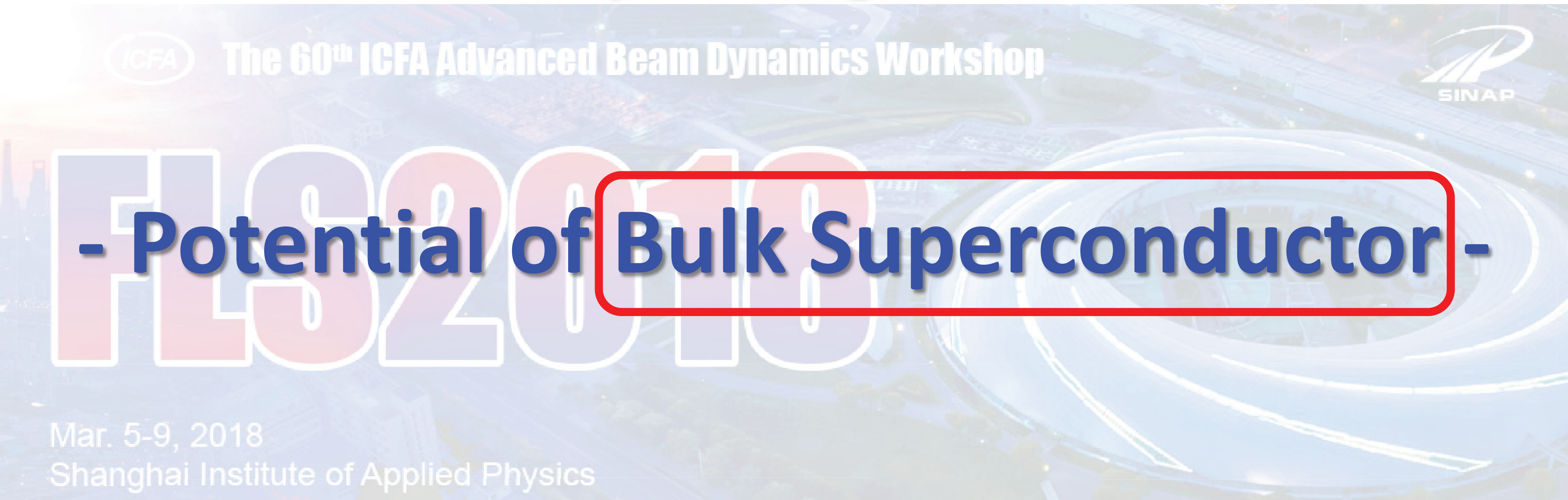
The 60th ICFA Advanced Beam Dynamics Workshop Future Light Source 2018
Mar. 8 2018, Shanghai Institute of Applied Physics

Ultra-short Period High Field Undultators for Compact Light Sources



- Potential of Bulk Superconductor -

Toshiteru KII

Institute of Advanced Energy, Kyoto University

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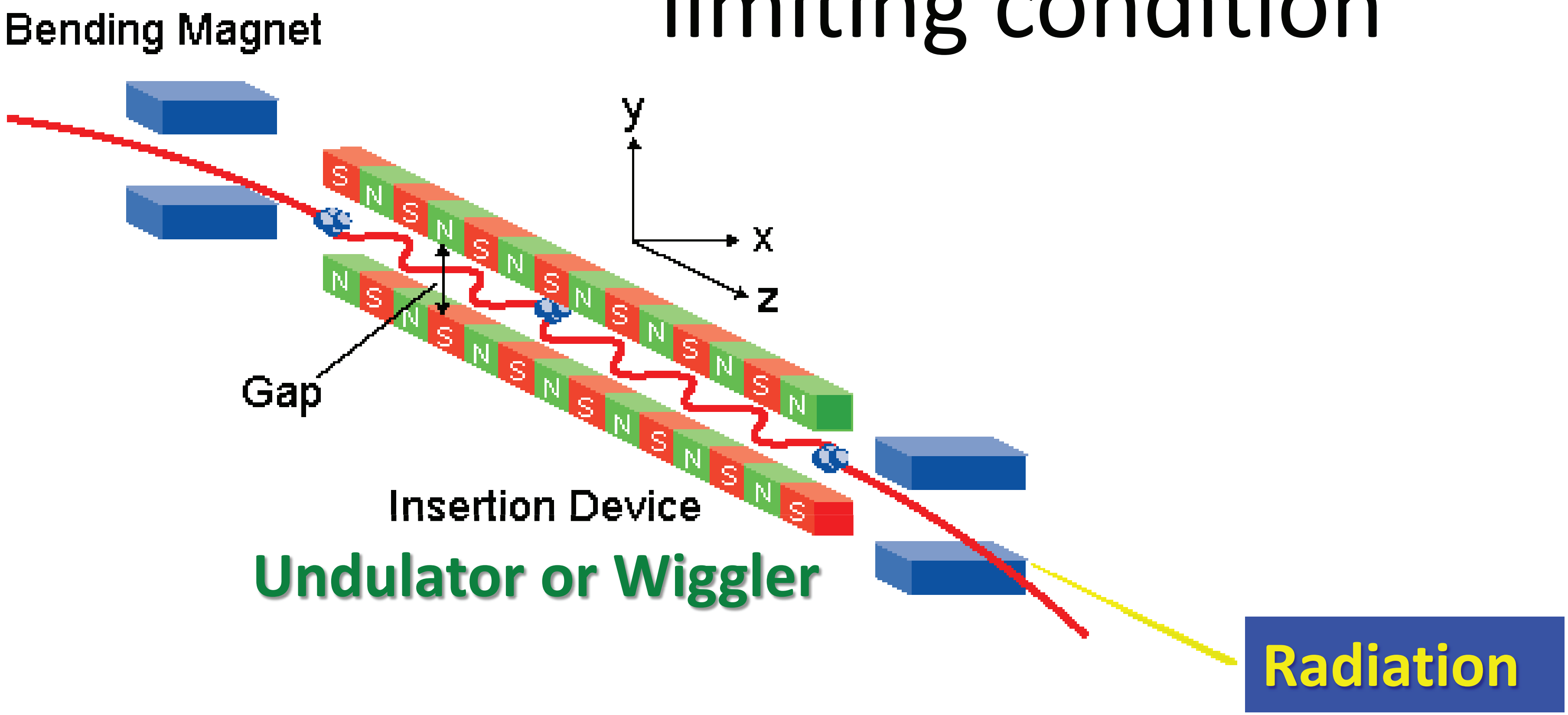
1. Introduction

Ultra-short:

Shorter than the established technology of permanent magnet and SC wire.

If we develop undulator using static material,
spin or transport current limit
the performance of the undulator.

limiting condition



$$\boxed{\lambda_R\,[\mathring{A}]} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \approx 13.056\,\frac{\boxed{\lambda_u\,[\mathrm{cm}]}}{\boxed{(E[\mathrm{GeV}])^2}}\left(1+\frac{K^2}{2}\right)$$

$$K = \frac{e\cdot B_0\cdot\lambda_u}{2\pi\cdot m_0 c} \approx 93.36\,\boxed{B_0[\mathrm{T}]}\cdot\boxed{\lambda_u[\mathrm{m}]}$$

Requirement

1. Strong field in Short period

2. Field amplitude error < 1%

3. Field phase error < 3.6 degree (1%)

For Hard X-ray > 10 keV

20 GeV λ_u = 36 mm, B_{und} = 1.25 T, K = 4.2

14 GeV λ_u = 30 mm, B_{und} = 1.1 T, K = 3

8 GeV λ_u = 18 mm, B_{und} = 1.3 T, K = 2.2

Technical gap

3 GeV λ_u = 5 mm, B_{und} = 2.5 T, K = 1.17

3 GeV λ_u = 6 mm, B_{und} = 1.6 T, K = 0.9

$$\boxed{\lambda_R[\mathring{A}]} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \approx 13.056\frac{\boxed{\lambda_u[\mathrm{cm}]}}{\boxed{(E[\mathrm{GeV}])^2}}\left(1+\frac{K^2}{2}\right)$$

$$K = \frac{e\cdot B_0\cdot\lambda_u}{2\pi\cdot m_0 c} \approx 93.36\boxed{B_0[\mathrm{T}]}\cdot\boxed{\lambda_u[\mathrm{m}]}$$

Recent trend of SR facility

Lower cost!

Higher performance!

Compact 3rd generation SR facility
with high quality electron beam
Max IV, NSLS-II, etc. : 3 GeV $\varepsilon < 1$ nmrad

6～8 GeV → 3 GeV → more compact!

Undulator period should be reduced to get hard X-ray (10 keV).

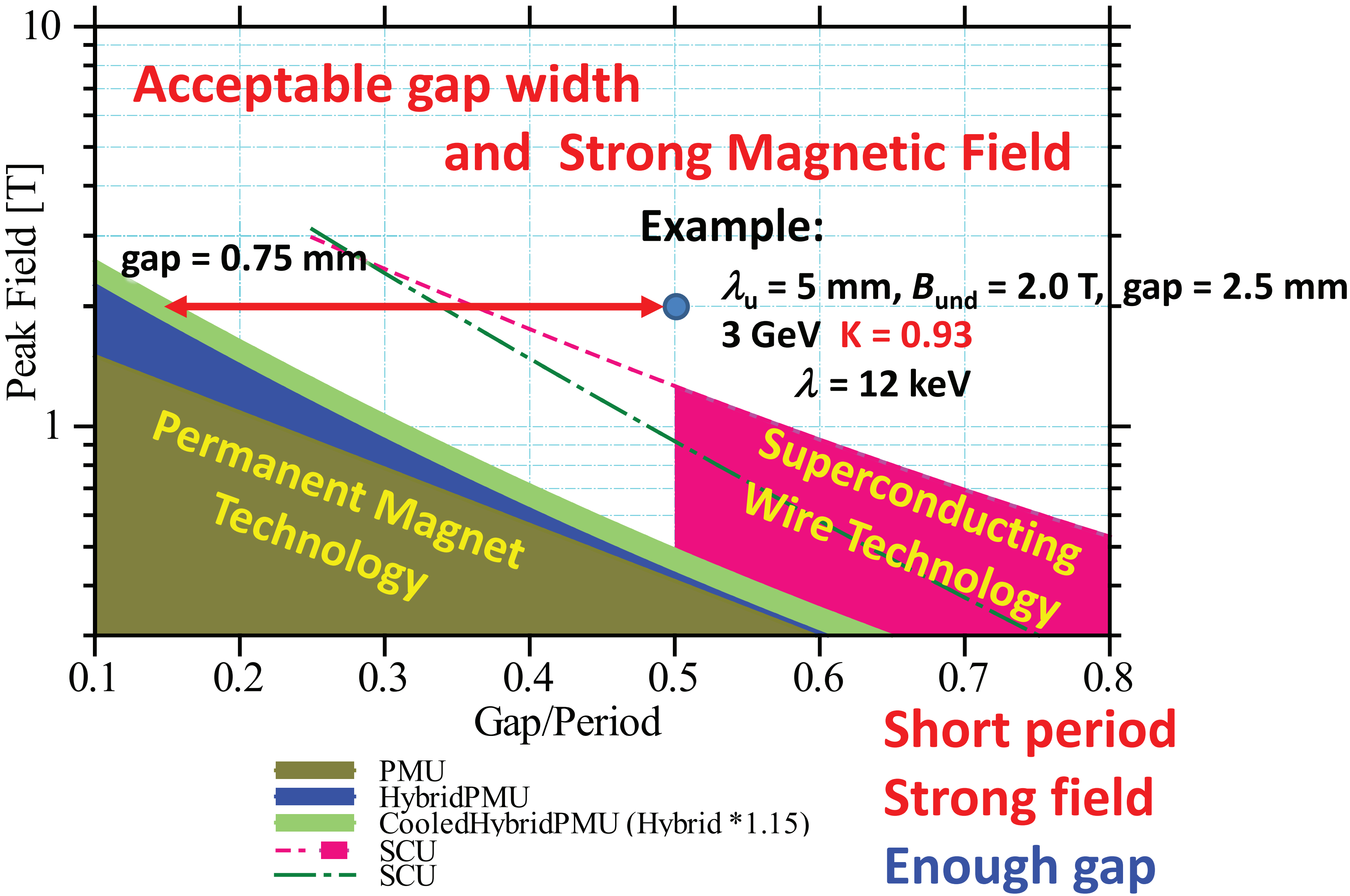
$$\boxed{\lambda_R[\mathring{A}]} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \approx 13.056\frac{\boxed{\lambda_u[\mathrm{cm}]}}{\boxed{(E[\mathrm{GeV}])^2}}\left(1+\frac{K^2}{2}\right)$$

Required magnet: (Example)

E_e = 3 GeV, 12 KeV require λ_u = 5 mm, B_{und} = 2 T

Such Ultra High-performance Undulator was not established!

Design flexibility of Compact LS using Ideal Undulators



Short period

Strong field

Enough gap

Toward inaccessible region

permanent magnet

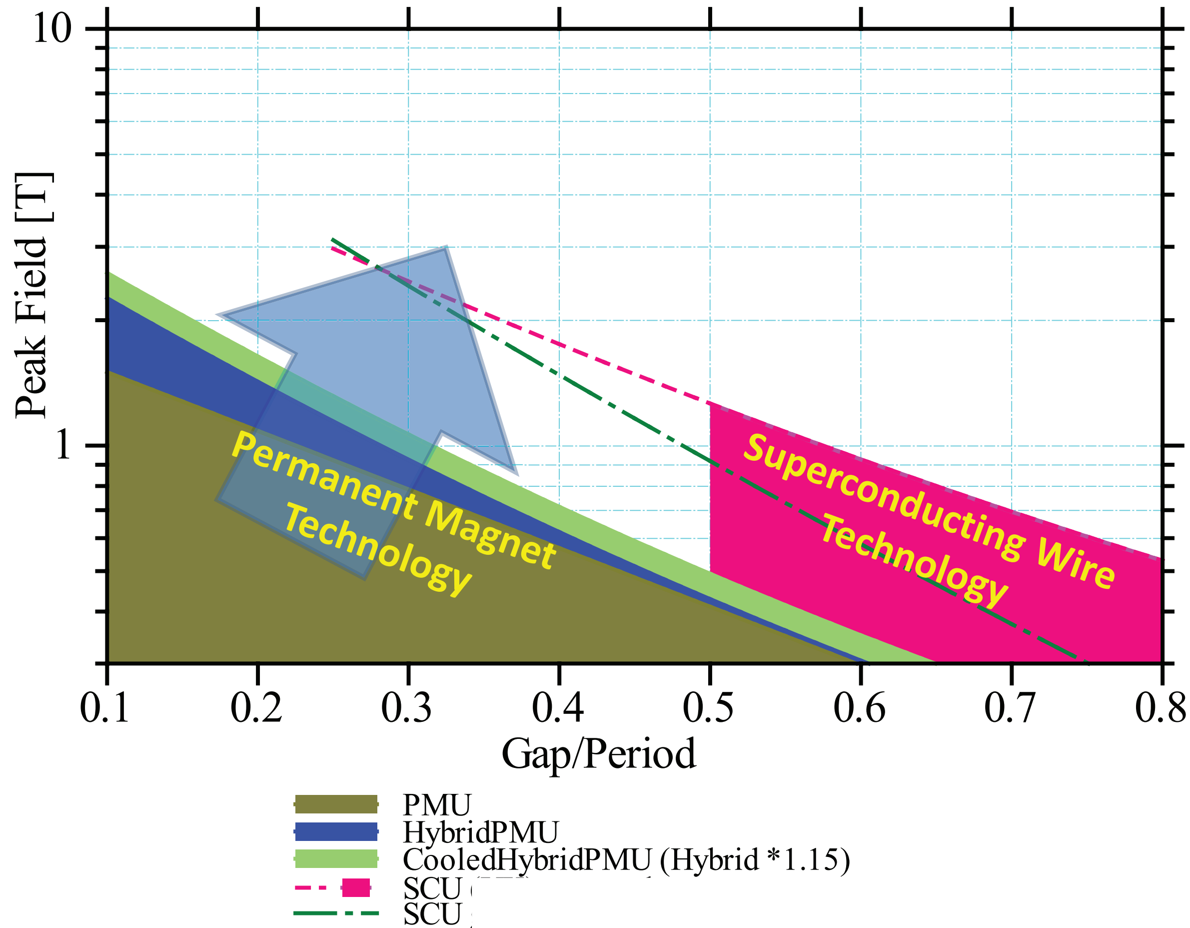
■ BH(max) is approaching to the theoretical limit.

■ New material?
■ New structure?

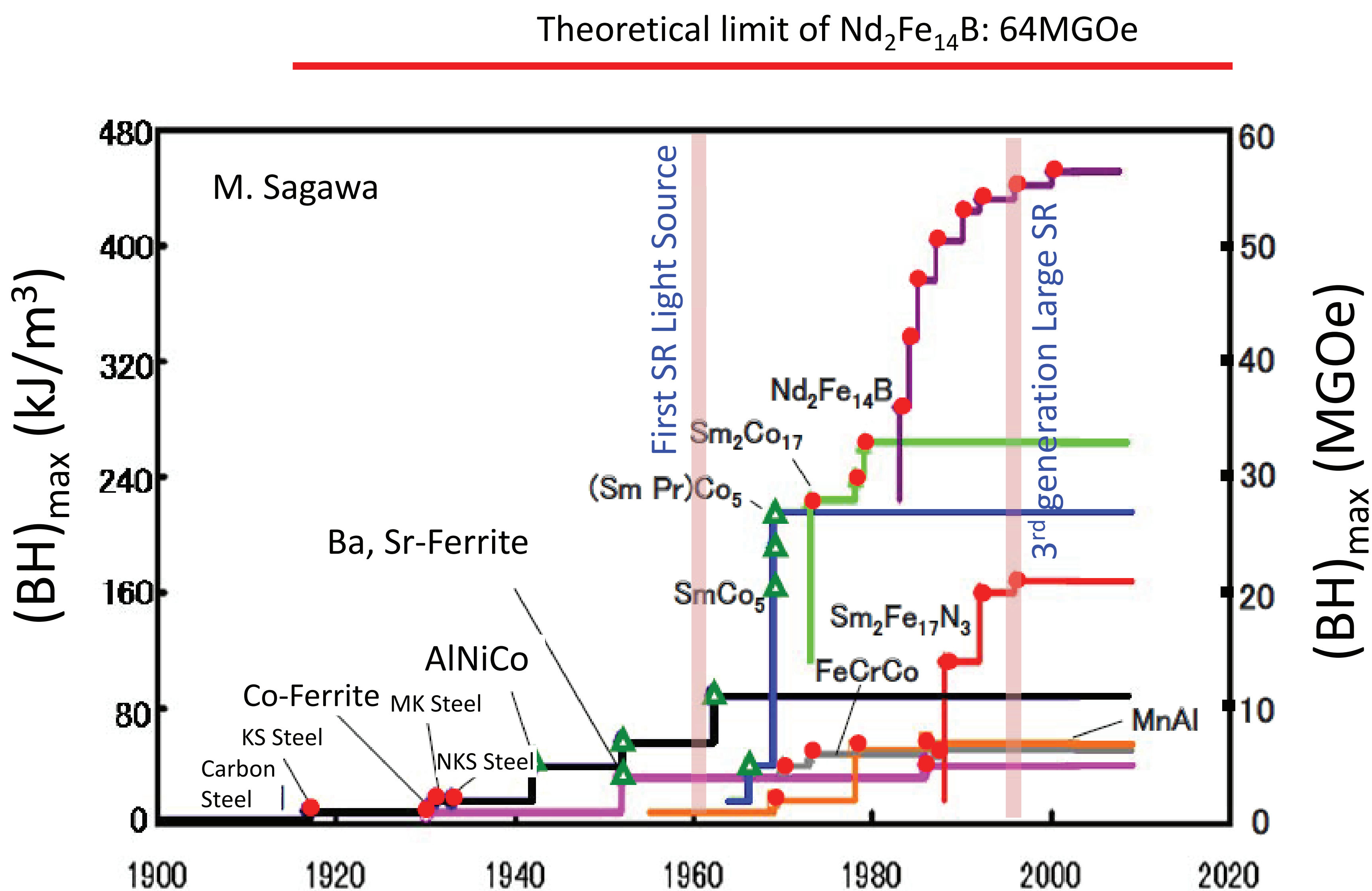
Anisotropic Nanocomposite

Superlattice Ordering

These new material/structure are not established yet.



History of Permanent Magnet



Toward inaccessible region

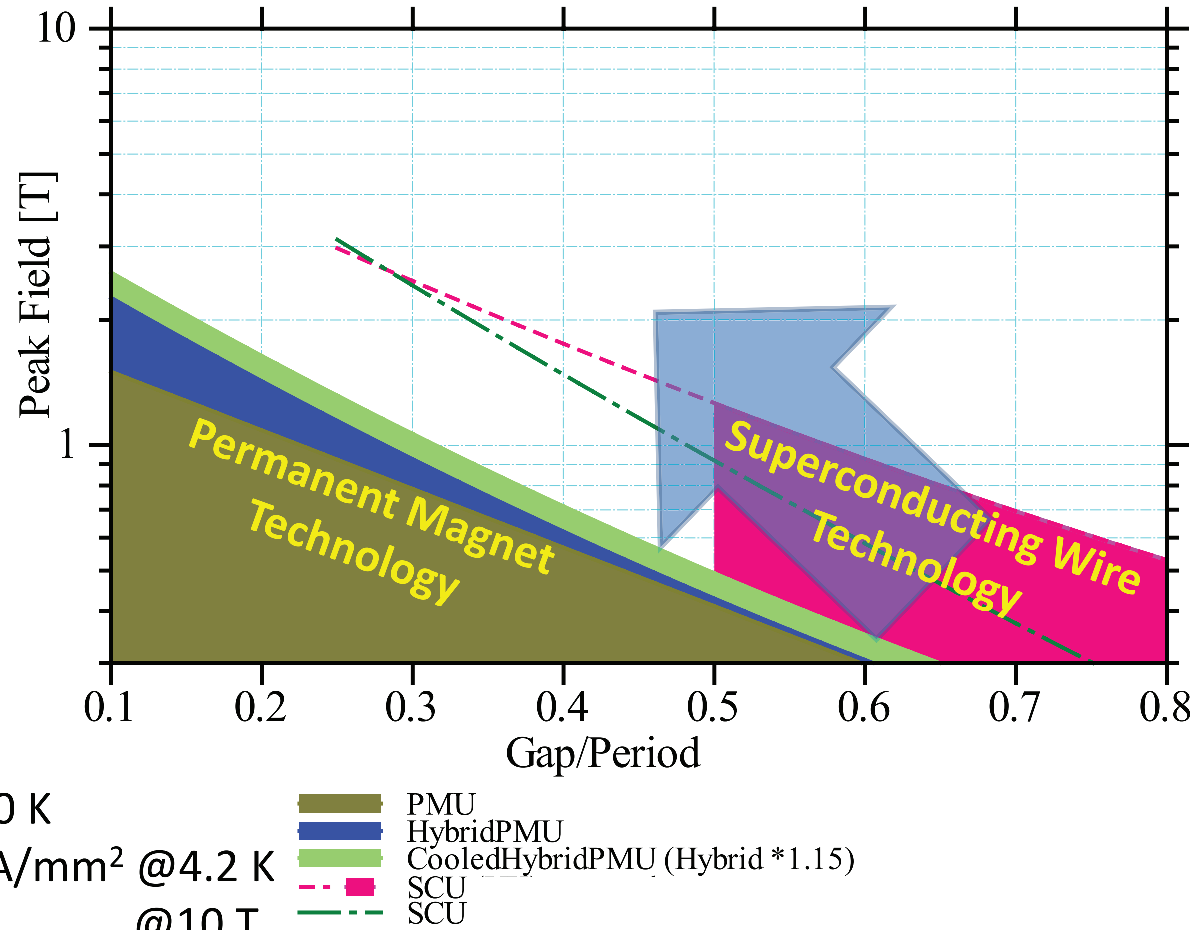
Superconducting wire

■ Engineering Critical Current Density of SC wires are still increasing!

■ Nb3Sn, NbTi, and REBCO CC are promising.
1 kA/mm^2 @ 4.2K or 2K

■ New material
MgB_2 (2001)/ FeSC (2008)?
FeSC has high potential.

