Design and calulations of the 4π-Continuous-Mode Target current leads

M. Bornstein*, E. Bickmann H. Dutz,
S. Goertz, S. Reeve, S. Runkel

Physikalisches Institut Universität Bonn

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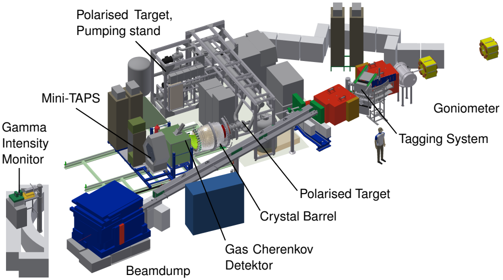
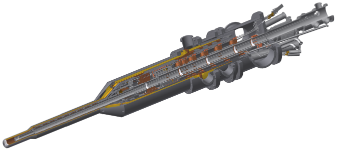
Table of contents

Motivation - Crystal-Barrel-Experiment

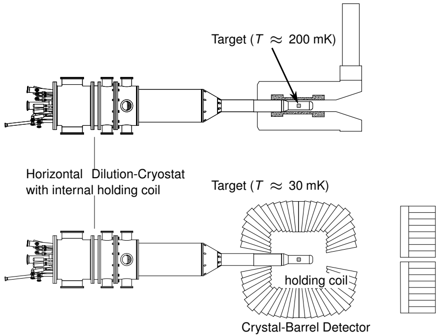


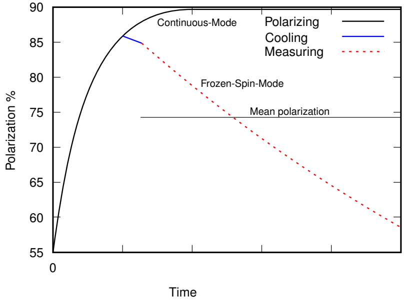
Dilution refrigerator



- Observation of excitation spectra of baryons with double-polarisation observables
- Cryogenic temperatures, high magnetic field, microwaves are needed for Dynamic Nucleon Polarisation (DNP)
- Polarized Target Bonn: Frozen-Spin-Technique

Motivation - 4π-Continuous-Mode Target



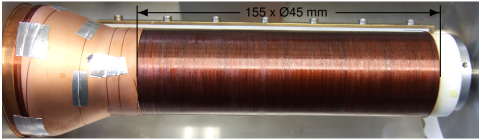


- Frozen-Spin-Target: External magnet (2.5 T), internal holding coil (0.6 T)
- Advantage: Large angular acceptance, 4π-Detector
- Disadvantage: Continuous loss of polarization during data taking, interruption of the experiment, complex handling, low particle flow (4 nA)

4π-Continuous-Mode Target

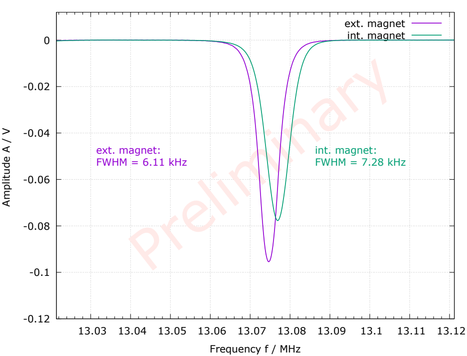
Combines the advantages of high polarisation and the large angular acceptance
Key element: Internal magnet with the same magnetic properties as the external magnet

Motivation - Inverse Notched Coil



- As thin as possible
  → Overall thinkness $\leq 2\,\text{mm}$
  → Passively cooled
- Internal magnet with $B_0 = 2.5\,\text{T}$ @ 90 A @ 1 K
- $\frac{\Delta B}{B_0} \ll 10^{-4}$ @ $1/40\,V_{\text{overall}}$
- Building process by wet wiring (with epoxy)
- Precondition: Homogeneous (orthocylcic) wire pattern!

