Cooling System of the Nuclotron Superconducting Magnets

19 Years of Operation Experience

Hamlet Khodzhibagiyan

Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

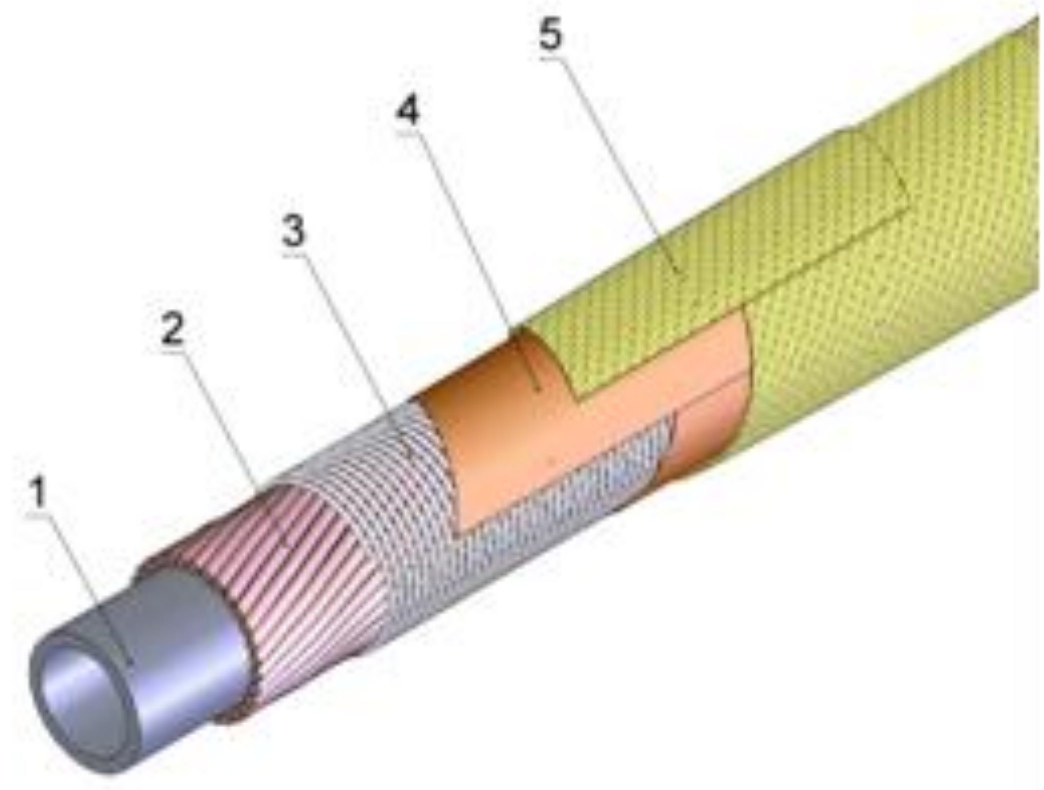
Requirements

- Nuclotron should operate at maximum ramping cycle of 2T, 4T/s and 1Hz.
- AC losses of a few tens of Watts may dissipated in the Nuclotron SC magnets and they should be remove.
- This requires a continuous good cooling conditions.
- To meet those requirements the Nuclotron cable was developed.

Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

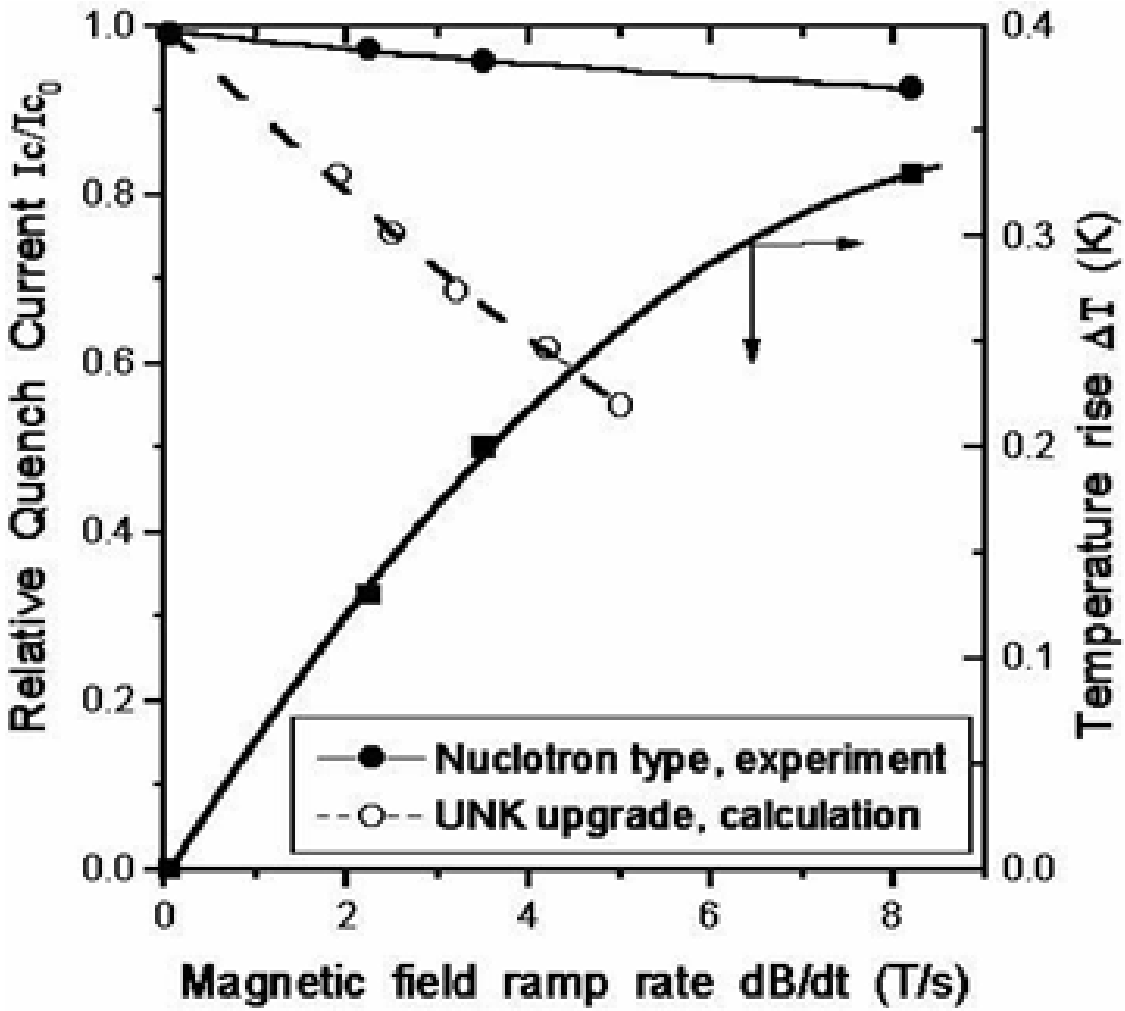
The Nuclotron Cable



1. Cooling tube
2. SC strands
3. Binding wire
4. Kapton tape
5. Glass fibre tape

Good cooling conditions are provided due to the fact that the electrical insulation is not impeded the heat flux from the superconductor to helium on its way

The Nuclotron Cable Cooling Condition



Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

Parallel cooling channels

- AC losses of a few tens of Watts per meter are dissipated in the Nuclotron SC magnets.
- Diameter of the channel should be as small to have a high engineering current density.
- Pressure drop within the cooling channel of each magnet about a few tenth of bar.
- As a consequence, the cooling channels must be connected in parallel.

Outline

- Requirements
- Cooling principle
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

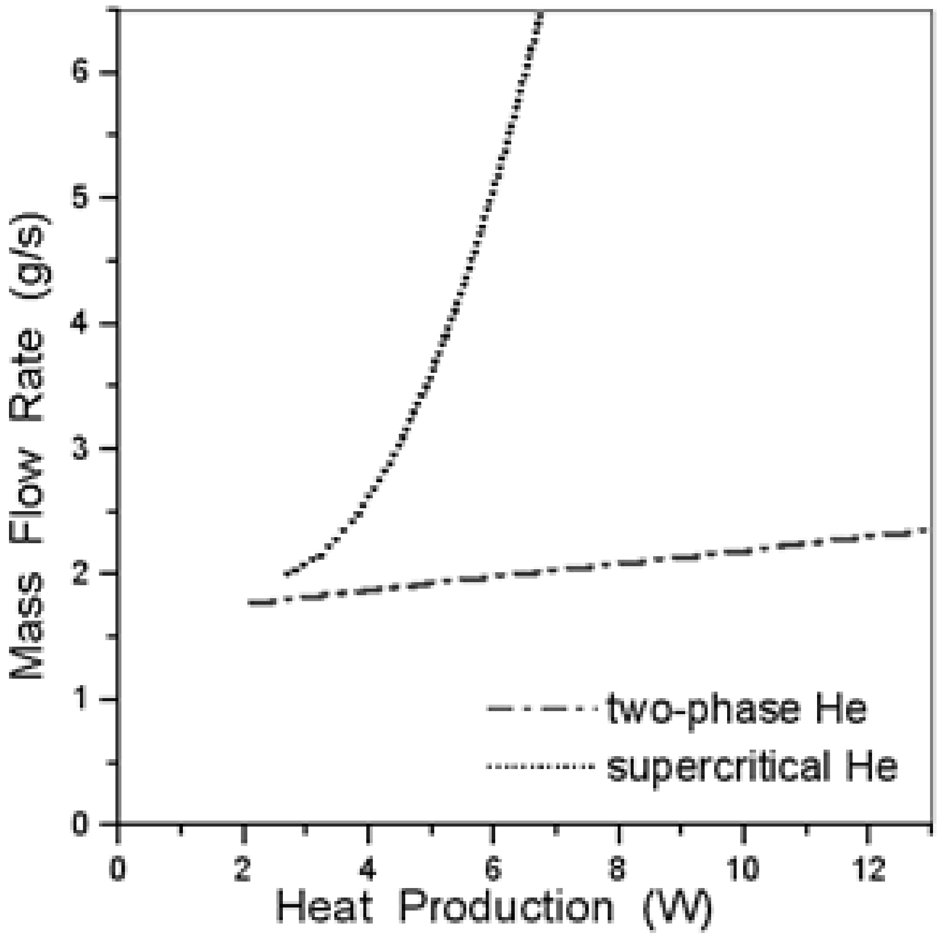
Two-phase coolant I/III

Which coolant more preferable for Nuclotron type magnets is: supercritical or two-phase helium flow?

