



Electromagnetic Design of HTS insert for NMR Magnet in Consideration of Screening Currents

Yi Li

28 August 2017



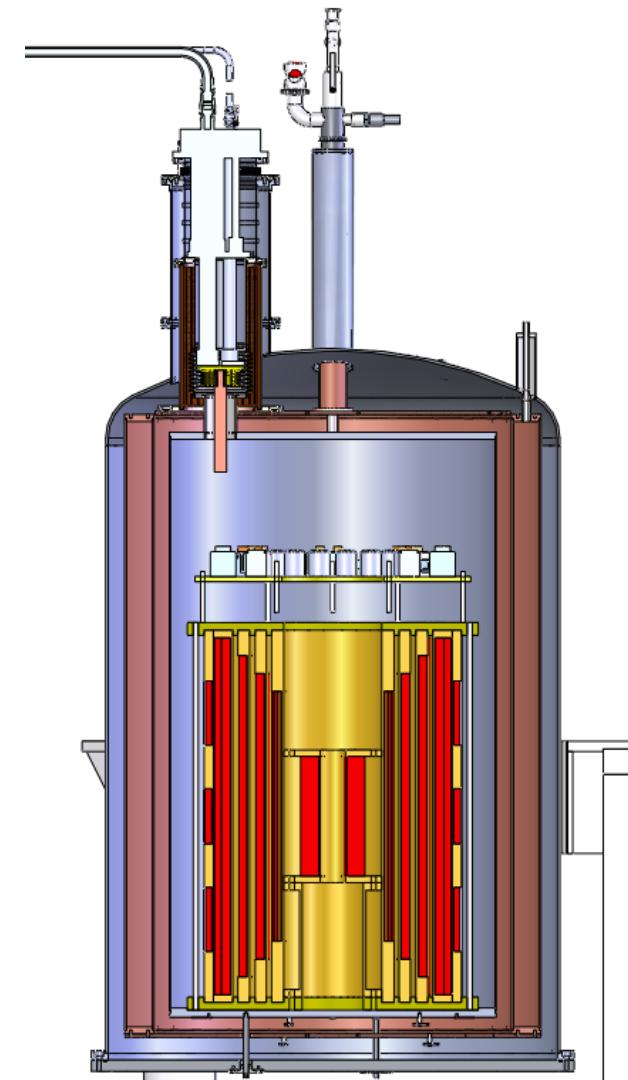
Outline

- **A design scheme of the HTS insert**
- **Parametric study of design inputs on the outputs**
- **Sensitivity analysis of homogeneity in consideration of screening current effect**
- **A design scheme with screening current taken into consideration**



Design Requirements

- **B₀=27T**
 - LTS outsert 15T
 - HTS insert 12T
- **Cold bore>50mm**
 - 62mm for design of insert
 - +Passive shimming, HTS shimming
- **Φ10 10ppm p2p Homog.**
 - 1ppm for design





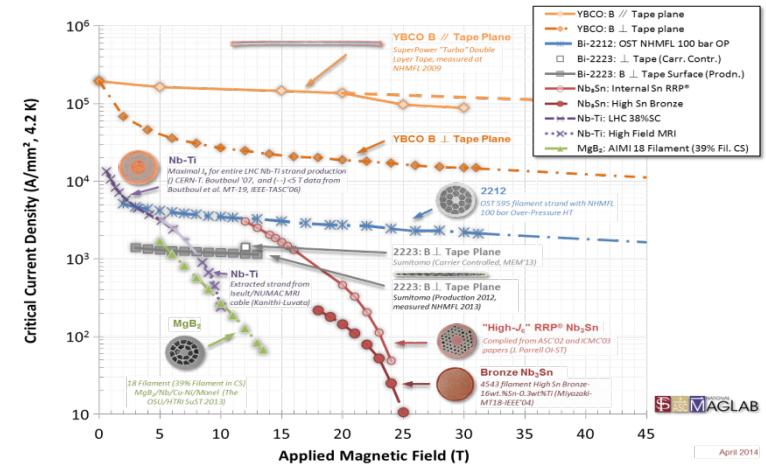
HTS Wire Options

Bi2212;

Bi2223;

YBCO:

- **High Critical Jeng:** ~2000MA/m² @ 27T Bpara, small Rout at 12T » limited outsert bore (cost↓)
- **High Critical tensile stress:** 550MPa
- **Double pancake**
no react process, easy for coil fabrication



MAGLAB

April 2014



Design with e.g. :
SuperPower YBCO
SCS4050, 4mm*0.1mm

One DP width:
Former + T_Plate
4mm+1mm+4mm+1m
=10mm



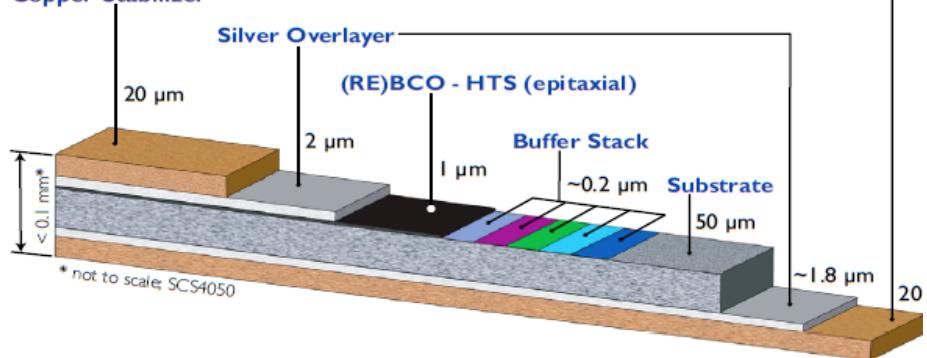
SuperPower® 2G HTS Wire Specifications

Spec SF = Stabilizer Free SCS = Surround Copper Stabilizer	SCS3050	SF4050	SCS4050	SF6050	SCS6050	SF1205
Minimum I_c	60	80	80	120	120	240
Widths	3	4	4	6	6	12
Total Wire Thickness	0.1	0.055	0.1	0.055	0.1	0.055
Standard Copper Stabilizer Thickness	0.04	n/a	0.04	n/a	0.04	n/a
Critical Tensile Stress	> 550		> 550		> 550	
Critical Axial Tensile Strain	0.45%	0.45%	0.45%	0.45%	0.45%	0.45%
Critical Bend Diameter in Tension	11	11	11	11	11	11
Critical Bend Diameter in Compression	11	11	11	11	11	11

Wire formulations

- **Cable Formulation (CF)** wire, utilizes standard wire chemistries that exhibit best performance at around 77K, the nitrogen temperature regime, and in very low magnetic fields for cable and other similar applications.
- **Advanced Pinning (AP)** wire exhibits superior performance at a range of temperatures from 77K to as low as 4K and is well suited for in-magnetic-field applications such as motors, generators and other high-field magnetics.
- **Fault Current Limiter (FCL)** wire utilizes the CF chemistry and begins with a thicker (100 micron), highly resistive Hastelloy® substrate suitable for these grid protection devices. This application, which does not call for any copper stabilizer, can also benefit from the option to vary the thickness of the silver cap layer.

Copper Stabilizer



Substrate Thickness:

50 μm Hastelloy® C-276 [or 100 μm for SF12100]

Substrate Yield Strength:

1200 MPa at 77 K [650 MPa for SF12100]

Substrate Resistivity:

125 $\mu\Omega\cdot\text{cm}$ – higher resistivity leads to lower current ac loss

Magnetic Properties:

non-magnetic, leads to lower ferromagnetic



Optimization Algorithm: Improvements for design of HTS magnet

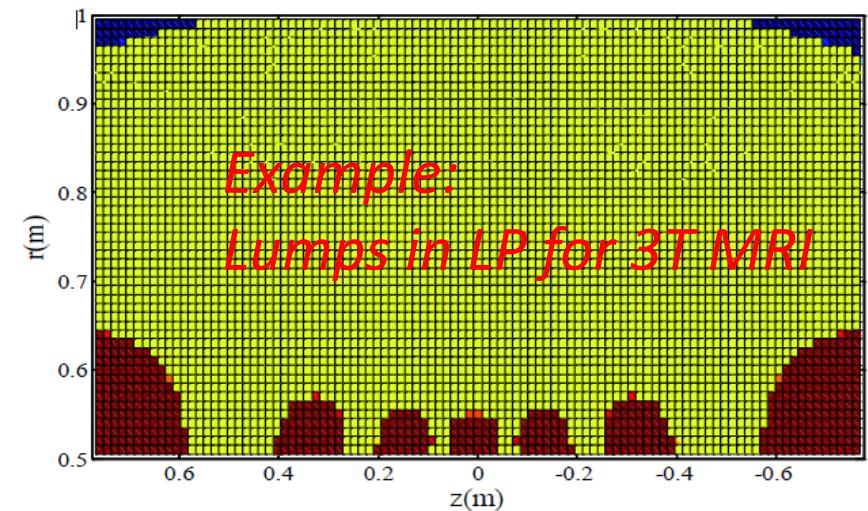
- Linear Programming for layer winding LTS magnet

$$\min V = \sum_{i=1}^N 2\pi r_i \frac{|I_i|}{J_0}$$

s.t. $|\mathbf{A} \cdot \mathbf{I} - B_0| / B_0 \leq$ Homogeneity,

$|\mathbf{B} \cdot \mathbf{I}| \leq$ Strayfield,

$-I_{\max} \leq I_i \leq I_{\max}, I_{\max} = J_0 \times A_{\text{mesh}}$.

