A versatile bulk S.C. MgB_2 cylinder generating self magnetic field and shielding

for polarized targets and nuclear fusion fuels

Ciullo Giuseppe

DFST (Dipartimento di Fisica e Scienze della Terra)

Università degli Studi di Ferrara

and

Istituto Nazionale di Fisica Nucleare

Sezione di Ferrara

Outlok of the presentation

- Interests on MgB_2 (polarized nuclear target – fusion fuel).
- A compact magnet, movable, no power connections, generating self magnetic fields and shielding surrounding magnetic fields.
- R&D in Ferrara:

a preliminay feasibility study

and

- new arrangment for sistematic studies.

Outlok of the presentation

- Interests on MgB_2 (polarized nuclear target – fusion fuel).
- A compact magnet, movable, no power connections, generating self magnetic fields and shielding surrounding magnetic fields.
- R&D in Ferrara

a preliminay feasibility study

and

- new arrangment for

sistematic studies.

Interests on MgB_2

In polarized nuclear targets a magnetic holding field is required.

Nuclear target might feel detector fields, therefore the polarization axis is frozen by it.

If we are interested in fundamental studies on the orientation between projectiles and targets, we need an indipendent field, and the shielding of the external field.

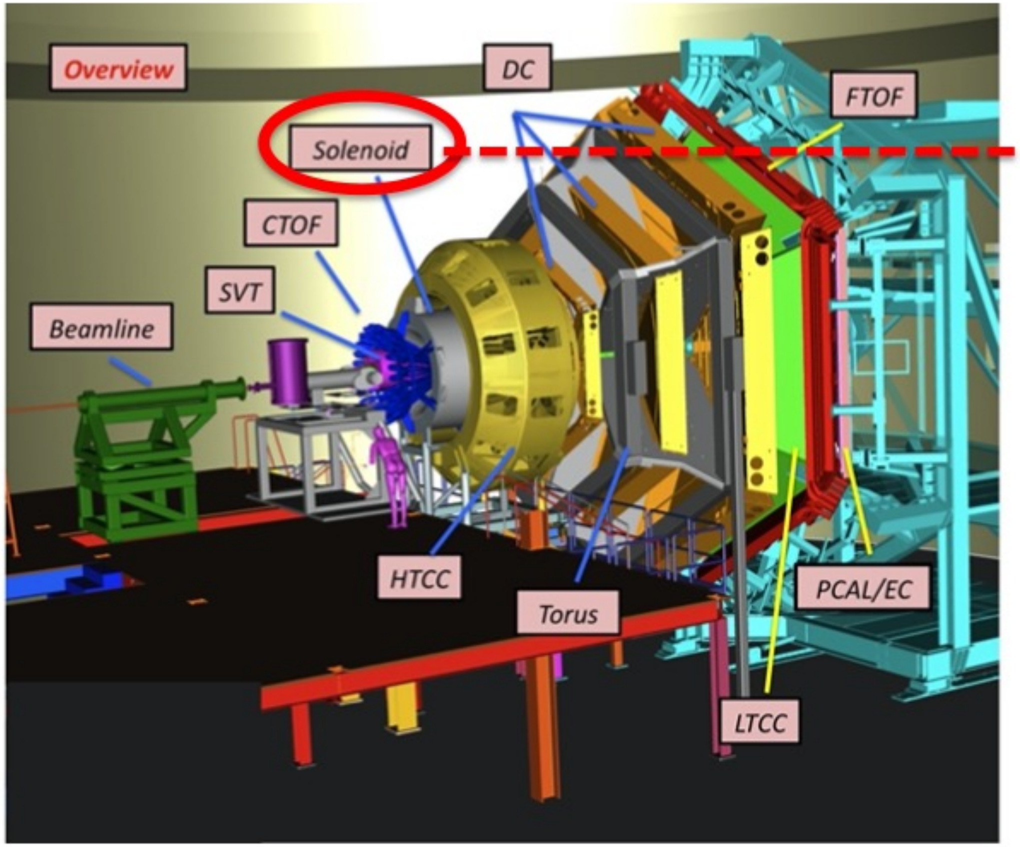
We are around the interaction point, then we look for low thickness of material, low *Z*, reducing, or avoiding, material for powering, transportability from the preparation laboratory to the experimental site.

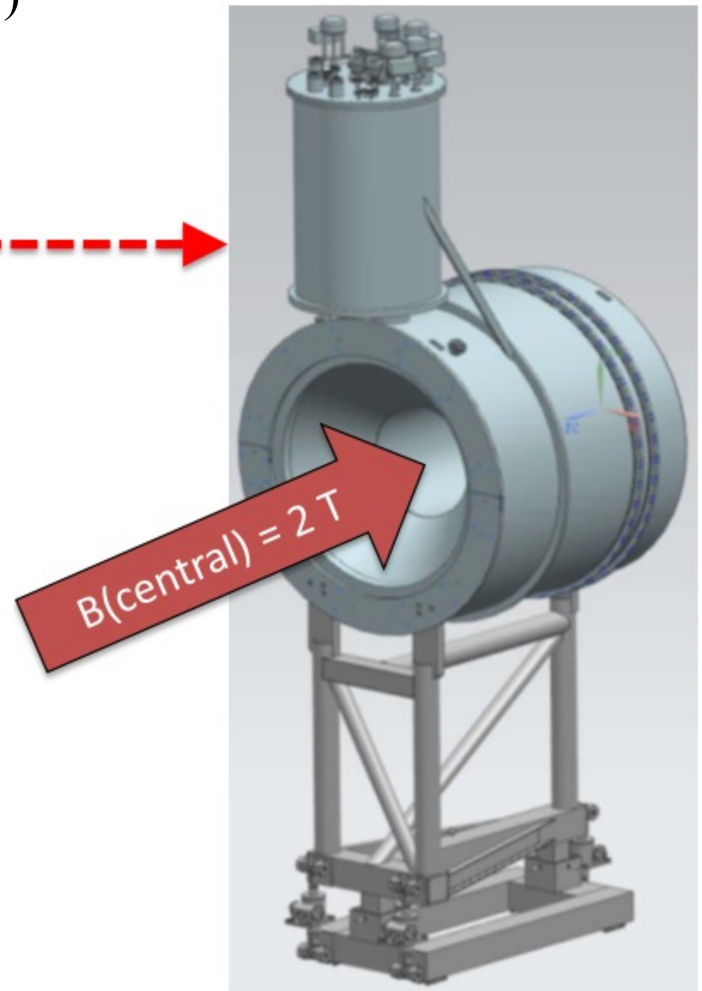
Subnuclear spin insights (back to 2020)

- **The CLAS12 run-group H** (RGH) comprises ***three experiments approved with rating A*** by PAC39 to run for a total of 110 days with a 11 GeV beam scattering off a transversely polarized target.
- • *C12-11-111 contact: M. Contalbrigo*, *Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using CLAS12: a multi-dimensional analysis of the semi-inclusive (SIDIS) reactions to access transversity and tensor charge, and the Sivers and Collins functions (among others) connected with the spin-orbit phenomena of the strong-force dynamics* [1];
- • C12-12-009 contact: H. Avakian, *Measurement of transversity with dihadron production in SIDIS with transversely polarized target: a multi-dimensional analysis of the SIDIS reactions exploiting the dynamics of the di-hadron final state to access transversity in the benchmark collinear limit and investigate novel parton correlations inaccessible on the single hadron case [2].*
- • C12-12-010 contact: L. Elouadrhiri, *Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector: a multi-dimensional analysis of the exclusive reactions to access the most elusive parton distributions entering the orbital momentum sum rule (Ji sum rule) [3].*

Common requirement for CLAS 12

CLAS (CEBAF Large Acceptance Spectrometer)

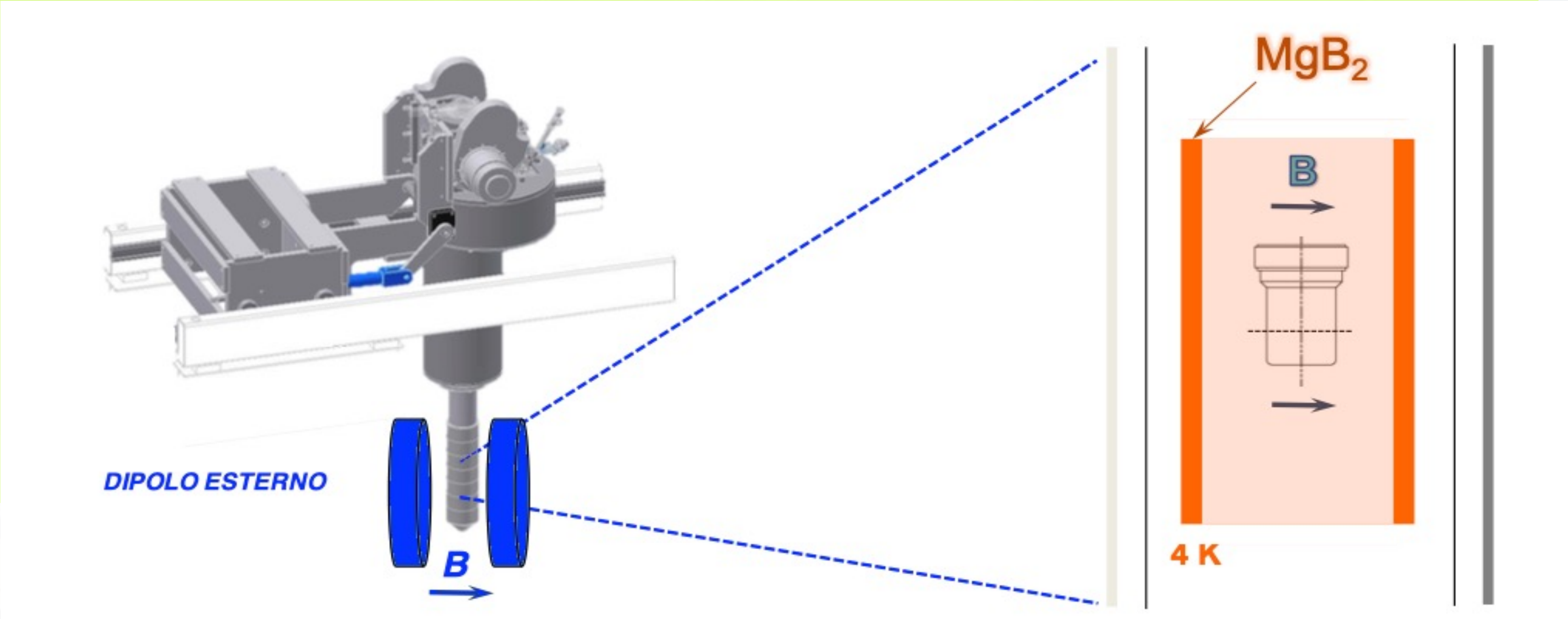




Keep a transverse magnetic holding field for the target inside the Solenoid of CLAS-12, and shield the field of the latter .

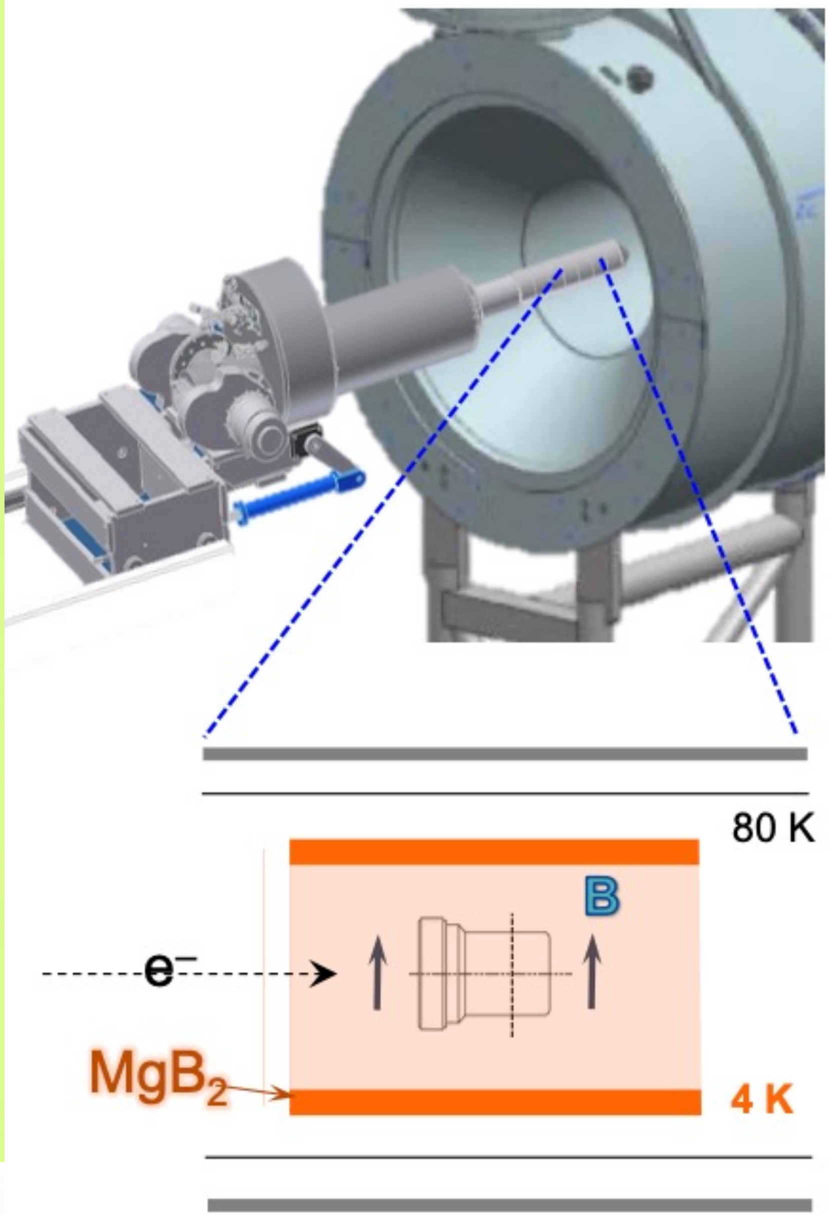
Preparing the holding field

- Choose a MgB_2 S.C. cylinder surrounding the target.
- Set an outer transverse field.
- Cool down the S.C. Cylinder in the IBC (In Beam Cryostat) at 4 K
- Ramp down the outer magnetic field.
- The perfect diamagnetism of the S.C. MgB_2 generates self supercurrents, which mantain the seen field inside the cylinder.



Moving to exp. site and shielding

- IBC (In Beam Cryostat) can be moved and inserted in CLAS-12.
- In case of increasing of CLAS-12 field: supplementary self supercurrents in the MgB_2 will mantain the transverse field.
- Everything without any power supply and corrent leads, or coils, in the surrounding.



Outlok of the presentation

- Interests on MgB_2 (polarized nuclear target – fusion fuel).
- A compact magnet, movable, no power connections, generating self magnetic fields and shielding surrounding magnetic fields.
- R&D in Ferrara

a preliminay feasibility study

and

- new arrangment for

sistematic studies.

Interests on polarized fuel for fusion

From the point of view of the nuclear physics, the use of **polarized fuel** seems the viable way in order to fulfill nuclear fusion for energy production thanks to:

- **enhancement** on fusion **cross section**,
- **control** on angular distribution of **reaction products**,
- possible **neutron lean** reactors.

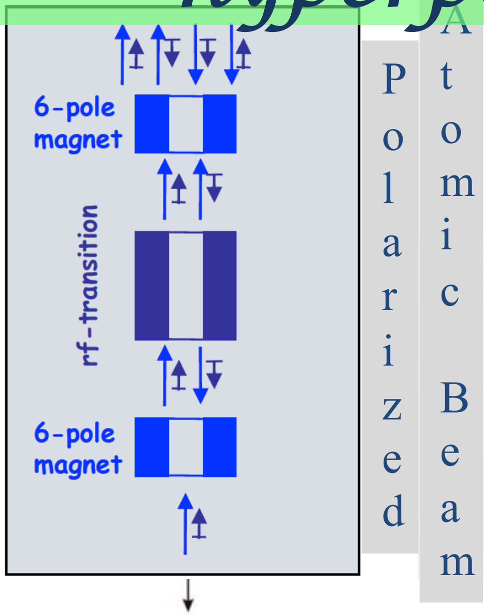
But practical use is still far away, mainly due to still open questions and requirements:

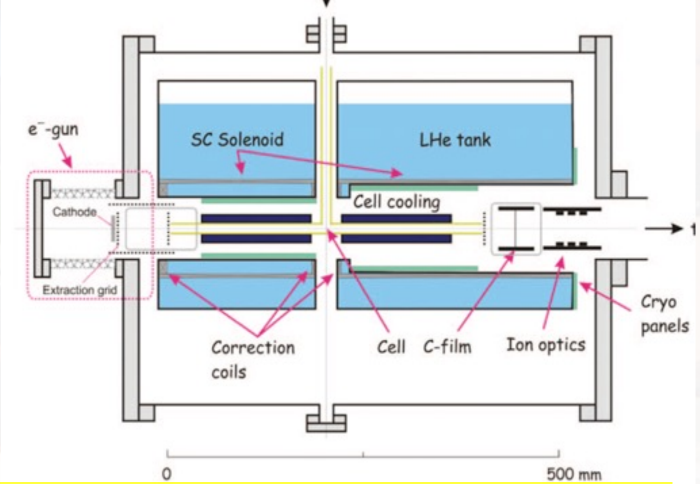
- polarized fuel, high polarization and high density (two or three order magnitude **higher than available** as nuclear polarized targets).
- **Preparation** of fuel for magnetic confinement or inertial confinement.
- **Survival** of polarized fuel in the fusion reactors or in inertial confinement.

It's a **challenging** deal providing **useful polarized fuel** for the purpose of testing the polarized **FUSION** in present (… future) constrains and contests.

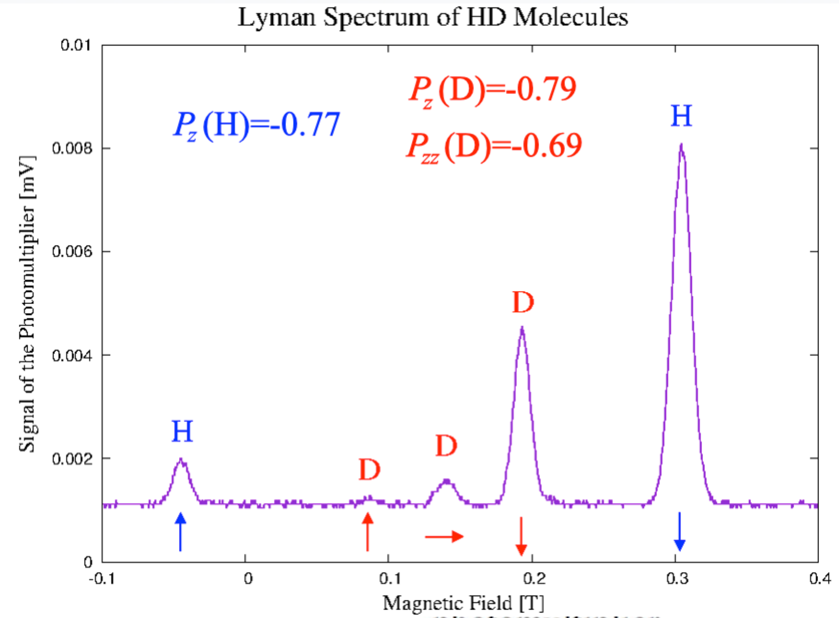
G. Ciullo, R. Engels, M. Büscher and A. Vassilyev
Nuclear Fusion with Polarized Fuel - Springer Proc. in Phys. **187** (2016)

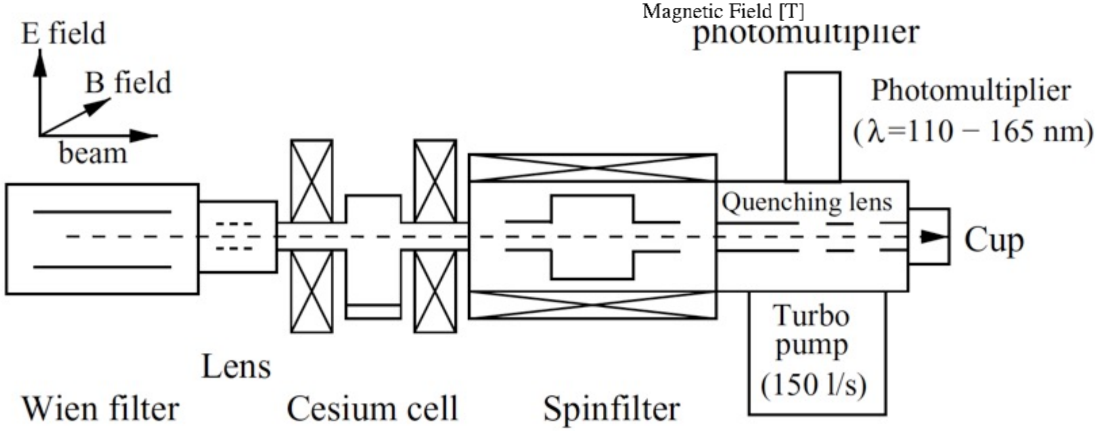
Polarized atoms recombined in hyperpolarized molecules then ...





Recombining Polarized Atoms in hyperpol. molecules

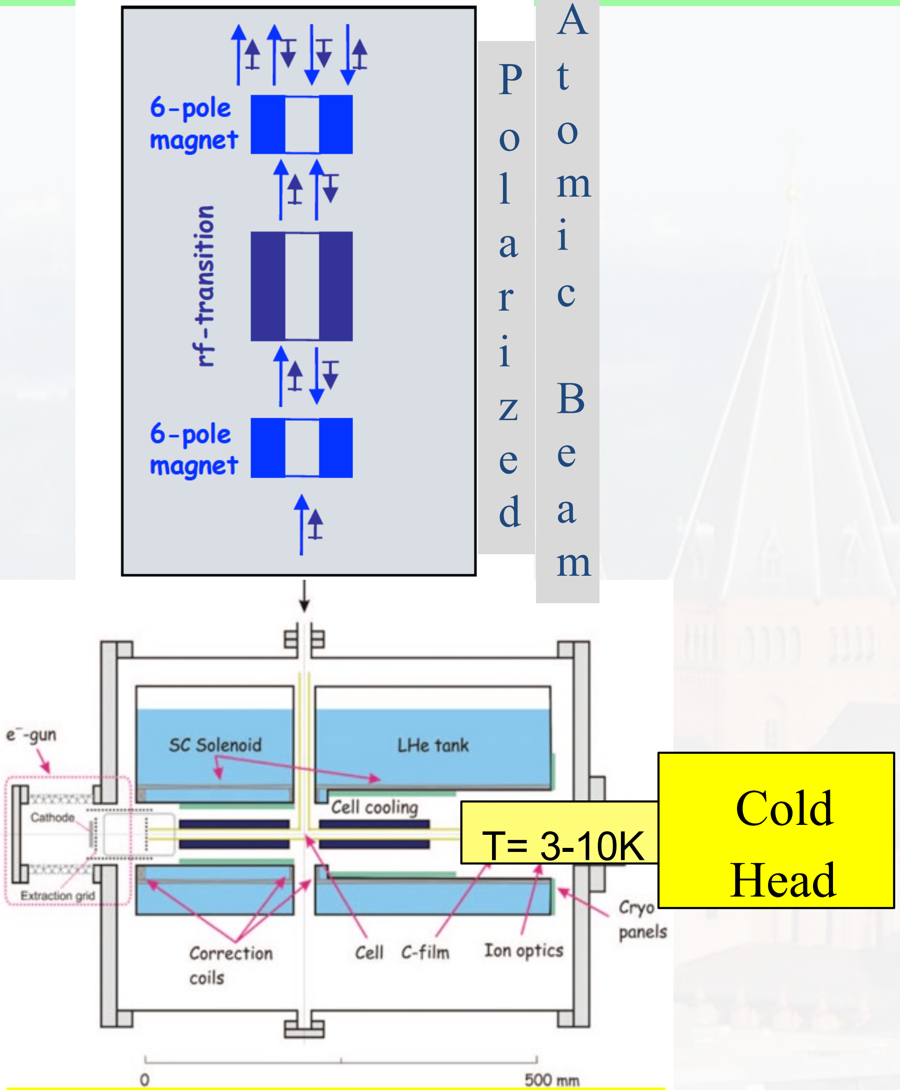


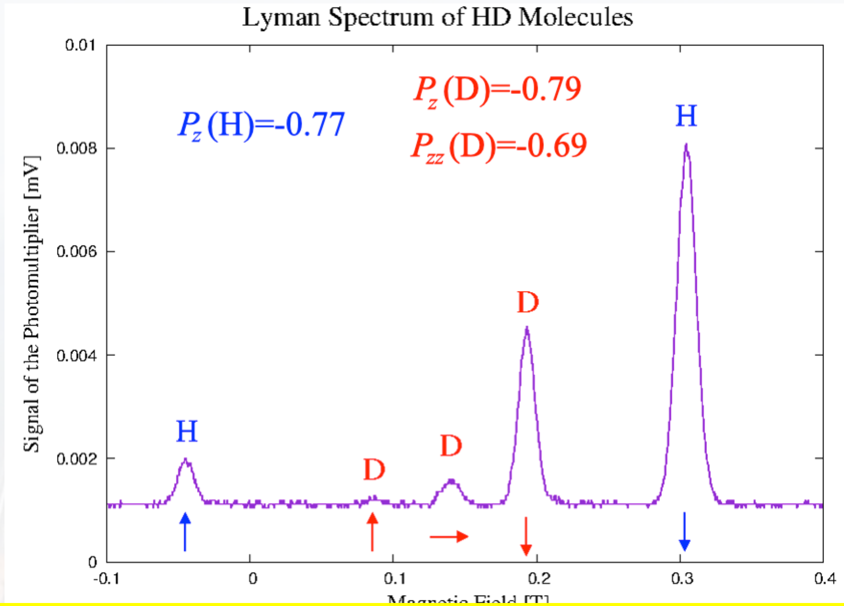


Lamb-shif polarimeter

[1] Ralf Engels et al. *Production of HD Molecules in Definite Hyperfine Substates* PRL 124 (2020) 113003

... MgB_2 cylinder for holding field





Recombinig Polarized Atoms in hyperpol. molecules

Cold Head with an MgB_2 cylinder providing a holding field, in this case it will parassitically mantain the solenoidal field of the recombination chamber.
The cylinder hosts inside substrate for condensation and it will be useful for transportation for fusion studies and tests.

