IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) January 2015.
Invited Presentation WT-19-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

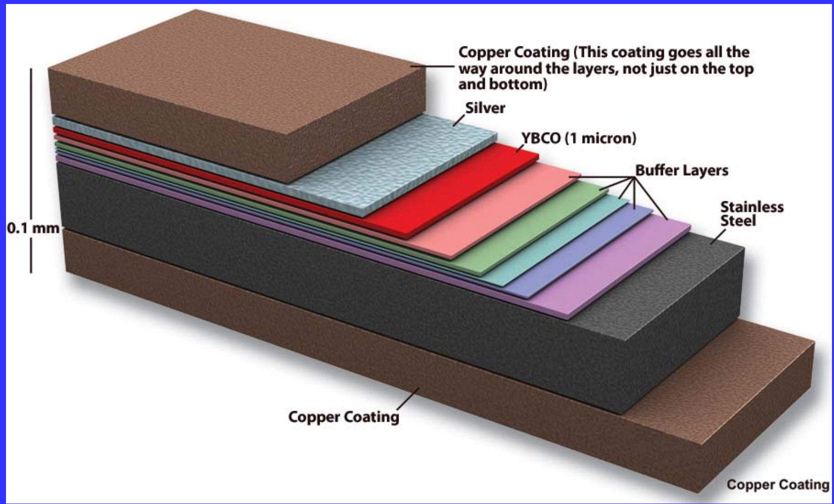
Jc anisotropy analysis in YBCO coated conductors: hybrid APC effect and modelling using 3D Time Dependent Ginzburg-Landau Equations

Kaname Matsumoto and Tomoya Horide

Dept. Materials Science and Engineering
Kyushu Institute of Technology

Kyushu Institute of Technology

Issues in Coated Conductor R & D



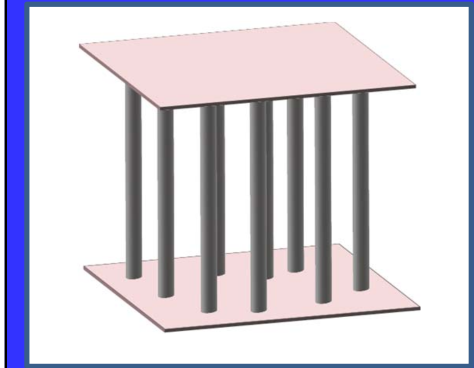
http://www.magnet.fsu.edu/mediacenter/publications/

http://www.fujikura.co.jp/f-news/1191427_4018.html

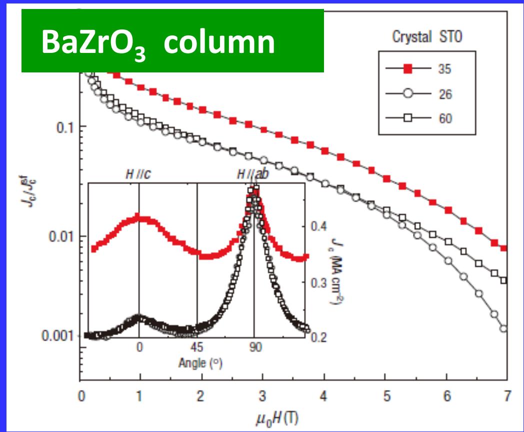
- ✓ Critical Current
- ✓ Anisotropy
- ✓ Grain Boundary
- ✓ Homogeneity
- ✓ AC loss
- ✓ Mechanical property
- ✓ Stability
- ✓ Mass production

Artificial pinning centers "APCs" －Nanorods

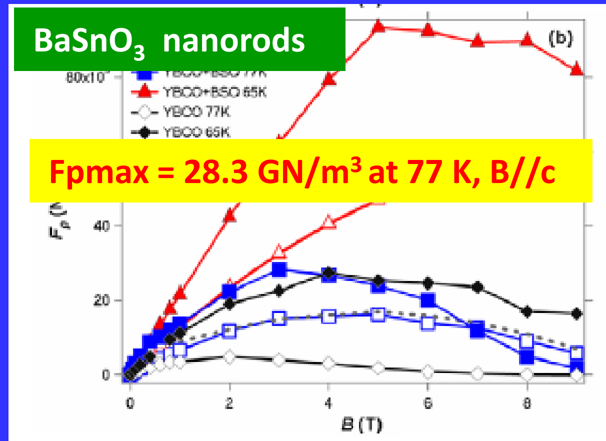
Nanorods



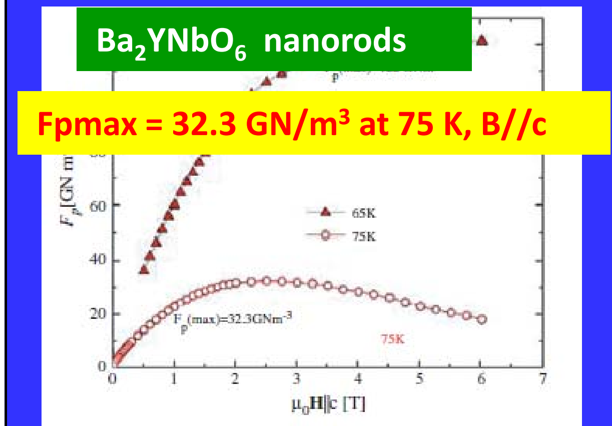
$BaZrO_3$, $BaSnO_3$, Double perovskite, $BaHfO_3$,etc



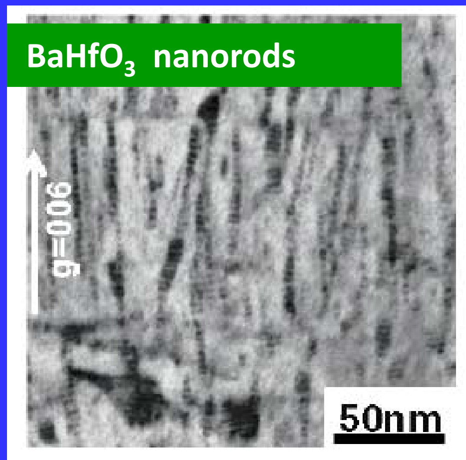
J. MacManus-Driscoll et al., Nature Mat. 3, 439 (2004)



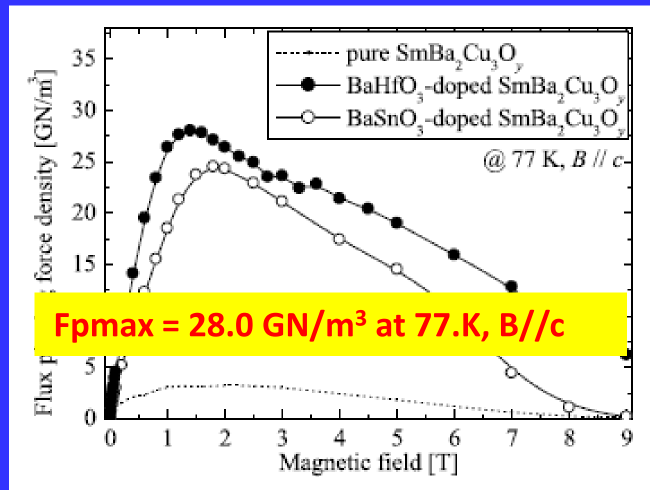
P. Mele et al., SUST 21, 032002 (2008)
C. Varanasi et al., APL 93, 092501 (2008)



D. Feldmann et al., SUST 23, 095004 (2010)



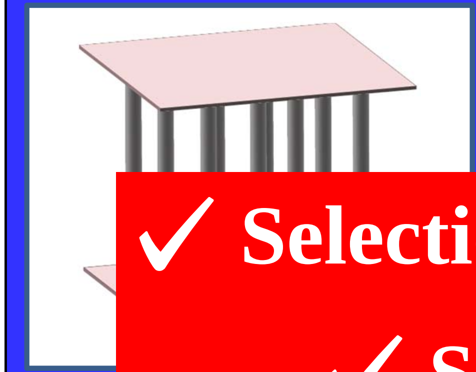
H. Tobita et al., SUST 25, 062002 (2012)
J. Hanisch et al., SUST 19, 534 (2006)

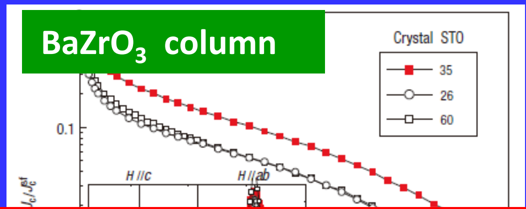


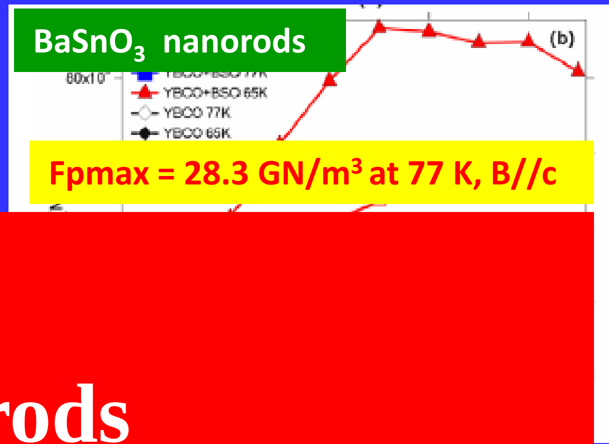
A. Tsuruta et al., SUST 27, 065001 (2014)

