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Influence of E-J characteristics of coated conductors and field ramp-up rates on the shielding-current-induced fields of magnets

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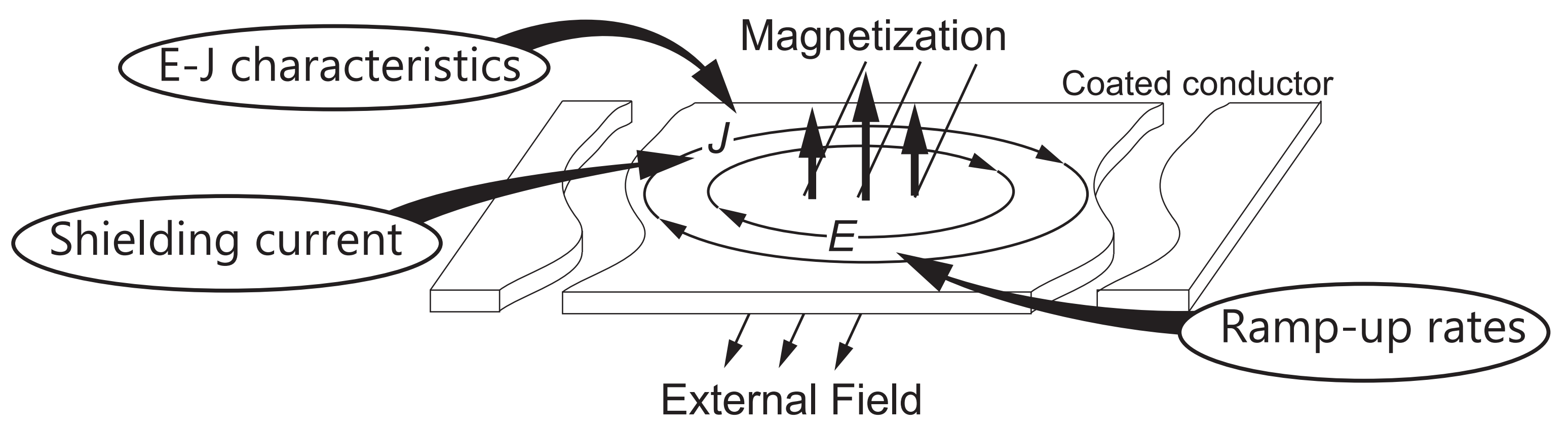
1. Background and objective

E-J characeristics, ramp-up rates, and shielding current



Cosine-theta magnet for rotating gantry for cancer therapy

- Wound with coated conductor
- Repeating ramp-up/down

Measurement method of *E-J* characteristics

- Transport measurement
- Magnetization measurement

Objective

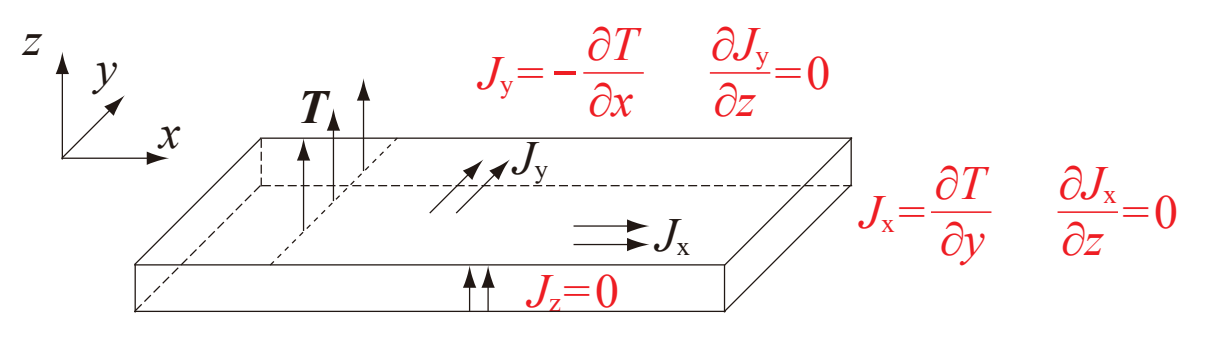
Revealing how *E-J* characteristics and ramp-up rates influences shielding current induced field

2. Analysis method and analyzed magnet

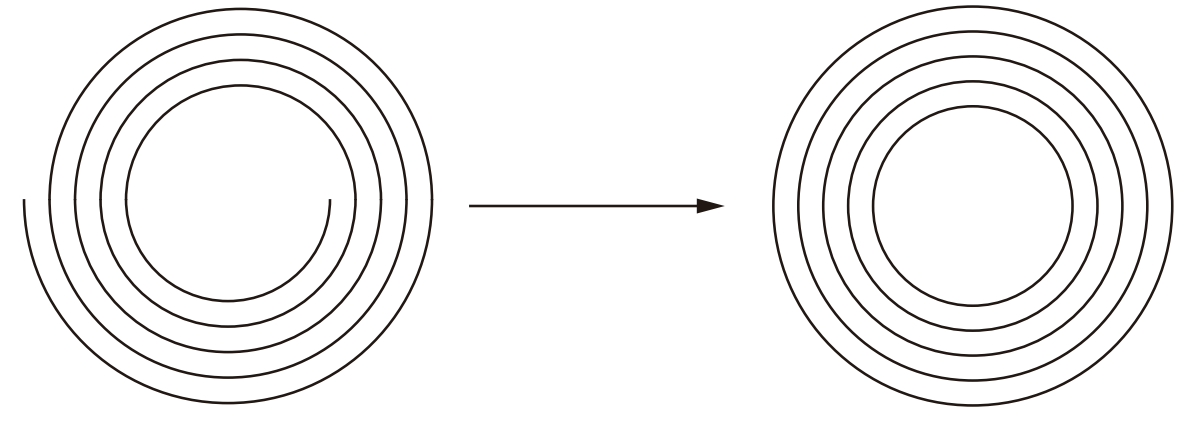
Equation to be solved in cross-sectional model

