Investigation of 2G HTS tapes irradiation towards applications in the space industry

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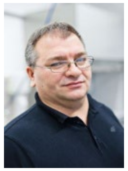

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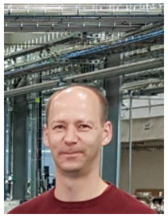

OUTLINE

- **Historical overview**
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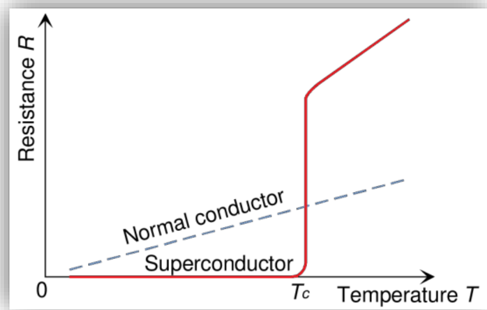
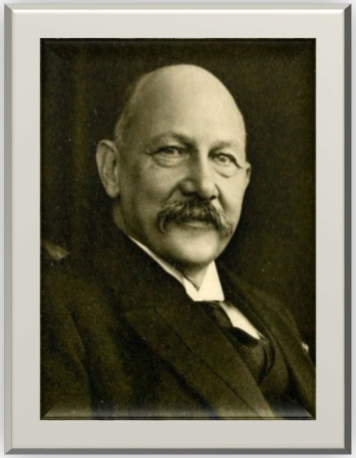


HISTORICAL OVERVIEW



Heike Kamerlingh Onnes

Superconductivity was discovered on April 8, 1911 by H.K. Onnes.

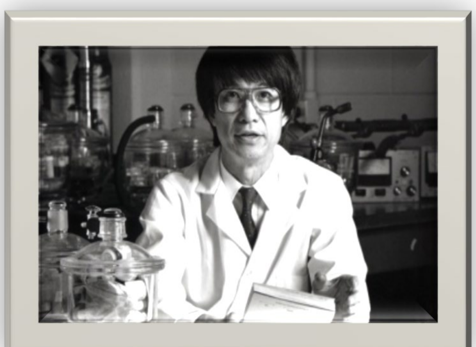
H.K. Onnes, *The resistance of pure mercury at helium temperatures*, Commun. Phys. Lab. Univ. Leiden. **12** (1911) p. 120.

J.G. Bednorz K.A. Müller discovered superconductivity in oxide materials (Nobel Prize in Physics, 1987).

J.G. Bednorz, K.A. Müller, *Superconductivity in $La_{2-x}Ba_xCuO_4$ in 36 K*, Z. Phys. B 64 (1986) p. 189.

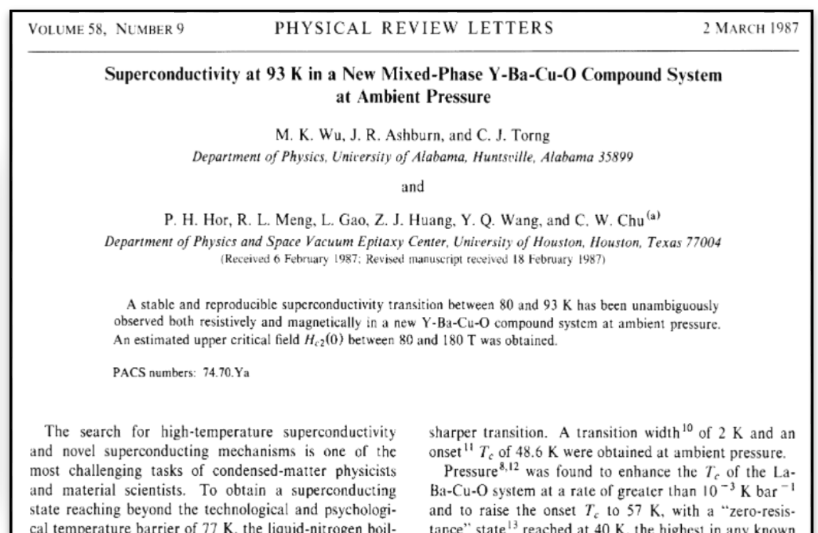
Johannes Georg Bednorz & Karl Alexander Müller

Replacing La with the smaller Y element (YBCO) raised the critical temperature to 93 K.



Paul Ching-Wu Chu

Maw-Kuen Wu



VOLUME 58, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1987

Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

M. K. Wu, J. R. Ashburn, and C. J. Torng
Department of Physics, University of Alabama, Huntsville, Alabama 35899

and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu[(a)]
Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004
(Received 6 February 1987; Revised manuscript received 18 February 1987)

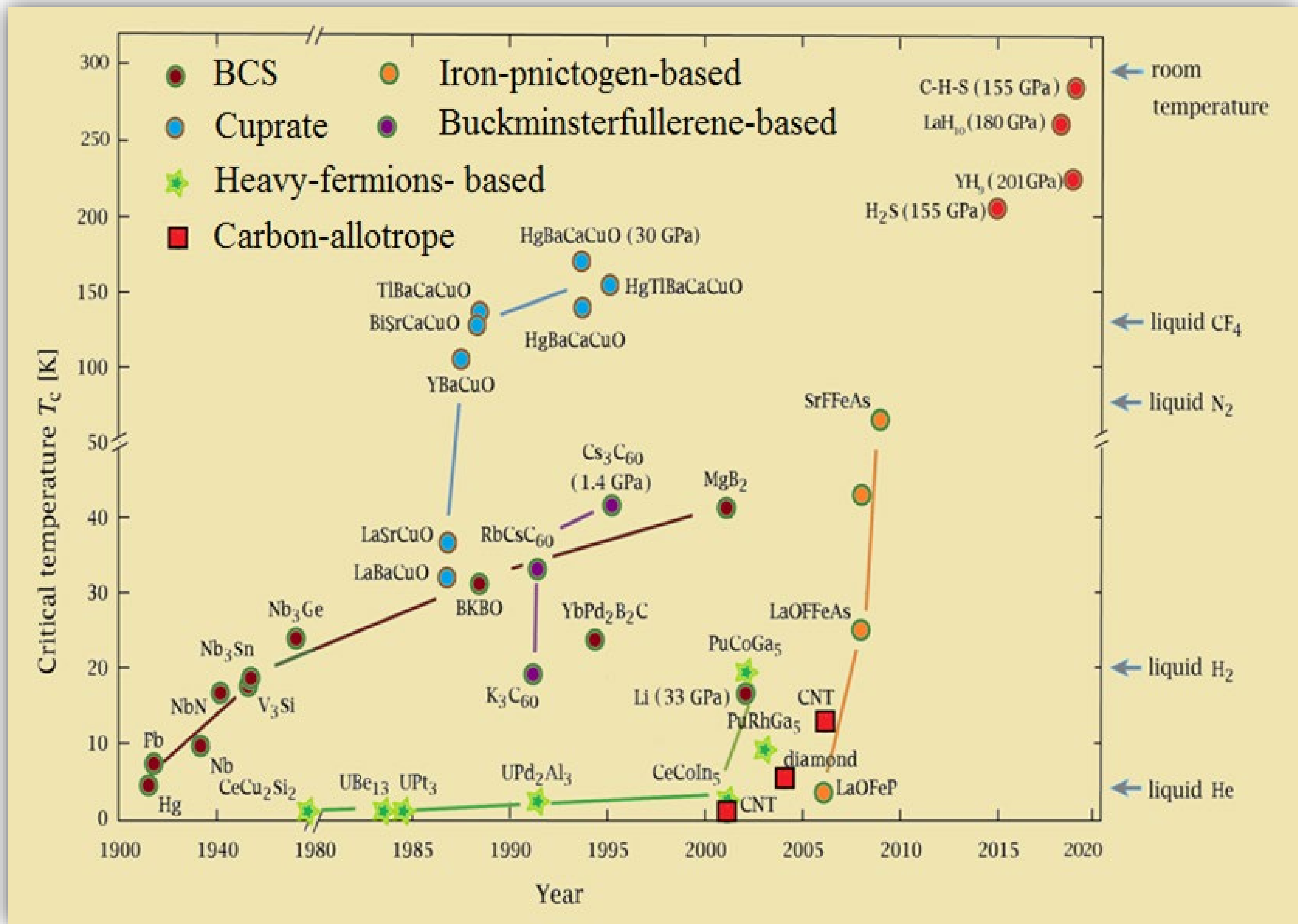
A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.

