Parametric analysis of GDT- and GDMT-based neutron sources

D. V. Yurov, V. V. Prikhodko and P. A. Bagryansky

Budker Institute of Nuclear Physics

Outline

- Introduction
- Models and algorithms
- Numerical experiment setup
- Results and Discussion
- Summary

Outline

- Introduction
- Models and algorithms
- Numerical experiment setup
- Results and Discussion
- Summary

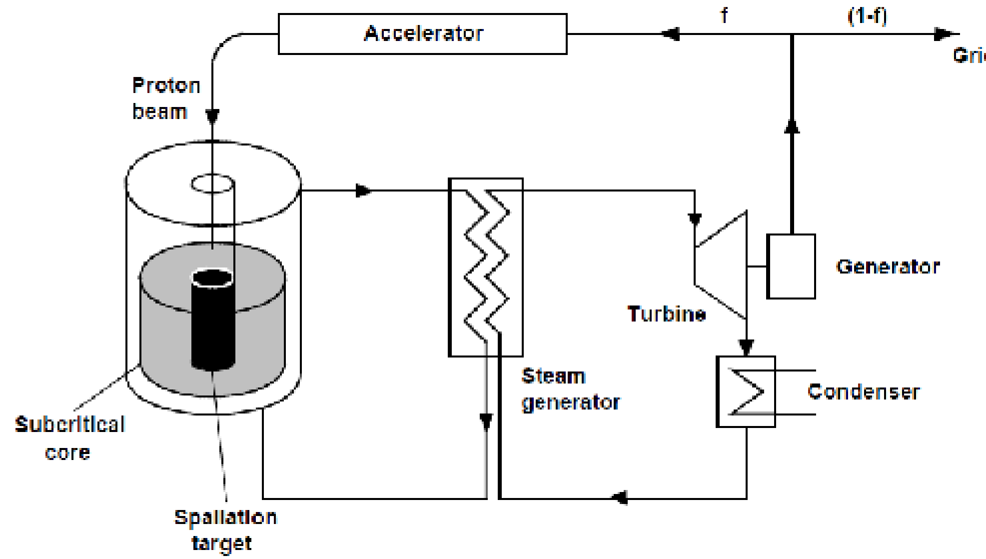
High-power neutron sources (NSs)

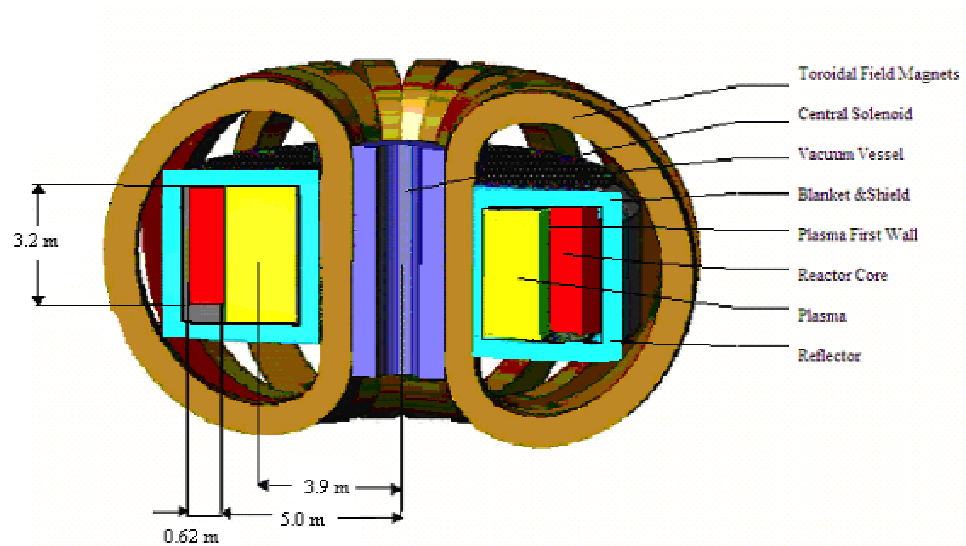
NS's types:

- ADSs – accelerator-driven systems
- FNSs – fusion neutron sources

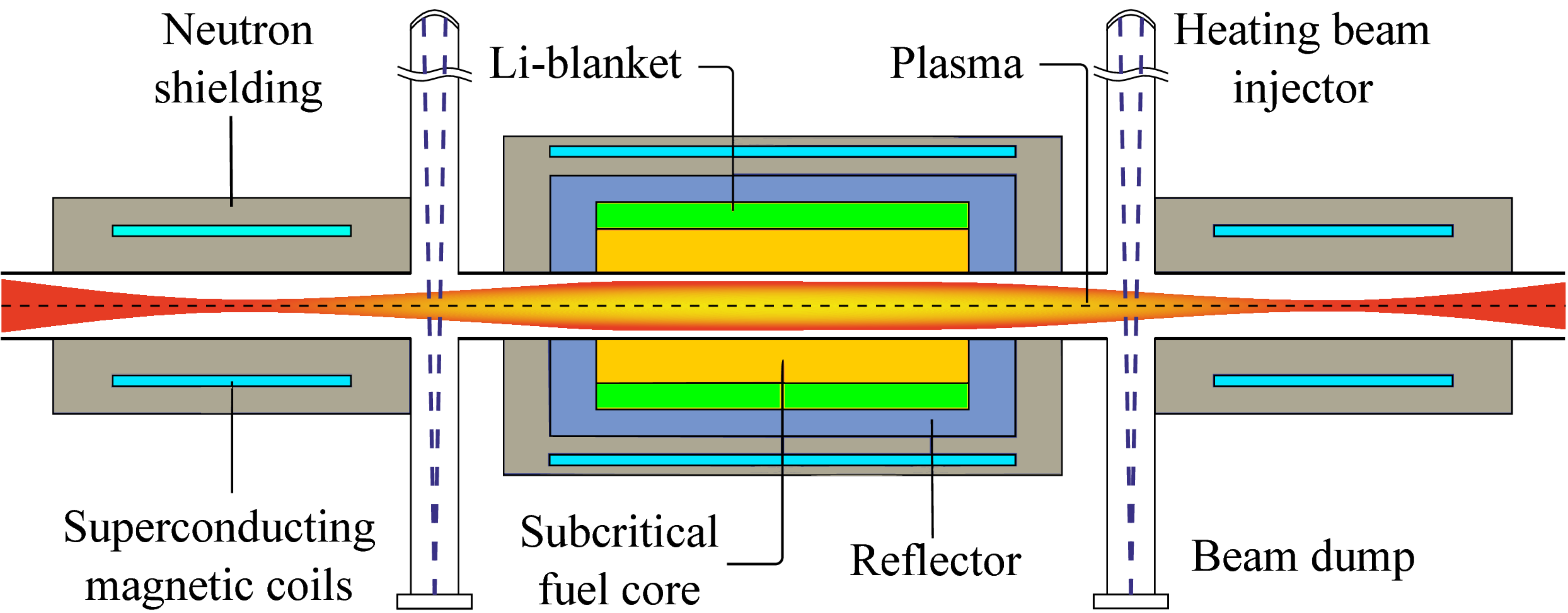
Possible applications:

- Material science
- Neutron scattering science
- <u>Using within subcritical hybrids</u>



