Numerical study and optimization of non-inductive current drive efficiency in FNS tokamak plasmas

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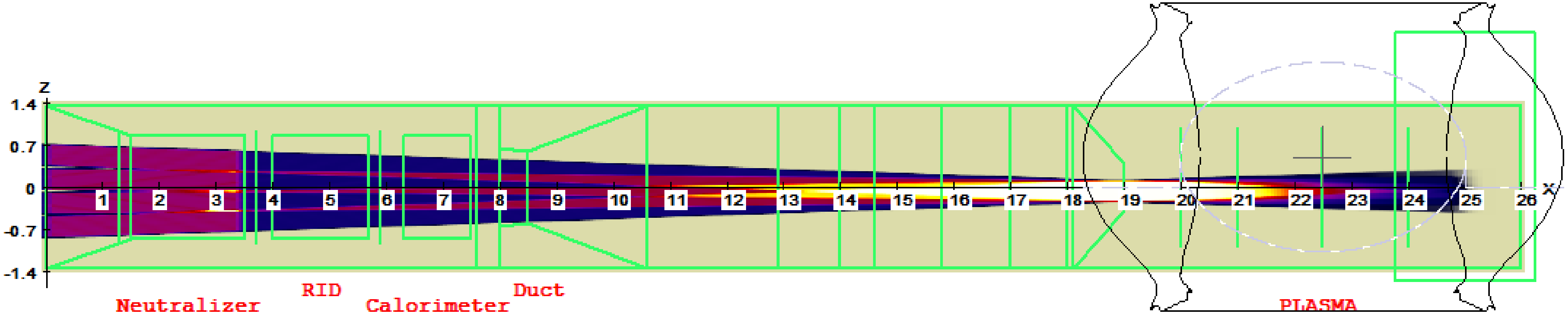


Second Technical Meeting on Long-Pulse Operation of Fusion Devices H&CD

BTR ref

BTR-code for NBI design (1995)

- ✓ Beam Tracking with Re-ionization, *Born-To-Run* (Windows, C++)
- ✓ Used by NBI teams in R&D (incl. ITER) - for 3D NBI beamlines optimization and detailed thermal loads analysis, losses, power deposition, MF shielding, etc.
- ✓ Tracks NB evolution and transmission through beamlines – from beam source until absorption by plasma or striking far wall
- ✓ Comprehensive and flexible tool, interactive, user-friendly (**GUI**)
- ✓ Verified (JET-2008, IO-2023), integrated in **BTOR** suite (2018), ~80 000

BTR website

BTR article

BTR INFO:
tasks,
features,
usage,
versions

Topics of today: SSOp in FNS, NBI

- ✓ **FNS** tokamaks: SSOp, designs, possibility to run by NBI, scenario specifics
- ✓ NBCD issues, performance evaluation, figures of merit, methods
- ✓ Results: EP losses, energy profiles, CD profiles - for FNS-ST design
- ✓ NBI performance limits and boosters - in SSOp context

FNS: mission, concept, specifics

NB DRIVEN SSOp

- **FNS tasks:** fusion and fission tech, material science, make pure fusion closer…
- **FNS concept:** intense neutron generation by use of fusion device with moderate plasma params (rel to pure fusion)
- **FNS main advantage**: lower physical demands, reduced size and cost → competitive for F&F engineering, core device for hybrid reactors
- **SSOp – critical issue for FNS**
- **NBI:** SSOp driver, non-inductive CD, intense neutron production (60-99%); + heating i/e, fueling, torque
- **Scenario**: 2E-component plasma (EP + thermal pop) in strongly toroidal MF; high pressure and power in *hot ions* (*EP*), higher gradients in profiles, no self-organization
- **NB high impact** → opportunities for plasma control; scenario optimized for NBCD or for desired current shape – hollow, peaked, uniform
- **Instruments:** include all the effects and FNS specifics, 3D/6D, non-cylinder, fast + accurate
- **BTR:** chosen as base for NBI simulator; detailed NB 6D structure, high perf (parallel), methods – analytical, deterministic; naturally extended to EP tracking in tokamak plasma

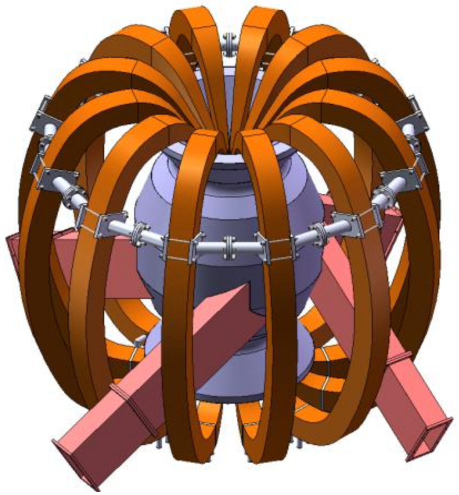
NBCD issues, concerns

NBI STOPPERS

- Main limit for NB applications – NBI **cost and perf**. (Plasma - main stopper)
- Overall NB perf is limited by the source ions neutralization (gas - < 60%), next reduced by transmission (scraping) and re-ionization losses in the **beamline** (- ~10%)
- **Non-inductive** current is driven by passing EP fraction, however EP orbit losses are highly sensitive to MF shape and NBI energy and geometry – spatial size, aiming point, axis inclination, internal divergence
- EP **deposition/velocity pitch profiles** are determined by plasma density (n_e) profile, while EP slowing (thermalization) conditions are ~ $\mathbf{T_e}^{3/2}/n_e$ (low collisions)
- **Collisions** and radial **drifts** decrease the NBCD values
- NBCD reshapes initial thermal profiles → BS current!
- Plasma **rotation**, **finite orbit width** - decrease NBCD due to thermal profiles reshaping
- **NBCD = passing + trapped (banana)** EP, ratio depends on EP r-V deposition
- For SSOp, NBI main function is toroidal CD; heating is a spillover;
- Although expensive, NBI can be the most **efficient** and **flexible** option among non-inductive CD methods; can be uses for **off-axis** and **on-axis** CD

