DRAFT I

Conceptual Cost and Schedule for an HTS Cable Test Facility

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1. MOTIVATION

The US DOE Office of Science High Energy Physics (HEP) and Fusion Energy Sciences (FES) programs are collaborating on the development of High Temperature Superconductors, and are exploring the possibility of developing an HTS cable testing facility.

We note that there is significant overlap with needs of the HEP community in terms of facility capabilities. This document summarizes cost and schedule considerations based on a conceptual plan for such a facility to be located at FNAL, leveraging conceptual magnet design work initiated some years ago at LBNL for DOE OHEP, as well as recent magnet scoping studies done by LBNL in collaboration with PSI and CERN for a possible replacement magnet for the EDIPO facility.

2. PRELIMINARY SPECIFICATIONS

The main goals and operational targets for the proposed facility for MDP were presented by G. Velev in a presentation at the MDP collaboration meeting [1] and a DOE FES office visit on June 7th, 2018. The operational targets for the FES test facility are described in S. Prestemon et al. [2].

2.1. TEST FACILITY INFRASTRUCTURE

Here we summarize the current proposed parameters/specifications that are directly relevant to MDP and FES communities:

- The test facility will be constructed in Industrial Building 1, APS-TD, Fermilab. To save money, the proposed place is selected based on the proximity to the needed base infrastructure for a such test stand, including cryogenic, power, water and crane.
- Minimum operating temperature of the facility is 1.9K for the magnet providing the background field and 4.2-4.3 K *(under discussion) for the test samples.
- The test pit cryostat should accommodate a dipole (cold mass) with maximum dimensions of 1.3 m and length of 3.0 m.
- The maximum weight of the dipole cold mass should not exceed 22 (Standard) tons, limited by the crane capacity.
- The test facility should be efficient and safe, minimizing the time for experiment preparation and no helium losses after quenches.
- The specifications for the magnet providing background field of 15 T (with possibility to reach 16 T after operational experience is gained) is described elsewhere.
- Operational lifetime of the facility at least 20 years.

2.2. Test facility magnet

The main goals and operational targets for the proposed facility are described in S. Prestemon et al., "High Temperature Superconductor Cable Test Facility Specifications", July 16, 2018. Here we summarize the parameters that are directly relevant to the design of the large aperture dipole:

- Background dipole field > 15T. This goal is higher than in previous facilities or other proposals. In order to respond to this requirement, we assume that the coil will be graded and the operating temperature will be 1.9K. The design will provide sufficient margin to reach 16 T after optimization and operational experience.
- Homogeneous field region >500-600 mm, preferably >1000 mm. This requirement has a strong influence on the magnet size and cost. The cost-performance trade-offs of 500 mm vs 1000 mm homogeneous length will be explored as part of the conceptual design phase.
- AC field at the level of 1T, 1Hz [lower priority]. We assume here that the dipole design field would not be exceeded due to the AC field; and that the system would be implemented using auxiliary coils without a significant impact on the dipole design.
- Cryostat to accommodate sufficient sample length to keep sample joint in low field. This is mostly a requirement on the cryogenic facility, but will be taken into account in the design of the dipole, for example regarding the coil and iron geometry to ensure a rapid decay of the field.
- Well dimension 90x140, and preferably 100x150. It would be preferable to make the well compatible with FRESCA2 samples - see Fig 2.1.
- Field quality in the transverse plane: The design target is to keep all harmonics below 20 units at 35 mm radius and 15 T field.
- Sample temperature control and mechanical loading: assuming that the required features would be implemented within the specified test well envelope, therefore reducing the space available for the sample itself.