... our starting point for faisibility study 1 T longitudinal field.

Outlok of the presentation

- Interest on MgB_2 (polarized nuclear target - fusion fuel).
- A compact magnet, movable, no power connections, generating self magnetic fields and shielding surrounding magnetic fields.
- R&D in Ferrara

a preliminay feasibility study

and

- new arrangment for

sistematic studies.

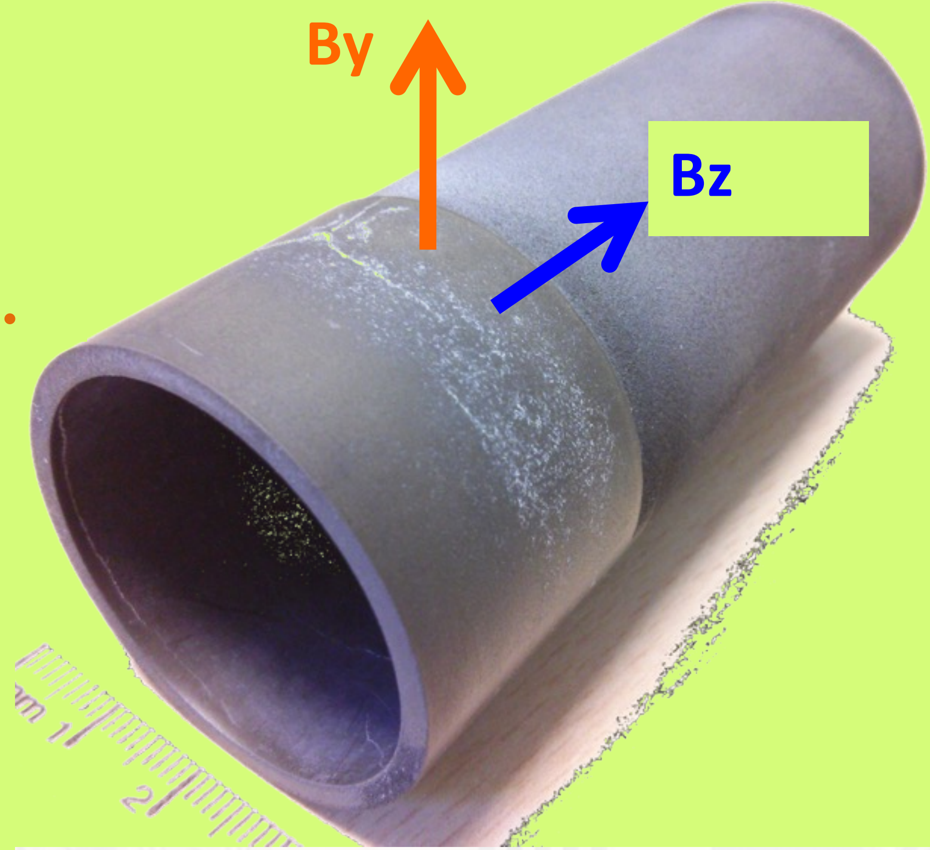
The compact «self» magnet

Cylinder

MgB_2

Shielding longitudinal fields

Mantaining transverse fields.



M. Statera et al. (2015). IEEE Tr Appl. S:C., vol. 115(3): 1 - DOI: 10.1109/TASC.2015.2388855

Advantages

No Power feeding

No Copper and Coils

Auto tuning

Semplicity

Low cost of production

few mm of thickness

External Magnet

Available Waste Material Machinable (G. Giunchi)

diameter 39 mm - length 90 mm

thickness ~1 mm

Production of MgB_2

➢ Discovered 2001 (J.Nagamatsu [1] Nature 410(2001) 63).

Different techinques of production:

- Japanese scientists: high pressure sintering – HIP (Hot Isostatic Pressing)[1] or UHP(Uniaxial Hot Pressing).

- American Scientists: Mg vapor sintering of B fibers [2]

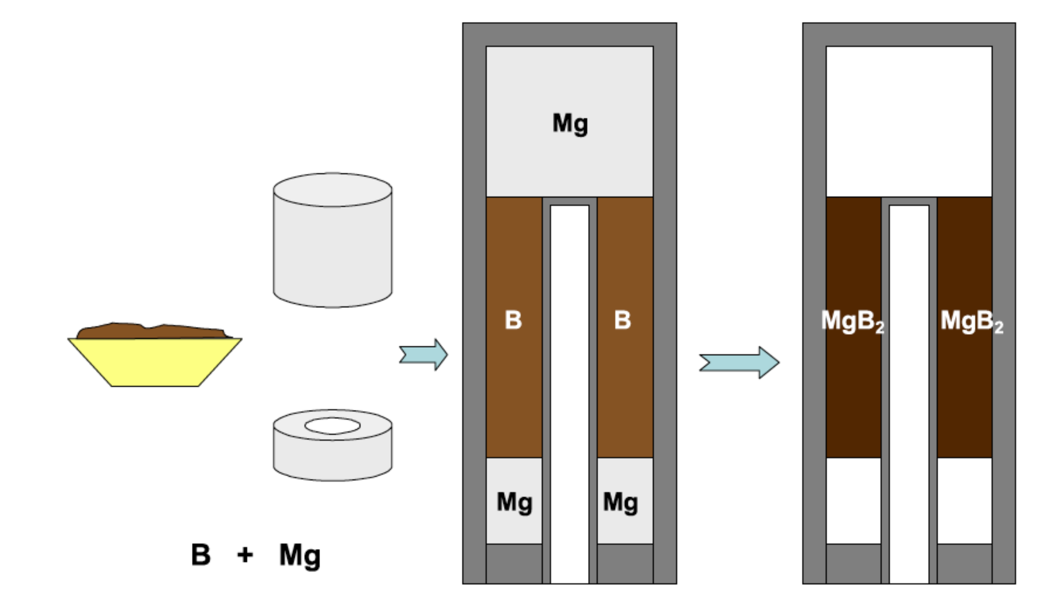
- Italian Scientists: Mg Reactive Liquid Infiltration [3]

(Italian Patent Edison Spa pat., G. Giunchi, S.Ceresara 2001)

[1] J.Nagamatsu et al. Nature **410** (2001) 63.
[2] P.C. Canfield et al. PRL 86 (2001) 2423].
[3] G. Giunchi et al. Int. J.Mod.Physics B 17 (2003) 453.

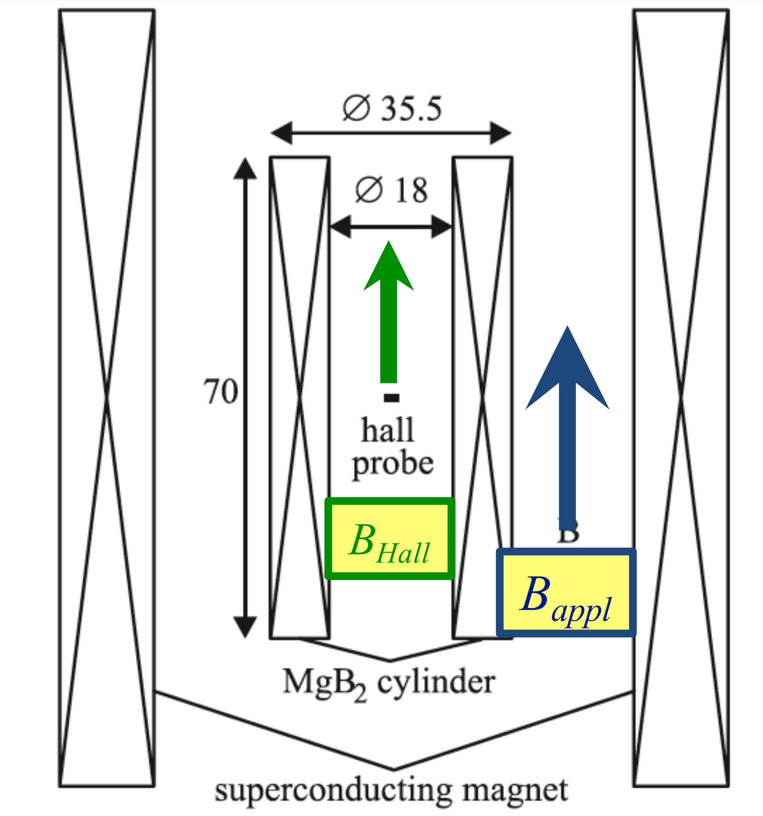
Production of MgB_2 by Mg-RLI
(Mg Reactive Liquid Infiltration)

Fill a steel container by B Power and large chunks of MgB_2,
weld the container and perform thermal treatment at about 900-950 °C in conventional oven for 12-24 h.

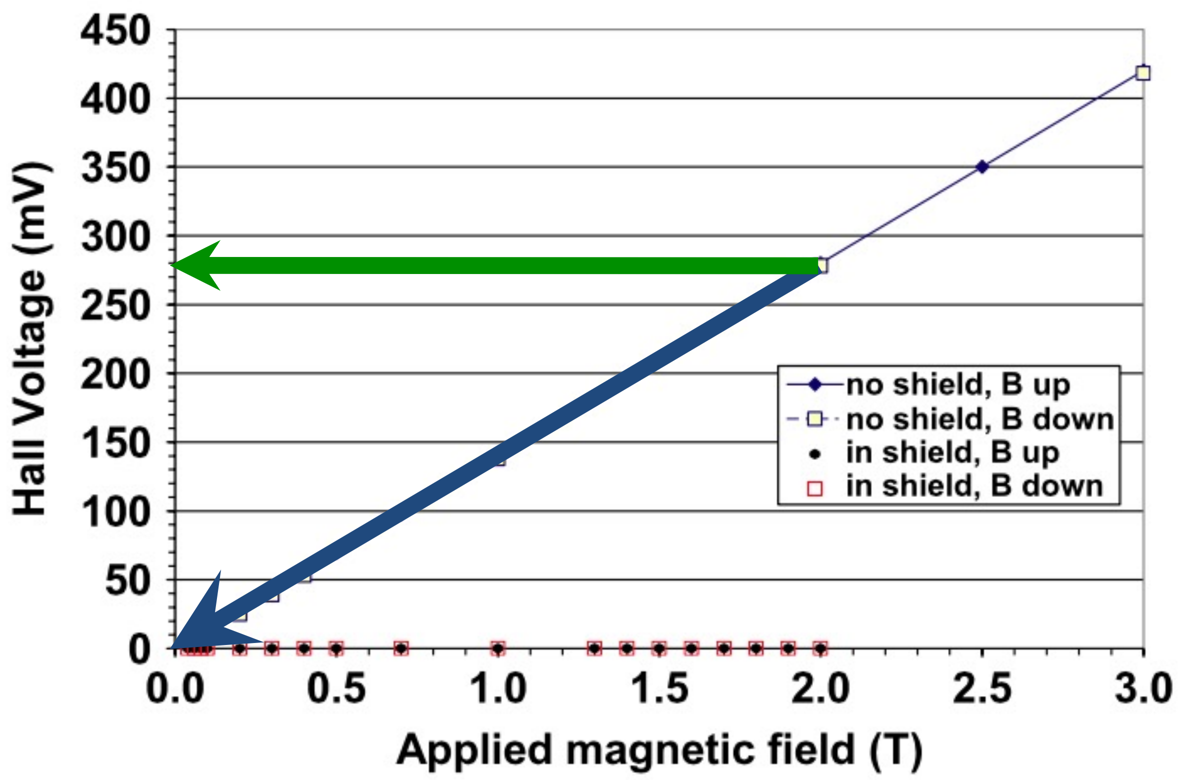


Critical temperature
(T_C) 39.5 K
High density 2.4 g/cm^3
High connectivity
Very high superconducting characteristics
High value of critical currents

Expectations on self field of MgB_2



Field Cooling (FC), early cooling with applied field of 2 T, lowering down the applied field B_{appl} , B_{hall} measures the self field.

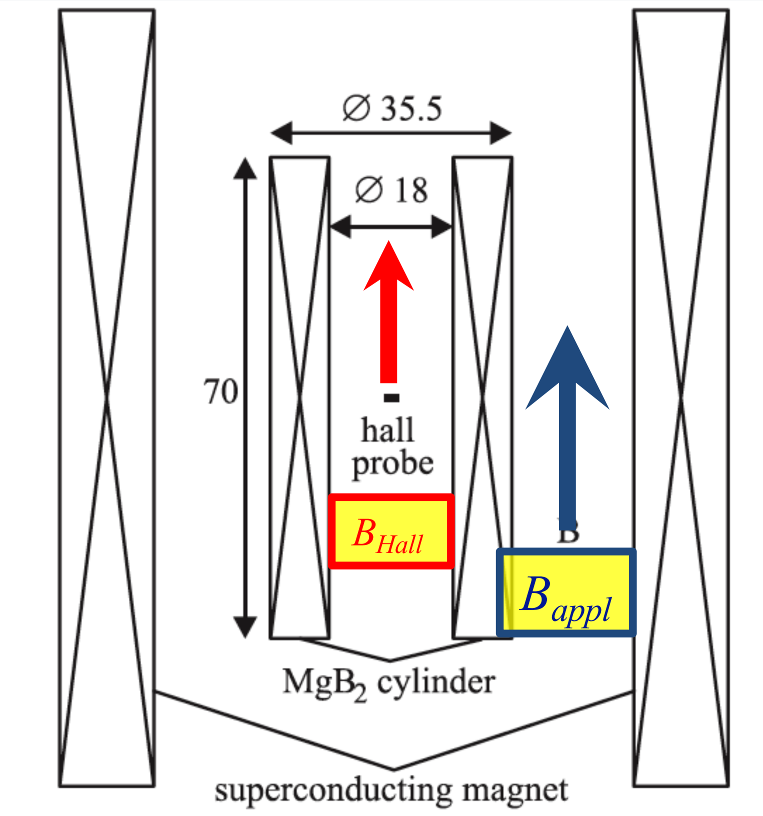


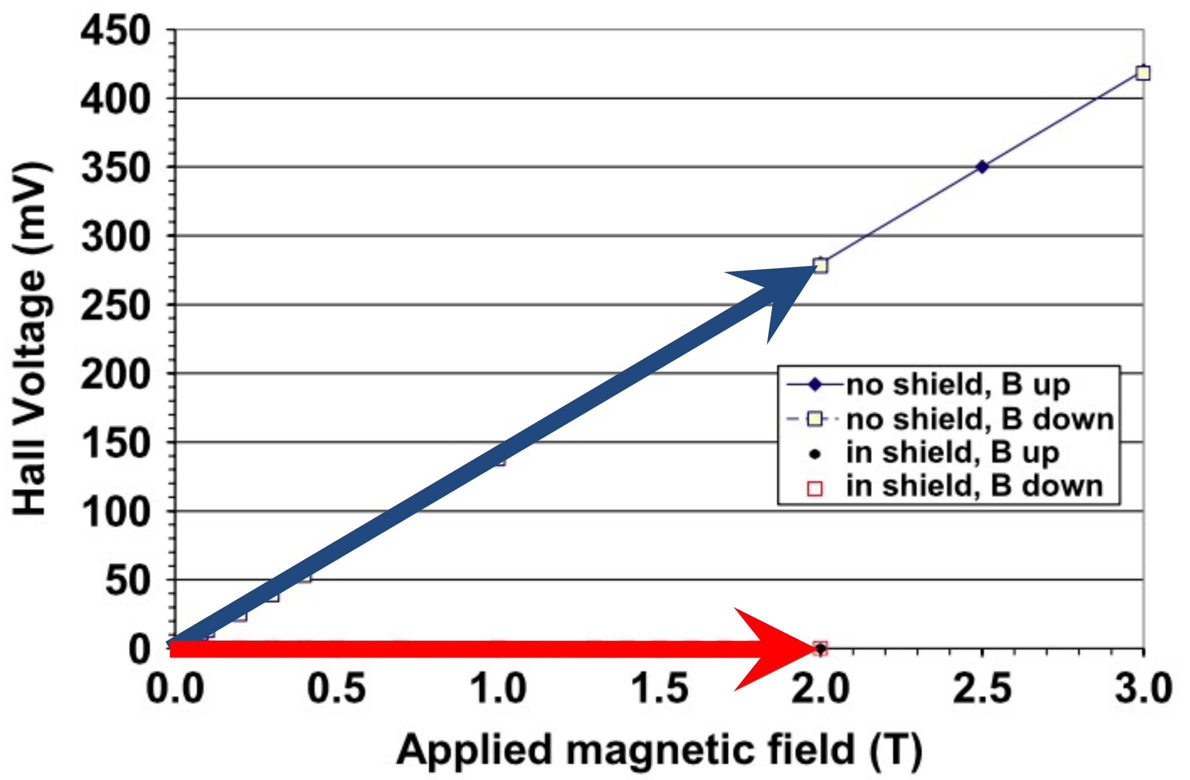
P100 MgB_2 $L = 70$ mm
R_{ext}=17.75 mm, R_{int}=9 mm

J. J. Rabbers et al. "Magnetic shielding capability of MgB2 cylinders" Supercond. Sci. Technol. Vol. **23**, 2010

Expectations on shielding of MgB_2

Zero Field Cooling (ZFC)
early cooling without external field, increasing up the applied field, B_{appl}, B_{Hall} provide the penetrated fields.





J. J. Rabbers et al. "Magnetic shielding capability of MgB_2 cylinders" Supercond. Sci. Technol. Vol. **23**, 2010

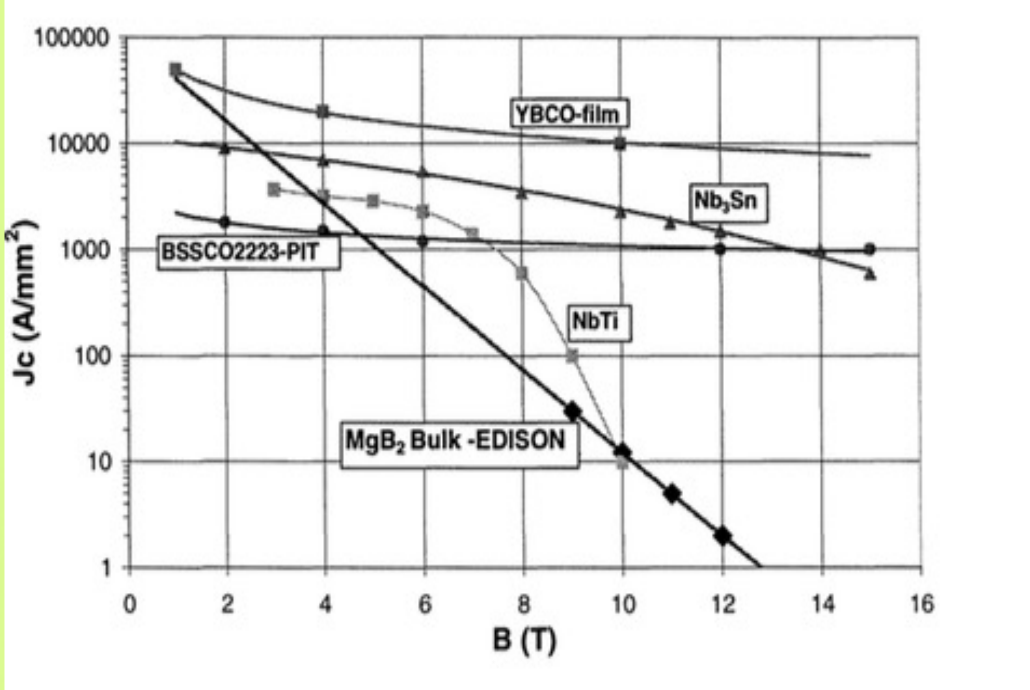
Why the MgB_2

Low Z

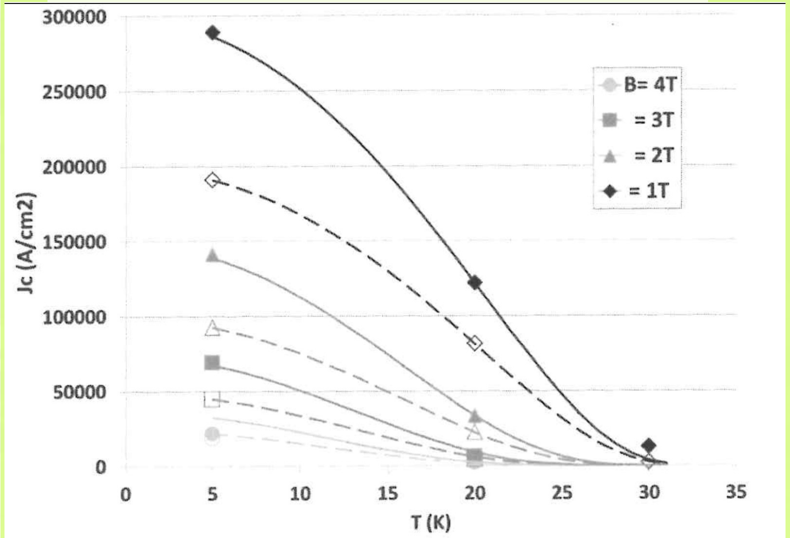
Cheapper than LTS and HTS

Machinable: spark erosion and diamond tools

For the condition of
HD-ice at 4 K
Current density
$J_c \geq 10\,000$ A mm^{-2}
(extrapolated)



G. Giunchi Internationl Journal of modern Physics B **17** (2003)



To be conservative we assumed
for our preliminary studies
$J_c \geq 1\,000$ A mm^{-2}

2022 J_c experimental data for
SG (Small Grain size) continuous
and LG (Large Grain size) dashed line

Outlok of the presentation

Where is coming from the interest on MgB_2 (polarized nuclear target)?

A compact magnet, movable, without power connections, generating auto-field and shielding surrounding magnetic field.

