HTS 2020 Modelling

7th international workshop on numerical modelling of high temperature superconductors

Coupled multiphysics modelling of the thermal-magnetic-mechanical instability in bulk superconductors during magnetization

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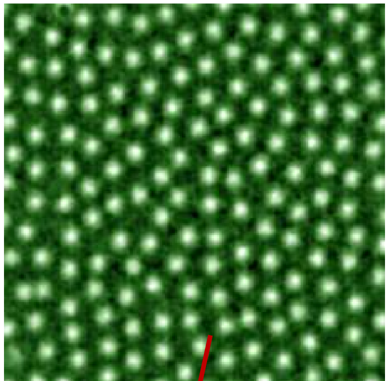
Contents

- Background
- Research Progress
  - ✓ Numerical modelling and formulisms
  - ✓ Flux jumps in Bulk MgB2
  - ✓ Results and Discussions
- Summary

Background：Vortices and Pinning

Type-II Superconductors

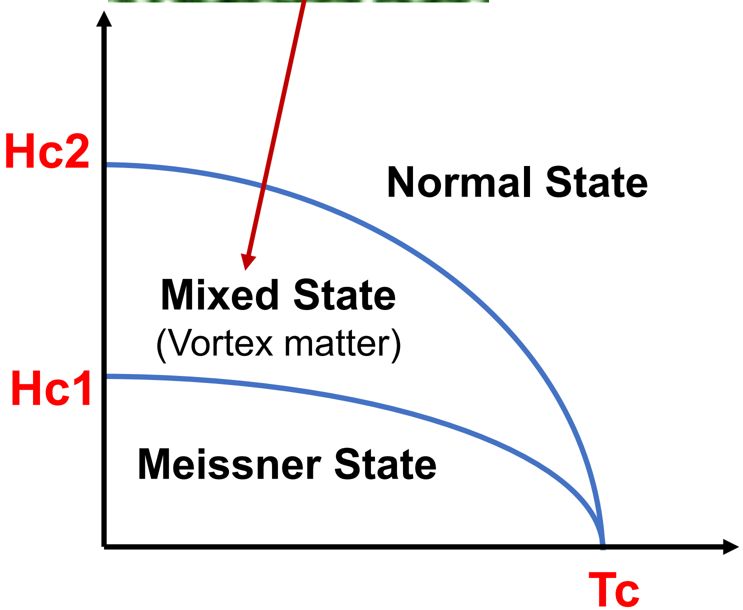


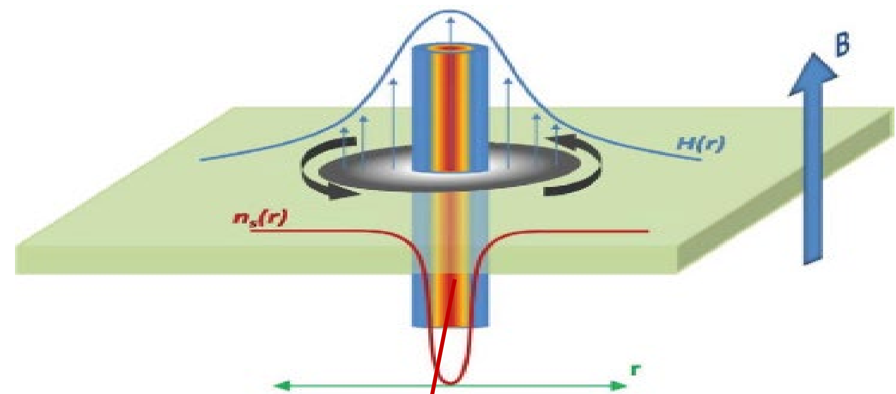
Vortex lattice

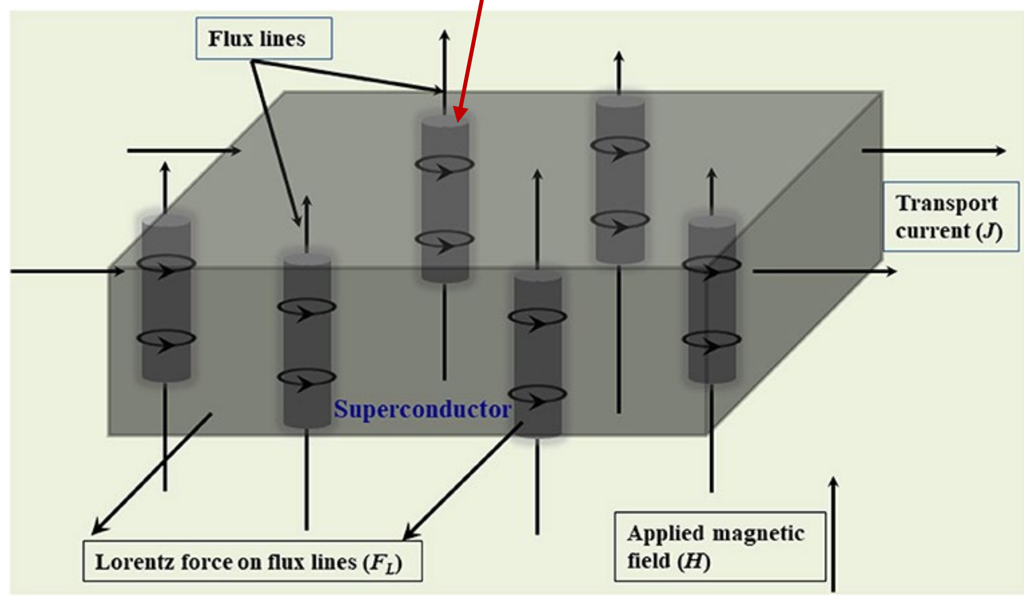
A. A. Abrikosov

2003

(published 1957)





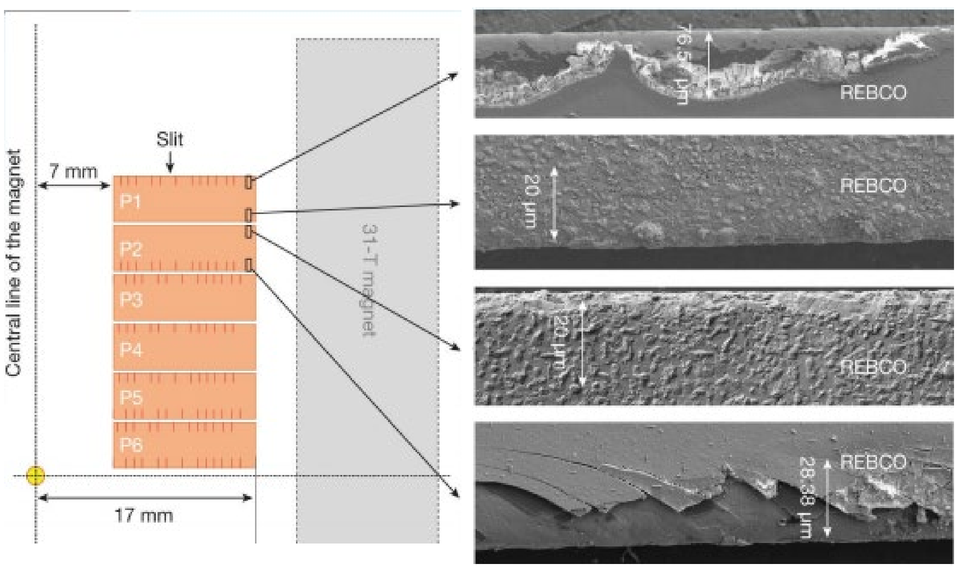


Background：Challenges in the applications

◆ Mechanical behaviors

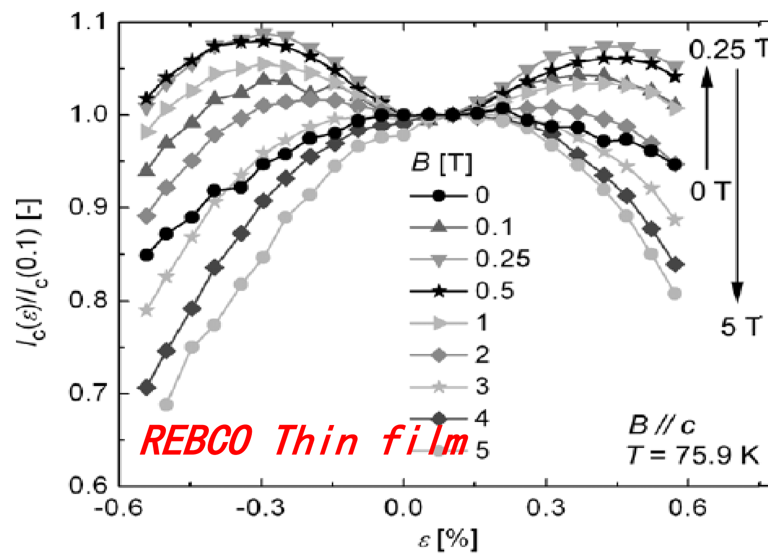
- **Electromagnetic force**
- **Thermal stress**
- **Manufacturing stress**
- …

Delamination of SC films



S. Hahn, Nature, 2019

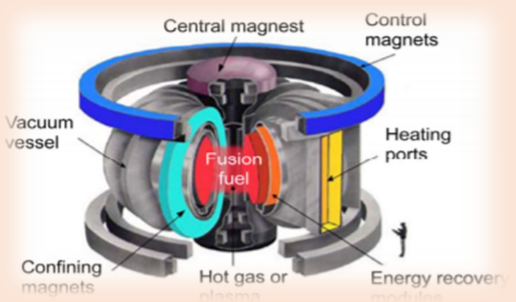
Degradagtion of critical parameters



van der Laan and Ekin (2010)

