IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation 2-MO-FP1-O11 given at EUCAS 2019, 01 - 05 September 2019, Glasgow (UK).

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

EUCAS 2019 GLASGOW

$YBa_2Cu_3O_{7-x}$ film with $Ba_2Y(Nb,Ta)O_6$ nano-inclusions for high field applications

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Glasgow, 2019 September 3rd

14th European Conference on Applied Superconductivity

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SEVENTH FRAMEWORK PROGRAMME

GFE Central Facility for Electron Microscopy RWTHAACHEN

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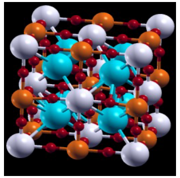
OUTLINE

Introduction



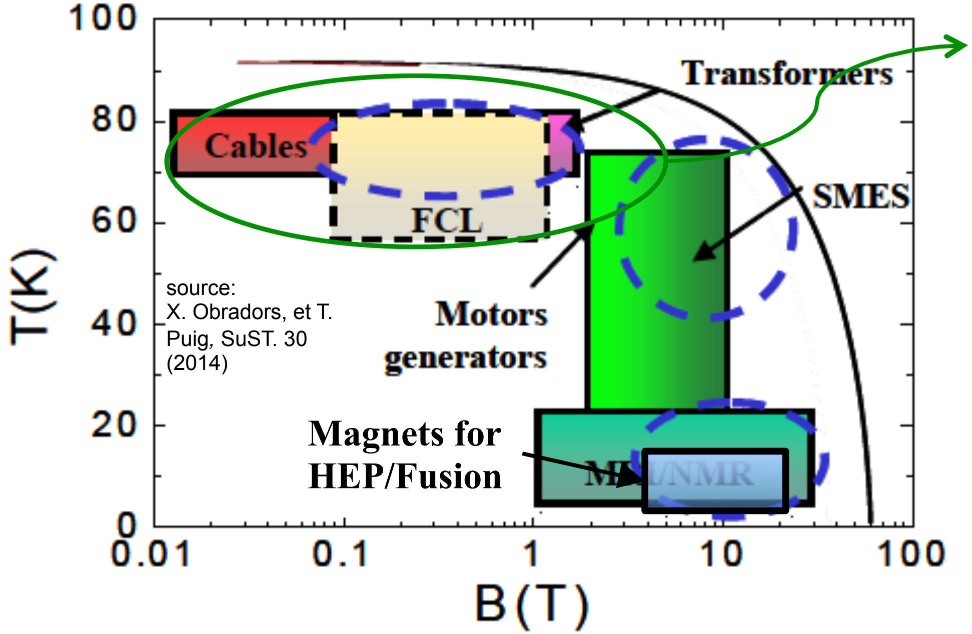
- Interest in high field applications for REBCO;
- Nb- and Ta-based APC for REBCO: state-of-the-art

Mixed doping by $Ba_2(Y,Ta)O_6$ + $Ba_2(Y,Nb)O_6$: 2.5 mol.% + 2.5 mol.%

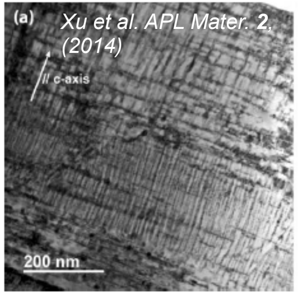
- BYTO single vs mixed BYTO + BYNO doping;
- Defects landscape tunability by growth rate;

Conclusions & Perspectives

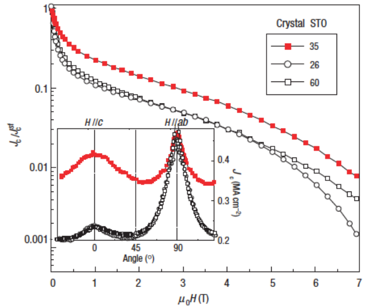
Intro – High fields: new perspectives of REBCO applications



Effective technology for control of pinning and J_c optimization @ LN2 and low/mid field



M.M. Driscoll, *et al.* Nature Mater. (2004)



APC by incorporation of $BaMO_3$ (M= Zr, Hf, Sn)

Self-assembled columnar structures/*c* – axis correlated defects

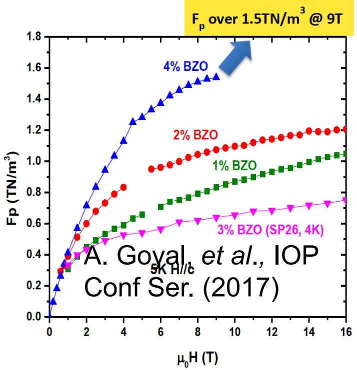
Nuclear fusion and accelerators requests are extremely demanding

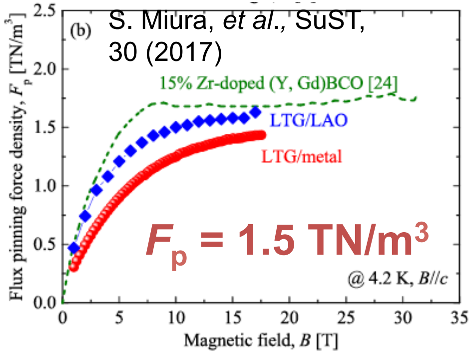
Nb_3Sn technology cannot fulfill these needs

For **REBCO** this is a unique opportunity to extend its **applicability to high field magnets sector**

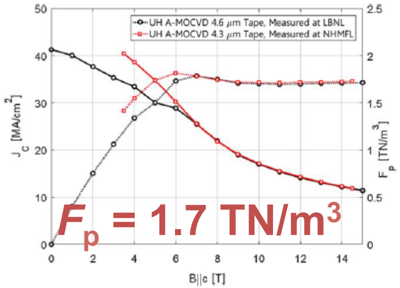
Intro – What we know @ Low T / High field conditions for REBCO

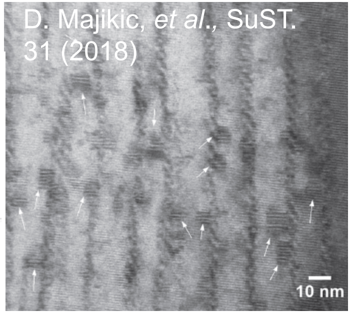
APC approach is still effective: APC + additional defects spontaneously generated by APC/YBCO interfacial strain accommodation





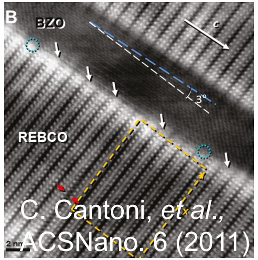
MOCVD-(Y,Gd)BCO with Zr





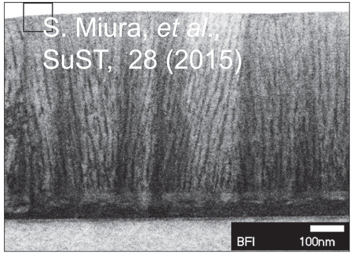
Very thin rods/columns + segregated RE_2O_3

