Magnet Technology Options for 6D cooling

We have a full catalogue based on US MAP original design (field on axis)

Here are few facts about the 6D cooling solenoids:

- 12 unique stages:
    - 4 cooling stages *before* bunch recombination (A1-A4)
    - 8 cooling stages *after* bunch recombination (B1-B8)
    - *Each stage has a repeating series of a cell type*
- High field, very compact solenoids
- Each cell has symmetric solenoids of opposite polarity
- Fields on axis: 2 to 14 T
- Cell Lengths: 0.8 to 2.7 m
- Total length of all Stages: ~ **1 km**
- Total number of solenoids: 2432

We are defining technologies: conductor and operation condition, i.e. temperature an cooling method.

Still have to be fully investigated:

- Conductor performance
- Conductor configuration
- Field quality
- Thermal/mechanical configuration

We evaluated several technologies for the solenoids (see Table 1) and selected two options: 4 K route using three conductors and 20 K route using HTS only (see Table 2).

The actual trend is going to the 20 K cooling, since it fulfills the three pillars of the design: Performance, Cost and Sustainability.

The aim to design Solenoids up to almost 20 T working at 20 K, based on HTS. An extensive R&D program is foreseen to improve the characteristic of the tapes, to build and test small coils by different conductor configurations and thus create and assess models for the conductor (windings). One of the main goal is to develop a reliable quench protection system for partial insulated magnets.

There is an important synergy with a NextGen EU program in Italy, called IRIS. The R&D for small coils construction and test is shared with this project.

The increase of TRL of the HTS windings working at 20 K may directly be usable for society applications i.e. Carbon hadrotherapy (HITRI, I.FAST, SIG).

The option of designing and building a test bed for room temperature RF test, having 7 T to 10 T field, is an opportunity to commission some selected technologies for conductor, winding and cryogenics.

Table 1 Overview of potential technologies for Solenoids

Technology	Pro's	Con's
LTS	Known technology (TRL 9)	Operating temperature
HTS ReBCCO Insulated	More compact than LTS/HTS Allows for operation at higher temperature Batch above 100 m demonstrated	R&D at low readiness (TRL 4/5) Quench detection protection Production of km batches to be demostrated
HTS ReBCCO Non-insulated	Most compact magnet winding Synergies with other fields of science and societal applications Batch above 100 m demonstrated Can profit from development by others (e.g. NHMFL)	R&D at low readiness (TRL 3/4/5) Ramping time and field stability need to be demonstrated Quench detection and protection Production of km batches to be demostrated
HTS BiSSCO/IBS	Round wire demonstrated for BiSSCO	R&D at low readiness (TRL 3/4) for IBS Production lengths (?)

Table 2 Main features of each cell and technology options.

Stage	[1]		[2]		Coil	[1] Input geometries from US MAP Study				[2] Calculated Parameters using COMSOL (cell in a lattice unless otherwise stated)							Technology Options			
	Cell Length [m]	Solenoids/Cell	Peak Bz field on axis [T]	Stored Magnetic Energy [MJ]		Length [mm]	Radius [mm]	Thickness [mm]	Current Density [A/mm2]	**Peak Bz Field in Coil (lattice configuration) [T]**	Peak Bz Field in Coil (Single Cell) [T]	Maximum (+)Peak Hoop stress (see 1) [MPa]	Minimum (-) Longitudinal Stress [MPa]	Maximum (+) Radial Stress [MPa]	Minimum (-) Radial Stress [MPa]	Peak Longitudinal Force [MN]	NbTi (4 K)	Nb3Sn (4 K)	HTS (4 K)	HTS (20 K)
A1	2	4	2,4	5,38	**A1-1**	210	450	100	63,25	4,1	4,4	34,2	-16,6	0,0	-4,6	3,8	X	X	X	X
A2	1,32	2	3,5	15,35	**A2-1**	260	410	130	126,6	9,5	9,9	137,4	-60,2	0,0	-28,3	0,0		X	X	X
A3	1	4	4,8	7,23	**A3-1**	110	270	110	165	9,4	10,2	138,1	-59,4	0,0	-28,5	10,9		X	X	X
A4	0,8	4	6,1	8,39	**A4-1**	90	220	140	195	11,6	13,0	195,9	-77,6	0,0	-49,4	16,1		X	X	X
B1	2,75	2	2,6	44,54	**B1-1**	500	770	150	69,8	6,9	7,2	94,5	-50,3	0,0	-13,5	7,9	X	X	X	X
B2	2	2	3,7	24,1	**B2-1**	360	500	150	90	8,4	9,0	113,9	-58,1	0,0	-20,1	7,7		X	X	X
B3	1,5	2	4,9	29,83	**B3-1**	370	410	150	123	11,2	12,8	173,5	-160,1	0,0	-36,6	36,8		X	X	X
B4	1,27	4	6	24,4	**B4-1**	92	175	200	94	9,2	11,9	231,4	-27,0	19,7	-0,1	7,5		X	X	X
					B4-2	320	410	240	70,3	7,8	8,8	65,5	-47,6	0,0	-23,5	7,4		X	X	X
B5	0,806	4	9,8	12,03	**B5-1**	100	113	88	157	13,9	18,7	336,1	-88,8	21,1	-0,7	5,5			X	X
					B5-2	196	217	165	168	12,3	14,4	158,7	-137,3	0,2	-55,7	19,1		X	X	X
B6	0,806	4	10,8	8,19	**B6-1**	100	84	92	185	14,2	18,9	313,8	-76,7	22,3	-1,4	4,3			X	X
					B6-2	177	215	160	155,1	10,3	12,3	117,8	-101,8	0,0	-43,1	14,7		X	X	X
B7	0,806	4	12,5	5,65	**B7-1**	100	50	74	198	14,3	18,4	244,2	-50,1	20,7	-1,1	1,4			X	X
					B7-2	170	210	145	155	10,1	12,0	118,5	-87,1	0,0	-37,4	11,1		X	X	X
B8	0,806	6	13,6	1,42	**B8-1**	120	45	65	220	15,1	16,9	118,5	-69,9	22,1	-3,0	1,5			X	X
					B8-2	80	140	80	135	6,2	6,3	109,8	-30,3	4,5	-2,4	2,0	X	X	X	X
					B8-3	100	250	120	153	6,2	3,4	41,2	-27,6	0,0	-22,9	1,4	X	X	X	X

In conclusion, an extensive R&D program focused on HTS conductor to be used at 20K started. A schedule is mostly ready and consistent, the program is supported also by synergie with other tasks and other projects.