Tests in ^{4}**He Kryostat**: 6LiD at 1 K



- A proton and a deuteron target could be dynamically polarized with an internal magnet

For operating an internal magnet

Two (electrical) **stable and low heat generating current leads** are necessary

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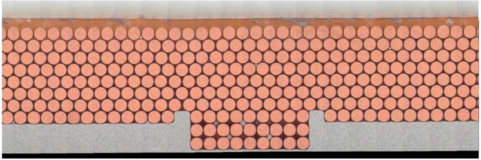

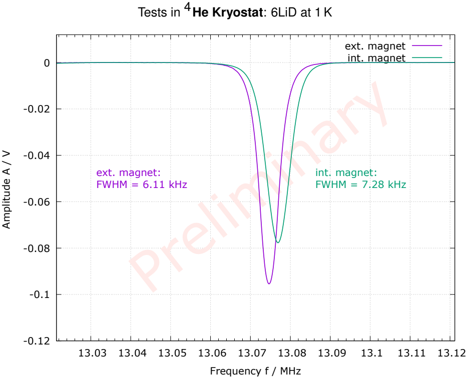

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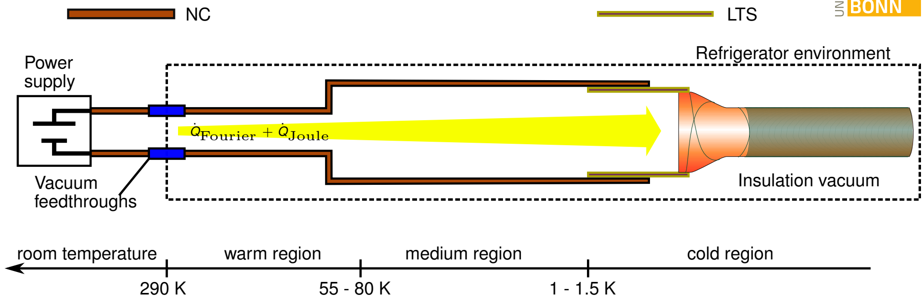
Stable and low heat generating current leads: Hybrid type



Problems with normal conducting (NC) current leads:

- Large heat load on the cold region due to Fourier's law
- Additional heat load due to Joule heating when energising the magnet
- Cooling of magnet and current leads only by conduction
- Large heat load can lead to a quench of the low temperature superconductor (LTS) / magnet
- There exist a minimum heat flow with $\dot{Q}_{\mathrm{Fourier}} = 0$

$$\dot{Q}_{\mathrm{Fourier}} = -kA\frac{\mathrm{d}T}{\mathrm{d}l}$$

$$\dot{Q}_{Joule} = \frac{I^2}{A}\sigma l$$

A: Cross section area
I: Current
k: Thermal conductivity
σ: Electrical conductivity
l: Length of the current lead
T_{h}: Temperature at the hot end
T_{c}: Temperature at the cold end

$$\dot{Q}_{\mathrm{c,min}} = I\left[2\int_{T_{\mathrm{c}}}^{T_{\mathrm{h}}} k(T)\sigma(T)\,\mathrm{d}T\right]^{\frac{1}{2}}$$

R. McFee, "Optimum Input Leads for Cryogenic Apparatus, Rev. Sci. Instrum. Vol. 30, American Institute of Physics, 1959

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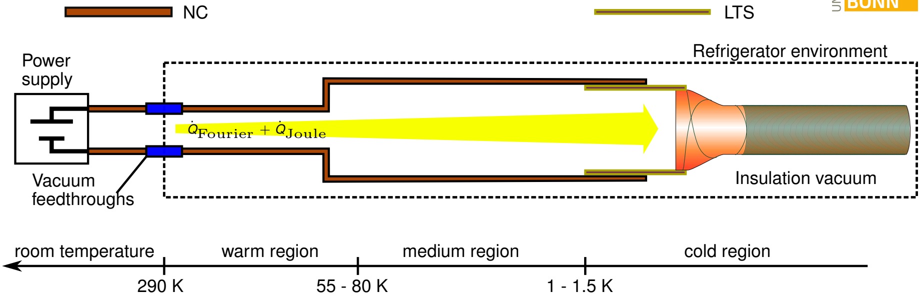