PLD-YBCO with BZO



Oxygen disorder in YBCO at interface

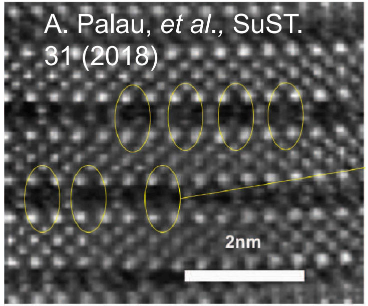
PLD-SmBCO with BHO



Careful control of rods size, density and inclination distribution

Cluster of Cu-O vacancies in stacking faults

CSD-YBCO with BZO np



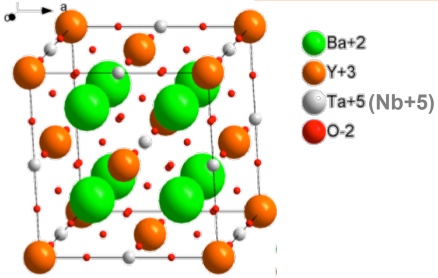
Little is known so far: **REBCO poorly investigated in low T/high field conditions**

More studies are needed

Intro: Ba_2YTaO_6 and Ba_2YNbO_6 doping: great performances at LN2

Ba_2RENbO_6 **Ba_2RETaO_6**

Double perovskite; cubic - Fm3m; *a* = 0.84 nm;

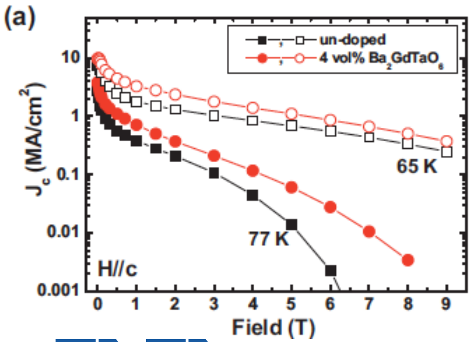


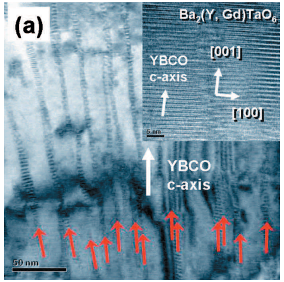
- Great phase stability (**chemically inert w.r.t. YBCO**);
- large mismatch w.r.t. YBCO: in plane **~ 9.4%**; *c*-axis **~ 8.3%**;
- $Nb^{+5} = Ta^{+5}$ = 0.78 Å (Zr^{+4} = 0.86 Å)
- Ta_2O_5 (Nb_2O_5) lower melting *T* than ZrO_2;
- **larger ion mobility than Zr** is expected;

G. Ercolano et al. SuST 23 (2010)
G. Wee et al. PRB 81 (2010)
G. Ercolano et al. SuST 24 (2011)

Ba_2RETaO_6 (RE=Yb, Er, Gd)

G. Wee et al. PRB 81 (2010)



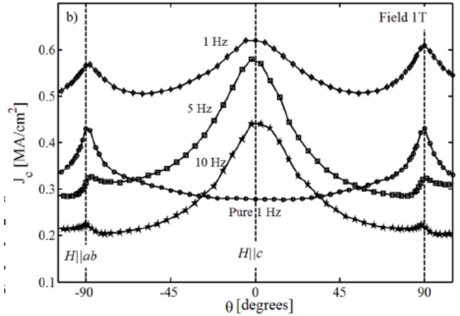


Splayed columns, dense and fine structure
$d \approx$ 6 - 7 nm,
$B_\phi \approx$ 5 - 9 T

Ba_2YNbO_6

G. Ercolano et al. JAP (2014)

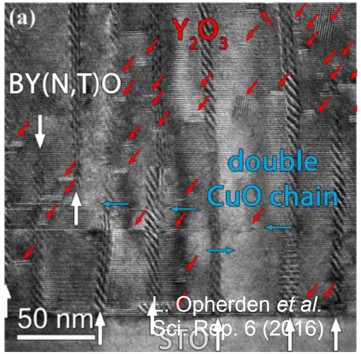
dense and fine **nanorods**
$d \approx$ 10 nm, $B_\phi \approx$ 2 - 5 T



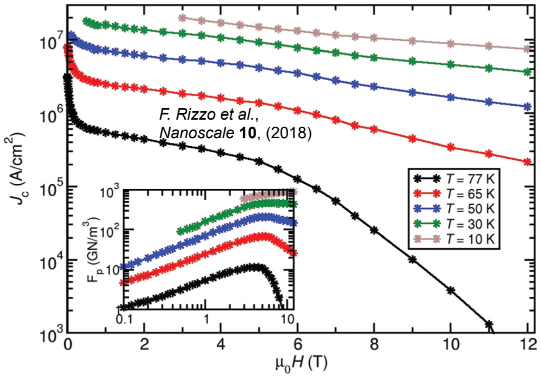
Intro: Nb and Ta- based double doping

More complex defect landscape

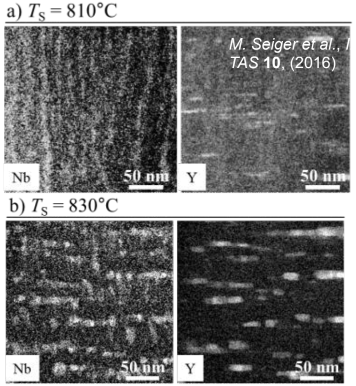
Mixed Ba_2YNbO_6 + Ba_2YTaO_6 doping



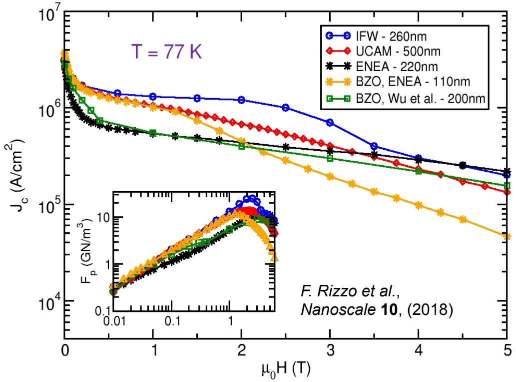
Complex landscape: $Ba_2Y(Nb,Ta)O_6$ continuous columns + Y_2O_3 nanoparticles



Tunable: switch to plate-like defects



Reproducible: similar performance for samples grown **in different Labs**



Good *T* and *B* - behavior: $Ba_2Y(Nb,Ta)O_6$ promising for low *T* and high fields regimes

OUTLINE

Mixed doping by $Ba_2(Y,Ta)O_6$ + $Ba_2(Y,Nb)O_6$: 2.5 mol.% + 2.5 mol.%

- BYTO single vs mixed BYTO + BYNO doping;
- Defects landscape tunability by growth rate;

