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High pressure research using muons at PSI

Beam-based Probes of Condensed Matter Physics in Canada: 03.06-0.4-0.2021

Outline

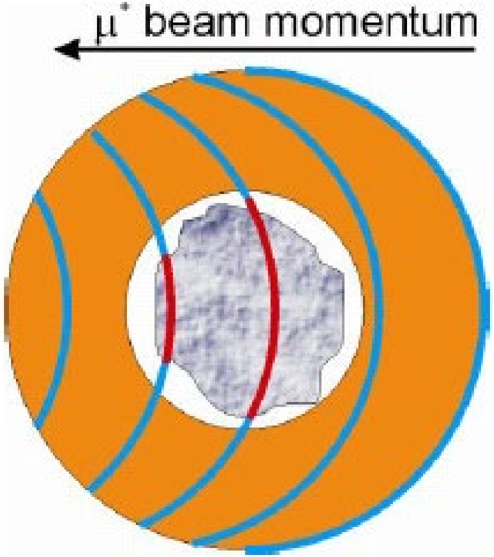
- μSR under pressure experiments:
- "Decay" beam-lines
- μE1 decay beam-line at PSI
- General Purpose Decay (GPD) spectrometer
- Pressure cell construction(s)
- Pressure measurements

- Scientific example
  - Unsplit superconducting and time-reversal symmetry breaking transitions in Sr2RuO4 under hydrostatic pressure

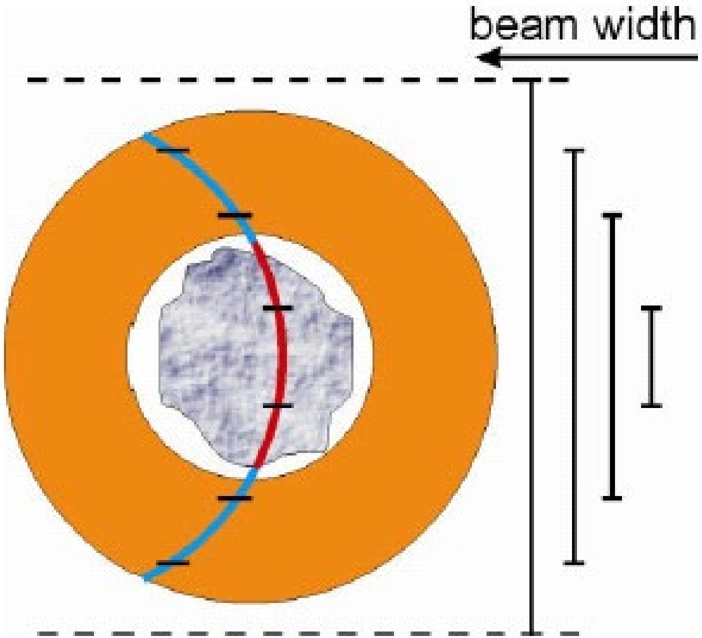
μSR under pressure: Basic principles

μSR under pressure experiments

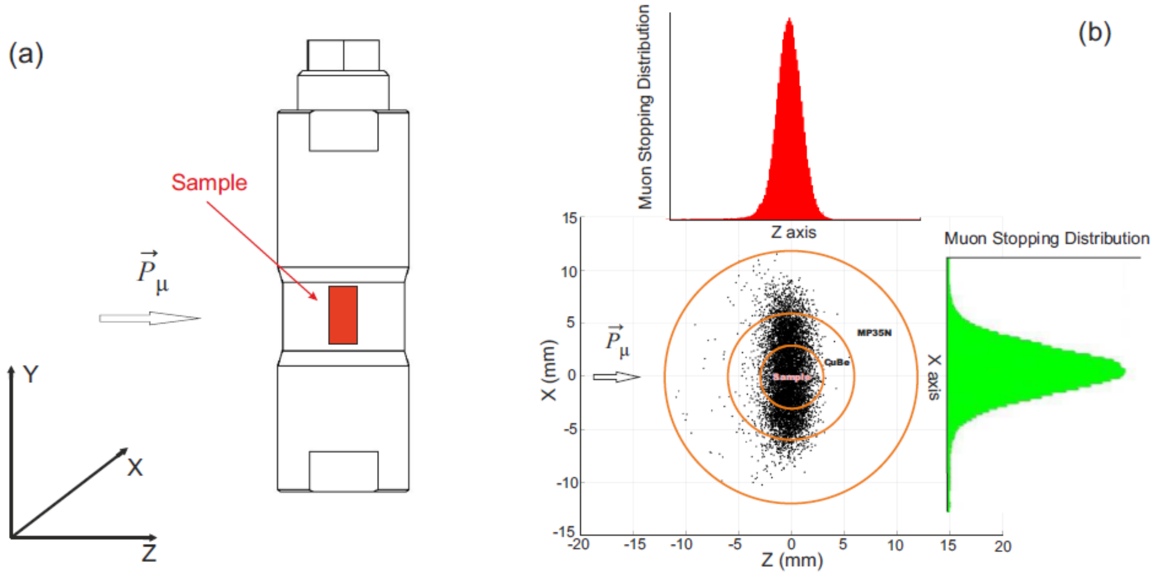
Muon momentum tuning



Beam-width tuning



μSR under pressure experiments



The schematic view of the pressure cell (black contour) with the sample (red rectangular). Muons are implanted along the vector P. (b) The cross sectional view (X-Z plane) of the double-wall pressure cell. The colored areas represent the muon stopping distributions in parallel (red) and perpendicular (green) direction to the muon beam. The energy of implanted muons is 44 MeV. The simulations were made by using TRIM.SP package. The simulations reveal that approximately 37% of all the muons stop within the sample, 43% within the inner and 10% within the outer cylinder.

μSR under pressure:
High-momentum muon beam-lines

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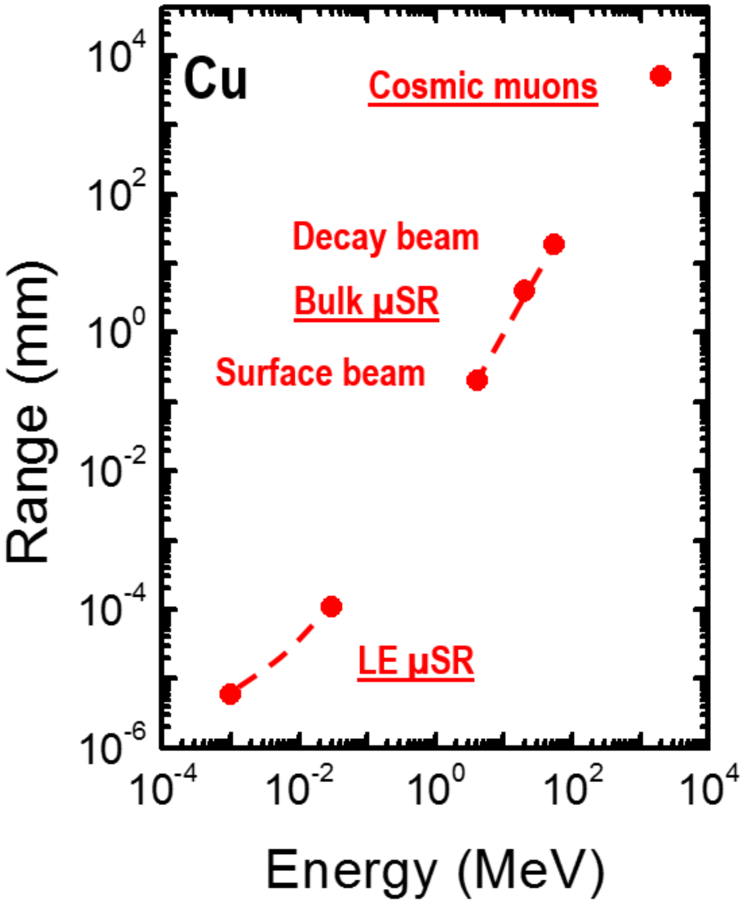
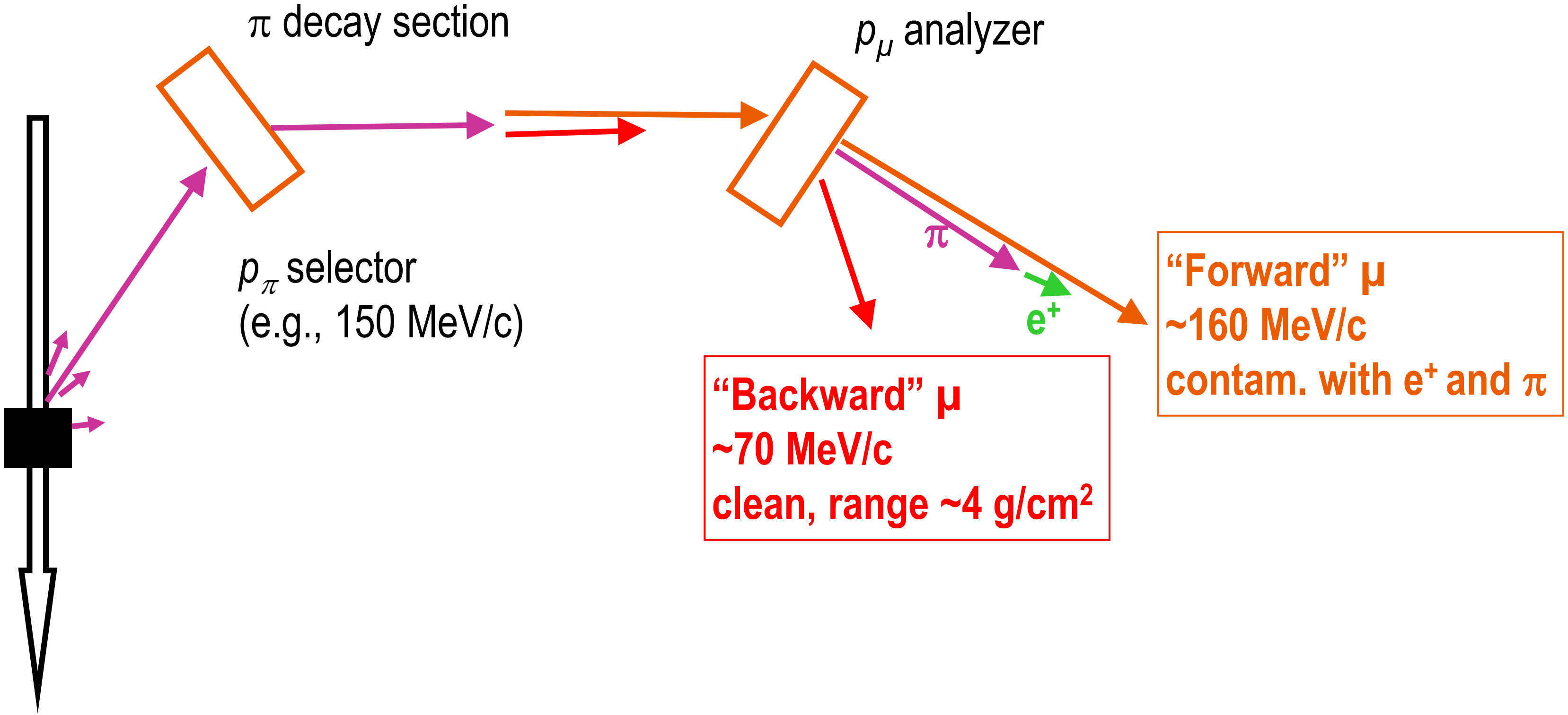
Muon implantation depth