$LaFeAsO_{1-x}F_x$ 1111
*Re*Fe*Pn*O family 1111



Tc: > 50 K
Jc: 1 kA/mm^2 @4.2 K
@10 T

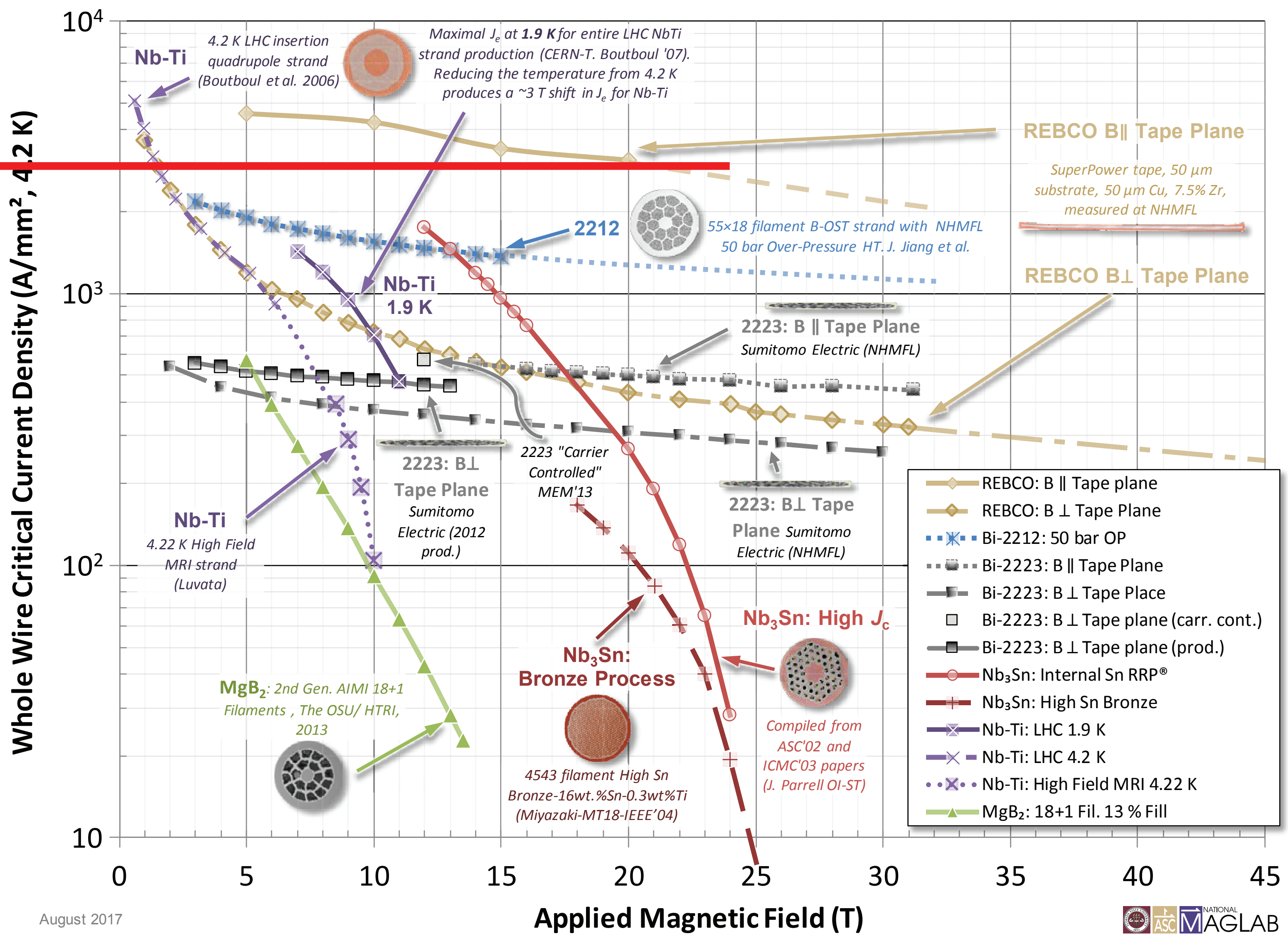
Good Jc-B property is obtained for small bulk or single crystal.

Engineering Critical Current Density vs. Applied Field

3 kA/mm²

Nb$_3$Sn wire is most promising.

3 kA/mm²
@4.2 K, 10 T



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2 Potential of bulk HTS ～How to make periodic field～

Permanent magnet: New material is not available.

Superconducting Wire: Practical level is 1 kA/mm^2.

Bulk HTS ?

Short-period Undulator and Design flexibility of Compact LS

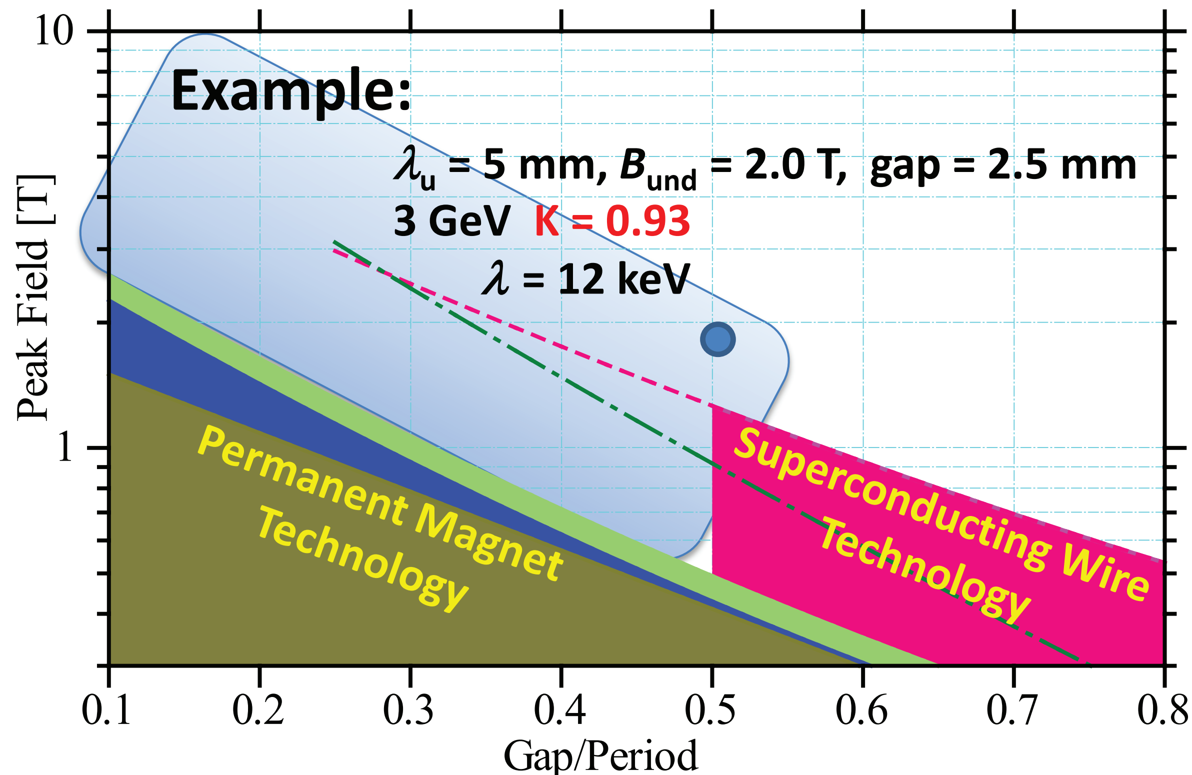
Short period **5 – 10 mm**

High field **> 1 T**

Enough gap **> 2 mm**

$$\boxed{\lambda_R[\mathring{A}]} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \approx 13.056\frac{\boxed{\lambda_u[\mathrm{cm}]}}{\boxed{(E[\mathrm{GeV}])^2}}\left(1+\frac{K^2}{2}\right)$$

Can we get to the "fresh ground" ?



Toward inaccessible region

3. Superconducting bulk

- Core part of superconducting wires have higher current density.

$$\frac{\text{Bulk } J_C}{\text{Overall Wire } J_C\ (J_E)}$$

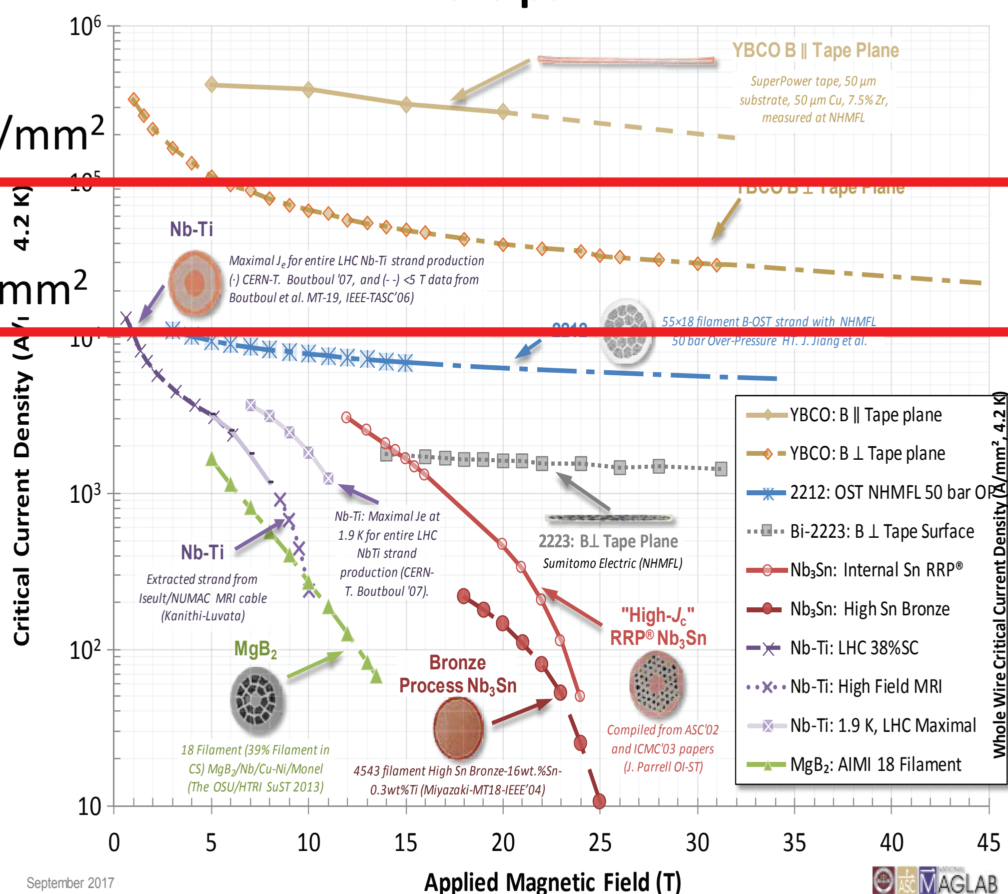
REBCO: ~5

MgB_2: ~3

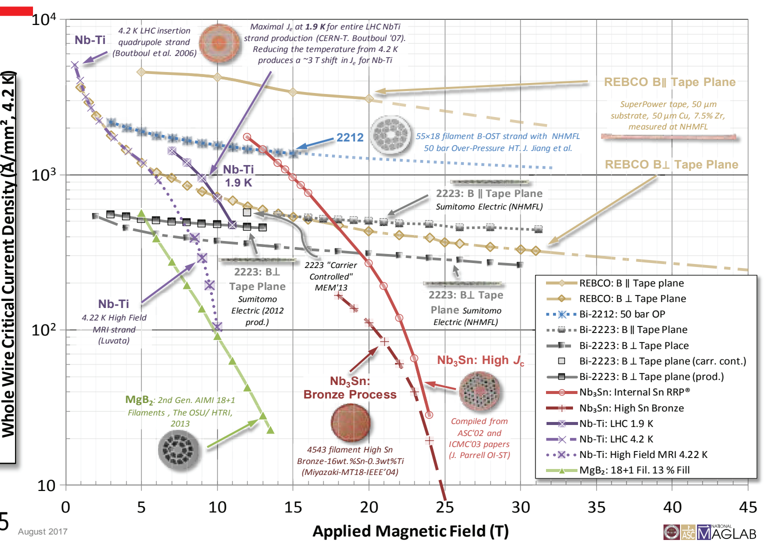
Core part

100 kA/mm²

10 kA/mm²



Overall

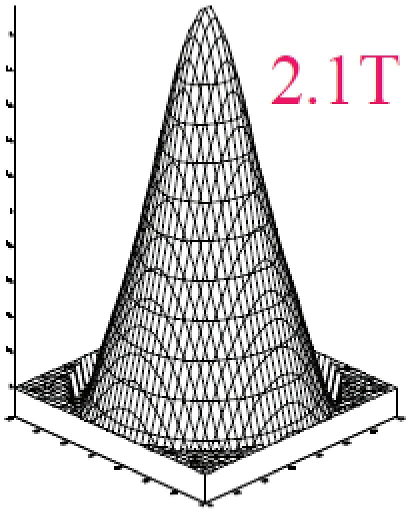


Potential of bulk Superconductor

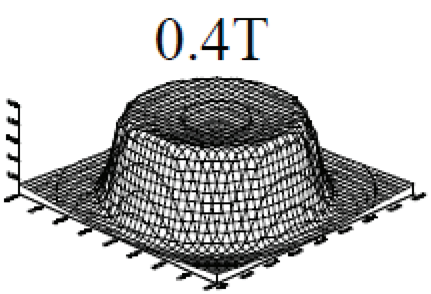
Bulk superconductor can be used as

Very Strong Permanent Magnet

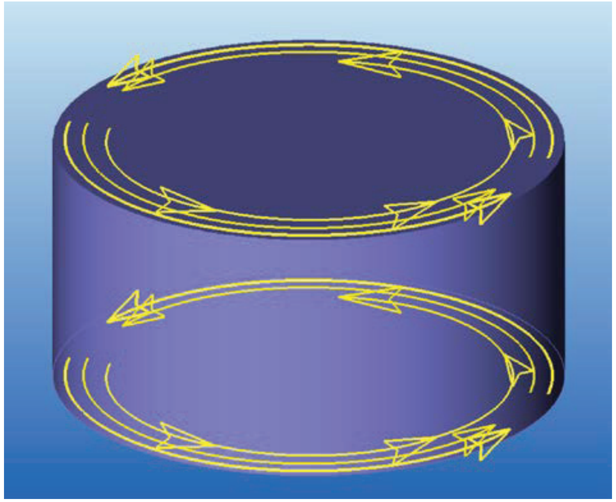
if it is successfully magnetized.



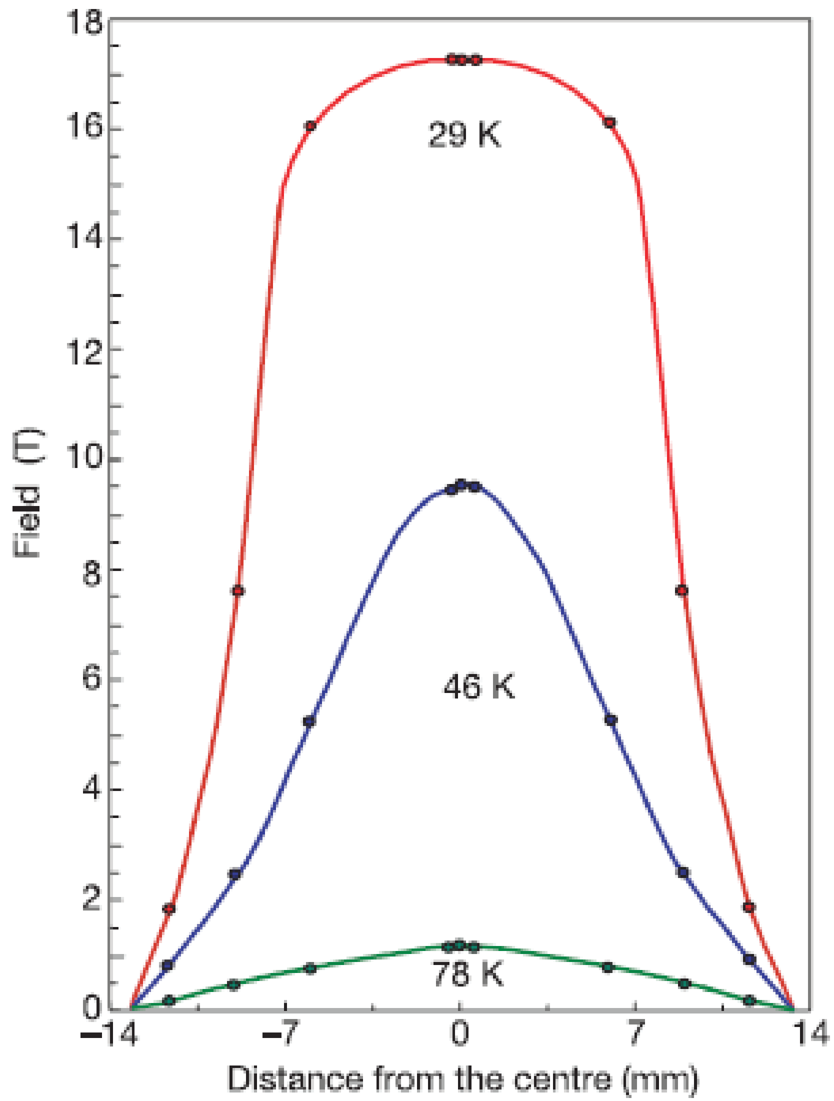
Bulk SC Magnet
Diameter : 60 mm
Temperature : 77 K



Permanent Magnet
NeFeB



Performance of bulk HTS at low temp.



M. Tomita, M. Murakami,

Y-Ba-Cu-O

Thickness :15 mm

Diameter: 26.5 mm

∼17 T @ 29K

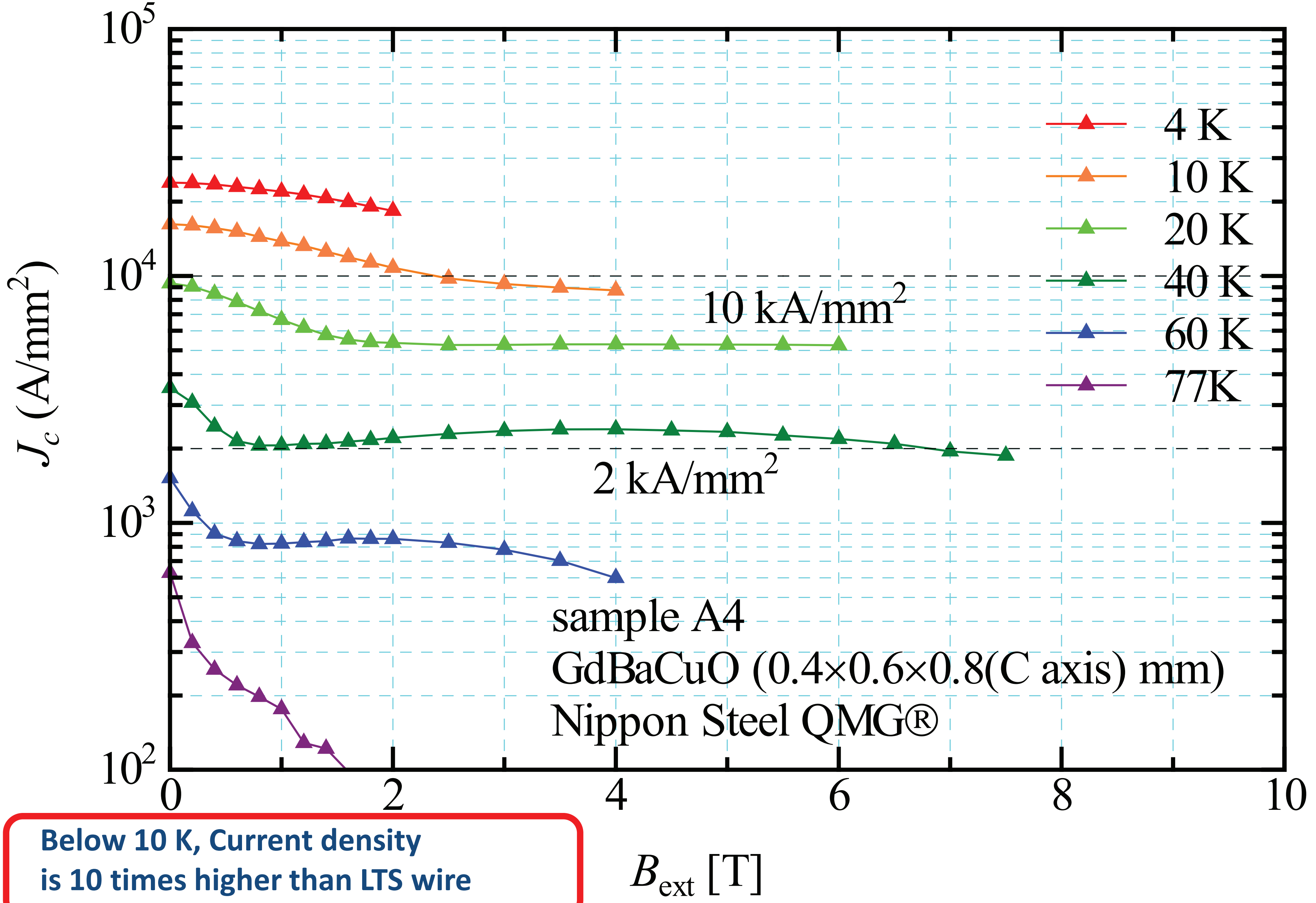
M. Tomita, M. Murakami,
NATURE Vol. 421, 30 January 2003

17.4 T

J. H. Durrell et al.,
Supercond. Sci. Technol. 27 0820001 2014

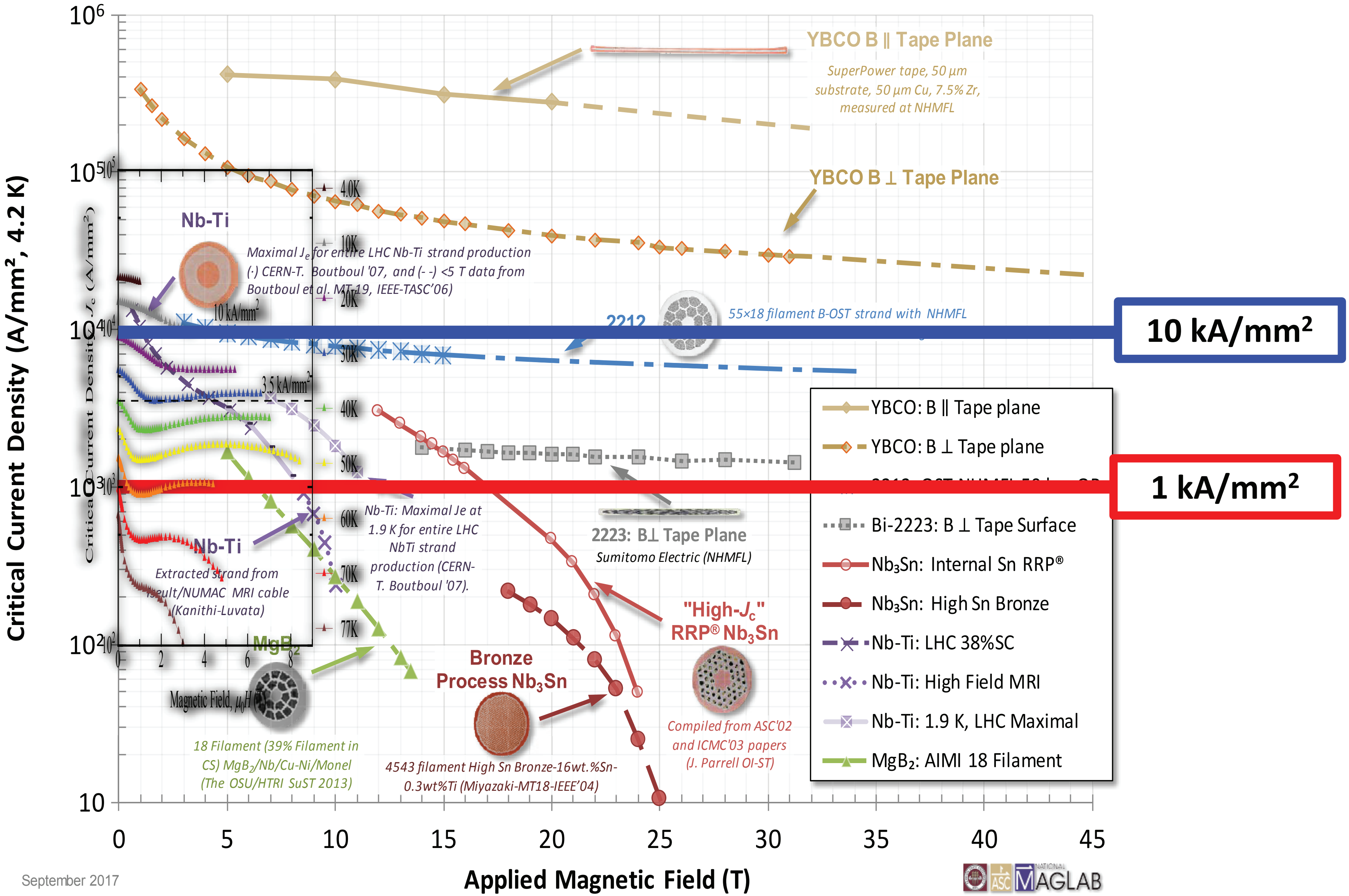
17.6 T

Performance of Bulk HTS material (GdBaCuO)



Below 10 K, Current density is 10 times higher than LTS wire

Material J_c = Core part of wires, Bulk HTS itself(overlay)



September 2017

How to make Periodic field using Bulk SC

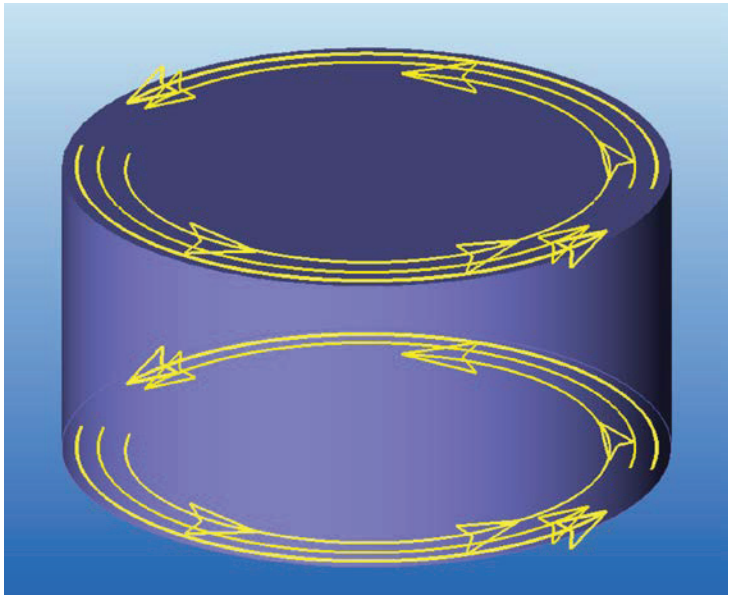
Magnetize bulk HTS in SC Magnet
then
Move bulk HTS and Assemble Array

NOT
Realistic!

Magnetize bulk HTS Array in SC Magnet

Possible?

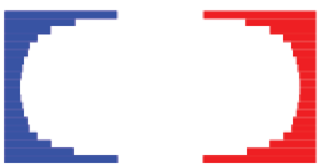
How to excite induction current in single bulk SC



External B-field is changed.
→ Induction currents appear to keep B-field in the bulk SC.

"External B-field is trapped by bulk SC."