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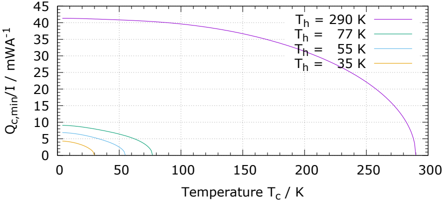

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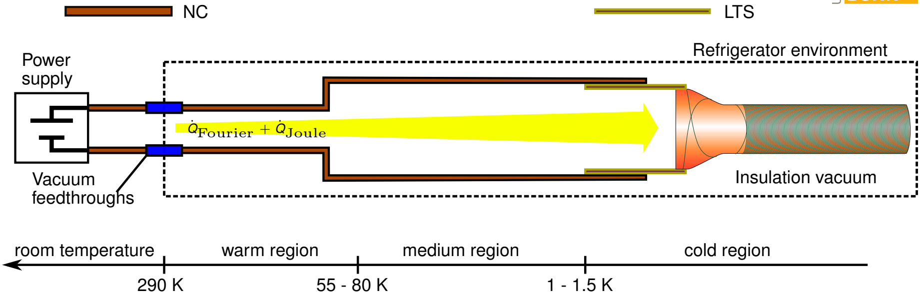

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Solution for the cold region:

- Thermal decoupling between warm and cold region/LTS
- Can be archived by using a high temperature superconductor (HTS, here: BSCCO)
- But nontheless: Heat load must be minimised up to the NC-HTS junction for not quenching the HTS

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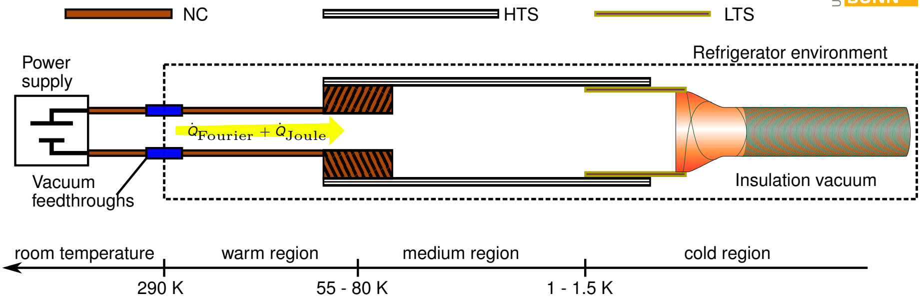

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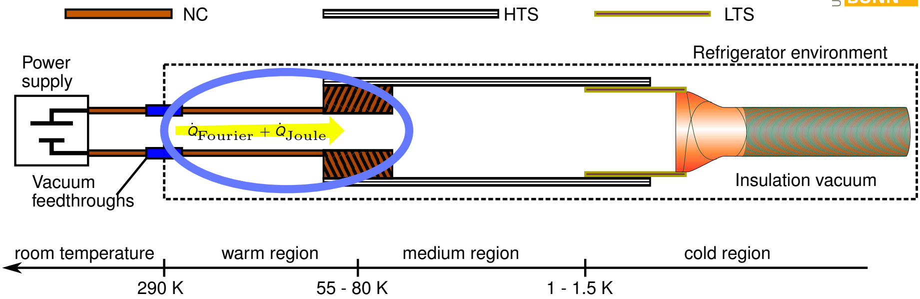