Artificial pinning centers “APCs” －Nanorods

Nanorods







Ba
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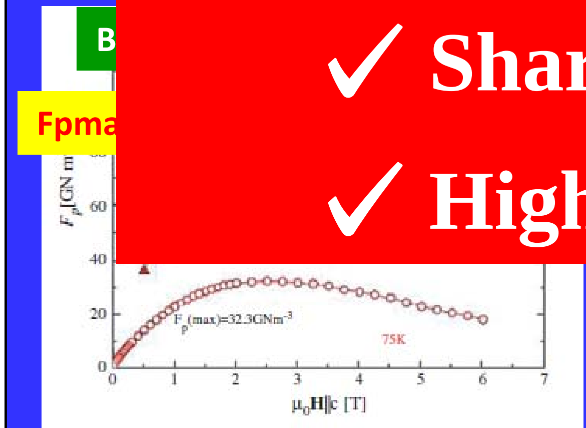
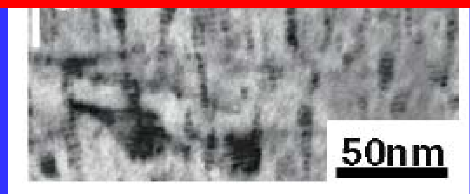
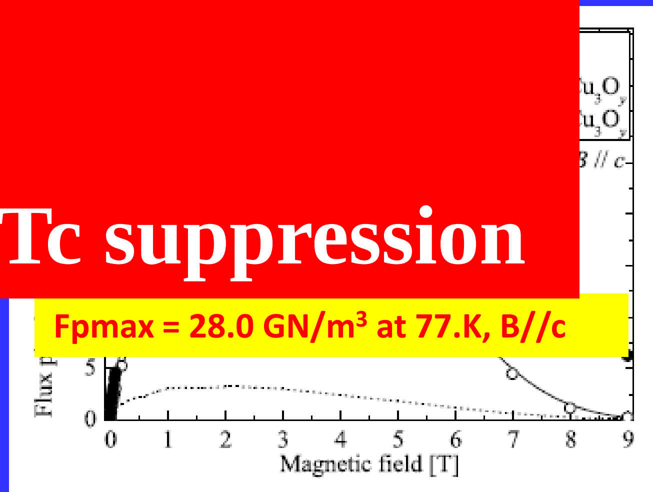
08)

- ✓ Selection of material and
  - ✓ Straightness of nanorods
  - ✓ Appropriate diameter of nanorods
  - ✓ Sharp interface
  - ✓ High density without Tc suppression







D. Feldmann et al., SUST 23, 095004 (2010)

H. Tobita et al., SUST 25, 062002 (2012)
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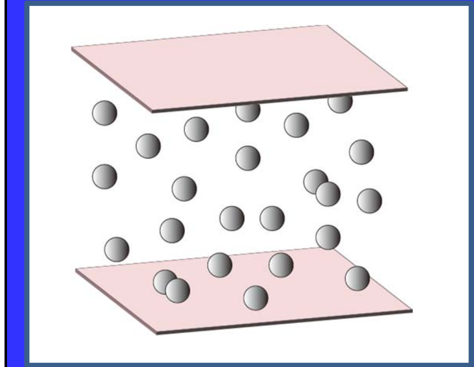
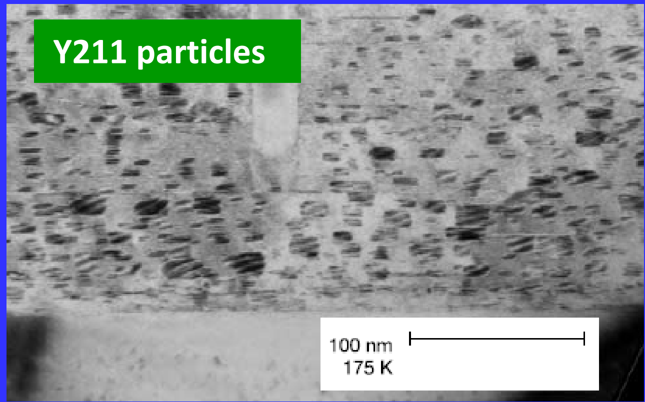
A. Tsuruta et al., SUST 27, 065001 (2014)

Artificial pinning centers －Nanoparticles

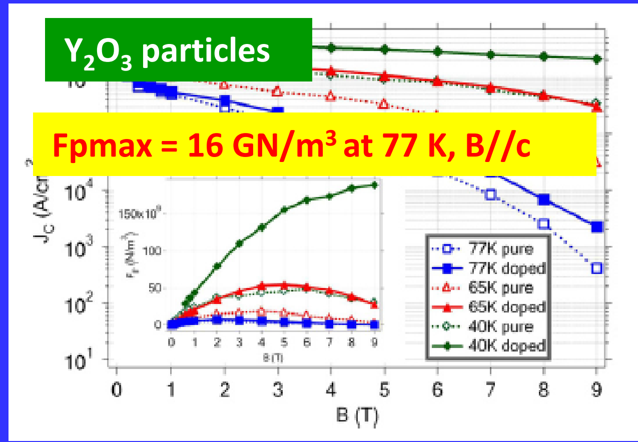
Nanoparticles



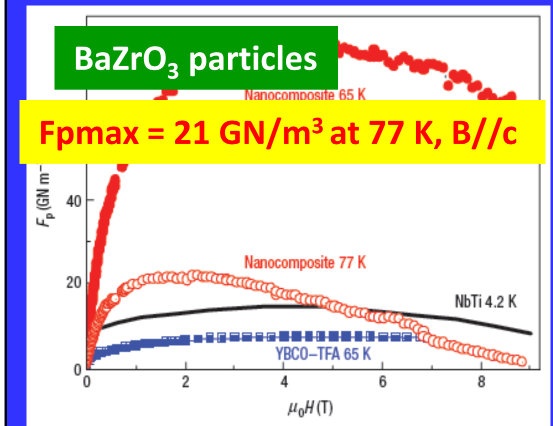
$Y211$, Y_2O_3, $BaZrO_3$, $BaSnO_3$, etc



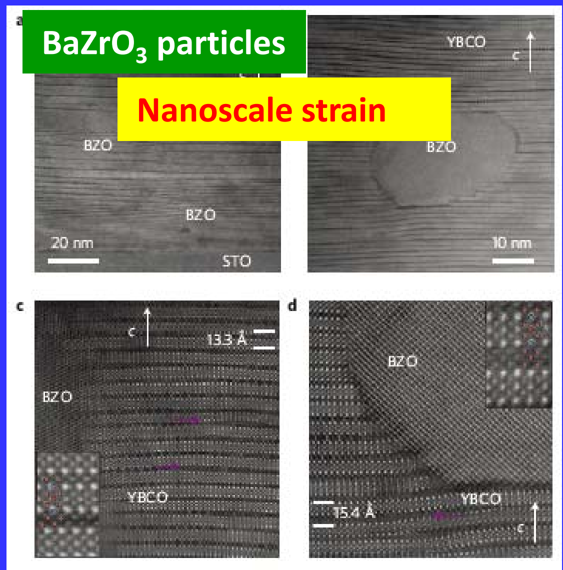
T. Haugan et al., Nature 430, 867 (2004)



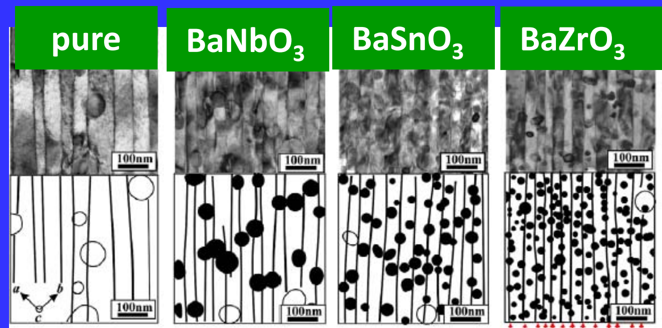
P. Mele et al., SUST 20, 616 (2007)



J. Gutierrez et al., Nature Mat. 6, 367 (2007)



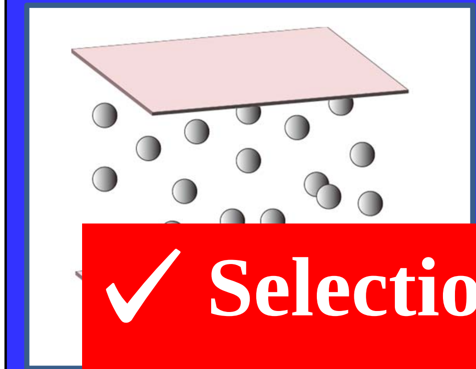
A. Llordes et al., Nature Mat. 11, 329 (2012)

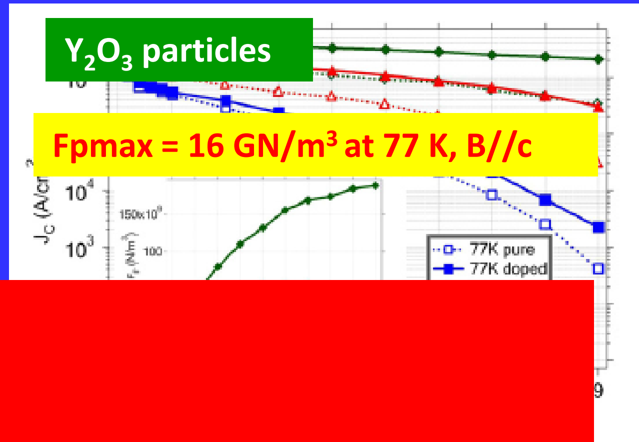


M. Miura et al., SUST 26, 035008 (2013)

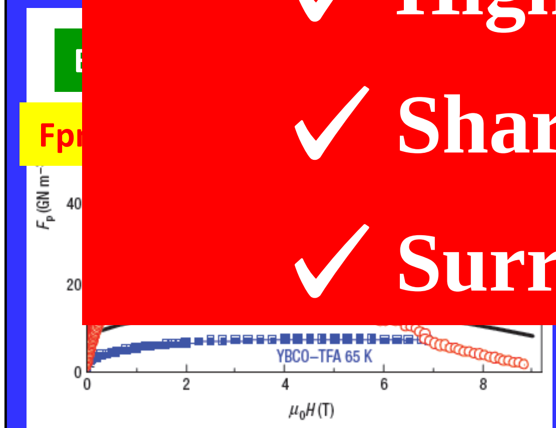
Artificial pinning centers －Nanoparticles

