CCA 2014
International Workshop on Coated Conductors for Applications 2014

November 30(Sun)~December 3(Wed), Jeju, Korea

Effect of artificial pinning centers dimensionality on in-field performance of $YBa_2Cu_3O_x$ thin films

Image from http://www.neilyoung.com/

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A. K. Jha, T. Horide, K. Matsumoto – KIT Kitakyushu, Japan

S. Awaji – Tohoku University, Japan

Y. Yoshida – Nagoya University, Japan

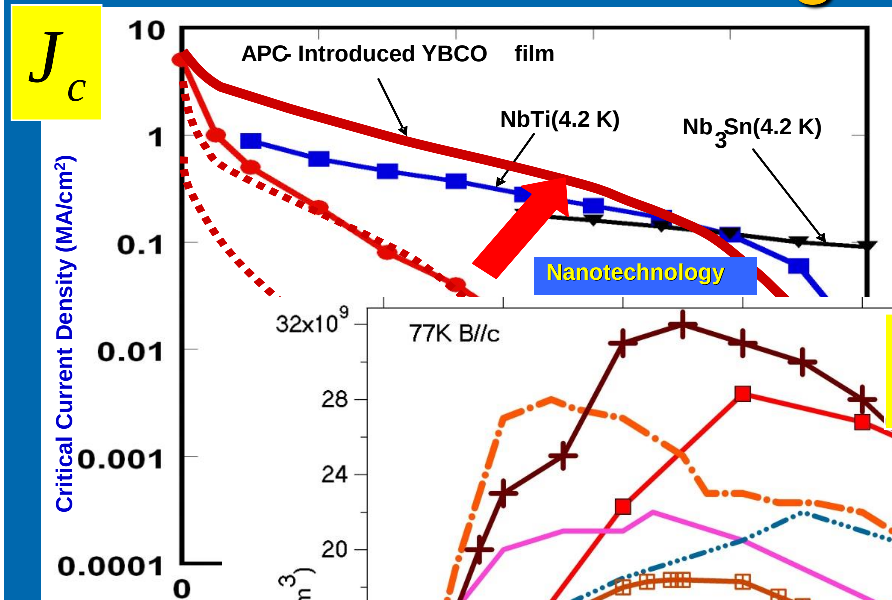
A. Ichinose – CRIEPI Yokosuka, Japan

R. Kita - Shizuoka University, Japan

J. Gazquez, R. Guzman, T. Puig, X. Obradors – ICMAB-CSIC, Barcelona, Spain

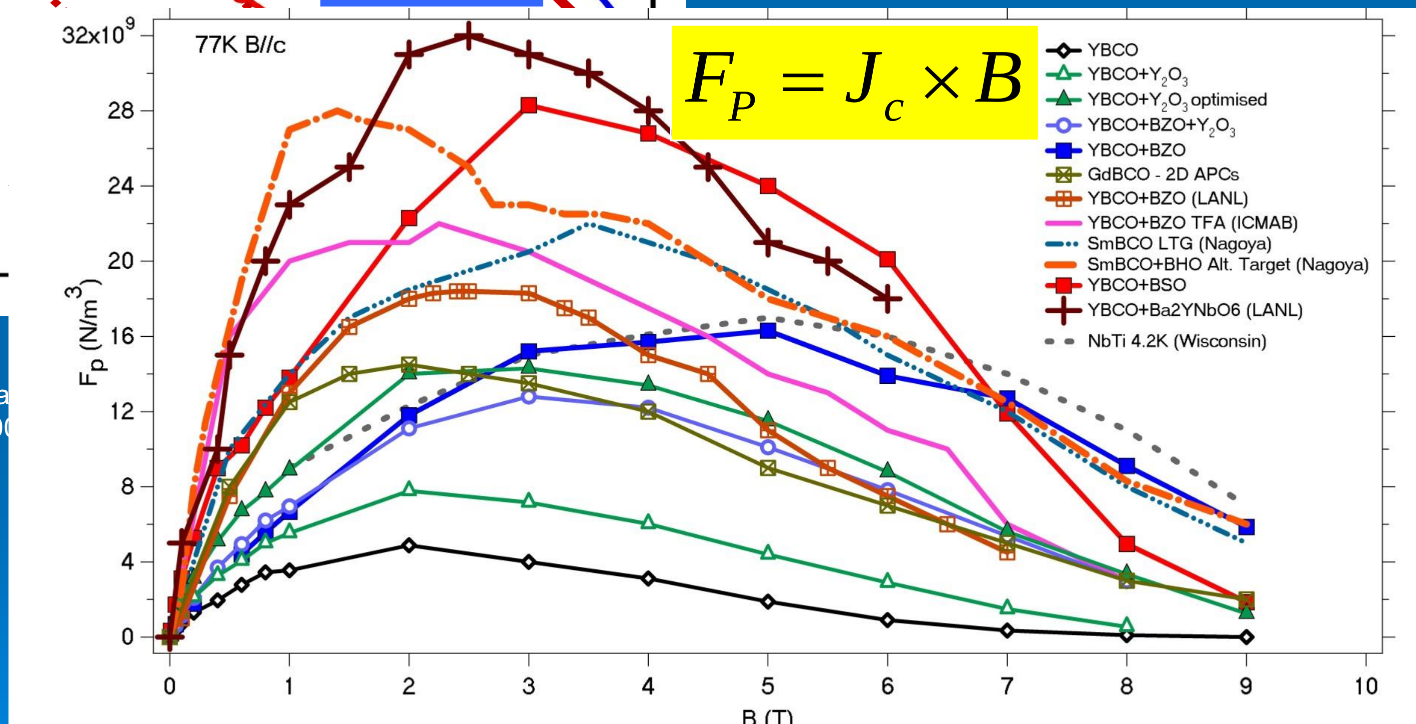
M. I. Adam, UniTeN, Selangor, Malaysia

Background



Extensive research on nanoengineered YBCO and REBCO thin films added with nanoscale Artificial Pinning Centers (APCs) by several techniques (PLD, MOD, MOCVD…)

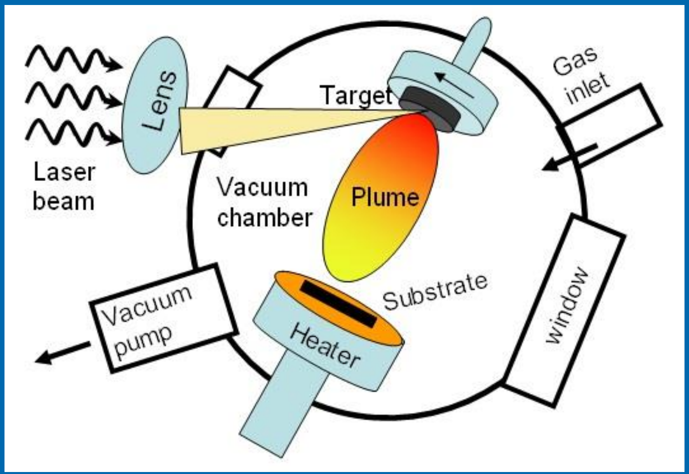
K. Matsumoto a
23 (2010) 01400



X. Obradors, T. Puig, A. Palau, A. Pomar, F. Sandiumenge, P. Mele and K. Matsumoto – "Nanostructured Superconductors with Efficient Vortex Pinning" in "Comprehensive nanoscience and nanotechnology, AP, Vol. 3 (2011) 303-349 [added with YBCO+Ba2YNbO6 and SmBCO+BHO]

Incorporation of APCs into YBCO films by PLD

Pulsed Laser Deposition (PLD)



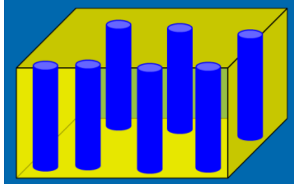
Experimental parameters

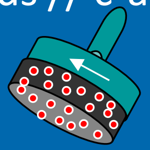
λ = 248 nm
E = 340mJ/pulse
T = 800-830 °C,
P_{O2} = 200mTorr
ν = 5-10 Hz; pulses = 6000-10000
substrate: $SrTiO_3$

Dimensionality of APCs

1D Nanorods // c-axis

c axis



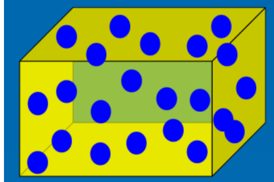


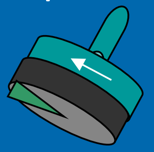
2, 4, 6, 8 wt
wt% $BaSnO_3$

YBCO+ $BaSnO_3$ mixed target→ $BaSnO_3$ nanorods

Large J_c (F_P) but anisotropic

3D Randomly dispersed





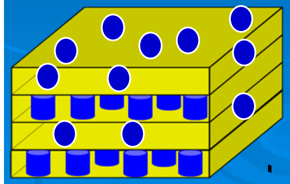
2.51, 5.44,
9.22 A% Y_2O_3

YBCO+Y_2O_3 modified surface → Y_2O_3 nanoparticles

Isotropic J_c (F_P) but smaller

1D+3D multilayer

Combinations of 4wt% $BaSnO_3$ and 2.5A% Y_2O_3



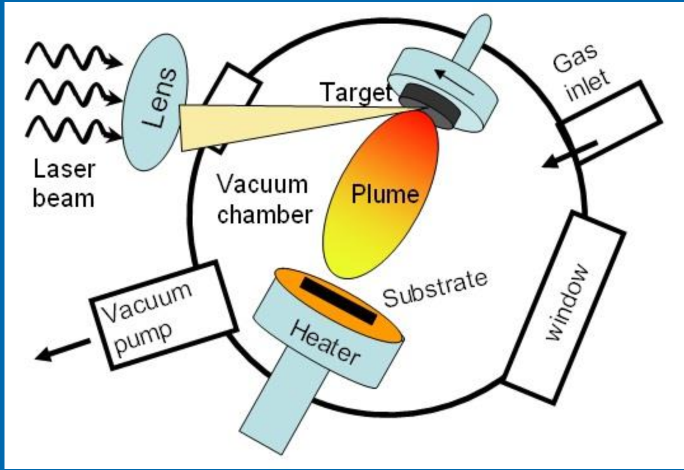
$BaSnO_3$ nanorods

Y_2O_3 nanoparticles

Isotropic and large J_c (F_P)????