Two coolants are compared:

• Two-phase flow need a much smaller mass flow rate to remove the same heat load

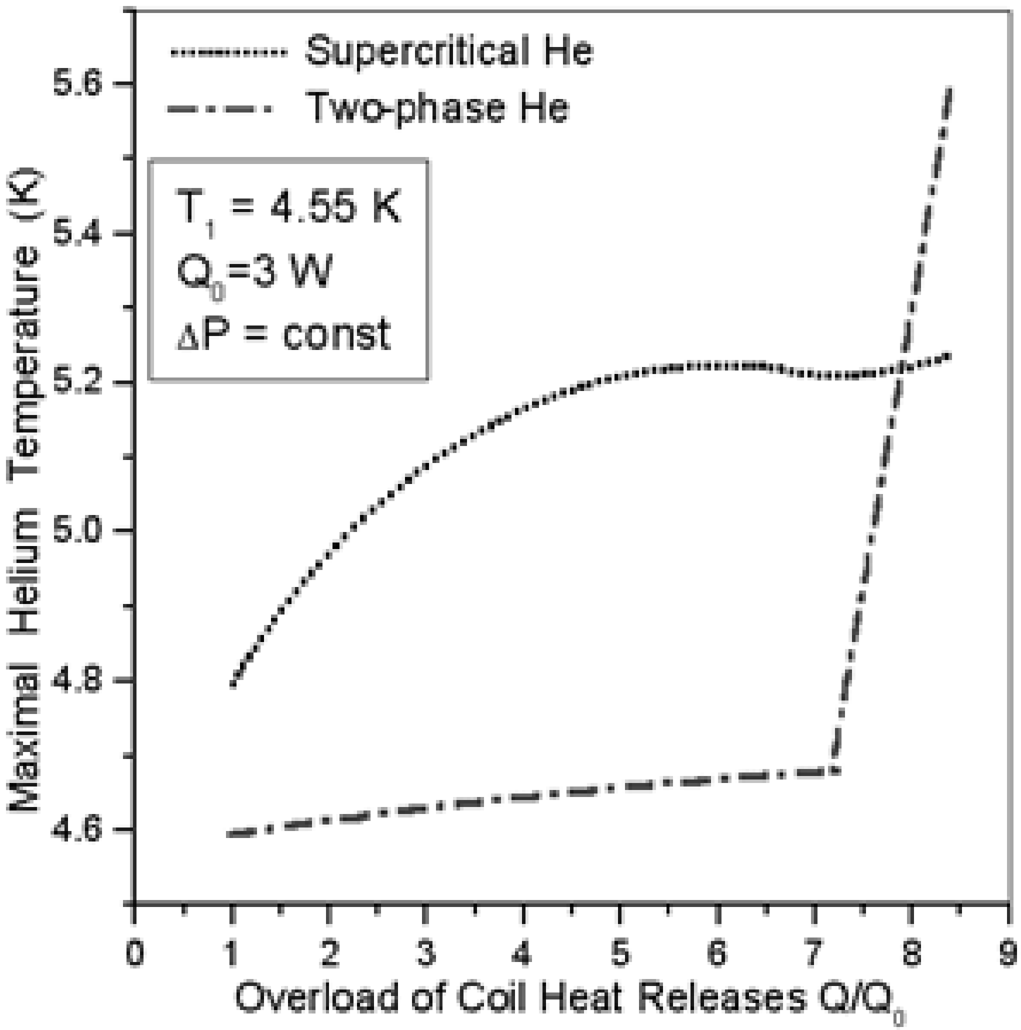
• Smaller mass flow means also larger engineering current density of the coil



3W $\leq Q_{coil} \leq$ *12 W* and Q_{yoke} = *31 W*

Two-phase coolant II/III

Maximum temperature of helium in the coil is practically constant over a wide range of overloads for two-phase coolant



Two-phase coolant III/III

• When the Nuclotron was designed, no operational experience was available worldwide for SC devices with a large number of the parallel channels cooled by a forced two-phase helium flow.

• Many believed that the use of two-phase helium is associated with greater risk. They feared pressure oscillation and mass flow rate variations of helium in the parallel channels, a significant decline of cooling conditions due to the separation of liquid and vapour phases and a boiling crisis, etc.

• In order to verify the stable operation of the Nuclotron magnets at different mass flow rates and helium void fractions, experimental studies of several single magnets, doublets of two magnets and a string of 16 magnets have been carried out.

Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- **String test results and coolant choose**
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

String Tests I/IV

- Test was conducted in February 1990
  - 12 dipoles, 4 quadrupole lenses.
  - The heat leak from the surroundings to the magnet string and two cryostats for the current leads was 100 W.
  - A subcooler was used to kept close to zero vapour content of helium in the supply header, which reliably measured by a void fraction sensor.