FNS designs (~ ready)

FNS-ST

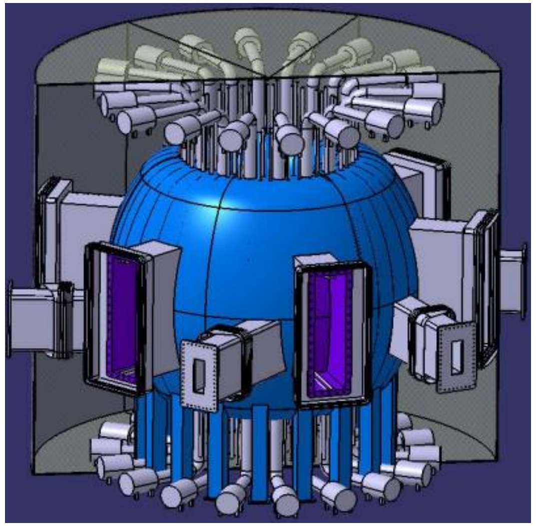


Compact Fusion Neutron Source – based on spherical tokamak (low aspect)

- Water-cooled EMS, twisted central pole CuCrZr
- Wall power - 60 MW
- DT fusion power - 3 MW (20:1)
- Neutron yield - 10^{18} 1/c (25:1)
- Beam driven fusion, NBCD + BS (high NB impact!)
- P_{NB} = 6 - 10 MW

R_0 = 0.5 m
A = 1.67
k = 2.75
δ = 0.5
B_0 = 1-1.5 T
I_p = 1-1.5 MA
Q ~ 0.2
T_e = 5 keV
n_e = ~ $1 \cdot 10^{20}$ m^{-3}

DEMO-FNS



Hybrid (F&F) reactor prototype (conventional)

- EMS - LTS (Nb_3Sn, NbTi)
- Wall power - 200 MW
- DT fusion power - 40 MW (5:1)
- Neutron yield – $1.3 \cdot 10^{19}$ 1/c (7:1)
- Fission power – 400 MW
- Thermal power – 700 MW
- Beam driven + thermal, NBCD
- P_{NB} = 30 MW (+ P_{ECR} = 6 MW)

R_0 = 3.2m
A = 3.2
k = ~2
δ = 0.5
B_0 = 5 T
I_p = 5 MA
Q ~ 1
T_e = 10-15 keV
n_e = ~ $1 \cdot 10^{20}$ m^{-3}

Modelling: beam, plasma, NB losses and effects

NB 6D statistics and EP deposition ← BTR code

NB stopping (atoms ionization) ← Janev or ADAS cross-sections

Magnetic field:

MHD equilibria (GSE), *loosely fixed* plasma bound, consistent with external currents

$$\frac{\partial^2\Psi}{\partial Z^2}+\frac{\partial^2\Psi}{\partial R^2}-\frac{1}{R}\frac{\partial\Psi}{\partial R}=-2\pi\mu_0 R\, j_\varphi$$

Hot ion slowing-down time:

$$\tau_s=\frac{\tau_{se}}{3}\cdot ln\left[1+\left(\frac{E_b}{E_c}\right)^{3/2}\right]$$

EP thermalization: classical theory

Spitzer time

$$\tau_{se}=\frac{3\sqrt{2\pi}T^{3/2}\,2\pi\varepsilon_0{}^2 m_b{}^2}{\sqrt{m_e}m_b\quad ne^4\,ln\Lambda}=Coeff_1\cdot T_e{}^{3/2}\cdot\frac{A_b}{n}$$

Critical energy

$$E_c=\left(\frac{3\sqrt{\pi}}{4}\right)^{2/3}\left(\frac{m_i}{m_e}\right)^{1/3}\frac{m_b}{m_i}\cdot T_e\ =Coeff_2\cdot\frac{A_b}{A_i{}^{2/3}}T_e$$

EP losses, trapping: local pitch ($V_{||}/V_0$)

- Trapped and passing EP fractions

NBI performance evaluation and comparison

figures
QA

- **Total NB perf =** beamline efficiency × NBI gain in plasma (here: NBCD)
- **Beamline:** neutralization, transmission, re-ionization
- **NB EP efficiency:** shine-through, orbits in MF (1^{st} Larmor, bananas, 3D MF, drifts), CX losses (< 100keV/a), turbulence, instabilities

CD figure of merit:

NBCD efficiency (P_{NB} 1MW)

$$\eta_{CD} = R_p I_{CD} \overline{n_e} / P_{NB} \times 10^{-20}$$

NB current multiplication (I_{NB} / P_{NB})