PLD growth of $YBa_2Cu_3O_{7-x}$ + tantalate/niobiate based APCs

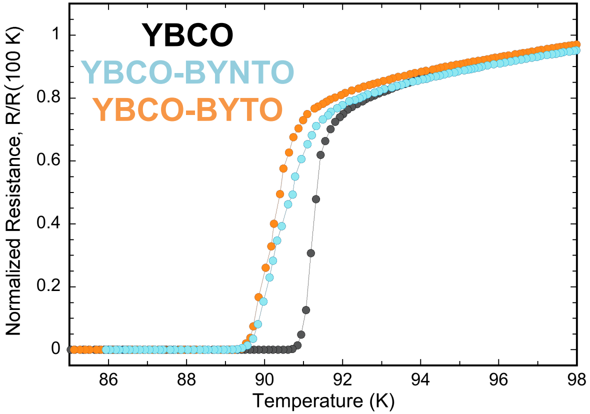
Single (BYTO) vs balanced mixed doping

YBCO composite targets

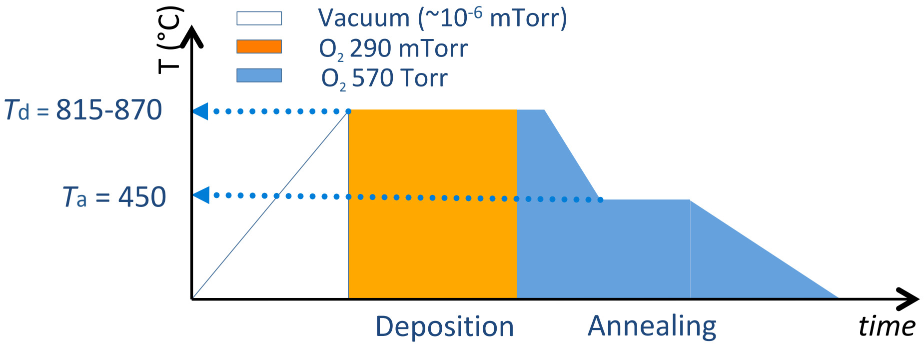
YBCO : Ba_2YTaO_6 5 mol. %

YBCO : Ba_2YTaO_6 2.5 mol. % + Ba_2YNbO_6 2.5 mol.

Best $T_c \approx 89$ K @ T_d = 840 °C



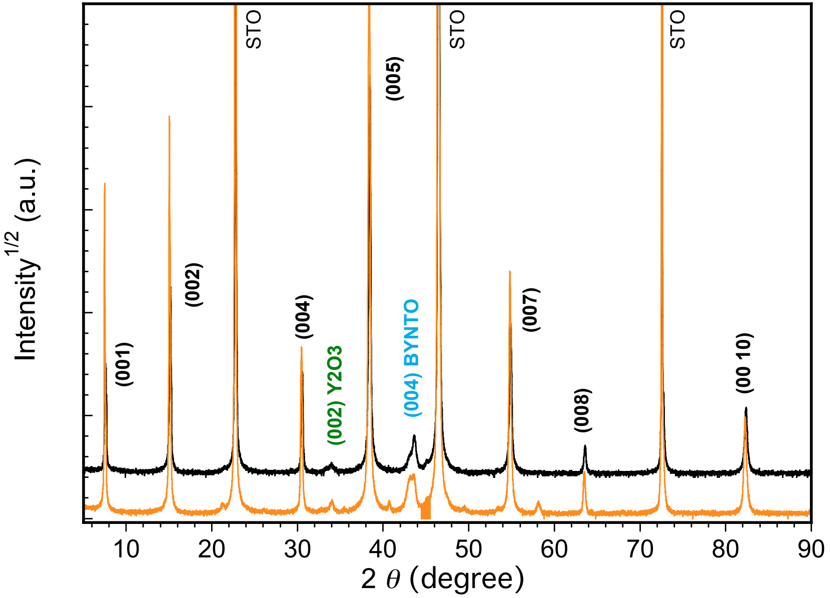
Film Deposition conditions



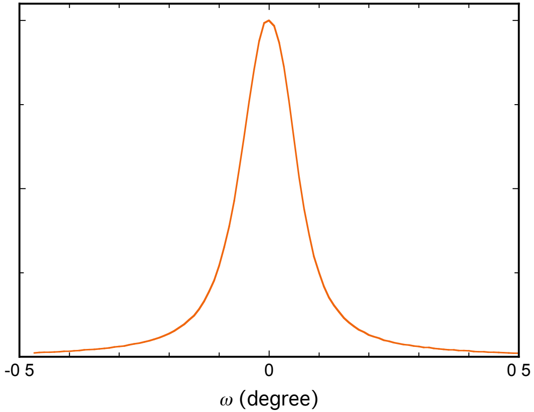
Film thickness ≈ 200 nm
Substrate: (00*l*) $SrTiO_3$
Growth rate, $\rho \approx 0.3$ nm s^{-1}

PLD setup
XeCl Excimer Laser
λ = 308 nm
f_L= 10 Hz
fluence ≈ 1.5 – 2 J/cm^2

BYTO 2.5 mol.% + BYNO 2.5 mol.% / BYTO 5 mol.%: structural properties



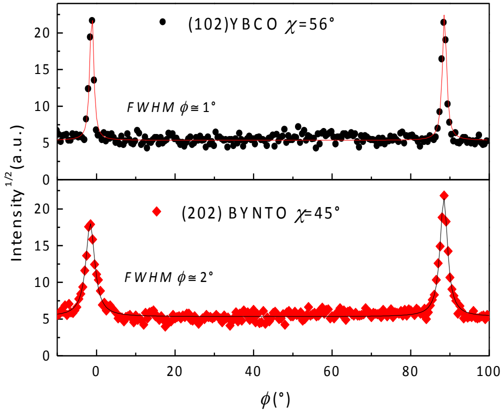
- good YBCO epitaxial growth
- BYNTO grows cube-on-cube with YBCO
- presence of Y_2O_3 related peaks



