Sergey S. Ananyev, E.D. Dlougach, A.A. Panasenkov, B.V. Kuteev
NRC Kurchatov Institute; Ac. Kurchatov sq., 1/1, Moscow RU-123182, Russia
E-mail contact of the corresponding author: Ananyev_SS@nrcki.ru

KURCHATOV INSTITUTE
NATIONAL RESEARCH CENTRE

Modelling and optimization of neutral beam injectors for fusion neutron source "DEMO-FNS"

Abstract

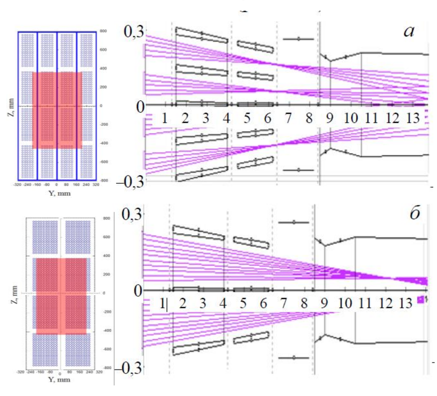
Neutral beam injection (NBI) system of the thermonuclear neutron source DEMO-FNS is suggested for plasma heating and current drive by means of high energy atoms injection. Six neutral beam injectors will provide DEMO-FNS machine with 30MW of a steady-state additional heating power, with neutral particles energy 500 keV. NBI systems developed for ITER are assumed as a prototype for DEMO-FNS NBI, as both injectors employ the similar ion source current, with the total beam power in ITER NBI (1MeV) being twice as large as in DEMO-FNS. The injector scheme incorporates a negative ions source coupled with accelerator delivering D⁻ beam accelerated to 500keV with the current 40A. The subsequent neutralization and ions removal from the beam, as well as its further path to plasma lead to a significant distance between beam source and injection point (~20 m).

An effective beam transmission to such a long distance with minimum losses is a real challenge, requiring a detailed 3D-modelling of the beam and a beamline structure optimization. The simulation includes minimization of beam losses due to direct interception and reasonable reduction of beam particles loss due to reionization. The optimization problem has proved to include a large amount of parameters, constraints, and it is rather sensitive to small deviations of input data, therefore the models should be fine-tuned and allow for high accuracy estimations.
The code-based optimization target is to obtain the NBI geometry and operational conditions which would allow for minimum beam losses along the beam path as well as the thermal loads reduction on the injector components with account of cooling circuits arrangement.

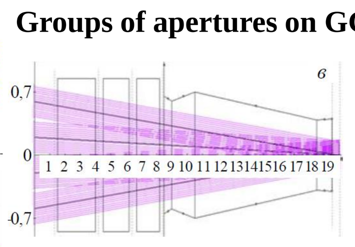
The general approach of NBI optimization and the specific methods of the solution related to DEMO-FNS injector are represented here. The main factors affecting the beam transportation efficiency, including beam steering inaccuracies and background magnetic fields, are considered, the relevant operational restrictions are stated. The simulation models are described with their implementations in computer codes. For geometry optimization and its «fine tune» we use PDP-code. For more detailed analysis, involving beam particles tracing with mutual transforms, as well as for thermal load calculations including all beam species, we use BTR-code. The results of the optimization technique include the most effective «self-consistent» geometry of the injector and the source beam, the operational intervals, the beam total losses during the neutralization and transportation, the beam power profile evolution and the thermal loads distributions — for all injector components, and under different scenarios of operation. These results are proposed for engineering design of target NBI system.

Introduction

Main **purpose**: to choose the injector configuration and operational parameters based on computer simulations;
Needed: **3D simulation** with dozens input parameters involved;
Main **factors** affecting beam transmission: steering inaccuracies and background magnetic fields;
Code-based optimization aimed at: minimum beam **losses**, thermal **loads reduction** on NBI components;
PDP-code: geometry optimization and fine-tuning;
BTR-code: detailed beam particles tracing, particles transformations, thermal load calculations for all beam species;
Results of optimization: self-consistent geometry of the injector and the source beam, the operational intervals (restrictions), the beam total losses during the neutralization and the transportation, the beam power profile evolution and the thermal loads distributions along all injector components, for different scenarios;



Groups of apertures on GG:



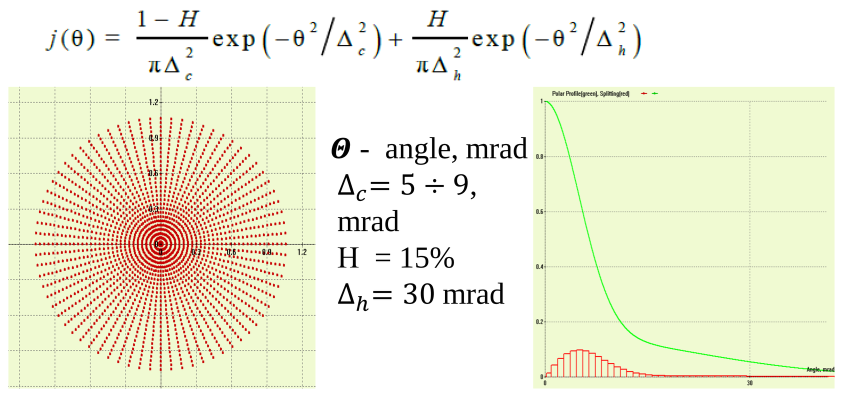
- 1280 beamlets
- 4 or 2 channels

Geometry should meet the following requirements:
-Total injected power 30 MW, 6 injectors (4 in operation)
-Beam energy 500kV
-Total length ~20m
-Injection port dimensions 0.4x0.8 m
-Minimum duct length 11m
-Gas target thickness - close to optimum, to ensure ~60% D- beam neutralization

MODELS and APPLICATIONS

Beamlet angular distribution

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



$\boldsymbol{\theta}$ - angle, mrad
$\Delta_c = 5 \div 9$, mrad
H = 15%
$\Delta_h = 30$ mrad

One beamlet beam and current distribution between the polar groups of particles

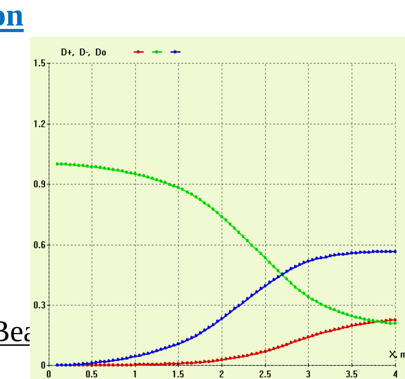
Neutralization

Cross-sections
$\boldsymbol{\sigma_{-10}}$ – electron stripping
$\boldsymbol{\sigma_{-11}}$ – double stripping
$\boldsymbol{\sigma_{01}}$ – ionization
$\boldsymbol{\sigma_{10}}$ - **recombination**

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

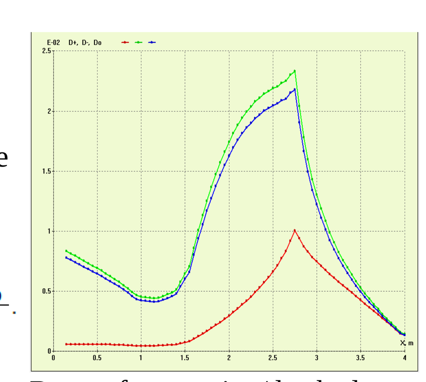
$$\frac{d\Gamma^0}{dx} = \Gamma^-\sigma_{-10}n + \Gamma^+\sigma_{10}n - \Gamma^0\sigma_{01}n;$$

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



Optimum target thickness is depend on the ratio of the rates of the main reactions - neutralization and reionization

$$NL_{opt} = \int_0^{\text{вых. нейтр.}} n_{D_2}(x)\,dx = \frac{1}{\sigma_{-10}-\sigma_{01}}\ln\frac{\sigma_{-10}}{\sigma_{01}}.$$



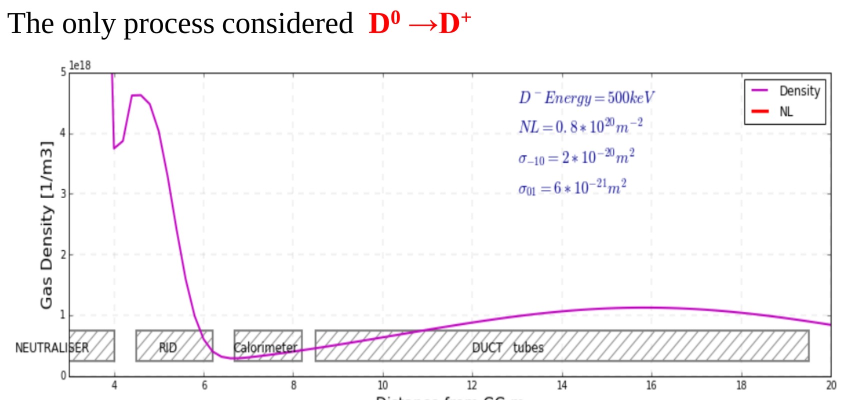
Result beam composition:
D⁰ ~60%, D⁻/D⁺ ~20%