$$\eta_{I(P)} = I_{CD} / I(P)_{NB}$$

NB power to replace full plasma current

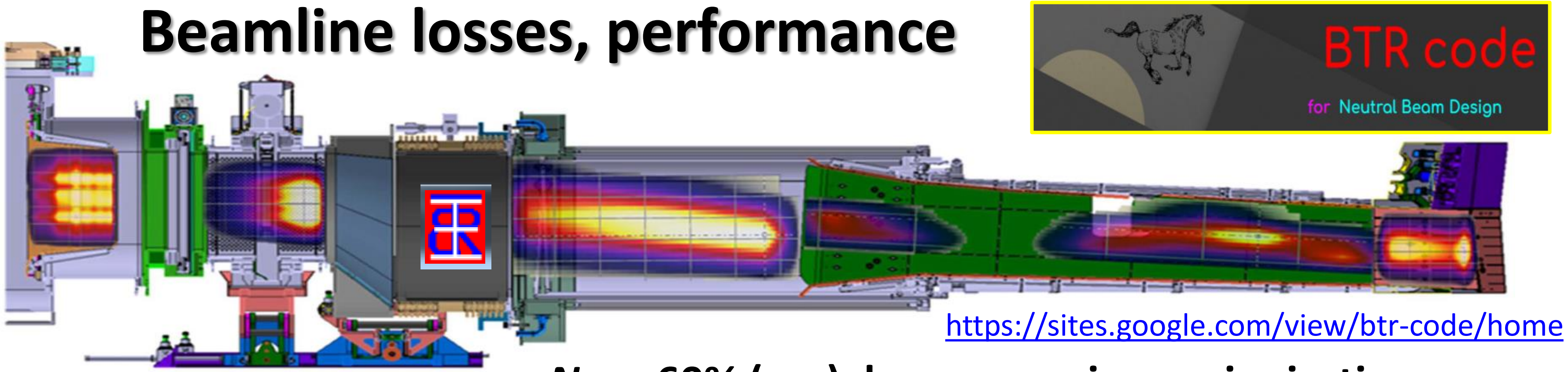
$$P_{SSO} = I_P / \eta_P$$

Other FNS indicators, not critical for SSOp

- ➢ NB fueling α_{fuel} at full current (I_{NBI})
- ➢ Hot-thermal neutron yield NY_{NB}, s^{-1} at full power P_{NBI}
- ➢ Hot / thermal ion burn-out ratio F_{fast} / F_{th}
- ➢ NB fusion power gain Q_{NB} (P_{NB}1MW) = EP energy *multiplication*

NB losses

Beamline losses, performance



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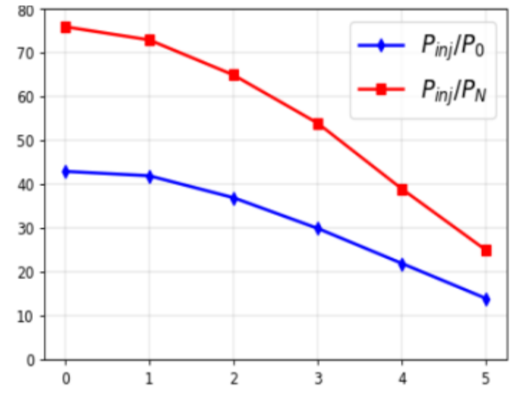
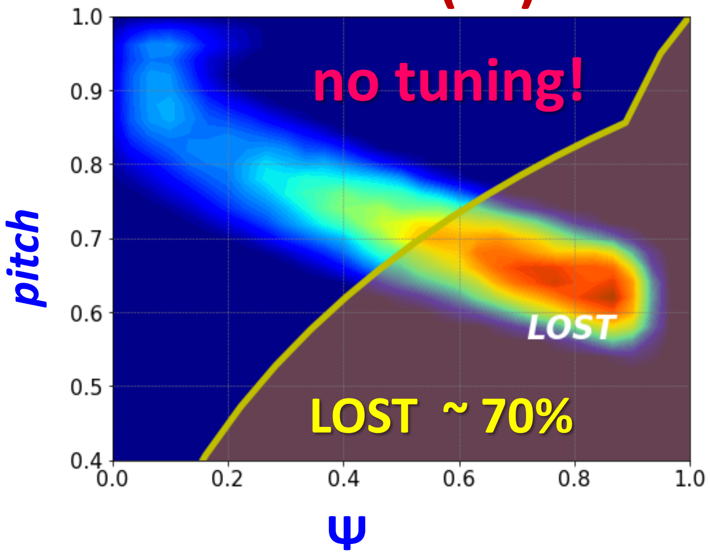
N_{eff} < 60% (gas), beam scraping, re-ionization on gas



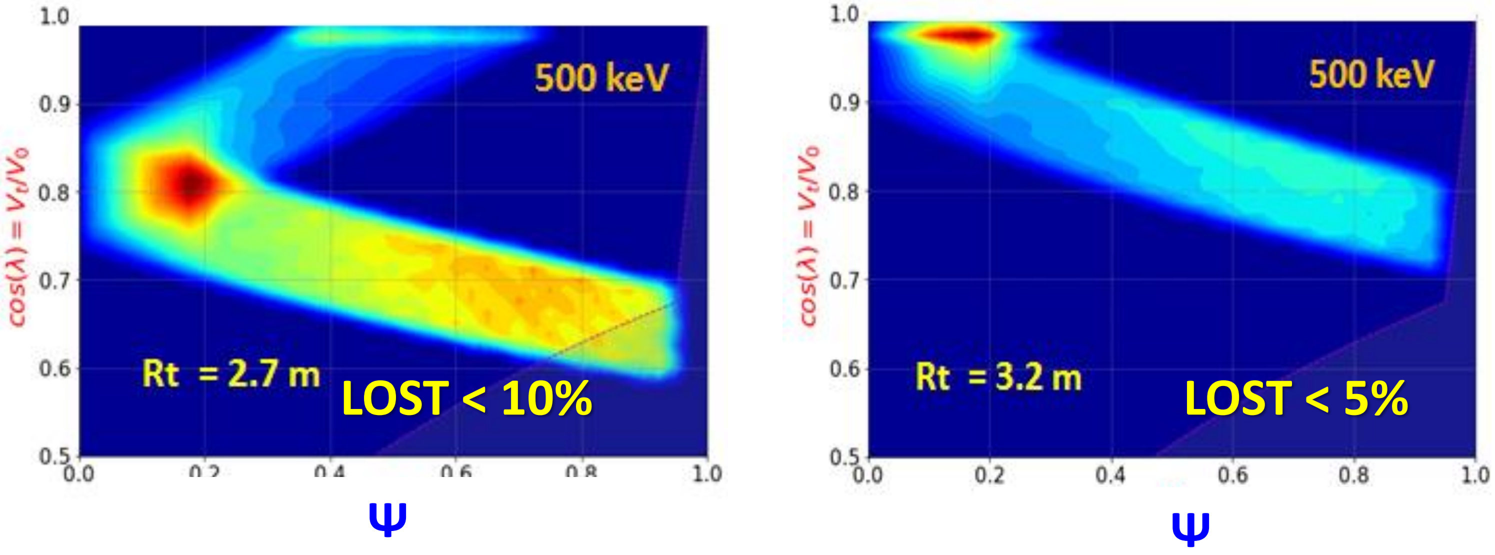
Magnetic field (Bz, G)