Background： Challenges in the applications

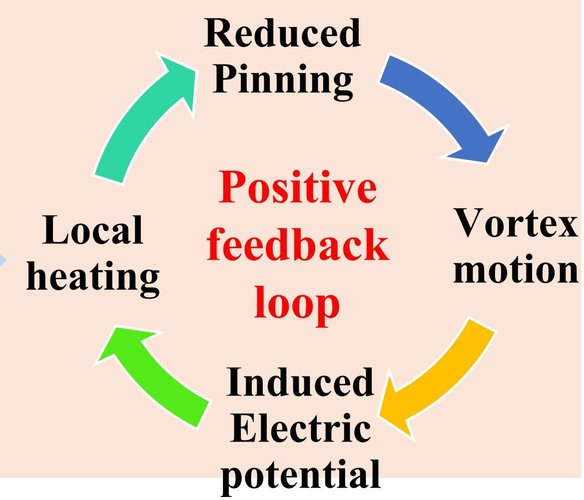
◆ Thermomagnetic instability



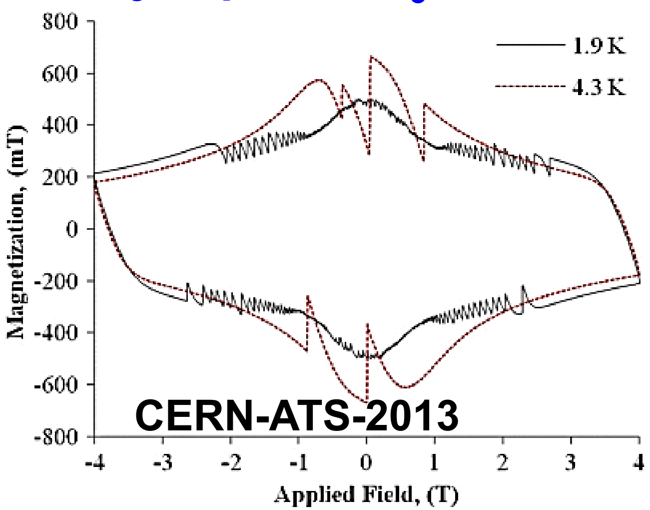
Varying magnetic fields

Thermal fluctuations

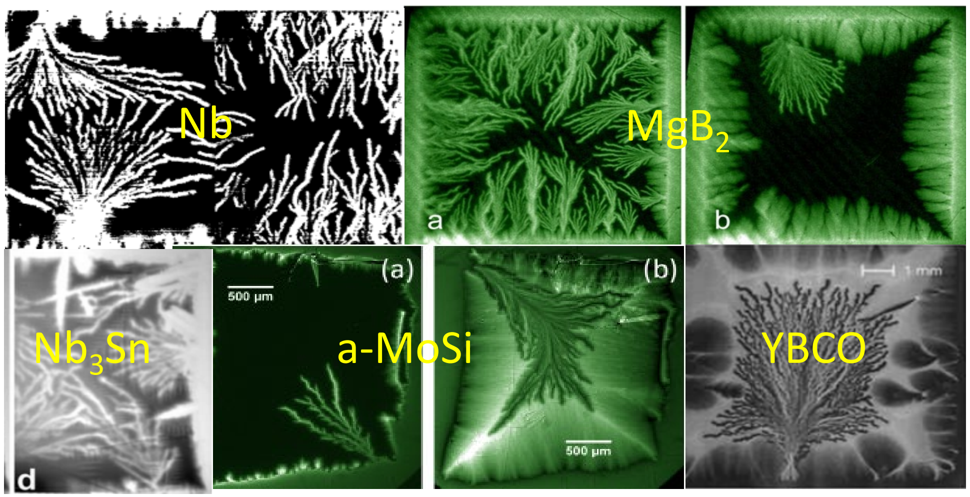
- Electromagnetic force induced motion
- Ac /Magnetization Loss
- Joule heating etc.



Flux jumps in Nb_3Sn strands



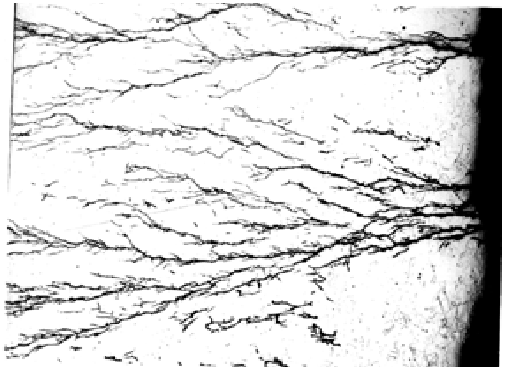
Flux avalanches in SC thin films



Background：Thermomagnetic instability

- ✓ **Instability phenomenon is widely encountered in nature and engineering, which sharing some common charecteristics**

Brittle fracture

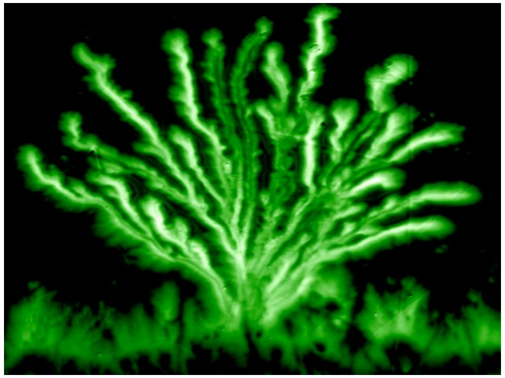


Mechanical breakdown

Electric breakdown

Lightning

Thermomagnetic instability

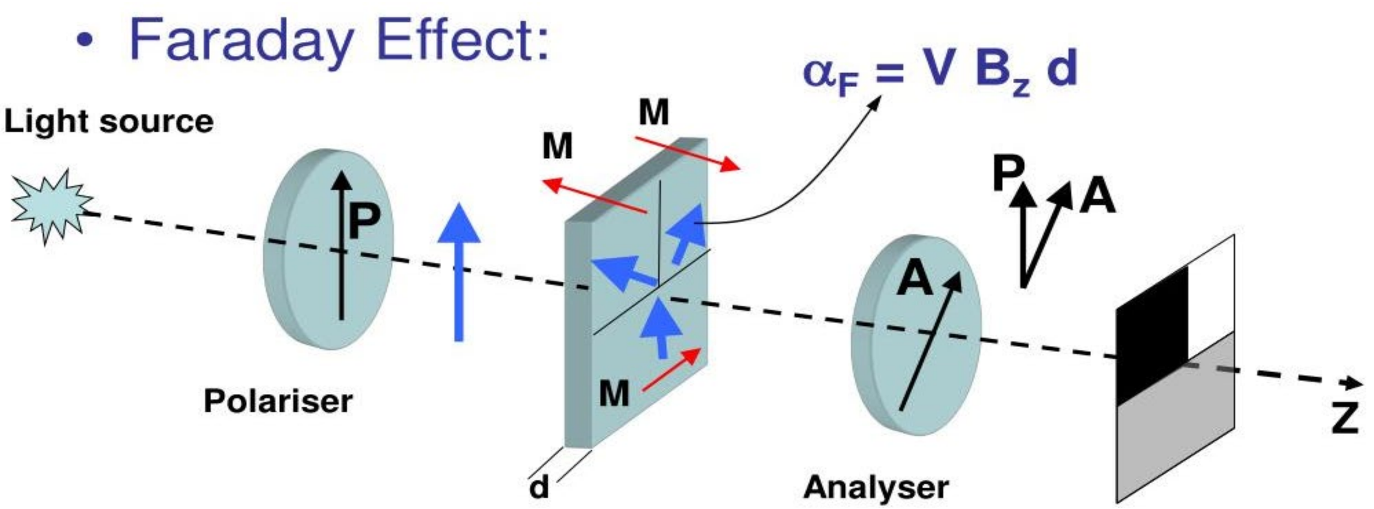


flux avalanches

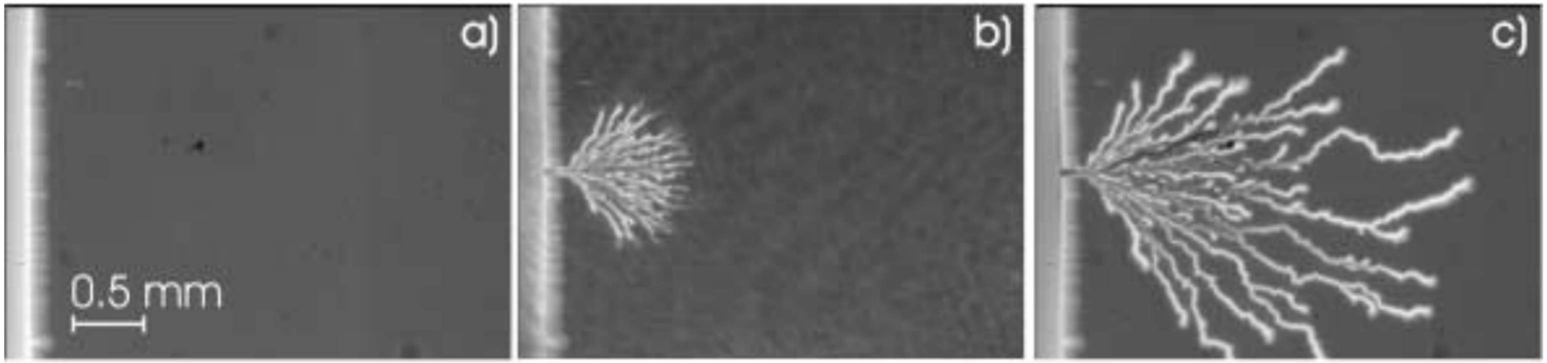
Loads	**force**	**Electric potential**	**Magnetic field**
Field	**Stress/strain**	**Electric-thermal field**	**Electromagnetic-thermal field**
Equations	**Force Equibrium**	**Charge Conservation and heat diffusion**	**Maxwell equations and heat diffusion**
Velocity	**supersonic**	**<μs**	**Sub-μs or ns**

