The corrections for one dimensional model of helical flux compression generators from two dimensional model

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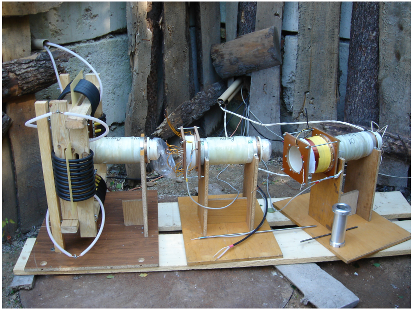
Introduction

- What is the Helical Flux Compression Generator (HFCG)?
- What is the problems of models?
- The corrections from 2D model to the 1D model.

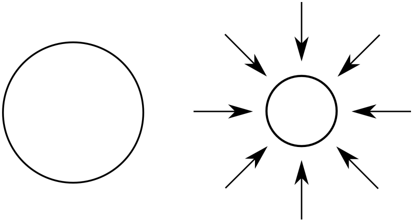
Helical Flux Compression Generator (HFCG) is a device based on compression magnetic field by a closed current-conducting circuit. It is used for high amplitude impulse of magnetic field and current.



The research supervisor is professor Baryshevsky.

Operation principle

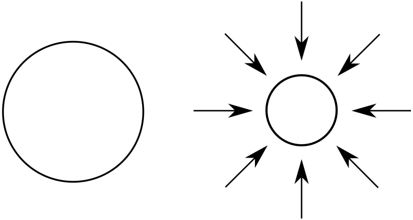
Let us take solitary motionless closed circuit with current. The circuit is superconducting as a rough approximation.



The conserved quantity of magnetic flux is:

$$\Phi = \int\int_S \mathbf{B} d\mathbf{S} = const \quad (1)$$

Let us take solitary motionless closed circuit with current. It is superconduction as a rough approximation.



The conserved quantity of magnetic flux is:

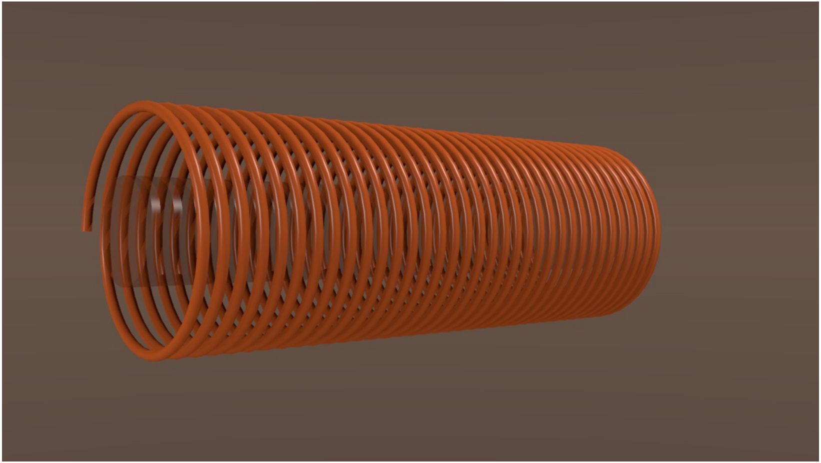
$$\Phi = L \cdot I = const \tag{2}$$

where L is the inductance of circuit, I is the current in circuit. Taking into account resistance and other magnetic flux loss

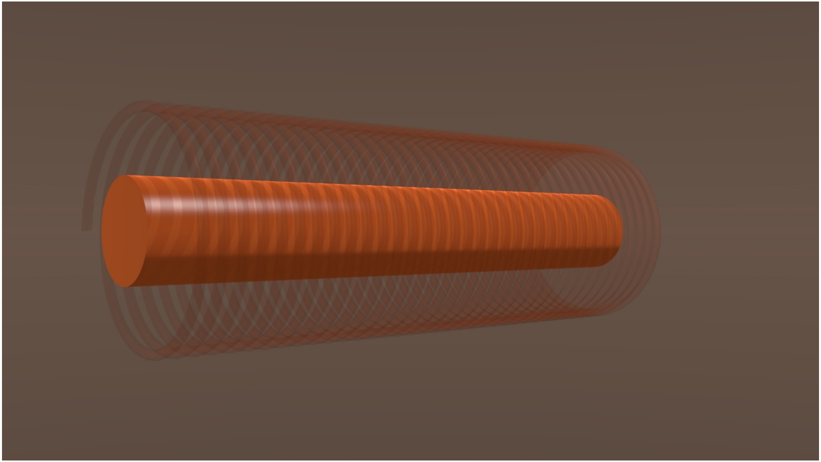
$$\frac{d(L \cdot I)}{dt} + RI = 0 \tag{3}$$