1D APCs into YBCO films by PLD

Pulsed Laser Deposition (PLD)



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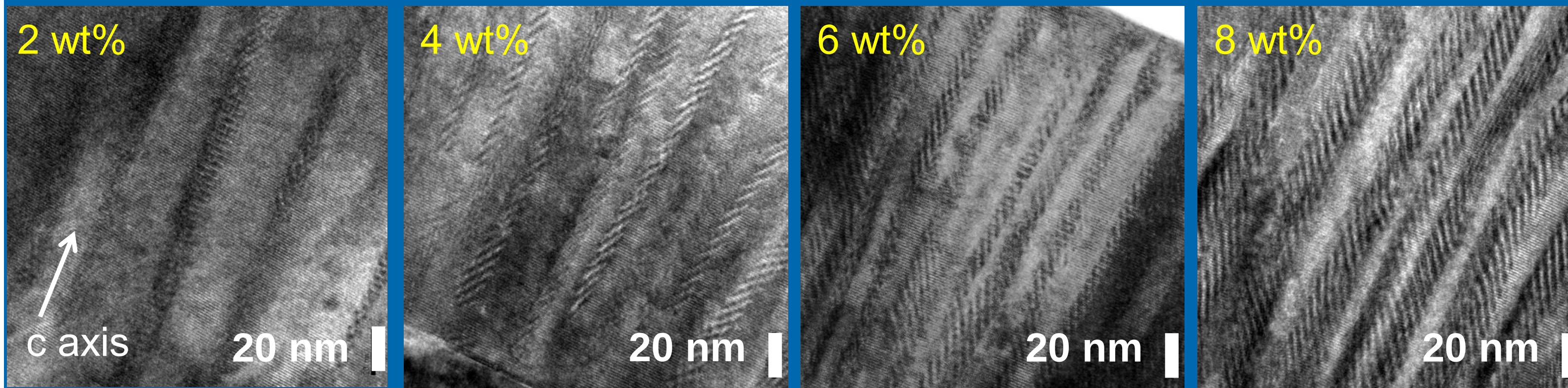
1D Nanorods // c-axis

YBCO+ $BaSnO_3$ mixed target→
$BaSnO_3$ nanorods

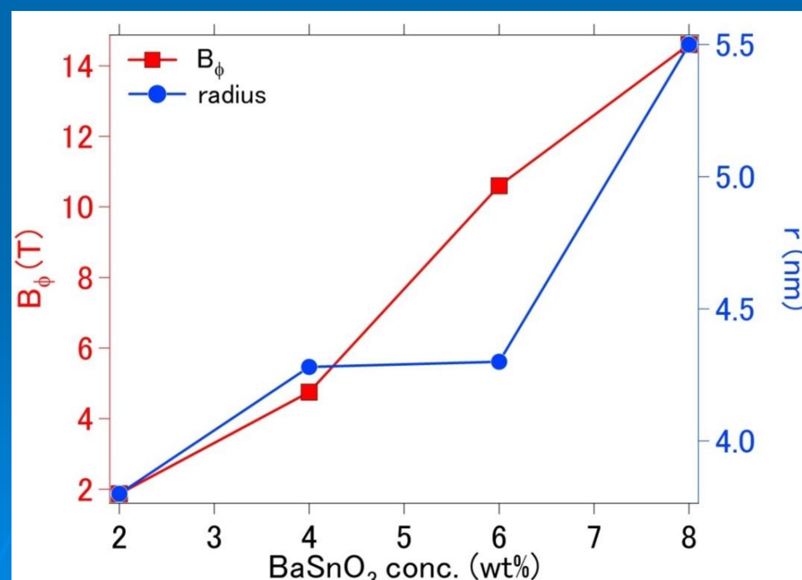
Large J_c (F_P) but anisotropic

Morphology of the $BaSnO_3$ nanorods inside YBCO films



d = 30 nm　d = 21 nm　d = 14 nm　d = 12 nm

d: average spacing



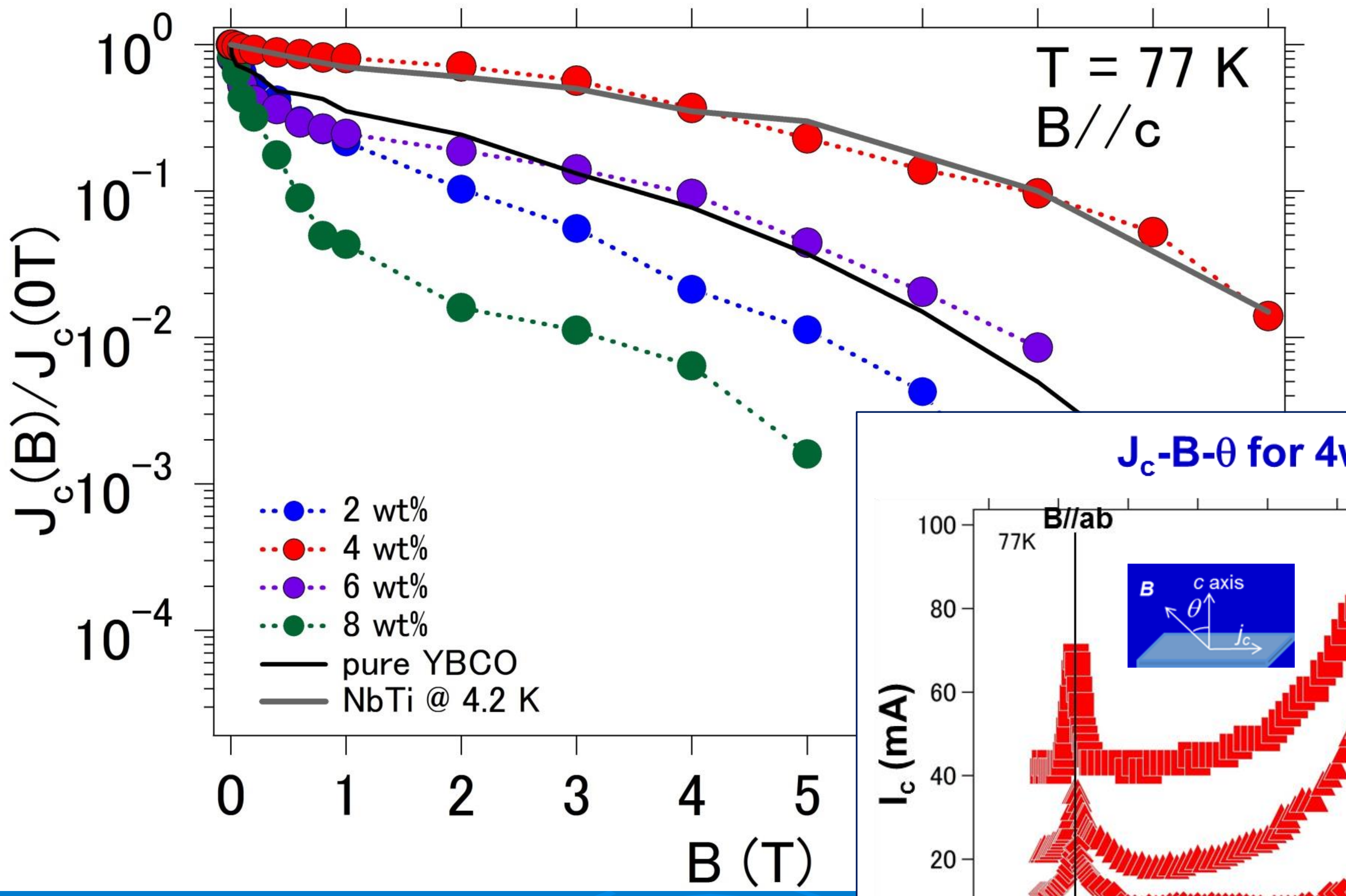
$B\phi = n\,\Phi_0$

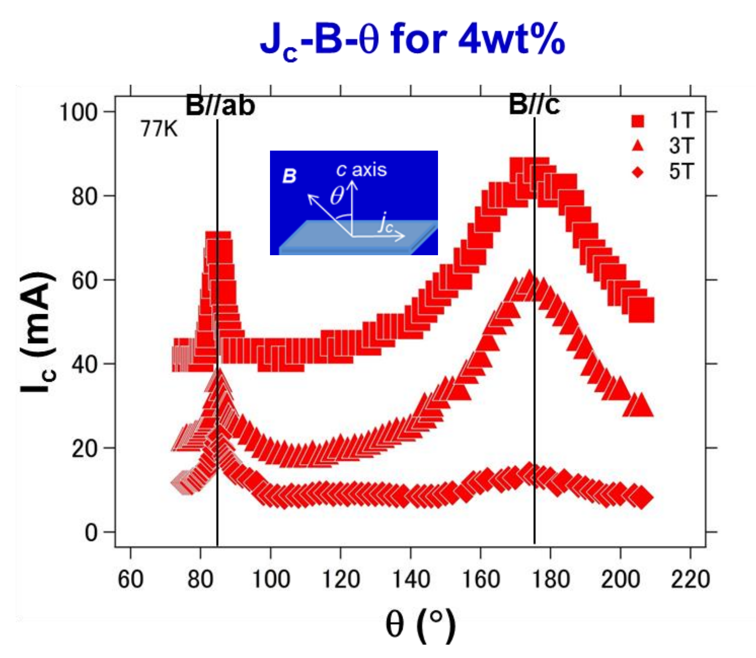
n = rods/m^2

$\Phi_0 = 2.068\times10^{-15}$ Wb

P. Mele et al, Supercond. Sci. Technol. 21 (2008) 125017

Critical current of $BaSnO_3$-added YBCO at 77 K





Modified from P. Mele et al, Supercond. Sci. Technol. 21 (2008) 125017

Pinning by $BaSnO_3$ nanorods

$$J_c = \frac{U_o}{\Phi_0 \xi_{ab}}$$

where

Vortex pinning energy per unit length

$$U_0 = \frac{1}{2}\varepsilon_0 \ln\left(1+\left(\frac{C_0}{\sqrt{2}\xi_{ab}}\right)^2\right)$$

$\varepsilon_0 = (\Phi_0/4\pi\lambda_{ab})^2$, $\Phi_0 = 2.068\times10^{-15}$ Wb

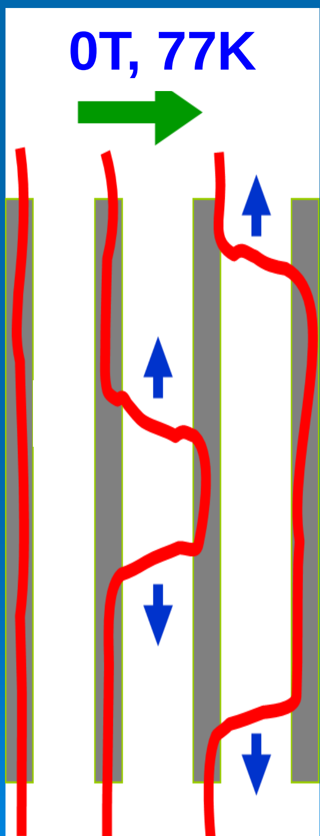
$\lambda_{ab} = \lambda_0(1-t^4)^{-0.5}$, $\xi_{ab} = \xi_0(1-t)^{-0.5}$, $t = T/T_c$