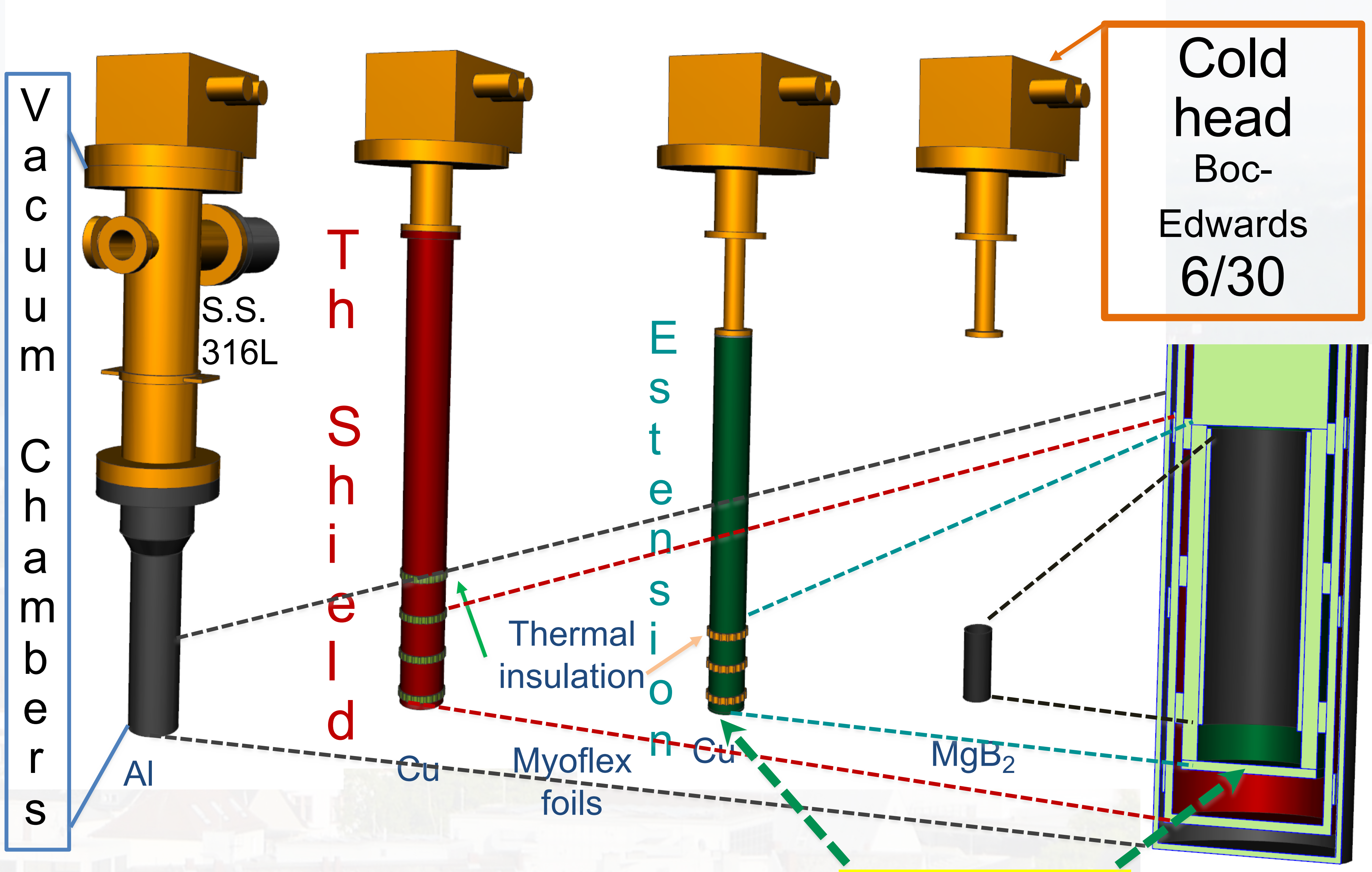
R&D in Ferrara

A preliminay feasibility study

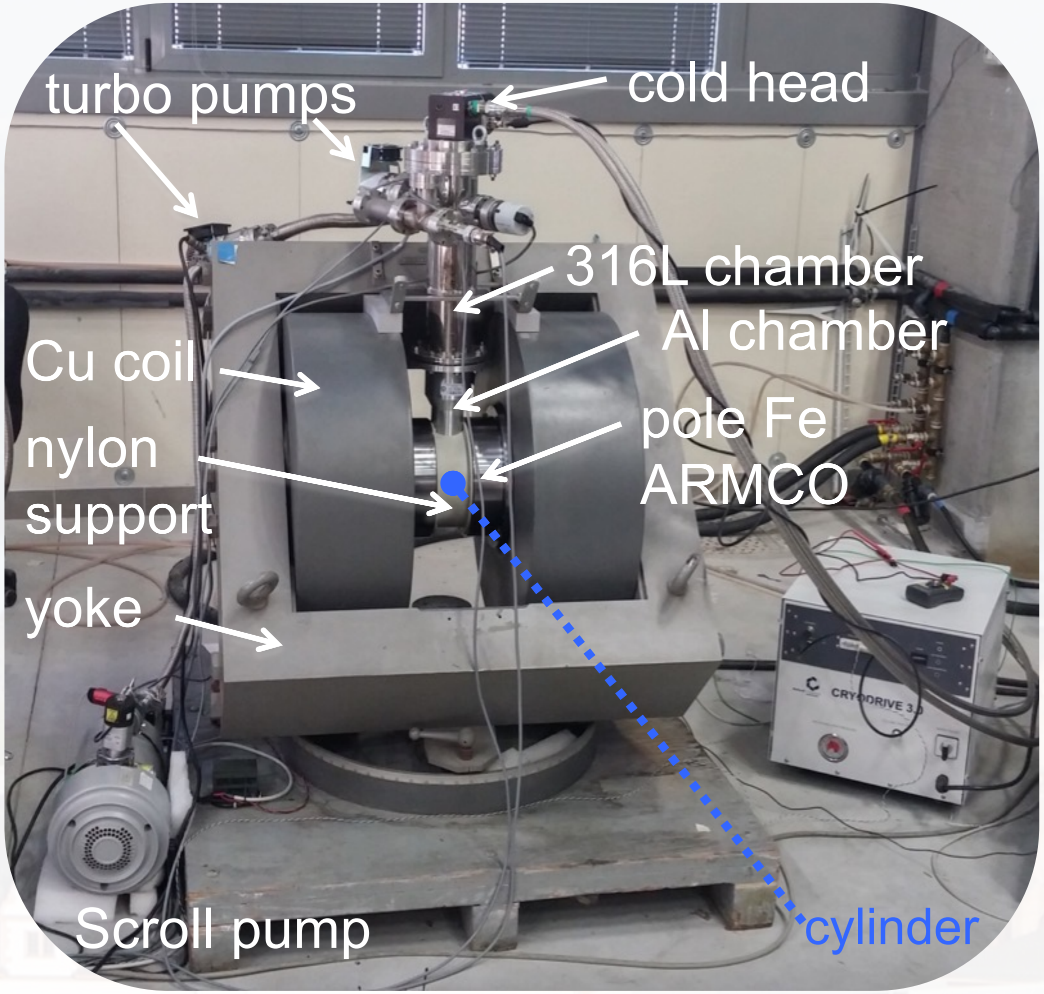
and new arrangment for

sistematic studies.

Cooling down of the MgB2 Cylinder



Experimental apparatus @ FE



Resistive magnet

Transverse Field

Polar expansion modified

Estimated field (at 110 A) 1 T

Vacuum chamber (316L e Al)

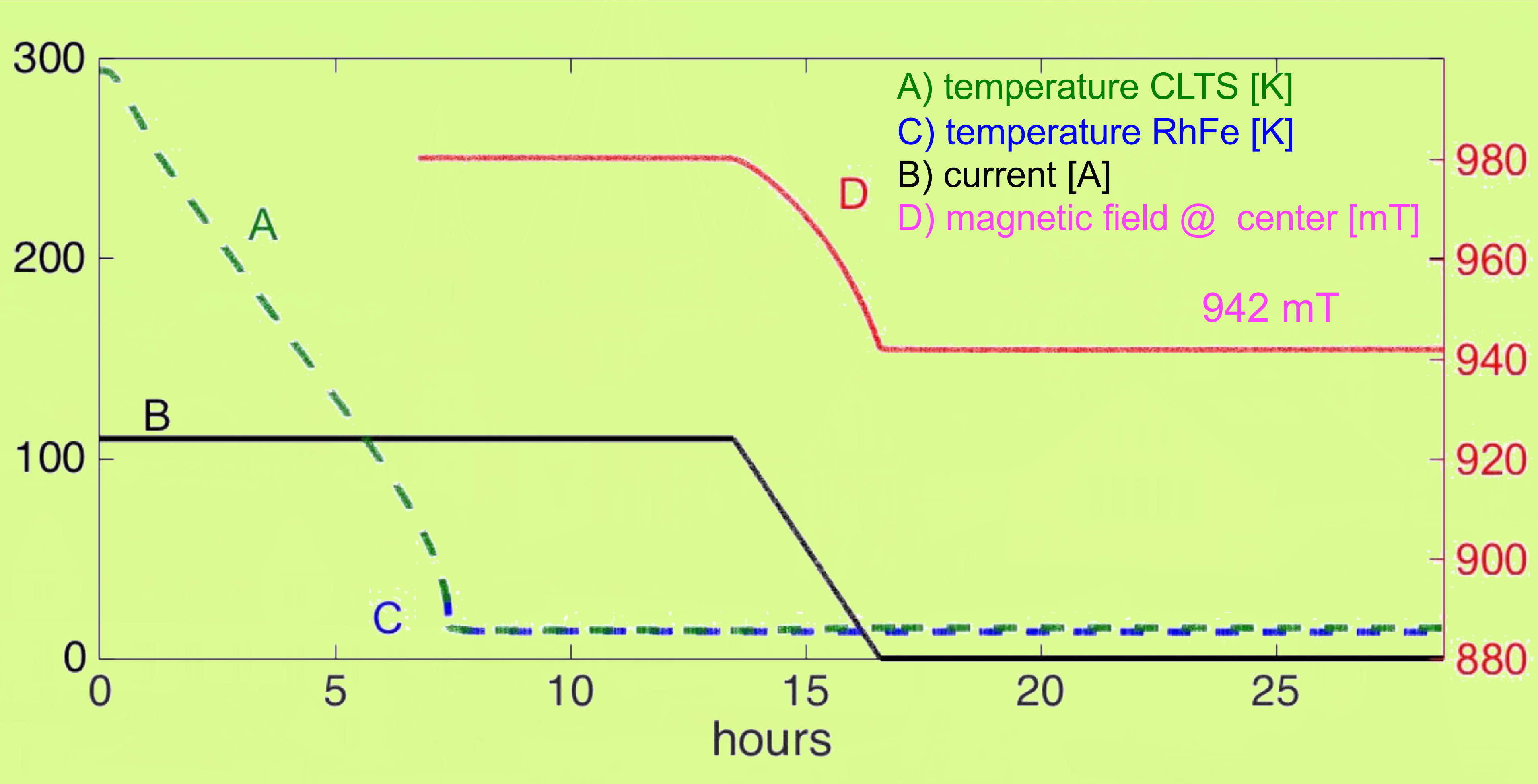
Cold Head

T control of the cylinder

Minimum Expected $T \approx 13$ K

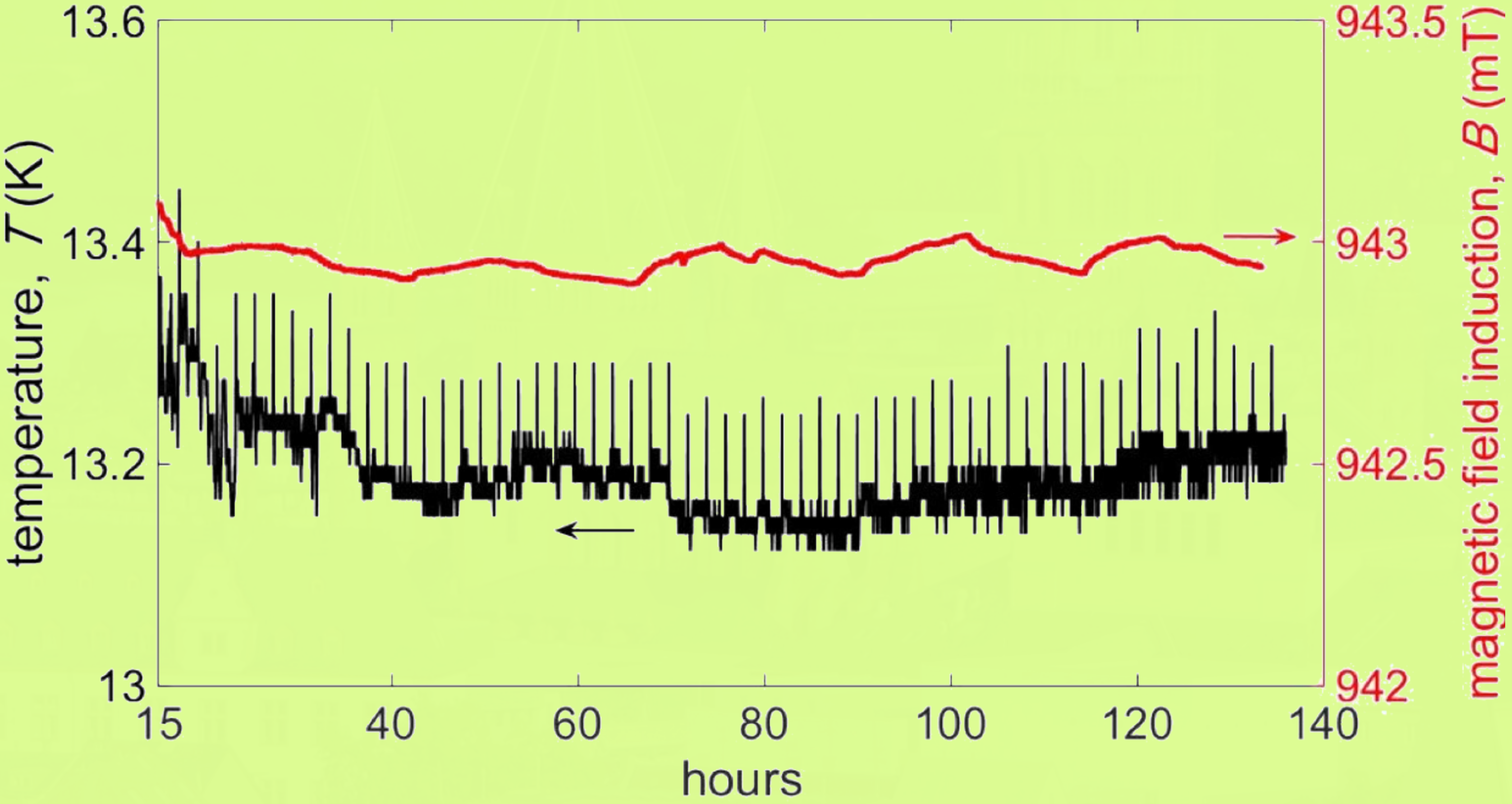
Field Trapping (Field Cooling)

7.5 hours to cool down from RT to 13 K
Field trapping after more than 12 (thermal homogeneity?)
Temperatura 13 K
Ramp down of the current feeding the magnet: : 0.25 A/4 s (0.06 A/s)



Long term stability

- Field trapped at the maximum of available power supply (110 A giving B_{ext} = 980 mT).

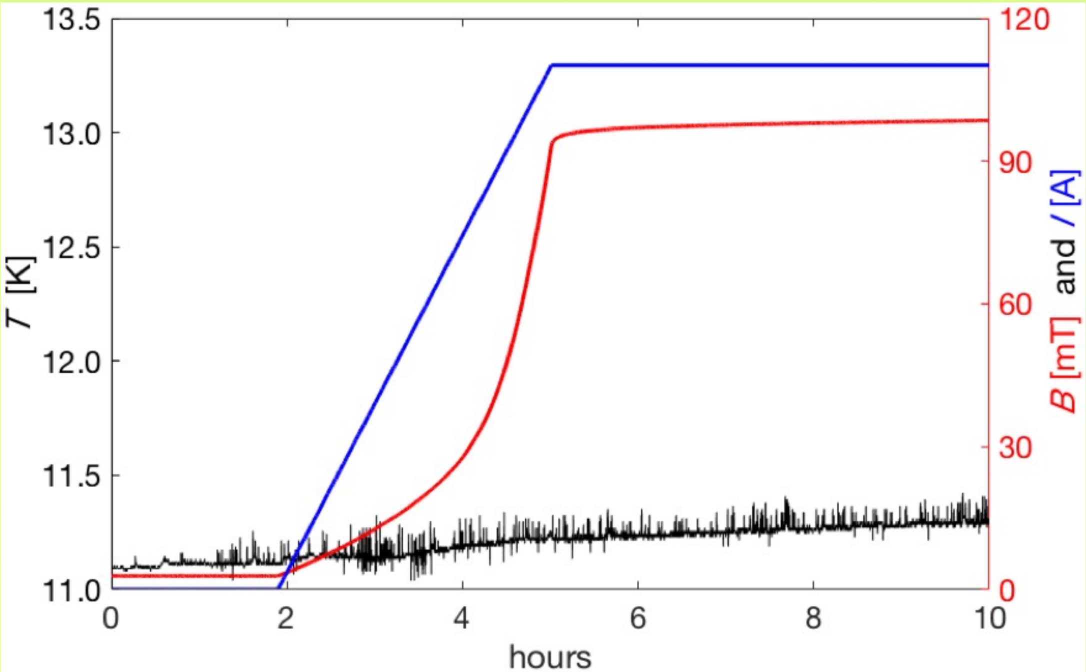


Shielding (ZFC Zero Field Cooling)

Cooling down the MgB_2

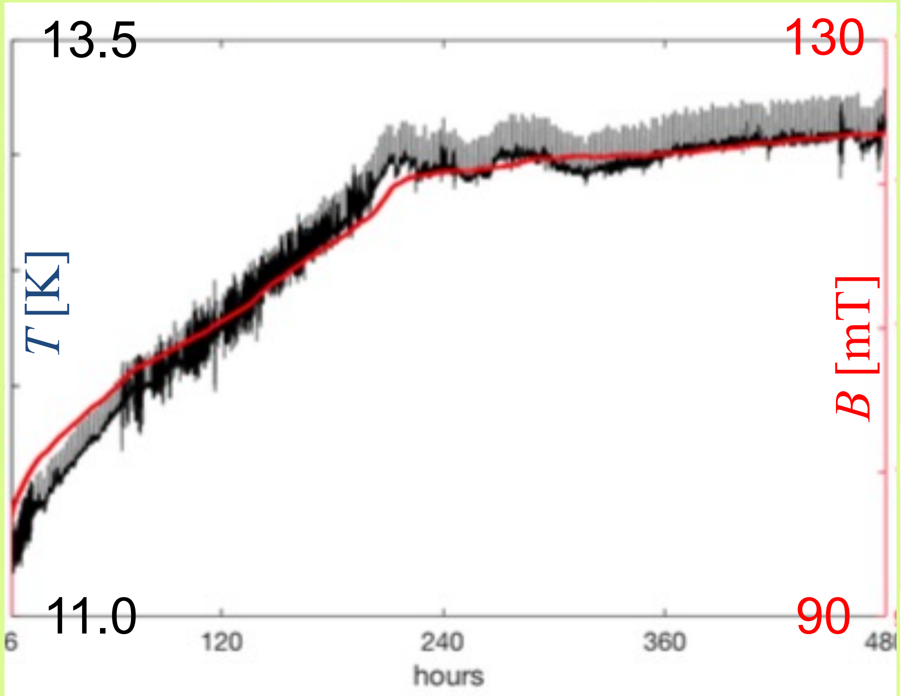
Ramping up the I_{magnet} (110 A) 0.01 A s^{-1}

Measuring B_{inside} at B_{out} (980 mT)



Shielding

T and Field drift in 480 h (20 days)



T correlation is suspicious

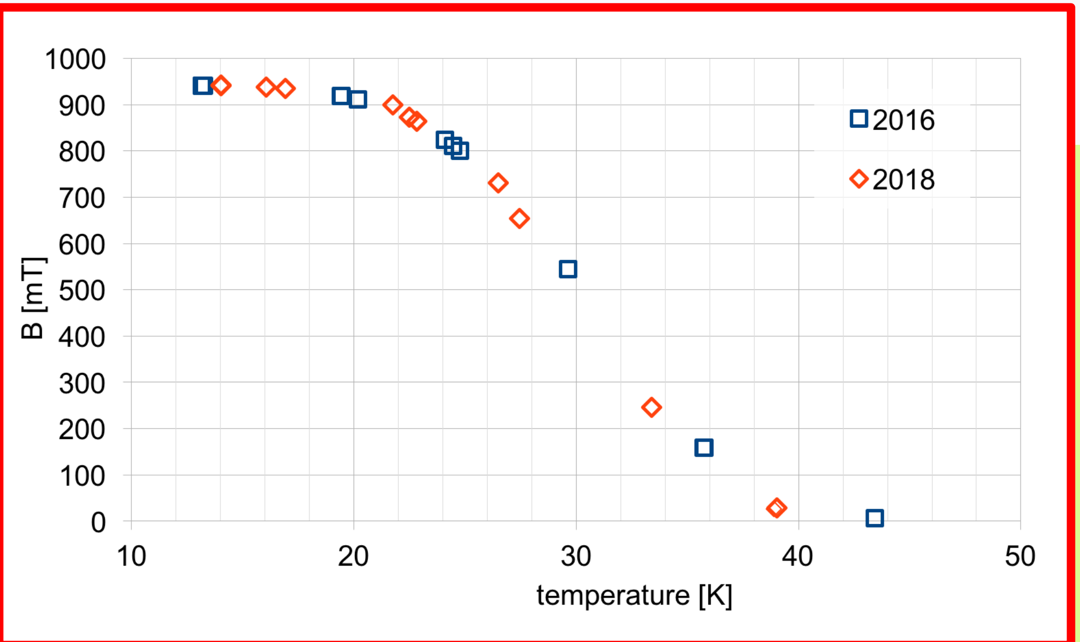
T Characterization

Trapping Field

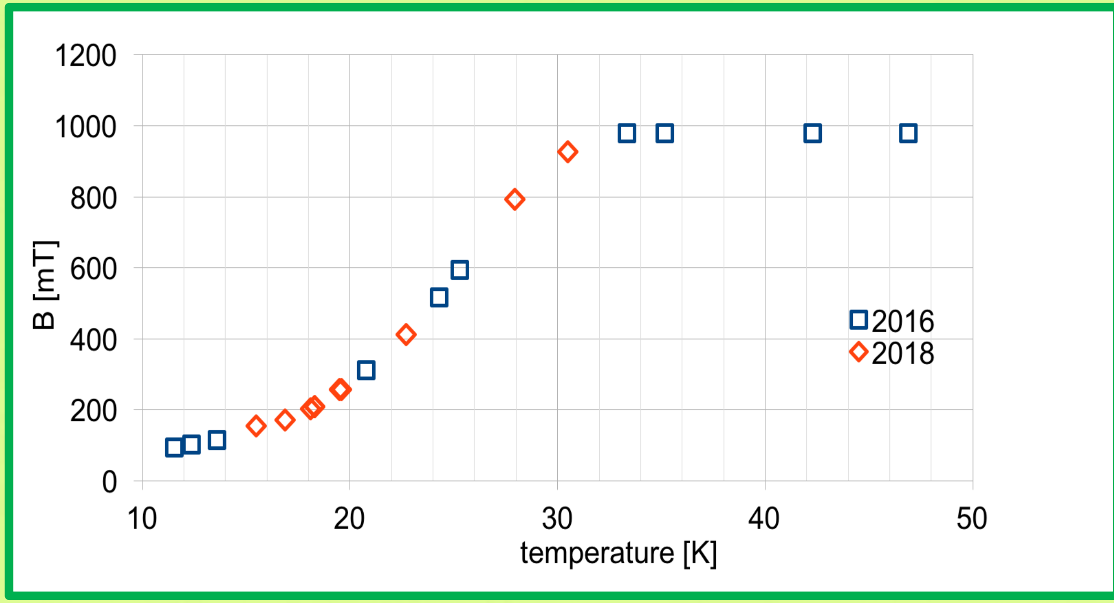
Evidence of T_c = 39.5 K

Good Performance @ T < 20 K

Good Reproducibility



Shielding



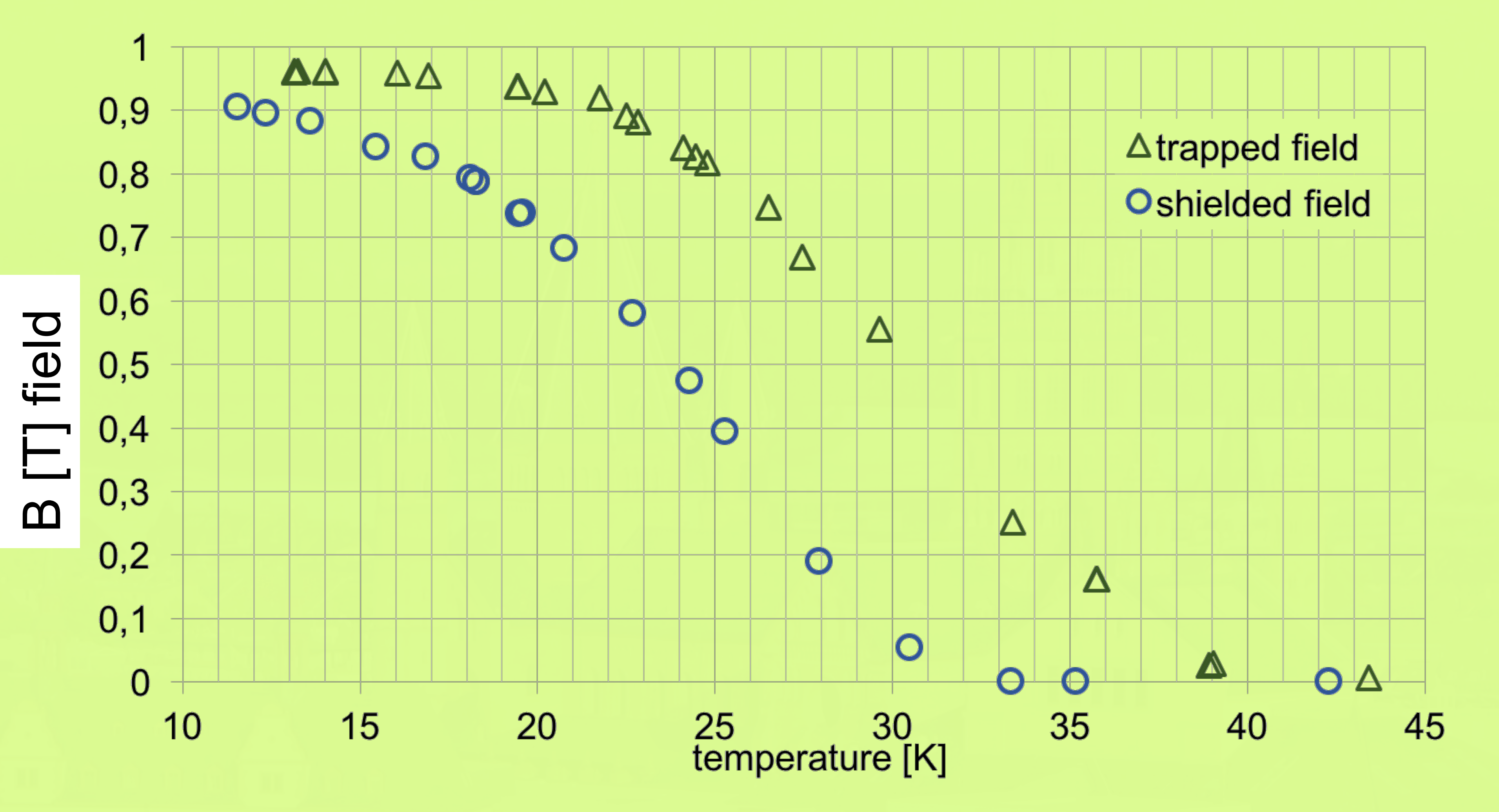
More sensitive to T

Good performance at lower T

Reproducibility after many thermal cycles, quenches or flux jumps, opening of system and change of thermal insulation materials

(2016 vs 2018)

Trapped and Shielded Field

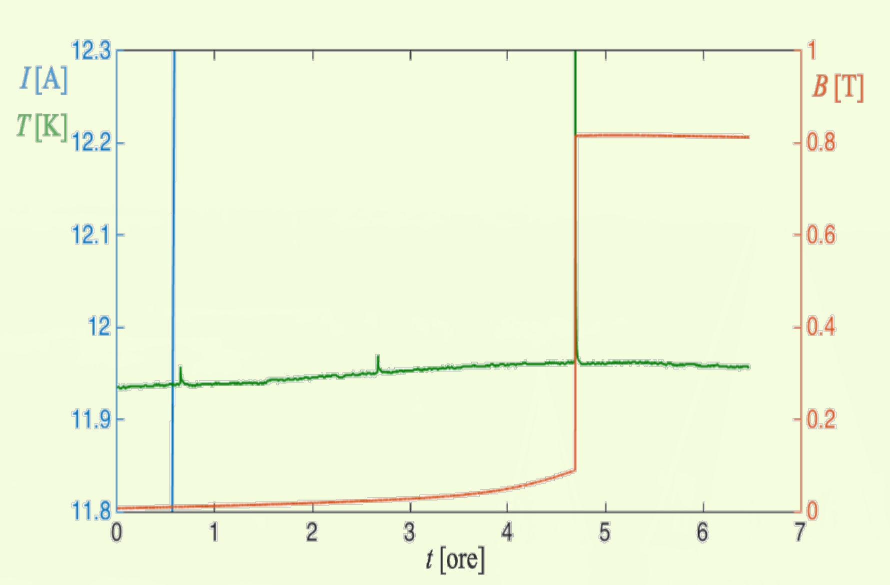


… affected by T spike, non long term.

