and from secondary fluxes. Power density map calculation involves the generation of a rectangular mesh to cover all surfaces, including beamline solid components and virtual transparent planes. Cell sizes defining mesh resolution are set individually or globally. The meshing approach varies through BTR versions, but in any case mesh resolution can be adjusted — either after the completion of beam tracing in BTR-1-4 (the Single-Run versions) or prior to launching a beam in BTR-5 (the new «Multi-Run» version). With the number of simulation particles to be run limited primarily by the user's time constraints (sometimes by RAM), the availability of comprehensive beam geometry and statistics allows to achieve high mesh quality and map resolution (with cells ~1 mm). The number of surfaces used in power map calculations is typically several hundred.

Conclusions. BTR models are fast and easy to verify. Basic BTR beam applies the most accurate beamlet based specification (3 coordinates + 3 velocity components + particle type). The beam tracing routine is fully deterministic, the particles tracks and conversions are simulated in realistic fields and gas environments. The model capacity (statistics) and the power maps resolution can be adjusted to a specific task. Resultant maps are subsequently applied to thermal cooling analysis of the NB-line components. BTR beam re-ionization model is extended to tokamak plasma, a detailed analysis of beam stopping and ions generation in plasma is performed, which delivers NB power and ionization footprints in the volume and shine-through maps at the 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 min — while executed on a humble (and old) 2-core Windows station. Comparing with analytical models, which run in a few seconds, BTR is slow. However, the analytical NB models do not apply electromagnetic effects, and do not trace any particles (primary or secondary). Therefore, BTR can be verified with these models (cross-verified) for ideal cases.

The results of secondary particles tracing and power loads were successfully cross-checked with SAMANTHA code [5]. SAMANTHA is intended to study additional phenomena in the beamlines, including secondary particles generation and dynamics in realistic electromagnetic fields. Although BTR ad SAMANTHA use different numerical methods (those employed by BTR are generally faster and less accurate), power load profiles obtained with the two codes were very similar (the difference was within 1%).

BTR USER INTERFACE

The main screen of BTR is shown in Fig. 6, *a*. BTR window is divided into four major sections. The sections names are:

— «Input Configuration» view with NBI geometry and beam layout;

— «Green panel» tool (BTR input data container);

— «Loads Summary» or «Map image» view;

— «Running Status» or «Profiles» view.

The interface element «Green panel» forms the basic interface engine of the code, its input processor, used for interactive data control and revision. When the user directly modifies any data field in the Green panel, the input data list («Config») is updated, and all the views are refreshed accordingly. The data can be stored in the output text file, which can be loaded later as input «Config» to BTR process.