$\lambda_{0\ YBCO}$ = 150 nm, $\xi_{0\ YBCO}$ = 1.5 nm

[D. Larbalestier et al., Nature 414 (2001) 368]

D. R. Nelson and V. M. Vinokur PRB 48 (1993) 13060

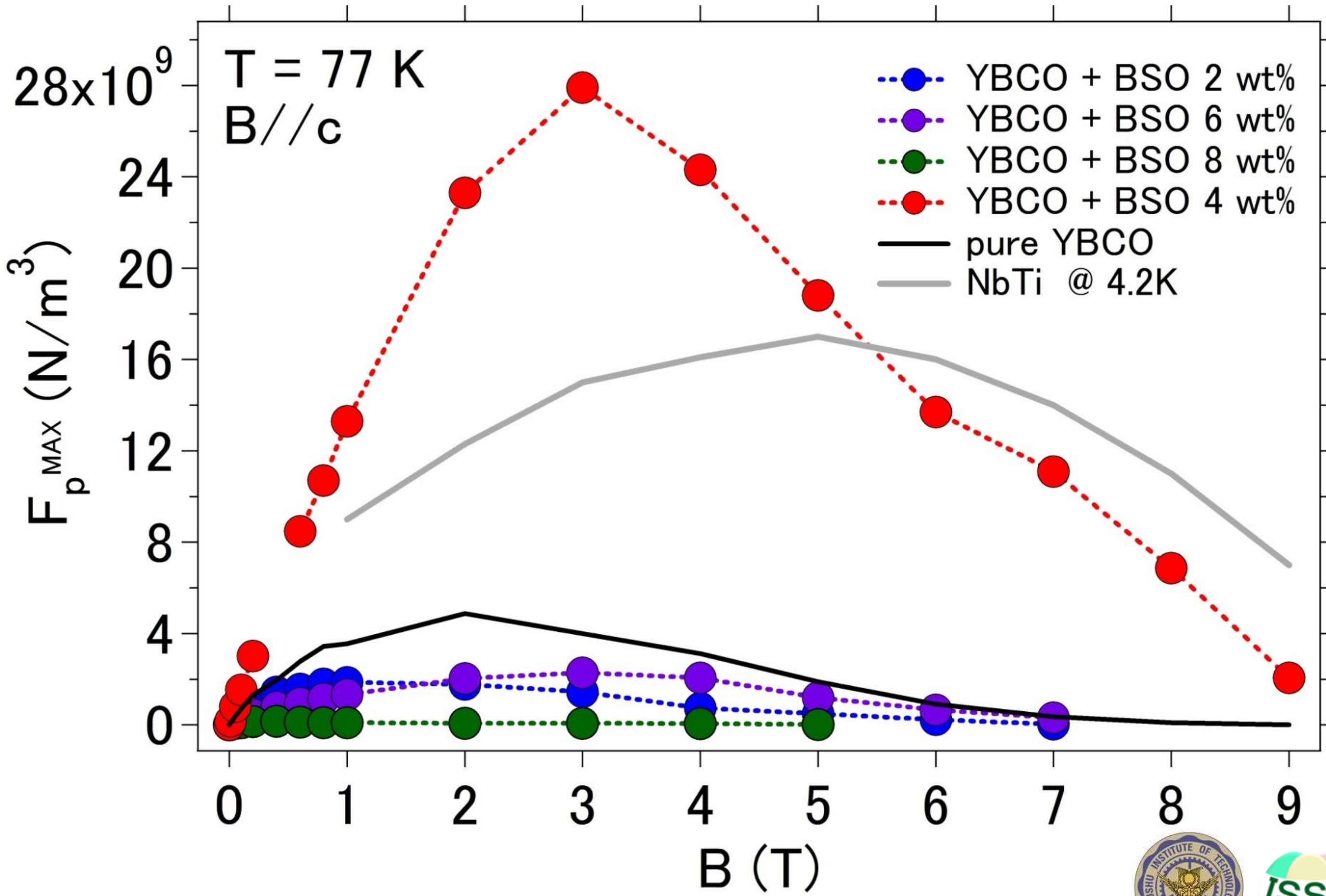
Solution of GL equations in the case of columnar pins, when $C_0 \sim \xi_{ab}$



$BaSnO_3$ content	2wt%	4wt%	6wt%	8wt%
Amount of APCs (m^{-2})	9.07×10^{14}	2.30×10^{15}	5.10×10^{15}	6.80×10^{15}
d (nm)	30	21	14	12
T_c (K)	88.68	88.57	86.46	83.08
C_0 (nm)	3.8	4.28	4.3	5.5
U_0 (N)	1.01×10^{-12}	1.4×10^{-12}	0.84×10^{-12}	0.59×10^{-12}
Calculated J_c (0T, 77K) (MA/cm^2) 1D	12	16.3	9	5
Measured J_c (0T, 77K) (MA/cm^2) 1D	0.89	1.64	0.54	0.23
J_c calc/J_c meas	13.5	9.94	16.7	22
Eff. current blocking	16%	37%	50%	71%

Reducing the separation between 1D APCs does not increase J_c due to current blocking by the pinning defect structure. 4wt% is best compromise between amount of pins and current obstruction

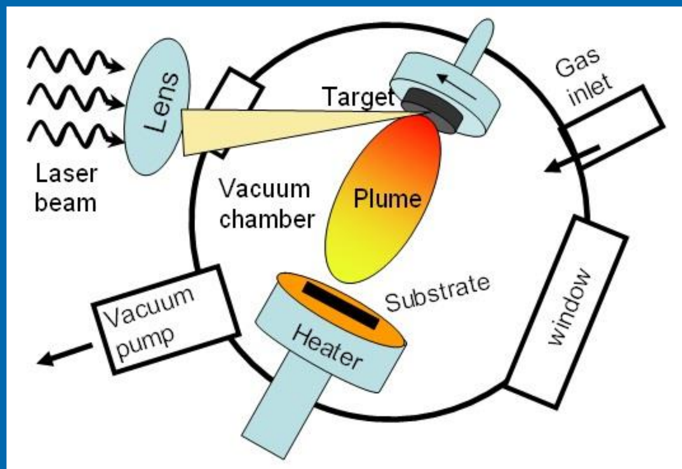
Influence of the $BaSnO_3$ nanorods on global pinning force



Modified figure from P. Mele et al, Supercond. Sci. Technol. 21 (2008) 125017

Incorporation of APCs into YBCO films by PLD

Pulsed Laser Deposition (PLD)



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Dimensionality of APCs

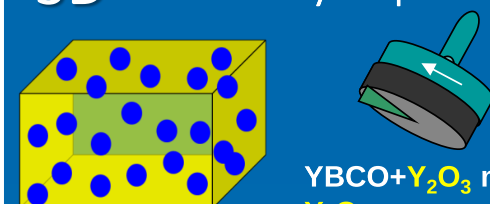
1D Nanorods // c-axis

2, 4, 6, 8 wt wt% $BaSnO_3$

YBCO+ $BaSnO_3$ mixed target→ $BaSnO_3$ nanorods

Large J_c (F_P) but anisotropic

3D Randomly dispersed



2.51, 5.44, 9.22 A% Y_2O_3

YBCO+Y_2O_3 modified surface → Y_2O_3 nanoparticles

Isotropic J_c (F_P) but smaller

1D+3D multilayer

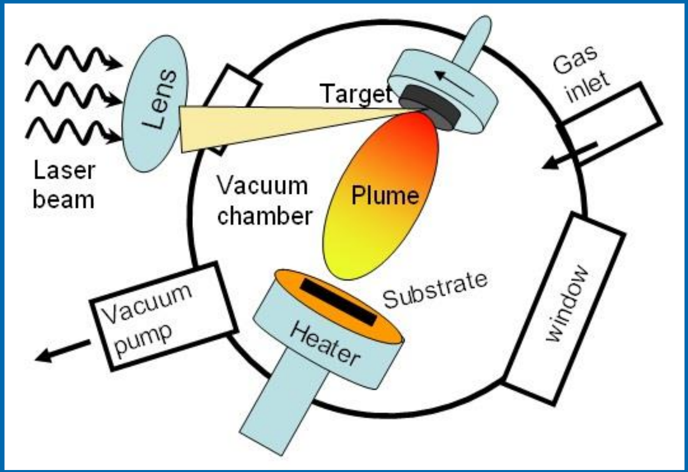
Combinations of 4wt% $BaSnO_3$ and 2.5A% Y_2O_3

$BaSnO_3$ nanorods **Y_2O_3 nanoparticles**

Isotropic and large J_c (F_P)????

Incorporation of 3D APCs into YBCO films by PLD

Pulsed Laser Deposition (PLD)



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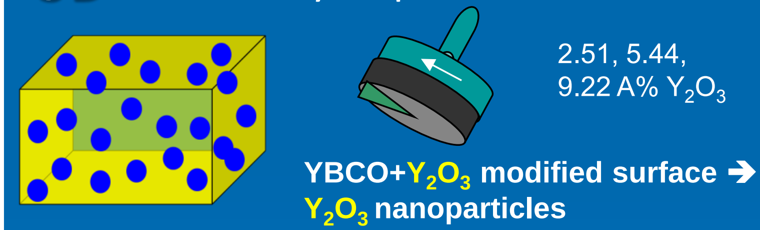
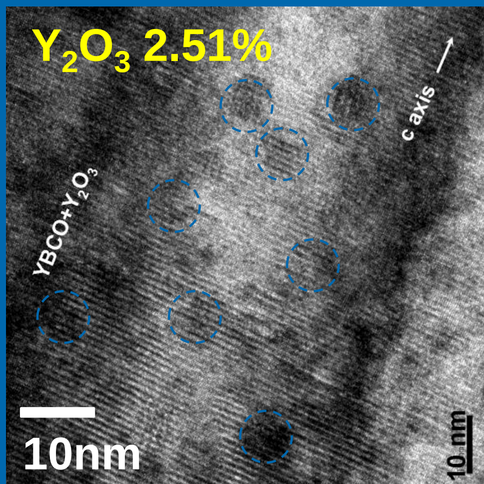
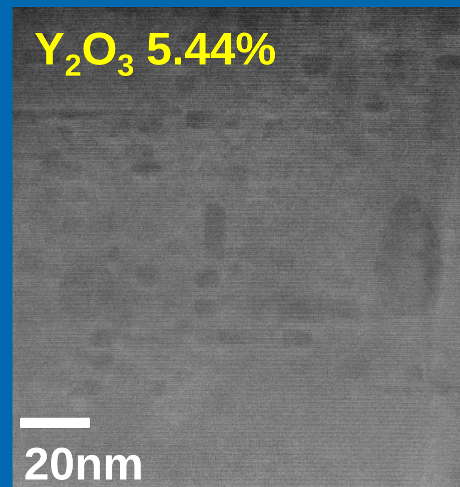
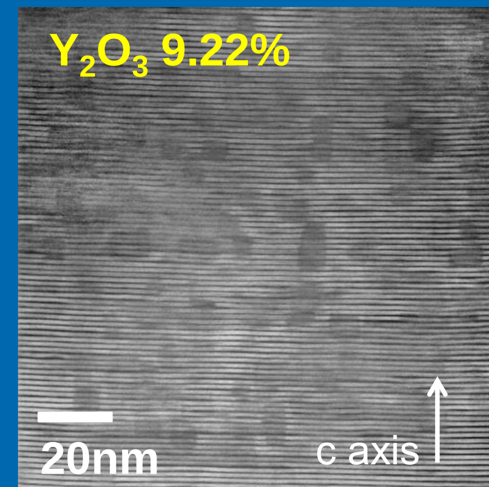


