# Mathematical simulation of the unclosed 2-G HTS shield

*Evgeny Kulikov[1], Gennady Dorofeev[1,2], Valery Drobin[1], Henryk Malinovski[1], Alexander Smirnov [1] , Grigory Trubnikov [1]*

1. JINR (VBLHEP), 141980 Dubna, Russian Federation
2. Kurchatov Institute, 123182 Moscow, Russian Federation

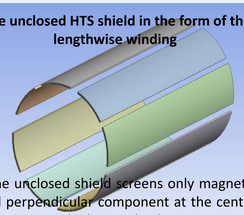
*E-mail: kulikov_box_work@mail.ru*

## Abstract

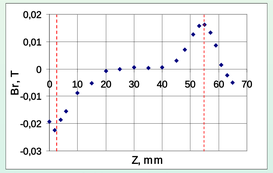
The mathematical model based upon the authors' previously introduced unclosed shield physical conception [1,3] was developed. This model allows calculation of the magnetic field radial and longitudinal components in shield systems. One-dimensional problem of a thin-wall coil with the unclosed shield for the various relative positions of the shield and the solenoid was solved. Evaluation of magnetic field homogeneity was carried out. Verification of the model was made on the small-size shields. The developed model makes it possible to calculate shield parameters subject to solenoid magnetic field characteristics and shield material. The obtained results are necessary to construct systems with the high magnetic field homogeneity, in particular, for the electron cooling system of charged particle beams at the new accelerator complex which is being developed at JINR in Dubna, Russia.

## Unclosed shield: what is it ?

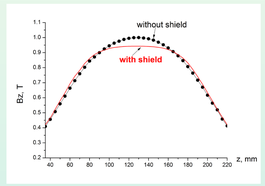
**The unclosed HTS shield in the form of the lengthwise winding**



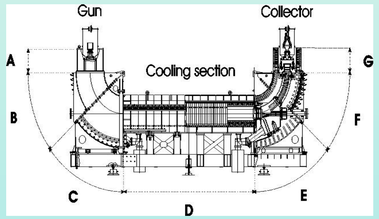
➢The unclosed shield screens only magnetic field perpendicular component at the centre and transmits the longitudinal component.




The magnetic field perpendicular component on the inner shield surface




## Application: Electron Cooling System (ECS) for NICA




**Scheme of the ECS magnetic system**
A, G – gun and collector solenoids, B,C,E,F – segments of the beam-bending magnets (toroids), D–central solenoid (cooling section).

Electron cooling is an extremely useful method to obtain high intensity ion beams with a low momentum spread [5].

| Parameters of the ECS [4] | |
|---|---|
| coolling section length, m | 4 - 6 |
| longitudinal magnetic field, kGs | up to 2 |
| magnetic field homogeneity, $\Delta B/B$ | 1e-05 |
| the electron energy, MeV | up to 4 |

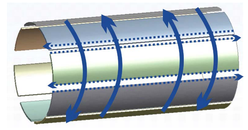
**The generation of the highly homogeneous magnetic field is the main requirement to construct an electron cooling system for charged-particle beams [4].**

## Conclusion

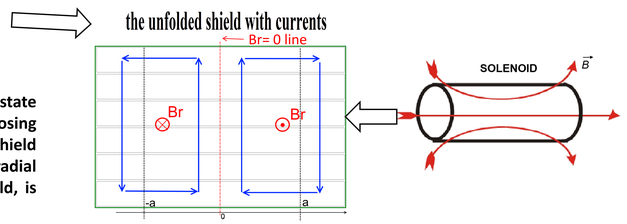
- The shielding problem is solved at the first approximation; the gained magnetic field components fit the experimental curves
- Length of the homogeneity area $\Delta B_Z / B_Z = 10^{-5}$ for the solenoid with 2*L* = 4 m and R = 150 mm is about 2.4 m
- The errors of the magnetic fields calculation is 7- 10 %
- We intend to continue perfecting the mathematical model.

## Physical conception and mathematical model

**shielding currents**



•In the first approximation, the "tile" lengthwise structure of the HTS tapes is similar to the plate that is not rolled in a tube yet and located in the external normal magnetic field.