Side View



Partially magnetized

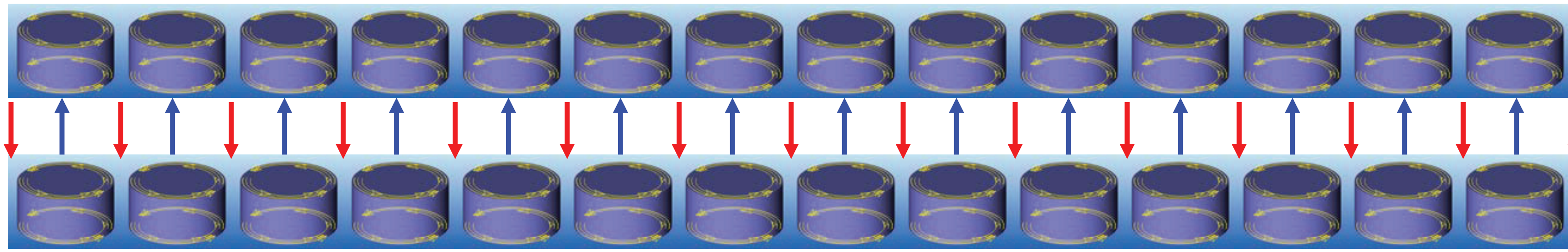
Side View

Fully magnetized

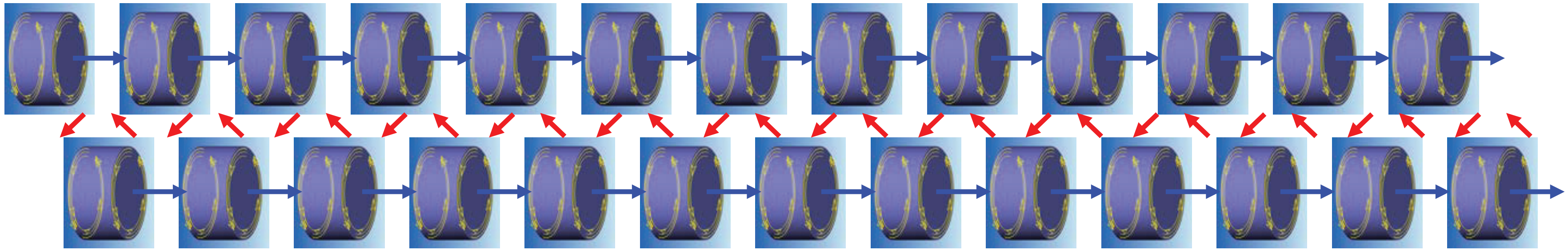
If HTS Array is placed in SC Magnet...

Two configurations of HTS array

1. SPring-8 T. Tanaka *et al.* (2005)



2. Kyoto-U T. Kii *et al.* (2006)



Periodic magnetic field is generated.

1. SCPMU (SPring-8)

Journal of
Synchrotron
Radiation

ISSN 0909-0495

Pure-type superconducting permanent-magnet undulator

2005

Takashi Tanaka,* Rieko Tsuru and Hideo Kitamura

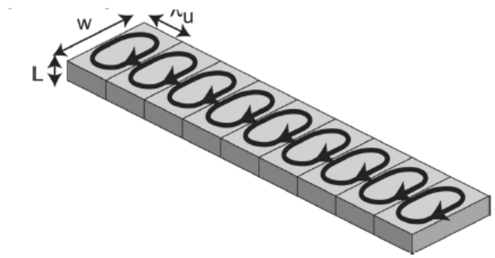


Figure 1
An array of magnetized superconducting blocks that work as PMs.

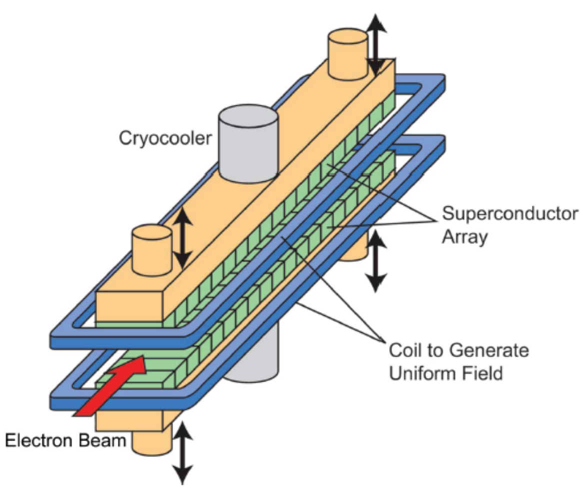


Figure 2
Schematic illustration of the SCPMU.

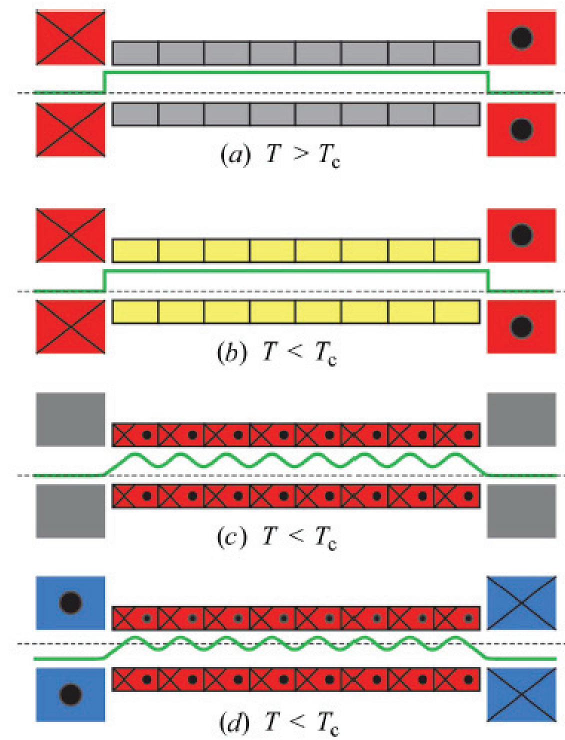


Figure 3
Method for magnetizing the HTSCs and eliminating the field offset in type A.

Bulks have to be fully magnetized.

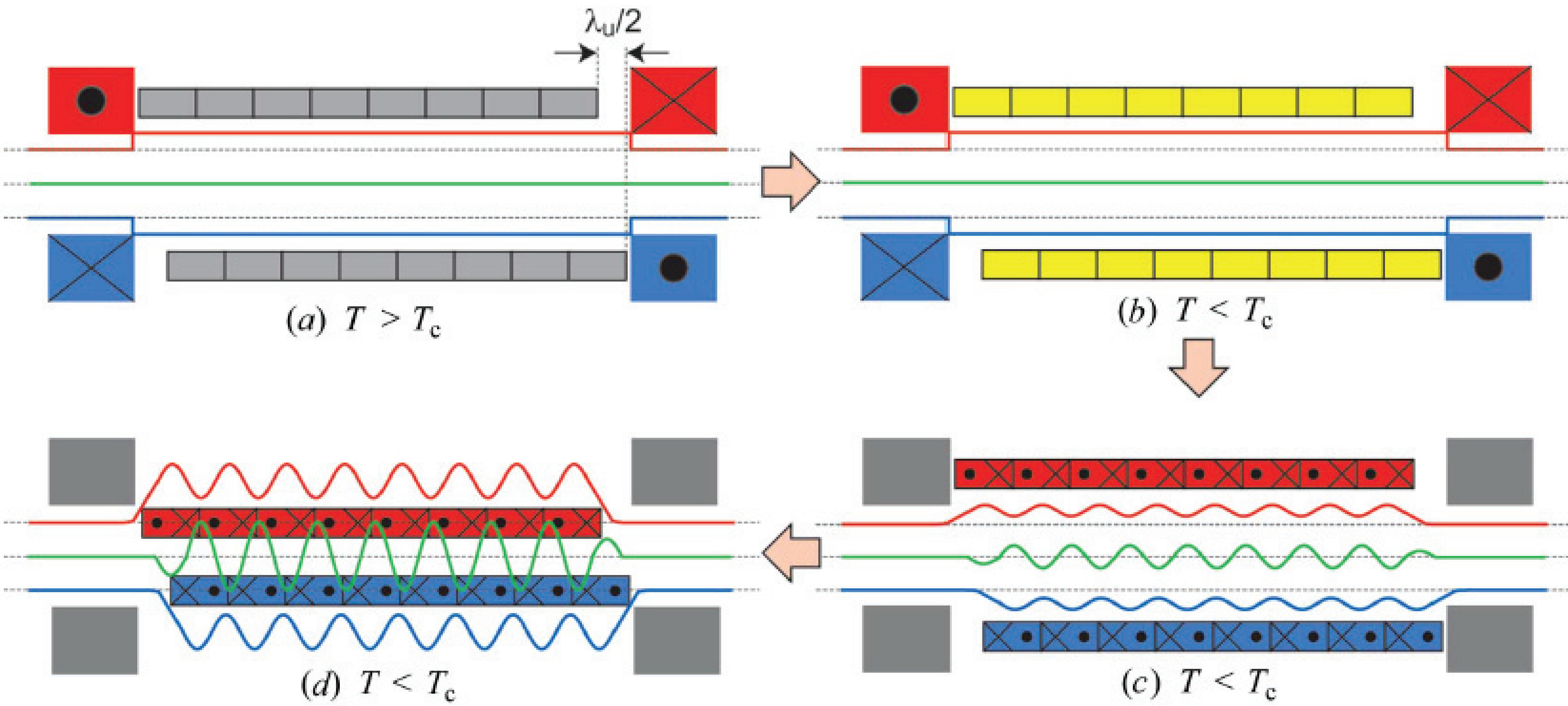


Figure 4
Method for magnetizing the HTSCs and eliminating the field offset in type B.

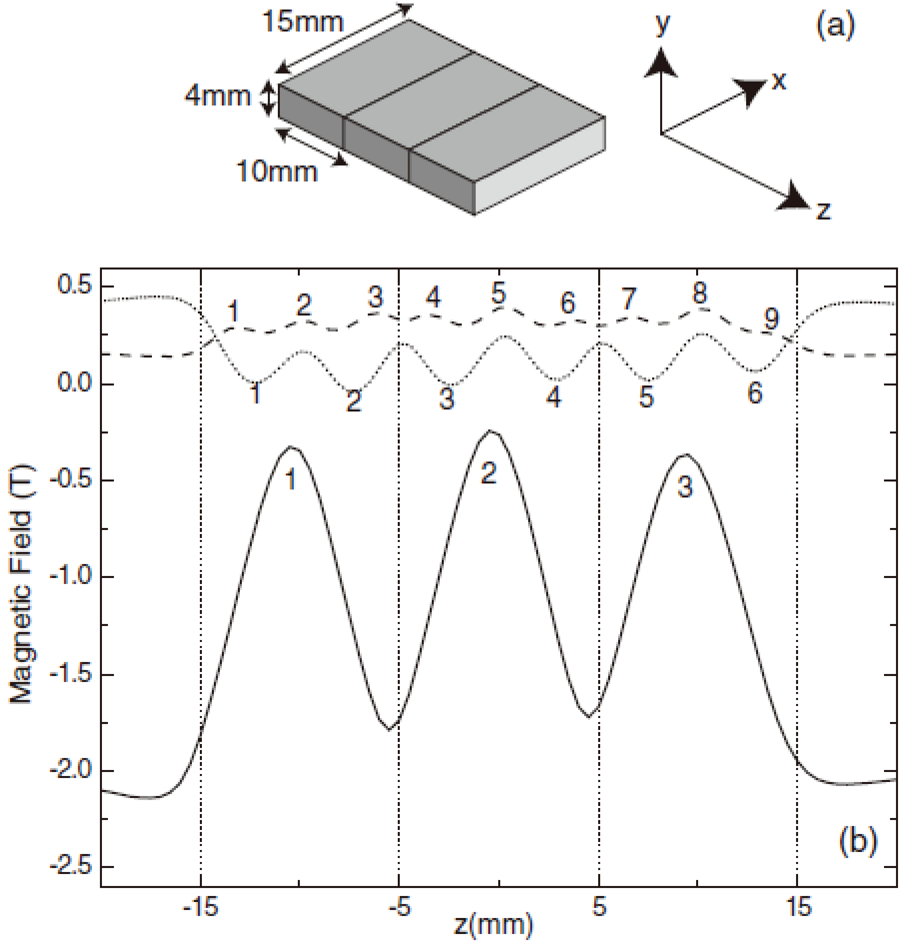


Figure 8. Measured magnetic distribution for the three pieces of HTS bulk magnets.

Period length of 10 mm
Gap is not defined
(half array)

Better performance will be obtained at lower temp.

Expected B_{und}

$$B_p = \frac{2\mu_0 I}{\lambda_u} \, \frac{1-\exp(-k_u b)}{k_u b} \, \frac{\sin(k_u a/2)}{k_u a/2} \exp(-k_u g/2). \qquad (6)$$

Contents

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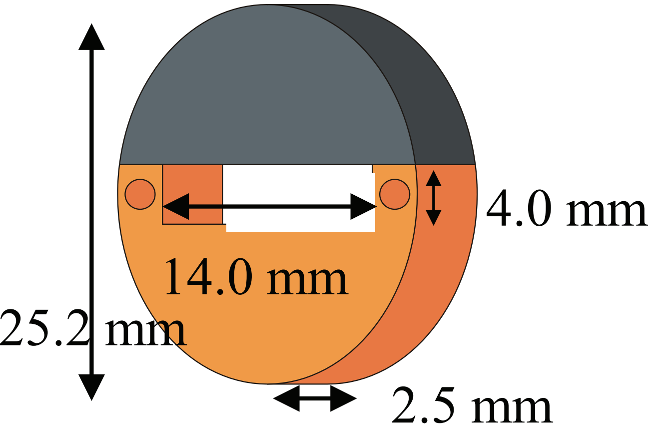
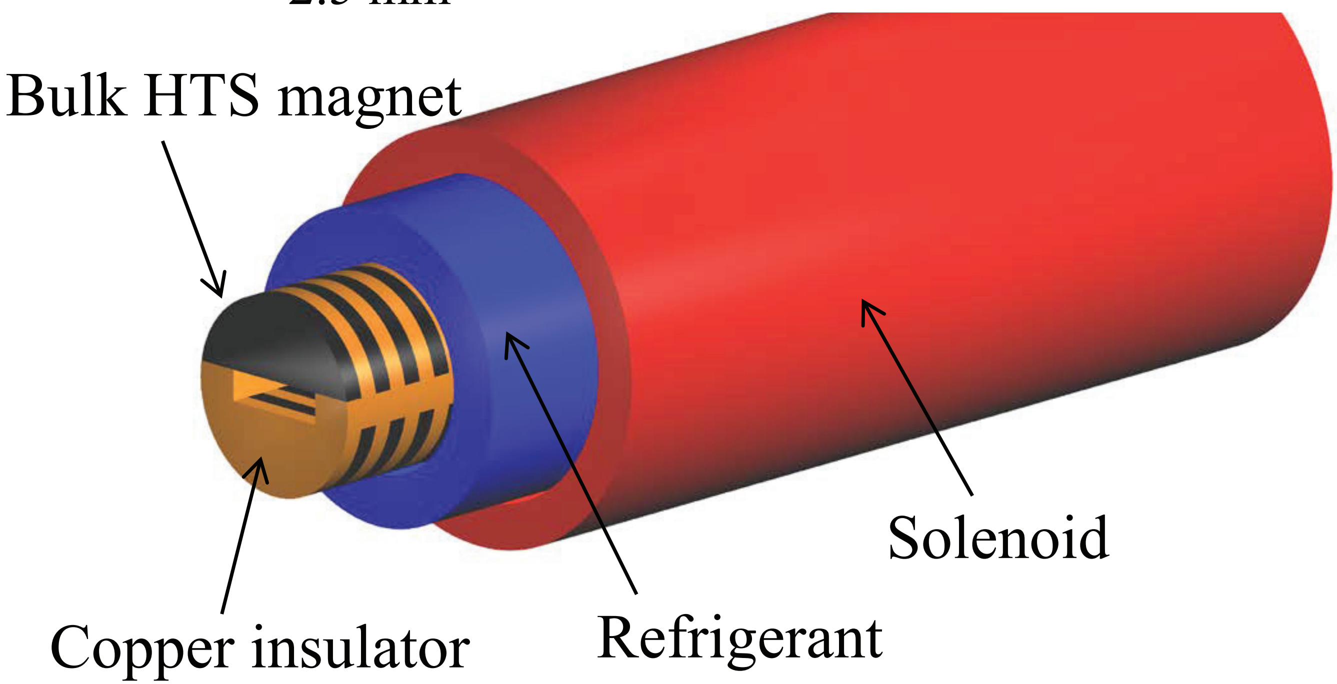
   ～ Limitation of Present Undulators ～
2. Bulk HTS
   ～ Potential of bulk HTS, How to make periodic field～
3. Bulk HTS SAU
   ～ Principle of Operation, Experimental results, Numerical model ～
4. Conclusion

Bulk HTS Undulator (Kyoto-U)

We proposed
new structure using bulk HTS

Bulk HTS SAU =
Stacked HTS array + Solenoid

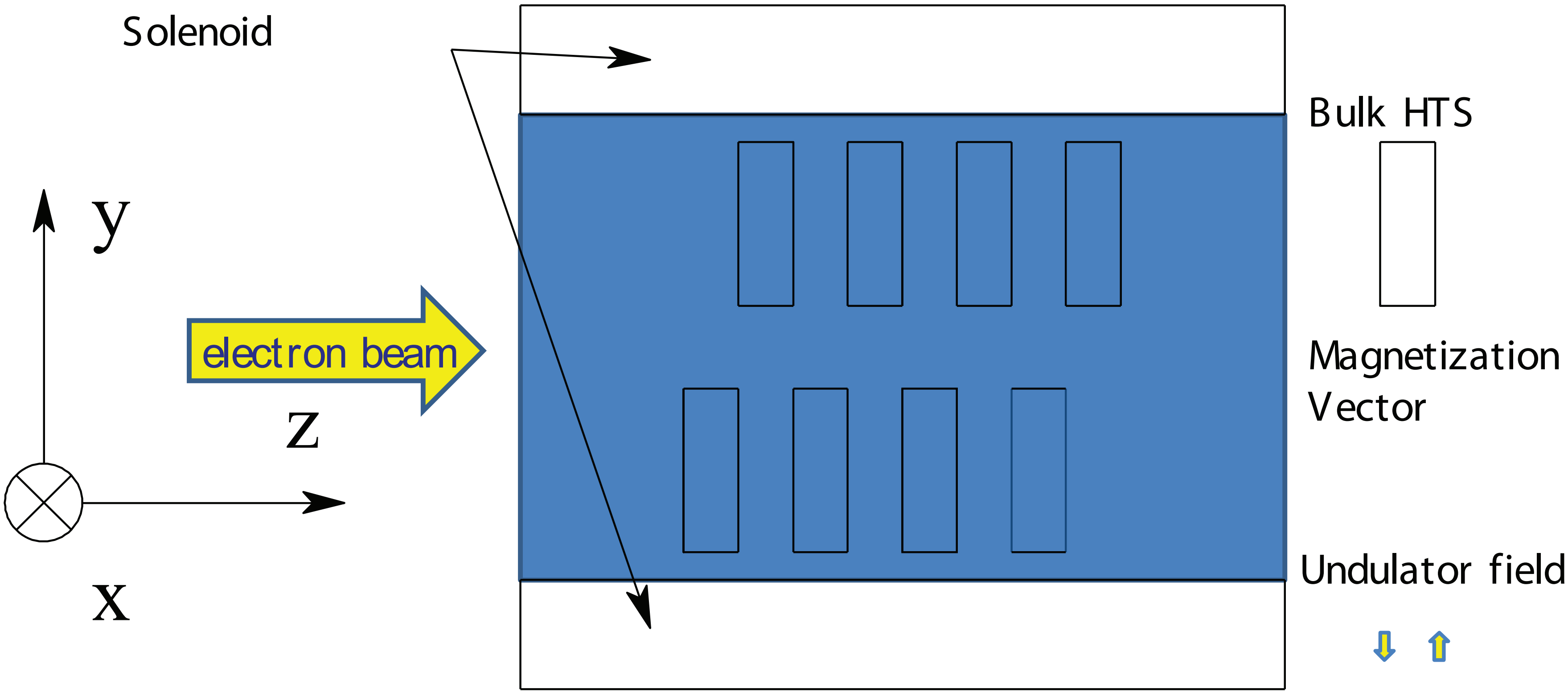




T. Kii, et al.: Proc. FEL2006 (2006) p. 653.

Principle of Operation bulk HTS SAU (1)

Side view of “Bulk HTSC SAU”

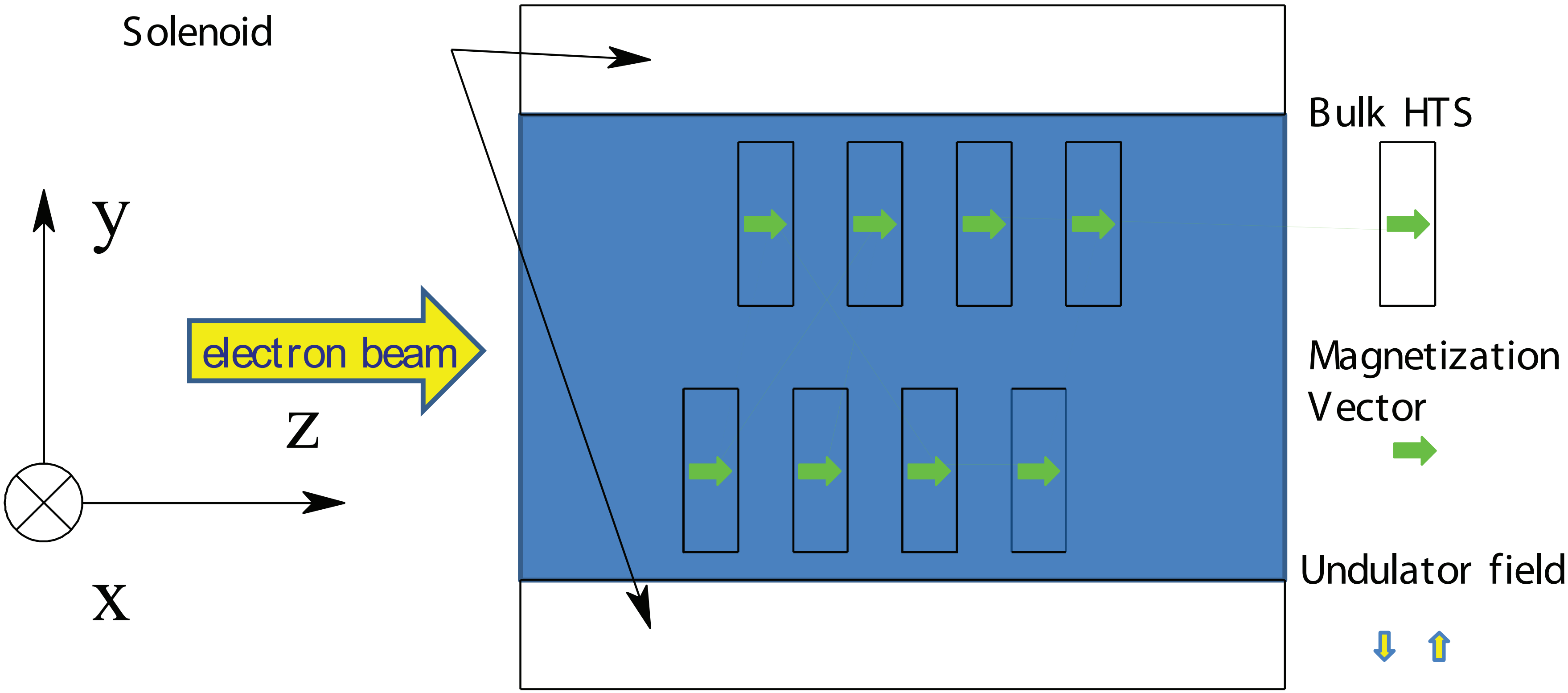


Magnetic field is changed. : $B_{start} \rightarrow B_{end}$

Undulator field is generated by superposition of magnetic field

Principle of Operation bulk HTS SAU (1)

Side view of “Bulk HTSC SAU”



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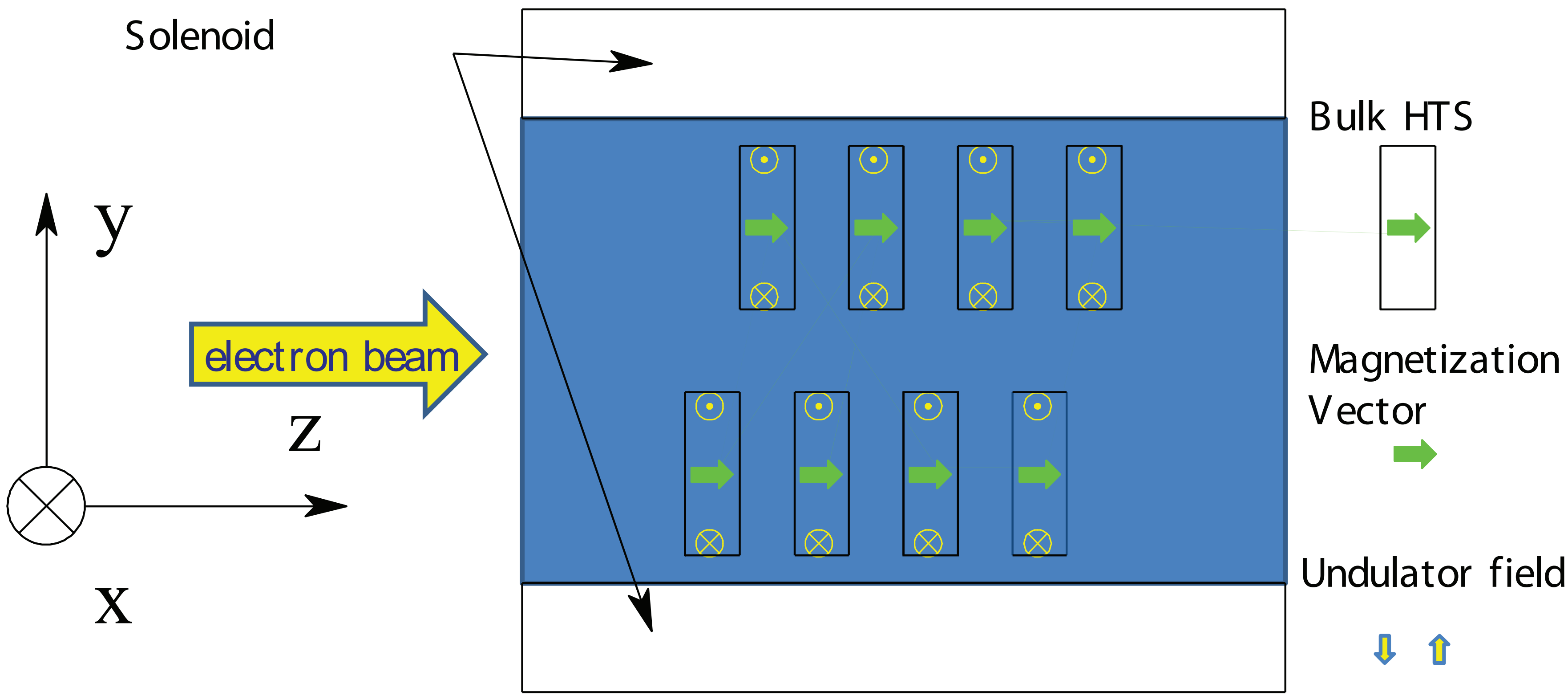