Nanoparticles

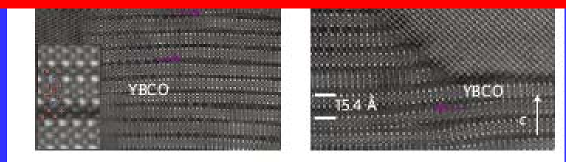




- ✓ **Selection of material and**
  - ✓ **Appropriate diameter of nanoparticles**
  - ✓ **High density without Tc suppression**
  - ✓ **Sharp interface**
  - ✓ **Surrounding additional defects**



J. Gutierrez et al., Nature Mat. 6, 367 (2007)



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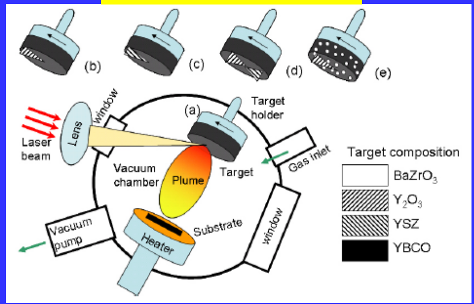
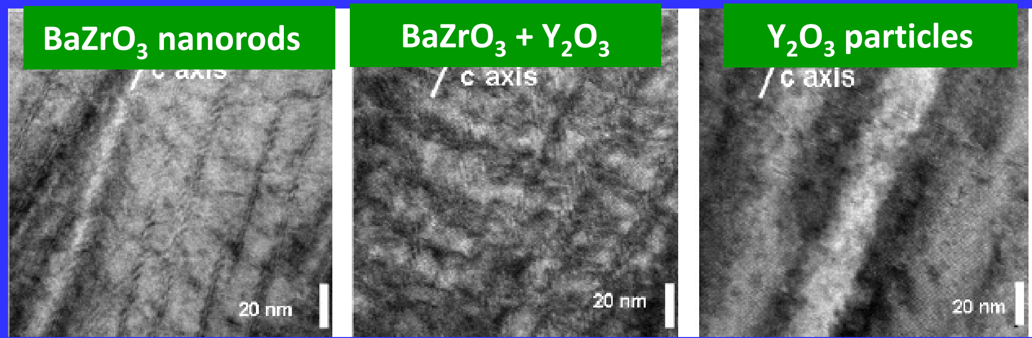
M. Miura et al., SUST 26, 035008 (2013)

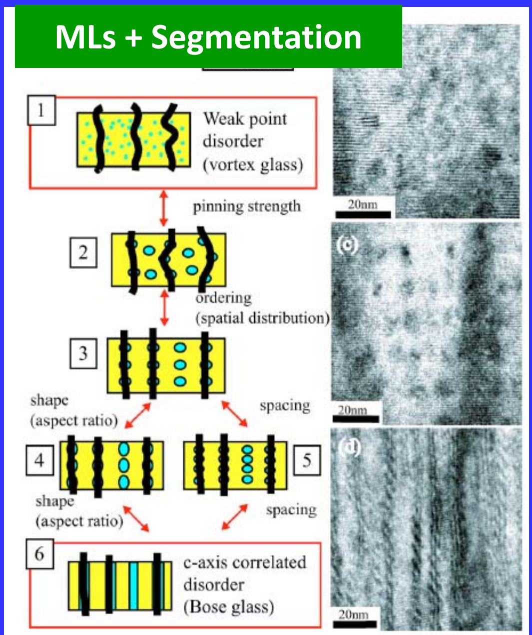
Advanced APC structures-Hybrid, MLs, segmentation

Hybrid APCs

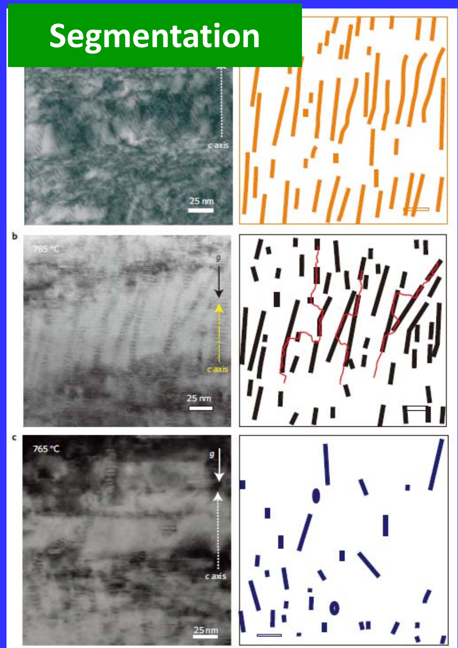




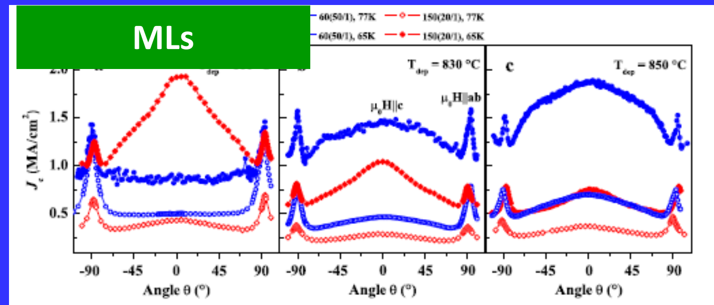
P. Mele et al., SUST 21, 015019 (2008)



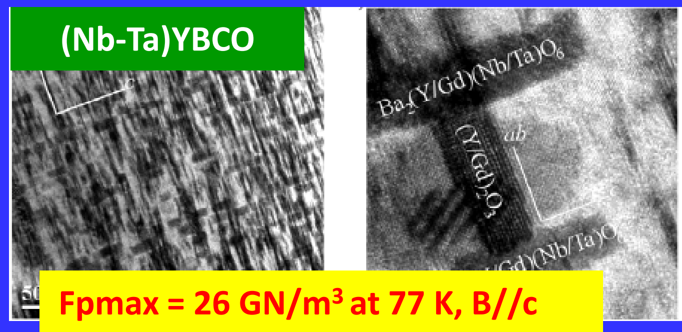
T. Horide et al., APL 92, 182511 (2008)



B. Maiorov et al., Nature Mat. 8, 398 (2009)



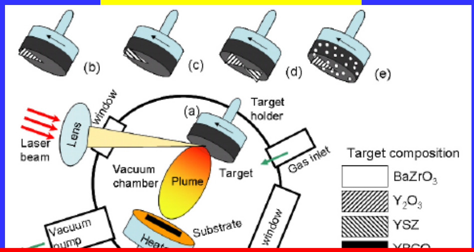
A. Kiessling et al., SUST 24, 055018 (2011)

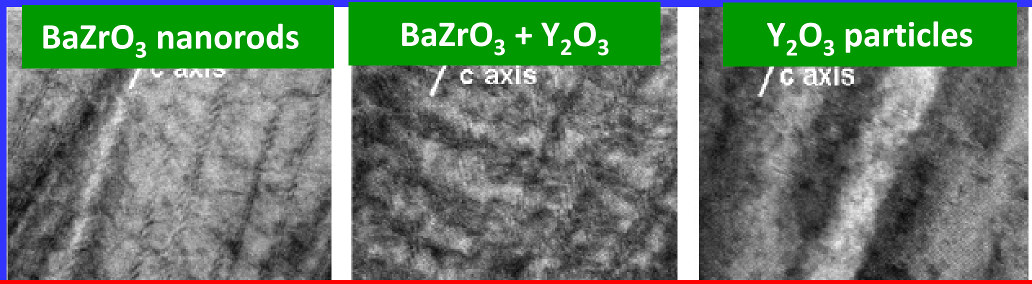


G. Ercolano et al., SUST 24, 095012 (2011)

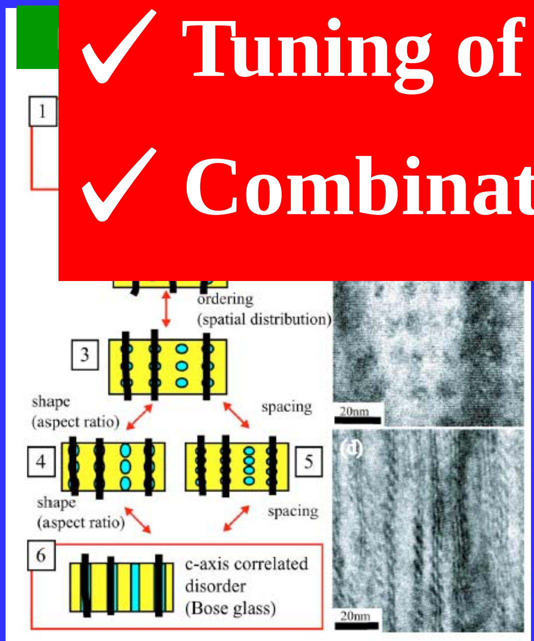
Advanced APC structures-Hybrid, MLs, segmentation

