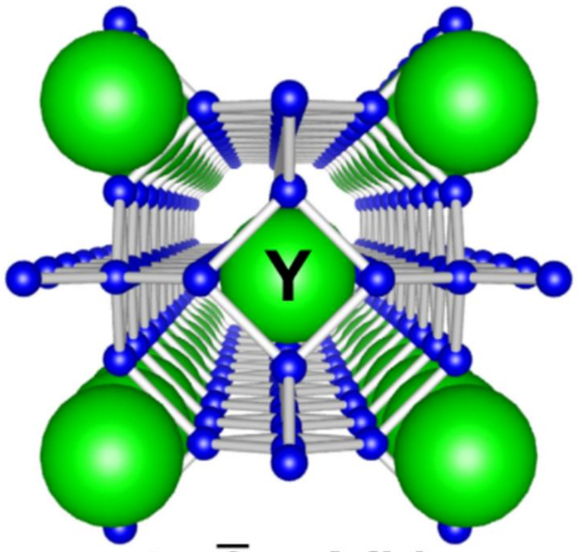
Studies of hydride superconductors in pulsed magnetic fields up to 80 T using special high-pressure DACs

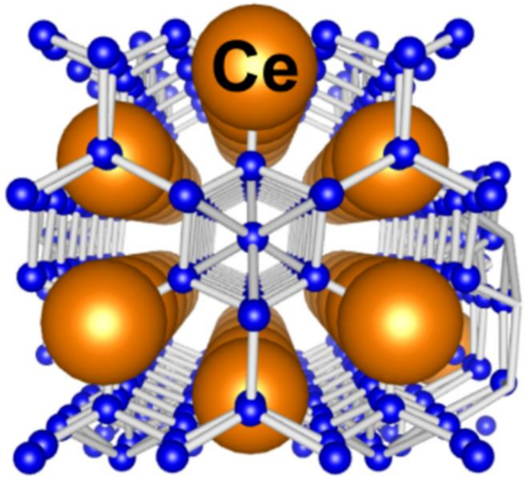
Dmitrii Semenok
HPSTAR Beijing

北京高压科学研究中心
Center for High Pressure Science &Technology Advanced Research
HPSTAR

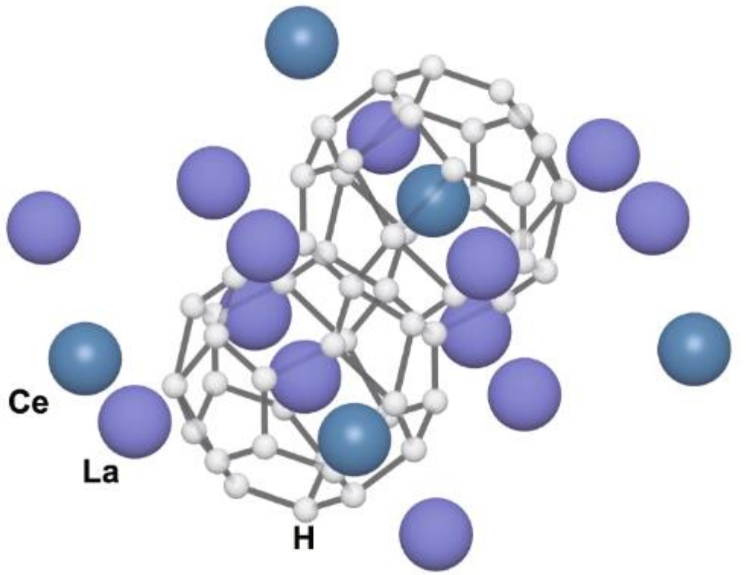
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



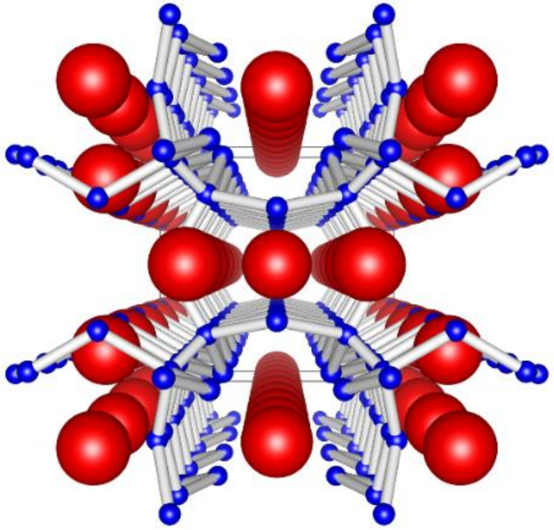
$Im\bar{3}m$-YH_6



$P6_3/mmc$-CeH_9



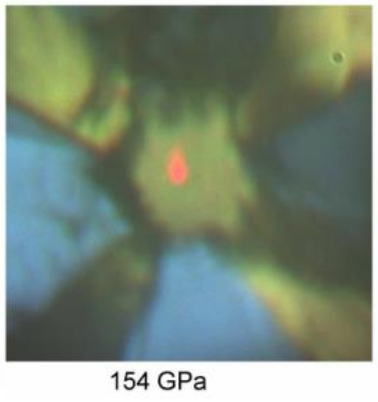
$P6_3/mmc$-$(La,Ce)H_{9\text{-}10}$

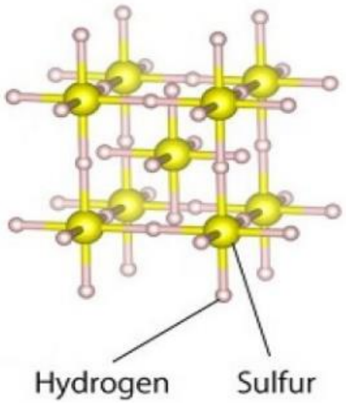


$A15$-La_4H_{23}

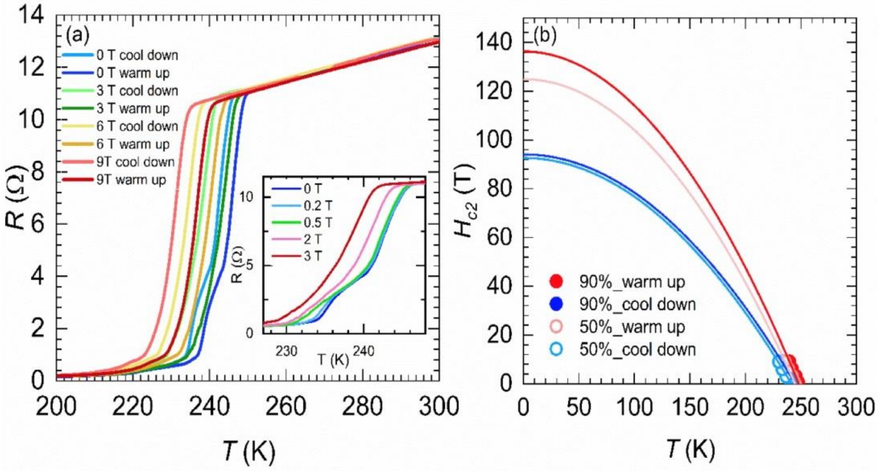
General properties of superhydrides I: record high T_c

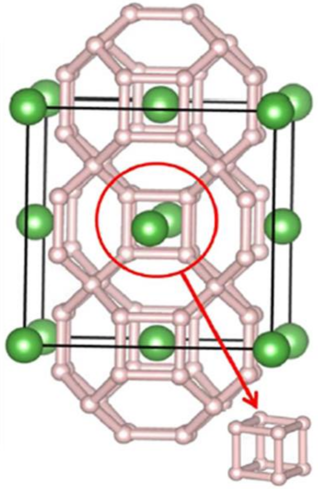
- They were discovered in 2015 in S-H system under pressure about 160-170 GPa. LaH_{10} was found in 2018.





2015





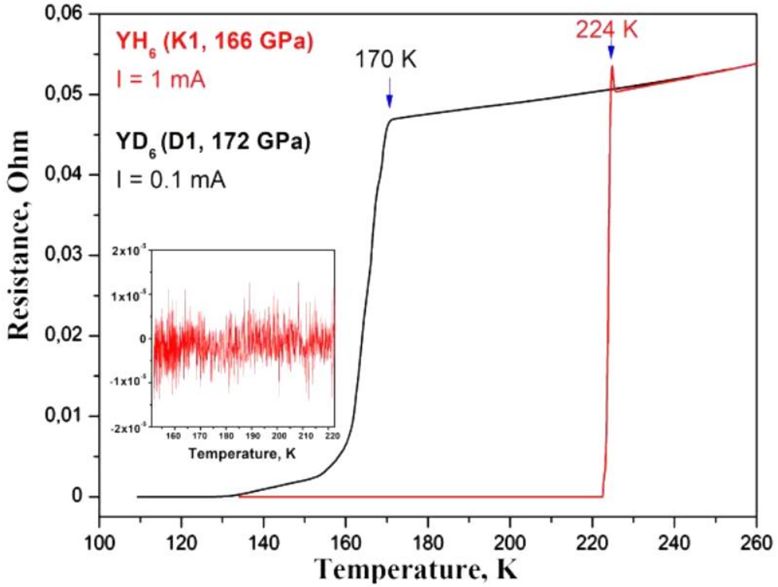
2018

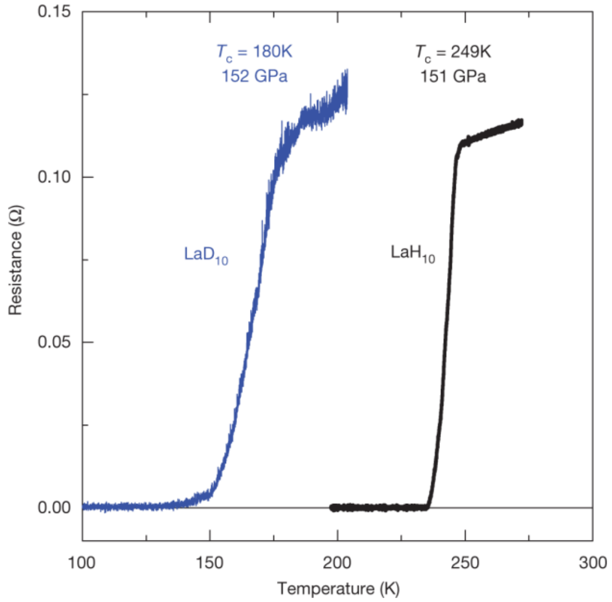
H_3S: T_C is up to 203 K at 155 GPa

LaH_{10}: T_C is 250 K at 150 GPa

- Electron-phonon coupling: hydrides demonstrate clear isotope effect (H → D), and their properties are predictable by DFT calculations

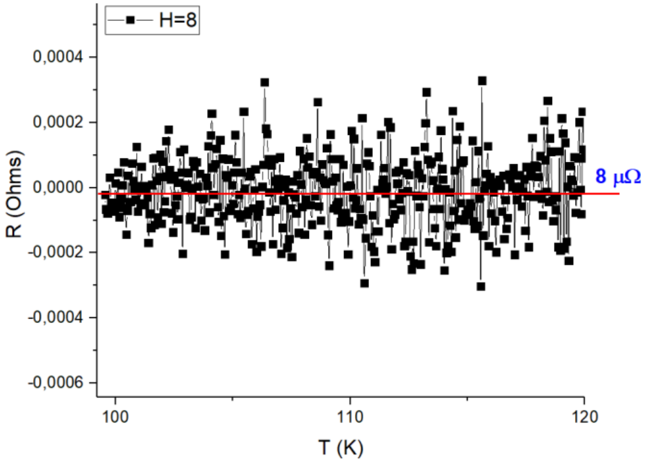
QUANTUMESPRESSO

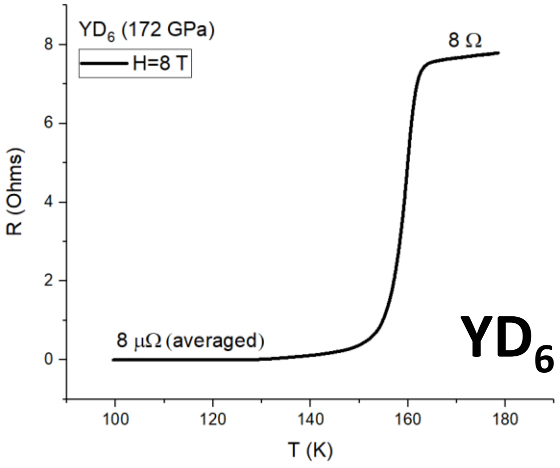


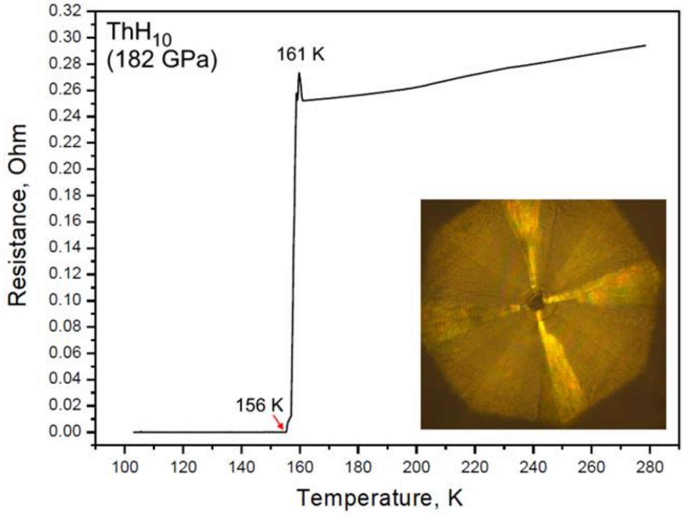


General properties of superhydrides II: isotropic materials - cubic and hexagonal lattices