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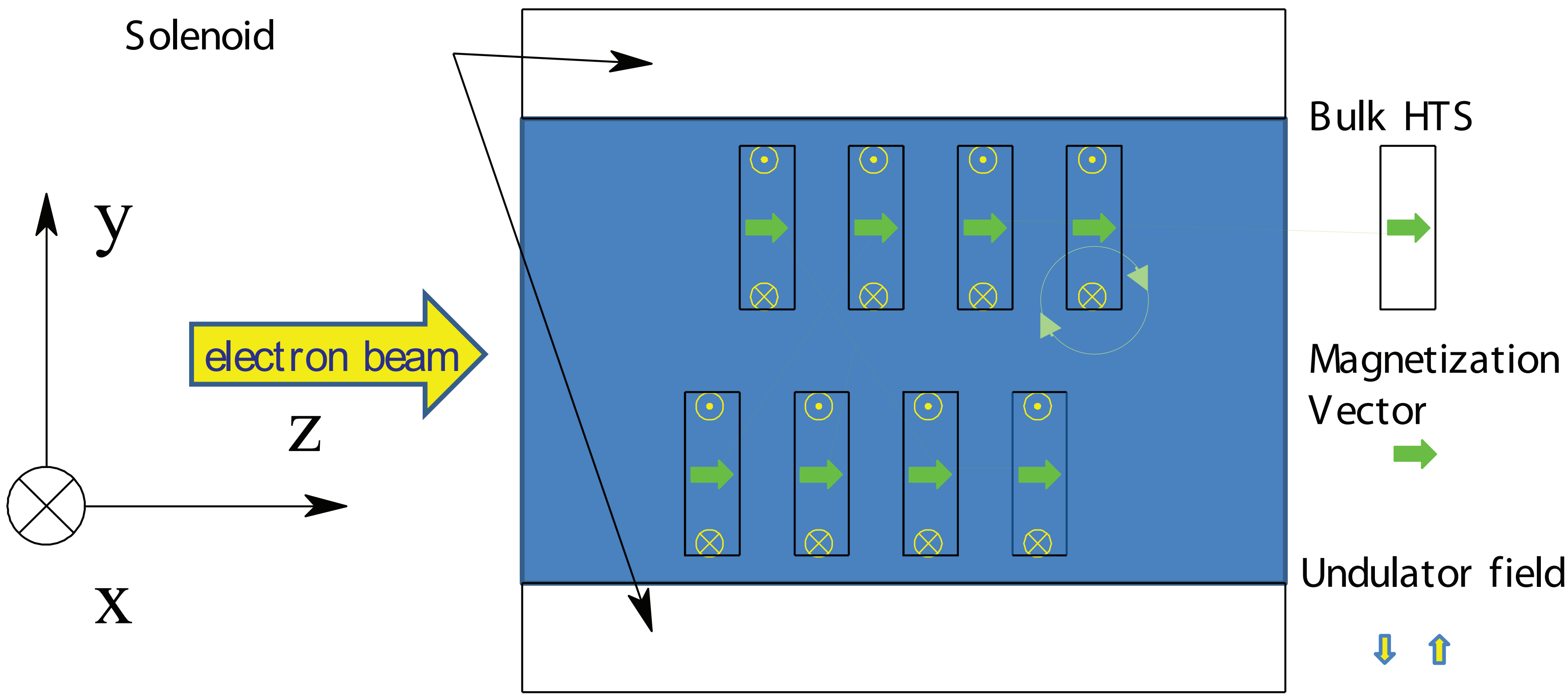
Principle of Operation bulk HTS SAU (1)

Side view of “Bulk HTSC SAU”



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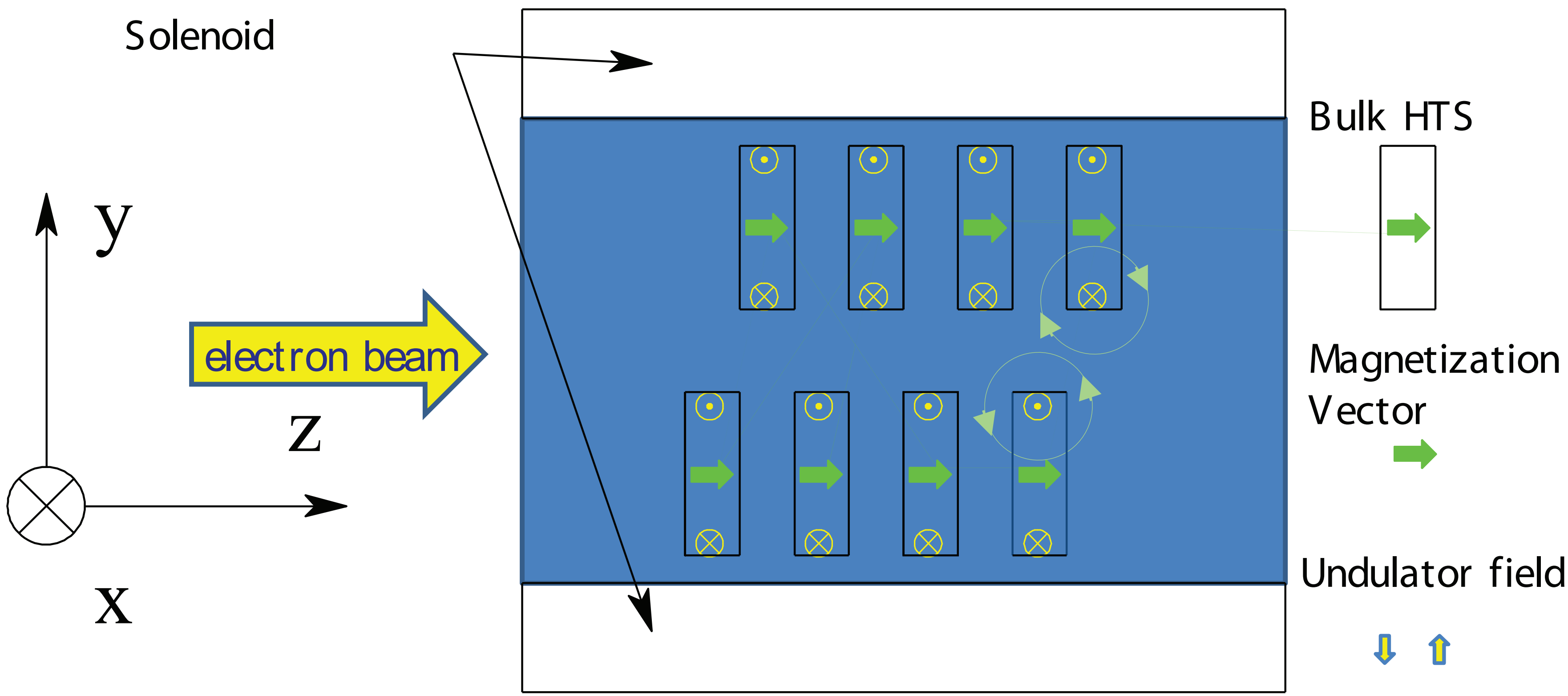
Principle of Operation bulk HTS SAU (1)

Side view of “Bulk HTSC SAU”

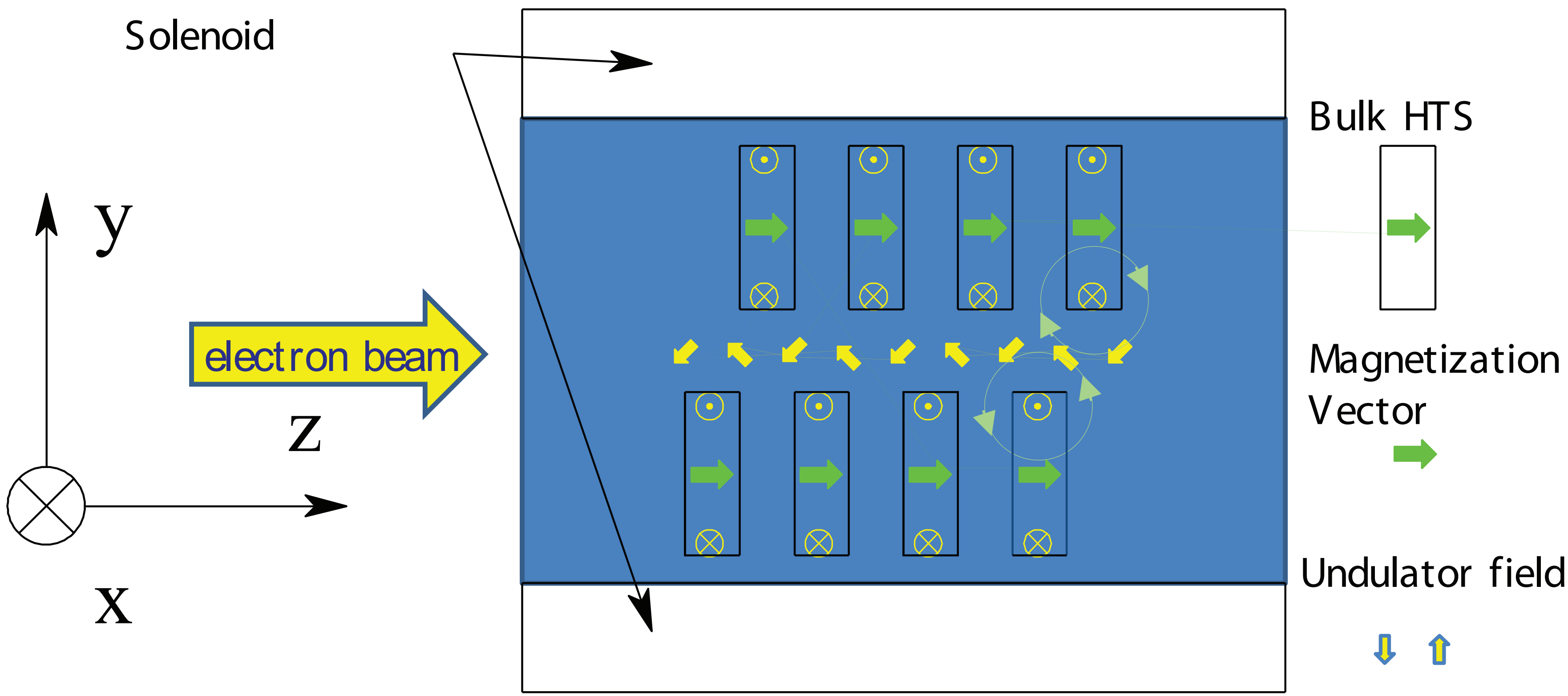


Magnetic field is changed. : $B_{start} \rightarrow B_{end}$

Undulator field is generated by superposition of magnetic field

Principle of Operation bulk HTS SAU (1)

Side view of "Bulk HTSC SAU"



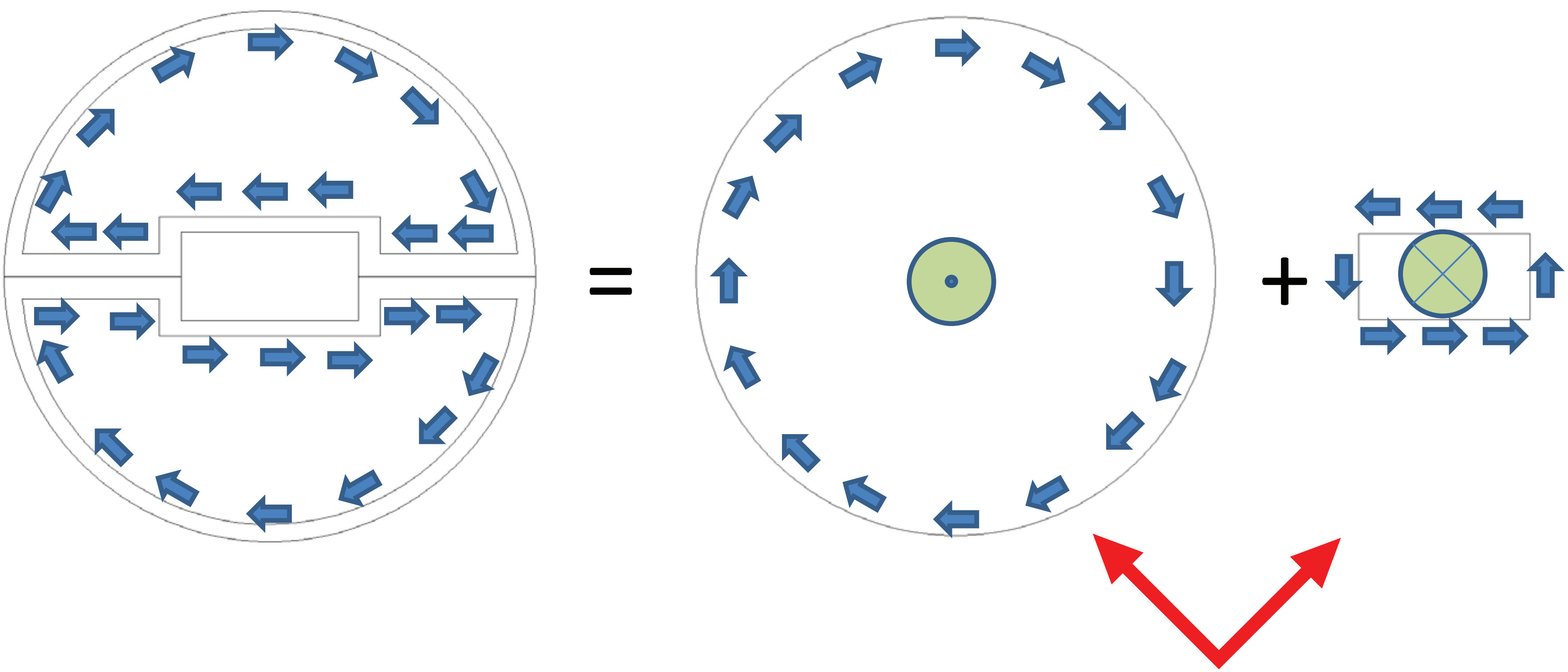
Magnetic field is changed. : $B_{start} \rightarrow B_{end}$

Undulator field is generated by superposition of magnetic field

Principle of Operation bulk HTS SAU (2)

Axial field component: Bz ≈ 0

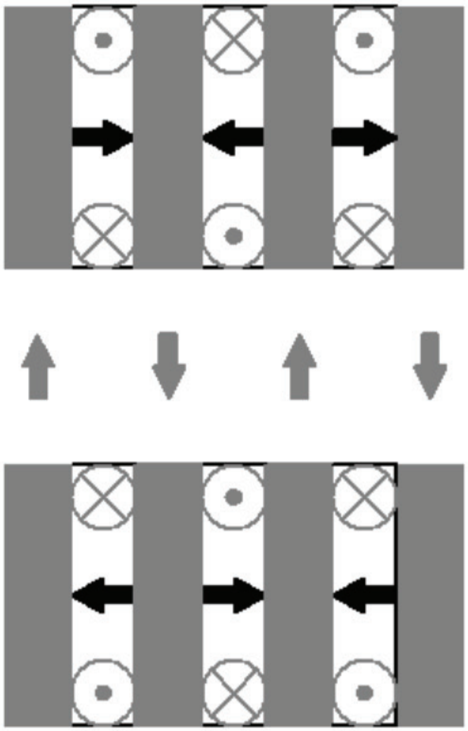
If undulator total length is long enough.



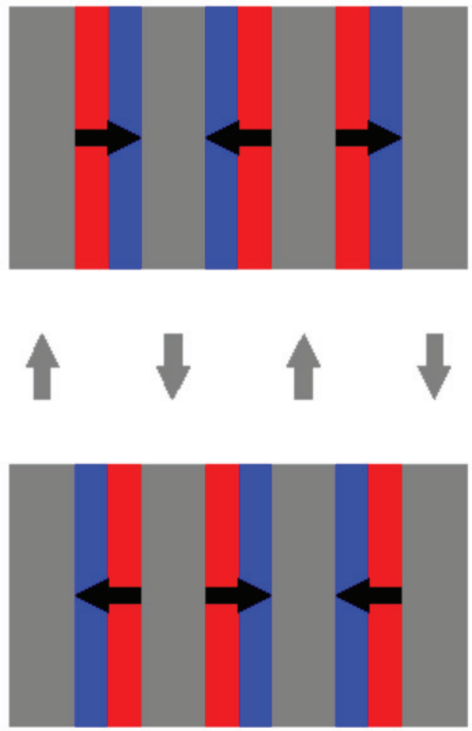
AT is same!

Analog to

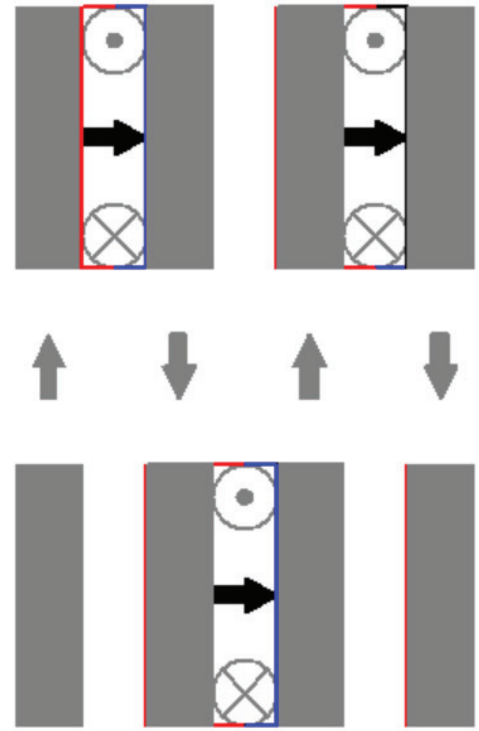
Wire SC
Hybrid Und.



Hybrid Und.



Bulk SC SAU



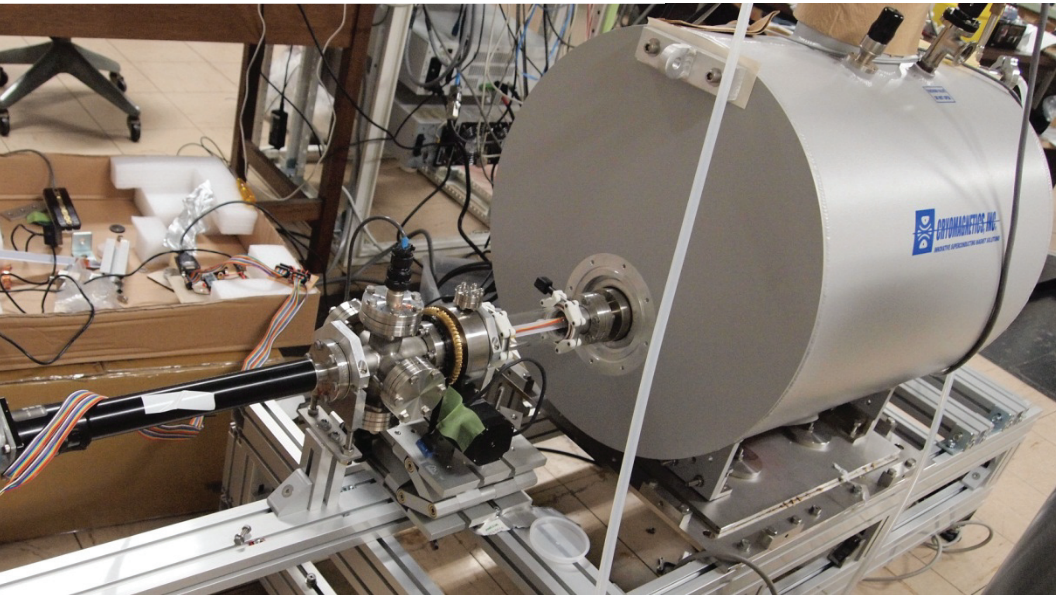
Advantage of the Bulk HTS SAU

(1) Bulk HTS can be magnetized **using single solenoid**.
(2) 10 K operation is enough. : **Easy cooling**.
(3) No mechanical component.
(4) Cold mass is very small.
(All the cooled component is placed in ϕ = 75 mm RT bore)
(5) Bulk HTS can be effectively **cooled by copper insulator**.
(6) Magnet sorting technique can be applicable.
(7) Radiation irradiation improve J_c performance. (Benefit > Damage)
(8) Fluctuation of the critical current density for each HTS is **automatically suppressed**.
(9) Local magnetic field property can be controlled by using **machined bulk HTS / ferromagnetic plate**.

Challenging issue of the Bulk HTS SAU

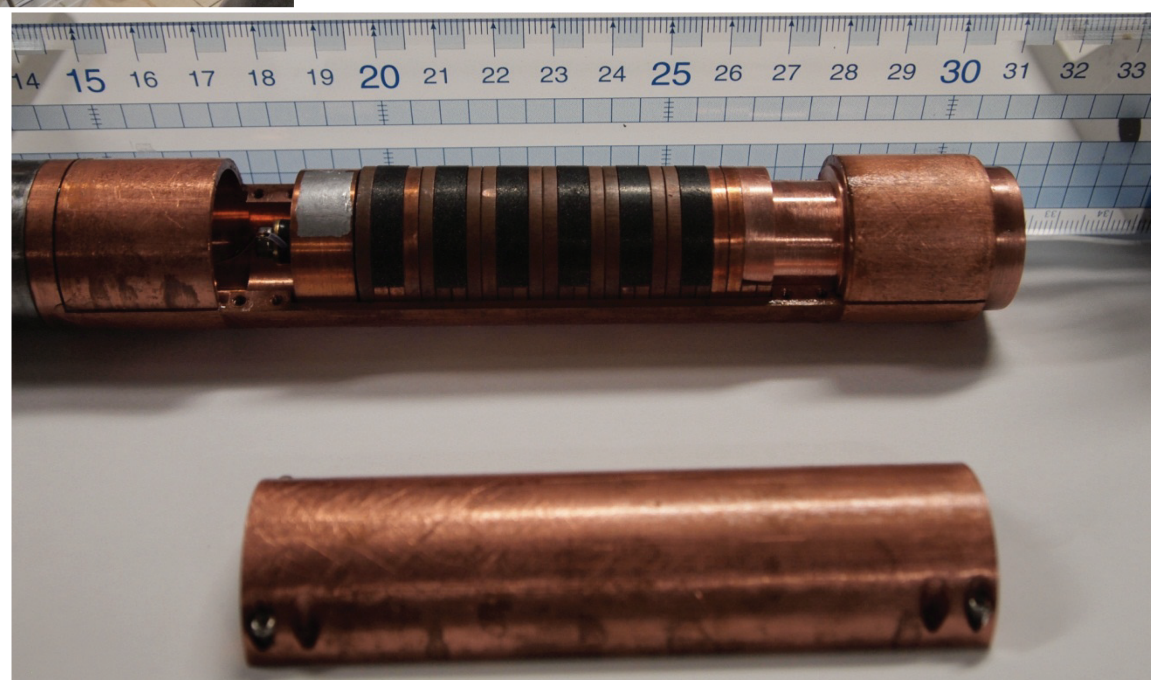
(1) End field termination is not easy.