Background: thermomagnetic instability of SCs

Experiments》Magneto-optical imaging



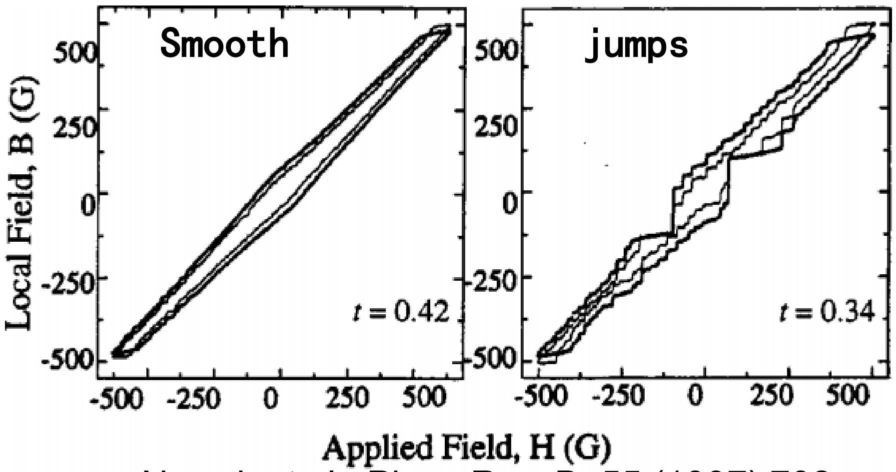
MOI of YBCO thin film at 10 K **~ km/s**



Europhys. Lett., 59 (2002) 599–605

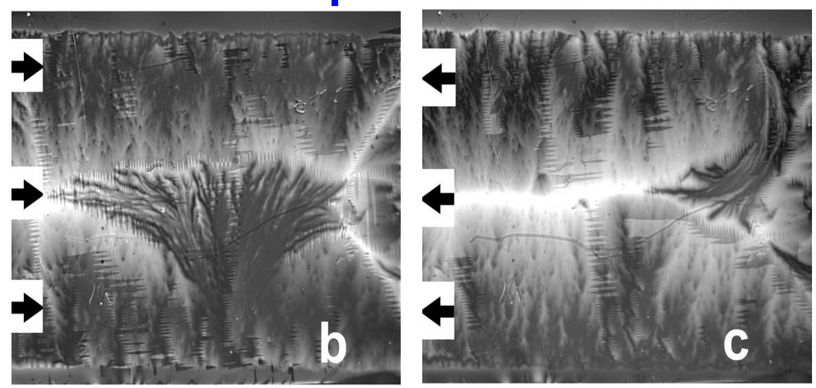
Background: thermomagnetic instability of SCs

Jumping in the magnetization curves



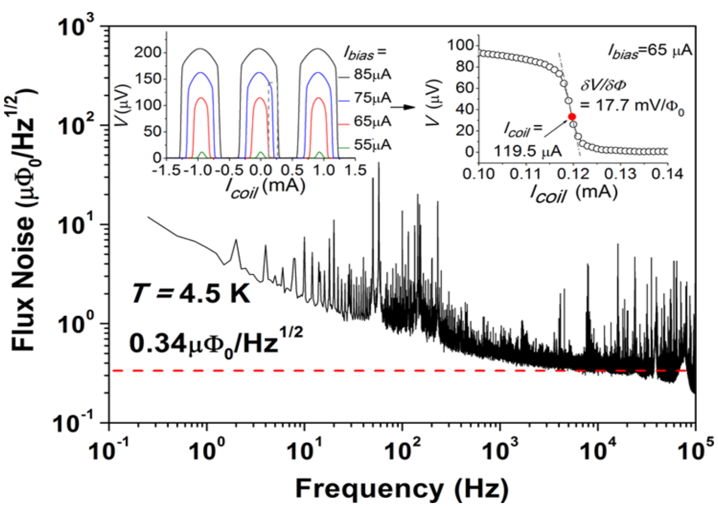
Nowak et al., Phys. Rev. B, 55 (1997) 702

Blocking the channel for transport current in superconductor film

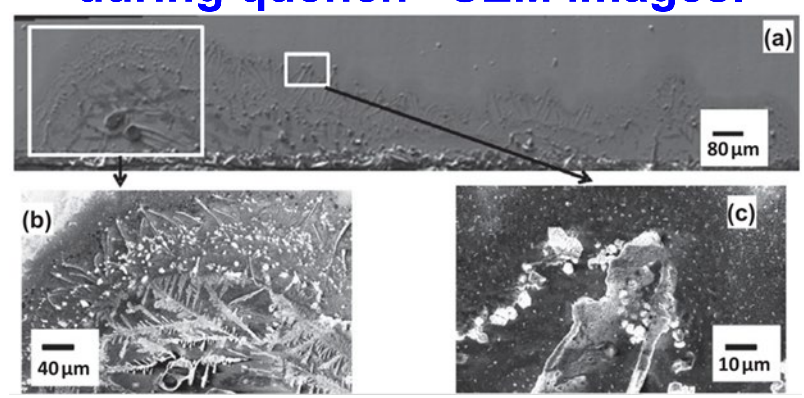


V.B. Alexander et al. Appl. Phys. Lett. 2002

Noise in the Nb Nano-SQUID



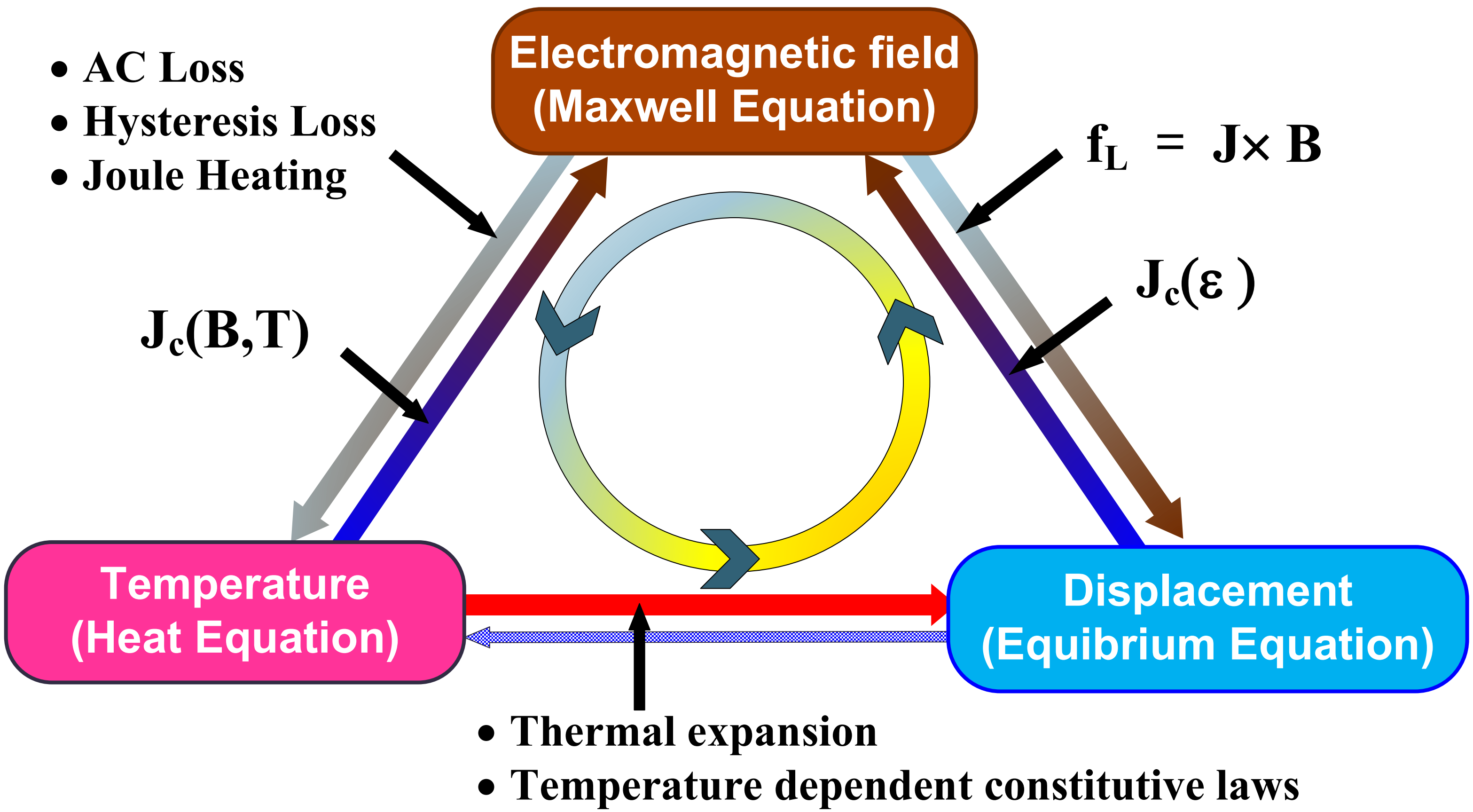
Microstrural degradation in the film during quench –SEM images.



