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Specification for the LEBT quadrupole and solenoid magnets

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Riassunto / Abstract

This Document, together with the enclosed drawings and technical notes, specifies the Solenoid and quadrupole magnets of the CNAO's LEBT transfer lines.
Magnetic performances to be obtained, material to be used, technical construction procedures, main dimensional tolerances, intermediate construction and final tests, packing and shipping procedures, are defined and they represent, if not otherwise allowed, the goals that CNAO must reach and the awarded builder must follow. Obviously the document cannot cover the all know how needed for such a realization, then, any missing specification or deviation from what specified will be object of discussion in collaboration with the builder and will have to be, in any case, approved by CNAO.

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INDICE / INDEX

1 GENERAL

1.1 INTRODUCTION

A synchrotron machine, capable of accelerating either light ions or protons, is the basic instrument of the CNAO (Centro Nazionale di Adroterapia Oncologica), the medical center dedicated to the cancer therapy, at Pavia, in Italy.
The machine complex includes a proton-carbon-ion linac that accelerate the particles till to the energy of 7 MeV/u. An injection line (LEBT and MEBT) transport them to the synchrotron ring where the injected particles are accelerated and extracted with an energy ranging from 60 to 250 MeV for protons and from 120 to 400 MeV/u for carbon ions. An extraction line (HEBT) drives the beam till to the treatment rooms, where the patients are located.

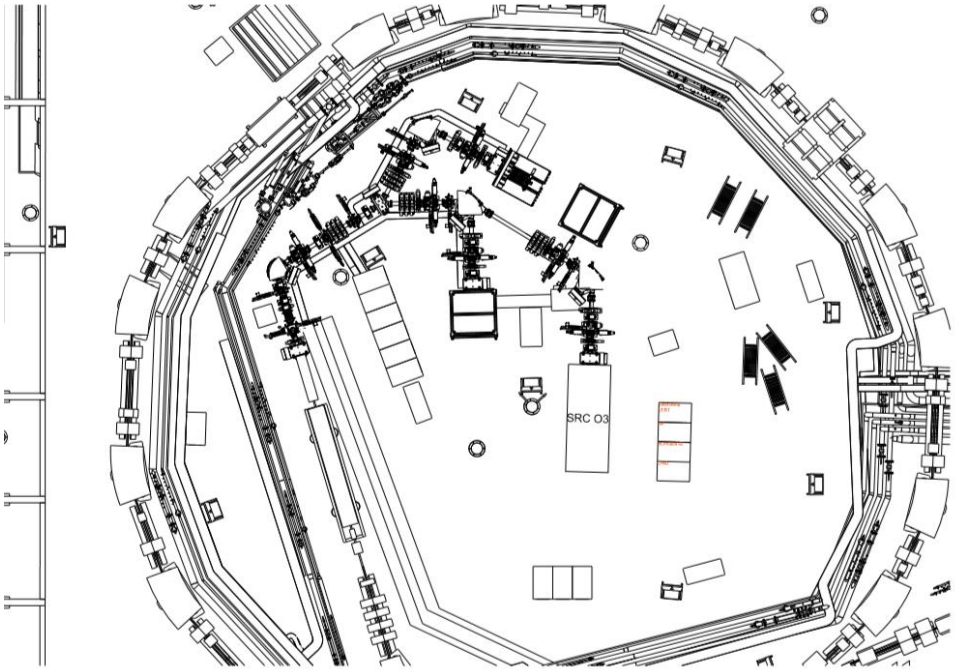

Figure 1 LEBT layout

This contract is mainly for industrial engineering, design, construction, testing and shipment of the LEBT quadrupole and solenoid. The magnetic measurements will be part of this contract.
The engineering parameter list and base line designs have also been established.
Seller is not expected to carry out this part of the work.
Any omissions in this document shall not relieve the seller of his obligation to furnish each magnet that is inherently complete and can be treated as a standalone turnkey entity. It must perform satisfactorily in accordance with this specification.

1.2 SCOPE OF WORK IN GENERAL

1.2.1 WORK INCLUDED

1.2.1.1 Seller shall provide appropriate manpower for production related engineering, mechanical detail design and appropriate detail drawings of the subject magnets governed by this specification. It is mandatory that all the design work to be carried out by utilizing CAD. CNAO project is using AUTODESK software package INVENTOR. All files provided by CNAO can be in INVENTOR format. The compatibility of said files with respect to his own system is the sole responsibility of the seller's. It is required that all the files, submitted by the seller, to be in INVENTOR format, or .DWG or .DXF format on CD disks and be compatible with CNAO's system.

1.2.1.2 Any modification to the magnet design must be approved by CNAO. The seller will be fully responsible in the production of subject magnets and their performances according to paragraph 1.9.

1.2.1.3 Seller shall furnish all the necessary labour, materials, tools, fixtures and facilities for the fabrication, assembly, testing, quality assurance, packaging and shipment of the subject magnets. He shall provide all the necessary equipment, materials, tools, instruments, facilities and labour to manufacture and test the magnets and demonstrate that this specification be met.

1.2.1.4 The seller shall prepare all the tool and fixture drawings, special to this contract, and submit a hard copy of "as built" drawings and INVENTOR files to CNAO for future references.

1.2.1.5 The seller shall prepare and submit a complete set of documents to CNAO at the conclusion of this contract, they shall include complete set of "as built" assembly and detail drawings of all the components associated with this contract, both in hard copies and on disks in accordance with item 1.2.1.1. The drawings, that must be approved by CNAO, shall be so prepared that a third party can use them to produce same components in the future without any difficulty. In addition, the copies of relevant quality assurance reports, the operation and maintenance manuals shall also be part of deliverable if appropriate.

1.2.1.6 The seller shall prepare a complete Quality Assurance procedures specifically designed for this contract. A general manual published by some trade organization or government agency is not acceptable.

1.2.1.7 All the documents, including drawings, shall be prepared in English language, shall follow ISO rules and shall be given also as files.

