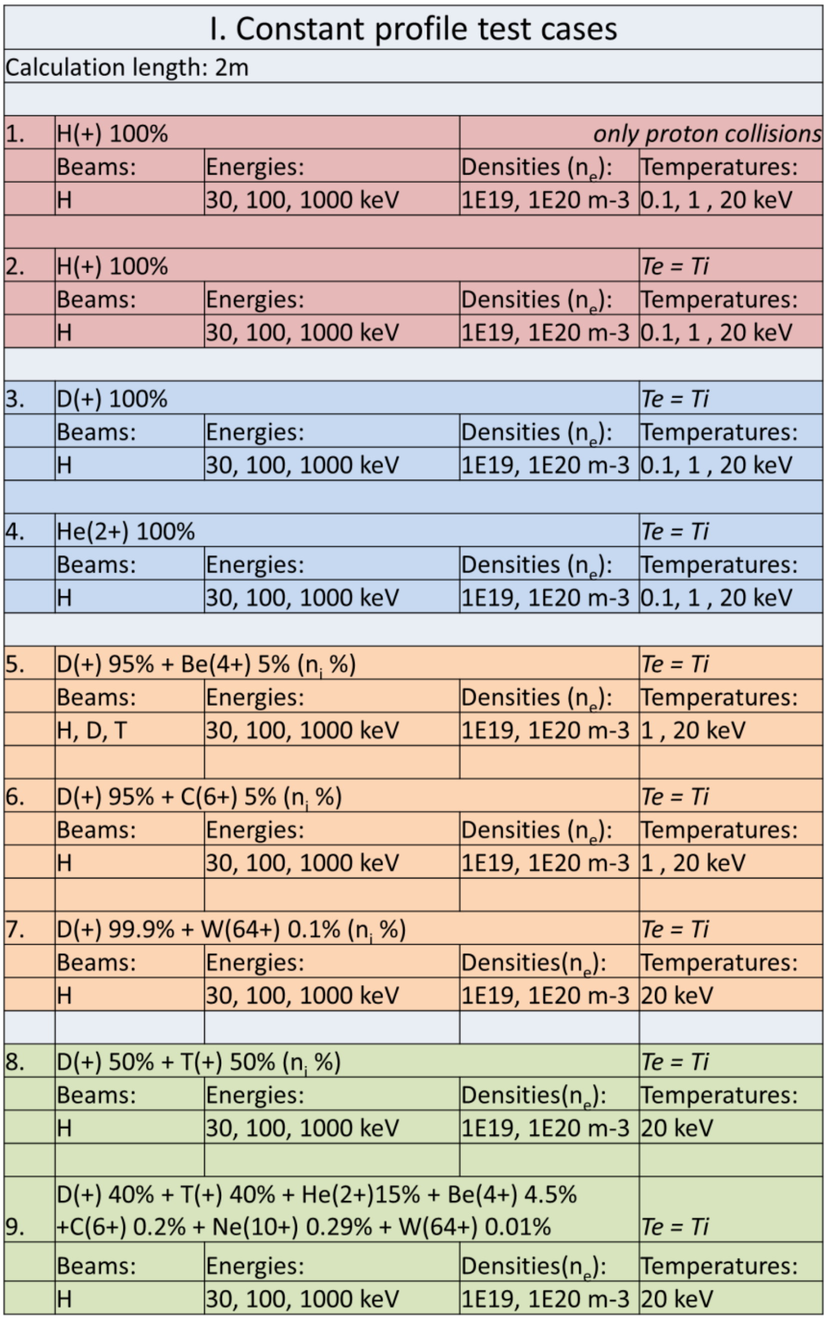
Neutral Beam Penetration and Photoemission Benchmark

G.I. Pokol[1,2], O. Asztalos[1,2], P. Balázs[1], B. Szondy[1], M. von Hellerman[3*], C. Hill[4],
O. Marchuk[3], M. O'Mullane[5], P.Zs. Poloskei[6], J. Varje[7], M. Tomes[8], K. Tőkési[9]
[1]*NTI, Budapest University of Technology and Economics, Budapest, Hungary*
[2]*Centre for Energy Research, Budapest, Hungary*
[3]*Forschungszentrum Jülich, Jülich, Germany*
[4]*International Atomic Energy Agency, Vienna, Austria*
[5]*University of Strathclyde, Glasgow, UK*
[6]*Max-Planck Institute for Plasma Physics, Greifswald, Germany*
[7]*Aalto University, Espoo, Finland*
[8]*IPP-CAS, Prague, Czechia*
[9]*Institute for Nuclear Research, Debrecen, Hungary*
[*] *retired*