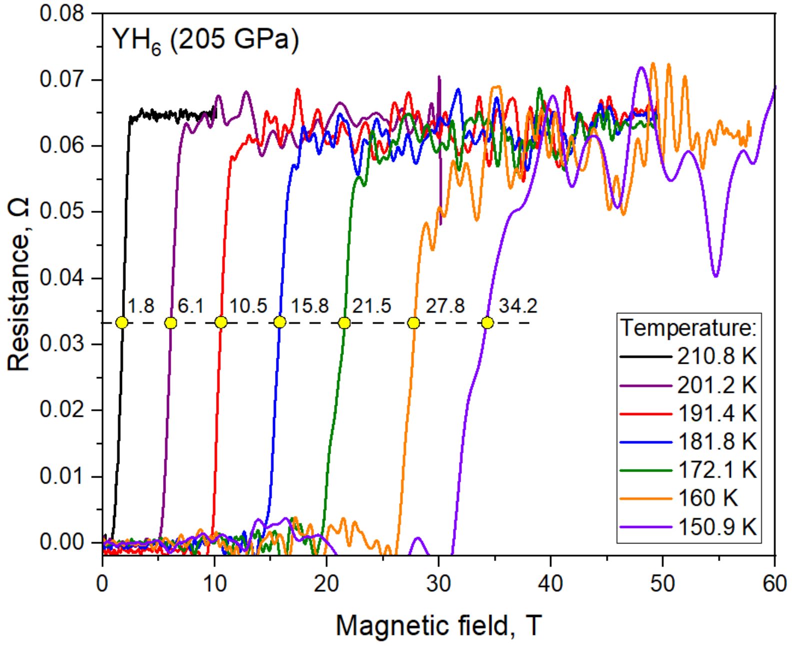
- “Zero resistance” state and superconducting transitions within 1-2 K

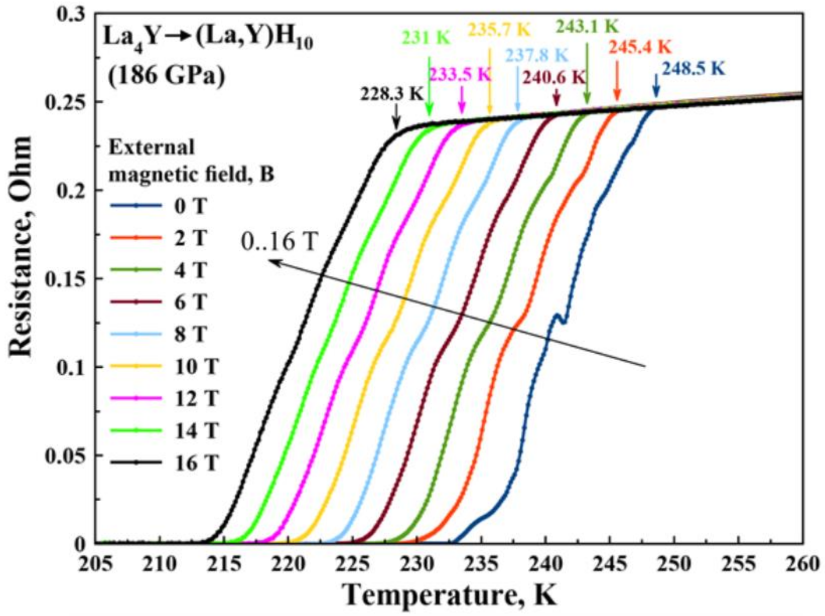


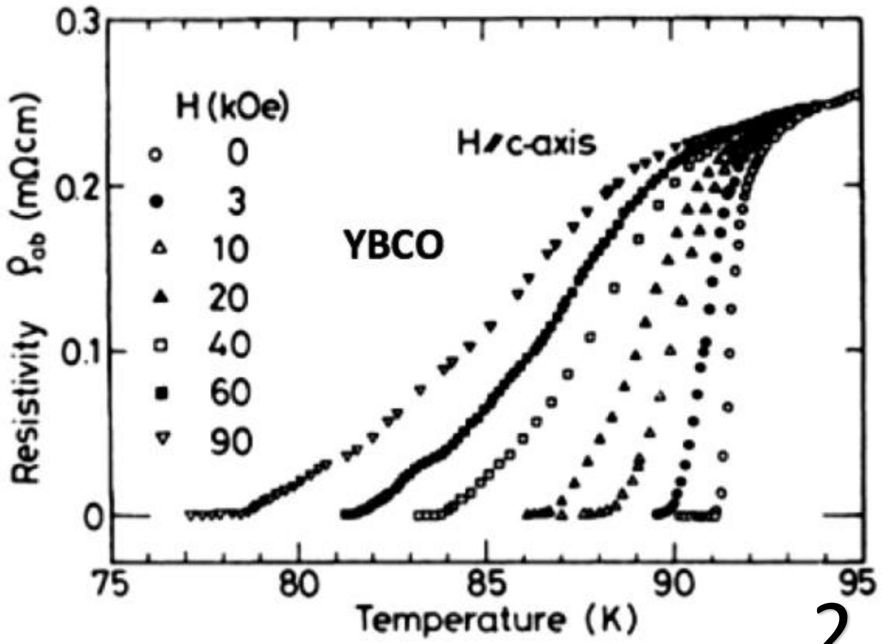




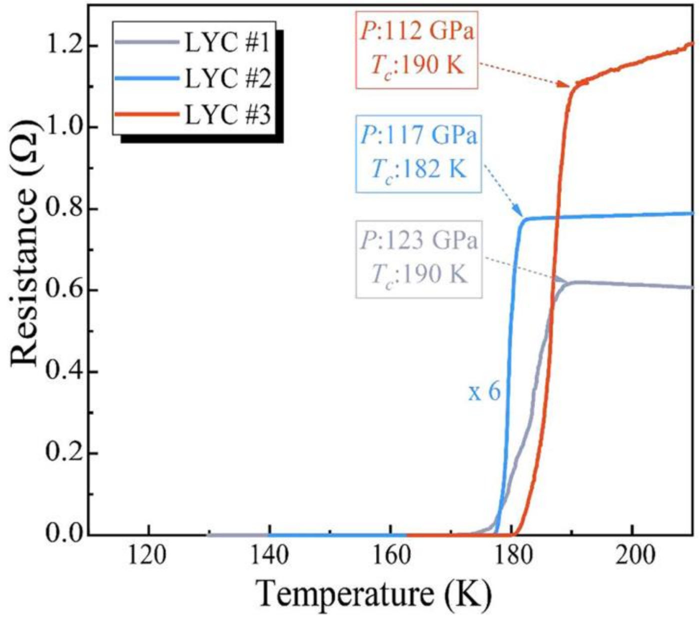
- Insignificant broadening of SC transitions in magnetic fields

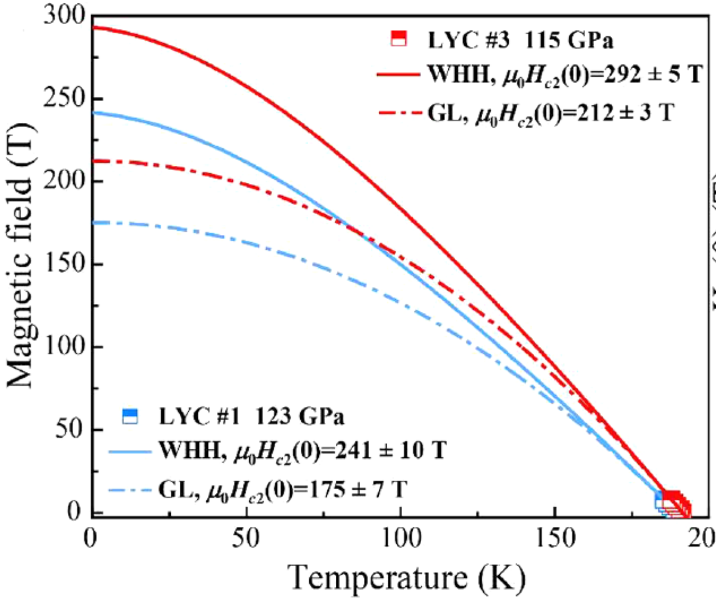


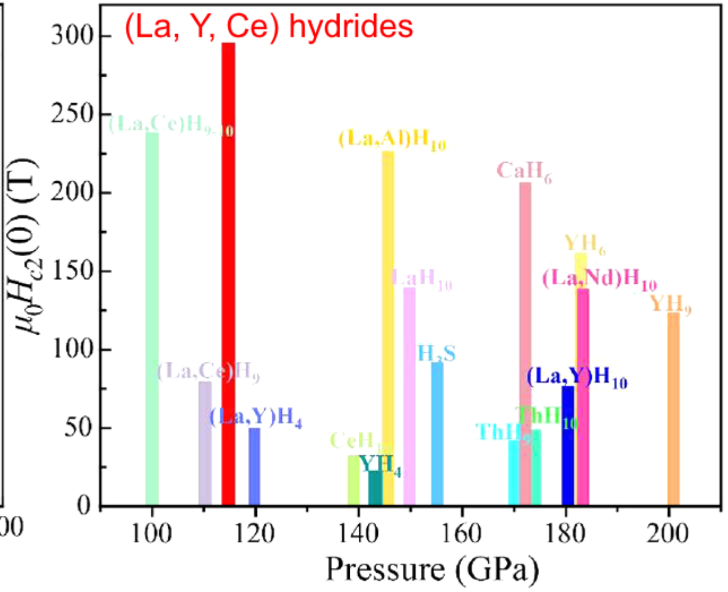




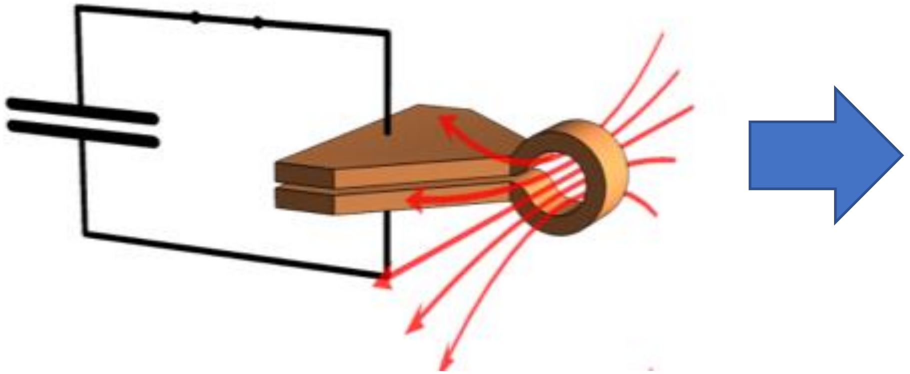
General properties of superhydrides III: record high H_{C2} up to 300 T and J_C



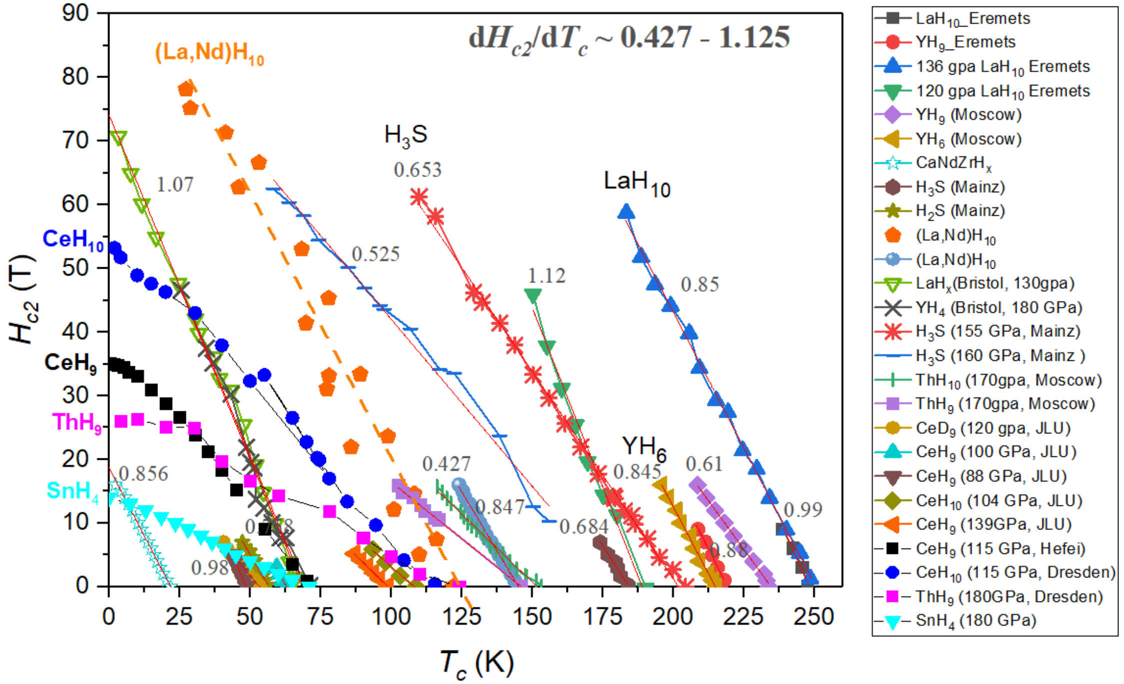




La + Y + Ce: (La, Y, Ce)H_{10} high entropy hydrides
Su Chen et al. *J. Am. Chem. Soc.* 2024, 146, 20, 14105–14113