Prototype



He Cryostat

2 T SC solenoid



Period : 10 mm

Gap : 4 mm

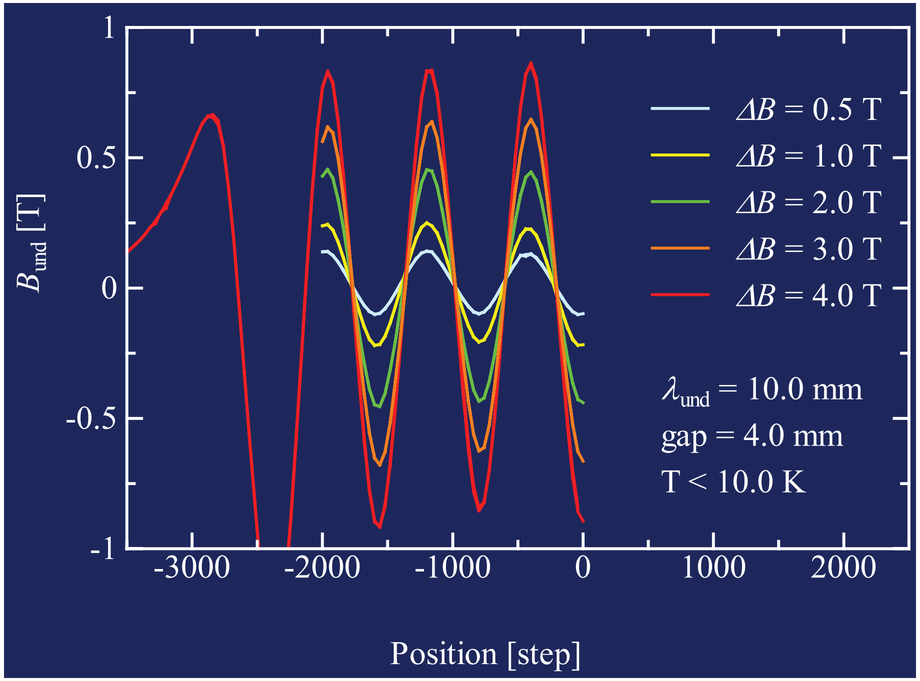
Number of Period

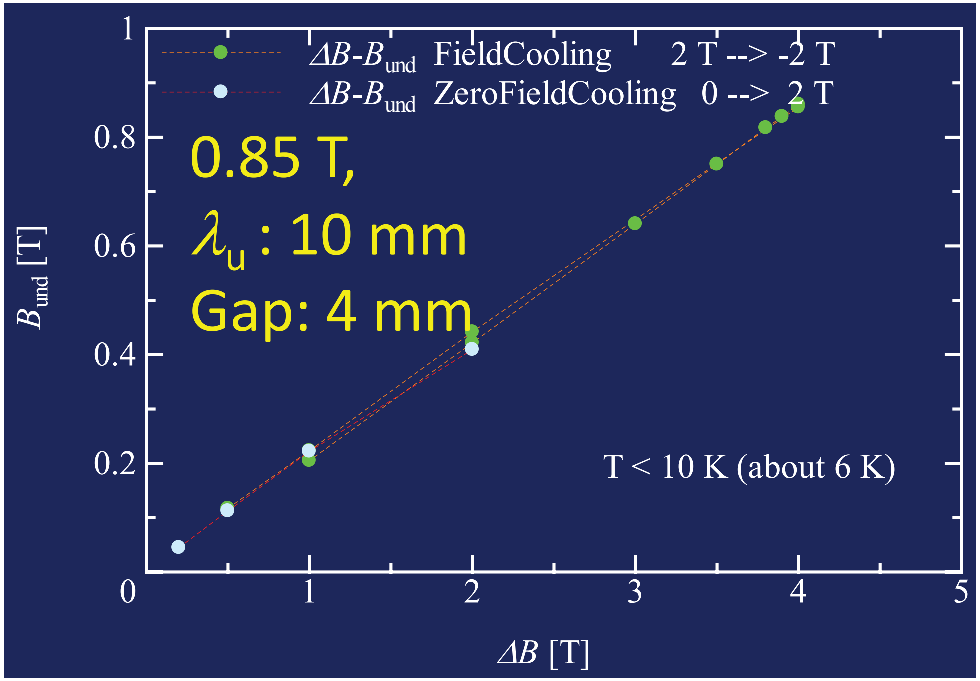
: 6

GdBaCuO Tc 91 K

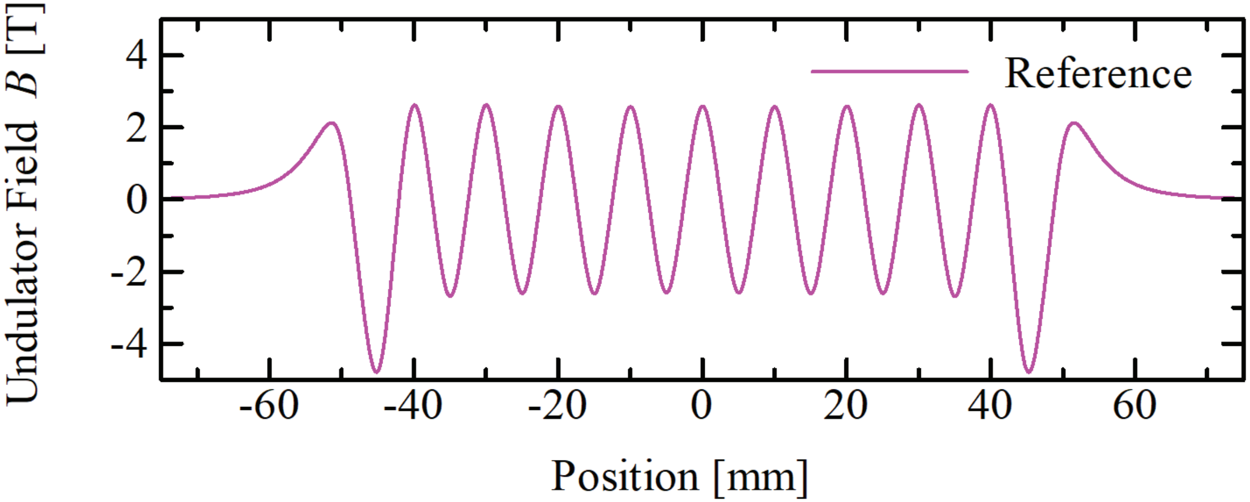
Experimental demonstration

R. Kinjo, et al., Appl. Phys. Express 6 (2013) 042701





Numerical expectation



J_c 18 kA/mm^2

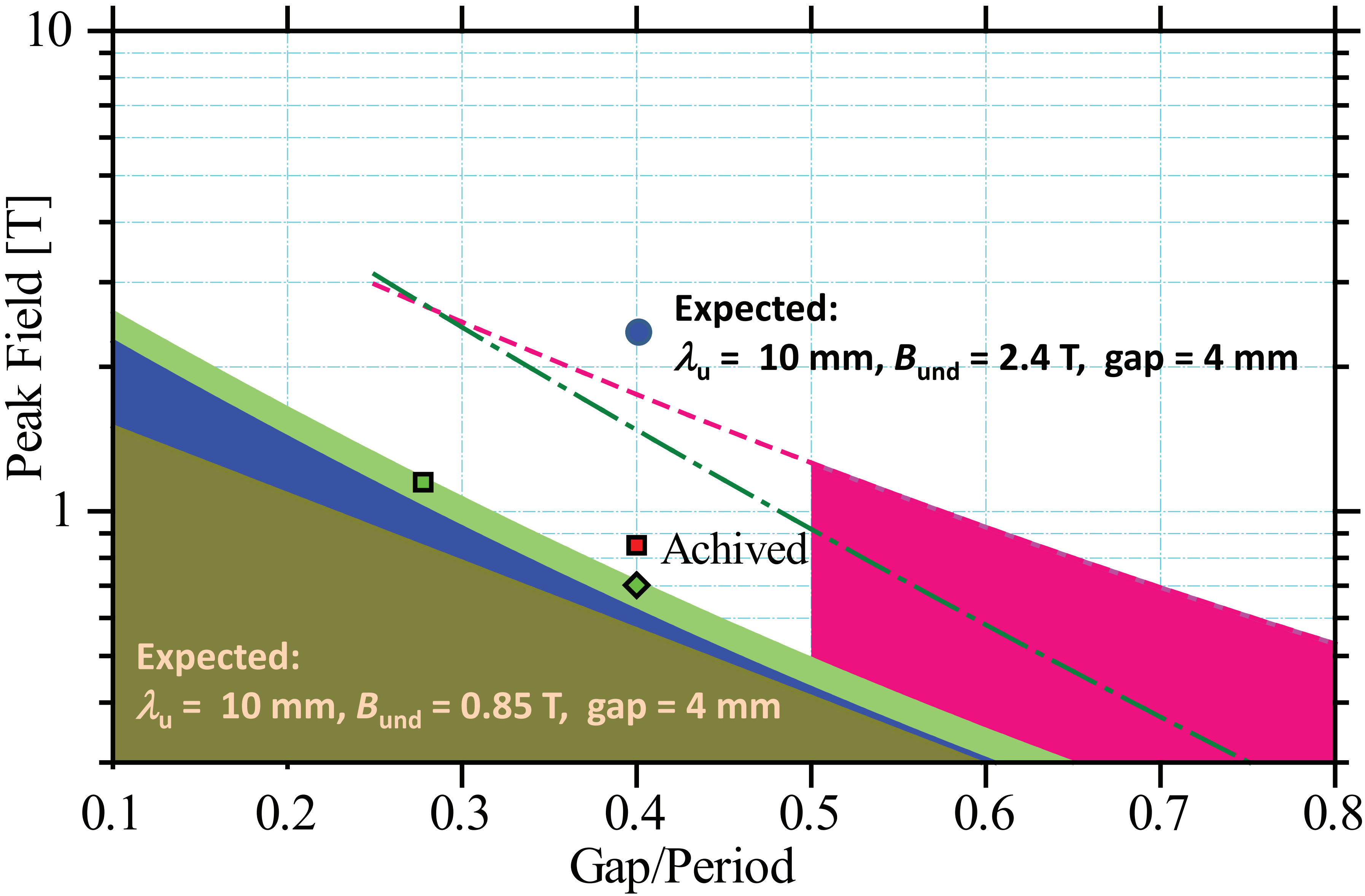
ΔB = 15 T

B_{und} = 2.4 T

Period λ_{und} = 10 mm

Gap g = 4.0 mm

Demonstrated and expected parameters



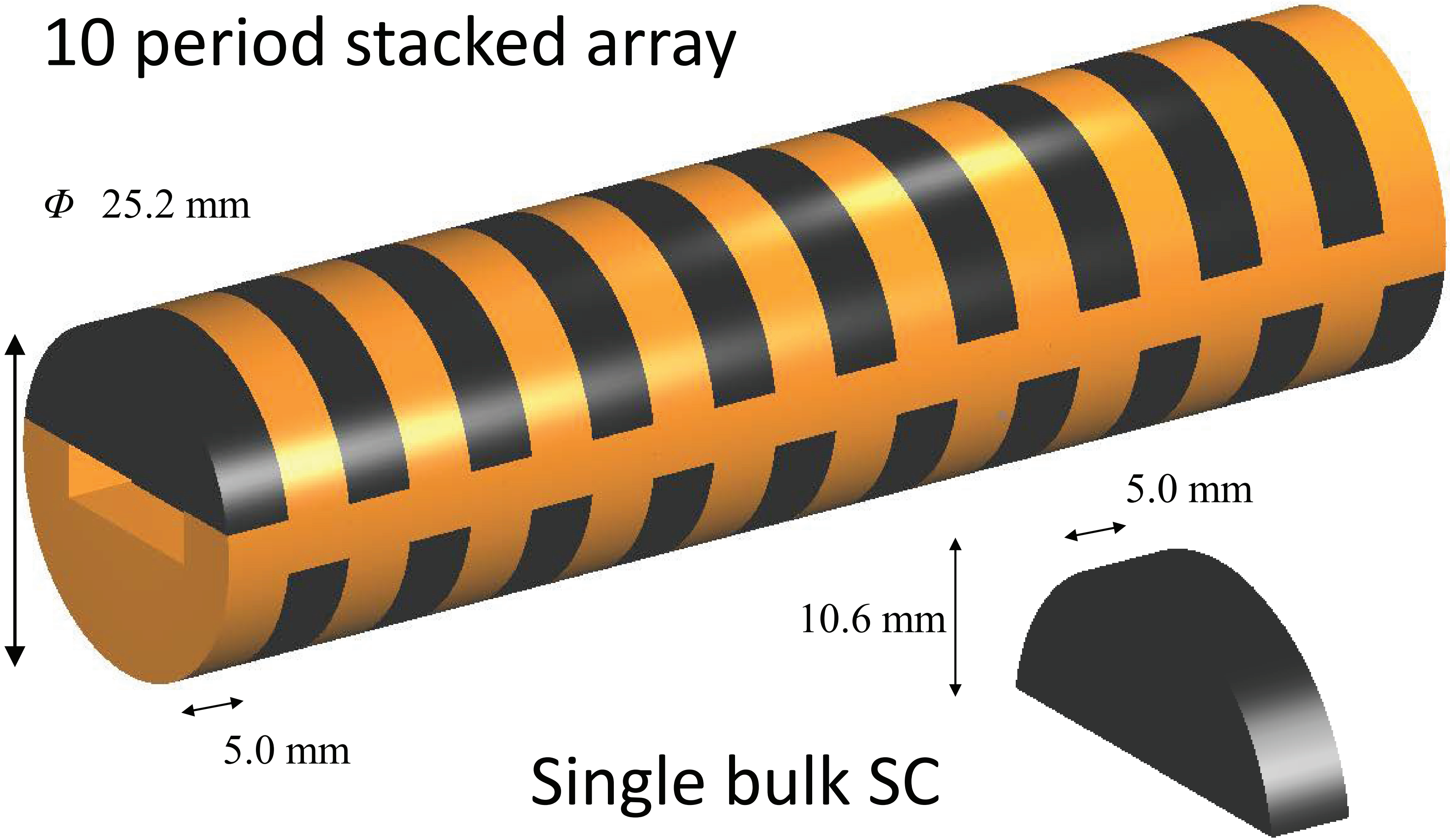
Status of development

1. Method to reduce field error.
2. Numerical model for Fast simulation.
3. Method for End Field Termination.
4. Next prototype.

1. Bulk sorting + Precise machining + Shim film
2. Loop current modeling
3. Additional bulks to the end part
4. 6 T solenoid + HTS array

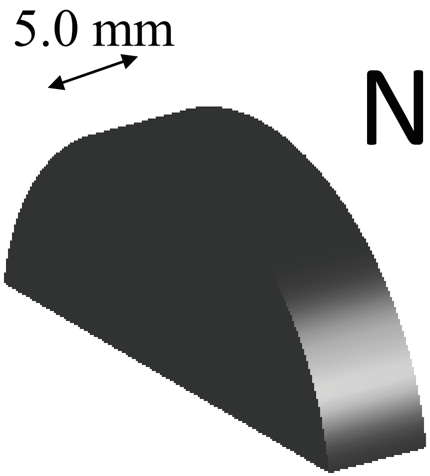
Numerical Model (1)

10 period stacked array

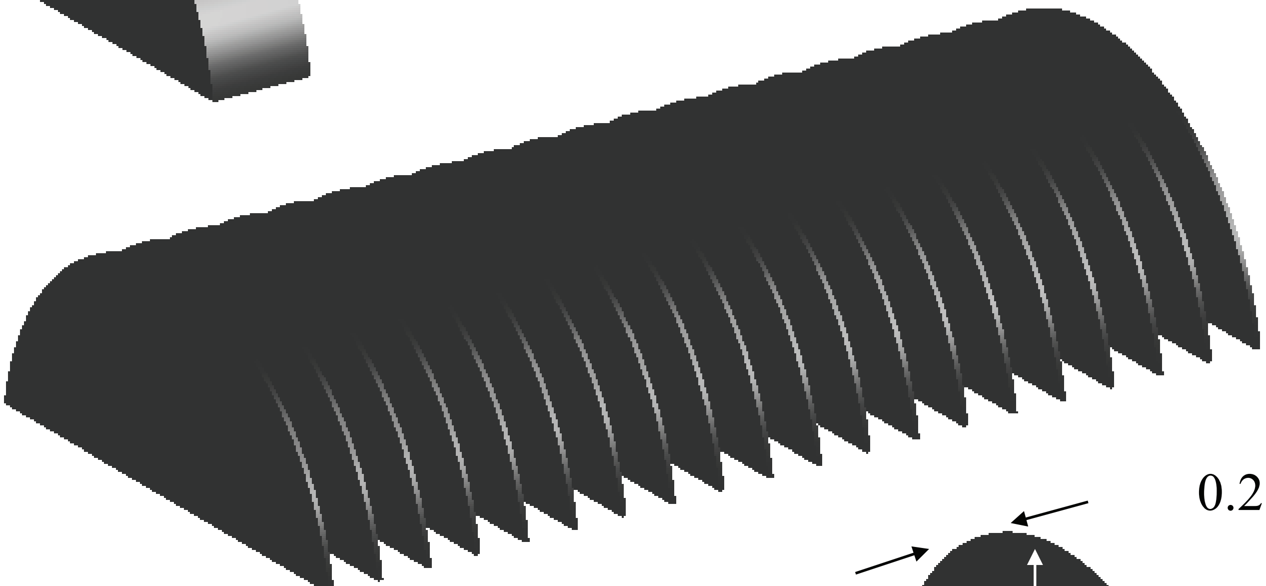


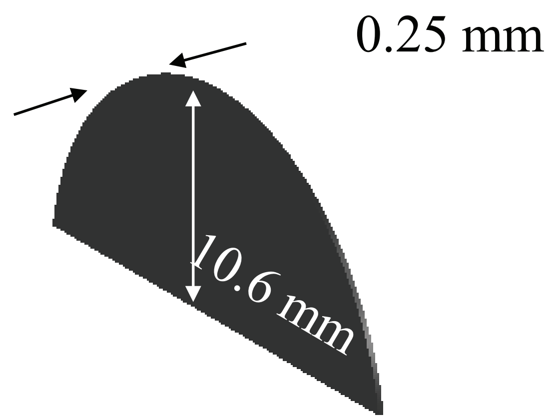
Single bulk SC

Numerical Model (2)



Single bulk SC



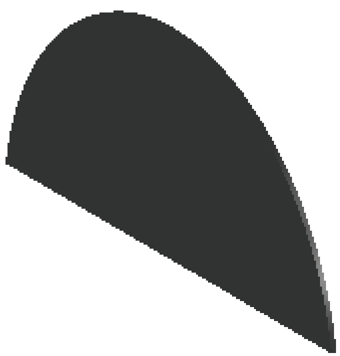


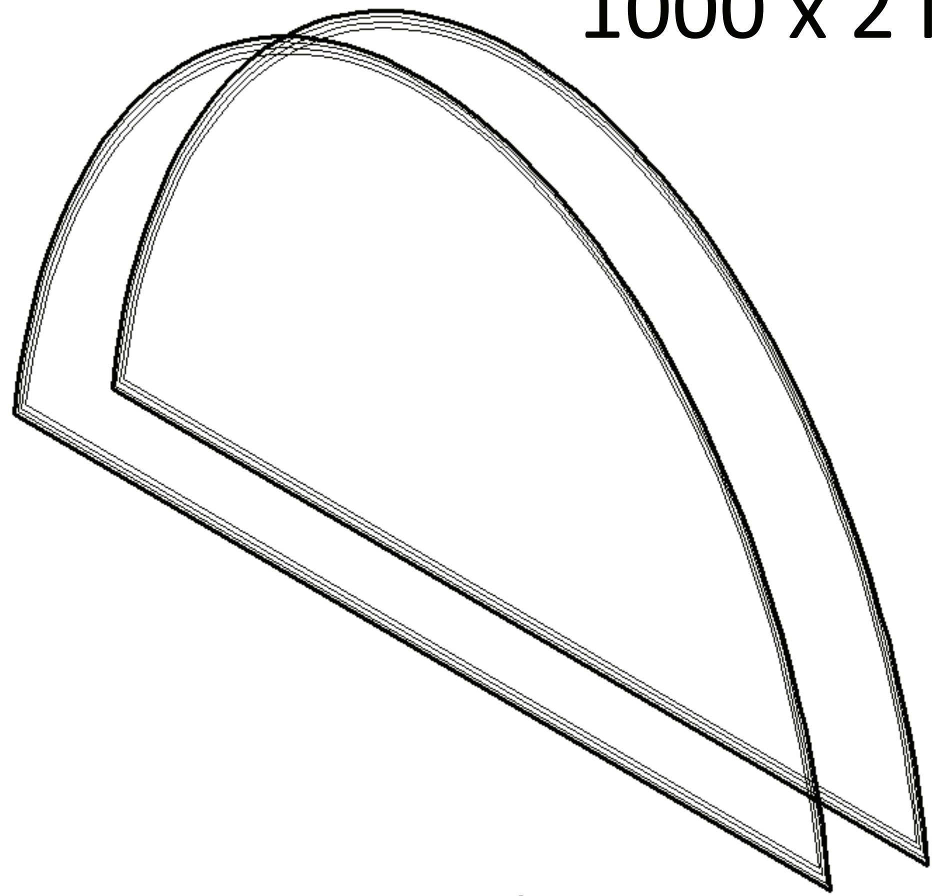
Sliced into 20 layer

Numerical Model (3)

1000 x 2 loops

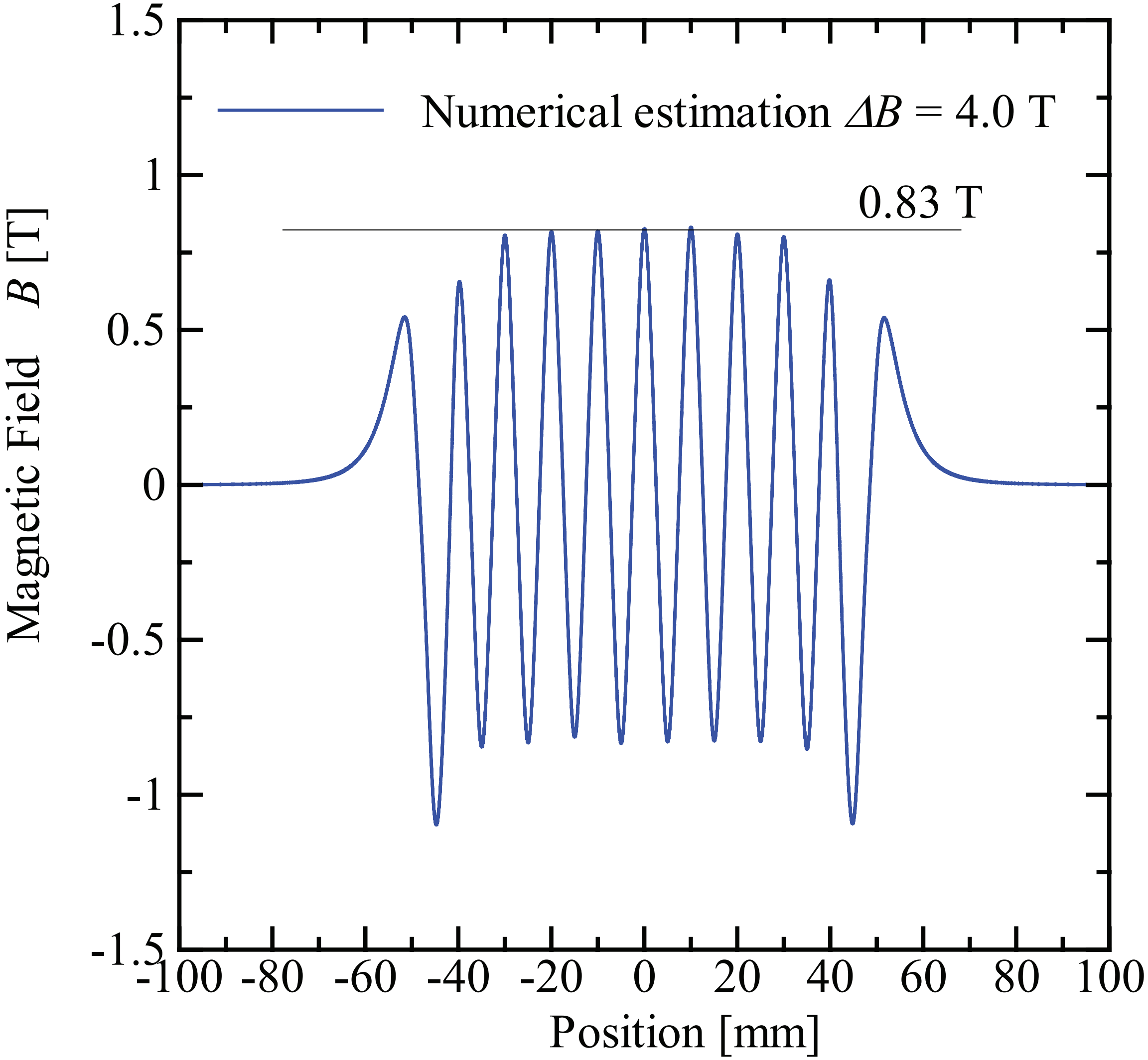
Single layer





1000 x 2 x 20 x20 = 800,000 loops

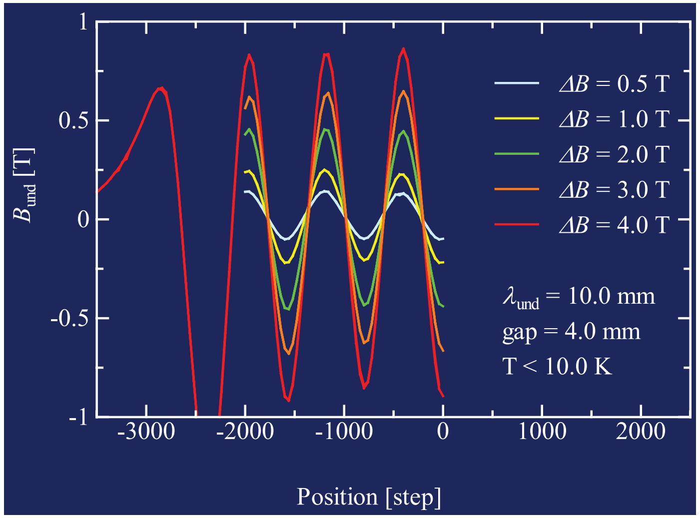
Numerical Results (1)



Undulator field amplitude is well reproduced.