HFCG Structure

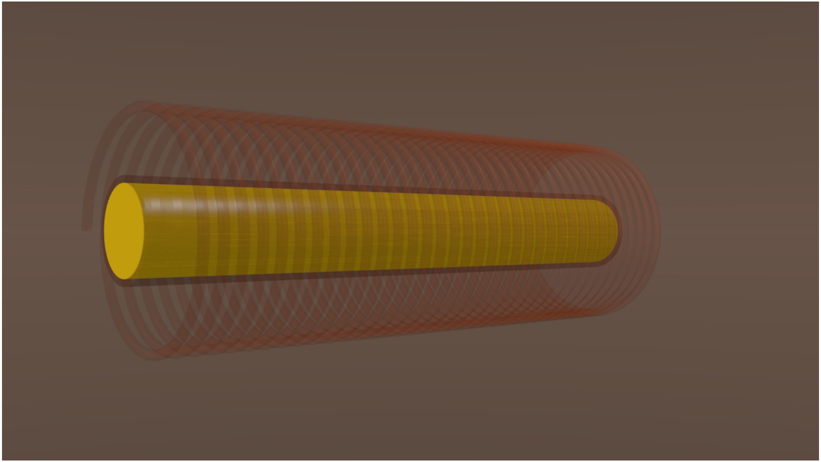
Stator is a solenoid



Armature is a conductive pipe

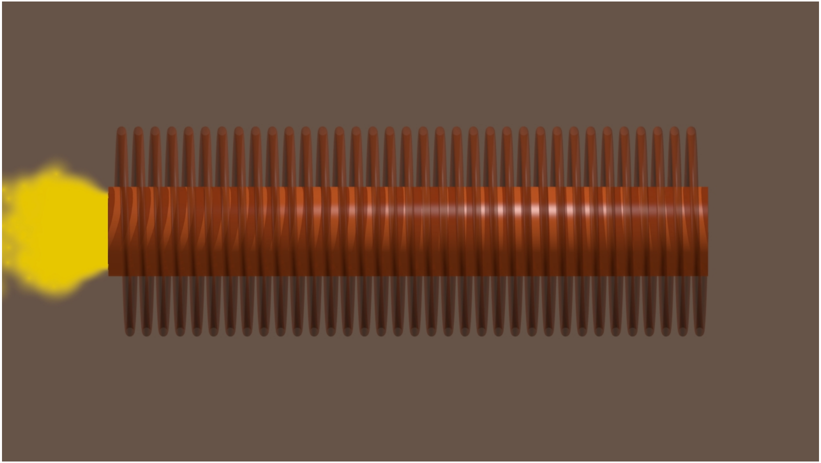


Explosives are inside armature



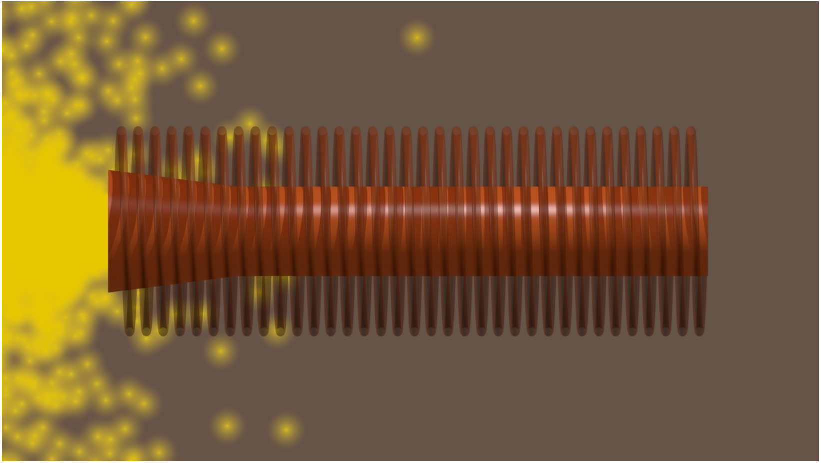
Operation principle

The initial current in the stator produces a magnetic