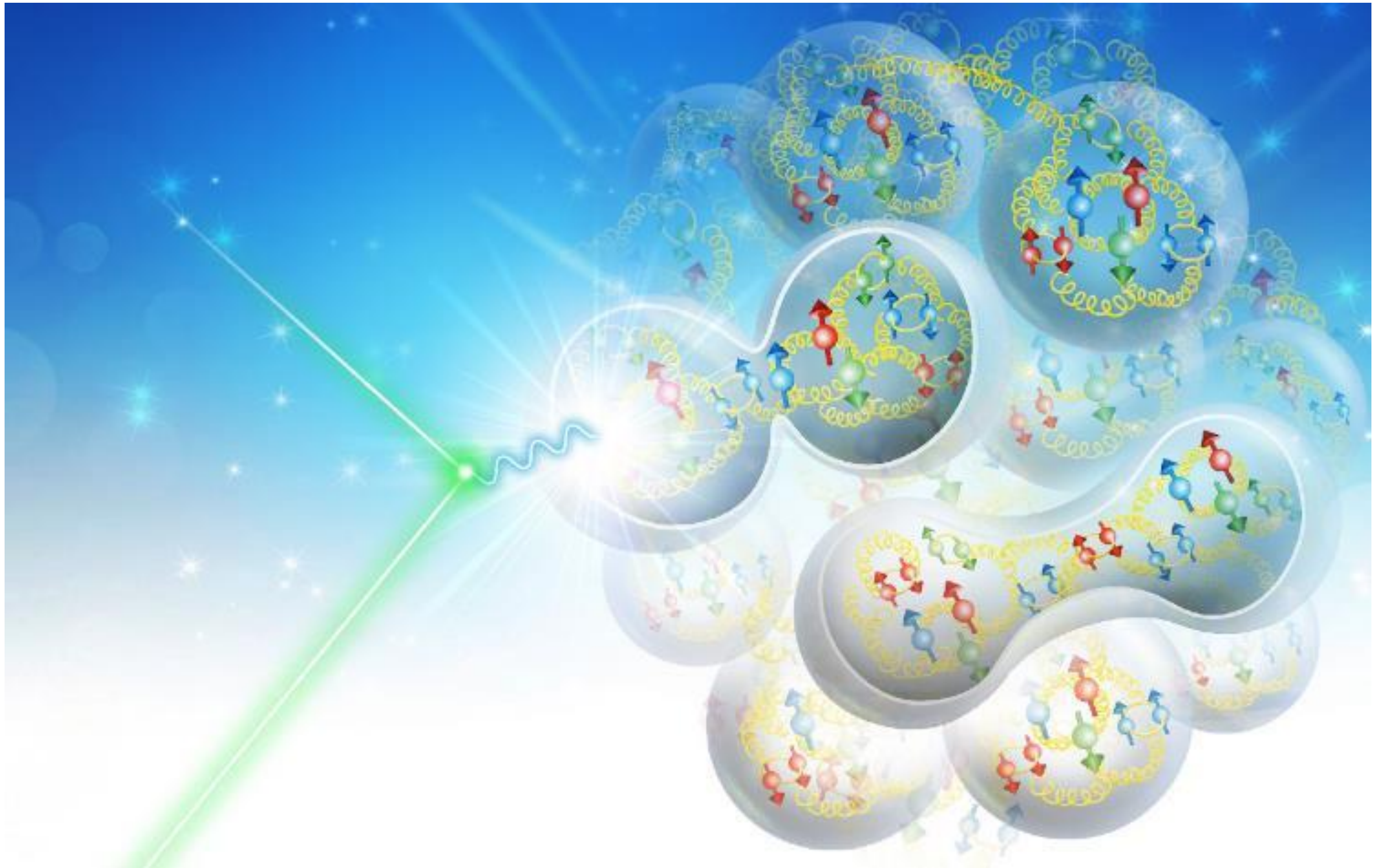
Optimization of an Interaction Region Quadrupole Magnet for a Future Electron-Ion Collider at JLab