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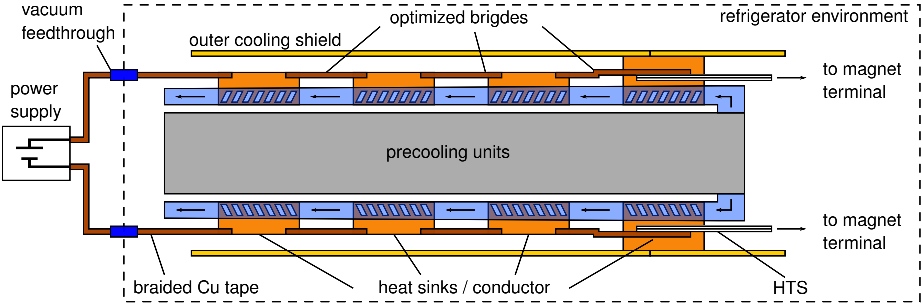
Block scheme for minimum heat load on NC-HTS junction



- Braided flexible copper tape ($A = 25\,\text{mm}^2$, $L = 1.4\,\text{m}$)
- 3 (turbine) heat sinks / copper-(half) rings for each terminal ($A = 260\,\text{mm}^2$)
- Ring-conductorss are connected by bridges ($A = 1.5\,\text{mm}^2$, $L = 4\,\text{cm}$))
- Bridges are designed for minimising thermal conduction from one sink to the next when energised
- Thermal decoupling between the heat sinks (McFee)

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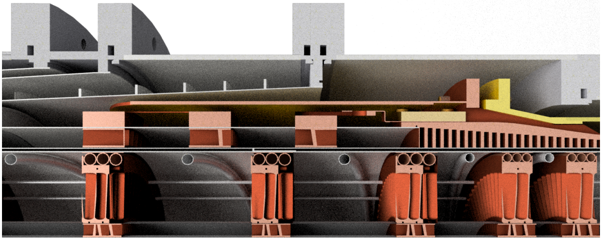
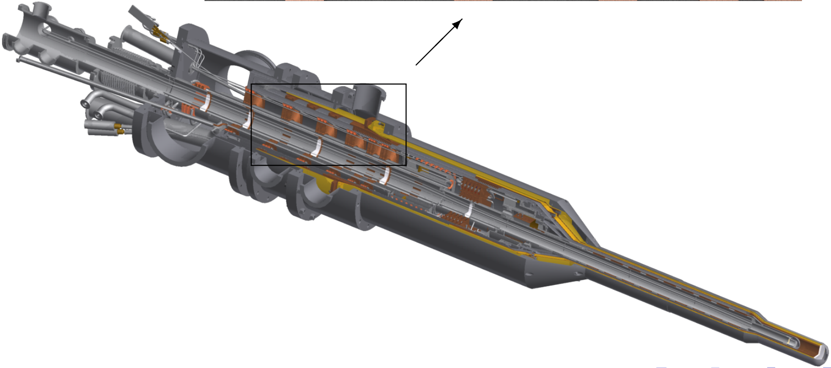
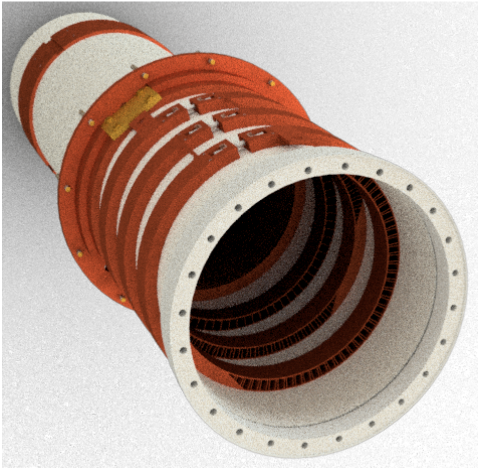
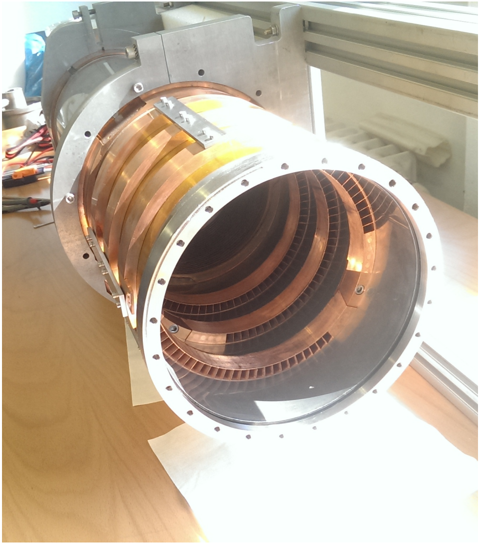




