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The HGQ-05 ANSYS version.

This paper presents finite element analysis results for the HGQ–05 collaring block during assembly, cool-down to 1.8 K, and excitation to a gradient of 235 T/m

Model Description

Finite element analysis for the collared coil block has been performed by ANSYS software.
The finite element model for the straight section is shown in Figure 1.

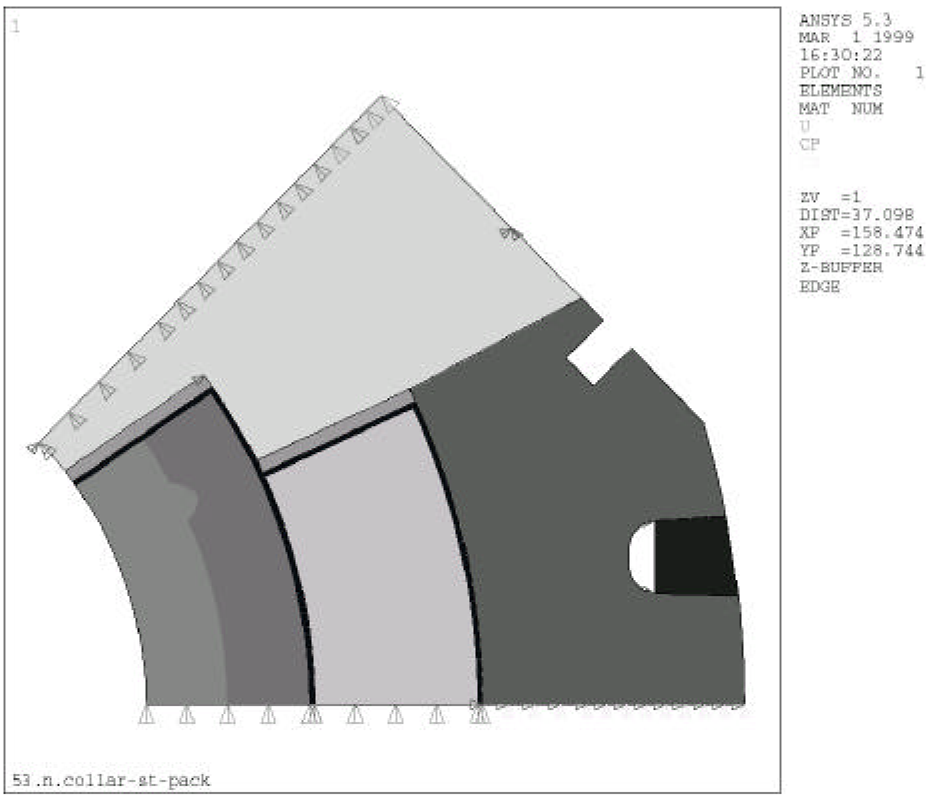

Figure 1. HGQ collared-coil finite element model.

To reduce model size and model computing time octant symmetry has been used.
The model includes the inner and outer coils surrounded by the stainless still collar's pack. The pack is modeled as three separated pieces: a front collar with a pole insert and a back collar. They are representing two laminations in depth. The pole insert and back collar joined together by two spot weld's points. The constraint equations are used on the collar mid-planes to enforce rotational symmetry. The inserted keys provide additional constraints for the collars. The coils, collars, ground insulation, bearing strips and key are modeled with 3 or 4-node plane elements (PLANE 2 and 42). Material interfaces are presented with one-dimensional gaps (COMBIN 40) oriented perpendicular to the interface without friction effect.

