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PSI

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Muon-spin rotation/relaxation under hydrostatic pressure: outlook and perspectives

TIUMF science week, July 31st – August 4th

science week /23
Jul 31 - Aug 4

Quantum materials

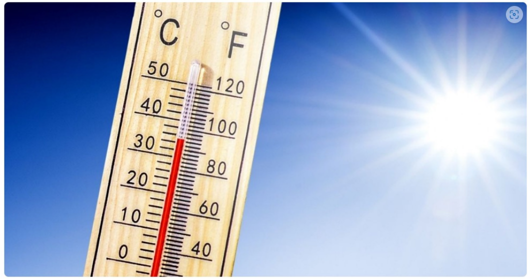
Quantum materials is an umbrella term in condensed matter physics that encompasses all materials whose essential properties cannot be described in terms of semiclassical particles and low-level quantum mechanics. These are materials that present strong electronic correlations or some type of electronic order, such as superconducting or magnetic orders, or materials whose electronic properties are linked to *non-generic* quantum effects – topological insulators, Dirac electron systems such as graphene, as well as systems whose collective properties are governed by genuinely quantum behavior, such as ultra-cold, cold excitons, polaritons, and so forth. On the microscopic level, four fundamental degrees of freedom – that of charge, spin, orbit and lattice – become intertwined, resulting in complex electronic states;[1] the concept of emergence is a common thread in the study of quantum materials.[2]

Quantum materials exhibit puzzling properties with no counterpart in the macroscopic world: quantum entanglement, quantum fluctuations, robust boundary states dependent on the topology of the materials' bulk wave functions, etc.[1] Quantum anomalies such as the chiral magnetic effect link some quantum materials with processes in high-energy physics of quark-gluon plasmas.

Quantum materials -- Wikipedia

Common tuning parameters

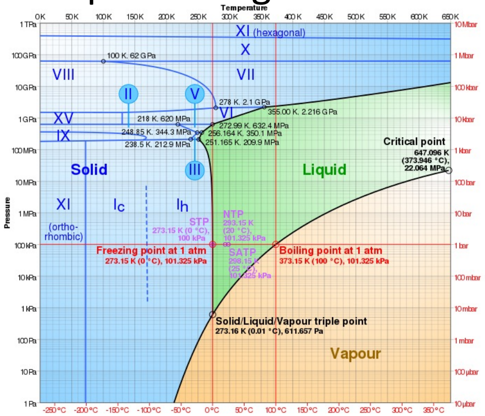
T



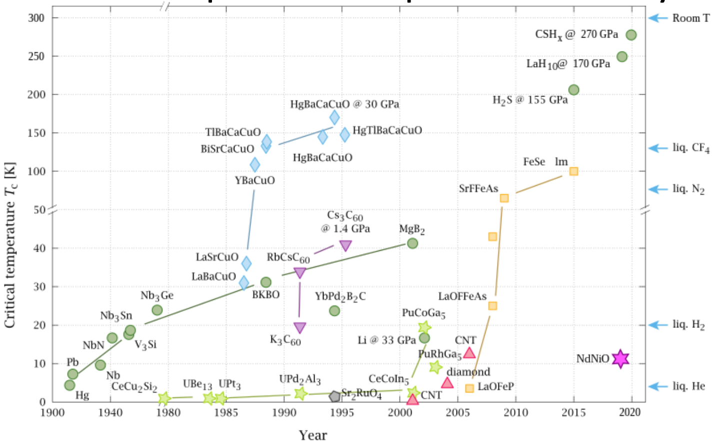
B

P

P-*T* phase diagram of water



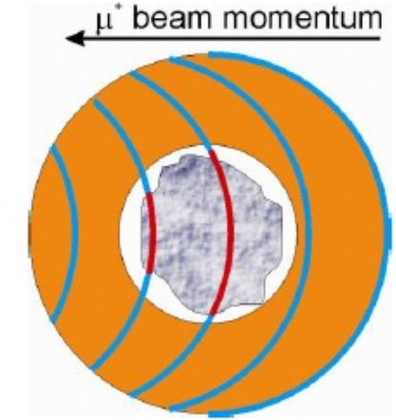
Room temperature superconductivity



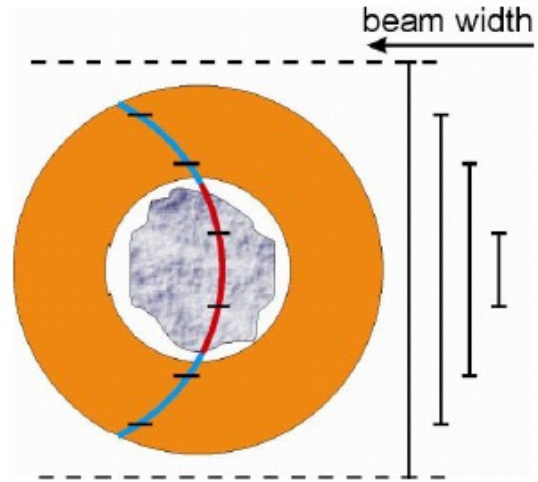
Wikipedia

μSR under pressure

Muon momentum tuning

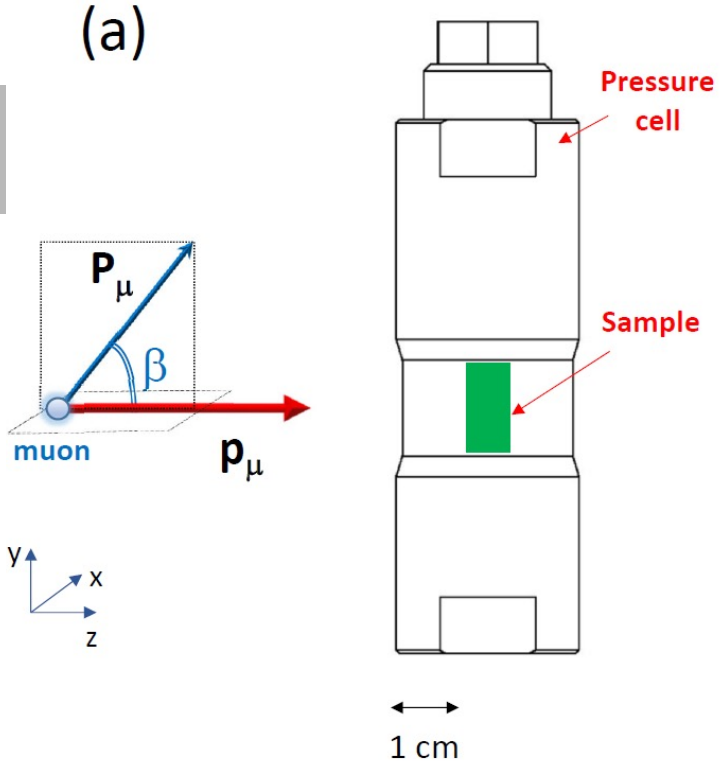


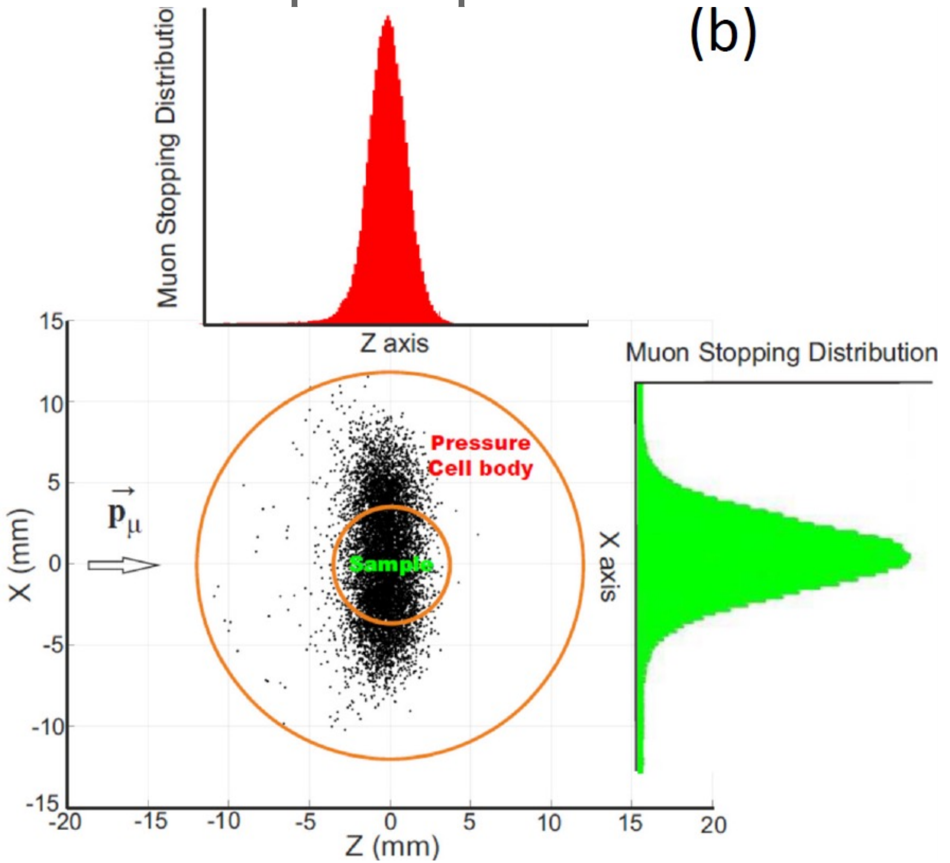
Beam-width tuning



Khasanov *et al.*, High Pr. Res. **36**, 140-166 (2016)