3. Scope of work and associated plans and assumptions

3.1. Test facility design and assumptions

The scope of work in this section includes all activities related to design of the test facility and purchasing of the necessary equipment and services. The design of the facility includes:

- The main magnet cryostat including the Lambda plate and top plate assembly.
- HTS test samples cryostat for the insertion in the magnet well with possibility to control the sample temperature to 1K in the region of 4.3 to 55 K. *(under discussion)

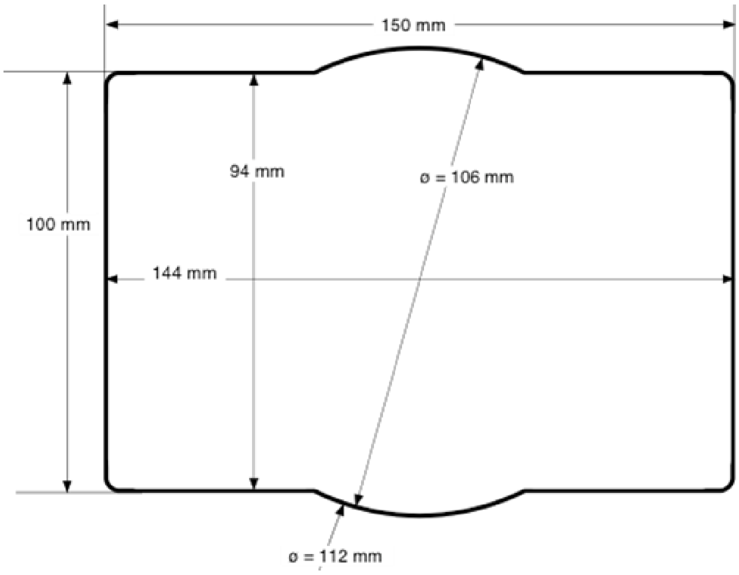


Figure 2.1: Preferred dimensions of sample test well.

- Design and assembly a reliable Quench monitoring and protection systems (QPS) for the main dipole and testing samples.
- Design and assembly automated Power supply control integrated with QPS.
- Together with FES to design and manufacture appropriate SC transformer for test samples. The alternative option is to use 100kA PS.

The M&S scope includes:

- Civil construction of the test pit.
- Purchasing of the 24 kA PS to energize the main dipole.
- Purchasing of the 15 kA PS for to energize MDP HTS small coil inserts or/and 100kA PS for FES sample testing, if transformer option is not adopted.
- Purchasing of the appropriate current leads for 24, 15 and/or 100kA. Depending on the design, the leads could be HTS or He vapor cooled.

For the purpose of this proposal, we take advantage of relevant studies, designs and activities performed at Fermilab in the past:

- Building and operating 4 vertical pits for SC magnet and SRF programs.
- Experience with designing, assembling and commissioning of complex quench/magnet monitoring and quench protection systems for the current High Field magnet test-stand, the mu2e experiment, and the HL-LHC production stand.
- Experience in the design and commissioning of complex measurement system, including magnetic field measurement devices.

3.2. Magnet development plan

The scope assumed here includes all activities related to magnet design, fabrication, and vertical test to demonstrate that the magnet meets performance requirements. For the purpose of this proposal, we take advantage of relevant studies and activities performed in the past, in particular:

- Experience from HD model development (design, fabrication and test) at LBNL;
- Experience from FRESCA2 dipole development (design, fabrication and test) at CERN/CEA;
- Design and analysis of the LD1 dipole at LBNL (2010-11);
- Design and analysis of the proposed EDIPO replacement dipole (HEPdipo) by a collaboration of scientists and engineers from PSI, CERN and LBNL (2017-18) [3];
- Availability of components procured for LD1 (conductor/cable, support shell and iron yoke laminations);
- Availability of cabling machine and large coil fabrication infrastructure at LBNL, including the reaction oven and potting vessel procured for LD1. Large coil fabrication infrastructure is also installed at FNAL and BNL but will likely not be available until completion of the IR quadrupole production for HL-LHC. We also assume that suitable infrastructure for cold testing the magnet will be developed at Fermilab as part of the preparations for hosting the facility (see section 3.1).