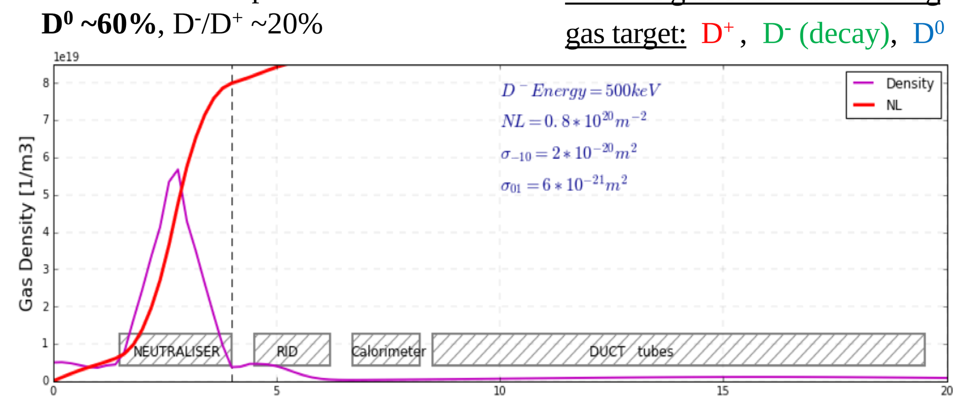
Rates of generation/death along gas target: D⁺, D⁻ (decay), D⁰

Re-ionization

Model is similar to neutralization.

The only process considered **D⁰ →D⁺**

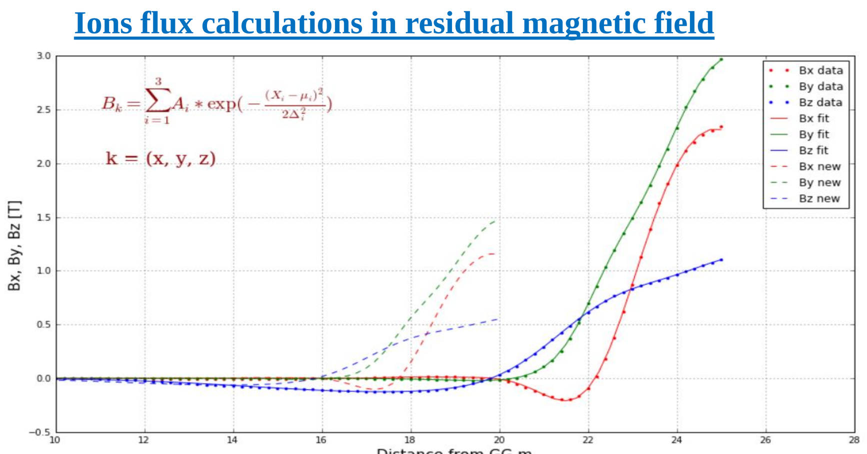




Gas density profile used to calculate beam composition along the beam path and during neutralization (right); due to re-ionization (left)

Beam loss due ton re-ionization ~ 11%

Ions flux calculations in residual magnetic field



Magnetic field profiles (example) applied to ions (re-ionized atoms)