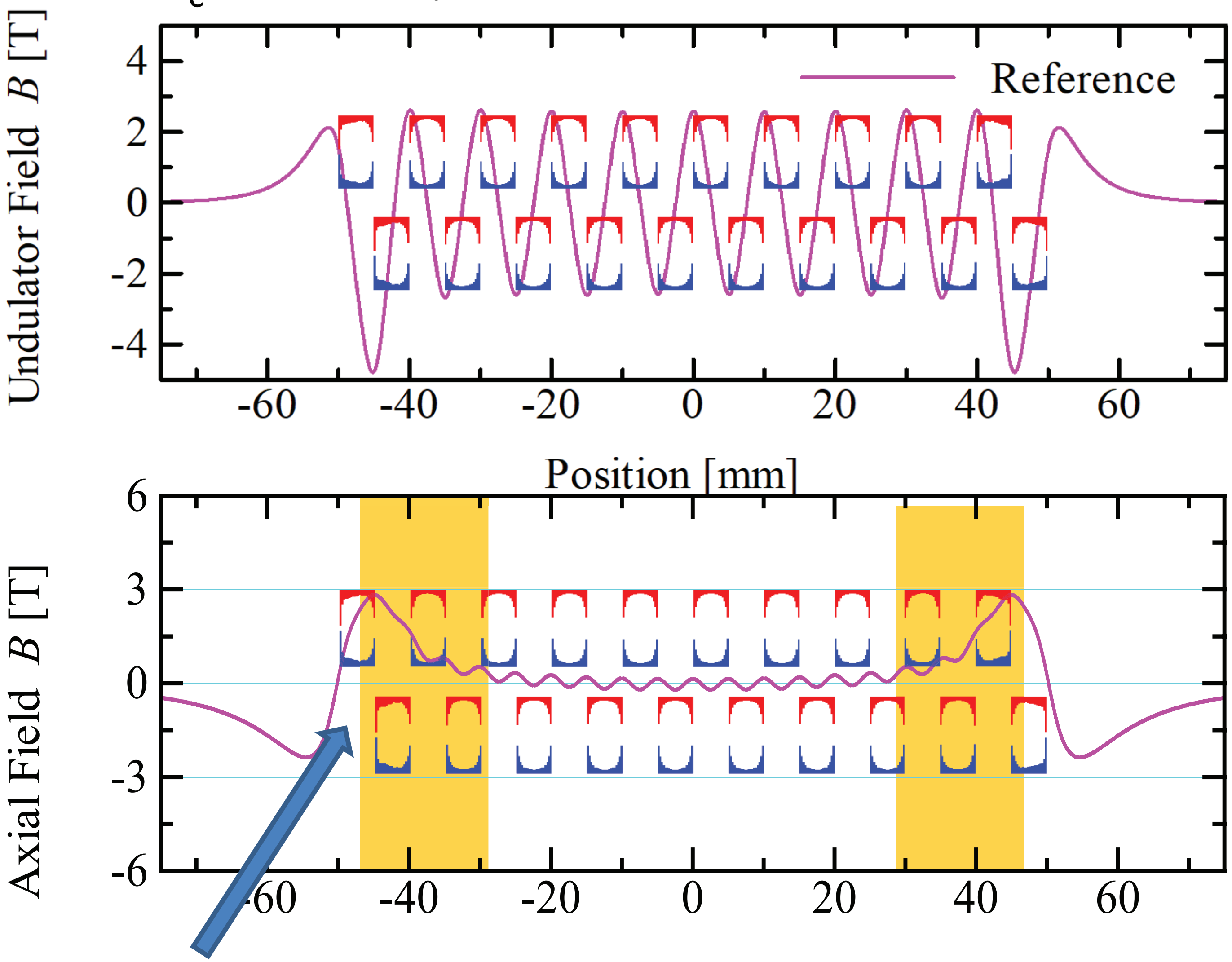
EXP. 0.85 T

Calc. 0.83 T



Numerical Results (2)

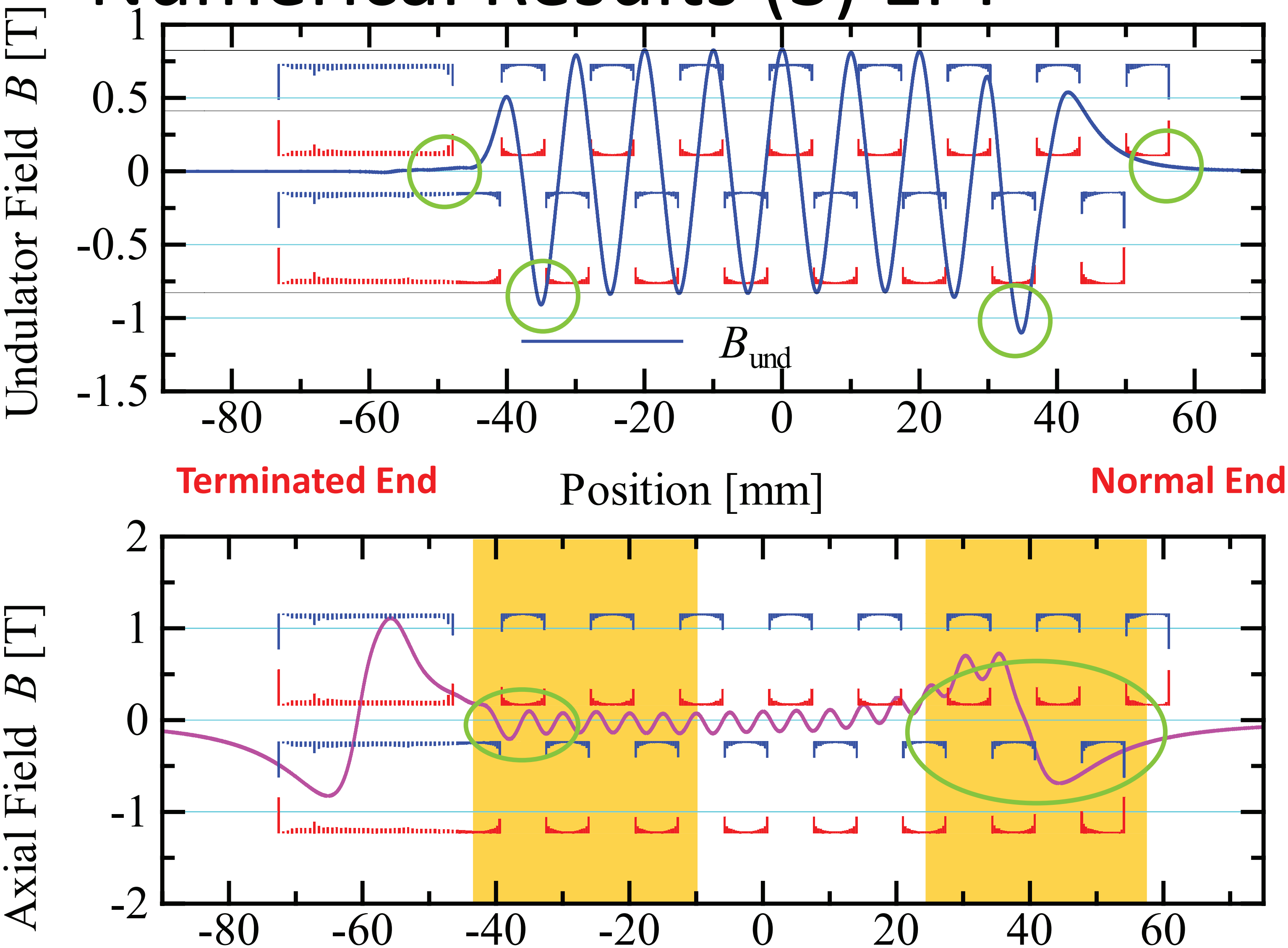
J_c = 18 kA/mm^2 ΔB = 15 T



B_{und} = 2.4 T
λ_{und} = 10 mm
Gap g = 4.0 mm

B_z remains at the end part.

Numerical Results (3) EFT



End part is well terminated.

B_z is reduced at the end part.

Contents

Conclusion

Potential of Bulk HTS:

Higher J_c 10 kA/mm^2 is possible at 10 K.

Bulk SC Array can be used as undulator.

Bulk SC SAU is under development.

Conclusion

Potential of Bulk HTS:

Higher J_c 10 kA/mm^2 is possible at 10 K.

Bulk SC Array can be used as undulator.

Bulk SC SAU is under development.

Possible configuration: λ_u = 10 mm gap = 4 mm

400 MeV B_{und}=1.23 T K=1.14 λ=13.5 nm

1 GeV B_{und}=2.00 T K=1.86 E_x=0.34 keV

3 GeV B_{und}=1.00 T K=0.93 E_x=5.95 keV

3 GeV B_{und}=1.23 T K=1.14 E_x=5.15 keV

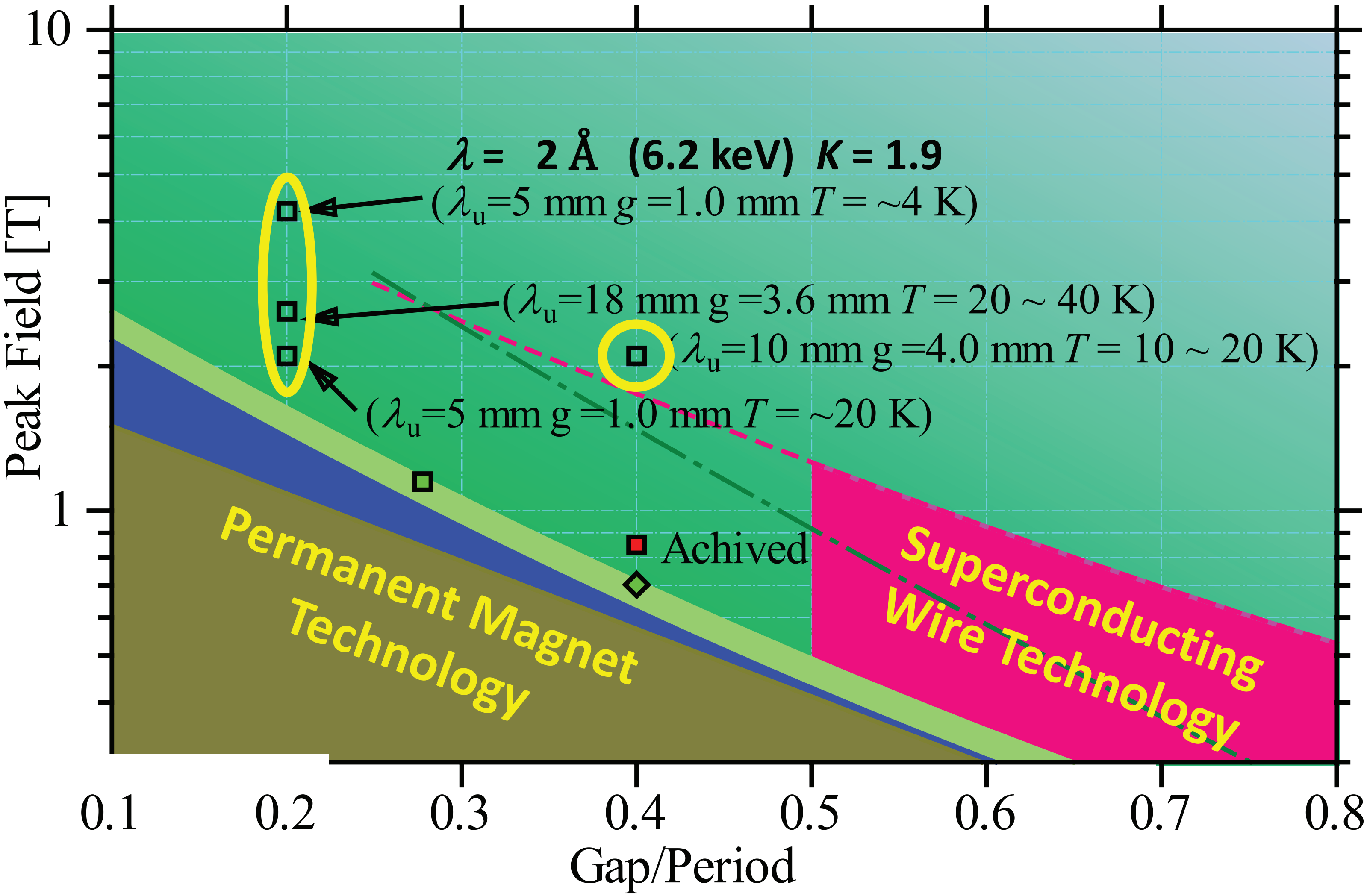
3 GeV B_{und}=2.40 T K=2.24 E_x=2.44 keV

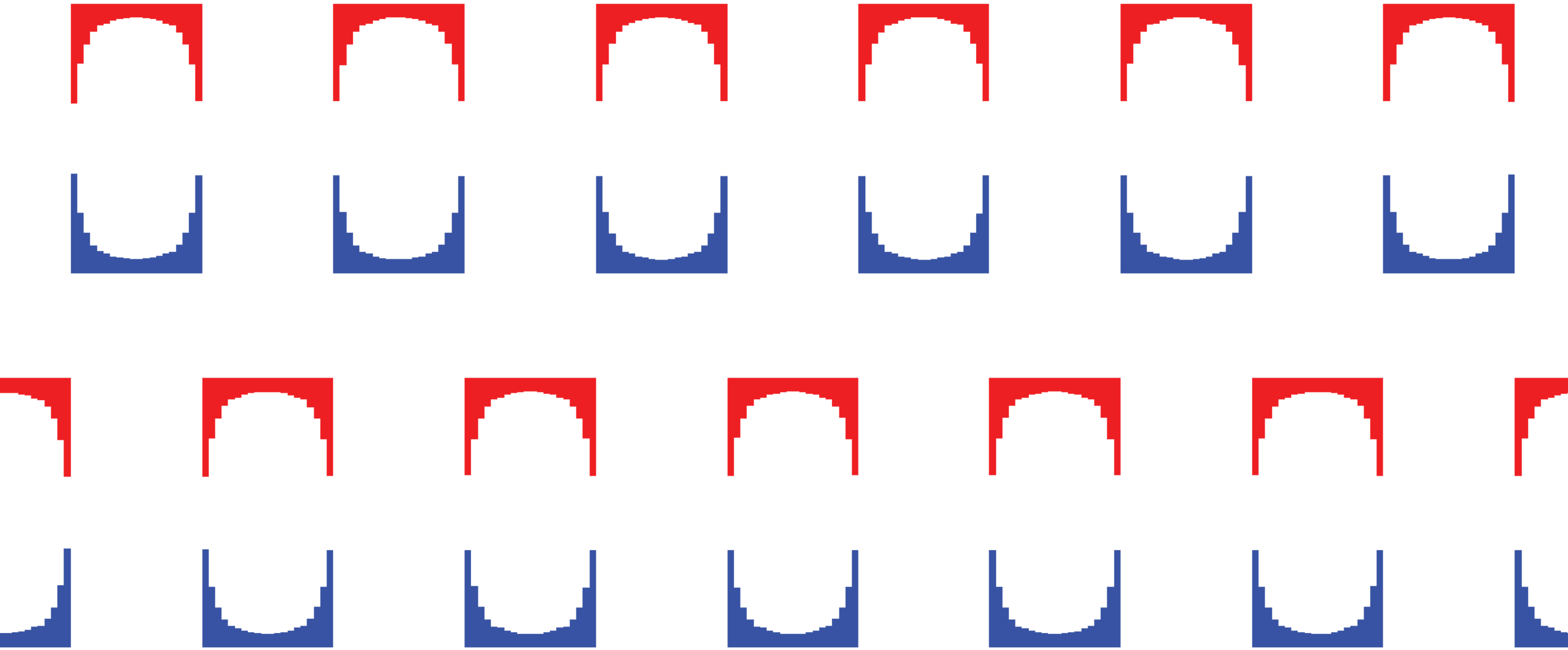
250 GeV B_{und}=1.00 T K=0.93 $E\gamma$=41.3 MeV

250 GeV B_{und}=1.23 T K=1.14 $E\gamma$=25.8 MeV

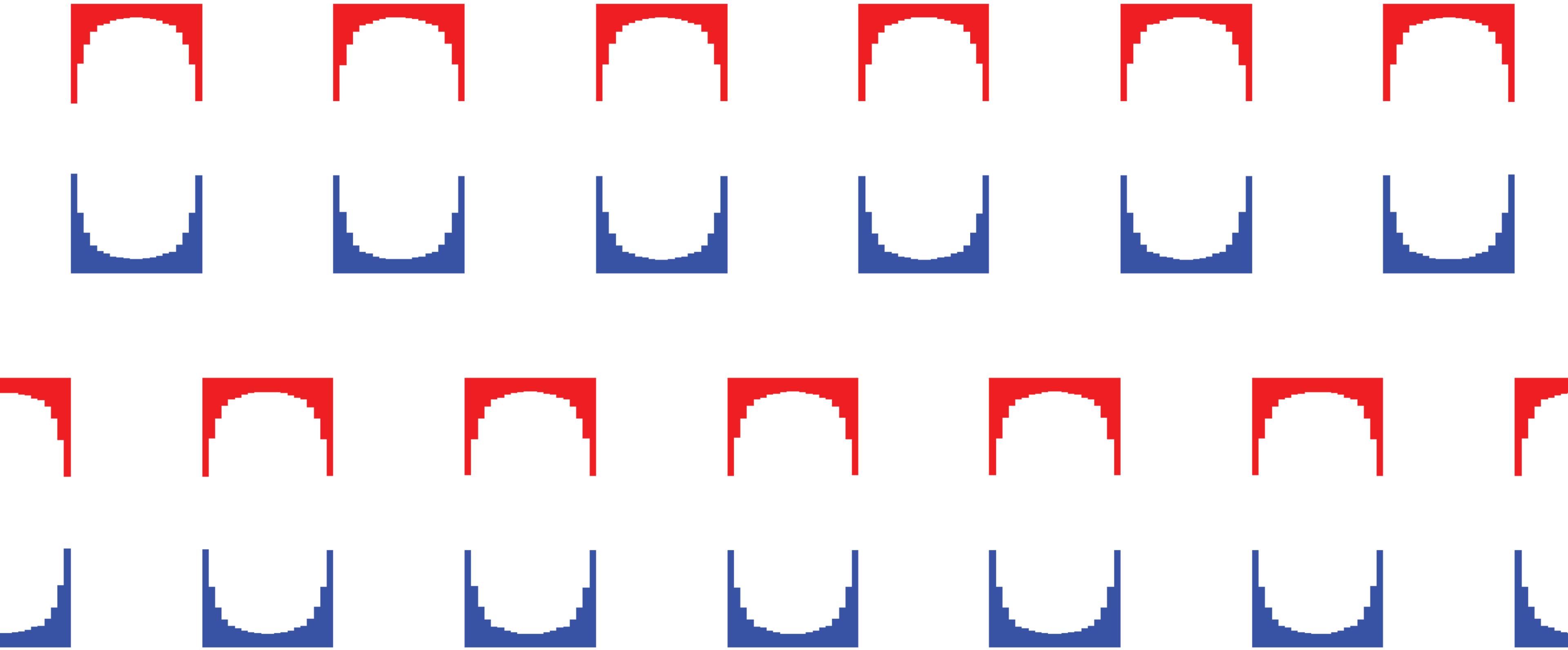
250 GeV B_{und}=2.40 T K=2.24 $E\gamma$=16.9 MeV

Bulk SC may lead us to **“fresh ground”**

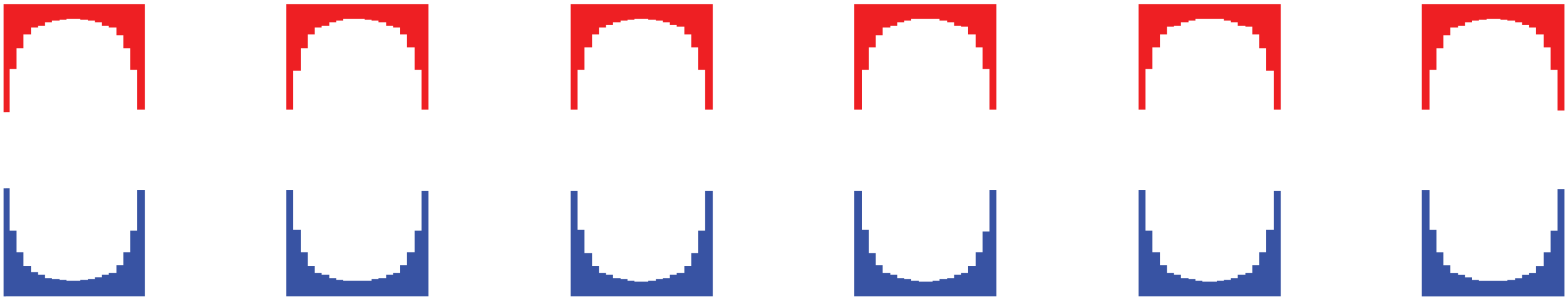




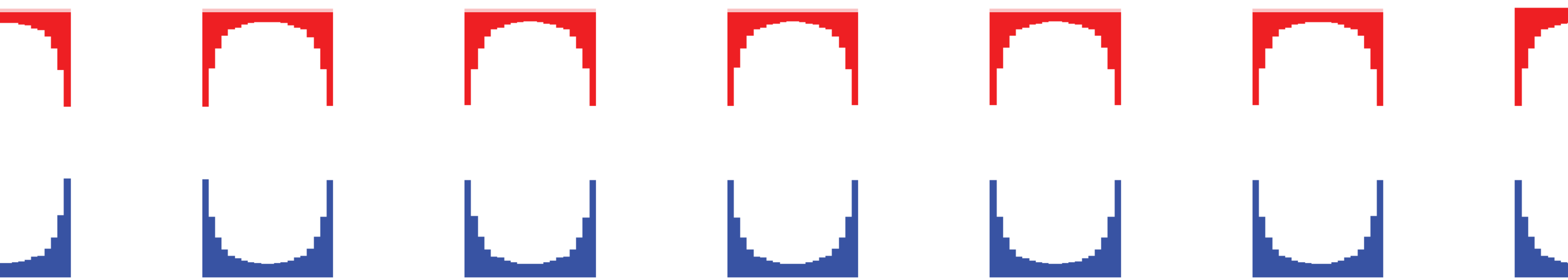
This work was supported by KAKENHI 17H01127



This work was supported by KAKENHI 17H01127



Thank you for your attention



This work was supported by KAKENHI 17H01127

Thank you for your attention

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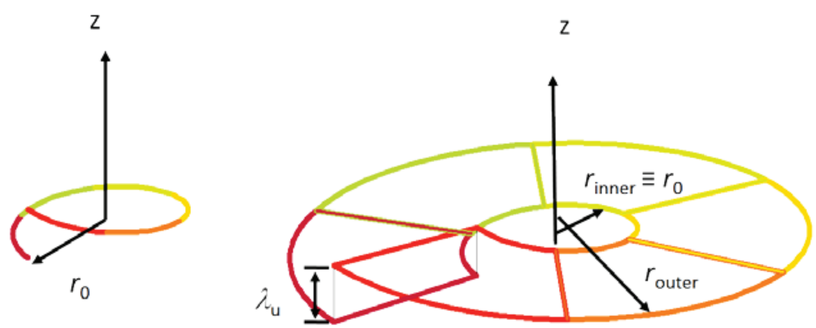
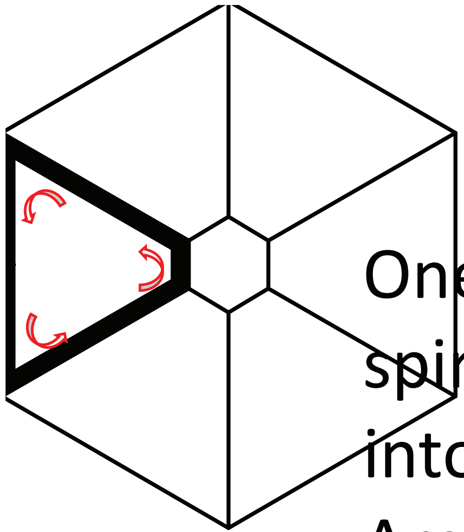
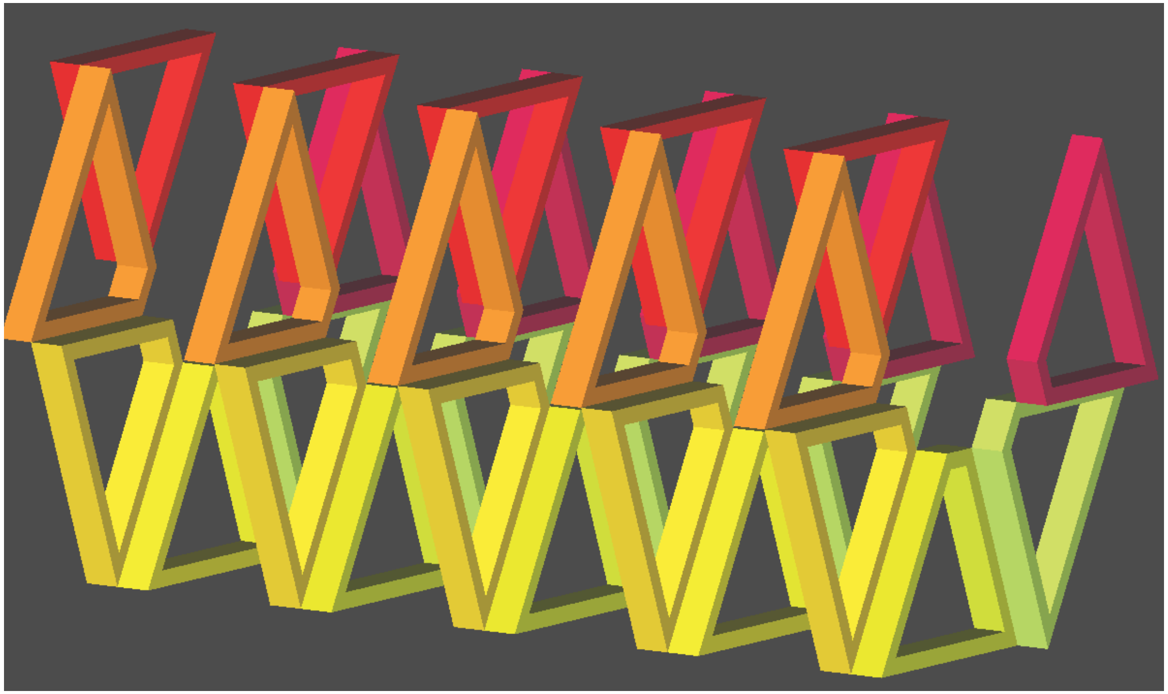
Design example for Helical SAU

a) b)





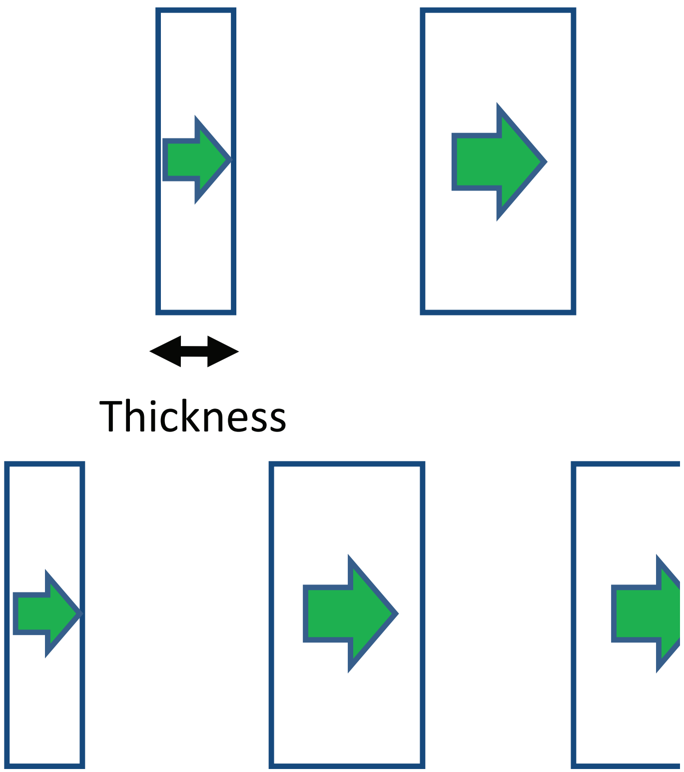


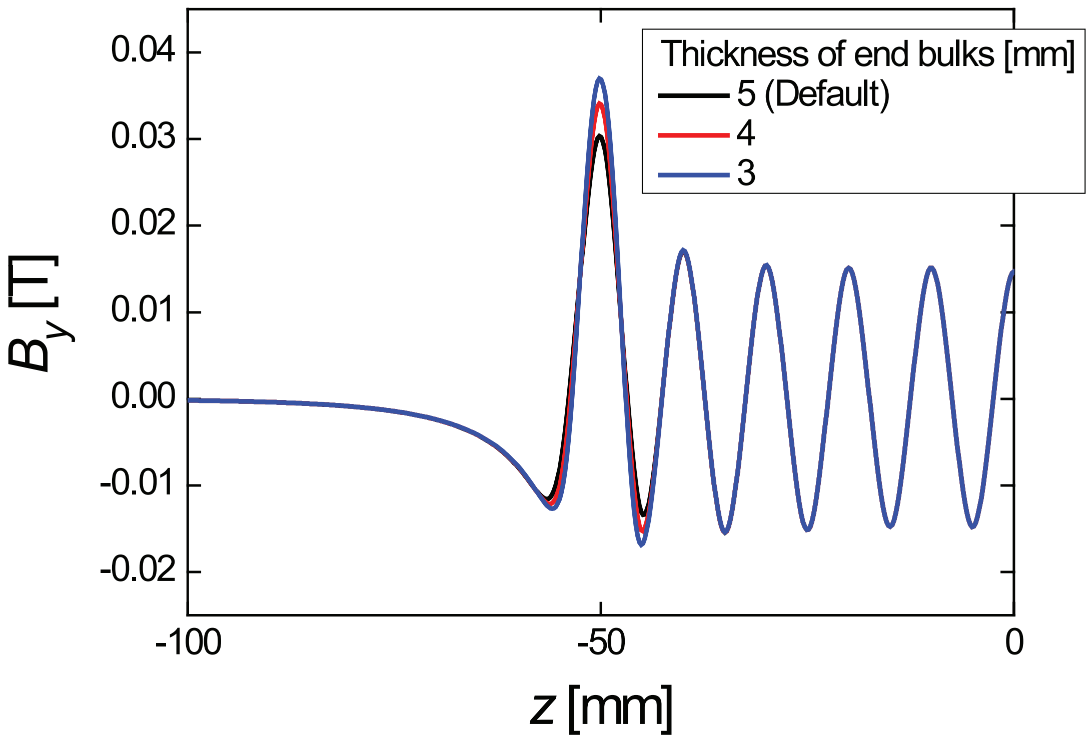
One period of spiral is divided into 6 bulk HTSs. Arc lines are modified to straight lines.