Current leads concept- Impressions





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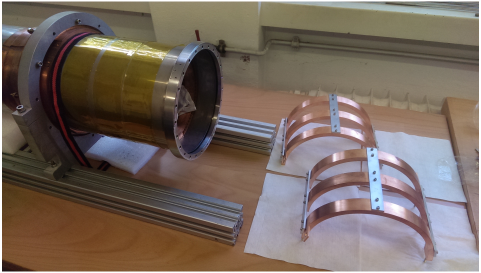

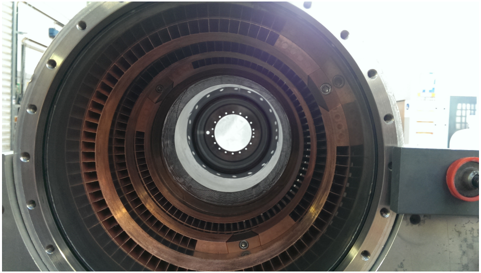

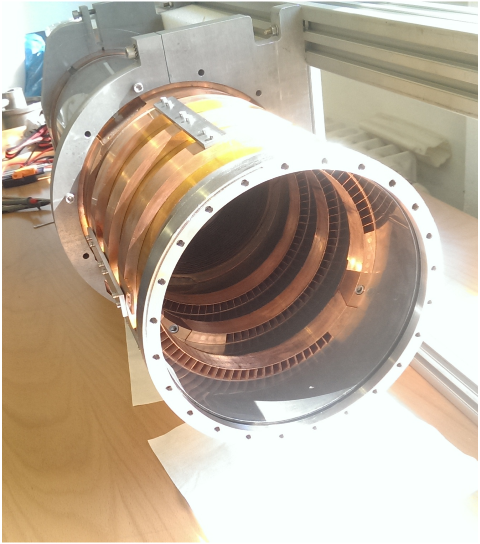

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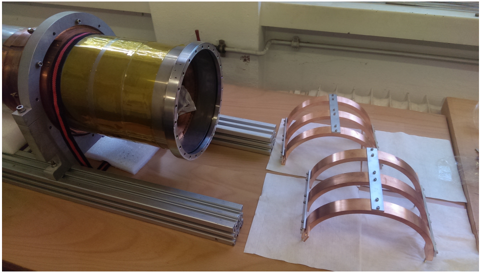