1.2.1.8 The seller shall nominate a senior specialist who will act as project leader and be responsible to CNAO for all aspects of this contract throughout the contractual period. In particular he shall provide regularly an updated detailed time schedule covering material procurement, magnet manufacturing and testing.

1.2.2 WORK NOT INCLUDED

1.2.2.1 Magnet engineering parameters.

1.2.2.2 Base line magnet design.

1.3 APPROVAL

1.3.1 Equivalent materials may be substituted for those identified with a particular supplier, but no such substitution shall be made prior to receipt of written approval from CNAO.

1.3.2 Before commencing construction the seller must submit to CNAO for approval all the major tool and fixture designs, but this approval process shall not relieve the seller from any of his responsibilities of performing satisfactory tasks governed by this specification

1.3.3 A special approval to the magnet assembly must be given by CNAO after verification of the full compatibility of the subject magnets with the existing equipment devices.

1.4 APPLICABLE DOCUMENTS

1.4.1 The drawings and specifications, supplied with this document, shall be considered as an integral part of this specification. These drawings and specifications depict the baseline design of the magnets.

1.4.2 Any conflicts, noted by the seller, among the requirements of any documents provided by CNAO shall be referred to its designated representative for clarification before proceeding with any work.

1.5 DESIGN REVIEWS

1.5.1 Subsequent to contract award, seller is expected to complete and deliver to CNAO a Preliminary Design Report (one copies plus files) within one month or less in duration. This PDR shall describe engineering and design of those parts which seller wishes to deviate from CNAO's baseline design. The submitted documents shall be in sufficient details so that CNAO can review and assess the merit of proposed changes. The tender is requested on the base of CNAO's baseline design; hence CNAO reserves the right to reject any or all of the proposed deviations without the obligation of giving any justifications. Seller shall not have the right to vary his quoted price due to this rejection. A preliminary design review meeting will be scheduled two weeks after receipt of the PDR. After the satisfactory review, CNAO will authorize the seller to proceed with the detail design and to purchase some of the long lead items.

1.5.2 Subsequent to written approval of the PDR by CNAO, the seller shall proceed expeditiously to complete all the necessary detail engineering; design and appropriate detail drawings of the components and associated tools and fixtures. CNAO will review all or part of the documents at its discretion to assure that the quality of the detail designs is commensurate with this specification. CNAO will authorize, after satisfactory review, the seller to proceed with production of all or part of the components under this contract.

1.5.3 The preliminary review meeting could take place at seller's premise. The review and approval processes shall not relieve the seller from his full responsibility of producing the subject magnets to meet the requirements as given herein.

1.6 INSPECTIONS AND TESTS AT SELLER'S PLANT

1.6.1 Representatives of the CNAO may visit seller and his collaborator's facilities at any reasonable time to review the progress of this contract.

1.6.2 The seller shall give two week advance notice of the tests or inspections to be performed under the provisions of this specification. CNAO may witness any or all of these procedures at its discretion.

1.7 ACCEPTANCE TESTS AT CNAO SITE

The final acceptance tests shall take place in the CNAO centre, Pavia, Italy. CNAO reserves the right to reject any magnet should there be defects discovered at that time.

1.8 QUANTITIES AND MILESTONES

1.8.1 QUANTITY

- LEBT quadrupoles 7
- LEBT solenoid 2

1.8.2 MILESTONES

The following target dates and major milestones are CNAO's objectives in the design, construction, inspection and delivery of the magnets; they shall be considered an integral part of this specification.

Time (months)	Milestones
T	Contract award date.
T+1	Preliminary design report received by CNAO.
T+1.5	Preliminary design review. Begin procurement of long lead items if authorized. Proceed with tooling manufacturing if authorized.
T+2.5	Detail design complete Construction of magnets Magnetic measurements
T+9	Magnets ready to acceptance tests at the company premises
T+10	Complete delivery on CNAO site of magnets

1.8.3 PROGRESS REPORT

Monthly progress report shall be delivered at CNAO on or before 15th day of each month. CNAO will use it to track the status of this contract.

1.9 MAGNET PARAMETER LIST

LEBT QUADRUPOLE MAGNET PARAMETER LIST

Maximum Field Gradient	T\m	2.5
Bore Radius	mm	60
Magnetic Length (at max energy)	mm	124
Good Field Region (all field levels)	mm	±42 (hor.) ±44 (vert.)
Int. Field Quality	ΔGL/GL	≤ $\pm 2 \times 10^{-3}$
Turns per Pole		16
Maximum Current	A	245
Conductor dimensions	mmxmm	6x6
Cooling hole diameters	mm	4
Resistance	mΩ	22.36
Inductance	mH	0.8
Voltage at warm	V	5.72
Power	W	1398.52
Number of cooling circuit		1
Temperature Rise	°C	12
Total Flow rate	L/min	1.52
Pressure Drop	bars	6

LEBT SOLENOID MAGNET PARAMETER LIST

Maximum Current	A	250
Magnetic field at maximum current	T	0.566
Magnetic length at maximum current	mm	310
Geometric characteristics:		
Mean Turn	mm	984.58
Inner Diameter	mm	110
Outer Diameter	mm	540
Axial Height	mm	300
Composition:		
Winding with hollow conductor		
Conductor dimensions	mmxmm	9x9
Cooling hole diameters	mm	6
Round corner	mm	1
Winding with pancakes		
Number of single pancakes		28
Number of turns per pancakes		20
Isolations:		
Hollow conductor: 1 layer of fibber glass	mm	0.25
Pancake: 1 layer of fibber glass	mm	0.20
Mass: 2 layers of fibber glass	mm	0.25
Electrical characteristics:		
Resistance at 20°	mOhm	183.27
Tension at warm	V	44.35
Nominal Current	A	236
Dissipated Power	W	10466
Cooling characteristics:		
Number of cooling circuits		14
Inlet water temperature	°C	25
Water temperature rise	°C	4
Total water flow rate	L/min	36.5
Corresponding pressure drop	KPa	303
Masses:		
Hollow conductor	Kg	256
Epoxy Resin	Kg	15.5
Total Coil Mass	Kg	271.5

2 MAGNETS AND SUPPORTS

2.1 GENERAL

2.1.1 CNAO provides engineering parameter list and specification drawings of magnet assemblies. The specification drawings, in very simplified form, show the baseline design of the magnets and associated parts. Manufacturing dimensions and tolerances, except where specified by CNAO, shall be the responsibility of the seller.