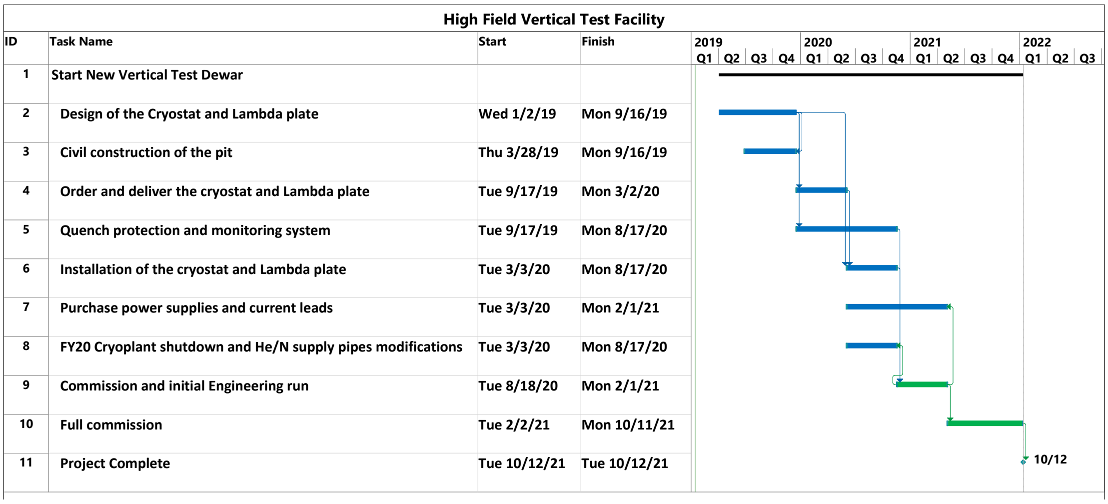
Consistent with the findings from the above studies, a block-coil based on a wide Rutherford cable, and supported by aluminum shell preloaded with keys and bladders, is used as reference. Due to the complexity of the proposed one-off, state of the art magnet system, the development plan incorporates a number of risk-mitigation measures:

- The coil fabrication plan includes practice and spare coils.
- The structure fabrication plan includes one assembly with dummy coils to verify the design calculations and strain gauge instrumentation.
- Two complete cycles of assembly and test are included to allow for an adjustment of pre-load and/or replacing one of the coils with a spare.

4. Project Schedule

4.1. Facility preparation and infrastructure schedule

The schedule for the facility work is shown in Fig. 4.1. It is based on previous experience with similar work at FNAL, and assumes that initial funds for design of the cryostat and civil construction will be available in FY19. For the civil excavation of the pit, the summer of FY19 is a preferable time to perform the task, before the onset of testing the HL-LHC interaction region quadrupoles. The goal is to finish the pit at the beginning of FY22 and begin serving the MDP test program. The facility is then ready to accept the large aperture high field dipole for fusion needs as soon as the magnet is ready.



High Field Vertical Test Facility

ID	Task Name	Start	Finish
1	Start New Vertical Test Dewar		
2	Design of the Cryostat and Lambda plate	Wed 1/2/19	Mon 9/16/19
3	Civil construction of the pit	Thu 3/28/19	Mon 9/16/19
4	Order and deliver the cryostat and Lambda plate	Tue 9/17/19	Mon 3/2/20
5	Quench protection and monitoring system	Tue 9/17/19	Mon 8/17/20
6	Installation of the cryostat and Lambda plate	Tue 3/3/20	Mon 8/17/20
7	Purchase power supplies and current leads	Tue 3/3/20	Mon 2/1/21
8	FY20 Cryoplant shutdown and He/N supply pipes modifications	Tue 3/3/20	Mon 8/17/20
9	Commission and initial Engineering run	Tue 8/18/20	Mon 2/1/21
10	Full commission	Tue 2/2/21	Mon 10/11/21
11	Project Complete	Tue 10/12/21	Tue 10/12/21

Figure 4.1: Conceptual schedule for the facility preparation at FNAL.

