Mechanical Design of a Nb_3Sn Superconducting Magnet System for a 45 GHz ECR Ion Source

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BERKELEY LAB

MT25

25th International Conference on Magnet Technology

RAI - Amsterdam

August 27 - September 1, 2017

Background

Lawrence Berkeley National Laboratory (LBNL) in collaboration with Institute Of Modern Physics (IMP) has designed a Nb_3Sn based superconducting magnet system for a new fourth-generation ECR ion-source that will be part of High Intensity Heavy Ion Accelerator Facility (HIAF) in Lanzhou, China.

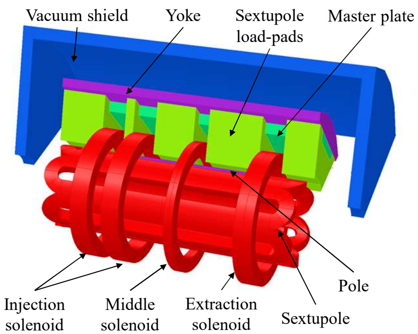
Magnetic Parameters of the System

Parameter	Unit	Value
Microwave frequency, f_{rf}	GHz	45
Resonant heating field, B_{ECR}	T	1.6
Injection confinement field, B_{inj}	T	>6.4
Extraction confinement field, B_{extr}	T	>3.4
Radial confinement field, B_{rad}	T	>3.2
Mirror length	mm	500
Plasma chamber ID	mm	150
Warm bore ID	mm	170

Challenges

- The target microwave frequency of **45 GHz** is a significant step beyond the current state of the art of 28 GHz
- Peak field of **12 T in the coil** requires the use of Nb_3Sn superconductor
- **Nb_3Sn is a brittle material** with strict **limits on the maximum stress** and strain that can be tolerated
- Traditional **sextupole-in-solenoid configuration** is used to minimize the magnetic field in the sextupole coil
- Complex configuration of **high Lorentz forces** due to combined sextupole and solenoid coil field
- New approach in utilization of aluminum shell-based support structure
  - The shell supports the sextupole through longitudinally segmented loading pads placed in-between solenoids, and a thin continuous collar
  - The solenoids are encased in a stainless steel forms and radially supported by a tensioned aluminum wire, with the aluminum shell providing additional support and alignment through a second set of loading pads.
  - Axial support is provided to both sextupole and solenoid sub-assemblies by aluminum rods and end plates.

Magnetic Design



Main Parameters of the Magnet Coils

Parameter	Unit	S	M	E	I
Nominal current I_{nom}	A	654	380	626	692
Peak conductor field at I_{nom}	T	11.3	5	9.7	11.8
Operating temperature	K	4.2	4.2	4.2	4.2
Inner diameter	mm	200	336	336	336
Outer diameter	mm	276	430	430	430
Coil length	mm	857.4	30	60	2x60
Conductor packing factor	-	0.65	0.7	0.7	0.7

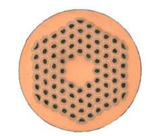
Conclusions

- The new Nb_3Sn magnet structure for the 45 GHz ECR ion source was designed.
- New approach of pre-loading a sextupole-in-solenoid coil system was applied to a shell-based structure concept.
- The support structure design was optimized in parallel with the magnetic design and the quench protection analysis.
- The stress in the sextupole coil was limited to 155 MPa in order to avoid higher stress concentration in high magnetic field zones.
- Stress in solenoid coils was limited to 126 MPa.
- Targets for the pre-load operation were optimized to prevent separation of the coils from poles or solenoid formers.

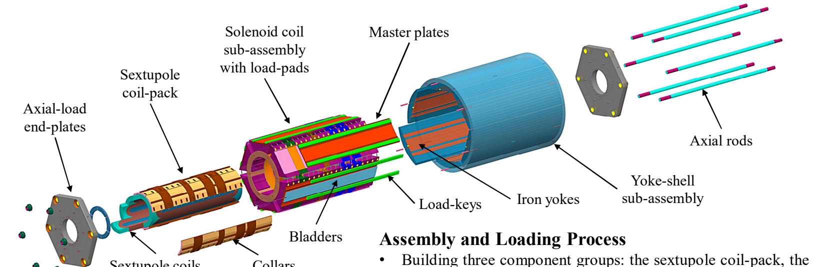
Nb_3SN RRP wire

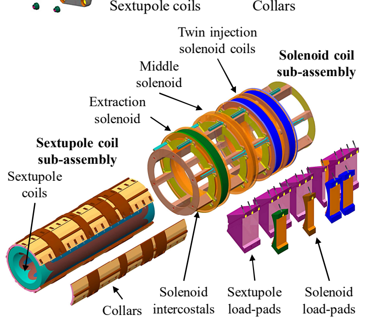
Conductor Parameters

Parameter	Unit	Value
Critical current density at 4.2 K, 12 T	$kAmm^{-2}$	2.4
Wire diameter	mm	1.3
Copper/non-Copper ratio	-	0.96
RRR of the copper matrix	-	250
Filament twist pitch	mm	42
Insulation thickness	μm	65