Isotropic J_c (F_P) but smaller

Morphology of the Y_2O_3 nanoparticles inside YBCO films

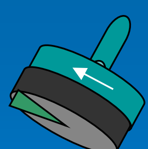


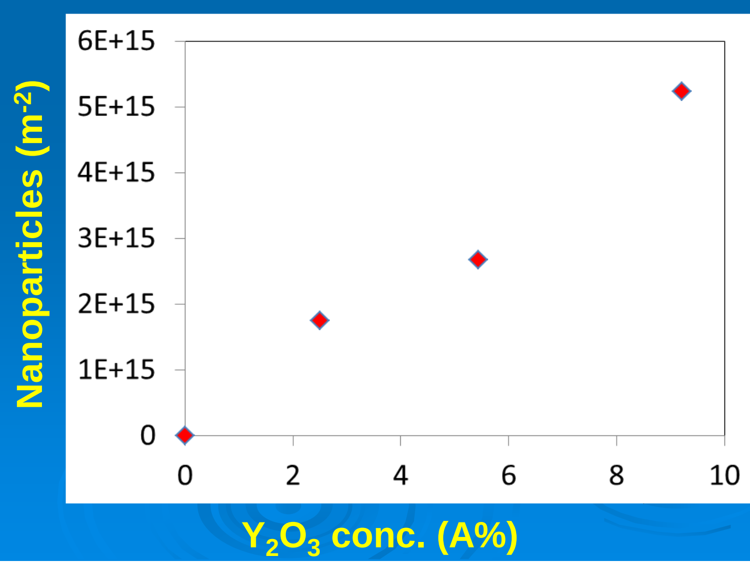




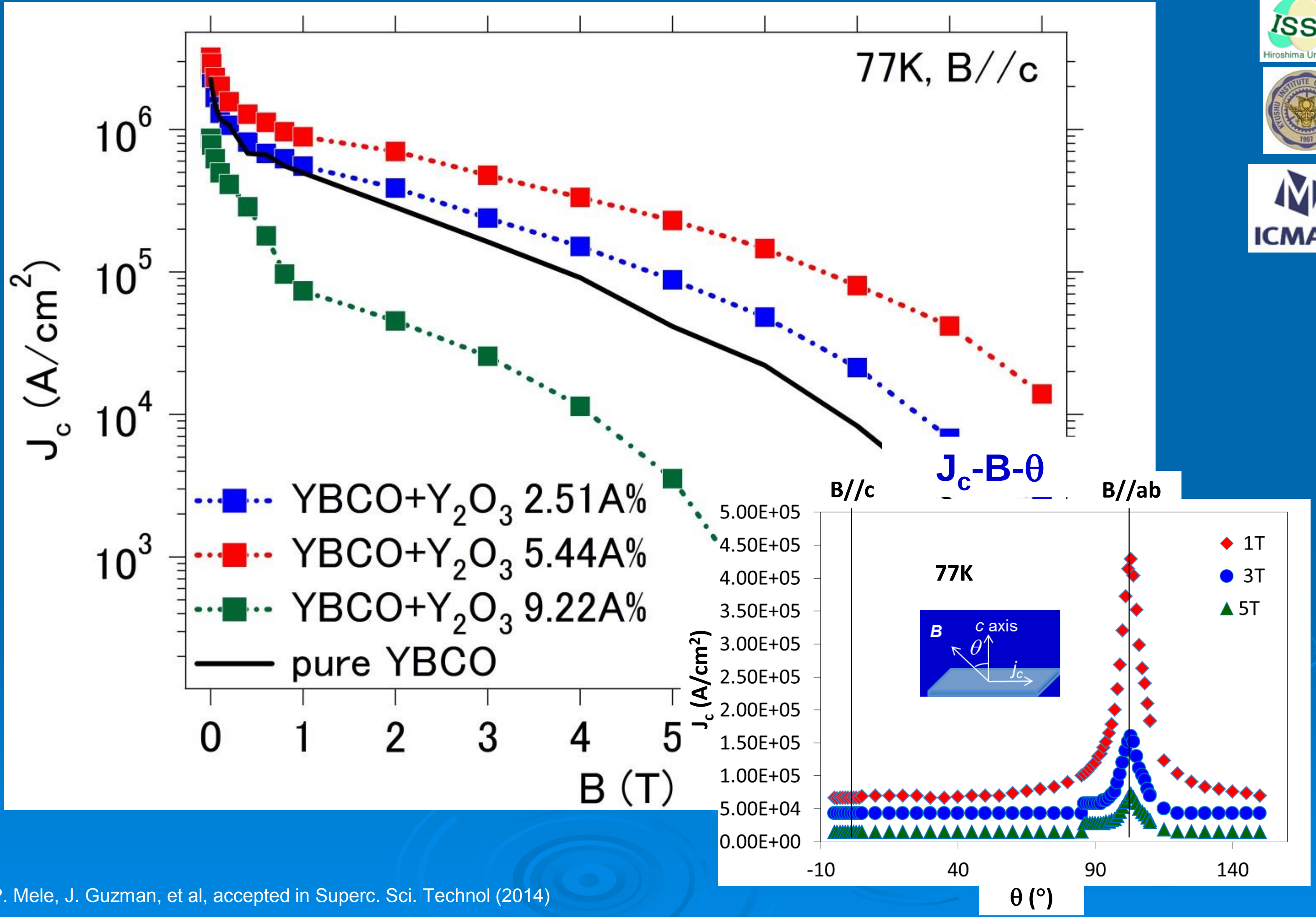
P. Mele et al Superc. Sci. Technol. 20 (2007) 616

P. Mele, J. Guzman, et al, accepted in Superc. Sci. Technol (2014)



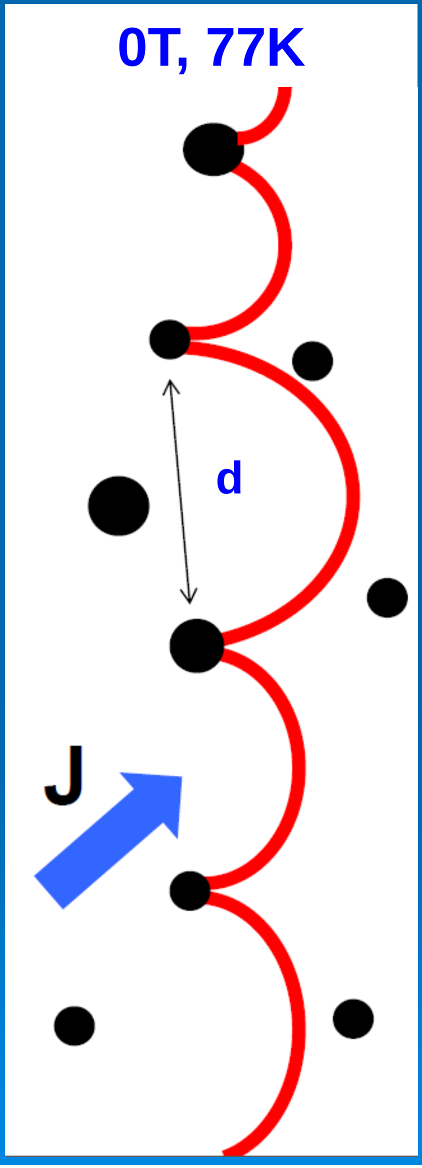


Critical current of Y_2O_3-added YBCO at 77 K



P. Mele, J. Guzman, et al, accepted in Superc. Sci. Technol (2014)

(Strong) pinning by Y_2O_3 nanoparticles



$$J_c = \frac{\Phi_0}{4\pi\mu_0\lambda_{ab}\lambda_c d}\ln\frac{d}{\xi_c}$$

A. Gurevich Supercond. Sci. Technol. 20 (2007) S128

$\Phi_0 = 2.068\times10^{-15}$ Wb

$\lambda_{ab} = \lambda_0(1-t^4)^{-0.5}$, $\xi_{ab} = \xi_0(1-t)^{-0.5}$, $t = T/T_c$