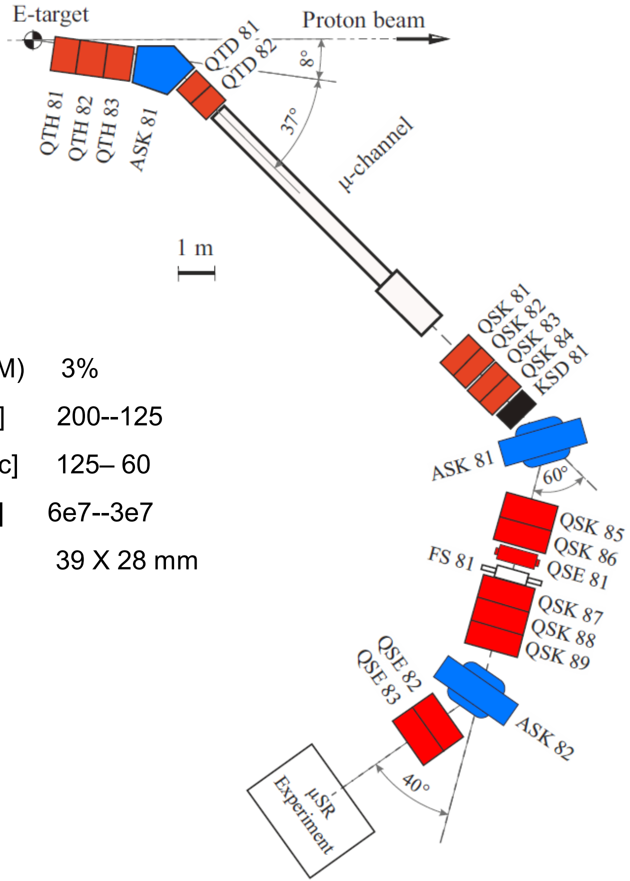


In order to perform muon experiments under pressure one needs to use the so-called ‘decay’ beam-lines

Decay muon beam-line

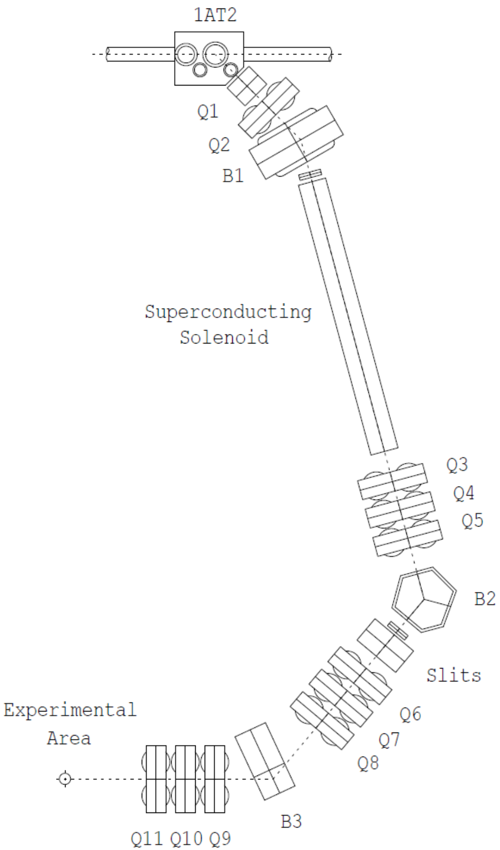


μE1 beam-line at PSI



Momentum acceptance (FWHM)	3%
Pion momentum range [MeV/c]	200--125
Muon momentum range [MeV/c]	125– 60
Rate of positive muon [$mA^{-1}s^{-1}$]	6e7--3e7
Spot size (FWHM)	39 X 28 mm

M9B beam-line at TRIUMF



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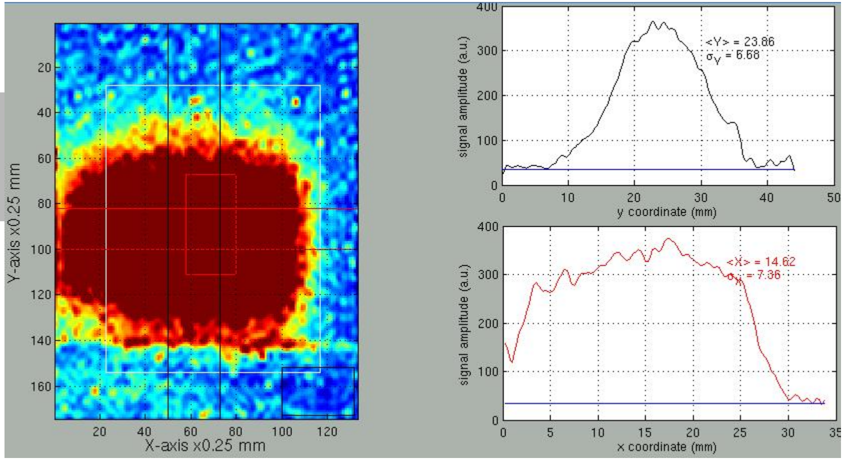
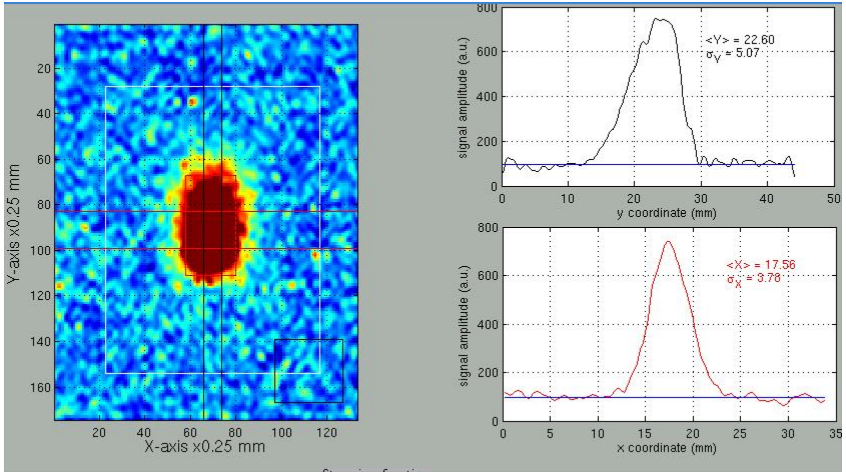
μE1 beam-spot