μSR under pressure: basic principles





R. Khasanov, Journal of Applied Physics **132**, 190903 (2022)

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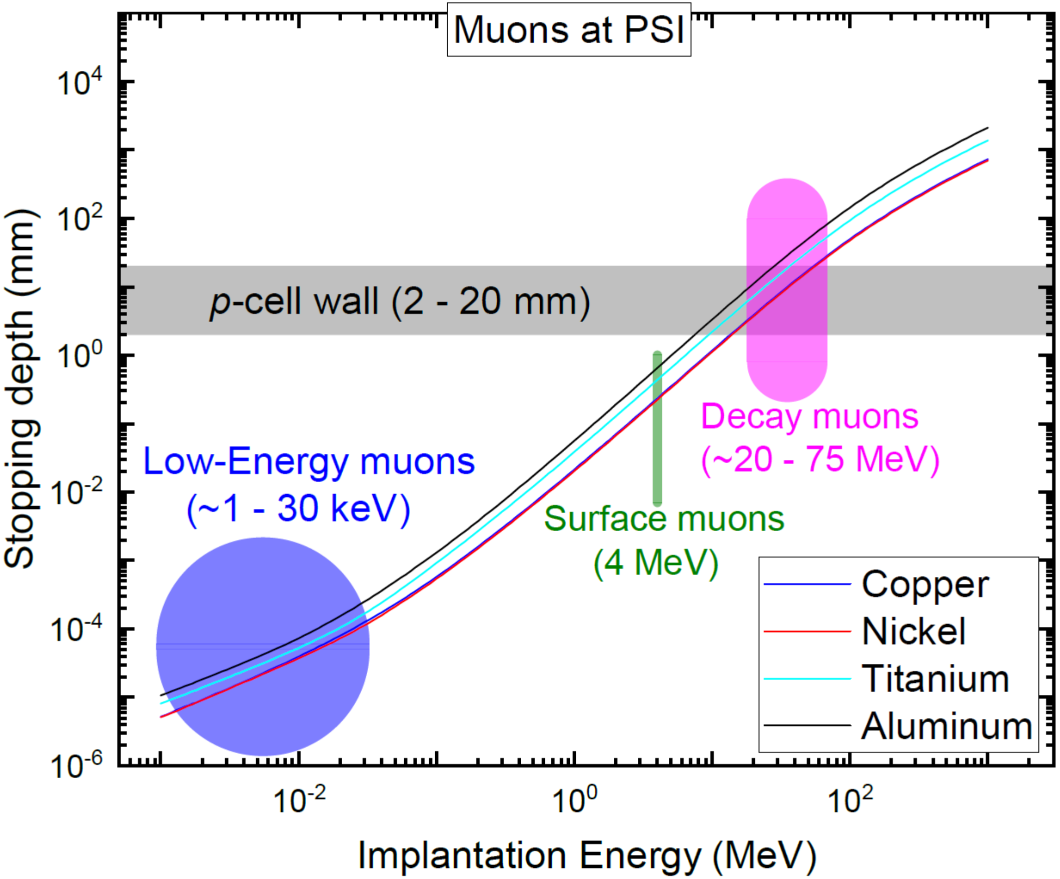
μSR under pressure

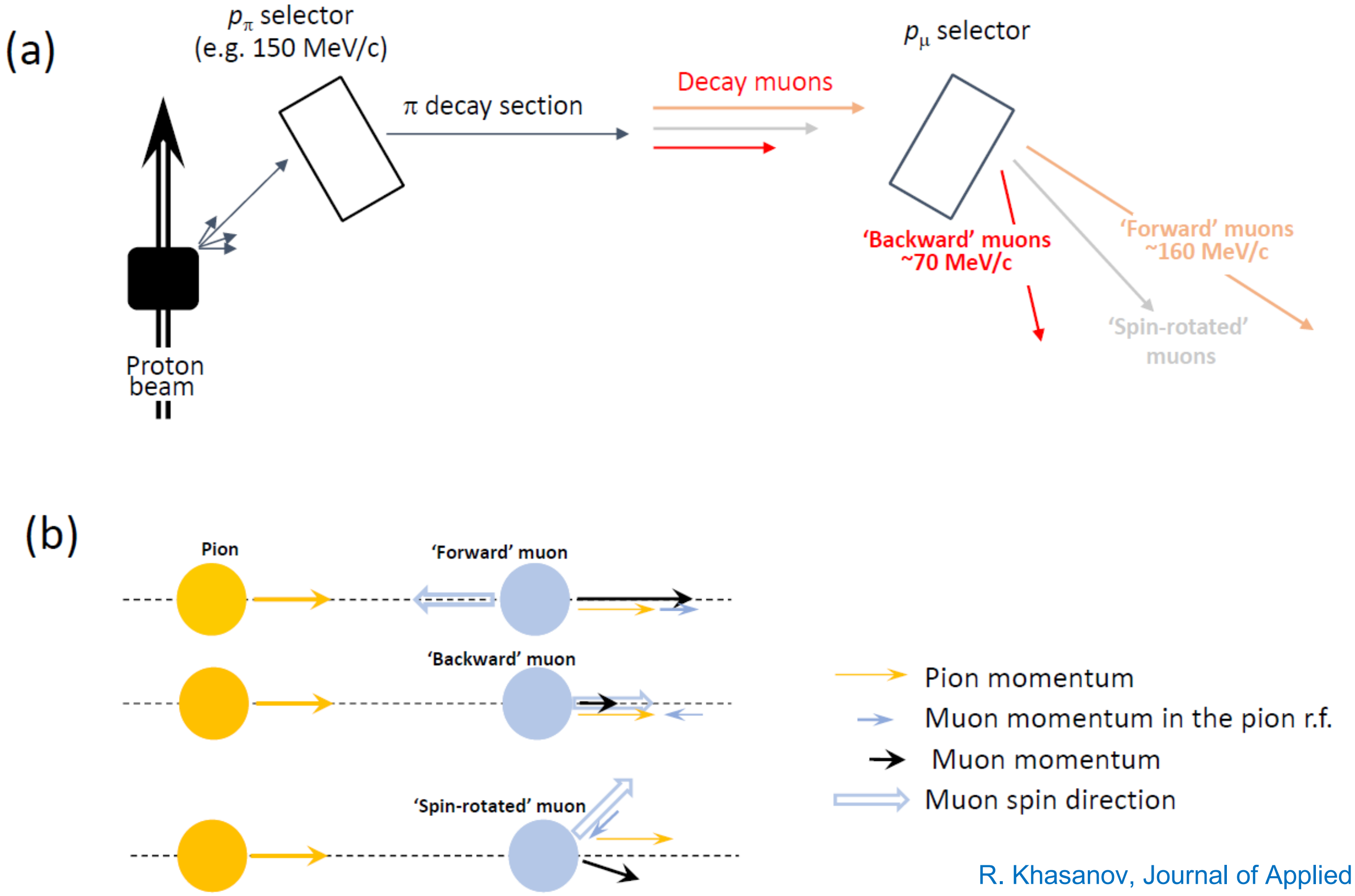
1. Muon beam-line – fast muons with tunable energy
2. μSR Spectrometer
3. μSR pressure cells

Muon beam



R. Khasanov, Journal of Applied Physics **132**, 190903 (2022)

Decay muon beam-line



R. Khasanov, Journal of Applied Physics **132**, 190903 (2022)

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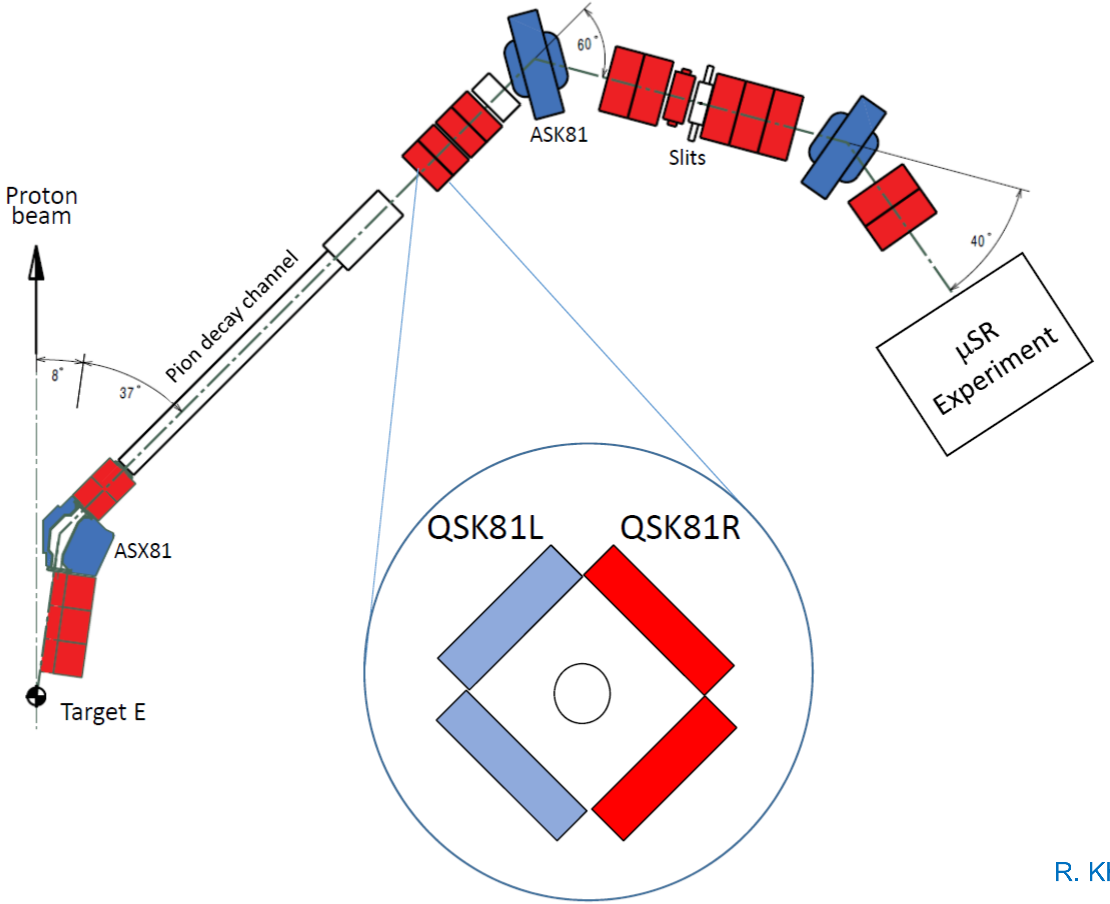
μE1 decay beam-line at PSI



The use of the spllited Quadrupolar magnet (QSK81) allows to collect muons with turned spins. This a unique possibility which is accessible for decay muon beam-lines only.