$\xi_c = \xi_{ab}/5$ $\lambda_c = \lambda_{ab} \times \Gamma$, $\Gamma = 7$

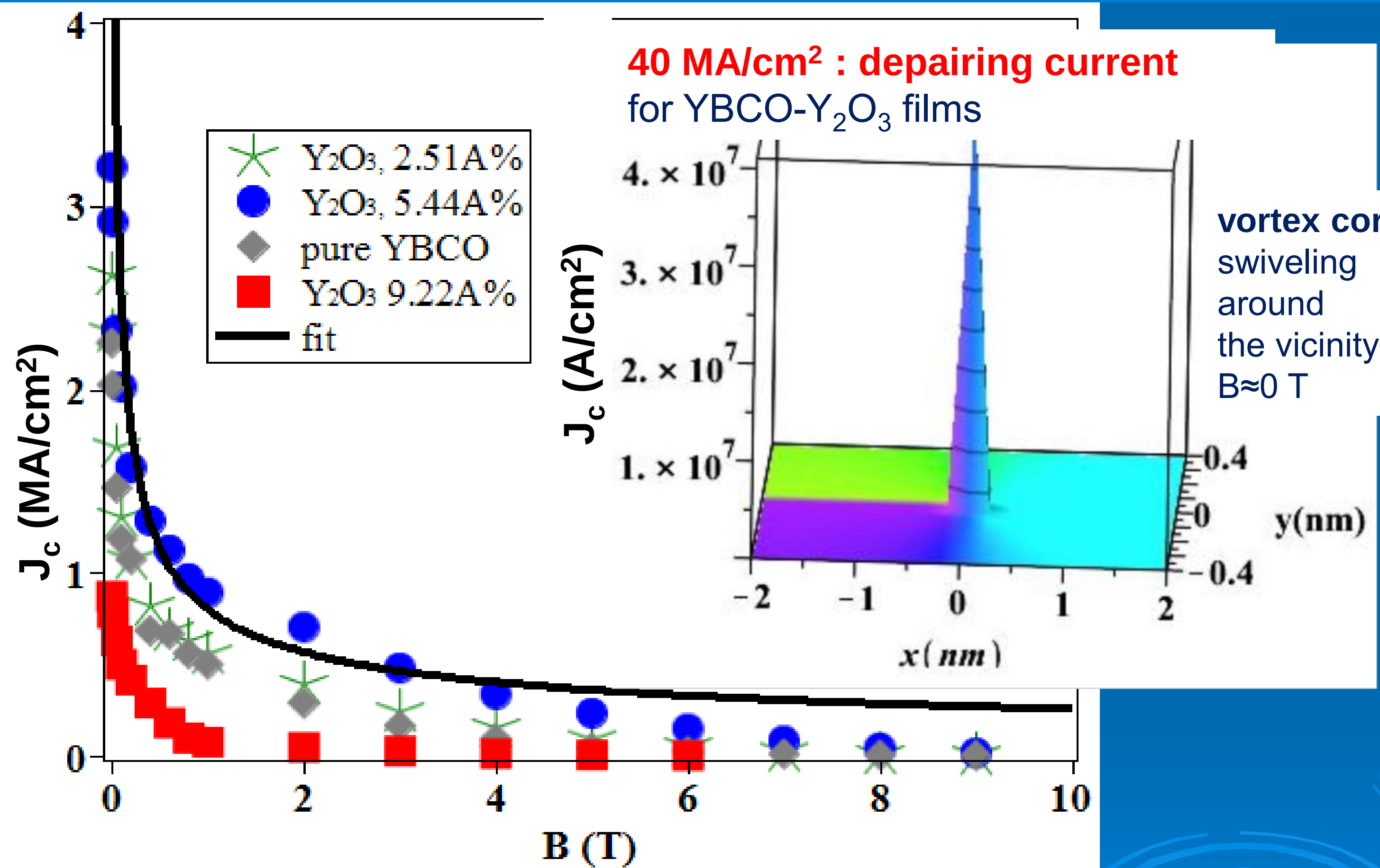
$\lambda_{0\ YBCO}$ = 150 nm, $\xi_{0\ YBCO}$ = 1.5 nm

Y_2O_3 content	2.51A%	5.44A%	9.22A%
Amount of APCs (m^{-2})	1.75×10^{15}	2.68×10^{15}	5.23×10^{15}
T_c (K)	89.26	89.2	87.78
d (nm)	20	18	12
Calculated J_c (0T, 77K) (MA/cm^2) **3D**	5.93	6.4	7.4
Measured J_c (0T, 77K) (MA/cm^2) **3D**	2.62	2.64	0.89
J_c calc/J_c meas	2.26	2.42	8.31
Effective current blocking	10%	13%	32%

Reducing the separation between 3D APCs does not increase J_c due to current blocking by the pinning defect structure

P. Mele, J. Guzman, et al, accepted in Superc. Sci. Technol (2014)

Fitting of J_c-B of YBCO-Y_2O_3 films: single-vortex dynamics



40 MA/cm² : depairing current for YBCO-Y_2O_3 films

vortex core swiveling around the vicinity of B≈0 T

Effective pinning along the vortex core length

2.51A% → 6.5%
5.44% → 8.0%
9.22A% → 2.2%

By M. I. Adam (UniTeN) – using Gurevich`s model [SuST 20 (2007) S128]

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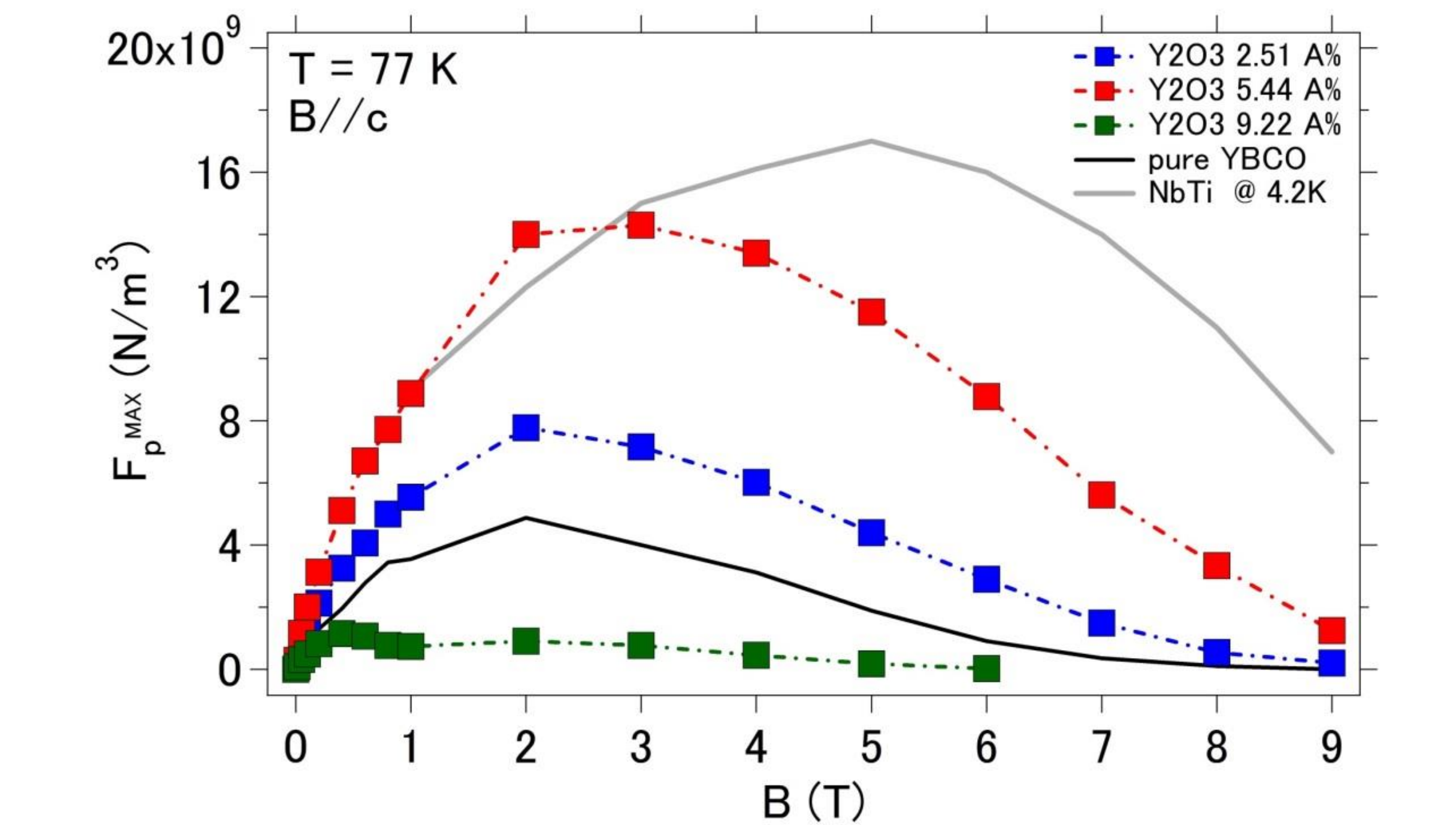
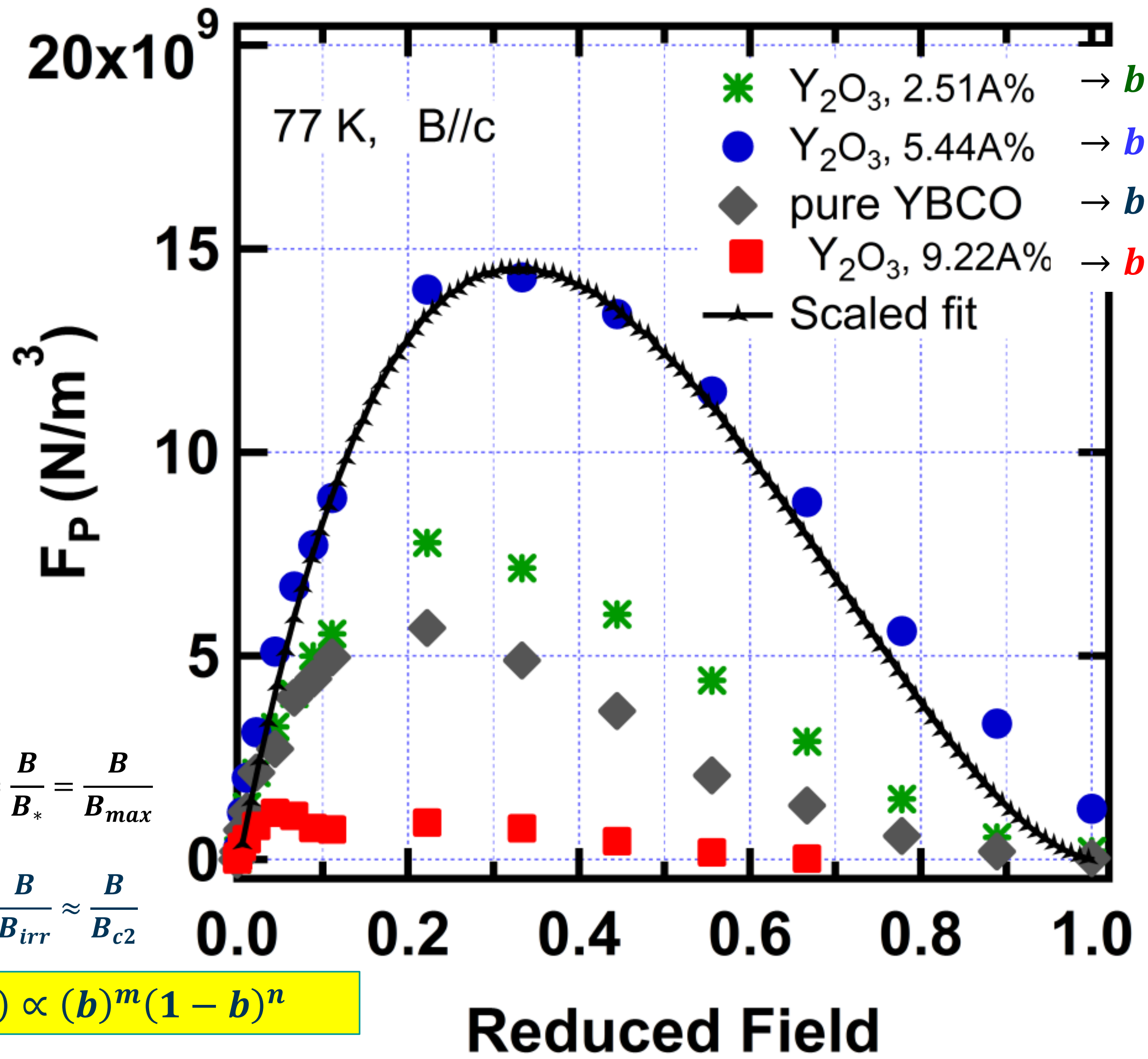
Influence of the Y_2O_3 nanoparticles on global pinning force