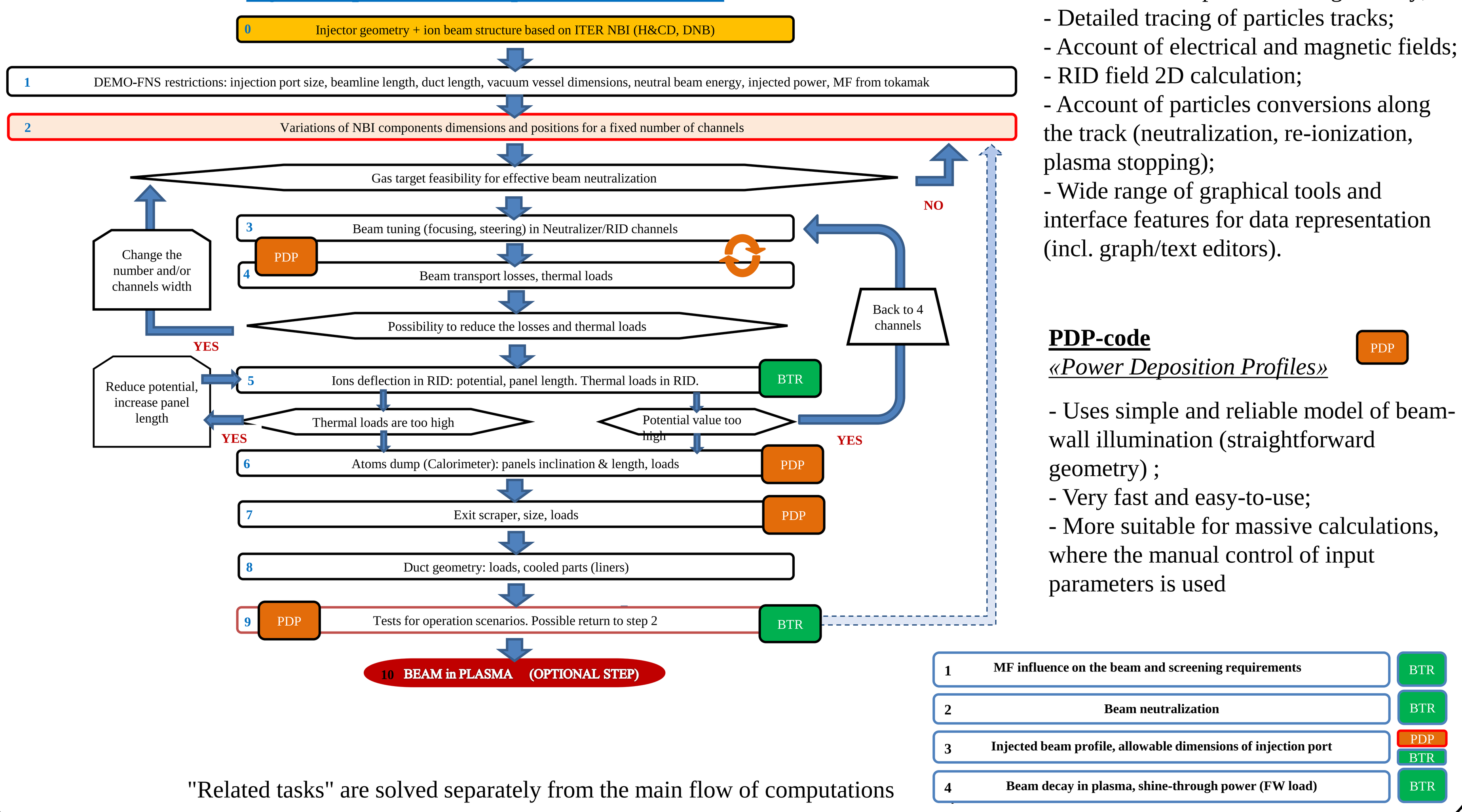
Beam decay in tokamak plasma

$$\frac{dI}{dx} = -n_e\sigma_S I(x)$$ - beam current decay rate along beam path

$$\sigma_S = \sigma_e + \frac{n_p}{n_e}(\sigma_p+\sigma_{cx}) + \frac{n_z}{n_e}\sigma_z \approx \sigma_e+\sigma_p+\sigma_{cx}+\frac{n_z}{n_e}\sigma_z$$

σ_S – beam stopping cross-section
σ_S calculation: Janev-Suzuki model

Injector optimization steps and related tasks



"Related tasks" are solved separately from the main flow of computations

CODES for modelling and optimization

BTR-code BTR
«Beam TRansport»

- Detailed description of NBI geometry;
- Detailed tracing of particles tracks;
- Account of electrical and magnetic fields;
- RID field 2D calculation;
- Account of particles conversions along the track (neutralization, re-ionization, plasma stopping);
- Wide range of graphical tools and interface features for data representation (incl. graph/text editors).

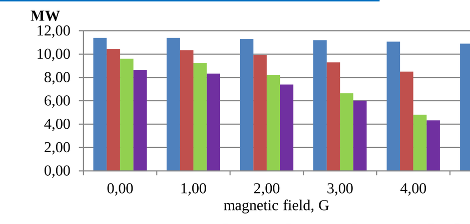
PDP-code PDP
«Power Deposition Profiles»

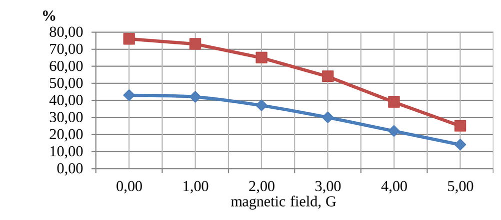
- Uses simple and reliable model of beam-wall illumination (straightforward geometry) ;
- Very fast and easy-to-use;
- More suitable for massive calculations, where the manual control of input parameters is used

Optimization workflow

1. Injector layout (multichannel scheme)

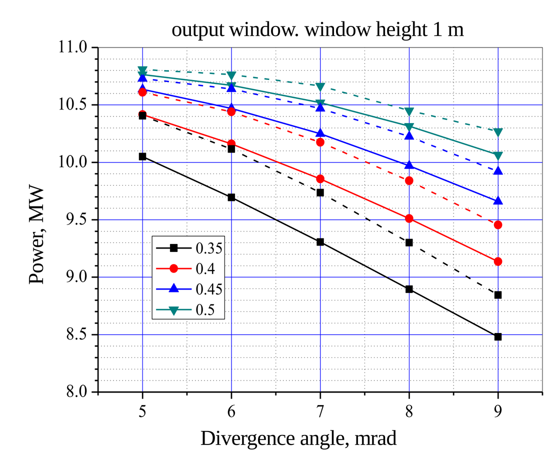
The choice should take into account:
- beam structure as beamlets 2D array with specific focusing
- limitations on NBI length, Injection port dimensions
- beamlets initial angular distribution, 2 fractions (core + halo)
- beam axis deviation due to adjustment inaccuracies and MF