The first spin-rotation experiments were conducted in TRIMF at M9B beamline

R. Khasanov, Journal of Applied Physics **132**, 190903 (2022)

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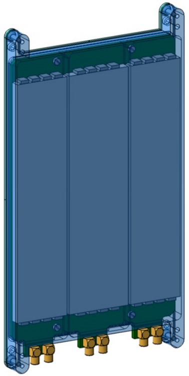
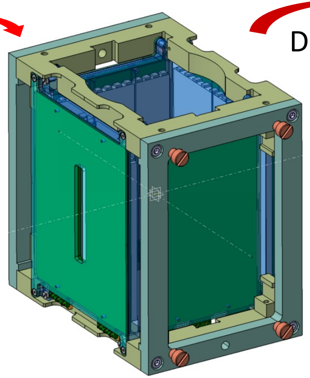
Detectors, GPD Spectrometer (2017)

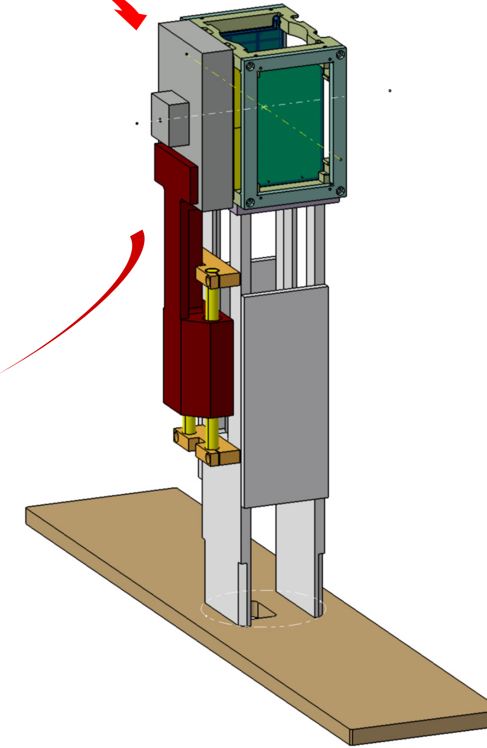
Individual Detector

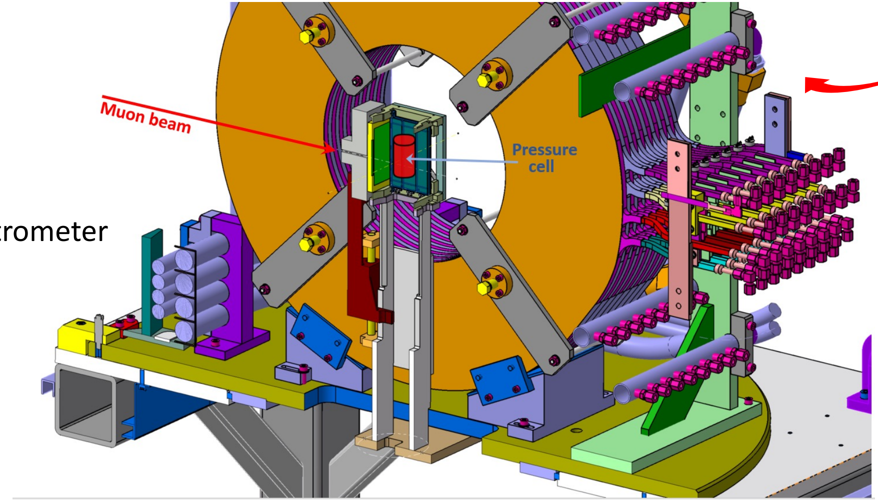




Detector head

Detector setup

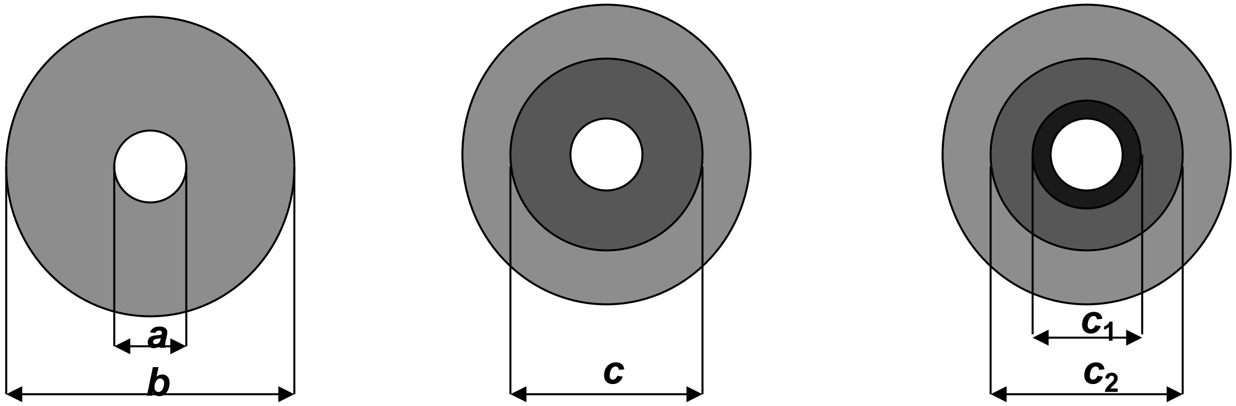




GPD spectrometer

Pressure cell construction: compound cylinder

Single wall cell | Double wall cell | Three wall cell



$$p_{max} \propto \frac{1}{2} - \frac{a^2}{2\,b^2}$$

$$p_{max} \propto 1 - \frac{a^2}{2\,c^2} - \frac{c^2}{2\,b^2}$$

$$p_{max} \propto \frac{3}{2} - \frac{a^2}{2\,c_1^{\,2}} - \frac{c_1^{\,2}}{2\,c_2^{\,2}} - \frac{c_2^{\,2}}{2\,b^2}$$

For ***a***=6 mm and ***b***=24 mm, $p_{max}^{s} \div p_{max}^{d} \div p_{max}^{t}$ = 1 / 1.6/ 1.96

Khasanov *et al.*, High Pr. Res. **42**, 29 (2022)

Construction material suitable for μSR

Nonmagnetic Alloys

	CuBe	$TiAl_6V_4$	NiCrAl	MP35N
Yield strength	1.1 Gpa (300 K)	1.05 Gpa (300 K)	2.06 Gpa (300 K)	2.15 GPa (300 K)
Young modulus	131 GPa (300 K)	97 Gpa (300 K)	190 Gpa (300 K)	215 Gpa (300 K)