flux. The explosives are ignited from the head of the armature.

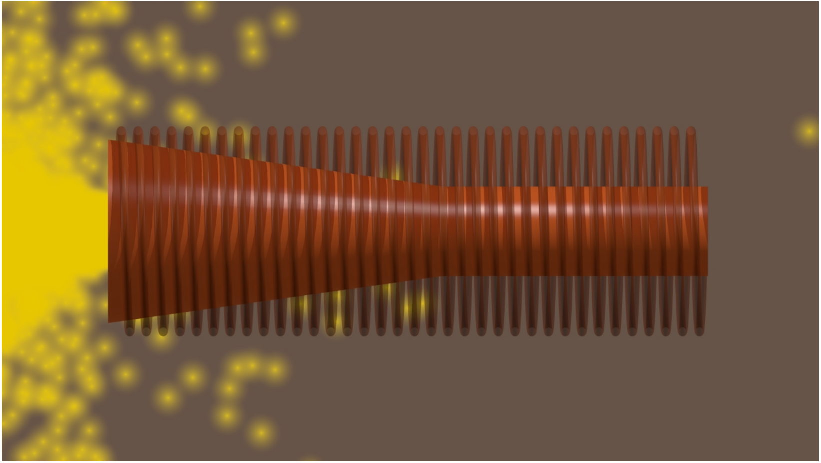


Operation principle

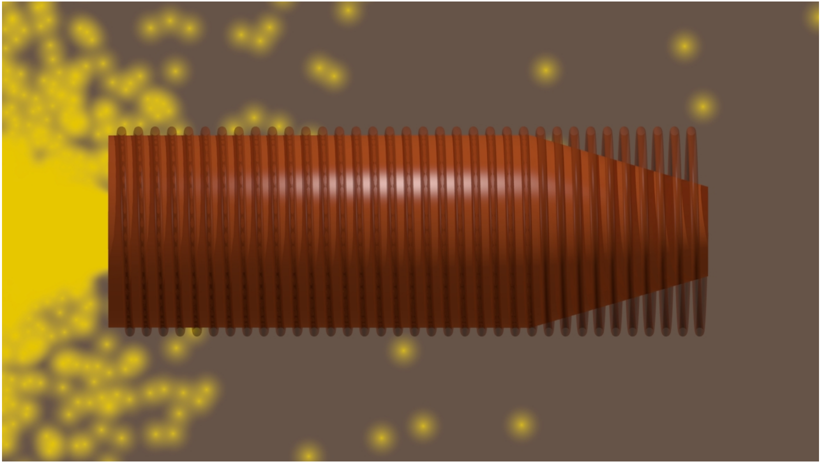
The expanded armature moves along the generator length like a cone, reaches the stator and shorts out sequentially the turns of the stator.