Semi-destructive pulsed fields – beyond 100 T

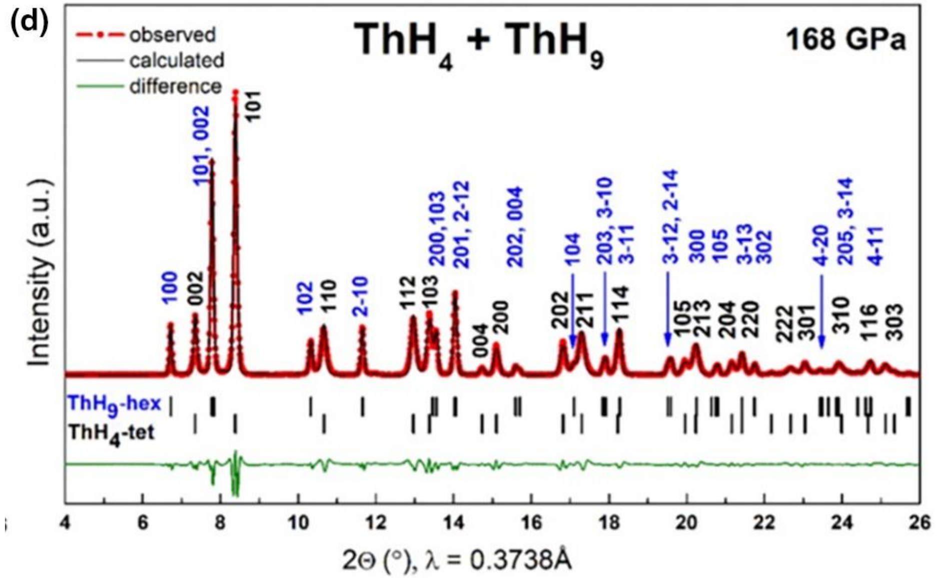


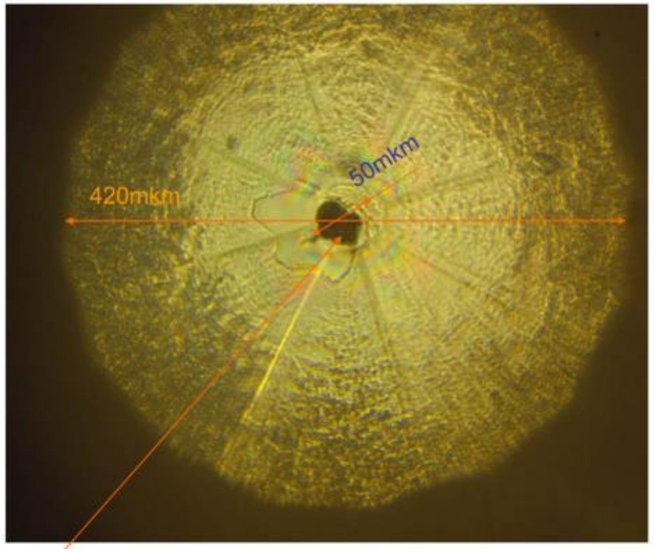
Disadvantage I: synchrotron sources required

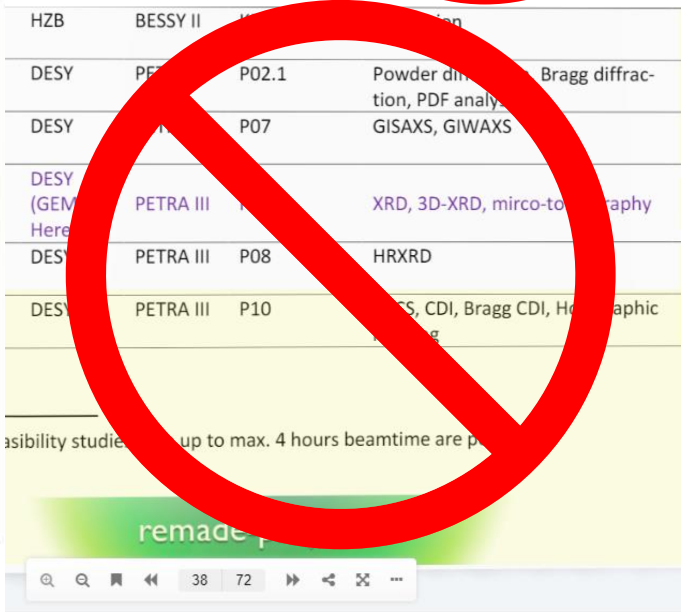
Sample size:

d = 30-100 um

h = 1-10 um

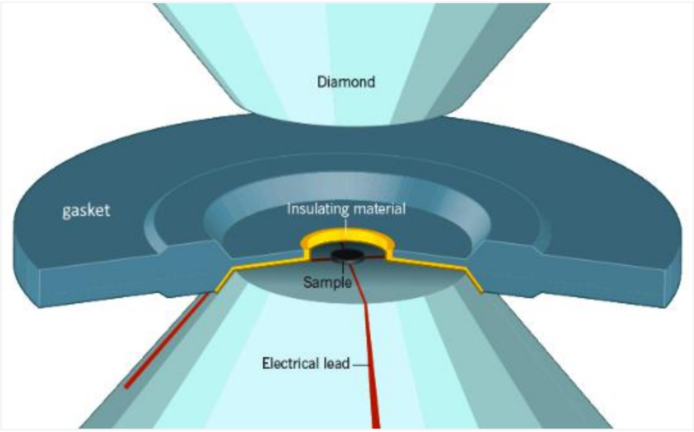


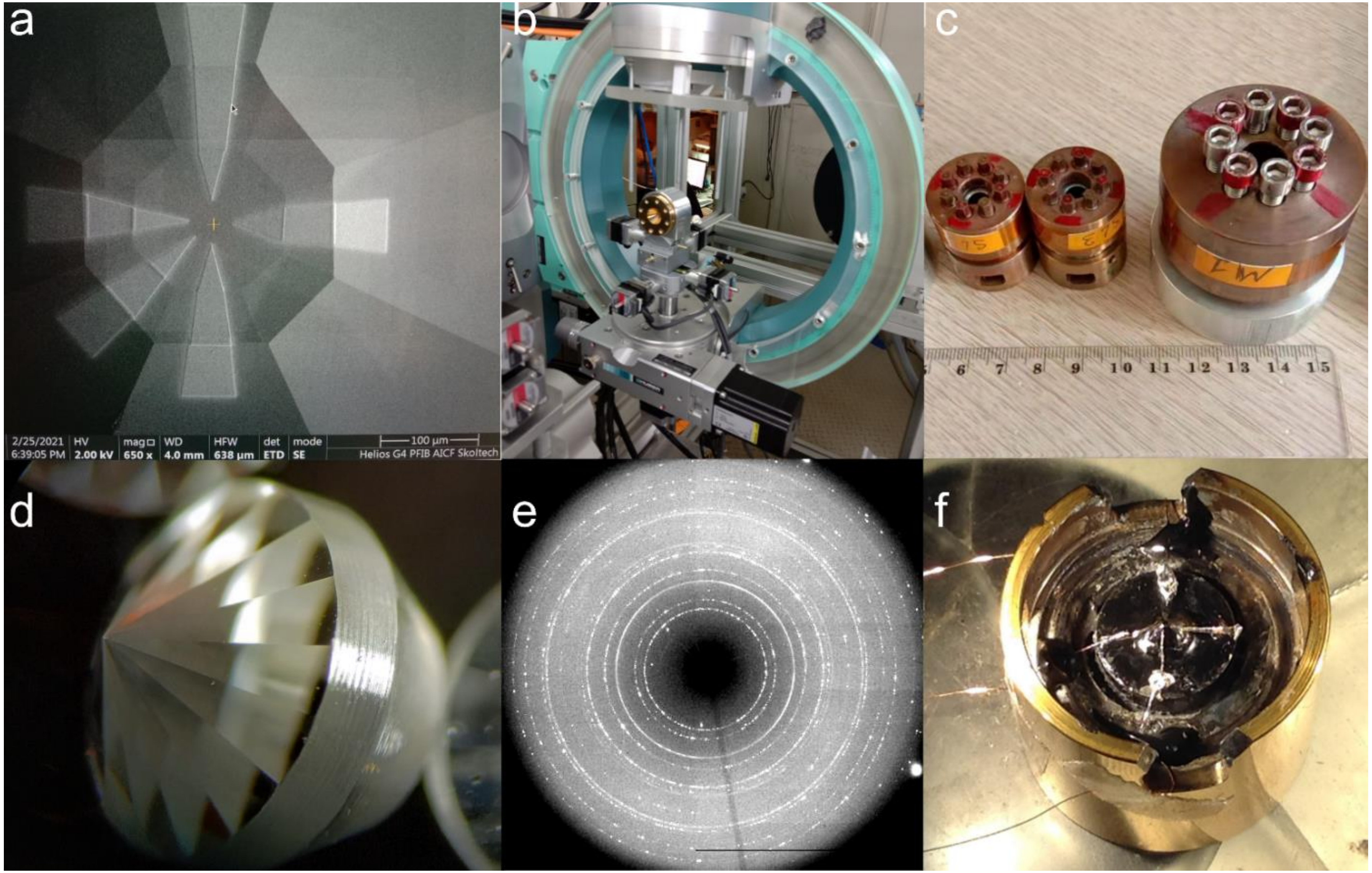




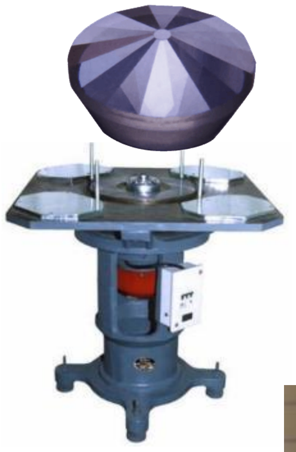
Disadvantage II: diamond anvils and diamond anvil cells

Diamond anvils
High pressure DACs

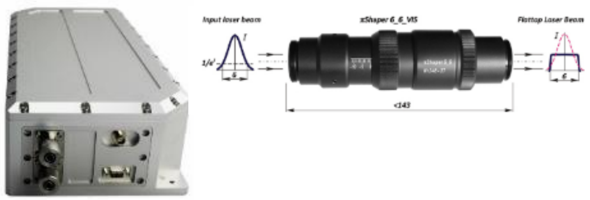




Modern industry of high-pressure research



Diamonds,
it's production,
polishing, recovery



Laser heating of samples

Thin film sputtering
and lithography

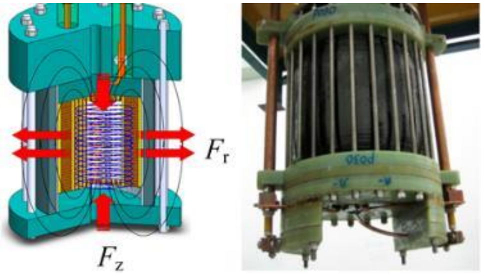
Production of cells
and their loading

DACs

XRD (powder + single crystal), IR
synchrotron research, neutrons(?)