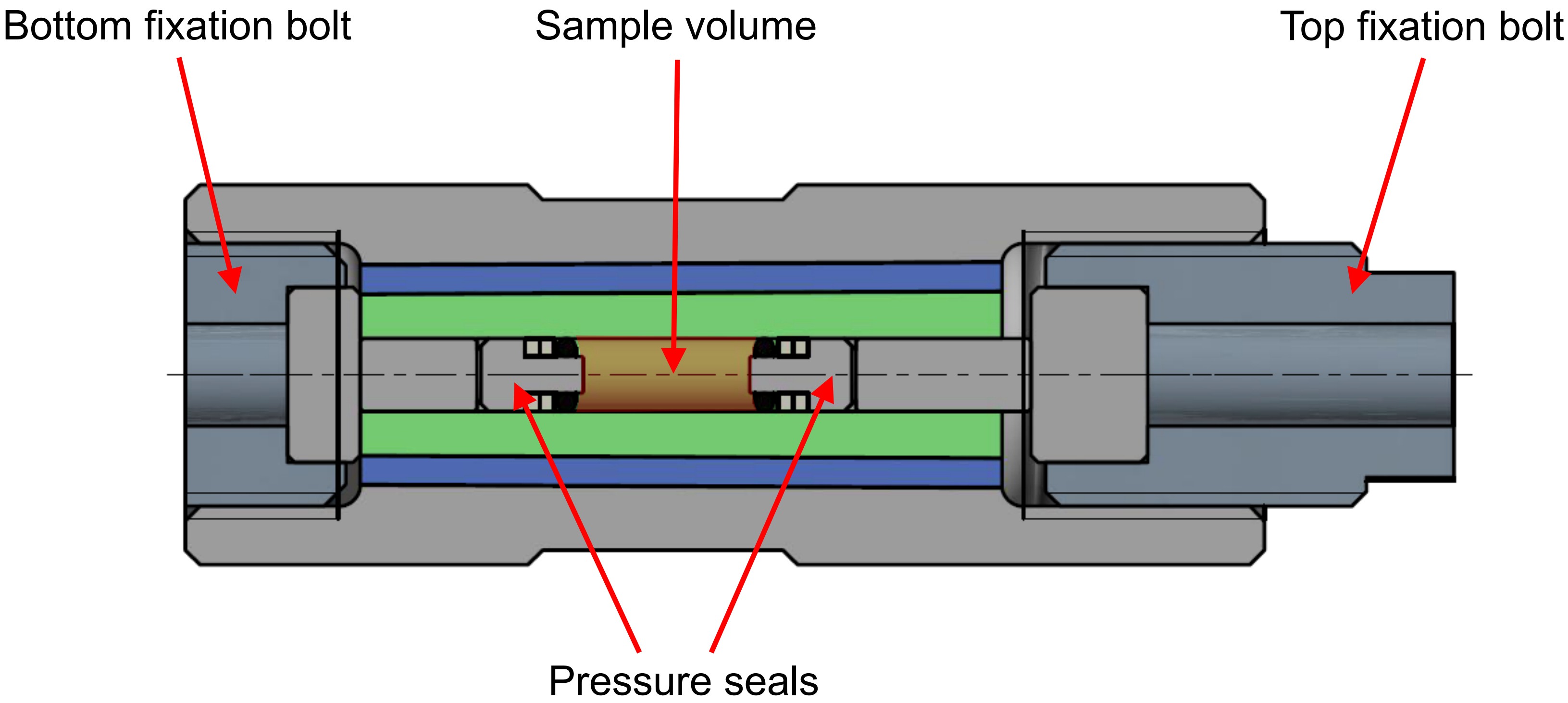
Sintered materials

	WC	cBN	SiC	ZrO_2-Y_2O_3	Al_2O_3-ZrO_2	Si_3N_4
Compressive strength	5.0-11.0 Gpa	2.9 GPa	7.6-8.3 GPa	2.20 GPa	4.7 GPa	5.1-5.5 GPa
Young modulus	600-670 Gpa		918 GPa	210 Gpa	357 GPa	241 GPa

- Strong enough to hold the pressure
- Should not have “strong” μSR response
- Should have temperature independent response

Khasanov *et al.*, High Pr. Res. **42**, 29 (2022)

Three-wall pressure cell construction

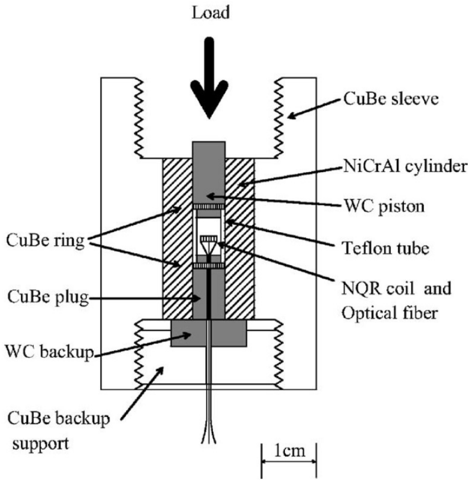


$p_{max}(RT)$ ~3.3 Gpa, p_{max} (LT) ~ 3.0 GPa

Khasanov *et al.*, High Pr. Res. **42**, 29 (2022)

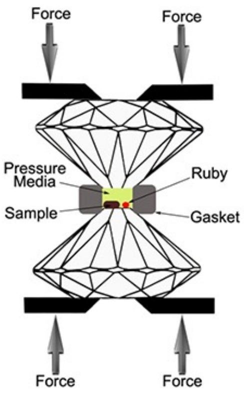
Pressure determination, pressure probes

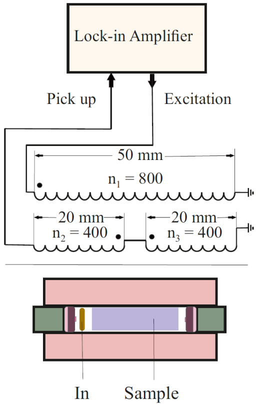
Contact (feedthroughs)