String Tests II/IV

- When the coils were excited by current pulses of triangular shape with an amplitude of 6 kA, a pulse duration of 3.1 s, and pulse repetition period of 3.55 s, the measured AC losses in the magnets were 140 W.

- The pressure difference between the supply and return headers was kept equal to 9 kPa.

- In this case the mass vapour content of helium in the return header was about 1 and the helium temperature approximately 4.5 K.

String Tests III/IV

- The magnet cooling and their operation were stable.
- No flow rate oscillations were observed in the parallel cooling channels.
- In the indicated mode the magnets operated 192 hours ($2 \cdot 10^5$ excitation cycles).
- The operation of the magnets was also stable if the cooling parameters deviated significantly from the nominal ones.

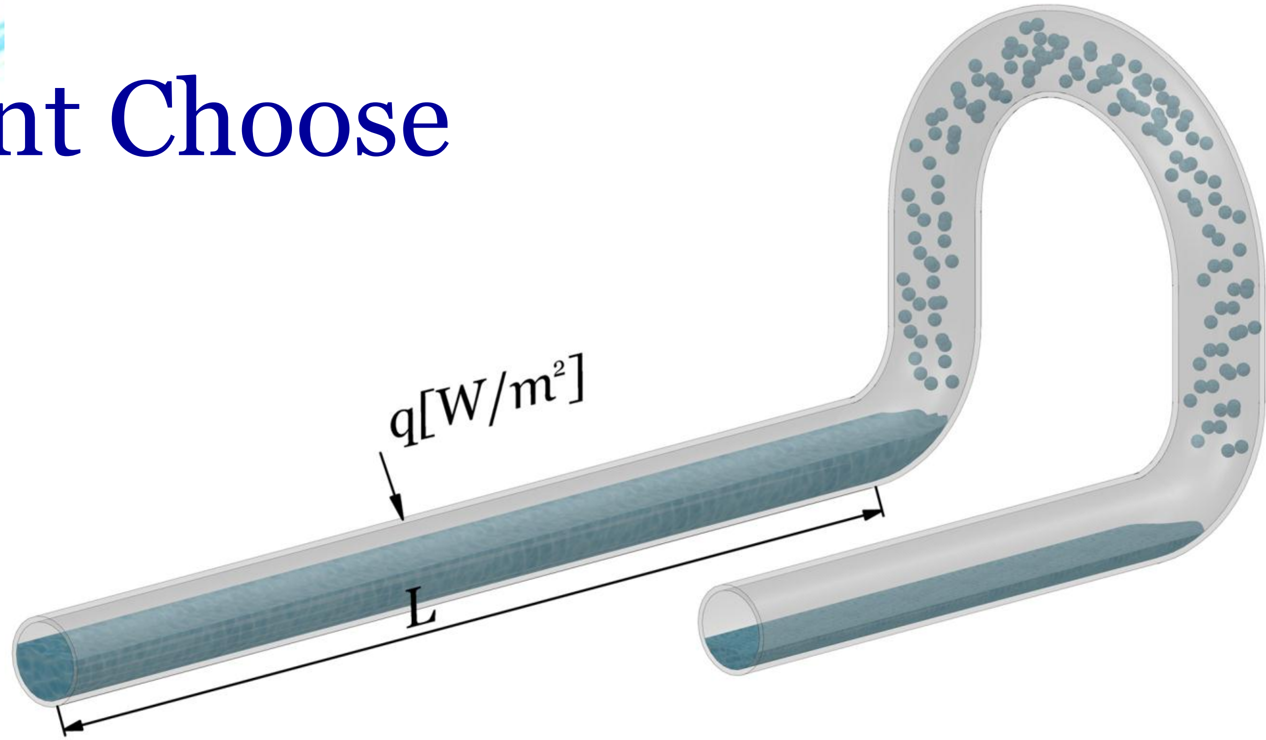
String Tests IV/IV

- The pressure difference between the supply and return headers was decreased to 6 kPa.
- In this case superheated vapour, having a temperature from 5.1 K for the magnet with the least hydraulic resistance to 7.8 K for the magnet with the largest hydraulic resistance of the cooling channels, came out of the channels cooling the yoke. The magnet operation was stable.

Stratification of Two-Phase Coolant

- Calculations show that the stratification of two-phase helium flow in the winding of the Nuclotron magnets does not significantly increase in the temperature of the superconductor.
- Thus, in case of the string operation with cycle duration of 3.55 s a specific heat flux from the channel wall to helium is about 4.5 W / m^2, which is easily removable by gaseous helium flow at a temperature difference between the channel wall and the helium of approximately 0.014 K.
- The flow of helium vapour in the 1.4 m long horizontal section of the coil is heated adsorbing the indicated heat flux by approximately 0.018 K.

