An approach to development of the HTS magnet for SMES at JINR

H Khodzhibagiyan[1], V Drobin[1], G Dorofeev[1], V Karpinskiy[1], A Shurygin[1], M Novikov*[1], D Kashaev[1], M Zaslavskiy[1], G Kachlishvili[1]

[1] Laboratory of High Energy Physics (LHEP), Joint Institute for Nuclear Research (JINR), Dubna, Moscow Region, Russia

*corresponding author, msnovikov@jinr.ru

Abstract. Particle accelerator complex NICA (Nuclotron-based Ion Collider fAcility) comprises superconducting Booster and Nuclotron synchrotrons which magnets operating at pulse mode in opposite phase with period of about 4 seconds. Summary stored energy of Booster and Nuclotron magnets will vary from 1 to 2.6 MJ during the period. NICA power supply system can be significantly improved by Superconducting Magnetic Energy Storage (SMES) application that will help to move the energy back and force between Booster and Nuclotron. The useful energy at this SMES must be about 1.6 MJ so the maximum total SMES energy should be 3-5 MJ. SMES with this energy should have several Tesla magnetic fields to keep a reasonable size. SMES operating current can be not less than Booster and Nuclotron magnets current so it might be 10-12 kA. It is better to make such a SMES magnet from an HTS (high temperature superconductor) cable for the stability at 6-7 T and 4 s pulse mode. The SMES magnet is planned to be wound as a short solenoid (Brooks coil) of cables optimized for several coaxial sections. HTS cables with helical structure similar to well-known CORC (conductors on round core) cables are under the development at JINR. The HTS cabling technology is based on the same principle as Nuclotron type cable manufacturing technology. HTS tapes, cables and magnets experimental study and testing methods are being developed on the base of an existing test facility at LHEP. First HTS cable short sample with 6 HTS tapes was prepared and tested at 77 K in self-field. Its critical current is about 800 A that will allow achieve required operating currents of SMES magnet with a reasonable amount of HTS tapes in cables. Developments of high field high current fast cycling HTS magnets for accelerators are also being planned at JINR.

1. Introduction

NICA Nuclotron and Booster magnets have current modes as shown in the figure 1 and there stored energies like in the figure 2. SMES will help to transfer magnetic energy back and force between Booster and Nuclotron. For this purpose SMES should store and supply up to 1.6 MJ and its total magnetic energy might be in the range of 3-5 MJ. SMES energies which keep the total system energy constant (3.3 and 4.8 MJ) are shown in the figure 3. Expected time dependencies of SMES current at “limit” energy values are shown in the figure 4.

2. Power system preliminary concept

Power system with SMES (figure 5) can be based on high-speed semiconductor switches and bridges with control units, buffer capacitors and resonant snubbers. Three circuits connected to SMES –

Booster circuit, Nuclotron circuit and power supply for energy losses compensation – will be isolated from each other due to different time periods of their operation inside the switches operation cycle.

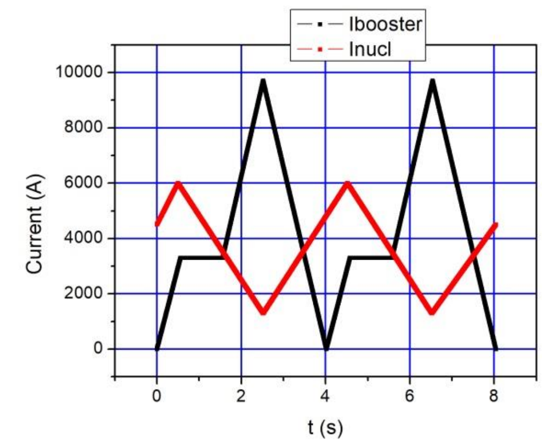

Figure 1. Nuclotron and Booster current modes.