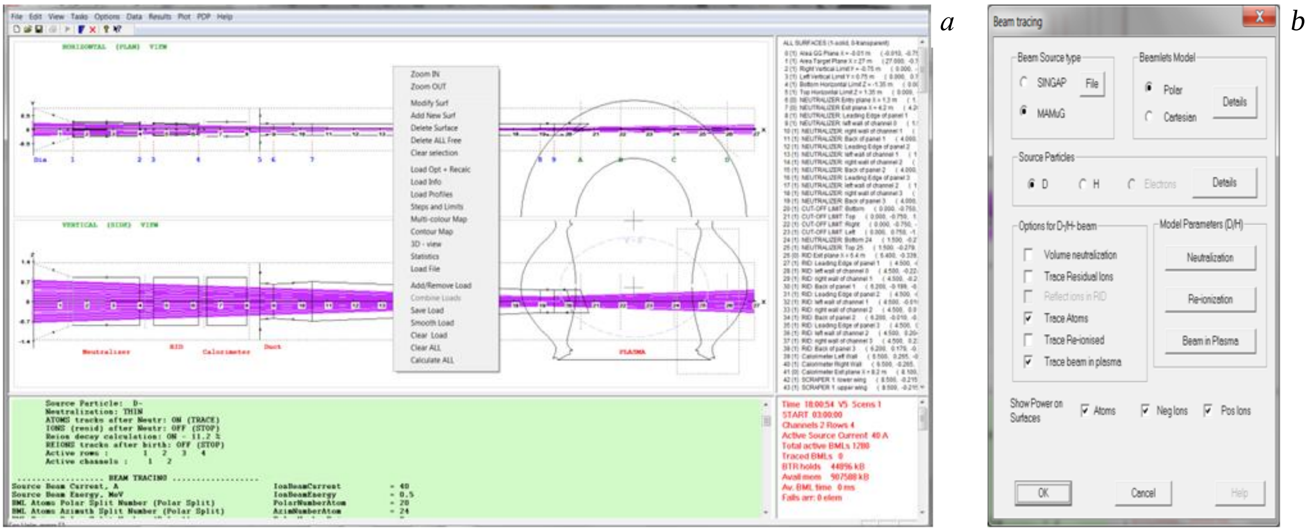


Fig. 6. BTR screen with the Windows: NBI geometry with beam (standard BTR config-file), the «Green panel» (bottom-left), «Loads Summary» (top-right), «Running Status» (bottom-righ) (*a*); «Beam Tracing» input dialog (*b*)

BTR main screen is supplied with the interface tool «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» interface tool (see Fig. 6, *a*), invoked by right mouse click. It is used for results zooming, scrolling and post-processing.

Among the many BTR input dialog-box tools selectable from the «Main menu» is the «Beam Tracing» dialog (see Fig. 6, *b*) that can be used optionally to set the parameters and options, such as the source particle species, beamlet split tracking options and steps, specific conditions, etc., for the beam tracing model.

Finally, the resultant power maps and profiles are represented by colored images (shown in the sections below); they become available as soon as the beam tracing is stopped or paused: they appear for the surfaces selected by the User in the main view by left mouse click. The beam footprints and profiles are shown in the same way — by simply clicking the virtual cross-planes («transparent» surfaces). All the maps and profiles are interactive too: when the user drags mouse over a map, local power densities are displayed; clicking on a desired point shows the local point (or cell) value.

BTR APPLICATIONS

BTR can be helpful at different stages of NBI design:

— to choose NBI scheme and to perform the beamline geometry optimization;

— when a specific NB design is ready and more or less «frozen», the code is applied for thermal loads calculations, sensitivity analysis, and to define the operational constraints of parameters, i.e. NBI «nominal values».

BTR main applications include: a «realistic» beam transmission, beam direct losses and power, beam formation in the neutralizer, magnetic field effects and tolerance, residual ions deflection and power in RID, reionized beam losses and power, beam stopping and ionization in plasma, shine-through losses and power, etc.

NBI performance. The plots in Fig. 7 illustrate three examples of NBI performance studies and optimiza-