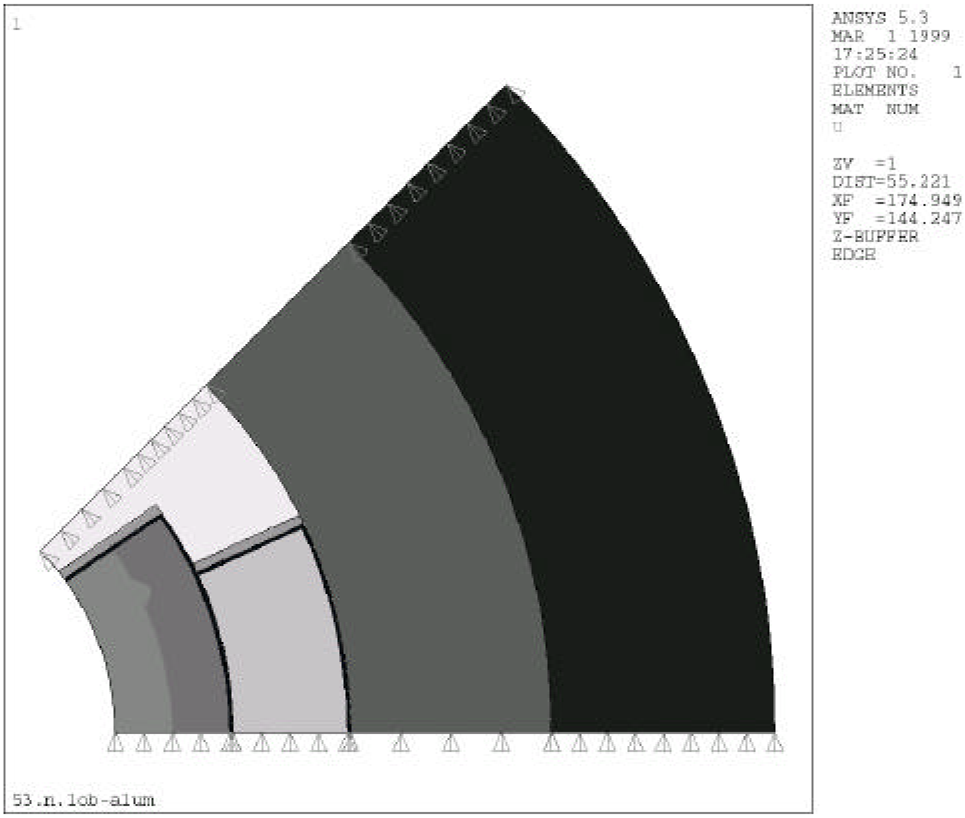

Figure 2. The finite element models of the end cans region.

The ANSYS model of end can design is presented in Fig 2. 2-D model includes the inner and outer coils surrounded by the G-10 collet and pole insert block. Aluminum ring restrain radial motions all parts of the model. The geometry corresponds to the cross-section at the end of the collared coils. Octant symmetry is used to reduce model size and model solution time. All design components are modeled with 4-node plane quadrilateral elements (PLANE 42); material interfaces are modeled with one-dimensional gaps (COMBIN 40) oriented perpendicular to the interface without friction.

Material properties

The material properties of the model components as temperature dependent are listed in Table 1.

Table 1. Material properties

		Elasticity Modulus [GPa]				ITC, [mm/m] 10^{-3} 1/K	
		300 K		1.8 K		300 - 1.8 K	
		Radial	Azimuthal	Radial	Azimuthal	Radial	Azimuthal
Inner Coil	Composite	25	16	29	16	2.9	3.9
Outer Coil	Composite	25	21	29	21	2.9	4.1
Insulation	Kapton	2.5	2.5	6	6	13	13

Bearing strip	Brass	120	120	135	135	3.3	3.3
Collar	SS	190	190	210	210	2.65	2.65
Key	SS	190	190	210	210	3	3
Spacer	G-10	21	28	26	35	7	3
Can	Al	70	70	84.1	84.1	4.14	4.14

ANSYS loading

The model load history includes three load steps.

The first load step for the model (LS-1) is a coil block assembling at room temperature (T=300 K). It represents the pre-stressed state of collars and coils after collaring and spring back relaxation. The model pre-load is applied by vertical displacements of mid-planes boundary for inner and outer coil layers separately. The mid-plane layer displacements are design variables here. The sum of reaction forces in the pole and mid-plane regions for each layers divided by layers area, maximum equivalent stress in collars material, maximum or average key stress can be controlled as objective functions for this analysis.

The model cool-down is a load step two (LS-2). As the magnet is cooled to 1.8 K differential thermal contraction between various material in the quadrupole produce stress changes in the assembly. Cool-down for the model is applied as uniform temperature change from 300 K to 1.8 K.

The load step three (LS-3) is the model excitation. The Lorentz forces decrease the azimuthal coils pre-stresses at poles and increase it in mid-plane. Excitation is simulated in the model by applying independently calculated Lorentz forces directly to the conductors' nodes at TUNIF=1.8 K. The C-program translated ROXIE force data to the ANSYS point loading.

The highest level of coil pressure is expected during key insertion. The coil has a sprang-back when collaring process has been finished. All following steps of a block loads are leaded to the coil stress relaxation at the pole regions. There are insulation creep, the cool down effect and the excitation effect in this subsequent.