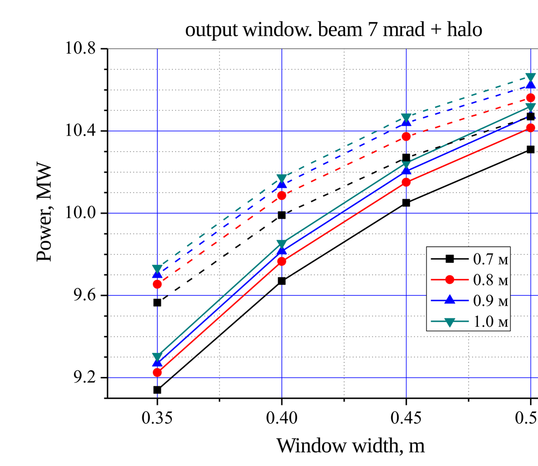


Beam power along beamline - **left** (■ — neutralizer, ■ - RID, ■ — duct, ■ — reionization losses of 10%) beam conversion (■) and transport (■) efficiency - **right** depending on Bz. Ideal focusing.

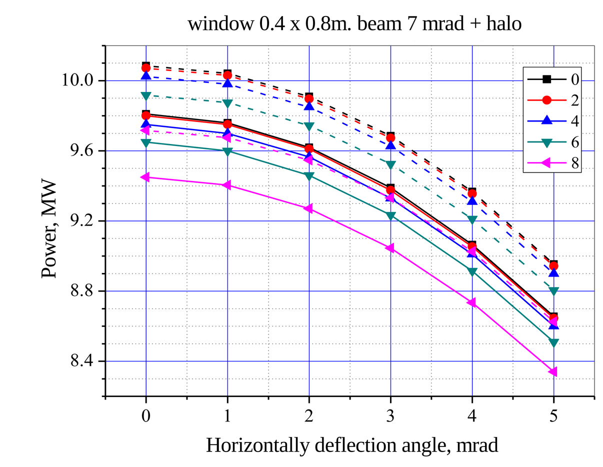
2. Components fine-tuning



Beam power dependence on the divergence angle

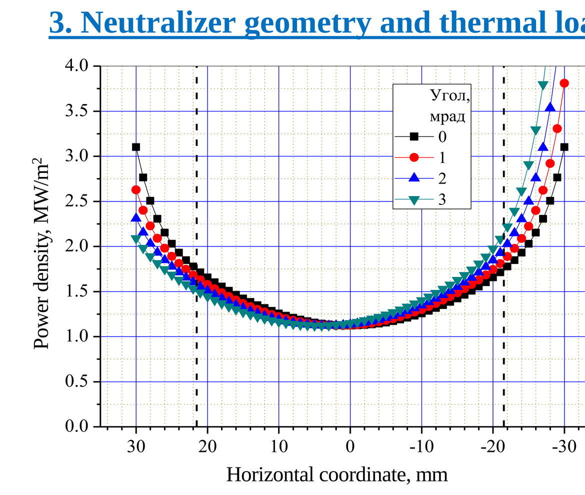


Beam power dependence on the window size

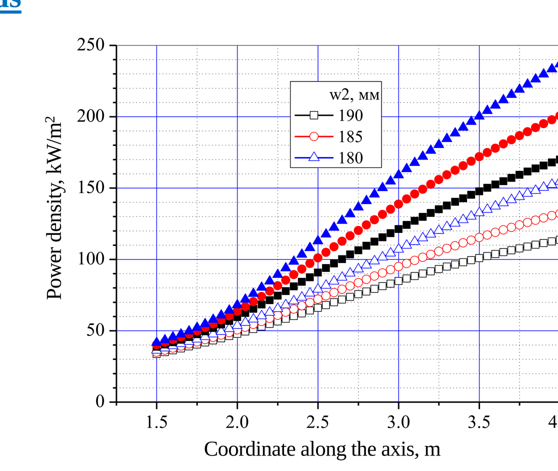


Beam power dependence on the horizontal beam axis deflection angle

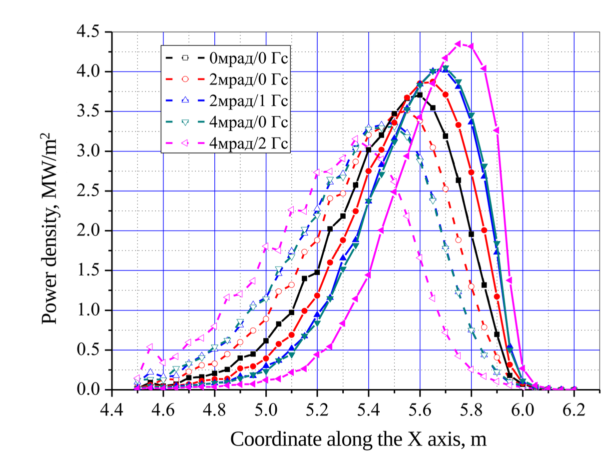
3. Neutralizer geometry and thermal loads