4.2. Magnet design, fabrication, and commissioning plan and schedule

Based on the magnet scope of work identified above (see section 3.2), a fairly detailed conceptual plan has been developed that identifies critical design, fabrication and commissioning steps for the large bore high field magnet. The main features of the preliminary design used for planning and costing purposes is described in Appendix A. The key elements of the plan are:

- Conductor development and procurement: new wire will be required for the high field cable, and for about half of the low field cable. Preliminary discussions with OST-Bruker indicate that the large diameter strand is within the proven capabilities but fabrication and comprehensive testing of a prototype wire length will be required prior to full production.
- Cable development and fabrication: no new development is required for the low field cable. The high field cable requires significant R&D. However, a similar cable with a 1.2 mm strand was developed at LBNL as part of the NED collaboration, providing a proof of feasibility and starting parameters. This effort should be started early and has broad relevance to high field dipoles for future colliders. Several prototype cables using representative strand will be required to evaluate mechanical stability and cabling degradation, and to select the final cable parameters (number of strands, width and thickness). Following the RD phase, the cable production includes:
  - Cable fabrication for winding tests and practice coils: one copper cable two Nb3Sn cables for each layer. Procurement of copper and low grade Nb3Sn wire should be planned in the early stage of the project
  - Cable fabrication for final coils: 2 production cable lengths of about 250 m each are included. Each cable length will support the fabrication of two coils (one inner and one outer double-layer).

- Cable fabrication for spare coils: 1 production cable length of 250 m, allowing fabrication of two coils (one of each type)

- Cable insulation: a fiberglass braid will be applied to the cable as currently performed for the HL-LHC IR quads. Two insulation vendors have been vetted for that project and can serve to insulate the cables for this project.
- Coil fabrication: five coils are required for each layer (two practice coils, two production coils, and one spare coil. The first practice coil could be fabricated using low grade Nb3Sn conductor). This tasks includes
  - Detailed design of tooling and components, including modifications based on feedback from the practice coils.
  - Procurement of tooling and components, tooling assembly and test.
  - Test winding using a copper cable.
  - Fabrication of 5 coils for each double-layer.
- Structure design and fabrication: the coil mechanical support is provided by iron pads, yokes and aluminum shell pre-loaded using pressurized bladders and interference keys. Several mechanical components are available from the HD/LD program and could be applied to the magnet. The plan includes:
  - Engineering drawings, procurement and QA of structure components.
  - Assembly test with dummy coils: yoke-shell assembly and instrumentation, the procurement and instrumentation of the dummy coils, the assembly of the dummy coils, pre-load and cool-down to LN, and the data analysis.
  - First assembly and QA: includes one coil pack assembly with Fuji paper, the final coil pack assembly, insertion and pre-load, splices, electrical QA.
  - A full cycle of disassembly and reassembly to allow for a pre-load adjustment and/or replacing one or two coils with spares.
- Magnet vertical test: it is assumed that the magnet qualification tests would be carried out at Fermilab using new infrastructure (cryostat, power supply etc.) installed as part of the preparations for hosting the facility. We plan two magnet tests, consistent with the magnet assembly plan.
- US/EU Collaboration: the option of fabricating two identical magnets should also be considered where the US and CERN share the development effort and take responsibility for a subset of the production steps for both magnets.

The conceptual schedule aligned with the above development plan is shown in Fig. 4.2.