We have assumed an elastic modulus of coils E-down approximately twice bigger than E-up and did not change through all load conditions.

Parameters for the body region

The average sizes for inner and outer coils for different 2-D sections along the magnet body are present on plot below.

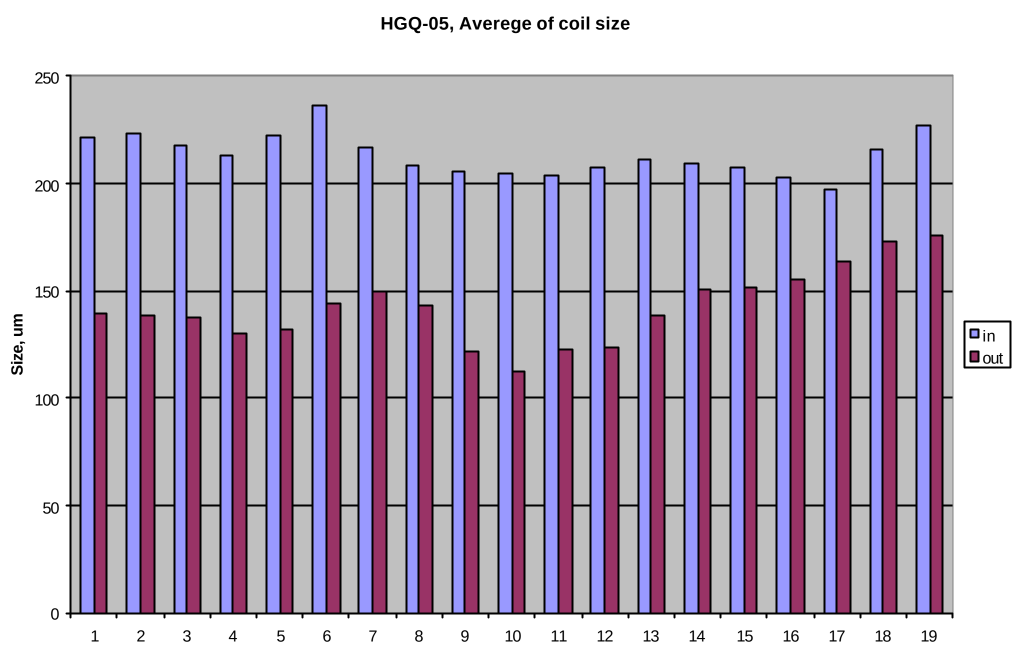

Figure. 3 Average coil sizes by quadrant.

Coil azimuthal dimension for the straight section.
The min case corresponds to position #10, the max case corresponds position # 19.

	Azimuthal coil oversizing *, μm	
	min case	max case
Inner layer	205	230
Outer layer	115	175

Coil azimuthal dimensions for the end can regions.
The min case corresponds to situation on LE and the max case corresponds to situation on RE.

	Azimuthal coil oversizing *, μm		Pole shim *, μm	Radial shim between outer coil OD and G10 spacer *,μm
	min case	max case		
Inner layer	220	230	-	125
Outer layer	140	175	50	

* design parameters used in FE analysis for stress generation.

Results

Coil pre-stress range.

		Azimuthal pressure , MPa				Radial pressure, MPa	
		Inner layer pole		Outer layer pole		Outer layer-Collar or G10 spacer	
		min case	max case	min case	max case	min case	max case
Collaring	body	79	83	31	60	19	26
	end	87	87	78	91	31	35
Cool-down	body	62	66	14	46	13	20
	end	79	80	78	92	35	40

Nom.current	body	11	18	0	15	31	35
	end	32	32	49	64	49	54

Deflection from " 0 " (warm) geometry.