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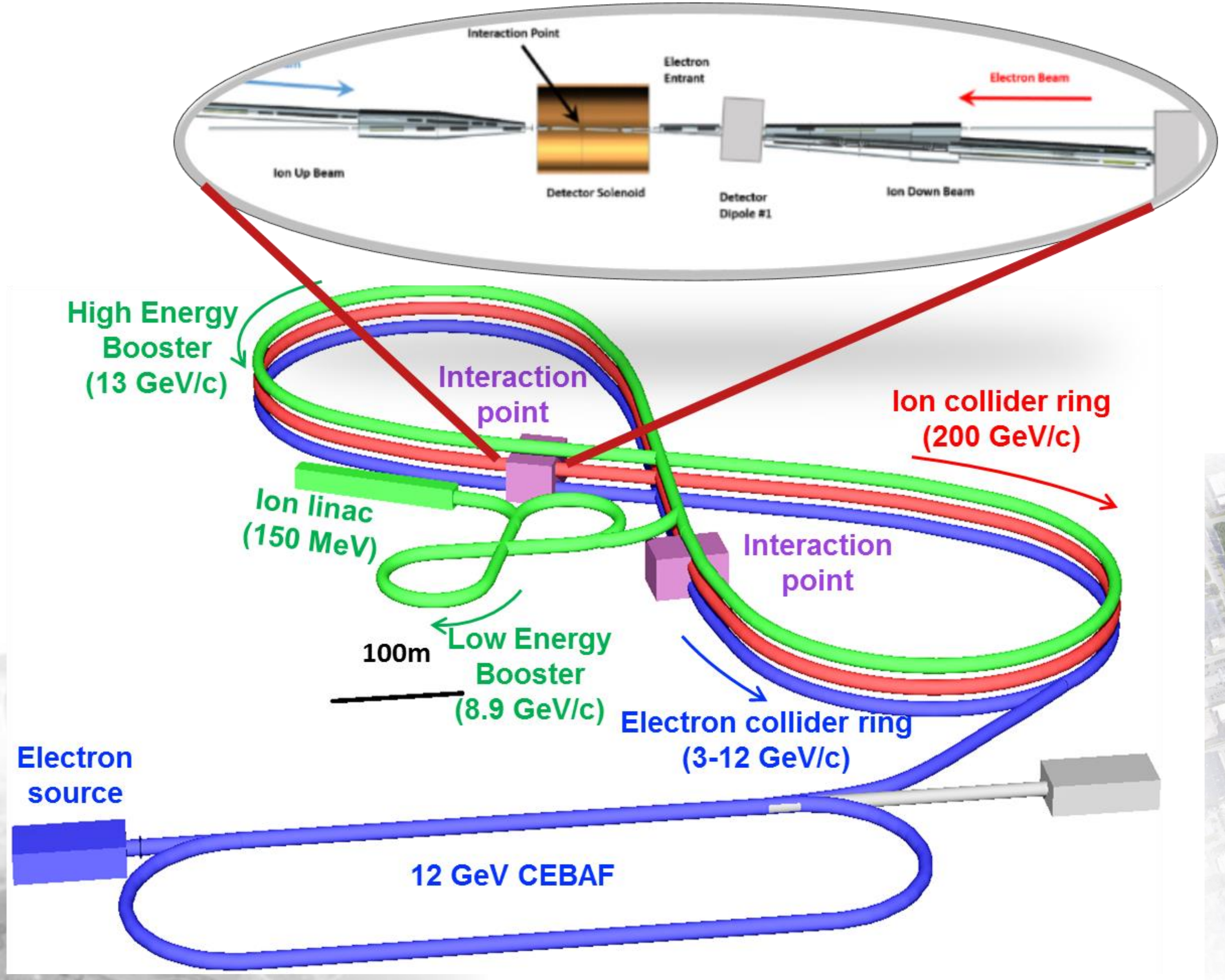
Content