P. Mele, J. Guzman, et al, accepted in Superc. Sci. Technol (2014)

Scaling of F_p-B for YBCO-Y_2O_3 films



$\rightarrow b^* \approx 0.23$

$\rightarrow b^* \approx 0.35$

$\rightarrow b^* \approx 0.23$

$\rightarrow b^* \approx 0.05$

$$b* = \frac{B}{B_*} = \frac{B}{B_{max}}$$

$$b = \frac{B}{B_{irr}} \approx \frac{B}{B_{c2}}$$

$$F_P(b) \propto (b)^m (1-b)^n$$

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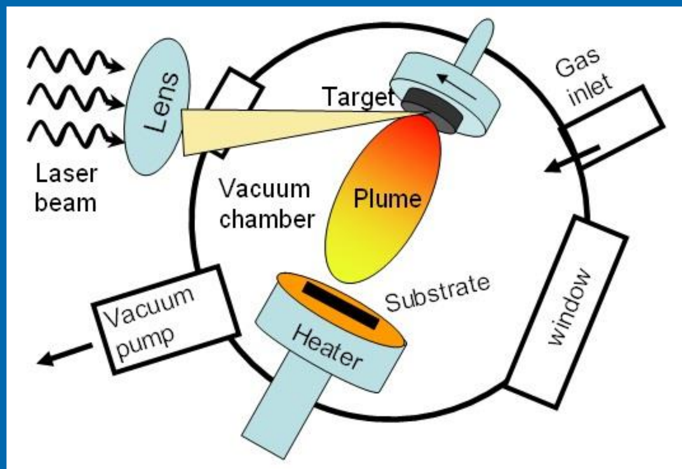

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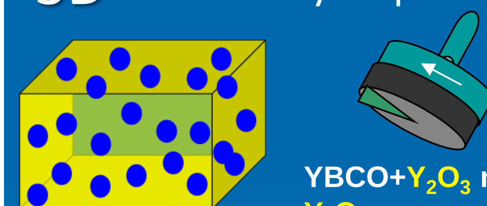

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1D+3D multilayer

Combinations of 4wt% $BaSnO_3$ and 2.5A% Y_2O_3

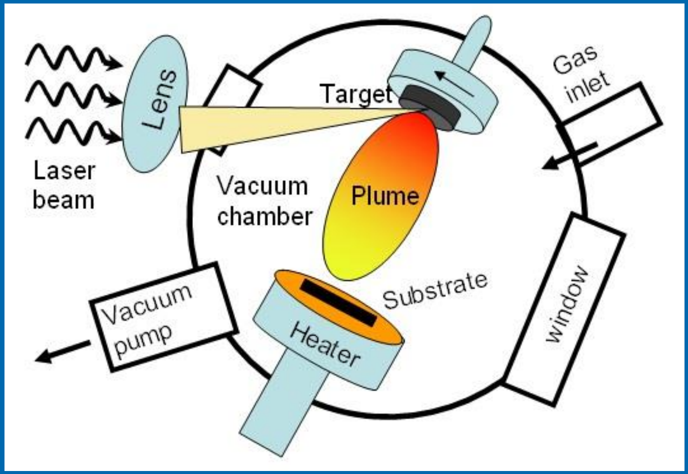
$BaSnO_3$ nanorods

Y_2O_3 nanoparticles

Isotropic and large J_c (F_P)????

Incorporation of 1D+3D APCs into YBCO multilayers by PLD

Pulsed Laser Deposition (PLD)



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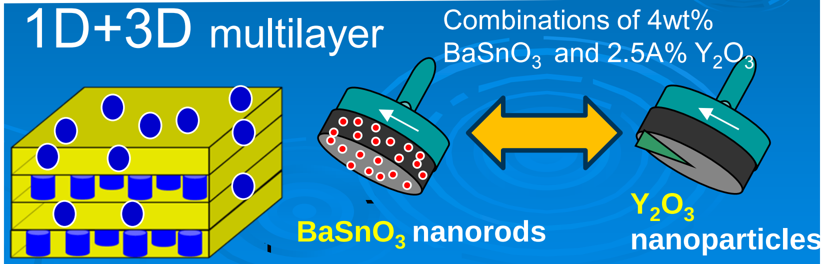
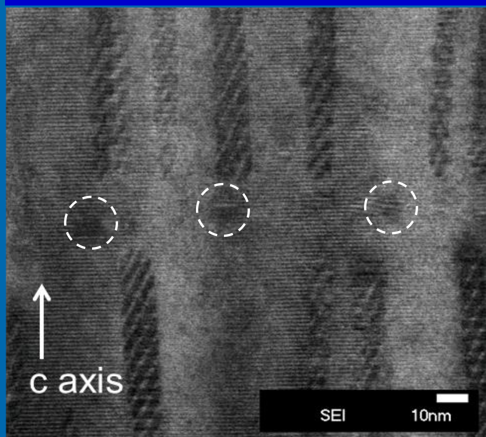
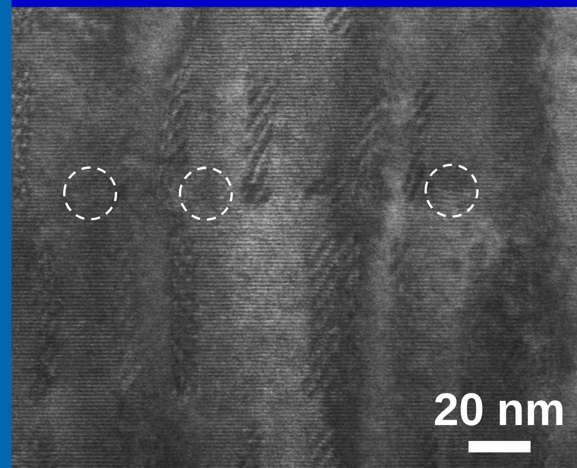
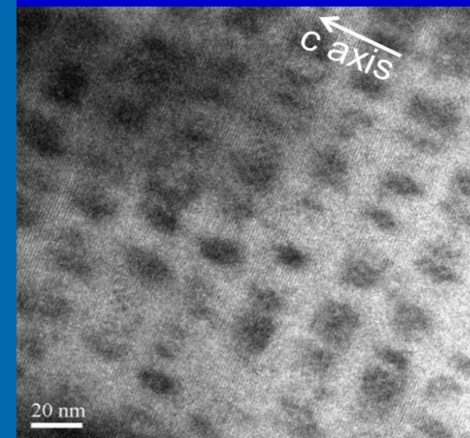
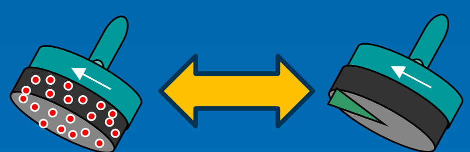
c axis



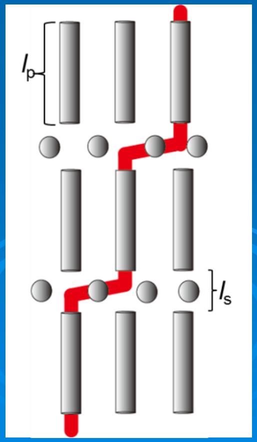
Isotropic and large J_c (F_P)????

Morphology of the YBCO+$BaSnO_3$/YBCO+Y_2O_3 multilayers

90/30	60/10	10/10
		
BSO nanorods and Y_2O_3 nanoparticles	BSO nanorods and Y_2O_3 nanoparticles	BSO nanoparticles only?!?