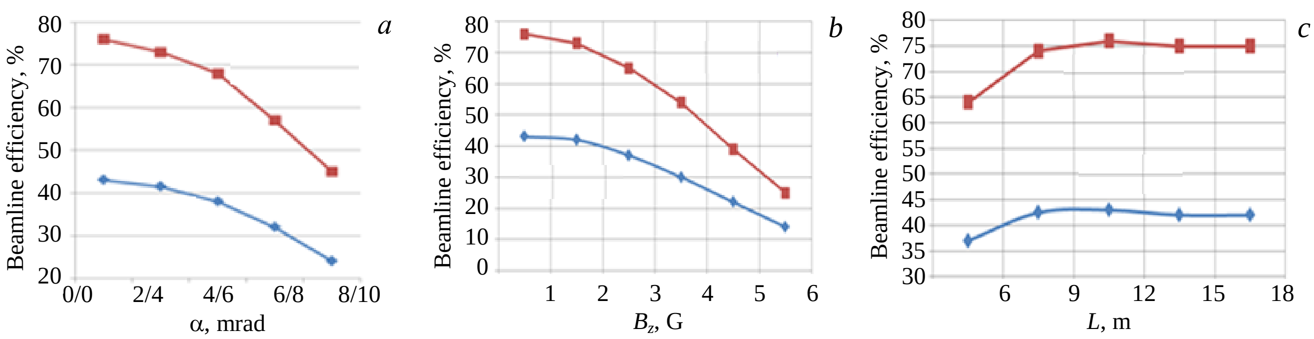


Fig. 7. Examples of NBI efficiency: NB misfocus effect (*a*), B_z effect at ideal focus (*b*), beamlet focusing distance (within a group) (*c*): geometry transmission (P_{inj}/P_{Neutr}) (——), total efficiency (P_{inj}/P_0) (——)

tion (for DEMO-FNS). Their general purpose is to set the range of nominal parameters for NBI operation, as well as the main design requirements, which include maximum beam misalignment, magnetic shielding level, 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 2 mrad, while vertical focusing is not as stringent and can be ~4—5 mrad. Vertical component of magnetic field should be limited to ~1 G, as it increases the deflection and scattering of the source beam. Finally, for the best beamline transmission, the beamlets within each group should be focused at 12 m from GG along the group axis, and this is done by tuning the grids geometry in the ion source accelerator.

To define the heat removal requirements, BTR delivers power maps and profiles on each surface, as shown in Fig. 8. They give all information needed for thermal load analysis — the total power deposition at each component, the peak power density and the expected power peak position — within the selected limits. The examples refer to a neutralizer wall (see Fig. 8, *a*), the duct walls (see Fig. 8, *b*), with the simplified duct model represented by a 4-sides box, and the scraper front edge (see Fig. 8, *c*), used to cut the beam tails at the duct entrance.

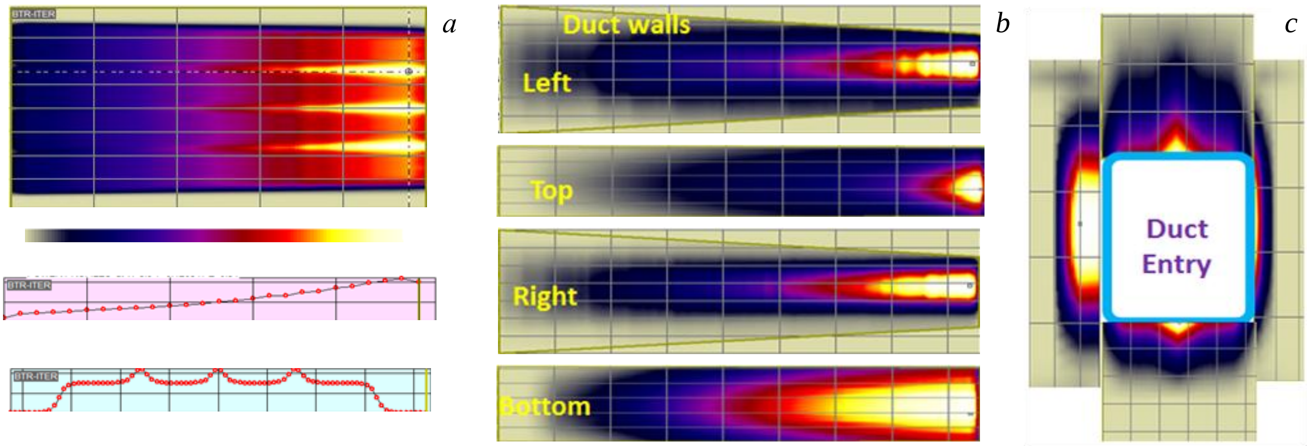


Fig. 8. BTR power maps and profiles used for thermal analysis: *a* — neutralizer wall; *b* — duct walls; *c* — scraper front

RID and re-ionized power loads. The residual ions fraction, i.e. the unwanted charged part of the beam after neutralization, is next removed and dumped in RID either magnetically or electrostatically. 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 of parameters — with scanned neutralization yield, beam tilting/focusing, divergence, and magnetic field. When the deflecting field (e.g. electrostatic potential) is optimized, the expected power maps/profiles can be calculated, the example power map for DEMO-FNS injector is shown in Fig. 9.