$$-\frac{\partial}{\partial y}\frac{1}{\sigma}\frac{\partial T}{\partial y}\boldsymbol{n}+\frac{\partial}{\partial t}\left(\sum\int \boldsymbol{B}_{\mathrm{s-f}}\cdot\boldsymbol{n}\frac{\partial T'}{\partial y'}\boldsymbol{n}' t_{\mathrm{s}}\mathrm{d}y'\right)=\boldsymbol{0}.$$

Thin strip approximation

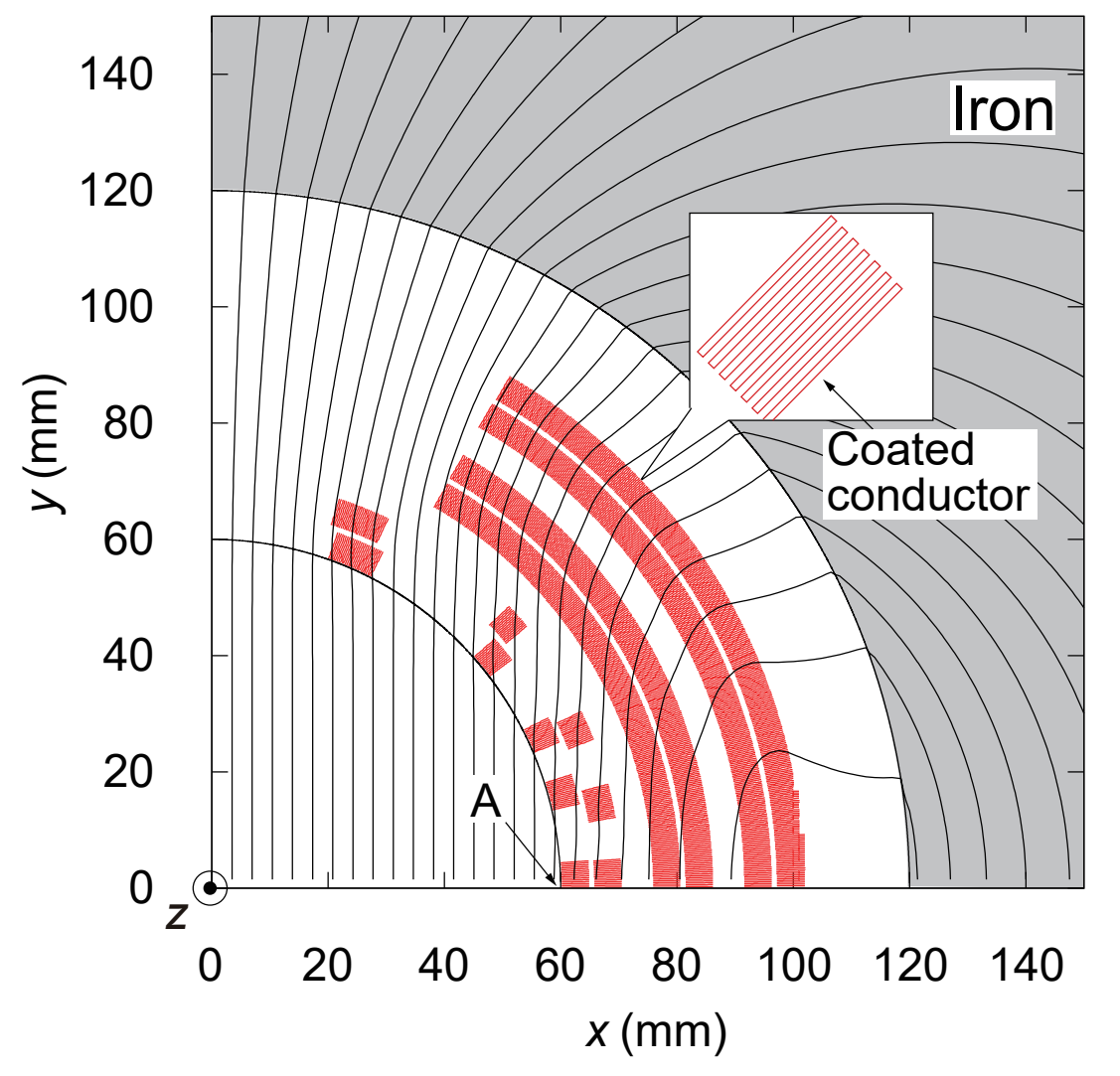


Axisymmetric approximation



Specifications of cosine-theta dipole magnets	
Reference radius	30 mm
Radius of magnet bore	60 mm
Inner radius iron yoke	120 mm
Width of coated conductor	5 mm
Thickness of coated conductor	0.2 mm
Thickness of superconductor layer	2 µm
Number of turns (both poles)	2774
Dipole magnetic field	2.9 T at 179 A
Magnitude of higher (n > 3) multipole coefficients	< 1 x 10^{-4}