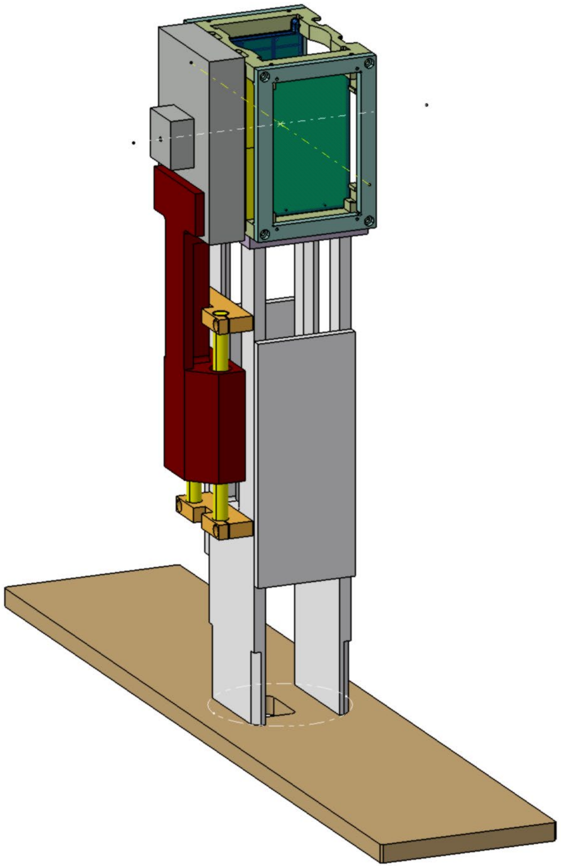
Direct beam. Beam setting p107apr09. Muon momentum 109 MeV/c



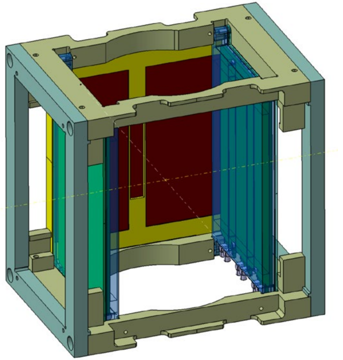
Collimated beam. Beam setting p107apr09. Muon momentum 109 MeV/c

μSR under pressure: spectrometer

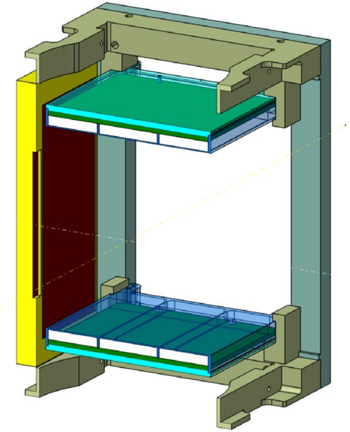
Construction of the detector block



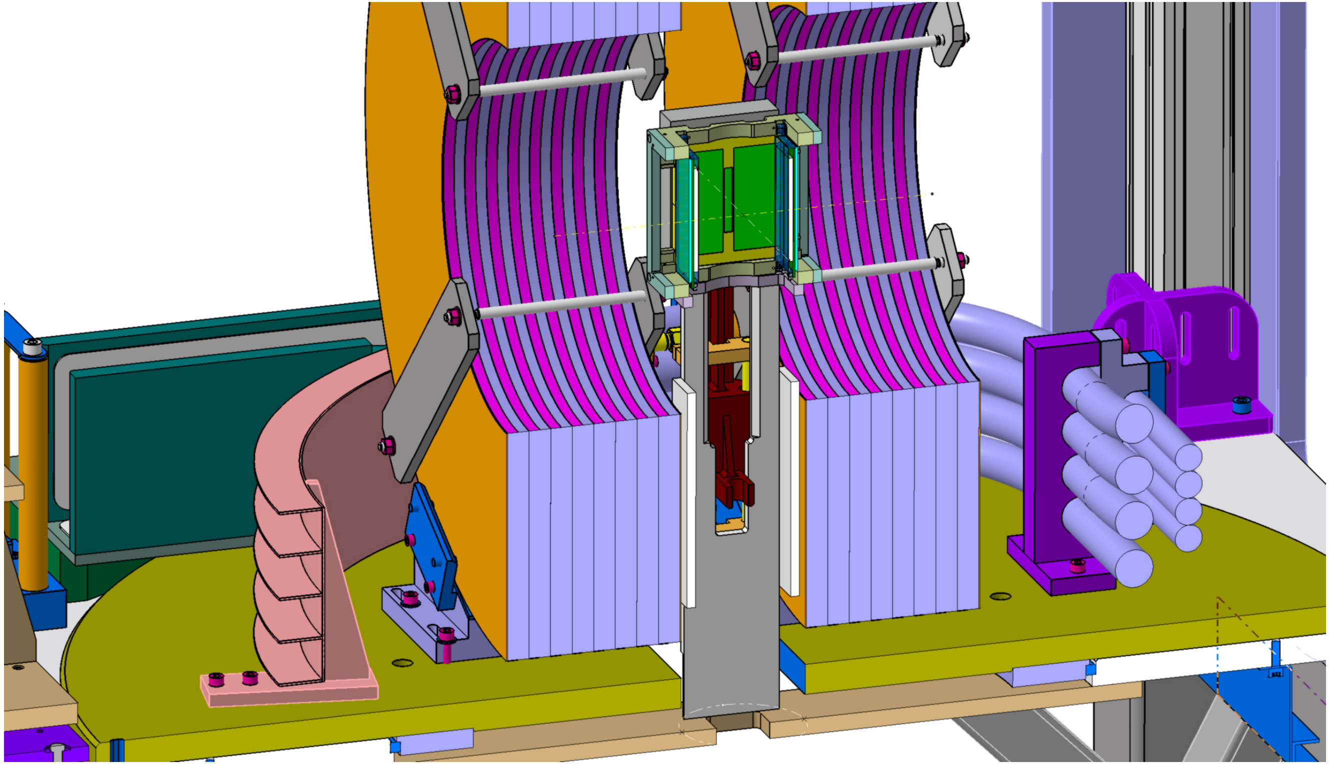
Vertical setup



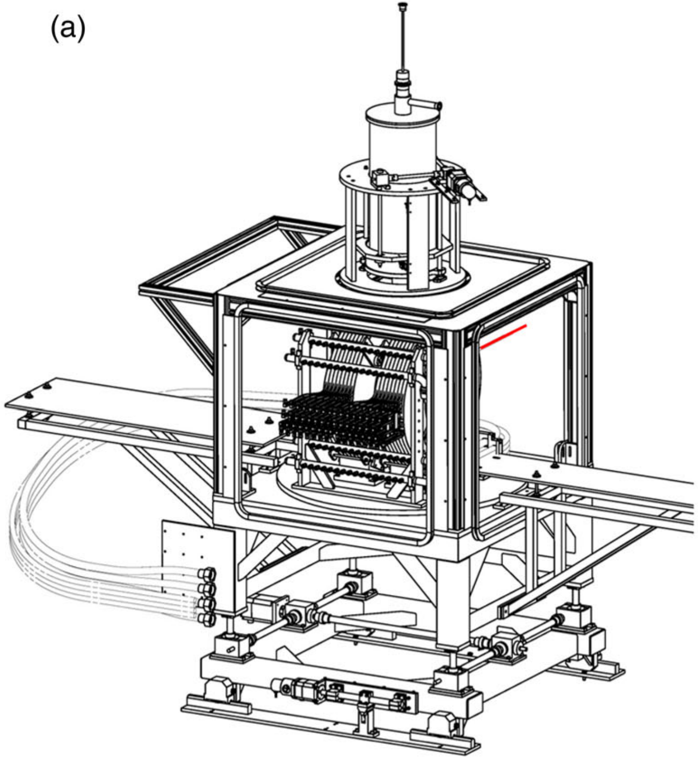
Horizontal setup

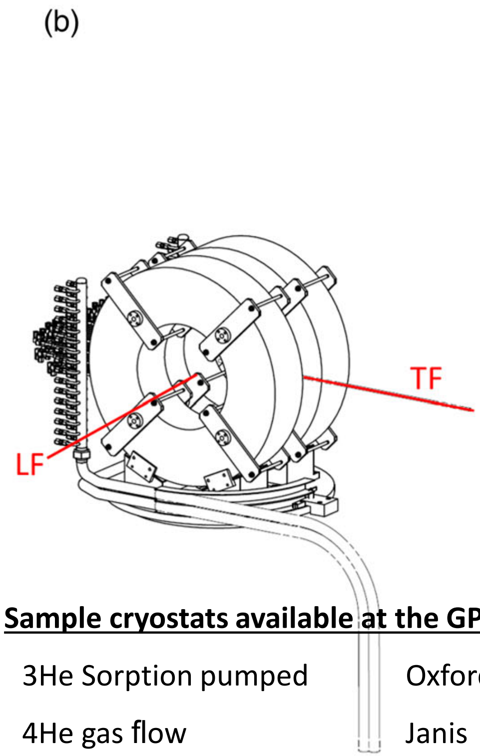


GPD instrument with the detectors



GPD instrument and cryostats



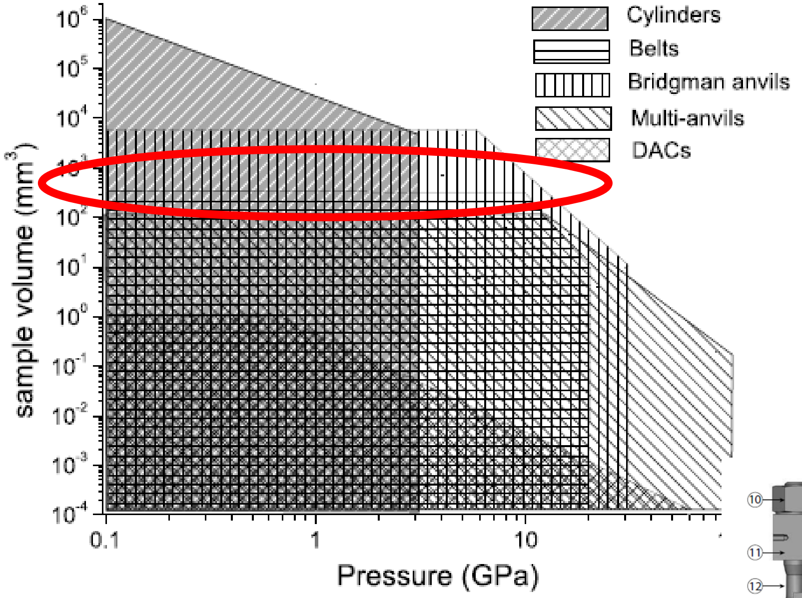


Sample cryostats available at the GPD instrument.