Summary of the feasibility study

- ✓ Surprisingly the waste MgB_2 cylinder performes fine (better for field trapping).
- ✓ For Shielding instead lower temperature are required. The cold head shown temperature spikes each ~ 2 h. Confusion between flux jumps, or induced instability.
- ✓ The mapping of the magnetic field is determinant for the estimation of the homogeneity inside the cylinder.
- ✓ Test at higher magnetic field.
- ✓ Test, after transverse field cooling, on shielding longitudinal magnetic field.

Spikes of temperature (?)

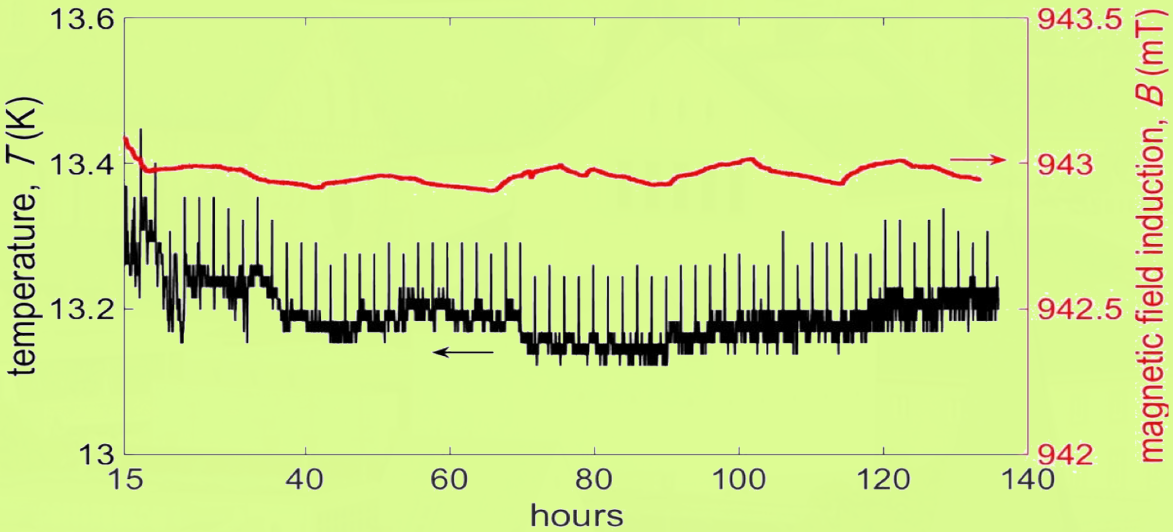


Temperature Spike problems

Some *spikes*, which could be at the beginning attributed to the MgB_2, we realized that they come from the compression cycle of the cryo-drive.

We observed in coincidence SC state breaking mainly on the shielding.

For the trapping, tuning in time properly the ramp down of magnet current, we were able to prepare the MgB2 in FC. The shielding procedure was limited in the long term stability, we didn't succeded to keep the shielding stable for long time at the contrary of the trapping.



Outlok of the presentation

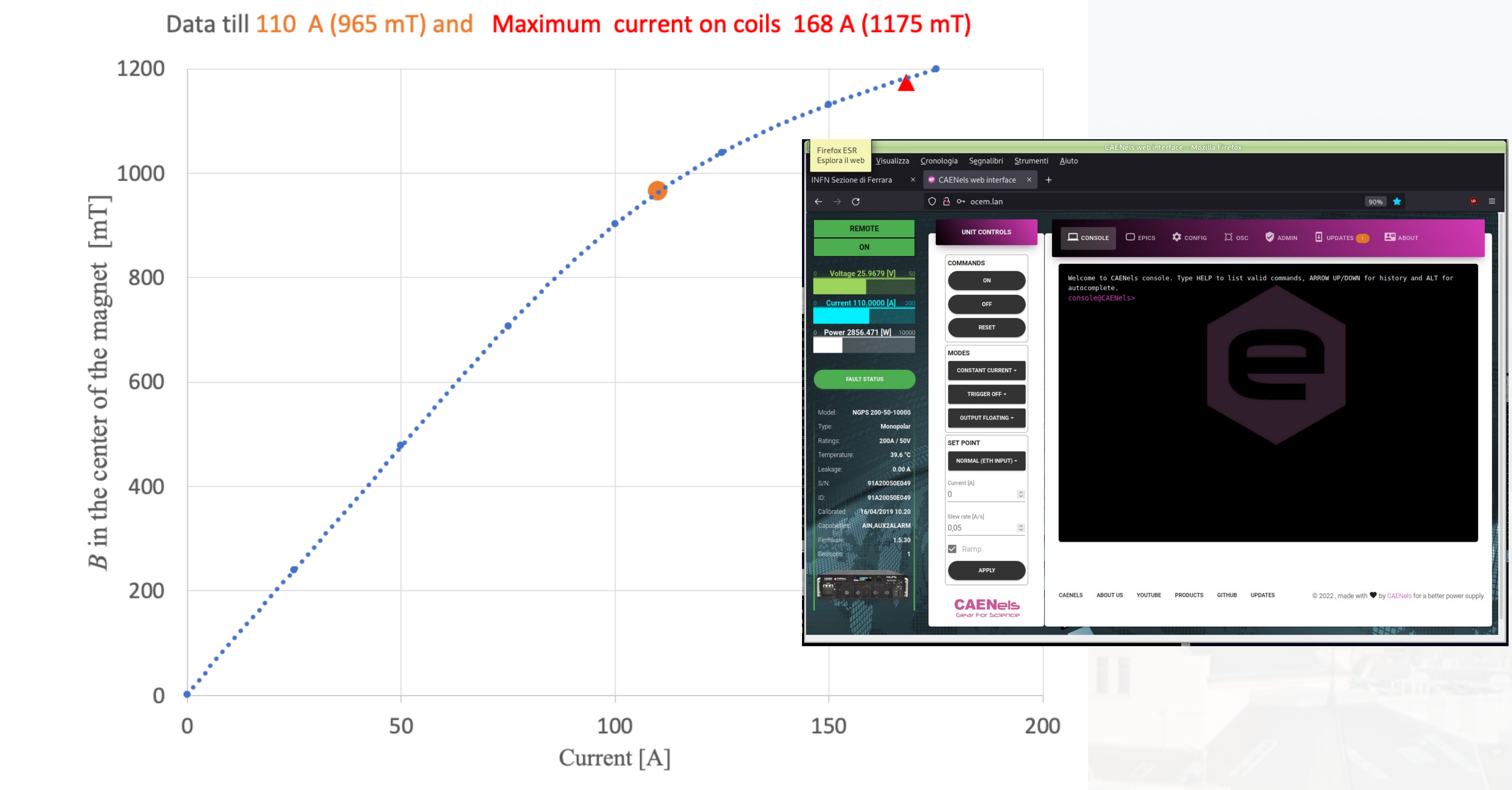
- Interest on MgB_2 (polarized nuclear target - fusion fuel).
- A compact magnet, movable, no power connections, generating self magnetic fields and shielding surrounding magnetic fields.
- R&D in Ferrara

a preliminay feasibility study

and

- new arrangment for sistematic studies.

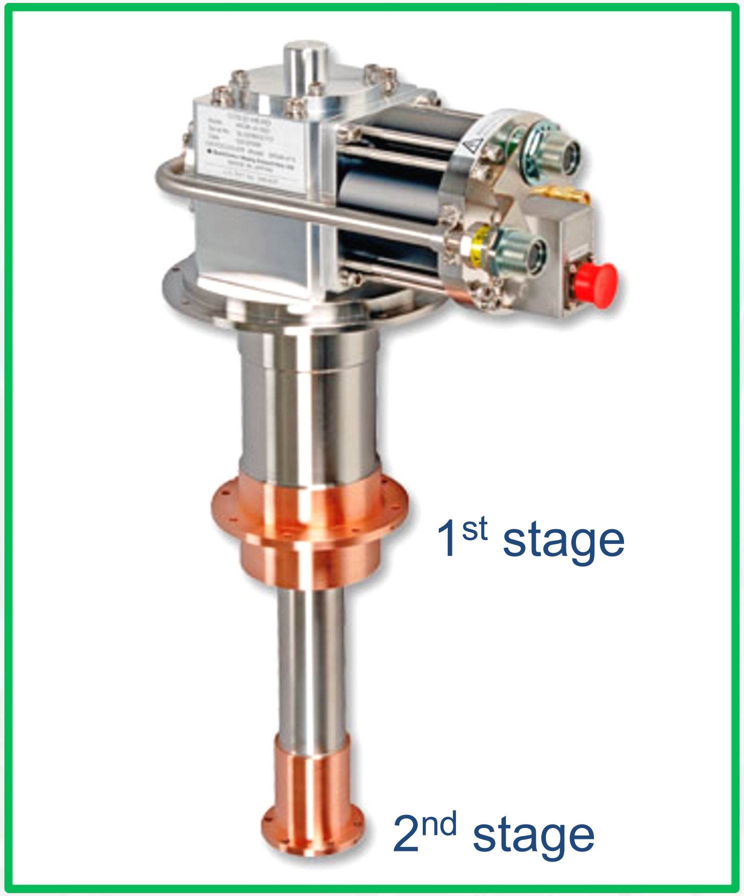
New power supply



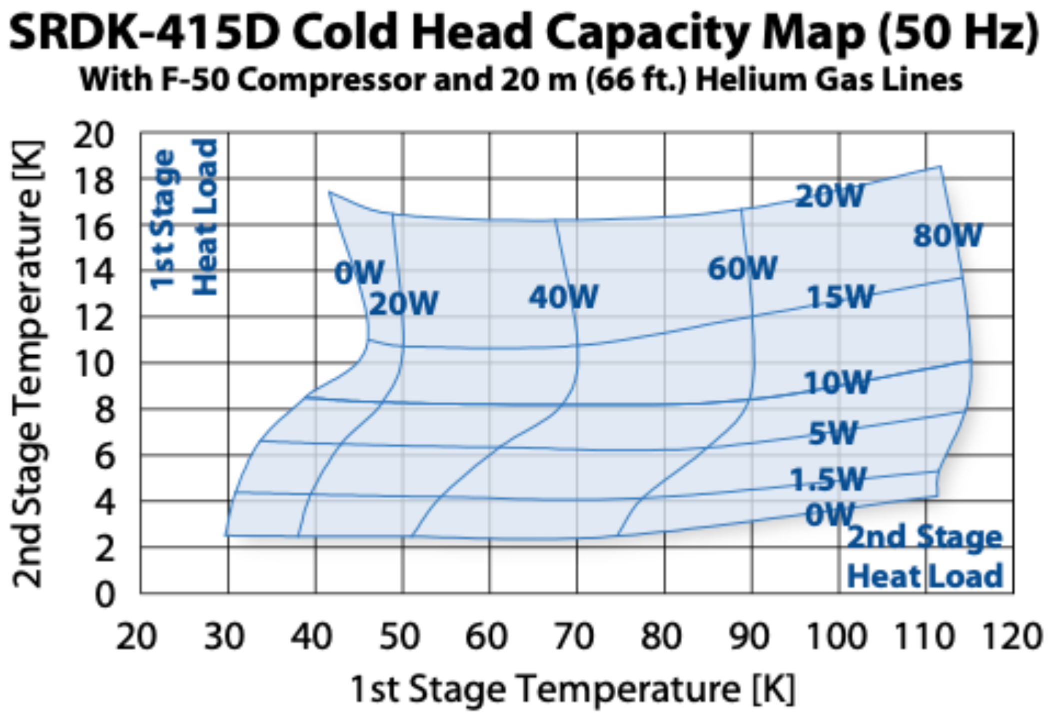
OCEM-CAEN - NGPS 200 A- 50 V
high stability power supply

this is the maximum magnetic field from our old system

New cold head (loaned by FZJ)



RDK-415D Sumitomo (SHI Cryogenics Group):
1° stage 35 W @ 50 K ,2° stage 1.5 W @ 4.2 K
(previous ome 60 W @ 77 K, 3 W @ 10 K) .



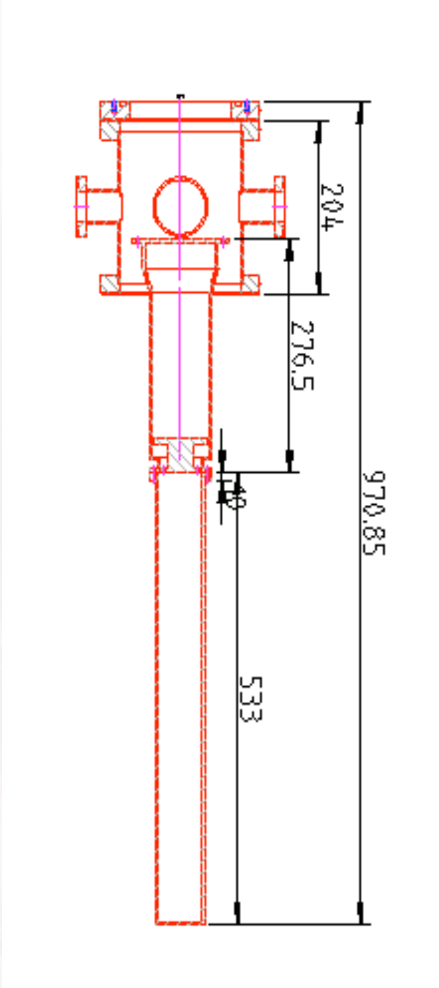
Better thermal stability and lower themperature

Upgrade of the system

(which allows us to come back to the old configuration)

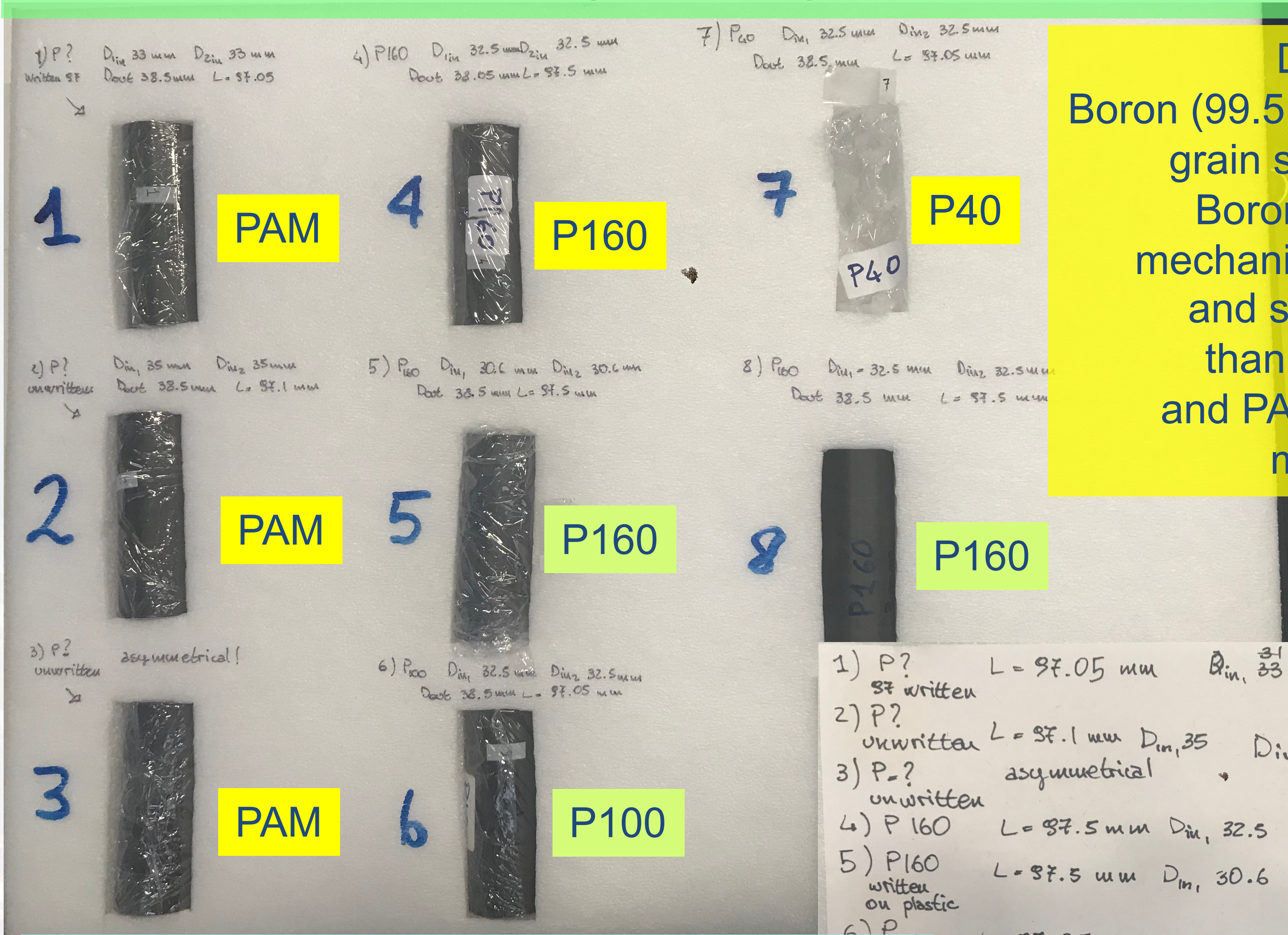
new top shielding

new bottom shielding

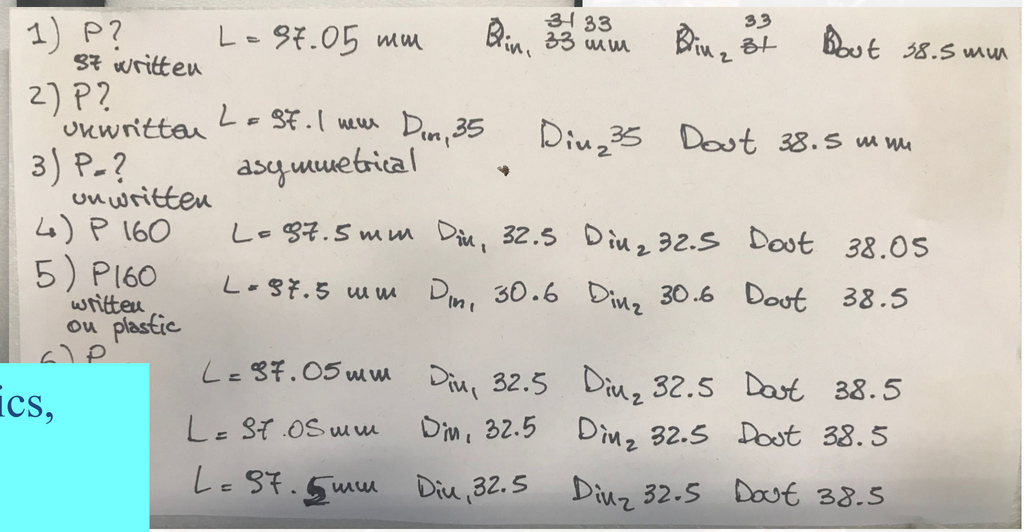


Different preparation for MgB2 cylinder

MgB_2 cylinders



Different Boron (99.5 % pure) precursor grain size (μm) from Boron chip (mm) mechanically grounded and sieved to less than (P)nnn μm, and PAM amourfous materials.



1) P? 97 written L = 97.05 mm D_{in_1} ~~31~~ 33 33 mm D_{in_2} ~~31~~ 33 D_{out} 38.5 mm

2) P? unwritten L = 97.1 mm D_{in_1} 35 D_{in_2} 35 D_{out} 38.5 mm

3) P-? unwritten asymmetrical

4) P 160 L = 97.5 mm D_{in_1} 32.5 D_{in_2} 32.5 D_{out} 38.05

5) P160 written on plastic L = 97.5 mm D_{in_1} 30.6 D_{in_2} 30.6 D_{out} 38.5

6) P L = 97.05 mm D_{in_1} 32.5 D_{in_2} 32.5 D_{out} 38.5

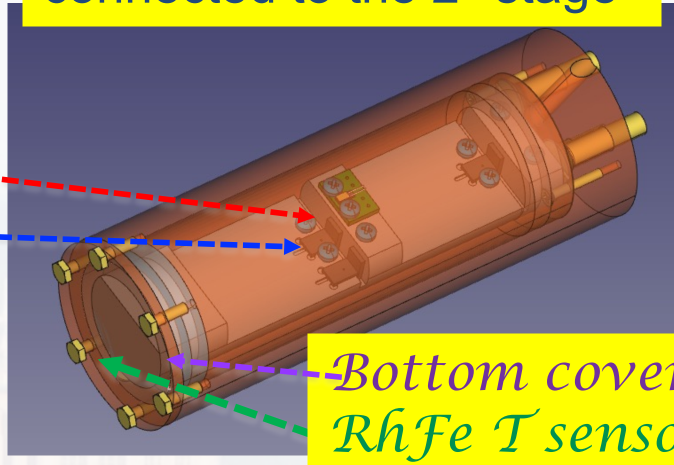
L = 97.05 mm D_{in_1} 32.5 D_{in_2} 32.5 D_{out} 38.5

L = 97.5 mm D_{in_1} 32.5 D_{in_2} 32.5 D_{out} 38.5

Smaller the grain size higher transport characteristics, but less thermal stability at lower *T* and lower *B*.
Connectivity P100 ~ 61 %, P40 ~89 %, PAM~73 %

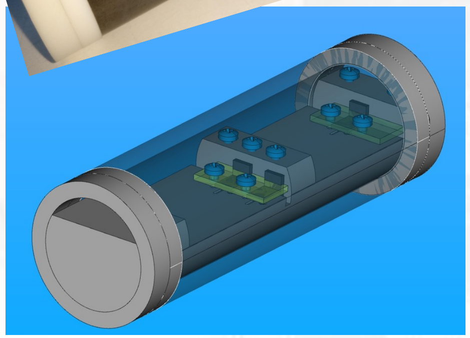
Mapping the field inside the cylinder

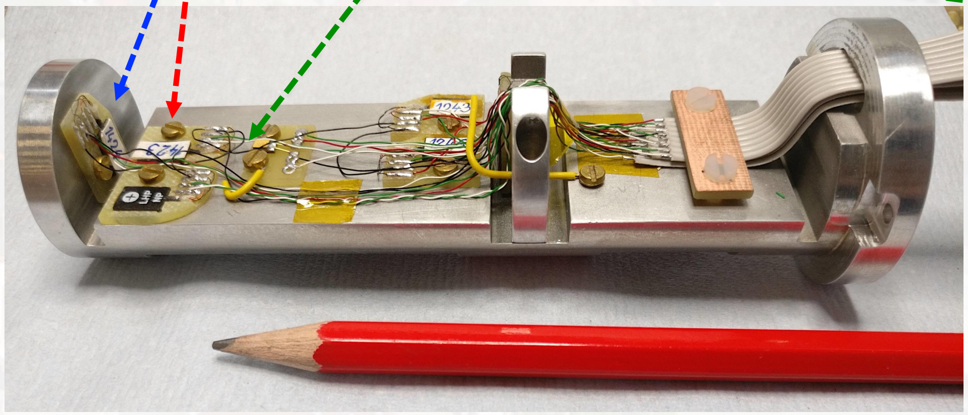
Drawing of the copper can connected to the 2° stage



Bottom cover, RhFe T sensor

- Hall probes in order to maps the field.
- **Hall probe couples**:
  - **one measuring the longitudinal field**
  - **the other measuring the transverse field.**
- One couple in the middle and at the radial center of the cylinder, one couple displaced radially on the middel.
- Same couples also on the **edge** of the cylinder.



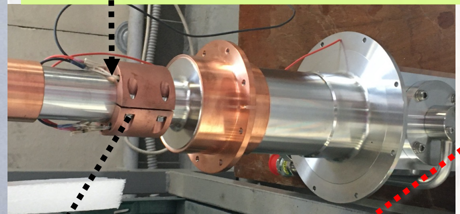


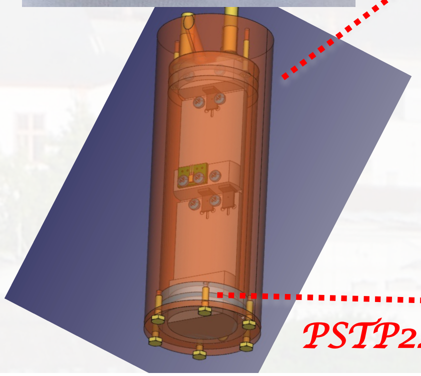
New Temperature sensor
Cernox on Hall probe holder

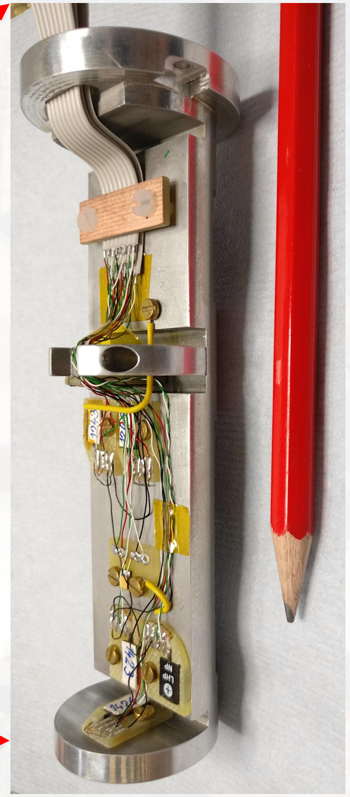
We can exchange the cylinder opening the *bottom cover*, without dismountling any electrical connection

Improvements (installation 15 July 2022)

- Reduced mass installed on 2nd stage
- Heater close to the cylinder can, to have a better temperature control.
- Sensor holder in Al to have a better thermal conductivity for higher homogeneity of inner part of the cylinder.