Hybrid APCs





- ✓ Structural design
- ✓ Tuning of crystal growth
- ✓ Combination of pinning centers



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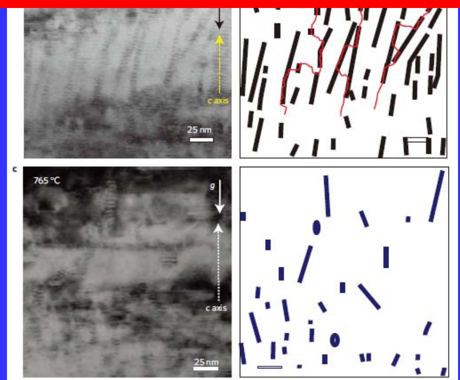

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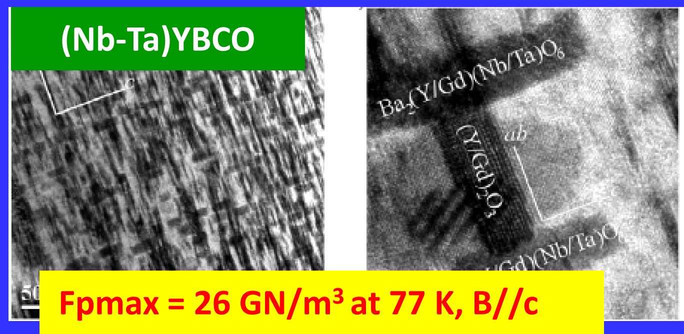

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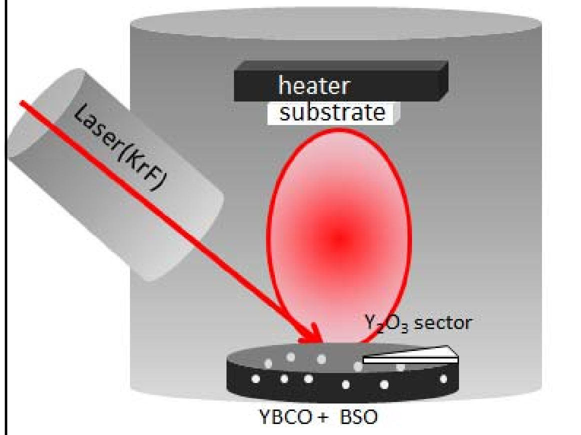
Understanding and Control of J_c angular dependence

✓ J_c measurement in the films with APCs

✓ 3D Time Dependent Ginzburg-Landau Equations

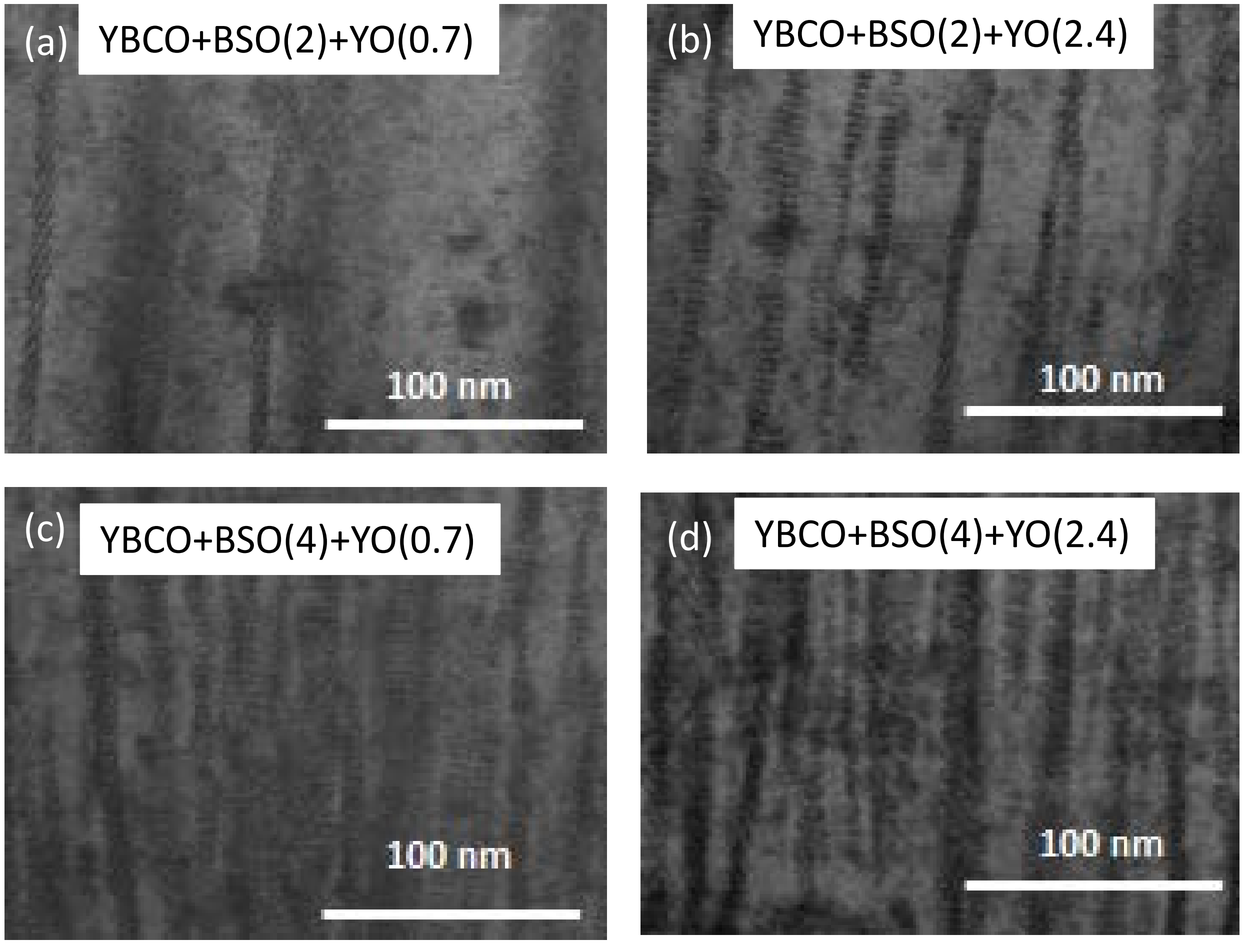
✓ Theoretical modeling of J_c-θ characteristics

Incorporation of hybrid APCs



YBCO+BSO Mixed target
with Y_2O_3 sector

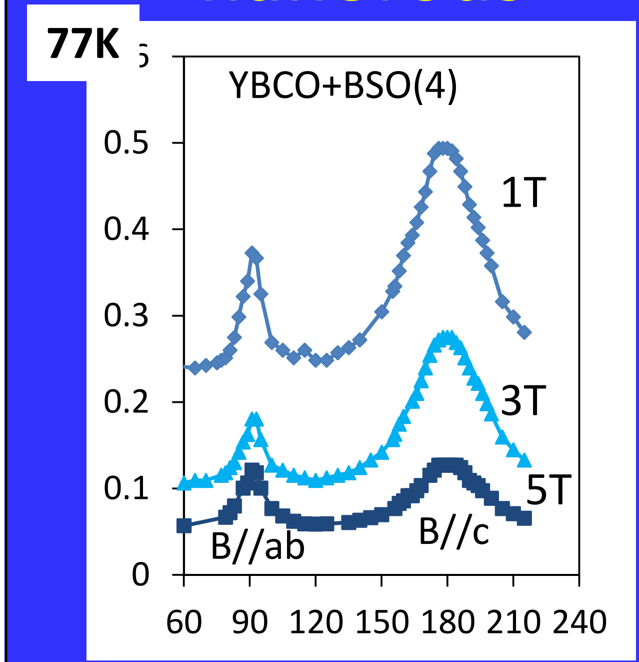
BSO: 2wt%, 4wt%
Y_2O_3: 0.7areal%, 2.4 areal%



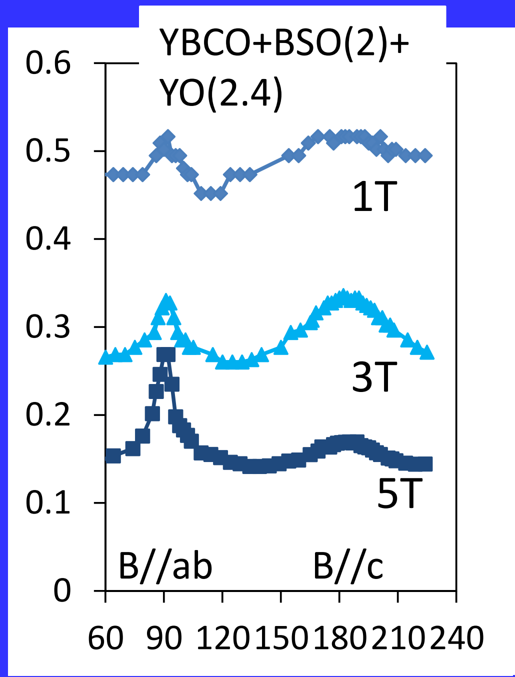
BSO nanorods and Y_2O_3 nanoparticles were successfully incorporated in YBCO films

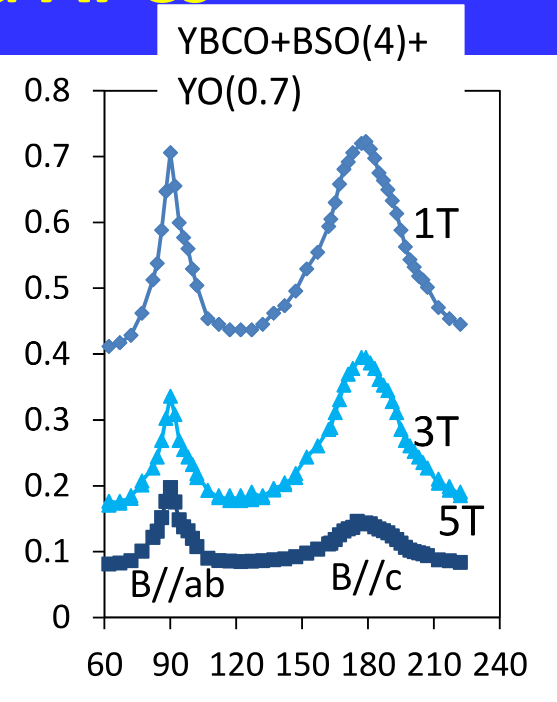
Jcθ characteristics

Conventional nanorods



Hybrid APCs





・In YBCO+BSO(4), c-axis peaks were observed regardless of magnetic field, but the peak became small in high magnetic field.