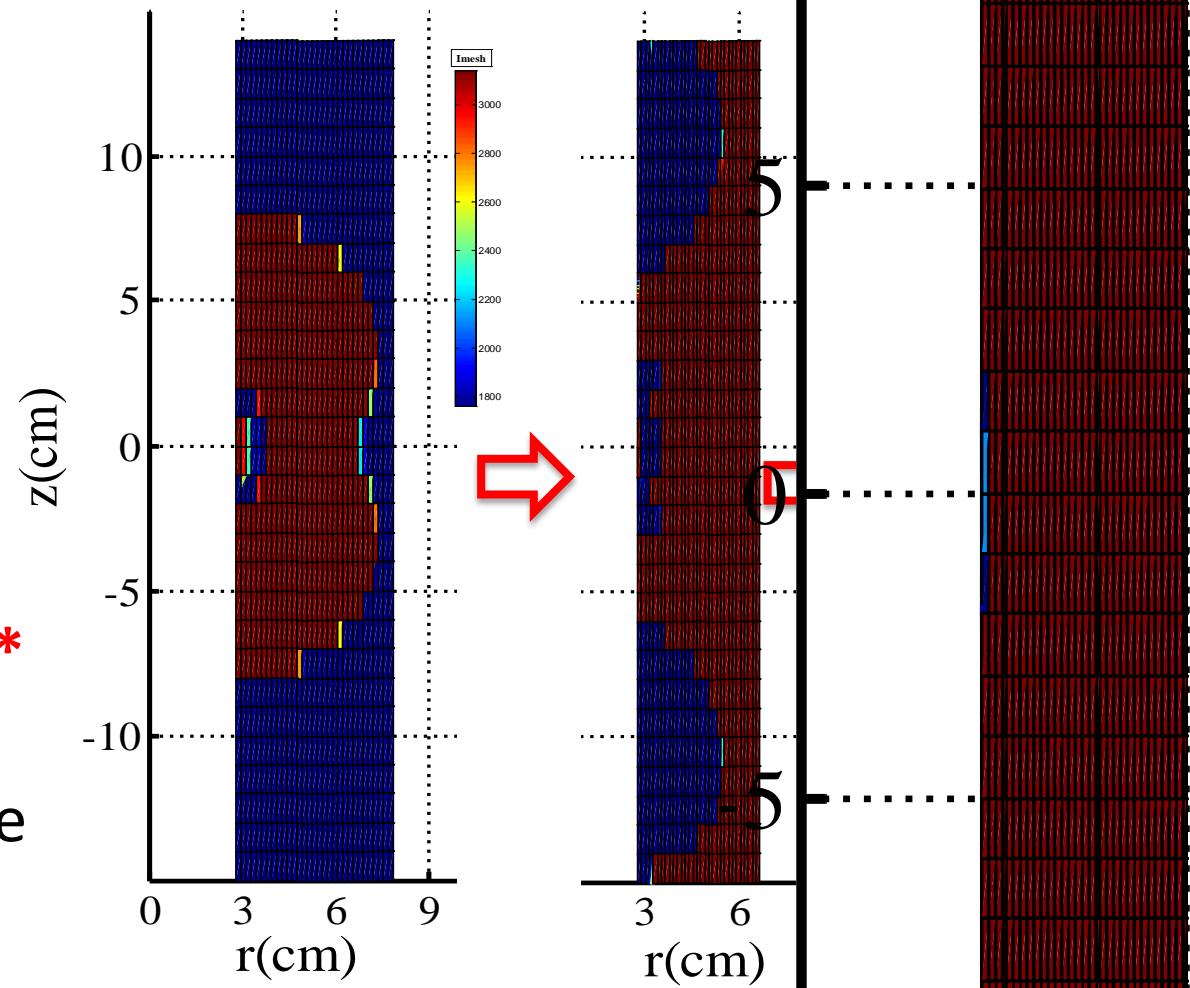


- each discretized mesh taken as a “current loop”
- a solution of current distribution will be several current lumps, normally: lumps attached to the inner boundary of the domain
- each lump shaped as a real-sized cross section of a coil in the next step



Linear Programming for design of DP winding HTS magnet

- current loop
→rectangular shape
- swap the ri of the meshes
→lumps with same outer boundary for joint making, and inside notch structure*
- still minimize volume
→simple notch structure



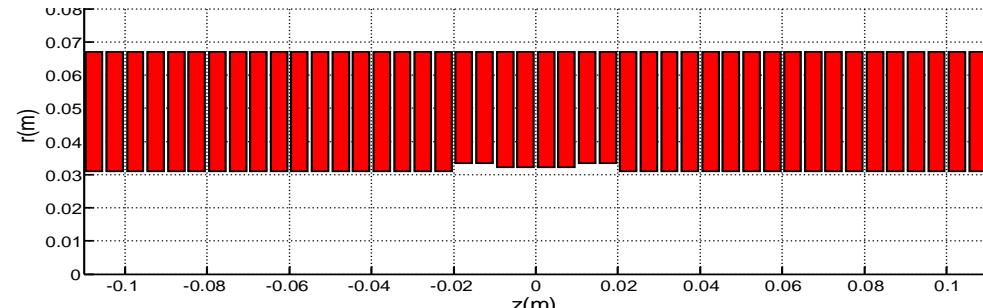
*Yukikazu Iwasa, et al., "A High-Resolution 1.3-GHz/54-mm LTS/HTS NMR Magnet"

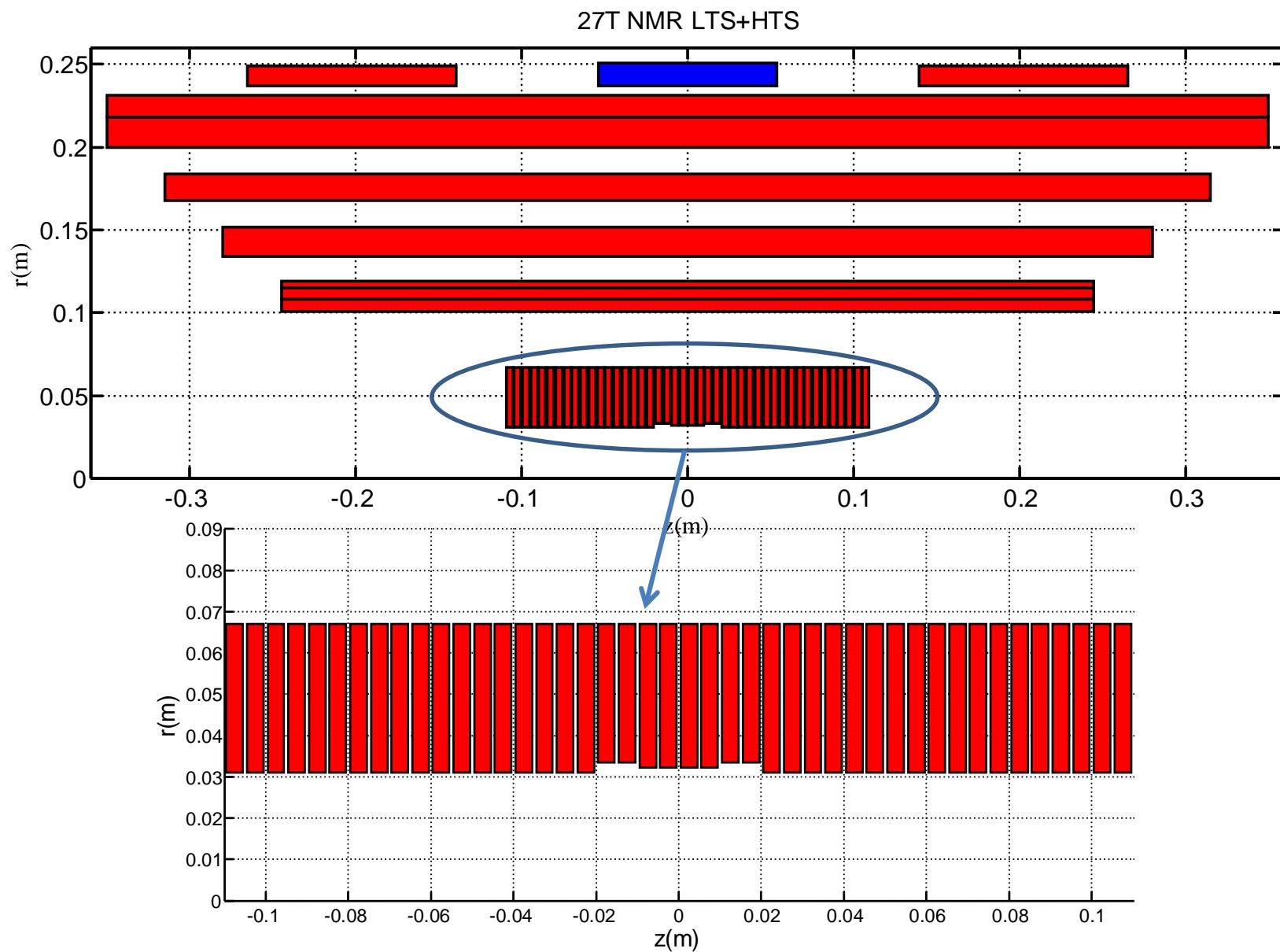


Design scheme example

HTS insert design result	
Magnet inner Dia.	62mm
Magnet outer Dia.	134mm
Magnet length	22cm
Central field	$L15+H12=27T$
Operating current Engineering J	150A $300MA/m^2$
Maximum Br (LTS part included)	4.7T
Current margin	56.7% @27T
Homo p2p	<1ppm

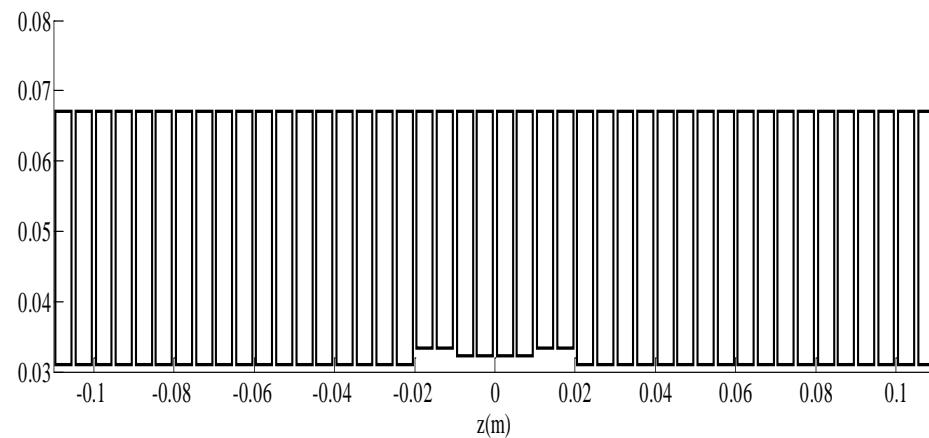
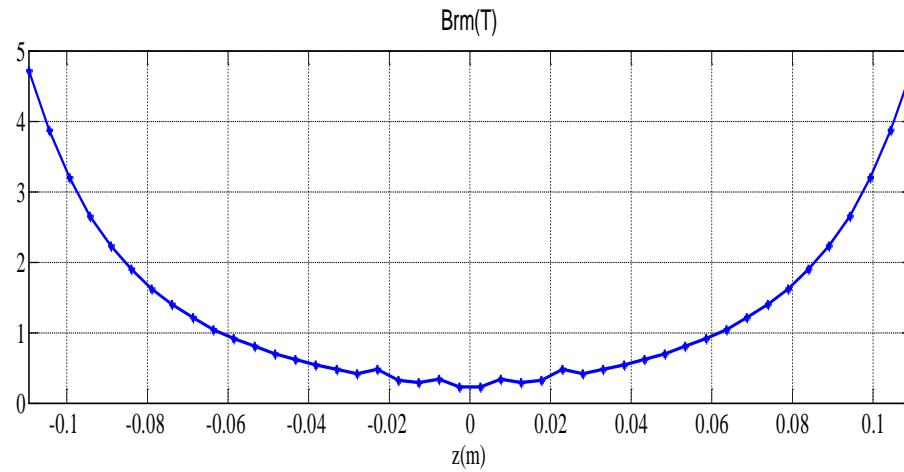
HTS insert design result	
DP thickness	36mm
DP width	10mm
Piece length /DP	$111m \times 2 = 222m$
Number of DPs	22
Number of notch DPs	4
Inner Dia. of notch DPs	$64.4mm \times 2$ $66.8mm \times 2$
Total tape length	$\sim 4.83km$