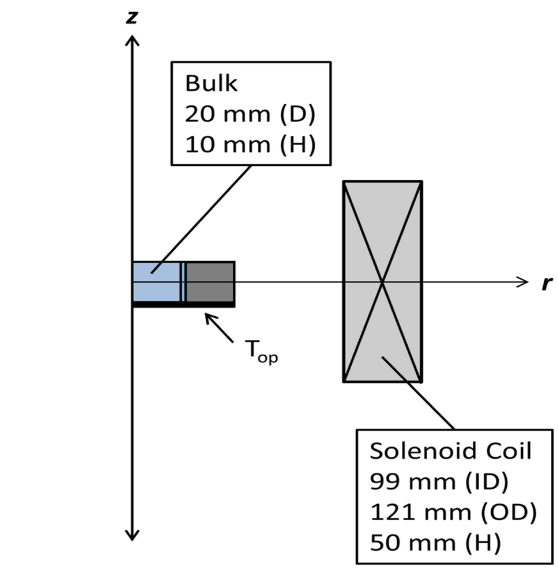
H. Song et al. Acta Mater. 60 (2012) 6991–7000

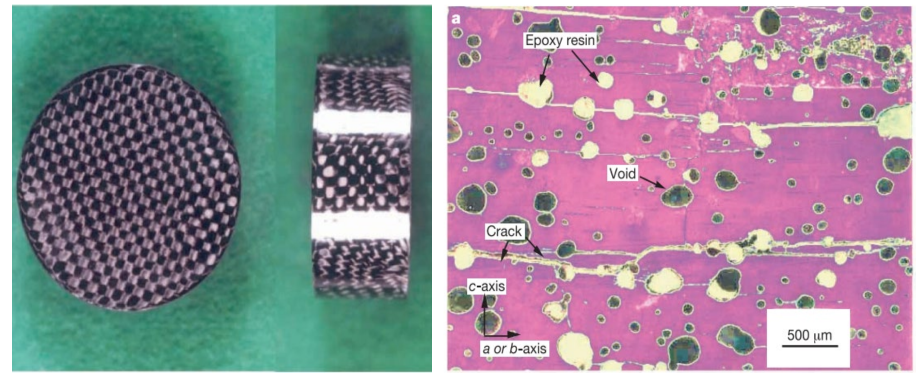
Background：Multiphysics coupling in application of SCs

- **Superconductors, under coupled multi-physical fields, experience severe thermomagnetic and mechanical instability problems.**



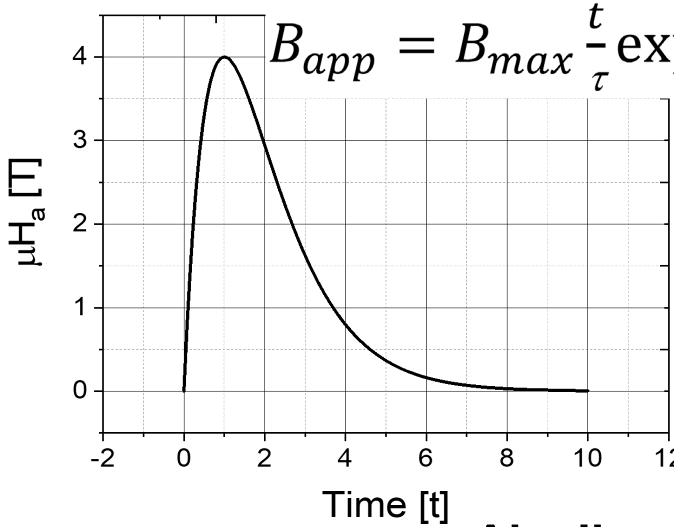
Background: Instability in bulk SCs

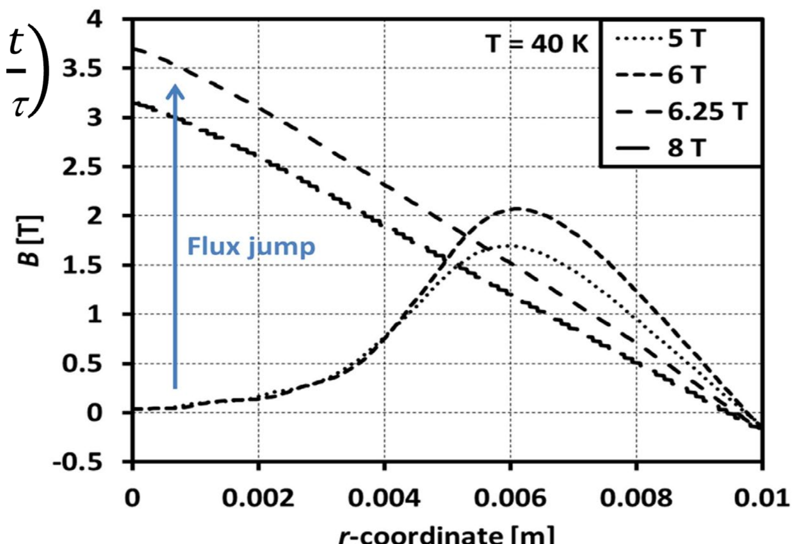




Nature, 421： 517, 2003

$$B_{app} = B_{max}\frac{t}{\tau}\exp\left(1 - \frac{t}{\tau}\right)$$





Ainslie et al. SuST. 29 (2016) 124004

Modelling framework

Governing Equations and workflow

Thermomagnetic instabilities

Maxwell Equations

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$

E-J power law $\boldsymbol{E} = E_0 \left| \boldsymbol{J}/J_{c\phi} \right|^n \quad J_{c\phi} = \left[(1-\phi)^2 + k \right] J_c(\mathrm{T}, \mathrm{B})$

Heat Equations $\rho C \frac{\partial \boldsymbol{T}}{\partial t} = \nabla \cdot (\kappa \nabla T) + \mathbf{E} \cdot \mathbf{J}$

Mechanical failure

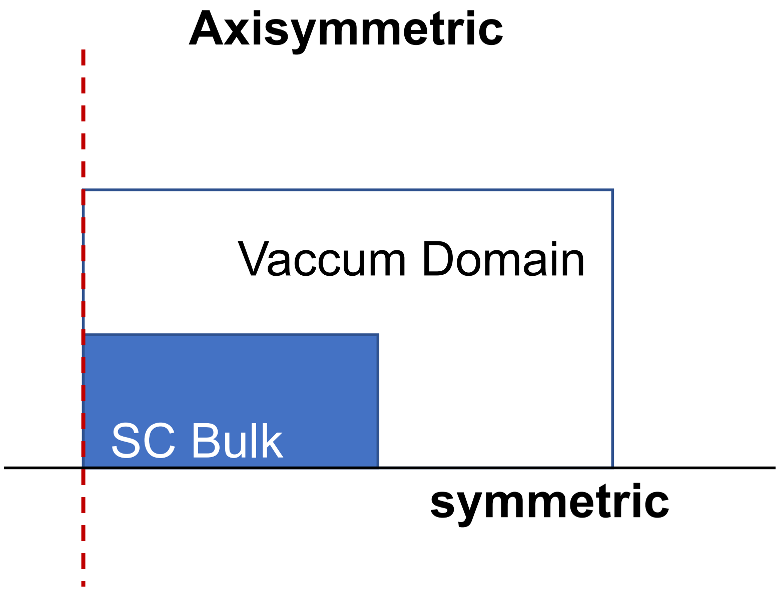
Mechanical equibrium $\rho \ddot{u}_i = \sigma_{ij,j} + f_i$

Hooke's Law $\boldsymbol{\sigma} = \left[(1-\phi)^2 + k \right] \left[\lambda \langle tr(\varepsilon) \rangle_+ \boldsymbol{I} + 2\mu\varepsilon_+ \right] + \left[\lambda \langle tr(\varepsilon) \rangle_- \boldsymbol{I} + 2\mu\varepsilon_- \right]$

Geometry relation $\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$

Phase field crack $\left(\frac{G_c}{2l_0} + \mathcal{H} \right) \phi - \frac{1}{2} G_c l_0 \Delta\phi = \mathcal{H} \quad in\Omega$

Research Progress: Instability in bulk SCs



E-J power law

$$E = E_0 \left| \frac{J}{J_c} \right|^{n-1} \frac{J}{J_c}$$

$$J_c(T, B, \varepsilon, \phi) = s_T s_B s_\phi J_{c0}$$

$$s_T = \left[1 - (T/T_c)^2\right]^{1.5}$$

$$s_B = \frac{B_0}{B_0 + B}$$

$$s_\phi = (1 - \phi)^2 + k$$

Electromagnetics:

Bulk – H-formulation

Thin film – T-A formulation

Thermal field: Comsol Multiphysics

Heat diffusion

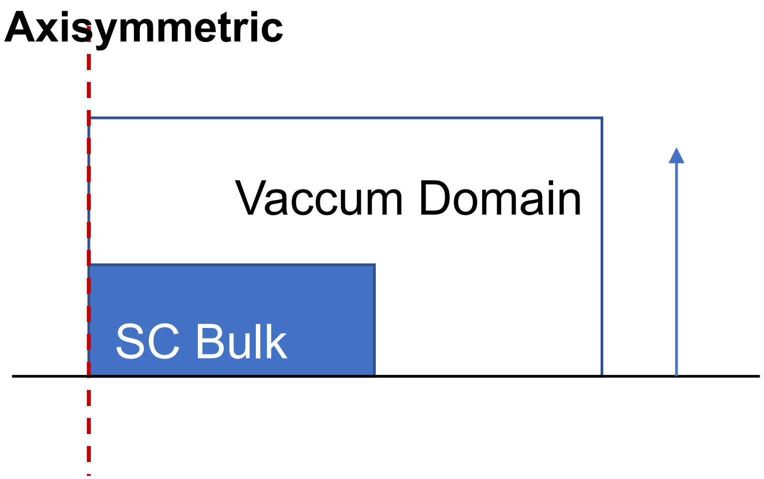
Mechanical stress and failure:

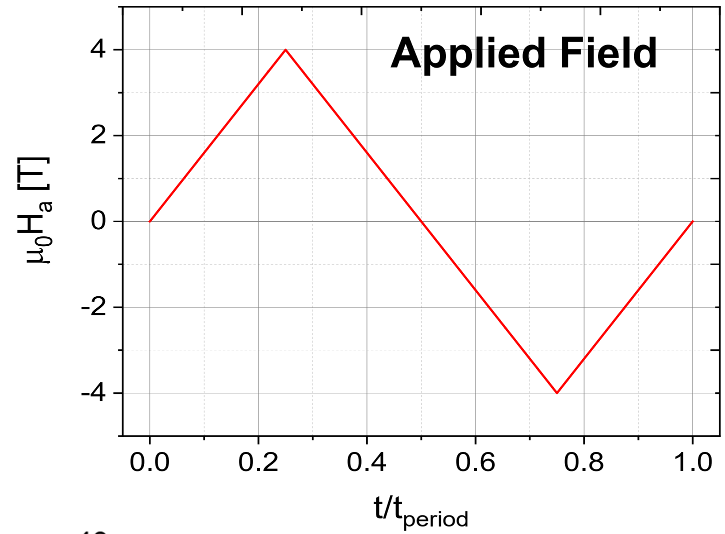
Solid mechanics+ Phase-field fracture

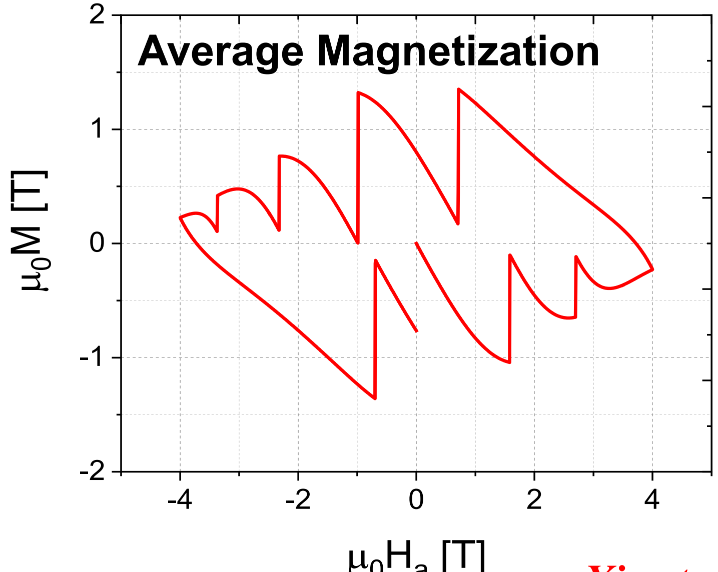
para	Description	Value
n_0	n value (E-J power law)	103
E_0	Characteristic voltage	1×10^{-4} V/m
J_{c0}	Critical current density in zero field	3.1×10^{9} A/m^2
T_c	Critical temperature	39 K
ρ_0	Normal state resistivity (MgB2)	7.0×10^{-8} Ω.m
E_{bulk}	Young's modulus (MgB2)	50 GPa
ν_{bulk}	Poisson's ratio (MgB2)	0.33
$\sigma_{c,bulk}$	Tensile strength (MgB2)	20 MPa
α_{bulk}	Thermal expansion coefficient (MgB2)	3.5×10^{-6} K^{-1}
$G_{c,bulk}$	Critical energy release rate (MgB2)	20 N/m

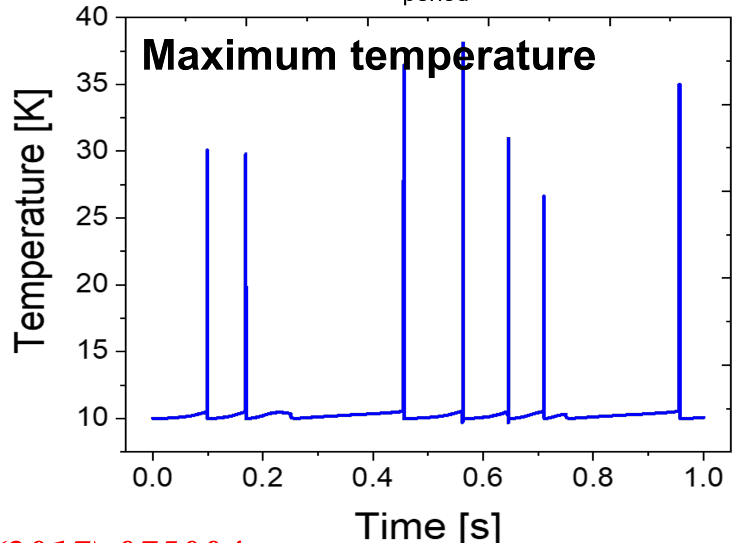
Research Progress: Instability in bulk SCs