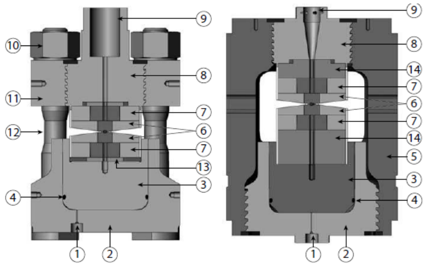
3He Sorption pumped	Oxford	0.24−325 K	Yes
4He gas flow	Janis	2.5−300 K	Yes
Closed Cycle Refr.	Home made	10−300 K	No
N_2 gas flow	Home made	80−500 K	No

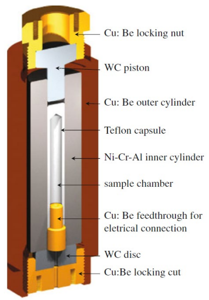
Type of the pressure cell selection

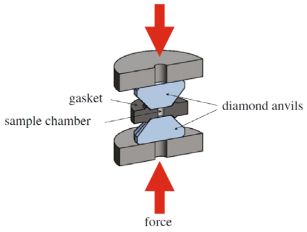
μSR experiments under pressure – cell type selection

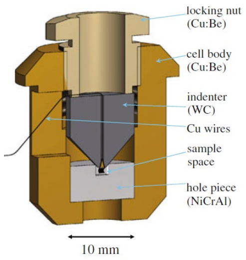


S. Klotz, Techniques in High Pressure Neutron Scattering









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Contradicting criteria

- The pressure cell need to be small enough to fit inside the detector block
  - The pressure cell need to carry at least few hundred mm^3 sample
    - The pressure cell need to carry the highest possible pressure

↓

Only the piston-cylinder type of cell could satisfy them

The highest pressure is limited by ~2.5 GPa

PSI pressure cells

- 1980. Clamp cell. p_{max}= 0.7 Gpa / oil. Fe and Ni. [Butz et al., Phys. Lett. A 75, 321, 1980]
- 1986. Clamp cell. p_{max} = 1.4 Gpa / Helium. [Butz et al., Hyp. Int, 32, 881, 1986]
- 2001. Clamp cell. p_{max} = 0.9-1.4 Gpa / Liquid [Andreica, PhD thesis, ETHZ, 2001]
- 2009. Double-wall clamp cells. p_{max} = 2.8 Gpa / Liquid [Khasanov et al., High Pr. Res. 36, 140, 2016]

ISIS pressure cells

- 2009. Clamp cell. p_{max} = 0.6 Gpa / Helium [Watanabe et al., Physica B, 404, 993, 2009]

TRIUMF

- 2008. Clamp cell. p_{max} = 2.3 Gpa / Liquid [Goko, private communication]

Pressure cell: design and construction

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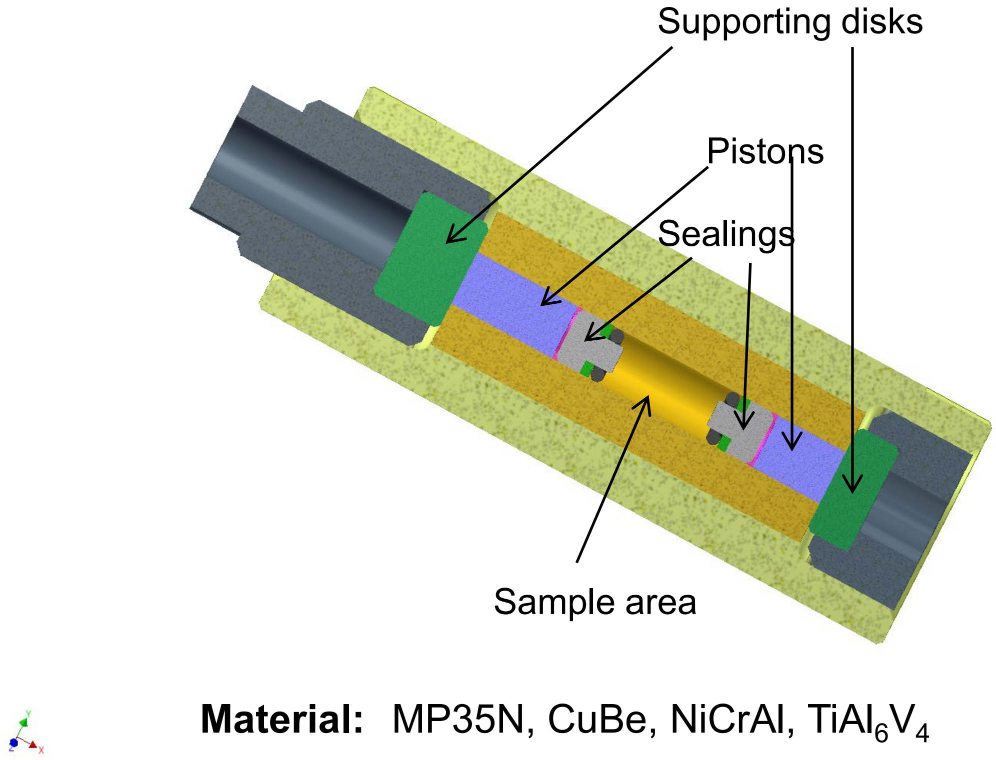
Construction



Material: MP35N, CuBe, NiCrAl, $TiAl_6V_4$

Sample area: ø 6mm, height 12mm.

Muon stopping fraction: ~50-55%

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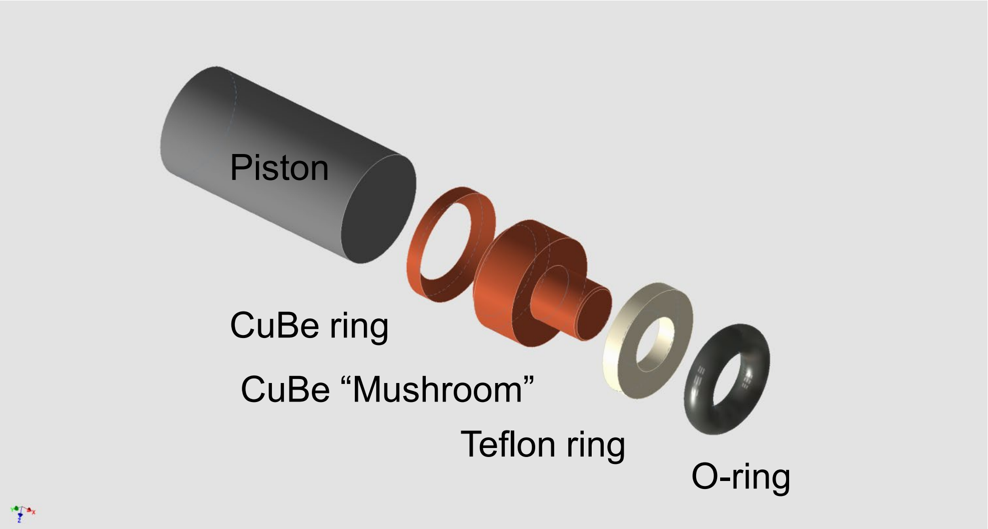
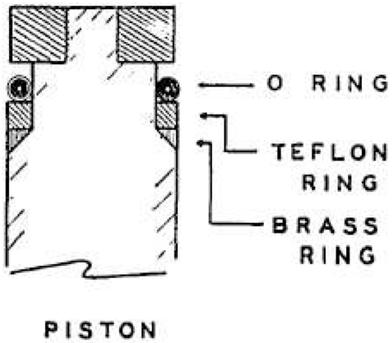
Sealing