Re-ionized particles form a lost fraction, which appears due to the beam interactions with background gas in the duct regions. The analysis is similar to residuals study in RID. The main specifics of the duct region are: the stray magnetic field is not shielded, and is many orders higher than in the RID area; the gas flow from tokamak cannot be efficiently pumped, therefore the ionization rates can grow and potentially produce high fluxes of ions. The main concern is to define the expected peak power densities at the duct surfaces caused by the re-ionized fluxes. The results are used to set the heat removal requirements in the duct region, given a reduced space available for cooling.

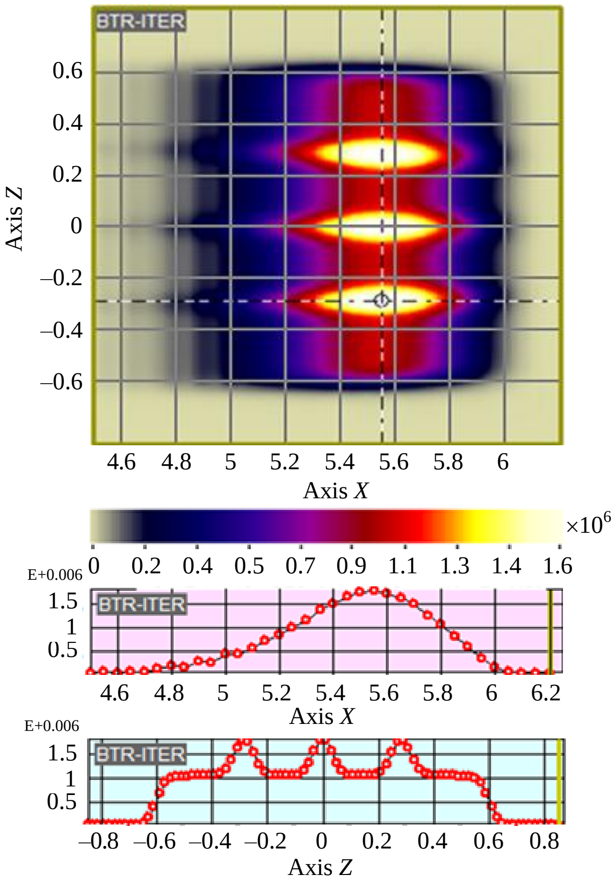


Fig. 9. BTR power map and profiles at RID panel (one of the channels' side wall). Ideal focusing, no magnetic field

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 that the injected beam envelope need to be minimized at the camera entrance. The source beam internal divergence and the beamline transmission define the lower bounds on the port dimensions, and even small deviations from nominal operation values can only increase it. While optimizing the port bounds, BTR is used for the injected power sensitivity analysis. Fig. 10 illustrates the efforts on this direction for DEMO-FNS tokamak. In particular, the injected power decrease from nominal value is shown, when the port nominal size is reduced by some 5 cm. The effects of beam misfocusing and magnetic field manifest themselves as reduced injected power (P_{inj}). The P_{inj} decrease is shown under the images.