Cryomagnetic transport
measurements (0-16 T, 0-0.2 A)
crit. field (H_{c2}), crit. current (I_c)
R(T, H) - resistance

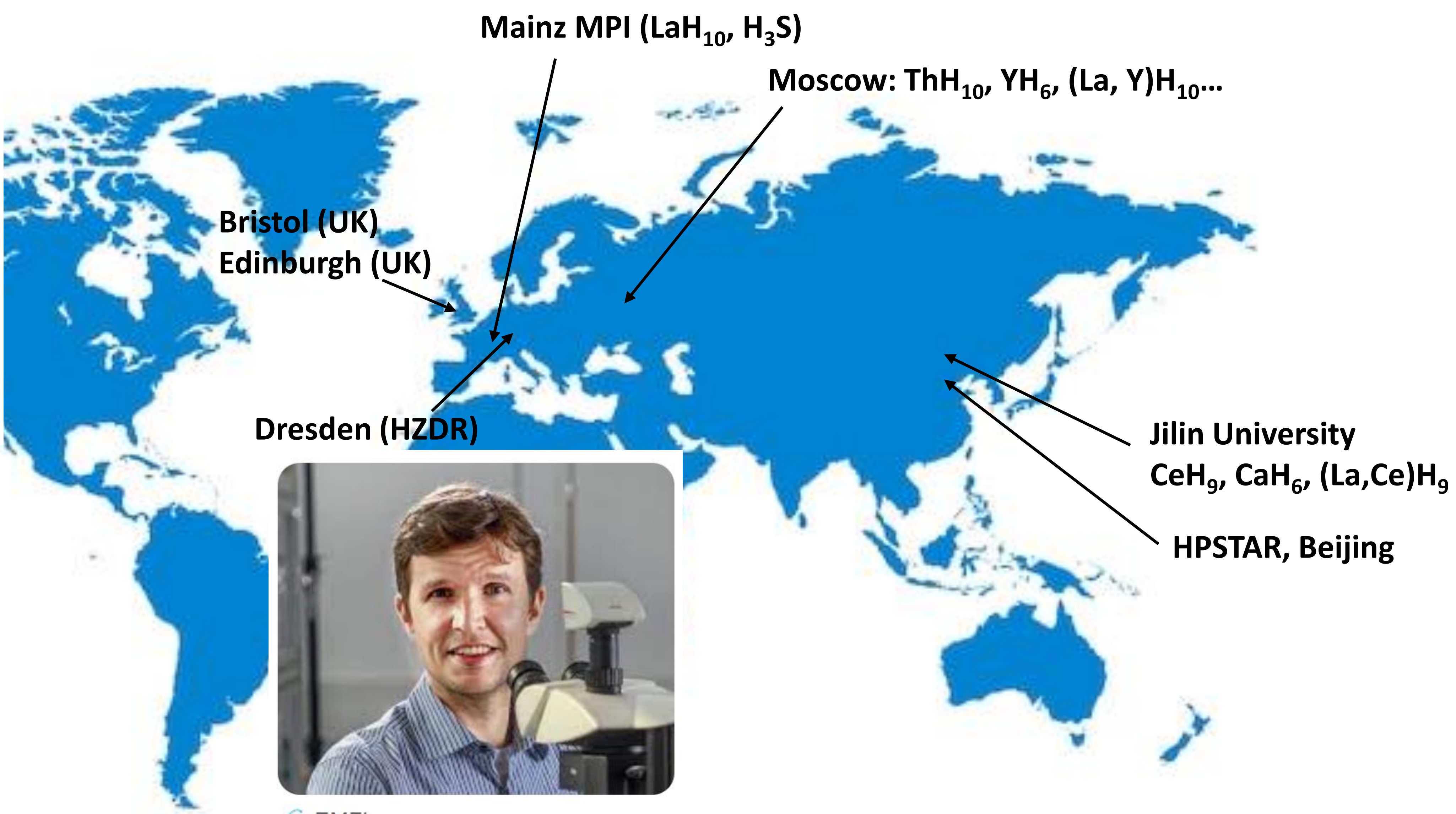
Raman measurements



Pulsed magnetic fields (70 T)

Superconductivity under pressure in the world: 5-7 exp papers per year

University of Bristol…
Sven Friedemann …



EMFL
Dr. Toni Helm - EMFL

Laboratory of high-pressure hydride superconductivity

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

DACs production → machinery workshop - **YES**

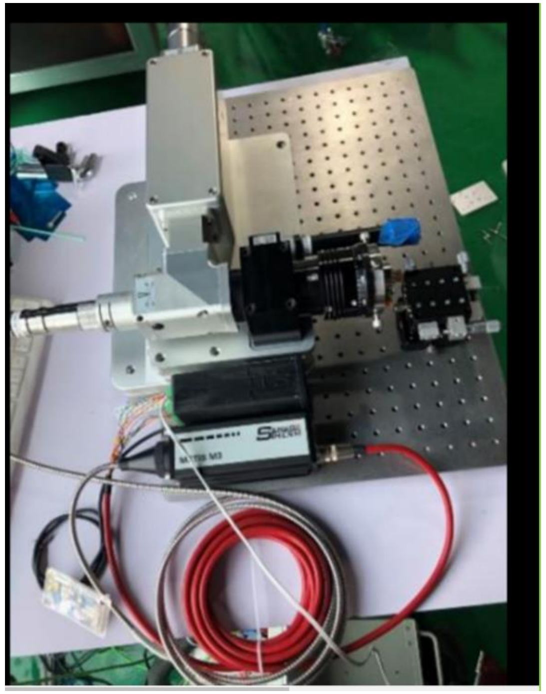
Sample preparation → Ar glovebox, furnances, **Ga FIB**

Sputtering systems for electrodes → **YES**, various magnetrons

Transport measurements → MPMS – **YES**, PPMS – **YES**, steady magnets – **YES**,
NMR magnets – **YES**, pulsed magnets → **YES**

Laser drilling system for gaskets – **EXPECTED in 2024**

Sample characterization → X-ray diffraction
ELBA ? PETRA-III in Hamburg ? - **UNDER QUESTION**



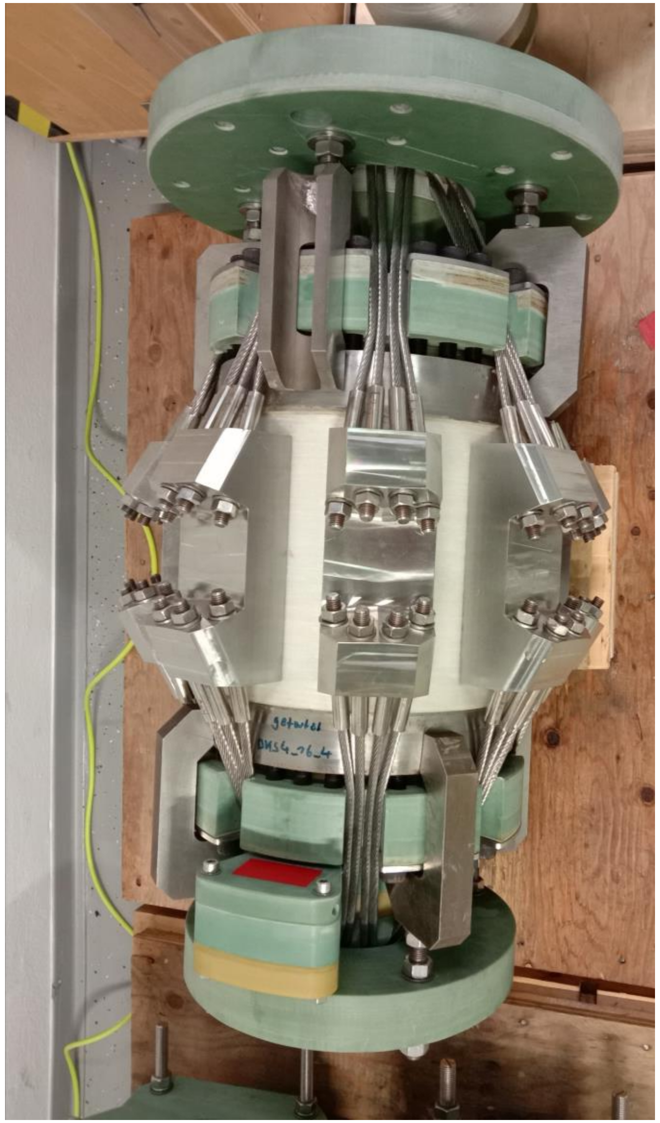
How to make HLD HZDR (Dresden) a world-class lab in high pressure physics ?

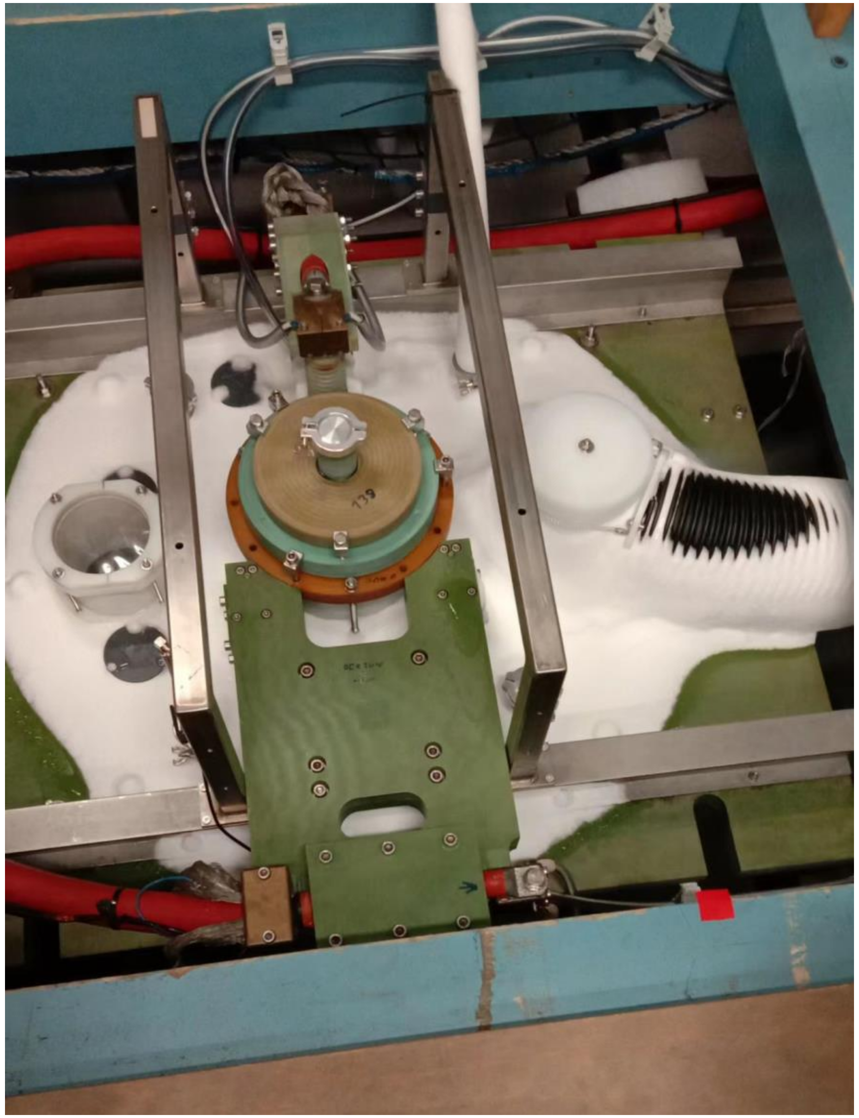
Laser heating system for microsamples – **NO**