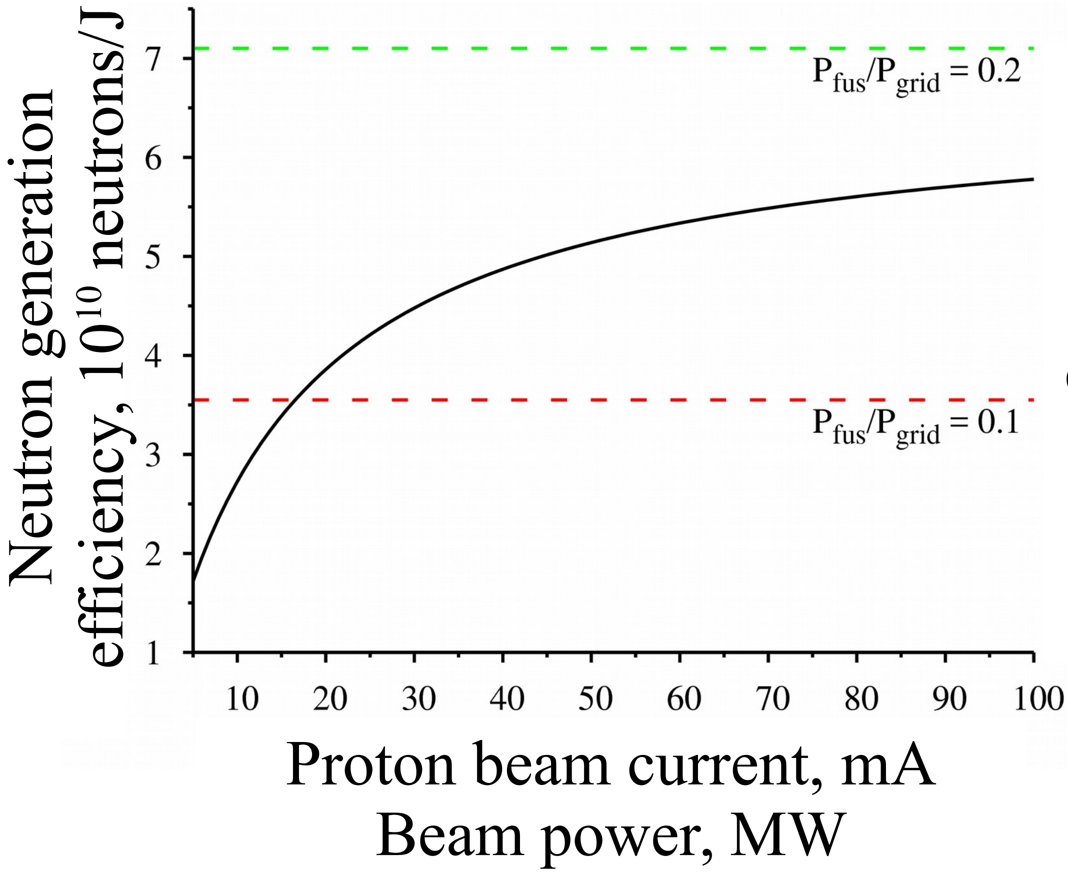


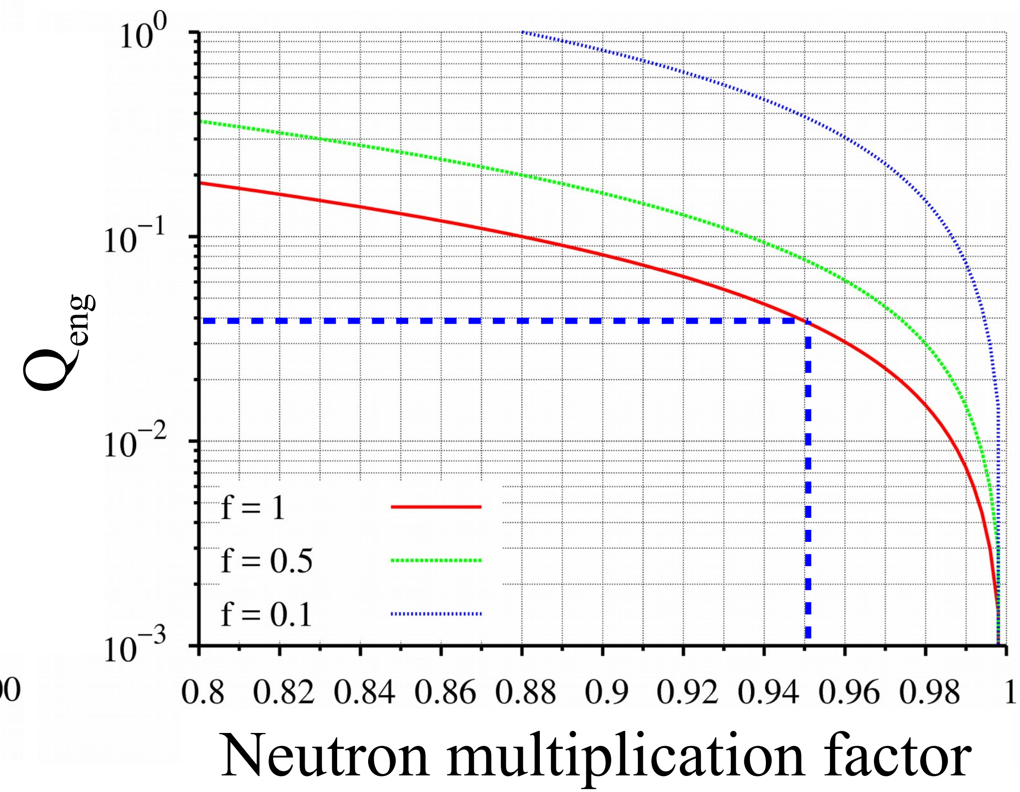
Hybrid with a mirror-based NS



The goal of the study

...is estimating capabilities of GDT- and GDMT-based fusion neutron sources as applied to using in hybrids

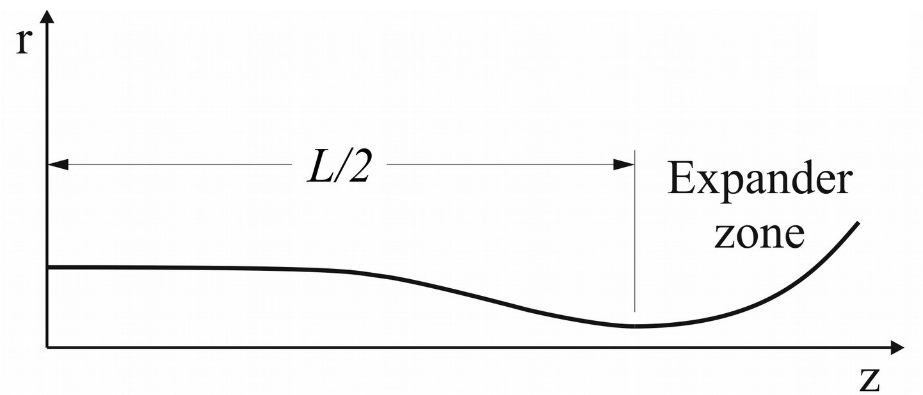


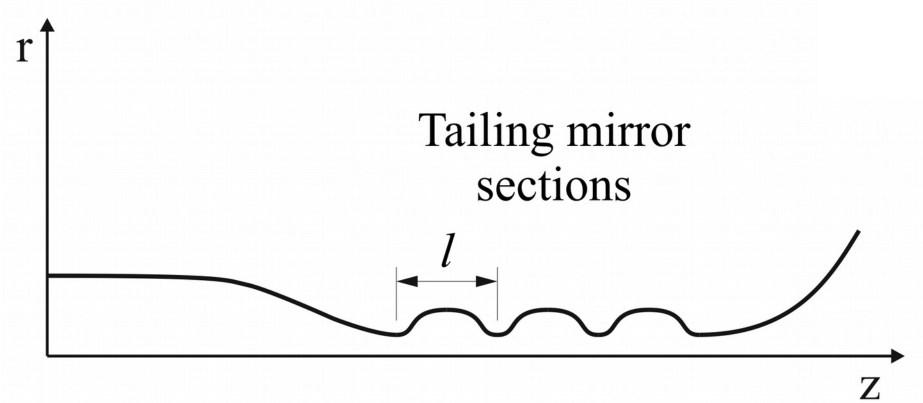


Searching for NS configurations with $Q_{eng} \approx 0.1 - 0.2$

Actually, Q_{eng} as low as $5 \cdot 10^{-2}$ is acceptable

GDT and GDMT concepts





- GDT:
  gas-dynamic trap, experimental facility at BINP

- GDMT:
  gas-dynamic multiple-mirror trap, a kind of "concatenation" of mirror facilities operated at BINP