Coolant Choose

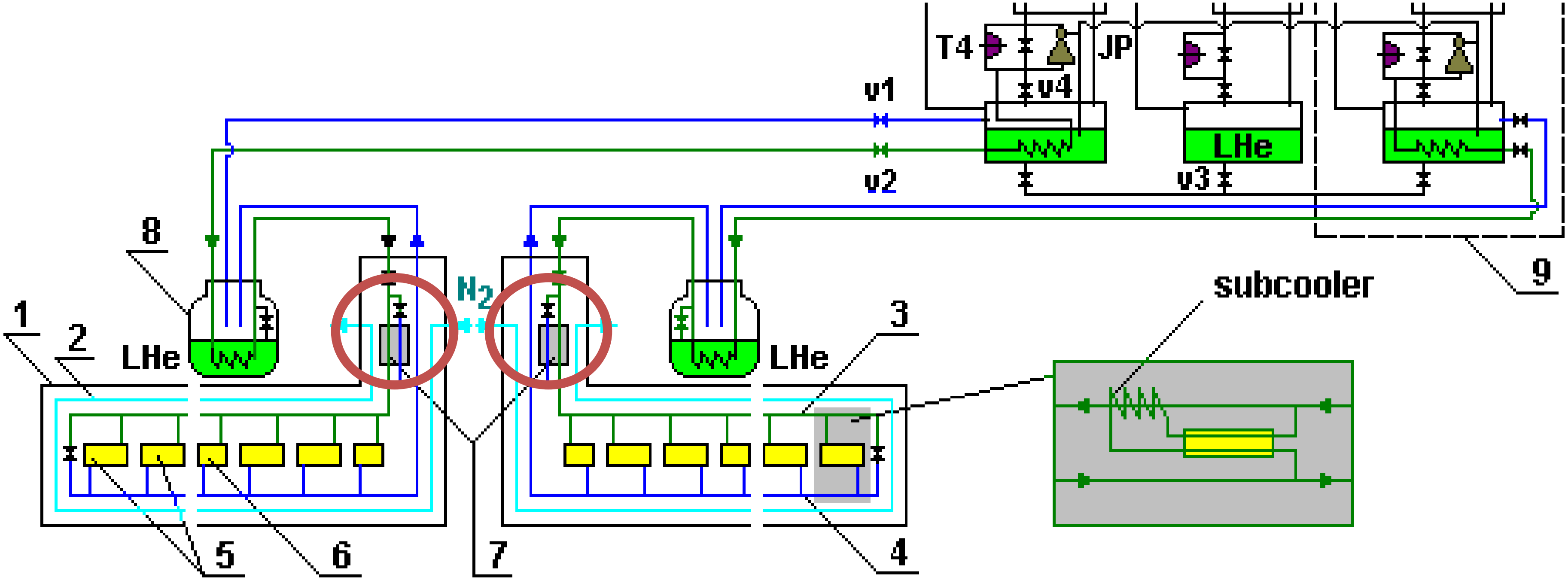


- After the horizontal part of coil the vapor and liquid phases of helium mixed in the vertical parts of the saddle shaped coil and the superheated vapor is cooled down to saturation temperature.
- After successful experimental test of the cooling conditions on string of the 16 magnets a two-phase helium flow was chosen as a coolant for the Nuclotron magnets.

Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

Cooling Scheme of the Magnets



1 …cryostat half-ring, 2 … LN shield, 3…supply header, 4 … return header, 5…dipoles, 6…quadrupoles, 7…main subcoolers, 8…phase separator, 9…refrigerator

Cooling Scheme of the Magnets

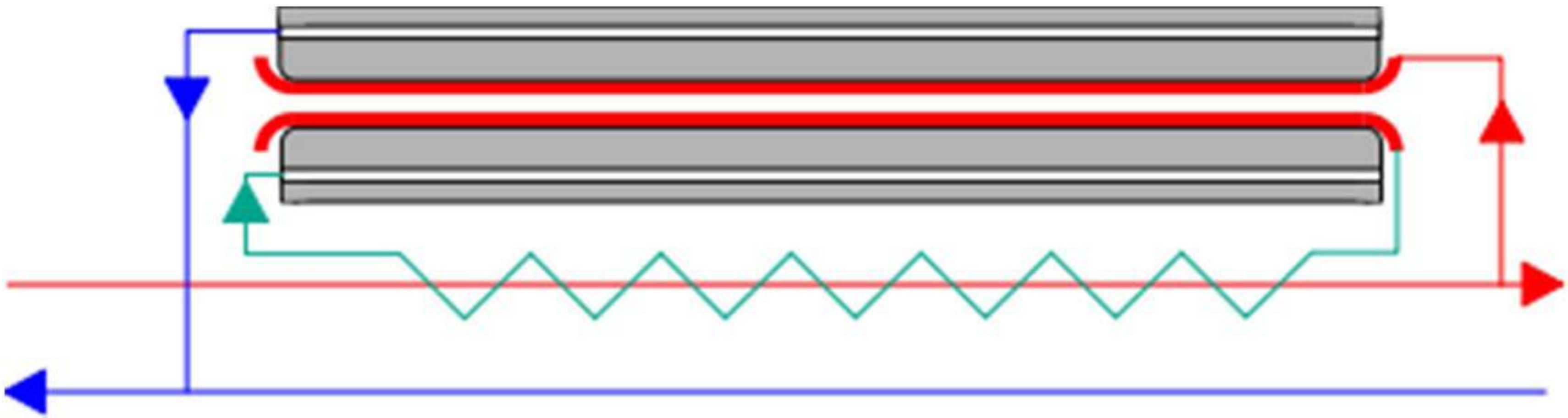
The problem of providing reliably cooling for each of more than 100 parallel channels having different thermal and hydraulic characteristics has been solved as follows:

* Hydraulic resistance of channels are adjusted so that the mass vapour content of helium at the outlet of the dipole and two type of quadrupoles was equal 90% at design operating mode with pulse repetition rate $f_0 = 0.5$ Hz. This was done by connecting special devices with an additional hydraulic resistance to each module with contained a quadrupole.