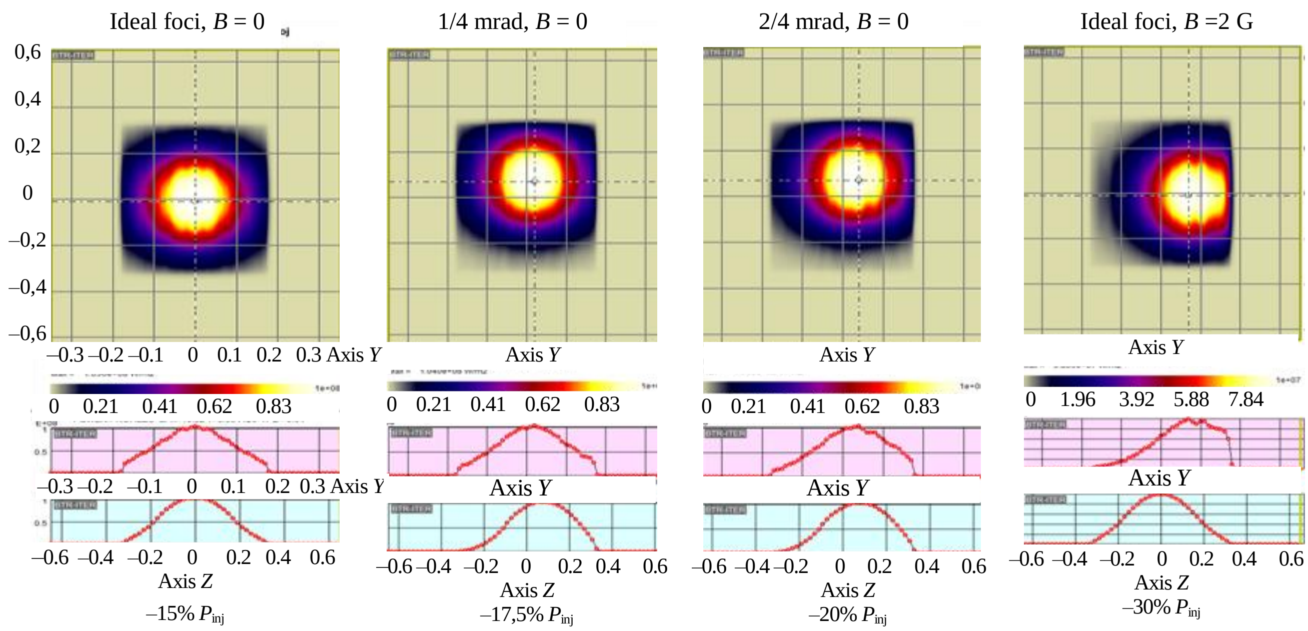


Fig. 10. BTR injected beam footprints and profiles at the duct exit plane: beam focusing and MF effects

NB capture and shine-through analysis. In addition to NBI study and optimization, BTR can be valuable in doing a plasma operation analysis. For example, BTR detailed beam model can be applied for beam stopping and beam ionization in tokamak plasma. For DEMO-FNS parameters the realistic magnetic configuration (taken from EQDSK file) affects the beam capture — as the beam thickness is comparable with the plasma cross-section, and the beam is injected far off-axis (see Fig. 11). The kinetic profiles were taken as $V_{max}(1 - \rho^{\gamma})$, where V_{max} is the value at magnetic axis, ρ is the normalized flux (radial coordinate associated with the magnetic surfaces), and γ is the power degree ($\gamma = 2$ for T_e, $\gamma = 3$ for n_e).

The detailed beam statistics (up to 10^{12} test particles) is able to deliver the most accurate fast ion source distributions in plasma volume with the ions angular dispersions, which could be beneficial for plasma scenarios 3D studies. The examples of beam ionization distributions (or imprints) in DEMO-FNS