2.1.2 It is mandatory that all the parts are inspected and found conforming to specification and drawing before proceeding with assembly operation. Seller shall inform CNAO of any non-conformance of the parts, and his intended method of repair. CNAO reserves the right not to accept any repairs or to reject the proposed repair method if it deems not compatible with the functionality and reliability of the component. The time needed to rectify or remake the rejected parts shall not constitute a cause for schedule delay.

2.1.3 The electrical terminals and the coolant manifolds are part of the magnet assembly, safety cover(s) shall be provided for personnel protection against electrical hazards. The hoses and fittings shall be done in accordance with CNAO standard which will be provided in the appendices of this specification.

2.1.4 Protective coating shall be applied to all the external surfaces. The external coating shall consist of one coat of rust inhibiting primer and finish with two coats of epoxy or polyurethane paint of CNAO agreed colour.

2.1.5 Every magnet must be equipped with appropriate welded grounding bolt and nut. The size of the hardware shall be in accordance with those specified in the appendices item 3.2. CNAO will supply the grounding cable.

2.1.6 The support components as shown on the specification drawings are part of this contract. CNAO has specific requirements on these supports for the reasons of initial alignment procedures and future maintenance of these magnets. Therefore, no deviation from the baseline design is allowed.

2.1.7 The magnets built for this contract must comply with the requirements of paragraphs 8.8, 8.9, 9.7, 11.1 of IEC EN 60601-1: 2007. At the end of the construction with the quality assurance documentation an explicit statement of compliance with the above standard and the minutes of the performed tests must be delivered.

2.2 YOKE ASSEMBLY

2.2.1 MATERIAL FOR LAMINATIONS

2.2.1.1. The lamination material must not only possess suitable characteristics for punching operation but also have superior magnetic properties, such as high saturation induction; low and uniform coercivity; very low aging effect; etc.
The steel shall have extra low carbon content; minimum amount of impurities; large grain size. The mill processing should be designed to provide a non aging product with a low coercivity and essentially non-directional magnetic characteristics. Sheet material shall have excellent flatness with minimum crown and smooth surface to achieve maximum packing factor.

2.2.1.2. Yoke material

The material of lamination for the quadrupole magnet shall be of non-oriented and annealed electrical grade silicon steel sheet. The magnetic and electrical properties shall be equivalent to or better than EBG grade STABOCOR 1200-100A. The thickness of lamination shall be 1.0 mm or thinner.

The material for the solenoid yoke is XC10 steel.

2.2.1.3. The chemical composition (% wt) of the plate material for the magnets shall be as follows:

Carbon 0.003 max.

The composition (%wt) of the other chemical elements must be specified by the offerer in his tender. CNAO suggests the following maximum content for each element type:

Manganese 0.200 max.
Phosphorus 0.005 max.
Sulfur 0.005 max.
Silicon 0.005 max.

2.2.1.4. The required permeability, for the magnets shall be equal to or better than those defined as follows:

H = 45 A/m, $B \geq 0.2$ T
H = 125 A/m, $B \geq 0.9$ T
H = 2450 A/m, $B \geq 1.5$ T
H= 13900 A/m $B \geq 1.8$ T

2.2.1.5. In principle, the steel supply should be entirely stable with respect to time in both coercivity and permeability. Since the operating temperature of the magnet core is expected not to exceed 25°C, stability of the magnet properties refers to many years of operation at this temperature.

2.2.1.6. In order to maintain constant magnetic characteristics, no mechanical processing of the steel, with exception of punching, can be permitted after the sampling for magnetic measurements. The steel sheets in their final condition must be suitable for precision punching and for assembling straight stacks with a large packing factor. The detailed specifications and the acceptance procedures will have to be established by the manufacturer and must be agreed upon by the steel-maker, the punching firm and CNAO.

2.2.1.7. The hardness of the material influences the dimensional accuracy of the laminations. Therefore, it is recommended that the steel-maker specify the hardness range of the sheet material to be between 20 to 40 on Rockwell B scale.

2.2.1.8. The sheets should be flat and free of internal stresses in order to avoid local perturbations in the stack and movements of the gap profile after punching. Although the acceptance criteria and tests will be the responsibility of the manufacturer, the following methods, which are based on CNAO experience, are suggested:

when a sheet of dimensions 500*1000 mm2 is laid on a marble, the distance from any point of the upper face to the marble must be smaller than 2.5 mm;

when a sheet is freely suspended, the sagitta in the rolling direction measured over a length of 1000 mm must be smaller than 10 mm.

2.2.1.9. The average thickness of the steel sheets contained in each delivery pallet must be maintained within an interval of ± 0.03 mm of the nominal value. The thickness of each individual steel sheet be kept within ± 0.09 mm of the nominal value as measured at any point of the sheet.

The spread in thickness transverse to the rolling direction shall be kept within ± 0.05 mm inside the region limited by two lateral strips of 10 mm width.

2.2.1.10. The surface of all sheets must be smooth. Flaws, cores and small pits, which should only be isolated ones, must not exceed the permissible thickness variation. The surface roughness shall be in the range 0.3 to 2 μm Ra (ISO/R4689).

2.2.1.11. The core plating is required; it shall be the type capable of providing better than 20 ohms-cm2 interface resistivity. The test shall be performed as per the latest revision of ASTM Standard Test Method A-717-81 or latest one.

