Summary for Internal Review of the Technology Options for the muon collider magnets

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The scope of this document is to provide to the internal review committee an overview of the possible technology options for the development of high field dipole and quadrupole combined function magnet for the collider ring compatible with the present requirements coming from beam dynamic considerations, evaluation of the beam induced heat load and radiation on the coil and cryogenic evaluations of the operating temperature of the magnets. The most restricting requirements for the magnet design comes from the machine lattice design in which peak field for the dipole and quadrupoles are scaled accordingly with magnet aperture (max 16 T peak field for arc magnet and 20 T peak field limit for IR). Due to the muon decay in the lattice the beam induced radiation load on the superconducting coils requires the use of a thick tungsten shielding solution to limit the maximum power on the cold mass area less than 5 W/m and a cumulative dose equals to 20-40 MGy for 10 years of the machine operation.

Since the necessity of the tungsten shielding affects heavily the aperture dimensions of the magnets a constant design iteration process involving magnet design, lattice evaluation and radiation load estimation is mandatory during the entire review process of the collider design. A first cryogenic evaluation of the collider ring and balance of the heat load coming from the muon decay pointed out a boundary on the superconducting coil operating temperature above 4.5 K to address a maximum overall electrical power consumption of the cryogenic system under 2.5 kW/m.

Based on all these considerations a first evaluation of the different superconducting materials has been performed. Even if LTS conductors (NbTi and Nb3Sn) can be considered known developed technologies their use in the collider ring could not meet all the magnet requirements especially if an operating temperature of 4.5 K or above is considered as a realistic goal. With these constraints, hybrid configurations involving Nb3Sn and HTS conductors could represent lower cost solutions compared to all-HTS designs despite the low level of readiness of HTS inserts and the limit of the operating temperature dictated by the LTS conductor.

Depending on the HTS developing path in the next years on the thermal stability of the magnets and the optimization of field quality provided, all-HTS designs could become feasible compact solutions operating at higher temperatures compared to LTS designs.

Three different magnet design options are presently considered for the magnet design: cos-theta coil design, block coil and canted cosine theta coil design. The different designs will be compared and analyzed basing also on the superconductor type used with particular focus on stress management at the coil level coming from the requirements of high field (above 10 T) and high values of beam aperture (150 mm). Each design has also to be evaluated for a combined function magnet design required for the lattice design in which dipole/quadrupole and dipole/sextupole independently tuneable field are considered.

Two different coil layouts: nested solutions or integrated asymmetric coils design are considered and evaluated in the design process.

Feedbacks on the evaluations of the technology options could be obtained from the results of the 20+ T development program in the US and the CERN HFM development program currently ongoing and driving the research development on high field Nb3Sn and hybrid Nb3Sn-HTS magnet designs. Technological considerations on the readiness of only HTS designs will be also derived from development program inside INFN for the PNRR-IRIS in which a 10 T steady state dipole design is foreseen with a beam aperture of 80x50 mm^2.

To rapidly evaluate the different superconductor technologies and evaluate the allowed region in the aperture-field space parameter for the lattice design, analytical formulae of the magnet performance are considered. Three different operating temperatures (1.9 K for NbTi, 4.2 K for Nb3Sn/*Re*BCO and 20 K for *Re*BCO) have been evaluated using scaling laws of the critical current density of the superconductor. As a starting point in the design iteration, analytical formulae for the generated dipole and quadrupolar field provided by cos-theta and sector-coil like magnet design are considered. Three limiting factors are considered for the magnet performances:

1) maximum cost of the coil fixed at 100 keuro/m (comparable with FCC requirement)
2) maximum stress on the midplane of the coil (100 MPa for NbTi, 150 MPa for Nb3Sn and 300 MPa for HTS)
3) maximum hot spot temperature during quench event (350 K for NbTi and Nb3Sn, 200 K for HTS)

To directly compare magnets with different magnetic field and different bore aperture, a common parameter value must be considered. Different approaches are currently under evaluation: fixed enthalpy margin from the superconductor critical surface, fixed engineering current density of maximum coil cost all aimed at evaluating the wider acceptable area in the aperture-field space parameters for the magnet performances. Inside the working plan, the collection of all magnet requirements and the iteration on possible magnet aperture-field combinations play a key role and must be addressed in the first year of the design study. The analytical formulae approach will be used to identify the magnet configuration on which detailed evaluation will be performed in the design study focusing mainly on the arc combined function magnets and providing considerations and limitations for the IR region magnet design.