Control, monitoring and DAQ

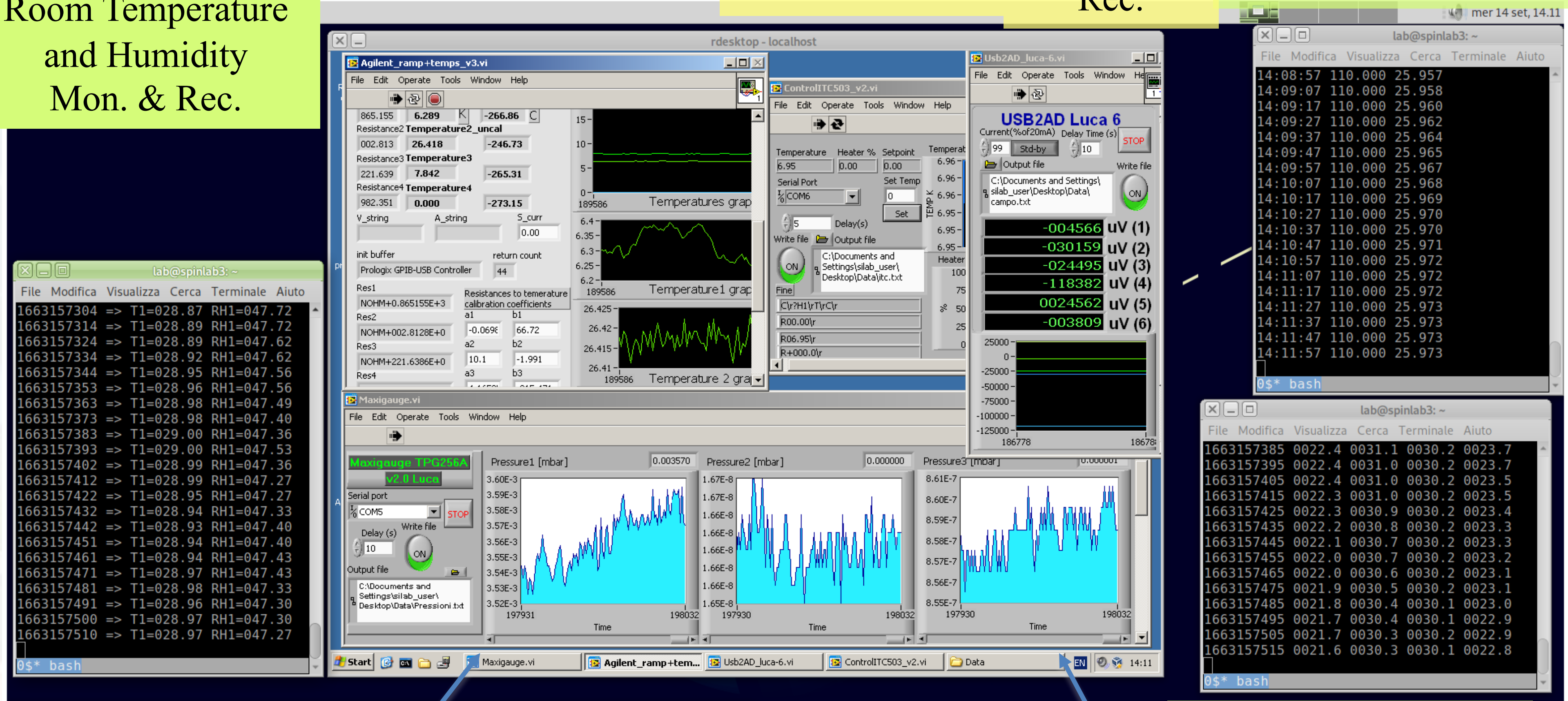
Room Temperature and Humidity Mon. & Rec.

Temperature sensor monit. & Rec.

Cold head heater contr. Monit. & Rec.

Hall probe Monit. & Rec.

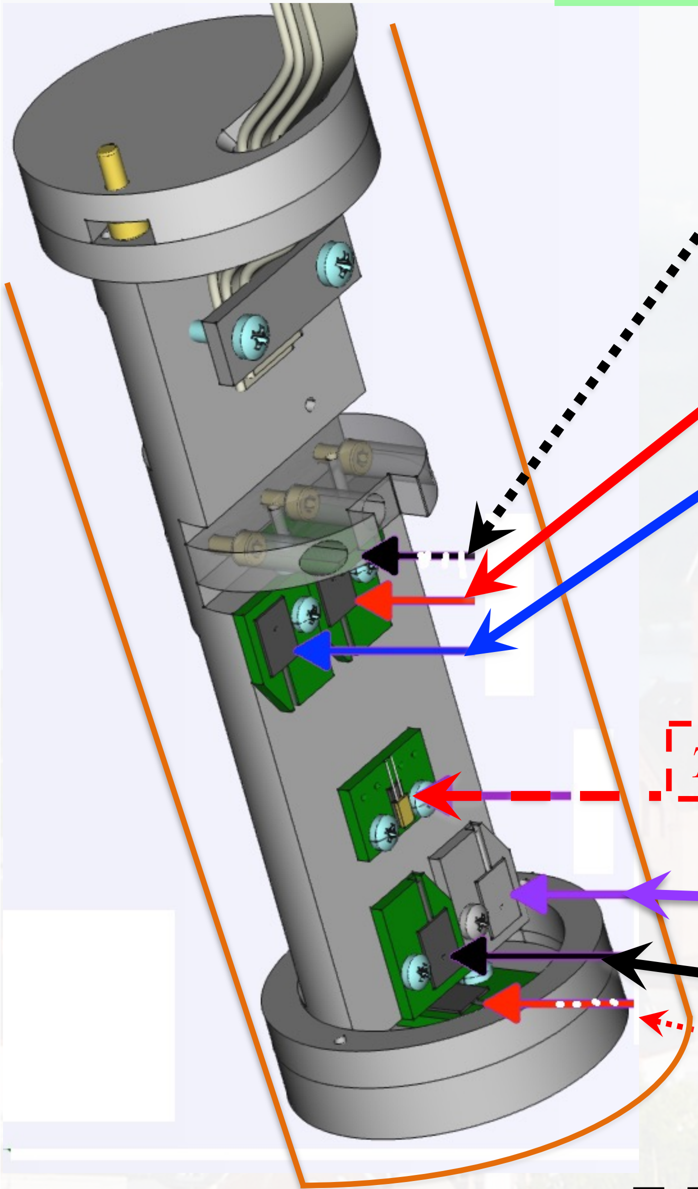
Magnet power supply Monit. & Rec.



Pressure Monitoring (Mon.) & Recording (Rec.)
($P_{pv} \sim 10^{-2}$ mbar, $P_{bp} \sim 10^{-6}$ mbar, $P_{ch} \sim 10^{-8}$ mbar)

Water circuit temperature
1) Water in,
2) Cryo Water out,
3) magnet body,
4) magnet water out.
Mon. & Rec.

Label of Sensors (meaning)



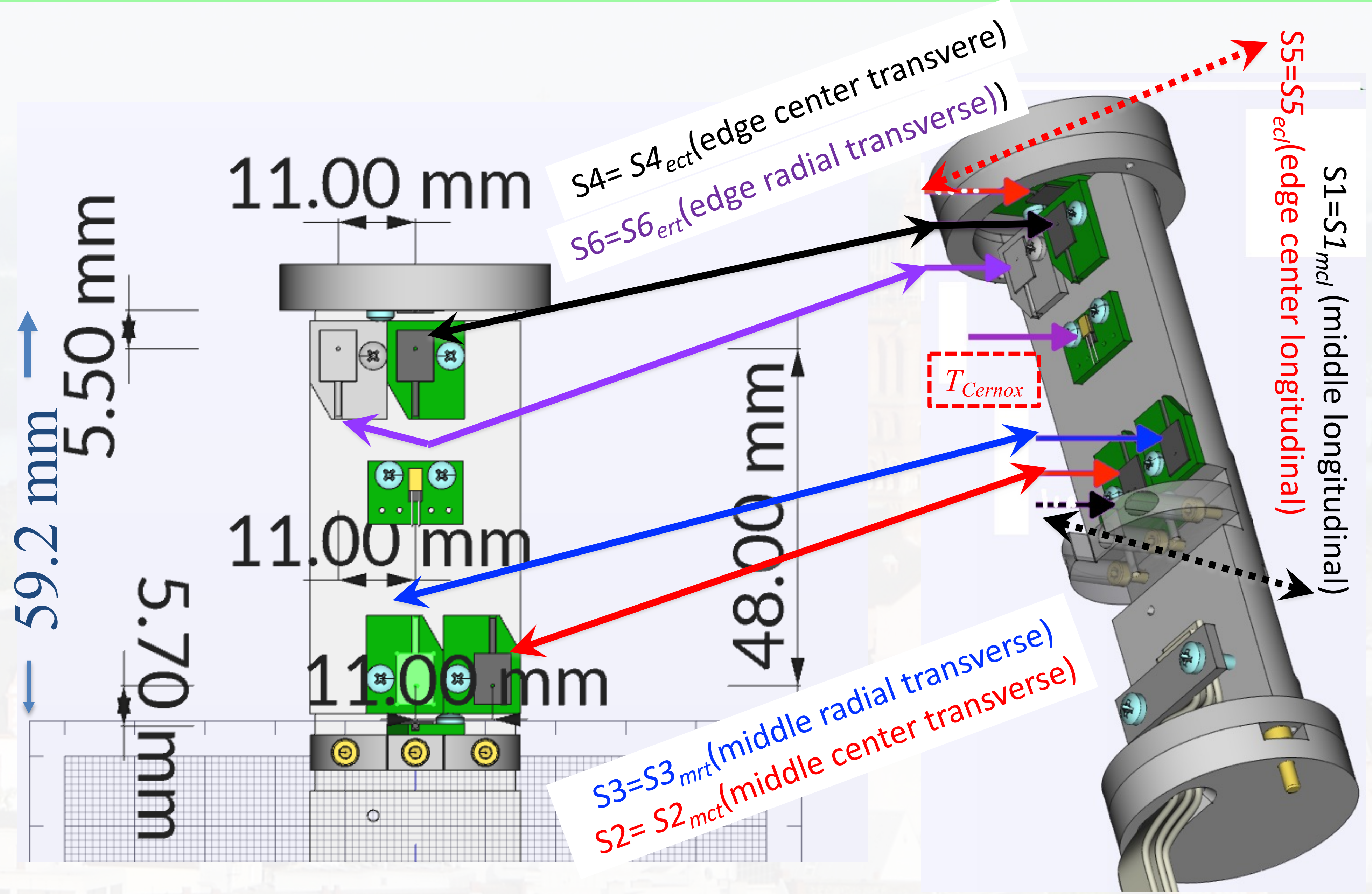
- S1=$S1_{mcl}$ (middle center longitudinal)
- S2= $S2_{mct}$(middle center transverse)
- S3=$S3_{mrt}$(middle radial transverse)

T_{Cernox} on the Al sensors' holder

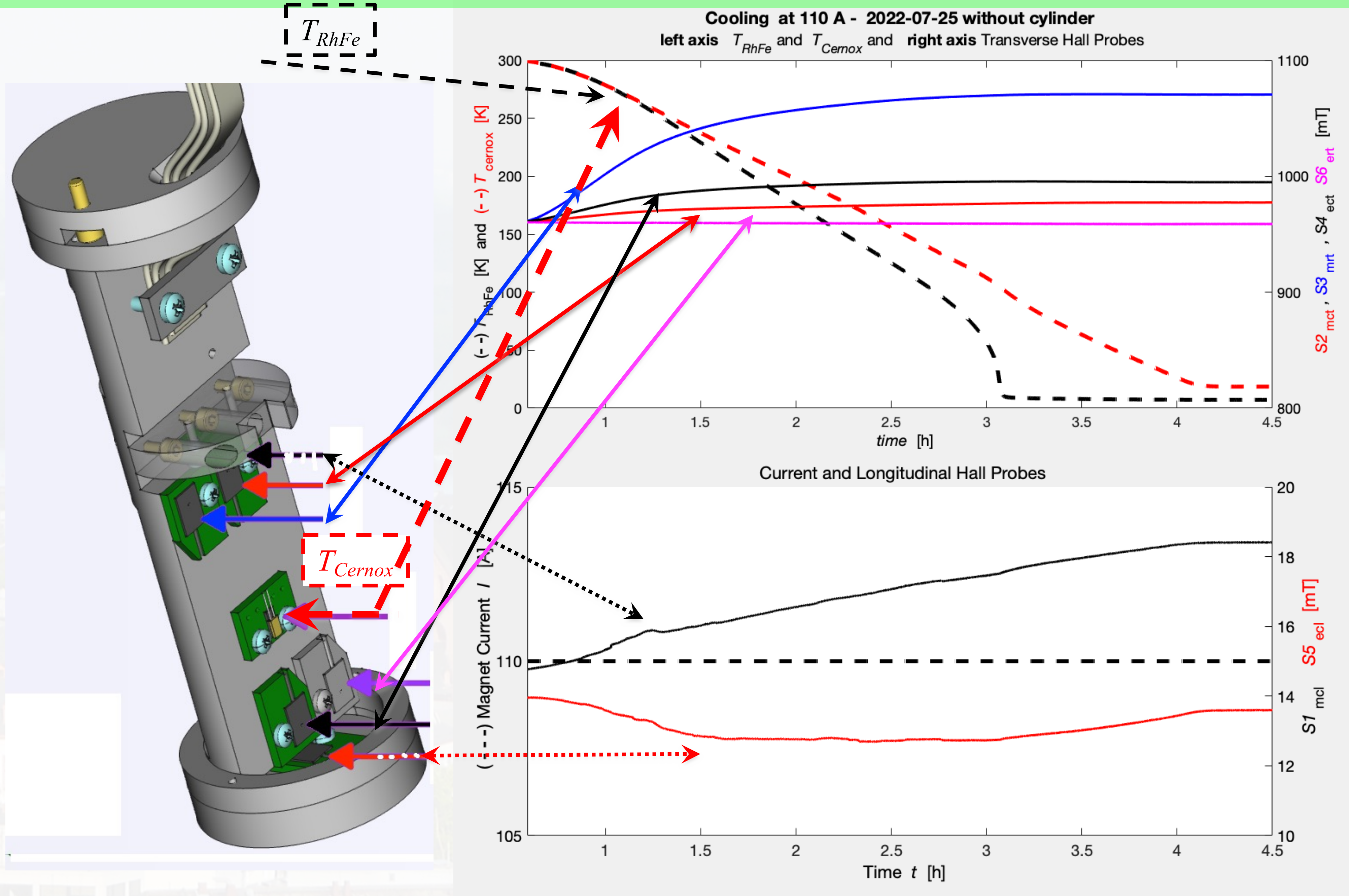
- S6=$S6_{ert}$(edge radial transverse)
- S4= $S4_{ect}$(edge center transverse)
- S5=$S5_{ecl}$(edge center longitudinal)

T_{RhFe} under the copper can holding and shielding sensors and cylinder

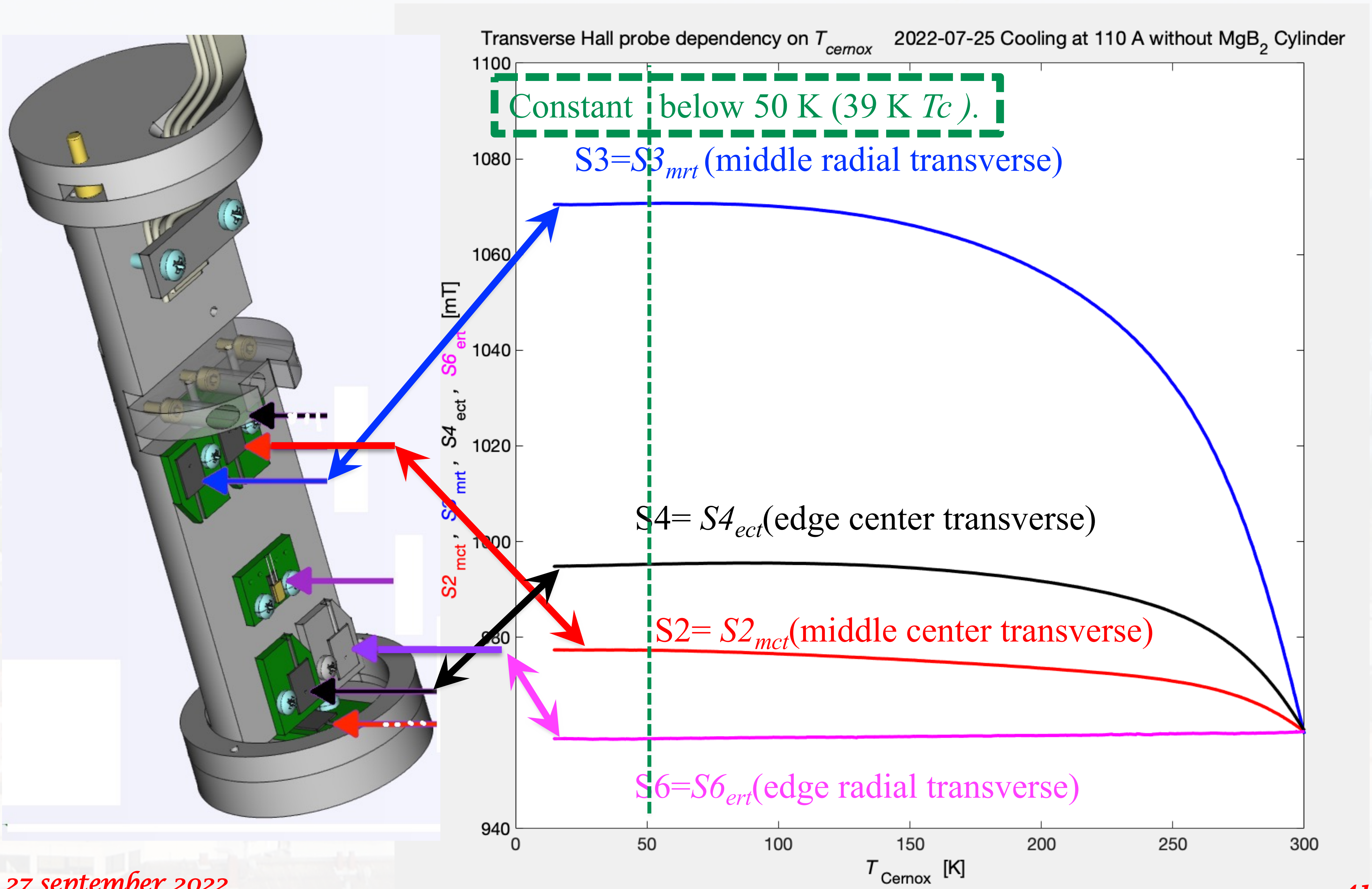
Locations of the transv. and long. Hall probes



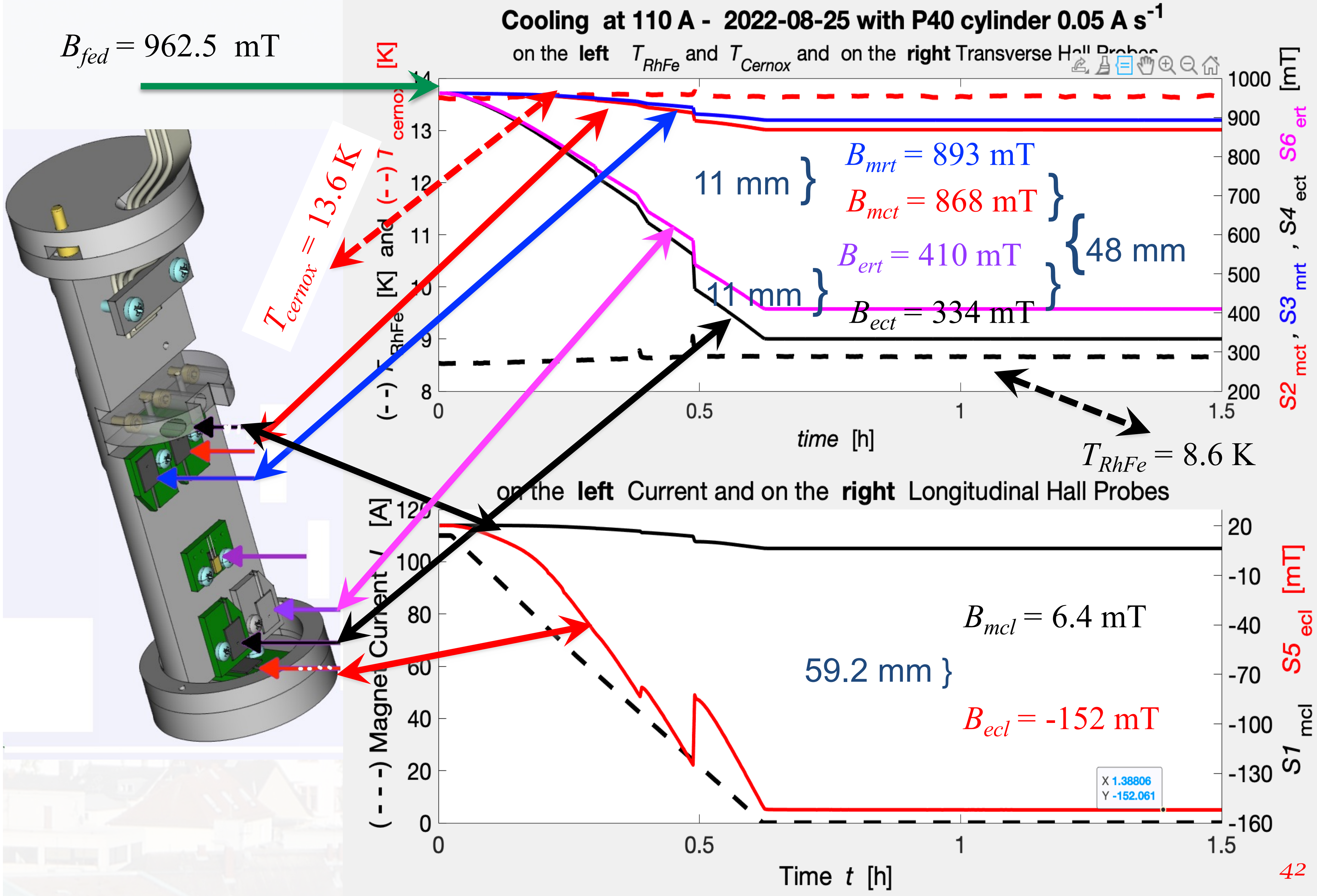
Cooling down less than 3.5 (4.5) h against > 7.5 h



