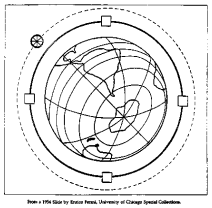
FNAL Common Coil Magnetic Design



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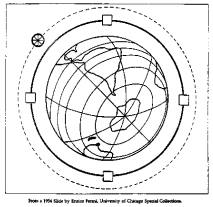
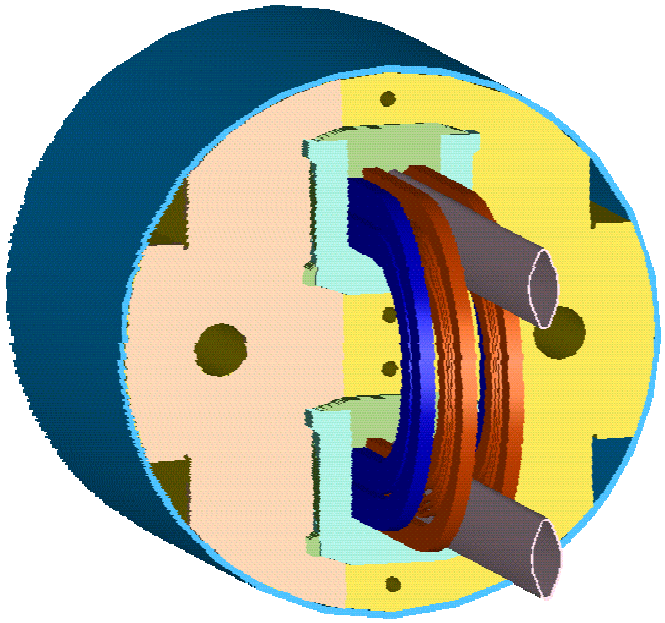
- Design update for Fermilab 11 T, 30 mm bore, hybrid dipole.
- Case studies for different field (11-14 T), aperture (20-45 mm) and layout.