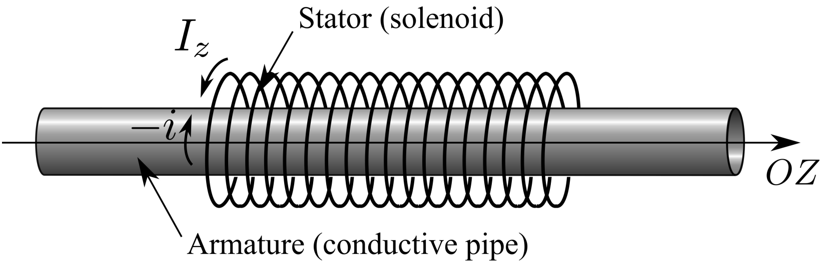
Operation principle



Operation principle



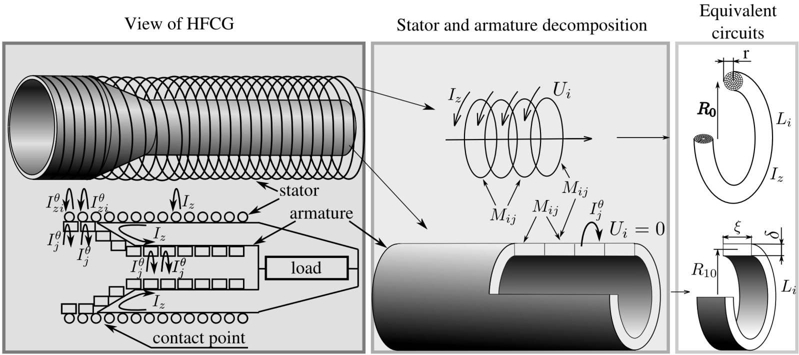
Operation principle



Equation for magnetic flux loss (simplified):

$$L\frac{dI_z}{dt} + \frac{dL}{dt}I_z + RI_z = 0 \tag{4}$$

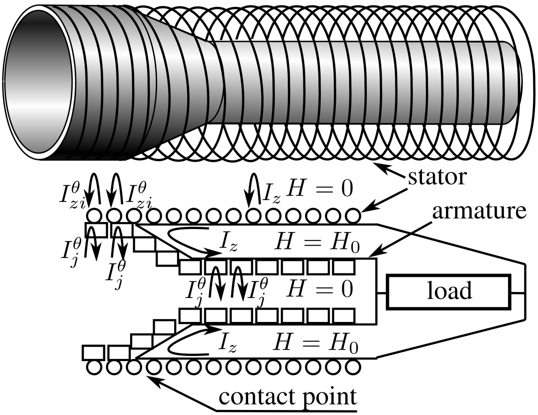
Two dimension model of the HFCG



Two dimension model is very complex and takes a lot of time to simulate. The model have predictable power. How we can make one dimensional model better?

Currents in the HFCG, contact point model

Currents I^{θ}_{zi} are cause of intrinsic magnetic flux losses.



$$L\frac{dI_z}{dt} + \frac{dL}{dt}I_z + RI_z + \frac{dL_{intrincic}}{dt}I = 0 \qquad (5)$$

The equations of the magnetic flux preservation will be written in the form of combined equations for each equivalent current circuit with self-inductance $L_i = M_{ii}$ and effective resistance R_i:

$$\sum_{j}^{n} \frac{d}{dt} \left(M_{ij} I_j \right) + R_i I_i = U_i \tag{6}$$

where U_i is the voltage because electric circuit, M_{ij} is the mutual inductance between equivalent current circuits i and j, n in the quantity of equivalent current circuits.

The difference

1D model

$$L(t) = \int\limits_0^{l_s} \frac{dL}{dx} dx$$

$$\frac{dL(t)}{dt} = v \int\limits_0^{l_s} \frac{d^2L}{dx dx_0} dx$$

$$R(t) = \int\limits_0^{l_s} \frac{dR}{dx} dx$$

2D model

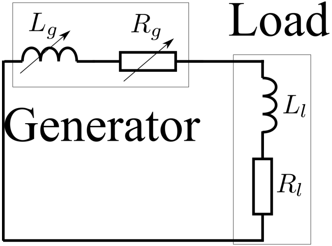
$$\sum_j^n \frac{d}{dt} (M_{ij} I_j) + R_i I_i = U_i$$

$$L = \frac{\Psi_L}{I}, \quad L = \frac{\Psi_s - \Psi_{arm}}{I}$$

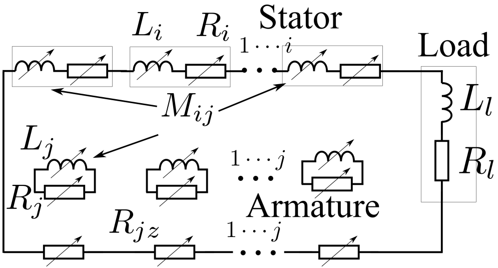
$\Psi = LI$, magnetic flux in non switched stator's turns

where Ψ_L is magnetic flux with worked stator, I is current in the HFCG.