Pressure measurements → Raman spectroscopy – **NO**

Examples of research

Dresden High Magnetic Field Laboratory



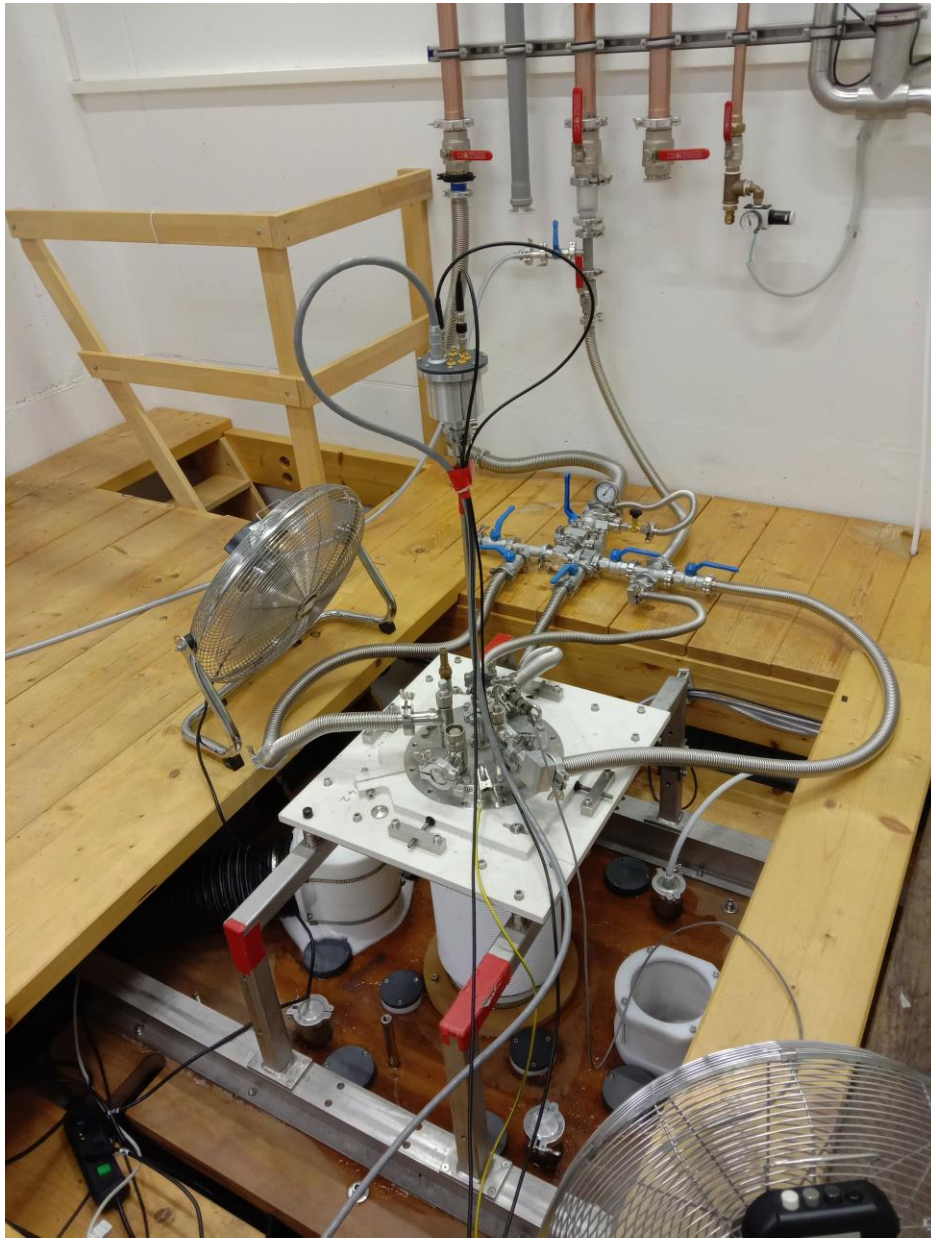


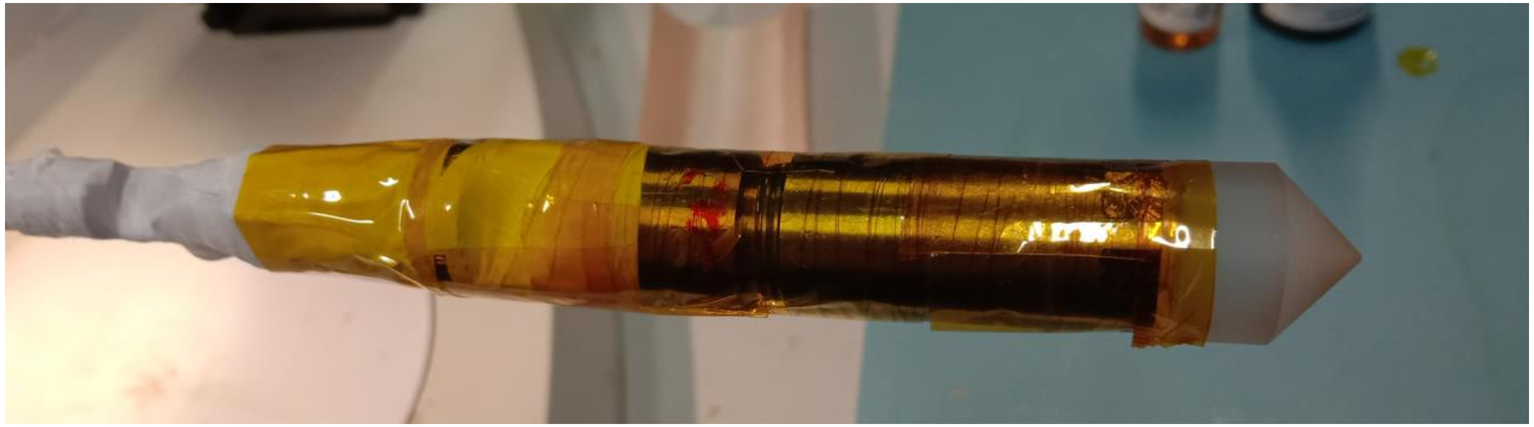
Measurements in strong pulsed magnetic fields up to 83 T in AC mode at 66 kHz

Frequency tested: 200 kHz, 500 kHz

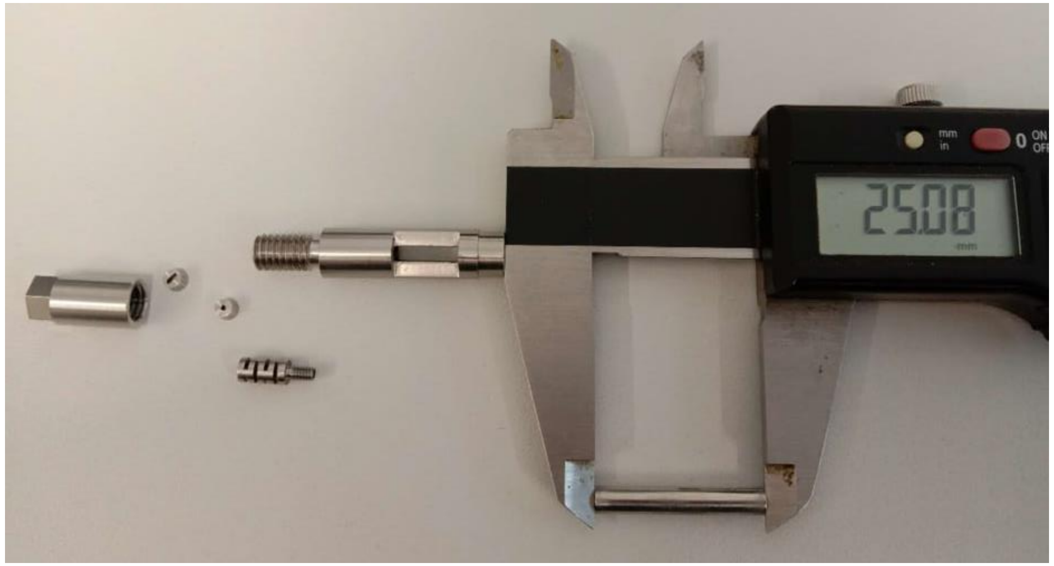
One of the strongest magnet in the world: it can reach 83 T in pulse.

Special DACs were developed and used (d = 8 mm, 9 mm, 12 and 15.3 mm)



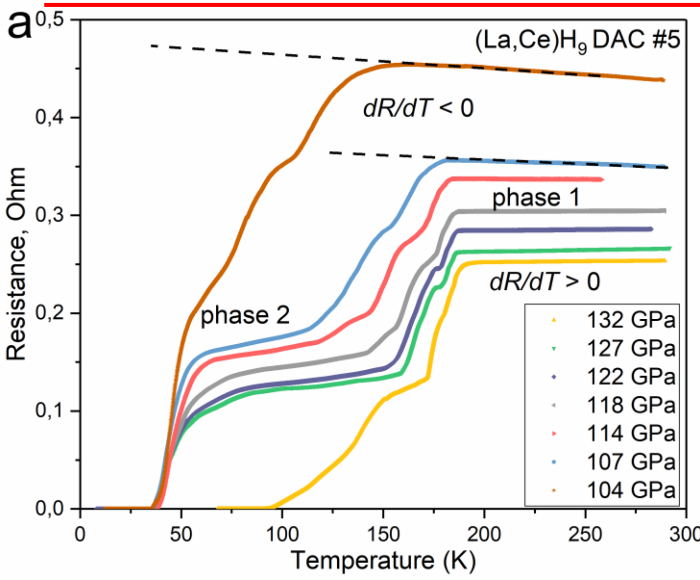


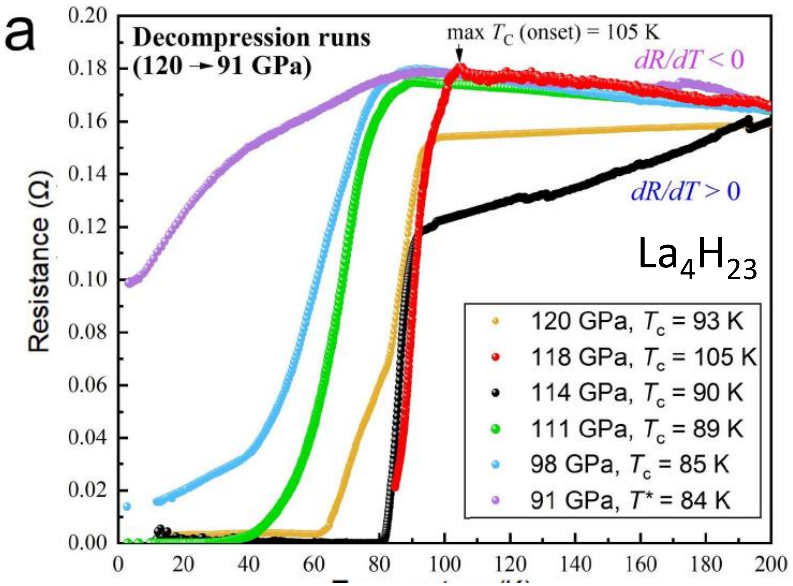
DAC for 85 T pulsed field, d = 15.3 mm, Ni-Cr-Al alloy



This is one of the smallest DAC that we manufactured
(d = 8 mm for SQUID)

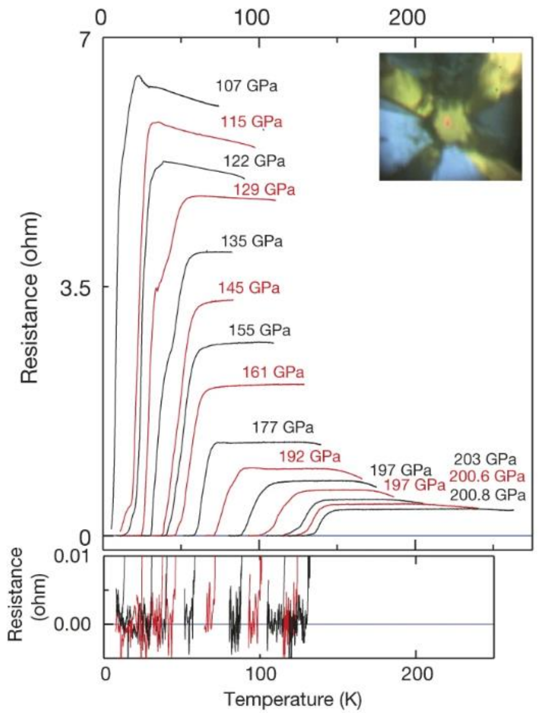
Focus on non-superconducting state behavior of hydrides