Colored area represents supercurrent in each HTS

End field termination 1

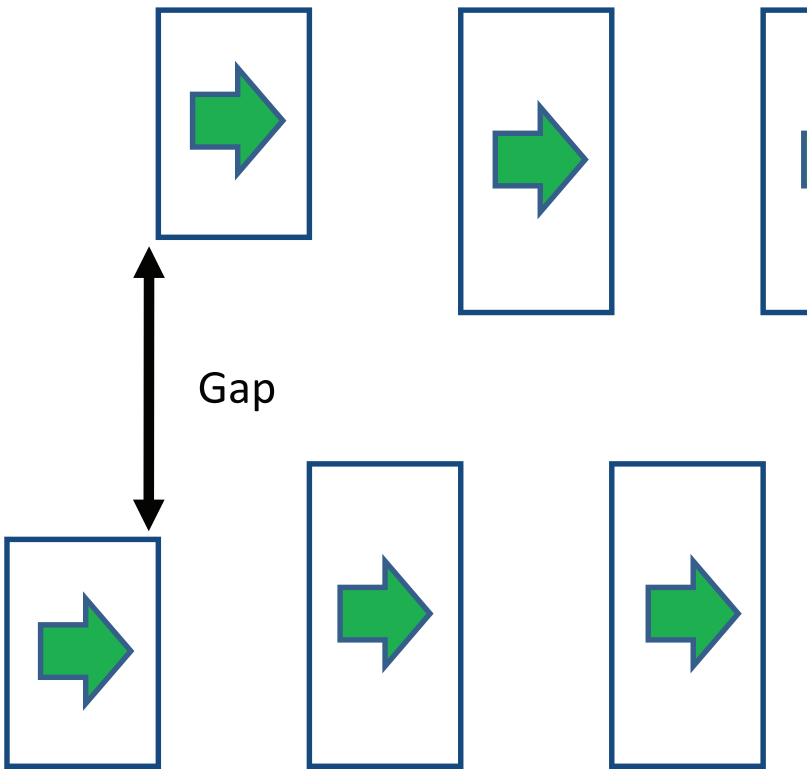
Thin bulks are used at the end

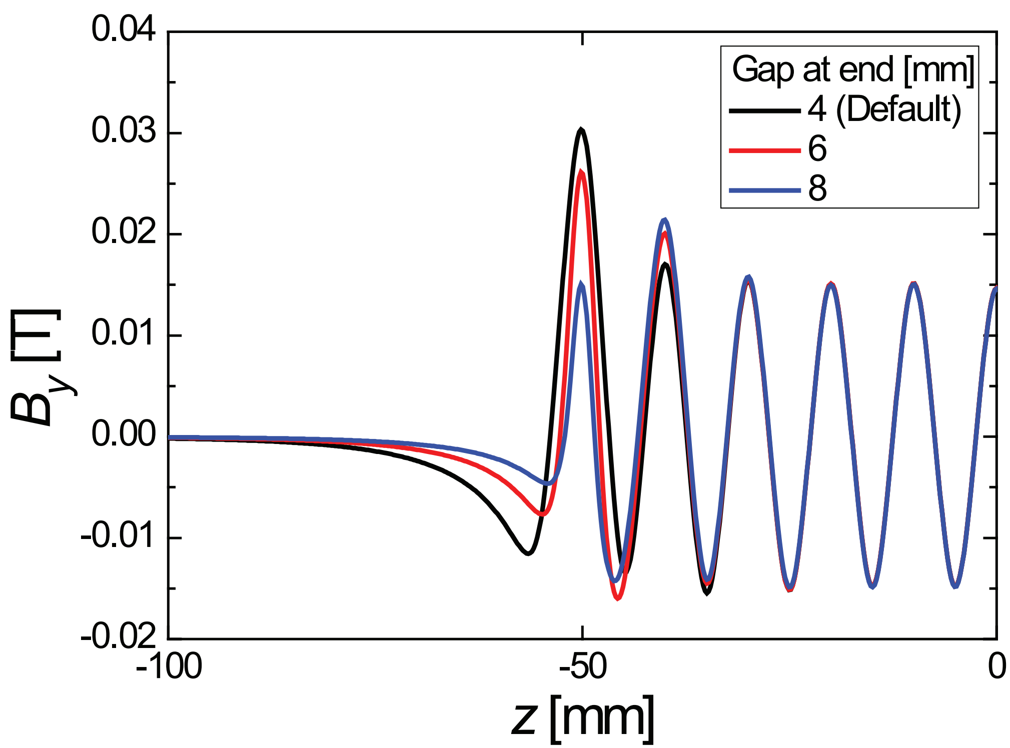




End field termination 2

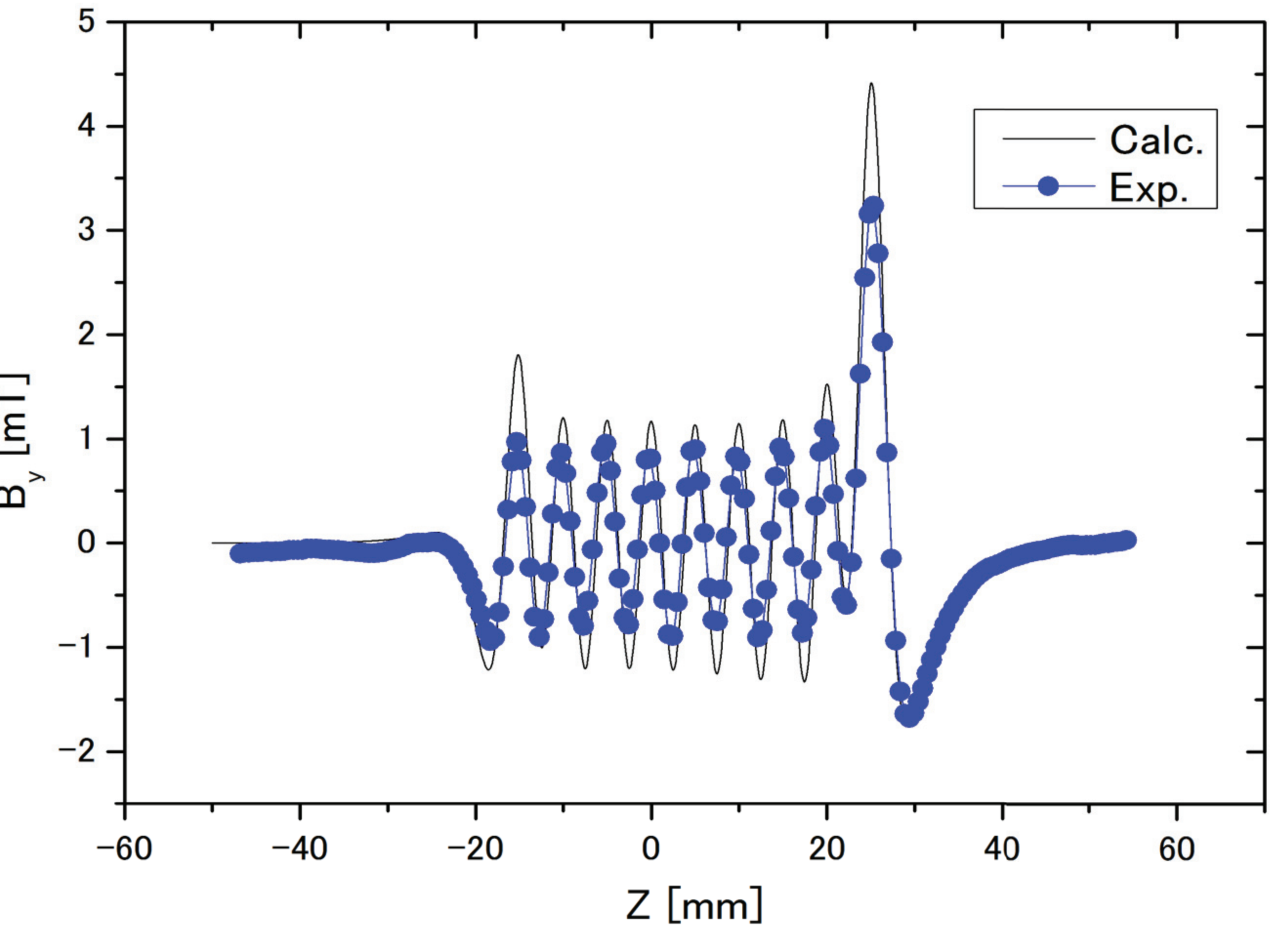
Gap is extended at the end   (Low height bulks)

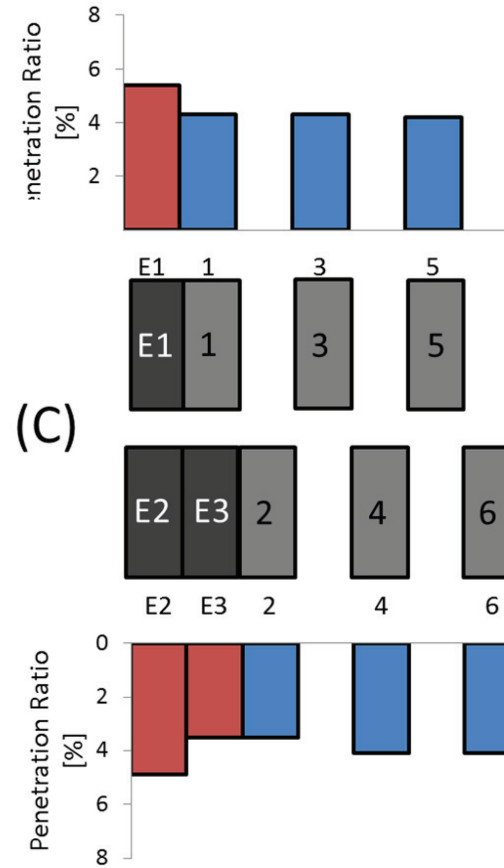




End field termination 3

Additional bulks are attached at the end





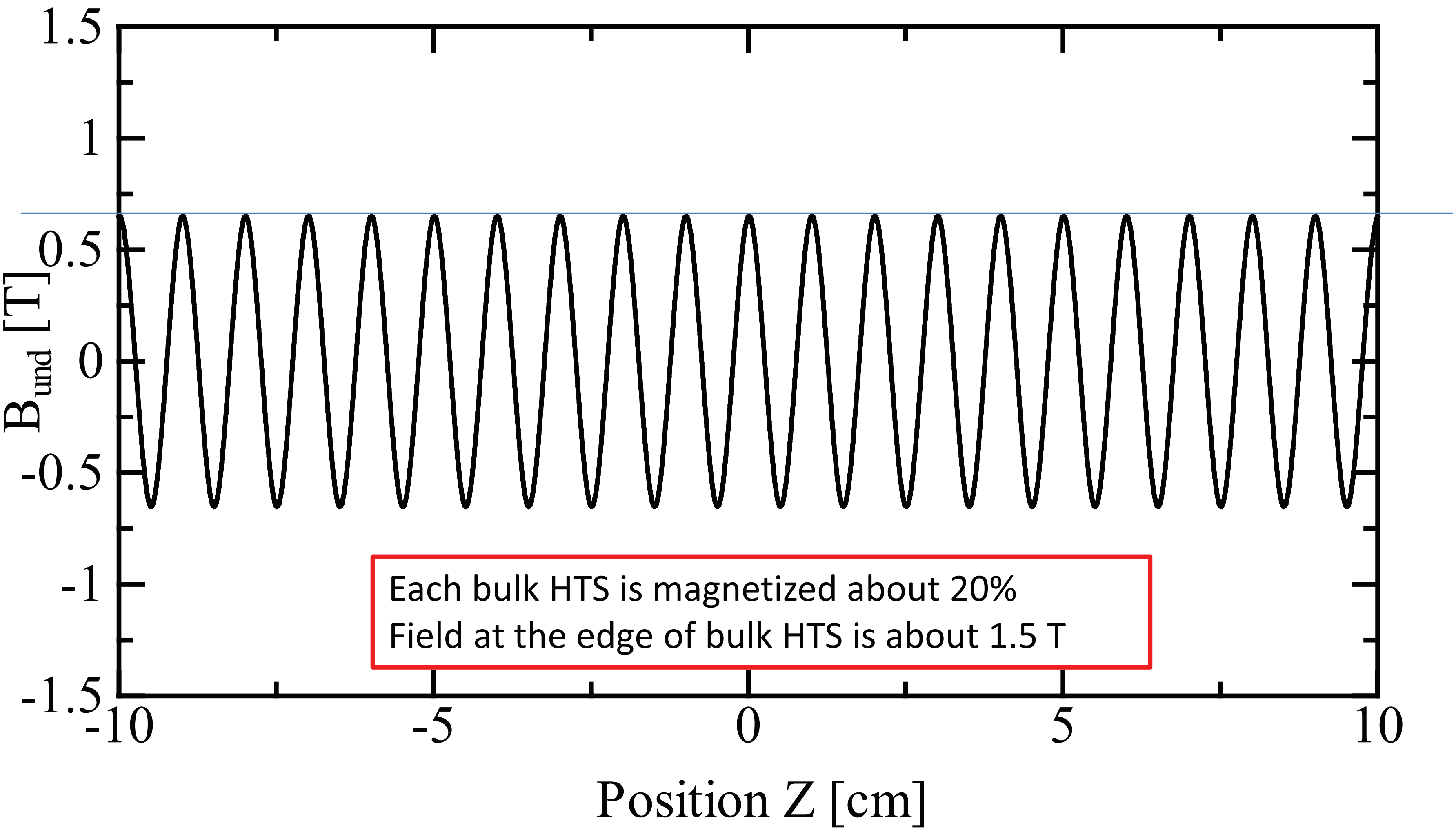
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm²

J_c σ 0% *B_{und} σ 0%*

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



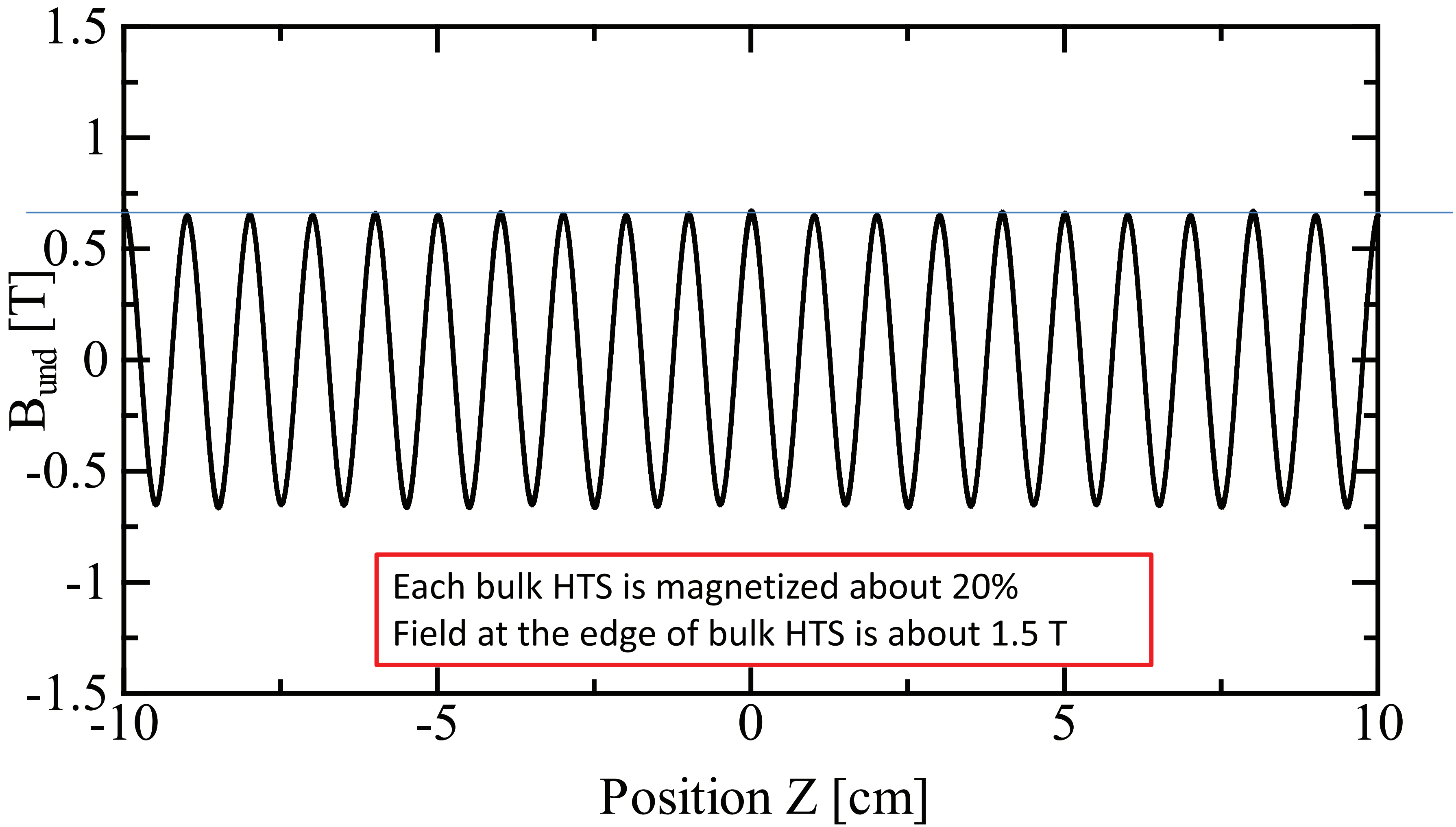
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ 0% *B_{und} σ 0%*

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



Influence of J_c difference (numerical simulation)

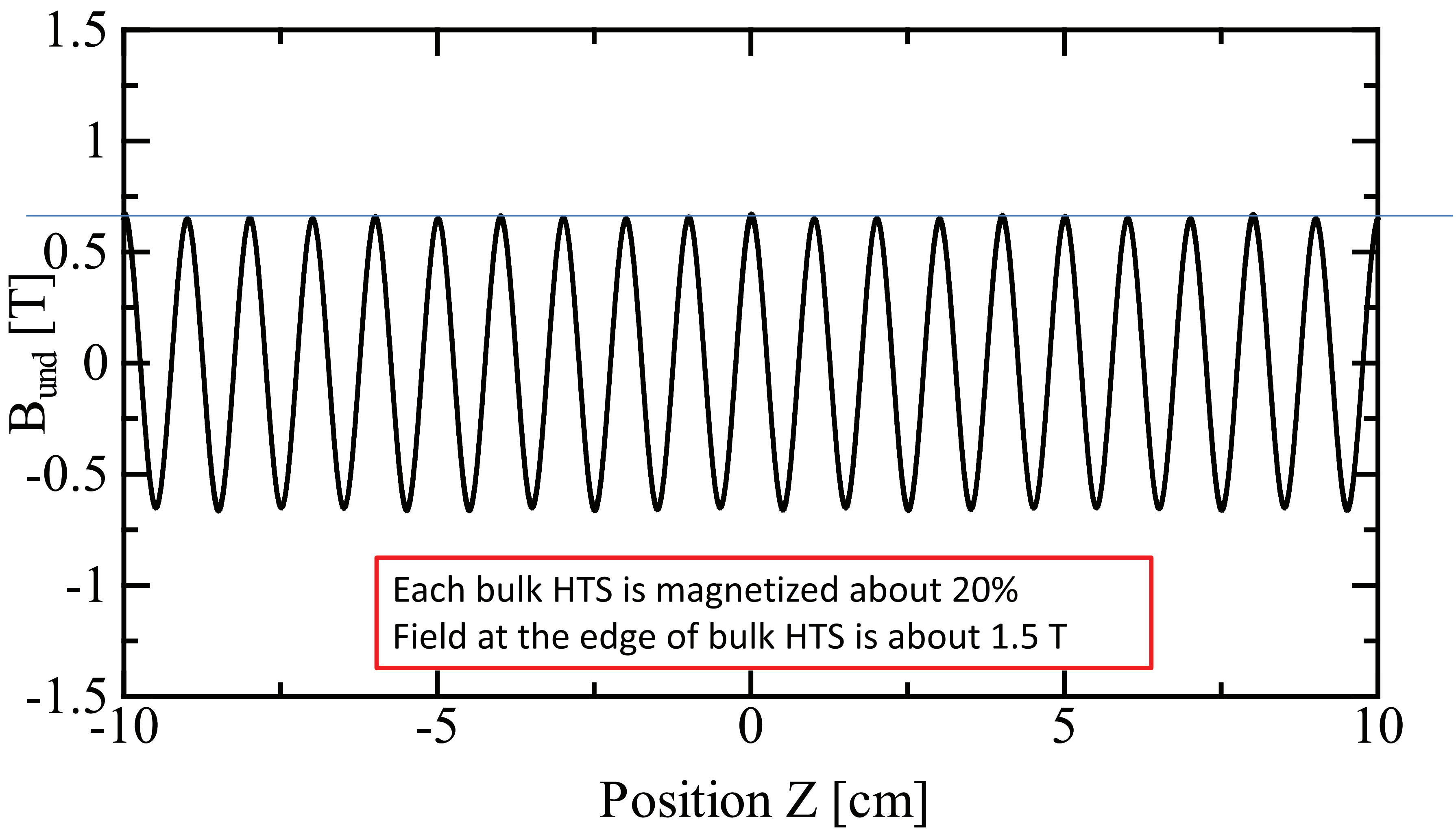
Assumed condition

J_c 5 kA/mm^2

J_c σ 0% 2%

B_{und} σ 0% 0.6%

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



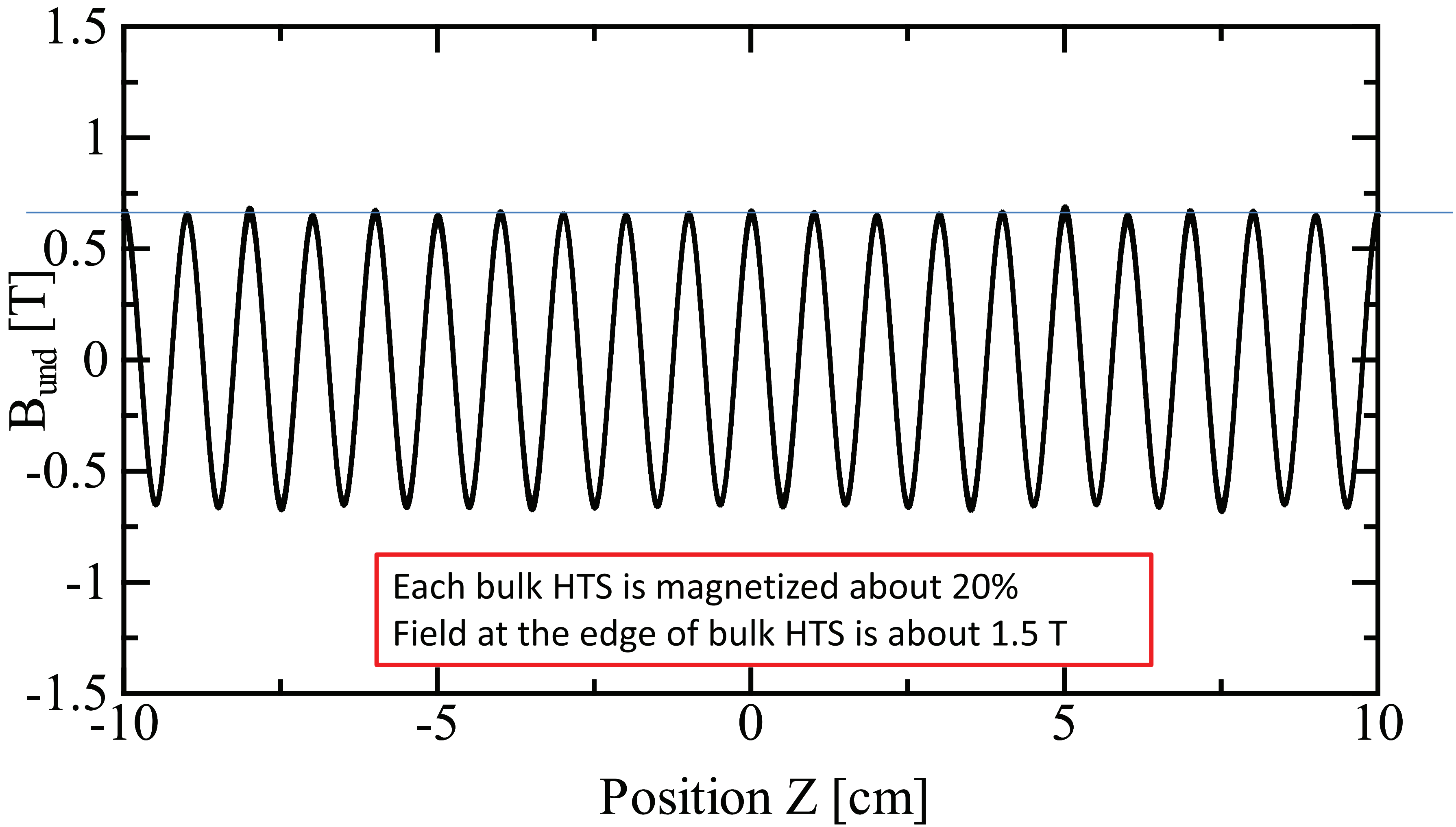
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ 0%/2% B_{und} σ 0%/0.6%