Model verification: flux jumps in MgB_2





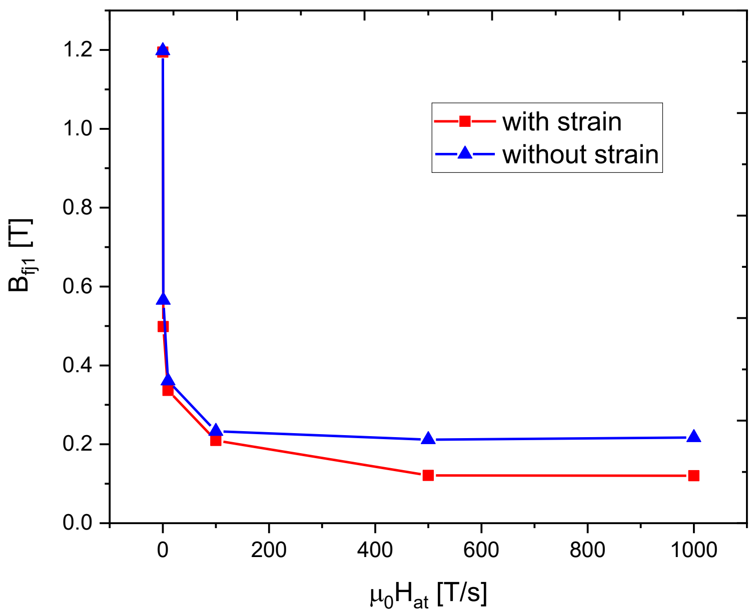




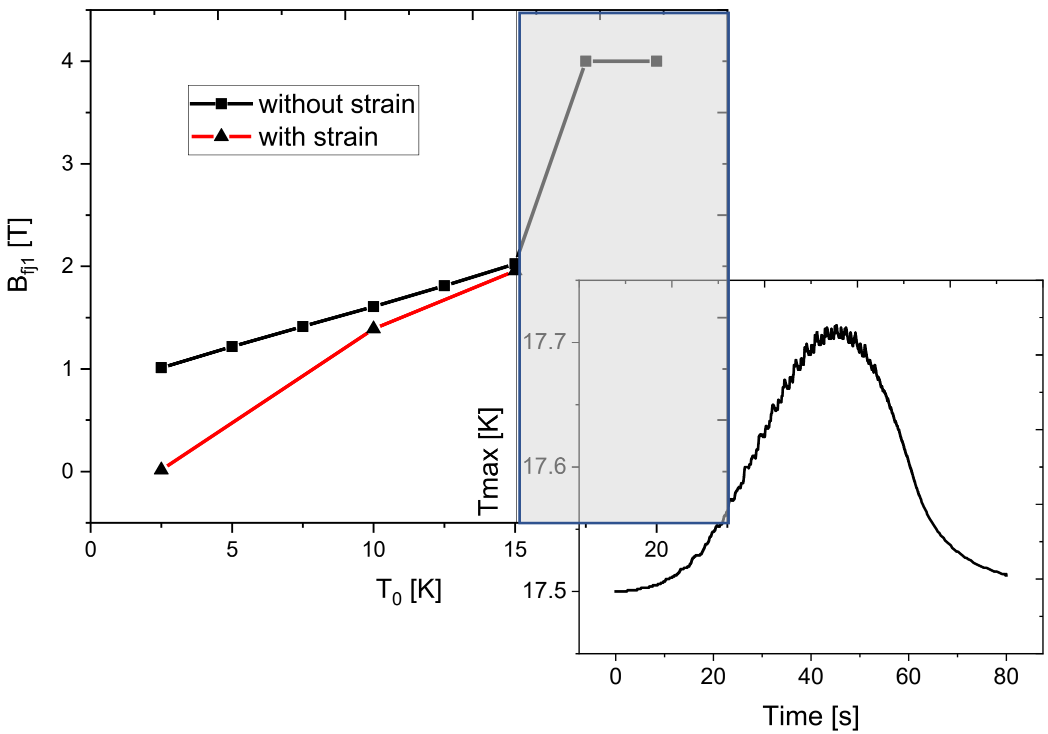
Xia et al, SuST 20(2017) 075004

Threshold magnetic fields Vs Parameters

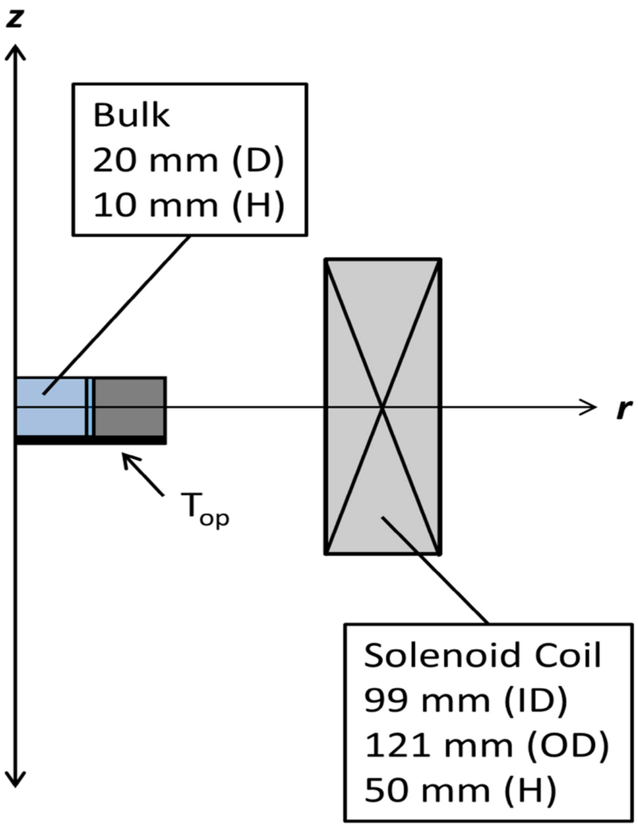
Field ramp rate



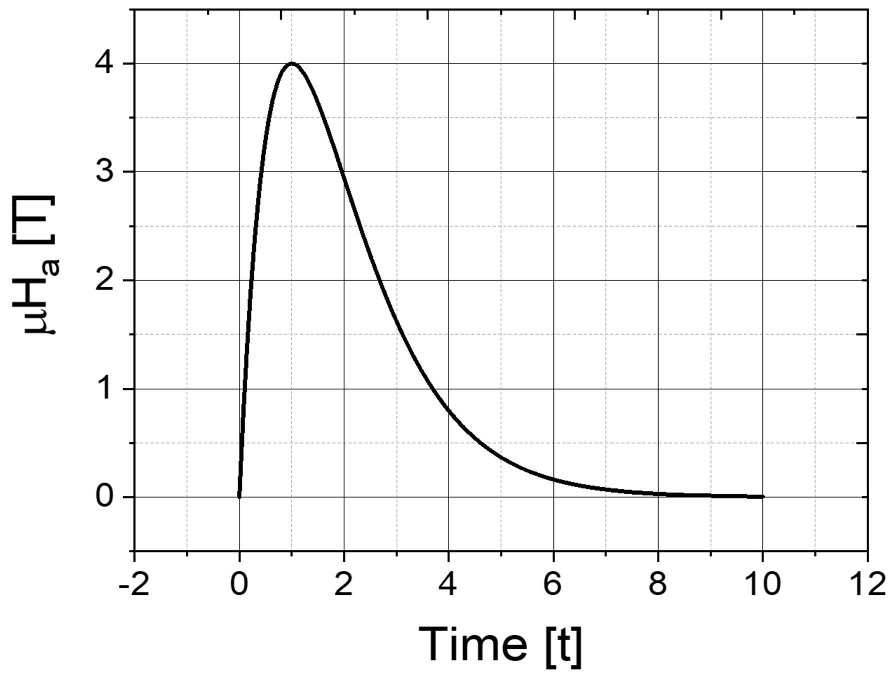
Ambient temperature



Model: bulk Superconductor in pulsed field

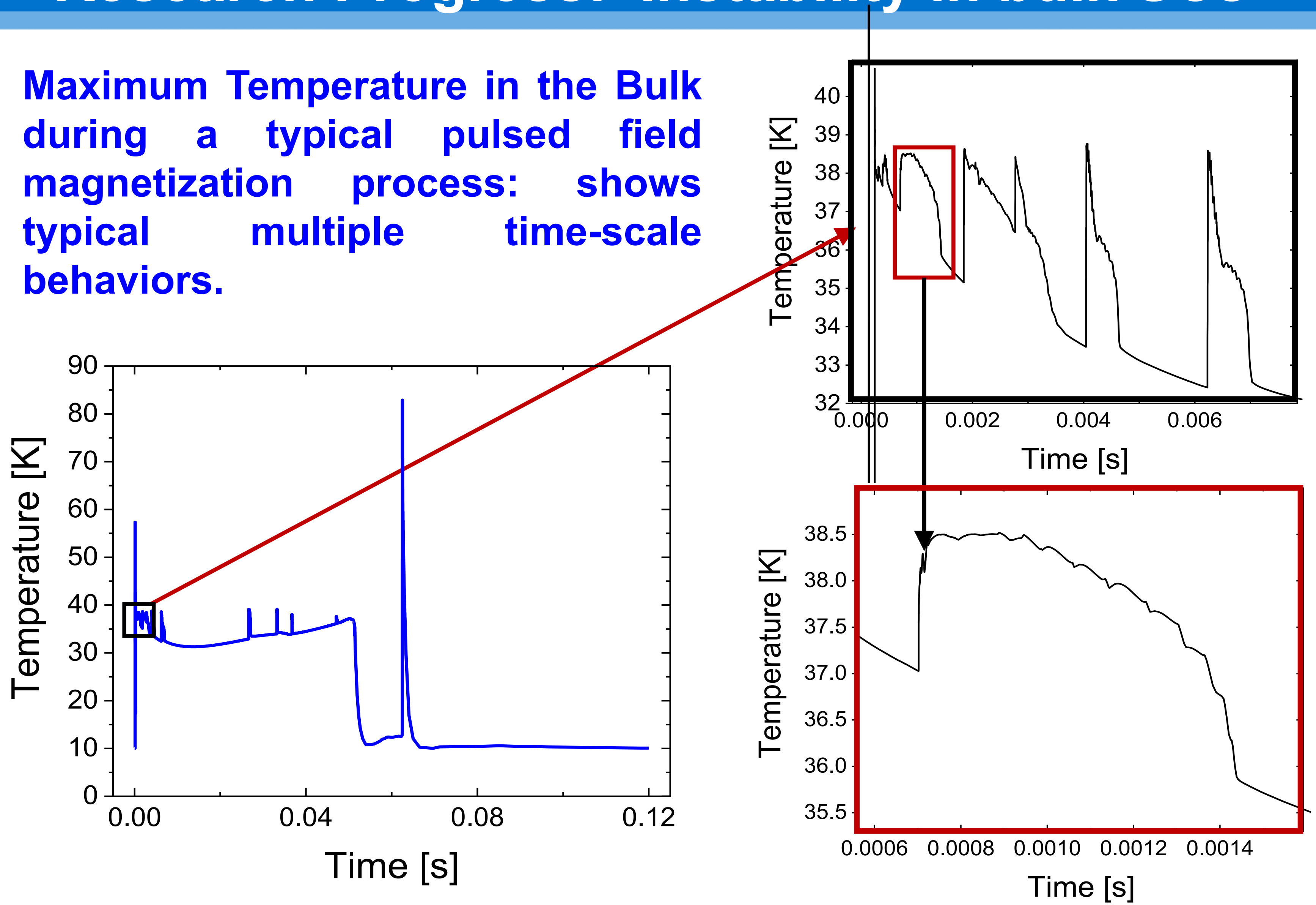


$$B_{app} = B_{max}\frac{t}{\tau}\exp\left(1-\frac{t}{\tau}\right)$$



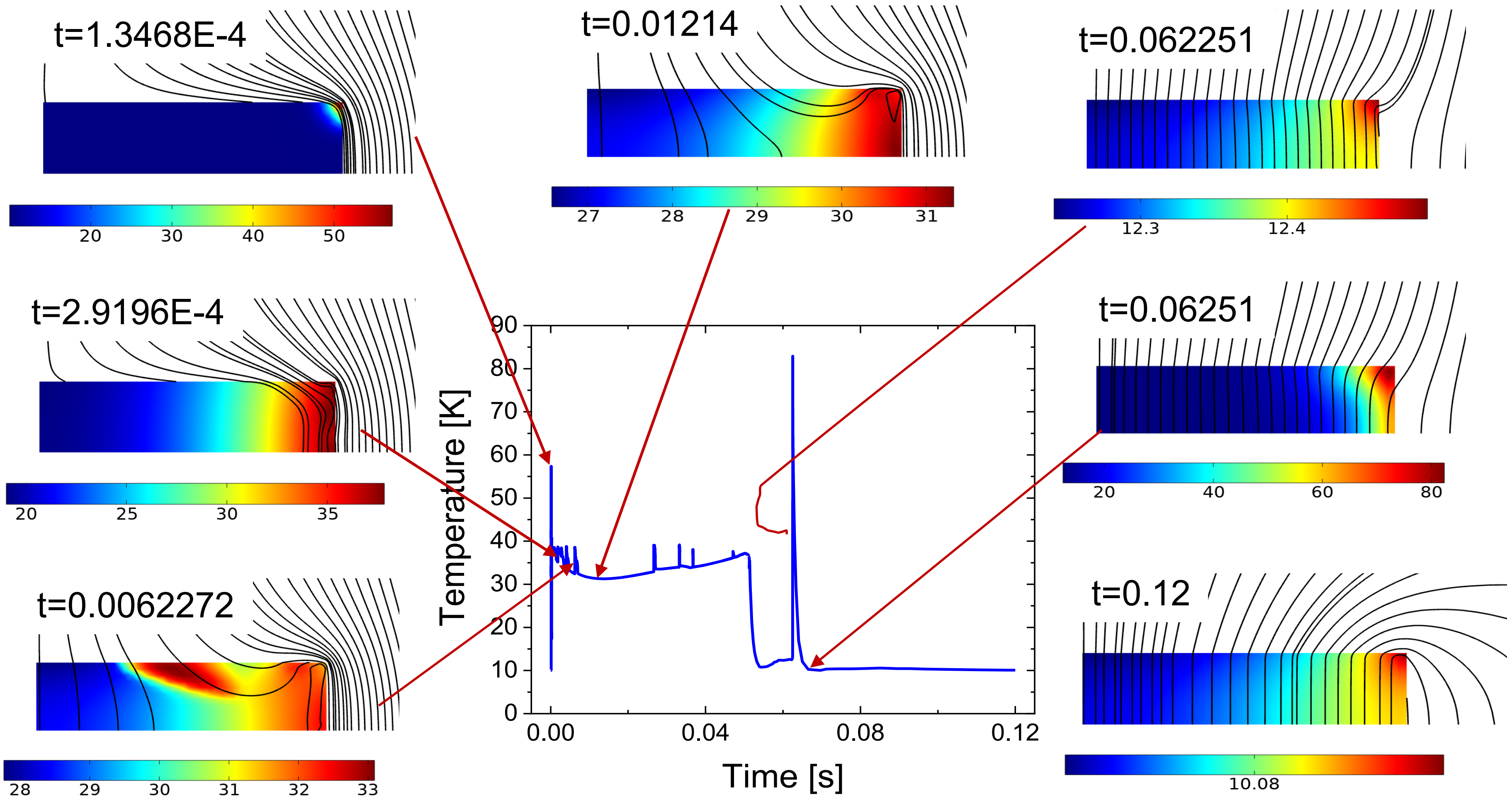
Research Progress: Instability in bulk SCs

Maximum Temperature in the Bulk during a typical pulsed field magnetization process: shows typical multiple time-scale behaviors.