5. Conceptual Cost Estimates

Cost estimates are based on a bottoms-up approach, leveraging a combination of hard-quotes, detailed labor estimates, and engineering judgment based on significant prior experience. We

ID	Task Name	Start	Finish
1	**HEPdipo Magnet**	**Mon 10/1/18**	**Thu 12/14/23**
2	Conceptual design	Mon 10/1/18	Mon 9/30/19
3	Strand R&D & prorotype	Mon 10/1/18	Mon 7/1/19
4	Cable R&D	Tue 7/2/19	Mon 9/30/19
5	Engineering Design	Tue 10/1/19	Mon 3/16/20
6	Design Review	Mon 3/16/20	Mon 3/16/20
7	Strand for production/spare coils	Tue 8/18/20	Mon 8/2/21
8	Strand for practice coils	Tue 3/17/20	Mon 8/17/20
9	Cable for production/spare coils	Tue 8/3/21	Mon 11/8/21
10	Cable for practice coils	Tue 8/18/20	Mon 12/21/20
11	Cable for copper coils	Tue 3/17/20	Mon 8/3/20
12	Parts/tooling for copper coils	Tue 3/17/20	Mon 8/3/20
13	Copper coil fabrication	Tue 8/4/20	Mon 12/21/20
14	Parts/tooling for practice/final coil	Tue 3/17/20	Mon 12/21/20
15	Practice coil fabrication	Tue 12/22/20	Fri 10/29/21
16	Production coil fabrication	Tue 11/9/21	Mon 7/18/22
17	Spare coil fabrication	Tue 7/19/22	Mon 1/30/23
18	Structure engineering design	Tue 3/17/20	Mon 10/12/20
19	Structure procurements	Tue 10/13/20	Mon 6/21/21
20	Dummy coil assembly	Tue 6/22/21	Mon 12/6/21
21	First assembly and pre-load	Tue 7/19/22	Fri 12/16/22
22	First qualification test	Mon 12/19/22	Fri 3/31/23
23	Second assembly and pre-load	Mon 4/3/23	Thu 8/31/23
24	Second qualification test	Fri 9/1/23	Thu 12/14/23

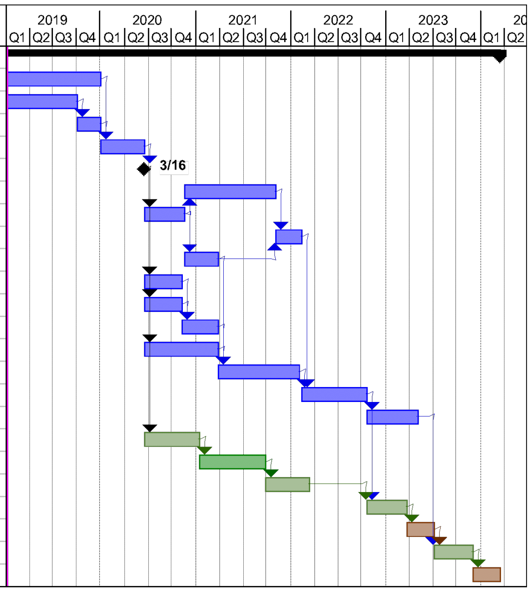


Figure 4.2: Conceptual schedule for the magnet development and commissioning.

note that the superconducting dipole magnet for this facility is a unique magnet that, although leveraging significant know-how and prior experience by experts within the DOE complex, will require some development. The cost and schedule outlined here take that development into account. There are three general cost elements associated with the HTS Cable Test Facility:

1. Infrastructure cost, including civil construction, cryostat and primary power supply, and quench protection and monitoring systems. Cost and schedule information is fairly advanced in this arena due to the availability of hard quotes and/or directly applicable recent experience.

2. Facility testing equipment/infrastructure, including a superconducting transformer and high current power supply to provide current to samples, and variable temperature insert for samples.

3. Magnet cost, including design, development/prototyping, fabrication, and testing of the magnet system. Contingency is not explicitly included; instead we took a different approach, wherein a development phase and two explicit magnet assembly and test campaigns are included in the estimate. This approach can be viewed as an "assigned

contingency" approach that serves to estimate the level of contingency needed for such an advanced one-off magnet system.