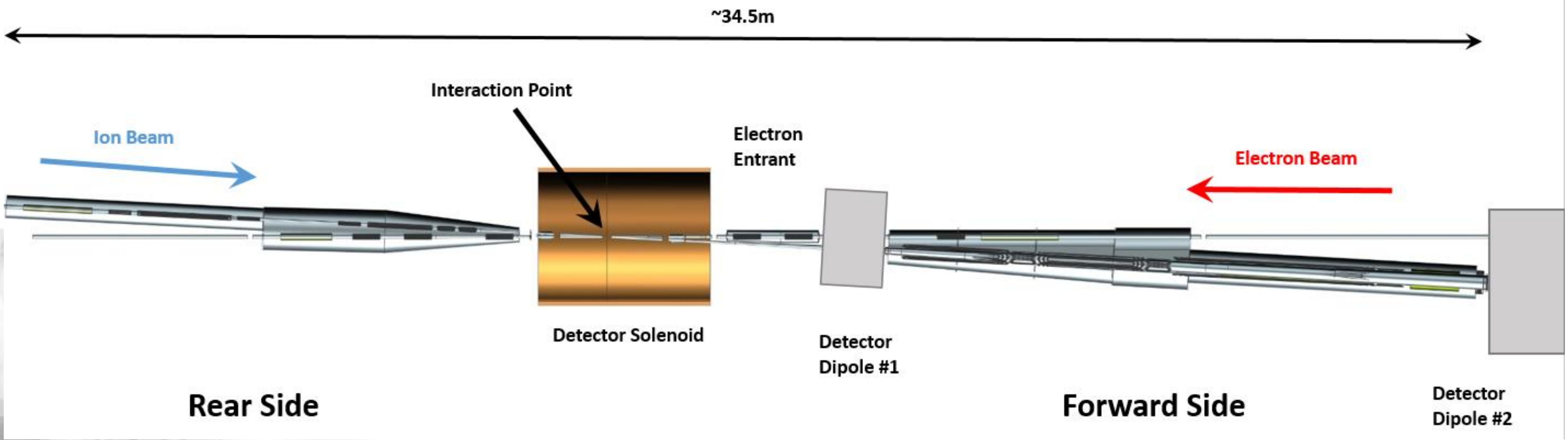
JLEIC Overview



- **Electron complex**
  - CEBAF as a full energy injector
  - Electron collider ring: 3-12 GeV/c
- **Ion complex**
  - Ion source, SRF linac: 150 MeV for protons
  - Low Energy Booster: 8.9 GeV/c
  - High Energy Booster: 13 GeV/c
  - Ion collider ring: 200 GeV/c
- **Up to two detectors** at minimum background locations
- **20-100 GeV CM, Upgradable to 140 GeV CM**

Interaction Region

- The electron and ion rings intersect at the interaction point (IP) and the region around IP is called interaction region (IR).
- Crossing angle is 50 mrad
- The IR contains a full acceptance detector built around a detector solenoid.
- Forward (down beam) ion FFQs have an opening of ±10 mrad



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IR Magnet Specifications and Design Parameters

- All final focus quadrupole magnets use NbTi
- Operating temperature between 4.5 K and 4.7 K
- All IR magnets are designed as cold bore, to lower the peak field in the coils

