Conceptual design of the mobile cryomagnets for novel microwave technologies

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1. Motivation

- There are demands for **mobile microwave power sources for** different applications [1,2]
- It was shown that millimeter-wave (MMW) directed energy from a gyrotron offers significant advantages [1,2].
- The magnetic fields **~3 T generated by a superconducting magnet** in a **mobile and rugged cryostat** are necessary.
- Our task was to analyze what kind of magnets could be optimal for such a device along with a cryogenic system for it.
- The superconducting magnet demands are in the Table I

TABLE I
PARAMETERS OF A SUPERCONDUCTING MAGNET DEMANDED

Parameter	`VALUE
Maximum magnetic field value in a homogeneous area, T	3
Warm bore, mm	100
Length of a homogeneous (±0.5% of maximum field) section, mm	60
Outer magnet diameter, mm	<600

References

1. P. Woskov and D. Cohn, “Annual report 2009: millimeter wave deep drilling for geothermal energy, natural gas and oil MITEI seed fund program”, *PSFC Report*, #PSFC/RR-09-11, 7 pages, 2009.
2. P. Woskov and P. Michael, “Millimeter-wave heating, radiometry, and calorimetry of granite rock to vaporization”, *J Infrared Milli Terahz Waves*, vol. 33, 2012, 82-95.
3. V.S. Vysotsky, A.A. Konjukhov, G.S. Kurljantsev, et al, Autonomous superconducting magnet systems - new conception for application with special conditions, *Proceedings of the MT-15*, Science Press, Beijing China, 1998, 506-509.
4. V. R. Karasik, A. A. Konjukhov, G. A. Agapov, et al, The First Mine Countermeasure Devices With Superconducting Magnets, *Advances in Cryogenic Engineering*, Vol. 41, 1996, 1057-1067.
5. M. Heiberger, A. Langhom, T.W. Hum et al, A Light-Weight Rugged Conduction-Cooled NbTi Superconducting Magnet For U.S. Navy Minesweeper Applications, *Advances in Cryogenic Engineering*, Vol. 41, 1996, 1087 – 1095.
6. B. Haid, H. Lee, Y. Iwasa, et al, Stand-Alone Solid Nitrogen Cooled “Permanent” High-Temperature Superconducting Magnet System, *IEEETransactions On Applied Superconductivity*, VOL. 11, NO. 1, 2001, 2244 -2247.
7. A. Molodyk, S. Samoilenkov, A. Markelov, A. et al. Development and large volume production of extremely high current density YBa2Cu3O7 superconducting wires for fusion. *Sci Rep* 11, (2021), 2084. https://doi.org/10.1038/s41598-021-81559-z
8. V.S. Vysotsky, V.R. Karasik, A.A. Konjukhov, A.I. Rusinov, Design and coil protection of the high current density autonomous superconducting magnets for mine sweeping, *Advances in Cryogenic Engineering*, v.41, 1996, 1069-1076.
9. Vysotsky V.S., Karasik V.R., Konjukhov A.A., Tsikhon V.N., Persistent mode switches and automatic power supply for autonomous superconducting magnets, *Advances in Cryogenic Engineering*, v.41, 1996, 1077-1086.
10. Y. Iwasa, Case Studies in Superconducting Magnets, New York andLondon: Plenum Press, 1994.
11. V.S. Vysotsky, V.R. Karasik. A.A. Konyukhov, Current leads with forced cooling for magnets operating in the "frozen mode", in: *"Problems of Applied Superconductivity"* (Proceedings of Lebedev Institute, v. 121) Moscow, Nauka, 1980, 83-88 *in Russian*.

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2.Two HTS and two LTS magnets were calculated for comparison

HTS magnets, 4 mm insulated tape from S-Innovation LLC

TABLE II
PARAMETERS OF THE 50 A HTS SUPERCONDUCTING MAGNET

Parameter	`Value
Outer magnet diameter, mm	257.2
Magnet length, mm	411.6
Radial number of turns	224
Axial number of turns	98
Total turns	21952
Total length of a tape necessary, m	10631
Energy stored, J	32735

TABLE III
PARAMETERS OF THE 100 A HTS SUPERCONDUCTING MAGNET

Parameter	`Value
Outer magnet diameter, mm	186.8
Magnet length, mm	378
Radial number of turns	109
Axial number of turns	90
Total turns	9810
Total length of a tape necessary, m	4208
Energy stored, J	21296

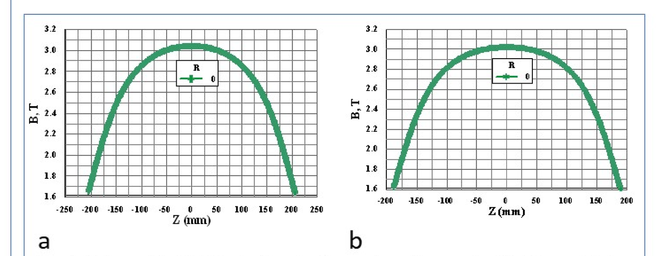

Fig.1. Magnet field distribution in the center of magnets (R=0). a – 50 A magnet, b – 100 A magnet

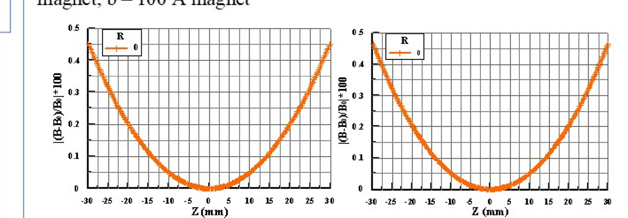

Fig. 2. Relative magnetic field along the axils of a magnet in ±30 mm distance. a – 50 A magnet, b – 100 A magnet. ΔB< 0.5%