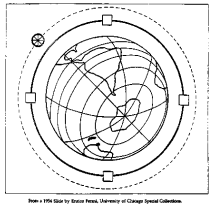
Magnet Design Features

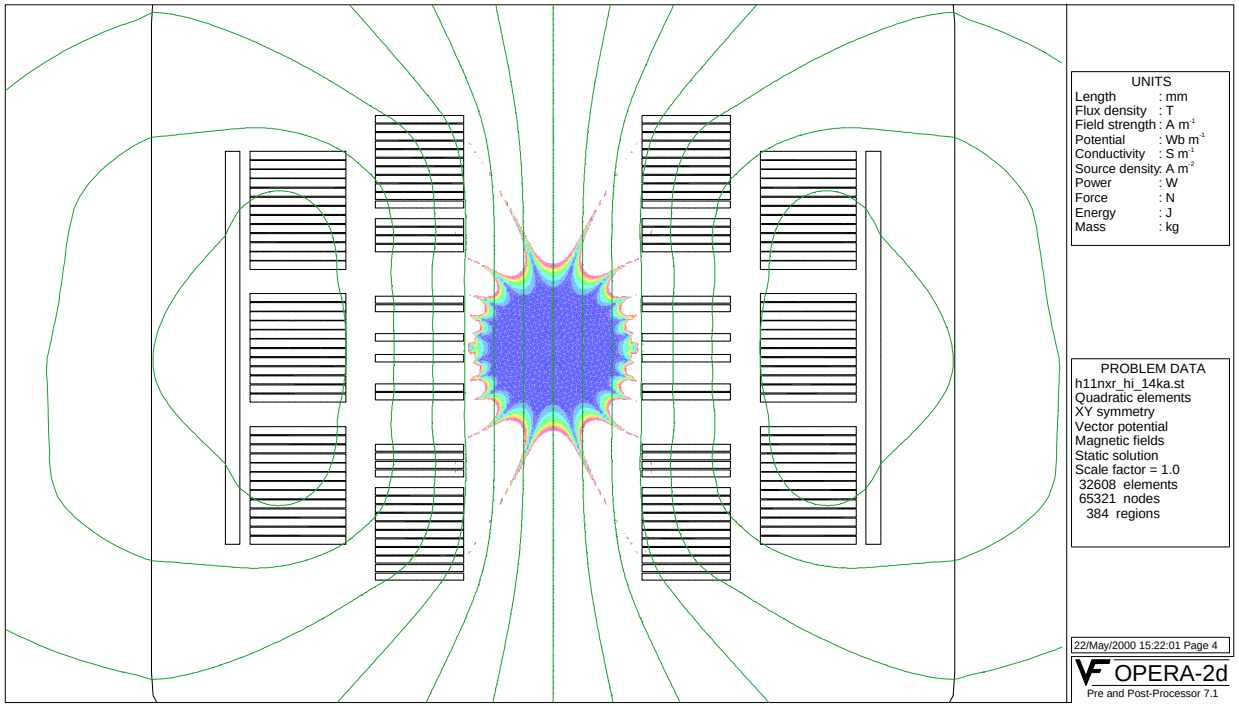


- Hybrid Nb_3Sn/NbTi
- 11 T short sample field
- 30 mm aperture
- Harmonics $<10^{-4}$
- No auxiliary coils
- Compensation of magnetization sextupole



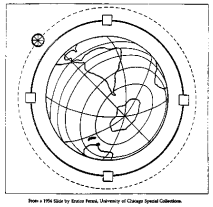
Coil Cross-Section

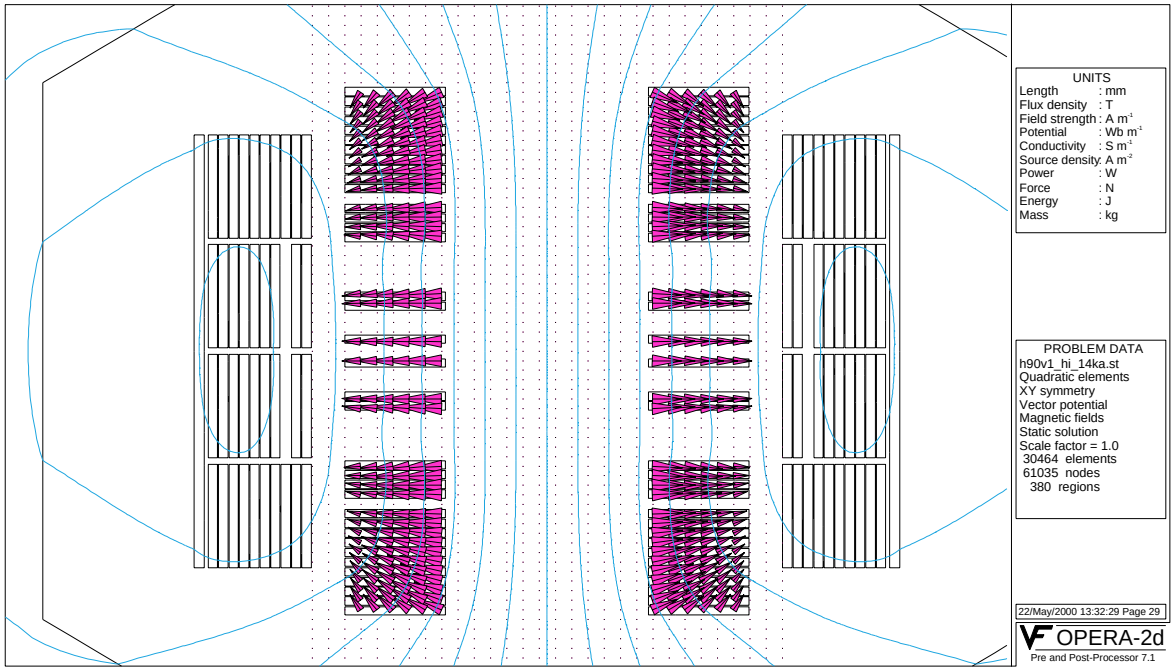




I=14 kA (B_0=10 T) - Field lines, field quality in 10^{-4} intervals

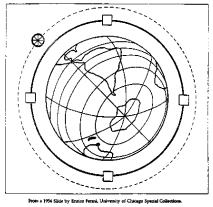
Cross-section B: face-loaded outer cable