Background Coordinated by the IAEA Atomic and Molecular Data Unit [1], the IAEA Coordinated Research Project (CRP) on Data for Atomic Processes of Neutral Beams in Fusion Plasma ("Neutral Beams") [2] is intended to provide evaluated and recommended data for the principal atomic processes relevant to heating and diagnostic neutral beams in fusion plasmas. A tool in this effort is the code comparison benchmark on beam penetration and emission. The purpose of the benchmark is twofold. First, to evaluate the collisional-radiative models (CRM) from the perspective of the atomic data applied, required complexity and treatment of missing atomic data. Second, to verify correct implementation and explore the applicability of different physics models. The participating codes apply different levels of detail and methodology to solve the governing rate equations: RENATE [3], RENATE-OD [4], BBNBI [5], FIDASIM [6], SOS [7], CHERAB [8], CRM by O. Marchuk [9]. The effect of the underlying physics approaches on beam attenuation and penetration is analyzed. Preliminary results are shown herein, but joining the benchmark is encouraged.

Constant profile test cases To this point, the analysis only considered hydrogen beams, as the input received on alkali beams is limited. The 1D beam initialized in purely ground state penetrates a homogeneous plasma with constant parameters, which corresponds to a step function in both density and temperature.

Test cases were set up to study the effects of finite temperature, isotopes, trace impurities, and finally, multi-component plasmas. Details are summarized in Table 1.



I. Constant profile test cases				
Calculation length: 2m				
1.	H(+) 100%		*only proton collisions*	
	Beams:	Energies:	Densities (n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	0.1, 1 , 20 keV
2.	H(+) 100%			*Te = Ti*
	Beams:	Energies:	Densities (n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	0.1, 1 , 20 keV
3.	D(+) 100%			*Te = Ti*
	Beams:	Energies:	Densities (n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	0.1, 1 , 20 keV
4.	He(2+) 100%			*Te = Ti*
	Beams:	Energies:	Densities (n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	0.1, 1 , 20 keV
5.	D(+) 95% + Be(4+) 5% (n_i %)			*Te = Ti*
	Beams:	Energies:	Densities (n_e):	Temperatures:
	H, D, T	30, 100, 1000 keV	1E19, 1E20 m-3	1 , 20 keV
6.	D(+) 95% + C(6+) 5% (n_i %)			*Te = Ti*
	Beams:	Energies:	Densities (n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	1 , 20 keV
7.	D(+) 99.9% + W(64+) 0.1% (n_i %)			*Te = Ti*
	Beams:	Energies:	Densities(n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	20 keV
8.	D(+) 50% + T(+) 50% (n_i %)			*Te = Ti*
	Beams:	Energies:	Densities(n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	20 keV
9.	D(+) 40% + T(+) 40% + He(2+)15% + Be(4+) 4.5% +C(6+) 0.2% + Ne(10+) 0.29% + W(64+) 0.01%			*Te = Ti*
	Beams:	Energies:	Densities(n_e):	Temperatures:
	H	30, 100, 1000 keV	1E19, 1E20 m-3	20 keV

Table 1 – Summary table of constant profile test cases.

Test case 1, considering only the proton contribution, is interesting from the CRM perspective but unphysical, so test case 2 of pure hydrogen plasma (Figure 1) serves as a reference to all further scenarios. Beam attenuation coefficients (μ) were derived from part of attenuation curves exhibiting secondary equilibrium: $\mathrm{n(x)} = \mathrm{n}_0 \mathrm{e}^{-\mu \mathrm{d}}$.