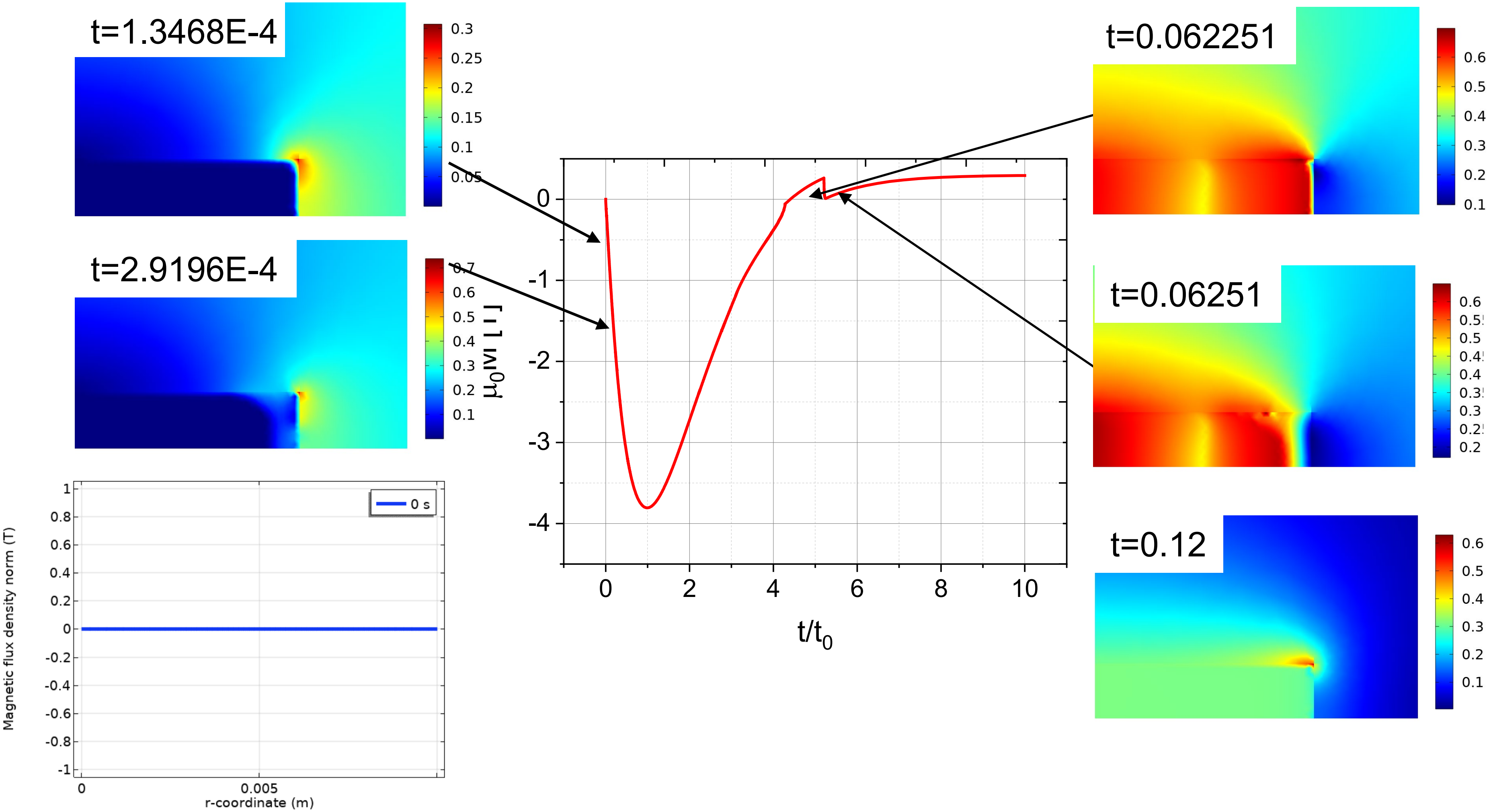
Research Progress: Instability in bulk SCs

Maximum Temperature Distribution within the bulk during flux jumps.



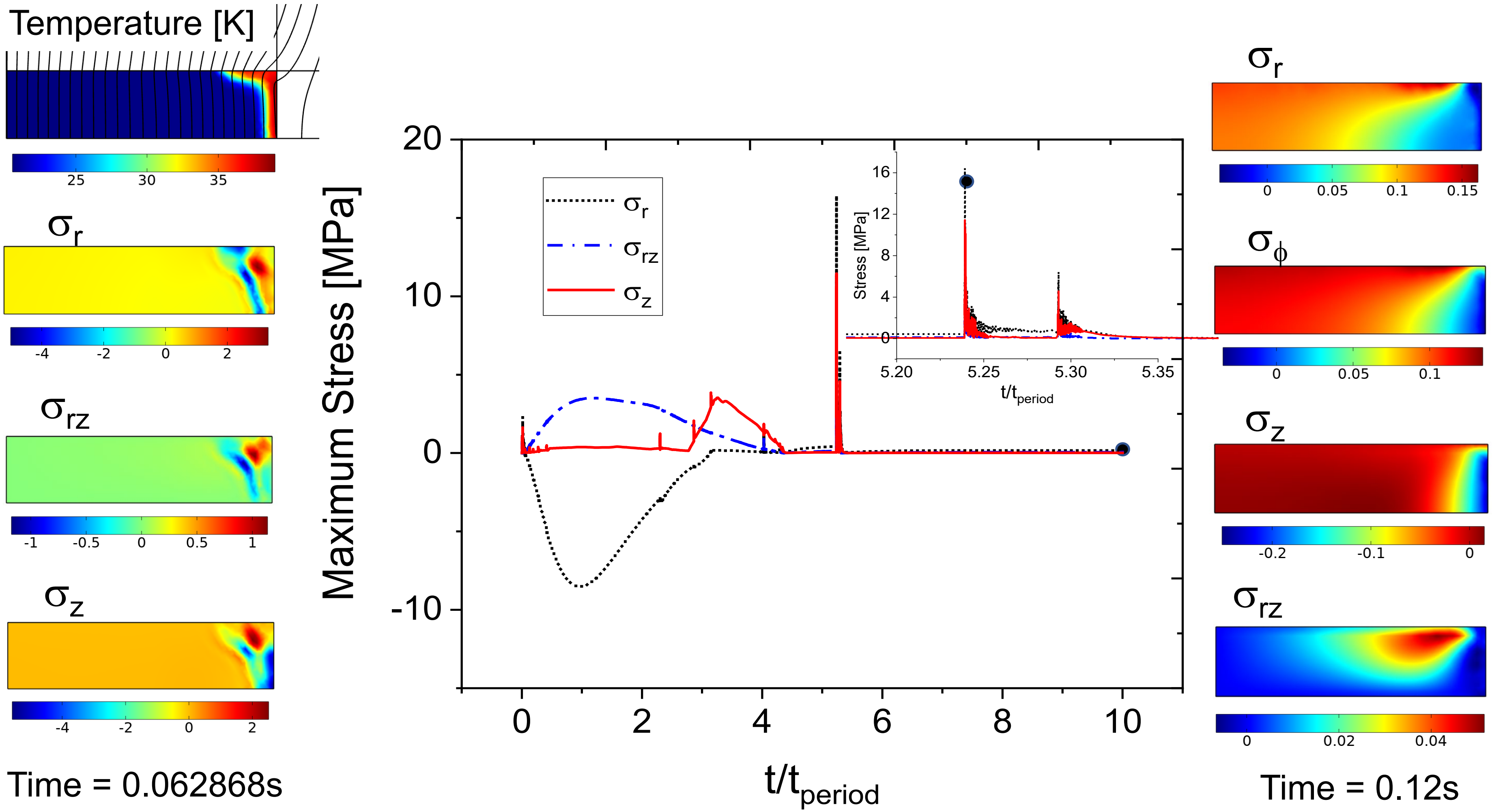
Research Progress: Instability in bulk SCs

Magnetic flux Distribution within the bulk during flux jumps.



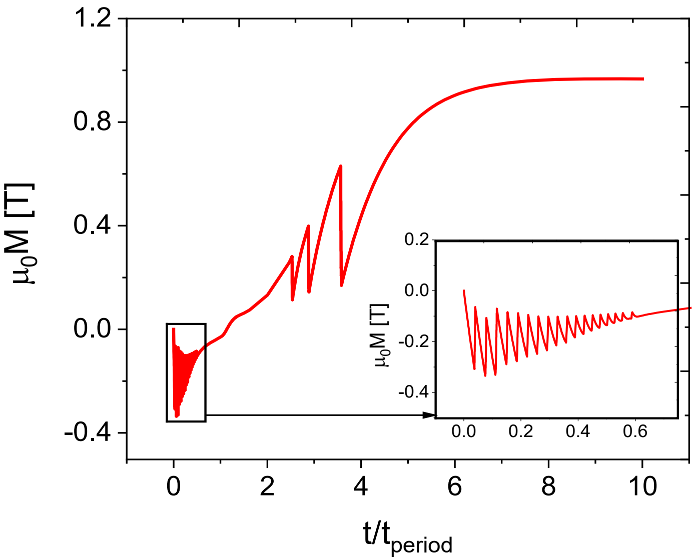
Research Progress: Instability in bulk SCs

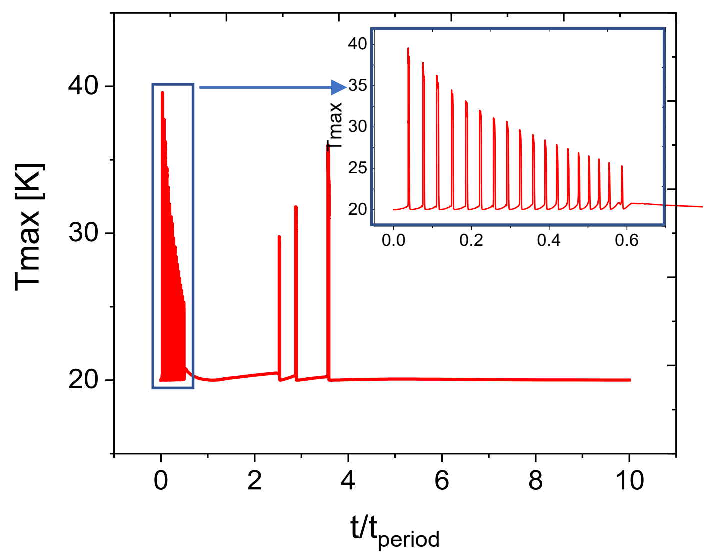
Stress/strain distribution within the bulk during flux jumps.