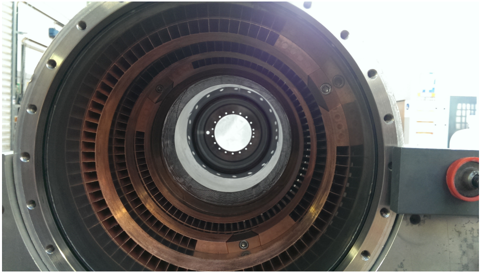

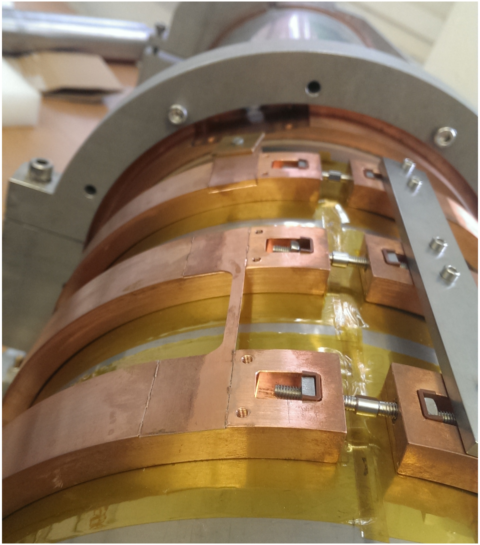

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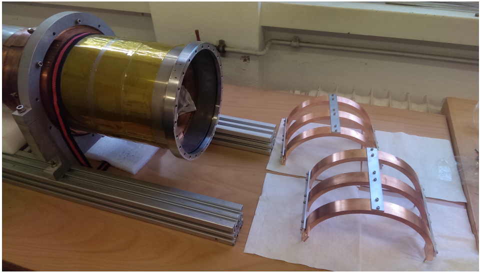
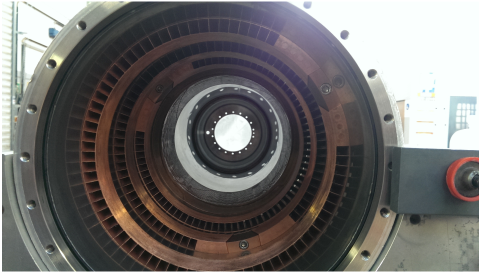




CFD-simulation

Idea

- Compare and optimize different bridge geometries
- Detailed information about the temperatures over the full length of a current lead and the heat sinks
- OpenFoam was successfully used for calculating the precooling stages of the refrigerator

But:

- There does not exist any solver for calculate electric currents (has to be added)
- An explicit heat source has to be addded to the heat diffusion solver
- Temperature dependency of σ and k has to be implemented since stock tools are not sufficient

Governing equations: Solid part

Stat. heat diffusion equation: $\nabla(k\nabla T) + \dot{q} = 0$

Joule's first law: $\dot{q} = \int_V \frac{1}{\sigma}\mathbf{J}^2 \mathrm{d}V$

Ohm's law: $\mathbf{J} = -\sigma\nabla\Phi$

resp. $0 = \nabla(-\sigma\nabla\Phi)$

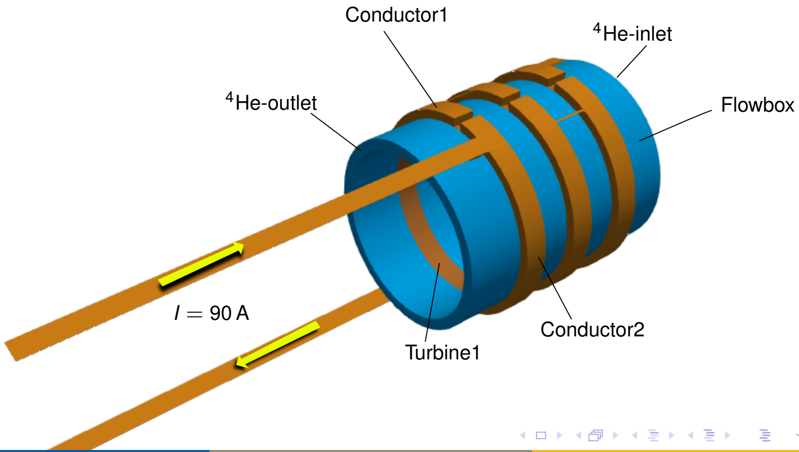
k	Thermal conductivity
σ	Electric conductivity
$\dot{q}$	Heat power density
$\mathbf{J}$	Current density
Φ	Electric potential field
V	Volume

Governing equations: Fluid part $\rightarrow$ Talk Stefan Runkel

Results - Temperature distribution

Boundary conditions

- Inlet: Gas-Temperature 40 K
- Flow: 13 mmol s^{-1}
- Outlet-Pressure 50 mbar
- Current: 90 A