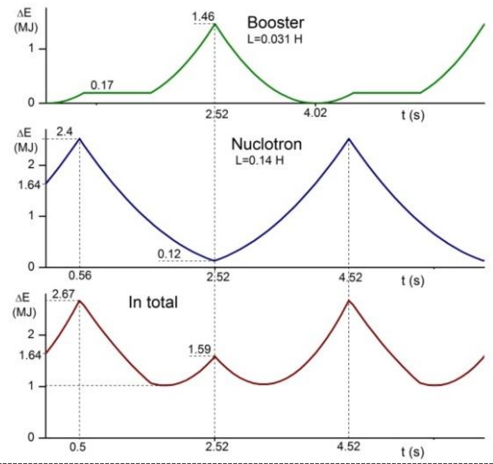

Figure 2. Stored energy of Booster and Nuclotron.

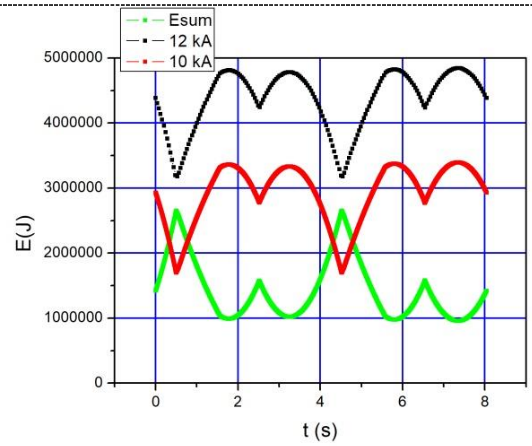

Figure 3. Energy range of SMES magnet.

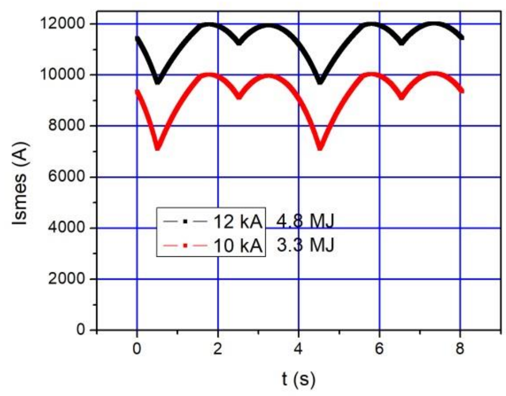

Figure 4. SMES currents for 3.3 and 4.8 MJ.

For a long term energy storage mode SMES can be shunted with superconducting switch (persistent mode with small losses at low resistive contacts with a decay time about several hours). High frequency pulse width modulation multi load power converter is based on MOSFET (or IGBTs) bridges and switches, capacitors of several tens µF and resonant snubbers (RS) operating at voltages up to 1 kV. Main frequency is 10 kHz or more. All the circuits operate at their own different time intervals inside the 100 µs cycle for power isolation of Booster and Nuclotron. Current direction through the bridges can be altered for charging or discharging of all the magnets. Current ramp rate control can be done by variation of time intervals of charging or discharging inside the 100 µs cycle. The power supply compensates (from the distribution grid) energy losses in resistive feeders, MOSFETs, snubbers, and superconducting magnets AC losses - they all are 1-2 order less (per cycle) than the total energy. Elements of switches and bridges of 10 kA class should consist of many parallel transistors with overvoltage protection circuits and fuses. Power converters developed earlier at JINR [1, 2] have similar principles, but multiple isolated loads insist to increase frequency and require 1 µs fronts of switches. It makes use MOSFETs or IGBTs instead of thyristors used earlier. The magnet must have magnetic field up to several Tesla at the winding for acceptability of the size. For reasonable stability such SMES magnet can be wound from high current HTS cables only and without any yoke, while earlier, for example see [3, 4].