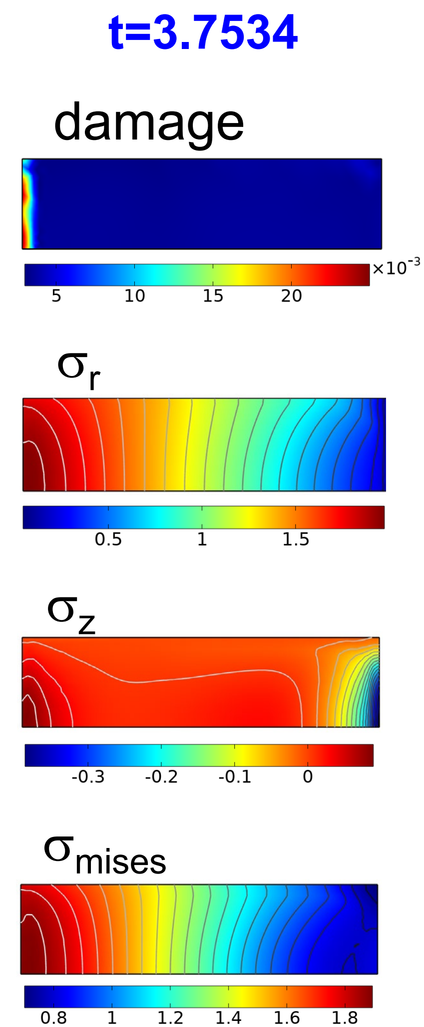


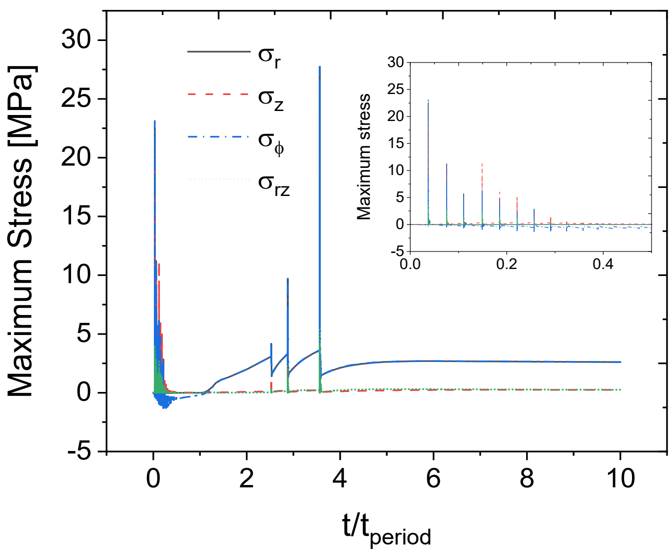
Research Progress: Instability in bulk SCs

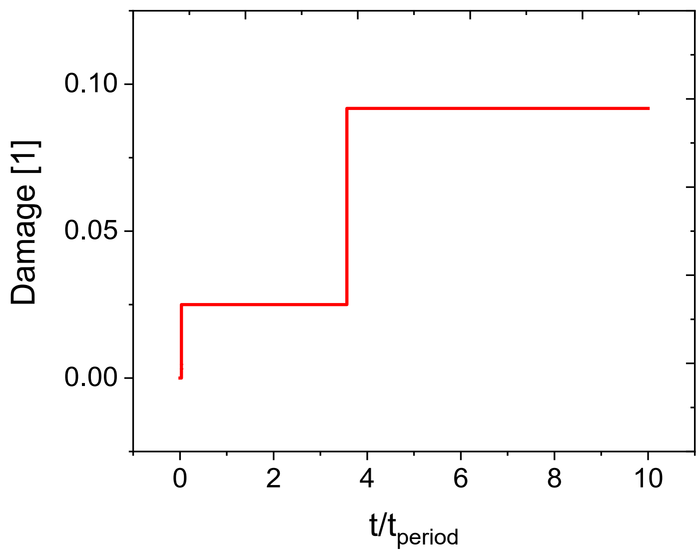
Influence of the ramp rate on the flux jumps (τ=120ms)





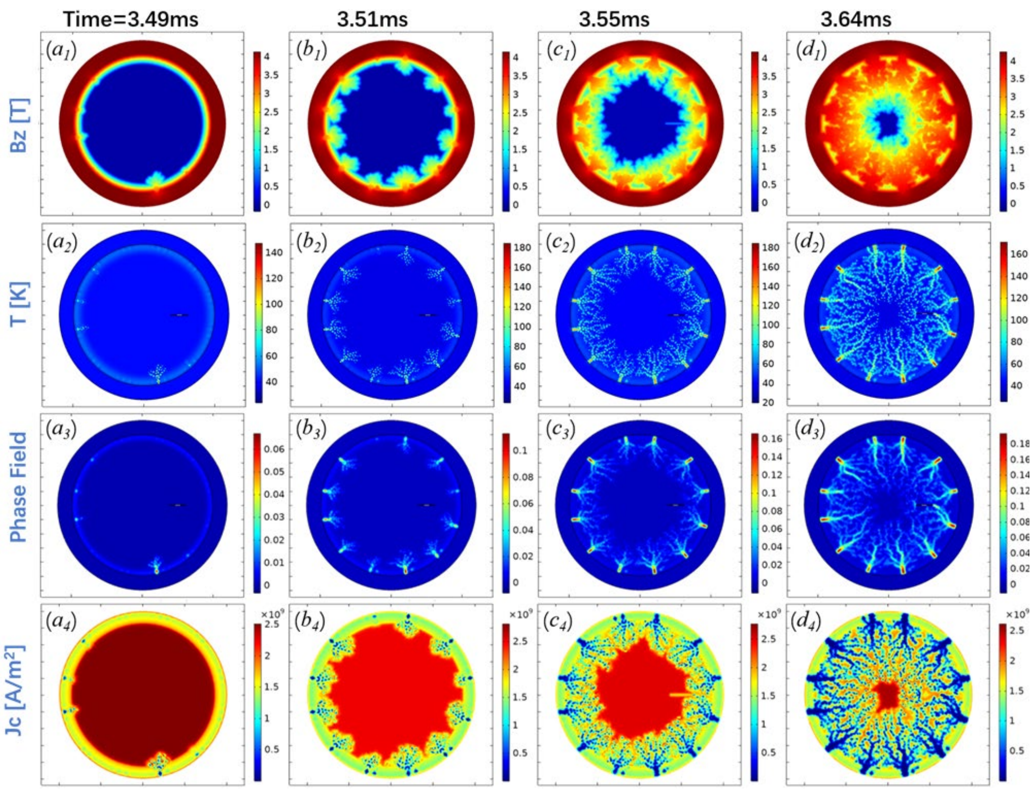


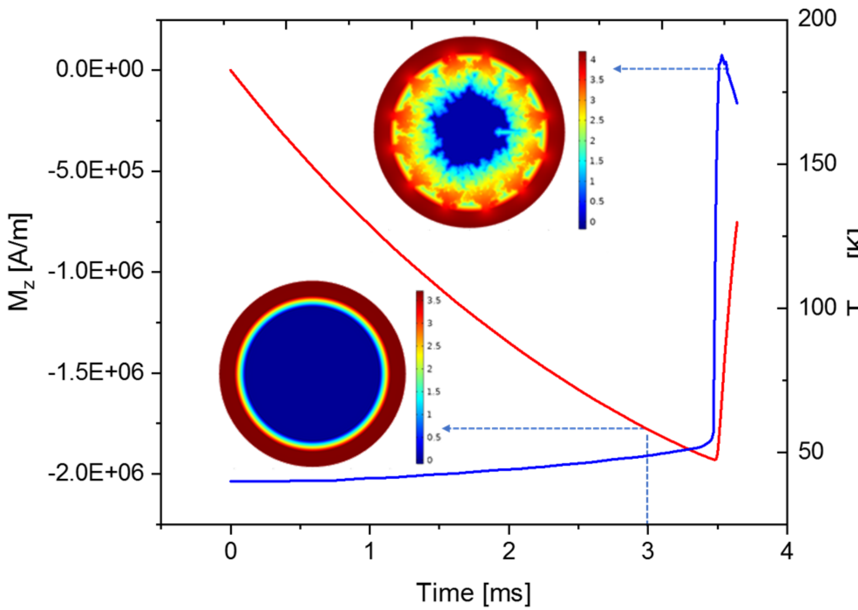




Research Progress: Flux Avalanches in bulk

Infinitely long cylinder bulk under pulsed field





Summary

- A numerical model is proposed to simulate the Flux jumps, stress/strain and structural degradation in Bulk superconductors during pulsed field magnetization.
- Due to the multiple timescales intrinsically involved in the instability behaviors, solving the coupled Multiphysics models numerically to simulate the thermo-magnetic-electro-mechanical instability is still a challenge task ahead.
- More efficient simulation methods (such as the FFT based scheme) are needed to simulate the coupled instability behavior.

Thanks for your attention!