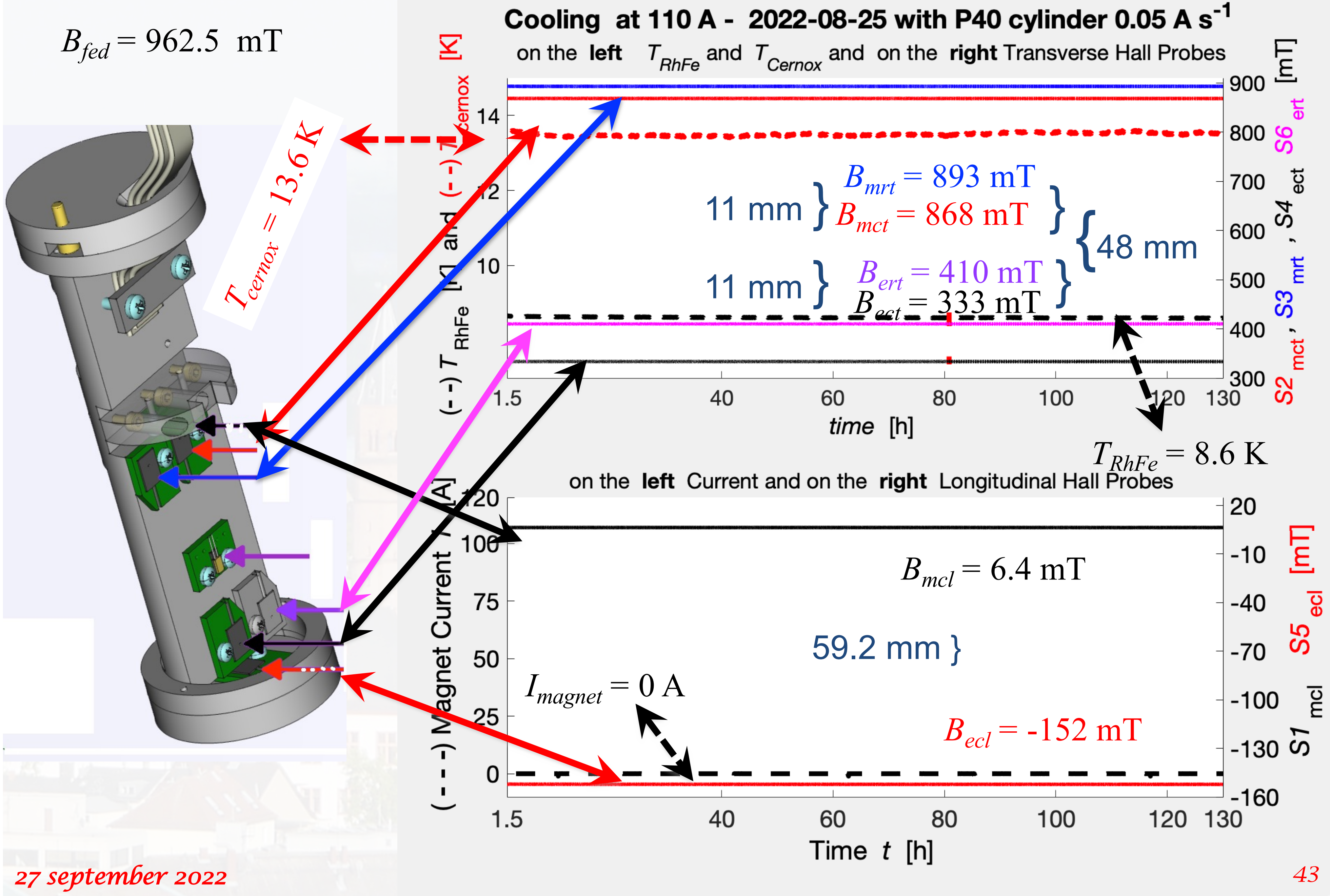
Temperature dependency of Hall probe



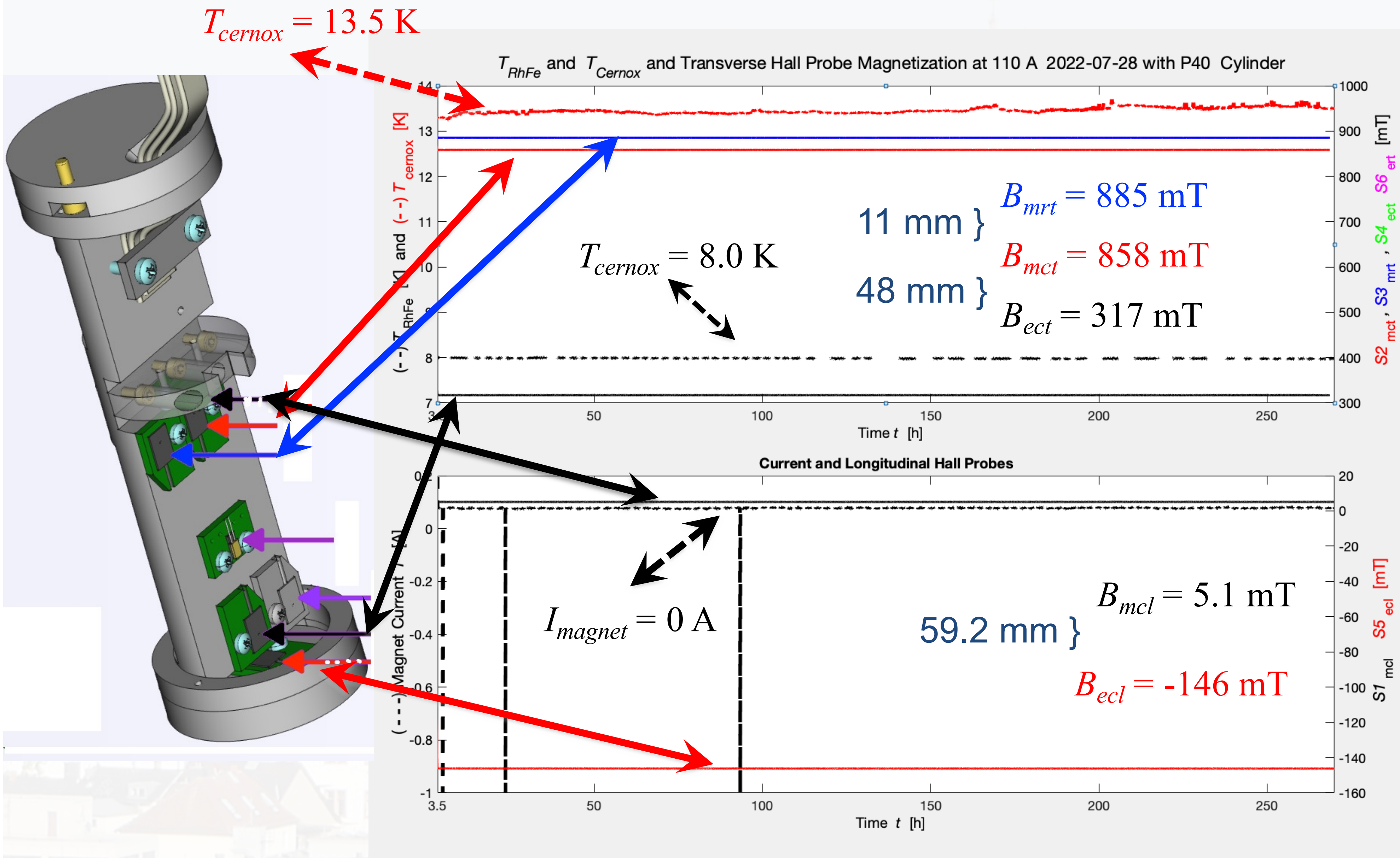
Ramp down 0.05 A/s



Ramp down 0.05 A/s long

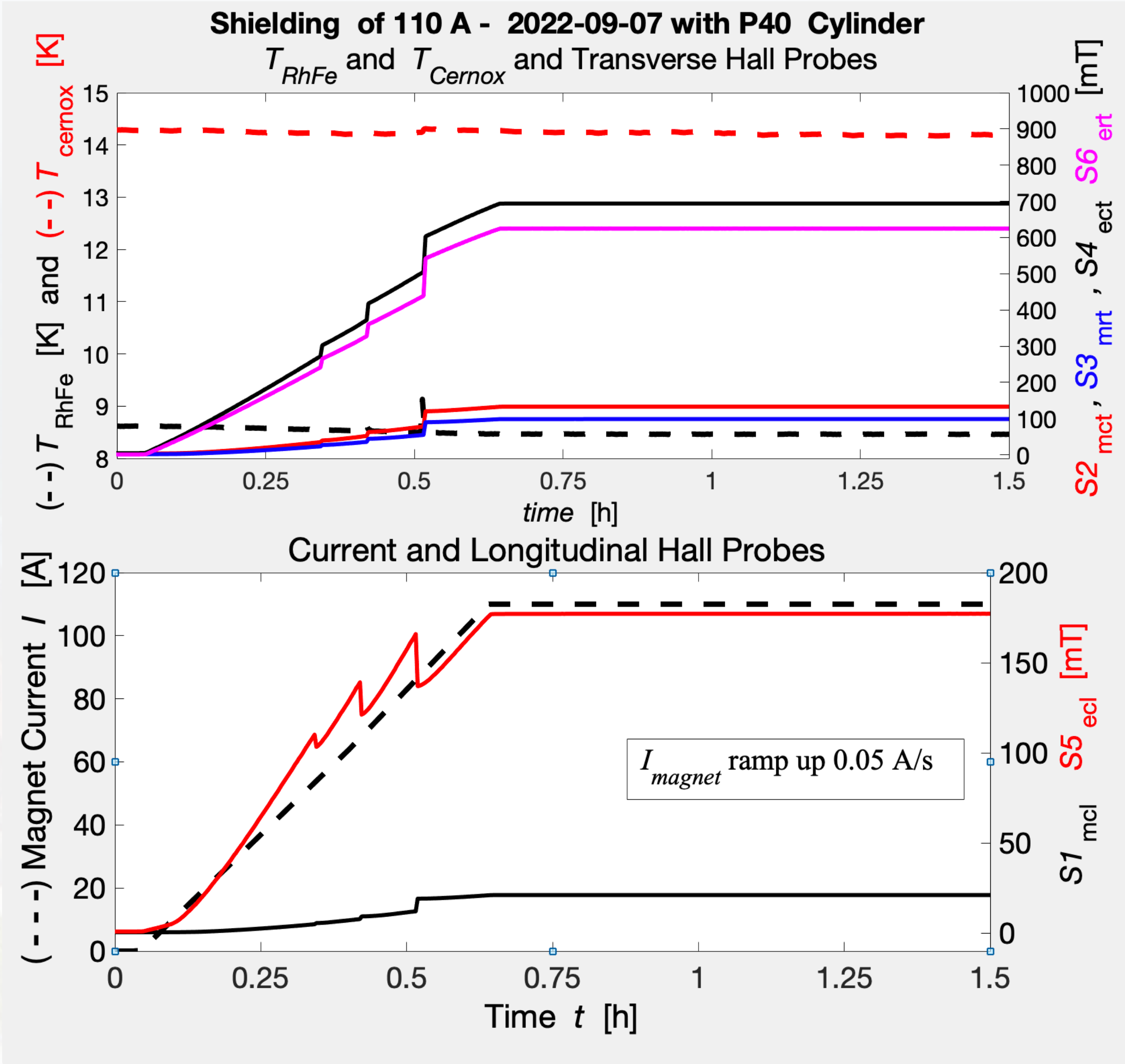


Long time stability (0.01 A/s)



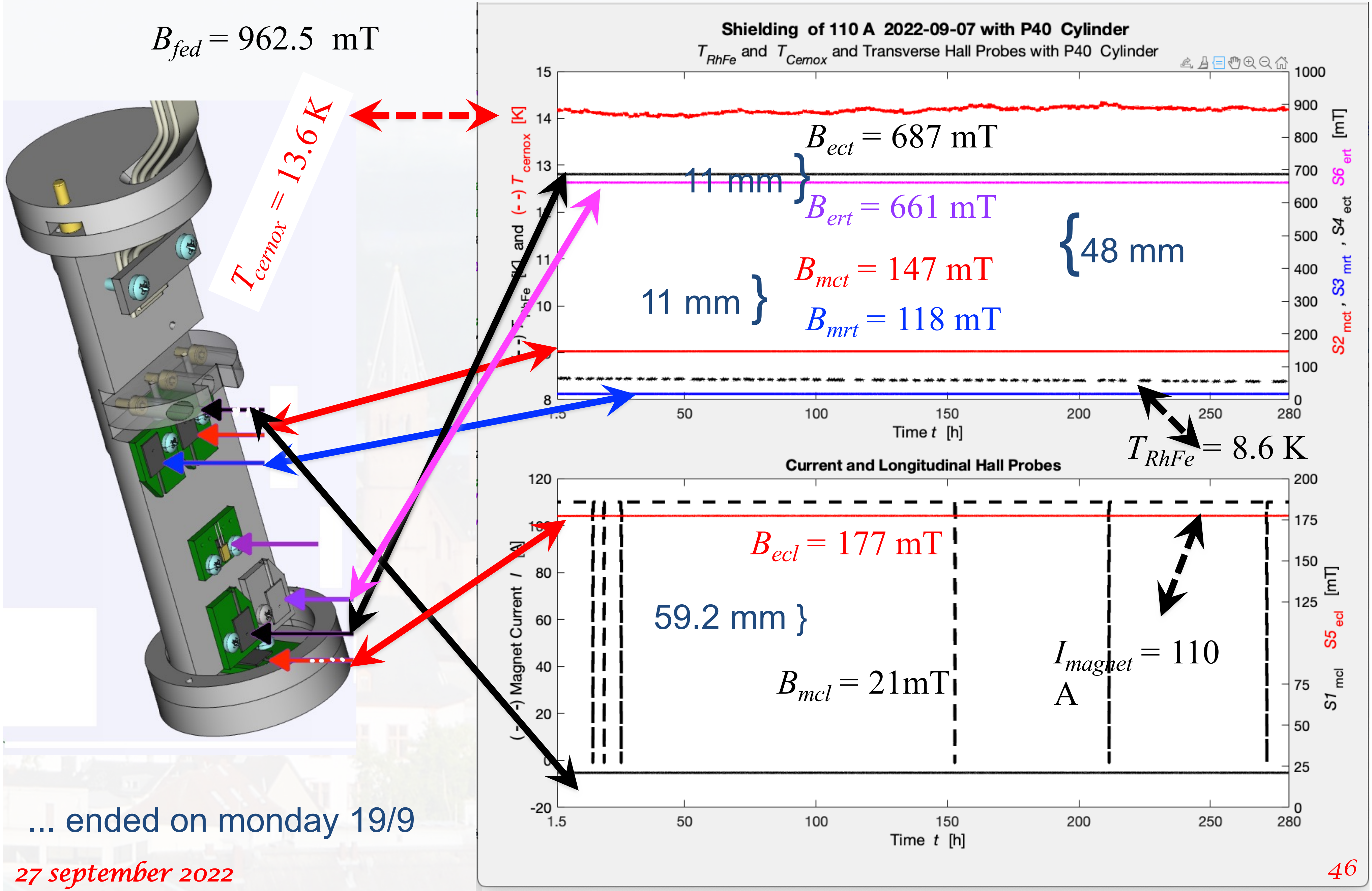
Shielding 110 A ramp up 0.05 A/s

Early
Zero Field Fooling
then after
reaching the lowest
temperature
Ramp up the
external field.



Shielding long term stability 1.5 -280 h.

B_{fed} = 962.5 mT



... ended on monday 19/9

Preliminary Results and Plans

- We can to measure the magnetic field in different locations inside the cylinder.
- We can correct the deviation of Hall probes with respect to the temperature.
- We can investigate the behavior of the cylinder with different preparation procedure also checking their reproducibility on the nominal label P160, P100, P40 and PAM cylinders.
- We can test the superconducting behavior from the reached low temperature (T_{RhFe} 9 K - T_{cernox} 13 K) to the normal state transition. Flux Jumps can be reduced at higher temperature.

FE apparatus at LASA-Milano

(Laboratorio di Acceleratori e Superconduttività Applicata)

- At LASA we plan to put in operation a 10 T superconducting solenoid.
- Experimental tests on
  - Trapping of Tranverse field and shielding of longitudinal field (target).
  - Trapping of longitudinal field (fusion)
  - Mapping of field for tranverse self field and external longitudinal field, mapping of longitudinal field.
- Checking theoretical model and tuning of them on data for field generation and shielding.
- Long time stability test for crossed beam in time interval for JLab targets and fusion test.
- Stability under movement in working conditions

I'd like to mention people involved presvioulsy and now in this work

Ferrara: Balossino Ilaria, Barion Luca, Canale Nicola, Contalbrigo Marco, Movisyan Aram, Vallarino Simone,

Ferrara: SQUID measurements on MgB_2 sample
Spizzo Federico and Lucia del Bianco

Bari: Tagliente Giuseppe – DAQ

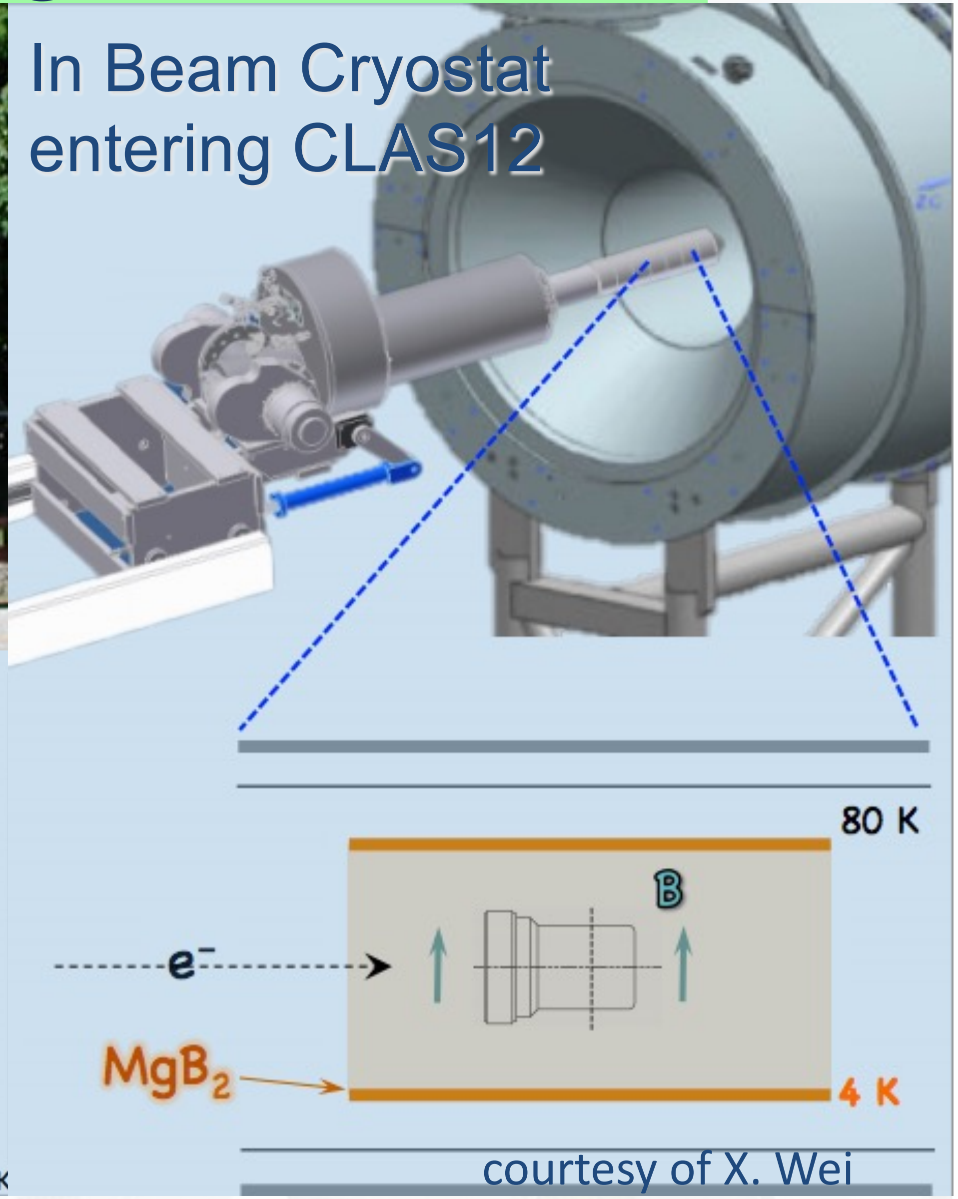
JLab: Lowry Michael, Sandorfi Andrew – HD-Ice and simulations

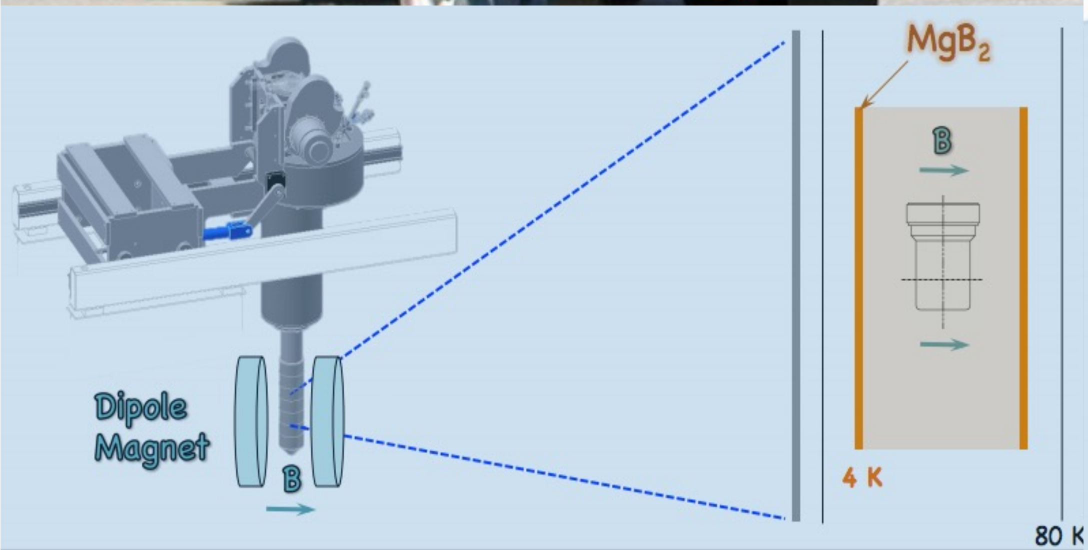
Milano: Statera Marco

Thanks to the organizers
and
to You for the attention

Spare Slides for details

CLAS12 INTEGRATION



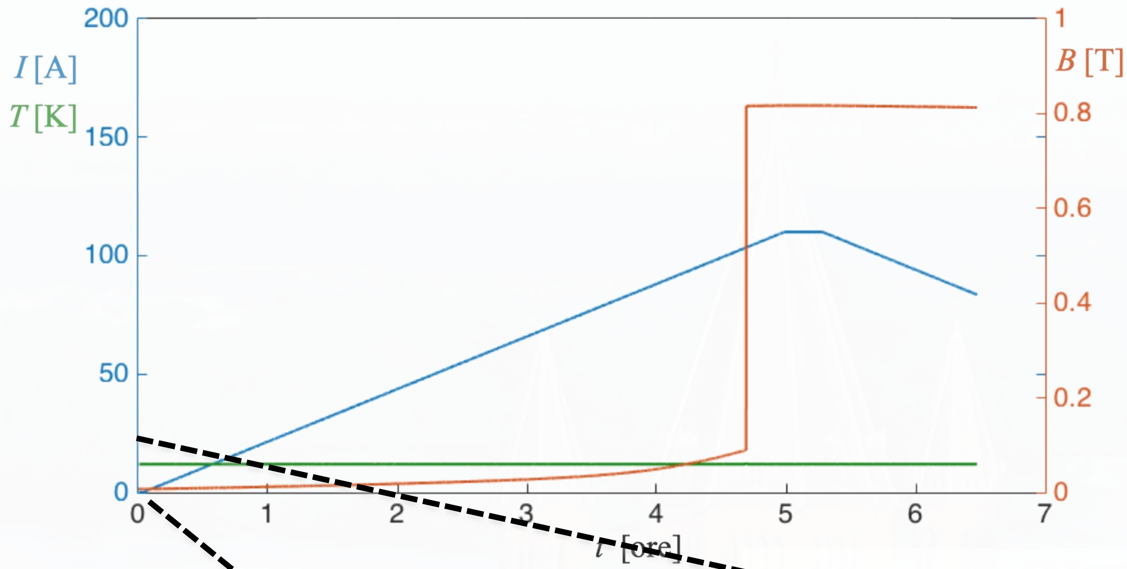


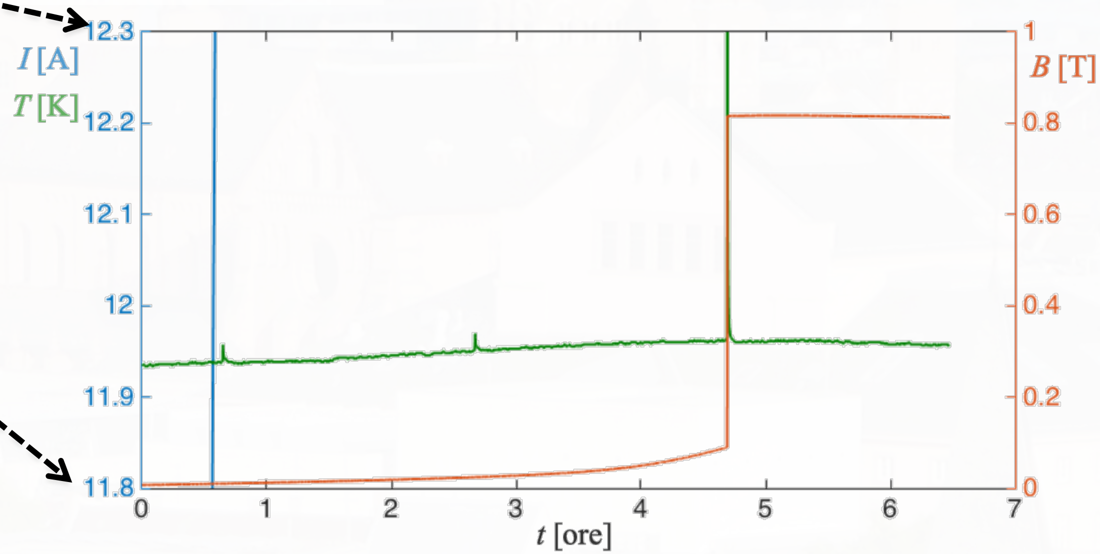
Longitudinal polarized target

Longitudinally Polarized Target - Technical Parameters

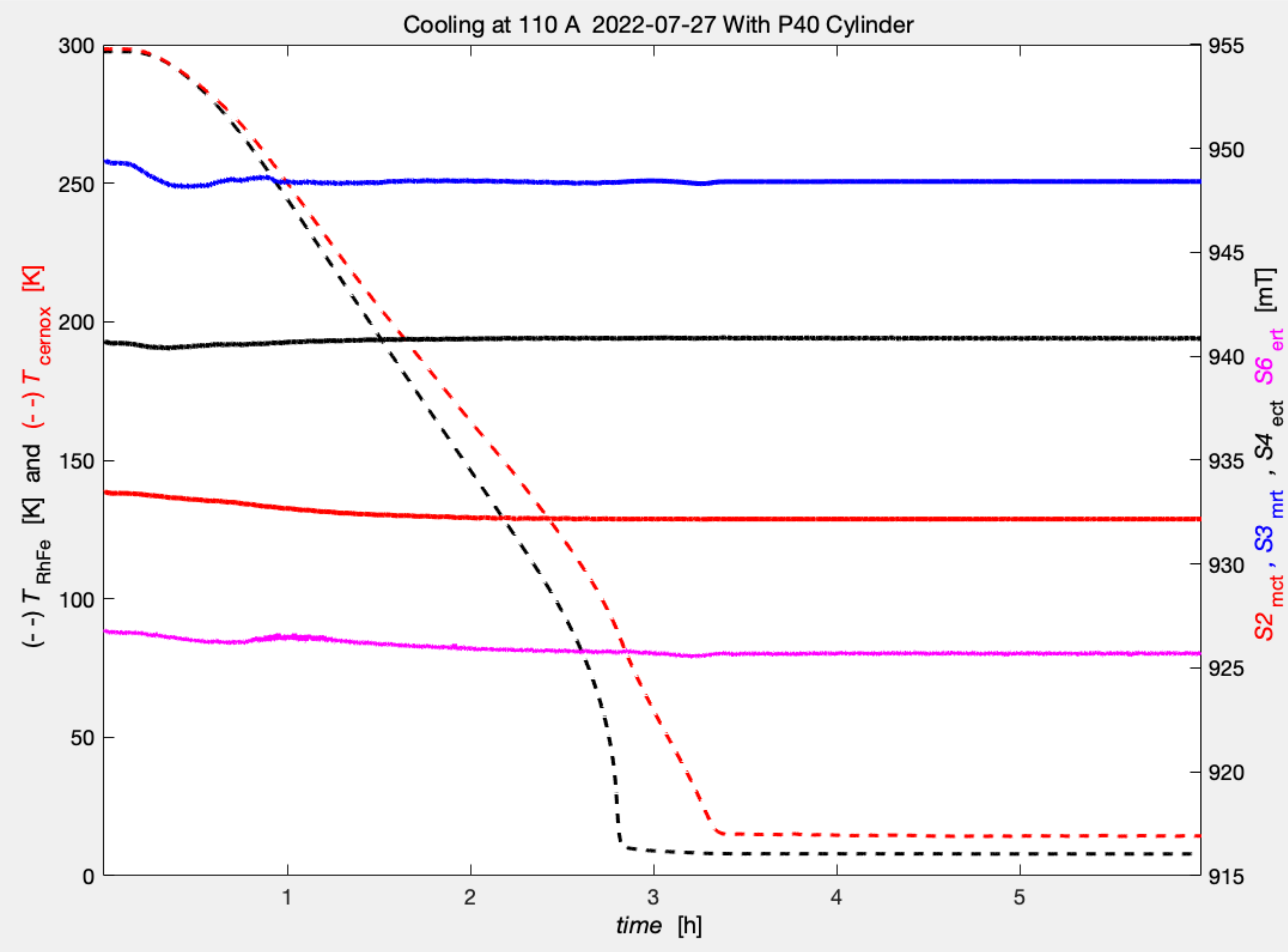
PARAMETER	DESIGN VALUE
Target material	Protons / deuterons (NH_3/ND_3, LiH, LiD)
Sample dimensions	2.5 cm diameter x 4 cm long, 60% filling factor
Polarization method	Dynamic Nuclear Polarization (DNP)
Magnetic field	5.0 Tesla
Temperature	1 Kelvin
Expected Performance	**DESIGN VALUE**
Proton polarization	>90%
Deuteron polarization	>40%
Proton & Neutron Luminosity	1.4×10^{33} cm^{-2} s^{-1} per nA beam current
Maximum Beam Current	30 nA