Tables 5.1, 5.2, 5.3 provide a summary of the costs for each of these three areas. Table 5.4 summarizes the facility costs, with the magnet development phase identified separately. The detailed breakdown of costs between production, base cost, and contingency for the magnet system is not included in this report but can be made available upon request. Note that magnet development corresponds to 43% of the total magnet cost, and that the magnet "contingency" is 57% when compared to the "Base cost" (i.e. the cost estimate of the actual magnet fabrication and test, excluding development cost).

Infrastructure element	**Cost [k$]**	**Contingency [k$]**	**Subtotal [k$]**
Civil	287.8	57.0	344.8
Cryostat & top plate	362.3	36.0	398.3
15kA leads	60.0	9.0	69.0
24kA leads	100.0	15.0	115.0
Cryostat & Lambda plate	430.0	43.0	473.0
24kA Power supply	458.7	0.0	458.7
Quench prot. & monitoring	958.8	136.0	1,094.8
Total			**2,953.6**

Table 5.1: Costs associated with the primary **Infrastructure** elements of the HTS Cable Test Facility. Note that the contingency for most elements are low since hard quotes are available.

Test equipment element	**Cost [k$]**	**Contingency [k$]**	**Subtotal [k$]**
100 kA SC transformer	200.0	50.0	250.0
100 kA Power supply option	*500.0*	*100.0*	*
Variable temp. insert	600.0	100.0	700.0
Total			**750.0**

Table 5.2: Costs associated with the primary **Test Equipment** elements of the HTS Cable Test Facility. The estimates are based on experience from other projects.

Magnet element	**Labor cost [k$]**	**M&S [k$]**	**Subtotal [k$]**
Conceptual design and analysis	165.0	-	165.0
Final design and analysis	165.0	-	165.0
SC wire	72.0	1,573.0	1,645.0
Cable development and fabrication	355.0	30.3	385.3
Coil tooling (Design, M&S, Assbly)	440.0	399.3	839.3
Coil parts (design and procurement)	258.5	1,016.4	1,274.9
Practice coil fabrication	1,510.0	24.2	1,534.2
Production and spare coil fabrication	1,680.0	84.7	1,764.7
Structure fabrication	190.5	416.4	606.9
Assembly test with dummy coils	240.0	72.6	312.6
First Assembly, QA and shipping	257.5	48.4	305.9
First test	207.5	84.7	292.2
Second assembly, QA and shipping	282.5	18.2	300.7
Second test	165.0	36.3	201.3
Coordination	42.5	24.2	66.7
Total			**9,859.6**

Table 5.3: Costs associated with the primary **Magnet** elements of the HTS Cable Test Facility. These estimates are based primarily on previous experience with the fabrication of magnet systems. The labor and MS costs are based on typical loaded LBNL rates.

Test facility element	**Dev. [k$]**	Base **Cost [k$]**	**Cont.** * **[k$]**	**Subtotal [k$]**
Infrastructure	-	2,657.55	296.00	**2,954**
. Test equipment	-	800.0	150.0	**750**
Magnet	4,364.0	3,552.5	2,059.1	**9,860**
Total	**4,364.0**	**4,552.5**	**2,505.1**	**13,563**

Table 5.4: Summary of cost for the HTS Cable Test Facility, including development, base costs, and contingency. The bottoms-up cost estimate of the magnet system includes a number of development efforts that are here separate from the core final magnet elements; similarly some specific conservative elements, such as the plan for a second magnet assembly and test, are viewed in this table as contingency.
* *Contingency for the magnet corresponds to costed work associated with higher-risk elements, such as spare coils and an iteration of magnet assembly and test. Note that those elements are included in the schedule.*

6. SUMMARY

A conceptual estimate of the cost of a state-of-the-art HTS Cable Test Facility has been developed based on facility specifications developed by the Fusion community, and leveraging expertise and interest from the DOE-OHEP magnet community. The total cost estimate with contingency is ~ M$13.6. We note that this cost estimate has not been subjected to a thorough review, that the appropriate resources have not been identified (nor their availability determined), and that these costs do not include advanced project management costs, such as those associated with earned-value-management (EVMS); the latter may be required for a project of this scale.