Outline

- Introduction
- Models and algorithms
- Numerical experiment setup
- Results and Discussion
- Summary

DOL: the model for simulation of plasma in an axisymmetric mirror

Considered in the model are:

- Bounce-averaged kinetic equation for sloshing ions
- Particle and energy balance in background plasma
- Kinetic equation for plasma interactions with injected fast atoms
- Calculation of fusion reaction rates (with the finiteness of Larmor radii taken into account)

DOL: background plasma confinement regimes

- 4 main confinement regimes for background ions:
  - Collisional confinement by magnetic mirrors
  - Adiabatic confinement by mirrors
  - Collisional confinement by electrostatic potential
  - Adiabatic confinement by electrostatic potential
- Transient regimes are described by simple sum of confinement times

$$\tau_{gd} \gg \tau_{kin} \Leftrightarrow L \gg \lambda \frac{\ln R}{R}\left(1 - \frac{e_i \Delta \varphi_{mir}}{T_e}\right), \Delta \varphi_{mir} \leq 0$$

Differential evolution

$f:\mathbb{R}^N \rightarrow \mathbb{R}$ Optimized function

$\boldsymbol{x}:\{x_1, x_2, \ldots x_N\} \in \mathbb{R}^N$ Parameter vector

$X:\{\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots \boldsymbol{x}_k\}$ Set of parameter vectors

1. Randomly get three different parameter vectors

$$\{\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}\} \subset X : \{\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}\} \cap \{\boldsymbol{x}_i\} = \emptyset$$

2. Construct trial parameter vector

$$\boldsymbol{x}_i' = \boldsymbol{a} + F(\boldsymbol{b} - \boldsymbol{c})$$

3. Assign new value if the result is better than previous

$$f(\boldsymbol{x}_i') > f(\boldsymbol{x}_i) : \boldsymbol{x}_i = \boldsymbol{x}_i'$$

4. Go to the step 1.

for each $\boldsymbol{x}_i \in X$

R. Storn, K. Price, *Journal of Global Optimization*, **11** (4), 341 (1997)

Direct search

$f: \mathbb{R}^N \rightarrow \mathbb{R}$ Optimized function

$\boldsymbol{x}: \{x_1, x_2, \dots x_N\} \in \mathbb{R}^N$ Parameter vector

1. Construct *2N* of trial parameter vectors

$$\boldsymbol{x_i} \quad : \quad \{x_1, x_2, \dots, x_i{}' = x_i + \Delta_i, \dots x_N\}$$
$$\boldsymbol{x_{i+1}} \quad : \quad \{x_1, x_2, \dots, x_i{}' = x_i - \Delta_i, \dots x_N\}$$

2. Choose the best option from the constructed set

$$\boldsymbol{x_{best}} : f(\boldsymbol{x_{best}}) = max[f(\boldsymbol{x_1}), f(\boldsymbol{x_2}), \dots, f(\boldsymbol{x_{2N}})]$$

3. Replace parameter vector or reduce the scope

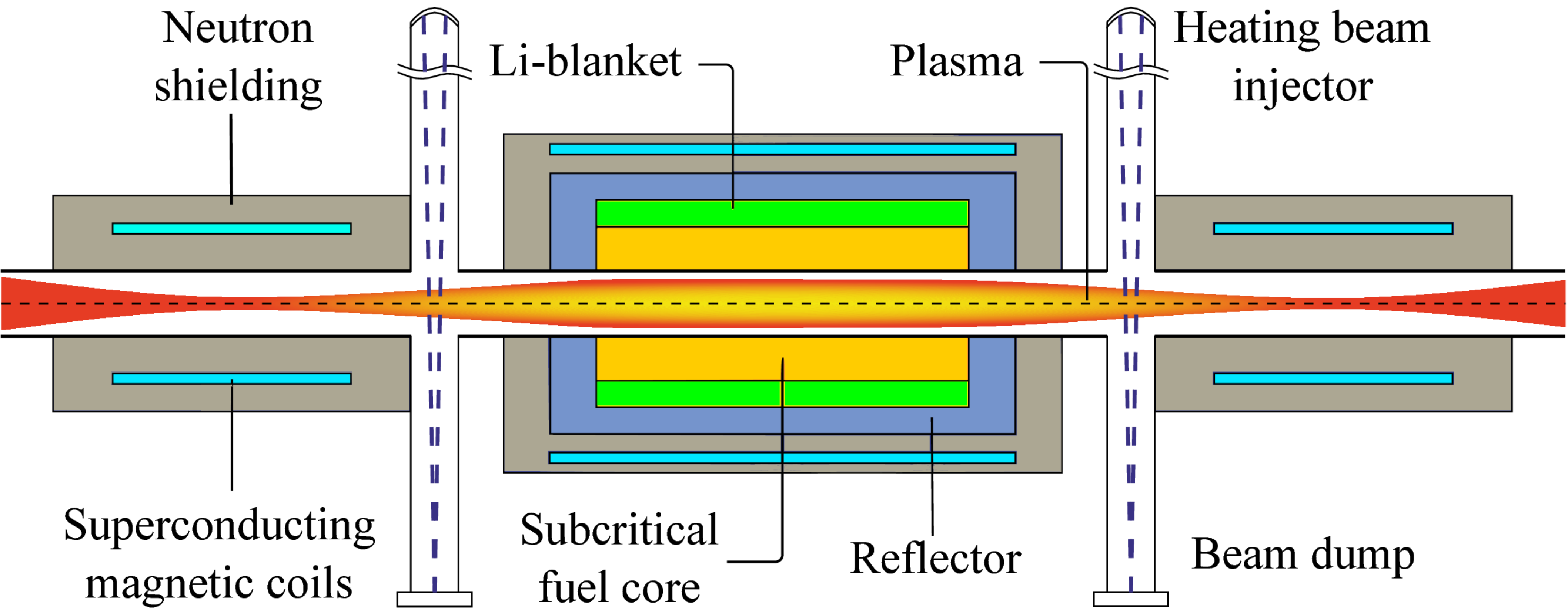
$$f(\boldsymbol{x_{best}}) > f(\boldsymbol{x}) \ ? \ \ \boldsymbol{x} = \boldsymbol{x_{best}} \ : \ \boldsymbol{\Delta} = \boldsymbol{\Delta}/2$$