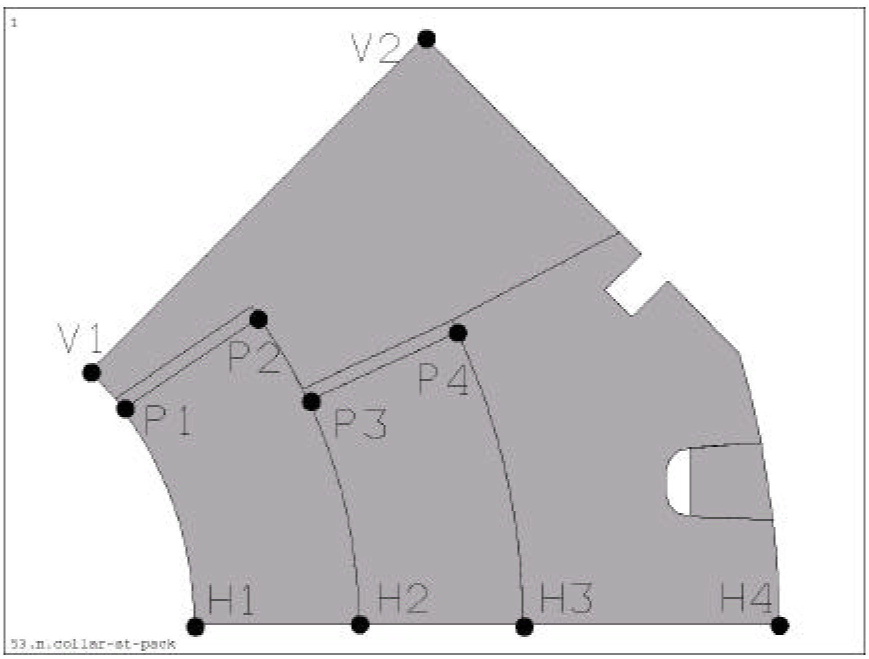

Figure 4. Body section.

		Radial displacement, µm mid-plane				Radial displacement, µm pole				Azimuthal displacement, µm pole			
		H1	H2	H3	H4	V1	P2	P4	V2	P1	P2	P3	P4
Collaring	min	68	86	91	89	112	113	95	107	32	37	43	36
	max	88	106	116	115	143	143	122	137	38	44	60	51
Cool-down	min	-43	-71	-118	-186	-13	-50	-112	-138	24	23	34	27

	max	-24	-51	-93	-161	16	-21	-86	-109	30	29	49	39
Nominal current	min	53	17	-44	-123	0	-38	-85	-129	-9	23	-23	16
	max	56	21	-36	-114	19	-18	-66	-108	5	28	22	33

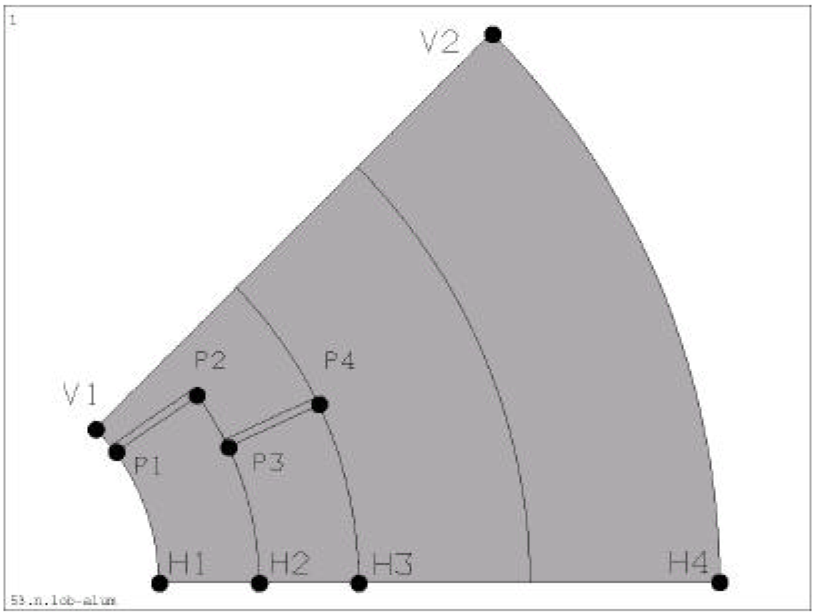

Figure 5. End can section.

		Radial displacement, µm mid-plane				Radial displacement, µm pole				Azimuthal displacement, µm pole			
		H1	H2	H3	H4	V1	P2	P4	V2	P1	P2	P3	P4
Collaring	min	17	37	42	120	83	84	67	131	45	48	34	33
	max	27	47	54	129	96	98	82	141	48	51	47	49
Cool-down	min	-113	-137	-177	-407	56	-56	-162	-417	50	34	23	11
	max	-103	-128	-165	-398	68	-42	-148	-407	52	37	35	26
Nominal current	min	-26	-57	-113	-367	38	-59	-144	-427	30	25	-6	-7
	max	-16	-48	-102	-358	51	-46	-129	-418	32	28	5	22