The corresponding project schedule suggests the infrastructure can be available on the 2-3 year timescale, with the magnet completion occurring $\sim 1-2$ years later. Having the infrastructure complete early is critical to enable testing of the facility infrastructure using high field magnets from the MDP in advance of the HTS Cable Test Facility magnet completion.

The magnet schedule incorporates all development and "assigned contingency" elements, and is based on an extensive experience base in developing, fabricating and testing magnets similar in nature to the proposed high field dipole.

Appendix

A. Magnetic design and reference parameters

Several conductor and coil layouts choices were investigated as part of the HD/LD and FRESCA2 development, and the recent design effort to identify and evaluate dipole magnet options for the replacement of the EDIPO magnet at PSI. The features and parameters which were considered in these studies include:

- Conductor architecture from 61 to 169 sub-elements
- Conductor diameter from 0.8 mm to 1.2 mm
- Critical current density from 1.5 kA/mm2 to 2 kA/mm2 (15T, 4.5K)
- Copper fraction from 0.7 to 1.2
- Coil area from 50 to 100 cm2 (1 quadrant)
- With or without grading
- Magnetic or non-magnetic pole piece

The main parameters of the design used as reference for this document are listed in figures A.1 and A.2

Parameter	Unit	Cable 1	Cable 2
Strand diam.	mm	1.1	0.8
No. strands		37	51
Cable width (bare)	mm	22.0	22.0
Cable thickness (bare)	mm	1.95	1.4
Insulation thickness	mm	0.15	0.15
Cable width (ins.)	mm	22.3	22.3
Cable thickness (ins.)	mm	2.25	1.7
Inter-layer insulation	mm	0.4	0.4

Strand area	Unit	Cable 1	Cable 2
Individual cable	mm^2	35.16	25.63
Magnet (1 quad)	cm^2	22.5	32.81

Figure A.1: Cable parameters used to develop the cost and schedule.

Each pole is composed two double-layers, one at the mid-plane (inner) and one at the pole (outer). Both double layers are graded, to maximize the magnetic efficiency. The low field conductor is the same as LD1 to take advantage of available cable lengths and reduce the new conductor procurement. It is assumed that the high field conductor can maintain the same effective filament size in the larger diameter wire by increasing the number of sub-elements.

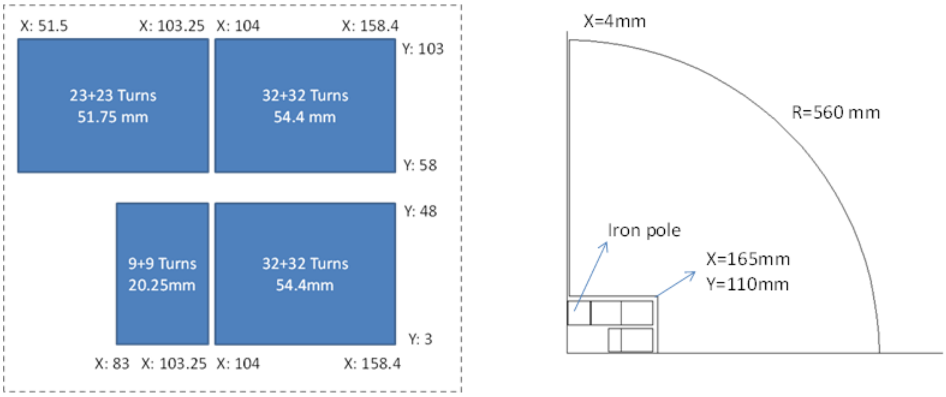


Figure A.2: Coil and magnet parameters used to develop the cost and schedule.

REFERENCES

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[3] P. B. et al., “Conceptual design of a large aperture dipole for testing of cables and insert coils at high field,” *IEEE Trans. Appl. Supercond*, vol. 28, no. 3, 2018.