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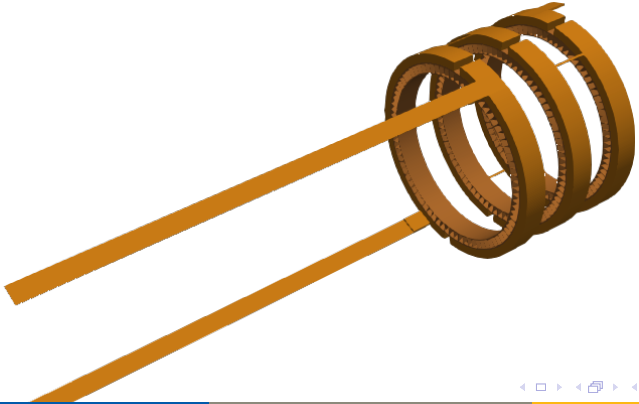

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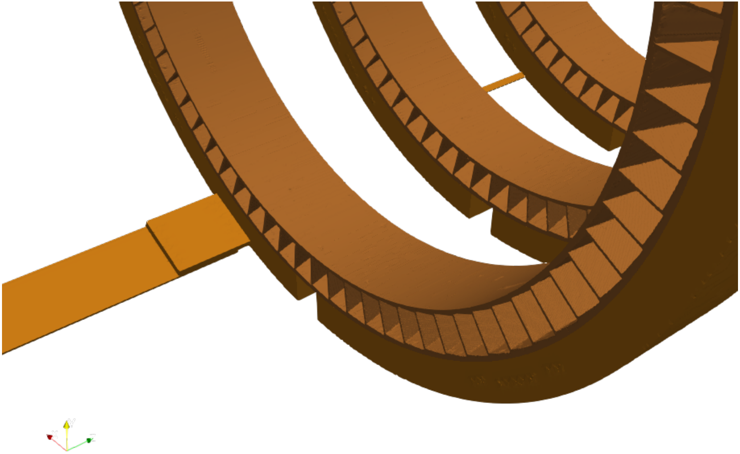

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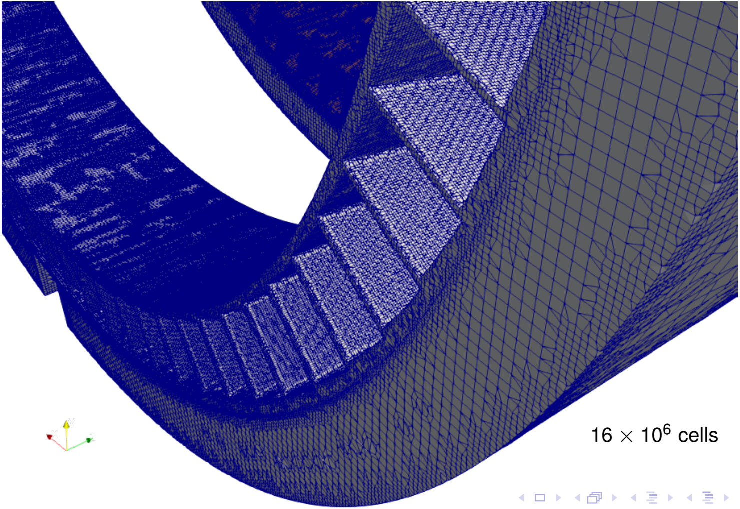

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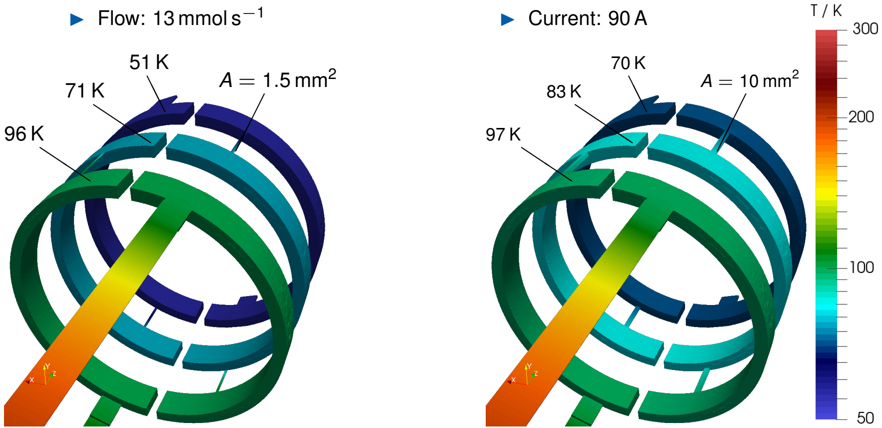