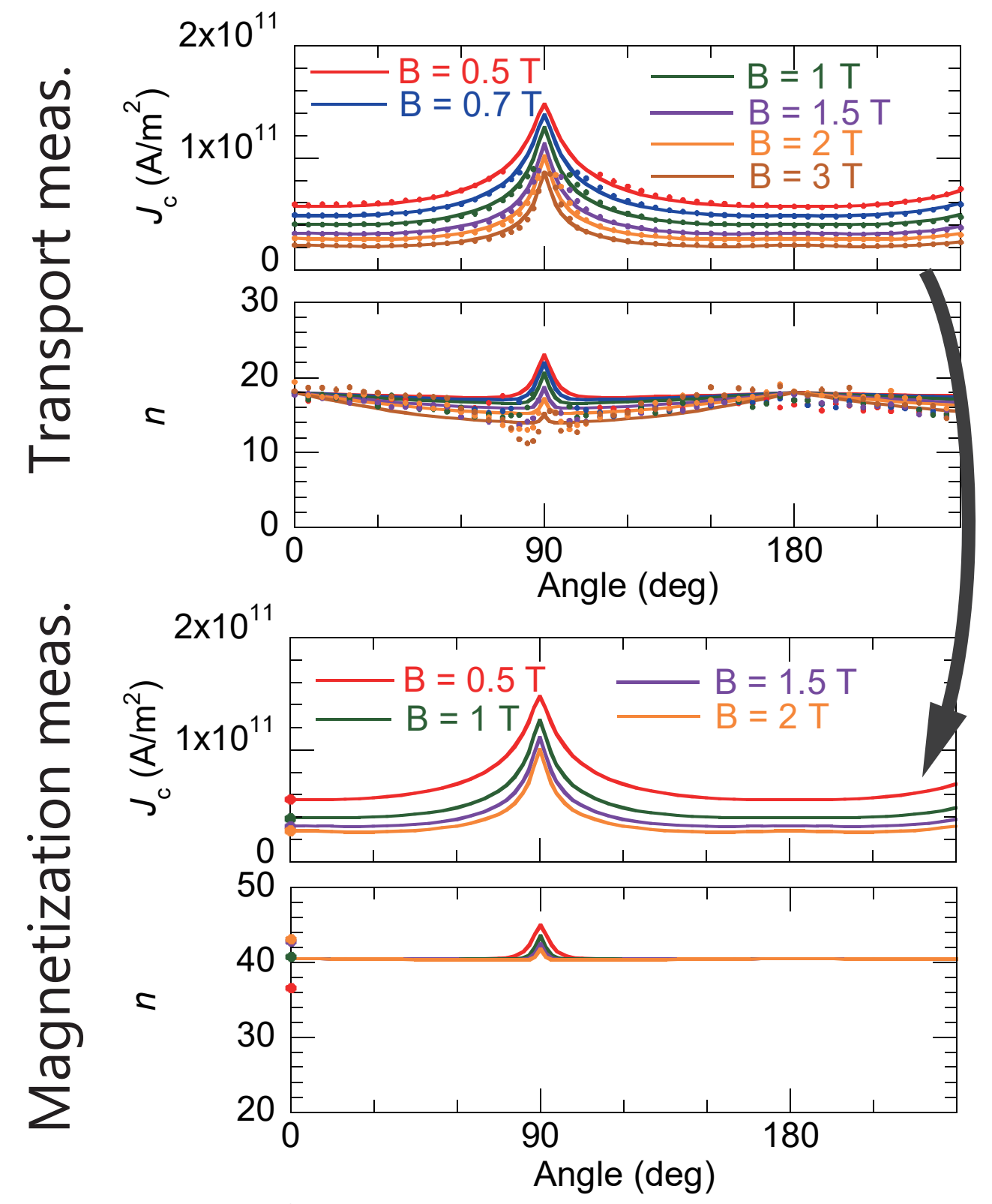
Cross-sectional view



3. Formulation of *E-J* characteristics

Specifications of conductors

Specifications of measured coated conductor	
Manufacturer	Fujikura Ltd.
Thickness of coated conductor	0.22 mm
Width of coated conductor	5.05 mm
Thickness of superconductor layer	1.9 µm