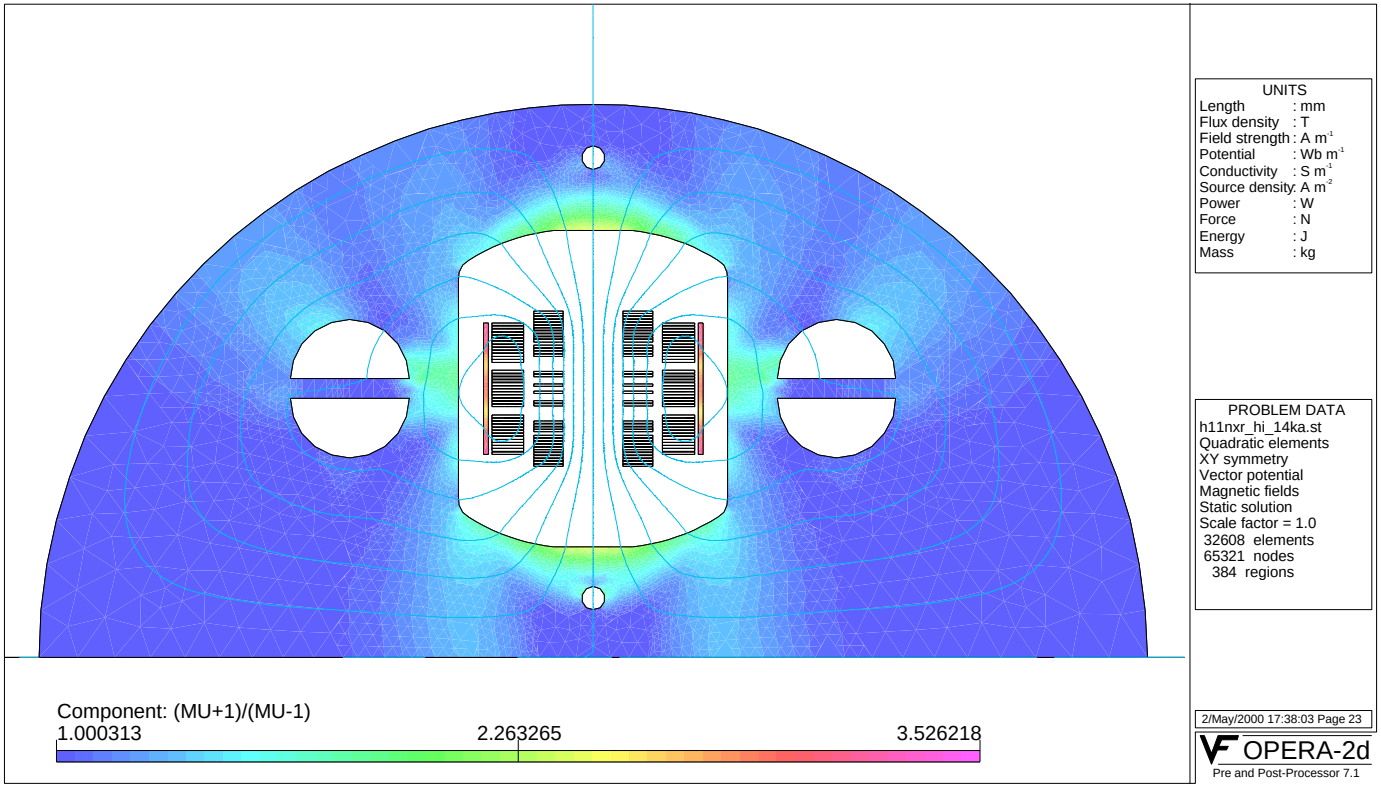




Inner layer: ΣF_x (1 coil, 1 aperture) = 3.8 MN/m @ 14 kA (10 T)