Element name	Type	Specifications									Design			
		Length [m]	Good field half-aperture [mm]	Inner Half-A [mm]	Outer Radius [mm]	Dipole field [T]		Quadrupole field [T/m]		Solenoid [T]	Coil Inner radius (mm)	Coil Outer Radius (mm)	Coil Width in Radial Direction (mm)	Peak Field in the coil (T)
Ion Upstream elements						Bx	By	Normal	Skew					
iASUS	SOLENOID	1.6	30	40	120	0	0	0	0	2	60	67	7	2.0
iQUS3S	QUADRUPOLE	0.5	30	40	120	0	0	0	3.38	0	45	47	2	0.3
iQUS2	QUADRUPOLE	2.1	30	40	120	0	0	94.07	0	0	45	78	33	5.7
iQUS2S	QUADRUPOLE	0.5	20	30	100	0	0	0	-9.26	0	35	40	5	0.6
iQUS1b	QUADRUPOLE	1.45	20	30	100	0	0	-97.88	0	0	34.5	49.5	15	5.1
iQUS1S	QUADRUPOLE	0.5	20	30	100	0	0	0	16.42	0	35	44	9	0.9
iQUS1A	QUADRUPOLE	1.45	20	30	100	0	0	-97.88	-3.08	0	34.5	57.5	23	5.1
iCUS1	KICKER	0.3	20	30	100	-3.90	0.076	0	0	0	34.5	52.5	18	6.3
iCUS2	KICKER	0.3	20	30	100	4.50	-0.019	0	0	0				
Ion Downstream elements														
iQDS1a	QUADRUPOLE	2.25	40	92	231	0.0	0	-37.23	-1.23	0	130	171	41	6.4
iQDS1S	QUADRUPOLE	0.5	40	99	248	0.0	0	0	14.85	0	130	142	12	3.9
iQDS1b	QUADRUPOLE	2.25	40	123	310	0.0	0	-37.23	0	0	130	163	33	6.4
iQDS2S	QUADRUPOLE	0.5	40	130	327	0.0	0	0	-7.83	0	136	145	9	2.3
iQDS2	**QUADRUPOLE**	**4.5**	**40**	**177**	**444**	**0.0**	**0**	**25.96**	**0**	**0**	**182**	**215**	**33**	**7.0**
iQDS3S	QUADRUPOLE	0.5	40	184	462	0.0	0	0	0.63	0	200	202	2	0.4
iASDS	SOLENOID	1.2	40	198	497	0.0	0	0	0	4	225	240	15	4.0
Electron Upstream elements														
eASDS	SOLENOID	12	22	45	11	0	0	0	0	-4	65	80	15	4.0
eQDS3	QUADRUPOLE	6	24	45	12	0	0	-18.72	-2.71	0				
eQDS2	QUADRUPOLE	6	28	45	13	0	0	36.22	5.25	0	49.5	65	15.5	3.6
eQDS1	QUADRUPOLE	6	17	45	14	0	0	-33.75	-4.89	0				
Electron Downstream elements														
eQUS1	QUADRUPOLE	6	20	45	10	0.0	0.00	-36.94	8.10	0				
eQUS2	QUADRUPOLE	6	32	45	11	0.0	0.00	33.66	-7.38	0	49.5	65	15.5	3.6
eQUS3	QUADRUPOLE	6	15	45	12	0.0	0	-20.80	4.56	0				
eASUS	SOLENOID	18	22	45	13	0.0	0	0	0	-4	65	80	15	4.0

JLab Design Bound Tools

- This tool developed at JLab is based on E. Todesco, "Magnetic Design of Superconducting Magnets" to optimize Cosine Ɵ and Cosine 2Ɵ current distribution designs
- All designs are based on sector coils - i.e. without wedges. Exclusion of wedges implies that multipoles have not been optimized (i.e. reduced).
- A linear approximation and curve shift is used for the NbTi J_c vs B curve for 4.5 K and 1.9 K, while a shifted hyperbola is used for the Nb_3Sn J_c vs B curve for 4.5 K and 1.9 K
- The present version of the design tool is limited to a maximum of 4 coil layers and does not deal with peak fields in the end region.
- In this design tool, there are some "fixed input" with an interface with user input and provides an output as shown. The calculated peak coil field for iQDS2 is 5.96 T.

'FIXED' INPUT			
Calculation margin		10	%
	a1	0.04	
	a-1	0.11	
Fraction of superconductor	K	0.3	
Superconducting strand (wire) diameter	dw	0.65	mm
No. of strands (wires) per cable	Nw	36	
Width of Rutherford cable	widc	15	mm
Thickness of Rutherford cable	thkc	1.5	mm
Coil sector angle	csecang	45	degrees
	Gamma	6.60E-07	T.m/A
Thk of beam tube wall + coil former wall	thk	5	mm
REQUIRED USER INPUT			
Required field gradient	G	25.96	Tesla/m
Beam tube inner diameter	btid	354	mm
Radial width or thickness of coil	w	30	mm
Length of coil (including ends)	Lcoil	4	m
CALCULATED OUTPUT			
Beam tube inner radius	btir	177	mm
Coil inner radius	r	182	mm
Coil inner diameter	d	364	mm
	Lambda	1.261	
Peak pole tip (coil) field	Bpcoil	5.96	Tesla
NbTi @4.5 K			
Magnet gradient short sample	Gss4.5K	33.82	Tesla/m
Pole tip (coil) peak short sample	Bpss4.5K	7.76	Tesla
Safe pole tip (coil) peak field (with margin)	B4.5K	6.83	Tesla
Coil short sample current density	Jss	335.86	A/mm^2
Coil operating current density	Jsc	257.79	A/mm^2
Critical temperature	Tc	6.33	K
Generation temperature	Tg	4.92	K
Current sharing temperature	Ts	5.63	K
Temperature margin	Tmargin	1.83	K
NbTi @ 1.9 K			
Magnet gradient short sample	Gss4.5K	43.97	Tesla/m
Pole tip (coil) peak short sample	Bpss1.9K	10.09	Tesla
Safe pole tip (coil) peak field (with margin)	B1.9K	8.88	Tesla
Coil short sample current density	Jss	436.62	A/mm^2
Coil operating current density	Jsc	257.79	A/mm^2
Critical temperature	Tc	5.27	K
Generation temperature	Tg	3.28	K
Current sharing temperature	Ts	4.27	K
Temperature margin	Tmargin	3.37	K