・In hybrid APCs, Jc near θ=135° was improved by Y_2O_3 nanoparticles, and isotropic Jc was obtained at 1 T in YBCO+BSO(2)+Y_2O_3(2.4).

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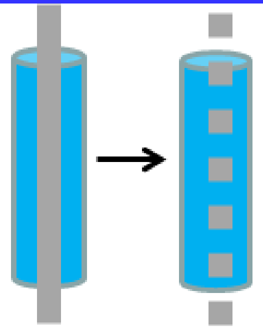
Jcθ modelling in YBCO films

B//c

YBCO+BSO

BSO nanorod



$$f_{p,nanorod} = \pi\xi_{ab}^2 \times L \times \frac{B_c^2}{2\mu_0} \times \frac{1}{\xi_{ab}}$$

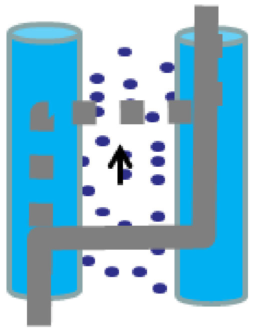
$$J_c = \frac{f_{p,nanorod}}{\phi_0 L}$$

J_c = 22 MA/cm^2

Tilted field

YBCO+BSO

Oxygen vacancy



$$f_{p,vacancy} = \frac{\pi D^2}{4} \times \xi_{ab0} \times \frac{B_c^2}{2\mu_0} \times \frac{1}{\xi_{ab}}$$

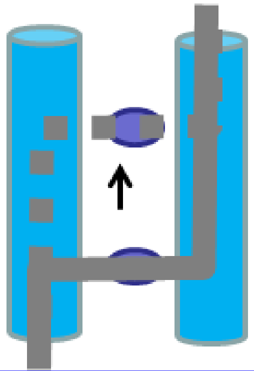
$$F_{p,vacancy} = f_{p,vacancy}\sqrt{n \times \xi_{ab}^2\, d}$$

$$J_c = \frac{F_{p,vacancy}}{\phi_0 d}$$

J_c = 0.0047 MA/cm^2

YBCO+BSO +Y_2O_3

Y_2O_3 nanoparticle



$$f_{p,nanoparticle} = \pi\xi_{ab}\xi_c \times 2r \times \frac{B_c^2}{2\mu_0} \times \frac{1}{r}$$

$$J_c = \frac{f_{p,nanoparticle}}{\phi_0 d}$$

J_c =0.90 MA/cm^2

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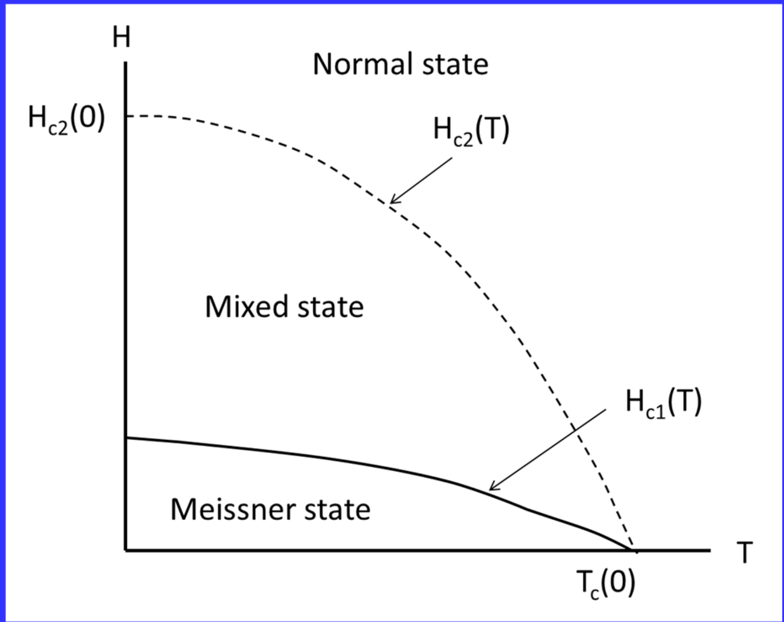
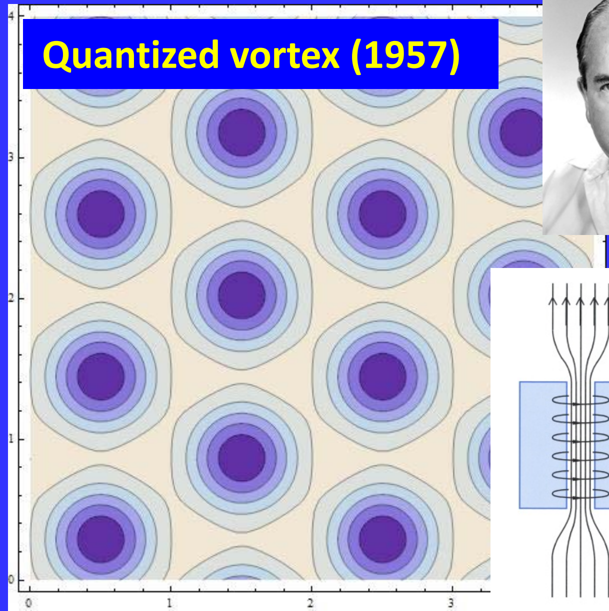
Jc analysis assuming staircase vortices

Mechanism	Calculated J_c		Experimental data J_c
YBCO+BSO, B//c BSO Nanorod	22 MA/cm^2	>>	1-3 MA/cm^2 (YBCO+BSO)
YBCO+BSO, tilted field Oxygen Vacancy	0.0047 MA/cm^2	<<	0.28 MA/cm^2 (pure YBCO)
YBCO+BSO+Y_2O_3, tilted field nanoparticle	0.90 MA/cm^2	~	0.46 MA/cm^2 (YBCO+Y_2O_3)

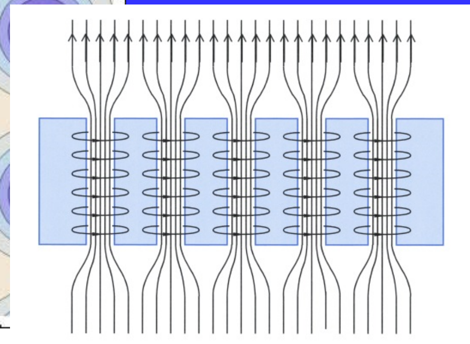
- **In YBCO+BSO, Vortices moves by forming double kink or half loop.**
- **When dominant pinning center is oxygen vacancies in YBCO+BSO for tilted magnetic field, not only vortex pinning, but also magnetic interaction and line tension determine J_c-θ.**
- **In YBCO+BSO+Y_2O_3 films, Y_2O_3 nanoparticles determine J_c-θ when magnetic field is tilted from the c-axis.**
- **These indicate staircase vortex configuration.**

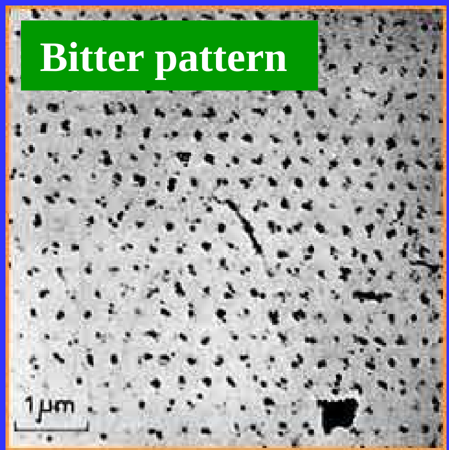
Type II superconductor – Abrikosov lattice