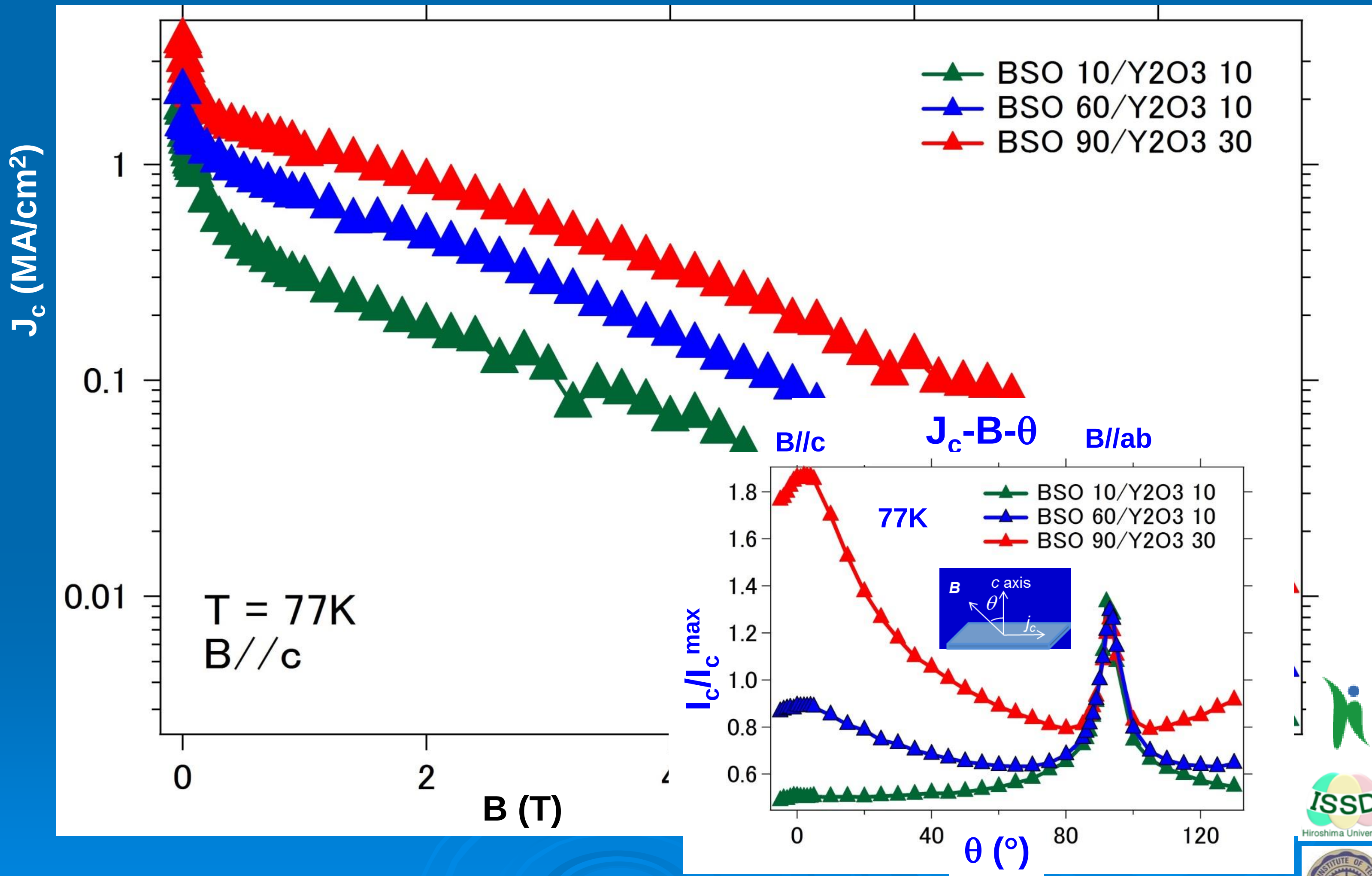
4wt%$BaSnO_3$ 2.5A%Y_2O_3



Multilayer configuration	90/30	60/10	10/10
$BaSnO_3$ nanorod l_p (nm)	71	57	18
Y_2O_3 added layer l_s (nm)	24	15	10

P. Mele, K. Matsumoto, A. K. Jha, S. Saini et al, unpublished

Critical current of $BaSnO_3/Y_2O_3$ -multilayered YBCO at 77 K



P. Mele, K. Matsumoto, A. K. Jha, S. Saini et al, unpublished

1D+3D pinning by $BaSnO_3$ and Y_2O_3 in multilayered YBCO

$\Phi_0 = 2.068\times10^{-15}$ Wb

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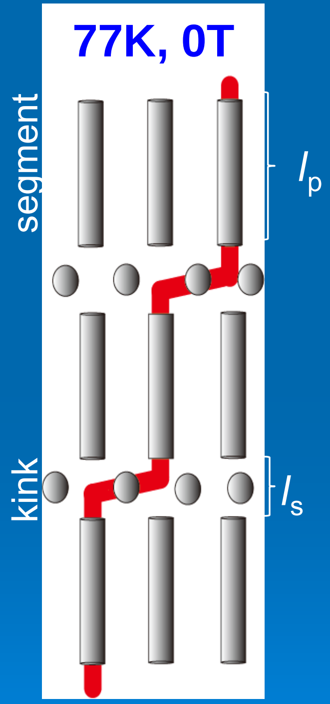
$\lambda_{0\ YBCO}$ = 150 nm, $\xi_{0\ YBCO}$ = 1.5 nm

$\xi_c = \xi_{ab}/5$

$$J_c^{1D+3D} = J_c^{1D-segmented} + J_c^{3D-kink}$$

$$J_c^{1D-segmented} = \frac{\Phi_0}{16\pi\mu_0\lambda_{ab}^2\xi_{ab}}\left[\frac{l_p}{l_p+l_s}\right]$$

$$J_c^{3D-kink} = \frac{\Phi_0}{16\pi\mu_0\lambda_{ab}^2\xi_{ab}}\left[\frac{\xi_c}{l_s}\right]$$

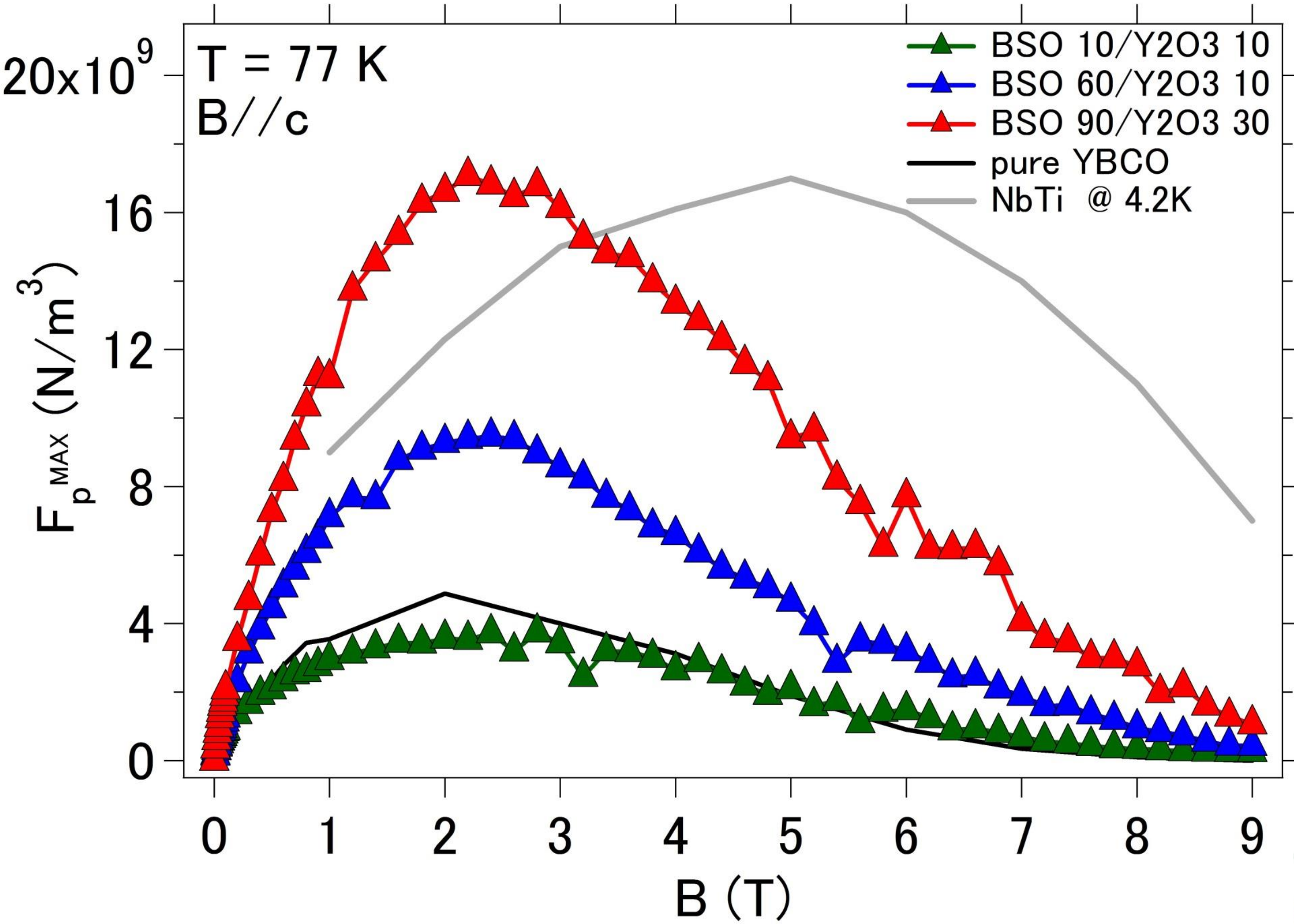


Multilayer configuration	90/30	60/10	10/10
$BaSnO_3$ nanorod l_p (nm)	71	57	18
Y_2O_3 added layer l_s (nm)	24	15	10
Calculated J_c (0T, 77K) (MA/cm^2) for segmented 1D	12	11.8	9.4
Calculated J_c (0T, 77K) (MA/cm^2) (3D kink)	0.54	0.82	0
Calculated J_c (0T, 77K) (MA/cm^2) (1D+3D)	12.54	12	9.4
Measured J_c (0T, 77K) (MA/cm^2) (1D+3D)	3.72	2.16	1.84
J_c calc/J_c meas	3.37	5.56	5.10
Effective current blocking (1D+3D)	15%	13%	33%

Ad hoc **analytical expression for J_c is required!**

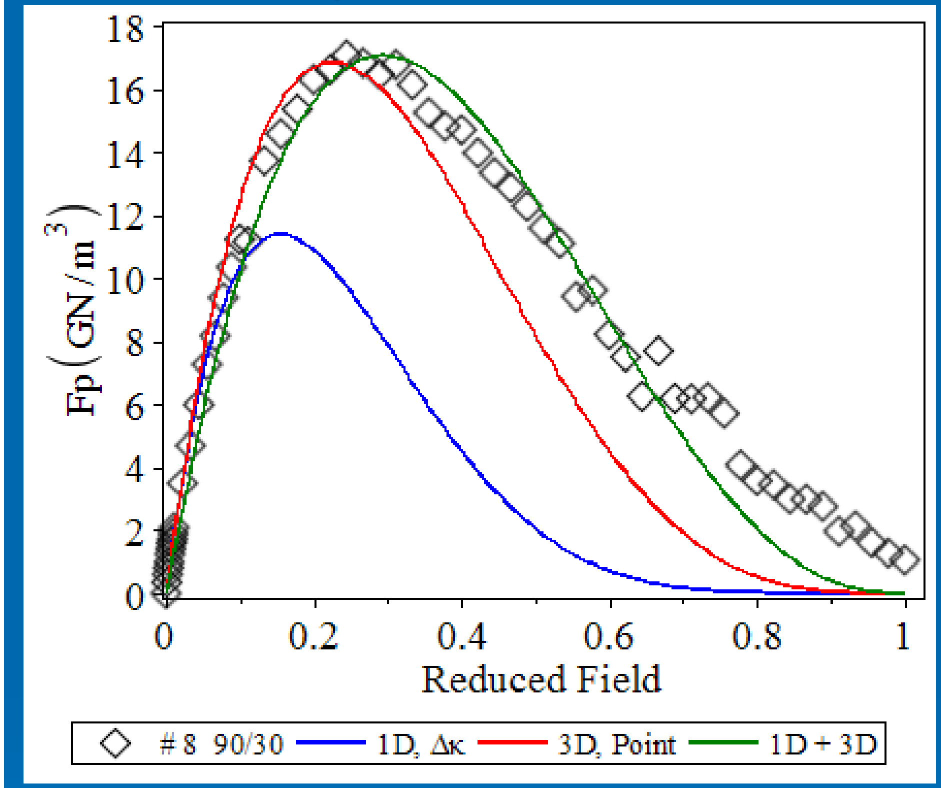
P. Mele, K. Matsumoto, A. K. Jha, S. Saini et al, unpublished