NB EP orbit losses vs aspect ratio: r-pitch maps

ε ≈ 0.6 (ST)

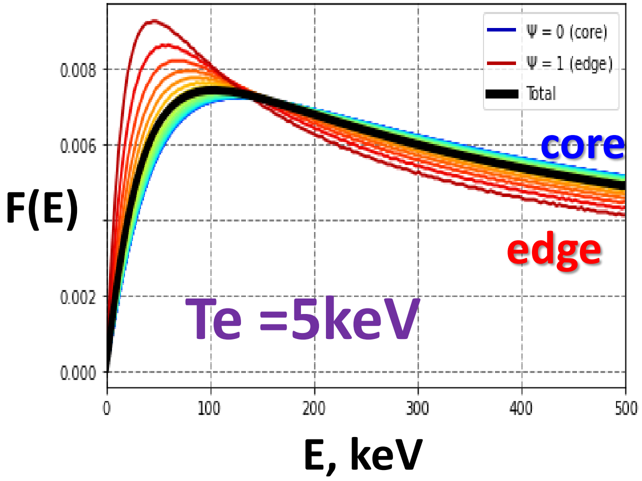


ε ≈ 0.3 (conventional)



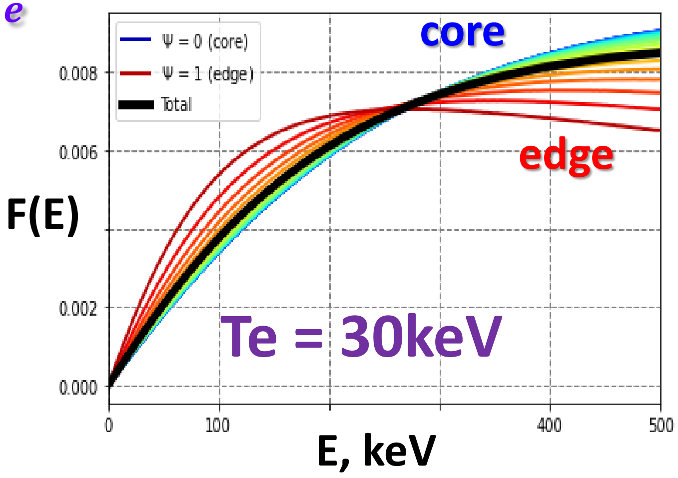
EP energy profile: toroidal/poloidal circulation + deceleration