2.2.1.12. The lamination should be produced by one or two steps stamping process with compound punch and die, according to the experience of the punching firm for achieving the requested tolerances. The stamping process procedure must be submitted to and approved by the manufacturer in concomitance with the CNAO. The material and thickness of the punching tool shall be commensurate with the quantity of the laminations required. Excessive sharpening, due to inferior material and heat treatment is strictly prohibited. The punch and die holders shall be made of appropriate material of sufficient thickness to prevent the distortion during punching operation.

2.2.1.13. The critical pole contour portion of the stamping tool shall be so designed and fabricated that the modification of this contour will not constitute either high cost or long schedule delay to CNAO.

2.2.1.14. The dimensional variation between the lamination shall be less than 10 μm. Burrs on the pole and its vicinity shall be less than 30 μm, if de-burring operation is needed, the manufacturer should exercise caution not to fold burrs over and not to destroy the core plating.

2.2.1.15. Witness mark shall be provided so that evidence of the appropriate orientation of the lamination during stacking procedure can be readily visualized.

2.2.1.16. Four sample of each type of lamination must be subjected to complete inspection by coordinate measurement machine and their report shall be submitted to CNAO for approval prior to actual production. During production, a sample lamination shall be pulled at interval to be determined by the manufacturer for inspection and for determining if tool sharpening is necessary. Two more lamination shall be subjected to same inspection procedures after each sharpening. Manufacturer shall inform CNAO of any deviation of lamination dimensions from the original set after sharpening procedures. No production run is allowed prior to written approval from CNAO. CNAO reserves the right to take sample laminations at any time for inspection, if any of the samples fail to meet the dimensional tolerances, all the laminations punched since the last accepted sample lamination will be rejected.

2.2.1.17. It is requested that each magnet yoke be assembled with a mixture of laminations from all batches of the sheet steel delivered by the steel-maker. Suitable marker is required of each batch of the steel so that properly mixed stacks can be visually identified. CNAO reserves the right to approve the mixing scheme proposed by the manufacturer.

2.2.1.18. The gluing of the laminations is mandatory in order to improve the torsional rigidity of the magnet assembly. The adhesive for gluing laminations shall be EBG Stabolit 70 or equivalent, to be approved by CNAO. The shear strength shall be better than 100 kg/cm^2. Manufacturer shall obtain a certified report concerning the test results of his glued samples.

2.2.1.19. CNAO requires that every 25 to 30 mm thick lamination stack to be oriented recto-verso so that systematic punching errors of the pole profile with respect to the median plane can be minimized.

2.2.1.20. The yoke assembly must be stacked with a pressure of 15-20 kg/cm^2 on a rigid fixture with well-machined reference surfaces. The stacking procedures and fixture design shall have CNAO's concurrence.

2.2.1.21. The packing factor, defined as the total weight of the laminations in the stack divided by the weight of solid steel of an equal volume to that of the stack, must be:

$$> 0.97 \pm 1\times10^{-2}.$$

The specified tolerance is the maximum accepted variation of the packing factor from magnet to magnet, throughout the whole production.

2.2.1.22. The yoke assembly must be dimensionally stable with time. The stacking pressure and the quality of the welds must be such that normal handling and transportation of the magnets will not alter their mechanical tolerances.

2.2.1.23. Each part of yoke shall be identified by a serial number stamped on some suitable location. The results of all tests on the yoke assembly must be referred to this number.

2.2.2 ACCEPTANCE TESTS AT MANUFACTURER PREMISES

2.2.2.1. Yoke assembly shall be inspected and the relevant data should be recorded on magnet assembly QA sheet.

2.2.2.2. Magnet assembly shall not be commenced until after CNAO has accepted the yoke assembly.

2.3 EXCITATION COILS

2.3.1 MATERIALS

2.3.1.1. The hollow conductors shall be oxygen free high conductivity copper (OFHC) or deoxidized low phosphorus copper (DLP) or boron deoxidized copper 1170 (B-DCU). The conductivity of the material shall be at least ninety-nine percent (99%) of the International Annealed Copper Standard (IACS), this value shall be met in the temper as used by the seller. The material shall be in accordance with ASTM Specification B-188-88 or latest revision thereof.

2.3.1.2. The seller shall obtain a certified copy of hydrogen embrittlement test report from his conductor supplier and forward it to CNAO for future reference. The specimens shall not show any gassing or open grain structure characteristic of embrittlement.

2.3.1.3. The size of the conductor shall be in accordance with parameter list. The length of the conductor shall be such that there will be no or minimum number of internal splices needed for a single coil.

2.3.1.4. Coil Electrical Terminals

Both external electrical terminals shall be made of oxygen free (OF) copper. The external terminal blocks shall be silver brazed to the conductor to produce a low electrical resistance and high mechanical strength joint. The electrical conducting surfaces of the external terminals shall be silver plated, the plating shall be continuous and of good adhesion. It shall not peel or crack when the joint pressure of 300 kg/cm2 is exerted. The internal terminal with spigot shall be brazed as per 2.3.3.4 of this specification.

2.3.1.5. Thermal Switch

Two thermal switches in parallel shall be provided for each water circuit to protect the coils from inadvertently over temperature during the operation. They shall be located at the warm ends of each electrical and water circuit and shall be set to activate at a temperature of 60 +/- 3 °C. The switch base plate shall be made of copper material and must be silver soldered to the conductor. The switches shall be capable of interfacing with computer system so that any faults can be located and corrected without undue delay. CNAO requires that Thermik sensor part number LK1.060.03.0600/0600, or equivalent, to be used for this purpose.

2.3.2 SAMPLES

2.3.2.1. General

Samples demonstrating the adequacy of the procedures and fabrication techniques shall be submitted to a reputable testing laboratory for evaluation prior to fabrication. Seller shall submit a copy of certified test report to CNAO for review and approval. Seller is not allowed to proceed with the fabrication without written approval of the sample test reports from CNAO.