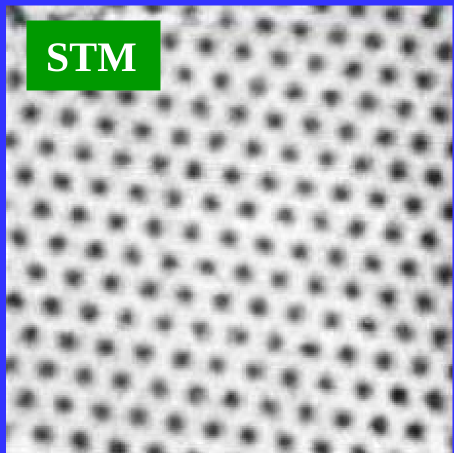


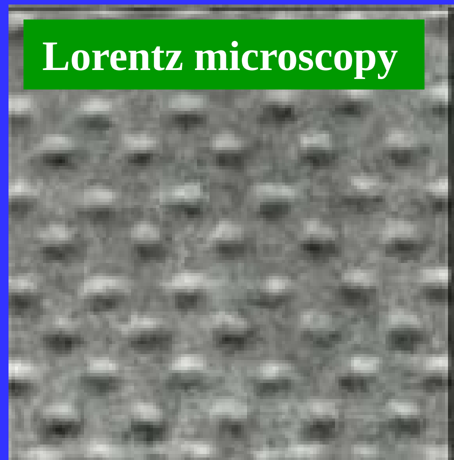


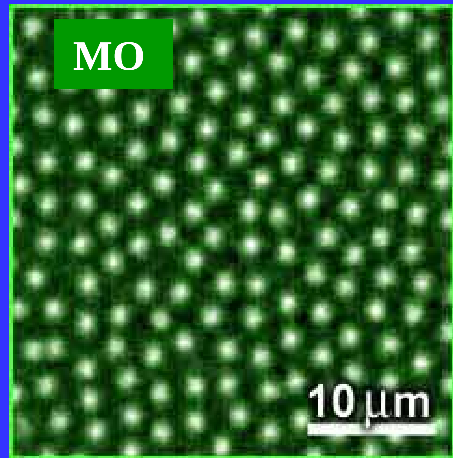
Abrikosov











U. Essmann et al., Physics Letters 24A, 526 (1967)

H. F. Hess et al., Phys. Rev. Lett. 62, 214 (1989)

K. Harada et al., Science 274, 1167 (1996)

P.E. Goa et al., Supercond. Sci. Technol. 14, 729 (2001)

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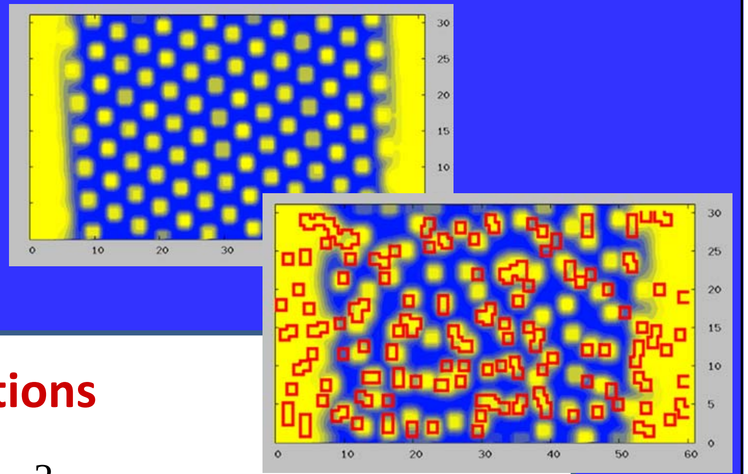
Time Dependent Ginzburg–Landau Equations

✓ **Langevin equation**

$$\frac{\partial}{\partial t}\psi(\mathbf{r},t) = -L\frac{\delta F}{\delta \psi} + \theta(\mathbf{r},t)$$



✓ **Time dependent Ginzburg- Landau equations**

$$\frac{\hbar^2}{2m_s}\left(\frac{\partial}{\partial t} + i\frac{e_s}{\hbar}\Phi\right)\psi = \frac{\hbar^2}{2m_s}\left(\nabla - i\frac{e_s}{\hbar}\right)^2\psi + \alpha|\psi| - \beta|\psi|^2\psi$$

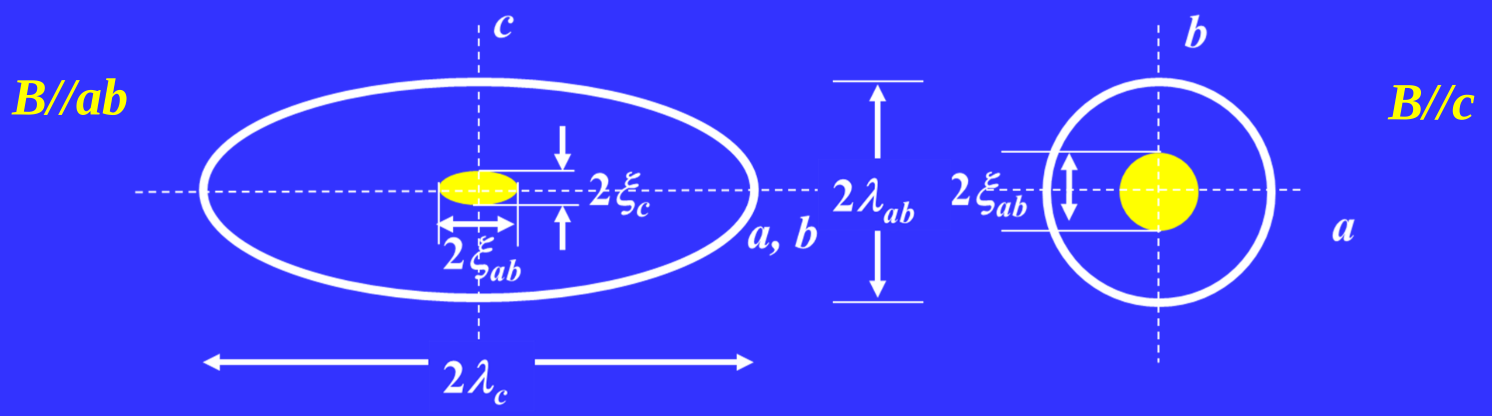
$$\frac{1}{\mu_0}\nabla\times(\nabla\times A - \mu_0 H) = j_s + j_n$$

$$j_s = \frac{\hbar e_s}{2m_s D}(\psi^*\nabla\psi - \psi\nabla\psi^*) - \frac{e_s{}^2}{m_s}|\psi|^2 A$$

$$j_n = \sigma\left(-\nabla\Phi - \frac{\partial A}{\partial t}\right)$$

R. Kato et al., PRB (1993)
M. Machida et al., PRL (1993)
Q. Du et al., PRB (1995)
G. Crabtree et al., PRB (2000)
T. Winiecki et al., PRB (2002)

Vortex anisotropies and 3D TDGL simulation



✓ Line tension energy

$$\tilde{\varepsilon}_1 \approx \frac{1}{\gamma^2}\varepsilon_1 = \frac{\Phi_0^{\,2}}{4\pi\mu_0\lambda_c^{\,2}}\ln\kappa \quad \textit{for anisotropic} \qquad \varepsilon_1 \approx \frac{\Phi_0^{\,2}}{4\pi\mu_0\lambda_{ab}^{\,2}}\ln\kappa \quad \textit{for isotropic}$$

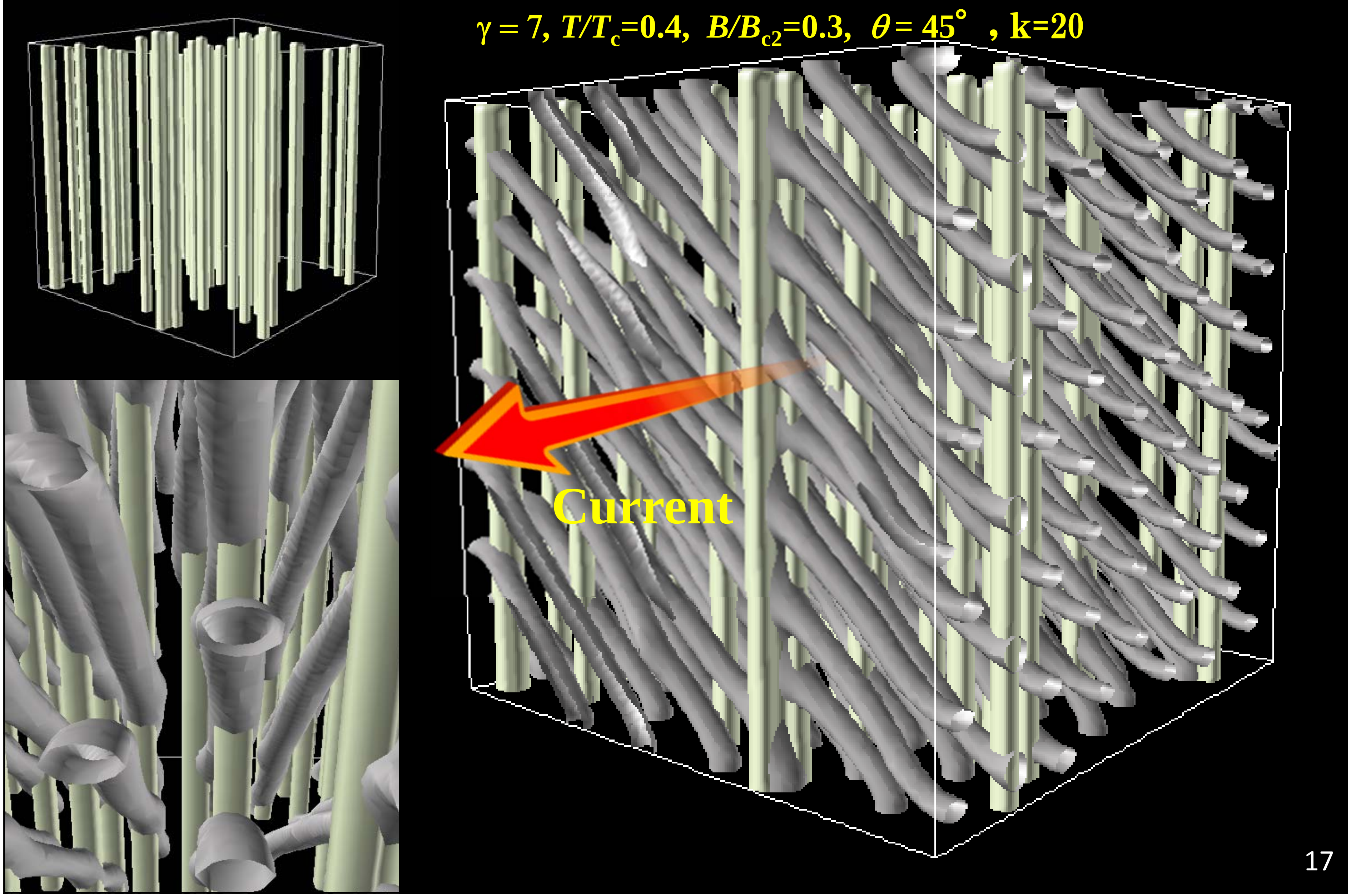
$$\left(\frac{m_c}{m_{ab}}\right)^{1/2} = \frac{\xi_{ab}}{\xi_c} = \frac{\lambda_c}{\lambda_{ab}} = \gamma \approx 5-7 \quad \textit{for YBCO} \qquad \tilde{\varepsilon}_1 << \varepsilon_1$$