Details on quench during ZFC

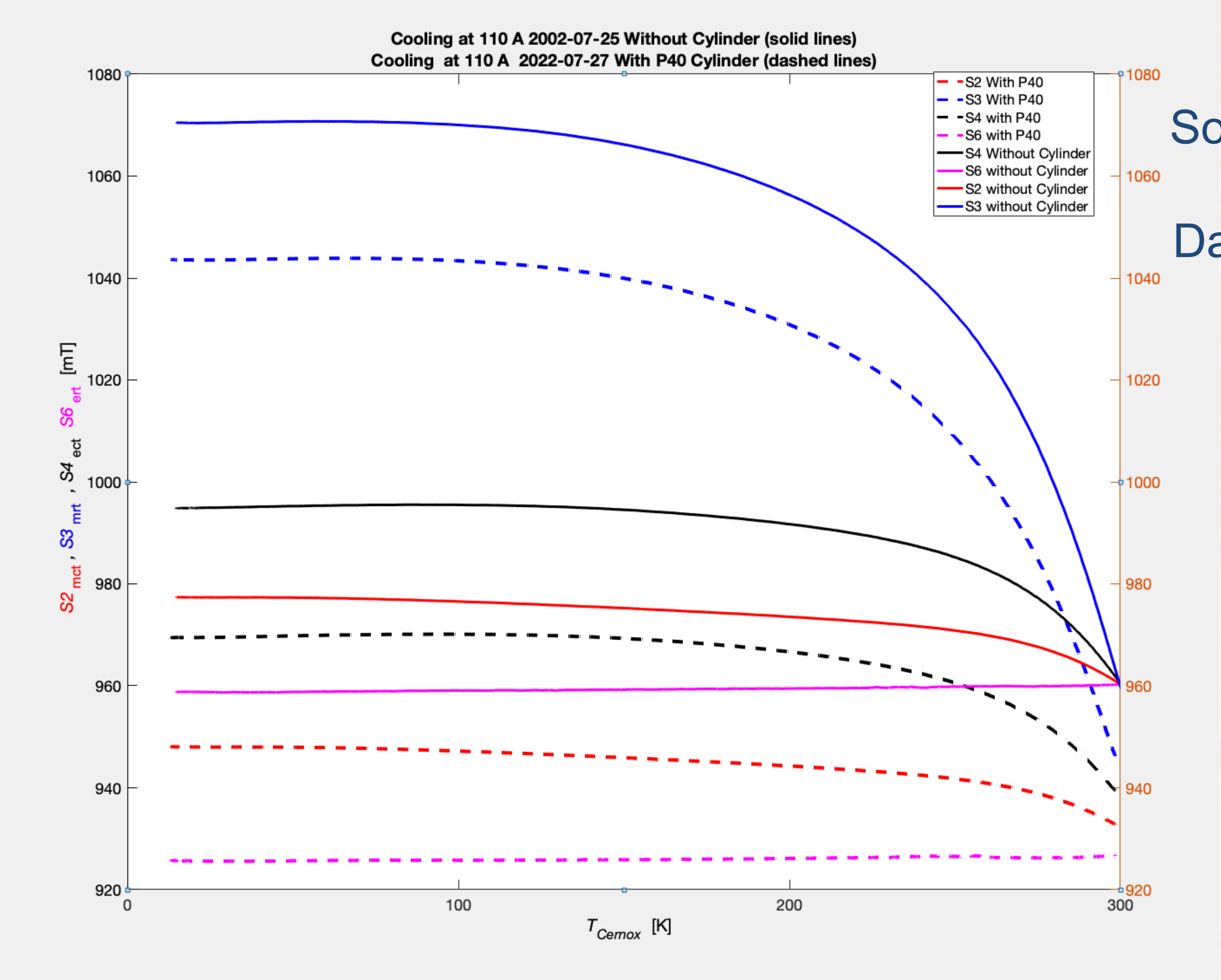




Calibration at 297 K and T correction with the Cylinder



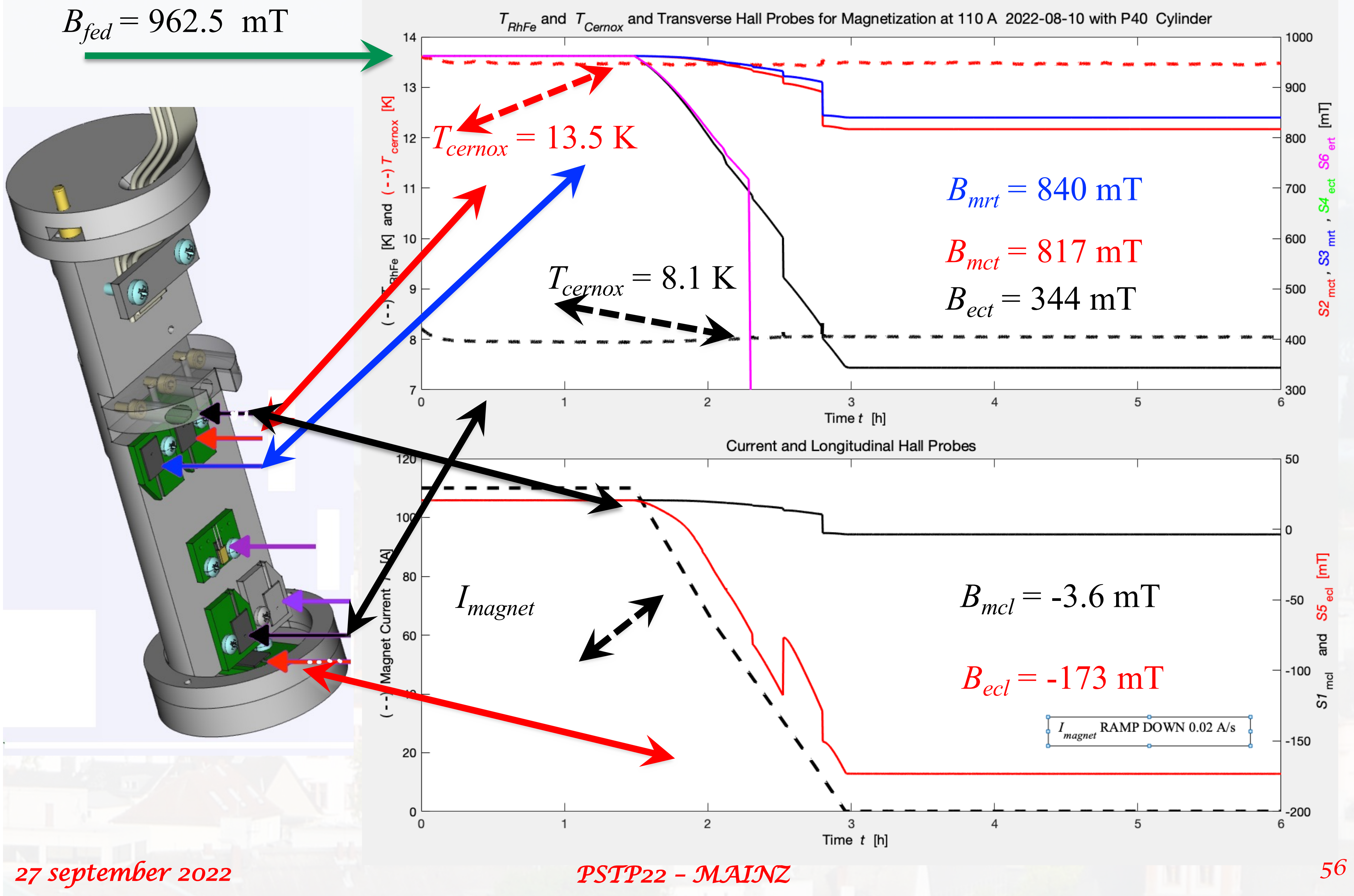
Hall probe read out without and with the cylinder alignement correction



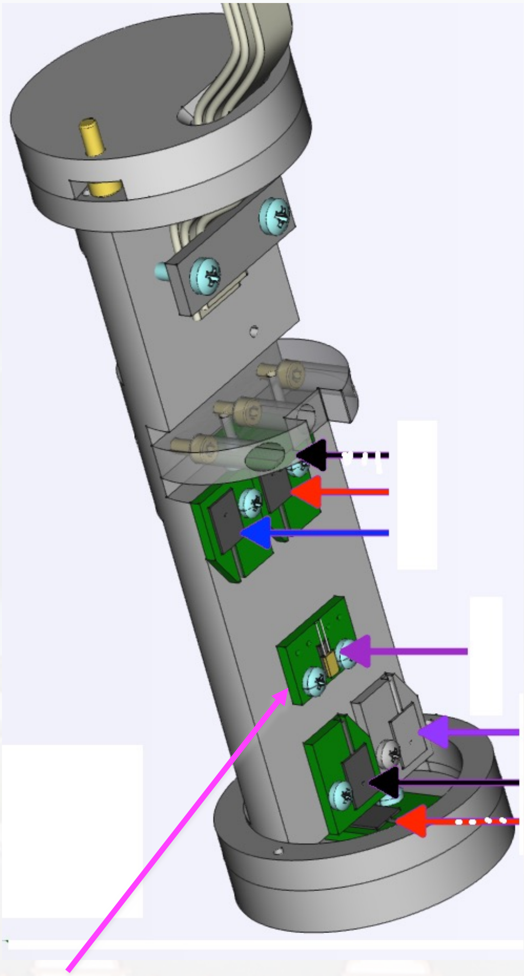
Solid lines without Cylinder

Dashed line with P40 Cylinder

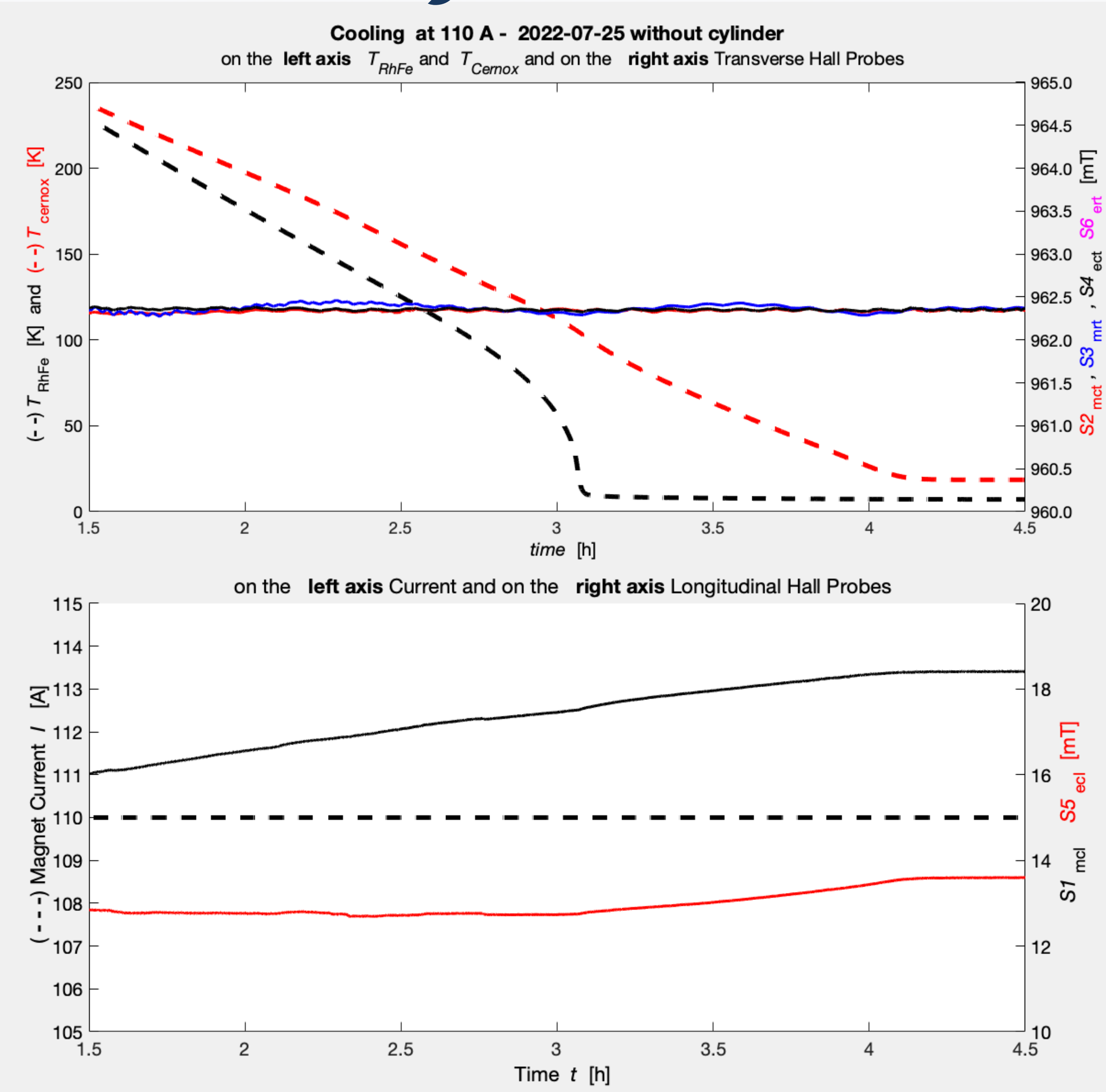
Ramp down 0.02 A/s



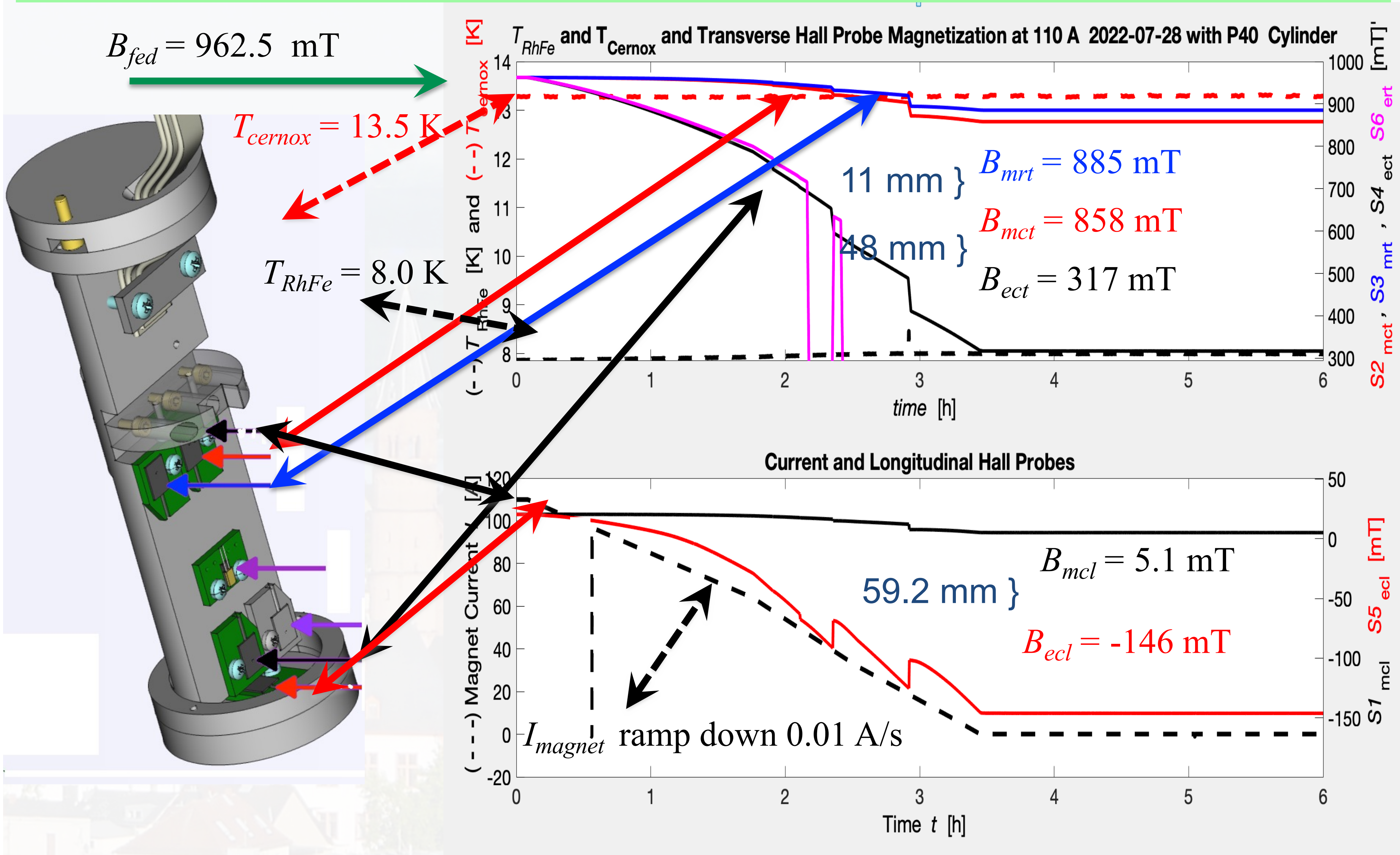
7 degree pol fit for Temperature correction without the Cylinder



T correction possible thanks to the temperature sensor installed on the Hall Probes holder

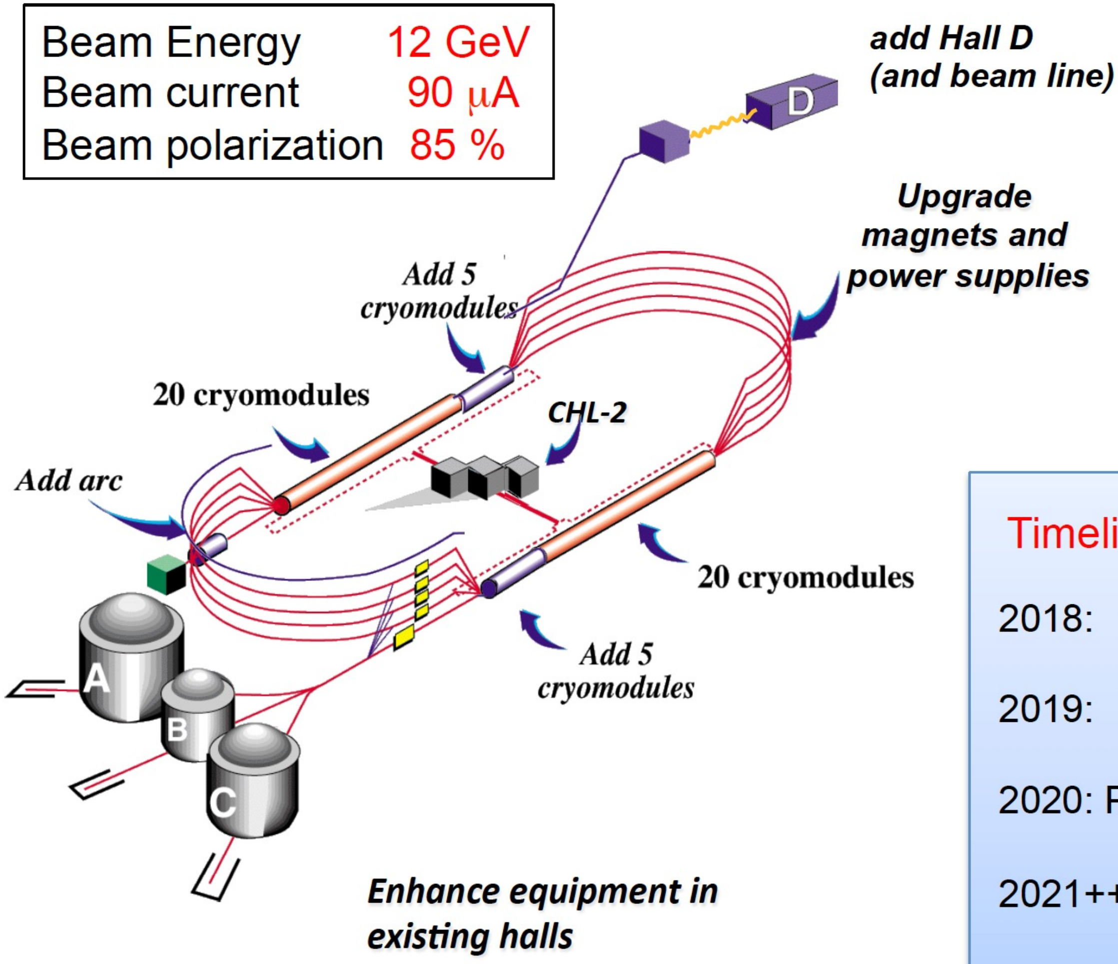


Preparation of self field (Field Cooling)



CEBAF Center - JLAB

Beam Energy	12 GeV
Beam current	90 μA
Beam polarization	85 %



Beam is being delivered to all the Halls

Timeline (indicative)

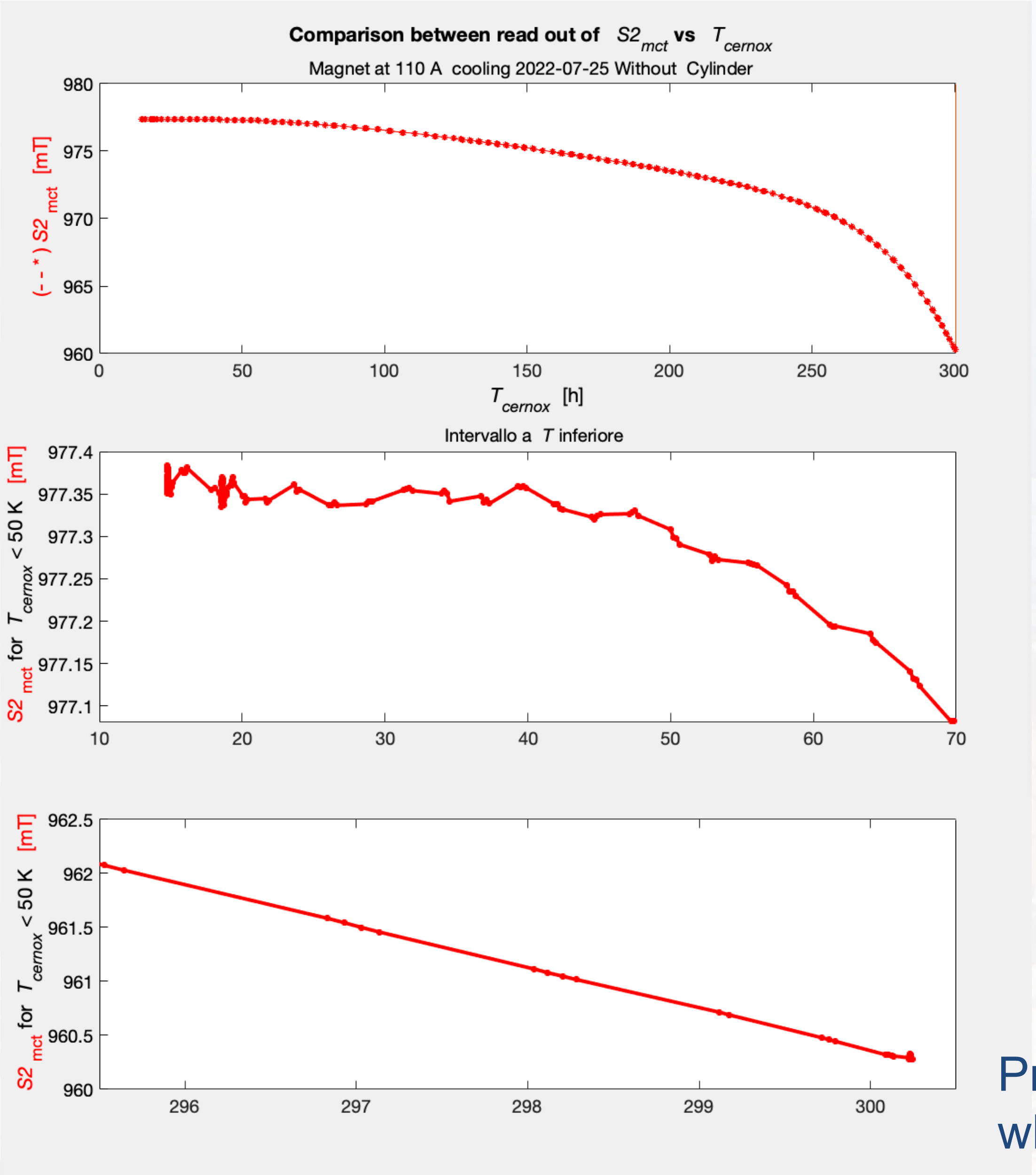
2018: Hydrogen Target (Hall-B)

2019: Deuterium Target (Hall-B)

2020: Polarized ^{3}He (Hall-C inclusive)

2021++: Polarized NH_3, ND_3, HDice (Hall-A, Hall-B)

Slide for details



Temperature dependency of Hall Probes

Constant Sensitivity for temperature below 50 K.