4. Go to the step 1.

Outline

- Introduction
- Models and algorithms
- Numerical experiment setup
- Results and Discussion
- Summary

Layout of NS Configuration



- Right-angle injection at mirror ratio $R_{inj} > 1$
- Fixed magnetic field in mirrors $B_{max} = 15$ T

Optimization layout

Optimization goal: $max(Q_{pl})$, $Q_{pl} = P_{fus}/P_{in}$

Varied parameters:

- R_{max} – max. mirror ratio
- R_{inj} – mirror ratio at the injector position
- E_{inj} – energy of injected fast particles
- J_g – gas feed to maintain background plasma density
- r_{pl} – the radius of plasma column

Constraints:

- Transverse relative pressure $\beta_\perp \leq 0.5$
- Fraction of captured beam power $P_{cap}/P_{in} \leq 0.9$
- Nearly gas-dynamic regime of background ions confinement

Series of Calculations

GDT	GDMT	NS-L	NS-P
$\tau_{kin} = k \times \tau_{gd}$	$\tau_{kin} = \tau_{gd}$	$\tau_{kin} = \tau_{gd}$	$\tau_{kin} = \tau_{gd}$
$k = 1, 2, 5, \infty$	$R_{eff} = N \times R_{max}$	$L \in [10, 100]$ m	$P_{\text{in}} \in [20, 140]$ MW
	$N = 5, 10, 20$	$P_{\text{in}} = P_{\text{in},0} \sqrt{L / L_0}$	$N = 1, 10$
		$N = 1, 10$	

GDT and GDMT: $P_{\text{in},0} = 100$ MW, $L_0 = 20$ m

NS-L and NS-P: $Q_{pl} = Q_0 P^X L^Y$

Outline

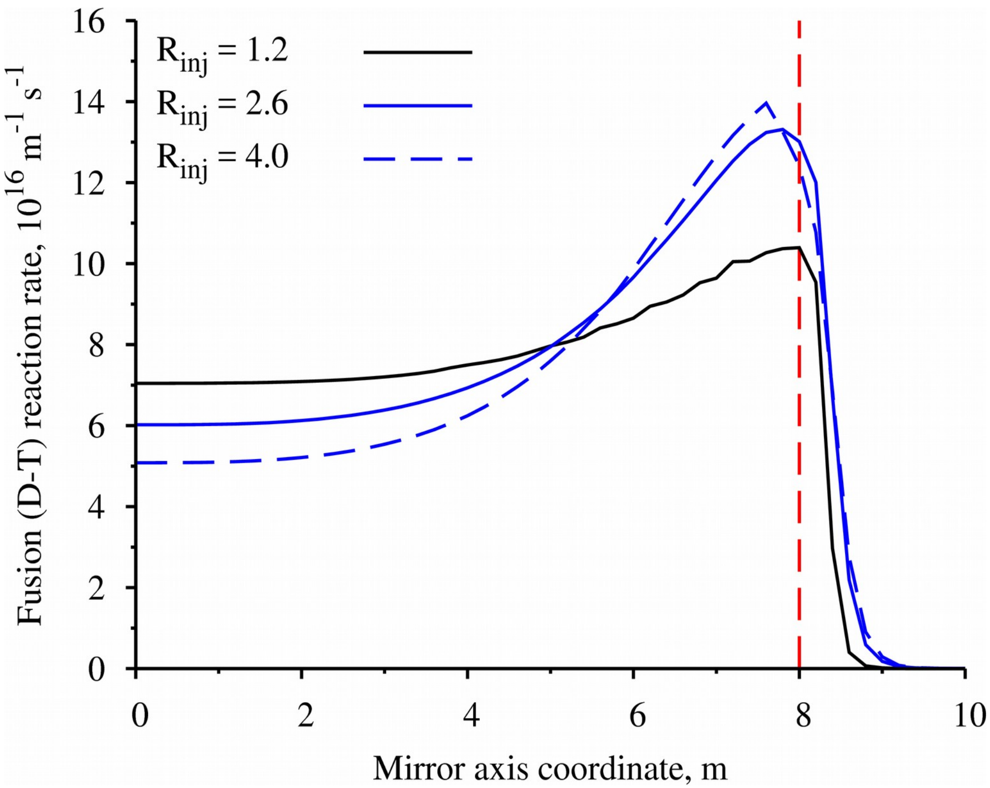
- Introduction
- Models and algorithms
- Numerical experiment setup
- Results and Discussion
- Summary