✓ GL equation for the anisotropic case

$$\frac{\delta F}{\delta\psi} = \alpha\psi + \beta|\psi|^2\psi - \frac{\hbar^2}{2}\left(\nabla - i\frac{e_s}{\hbar}\mathbf{A}\right)\cdot m^{-1}\cdot\left(\nabla - i\frac{e_s}{\hbar}\mathbf{A}\right)\psi \qquad \frac{1}{m_{ab}},\ \frac{1}{m_{ab}},\ \frac{1}{m_c}$$

IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) January 2015.
Invited Presentation WT-19-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

Flux pinning by *c*–axis correlated columnar defects

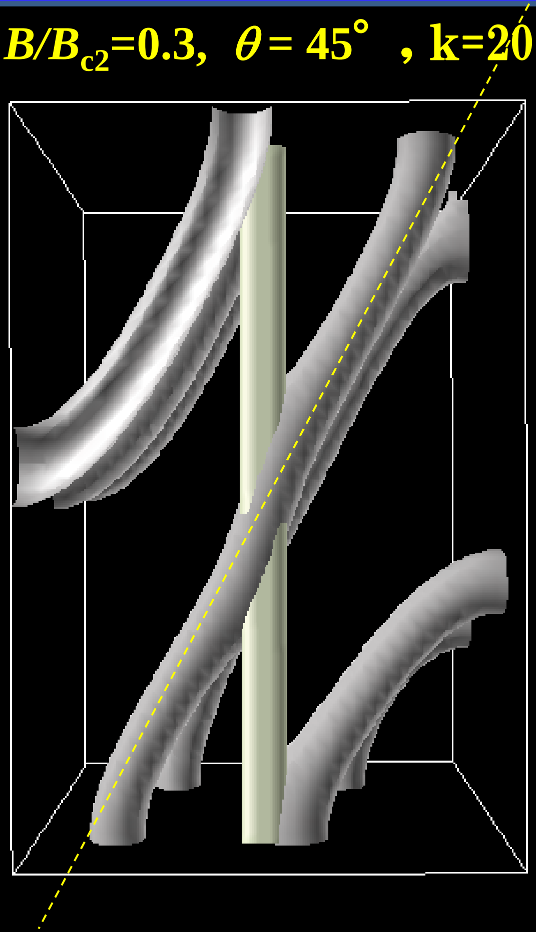


IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) January 2015.
Invited Presentation WT-19-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

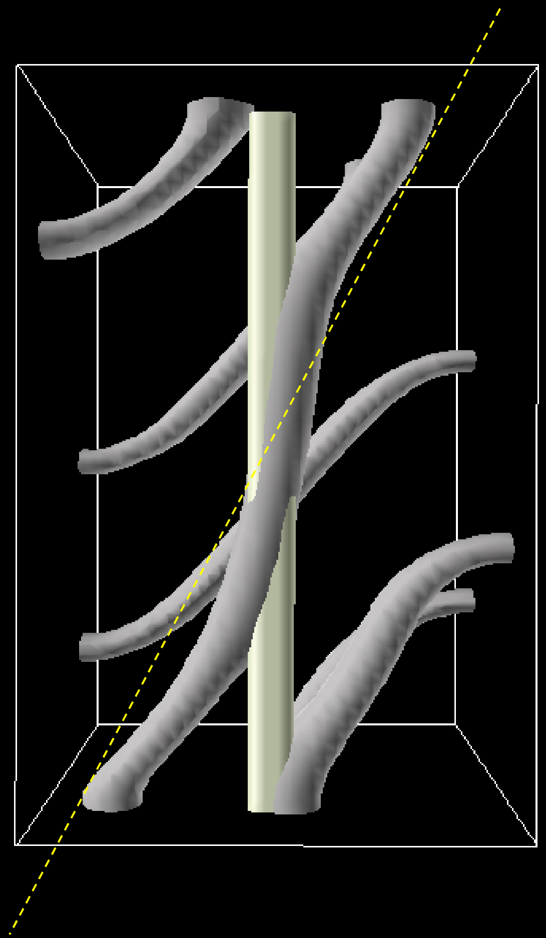
Vortex staircase in anisotropic superconductors

T/T_c=0.4, B/B_{c2}=0.3, θ= 45°, k=20

$\gamma = 1$



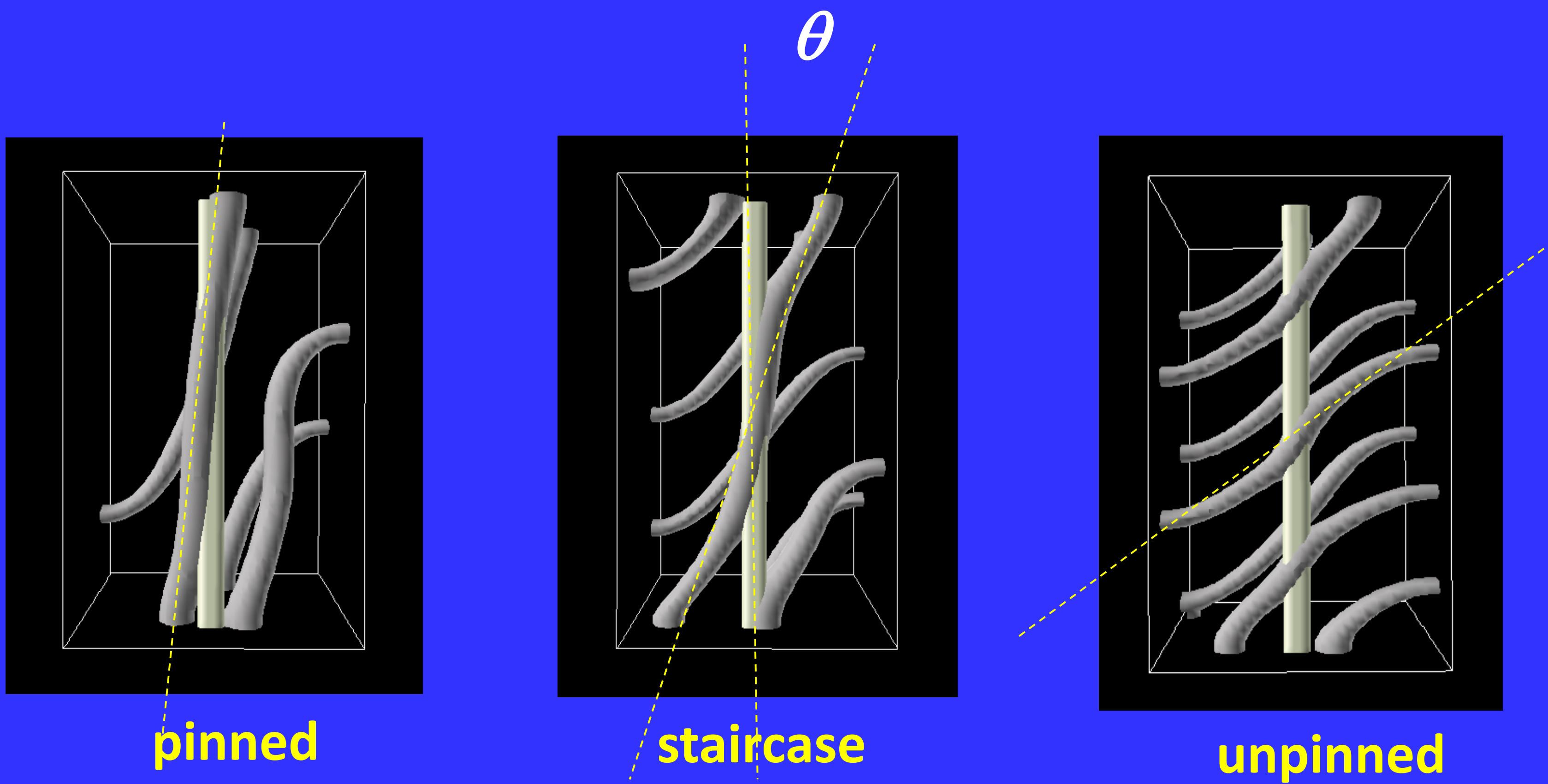
$\gamma = 7$



$$\varepsilon_1 \approx \frac{\Phi_0^{\ 2}}{4\pi\mu_0\lambda_{ab}^{\ 2}} \ln\kappa$$