FWHM

RC (005) YBCO = 0.12°

RC (004) BYNTO = 0.6°

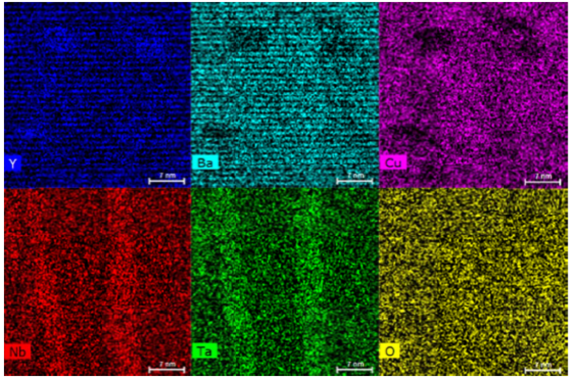


FWHM

Φ – scan YBCO (102) = 1°

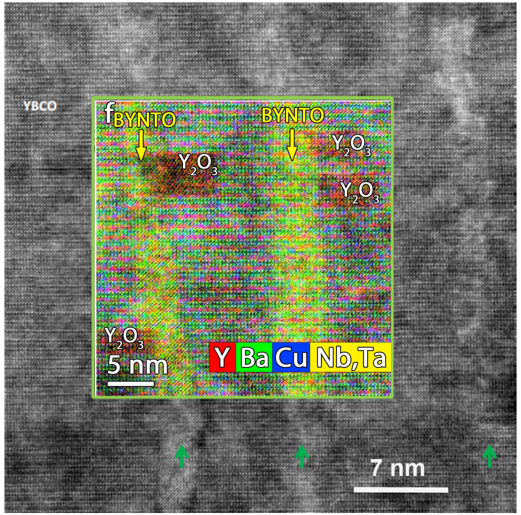
Φ – scan BYNTO (202) = 2°

BYTO 2.5 mol.% + BYNO 2.5 mol.%: TEM/EDX

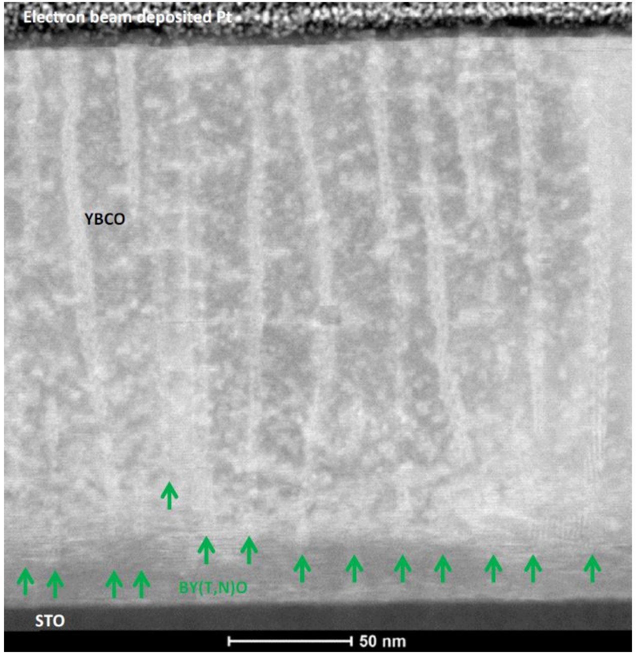


EDX elemental maps:
Excess of Ta and Nb is present in the columns

- Continue splayed columns are present $(001)_{BYNTO}//(001)_{YBCO}$, $(100)_{BYNTO}//(100)_{YBCO}$
- High density of Y_2O_3 nanoparticles is recognized



Y_2O_3 nanoparticles
- size ≤ 10 nm;
- structural relationship: $(001)_{Y2O3}//(001)_{YBCO}$, $(110)_{Y2O3}//(100)_{YBCO}$

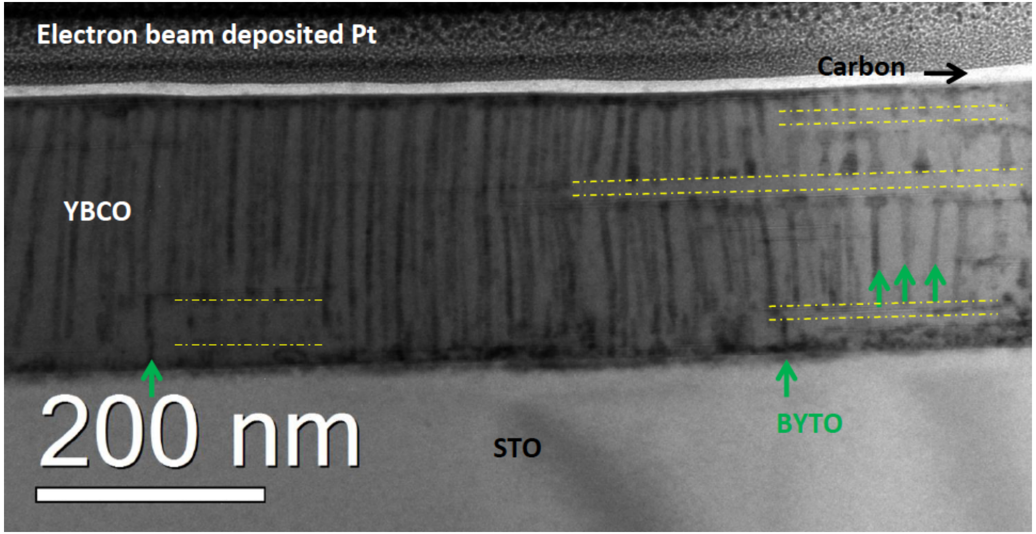


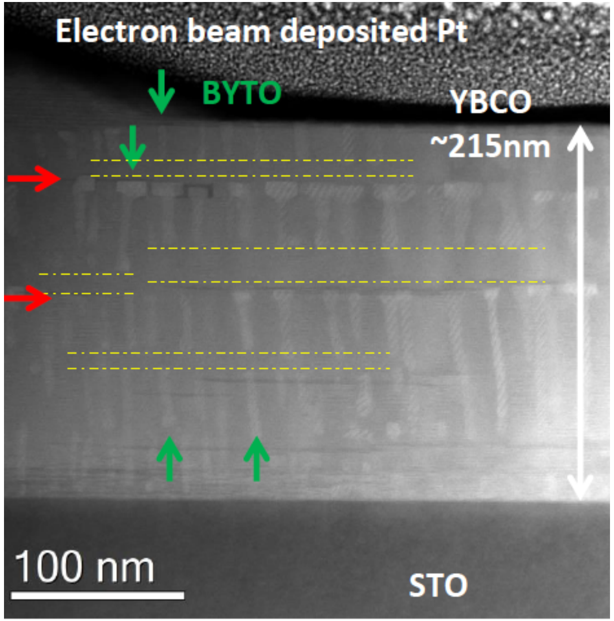
Column size d ~ 5 nm
Inter-column distance ~ 20 nm
($\boldsymbol{n}$ ~ 2500 μm^{-2}, $B_\phi \approx 5.2$ T)

BYTO 5 mol.%: TEM/EDX

Two type of columnar structures:

- **continuous** through the full YBCO thickness
- and **truncated, some of them with hammerhead**





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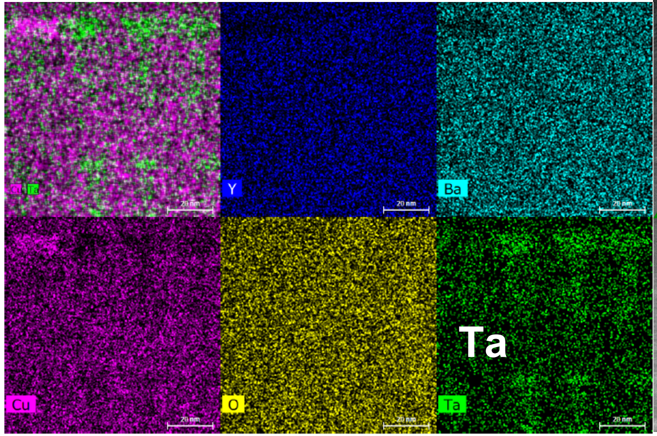
BYTO 5 mol.%: TEM/EDX