* A separator of the liquid and the vapour phase, main and 62 additional subcoolers are installed in each half-ring for keeping the helium in liquid state inside the supply header.

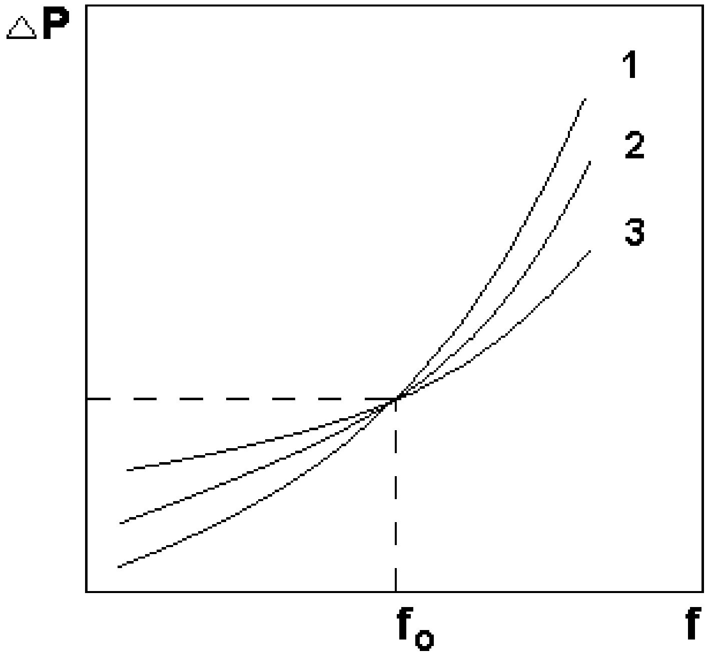
* A bypass valve is installed at the end of both supply headers for direction of helium vapour in the return headers.

Additional Subcooler



Additional subcooler is added on the way of flow between the coil and the yoke of each dipole magnet. It is designed to remove the heat leak to the supply header.

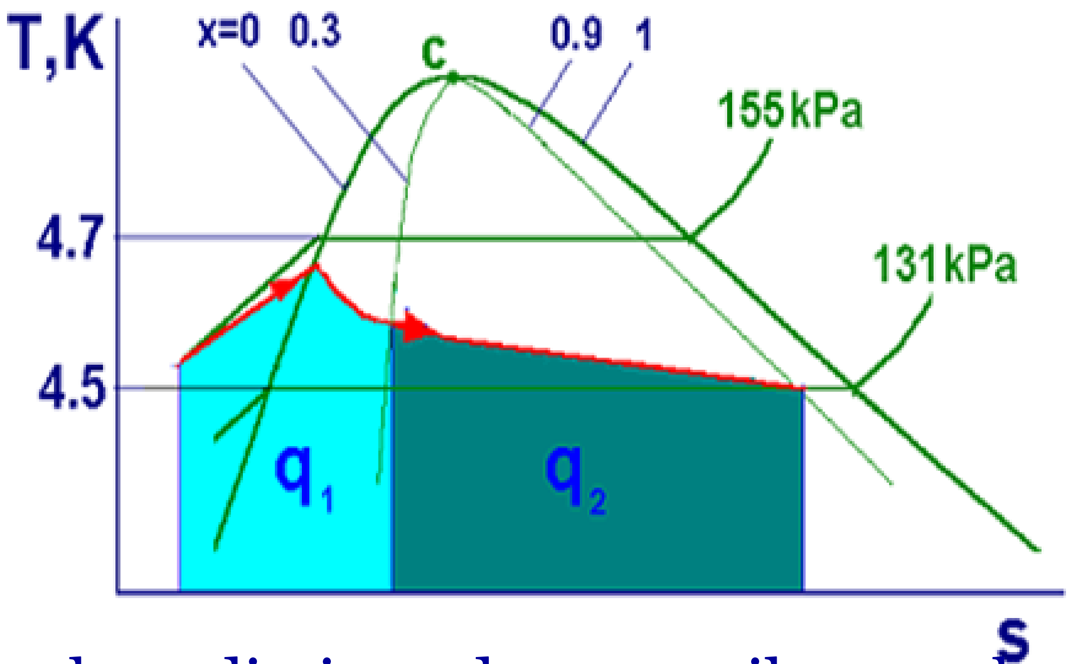
Characteristics of Adjusted Cooling Channels



- Pressure drop ***ΔP*** in the cooling channels versus the pulse repetition rate ***f*** for the dipole (1) and two types of quadrupoles (2,3) after adjustment for a outlet mass vapour content of helium x = 0.9, f_o – pulse repetition rate at design operating mode.