Formulation of $J_c(\mathrm{B},\phi)$ & $n(\mathrm{B},\phi)$

$$x(B,\varphi)=\left(x_{ab}^{m}+x_{c}^{m}\right)^{1/m},$$

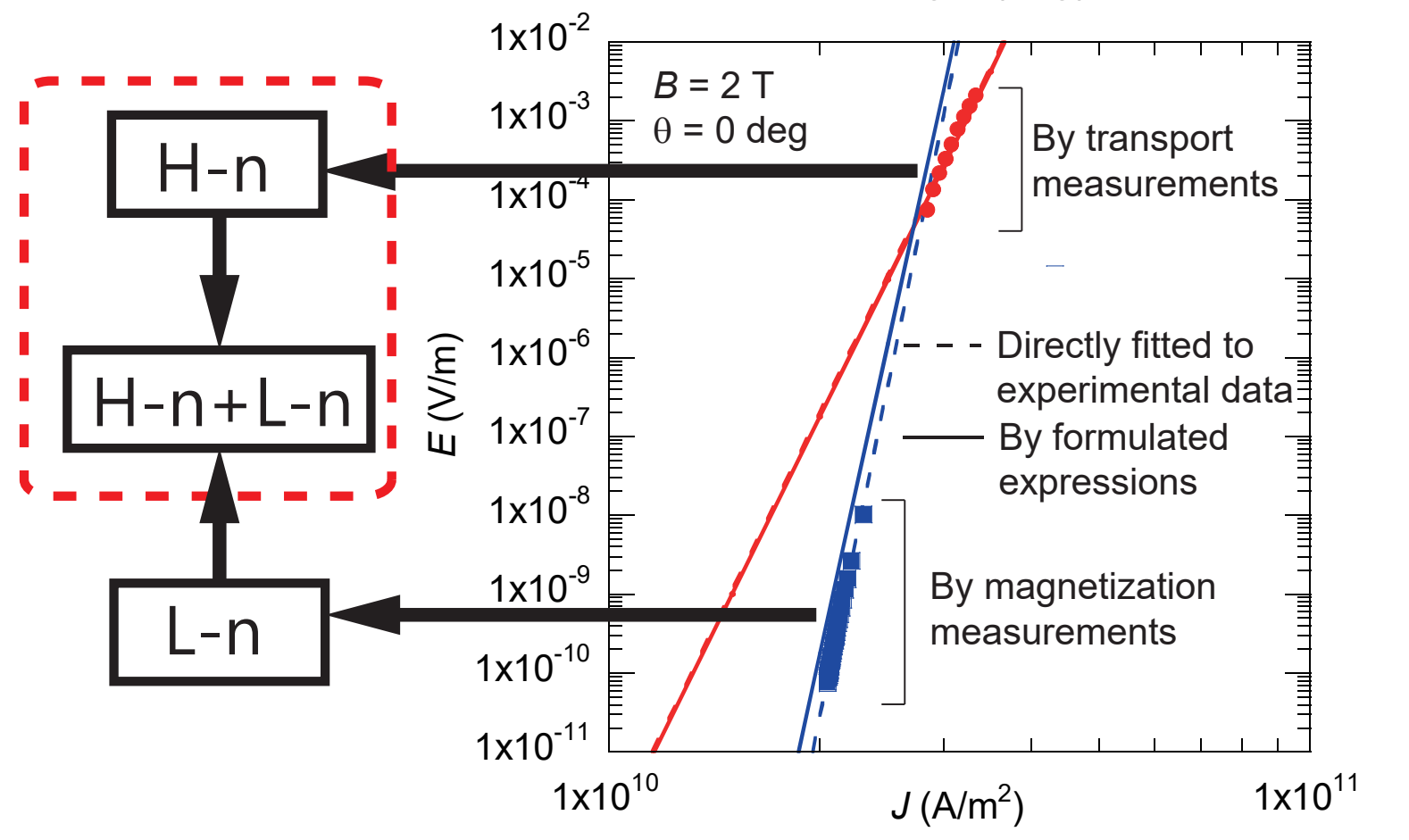
$$x_{ab,c}(B,\varphi)=x_{0ab,c}\Big/\left(1+Bf_{ab,c}(\varphi)/B_{0ab,c}\right)^{\beta_{ab,c}}.$$

x means J_c or *n*,
and the subscription *ab,c* means *ab* or *c*

$$f_{ab}(\varphi)=\sqrt{u_{ab}{}^{2}\cos^{2}(\varphi-\delta_{ab})+\sin^{2}(\varphi-\delta_{ab})},$$

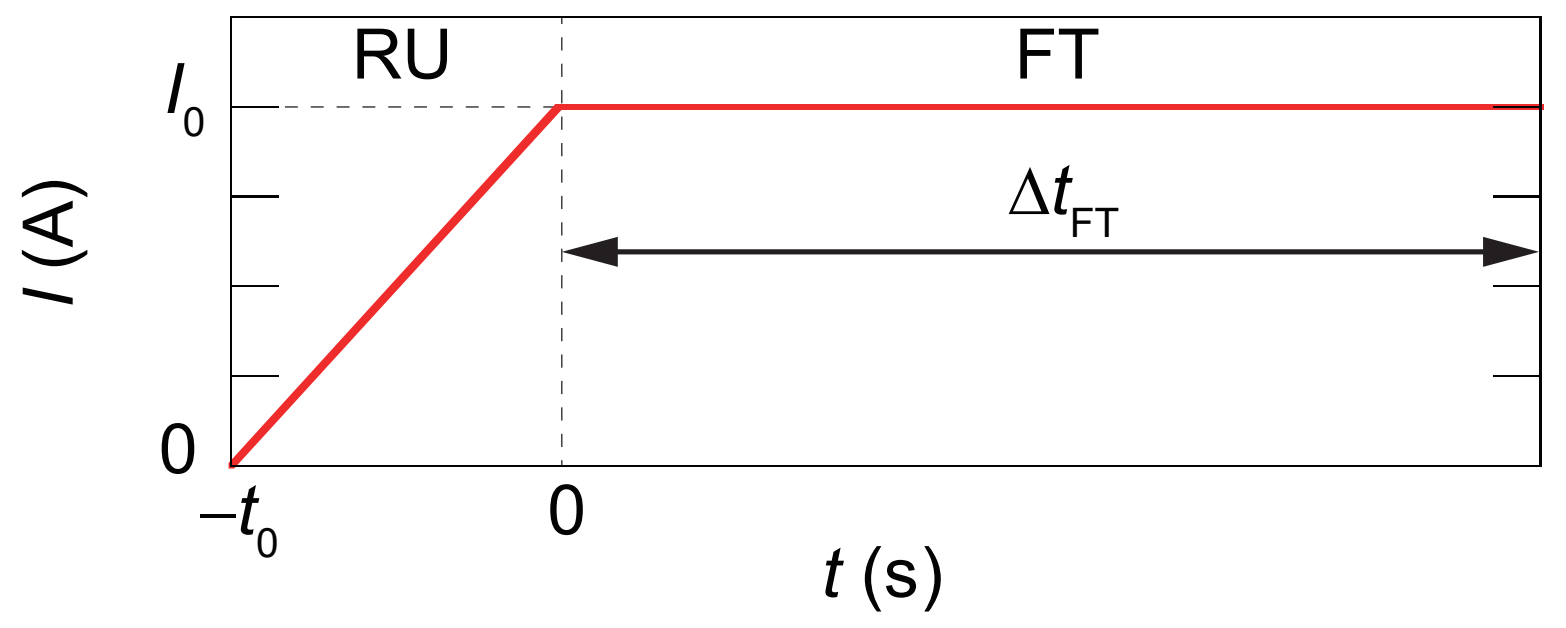
$$f_{c}(\varphi)=\begin{cases}\sqrt{\cos^{2}(\varphi-\delta_{c})+u_{c}{}^{2}\sin^{2}(\varphi-\delta_{c})} & (-90^\circ+\delta_{c}\le\varphi\le 90^\circ+\delta_{c})\\ \sqrt{v^{2}\cos^{2}(\varphi-\delta_{c})+u_{c}{}^{2}\sin^{2}(\varphi-\delta_{c})} & (otherwise)\end{cases}.$$