PACS numbers: 74.70.Ya

The search for high-temperature superconductivity and novel superconducting mechanisms is one of the most challenging tasks of condensed-matter physicists and material scientists. To obtain a superconducting state reaching beyond the technological and psychological temperature barrier of 77 K, the liquid-nitrogen boil-

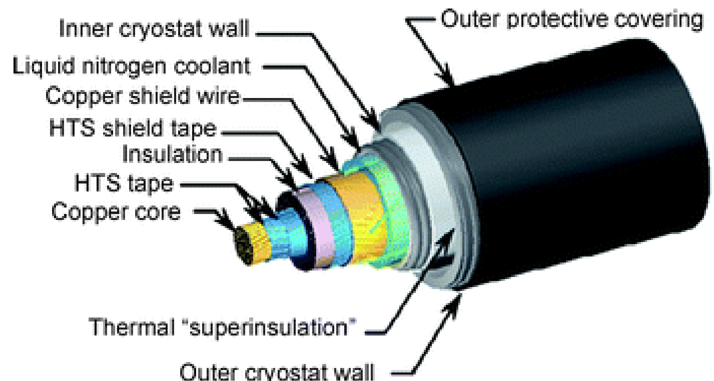
sharper transition. A transition width[10] of 2 K and an onset[11] T_c of 48.6 K were obtained at ambient pressure. Pressure[8,12] was found to enhance the T_c of the La-Ba-Cu-O system at a rate of greater than 10^{-3} K bar^{-1} and to raise the onset T_c to 57 K, with a "zero-resistance" state[13] reached at 40 K, the highest in any known

HIGH-T_C SUPERCONDUCTORS



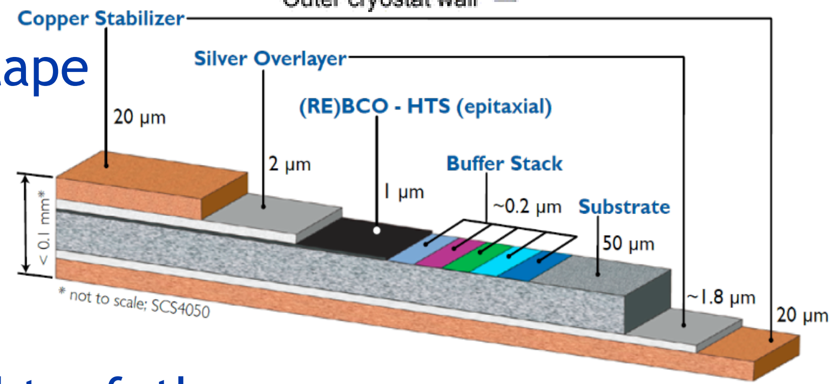
MOTIVATIONS

High-temperature superconducting (HTS) cables based on *RE*BCO-coated conductors in 2G architecture



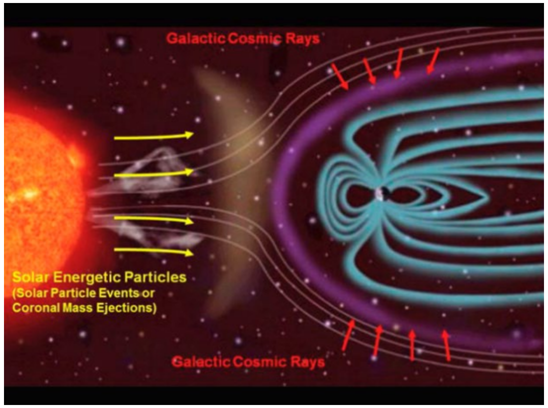
$J_c \sim 10^6\ \mathrm{A\ cm^{-2}}$

(RE)BCO-based HTS-2G tape



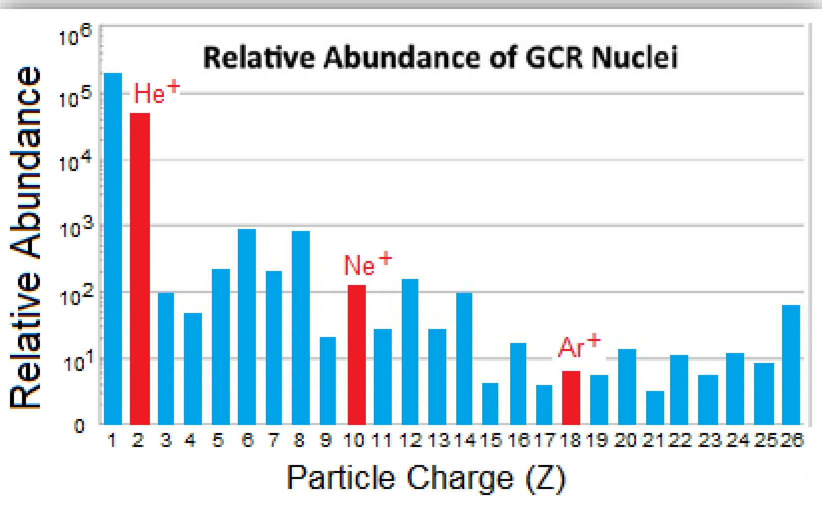
D.W. Hazelton (2014), *SuperPower 2G HTS Conductor*, WAM 1st Workshop on Accelerator Magnets in HTS, May 21-23, Hamburg, Germany.

The small dimensions and weight of the tape are very promising features to be used in the construction of magnetic shields protecting crews of spacecraft against cosmic radiation. The astronauts exposure to cosmic rays is one of the most dangerous factors threatening life and health in long manned missions.

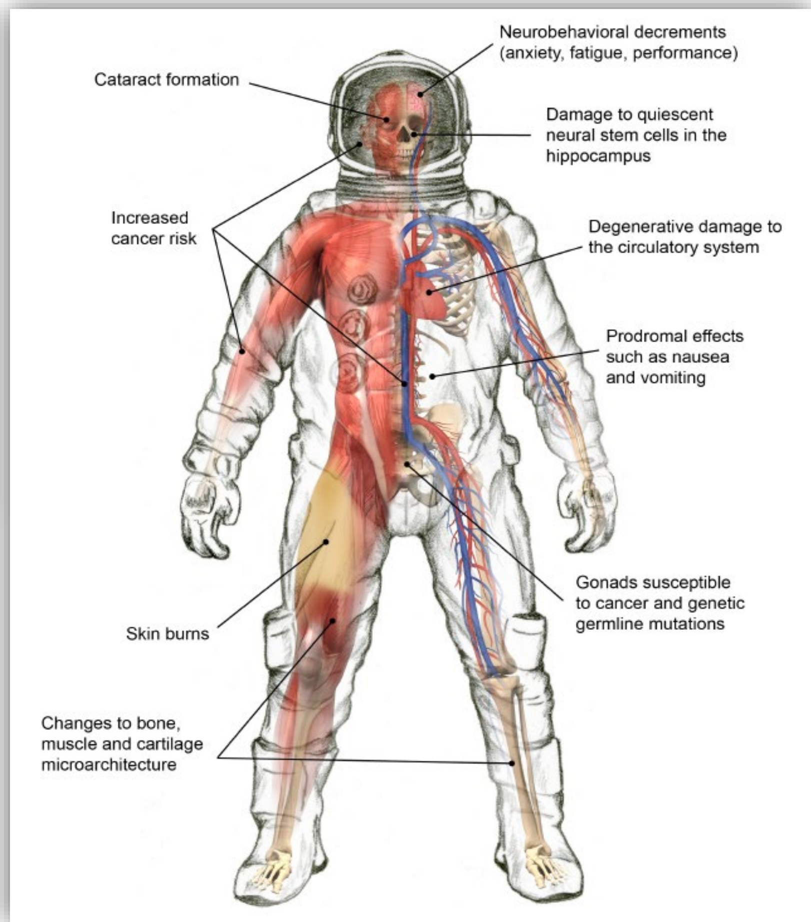


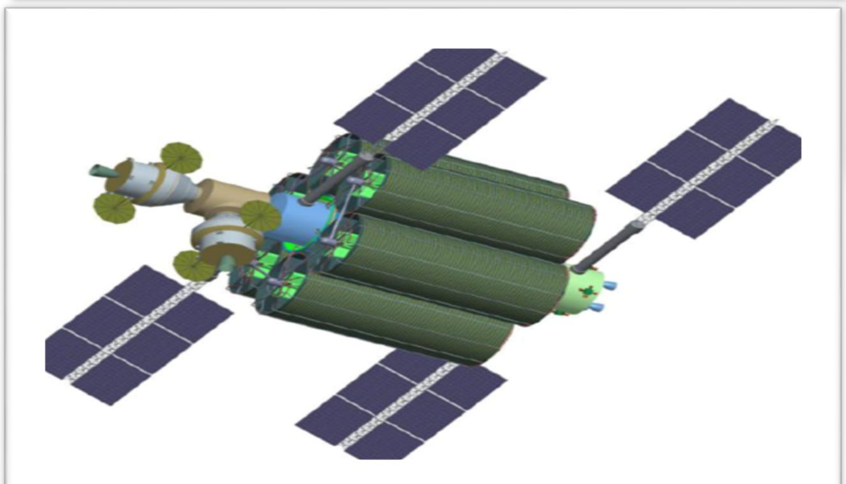
R. Kerr (31 May 2013), *Radiation Will Make Astronauts' Trip to Mars Even Riskier*, Science 340 (6136): 1031.