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



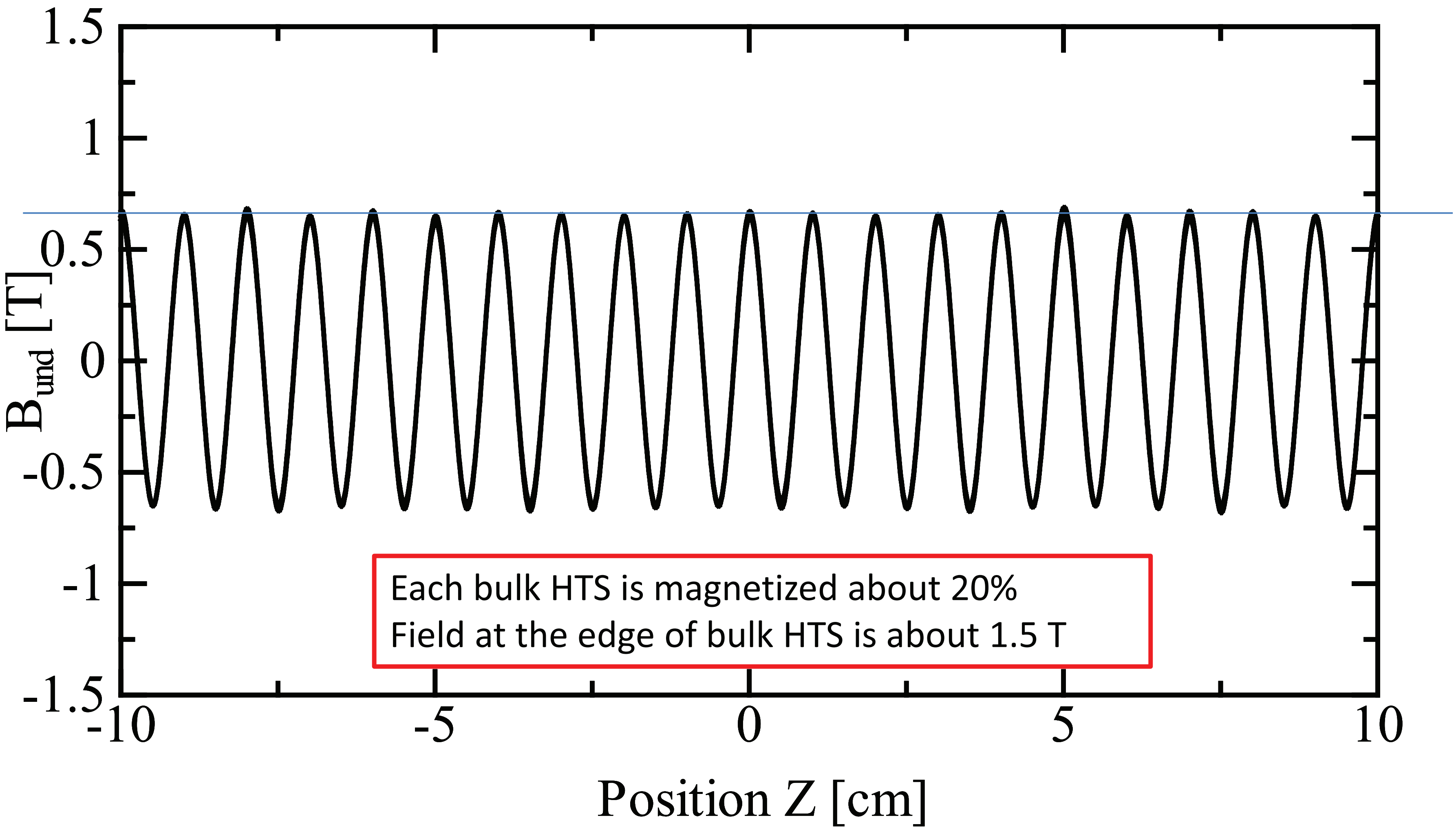
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ 2% B_{und} σ 0.9%

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



Each bulk HTS is magnetized about 20%
Field at the edge of bulk HTS is about 1.5 T

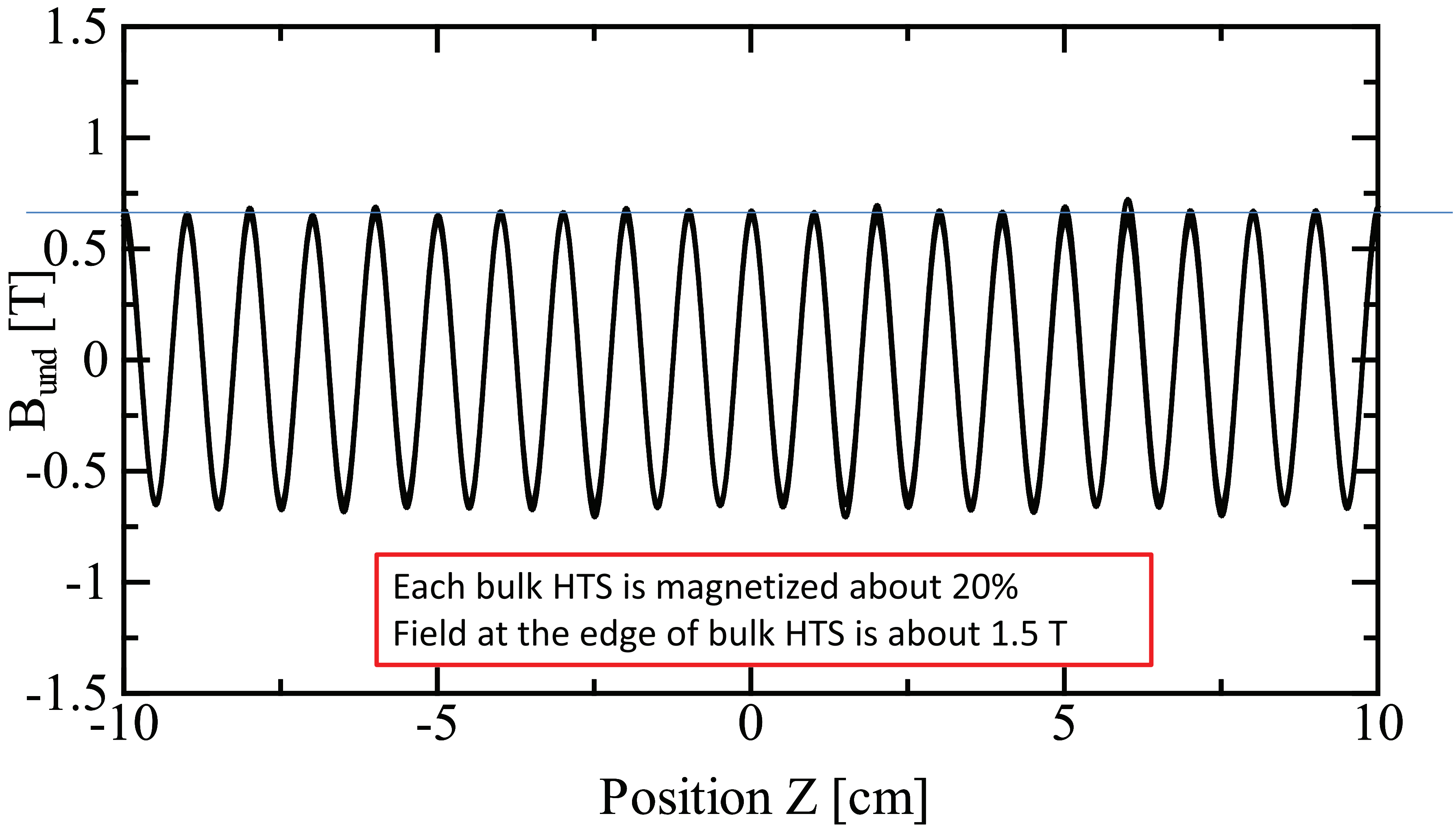
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ 2% / 0%　　B_{und} σ 0.9% / 0.5%

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



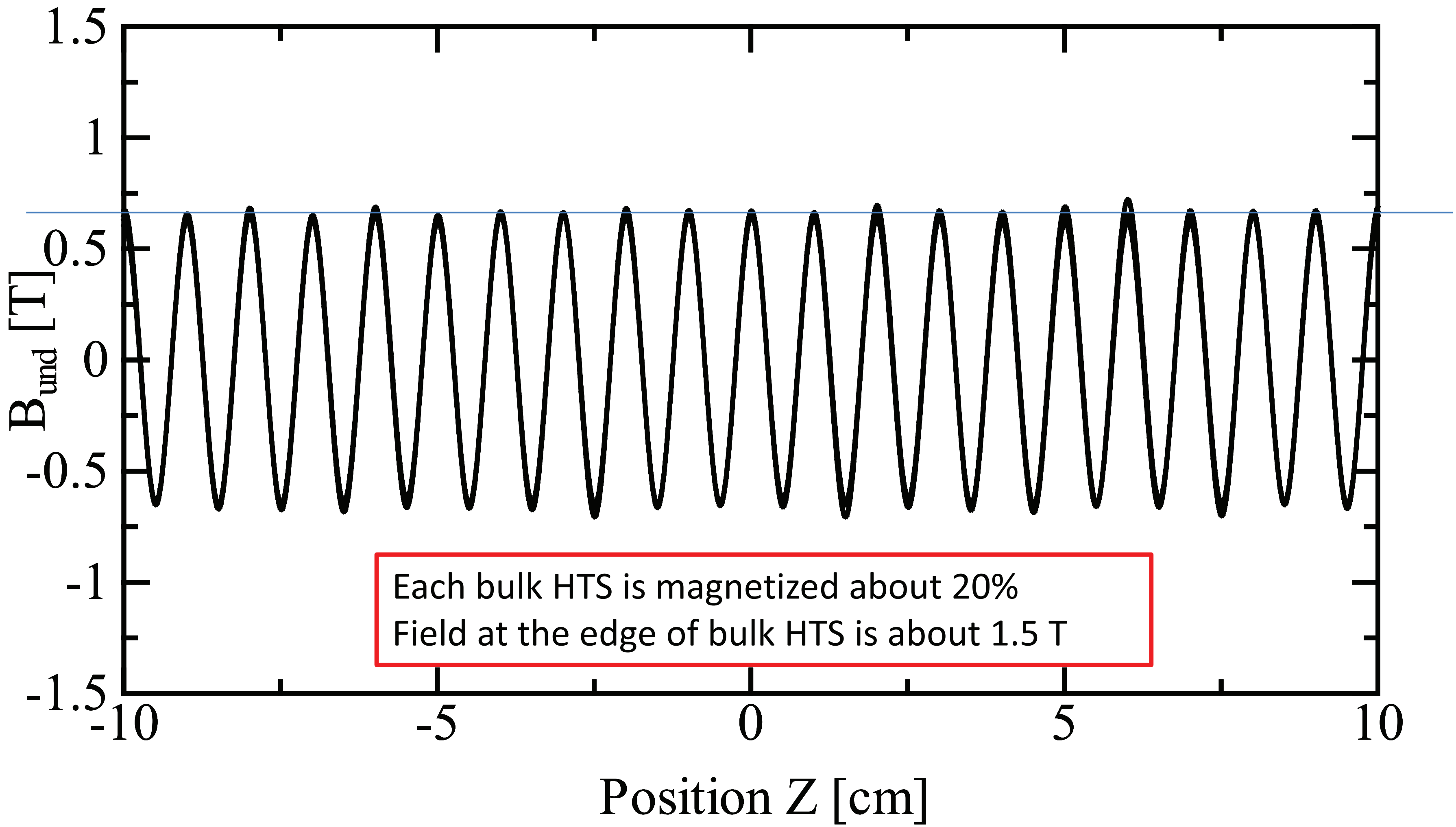
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ 10%　　B_{und} σ 0.9%

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



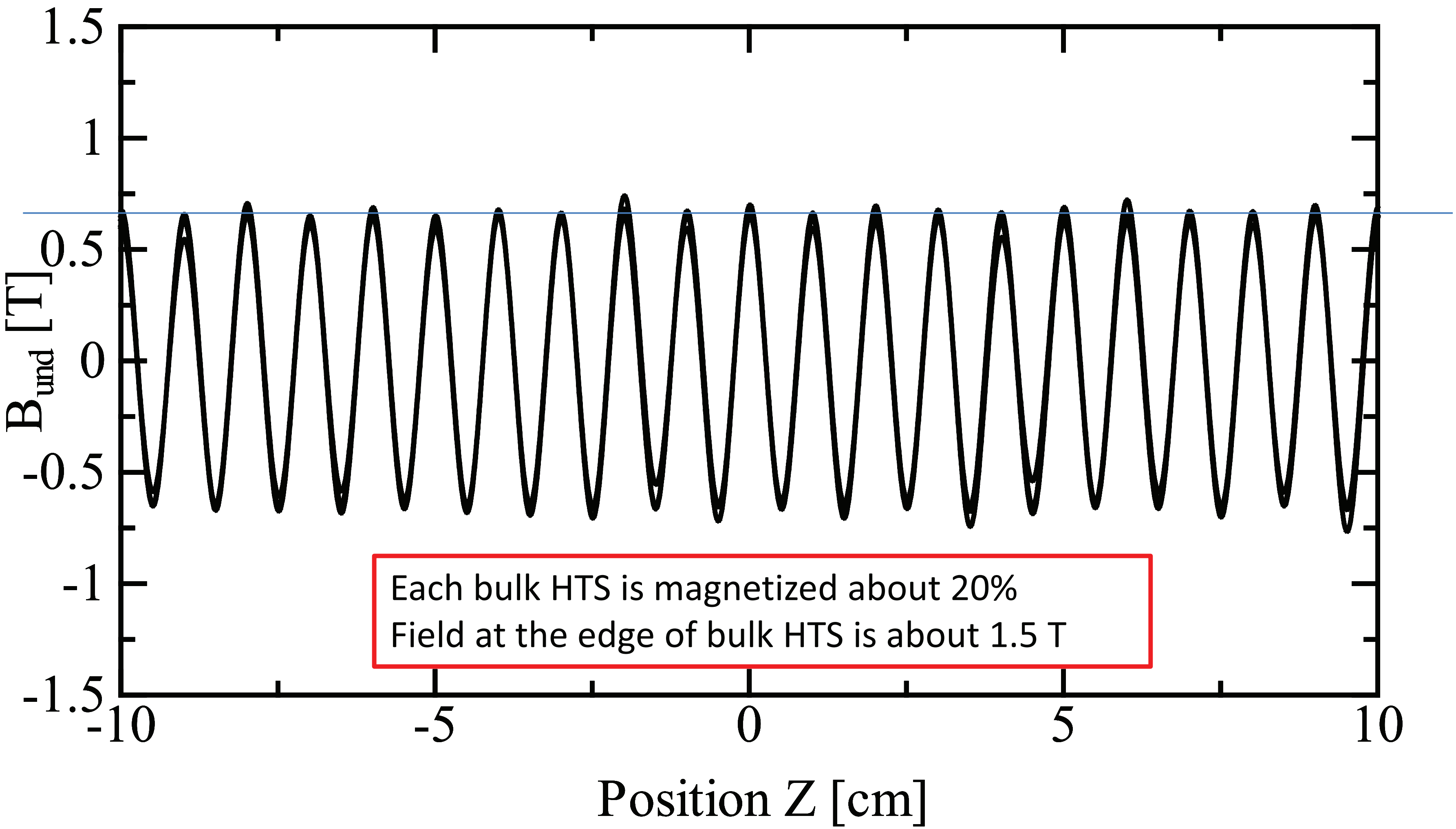
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ 10% B_{und} σ 0.9%

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



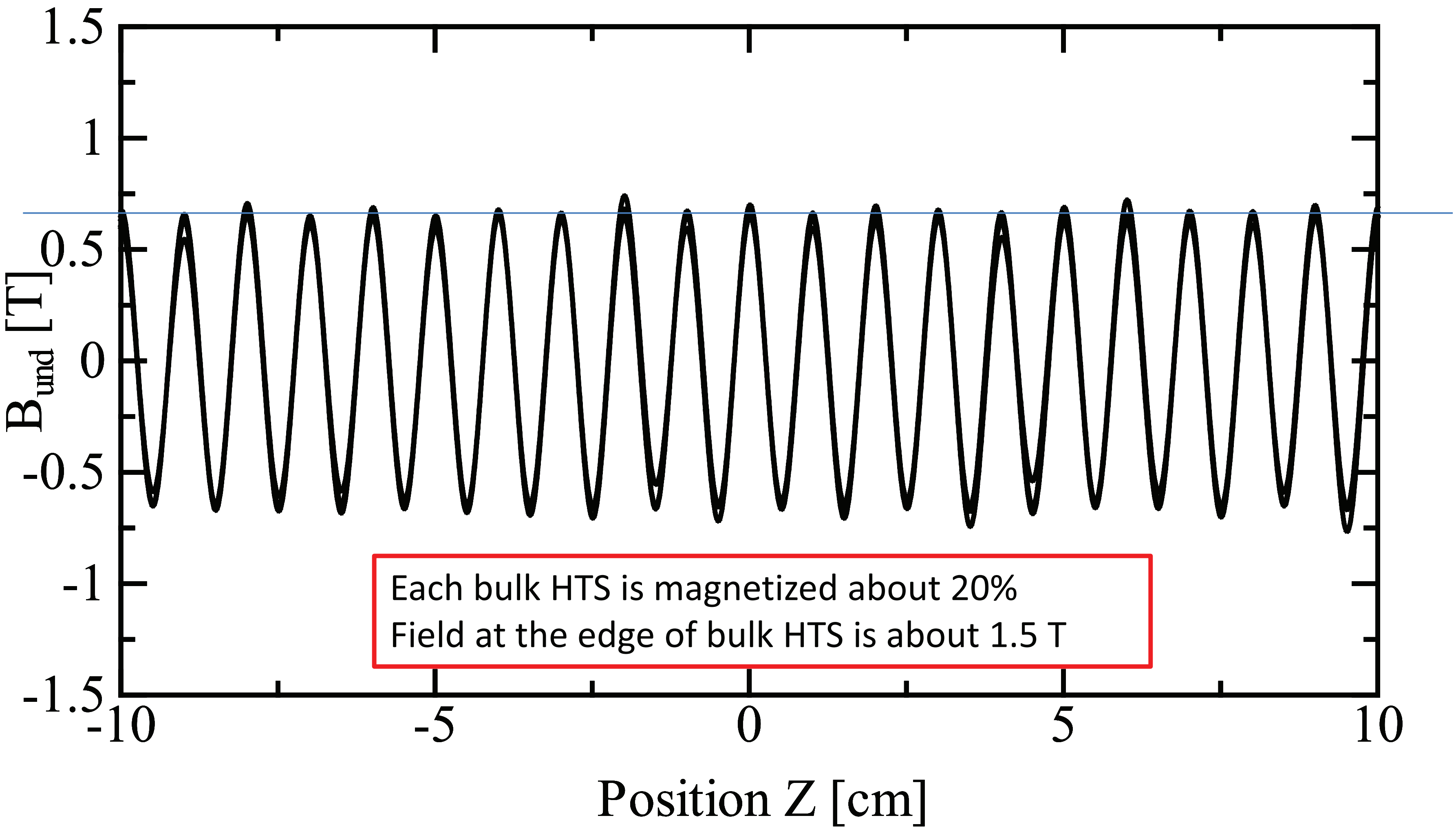
Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

J_c σ [illegible] B_{und} σ [illegible]

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



Influence of J_c difference (numerical simulation)

Assumed condition

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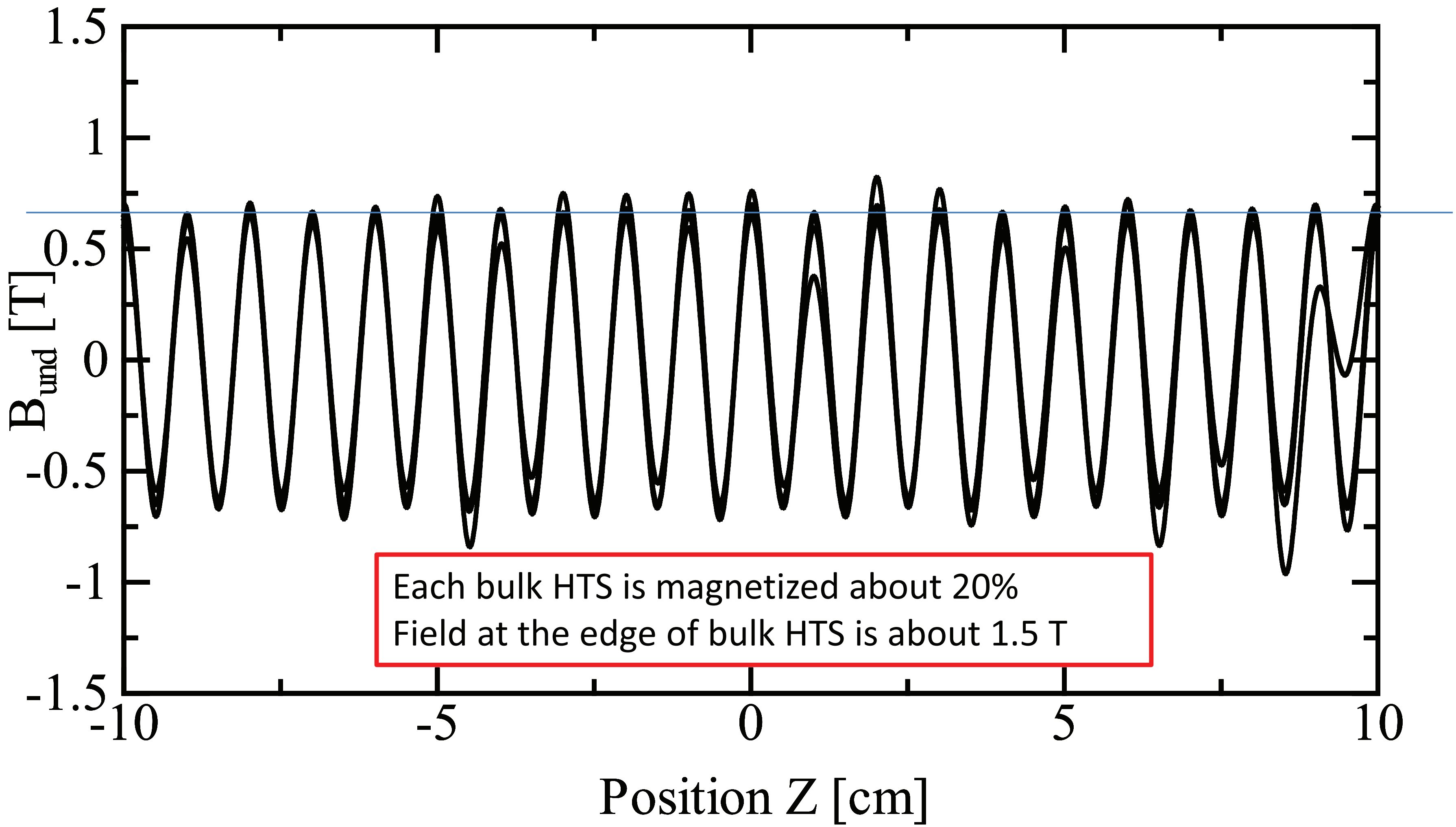
J_c σ [illegible] B_{und} σ [illegible]

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%



Influence of J_c difference (numerical simulation)

Assumed condition

J_c 5 kA/mm^2

$J_c\ \sigma$ 10% 20% $B_{und}\ \sigma$ [illegible]

Target peak field uniformity < 1% will be obtaind for Jc uniformity of 5%