Resistivity, AC susceptibility, NMR, NQR, specific heat, optical …

Contactless

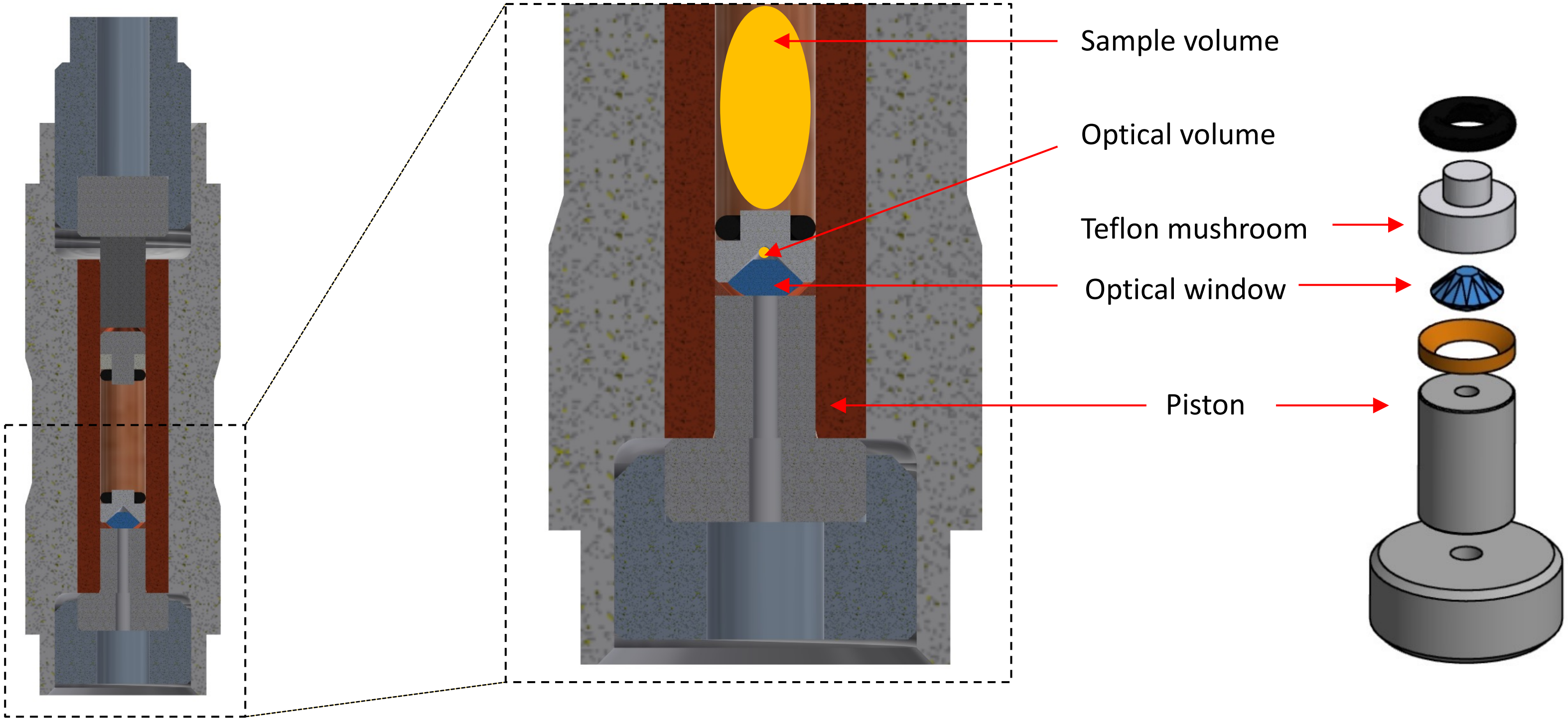




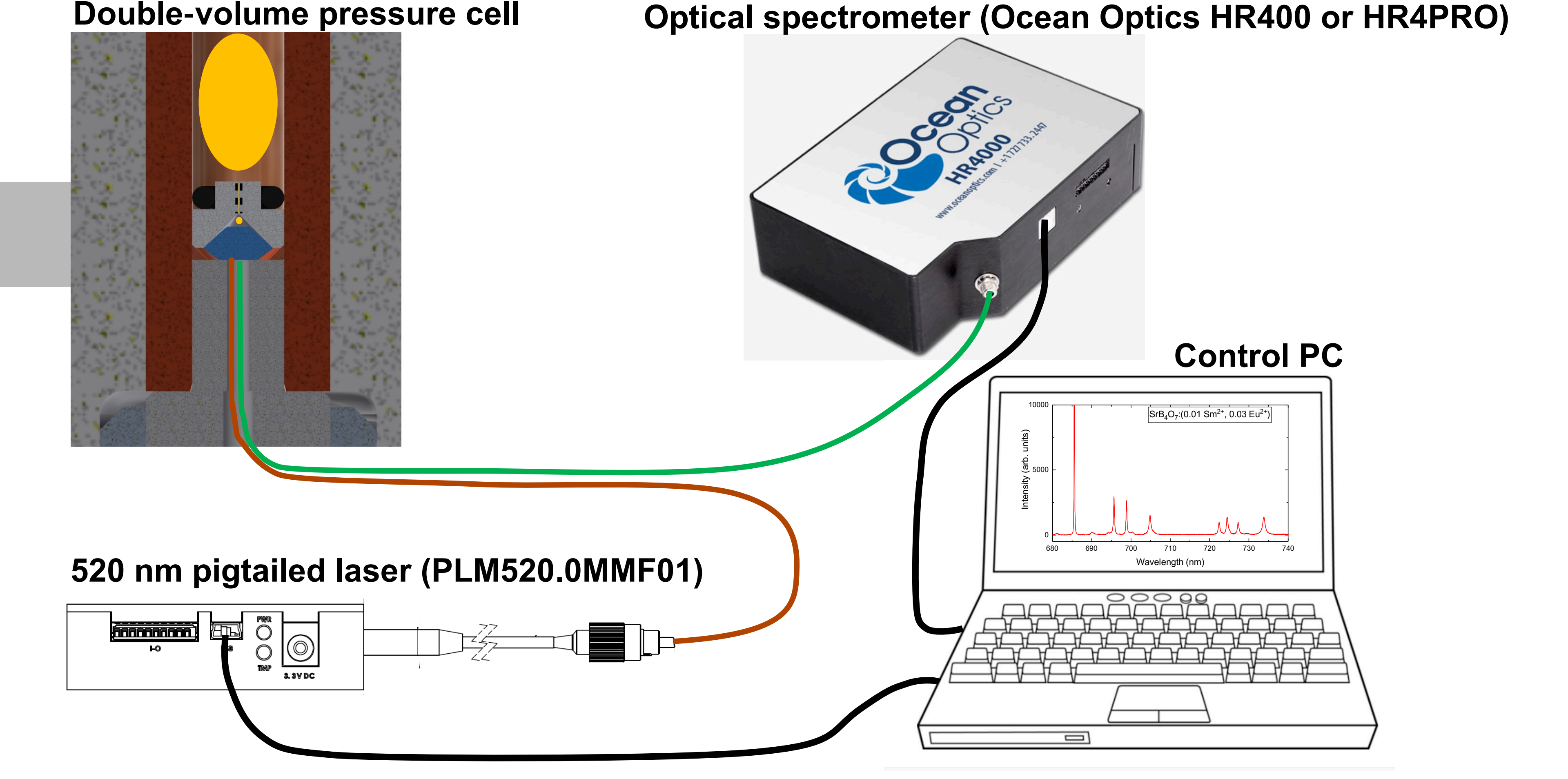
Optical, AC susceptibility, NMR, NQR, specific heat, Neutron scattering (equation of state)…

Substantial part of the pressure cell volume is occupied by the pressure indicator

Double volume piston-cylinder cell

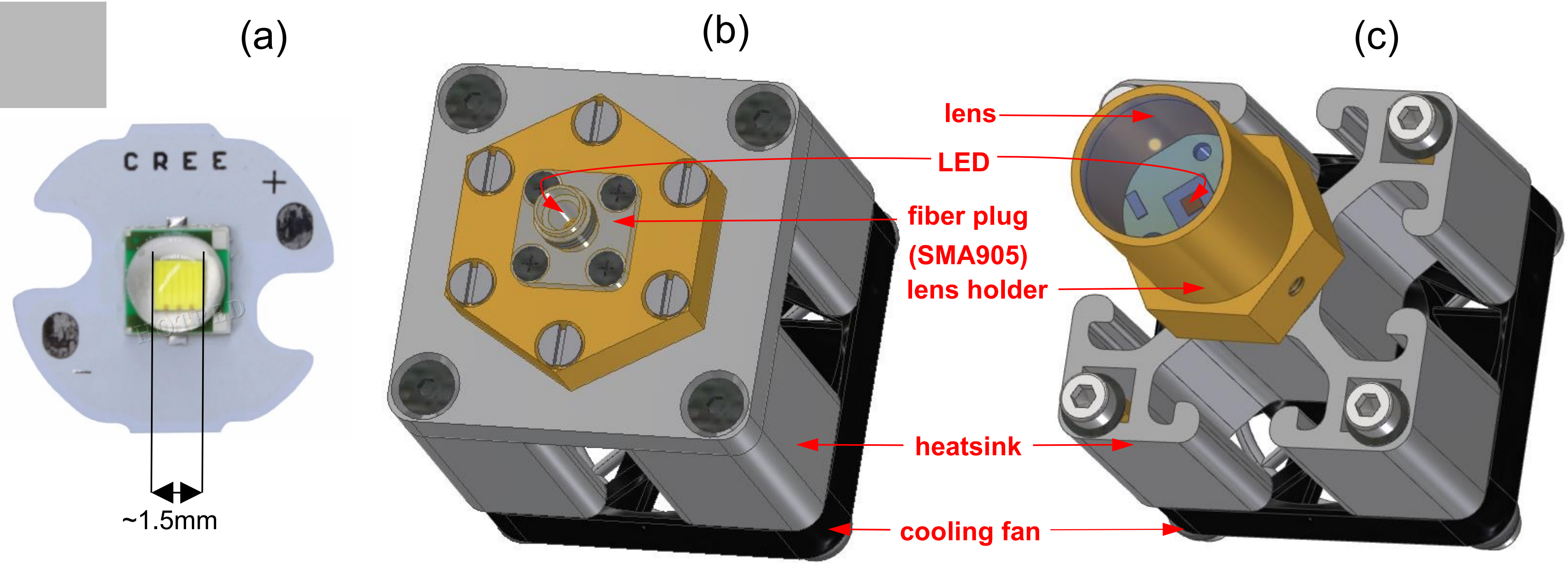


Naumov … Khasanov*, Phys. Rev. Applied **17**, 024065 (2022)



Naumov … Khasanov*, Phys. Rev. Applied **17**, 024065 (2022)

Safety concern: Laser *vs.* LED light



Khasanov *et al.*, High Pr. Res. (2023)