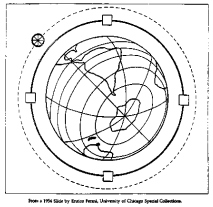
Yoke Cross-Section





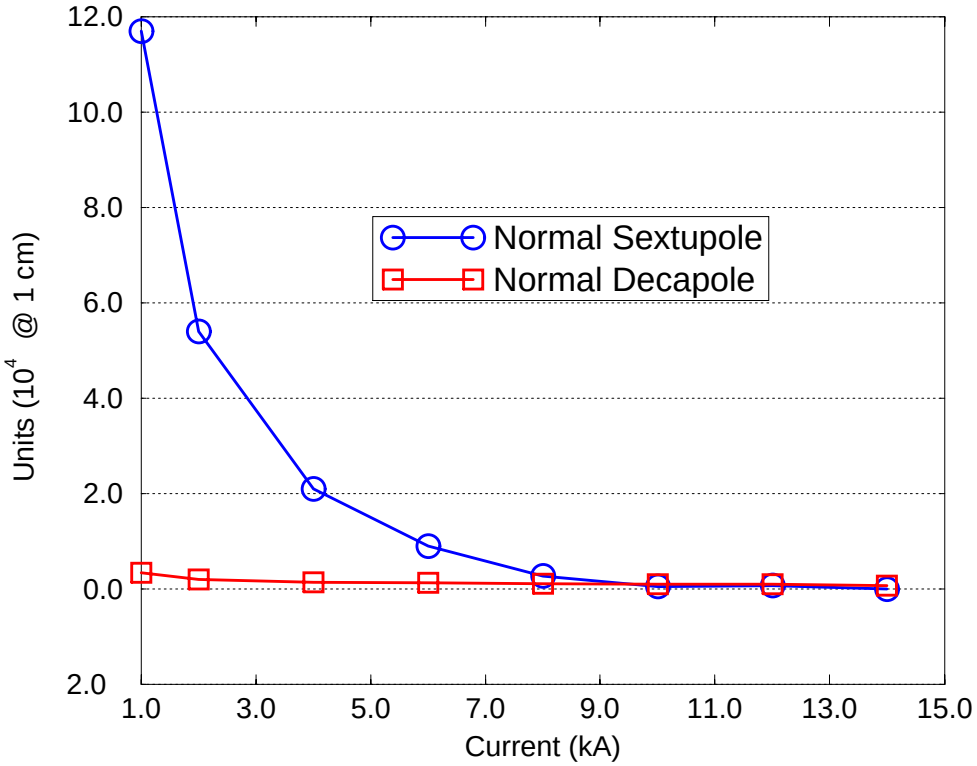
Yoke OD: 56 cm Aperture Separation: 27.2 cm

Straight Section Harmonics

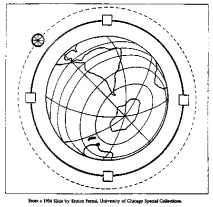


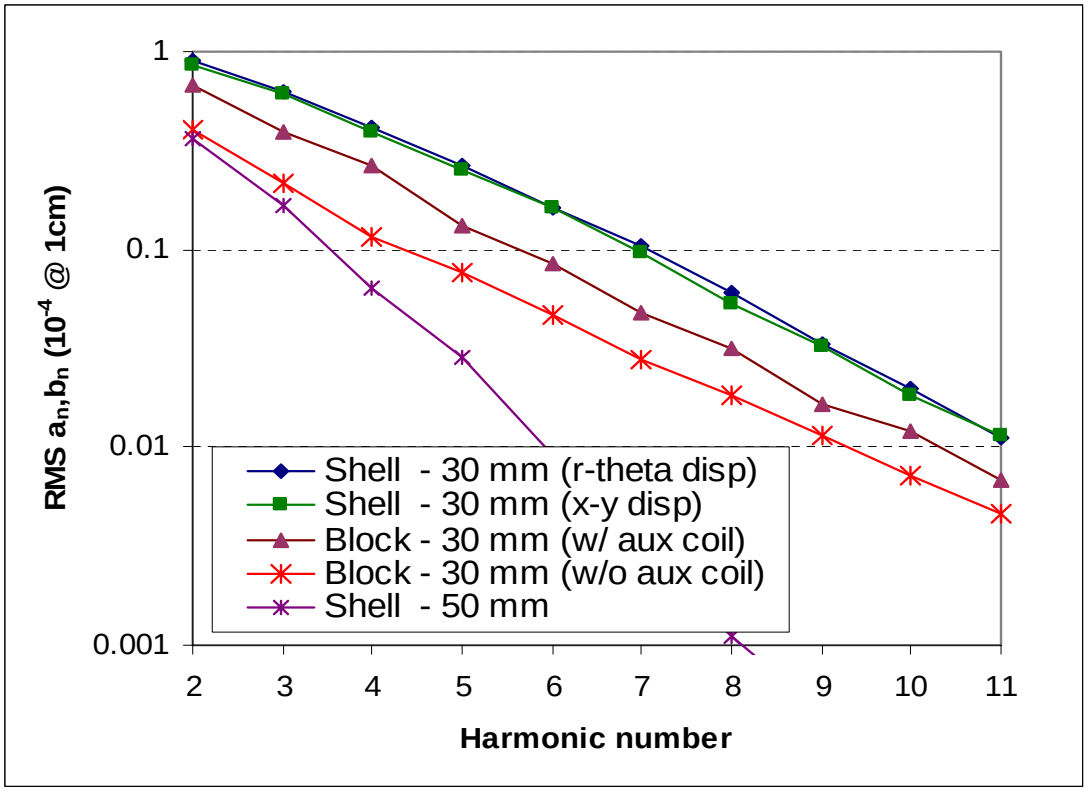
I =14 kA, r_0 = 10 mm

Comp.	Vs. 2	MT-16
b_3	0.1	0.6
b_5	-0.1	0.4
b_7	0.4	0.1
b_9	-0.3	-0.4
b_{11}	0.2	0.2
a_2	-0.1	-1.2
a_4	0.1	0.7
a_6	0.0	0.1