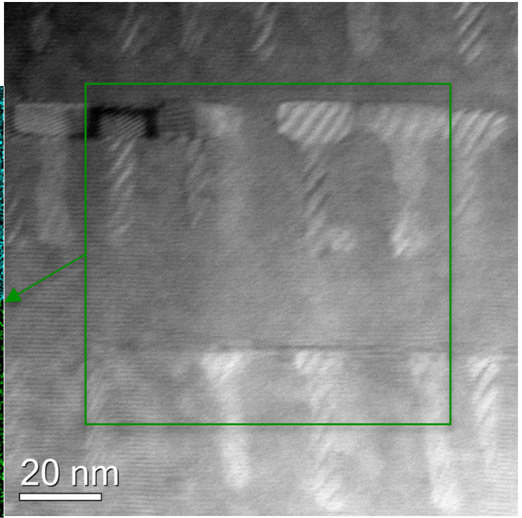
Two type of columnar structures:

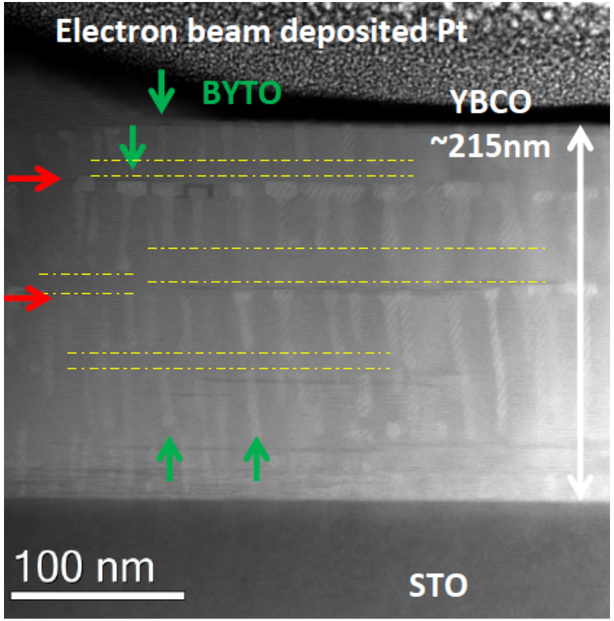
- **continuous** through the full YBCO thickness
- and **truncated, some of them with hammerhead**

EDX elemental maps:

Excess of Ta is present in the column hammerheads





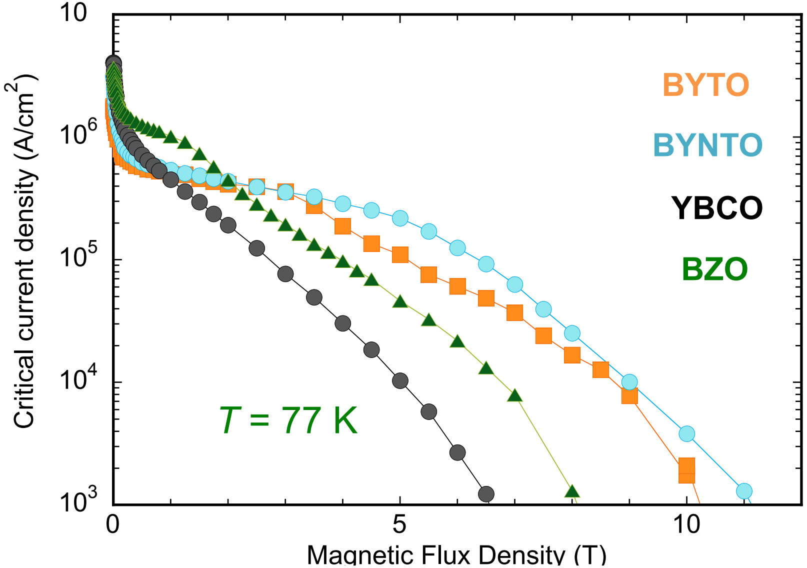


Column size d ~ 5 nm

Inter-column distance ~ 20 nm

($\boldsymbol{n}$ ~ 2500 μm^{-2}, $B_{\phi} \approx 5.2$ T)

BYTO 2.5 mol.% + BYNO 2.5 mol.% / BYTO 5 mol.%: J_c behaviour @ 77 K



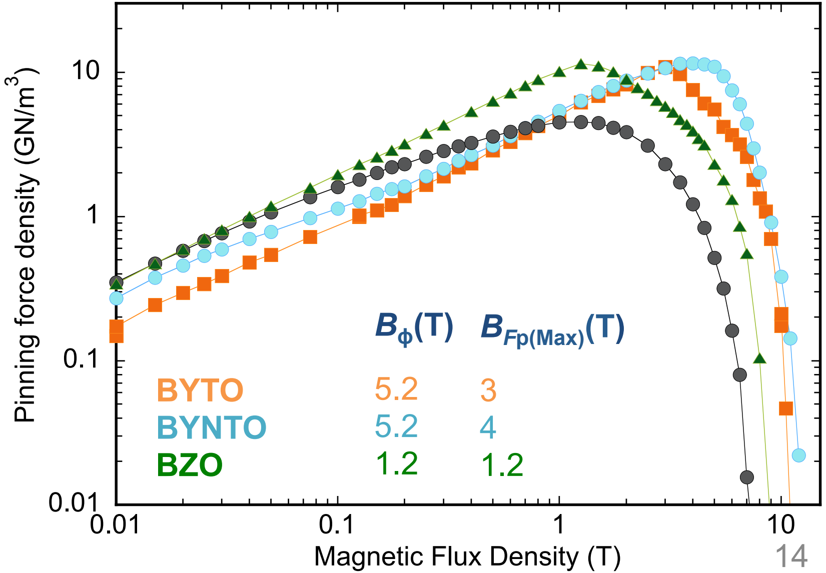
77 K	BYTO	BYNTO	YBCO	BZO
$J_c(0)$	1.6	3.2	4.0	3.7
α, $J_c \approx B^{-\alpha}$	0.23	0.28	0.44	0.27
B_{irr}	10.2	11.1	6.7	8
F_p(max)	10.9	11.5	4.5	11.4

Comparison with YBCO and YBCO + 5 mol.% BZO
deposited by PLD in similar conditions

$d_{BZO} \approx$ 5 - 7 nm, $n_{BZO} \approx$ 600 µm^{-2} ($B_\phi \approx$ 1.2 T)

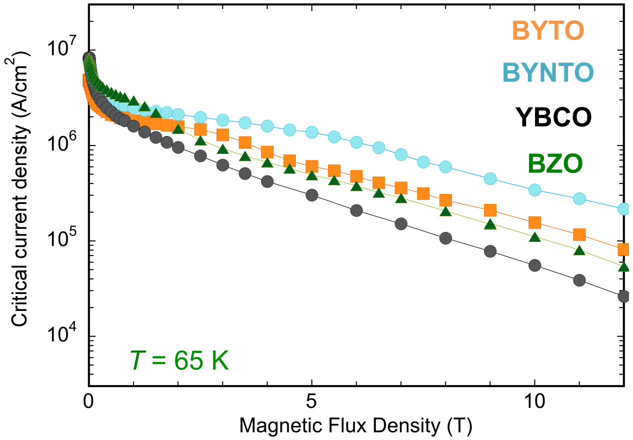
A. Augieri, *et al.*, JAP. 108 (2010)