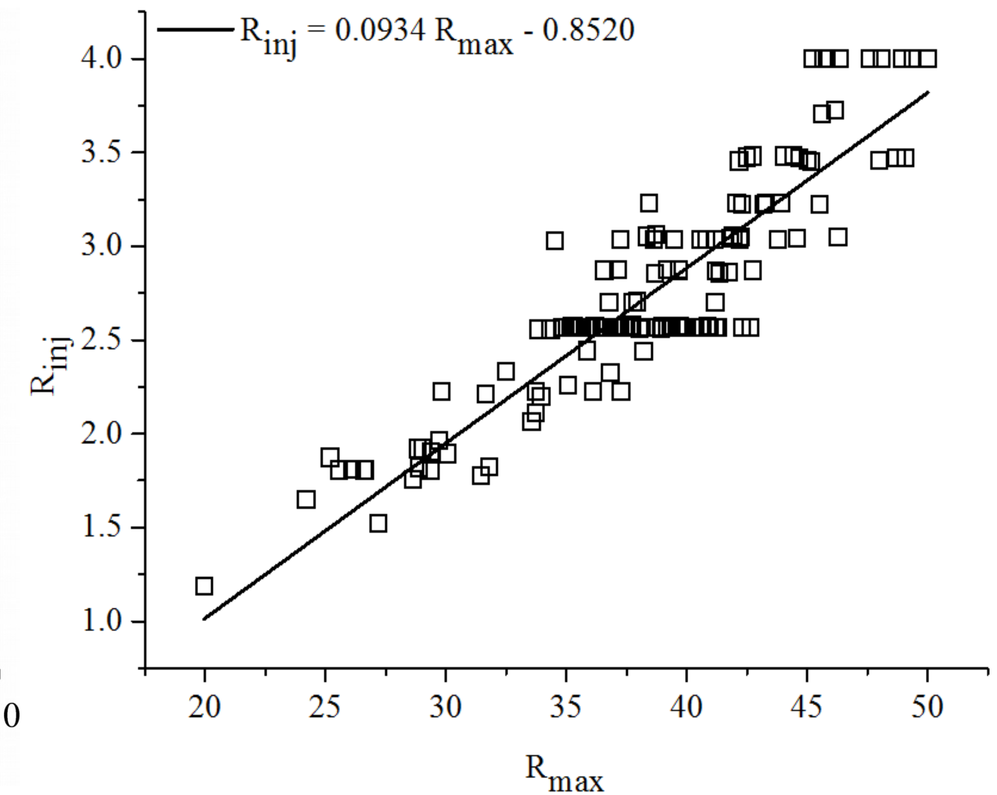
GDT Series

Parameter	k = 1	k = 2	k = 5	k = ∞
E_{inj}, keV	122	123	120	230
J_g, eq. kA	9.0	8.4	6.6	0
T_e, keV	1.0	1.1	1.3	21.2
τ_{gd}/τ_{kin}	1	0.5	0.2	0
$\beta_\perp$		≈ 0.5		
P_{cap}/P_{in}	0.70	0.74	0.80	0.90
$10^2\ Q_{pl}$	4.0	5.2	7.7	135.3

Fusion gain factors of GDT-based sources proved to be quite limited. The results leave a room for using GDT-based NSs in proof-of-principal facilities or testing stands