Preliminary results are presented in Table 2, and subsequent relative deviations in Table 3. These show matching attenuation coefficients within a few percent. BBNBI and CHERAB use the effective attenuation coefficients calculated by ADAS [10]; however, BBNBI data features stochasticity due to the Monte-Carlo nature of the code. Both RENATE and

RENATE-OD are based on the ALADDIN [11] database and solve bundled-n CRM, so no difference is observed for pure plasmas. FIDASIM and CRM-stat (by O. Marchuk) also solves bundled-n CRM but based on ADAS; consequently, their agreement is excellent.

All codes agree on a tendency of a significant effect of plasma temperature and appear to produce reliable results for the 30-100 keV test cases. Contrarily, 1 MeV beams are clearly out of the range of validity for some codes.

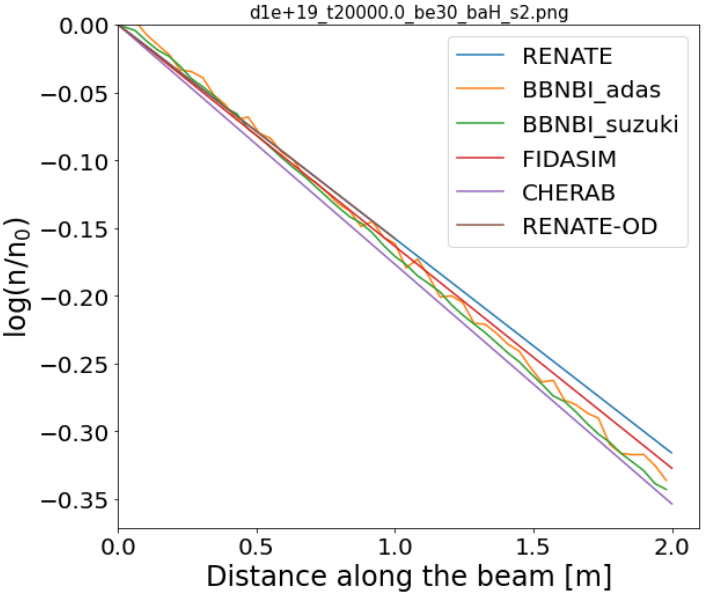


Fig. 1 – Beam attenuation in pure hydrogen plasma

					Attenuation coefficient (1/m)							
Density [1/m3]	Temp [eV]	Beam energy [keV]	Beam atom	Scenario	RENATE	BBNBI-ADAS	BBNBI-Suzuki	FIDASIM	CHERAB	RENATE-OD	CRM-stat	**average**
1E+19	100	30	H	2	0,543	0,588	0,589	0,562	0,595	0,543	0,562	**0,569**
1E+19	1000	30	H	2	0,494	0,499	0,504	0,510	0,526	0,494	0,510	**0,505**
1E+19	20000	30	H	2	0,364	0,382	0,399	0,377	0,407	0,364	0,376	**0,381**

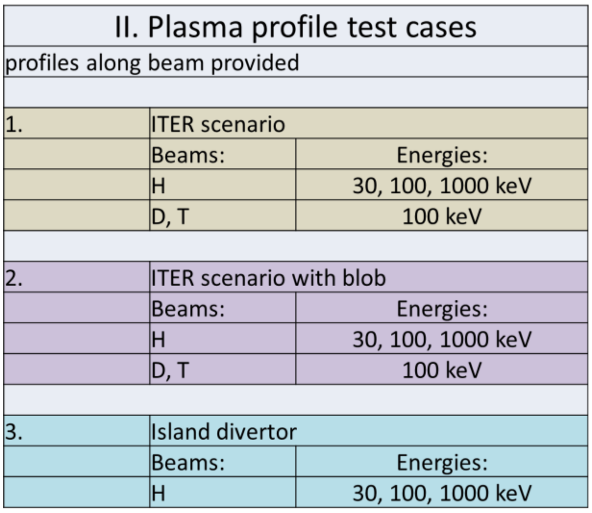
Table 2 – Attenuation coefficients for H beam into H showing for different plasma temperatures.