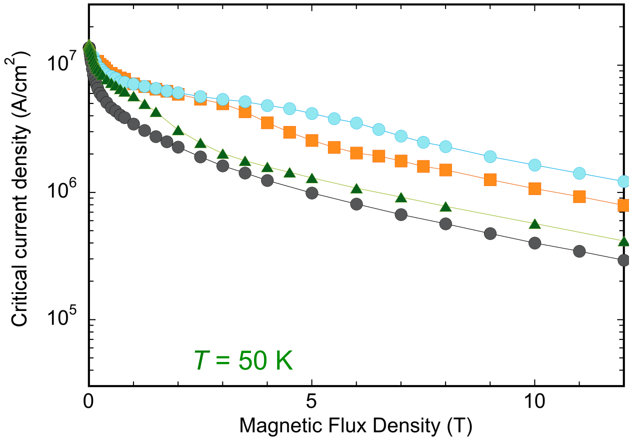
BYNTO best mid field performances @ 77 K



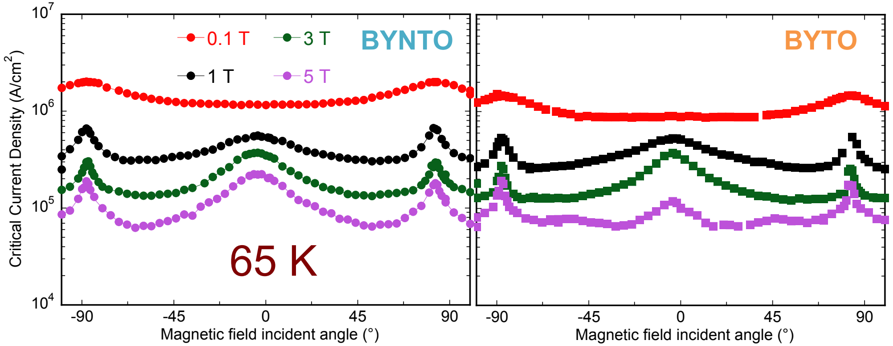
BYTO 2.5 mol.% + BYNO 2.5 mol.% / BYTO 5 mol.%: J_c behaviour @ intermediate T

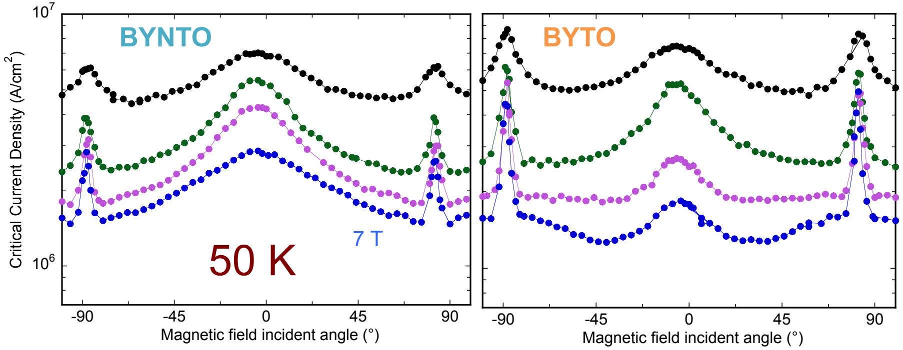
- Both BYTO and BYNTO **improve YBCO**
- BYNTO shows a stronger J_c retention in high field



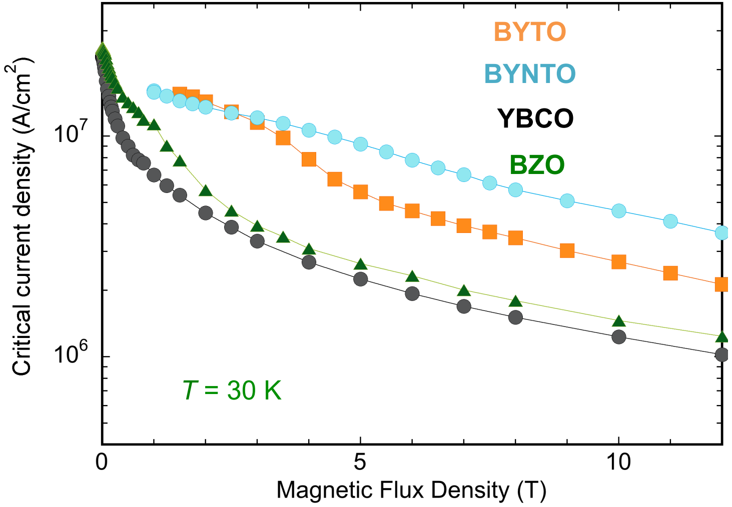


$J_c(\theta)$: BYNTO is more efficient
- Broader peaks and more intense at higher fields