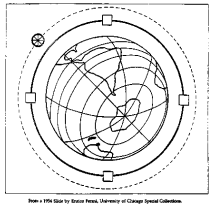
Random Error Analysis

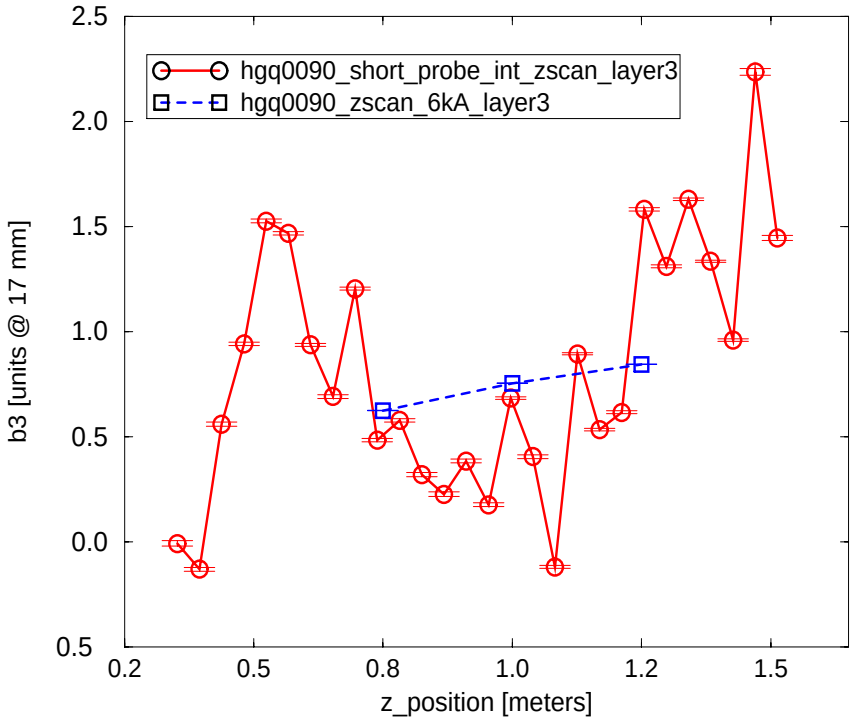




Random block displacements by +/- 20 μm, uniform distribution

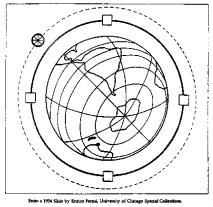
LHC IR Quad Random Errors





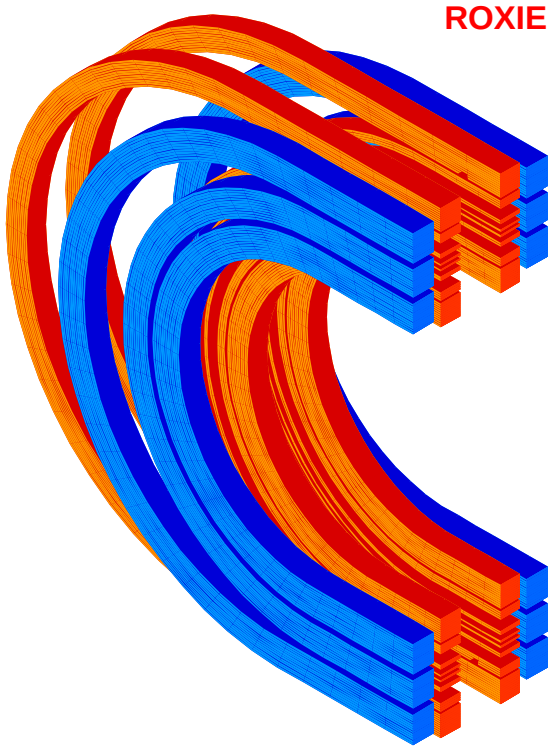
Comp.	L_p=82 cm	L_p=4.3 cm	±20 μm
b_3	0.26	0.61	0.59
a_3	0.28	0.54	0.58
b_4	0.09	0.28	0.36
a_4	0.31	0.40	0.34
b_5	0.04	0.10	0.16
a_5	0.16	0.19	0.16
b_6	0.19	0.25	0.07
a_6	0.03	0.07	0.07