- Joule heating: 2 x 4.15 W
(consistent with McFee)

- Joule heating: 2 x 3 W

Result: Lower end temperatures by thermal decoupling of each sink with optimised bridges

Summary

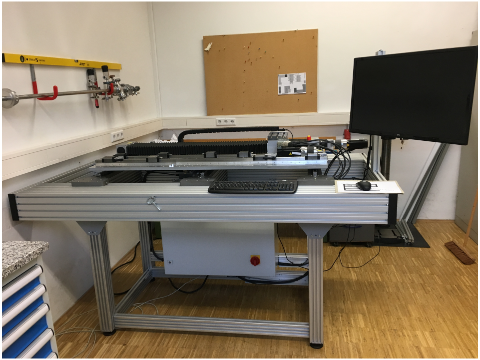
- Motivation for development: 4π-Continuous-Mode-Target with the "Inverse Notched Coil" as a key part
- Two stable and low heat generating current leads are necessary for operating a high current magnet within a refrigerator
- CFD-simulation as an optimizing tool for the normal conducting part of the leads
- Result of CFD-simulation: Lower end temperatures by thermal decoupling of each sink with optimised bridges

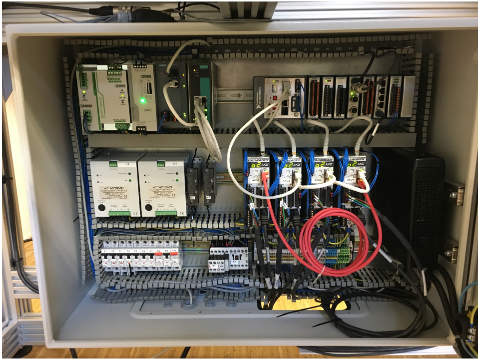
Outlook

- Mounting and take measurements to validate the calculations
- If validated, Openfoam can be used to simulate gas-cooled current leads for certain geometries

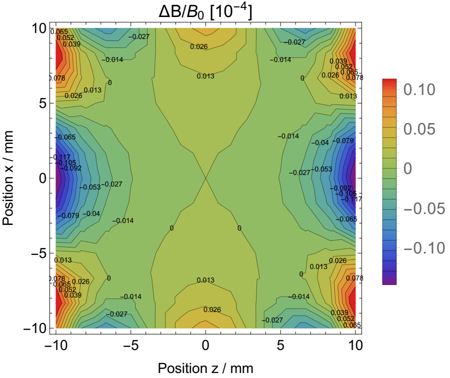
Outlook- New winding machine

- FPGA-based controller for high precision (absolute positioning 10 µm)
- Possible magnet length 1 m x Ø20 cm (Scaling internal magnets/ tracking magnet)
- Option for building transversal (shrinked coils) / saddle coils





Construction of an improved version (prototype 3)



d_{eff}	0.265	mm
length	176.225	mm
radius	23.3	mm
Correcton width	9	d_{eff}
Correction position	105 to 116	d_{eff}
Current	70	A
Center field B_0	2.574	T
Homogeneity $\lvert\Delta B/B_0\rvert$	1.5×10^{-5}	

Additional Information - LIA

$$JL = \frac{1}{\sqrt{2}} \int_{T_c}^{T_h} \frac{k(T)\,\mathrm{d}T'}{\left[\int_{T'}^{T_h} k(T)\rho(T)\,\mathrm{d}T\right]^{\frac{1}{2}}}$$