Magnet Cooling: Coil Stability

In the standard operating mode, helium with a mass vapor content of about 0.35 leave the SC winding and then the iron yoke with a vapor content of 0.9. The yoke is the basic source of heat load of the magnet.



heat dissipated: q_1 … coil, q_2 …yoke

This allows one to permit a good deal of discrepancy between the values of hydraulic resistance and heat load for the cooling channels of the magnets.

Outline

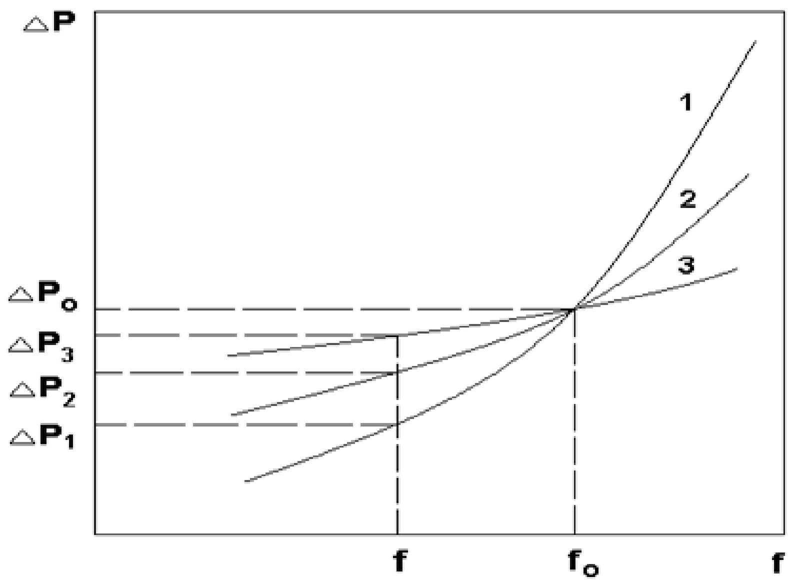
- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

Cooling Experience: Stability

- Many years of operating experience has confirmed the reliability of cooling the Nuclotron magnets for all cycles. The instability of the cooling is observed only in the following cases:

- low level of liquid helium in the separator;
- a small pressure difference between the helium headers, as a result, additional subcoolers stop serve.

Cooling Experience: Low Loss Cycles I



In case of operation in a mode with pulse repetition rate essentially less design value, distribution of helium flows on magnets became not optimum.

Cooling Experience: Low Loss Cycles II

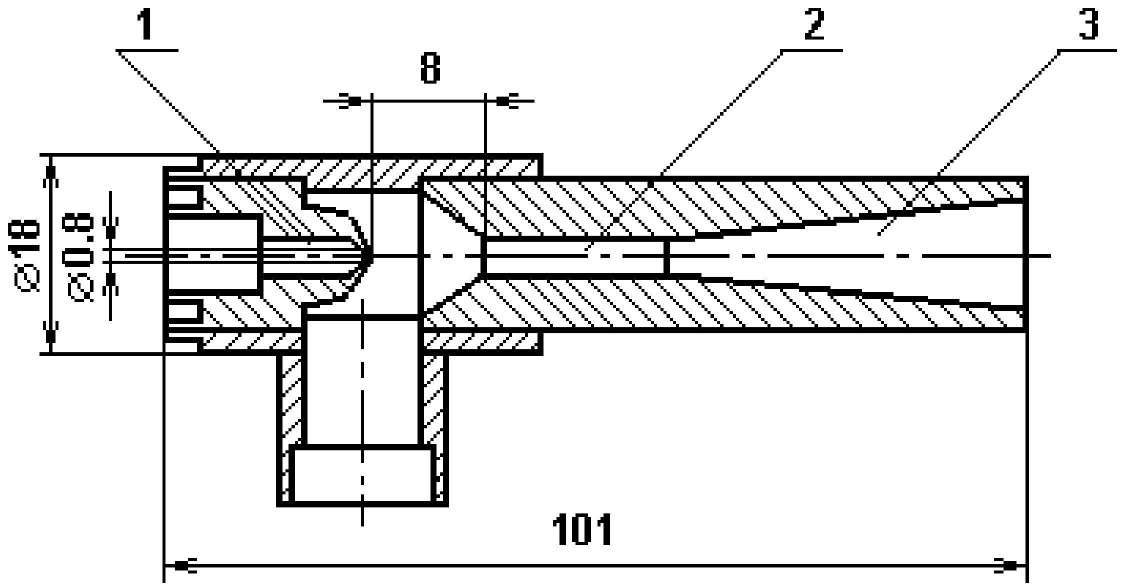
- Instability for cycles with low AC losses was expected and occurred if the pressure difference of the headers was too low.

- This was eliminated increasing the pressure difference to a level higher than necessary for heat removal, but lead to a no optimal economic operation of the cooling scheme.

Cooling Experience: Low Loss Cycles III

- We had surplus of refrigerator capacity, but have been forced to pass the overmuch flow rate of helium through all magnets to exclude quenches in magnets of type 3. It resulted in extra power consumption and the refrigerator efficiency reduction due to deviation from optimum mode.
- For economic reasons an ejector was installed during the upgrade of the cooling scheme.