SIMULA Opera optimization module

- The SIMULIA Opera Optimizer tool is used to assist achieving the optimized design.

- The general aim during optimization is to minimize **objective functions** subject to a set of **constraints** guided by a set of critical design variable.

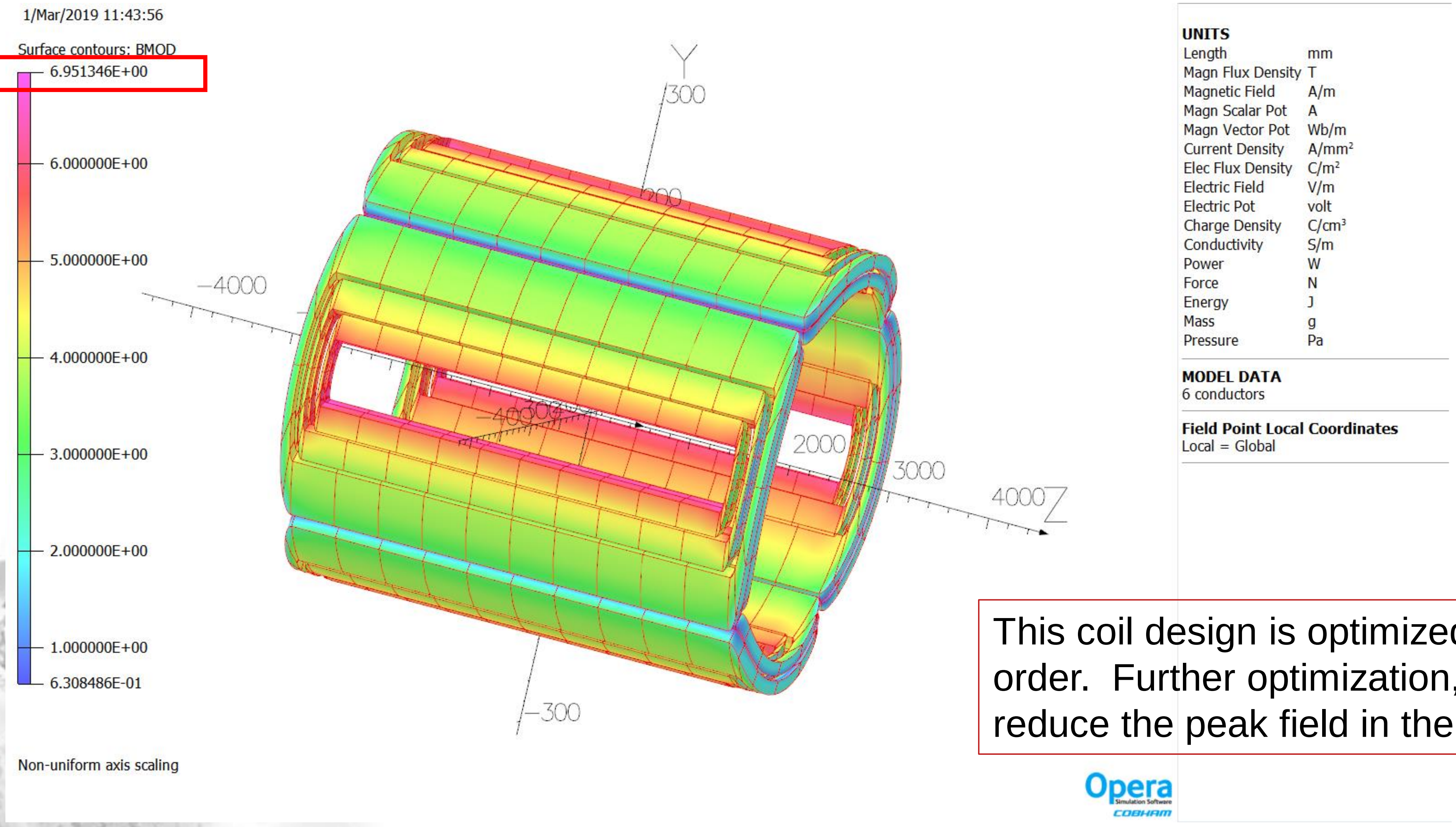
- Each variables are defined based on upper and lower limits are USER defined.
  - This is bounded by design requirements, that sets the standard formulation for optimization,
  - In the design iteration process, each objective function is either maximized or minimized, and
  - Each constraint are rewritten in multiple ways.