Example of redundancy: magnetic field influence on fusion gain factors





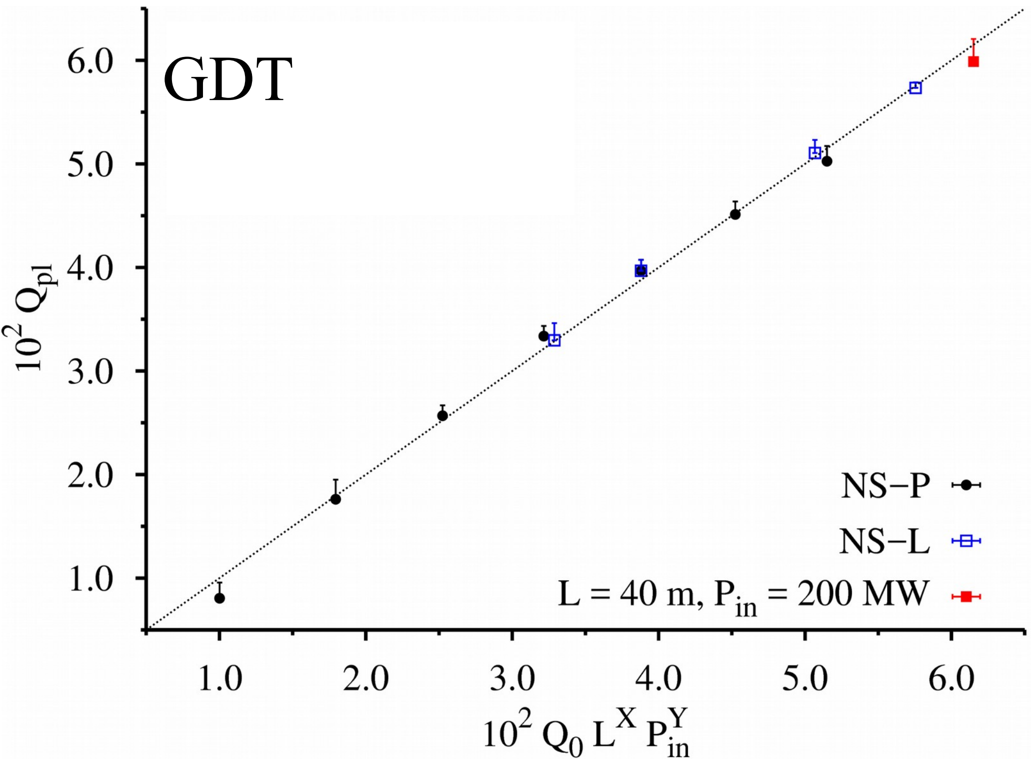
- R_{inj} and R_{max} variables taken separately do not strongly affect achieved fusion gains
- However, smaller R_{inj} and R_{max} values are more favorable for using NS in a hybrid system

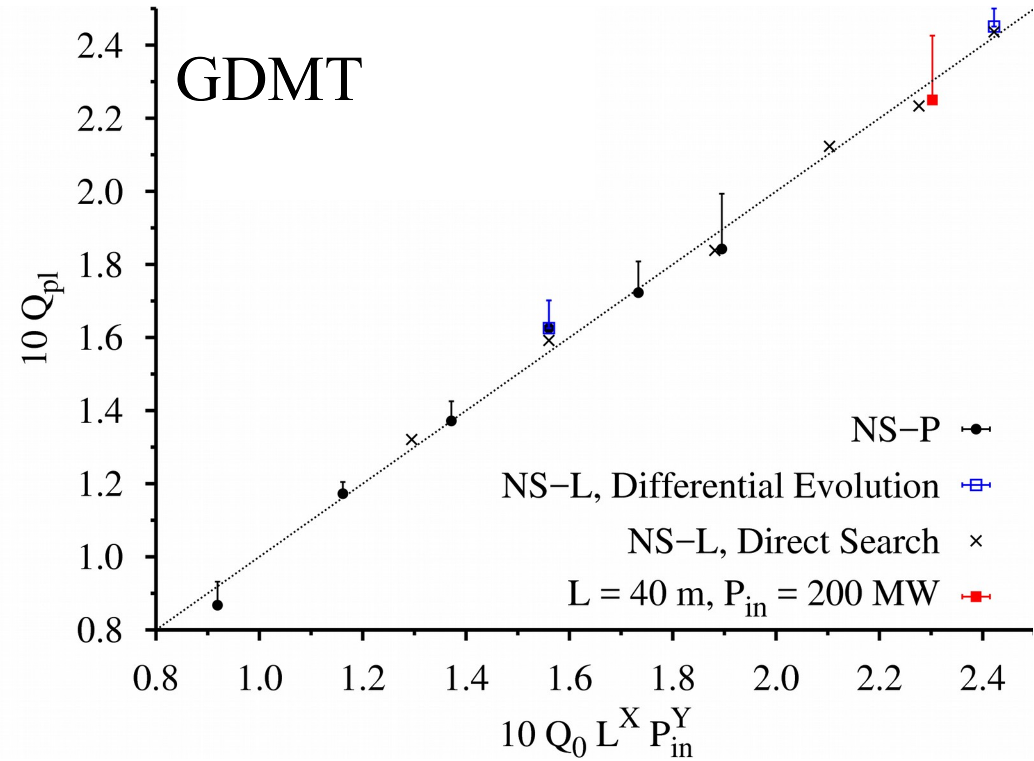
GDMT Series

Parameter	N = 5	N = 10	N = 20
E_{inj}, keV	135	129	144
J_g, eq. kA	4.8	3.8	3.1
T_e, keV	1.7	2.1	2.5
τ_{gd}/τ_{kin}		≈ 1	
$\beta_\perp$		≈ 0.5	
P_{cap}/P_{in}	0.78	0.86	0.87
$10^2\ Q_{pl}$	10.4	16.3	22.7

Neutron generation efficiency comparable to that of ADSs can be reached for GDMT-based source at mirror-to-mirror distance $L_0 = 20$ m and heating power $P_{in,0} = 100$ MW

Fusion gain as a function of NS length and heating power





$$\boldsymbol{Q_{pl} = Q_0 L^X P^Y}, [L] = \mathrm{m}, [P_{\mathrm{in}}] = \mathrm{MW}$$

$$Q_0 = 1.4\cdot10^{-3} \pm 2\cdot10^{-4}$$
$$X = -1.8\cdot10^{-1} \pm 2\cdot10^{-2}$$
$$Y = 8.4\cdot10^{-1} \pm 3\cdot10^{-2}$$

$$Q_0 = 1.1\cdot10^{-2} \pm 1\cdot10^{-3}$$
$$X = -1.6\cdot10^{-2} \pm 1.8\cdot10^{-2}$$
$$Y = 5.8\cdot10^{-1} \pm 3\cdot10^{-2}$$