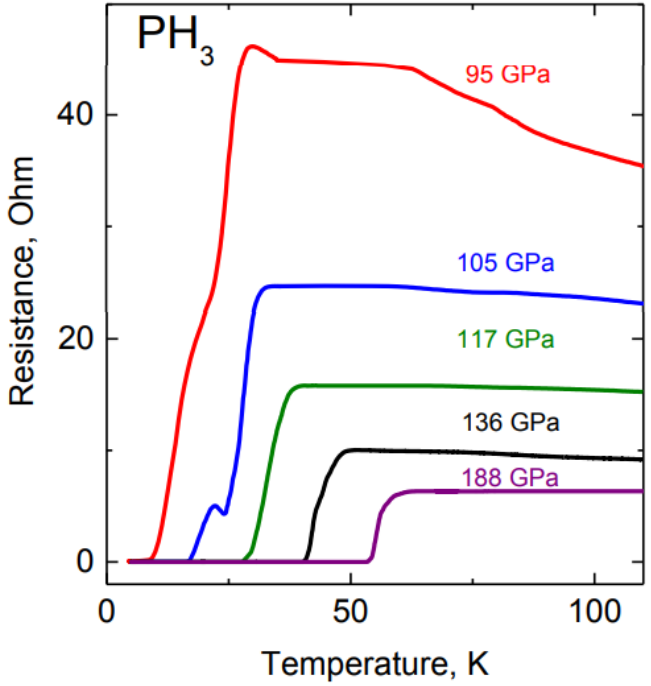


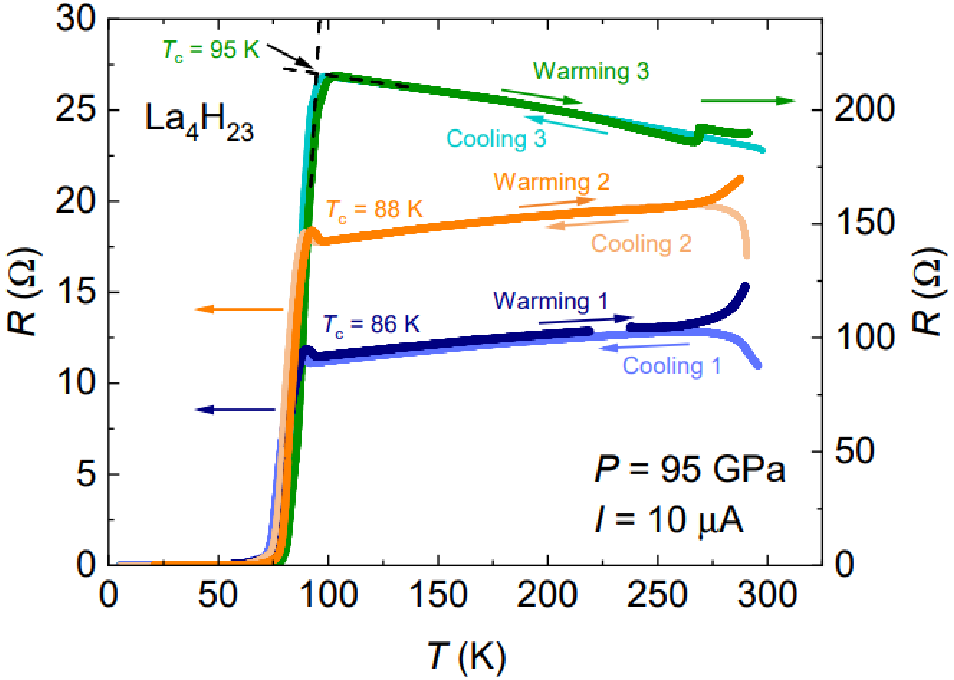


Negative temperature coefficient of resistance in hydrides

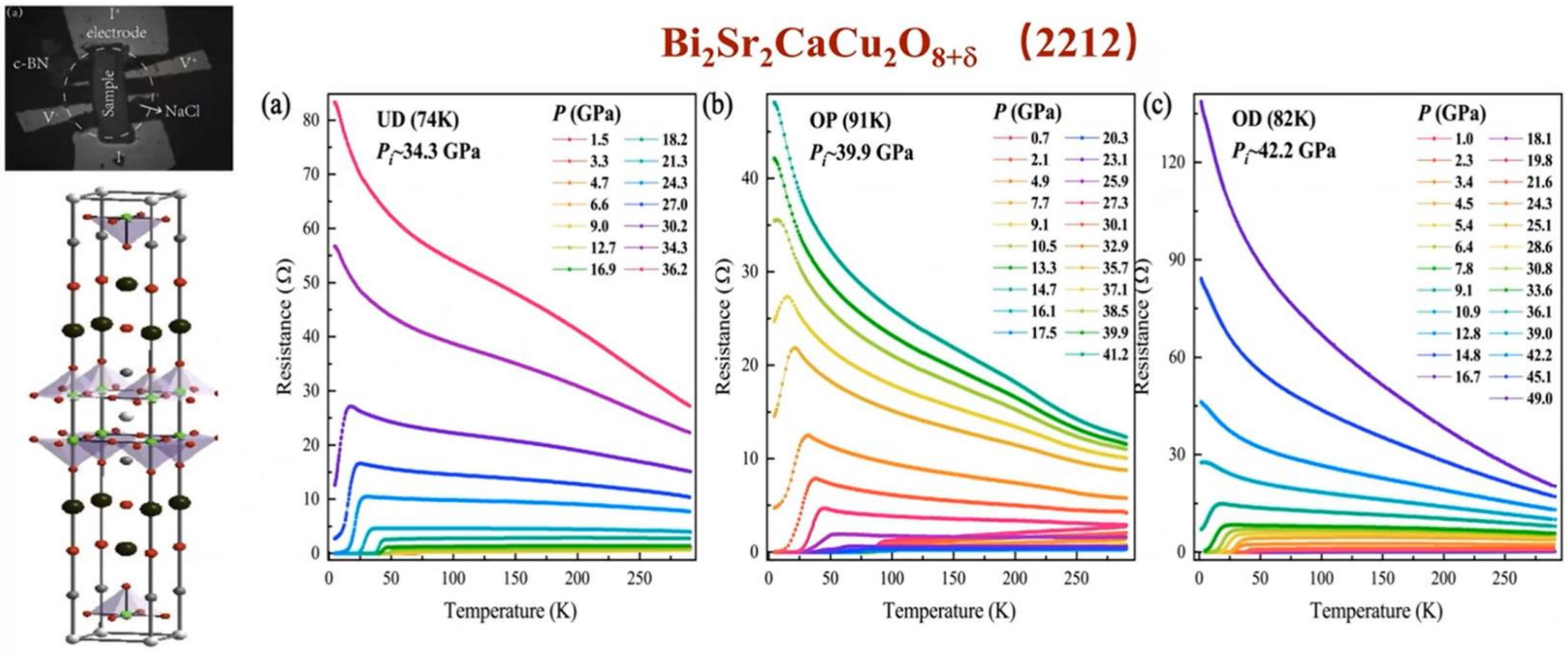
$dR/dT < 0$





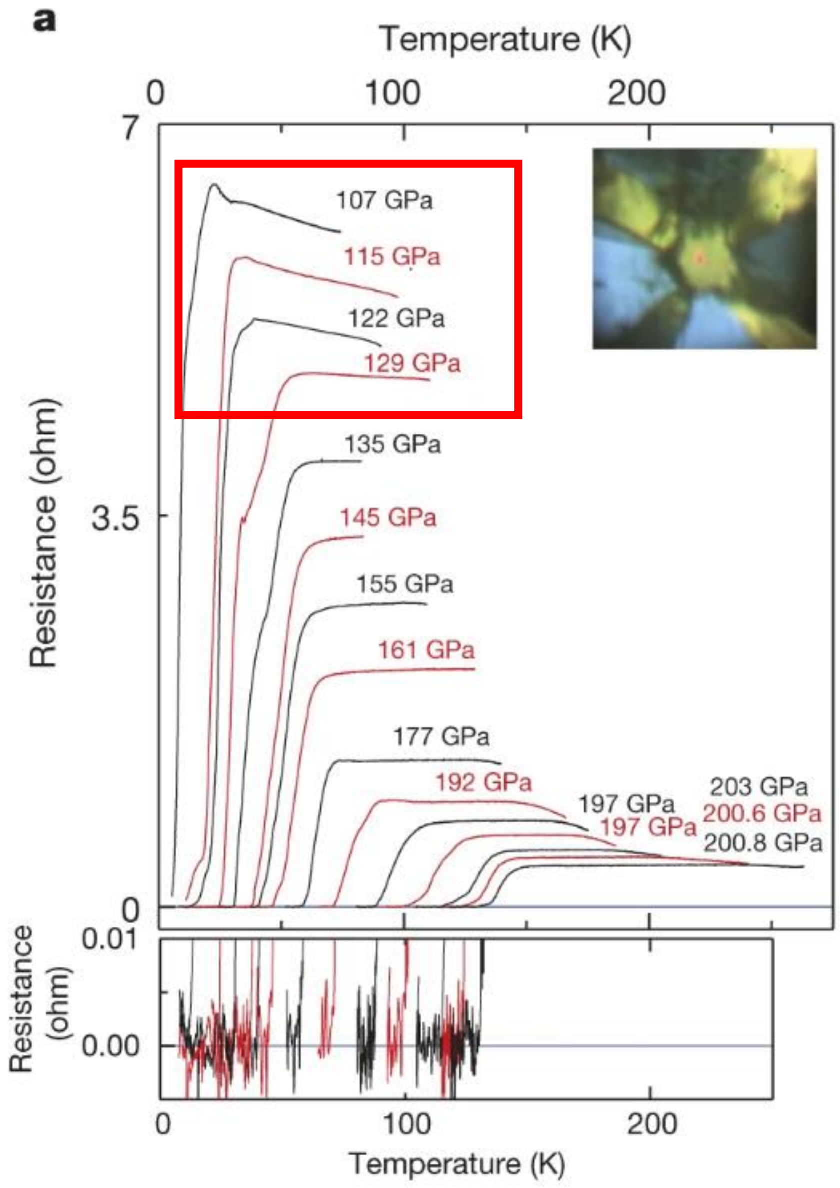


Similarity to cuprate superconductors



SC → pseudogap phase → insulator

YZ Zhou et al. Nature Physics 18 406(2022)

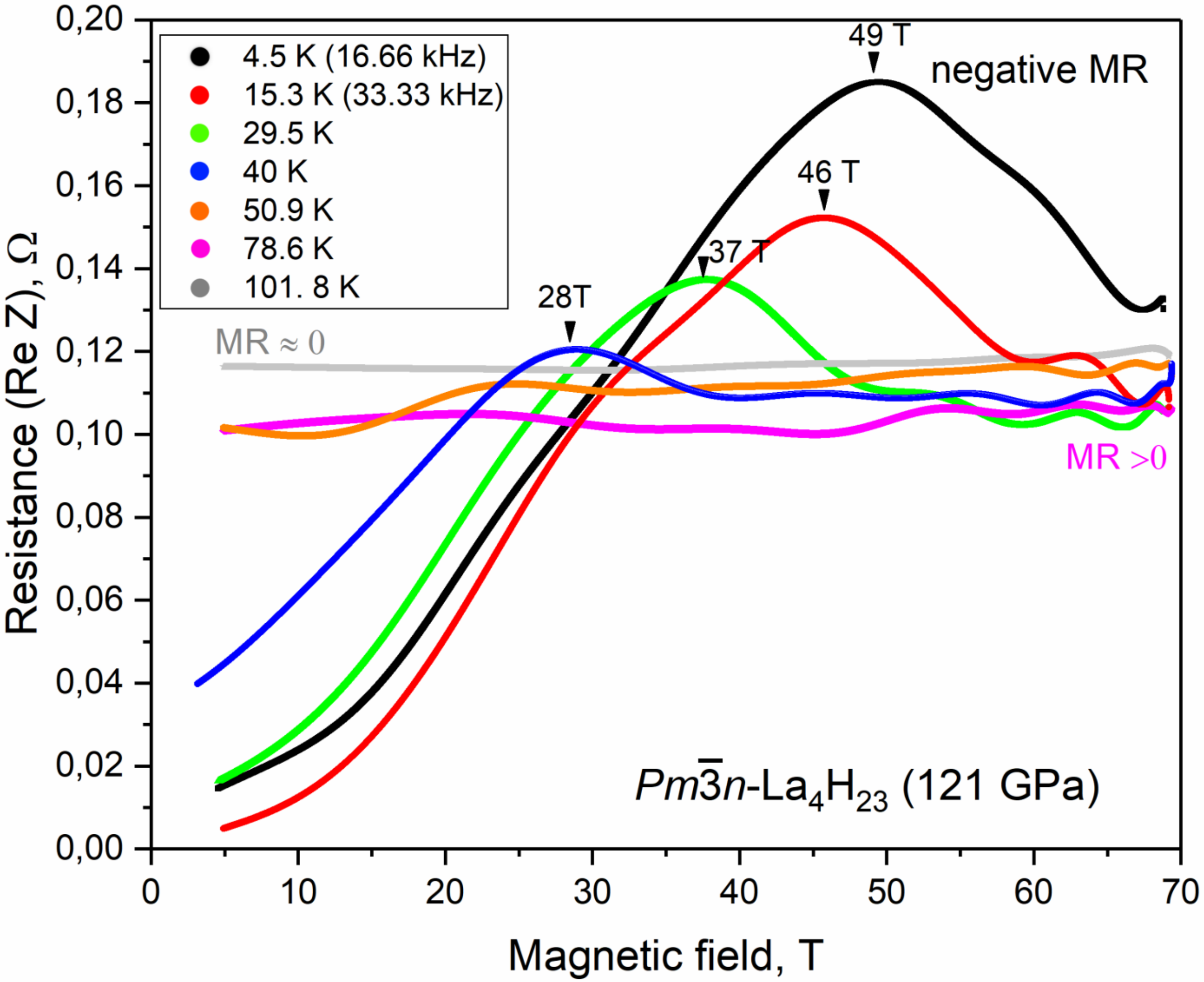


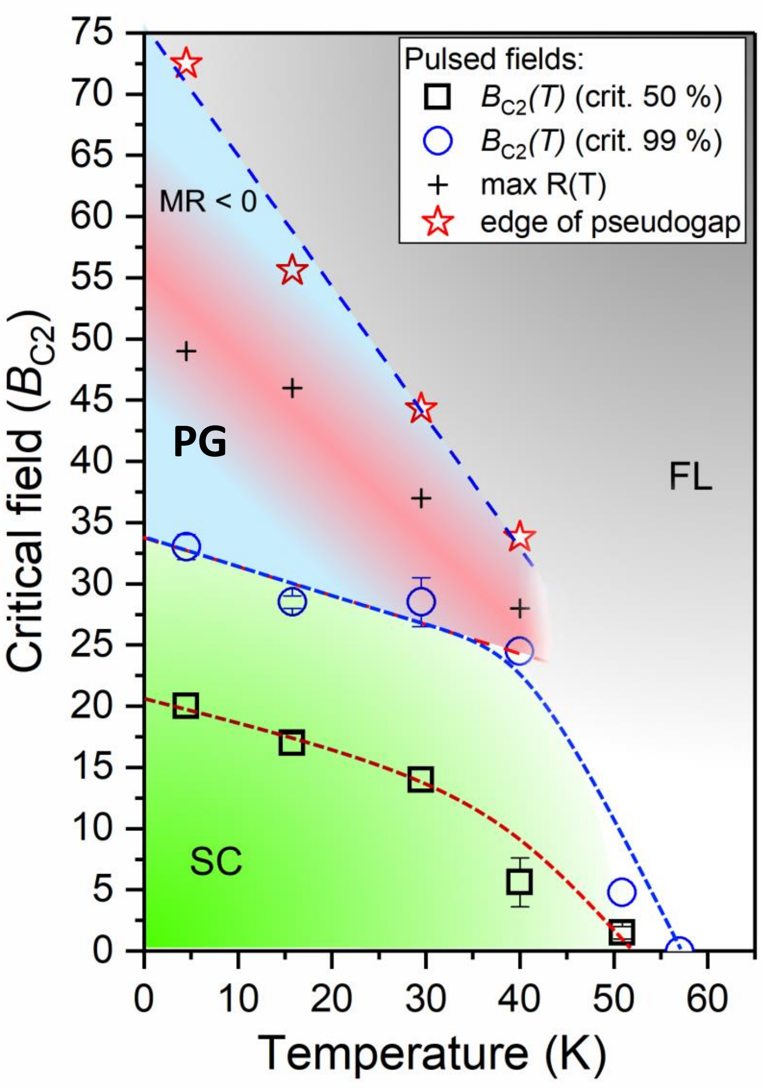
R(T) behavior of sulfur hydride H_3S with decreasing pressure is completely similar to the behavior of cuprates