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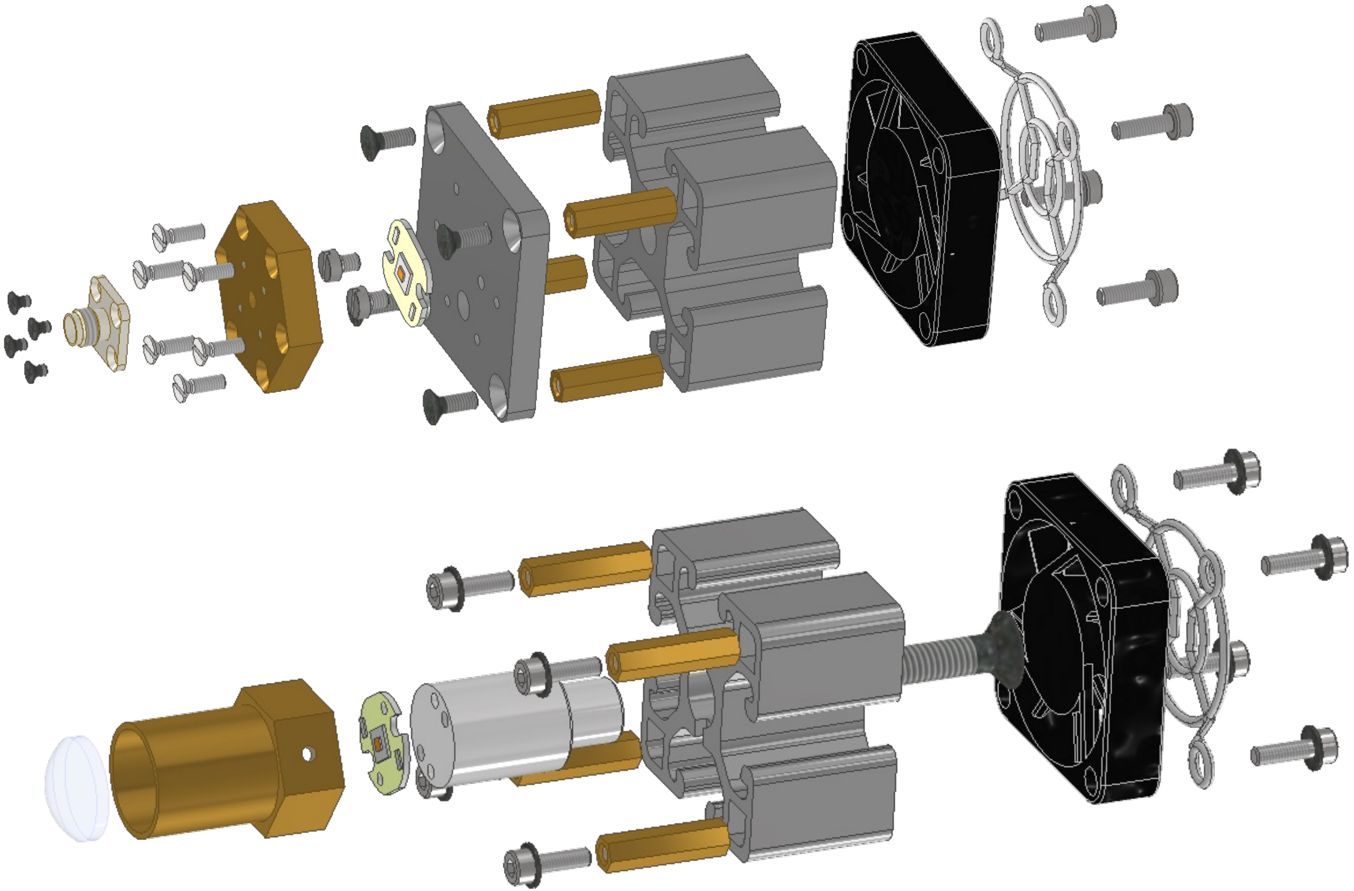
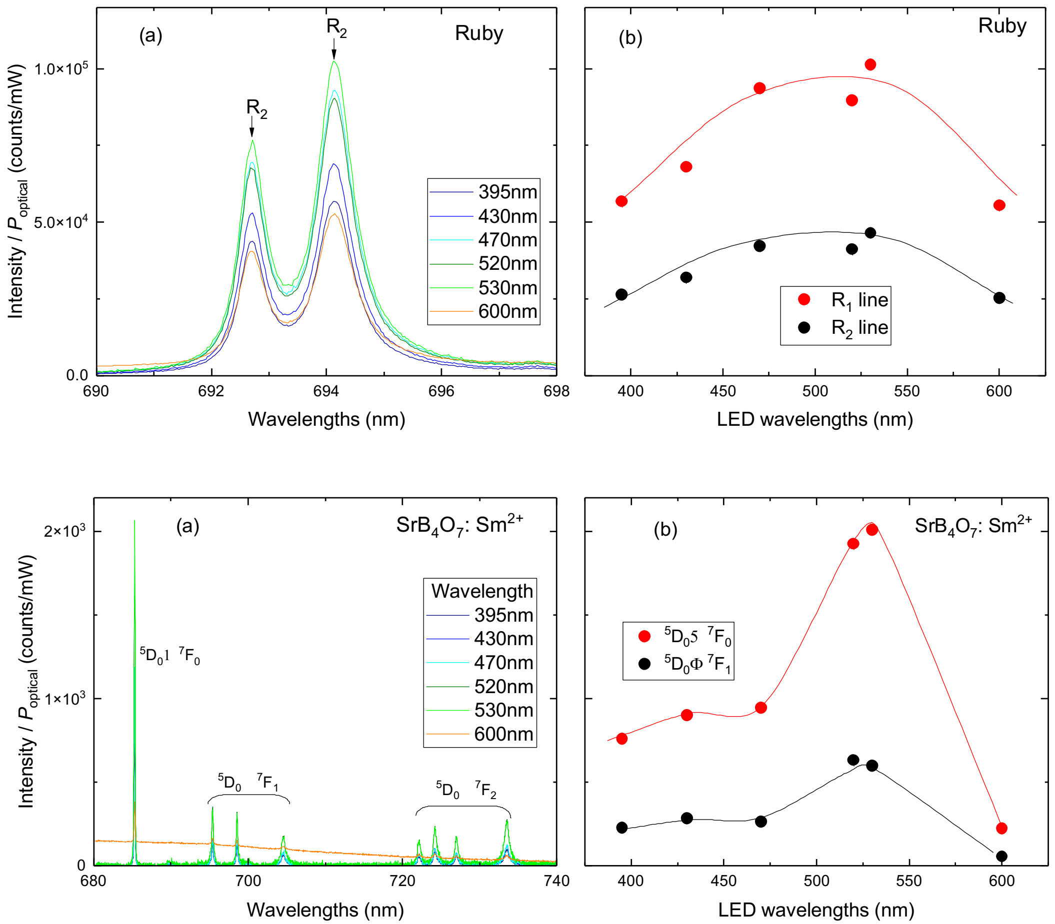
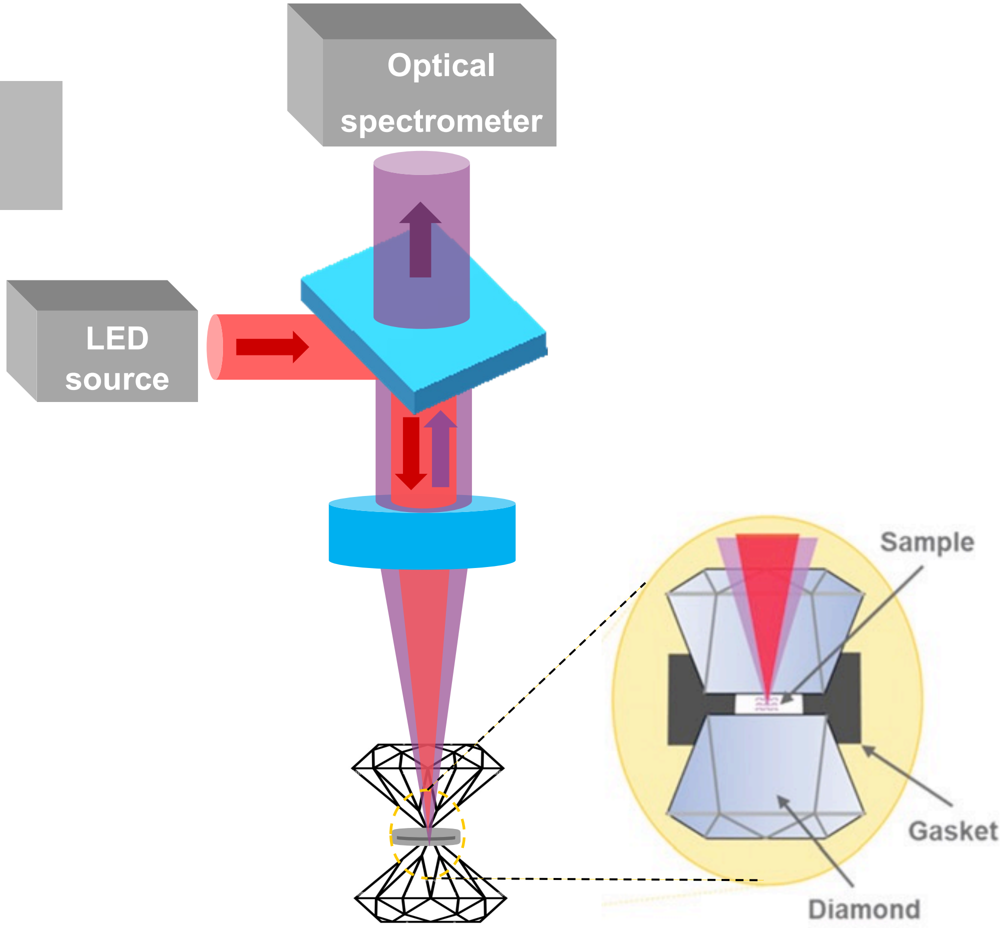
LED light sources for fluorescense

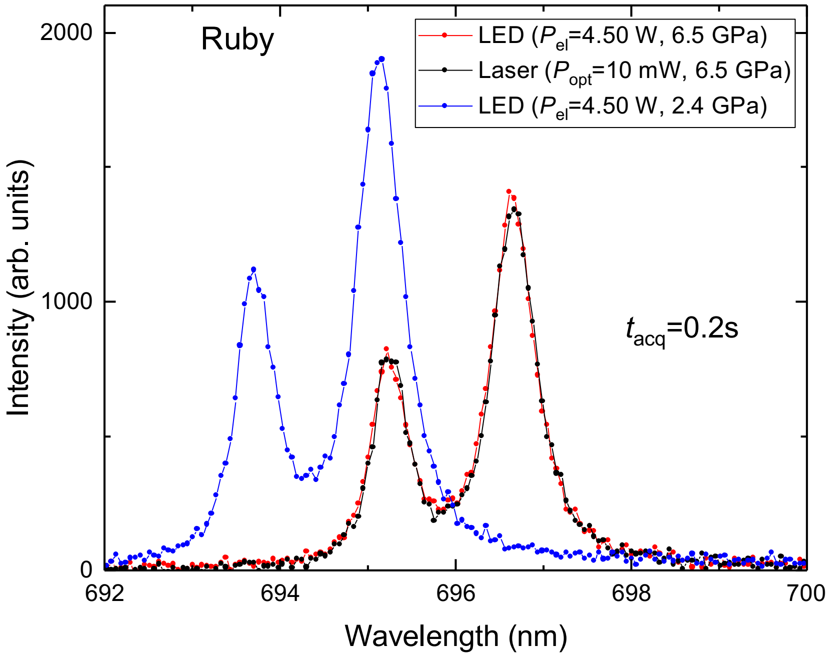


Ruby and Sr tetraborite



Diamond anvil setup





Khasanov *et al.*, High Pr. Res. (2023)

Strain cell – uniaxial pressure

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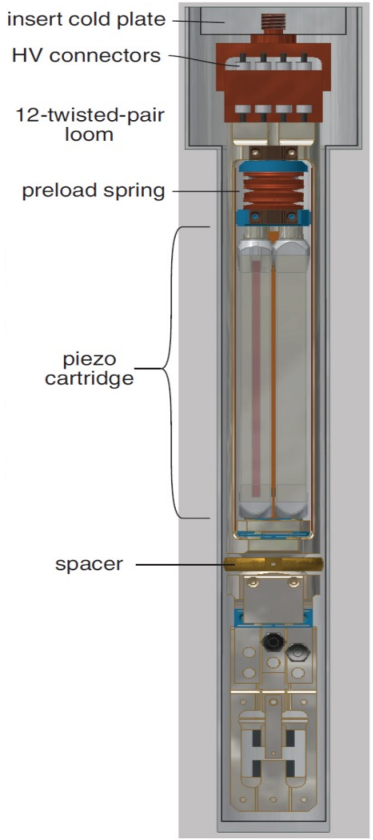
Hubertus Luetkens

Zurab Guguchia

Matthias Elender

MAX-PLANCK-INSTITUT
FÜR CHEMISCHE PHYSIK FESTER STOFFE

Clifford Hicks



TECHNISCHE UNIVERSITÄT DRESDEN

Hans-Henning Klauss
Rajib Sarkar

Vadim Grinenko

Shreenanda Ghosh

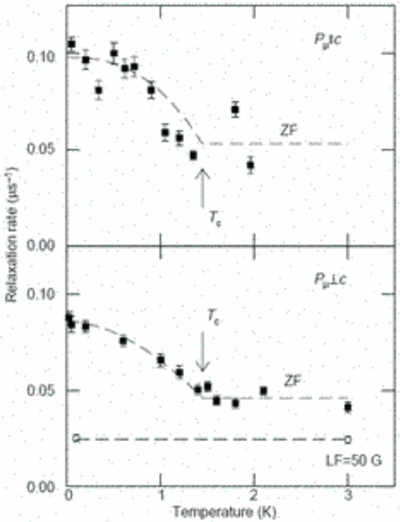
Goosh et al., Rev Sci Instrum **91**, 103902 (2020)