- For iQDS2 quadrupole
  - coil peak magnetic field, is assigned as the objective function required to be **minimized**, and
  - **maintaining** the field at the good field radius (GFR) as second objective function.

- The coil inner radius and coil width (radial direction) are defined as the constraints.

- Normally in racetrack and constant perimeter end coils, maximum coil field is at the coil ends. In order to reduce the peak field, coil ends are stretched and/or segregated.
  - Therefore, all three coils in iQDS2 are of increasing length (inside to outside).
  - The variation in length is used as a variable to optimize.

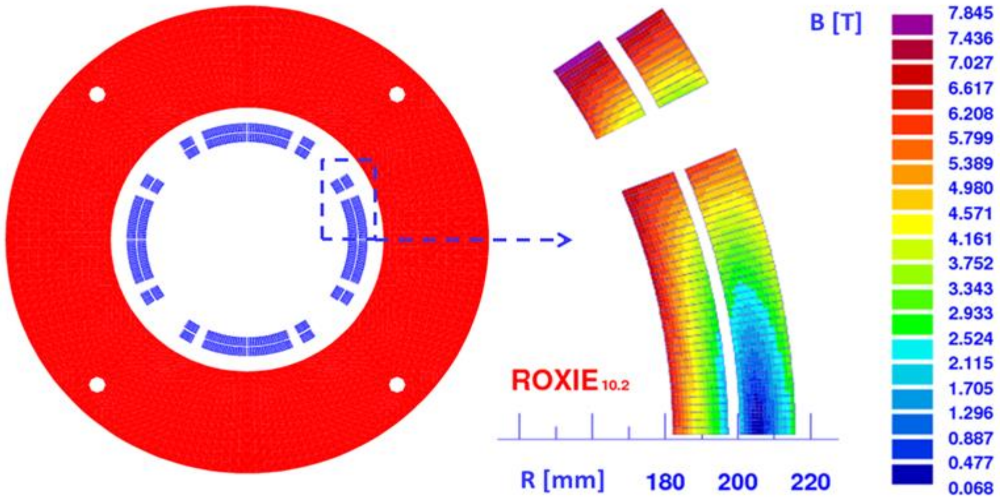
SIMULA Opera optimization module

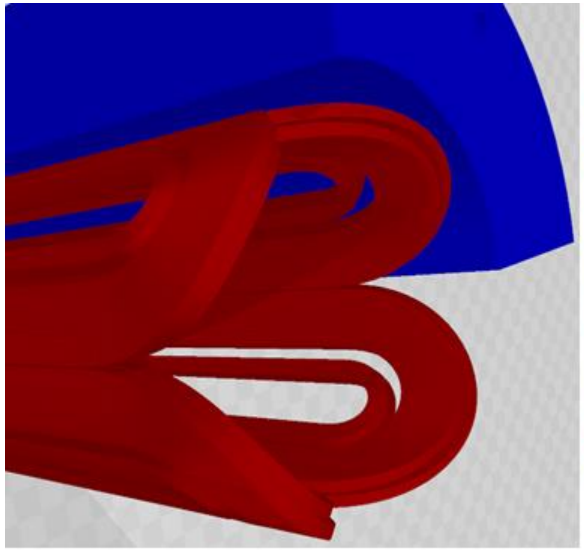


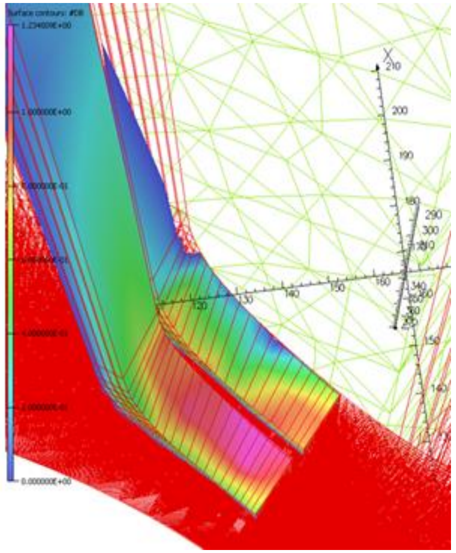
This coil design is optimized to the first order. Further optimization, is likely to reduce the peak field in the coils.

Roxie Optimization

- A 2-layer layout with a 33.5 mm total (insulated) coil width, selected as a starting point for the magnetic analysis.
- The iron yoke has a simple round geometry with inner radius of 245 mm and outer radius of 434 mm.
  - A radial gap of 29.5 mm is reserved between coil and yoke to accommodate a collar-based mechanical support structure, and
  - A 10 mm radial gap for an outer shell providing longitudinal rigidity, alignment, and helium containment.
- The corresponding maximum field in the coil (including the strand self-field) is 5.7 T in 2D compares well with the JLab design tool
- The peak field at nominal current is about 1.2 T higher in the coil ends than in the straight section (i.e. a **peak field of 6.9 T**), and is located near the pole tip in the inner layer







CONDUCTOR PARAMETERS

Parameter	Unit	Value
Strand diameter	mm	1.065
Copper fraction	-	1.65
Critical current density (5 T, 4.2 K)	kA/mm^2	1.85
Number of strands	-	28
Cable width	mm	15.1