Alex Drozdov et al. *Nature* 525, pp. 73–76 (2015)

Negative magnetoresistance in La_4H_{23} superhydride

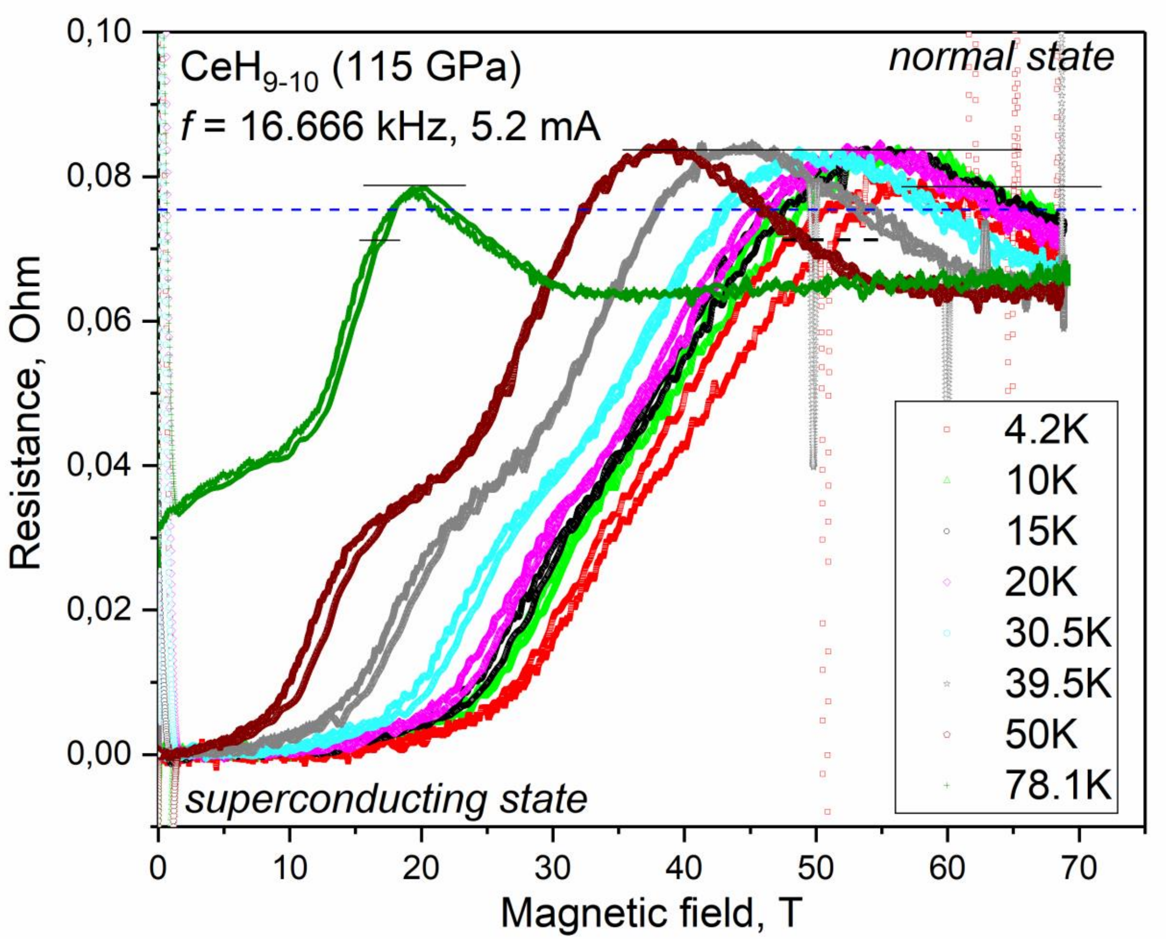
T_C of A15 La_4H_{23} is not very high, 70-75 K, but it has very large negative magnetoresistance region and demonstrates pronounced non-Fermi liquid behavior in pseudogap phase.

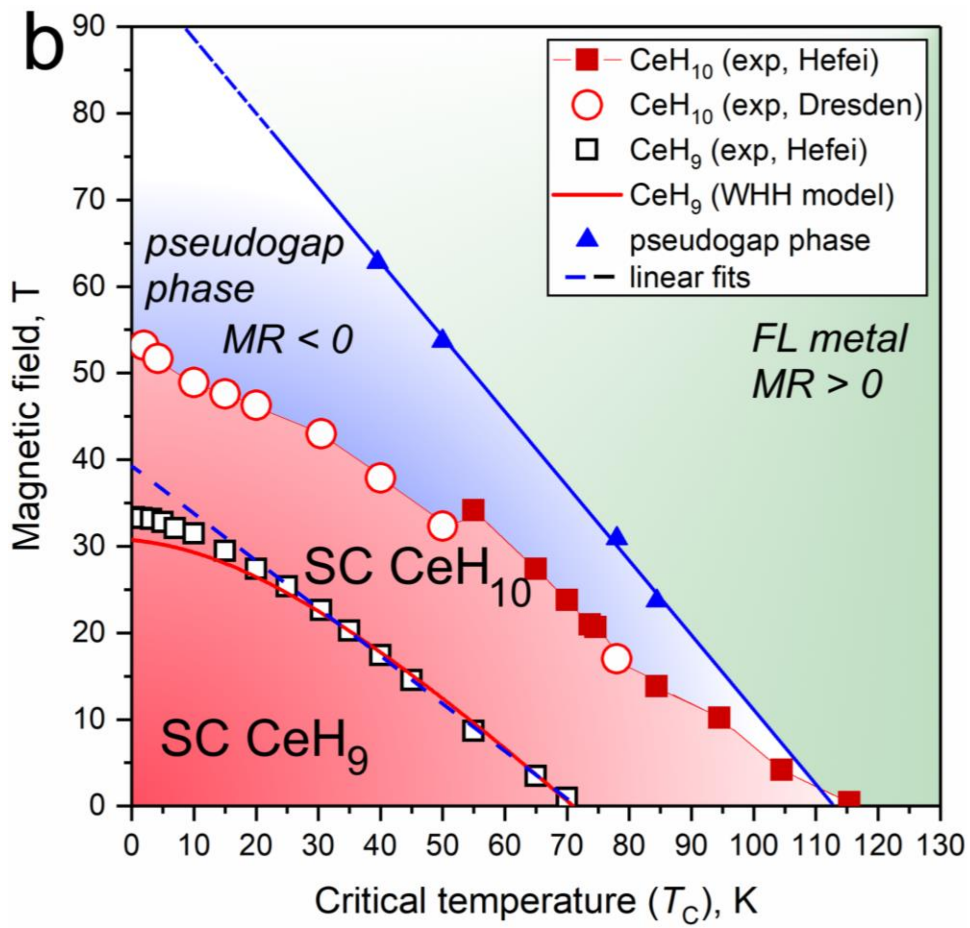




Negative magnetoresistance in CeH_{9-10} (115-125 GPa)

Dresden (up to 68 T, HLD HZDR)