Cold EP dominate

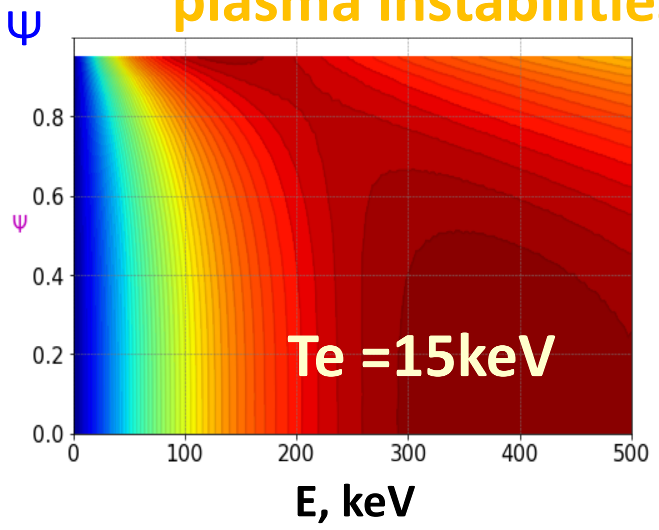


$\frac{E_{NB}}{T_e}$

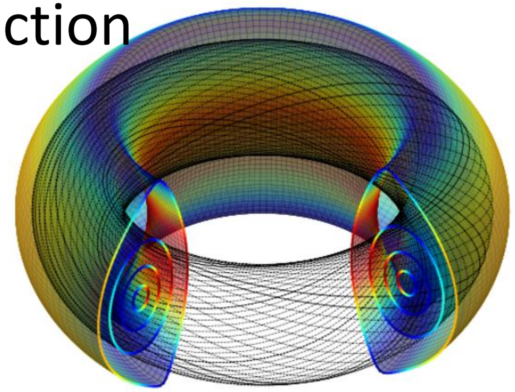
Hot EP dominate



→ Ti peaking, Te smoothing, plasma instabilities

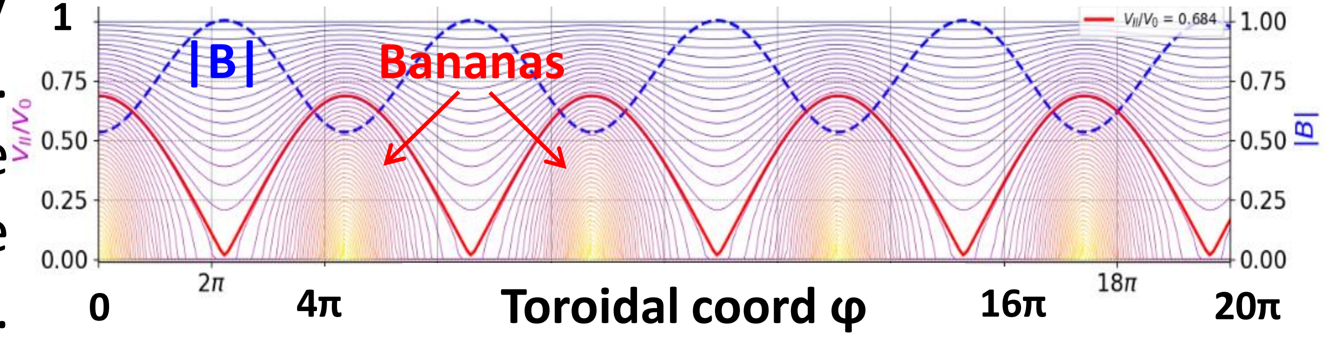


ASTOR+ : plasma equilibrium with high EP fraction



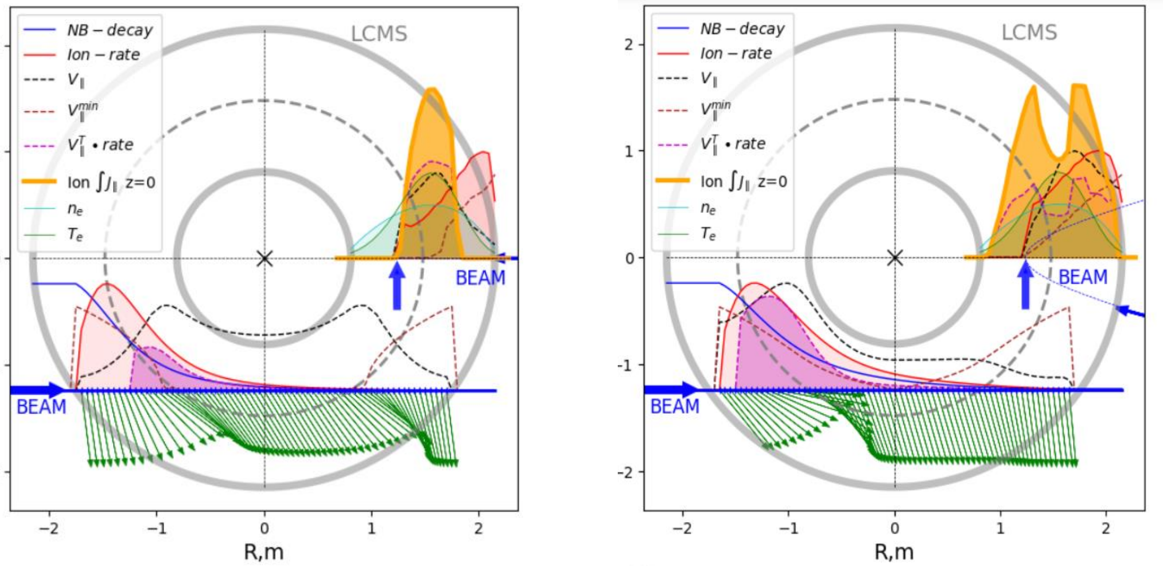
Poloidal rotation of MF lines → EP parallel velocity oscillations. Amplitude depends on the start pitch.

$V_{//}$ oscillations vs initial pitch $= V^0_{//}$
Mag. surf q = 2.2, low MF start ($\theta_0 = 0$)