Beam power horizontal profiles at neutralizer central panel front at various beam axis deflection angles

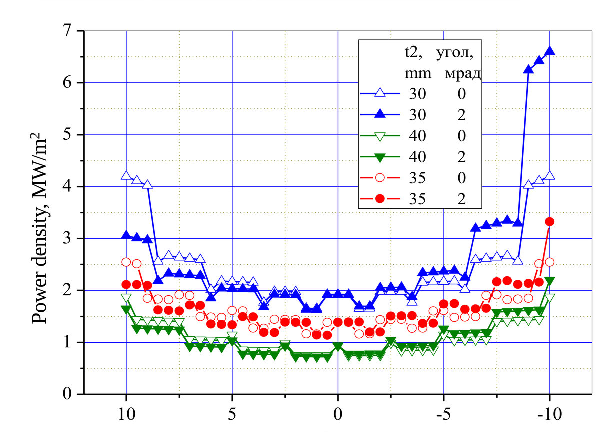


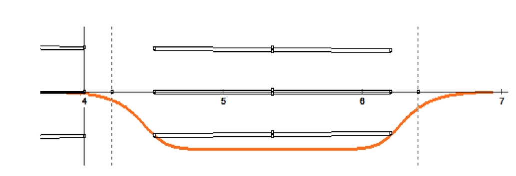
Power density profiles (on the left channel wall) for different output window in case of ideal beam axis adjustment (open symbols) and for angle (2 mrad) of deviation from axis



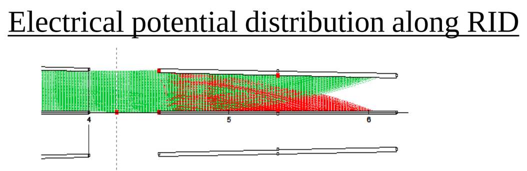
Horizontal ion load profiles (on the left and right panels of the RID). The effect of the total beam deflection (due to focusing and magnetic deviation in the neutralizer)

4. RID geometry and thermal loads





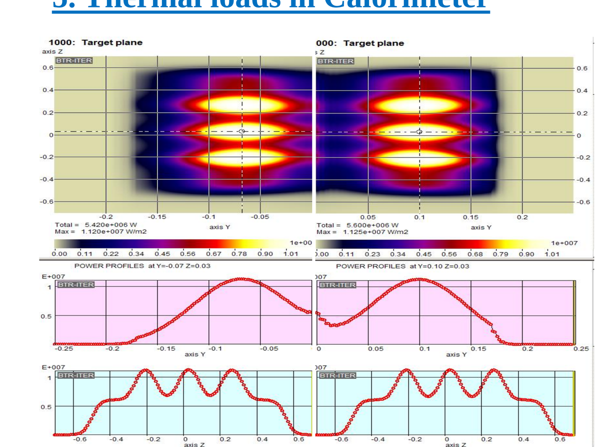
Electrical potential distribution along RID



Ions trajectories in RID (D⁺, D⁻)

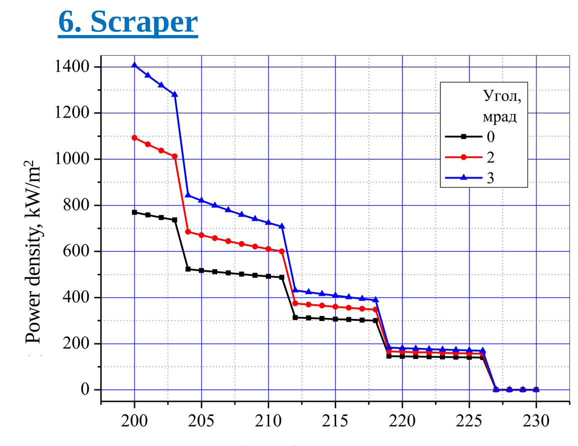
Beam power horizontal profiles at RID central panel front for different thicknesses of the neutralizer panels at its output