ϕ = 0 is the direction of normal vector of wide face of conductor



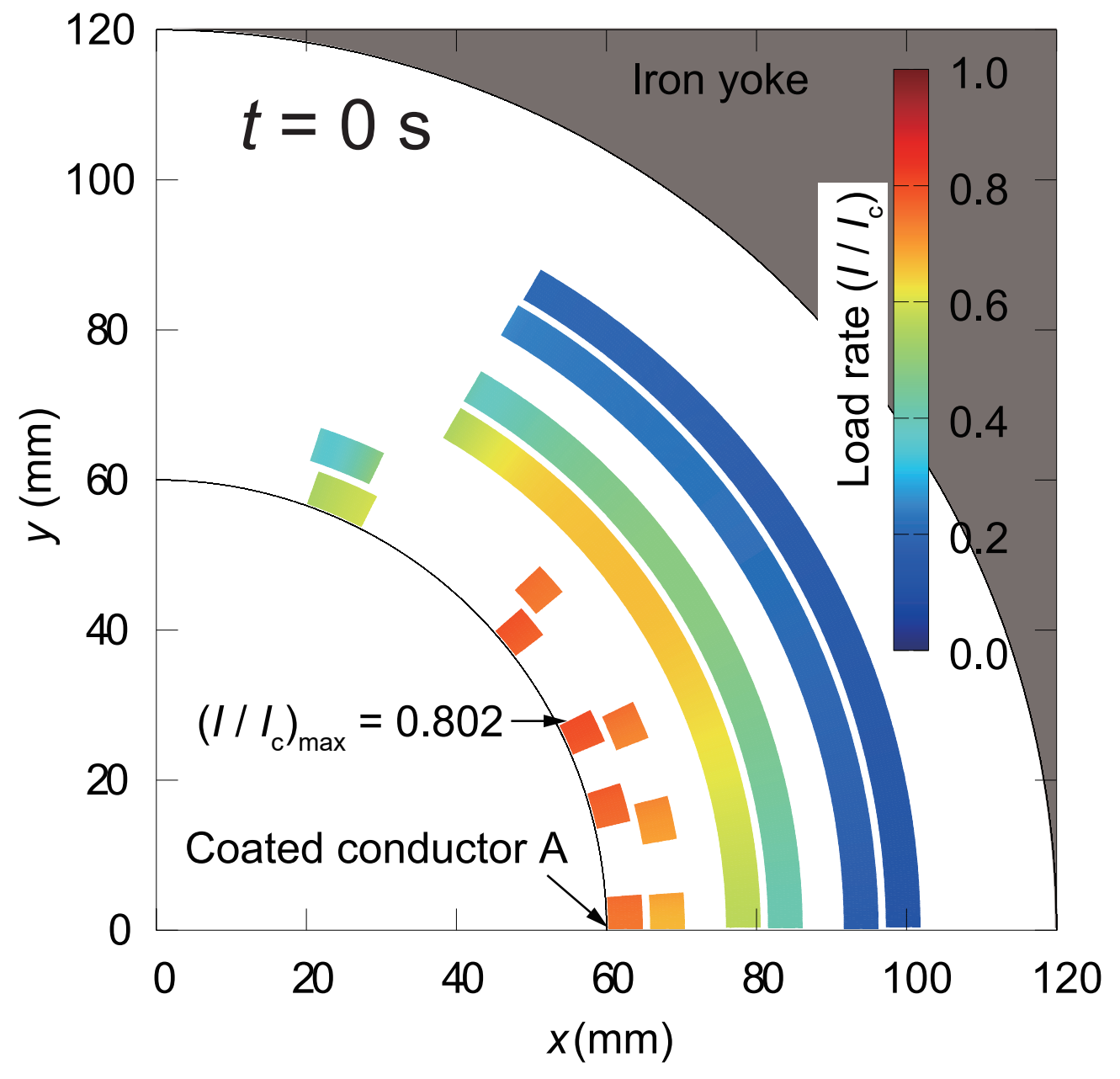
4. Exciation patterns and shielding current