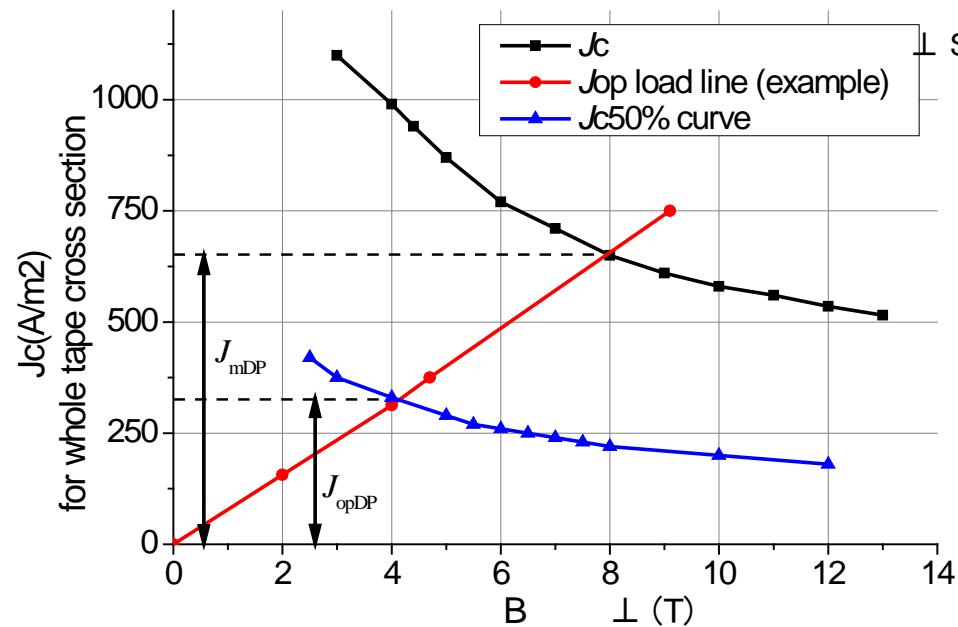




Max. Br in each pancake and current margin of the HTS magnet



- Brmax: 4.7T
- Imargin: ~57%

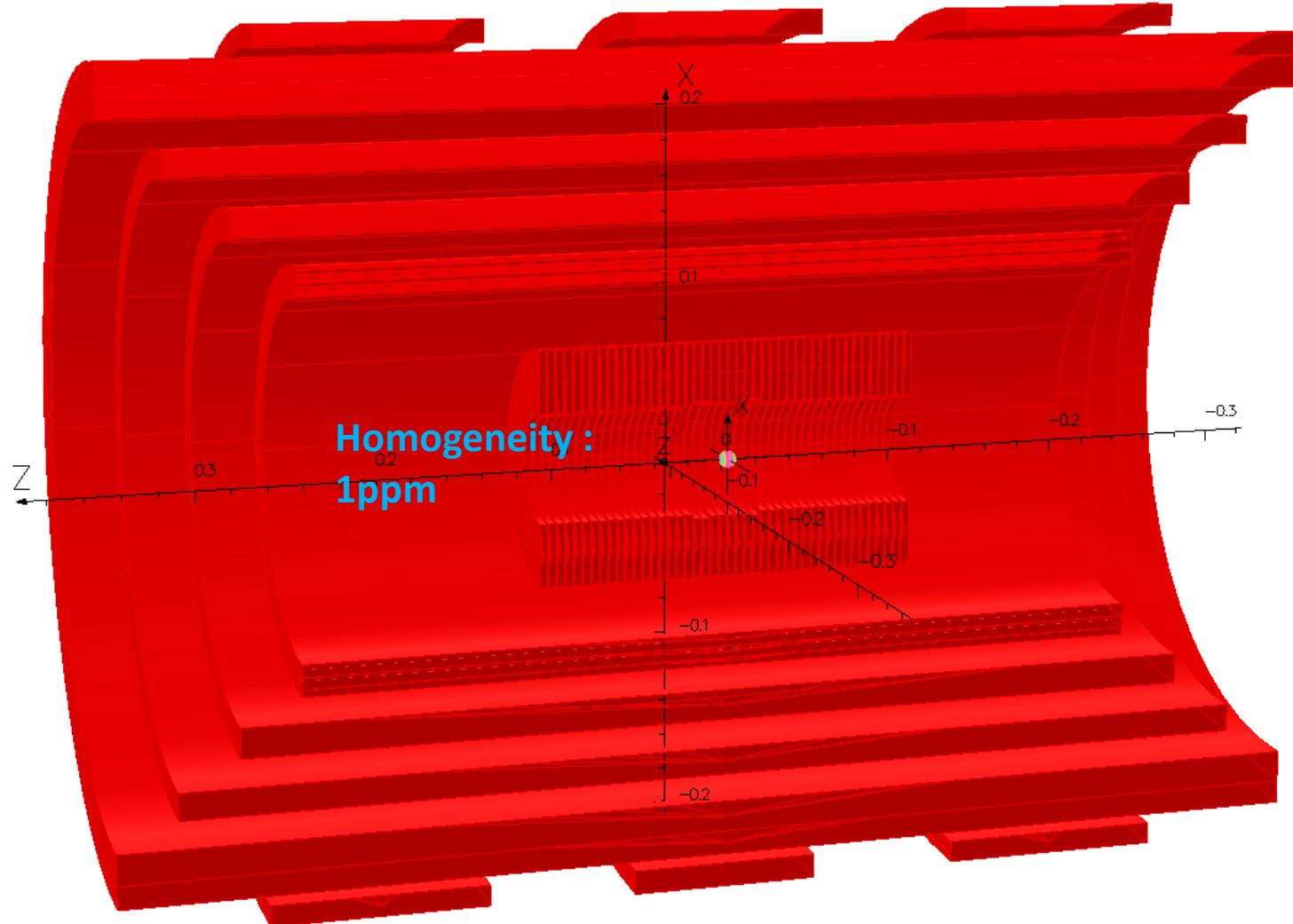


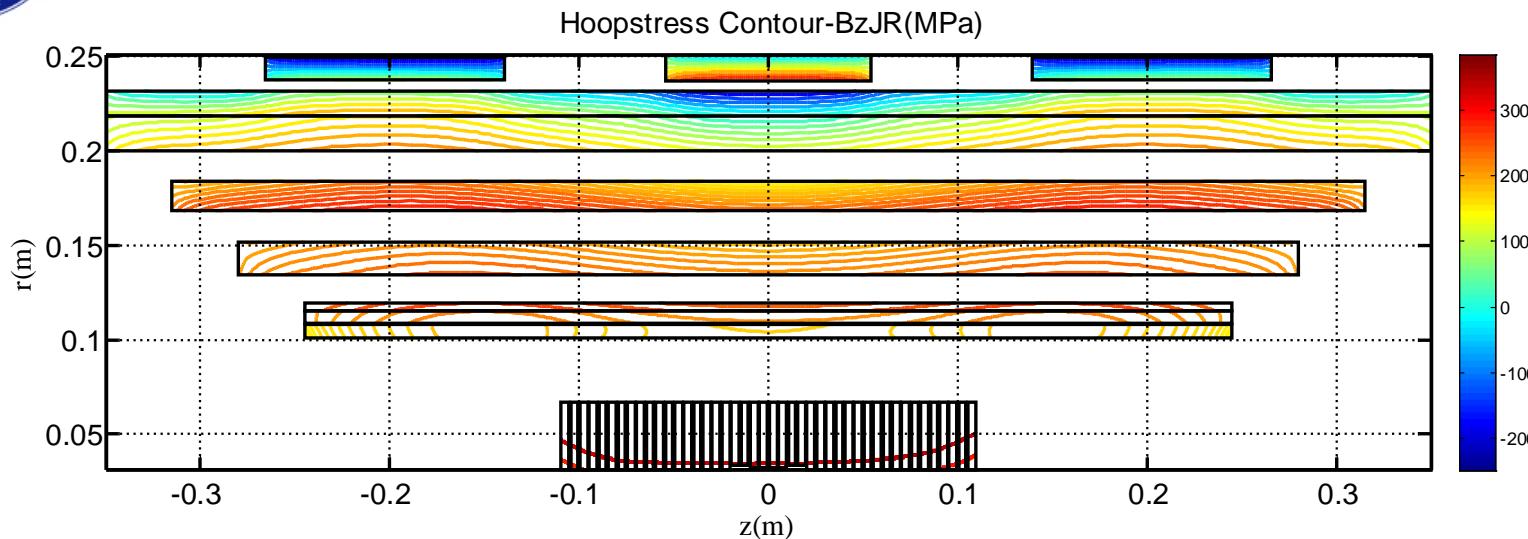


4/??/2016 19:29:52

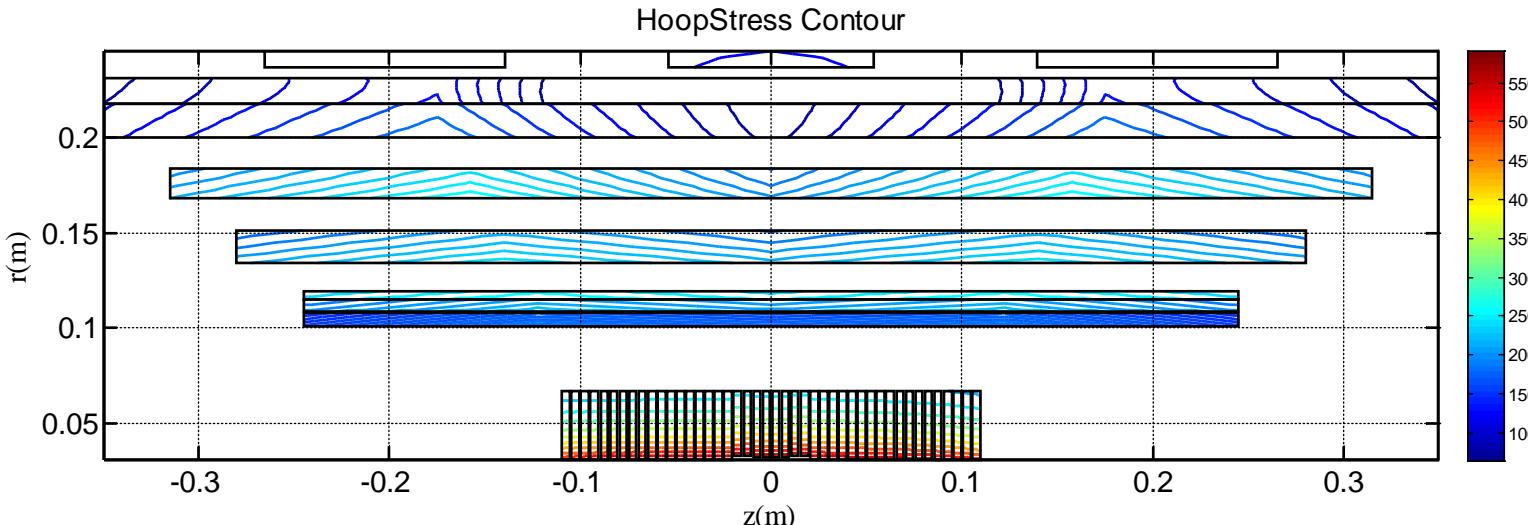
Map contours: BZ

2.702870E+001
2.702870E+001
2.702869E+001
2.702869E+001
2.702868E+001
2.702868E+001
2.702867E+001
2.702867E+001
Integral = 8.385524E-003