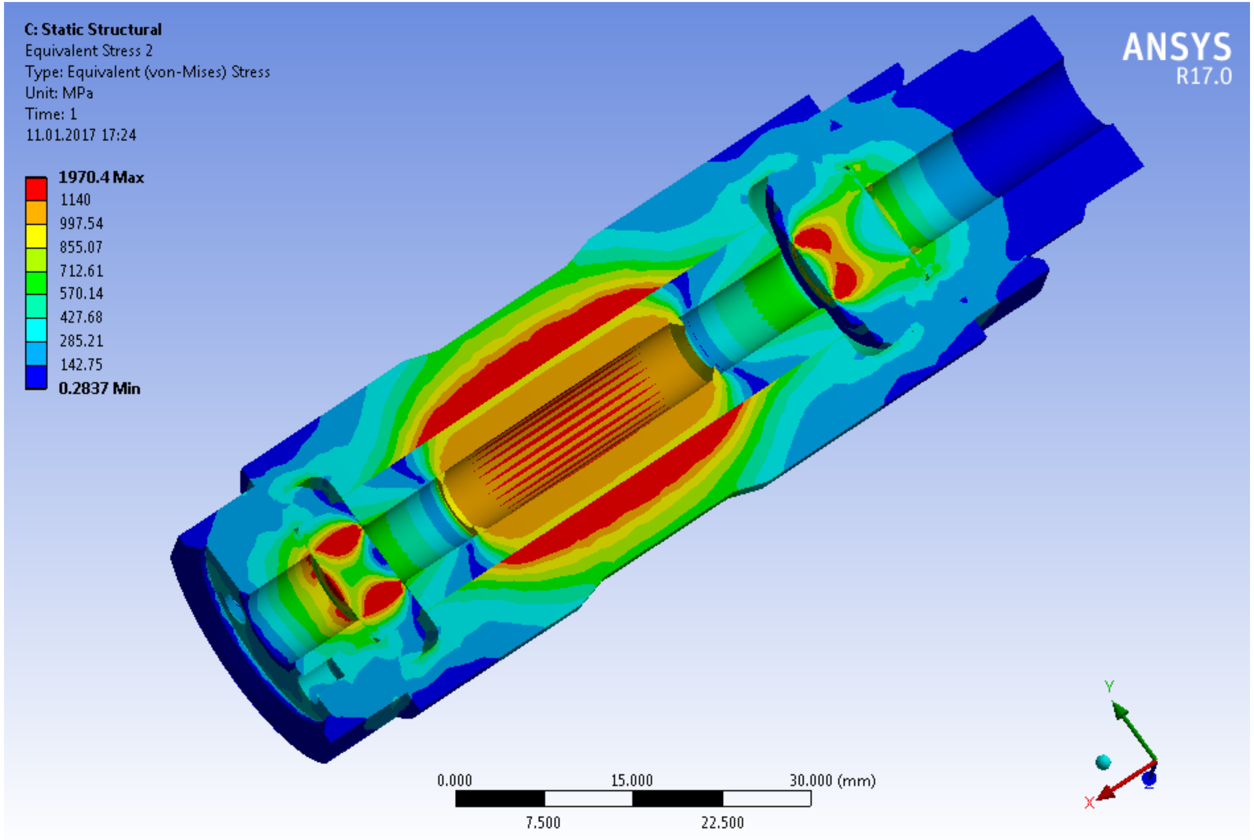
Modified Bridgman sealing



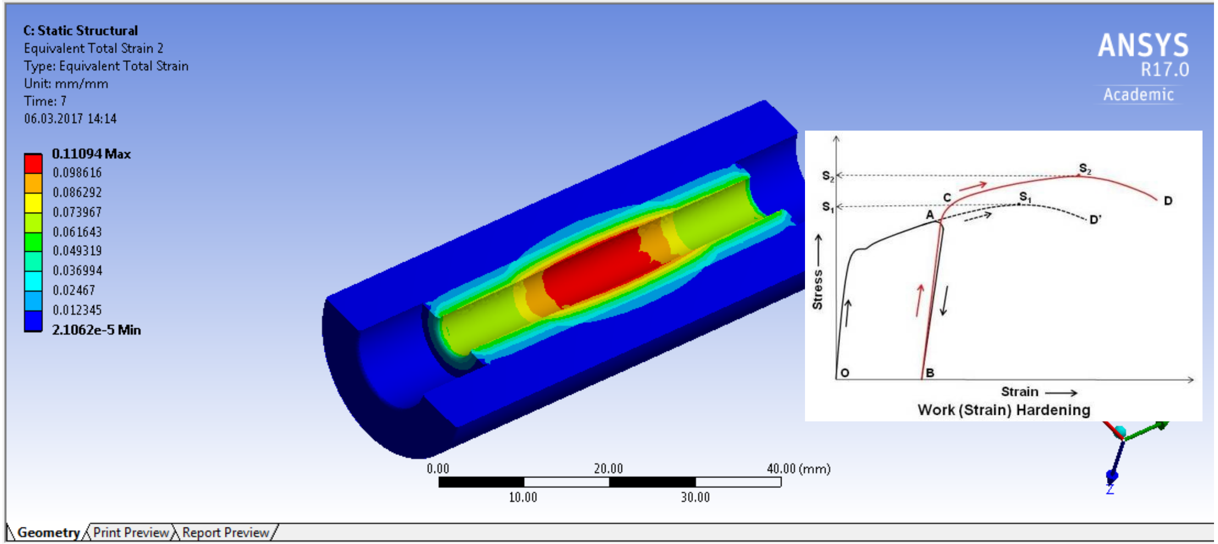


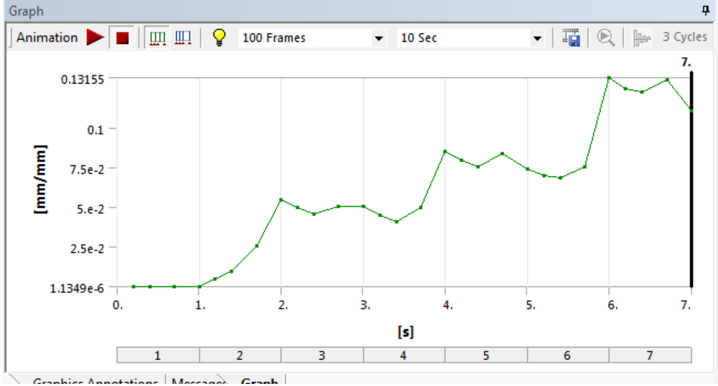
D. S. Hughes, W. W. Robertson, J. Opt. Soc. Am. **46,** 557 (1956)

Finite-Element analysis [CuBe/MP35N cell]



CuBe/MP35N frettage





Tabular Data

	Time [s]	Minimum [mm/mm]	Maximum [mm/mm]
1	0.2	2.9999e-010	1.1349e-006
2	0.4	5.2238e-010	1.7695e-006
3	0.7	9.1463e-010	3.2442e-006
4	1.	1.5e-009	5.6745e-006
5	1.2	3.8509e-006	5.0341e-003
6	1.4	7.1392e-006	9.7047e-003
7	1.7	1.3029e-005	2.5306e-002
8	2.	2.2374e-005	5.4436e-002
9	2.2	1.9996e-005	4.9825e-002
10	2.4	1.8726e-005	4.5431e-002
11	2.7	1.5948e-005	5.0306e-002
12	3.	1.2739e-005	5.0457e-002
13	3.2	1.4555e-005	4.4858e-002
14	3.4	1.6067e-005	4.1189e-002
15	3.7	2.0526e-005	4.9642e-002
16	4.	3.4064e-005	8.535e-002
17	4.2	2.9691e-005	7.9673e-002
18	4.4	2.8809e-005	7.5342e-002

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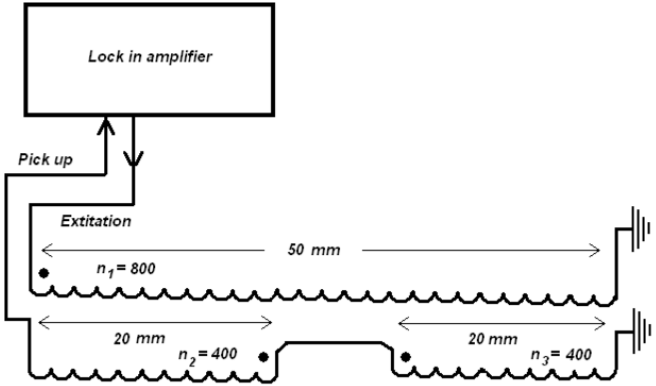
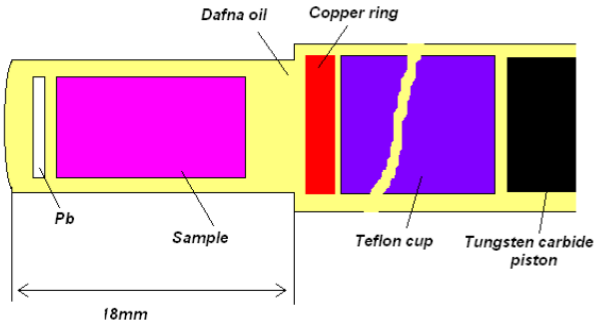
Pressure determination

Pressure determination





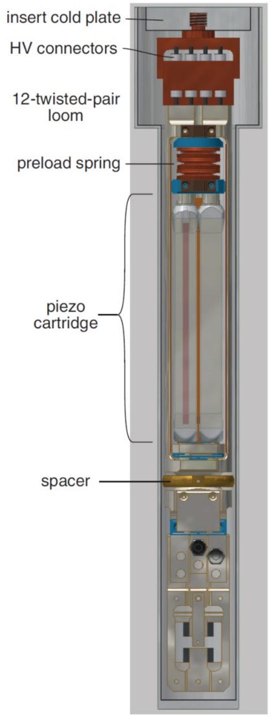
Piezo-based uniaxial pressure (Strain) devices for μSR