Difference in electrical circuit diagram



1D model



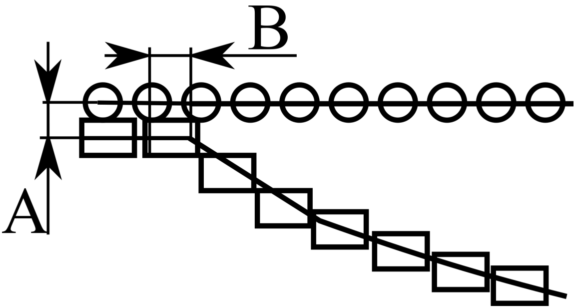
2D model

The difference is very strong, but the description of HFCG work have to be same.

The most important differences

- Intrinsic magnetic flux loss
- Inductance
- Resistance
- Pressure of magnetic field

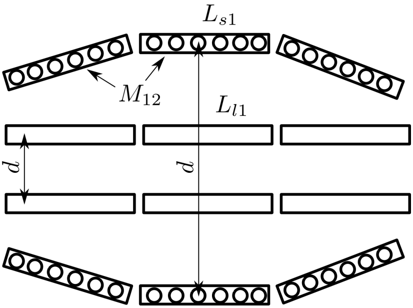
Intrinsic flux losses in contact point, pressure of magnetic field



The self inductance of closed part HFCG (between A and B) is intrinsic flux losses.

$$\frac{dL}{dt} = \frac{\Delta L_z}{\Delta t} + \frac{\Delta L_g}{\Delta t} \qquad (7)$$

Inductance for multi section HFCG

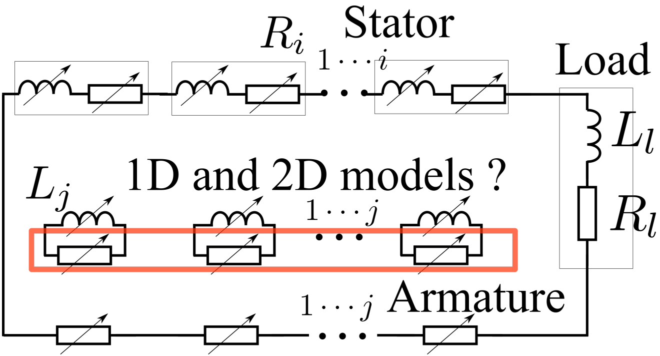


$$L = \sum_i L_{si} - \sum_i L_{li} + \sum_{i,j \geq i+1} M_{ij} \quad (8)$$

where L_s is self inductance of generator section, L_l is self inductance of mirrored currents in armature, M is mutual inductance between generator sections.

- This is very fast and sufficiently accurate.

Resistance



- 1D: Loses in armature are included in effective resistance of HFCG $R = R_s + R_l$
- 2D: Loses in armature are calculated separately

The system of Maxwell's equations

Effective resistance from non-linear magnetic diffusion.

$$\frac{\partial H_z}{\partial x} = -\frac{1}{\rho_0(1+\beta Q)} E_y = -j_y, \tag{9}$$

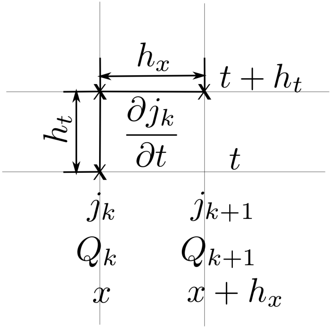
$$\frac{\partial E_y}{\partial x} = -\mu_0 \frac{\partial H_z}{\partial t}, \tag{10}$$

$$\frac{\partial Q}{\partial t} = (1+\beta Q)\rho_0 \left(\frac{\partial H_z}{\partial x}\right)^2. \tag{11}$$