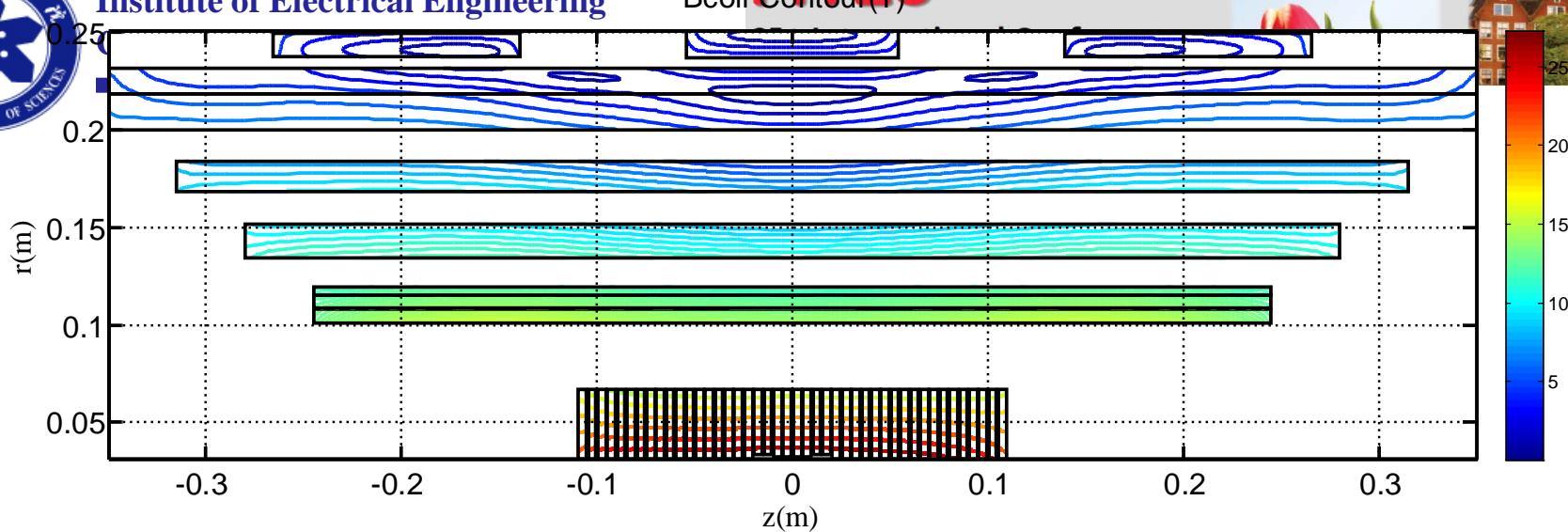




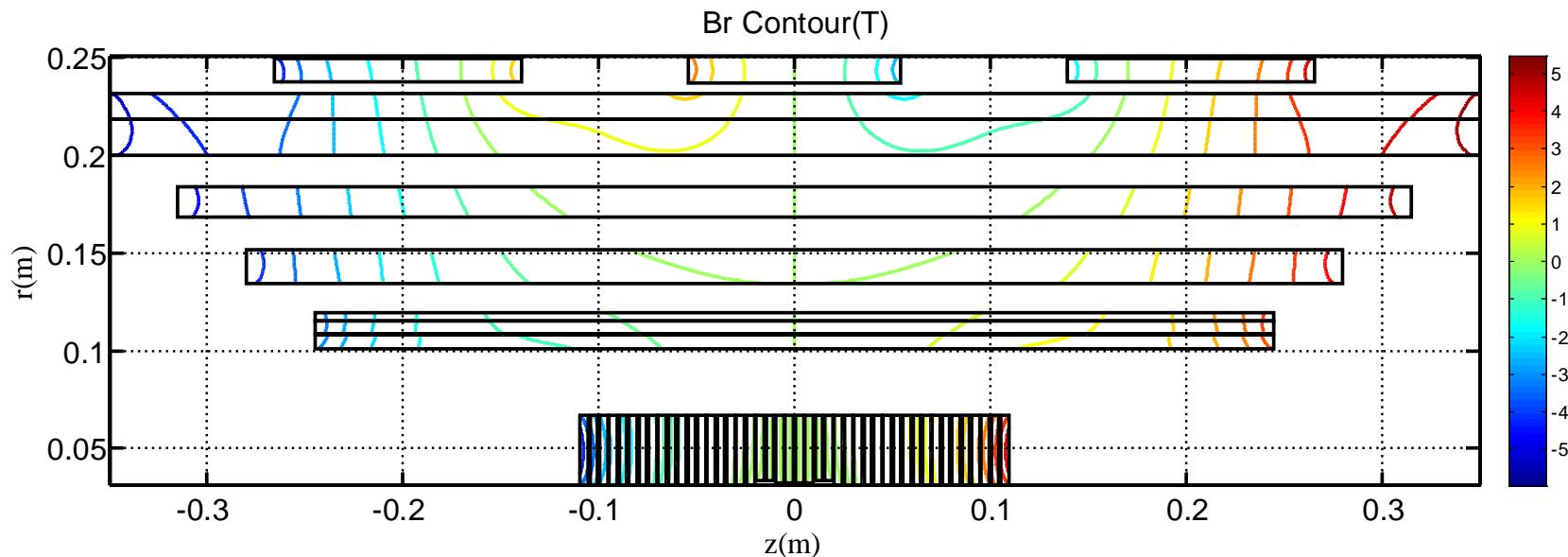
- **HoopStress-BzJR :** ~375MPa as Max.
- **HoopStress-Integration***: ~550MPa as Max.



*J. Caldwell, "Electromagnetic forces in high field magnet coils", *Appt. Math. Modelling*, vol. 6, no.3, pp.157-160, June 1982



- B_{max} in HTS: 27.1T
- B_{rmax} in HTS: 4.7T



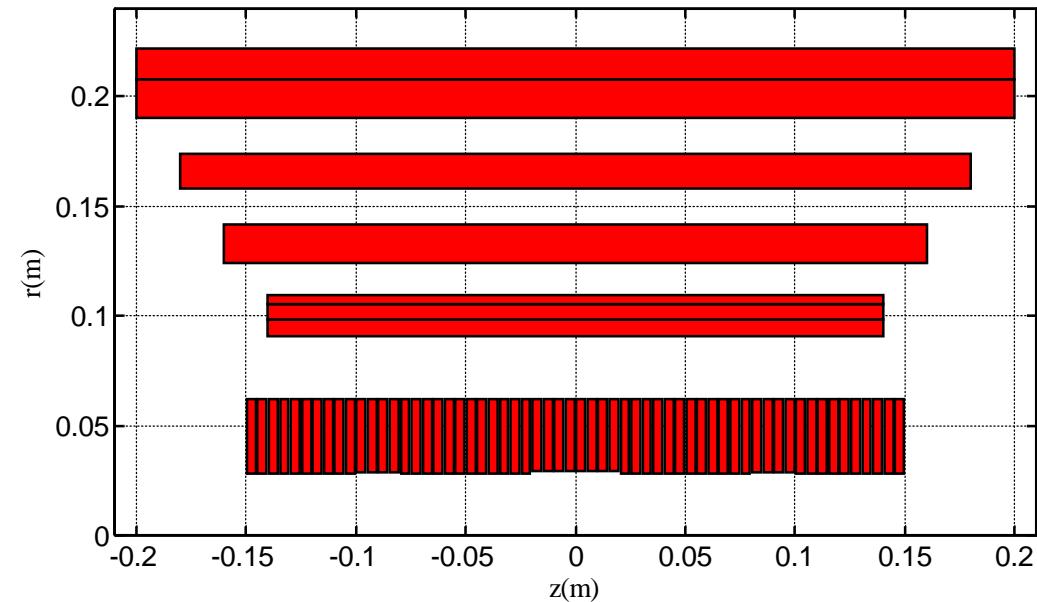


Design scheme with an LTS outsert with poor homogeneity

Coils	A ₁ (mm)	A ₂ (mm)	B ₁ (mm)	B ₂ (mm)	Current density (MA/m ²)
NbTi	137.00	164.50	-246.10	246.10	149.98
	172.50	177.50	-270.00	270.00	126.38
	177.50	182.50	-270.00	270.00	190.69
	184.00	211.50	-270.00	270.00	245.79
Nb ₃ Sn	80.00	88.60	-189.20	189.20	60.80
	93.60	117.00	-204.70	204.70	72.66
	122.00	132.00	-223.00	223.00	105.81

- LTS outsert:
~450 ppm

27T NMR LTS+HTS



LTS+HTS: 1ppm

- Strong compensating capability of the inside notch structure



Parametric study of the HTS magnet design inputs

Input parameters:

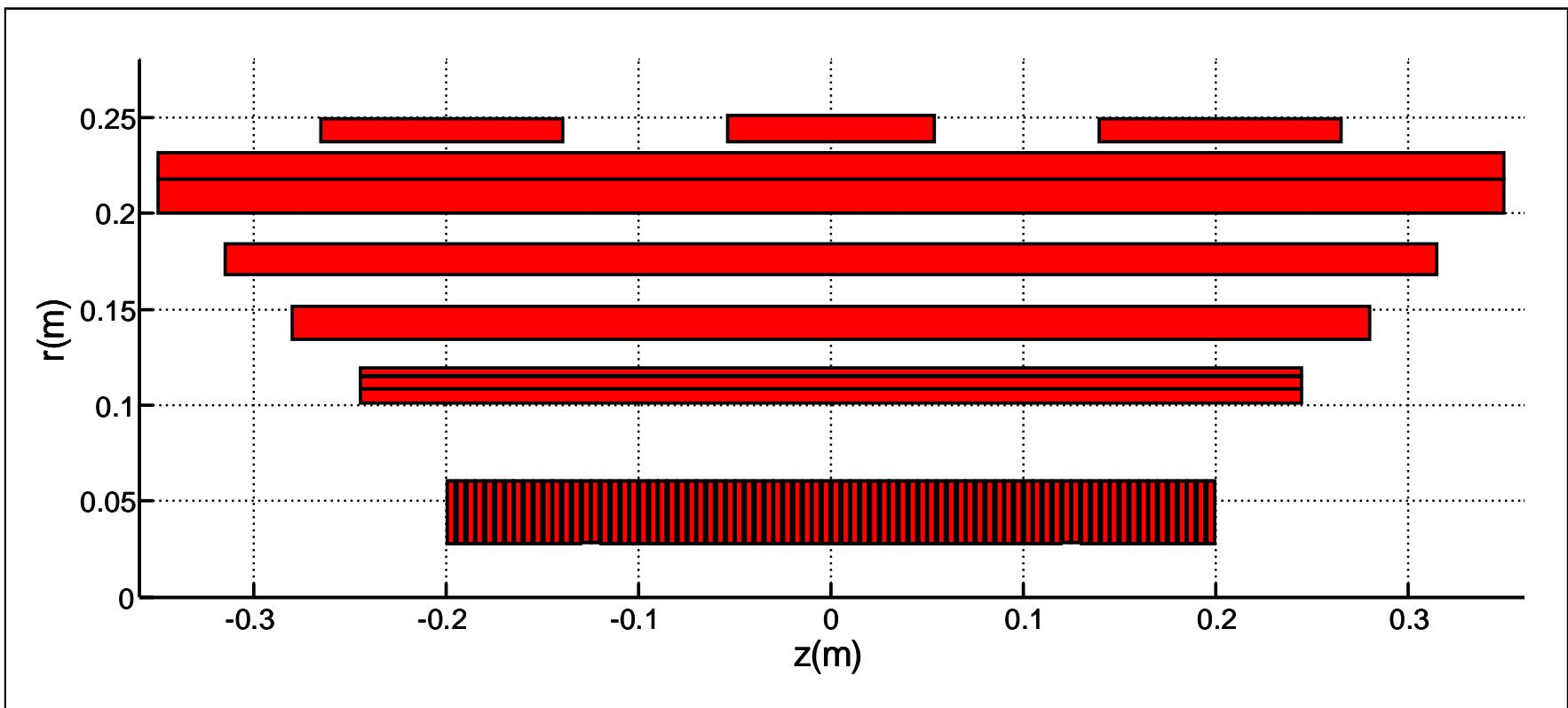
- **Magnet length:** number of DPs
- **Magnet inner diameter:** cold bore
- **Engineering current density:** operating current