					Attenuation coefficient deviation from average (%)						
Density [1/m3]	Temp [eV]	Beam energy [keV]	Beam atom	Scenario	RENATE	BBNBI-ADAS	BBNBI-Suzuki	FIDASIM	CHERAB	RENATE-OD	CRM-stat
1E+19	100	30	H	2	-4,6	3,3	3,5	-1,3	4,7	-4,6	-1,2
1E+19	1000	30	H	2	-2,2	-1,2	-0,2	0,8	4,0	-2,2	0,9
1E+19	20000	30	H	2	-4,6	0,2	4,6	-1,1	6,8	-4,6	-1,3

Table 3 – Deviation of attenuation coefficients from average for the cases in Table 2.

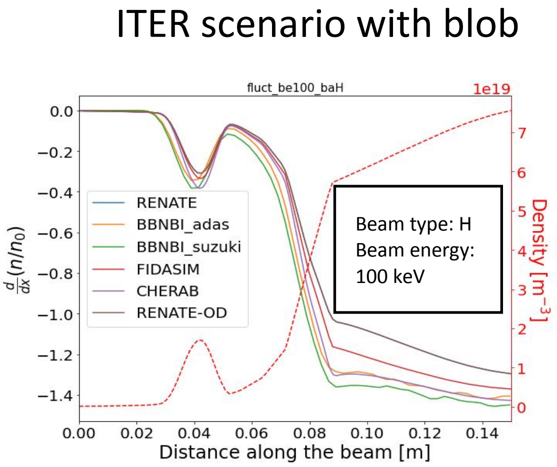
As the other test cases go, cases 3-6 and 8 of Table 1 could be evaluated, as modelling with Tungsten impurity proved challenging. Comparison of H and D plasma showed a small isotope effect, resembling a slight change in temperature. The effect of impurities – provided the same electron density and quasi-neutrality – is a decrease in the attenuation rate. All codes reproduce this trend, and a more detailed analysis is in progress.

Plasma profile test cases Realistic density and temperature profile test cases were also set up to study the applicability of the different approaches to practical beam-plasma modelling. One is a standard ITER-like profile, the second test case is an ITER-like profile with a large blob in the SOL, while the last is a W7-X-like profile with an edge island (Table 4).



II. Plasma profile test cases		
profiles along beam provided		
1.	ITER scenario	
	Beams:	Energies:
	H	30, 100, 1000 keV
	D, T	100 keV
2.	ITER scenario with blob	
	Beams:	Energies:
	H	30, 100, 1000 keV
	D, T	100 keV
3.	Island divertor	
	Beams:	Energies:
	H	30, 100, 1000 keV

Table 4 – Test cases with realistic plasma profiles



ITER scenario with blob

Fig. 2 – ITER profile test case

Results (e.g. in Figure 2) show good agreement of all codes, with the CRM-solvers (FIDASIM and RENATE(-OD)) featuring a slightly delayed response to the density changes.

Summary and outlook Benchmark of beam codes is in progress in the scope of the IAEA „Neutral Beams" CRP [2]. 7 participating codes, so far, but still possible to join. Preliminary results regarding beam attenuation in various conditions were presented.

Further plans include: 1. extending benchmark to all available codes for H-beam attenuation, 2. study of H-beam emissivity, 3. extending benchmark to alkali beam codes (Lithium, Sodium), 4. concluding at next IAEA Research Coordination Meeting (2021 autumn).

Acknowledgement This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom Research and Training Programme 2014–2018 and 2019–2020 under Grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. G I Pokol and O. Asztalos acknowledge the support of the National Research, Development and Innovation Office (NKFIH) Grant FK132134.

References:

[1] https://amdis.iaea.org/
[2] https://amdis.iaea.org/CRP/neutral-beams
[3] D. Guszejnov, et al. RSI, 83, 113501 (2012)
[4] https://github.com/gergopokol/renate-od
[5] O. Asunta, et al., Comp. Phys. Comm., 188, 33-46 (2015)
[6] B. Geiger, et al., PPCF, 62, 105008 (2020)
[7] M. von Hellermann, et al., Atoms, 7 (2019)
[8] M. Carr, et al., RSI, 90, 043504 (2019)
[9] O. Marchuk, et al., Journal Phys. B, 43, 011002 (2019)
[10] H.P. Summers, et al., AIP Conf. Proc., 1344, 179-187 (2011)
[11] R.A. Husle, AIP Conf. Proc., 206, 63-72 (1990)