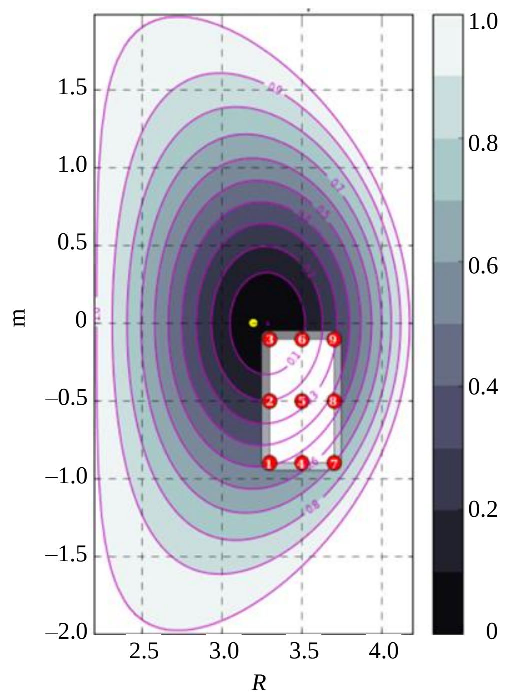
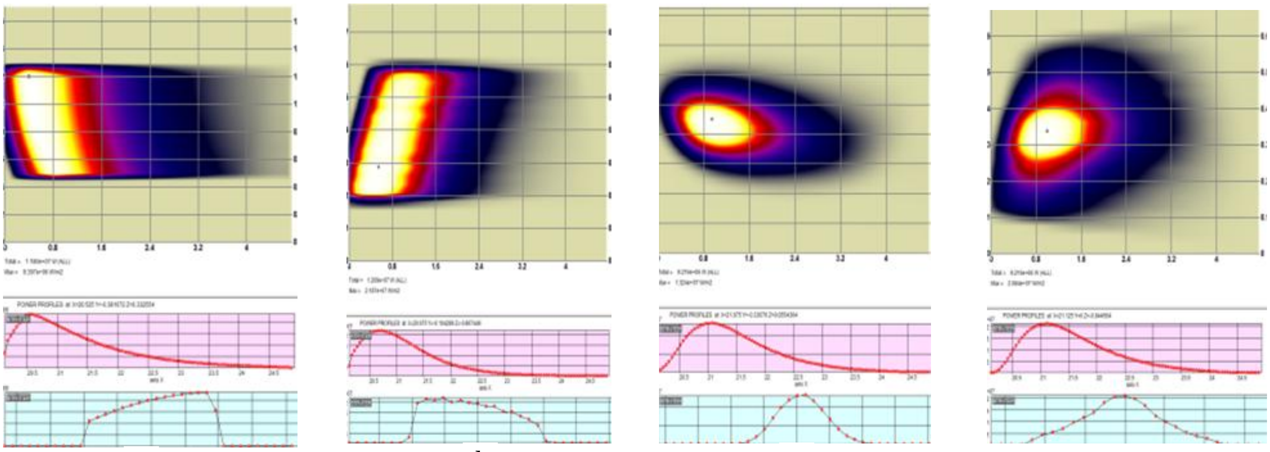


Fig. 11. Magnetic 2D-configuration of DEMO-FNS plasma (EQDSK standard file), used by BTR for beam ionization in plasma and shine-through calculations. The beam window is represented by red points

plasma are shown in Fig. 12. The imprints shown are calculated in the vertical and horizontal planes along the neutral beam axis direction with account of the beam statistics reduced to ~10^6 test-atoms. The decay of each test atom and the produced ions instant profile is calculated with expression (5). The comparative analysis of the beam imprints has proved the shape effect to be essential for the beam deposition and resulting beam-driven quantities. The effect is clearly observed in Fig. 12, where two characteristic beam geometries are compared: a «rectangular» beam (a bunch of parallel rays) and a «Gaussian» beam of 1280 beamlets with realistic focusing and internal 7 mrad divergence, with 15% of wider halo fraction (30 mrad).



a *b* *c* *d*

Fig. 12. Beam ionization distribution in DEMO-FNS plasma, calculated by BTR, for two beam options: *a*, *b* — rectangular (parallel) beam, *c*, *d* — realistic (focused + gaussian with 7 mrad and halo); *a*, *c* — vertical imprints, *b*, *d* — horizontal imprints along the beam axis. Beam statistics is ~10^6 test-atoms

Finally, BTR is used to calculate the beam shine-through losses and to obtain the detailed power images at the first wall, see Fig. 13. These results are important for primary optimization of the injected beam parameters and targeting geometry, as well as for plasma density range required for the effective beam capture and tokamak safe operation.