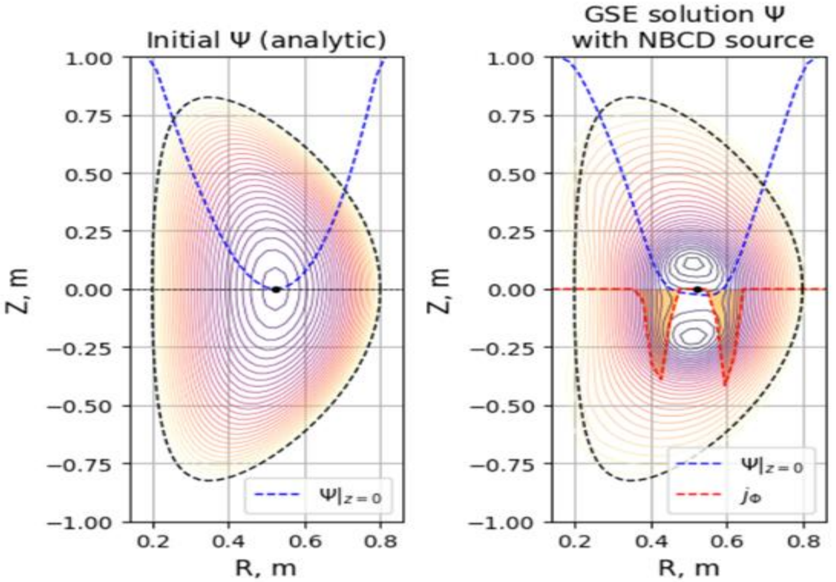


NBCD profiles vs NB aiming

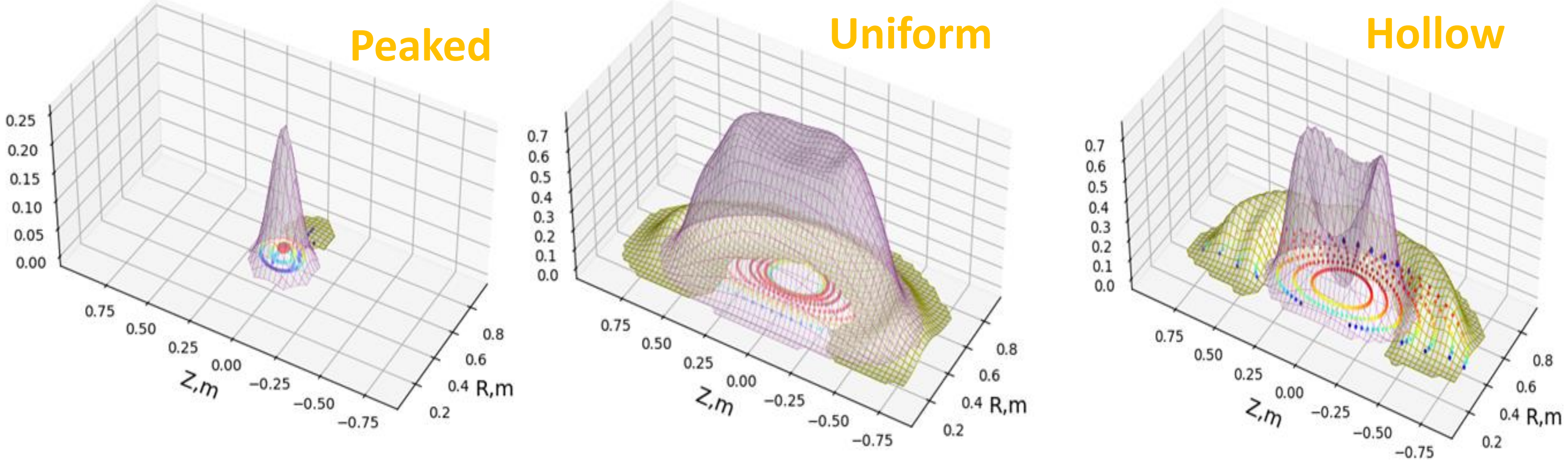
ASTOR+ NBI



GSE solution with NBCD



NBCD profiles in poloidal plane



NBCD results for FNS-ST

E_{NB} = 100 keV (D)

R_0 = 0.5m

T_e = 5keV

$n_e = 10^{20} m^{-3}$

B_0 = 1T

I_p = 1MA

R_{NB}, m	Inclination α_{NB}, deg	FW loss	I_{CD} / I_{NB}, A/A	I_{CD} / P_{NB}, A/MW	P_{NB}, MW $I_{CD} = I_p$
0.3	0	0.005	1226	12263	82
0.3	30	0.008	14101	141014	7.1
0.3	40	0.009	15776	157760	6.3
0.4	0	0.005	1873	18728	53.4
0.4	30	0.006	13560	135602	7.4
0.5	0	0.008	2243	22434	44.6
0.5	30	0.01	11362	113623	8.8
0.6	0	NBCD = 0 (cut-off)			
0.6	30	0.03	5283	52831	18.9
0.6	40	0.03	14721	147213	6.8

- Full replacement of current by NBCD in low aspect ST plasma is only possible for inclined NB axis, due to max aver. pitch of EP population
- R "cut-off" for horizontal injection (in ST): no passing EP (only bananas)
- Off-axis injection is more efficient than on-axis, GSE solution - more stable! (to check)

ST results

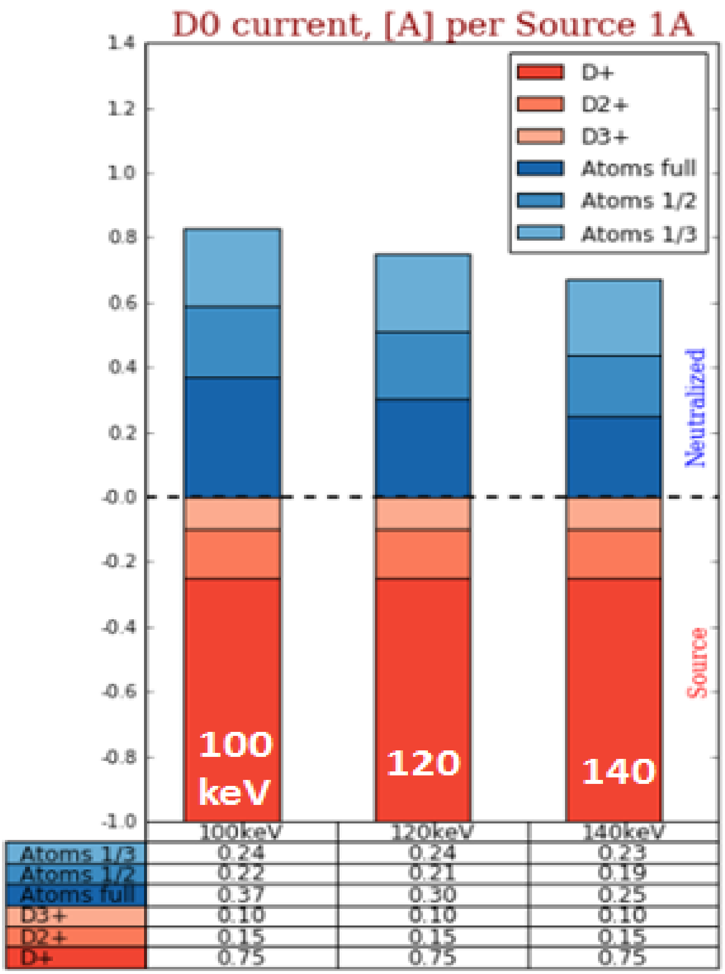
NBI integral performance analysis (optimized NB aiming)