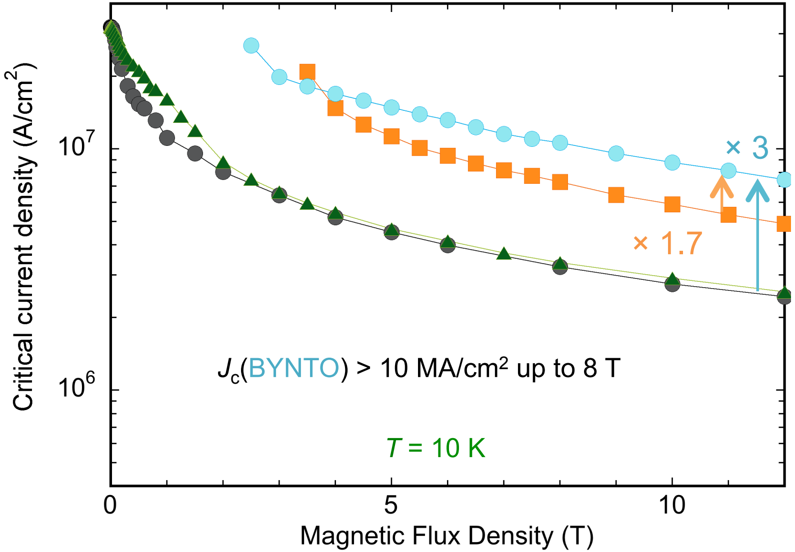




BYTO 2.5 mol.% + BYNO 2.5 mol.% / BYTO 5 mol.%: J_c behaviour @ low T

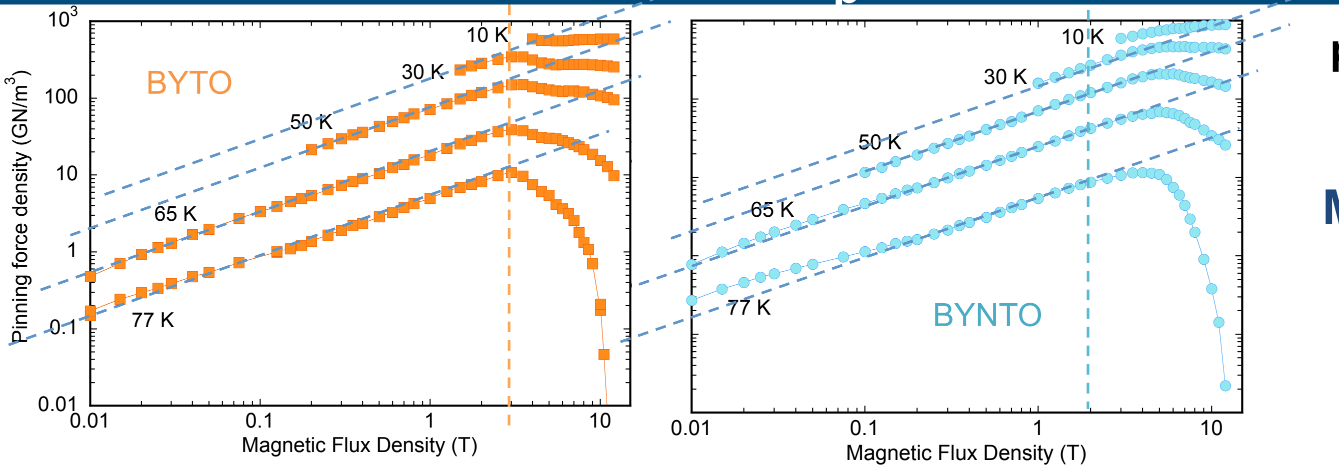


- **BYNTO** & **BYTO similar low field** behaviour (up to $B \approx 3$ - 4 T)
- **BYNTO** has **better *high-field*** behaviour than **BYTO** (@ 10 K, 12 T J_c(BYNTO) = 1.7x J_c(BYTO))



Both **BYTO** and **BYNTO** largely **improve YBCO** performances in **whole *T*- and *B*- range** (@ 10 K, 12 T J_c(BYNTO) = 3x J_c(YBCO))

BYTO 2.5 mol.% + BYNO 2.5 mol.% / BYTO 5 mol.%: Pinning Force Density, F_p



power law exponents are *T*-independent

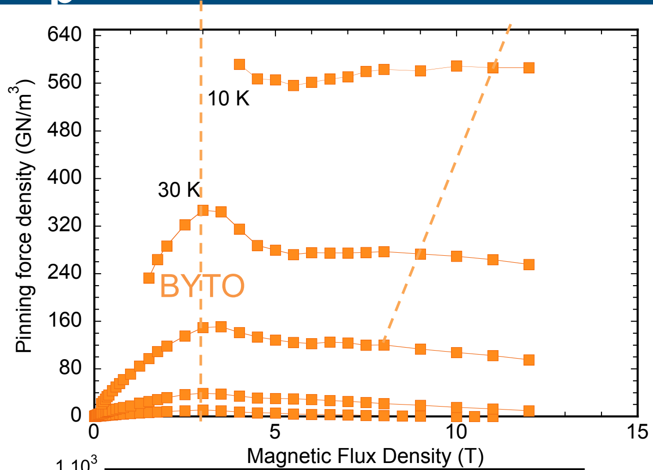
Matching field effect

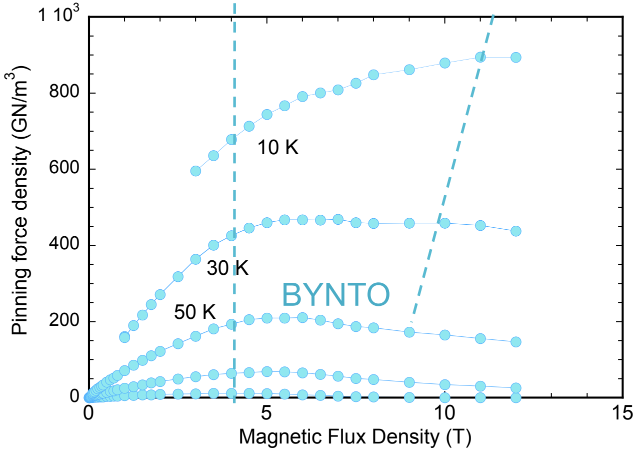
BYTO	77 K	65 K	50 K	30 K	10 K
α, $J_c \approx B^{-\alpha}$	0.23	0.26	0.22	0.26	---

BYNTO	77 K	65 K	50 K	30 K	10 K
α, $J_c \approx B^{-\alpha}$	0.28	0.24	0.21	0.26	---

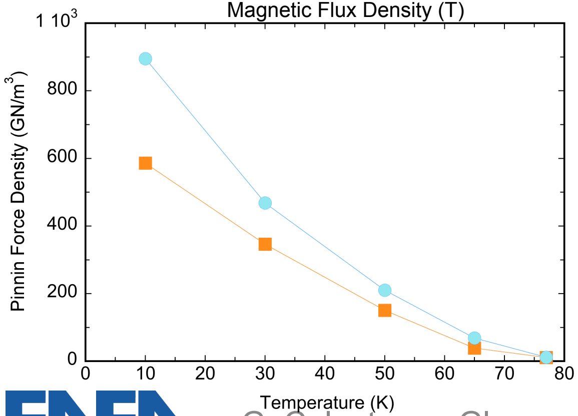
BYTO/BYNTO columnar systems is effective in the whole *T*-range and dominate for **B [0 – B_Φ]**

BYTO 2.5 mol.% + BYNO 2.5 mol.% / BYTO 5 mol.%: F_p behaviour @ low T





BYNTO/**BYTO** presence of a **second high field F_p component** emerging **at low T**



BYNTO	77 K	65 K	50 K	30 K	10 K
F_p(max) (GN/m³)	12	69	210	469	895
B @ F_p(max)	4	5	6	7	11

BYNTO has a **second high field F_p component** which makes it more performing wrt to BYTO **at low T**

Conclusions 1/2

Mixed doping by $Ba_2(Y,Ta)O_6$ + $Ba_2(Y,Nb)O_6$: 2.5 mol.% + 2.5 mol.%

- BYTO single vs mixed BYTO + BYNO doping;

BYNTO **exhibits the best J_c in extended T and B ranges**

This results from a **synergetic combination** of:
- **density** of columns;
- **size** of columns;
- **continuity**;
- **splay**;
- **Y_2O_3 nanoparticles** decorating BYNTO columns;
- CuO **intergrowth** density;

key factors (by comparison with BYTO)

This landscape provide an **effective contribution to vortex pinning at low T < 30 K**

Can the defect landscape be tuned?