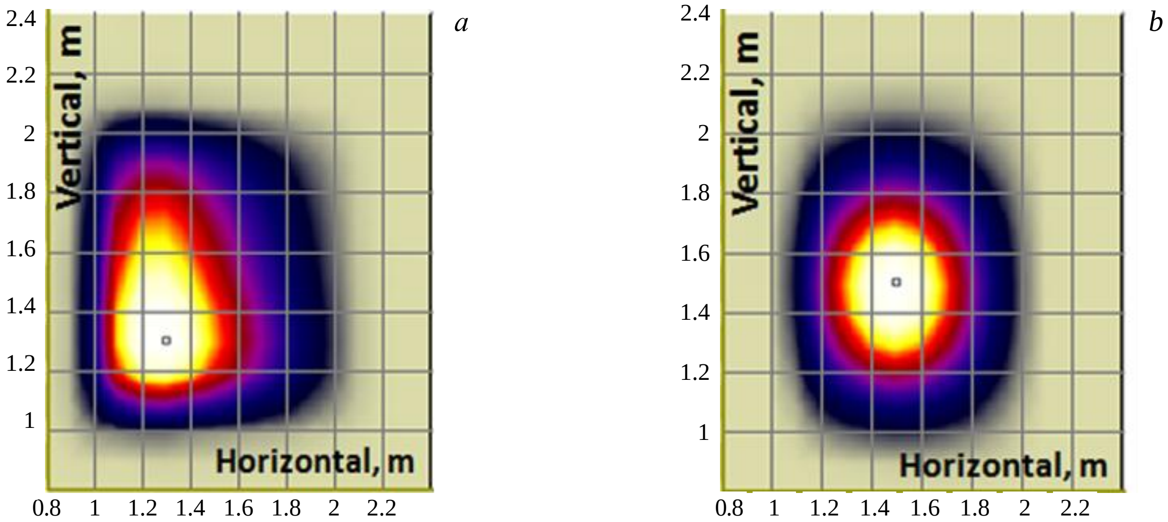


Fig. 13. BTR beam shine-through power map at the first wall: *a* — rectangular beam; *b* — gauss beam

CONCLUSIONS

BTR has a long development and refinement history. It was conceived in 1995, and officially released in 2005 (i.e. truly «Born To Run») — after moving from Turbo Pascal to MS Visual C^{++}. It has got five versions so far, with the last BTR-5 released in 2020. BTR is intended to provide a set of numerical and graphical tools for NBI accurate studies. From the very beginning the code was created for public usage. As compared to other well-established direct tracing models, BTR is fairly fast. BTR has a Windows-like user-friendly interface, allowing it to be used for training purposes as an NBI simulation stand. The parallel execution capability enables BTR to trace up to 10^{10} beam particles in a matter of hours on a relatively aged Windows machine, while the best performance is evident on multiprocessor PCs (with 4—8 cores). BTR numerical models are light and tunable, easily reproducible and analytically verifiable, the entire model capacity and output plots resolution can be easily fit for specific tasks. BTR is still evolving code, and full support is available to its Users. The information on BTR upgrades and code Manual can be found online.

ACKNOWLEDGMENTS

BTR was developed with ITER partial support and eventually became useful only thanks to BTR Users' enormous patience and a strong will to make it better. In fact, waiting for the new code versions to come, the code testing and debugging always required a great deal of time and efforts. Thuswise, the Users are true Co-authors of BTR code.

My special thanks are going to all BTR testers and Users —
for their painstaking, devoted work, creativity and persevering optimism:
Ronald Hemsworth, Hubert de Esch, Alexander Panasenkov,
Byung-Hoon Oh, Mahendrajit Singh, Damian King, Pierluigi Veltri,
and to all unknown BTR players!

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Received 12 December 2020
Revised 10 January 2021
Accepted 14 January 2021
Problems of Atomic Science and Technology
Ser. Thermonuclear Fusion, 2021, vol. 44, issue 1, pp. 68—79