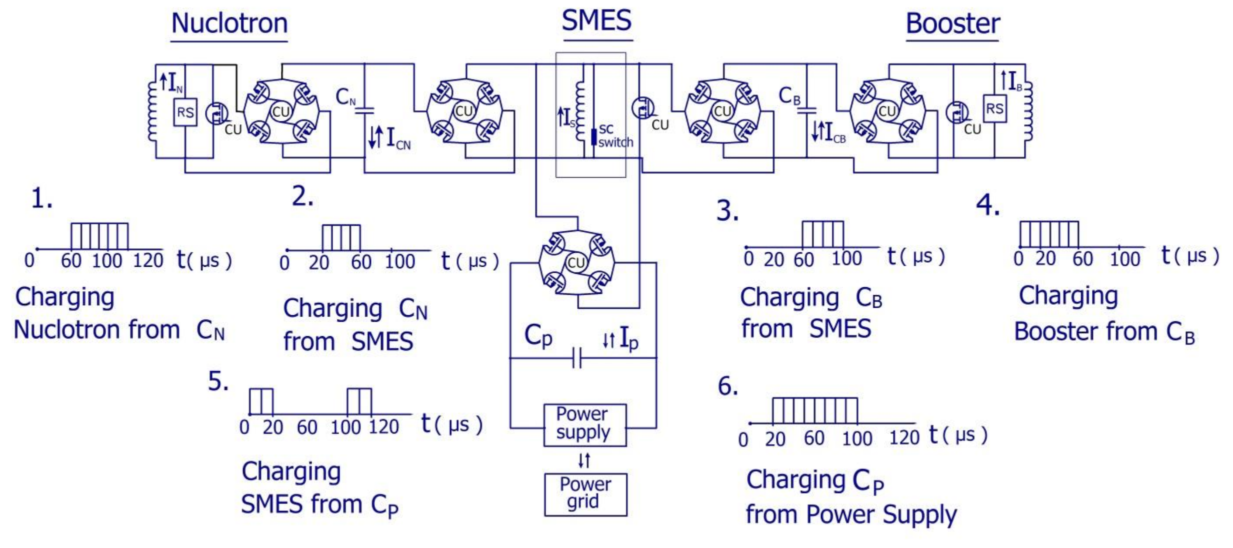

Figure 5. Flow chart and timing charts of the Nuclotron and Booster power system with SMES.

The timing charts 1 and 2 shown in the figure 5 illustrates the temporal separation of Nuclotron current setting from the capacitor and SMES operation with this capacitor. Charts 3 and 4 show the same for Booster magnets. In the charts 5 and 6 we can see this type separation of SMES magnet from the power supply. Charts 2, 3 and 5 show that SMES magnet works with all the three circuits of the power system at different time intervals providing power isolation of them from each other. A power system with total galvanic isolation of SMES, Booster and Nuclotron magnets is also under consideration. Such a system – a "transformer type" SMES – could include a SMES magnet comprising three isolated coils with bound magnetic flux (e.g. coaxial coils or groups of coaxial sections). Two of the coils can be connected to the power converters of Booster and Nuclotron, and the third coil – to the power supply. However this more perfect power system is more complicated from a point of view of SMES magnet operation reliability – mechanical and thermodynamic stability.

3. HTS cables for SMES

Different possible types of HTS cables for industrial physics facility magnets are described well at [5]. It worth to consider one of them properly here – well known CORC cable with helical SC wires winding like in Nuclotron type cable, but made of HTS tapes. CORC development beginning at 2009, described at [6], have not been stopped because this type of an HTS cable combines high operating current [7], flexibility, particularly transposed wires, cooling by a hollow former, not very complicated manufacturing technology. Due to these options the cable was proposed for accelerator magnets [8]. The cable also can withstand cyclic mechanical load [9] – it is one else reason to apply it in SMES magnet operating in cycling mode for hundreds of millions cycles for its lifetime. A similar cable design and technology were also been being developed successfully with a participation of one of this article authors [10, 11].