Exciation pattern

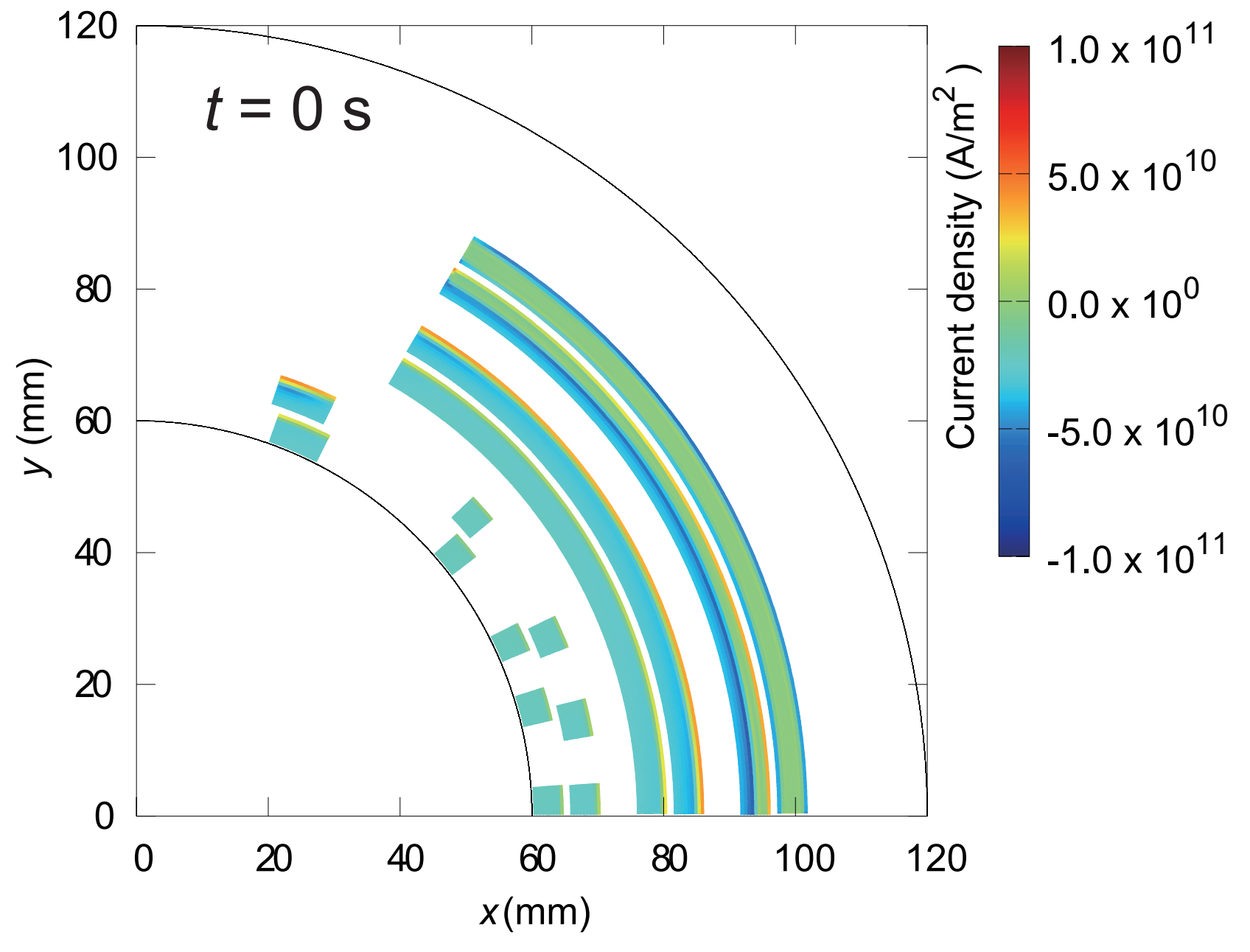


Parameters of excitation pattern	
I_0	179 A
Δt_F	300 s
I_0 / t_0	1 A/s, 10 A/s

Load rates



Current density



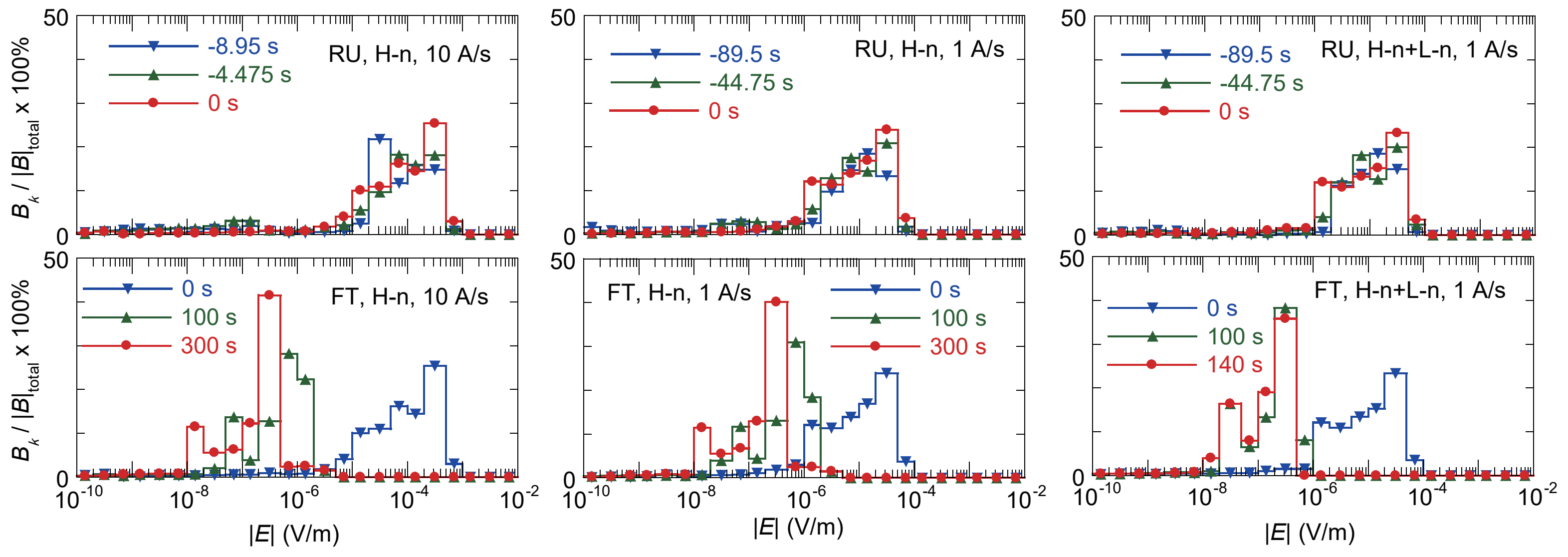
5. Field-deciding electric field

Given a range of electric field, its contributions to the magnetic field among all range of electric field can be evaluated by:

$$B_k\left(E_k,E_{k+1}\right)=\sum_{i=1}^{N}\left|B_i\right|\delta_i,\ \delta_i=\begin{cases}1, & \text{if } E_k<\left|E_i\right|\le E_{k+1}\\ 0, & \text{otherwise}\end{cases}$$

N is the number of elements of the calculation model, E_i is the electric field of the element, B_k is the magnetic field induced by the current of corresponding element *i* at *x* = *y* = 0.

Influence of *E-J* characteristics and ramp-up rates on field-deciding electric field are shown below:



For the comparison, B_k is normalized by dividing $|B|_{\text{total}}=\sum_{i=1}^{N}|B_i|$