Strain cell

Artem Nikitin

Matthias Elender

Clifford Hicks



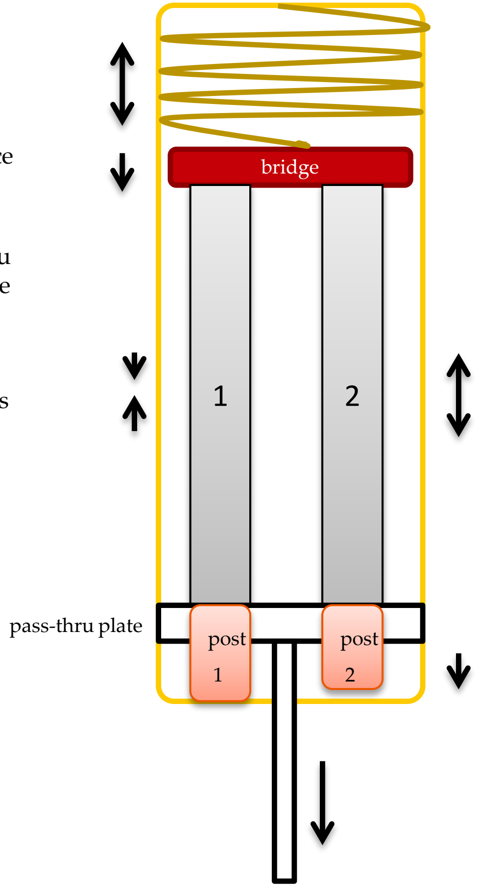
Hans-Henning Klauss
Rajib Sarkar

Vadim Grinenko

Shreenanda Ghosh

Working principle

- the cell is preloaded with force on the spring of 1000 N
- post 1 is epoxied to the cell frame, but not to the pass-thru plate, pass-thru plate can slide over the post 1
- **apply - 500 N on the piezo 1**
- the piezo 1 shrinks and moves the bridge downwards
- the spring expands



- **apply + 500 N on the piezo 2**
- the piezo 2 expands
- the piezo moves the post downwards
- the post 2 is epoxied to the pass-thru plate
- pass-thru plate moves downwards with force of + 500 N
- +500 N applies to the sample

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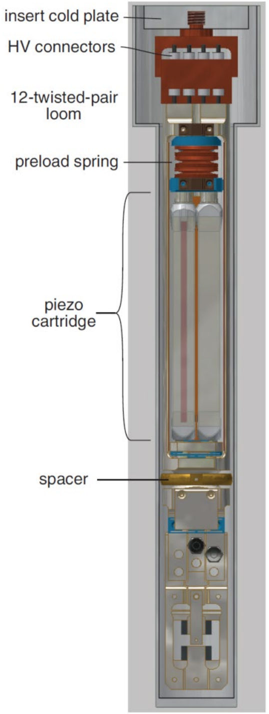
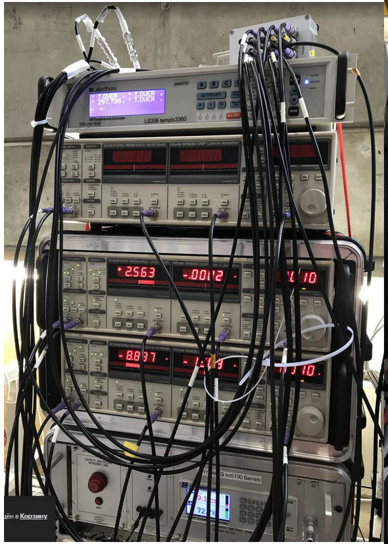
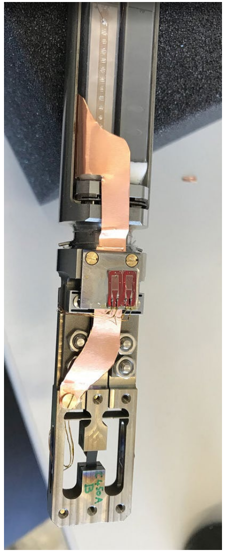
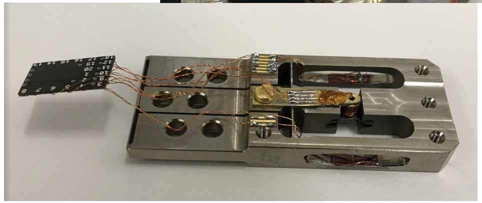




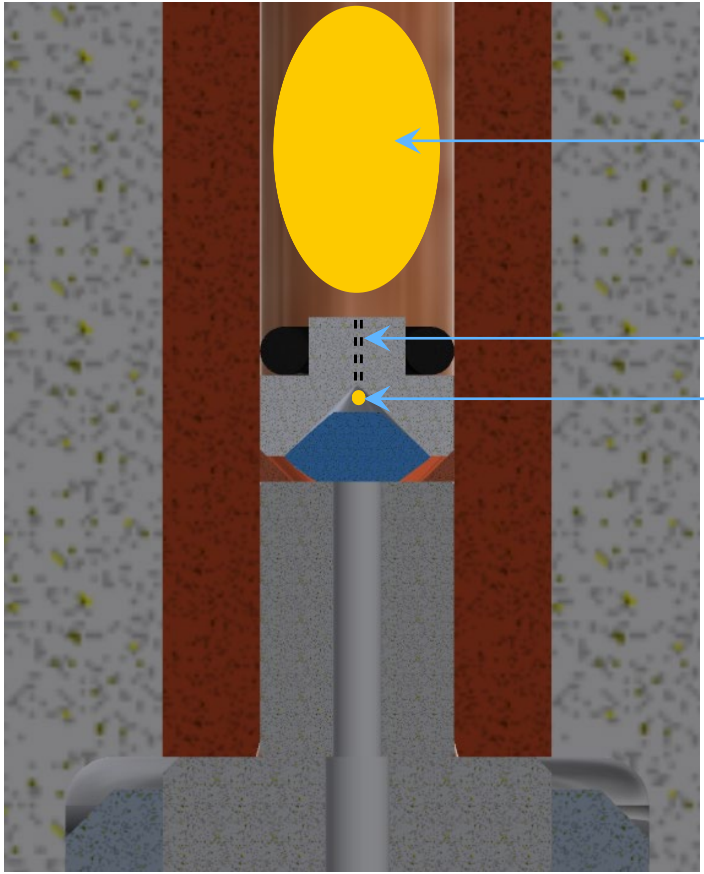




Lowest T = 0.7 K
in ^{3}He cryostat

Future developments

Optical pressure reading: double volume cell



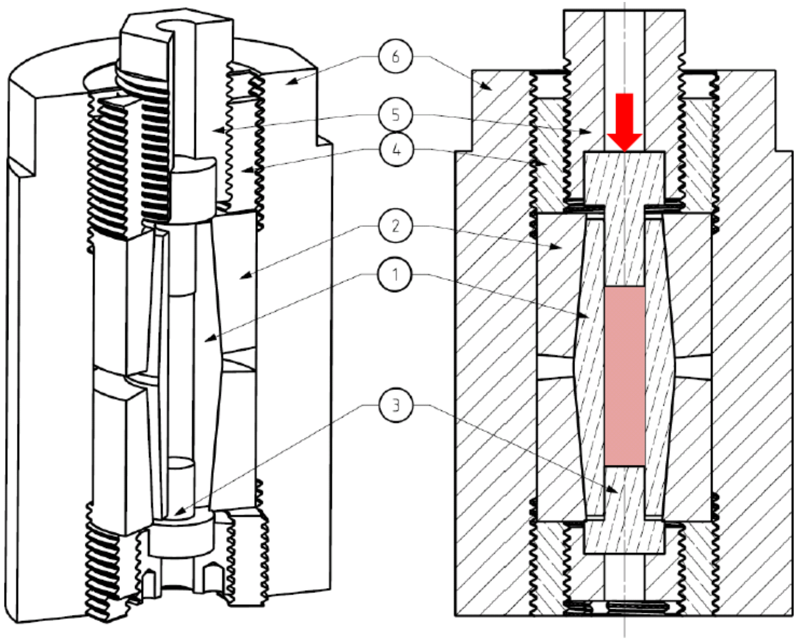
Sample volume

Possible connection between volumes

Optical volume

- The volumes of the "Sample" and the "Optical" cavities are ~0.3-0.35 cm^3 and ~1-1.5 mm^3, respectively
- Materials in both volumes are not mixed.
- The pressure media in both volumes could be the same or might be different
- One may connect both volumes by drilling a hole (~0.5-1mm in diameter) in a Teflon mushroom.