4. R&D program for SMES magnet and HTS cables at JINR

Such an R&D must include a lot of items. First of them is a preliminary numerical estimation of the magnet parameters. Further the 3D FEM simulation of magnetic field, stresses and strains, AC losses, cooling parameters, temperature distribution etc. must be completed. HTS cabling and winding facilities, making HTS cables and winding samples preparation as well as testing facility upgrade for the HTS tasks should be made. Cables and windings samples critical current, AC losses, mechanical loading tests including multicycling test of winding fragments at cryogenic temperature should be done at all the stages of this R&D. The task of the same importance with magnet is the power system (in 2 options) numerical simulation and then experimental sample preparation and testing, with small scale magnets of HTS tape, and with 0.1-1% of the real system energy. Design of the cables and the solenoid, a cryogenic system with a cryostat and current leads, a power converter, a magnetic shielding, cabling and winding machines, a quench protection system, etc. must be carried out at the final stage after all the items mentioned above.

5. SMES magnet and HTS cables draft concepts

According to preliminary calculations the SMES magnet can be made as a short solenoid (Brooks coil) of many coaxial sections with optimized HTS cables in each sections to decrease the cost of HTS. Magnet inductance should be about 0.07 Henry to provide the total energy 3-5 MJ at operating currents 10-12 kA. Therefore the magnet can have 16 layers (sections) of 16 turns in each one, outer diameter is (approximately) 1.6 m, inner diameter 0.8 m, height 0.4 m. The cables of the sections can consist of several layers of helically wound HTS tapes with a flow cooling throw their formers. Quantities of HTS tapes in a cable of a section can vary from 20 to 50, correspondently to maximum magnetic field at the sections, up to 7 T in at the inner one. Wrapping angles can be in the range from 40 to 20 degrees. A total amount of an HTS tape in the magnet will not be more than 40 km. Maximum Lorentz force tensile stress is estimated to be about 60 MPa per the whole winding but local concentrations are expected. Structure materials must be dielectric to prevent eddy currents heating (e.g. epoxy impregnated glass fiber) but they might include radial and vertical bandages of stainless steel tapes. Forced flow cooling can be done by 2-phase helium or supercritical helium at operating temperatures 7-15 K with a parallel hydraulic connection of the sections. A cryostat must be nonmetallic vacuum vessel with a liquid nitrogen shield. Current leads should include an HTS part with liquid nitrogen interception. Stray field shielding is strongly recommended to protect the particle accelerators. Electric connections of the sections can be serial or others. The design of the magnet allows making a complete galvanic isolation power system by dividing the solenoid into three groups of isolated coaxial sections with bound magnetic flux (the “transformer” SMES mentioned above).

6. HTS Cabling and winding device concept and experimental facility at LHEP

Photographs of the experimental HTS cabling device are shown in the figure 6, and its flow chart – in the figure 7. The concept implies modular design of the cabling device – it is easy to add more various wrapping units. Adjustable and easy to remount to vary geometrical parameters device is made of a universal details set. Solenoid winding might be produced from the cable bobbin right at the cabling machine - magnets bobbin can be positioned on the frame of the machine. This way an industrial HTS cabling device can be developed on the base of an experimental one.

Figure 6. Photographs of the experimental HTS cabling device during mounting and winding.

The requirements to 2G HTS tapes for the SMES magnet cables can be the following:
Critical current at 77 K in self-field not less than 120 A, at 4.2 K in external magnetic field 10 T (perpendicular to the wire surface) – not less than 400 A all over a piece, and at 20 K in external