MOTIVATIONS



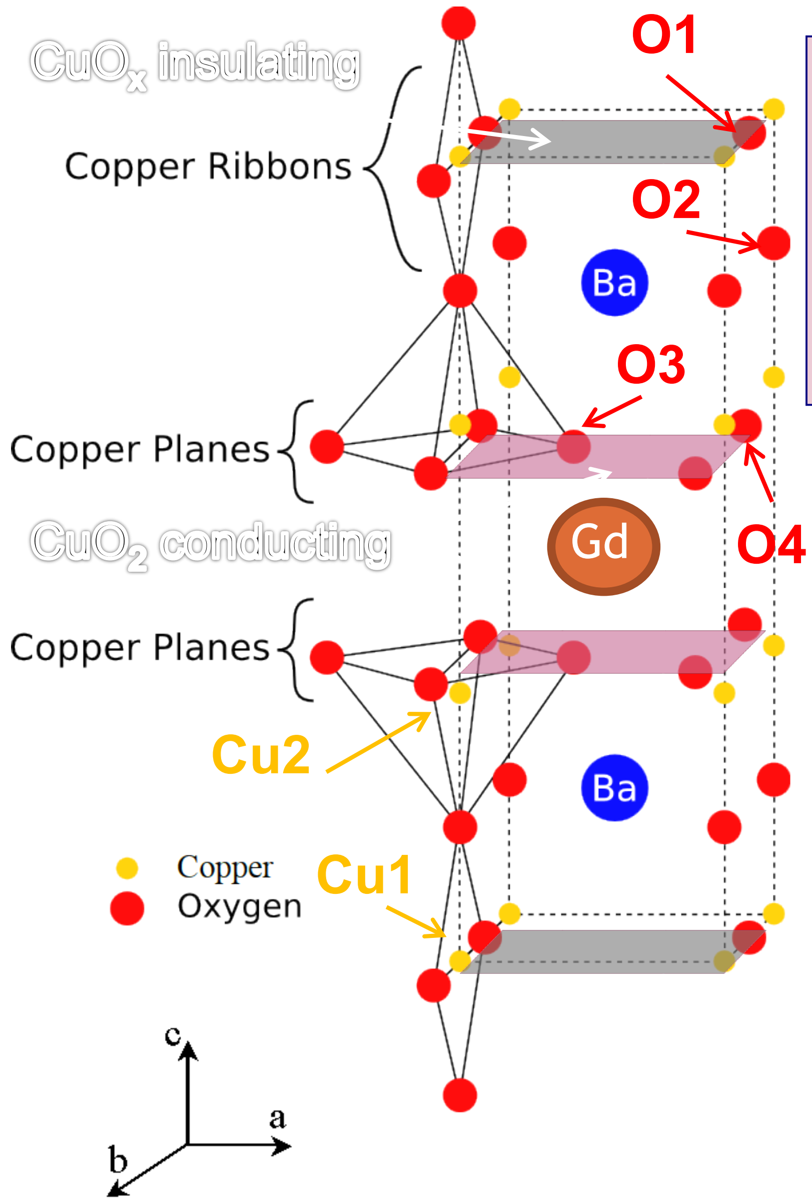
J.C. Chancellor, G.B.I. Scott, J.P. Sutton, *Space Radiation: The number one risk to astronaut health beyond low Earth orbit*, Life 4 (2014) 491 – 510.





NASA's proposed ARS (*Active Radiation Shielding)* design. Six expandable coils and one compensator coil are wrapped around the crew module for radiation protection.

SUPERCONDUTING MATERIAL



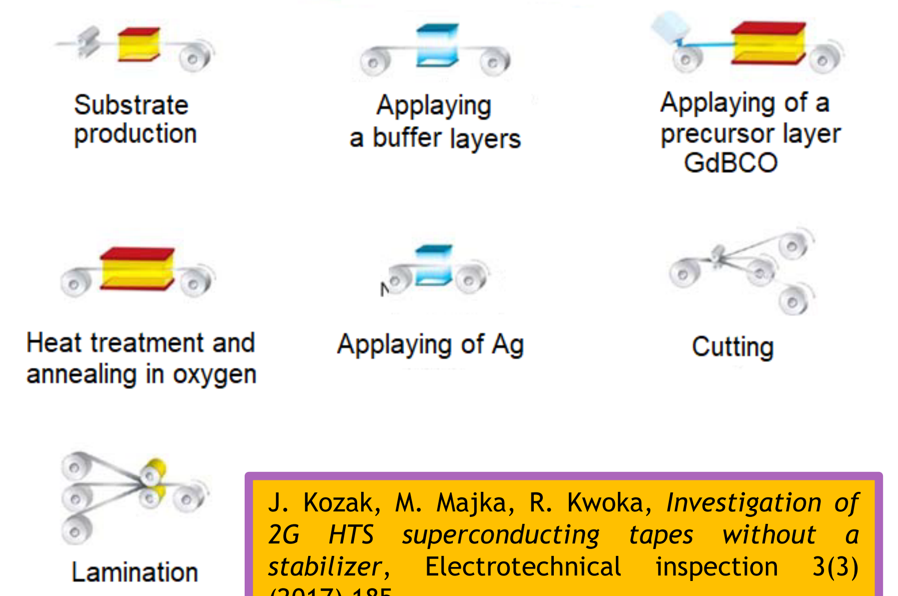
$GdBa_2Cu_3O_{7-\delta}$ ($0 \leq \delta \leq 1$)

$\delta < 0.35$
orthorhombic *Pmmm* (No. 47)
a = 3.819 Å, b = 3.886 Å, c = 11.681 Å

T_C ~ 92 – 94 K

atom	Wyckoff	x	y	z
Gd	1h	1/2	1/2	1/2
Ba	2t	1/2	1/2	0.1838
Cu1	1a	0	0	0
Cu2	2q	0	0	0.3549
O1	1e	0	1/2	0
O2	2s	1/2	0	0.3786
O3	2r	0	1/2	0.3781
O4	2q	0	0	0.1589

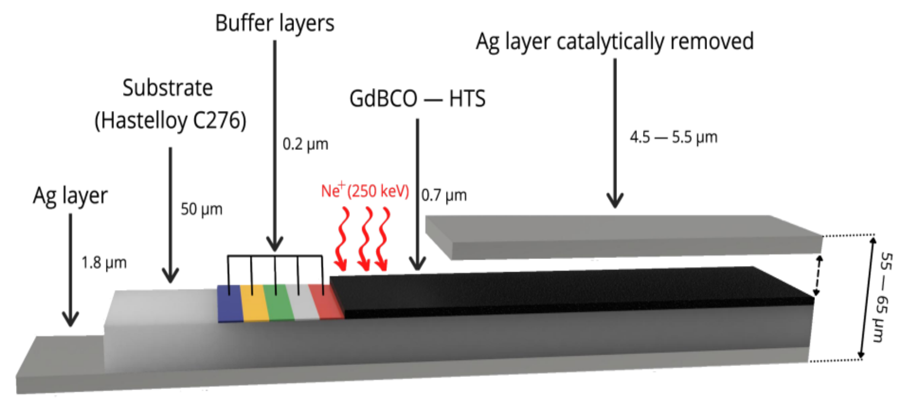
CONSTRACTION OF 2G HTS TAPES



J. Kozak, M. Majka, R. Kwoka, *Investigation of 2G HTS superconducting tapes without a stabilizer*, Electrotechnical inspection 3(3) (2017) 185.