NbTi magnets. Wire- see Table IV

TABLE IV
PARAMETERS OF THE NBTI SUPERCONDUCTING WIRE

Parameter	`Value
Wire diameter, mm	0,85
Superconducting filaments diameter, μm	6,0
Twist pitch of superconducting filaments, mm	12
J_c(4,2K;5T), kA/mm²	2,36
Cu/SC ratio	1,4
RRR	>70
Insulation thickness, mm	0.05

TABLE V
PARAMETERS OF THE NBTI 100 A SUPERCONDUCTING MAGNET

Parameter	`Value
Outer magnet diameter, mm	159
Magnet length, mm	400
Radial number of turns	22
Axial number of turns	460
Total turns	10120
Total length of wires necessary, m	4110
Energy stored, J	19128

TABLE VI
PARAMETERS OF THE NBTI 275 A SUPERCONDUCTING MAGNET

Parameter	`Value
Outer magnet diameter, mm	134
Magnet length, mm	400
Radial number of turns	8
Axial number of turns	460
Total turns	3680
Total length of wires necessary, m	1425
Energy stored, J	17144

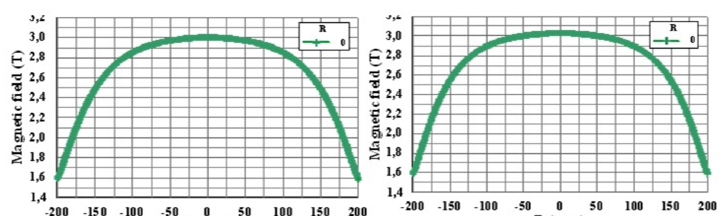

Fig. 3. Magnet field distribution in the center of NbTi magnets (R=0). a – 100 A magnet, b – 275 A magnet

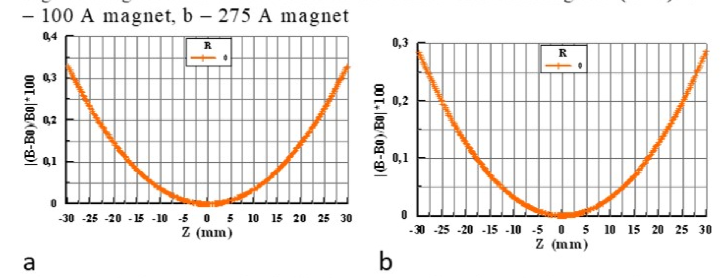

Fig. 4. Relative magnetic field along the axils of a NbTi magnet in ±30 mm distance. a – 100 A magnet, b – 275 A magnet. ΔB< 0.30-0.35% along ±30 mm of the axis for both magnets.

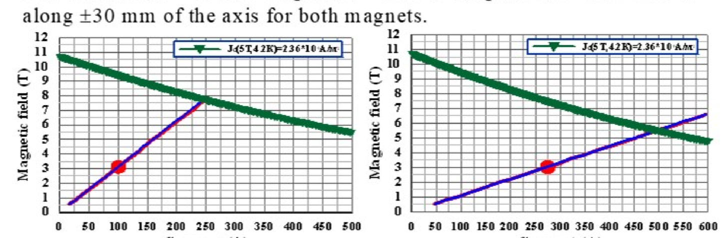

Fig. 5. Load curves for NbTi magnets. a – 100 A magnet, b – 275 A magnet.

Comparison HTS and LTS 3 T superconducting manets

Magnet	HTS 50 A	HTS 100 A	LTS 100 A	LTS 275 A
Length of wires	10,6 km	4,2 km	4.1 km	1.4 km
Cost of wires	~ $ 160 000	~$ 130 000	~$ 5000	~$ 4500
Stored energy	32 kJ	21 kJ	~19 kJ	17 kJ
Mechanical Stability	High in solid nitrogen	High in solid nitrogen	High for impregnated winding	High for impregnated winding
Superconducting Stability	High, very low normal zone propagation velocity	High, very low normal zone propagation velocity	Good, with 1.5 – 2 safety margins	Good, with 1.5 – 2 safety margins
Protection issues	Unclear	Unclear	Well-known and without problems	Well-known and without problems
Cooling methods	Solid nitrogen, new and not well developed Undirect cooling by crycoolers	Solid nitrogen, new and not well developed Undirect cooling by crycoolers	Undirect cooling by crycoolers Liquid helium cryostat	Undirect cooling by crycoolers Liquid helium cryostat

3. Cryostats

To map out the ways of development of mobile cryostats for MMW, three ideas from literature were considered

Cryocooler cooled cryostats [5] – well developed but large mass and need a lot of power for compressors and cryocoolers.

Solid nitrogen cryostat [6] – interesting new idea, but could a be problem how to keep the nitrogen solid.

Autonomous cryostats [3,4] – well developed and tested in rough conditions [4], but needs periodical liquid helium supply. Anyway, 96 hours of interrupted work are feasible [3,4].

4. Conclusions

We considered approaches to develop mobile MMW devices with 3 T magnetic field generated by a superconducting magnet. Two types of HTS and LTS superconducting magnets analyzed. All magnet can provide magnetic field parameters demanded with proper field uniformity. HTS wires are by the order of value more expensive than LTS wires.

Three possible cooling methods and cryostats are discussed based on previously published and tested experiences [3-6]. Each method is feasible, but optimization and cost analysis is necessary

The future look of the mobile 3 T MMW system with superconducting magnets will be developed in future based on the ideas of this paper.