2.3.2.2. Brazed Joints

Three sample joints are required for each individual who will make if necessary brazed joints for this contract. These sample joints will be sectioned and examined for complete filling of the brazed joint, voids and leaks, and excess brazing material, which might obstruct the water passage. The sample joints will also be pull tested, the brazed joint shall develop, in tension, at least 80% of the strength of virgin copper of the same net cross section.

2.3.2.3. Epoxy Bond Strength

The seller shall furnish two samples of coil cross section. The samples must demonstrate that the cleaning and impregnation procedures, intended for production, are capable of developing minimum bond strength of 60 kg/cm2 in shear. The samples will be tested by slicing a section 20 mm long by three turns thick from central portion of the samples, the fiber glass epoxy layers shall be removed from all the external surfaces by appropriate method. The shear strength shall be estimated from the compressive force required to shear out the middle conductor from between its two adjoining conductors divided by the total bonded area. The impregnated sample shall be 250 mm or longer in length.

2.3.3 COIL FABRICATION

2.3.3.1. Environment

Coils shall be fabricated in an area free of metallic particles, dirt, and welding or chemical fumes. Conductors, insulation materials and already insulated but not impregnated coils shall be stored in a clean and dry area.

2.3.3.2. Cleaning and Handling

Exterior surfaces of all the conductors shall be thoroughly degreased prior to the insulation procedure. The cleaned copper surfaces and insulation material shall be handled by personnel wearing clean gloves.

2.3.3.3. Grit Blasting

Grit blasting is optional. Pre-production impregnation samples shall be prepared by the same intended procedure.

2.3.3.4. Brazing

All conductor splices shall be located on the external side of the coil. They shall be hard brazed without flux of any kind. The solder alloy shall be of AWS-ASTM BCUP-5 or its equivalent. There are various methods for brazing process; CNAO prefers either electrical resistance or induction heating method for better temperature control reason. The coolant duct must be shielded with inert gas during the brazing cycle. Two thermocouples shall be attached to the conductor, one on each side of the joint approximately 30 mm away from it, the brazing temperature, as indicated by the thermocouple instrument, shall be maintained at appropriate level in commensurate with the solder alloy. The thermocouples shall be calibrated at mutually agreed periods. All the external excess solder material shall be removed by filing or grinding flush with the adjacent solder-free areas. All the metallic chips, shavings, dirt, and

other foreign matter shall be removed prior to insulation process. Seller shall exercise caution not to have coolant path obstructed by excessive solder alloy.

2.3.3.5. Leak Tests After Splicing

Upon completion of each splice, the brazed joint shall be tested for tightness; this test shall be made by using a helium sensitive mass spectrometer leak detector. As a substitute check, a halogen sensitive detector may be utilized by using halogen compound under 10 kg/cm2 pressure in the bore of the conductor while the joints are being probed. All joints, which show evidence of any leak under either test option, shall be replaced with new joint. CNAO does not accept any repaired splices.

2.3.3.6. Corner Build-ups

In making the bends it is anticipated that the copper will upset and assume a trapezoidal shape. It is also anticipated that there may be a build-up at the inner corners due to ground insulation overlap. In no event shall the total build-up, due to either or both causes, prevent seller from producing dimensionally satisfactory coils. If necessary, the upset material is allowed to be removed (maximum cross-section reduction at the corner = 1% of original conductor's) either by filing or by grinding, the coils so treated shall be cleaned of all the metallic chips, shavings, dirt and other foreign matter before application of insulation.

2.3.3.7. Electrical Insulation

The following insulation are assumed.

2.3.3.7.1 Inter Turn Insulation

The inter turn resistance shall be provided by one serving of Amino Silan or equivalent treated, medium plain weave fiber glass tape, half overlapped..

2.3.3.7.2 Ground Insulation

The ground insulation shall be provided by two servings of Amino Silan or equivalent treated, medium plain weave fiber glass tape, half overlapped.

2.3.3.7.3 Fillers

All voids within the coil shall be packed with glass roving or glass laminates such as NEMA G-10 or equivalent, seller shall avoid resin rich area within the coil package in order to prevent internal crack or delamination.

2.3.3.8. Resin System, Impregnation and Curing

2.3.3.8.1 The coils will be subjected to long term radiation exposure. The coil insulation system must not only be suitable for electrical and mechanical properties, but also be able to withstand minimum radiation doses of $10^{\wedge 7}$ Gy without harmful effects. The flexural strength measured on irradiated samples after being exposed to the integrated dose of $10^{\wedge 7}$ Gy must be not less than 50% of the value measured on non irradiated samples. The recommended fiberglass tape is known to have excellent radiation resistance property. The tenderers are required to state in his tender specifically the type of the resin system, impregnation and curing procedures, which he will use for the coils. The radiation resistant capability of such system shall also be demonstrated with proper back up test data or data from some creditable literature. The maximum operating temperature of the coil can reach 63 °C, therefore, it is essential that the insulation system must retain its mechanical and electrical properties beyond that temperature, and must withstand repeated thermal cycling without failure.

2.3.3.8.2 The coils must be vacuum-pressure impregnated in a single operation. CNAO requires that the coil to be casted in a suitable closed mold.

2.3.3.8.3 The thickness of unreinforced resin on the surface of a finished coil must not exceed 0.5 mm. Sacrifice tape is allowed if seller deems necessary.

2.3.3.8.4 The insulation in the vicinity of the coil leads will need special attention. The seller is required to show, prior to production, that his design will provide adequate strength and also will avoid excessive resin build-up in that area. It is

suggested to use TedlarTM tape along the straight parts and the coil heads as release agent.

2.3.3.8.5 The finished coils shall be free of voids, fissures, cracks, dry spots or other defects. Coils with internal defects shall be rejected, no repair is allowed. External defects may be repaired, contingent in each instance upon prior authorization from CNAO, including approval of the procedure and material.

2.3.3.8.6 The external surfaces may be cleaned if necessary to improve their appearance. Painting on any part of the coil surfaces is not permitted unless otherwise provided in this specification.