McWhan pressure cell

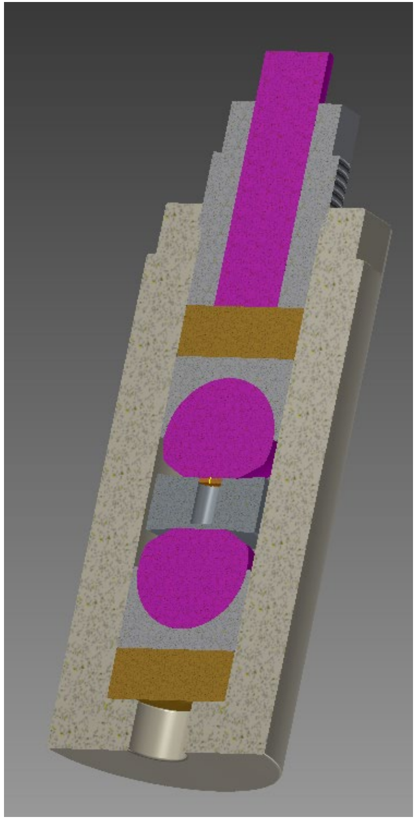


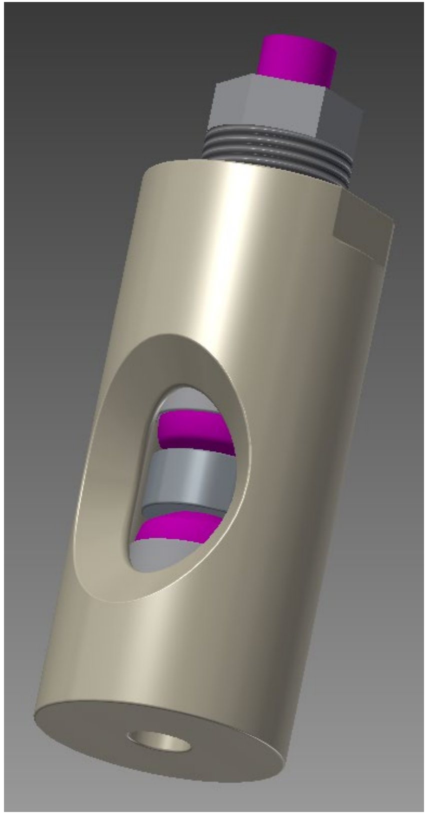
Components:
(1) bicone,
(2) compression pad,
(3) piston,
(4) outside locking pad,
(5) inside locking pad,
(6) Body

Materials:
- (1), (3): tungsten carbide
- (2), (5), (6): MP35N
- (4): copper beryllium

McWhan pressure cell

Anvil-type pressure cell





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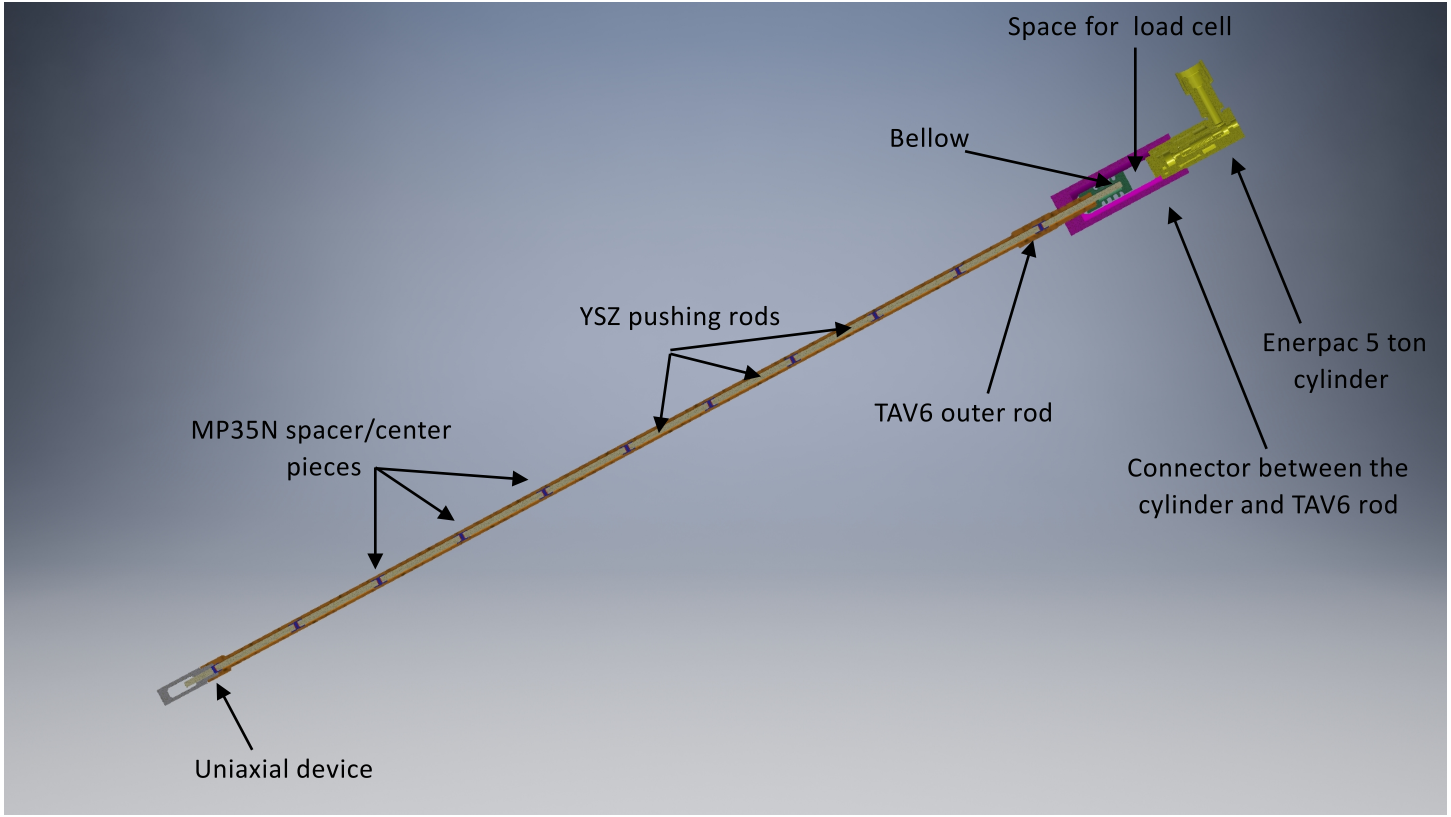
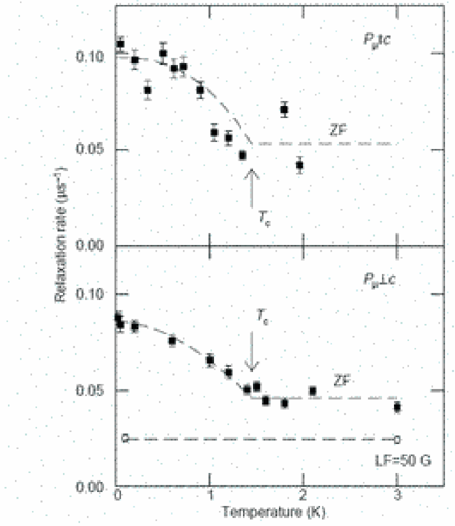
Low-temperature press