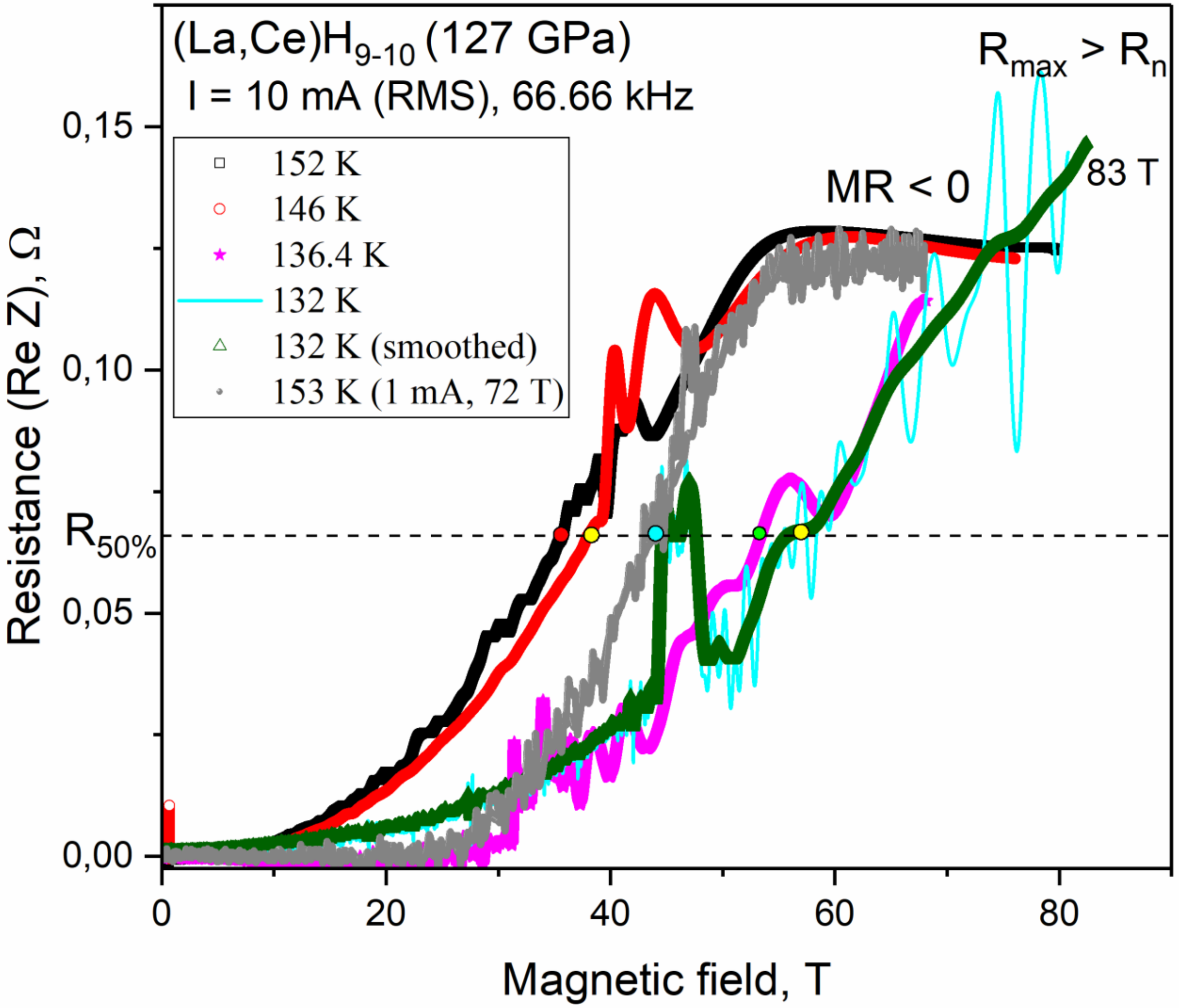


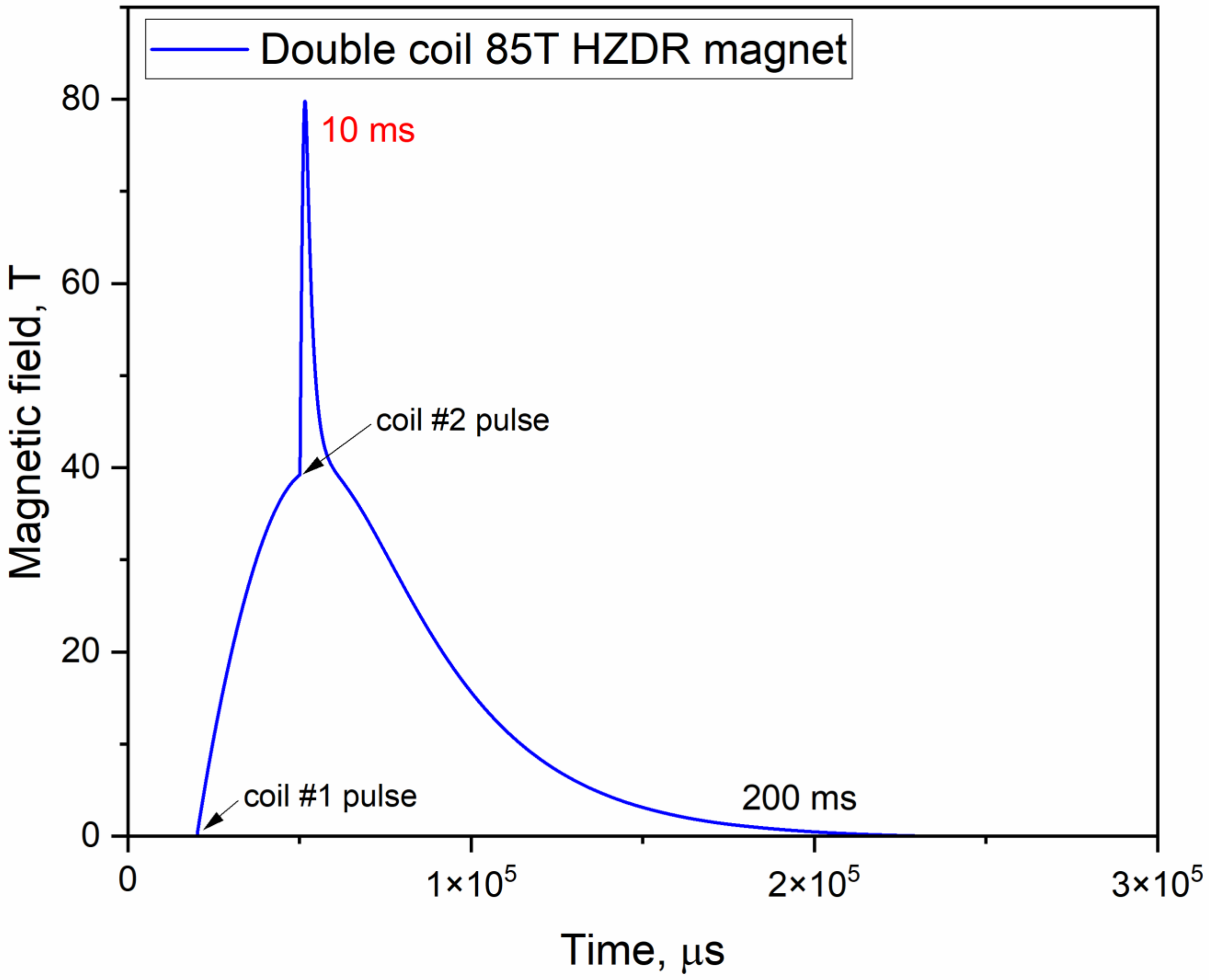


We have studied cerium hydrides CeH_{9-10} in steady (up to 33 T) and pulsed (up to 68 T) magnetic fields. When superconductivity is suppressed, a pronounced jump in magnetoresistance is detected with a change in its sign at a certain critical field.

Negative magnetoresistance in superhydrides

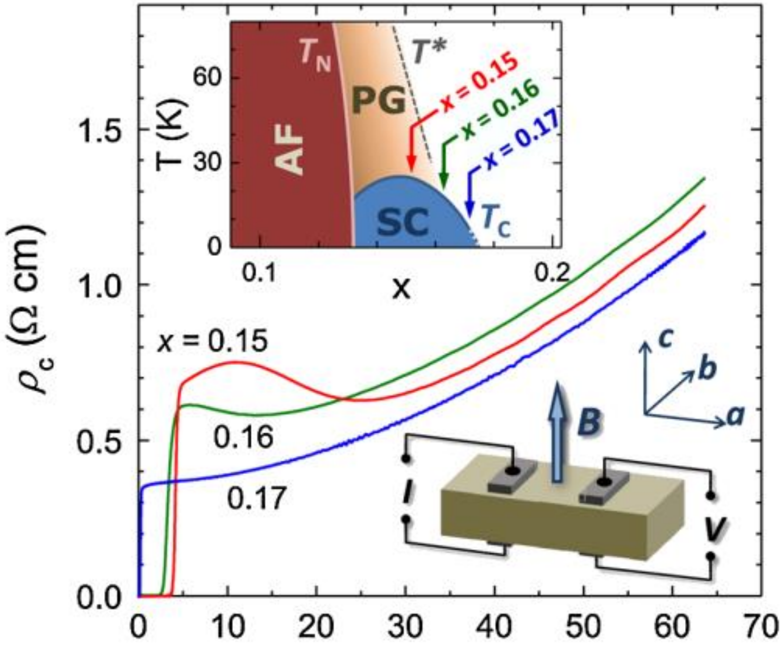
T_C(onset) of $(La,Ce)H_{10}$ is about 200 K at 127 GPa – one of the highest T_C at the lowest pressure (80-100 GPa)





Problems: stronger noise, T > 78 K, heating of DAC and strong pulling force

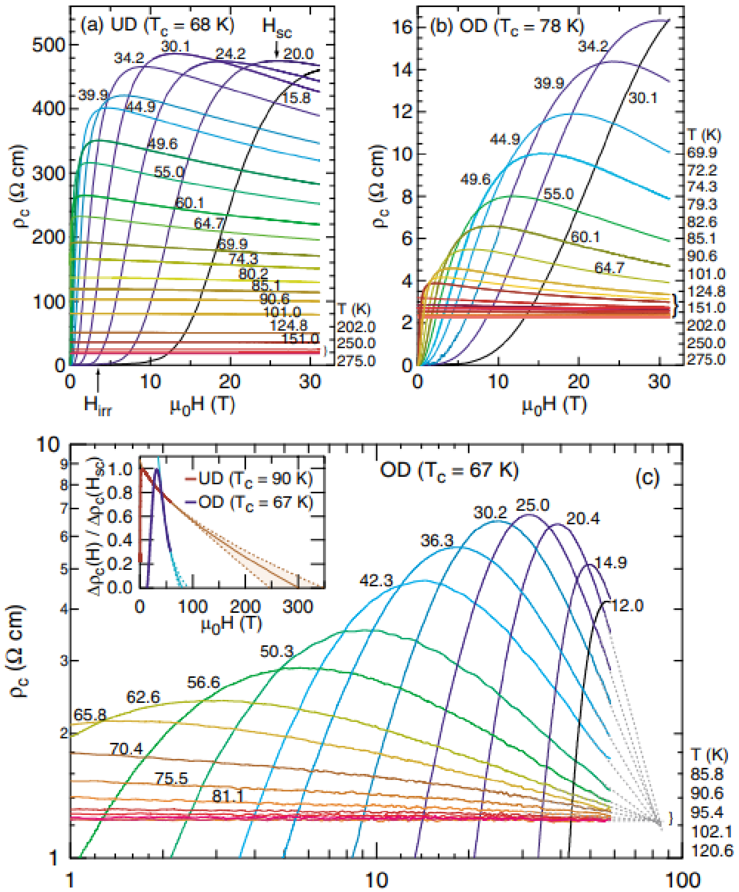
Similarity to cuprate superconductors



$Nd_{2-x}Ce_xCuO_4$ (NCCO)

FIG. 1 (color online). c-axis resistivity ρ_c of NCCO plotted vs magnetic field applied perpendicular to the CuO_2 planes at $T = 4$ K for different doping levels x. The upper inset shows schematically the currently accepted phase diagram of NCCO with the superconducting (SC), antiferromagnetic (AF), and pseudogap (PG) regions. The arrows mark the compositions studied in this work. The lower inset illustrates the geometry of the experiment.

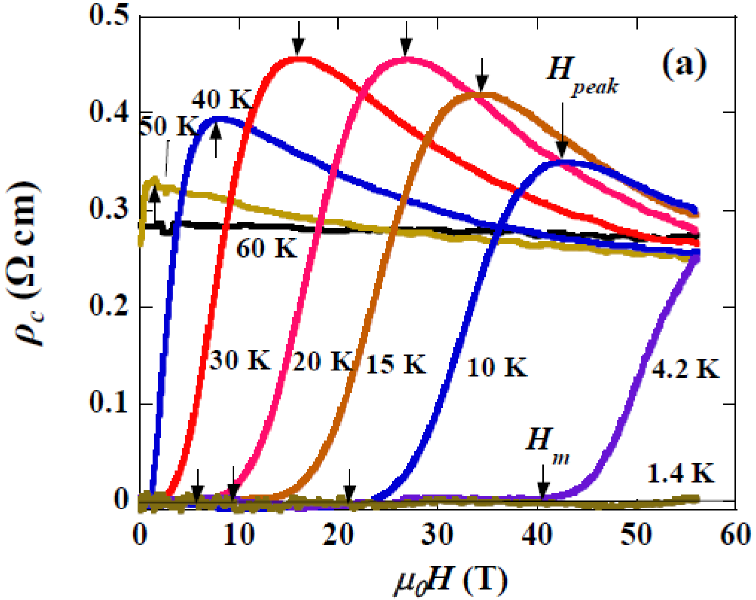
T. Helm et al. Phys. Rev. Lett. **103**, 157002 (2009)



$Bi_2Sr_2CaCu_2O_{8+y}$

FIG. 1 (color). c-axis resistivity ρ_c (labeled by temperatures) vs magnetic field $H(\| c)$ in an underdoped (UD) BSCCO crystal (a) and two overdoped (OD) crystals (b),(c). In the superconducting state, $\rho_c(H)$ becomes finite above the irreversibility field H_{irr} and exhibits a peak at H_{sc}. The core feature in $\rho_c(H)$ that changes with doping is the slope of the high-field negative

T. Shibauchi et al. Phys. Rev. Lett. 86, 5763, 2001



$Bi_{1.6}Pb_{0.4}Sr_2CaCu_{1.96}Fe_{0.04}O_{8+\delta}$

Takao Watanabe et al. Phys. Rev. B 94, 174517

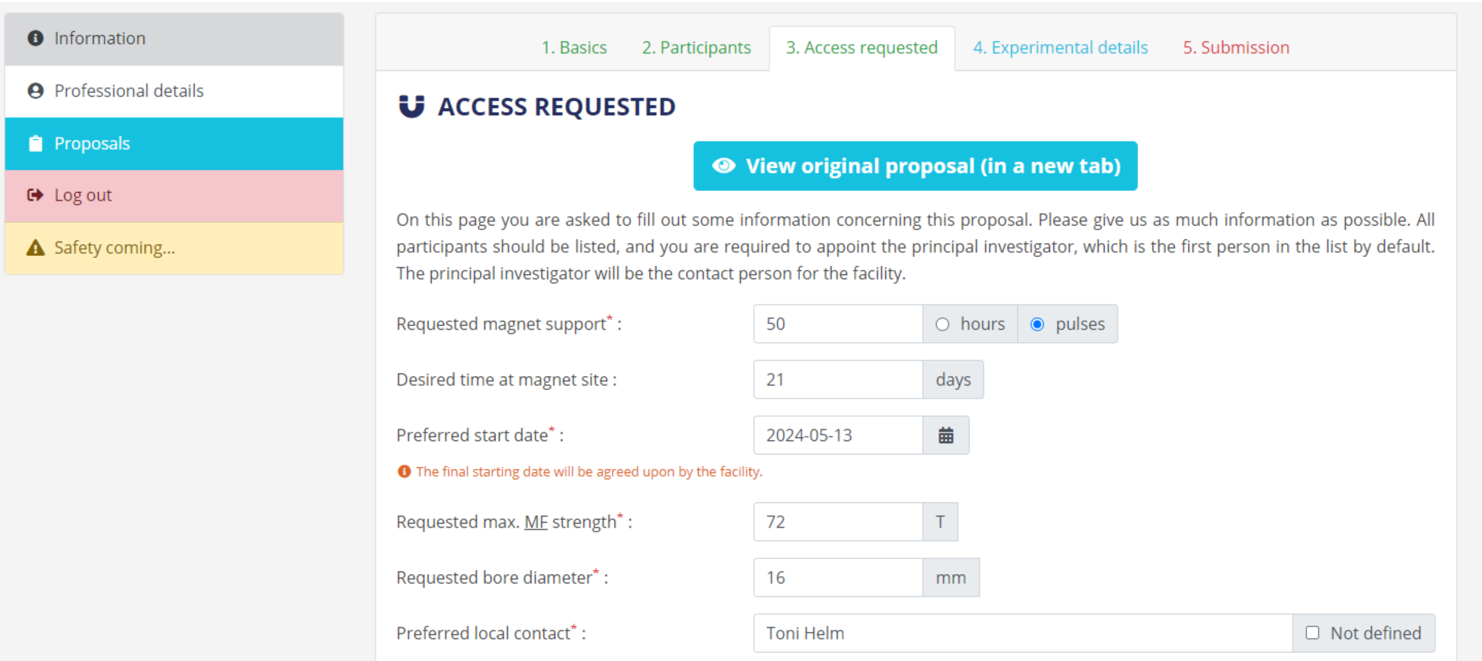
Such a jump in MR is observed in the pseudogap phase of cuprates and is caused by SC fluctuations

Conclusions

Research on superhydrides at high pressure in pulsed magnetic fields is going well: 3 years = 3 papers.

1. D. V. Semenok et al. Effect of Magnetic Impurities on Superconductivity in LaH_{10}. *Advanced Materials* 2022, 34, 2204038.
2. A. Troyan, D. Semenok et al. Non-Fermi-Liquid Behavior of Superconducting SnH_4. *Advanced Science* 2023, 10, 2303622.
3. J. Guo, D. Semenok et al. Unusual metallic state in superconducting A15-type La_4H_{23}, *National Science Review*, 2024, nwae149.

From a user's point of view, we would like to be able to book additional equipment at the stage of applying for pulse filed



- Except pulsed magnets HZDR HLD has a lot of equipment available only for scientists, not for users.

  I would suggest to include in the booking system an option to book **PPMS, MPMS, steady magnets, Raman, FIB** 2-3 months in advance.