2.3.4 ACCEPTANCE TESTS AT SELLER'S PREMISES

2.3.4.1. Visual Inspection

All coils shall be visually inspected, and must be free of cracks, voids, delaminations, dry spots and other flaws or defects. The insulation shall not exhibit resin rich areas not exceeding 1.0 mm; the coils, which fail to satisfy any of these criteria, shall be rejected.

2.3.4.2. Dimensions

All coil dimensions shall be measured and shall be correct to within the specified tolerances.

2.3.4.3. Electrical Resistance

The electrical resistance of all the coils shall be measured by using a bridge capable of measuring DC resistance to within 1%. Tested data shall be recorded on the coil data sheet. The values shall be corrected to 20° C, and shall be within ± 2% of the mean value of all the coils.

2.3.4.4. Inter Turn Insulation

All the coils shall be tested for inter turn voltage hold off capability. Coil shall be treated as the secondary winding of a transformer, a voltage of 2.5 kV shall be induced across the coil termination for a period of one minute, and the corresponding primary current recorded. Any indication of short circuit between turns shall result in rejection of the coil. Seller can propose an alternative test method for CNAO's approval.

2.3.4.5. Ground Insulation

2.3.4.5.1 Ground insulation of the coil shall be tested by immersing coil in ambient temperature tap water with the terminals exposed above the water level (preferred procedure) or by wrapping the whole coil tightly with aluminum foil. A DC voltage of 2.5 kV shall be applied between one of the coil terminals and water bath or aluminum foil for one minute, the leakage current shall be recorded in the coil data sheet. A ground insulation resistance of one hundred (100) mega-ohm or higher is required.

2.3.4.5.2 Apply an AC voltage of 3.5 kV between coil and water bath or aluminum foil for one minute, and record the leakage current in the coil data sheet.

2.3.4.5.3 Repeat Measurement as in 2.3.4.5.1, and record the leakage current in coil data sheet.

2.3.4.5.4 Any coil exhibiting evidence of breakdown or significant changes of insulation resistance during these tests shall be rejected.

2.3.4.6. Coil leak test

All finished coils, including its fittings, shall be tested for possible leakage by water at a minimum pressure of 3MPa for one hour. Any evidence of leakage from the coils or its connector shall results in rejection of the coil.

2.3.4.7. Flow rate test

Water flow rates shall be measured and recorded by applying 0.7MPa nominal differential pressure between coil inlet and outlet ports. The flow rates with respect

to pressure drop shall not deviate from that stated in parameter list by more than 20%. The pressor gauge adopted for the test shall have a range of about twice the the measured pressure and should be recently calibrated, with a total accuracy better than 5% of its range. It is acceptable to apply the pressure only at one end, measuring the flow at the otters by a graduate thank and a chronograph for at least one minute. In that case the inlet nominal differential pressure shall be 0.7MPa, neglecting the outlet pressure drop.

2.3.5 DOCUMENTATION

2.3.5.1 **QA**

Data of each coil shall enter into QA document of the individual magnet assembly where it resides.

2.3.5.2 **Coil Identification**

Each coil shall be identified by a serial number consisting of drawing number plus a three-digit serial number. The number shall be stenciled in an area readily visible.

2.4 MAGNET ASSEMBLY

2.4.1 The magnet assembly shall include yoke, coils and their supports, manifolds, terminals, bus bars, hardware and all the other necessary parts to make the magnet assembly a stand alone turn-key entity.

2.4.2 1-2 mm thick epoxy glass fiber sheet shall be used as a spacer between steel surface and coil, a layer of 1-2 mm thick polyurethane rubber sheet shall be placed between the coils to compensate for pancake surface irregularities and to allow for thermal expansion.

2.4.3 Electrical terminals shall be part of the magnet assembly, the terminals shall be so dimensioned that they will accept standard lugs determined by CNAO and listed in the appendices of this specification. All the current carrying contact surfaces shall be silver plated as per 2.3.1.4 of this specification.

2.4.4 CNAO has adopted an electrically non-conducting reinforced hoses and stainless steel fittings as its nominal standard throughout the whole project. Seller shall provide hoses and fittings between coils and manifolds in accordance with CNAO's standard, which is included in the appendices of this specification. CNAO shall provide hose assemblies from the magnet manifolds to water mains.

2.4.5 All exposed electrical parts shall be properly protected from personnel by suitable enclosure. Water manifolds shall be properly supported and isolated by using insulating material brackets. The terminal blocks for interlock devices and their locations shall be agreed with CNAO.

2.4.6 A name plate will be required for each magnet, the design and location of the plate will be discussed with the seller in due time. The following information shall appear on the nameplate:

1 Magnet Name
2 Serial No.
3 Nominal Field (in Tesla) or gradient (in Tesla/m)
4 Nominal Voltage (in Volts)
5 Nominal Current (in Ampere)
6 Magnet Resistance (in ohm)
7 Magnet Inductance (in Henry)
8 Magnet Weight

9 Date manufactured (day-month-year)
10 Drawing Number

2.4.7 ACCEPTANCE TESTS AT SELLER'S PREMISES

2.4.7.1. The completely assembled magnet water system, including manifolds, hoses, etc., shall undergo a hydrostatic test at 3MPa pressure for a minimum of 15 minutes. No leakage of any kind shall be permitted.

2.4.7.2. The completed magnet assembly shall be subjected to high voltage test between coils and yoke. A DC voltage of 2.5 kV shall be applied between coil terminal and steel yoke for one minute or longer. Insulation resistance shall be greater than one hundred (100) mega-ohm.

2.4.7.3. Electrical resistance measurement at the coil terminals.

2.4.7.4. Proper functioning of the interlock system.

2.4.7.5. The water flow rate corresponding to a pressure drop of 0.7 MPa shall be measured for each hydraulic circuit. They should be within 2% of those anticipated. They shall be recorded on component QA list for future reference. Directly following these tests, the water remaining in the cooling circuit must be completely evacuated by dry compressed air flow in order to avoid damage due to freezing.