Magnet Structure Components



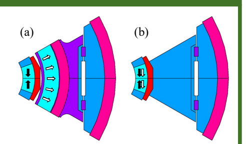


Assembly and Loading Process

- Building three component groups: the sextupole coil-pack, the solenoid sub-assembly and the yoke-shell sub-assembly.
- The sextupole coil-pack is inserted into the solenoid sub-assembly or, alternatively, the solenoids sub-assembly is build around the sextupole coil-pack.
- Arrangement of sextupole and solenoid load-pads are bolted around the coil system to form a final coil-pack.
- The coil-pack is inserted into the yoke-shell sub-assembly along with the master plates, bladders and initial load-keys.
- Water pressurized bladders pre-tension the cylinder and allow to shim the load-keys.
- Deflating bladders, load-keys are locked between pre-tensioned cylinder and compressed coil-pack.
- End-plates, drawn together by pre-tensioned axial rods, push on the sextupole coil-ends and the solenoid sub-assembly.
- Shrinkage of the shell, the solenoid aluminum banding and axial rods increases the pre-load during cool-down.

Magnetic Forces

Right: Two critical sections of the magnet: (a) at the solenoid center; (b) between solenoids, and directions of magnetic forces due to the sextupole field (black) and the solenoid field (white).

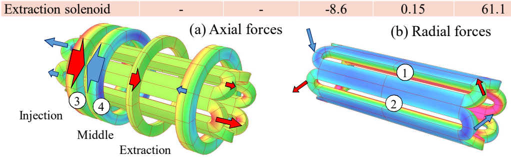


Bottom: Direction of (a) axial and (b) radial forces acting on solenoids and sextupole coil-end due to combined magnetic field of the sextupole-in-solenoid coil system.

Table: The integrated radial (F_r), azimuthal (F_Θ) and axial (F_z) components of the force acting on the coil system components are given. For solenoid coils, axial and radial components of the force are also expressed as an equivalent axial (P_z) and radial (P_r) magnetic pressure acting on the external axial surface and inner radius surface of each solenoid coil, correspondingly.

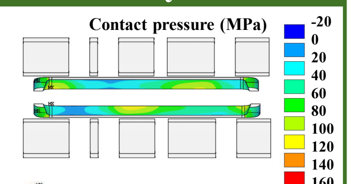
Magnetic Forces in Magnet Coils

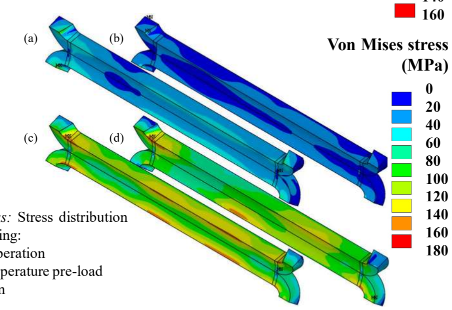
Coil Segment	F_R [kN]	F_Θ [kN]	F_Z [kN]	P_Z [MPa]	P_R [MPa]
Sextupole 1 end (E)	99.7	-	49.4	-	-
Sextupole 2 end (E)	-121.7	-	165.8	-	-
Sextupole 1 straight	421	-1057	-	-	-
Sextupole 2 straight	406	994	-	-	-
Sextupole 1 end (I)	-105.9	-	-166.2	-	-
Sextupole 2 end (I)	88.4	-	-55.3	-	-
Injection solenoid (3)	-	-	1749	30.9	82.4
Injection solenoid (4)	-	-	-1994	35.3	82.4
Middle solenoid	-	-	165.6	2.9	12
Extraction solenoid	-	-	-8.6	0.15	61.1



Coil Pre-load Analysis

Contact pressure: Status of the contact between the sextupole coil conductor and its support components (pole, end-shoe). Coil remains compressed and does not separate from the pole.





Von Mises stress: Stress distribution in the coil during:
(a) Bladder operation
(b) Room temperature pre-load
(c) Cool-down
(d) Excitation

Peak stress during bladder operation with all 6 bladders is 116 MPa but when using a single bladder should drop to a similar value as with load-keys inserted, which is 67 MPa. The stresses after cool-down and with magnetic forces are below 155 MPa and the peak is located in the coil-ends. The maximum stress in solenoid coils is 100 MPa after cool-down and 126 MPa when magnetic forces are applied.

This work was supported by NSFC (Contract No. 11427904).