New 2G HTS tapes

2 years of aging (in the fridge)

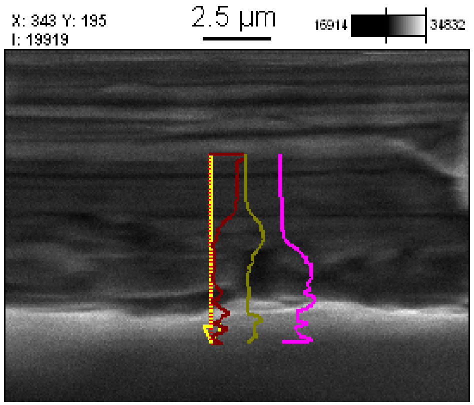


The structure of the 2G HTS SF (Stabilizer Free) 12050 superconducting tape by SuperPower Inc. The top Ag layer was removed by catalytic method. A superconducting GdBCO layer irradiated with Ne^{+} ions.

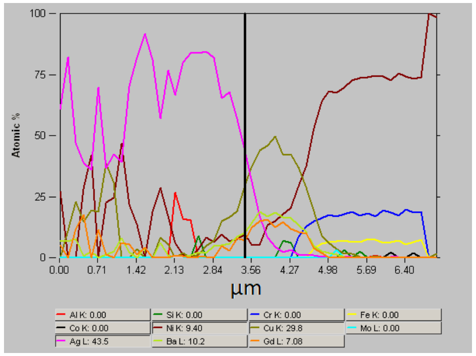
The Ag protective layer from the 2G HTS tapes was removed by prof. Elżbieta Szostak at the Faculty of Chemistry of the Jagiellonian University

PARAMETERS OF 2G HTS TAPES

HTS-2G tapes	SF 12050	SF 12100
Width	12 mm	12 mm
Length (segmental)	to 700 mm	to 600 mm
Thickness	55 µm	105 µm
Ag layer thickness	~1 µm	~ 1 µm
Substrate thickness	50 µm	100 µm
Yield point	1200 MPa	650 MPa
Minimum bending diameter	11 mm	25 mm
Substrate material	C276	C276
Critical current $I_{c\ (77\ K)}$	200 – 450 A	200 – 450 A
Critical temperature T_c	~ 92 – 94 K	~ 92 – 94 K



Accelerating Voltage: 25.0 kV
Magnification: 8000



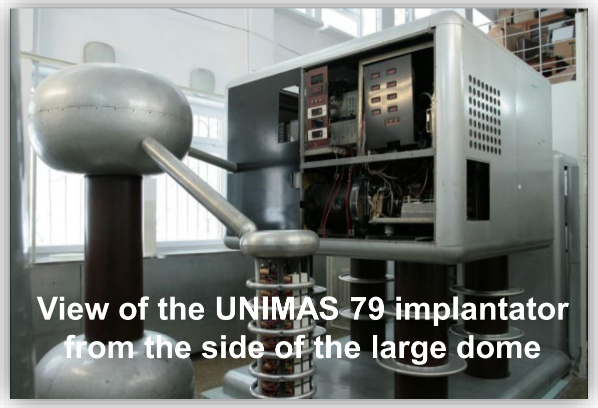
For the tape substrate, the non-magnetic Hastelloy C276 alloy (Ni-57.00%, Mo-16.00%, Cr-15.50%, Fe-5.50%, W-4.00%, Co-2.50%) is used about thickness 50 µm for the SF12050 and thickness 100 µm for the SF12100. The superconducting material (*RE*)-BCO in SF tapes has a thickness of up to 1 µm.

IMPLANTATION WITH NEON IONS

Ion implantations were performed using **UNIMAS-79 implanter** at Institute of Physics of the Maria Curie-Skłodowska University in Lublin. Arc discharge ion source was employed to produce **Ne^+ ion beam**. The ion beam was ecxtracted using 25 kV voltage and mass-separated using 90° sector electromagnet, and finally accelerated to **250 keV**. The base pressure in the target chamber was of order 10^{-7} mbar. All implantations were performed to the target in room temperature.

The samples with fluences:

10^{12} Ne^+/cm^2,
$5 \cdot 10^{12}$ Ne^+/cm^2,
10^{13} Ne^+/cm^2,
10^{14} Ne^+/cm^2.



View of the UNIMAS 79 implantator from the side of the large dome

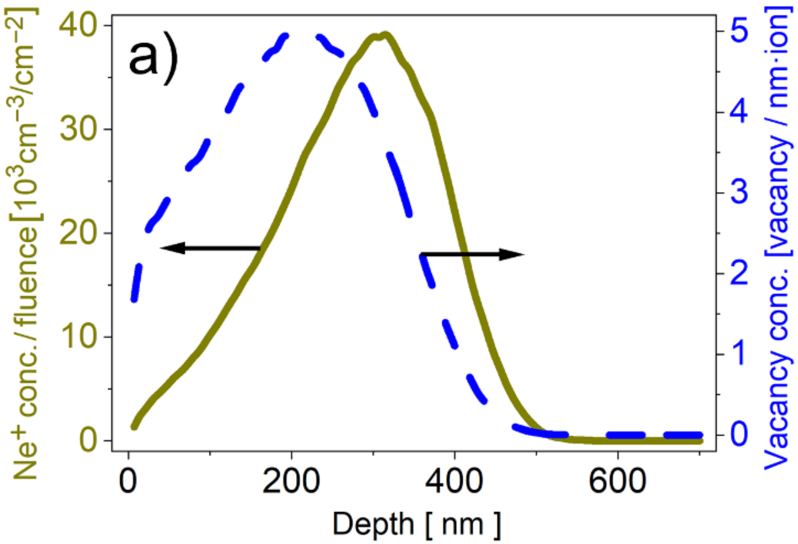
M. Turek, S. Prucnal, A. Droździel, K. Pyszniak, *Arc discharge ion source for europium and other refractory metals implantation*, Review of Scientific Instruments 80 (2009) 043304

M. Turek, S. Prucnal, A. Drozdziel, K. Pyszniak, *Versatile plasma ion source with an internal evaporator*, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 269 (2011) 700

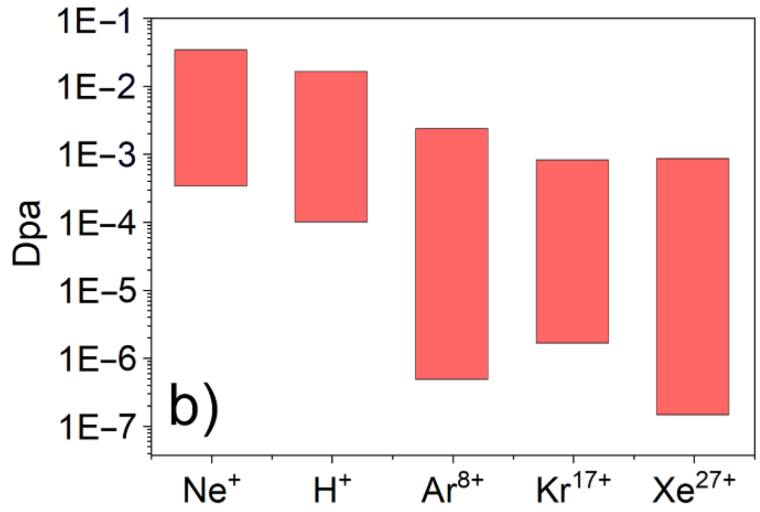
The irradiation current for the two lowest fluence implantations was ~20 nA/cm^2 and by order of magnitude larger for the other two processes.

The 2G HTS tape implantation was carried out by prof. Turek at UMCS in Lublin

IMPLANTATION WITH NEON IONS



Depth distribution of Ne^+ introduced into the 2G HTS layer (**solid line**) and depth distribution of vacancies (dashed line) produced during the bombardment.