Strong dependence a temperature close to the calibrated sensitivity at 297 K.

Preliminary 7 degrees polinomial fit which is accurate at lower temperature.

Our starting point for faisibility study

Transversely Polarized Target – Technical Parameters

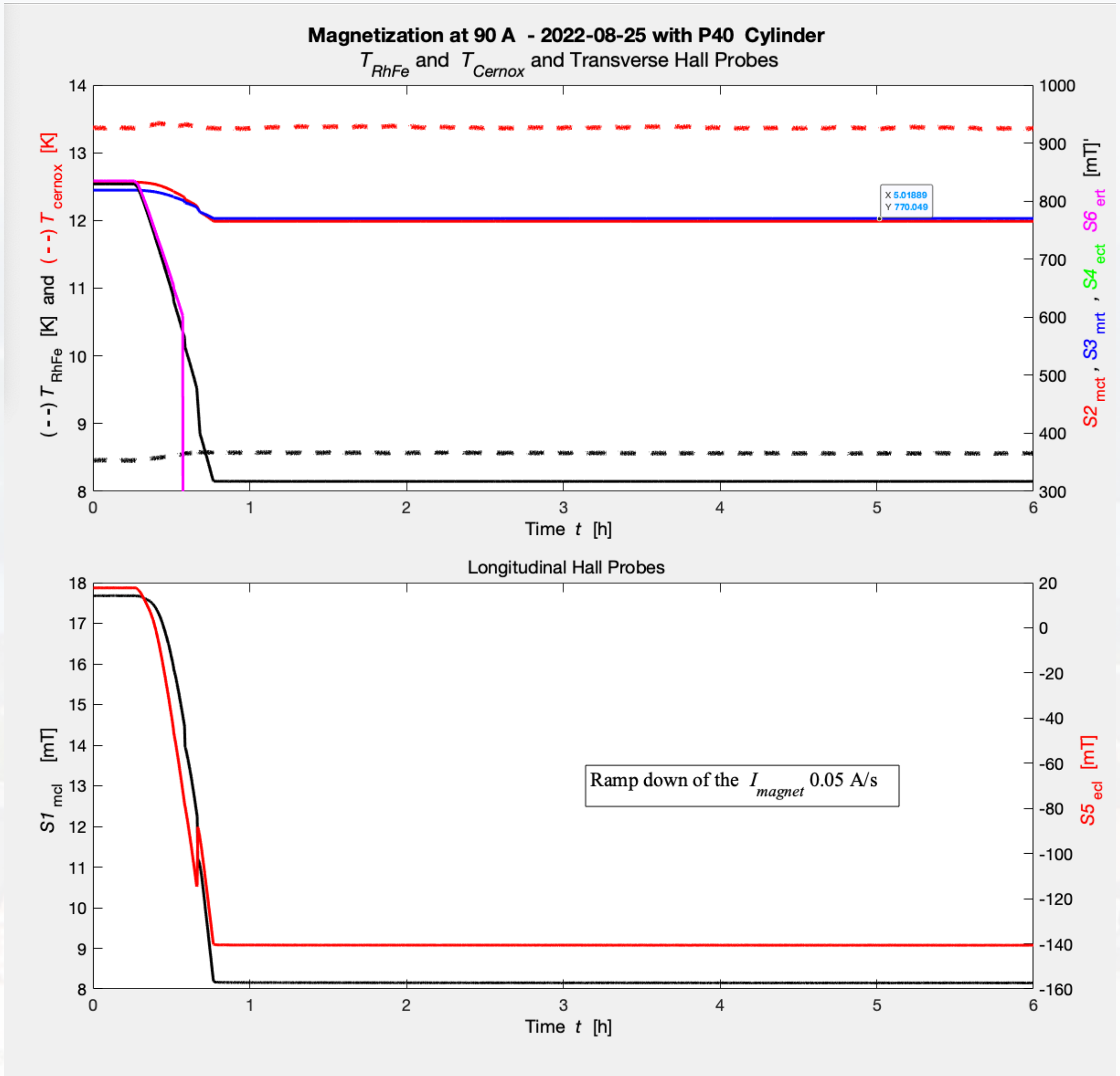
Parameter	Design Value
Polarizable target material; mass fraction	HD; 80%
Unpolarizable material; mass fraction	Al (as wire); 20%
Target dimensions	2.5 cm ∅ × 2.5 cm long
Polarization method	High-field, Low-temp equilibrium
In-beam holding field B × dL	1.2 tesla × 15 – 25 cm
H polarization	> 60%
H Luminosity	5 10^{33} cm^{-2} s^{-1} per 2 nA
In-beam lifetime	≥1 nA-week per target

Arepoc Hall probe

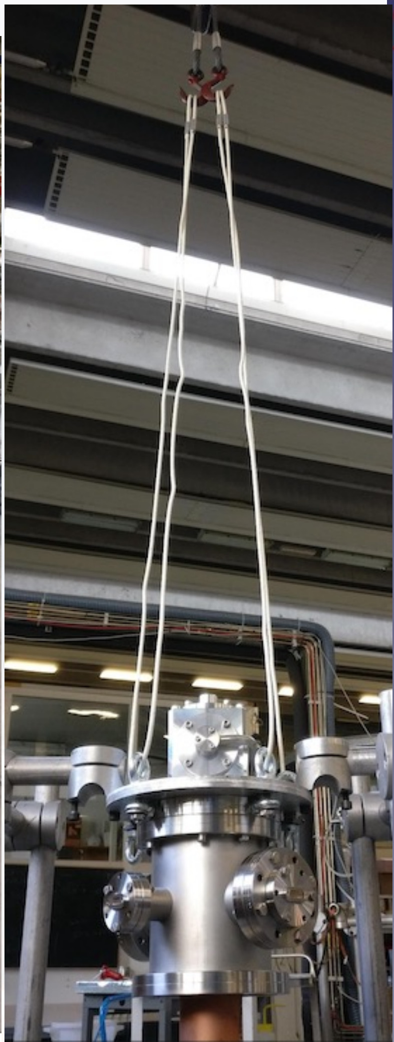
TYPE:	HHP-NP	PRODUCT NUMBER:	1424

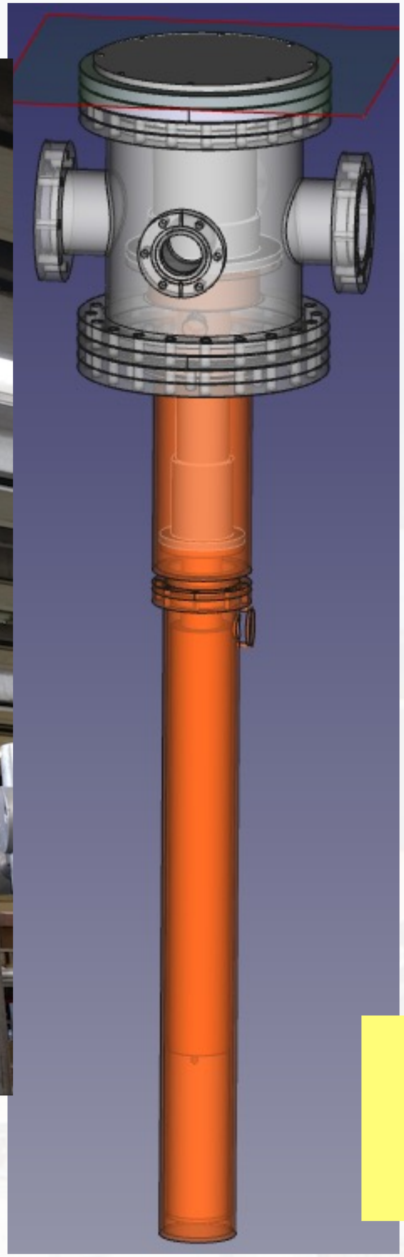
PARAMETER	UNIT	297 K	77 K	4.2 K
Nominal control current, I_n	mA	20	20	20
Maximum control current	mA	25	30	30
Sensitivity at I_n	mV/T	138.5		
Offset voltage at I_n	μV	11	132	
Input resistance	Ω	7.5	6.5	
Output resistance	Ω	22	20	
Linearity error up to 1 T	%	< 0.2		
Change of sensitivity due to reversing of the magnetic field	%	< 1		
Operating temperature range	K	1.5 - 330		
Active area dimension	μm	500 x 100		
Overall dimension (w x l x h)	mm	5 x 7 x 1		
Wires length	mm	150		

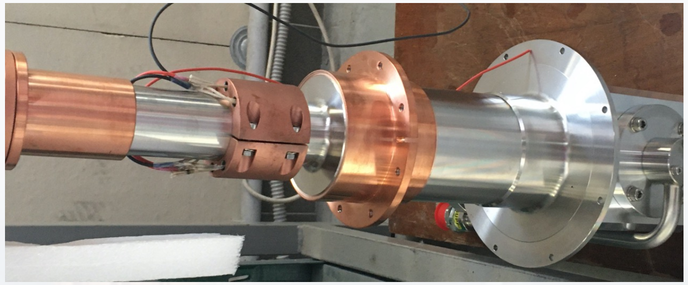
unfortunately the company close few years ago, problem on finding same compact and thin hall probes

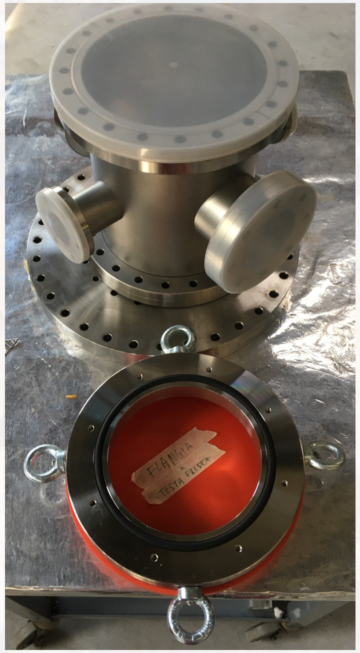

Magnetization at 90 A - 2022-08-25 with P40 Cylinder
T_RhFe and T_Cernox and Transverse Hall Probes
(- -) T_RhFe [K] and (- -) T_cernox [K]
S2_mct , S3_mrt , S4_ect , S6_ert [mT]
X 5.01889
Y 770.049
Time t [h]
Longitudinal Hall Probes
S1_mcl [mT]
S5_ecl [mT]
Ramp down of the I_magnet 0.05 A/s
Time t [h]

Mounting and installing the cold head



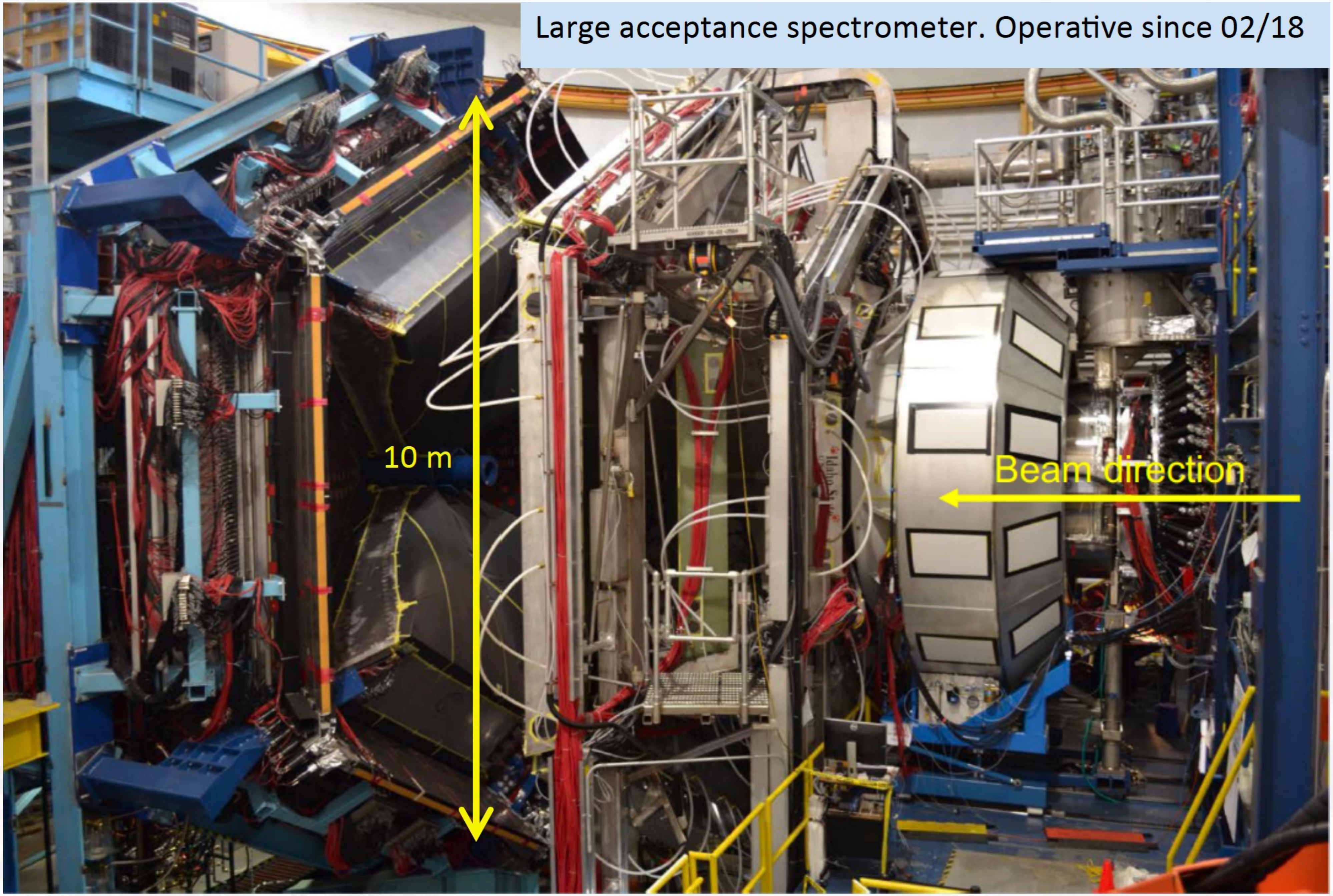




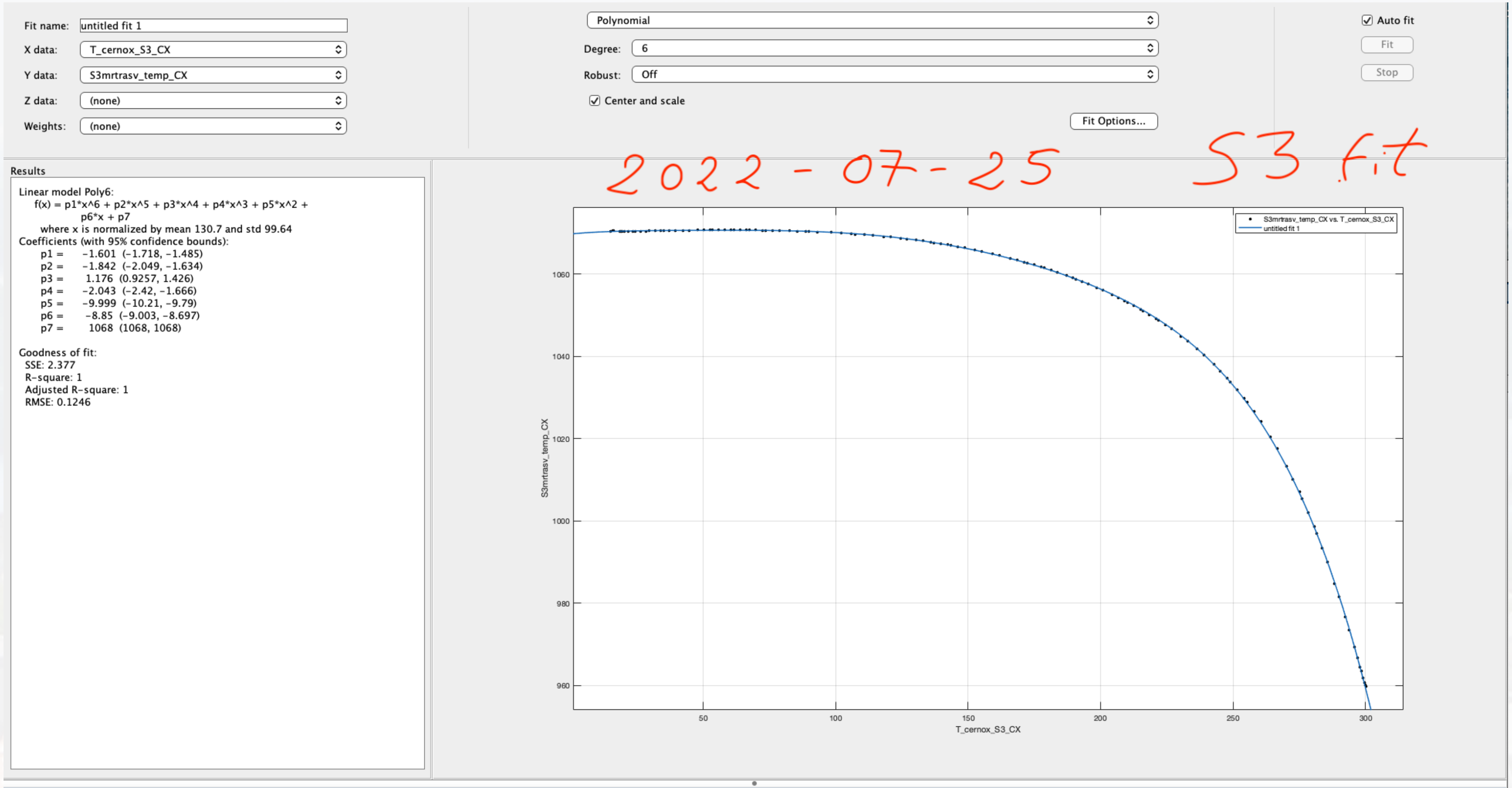


Problems on cold head, give us the chance
to improve the system

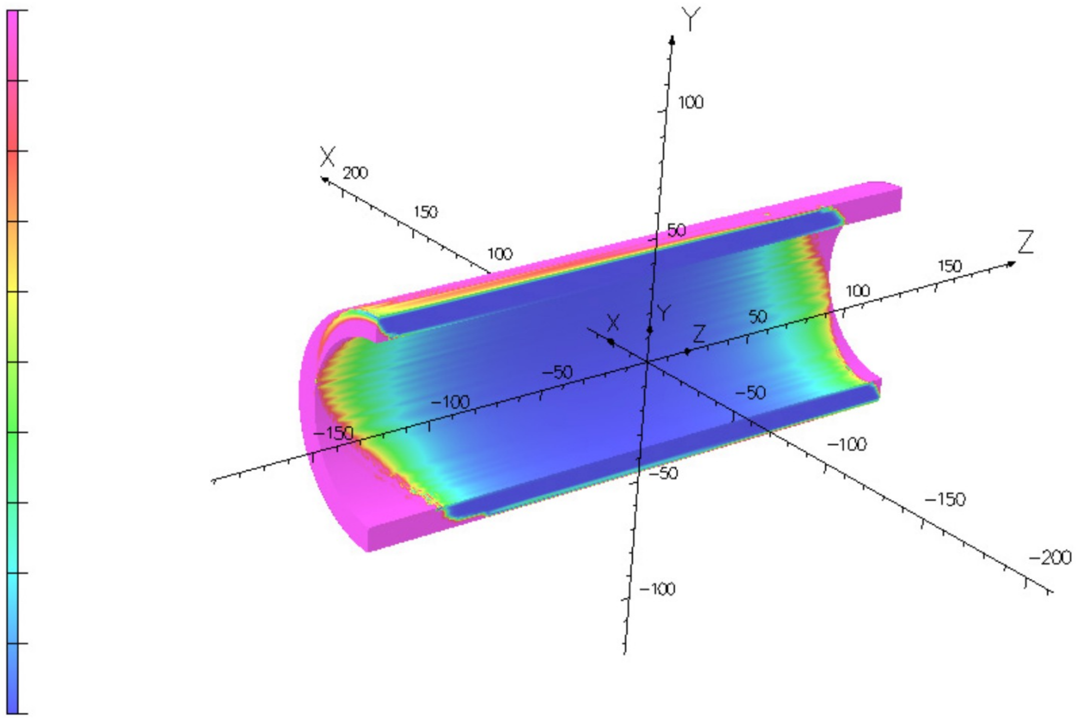
Large acceptance spectrometer. Operative since 02/18



Polinomial fit for T correction



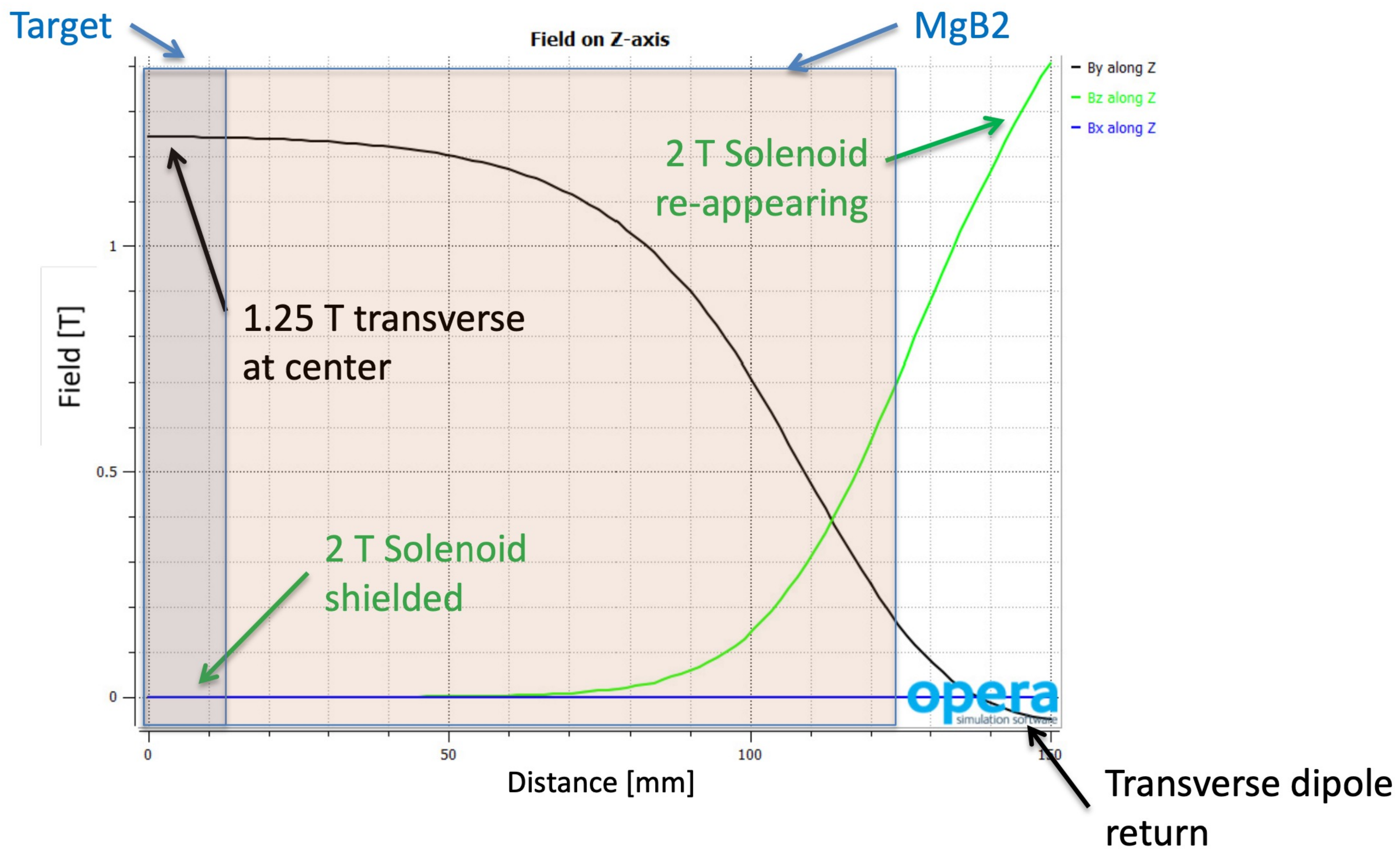
Lowry simulations



MgB2 cylinder:
86 mm Ø
250 mm long
7 mm wall

1.25 T transverse magnetization
2.0 T axial shield
5x10-3 uniformity (Y_{20}/Y_{00})
over 20 mm radius sphere

Lowry simulations



Hall probe holder and its temperature monitor