Cryoscheme Upgrade: Ejector



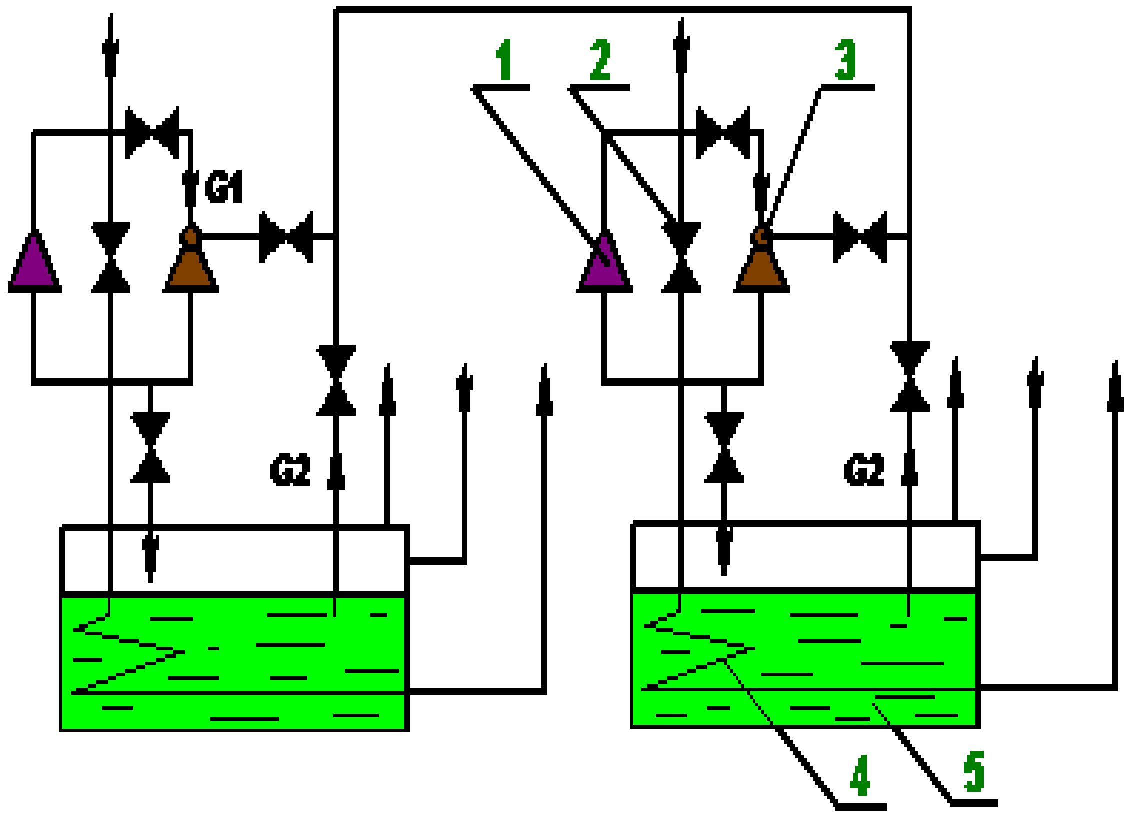
1- nozzle
2 - cylindrical mixing tube
3 - inlet diffuser

- Jet pump is switched on since 2004 at operation in mode with low AC losses

Cryoscheme Upgrade: Ejector

Ejector increases the helium flow through the magnets by 50% and allows to shutdown one compressor.

This decreases the cooling efficiency by only 10%.



1 - wet turbine, 2 - throttle valve, 3 - jet pump, 4 - heat exchanger 5 - liquid helium collector

Nuclotron Cooling: Operation Experience

- Many years of operating experience has confirmed the reliability of the cooling scheme used for the Nuclotron magnets.
- Instabilities of cooling were only observed if the helium level was low in the separator or the pressure difference between the headers was too small. The instability is eliminated by increasing the pressure difference between the helium headers, for example using a jet pump, which operate since 2004.

Outline

- Requirements
- Cooling principle:
  - Hollow superconductor
  - Parallel cooling channels
  - Two-phase coolant
- String test results and coolant choose
- Cooling scheme of the Nuclotron magnets
- Operation experience
- Conclusion

Conclusion I/III

- To ensure the operation of the magnets with the magnetic field ramp rate of 4 T/s and the cycle's repetition frequency of 1 Hz a special SC cable, called the Nuclotron cable was created.
- High heat loads in the fast-cycling magnets require the use of parallel cooling channels because of the large pressure drop in a long cooling channel of the Nuclotron cable.
- Theoretical and numerical analysis had shown that the two-phase helium cooling of the Nuclotron magnets is more effective in comparison with supercritical helium cooling.

Conclusion II/III

- These results are proven by a large amount of experimental work on single magnets as well as on a parallel chain of 16 magnets.
- Many years of operating experience has confirmed the reliability of the cooling scheme used for the Nuclotron magnets.
- Helium pressure oscillations or mass flow rate variations were not observed in the parallel channels.
- The stratification of the liquid and the vapour phases in the cooling channels of the coils is not a problem.

Conclusion III/III

- Cooling instabilities were only observed if the helium level was low in the separator or the pressure difference between the headers was too small. The instability is eliminated by increasing the pressure difference between the helium headers, for example using a jet pump, practically operated since 2004.