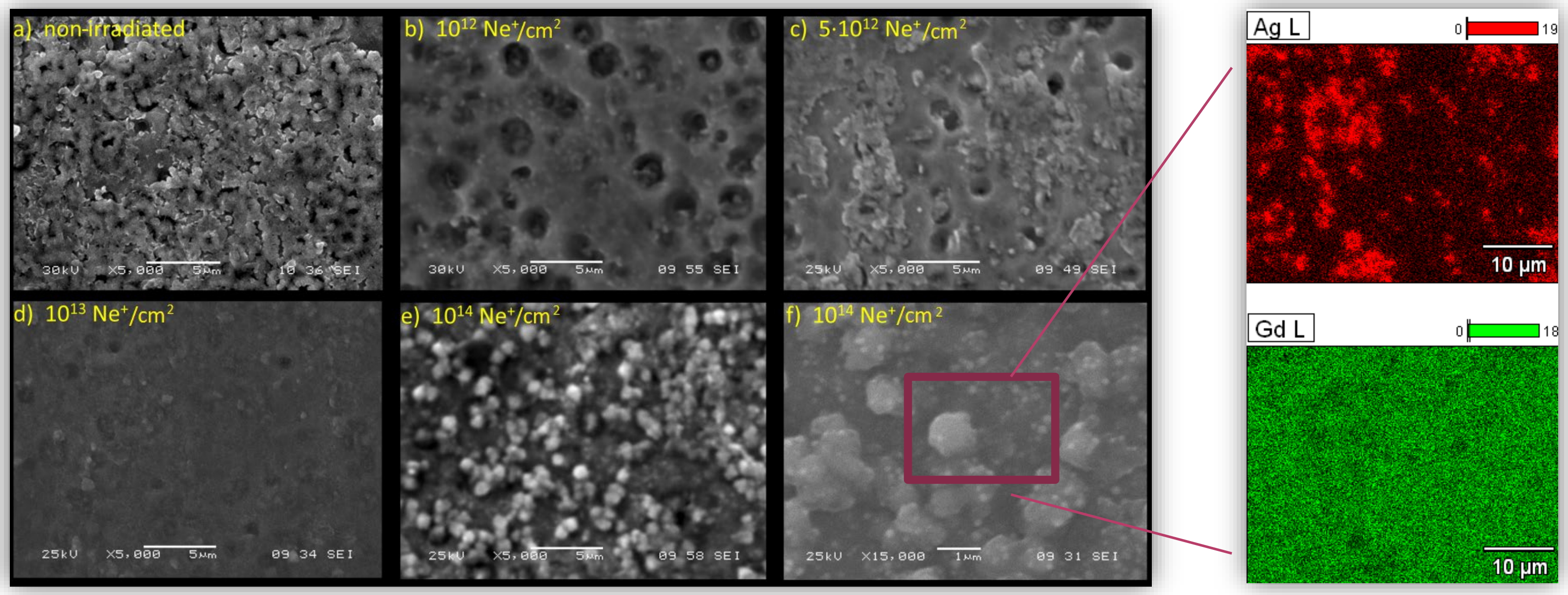


Dpa - displacements per atom (logarithmic scale) for Ne^+ and comparison at the same fluences for H^+ [1], and $^{40}Ar^{8+}$ [2], $^{84}Kr^{17+}$ [2], $^{132}Xe^{27+}$ [2].

[1] A. V. Troitskii, T. E. Demikhov, L. K. Antonova, A. Y. Didik, G. N. Mikhailova, *Radiation effects in high-temperature composite superconductors*, J. Surf. Invest. X-ray, *Synchrotron Neutron Tech*. 10 (2016) 381–392.

[2] L. Antonova, A. Troitskii, G. Maikhailova, T. Demikhov, S. Kuzmichev, V. Skuratov, V. Semina, *Changes in critical parameters of $GdBa_2Cu_3O_{7-x}$ HTS-2G due of swift-ion irradiation*, *Phys. Stat. Soli. B* 256(5) (2019) 1800255.

MICROSTRUCTURE ANALYSIS

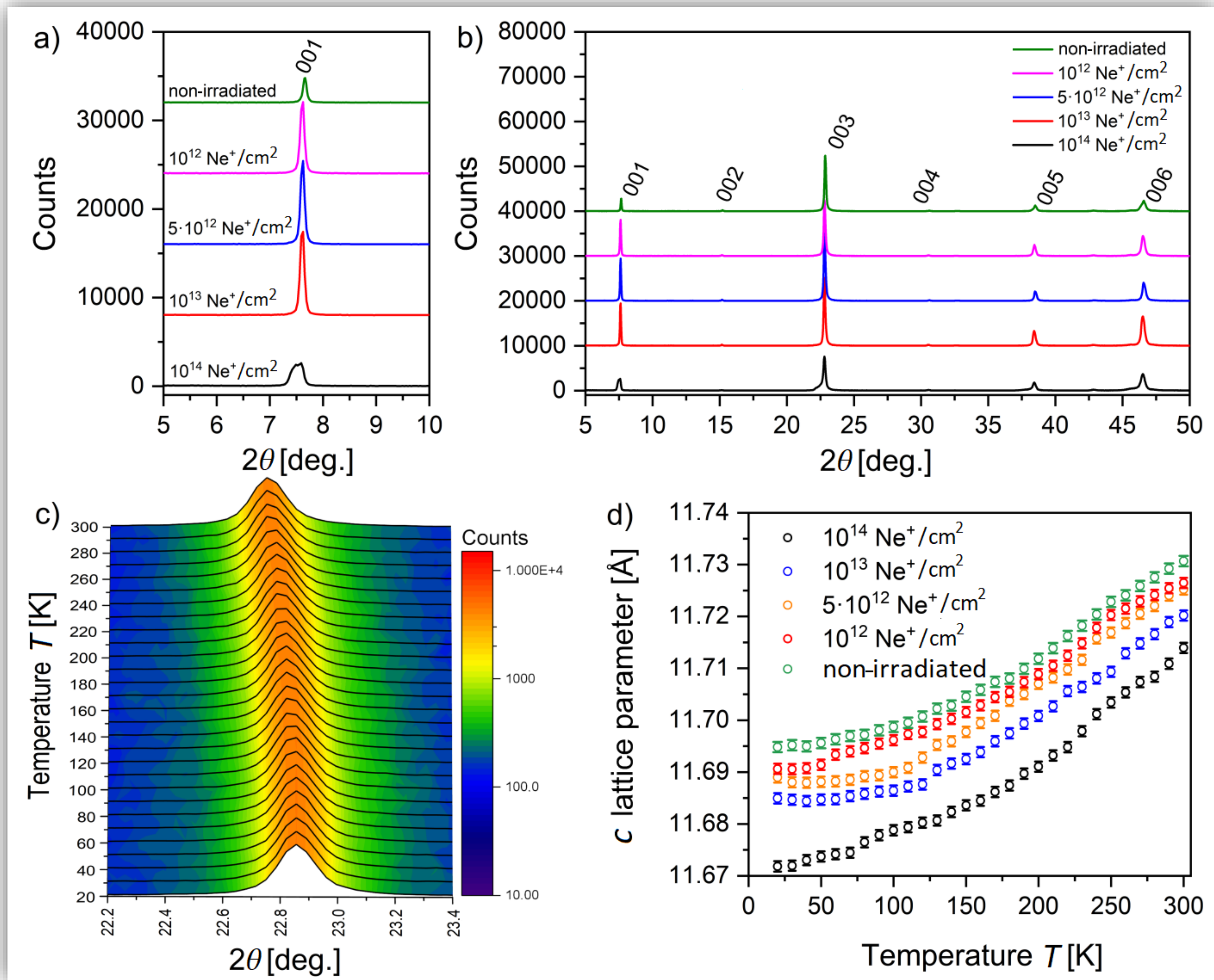


The superconducting layer shows porous microstructure with pores from about 1 to 4 µm.