Output concerns:

- **R_{out}:** outer diameter of the insert
- **S_{tot}:** total length of HTS tape used
- **B_{rm}:** maximum radial field in the insert
- **η :** current margin
- **σ_{max} :** maximum hoop stress
- **Sensitivity** of field homogeneity

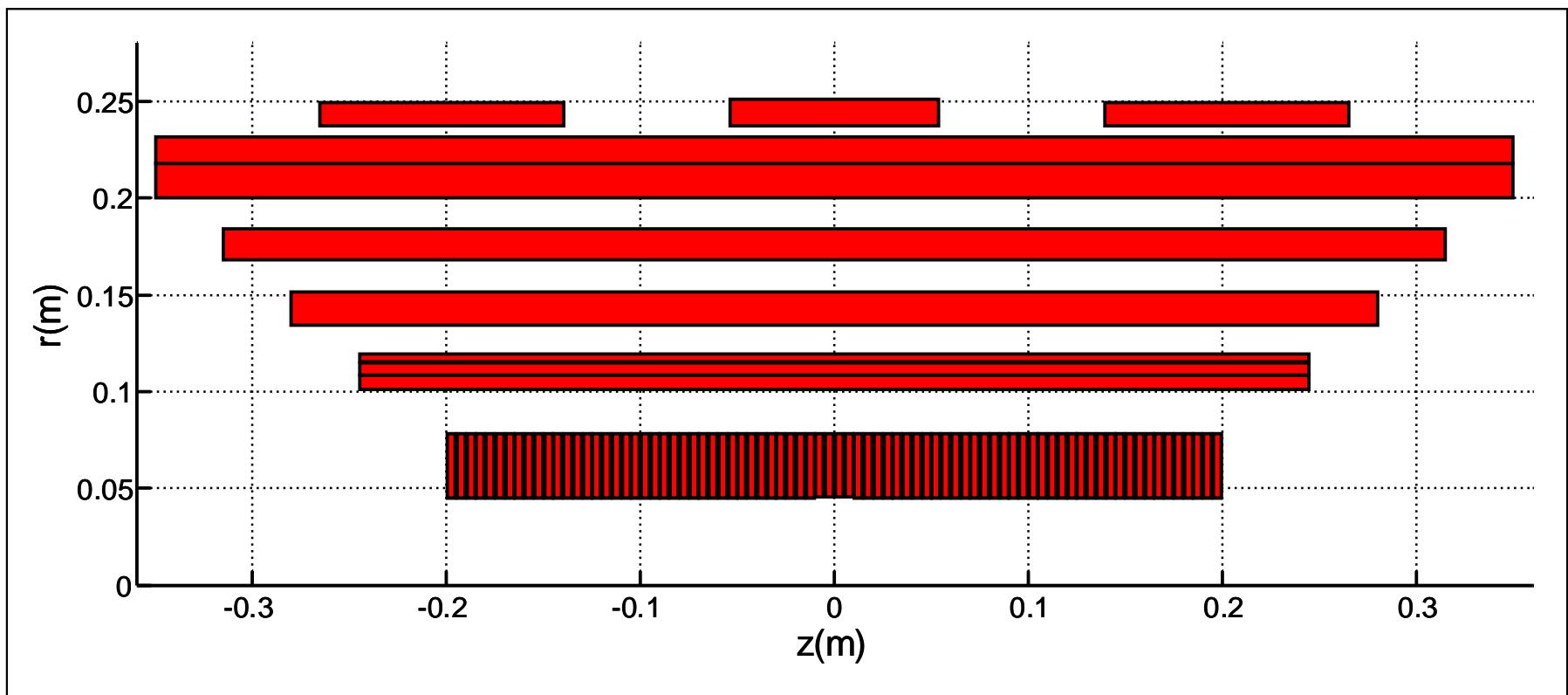


Magnet lengths



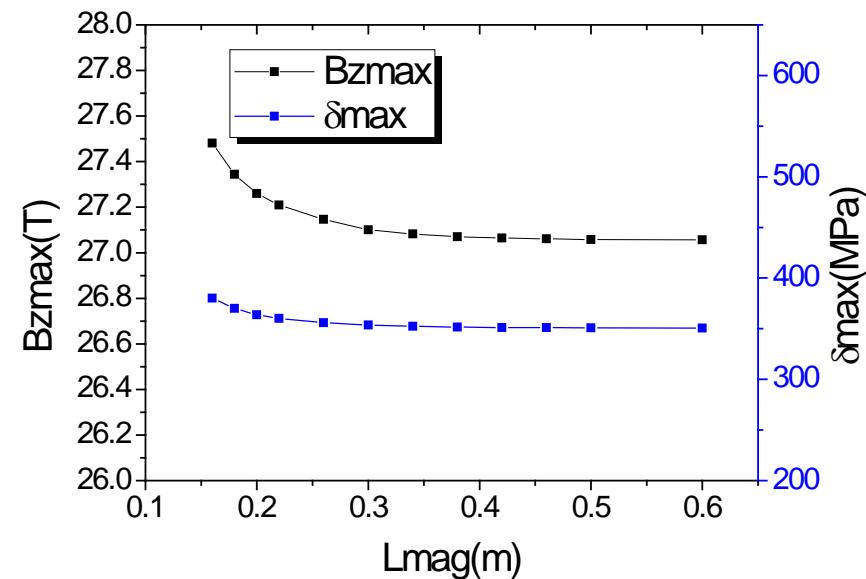
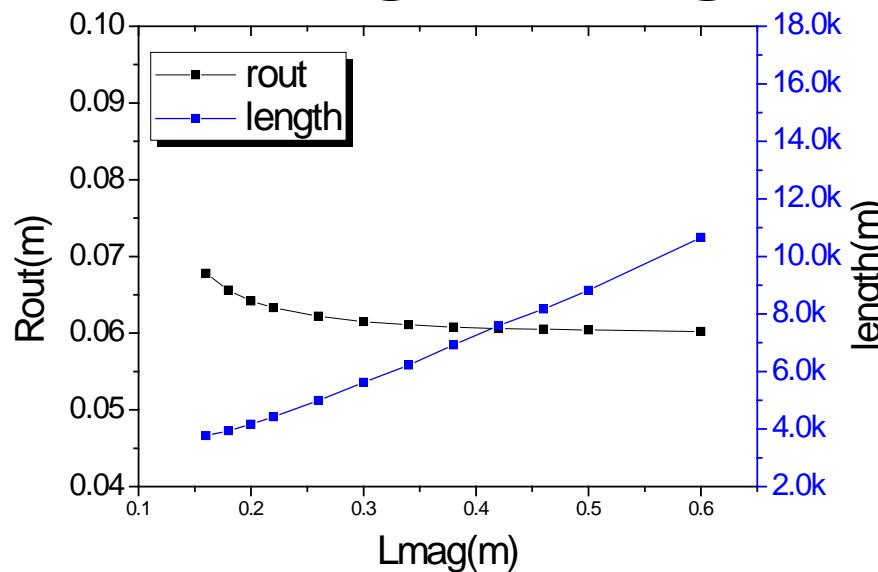