Beam full energy: E_b = 100, 120, 140keV

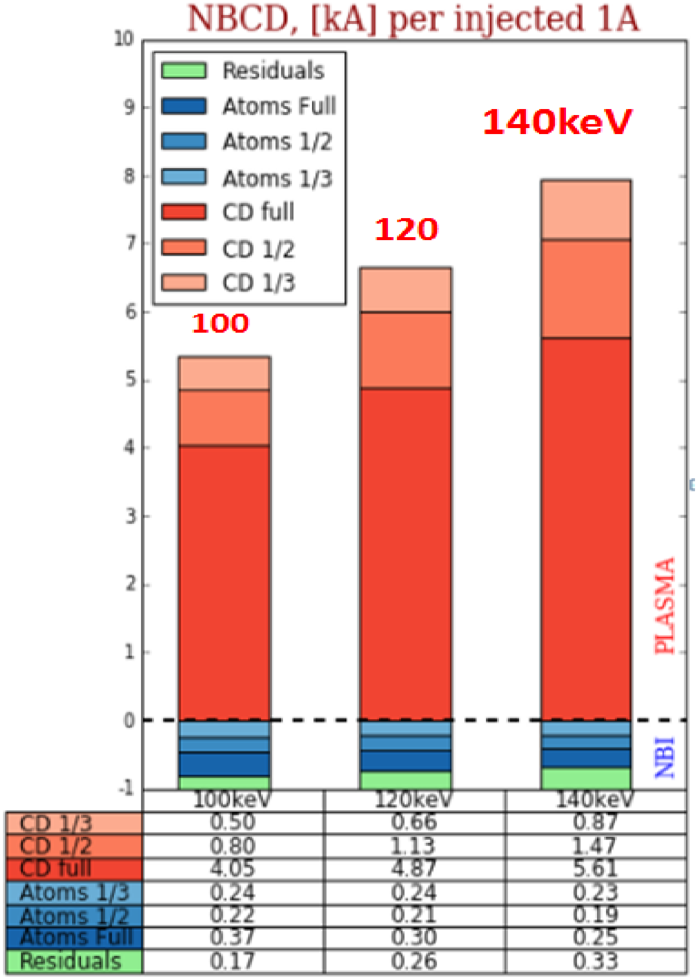
Beamline efficiency

NB output fractions: E_{full}, $E_{1/2}$, $E_{1/3}$

Ion source fractions D^+/ D_2^+ / D_3^+



	100keV	120keV	140keV
Atoms 1/3	0.24	0.24	0.23
Atoms 1/2	0.22	0.21	0.19
Atoms full	0.37	0.30	0.25
D3+	0.10	0.10	0.10
D2+	0.15	0.15	0.15
D+	0.75	0.75	0.75



	100keV	120keV	140keV
CD 1/3	0.50	0.66	0.87
CD 1/2	0.80	1.13	1.47
CD full	4.05	4.87	5.61
Atoms 1/3	0.24	0.24	0.23
Atoms 1/2	0.22	0.21	0.19
Atoms Full	0.37	0.30	0.25
Residuals	0.17	0.26	0.33

NBCD efficiency (η_I)

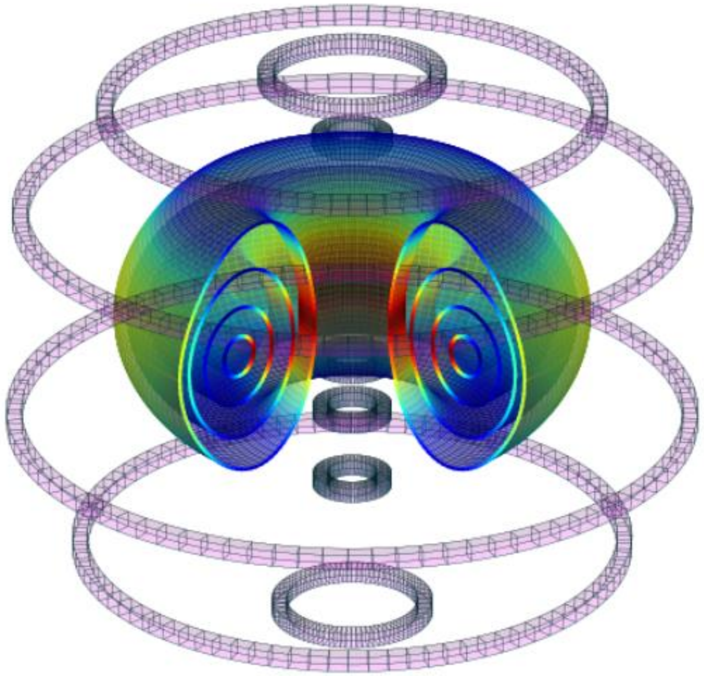
EP perf: NBCD sum from all energy fractions

Max NB current multiplication – for 140keV

- **Lower beamline perf leads to higher total NB perf (NBCD prevails!)**

RESUME

- ❑ NBI is a viable tool for sustaining fully non-inductive discharges in LP/SS plasmas, albeit rather expensive
- ❑ SSOp is supposed to be accessed in FNS by NBI (NBCD + heating + profiles control)
- ❑ For all FNS designs, high values of MF are critical to achievde SSOp;
- ❑ Off/on-axis NB produce EP population, direct parallel current is driven predominantly by ‘passing’ hot ions (‘trapped’ ions drive NB-BS current)
- ❑ NBCD and other perf values (Q_{NB}, NY) are guided by incident EP spatial/pitch profiles
- ❑ Beam parameters can be tuned either to get maximum NBCD or optimum current profile – peaked/hollow/uniform
- ❑ Small FNS based reactors can be more competitive, their design being driven by plasma physics rather than technology