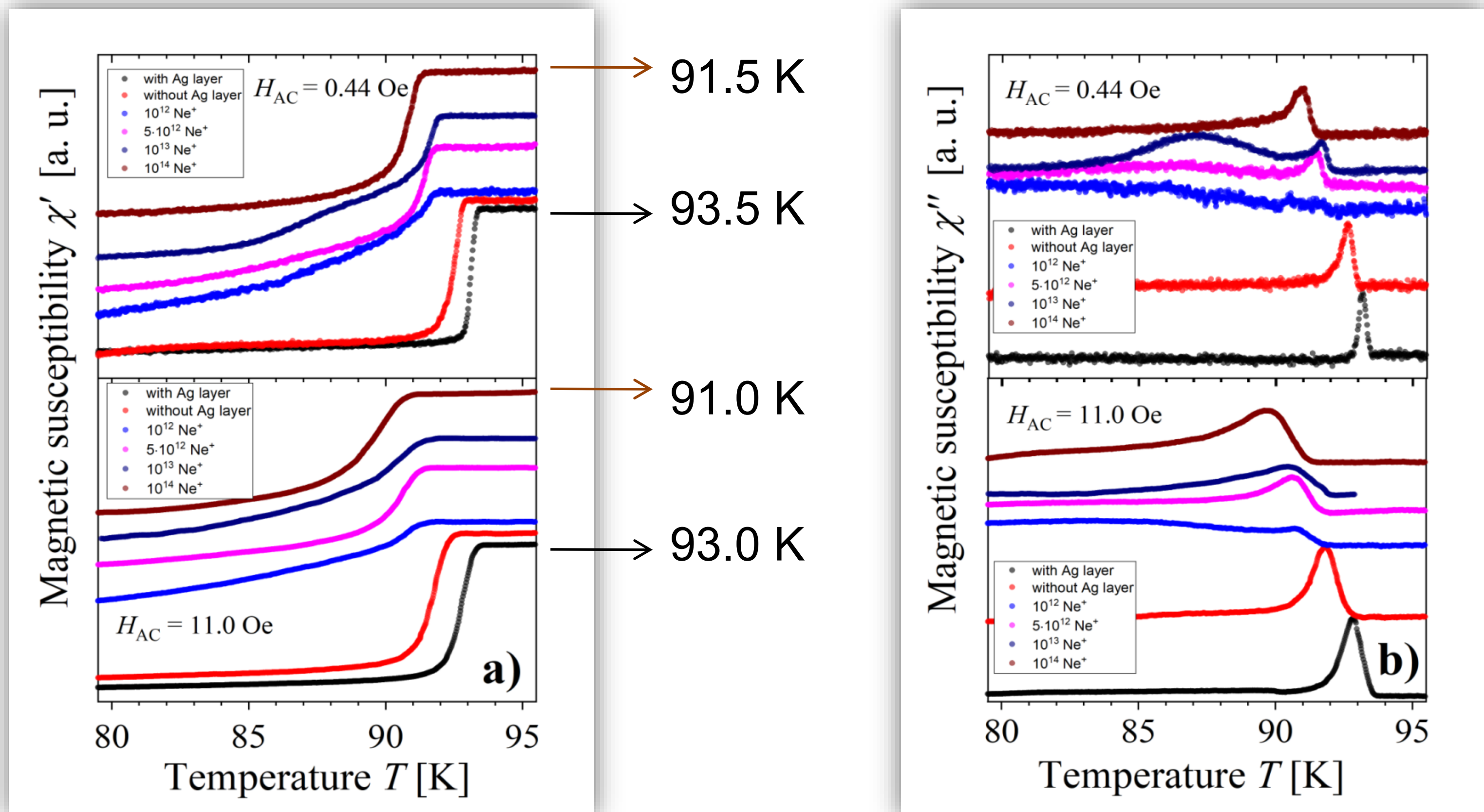
- The microstructures of raw and moderately irradiated samples (up to $5\cdot10^{12}$ Ne^+/cm^2) are similar.
- For fluence of 10^{13} Ne^+/cm^2 the superconducting layer exhibits exfoliation, resulting with covering the pores with partially loose HTS material.
- For heavily irradiated tape (10^{14} Ne^+/cm^2) the exfoliated HTS material forms bubbles on the surface with uniform diameter of about 1 µm.
- Small bright spots visible in the Figs. e) and f) are Ag precipitations (according to EDS).

<u>Concluding:</u> only heavy irradiation is capable of introducing significant modifications to the microstructure.