Magnet inner radii

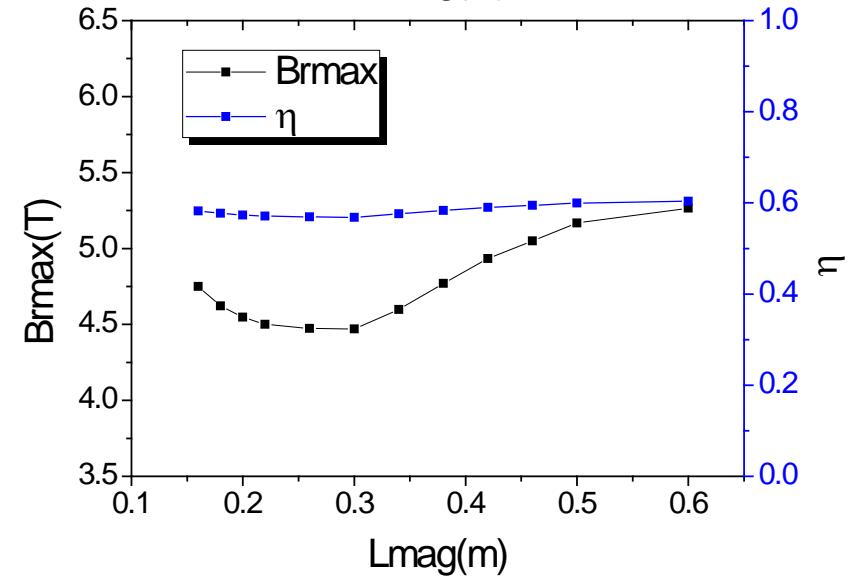




Magnet length vs output concerns

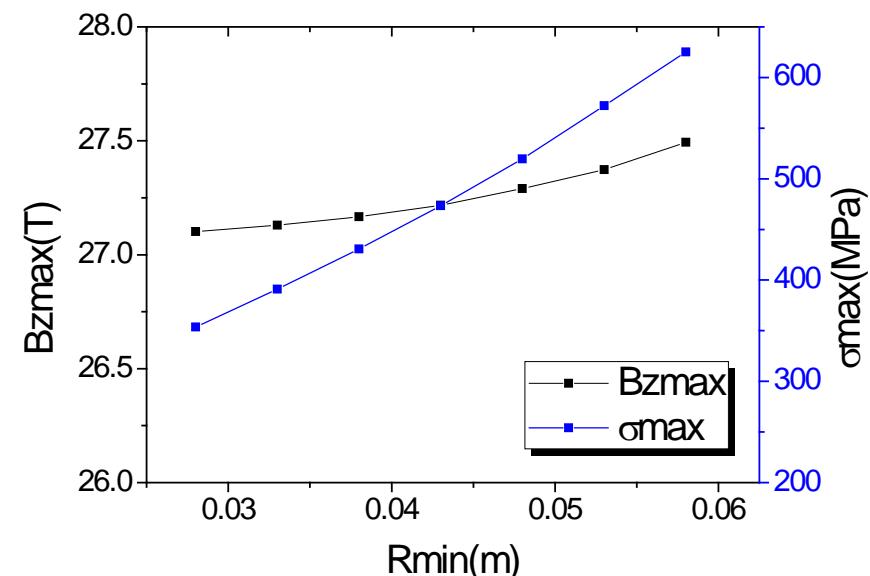
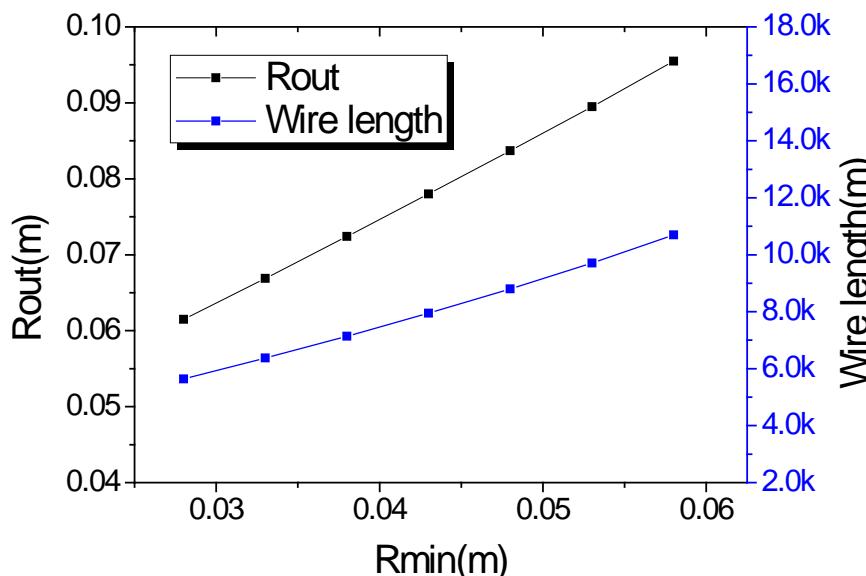


- long magnet has little influence on R_{out} , σ_{max} , η
- wire length approx. proportional to magnet length

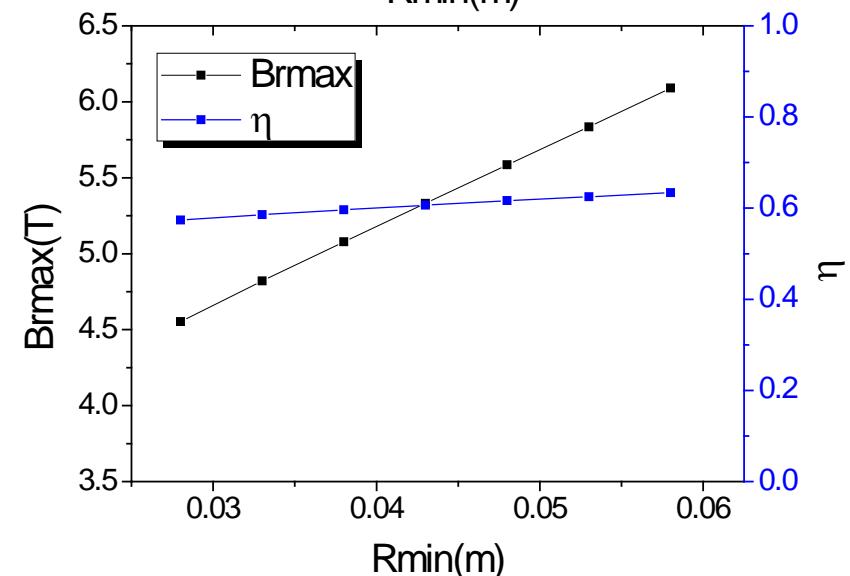




Magnet inner dia. vs output concerns

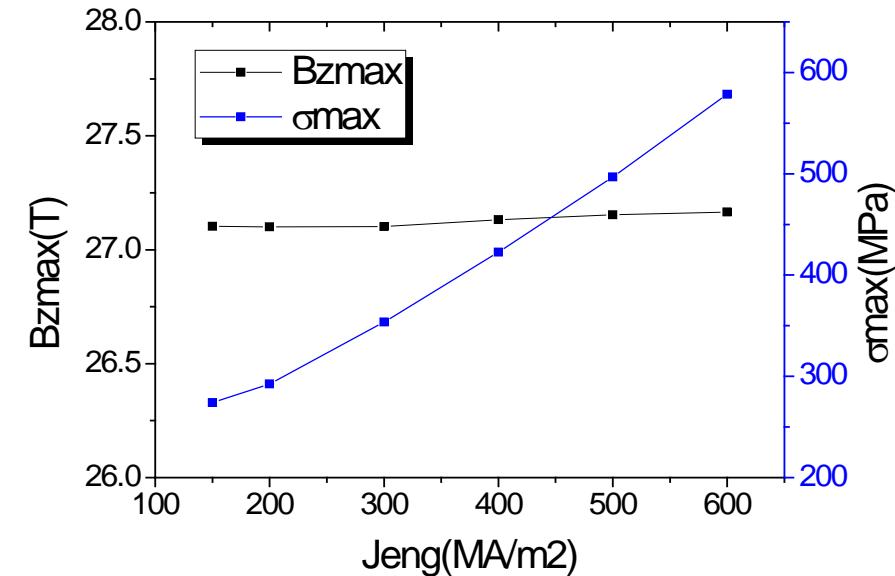
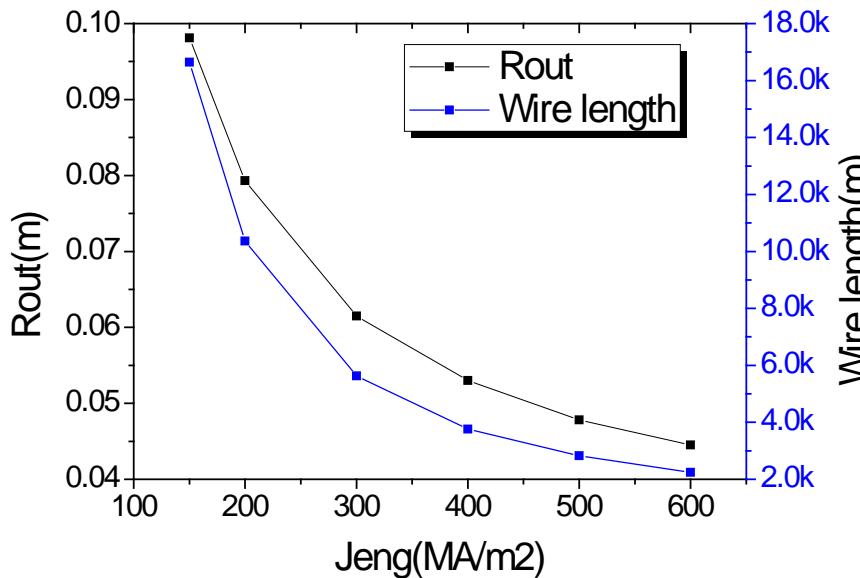


- Inner dia. approx. linear to Rout, wire length, σ_{max}
- Radially big magnet has no influence on η

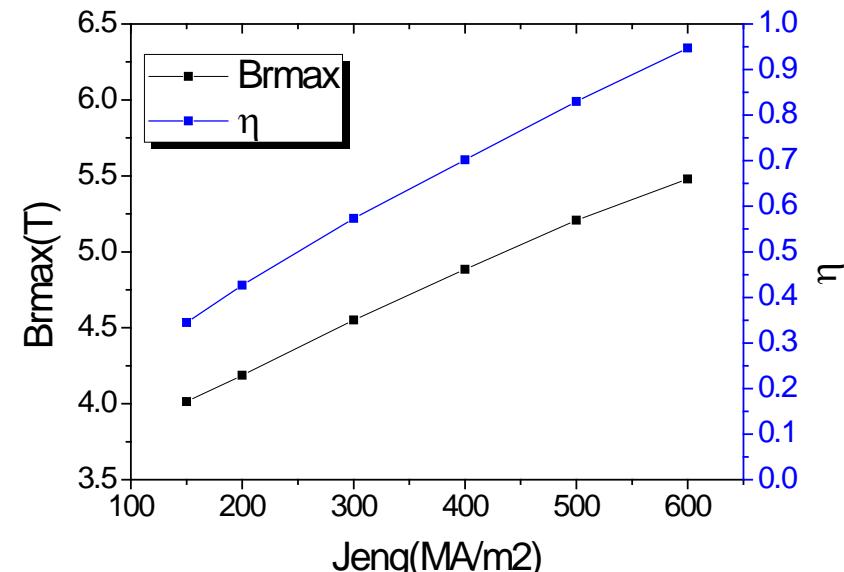




Jeng vs output concerns



- large Jeng reduces much of length of wire and R_{out}
- but increases σ_{max} and η , ~linearly

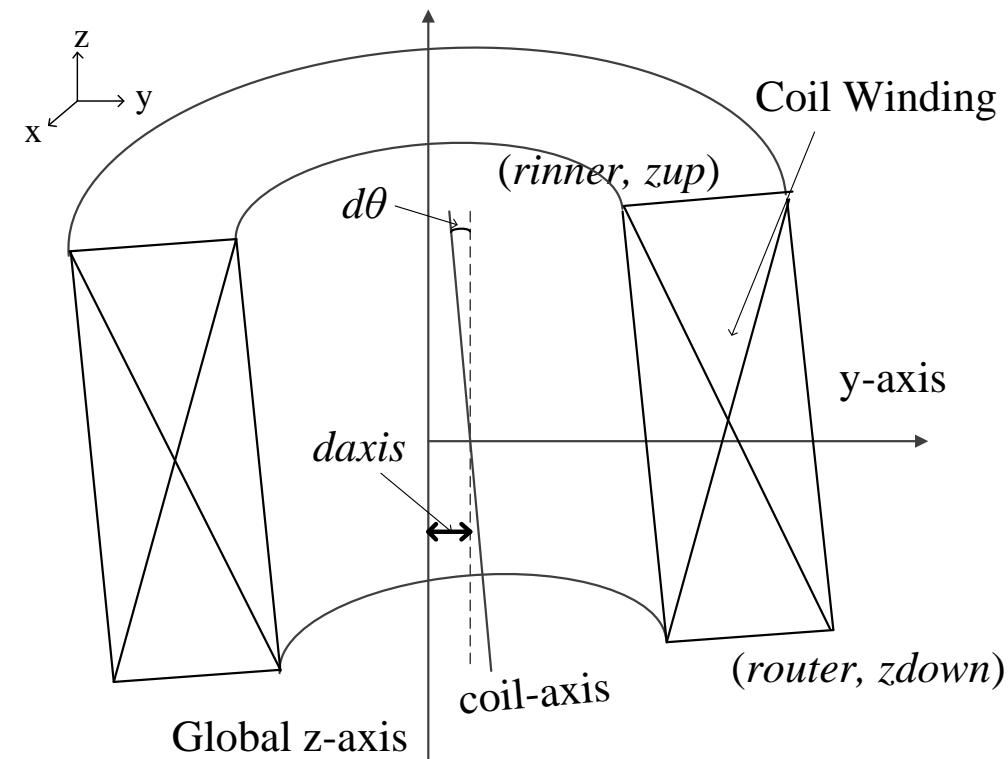




Sensitivity Analysis on Homogeneity

Dimension errors of a pancake coil:

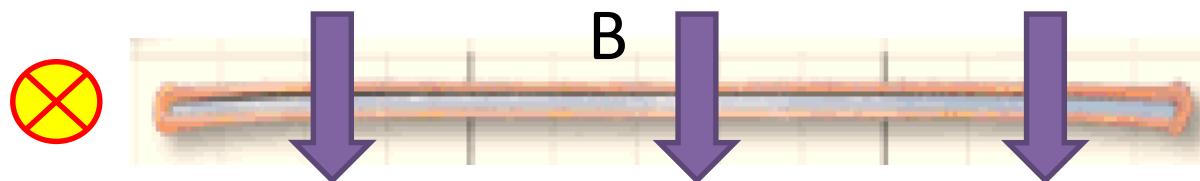
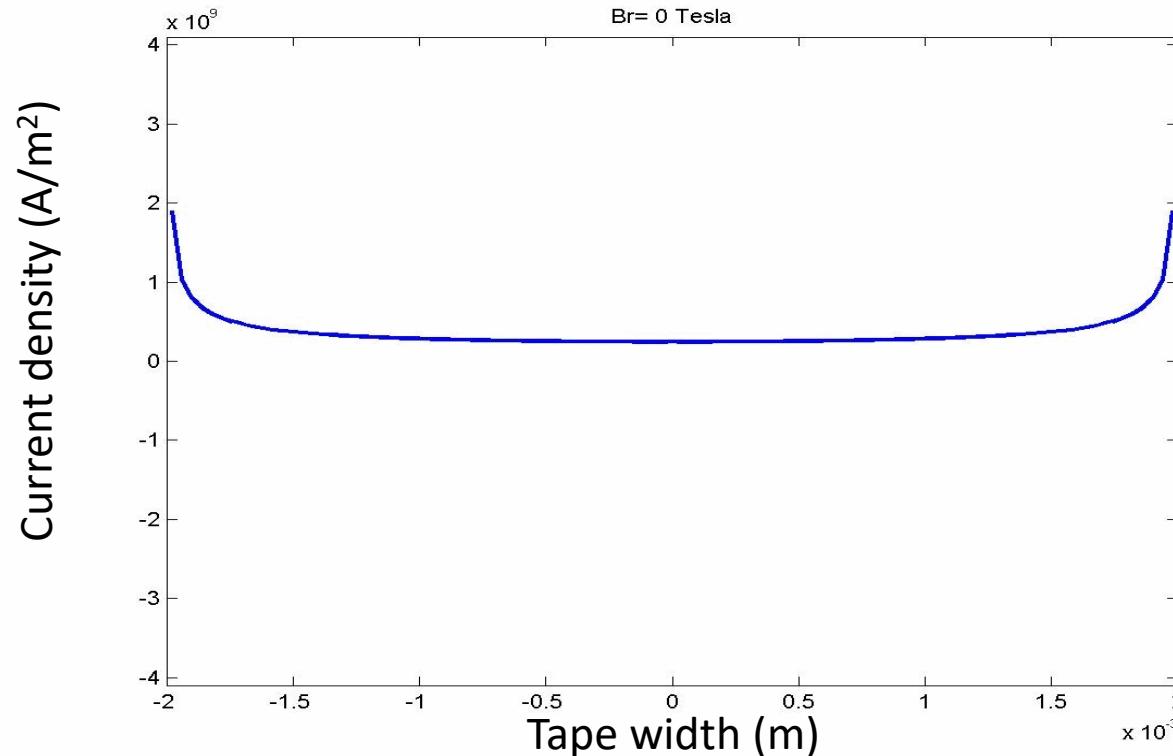
- **inner and outer radius** (r_{inner} , r_{outer}) varies randomly within 0.2 mm
- **axial positions** of the two ends, (z_{down} and z_{up}) : 0.2 mm,
- **deviation** (d_{axis}) of coil axis from the global z-axis : 0.2 mm
- **angle misalignments** $d\theta$ of coil axis from the global z-axis : 0.2°





Transport current density

plus screening current density

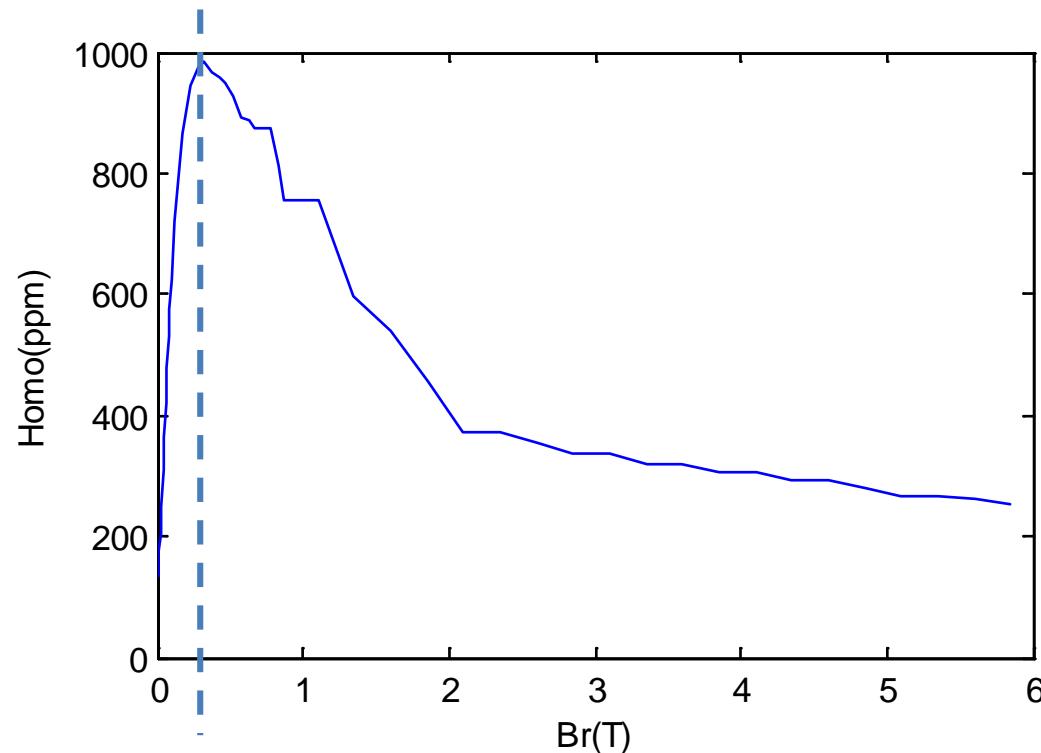




Homogeneity for an pair of Helmholtz HTS tape belts

Coil No.	R1	R2	Z1	Z2	Iop
1	0.05m	0.06m	-0.0295m	-0.0255m	150A
2	0.05m	0.06m	0.0255m	0.0295 m	150A

- Screening current effect strongest at $\sim 0.3T$
- Screening current effect restrained by increased B_r

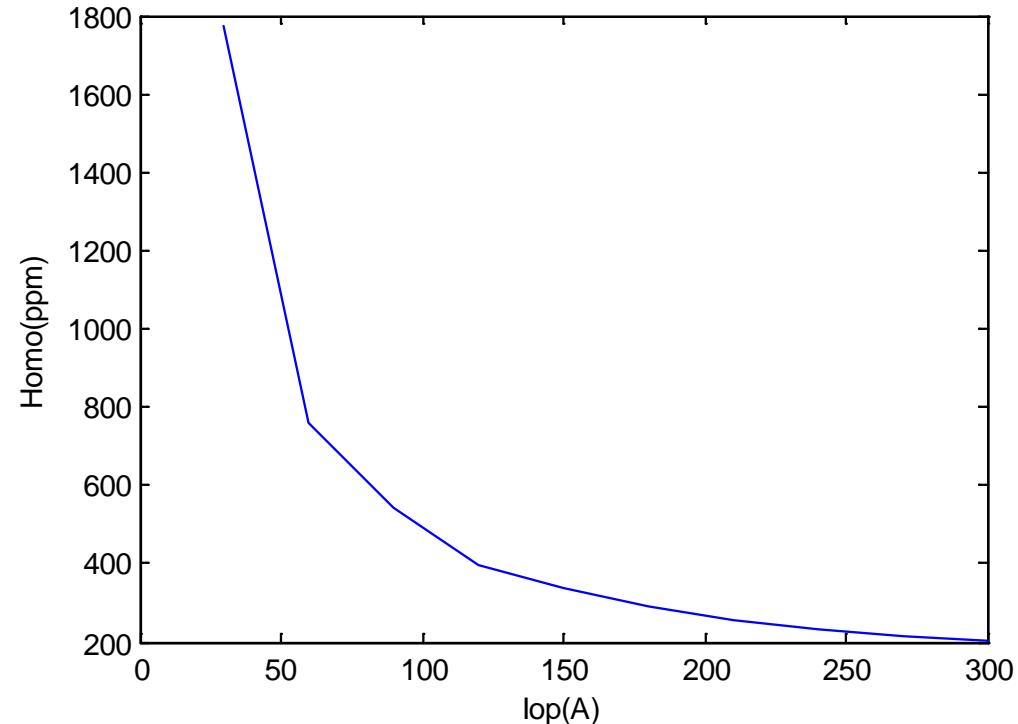




Homogeneity for an pair of Helmholtz HTS tape belts

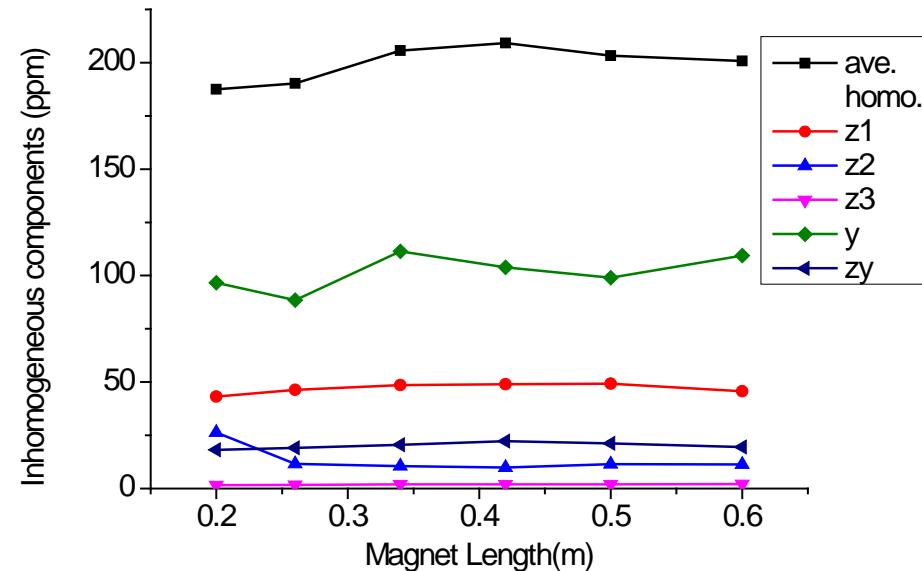
Coil No.	R1	R2	Z1	Z2	Br
1	0.05m	0.06m	-0.0295m	-0.0255m	3T
2	0.05m	0.06m	0.0255m	0.0295 m	3T