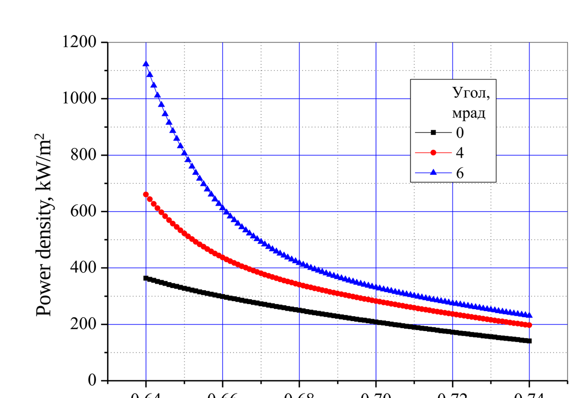
5. Thermal loads in Calorimeter



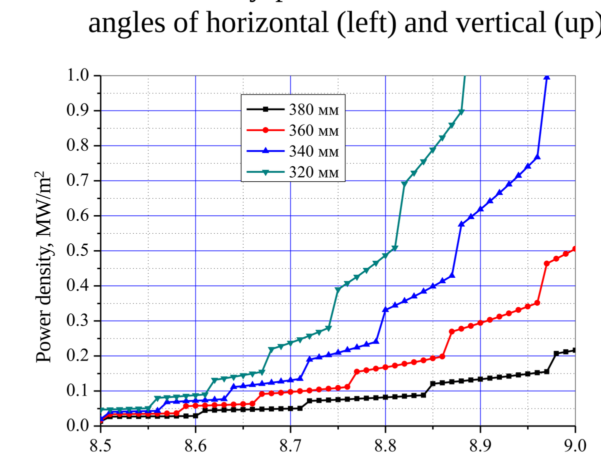
Thermal load in calorimeter (horizontally shifted due to horizontal misalignment 2mrad)

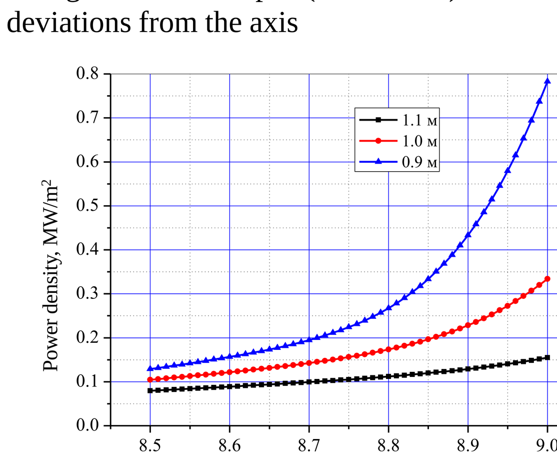
6. Scraper





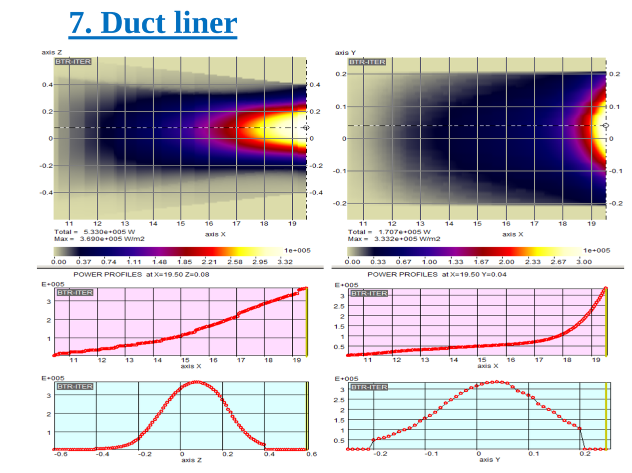
Power density profiles at the neutral beam edges on the scraper (X = 8.5 m) at different angles of horizontal (left) and vertical (up) deviations from the axis





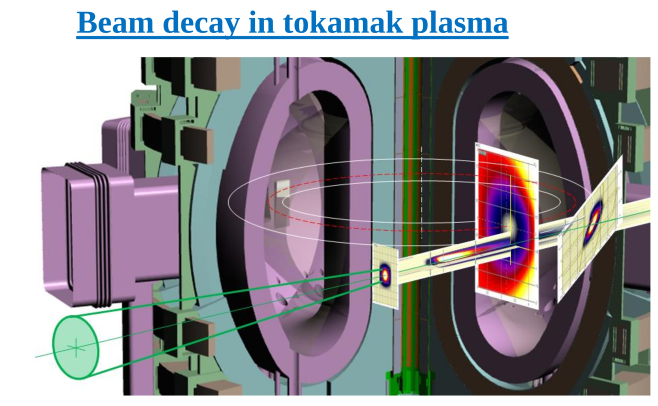
Load distribution: a) on the left scraper wall with different exit window width and unlimited height, b) on the top scraper wall at different exit window heights

7. Duct liner



Power loads in the Duct liner. Left and top panels are shown. Beam misalignment 2/4 mrad (h/v).