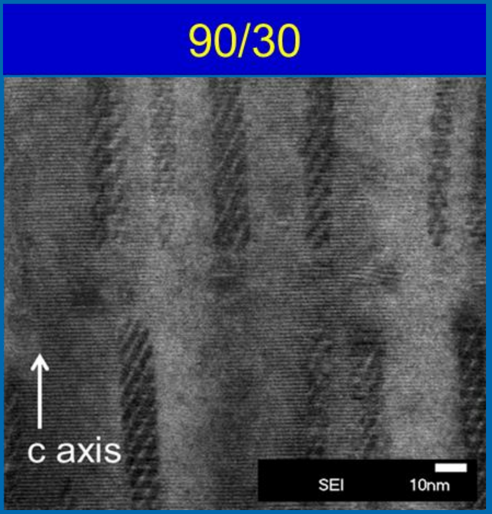
Influence of the $BaSnO_3/Y_2O_3$ layers on global pinning force



P. Mele, K. Matsumoto, A. K. Jha, S. Saini et al, unpublished

Scaling of F_p-B for [YBCO+BSO 90] / [YBCO+ Y_2O_3 30] multilayers





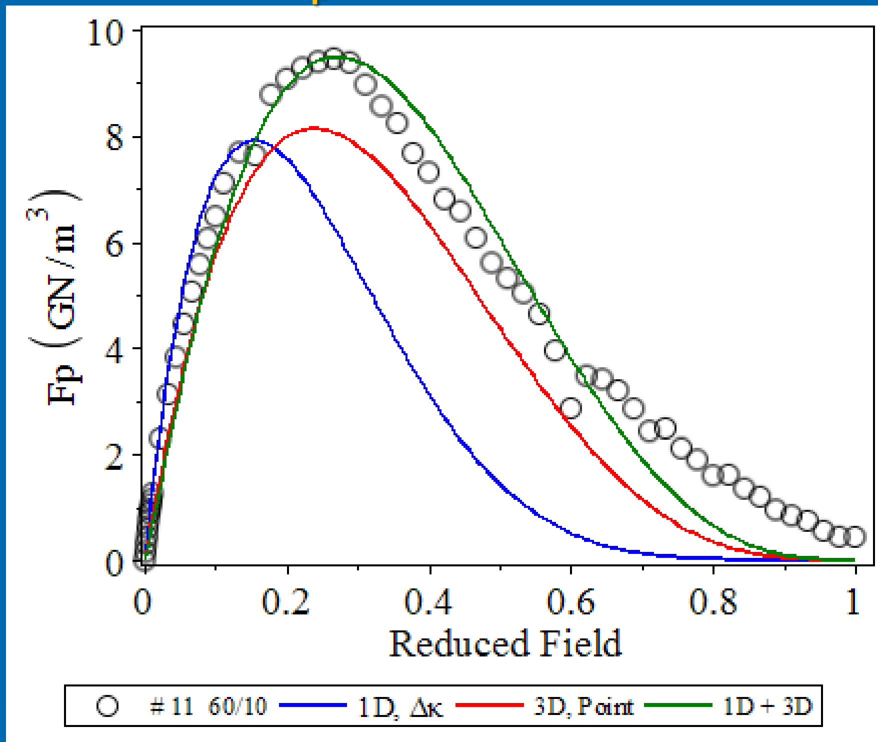
$$F_P(b) = Ab^*(b)^m(1-b)^n$$

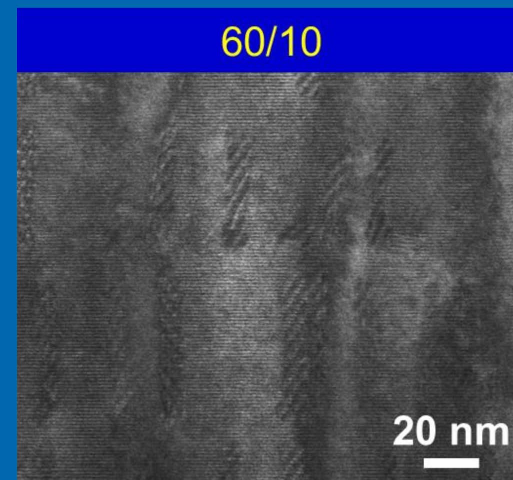
$$b = \frac{B}{B_{irr}} \approx \frac{B}{B_{c2}} \qquad b* = \frac{B}{B_*} = \frac{B}{B_{max}}$$

90/30	1D pinning	3D pinning	1D+3D pinning
B*	0.9	2.2	2.4
m	1.01	1.02	1.04
n	5.5	3.5	2.5

P. Mele, M.I. Adam et al, unpublished

Scaling of F_p-B for [YBCO+BSO 60] / [YBCO+ Y_2O_3 10] multilayers





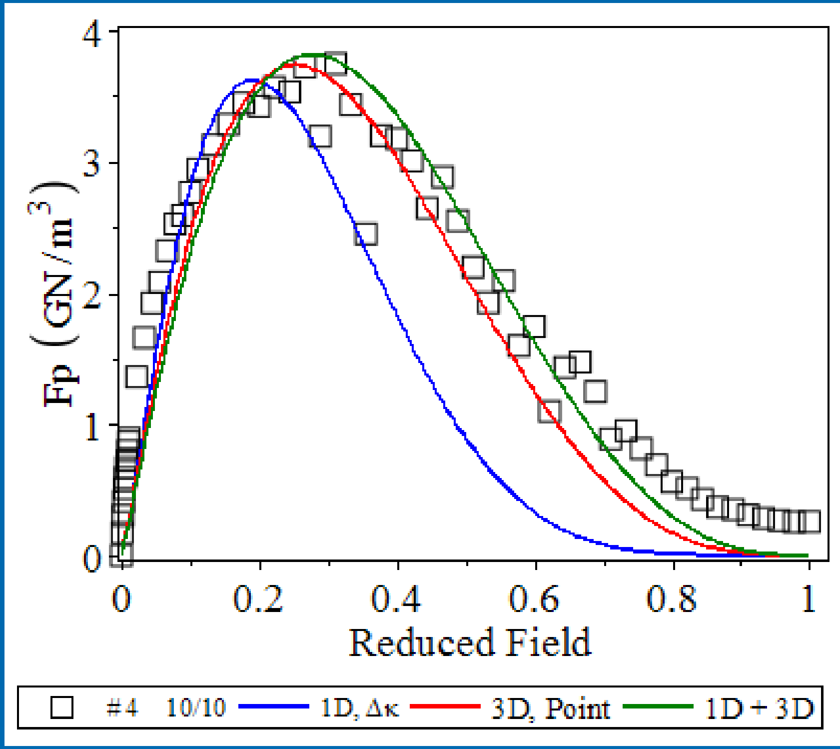
$$F_P(b) = Ab^*(b)^m(1-b)^n$$

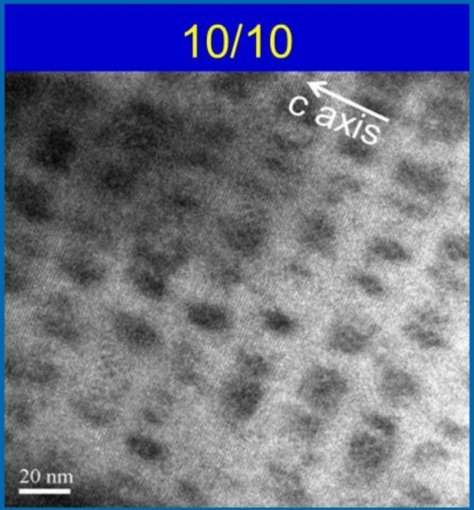
$$b = \frac{B}{B_{irr}} \approx \frac{B}{B_{c2}} \qquad b* = \frac{B}{B_*} = \frac{B}{B_{max}}$$

60/10	1D pinning	3D pinning	1D+3D pinning
B*	1.4	2.3	2.4
m	1.01	1.02	1.03
n	5.5	2.8	3.3

P. Mele, M.I. Adam et al, unpublished

Scaling of F_p-B for [YBCO+BSO 10] / [YBCO+ Y_2O_3 10] multilayers





$$F_P(b) = Ab^*(b)^m(1-b)^n$$

$$b = \frac{B}{B_{irr}} \approx \frac{B}{B_{c2}} \qquad b* = \frac{B}{B_*} = \frac{B}{B_{max}}$$

10/10	1D pinning	3D pinning	1D+3D pinning
B*	1.6	2.0	2.6
m	1.01	1.02	1.02
n	5.2	3.3	2.9

P. Mele, M.I. Adam et al, unpublished

Summary

- Addition of nanoscale APCs of different dimensionality in YBCO films: systematic study is proposed

- 1D-APCs ($BaSnO_3$ nanorods)
  Anisotropic behaviour (c-axis correlated pinning). Easy control of nanorods density and spacing.
  F_p^{MAX} = 28.3 GN/m^3 at 3T, 77K in 4wt% BSO-added YBCO

- 3D-APCs (Y_2O_3 nanoparticles)
  Isotropic pinning but lower J_c, F_p respect to 1D-APCs and segmented nanorods.
  Difficult control of nanoparticles density and spacing.
  F_p^{MAX} = 14.3 GN/m^3 at 3T, 77K for YBCO+ 5.44 A% Y_2O_3
  According to single vortex dynamics model, Y_2O_3 5.44A% nanoparticles generate 8.0% effective pinning along the vortex core length

- Multilayered1D-APCs+3D-APCs
  Simultaneous c-axis and random pinning in YBCO+ 4wt% $BaSnO_3$/ YBCO+ 2.5 A% Y_2O_3 multilayers.
  F_p^{MAX} = 17.6 GN/m^3 at 2.2T, 77K in 90 nm YBCO+$BaSnO_3$/ 30 nm YBCO+Y_2O_3
  According to scaling law, the global pinning behavior of the samples is a direct manifestation of the presence of different pinning centers in their structure
  Highest maximum field B* corresponds to the coexistence of 1D + 3D pinning