Summary

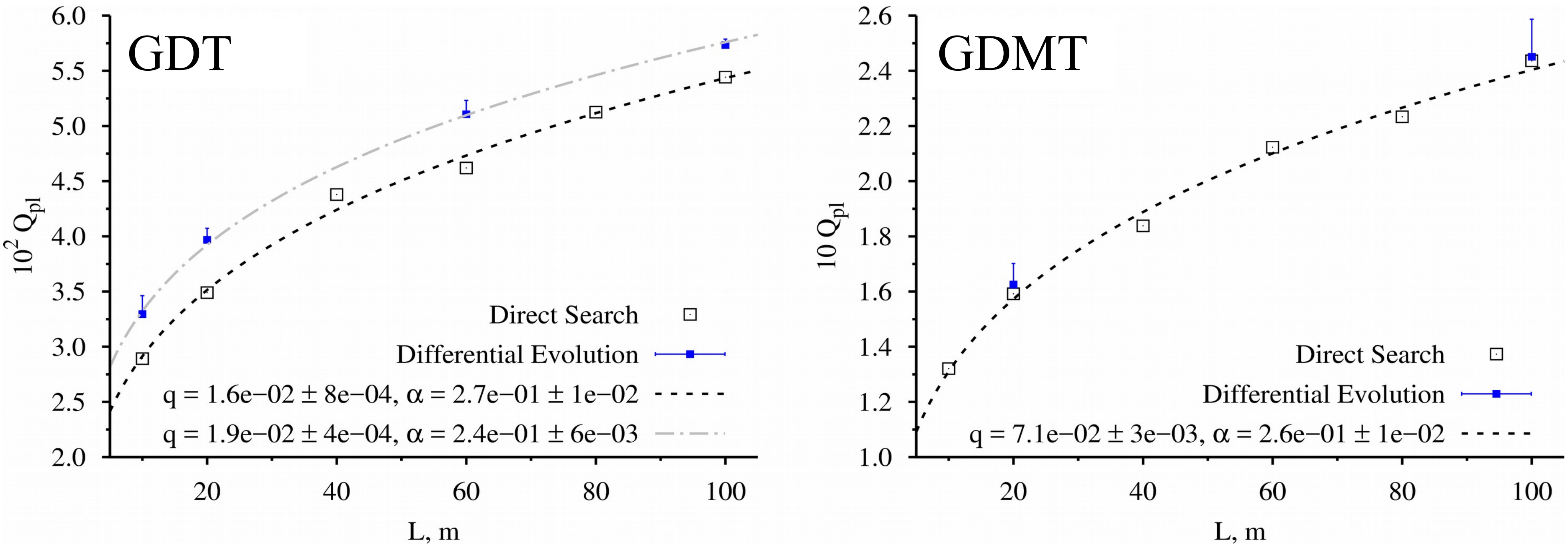
- Performance of several NSs based on GDT and GDMT concepts has been considered.
- Each considered configuration has been optimized in order to determine the maximum achievable fusion gain
- The results listed further are valid for trap configurations with mirror-to-mirror distances $L \in [10, 100]$ m, heating powers $P_{in} \in [20, 200]$ MW and magnetic field in the mirrors $B_{max} = 15$ T.
- Provided background plasma is kept in nearly gas-dynamic regime of confinement, one can expect achieving $Q_{pl} \approx 5 \cdot 10^{-2}$ in GDT-based NS and $Q_{pl} \approx 1.5 \cdot 10^{-1}$ in GDMT-based NS.
- Power-law relation between fusion gain, heating power and mirror-to-mirror distance has been obtained. It can be used further for fast upper-bound estimates of fusion gain factors achievable in mirror-based NSs similar to those considered in this study.

References

1. D. V. Yurov, V. V. Prikhodko, "Hybrid systems for transuranic waste transmutation in nuclear power reactors: state of the art and future prospects", *Physics-Uspekhi*, **57** (11), 1118-1129 (2014)
2. D. V. Yurov, V. V. Prikhodko, Yu. A. Tsidulko, "Nonstationary model of an axisymmetric mirror trap with nonequilibrium plasma", *Plasma Physics Reports*, **42** (3), 210-225 (2016)
3. D. V. Yurov, V. V. Prikhodko, "Optimization of a mirror-based neutron source using Diferential Evolution algorithm", *Nuclear Fusion* (accepted)
4. D. V. Yurov, V. V. Prikhodko, P. A. Bagryansky, "Length and Power Scalings of GDT- and GDMT-based Neutron Sources", AIP Conf. Proc. (proceedings of this conference)

Thank you for your attention!

Differential evolution and Direct search algorithms: difference in the results



$$Q_{pl} = q\,L^{\alpha}, [L] = \mathrm{m}$$

- Approximately the same power factors (α) in the scalings
- In the case of GDMT-based NS the difference between fusion gain factors at equal lengths and heating powers is below 5 %