Cable mid-thickness	mm	1.90
Keystone angle	deg.	0.61
Insulation thickness (azimuthal)	mm	0.135
Insulation thickness (radial)	mm	0.16

Comparison of the optimized results

One of the Downstream Ion Quadrupole, iQDS2 (optimized)

➢JLab design bound tool

- The peak field in the coils is estimated to be 5.96 T
- that does not deal with the end field region
- useful first-pass design evaluation tool

➢SIMULIA Opera optimized

- The peak field in the coils is about 6.95 T (at the ends)
- With all user defined objective functions and constraints
- About 1 T higher than 2D value calculated using JLab design bound tool

➢ ROXIE optimized

- coil peak field is approximately 6.9 T
- accounting for the keystone angle to obtain a radial orientation of the turns along the coil circumference.
- Also about 1 T higher than 2D calculated using JLab design bound tool

Summary

- Preliminary designs for all the IR magnets are complete.
- The peak fields in the coils are less than 7 T.
- Preliminary optimizations for the coil peak field has been completed for the largest bore quadrupole.
- The peak field in the coils from the JLab design bound tools *(does not deal with the end field region)* for this quadrupole is estimated to be 5.96 T, the peak field in SIMULIA Opera optimized iQDS2 coils is about 6.95 T, and peak field in the coils in ROXIE optimized coil is approximately 6.9 T.
- This is a useful first-pass design but with the compact end geometry the peak field about 1.2 T higher in the ends than in the magnet center, which would cause a significant loss of margin.
- Further optimization of the coil and yoke is planned to lower the peak field in the end regions while also improving the field quality.
- The field quality and multipoles will be affected by the neighboring magnets in the lattice, this effect and further optimization will be done in the next phase of the project.