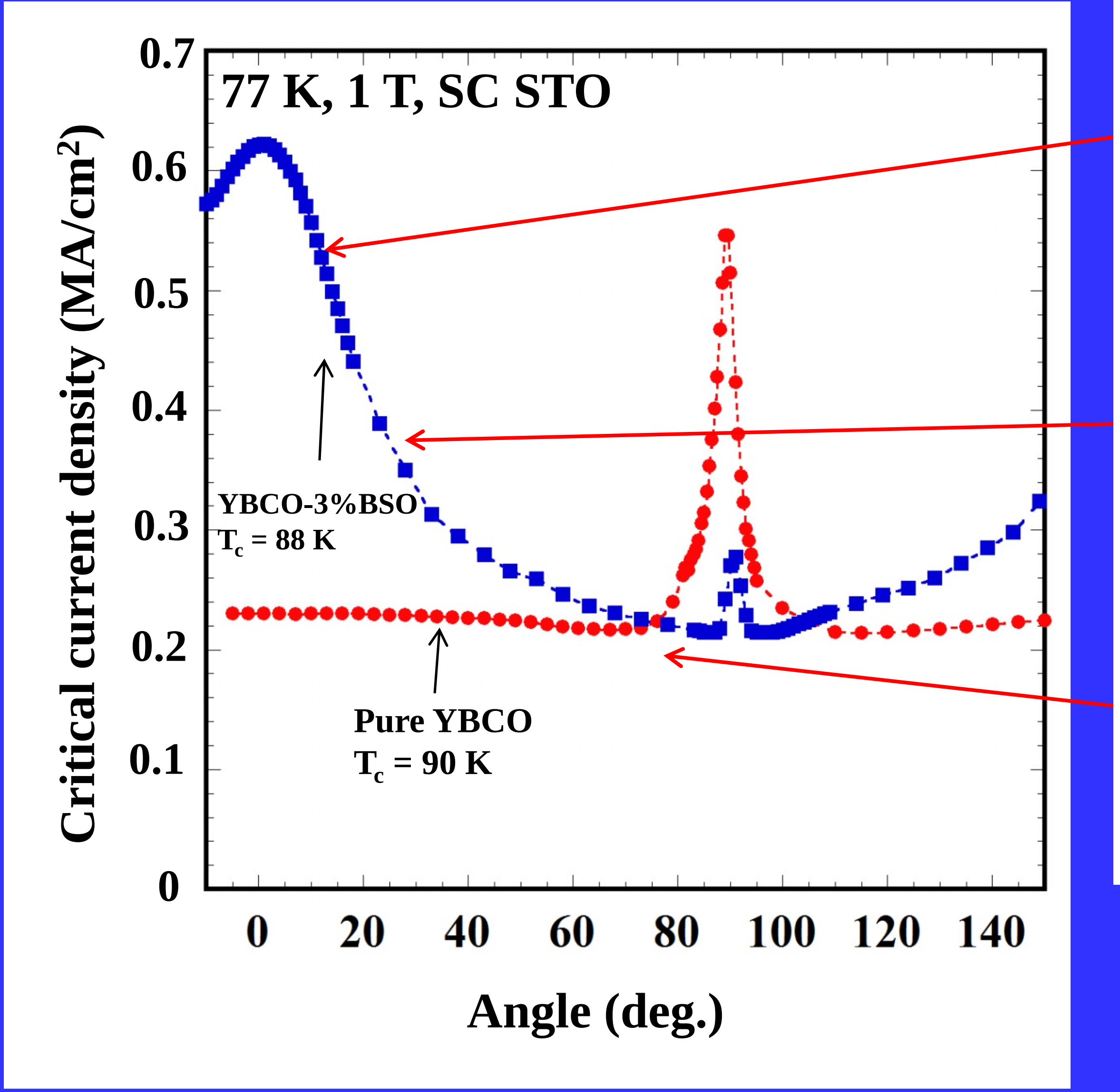
$$\tilde{\varepsilon}_1 \approx \frac{1}{\gamma^2}\varepsilon_1$$

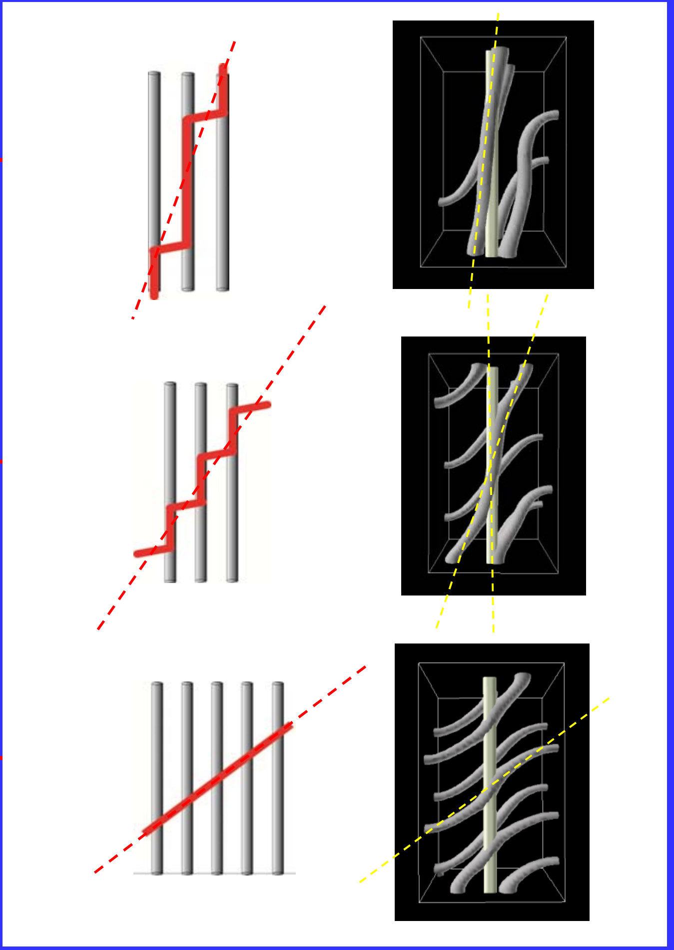
Anisotropic J_c behaviors due to staircase vortices



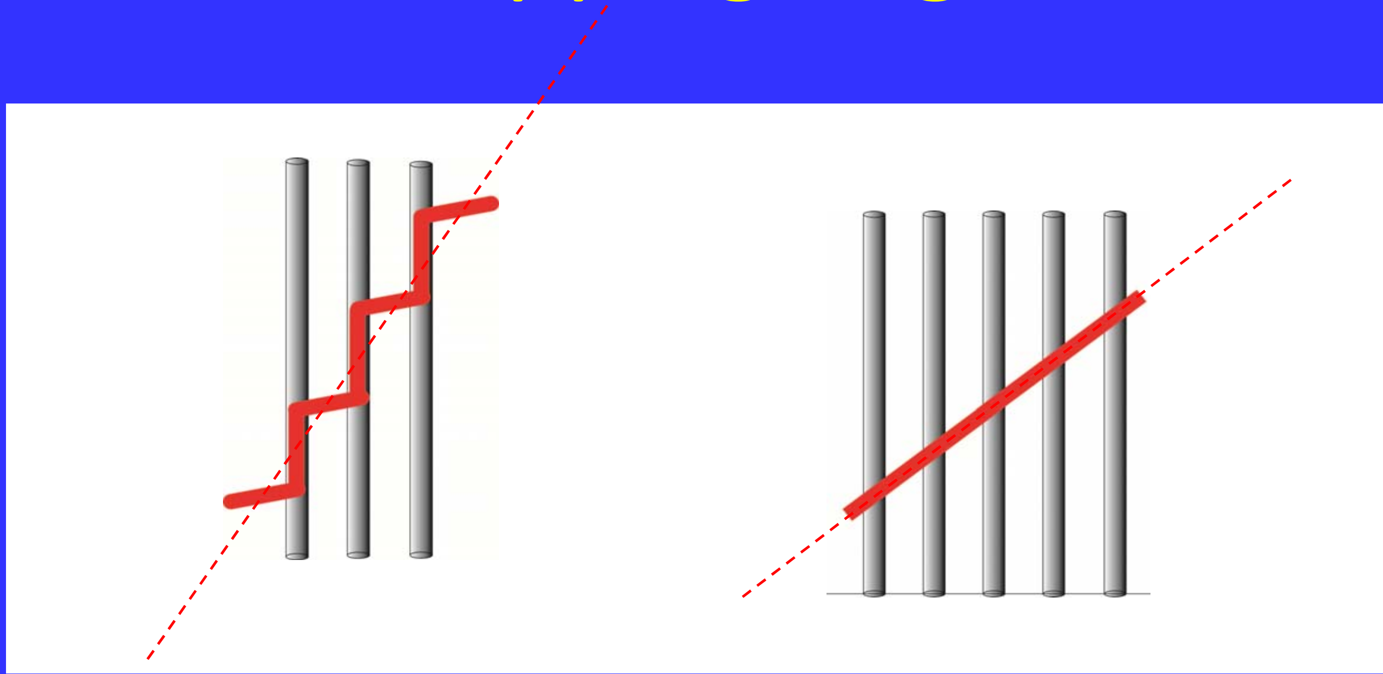
Angular dependence of vortex configuration (pinned, staircase, unpinned) strongly affects J_c-θ characteristics.

Angular dependent $J_c(\theta)$ in YBCO with nanorods





Trapping angle



- Trapping angle =$(2U/\varepsilon_l)^{1/2}$
- For tilted magnetic field, nanoparticle incorporation in addition to nanorods is very effective.
- When field angle is larger than trapping angle, nanorods do not work as pinning centers.

Summary

✓ Recent progress in flux pinning APCs was discussed.

✓ $J_c\theta$ characteristics were measured in YBCO films with hybrid APCs of BSO nanorods and Y_2O_3 nanoparticles.

✓ 3D TDGL equation clarified vortex configuration in tilted magnetic field.

✓ Vortex configuration was discussed by considering vortex energy of magnetic interaction, pinning potential, and line tension.