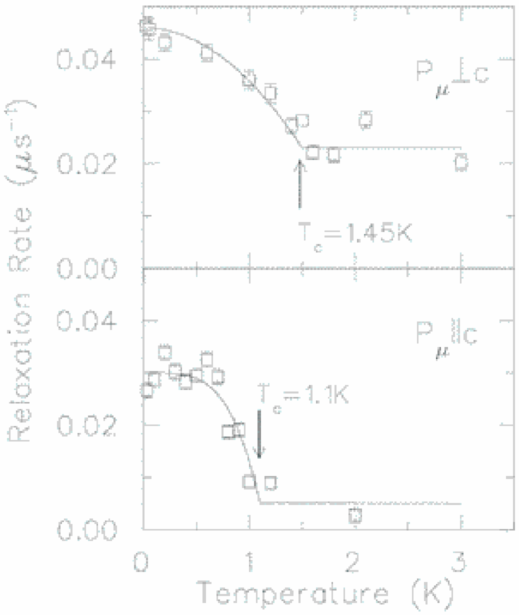


Scientific example: Sr_2RuO_4

Time-reversal symmetry breaking in Sr_2RuO_4

Broken Time Reversal Symmetry

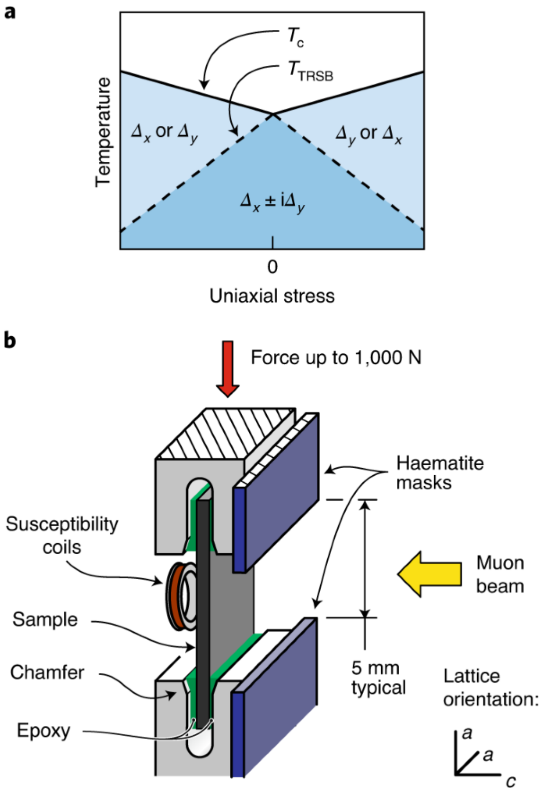


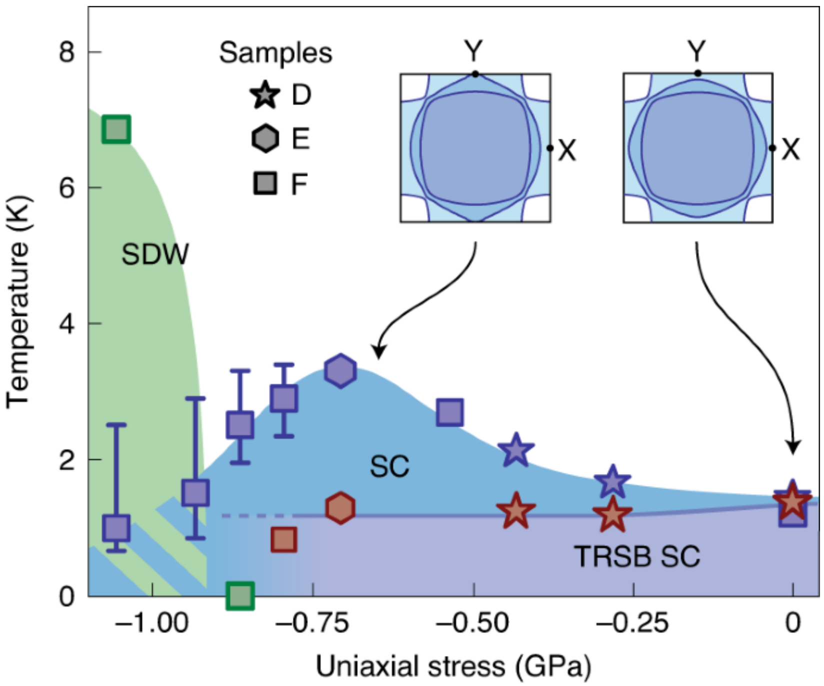


- Spontaneous field seen below T_c, for P_m//c, //a.
- B_{loc}~1G.

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

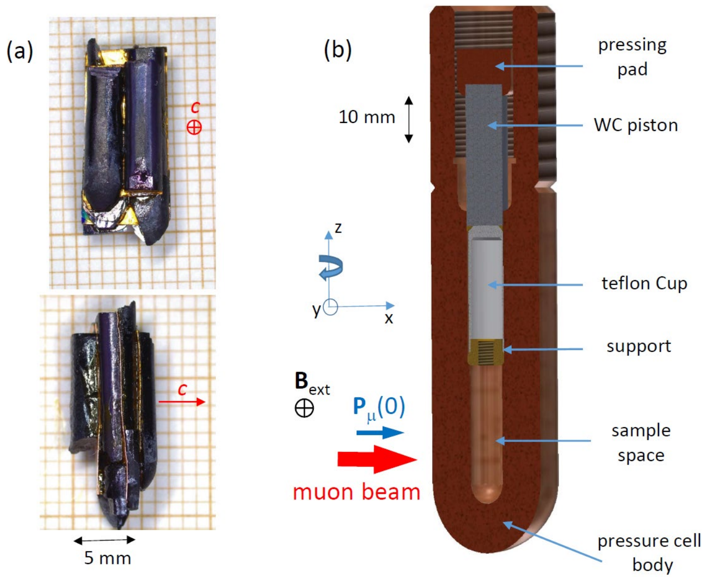
Uniaxial strain

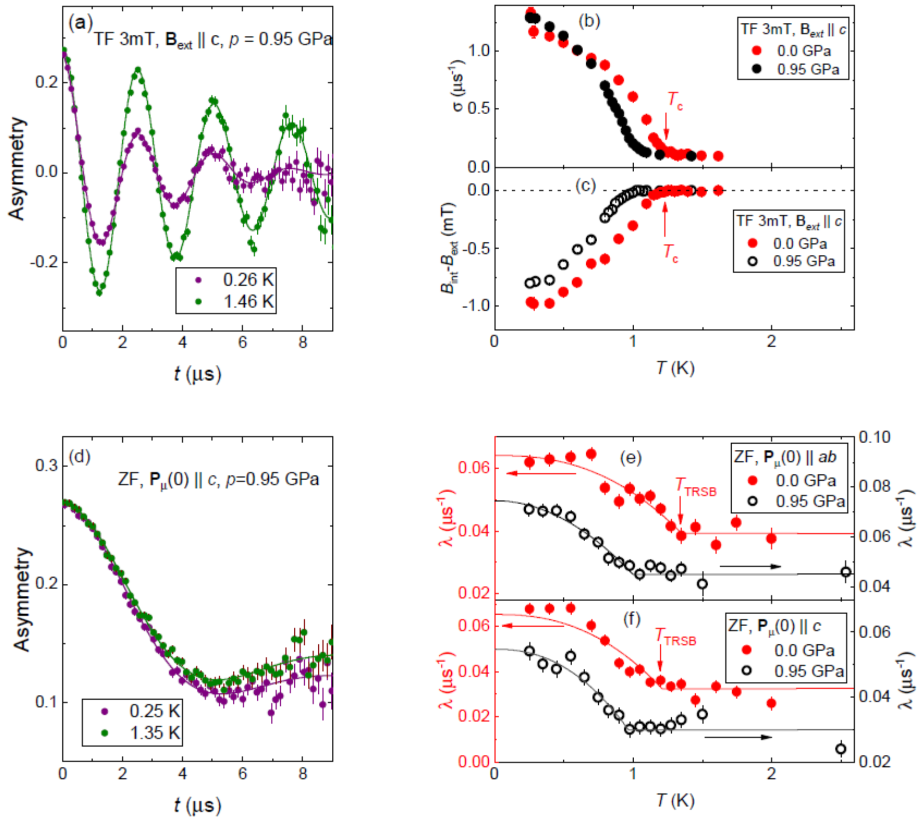




Grinenko *et al.*, Nature Phys. 2021

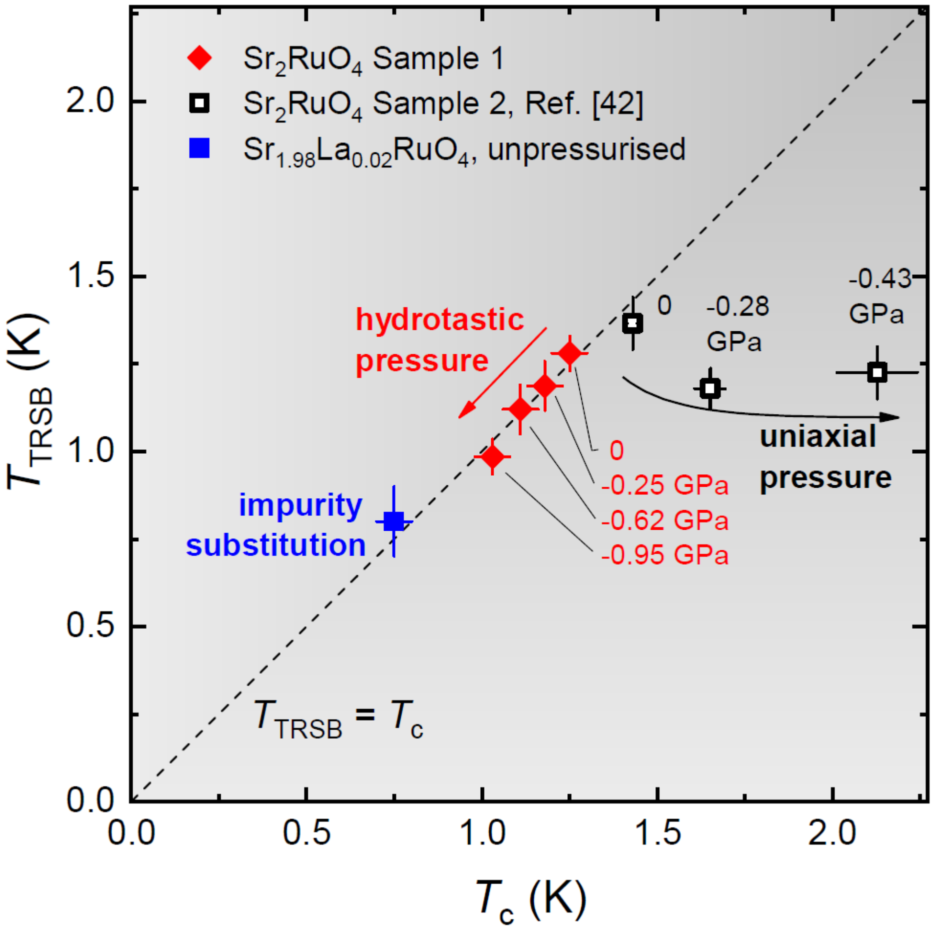
Hydrostatic pressure experiments





Grinenko *et al.*, to appear in Nature Comm. 2021

Combined graph data



Wir schaffen Wissen – heute für morgen

My thanks go to

- Matthias Elender
- Alexander Maisuradze
- Zurab Guguchia
- Zurab Shermadini
- Tatsuo Goko
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- Alex Amato
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- Daniel Andreica
- Stefan Klotz
- Konstantin Kamenev