**•According to the critical-state model, the density of these closing currents which flow in the shield areas penetrated by the radial component of the solenoid field, is supposed to be critical**

### Basic equations

Let $I(z)$ be the effective shielding current at the point $z$:

$$I(z) = \frac{2}{\mu_0}\frac{\partial B^{ext}_{\ \rho}}{\partial z} a\delta$$

Since the total current in the shield must be zero it follows that

$$\int_{-a}^{a} \frac{I(z)}{\delta} dz - 2J_c\delta\left(L_s - a\right) = 0$$

$$\Downarrow$$

$$\frac{2aB^{ext}_{\ \rho}(a)}{\mu_0} = J_c\delta\left(L_s - a\right)$$

### Assumptions:

- Cylindrical coordinates are used with the origin taken in the shield centre
- The magnetic field has an axial symmetry $\Rightarrow B_\varphi = 0$
- $\delta \ll R_s$ where $\delta$ - the shield thickness, $R_s$ - its radius
- $\frac{\partial H_z}{\partial \rho} \ll \frac{\partial H_\rho}{\partial z}$
- Suppose the shield is the system of closed turns

### The radial magnetic field on the external shield surface

$$B_\rho(x) \approx \int_{-a}^{a} \frac{\mu_0}{2\pi}\frac{I(z)}{\delta}\frac{dz}{z-x} + \frac{\mu_0}{2\pi} J_c\delta \times \ln\left|\frac{L-x}{L+x}\frac{a+x}{a-x}\right| - B^{ext}_\rho(x)$$

where $B^{ext}_\rho(x) = \beta_1 x + \beta_n x_n^n, \quad n = 3,5...2\mathbb{N}+1$

### The longitudinal magnetic field inside the shield

$$B^{\Sigma}_Z(x) = B_Z(x) + B''_z(x) - \int_{-a}^{a} \frac{\mu_0 I(z)}{2\delta} \frac{R_s^{\ 2}}{\left(R_s^{\ 2} + \left(z-x\right)^2\right)^{3/2}} dz$$

$$B''_z(x) = \sum_{n=1,2} \frac{\mu_0 J_c \delta}{2}\left[\frac{0.5l_1 - \xi_n}{\sqrt{R_s^{\ 2} + \left(0.5l_1 - \xi_n\right)^2}} + \frac{0.5l_1 + \xi_n}{\sqrt{R_s^{\ 2} + \left(0.5l_1 + \xi_n\right)^2}}\right]$$

$l_1 = L - a$

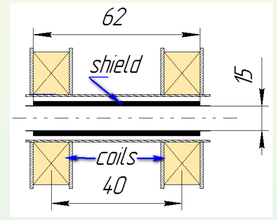
$\xi_n = a + (-1)^n x + \frac{l_1}{2}$

*a* - the half-width of the area occupied by the non-saturated currents *I(z)*
*L*- the half-length of the shield
*Jc* - critical current density

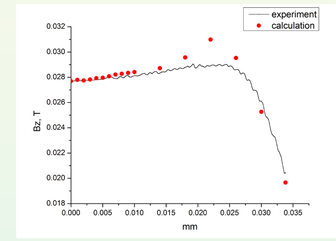
$B^{ext}_\rho(x)$ - the external radial magnetic field

$B_Z(x)$ - the longitudinal magnetic field of the solenoid

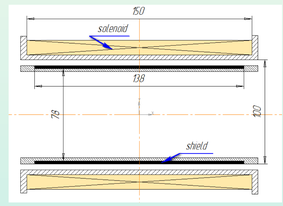
## Verification and results



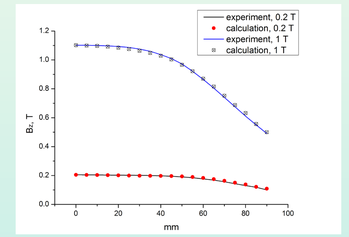

Construction of the magnetic system N1



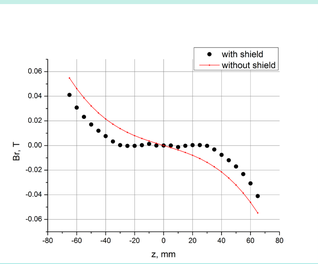

Comparison the experimental data with calculated data for ***Bz*** component of the magnetic field



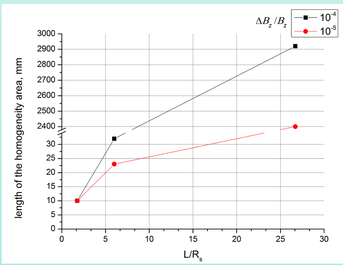

Construction of the magnetic system N2




Comparison the experimental data with calculated data for ***Bz*** component of the magnetic field




Calculated ***Br*** components on the external shield surface under ***Bz*** = 0.2 T




Length of the homogeneity area ***Bz*** *vs.* reduced length of the shield

**References**

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