magnetic field 10 T (perpendicular to the wire surface) – not less than 200 A. Minimal critical bending diameter (critical current is 95% of straight sample critical current) should be not more than 25 mm. Wire (tape) width – not more than 4.2 mm and not less than 4 mm. Substrate material (Hastelloy C276) thickness should be not more than 45 µm for lower critical diameter and for better cable current density. Copper coating thickness should not less than 3 µm for proper soldering, and not more than 5 µm to decrease eddy current losses. PbSn solder (with temperature of melting not more than 190 ºC) coating thickness from 5 to 10 µm (layer thickness permissible deviation – not more than 2 µm over the entire wire batch) for better cooling of all the layers. The "high field type" HTS tape described at [12, 13] manufactured by SuperOx meets these requirements. SuperPower production is good both by its critical current and flexibility, but more expensive. SuNAM HTS tape is flexible enough, but has lower critical currents in magnetic fields. It worth to consider HTS tape described at [14] but it is a completely new conductor from the new HTS manufacturer – its properties are not studied well yet. Experimental cabling device was mounted; its parameters are as follows:

HTS cable length up to 160 m; it can wind up to 12 HTS tapes (2 layers) by one pass; total number of tapes is not limited; cable tension can be 300-1500 N, tape tension – 10-60 N. Exact tension produced by DC gear motors can be independent of wrapping rate and direction.

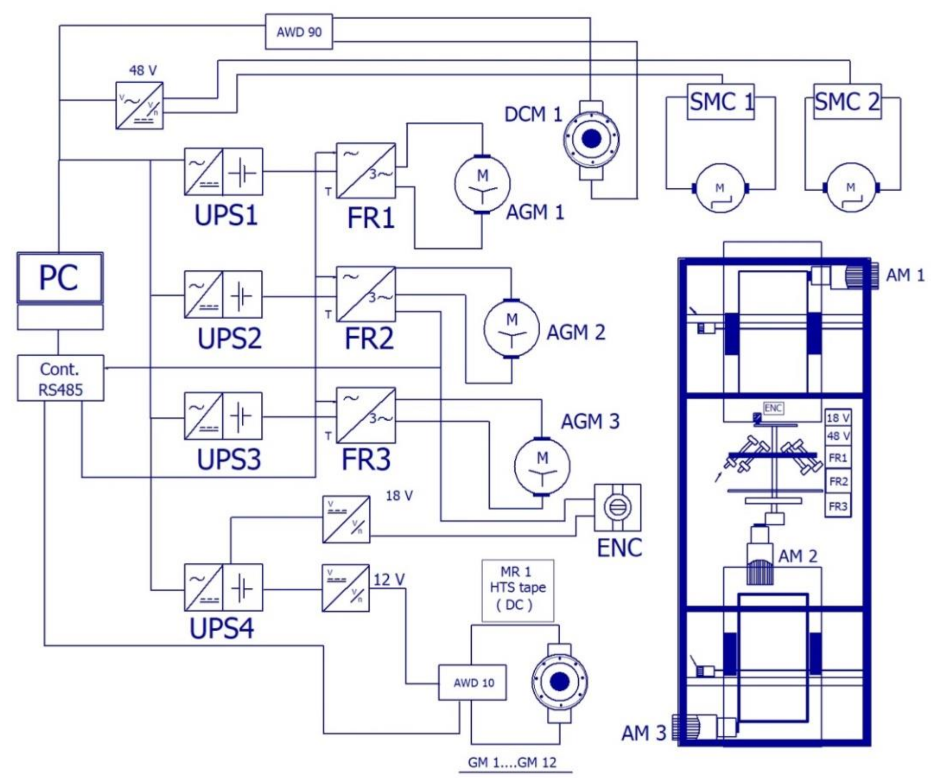

Figure 7. Flow chart of the cabling device.