Mixed doping BYTO 2.5% + BYNO 2.5%: analysis of the film growth rate

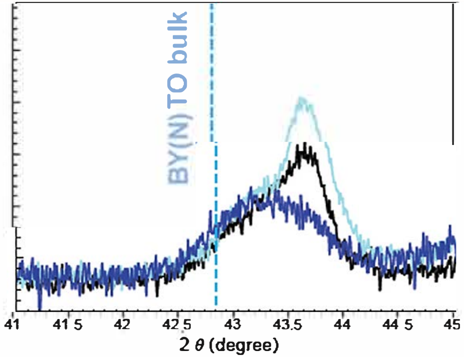
Film growth rate (ρ) tuned in the range $\rho \approx 0.02 - 1.8$ nm s^{-1} **by:**

- laser repetition rate;
- laser wavelength;

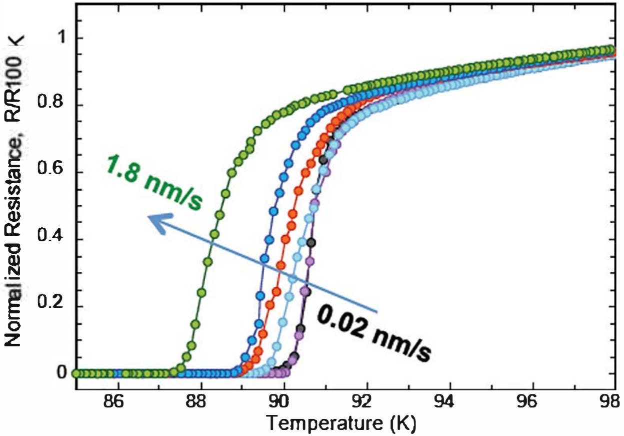
rate per pulse @248 nm ≈ 3 × @308 nm

PLD setup
XeCl/KrF Excimer Laser
λ = 308 nm
λ = 248 nm
f_L = 1 - 15 Hz
fluence ≈ 1.5 – 2 J/cm^2

Film thickness ≈ 200 nm



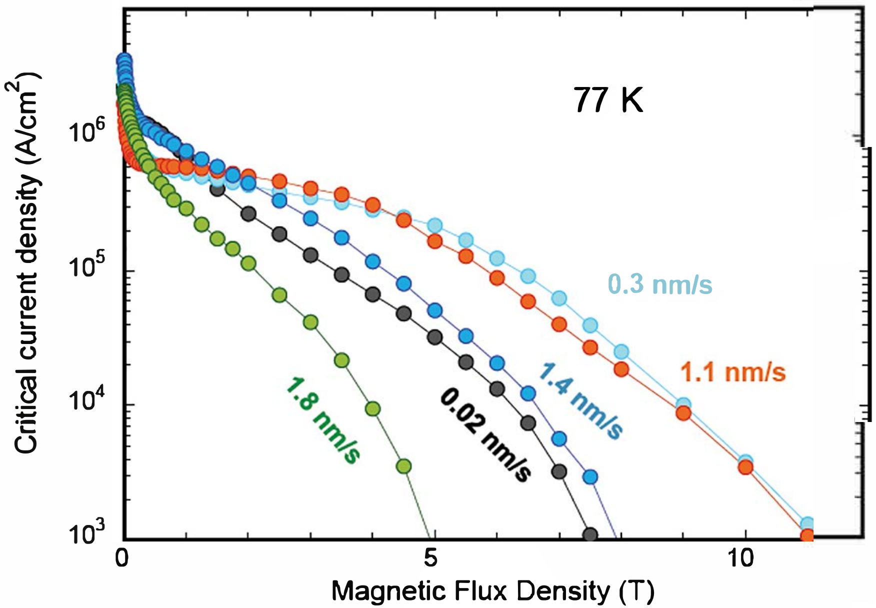
Growth rate (nm/s)	0.02	0.3	1.4
c_{YBCO} (Å ± 0.007)	11.696	11.692	11.714
$a_{BY(N)TO}$ (Å ± 0.01)	8.31	8.30	8.36
FWHM (005)	0.12	0.13	0.13

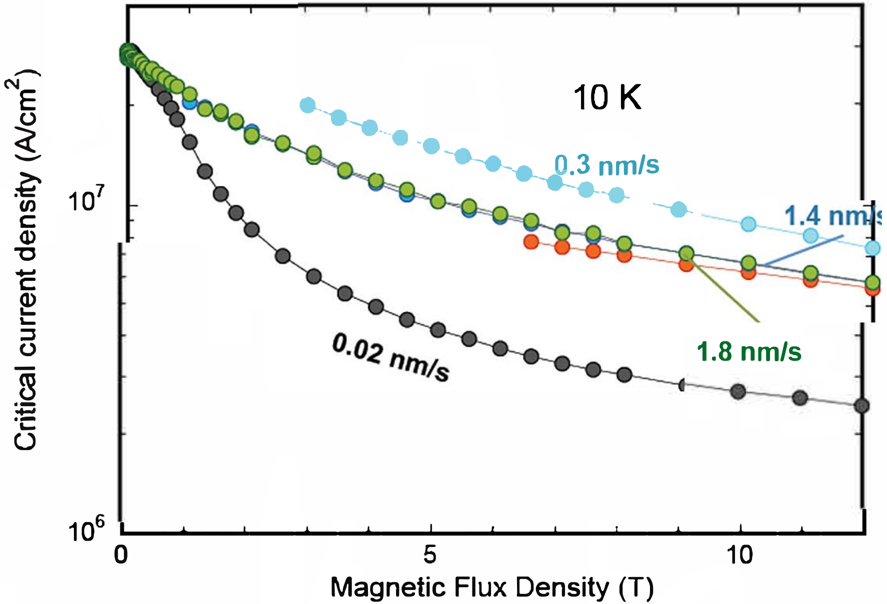


With higher rates:

- higher strain in YBCO;
- change in BYNTO;
- lower T_c;

more details will be provided by F. Rizzo in his talk, today





@ 77 K, best J_c in field behaviour for rates within 0.3 – 1.1 nm/s with extended plateau and highest H_{irr}

@ 10 K, $J_c(B)$ for high rates very similar (1.4 nm/s and 1.8 nm/s fully overlap!)
J_c(12 T) = 7.4 , 5.8, 6.0, 6.0 MA/cm²

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Conclusions 2/2

Mixed doping by $Ba_2(Y,Ta)O_6$ + $Ba_2(Y,Nb)O_6$: 2.5 mol.% + 2.5 mol.%

- BYTO single vs mixed BYTO + BYNO doping;

BYNTO exhibits the best in **extended angular, *T* and *B* ranges**

The landscape provides an **effective contribution to vortex pinning at low *T* < 30 K**

- Defects landscape tunability by growth rate;

Very low rate (0.02 nm/s ←): *continuous columns with reduced density and increased diameter + Y_2O_3 nanoparticles*
high rate (→ 1.8 nm/s): *ab-plane platelets + c-axis rods*

crossing 0.3 - 1.1 nm/s
high performances in the whole T-range

Growth rates (nm/s)	High T	low T
low rates	☺	☹
intermediate (0.3-1.1)	☺	☺
high rates	☹	☺

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Thank you for your attention