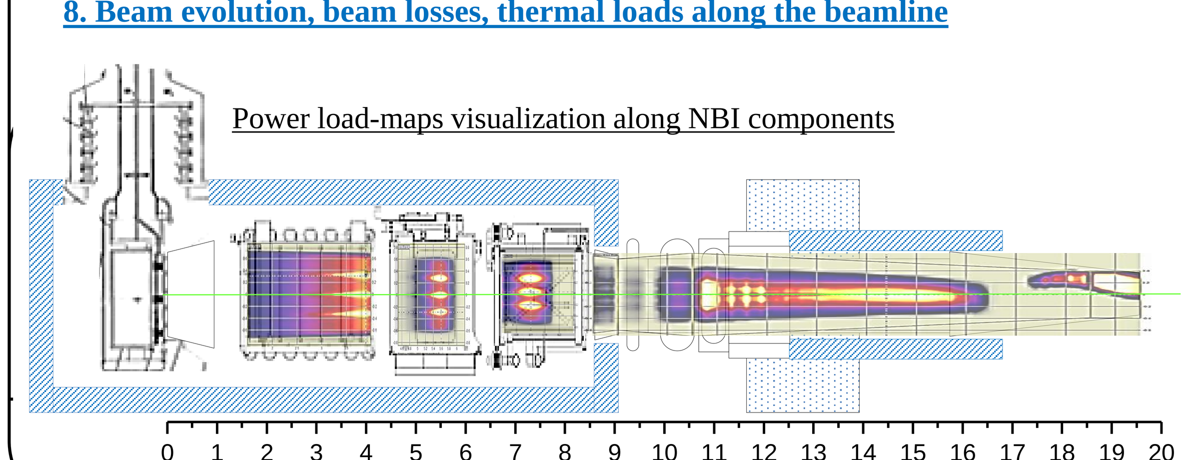
Beam decay in tokamak plasma

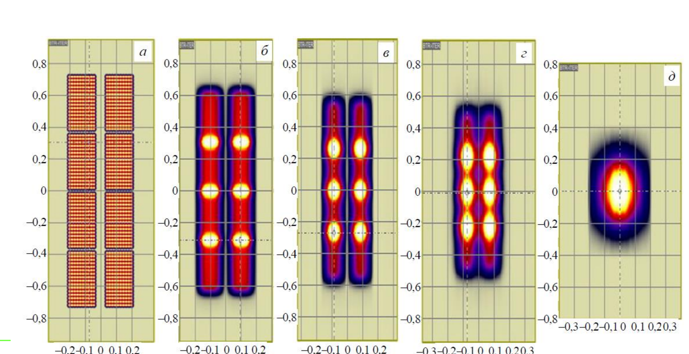


Beam decay and shine-through power load at FW

8. Beam evolution, beam losses, thermal loads along the beamline

Power load-maps visualization along NBI components

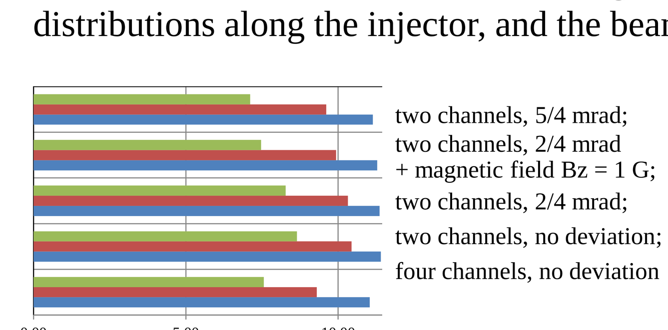


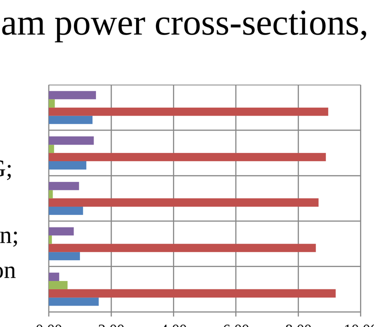


Beam profiles: a - ion source output, b – neutralizer output, c – RID output, d – duct input, e - injection window. Without magnetic field (B = 0), ideal beam focusing along the injection axis.

Conclusion

A general methodology used for beam line geometry optimization is described. This procedure allows to choose the most effective NB injector configuration for a fusion neutron source DEMO-FNS and to calculate the components optimum geometry. The entire injector geometry and the beam array structure and focusing are mutually consistent. The influence of various factors on the efficiency of beam transformation and transmission is discussed, the operating intervals are specified for each factor. Beam losses, including the direct interception and reionization, are estimated. Detailed thermal loads distributions along the injector, and the beam power cross-sections, including the result "footprint" injected to plasma, are plotted. Preliminary calculations of the neutral beam decay in tokamak plasma are carried out, and load profiles on the chamber wall are plotted. The simulations are performed by means of the codes PDP and BTR, specially developed in the "Kurchatov Institute" for the purposes of ITER injectors design, both codes have passed through verification procedures in ITER parties.





Beam power evolution (left) and distribution of loads to components (right)

NIBS 2018

The 6th International symposium on Negative Ions, Beams and Sources (NIBS'18)
3-7 September 2018, Novosibirsk, Budker Institute of Nuclear Physics SB RAS