Thanks for your attention

BTR website

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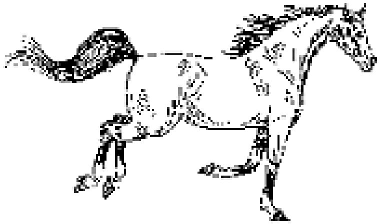

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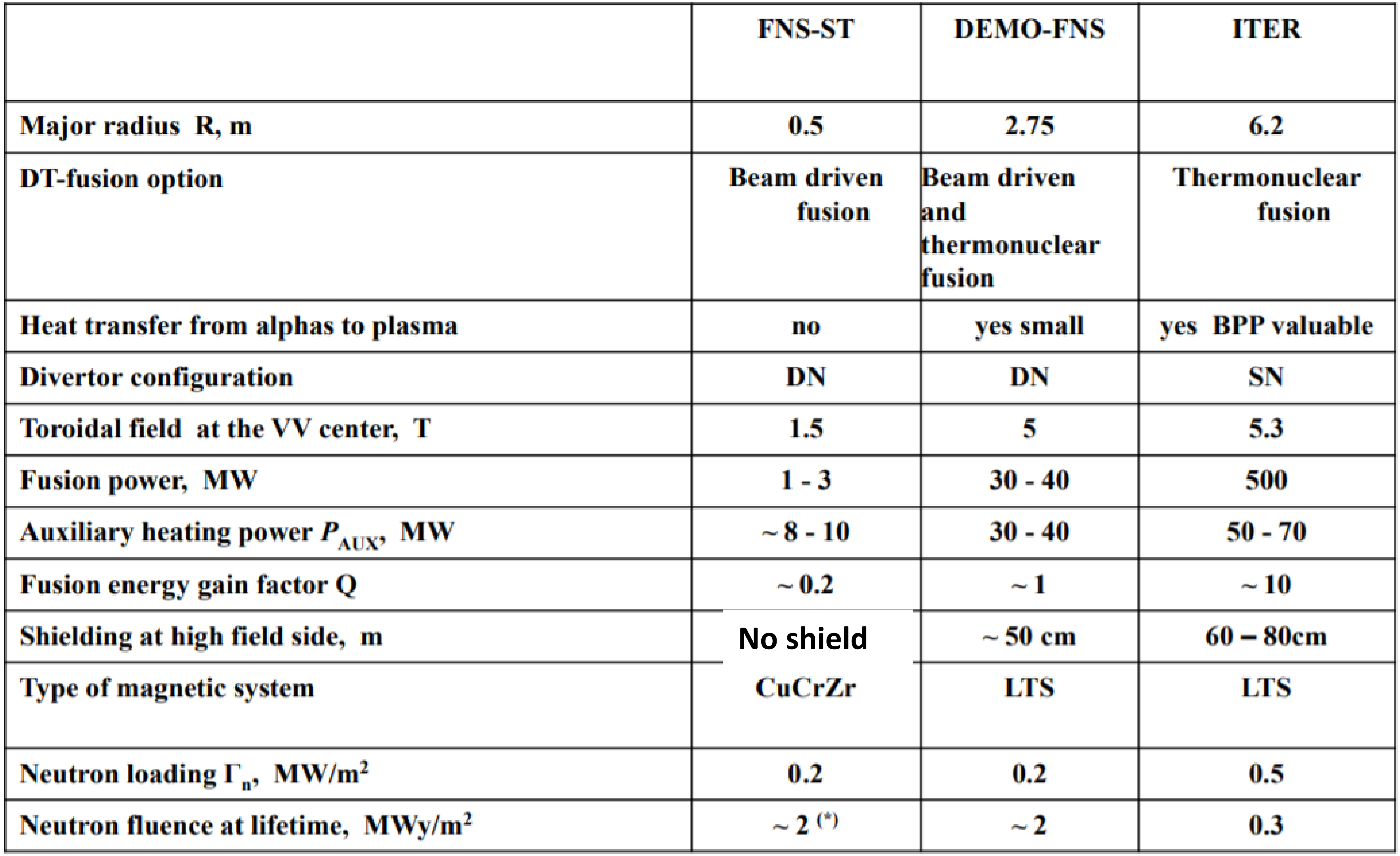
FNS-ST, DEMO-FNS and ITER parameters



	FNS-ST	**DEMO-FNS**	**ITER**
Major radius R, m	**0.5**	**2.75**	**6.2**
DT-fusion option	**Beam driven fusion**	**Beam driven and thermonuclear fusion**	**Thermonuclear fusion**
Heat transfer from alphas to plasma	**no**	**yes small**	**yes BPP valuable**
Divertor configuration	**DN**	**DN**	**SN**
Toroidal field at the VV center, T	**1.5**	**5**	**5.3**
Fusion power, MW	**1 - 3**	**30 - 40**	**500**
Auxiliary heating power P_{AUX}, MW	**~ 8 - 10**	**30 - 40**	**50 - 70**
Fusion energy gain factor Q	**~ 0.2**	**~ 1**	**~ 10**
Shielding at high field side, m	No shield	**~ 50 cm**	**60 – 80cm**
Type of magnetic system	**CuCrZr**	**LTS**	**LTS**
Neutron loading Γ_n, MW/m^2	**0.2**	**0.2**	**0.5**
Neutron fluence at lifetime, MWy/m^2	**~ 2 $^{(*)}$**	**~ 2**	**0.3**