At the flow chart of the experimental cabling device: AGM1-3 - asynchronous gear-motors, 1- for cable receiving bobbin, 2 - for wrapping unit and 3 – for backward cable reeling; ENC - optical incremental encoder synchronizing wrapping and reeling; wrapping synchronization can also be provided by manual setting of frequencies of FR1 and FR2 ratio; GM 1-12 - DC gear-motors for HTS tapes tension; DCM1 - cable tension DC motor; AWD 90 - DC motor controller; FR1-3 - frequency regulators for AGM1-3; SMC 1-2 – step motor controllers for linear positioning of the cable bobbins. After installation and programming a controller and sensors this cabling device will be able to wind automatically with exact tensions and velocities set in a fairly wide range. The device adjustment is in progress, and a first short cable sample was successfully wound and tested. The sample consists of two layers with three HTS tapes in each layer. The tapes were wound onto 5.7 mm Melchior tube at an angle of 40º. Length of the sample between current terminals is 750 mm and the sample was bent to 170 mm diameter. Critical current was various along the sample due to a mechanical degradation of some HTS tapes during winding. The particular damage was done because of several detected during this test winding "mechanical" and "automation" cabling device bugs which are under fixing now. We had expected that critical current at 77 K in self-field will be 900-1000 A from HTS tape specification, but it has been about 800 A at "low damage" parts (including the bent part), and about 700 A in a place with a higher damage. Obtained critical currents and comprehension of their decrease reasons allow achieving required operating currents of the SMES magnet using affordable quantity of up to 40-50 HTS tapes in the cables. The cable design, cabling device principles and the HTS tape chosen design can provide corresponding current capacity 10-12 kA at 10-15 K in 6-7 T, with 40-50 tapes.

7. Conclusions

HTS pulse mode high current cables and magnets development has been started at JINR. The first planned is the SMES HTS magnet for Booster and Nuclotron power supply. The magnet can be wound as a short solenoid (Brooks coil) from 10-12 kA 2G HTS cable with helical structure similar to the Nuclotron cable and CORC. After preliminary numerical estimations known maximum magnetic field is 6-7 T, operating temperature is from 10 to 15 K, outer diameter is about 1.6 m and the number of turns is about 250. The cables will be optimized by coaxial sections with parallel cooling by supercritical helium. Cabling and winding equipment for HTS 2G tapes, cables and magnets preparation is under the construction in the frames of this R&D program. An experimental cabling device is already mounted and a first cable sample was wound and tested for the beginning of the device adjustments. The existing Nuclotron magnets testing facility is under a reconstruction for the purposes of the project. The further possible applications are accelerator magnets and other magnet for industrial physics… up to 20 T and more.

Acknowledgments

This work was supported by the Ministry of Education and Science of the Russian Federation under Contract No.05.615.21.0005 in the framework of the project RFMEFI61518X0007.

References

[1] Kudashkin A, Karpinsky V, Khodzhibagiyan H, Sidorin A 2010 *Proceedings of RuPAC-2010*
[2] Karpinskii V et al 2010 *Physics of Particles and Nuclei Letters* **7** pp 517–21
[3] Baldin A et al 1995 *IEEE Trans. on Appl. Supercond.* ***5*** No 2
[4] Khodzhibagiyan H, Kovalenko A and Fisher E 2004 *IEEE Trans. Appl. Supercond.* **14** pp 1031-34
[5] Bruzzone P et al 2018 *Nucl. Fusion* **58** 103001
[6] van der Laan D C 2009 *Supercond. Sci. Technol.* **22** 065013
[7] van der Laan D C et al 2015 *Supercond. Sci. Technol.* **28** 124001
[8] Wang X et al 2018 *Supercond. Sci. Technol.* **31** 045007
[9] van der Laan D C et al 2019 *Supercond. Sci. Technol.* **32** 015002
[10] Keilin V et al 2013 *IEEE Trans. on Appl. Supercond.* **23** No 3
[11] Novikov M et al 2015 *Physics of Atomic Nuclei* **78**, No 10 pp 1148–54
[12] Available online: http://eng.s-innovations.ru/vtsp-provod/
[13] Molodyk A et al 2019 *presented at EUCAS-2019,* Glasgow UK, 2 September 2019
[14] Li Y, Liu L, Hong Z, Wu X, *IEEE Trans. on Appl. Supercond.* DOI 10.1109/TASC.2018.2801349