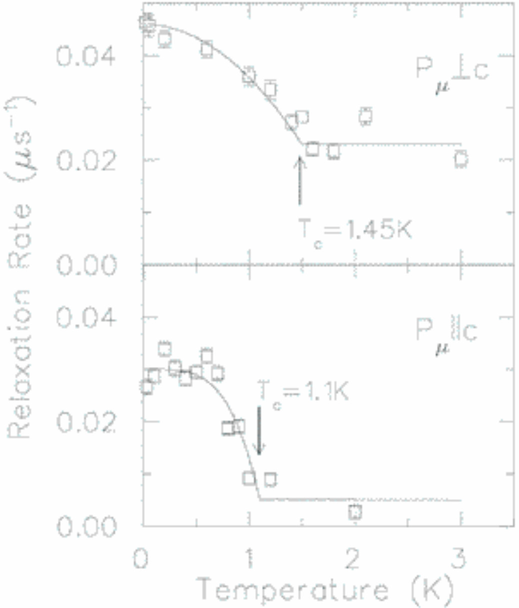
Scientific examples

1. The uniaxial and hydrostatic pressure effects on TRSB in Sr_2RuO_4
2. Pressure-induced critical and multicritical points in frustrated spin liquid

Time-reversal symmetry breaking in Sr_2RuO_4

Broken Time Reversal Symmetry

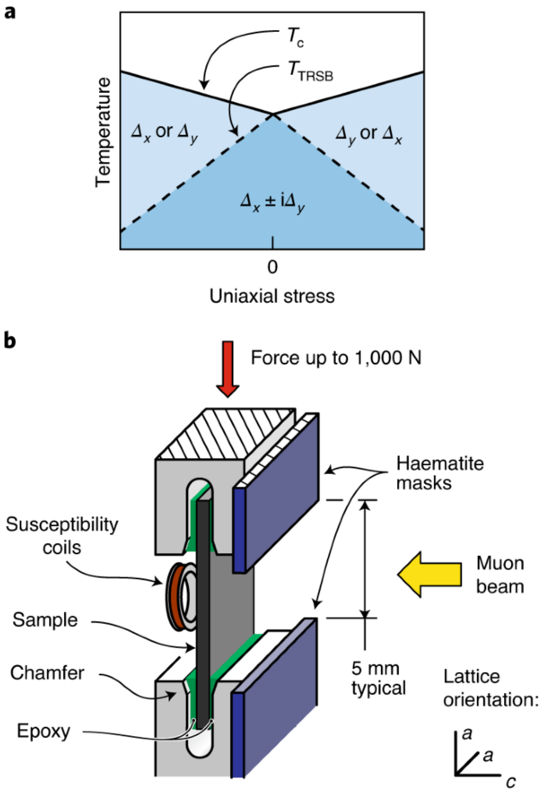


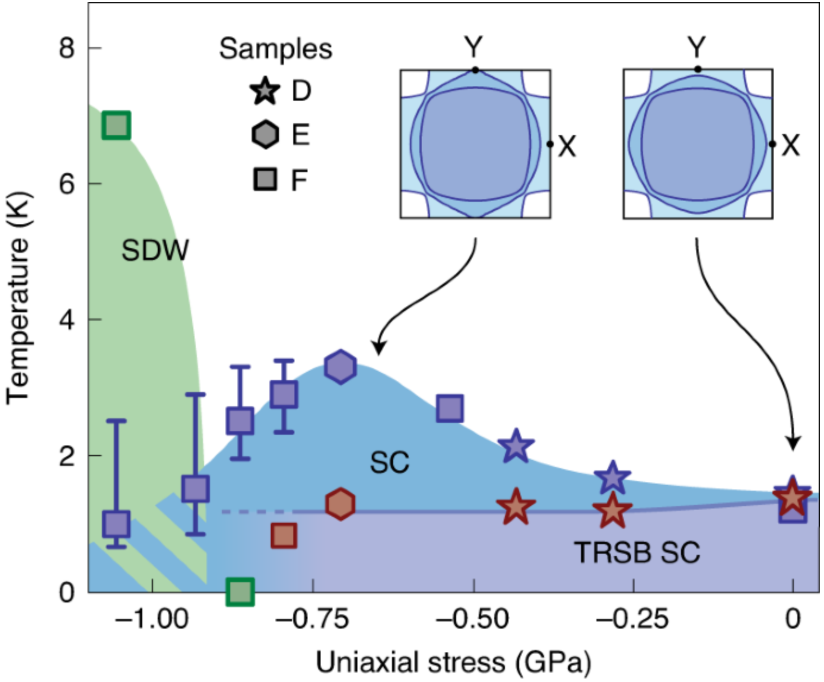


- Spontaneous field seen below T_c, for P_m//c, //a.
- B_{loc}~1G.

Luke et al., Nature **394**, 558 (1998).

Uniaxial strain

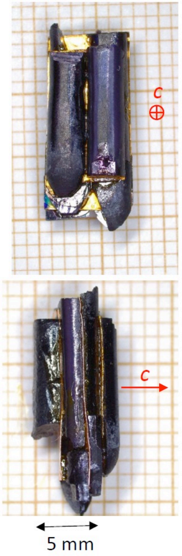




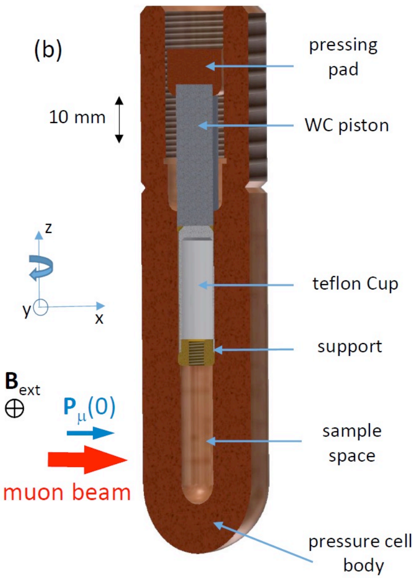
Grinenko *et al.*, Nature Phys. **17**, 748 (2021).

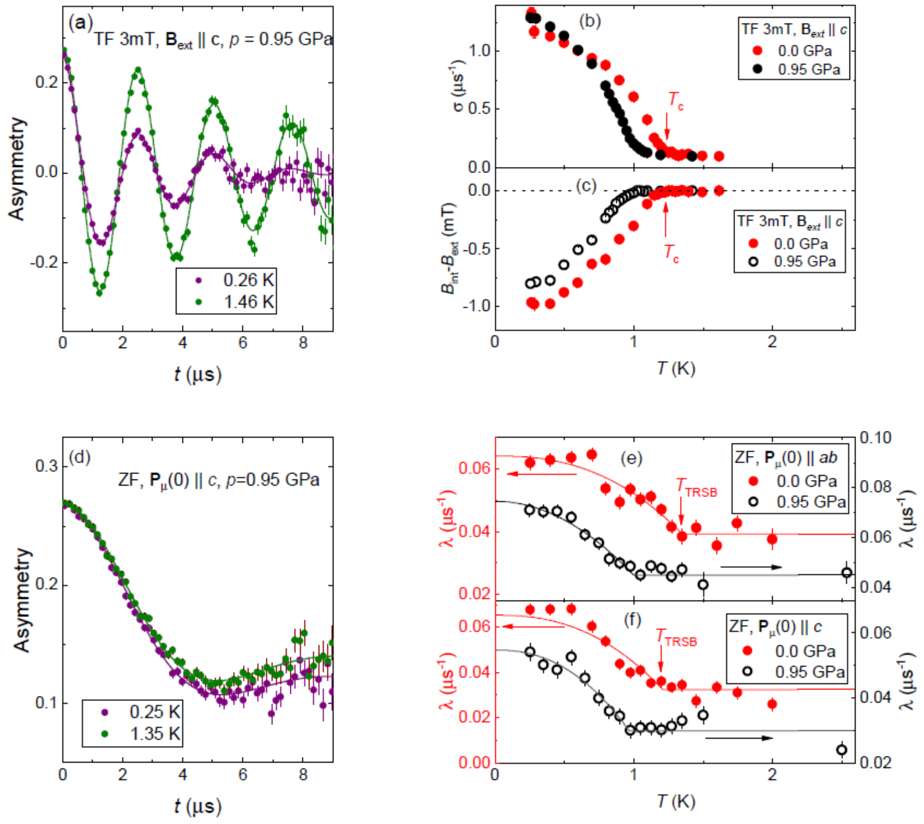
Hydrostatic pressure experiments

(a)