6. Influences on multipole magnetic field

Average electric field powered by its contribution to magnetic field

$$\overline{|E|}=\frac{\sum_{i=1}^{N}|B_i||E_i|}{\sum_{i=1}^{N}|B_i|}$$

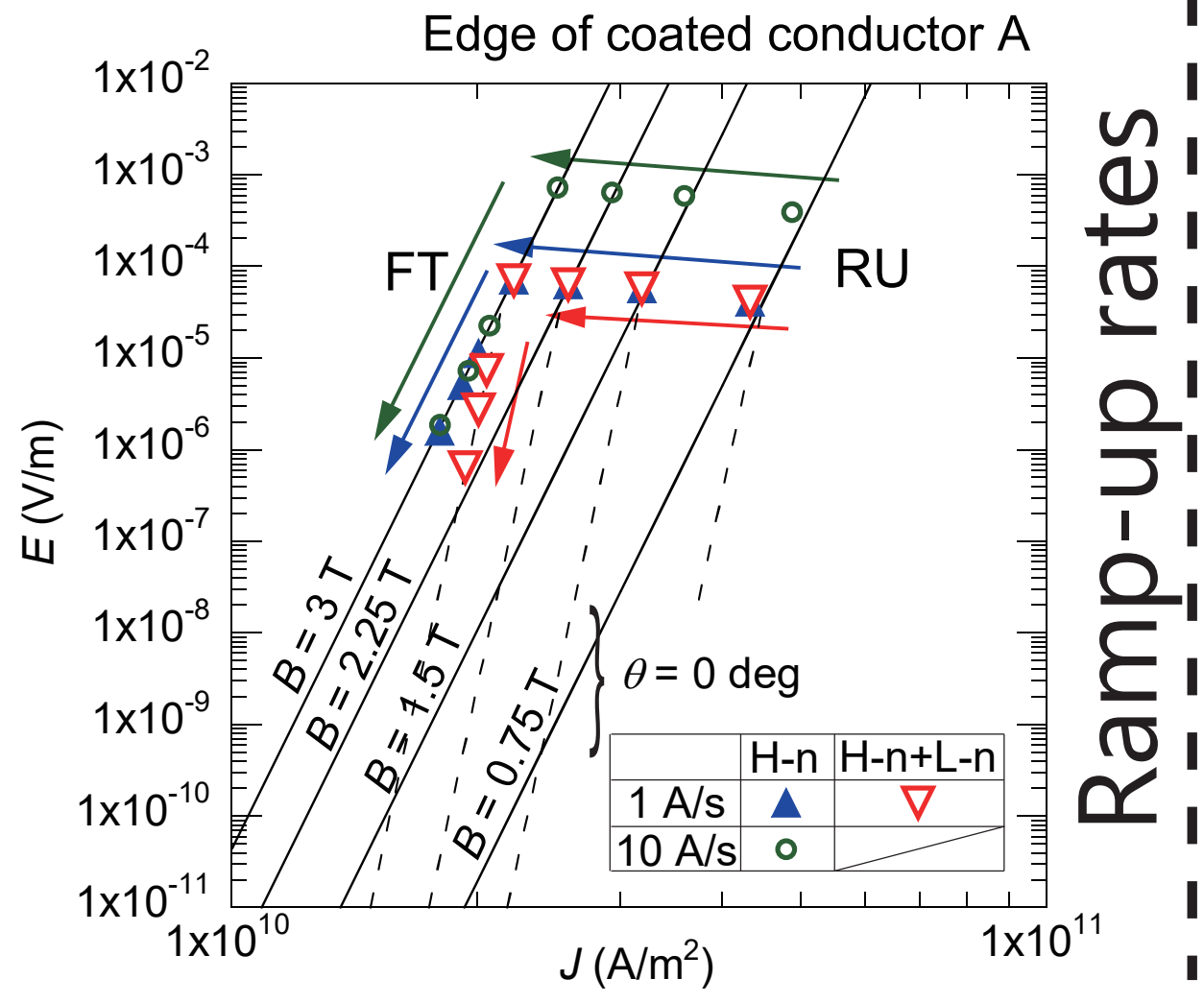
Multipole expansion

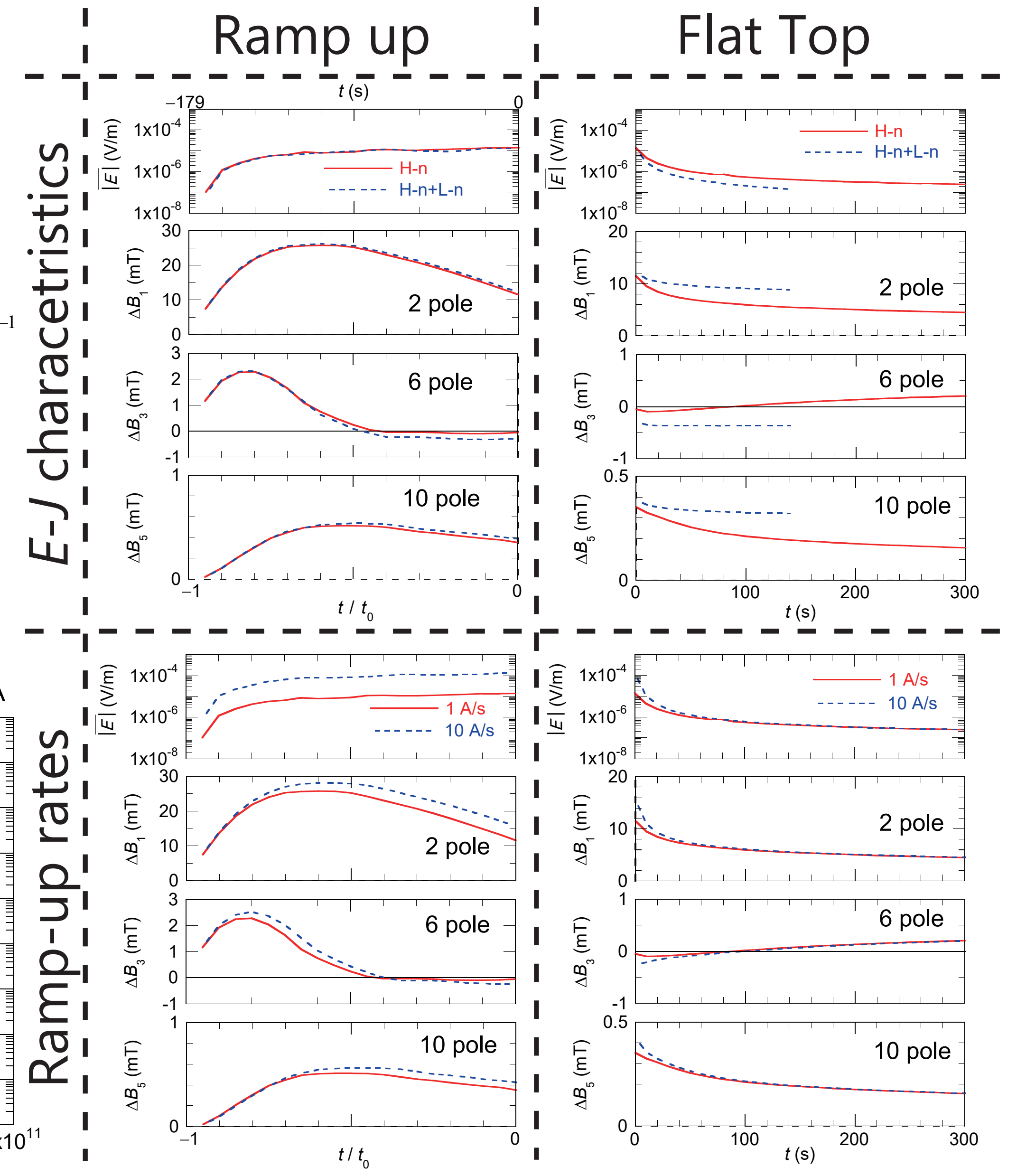
$$B_y+jB_x=\sum_{n=1}^{\infty}(B_n+jA_n)\left(\frac{x+jy}{r_0}\right)^{n-1}$$

for dipole symmetric currents

$$B_n=\frac{2\mu_0 I r_0^{n-1}}{\pi a}\cos n\phi, n\in odd$$

$$A_n=0$$





Acknowledgement

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