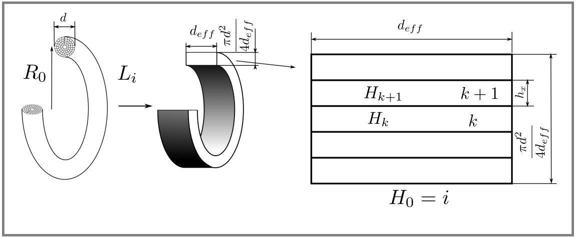
boundary condition:
$x = 0 : H_z(0,t) = H_0(t), t \geq 0,$
$t = 0 : H_z(x,0) = 0, x \geq 0.$

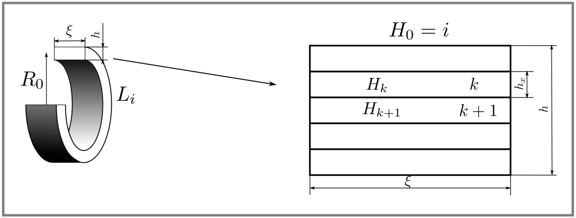
The finite difference scheme of the nonlinear magnetic diffusion equation for the implicit Euler method

$$\rho_0\beta j_{k+1}^{t+h_t}\frac{Q_{k+1}^t-Q_k^t}{h_x}+\rho_0(1+\beta Q_{k+1}^t)\frac{j_{k+1}^{t+h_t}-j_k^{t+h_t}}{h_x}= \\ =-\mu_0\left(\frac{\partial H_0}{\partial t}-h_x\sum_{p=1}^{k}\frac{j_p^{t+h_t}-j_p^t}{h_t}\right). \quad (12)$$



Spatial decomposition for nonlinear magnetic diffusion





Effective resistance

$$-\int\limits_S \mathbf{P} ds = \int\limits_V \frac{\partial}{\partial t}(Q+W)dV, \tag{13}$$

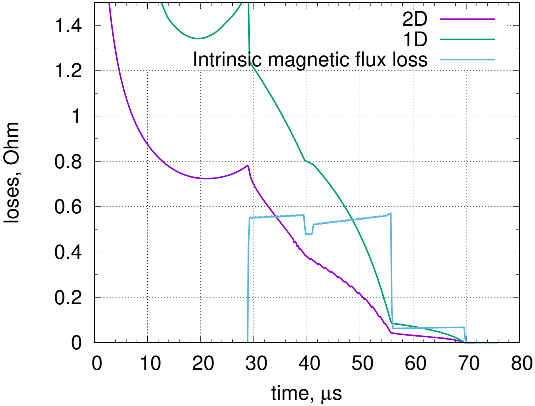
where P is Poynting vector (the energy transfer per unit area per unit time), Q is Ohmic losses and W is diffused energy of electromagnetic field.

$$R = \frac{\sum\limits_{k=1}^{n} \left(Q_k^{t+h_t} - Q_k^t + W_k^{t+h_t} - W_k^t\right)}{I^2 h_t}. \tag{14}$$

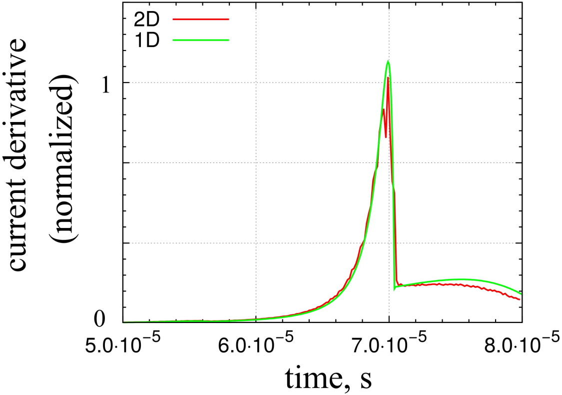
where R is effective resistance of circuit, I is current, h_t is time step.

- This is good way to take into account conductors heating correctly.

Effective resistance and intrinsic flux loss



Current derivative



Thank you

Thank you for your attention!