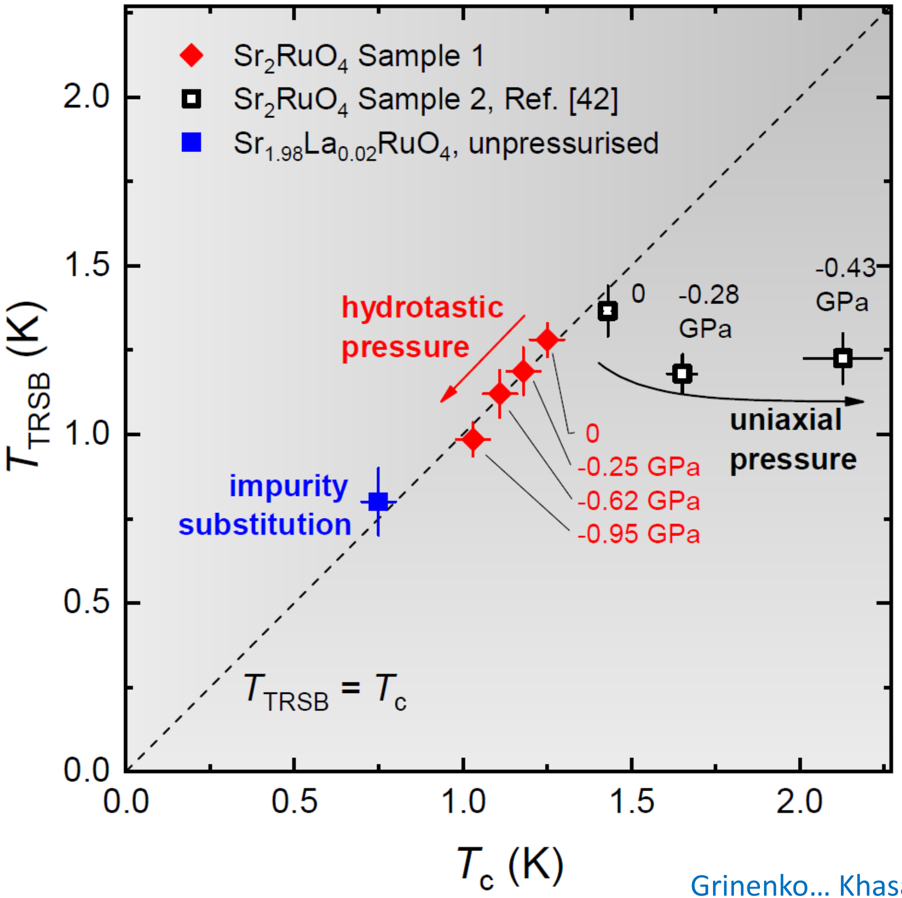
(b)





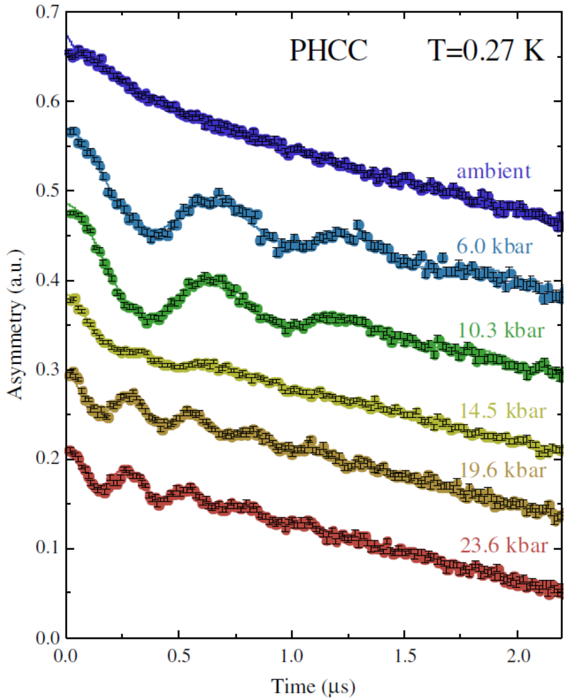
Grinenko… Khasanov*, Nature Comm. **12**, 3920 (2021).

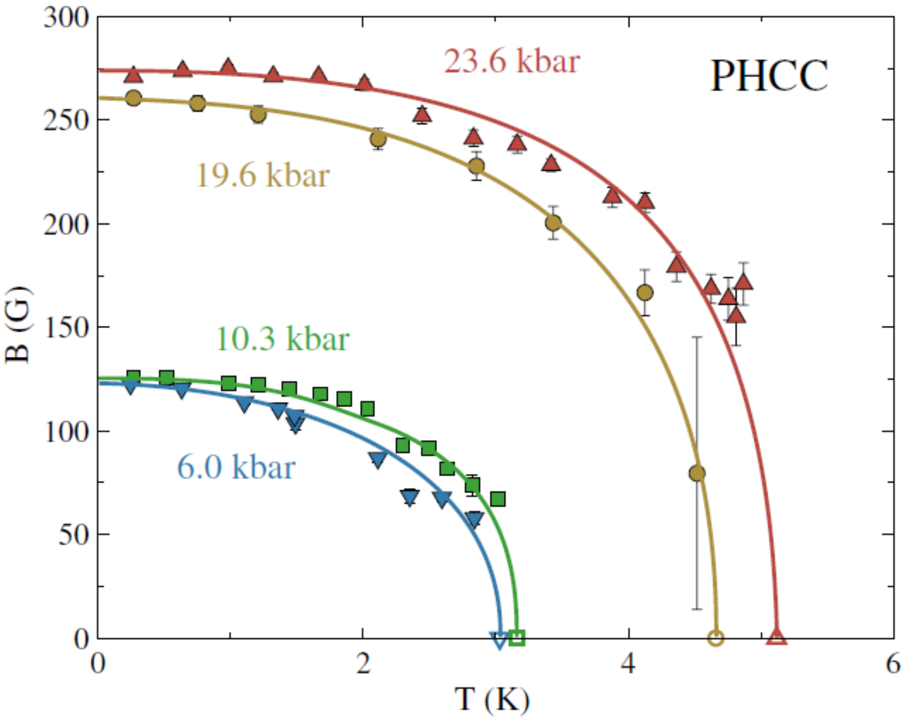
Combined graph data



Grinenko… Khasanov*, Nature Comm. **12**, 3920 (2021).

$(C_4H_{12}N_2)Cu_2Cl_6$ (PHCC)





Thede et al., Phys. Rev. Lett. **112**, 087204 (2014).

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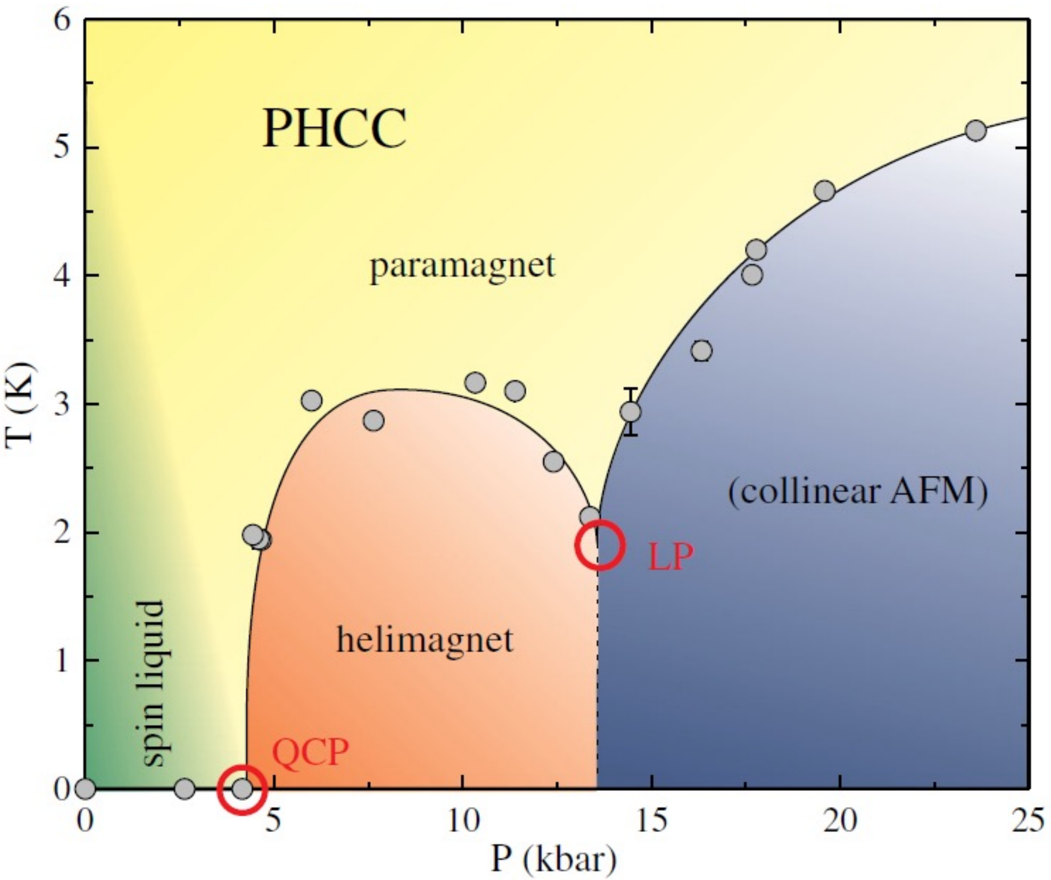
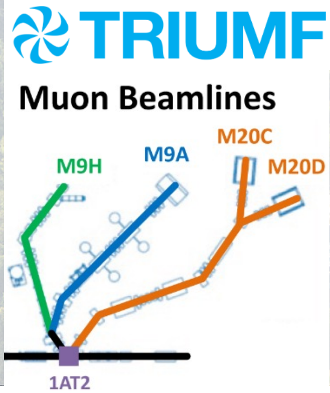
p-T phase diagram of PHCC



Thede et al., Phys. Rev. Lett. **112**, 087204 (2014).

μSR under pressure suppose to be powerful technique for condensed matter research.

Hope, we would be able to share our knowledge with physicists from TRIUMF at the new M9H beamline



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