STRUCTURE ANALYSIS

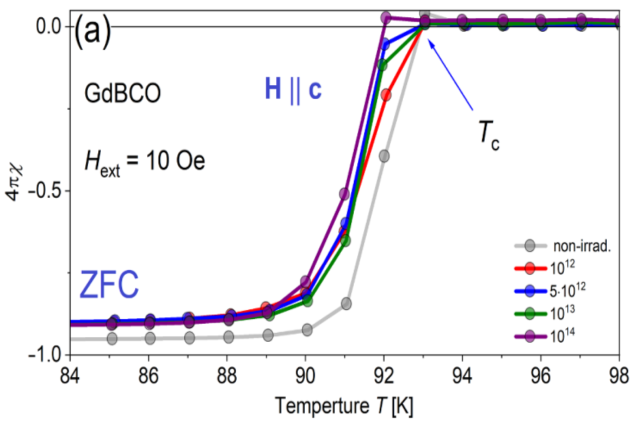


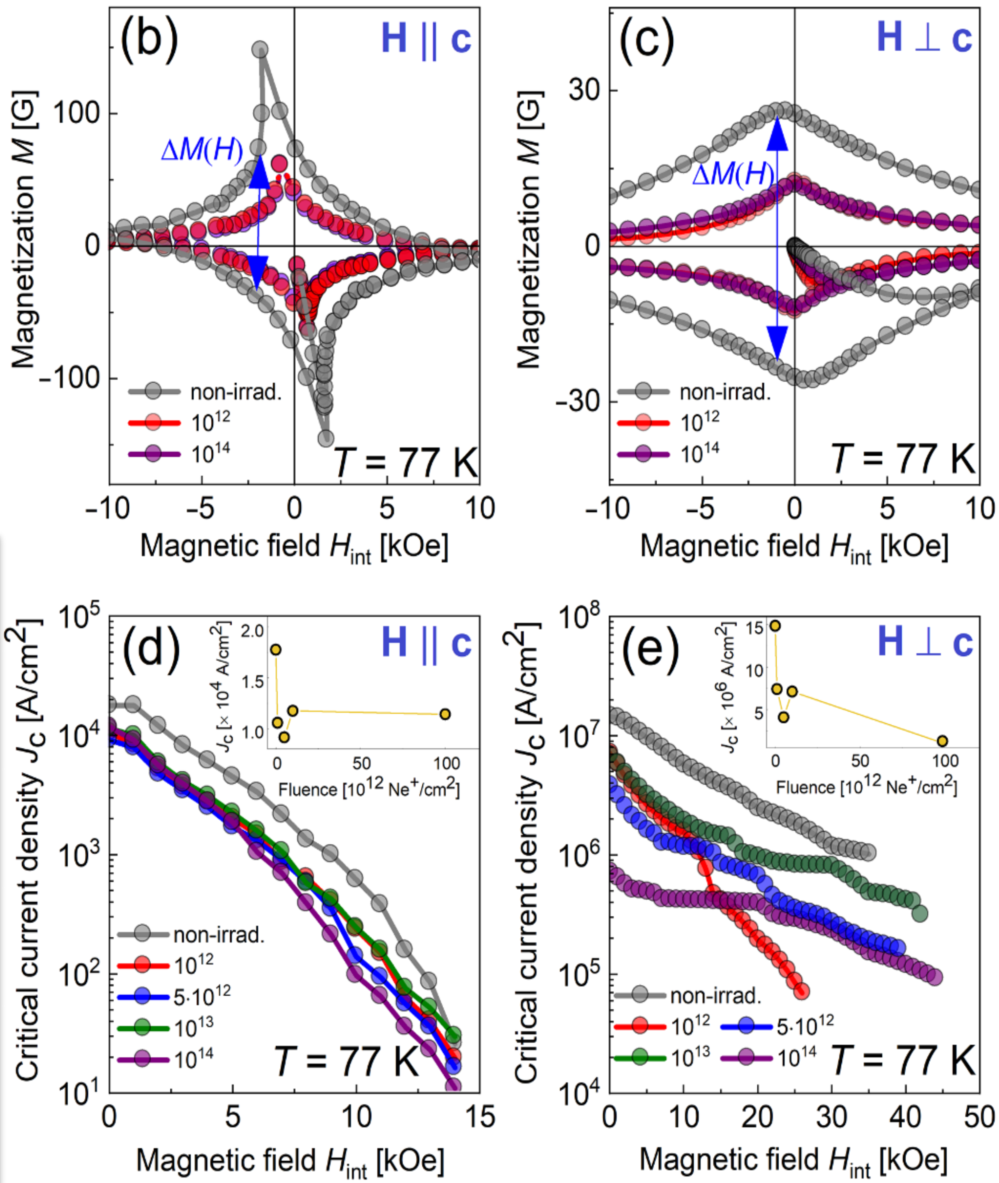
SUPERCONDUCTING MEASUREMENTS

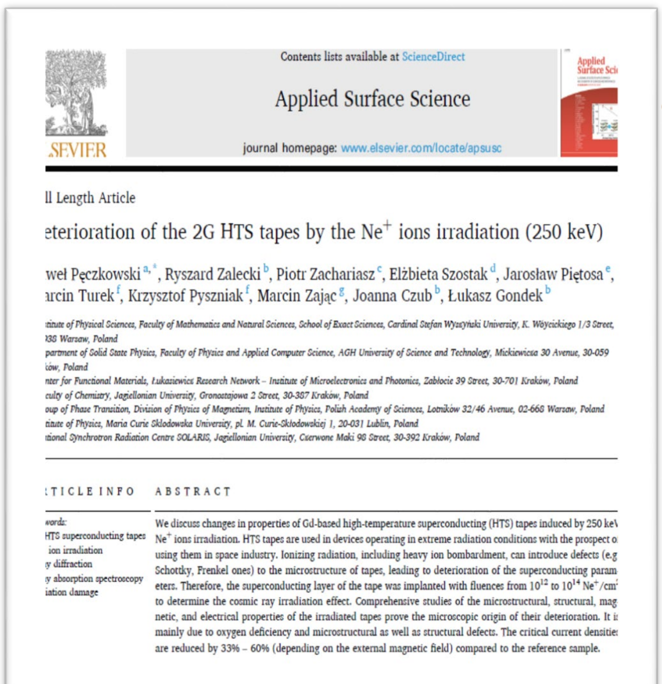


- ✓ Removing the Ag layer from the surface of the tape worsened its transport properties. It can be seen a slight decrease in the critical temperature.
- ✓ Exposing the tape to the Ne^{+} ion beam partially destroyed the integrain junctions and widening absorption peaks.
- ✓ The peak maxima show a clear shift to lower temperatures as the magnetic field amplitude increases.

SUPERCONDUCTING MEASUREMENTS







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ll Length Article

eterioration of the 2G HTS tapes by the Ne^+ ions irradiation (250 keV)

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ːTICLE INFO

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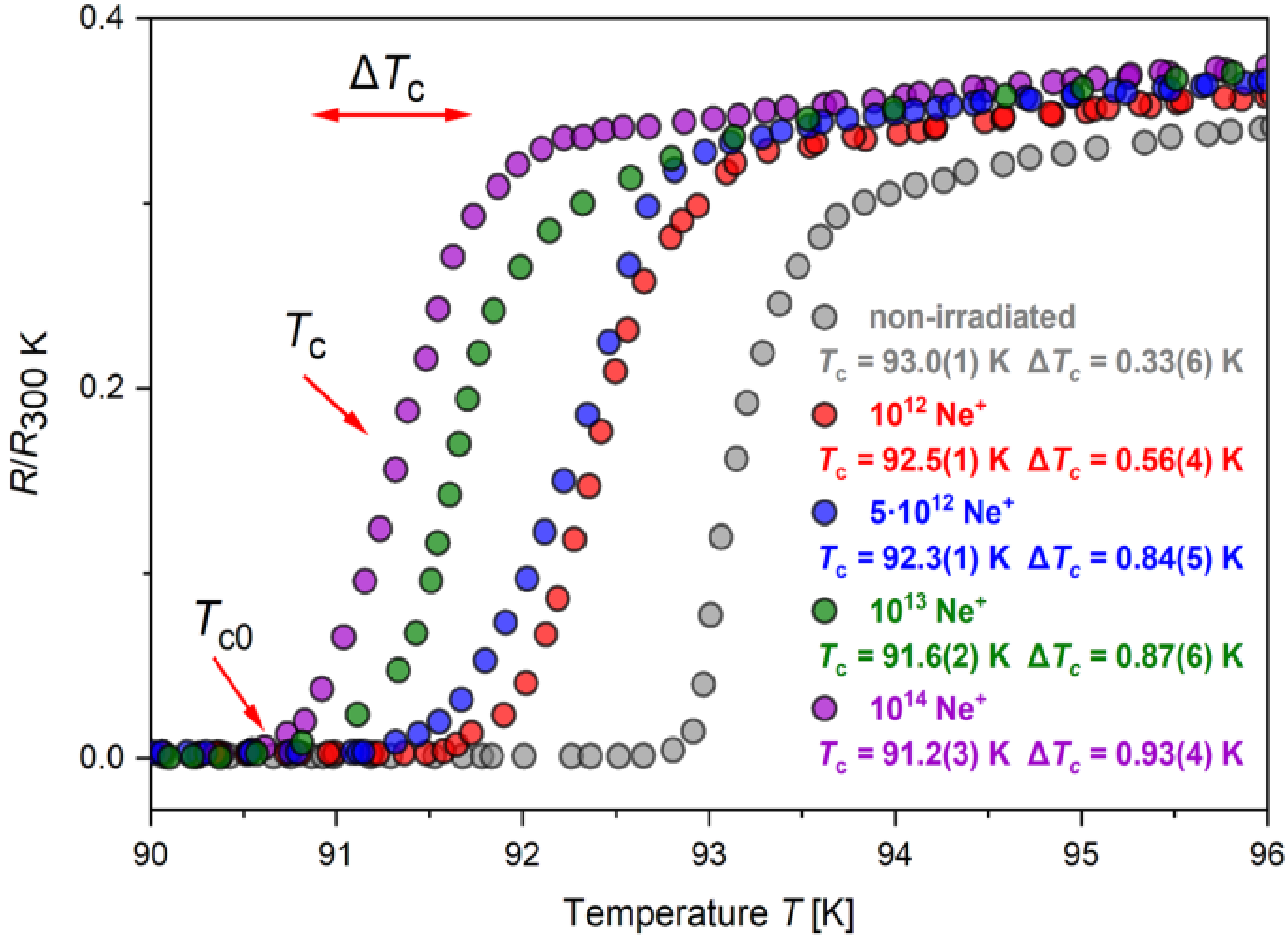
y diffraction
y absorption spectroscopy
iation damage

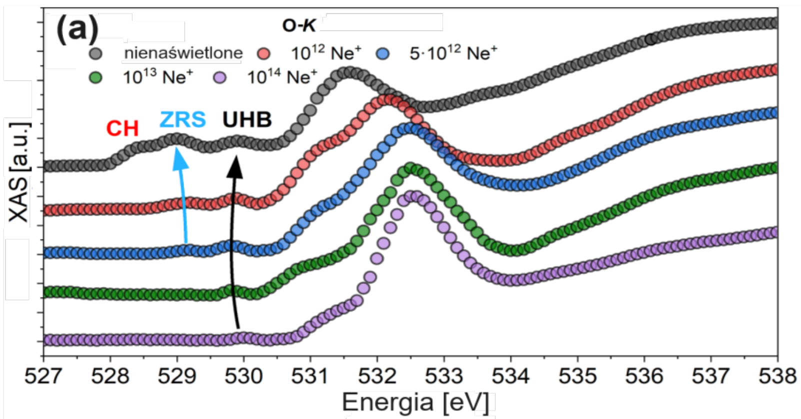
ABSTRACT

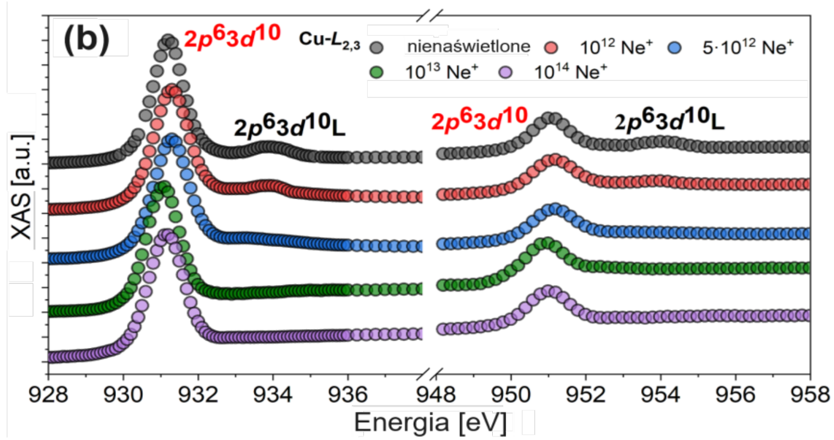
We discuss changes in properties of Gd-based high-temperature superconducting (HTS) tapes induced by 250 keV Ne^+ ions irradiation. HTS tapes are used in devices operating in extreme radiation conditions with the prospect o using them in space industry. Ionizing radiation, including heavy ion bombardment, can introduce defects (e.g Schottky, Frenkel ones) to the microstructure of tapes, leading to deterioration of the superconducting parameters. Therefore, the superconducting layer of the tape was implanted with fluences from 10^{12} to 10^{14} Ne^+/cm^2 to determine the cosmic ray irradiation effect. Comprehensive studies of the microstructural, structural, magnetic, and electrical properties of the irradiated tapes prove the microscopic origin of their deterioration. It is mainly due to oxygen deficiency and microstructural as well as structural defects. The critical current densities are reduced by 33% – 60% (depending on the external magnetic field) compared to the reference sample.