2.4.7.6. The magnetic measurements must be performed as stated in 2.7.

2.4.8 DOCUMENTATION

QA documents shall accompany individual magnet at the time of delivery. The format of this document shall be established in consultation with CNAO.

2.5 MAGNET SUPPORTS

2.5.1 The baseline design of the support system has been completed by CNAO. Also special eye-bolts to move and put in the right position these magnets must be foreseen. The design has taken into account the special alignment procedure requirements and future maintenance for these devices in the accelerator. Manufacturer is not allowed to alter the baseline design, without any written approval from CNAO.

2.5.2 The materials for support system are mainly Aluminium AL 6082 type, black anodized. The protective coating against corrosion for low carbon steel is required; it shall consist of one coat of rust inhibiting primer and finish with two coats of either epoxy or polyurethane paint. The colour shall be that of magnet yoke assembly.

2.5.3 The locating pins are required between magnet legs and the removable spacer. The removable spacer will be removed from the magnet assembly during the installation or removal of the vacuum chamber. CNAO requires that the already aligned magnets must recover their precise position to within ±0.02 mm after such operation by appropriately designed locating pins and holes. It is mandatory that the hardened sleeve must be inserted into aluminium hole to prevent excessive wear. Pins shall be attached to the support by chain or other means to prevent being misplaced.

2.5.4 All the individual parts shall be identified with their associated magnet and properly marked in readily visible locations.

2.6 TRANSPORT AND PRECAUTION TO BE TAKEN

2.6.1 It is responsibility of the manufacturer to deliver all magnets well protected and without damage to a site to be indicated by CNAO.

2.6.2 All cooling ducts must be dried out properly and closed off in order to avoid damage by freezing.

2.6.3 Parts sticking out of the magnet core, especially coil heads and magnet connections have to be protected by mechanically rigid covers.

2.6.4 The whole magnet shall be covered with protective plastic foil.

2.6.5 In order to avoid deformation and permanent damage closed solid transport structures (containers) should be used. Several magnets may be transported in the same container.

2.7 MAGNETIC MESUREMENTS

For excitation curve, 2D mapping and magnetic length a hall probe mounted on a micro controlled coordinameter is strongly recommended. For integrated field homogeneity a rotating coil method is recommended. Seller must agree with CNAO for alternative method.
The seller shall provide a magnetic measurements analysis report and row data with detailed information on the experimental set-up to allow data analysis. Data and report have to be provided in electronic format (Excel for data and Word for report, **not only Pdf**).
Seller must indicate in the offer the method that will be used for the measurements and the instrumentation set-up.
The seller is required to measure the following quantities.

2.7.1 Quadrupole Magnets:

- Harmonic measurements and Measurements of magnetic axes with respect to mechanical axes at 10 exciting current (I=15,40,65,90,115,140,165,190,215,245A) at a reference radius of 47mm.
- Magnetic length at same currents.
- Excitation curve at same currents.

2.7.2 Solenoid Magnet:

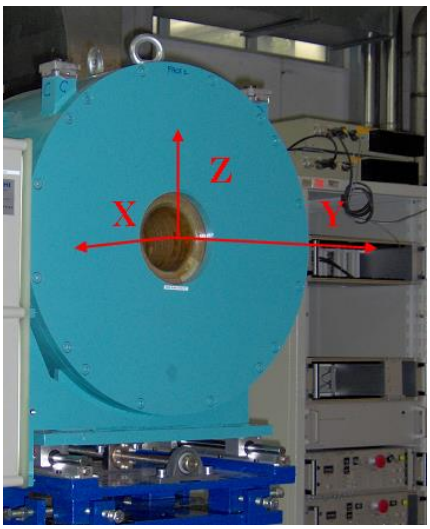

Figure 2 Solenoid measurement reference axes

- Excitation Curve
  The magnetic field is measured at the magnet mechanical centre (0;0;0) ramping the power supply from 0 A to Imax (250 A) with step $\Delta I = 10A$.
  The behaviour of the field must be linear (within $2\ 10^{-3}$ on average) over the whole current range. The relative error (relative to the maximum field)
  $$(B_{Meas}-B_{Fit})/B_{Meas\_250\ A}$$
  Must be less than $2\cdot10^{-3}$ for every current setting.
- Field profile and integrated field
  Measure the magnetic field along the mechanical axis at different excitation currents. The measurement range is:
  Y=[-400 ; +400] mm step: 10 mm, at the following current values: I =5, 20, 60, 100, 140, 180, 220, 250A.
  A linear fit of the data from solenoid reconstructs the integrated field with an average error of about $2\ 10^{-3}$.
- 2D mapping of the good filed region
  Measure the 2D mapping of the solenoids at 100A current setting.
  The 2D map is acquired at different y coordinate (i.e. along the solenoid mechanical axis)
  y =[-320 ; +320] mm step: 40 mm.
  For each $\tilde{Y}$ value the coordinate $(X_C;Z_C)_{\tilde{Y}}$ of the magnetic centre is evaluated fitting the data with the expression:
  $B_Y\,(x;z)_{\tilde{Y}} = B_{0\tilde{Y}} + a_{x\tilde{Y}} \cdot (x-X_C)^2 + a_{z\tilde{Y}} \cdot (z-Z_C)^2$.
  The magnetic centre is therefore the minimum (or maximum) of the paraboloid for each given y coordinate.
  The selected mesh is:
  x=[-20 ; +20] mm - step x = 4 mm
  z=[-20 ; +20] mm - step z = 4 mm
  The centre coordinates alone are not an exhaustive description of the magnet behaviour. The solenoid field (as far as the longitudinal component is considered) is very "flat" inside the magnet therefore we will consider an "error bar" defined as the radius r_ε of the circumference (centred $(X_C;Z_C)_{\tilde{Y}}$) whose points (x;z) satisfy:
  $$B_Y(x,z) = B_Y(X_C;Z_C) \cdot (1 \pm \varepsilon)\ ;$$
  $$x^2 + z^2 = r_\varepsilon^2\ ;$$
  where ε is a uniformity parameter equal to $5\ 10^{-4}$.
  Therefore instead of looking for the magnet axis, which is the best fit line through the $(X_C;Z_C)_{\tilde{Y}}$ points, we will instead consider the ellipsoid defined by the $(X_C;Z_C)_{\tilde{Y}}$ points and their radial error bars at the different y coordinates.
  The "X_{min}" and "X_{max}" lines ["Z_{min}" and "Z_{max}"] are defined as:
  $X_{min} = X_C - r_\varepsilon$ [$Z_{min} = Z_C - r_\varepsilon$]
  $Xmax = X_C + r_\varepsilon$ [$Zmax = Z_C - r_\varepsilon$]
  A weighted fit (least square method) on the data gives the following expression for the magnets axis, from which the tilt and shift to be applied for alignment can be deduced.
  $$X_C(y) = A_X\ y + B_X\ [mm]$$
  $$Z_C(y) = A_Z\ y - B_Z\ [mm]$$