- Screening current effect restrained by increased I_{op}

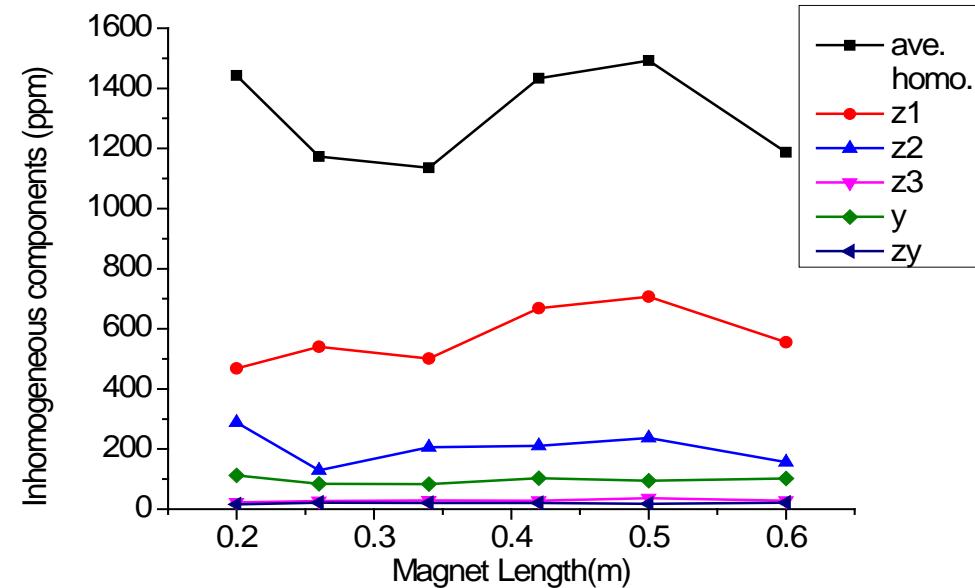




Ave. homogeneity and strong impure components vs **magnet lengths** w/o consideration of the screening current effect.

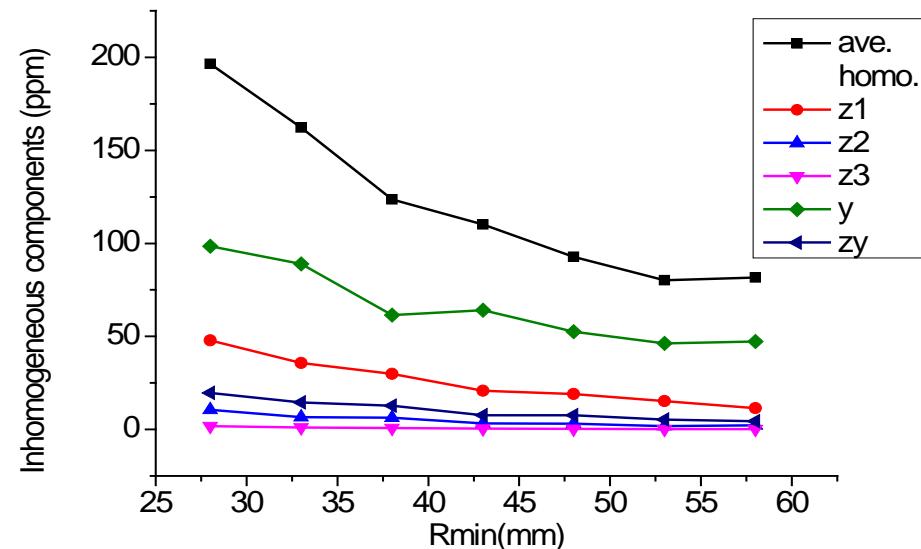


Ave. homogeneity and strong impure components vs **magnet lengths** with consideration of the screening current effect.

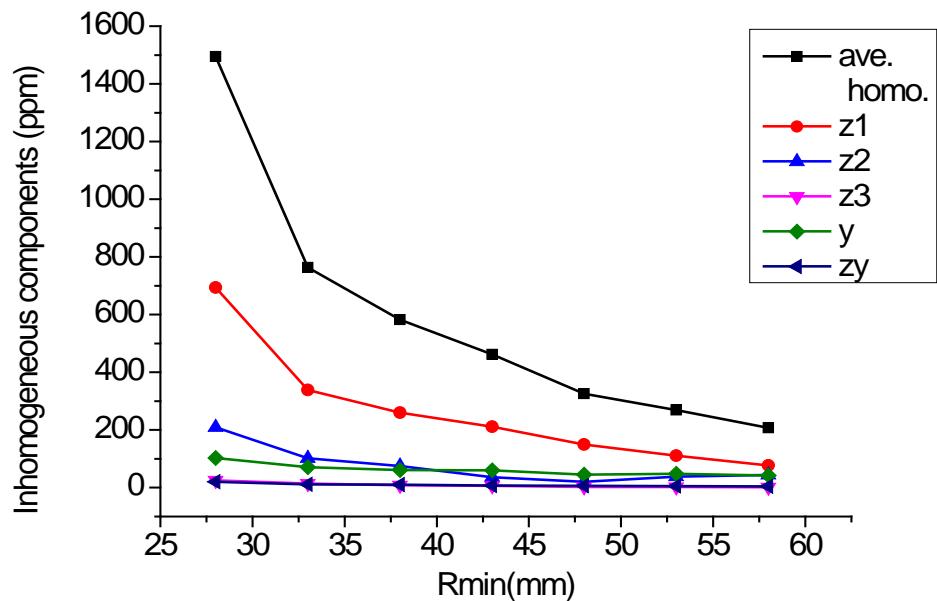




Ave. homogeneity and strong impure components vs **magnet inner radii w/o** consideration of the screening current effect.



Ave. homogeneity and strong impure components vs **magnet inner radii with** consideration of the screening current effect.





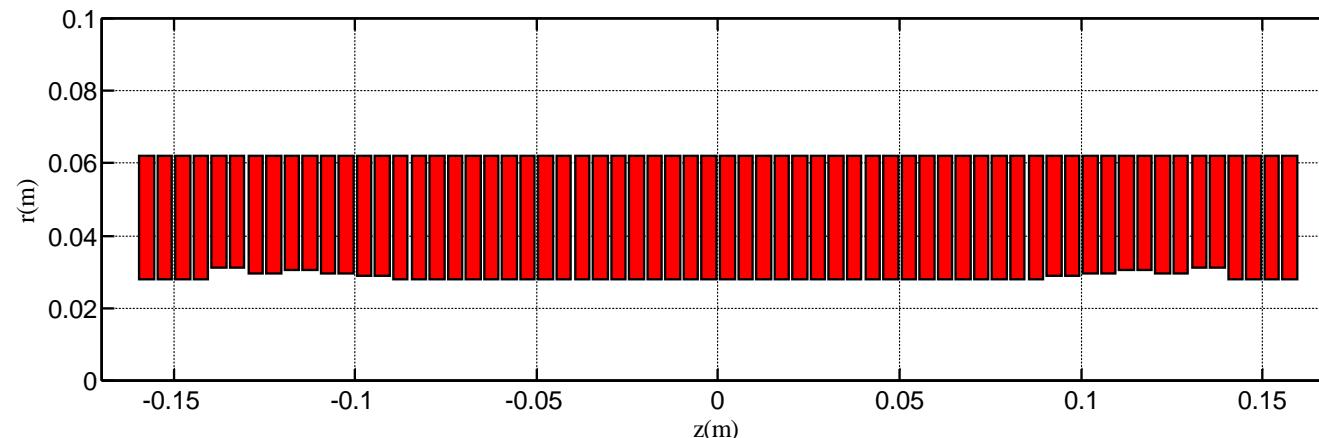
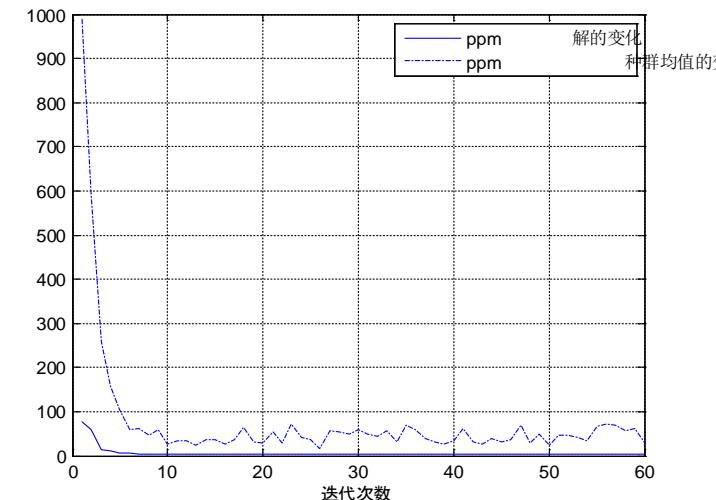
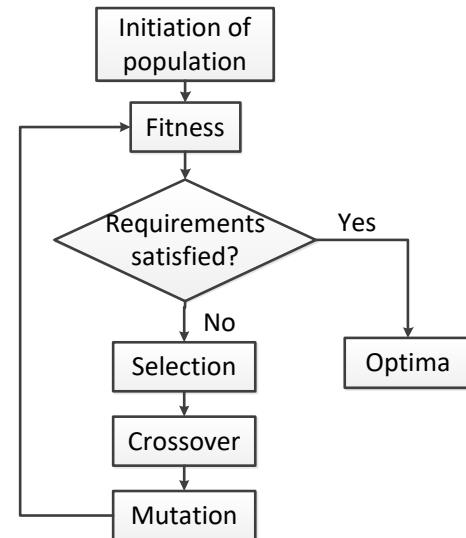
Some conclusions

- Magnet lengths has little thing to do with **REAL** field homogeneity: **No need** to build long insert magnet, in the split form of DPs
- The bigger the Rinner, the better the homogeneity: But **COST of outsert** with larger bore can increase dramatically
- Screening current deteriorates homogeneity about **1 order or less** of magnitude, only zonally: must be handled (Shimming, Shaking coil)



Electromagnetic design with screening current effect considered

- Screening current **LOCKed** by “current sweep reversal”
- Optimization algorithm: **NGA** (Niching genetic algorithm)





Thank you !
谢谢！