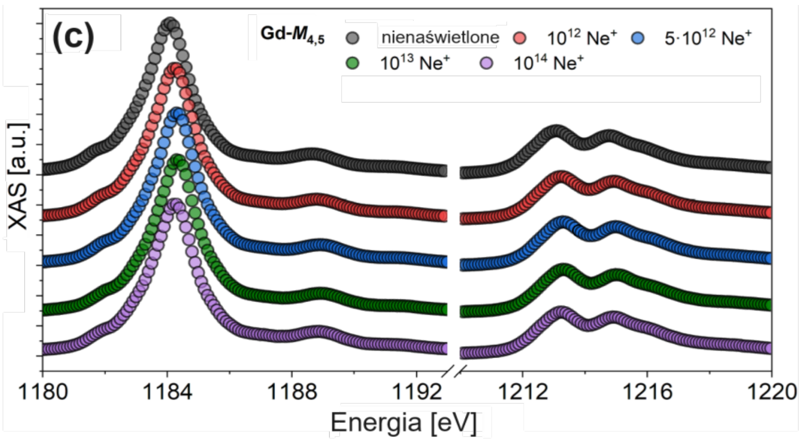
SUPERCONDUCTING MEASUREMENTS



X-RAY ABSORPTION SPECTROSCOPY



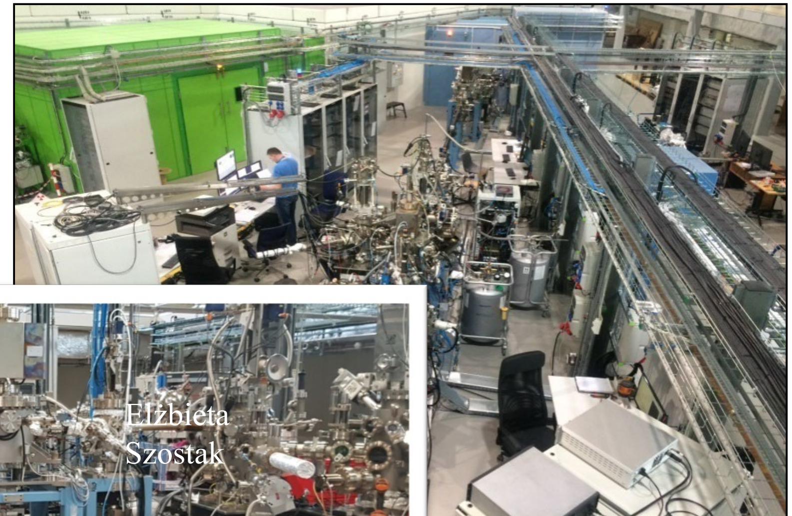


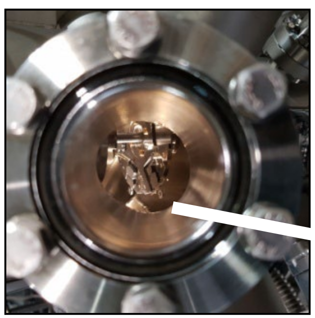


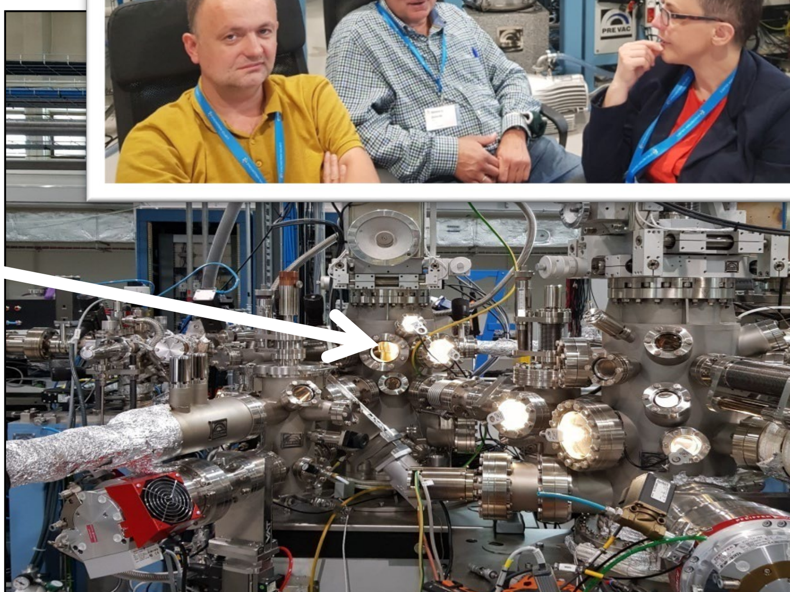
X-ray absorption (XAS) edges for non-irradiated GdBCO tape and for irradiated GdBCO tapes with fluences 10^{12}, $5\cdot10^{12}$, and 10^{14} Ne^+/cm^2: Gd $M_{4,5}$-edges **(a)**, Cu $L_{2,3}$-edges **(b)**, O K-edge **(c)**. The used abbreviations: CH - chain hole, ZRS - Zhang-Rice singlet, UHB - upper Hubbard band

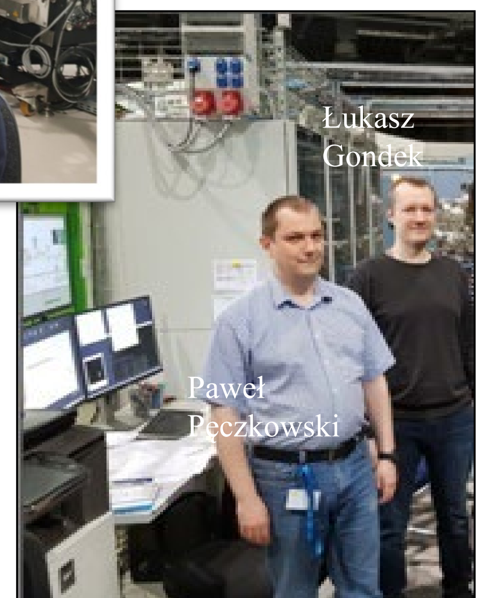
- The Gd $M_{4,5}$-edges enable the estimation of the Gd valence state (<u>Figure **a**</u>).
- The Cu-$L_{2,3}$ edges (<u>Figure **b**</u>) provides crucial information on the mobility of electrical carriers from the Cu–O_2 planes. The XAS signal change for tapes with fluence of 10^{14} Ne^+/cm^2 shows deterioration of superconducting properties.
- Taking into account the $2p_{xy}$ orbitals of oxygen are hybridized with the $3d_{x^2-y^2}$ Cu orbitals, the data inspection provides crucial information on the electronic doping of the Cu–O_2 planes (<u>Figure **c**</u>).

EXPERIMENT AT THE SOLARIS









CONCLUSIONS

- The microstructures of non-irradiated and moderately irradiated samples are similar. For heavily irradiated tape exfoliated HTS material forms bubbles on the surface.
- The XRD shows that the structure of the tape deteriorates for the tape implanted with the Ne^+ ion beam of fluence with 10^{14} Ne^+/cm^2.
- For the magnetic field amplitude 0.44 Oe, the critical temperature dropped from 93.5 K for the non-irradiated sample in the Ag protective layer to 91.5 K for the implanted tape with the maximum fluidity 10^{14} Ne^+/cm^2. For the magnetic field amplitude 11.0 Oe, both these critical temperatures are 0.5 K lower.
- There is a decrease of critical current density by three times for the irradiated samples, when compared to the non-irradiated tape.
- The Cu$L_{3,2}$-edges provides crucial information on the mobility of electrical carriers from the Cu–O_2 planes. The XAS signal change for tapes with fluence 10^{14} Ne^+/cm^2 shows deterioration of superconducting properties.

REFERENCES

H.K. Onnes, *The resistance of pure mercury at helium temperatures,* Commun. Phys. Lab. Univ. Leiden. **12** (1911) p. 120.

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THANK YOU FOR YOUR ATTENTION

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