3 APPENDICES

3.1 ELECTRICAL CONNECTION STANDARD

3.1.1 A set of electrical terminals shall be part of the magnet assembly, the terminal shall be so dimensioned that they will accept the cable lugs as specified in the following.

MAGNET TYPE	***# of cable lugs per terminal***	***cable cross section (mm²)***
Quadrupole	1	185
Solenoid	1	120

3.1.2 The magnetic structure must be grounded at least in one point by means of a suitable ground cable (green-yellow) having the following cross section:

Power conductor cross-section (mm^2)	***Ground conductor cross-section*** (mm^2)
$S \leq 16$	$S_{ground} = S$
$6 < S < 35$	16
$S > 35$	$S_{ground} = S/2$

3.2 HYDRAULIC HOSES AND FITTINGS

3.2.1 HOSES

Special hoses, if used, are required for all flexible hydraulic connections.

Special Characteristics of the hoses:

Electrical resistance: $50x10^6$ Ohm/meter minimum dry. (The hose shall be pressured with 1.5 MPa distilled water for one week prior to test).

Operating medium: De-ionized water; with minimum resistivity of $3.3X10^6$ Ohm×cm.

Maximum operating pressure: 1MPa.

Maximum pressure allowable: 3 MPa.

Maximum operating temperature: 80 °C.

Cumulative radiation doses: 5×10^5 Gy.

Hose I.D.: 10 mm or 20 mm.

Flexibility: 90 mm bend radius min. for 10 mm I.D.

Color of covering: Blue (or alternative colours with CNAO's approval).

Requested material -- EPDM rubber reinforced with polyester.

3.2.2 FITTINGS

The coils will terminate with fittings made of AISI 316 stainless steel.

The bending of the terminals of the coils shall be done in such a way to avoid any water dripping towards the coil in case of accidental leakage from the connections.

The terminals of coils shall be brazed to the fittings avoiding any section reduction of the flow or any weakening of the coil or of the fitting itself. The fittings will therefore have a housing to fit the rounded coil terminal with the clearance needed to brazing.

The fittings shall be:

male JIC sv.74° 9/16 - 18 for the connection to the 10mm ID hose

male JIC sv.74° 11/16 - 12 for the connection to the 20mm ID hose

Standard applicable SAE J514

Any flexible connection in the magnet assembly shall employ rotating female fittings at both ends of the hose, with the same thread as above. The fittings shall be clamped on the hose by a machine pressed sleeve.

Only in particular case of lack of space, a connection made by spigot and screw clips will be tolerated. Only stainless steel clips shall be adopted.

Suggested product: NORMACLAMP S, stainless steel - producer: Norma Group - Rasmussen GMBH (Germany)

3.2.3 HOSE ASSEMBLY

The nominal maximum pressure of the hose assembly shall be 3 MPa.

Hose assembly samples (with their fittings) shall be pressure tested to 1.5 MPa by 1 hour.

3.2.4 MANIFOLDS

All manifolds, if used, shall be of proper size and realized in AISI 316 stainless steel as well as any other particular mounted on it. The manifold assembly shall be TIG welded with argon filling. After welding, the assembly shall be internally rinsed in demineralized water and all the welded connections shall be brushed externally only by a stainless steel brush.

Each manifold shall be equipped with a main valve, a bleeder vent valve, a drain valve and a connection for a pressure gauge.

All the valves and fittings shall be of AISI 316 stainless steel.

All the valves shall be mounted on the manifold by a threaded sleeve welded on it, and thread sealing shall be done by a suitable hardening paste, compatible with the demineralized water.

No hemp packing shall be allowed.

4 BASE LINE DESIGN DRAWINGS

4.1 GENERAL

Drawings (AUTODESK INVENTOR files and eventually Hard copies) included in this section are the CNAO's baseline design of magnets; they must be used as a base for all the detail design work. Set files are provided for tenderers to prepare their submissions. CNAO has assigned some dimensions and tolerances to more important details. Seller is expected to make up all the other necessary dimensions and tolerances for manufacturing purposes. Seller

is also expected to make up all the other necessary detail drawings for manufacturing such magnet. Seller produced drawings shall have such quality that a third party will be able to produce the subject item without any difficulty. The drawings and specifications shall be prepared in English language and metric units. AUTODESK files shall be as per 1.2.1.1 of this specification.

4.2 DRAWING LIST

DRWMC-DDLEB-00363	SOLENOID (LEBT SOLENOID ASSEMBLY)
DRWMC-DDLEB-00364	SOLENOID (LEBT FRAME YOKE)
DRWMC-DDLEB-00365	QUADRUPOLE (LEBT LAMINATION)
DRWMC-DDLEB-00366	QUADRUPOLE (LEBT COIL)

4.3 MAGNET COLOR

Quadrupole magnets	RAL 6019 (light green)
Solenoid magnet	RAL 5251 (Blue)