End Harmonics (no iron yoke in end region)



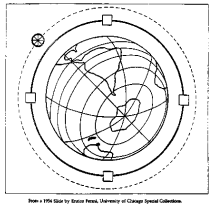
Unit-m @ 1 cm

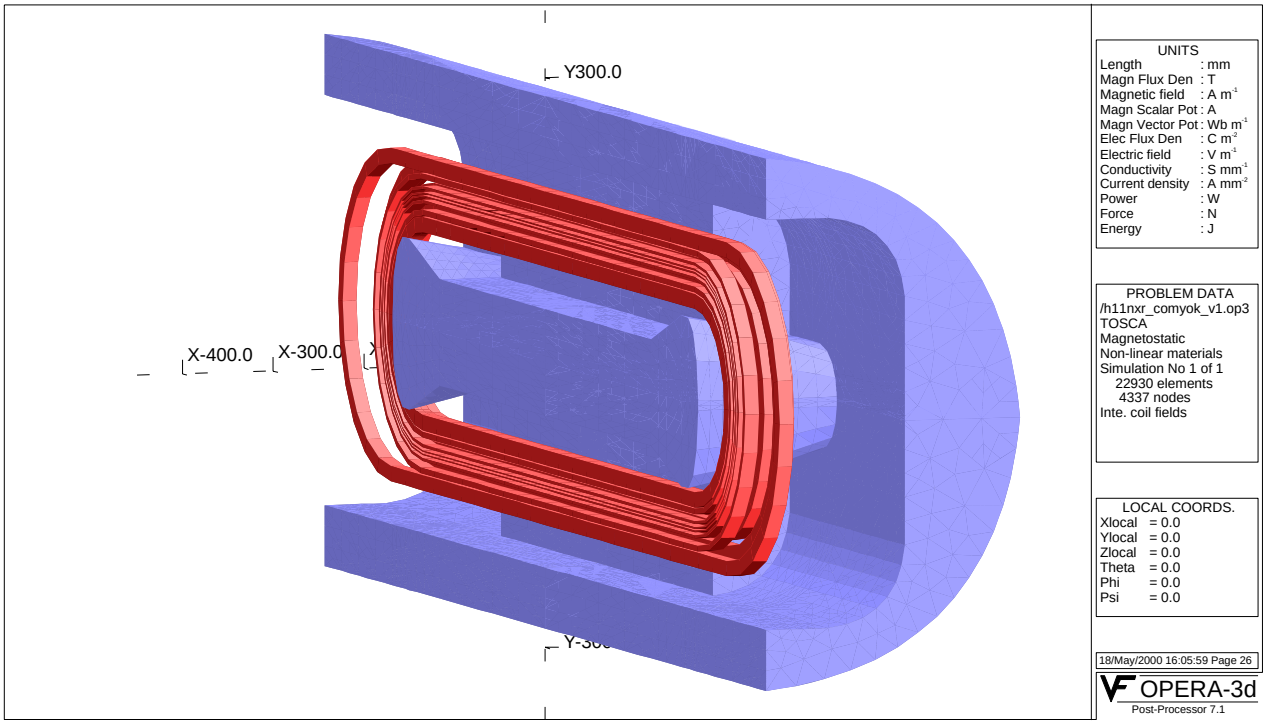
Param.	Vs. 2	MT-16
L_m [m]	0.16	0.21
b_3	0.4	0.4
b_5	-0.3	-0.9
b_7	0.1	0.1
b_9	0.0	-0.1
a_2	-1.2	-21.8
a_4	0.5	0.5
a_6	0.2	0.5
a_8	0.1	0.0



Harmonics ok, but end peak field for outer conductor is at same level as in magnet body

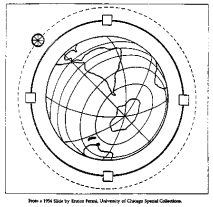
Preliminary yoke design for end regions





In progress: approximate iron geometry to more practical shape; re-adjust field quality

Design Study Parameters



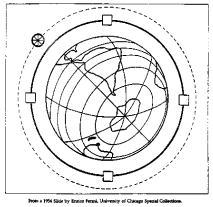
Short sample field : 11 - 14 T
Bore diameter : 20 - 45 mm
Outer layer cable : hybrid - graded - same as inner

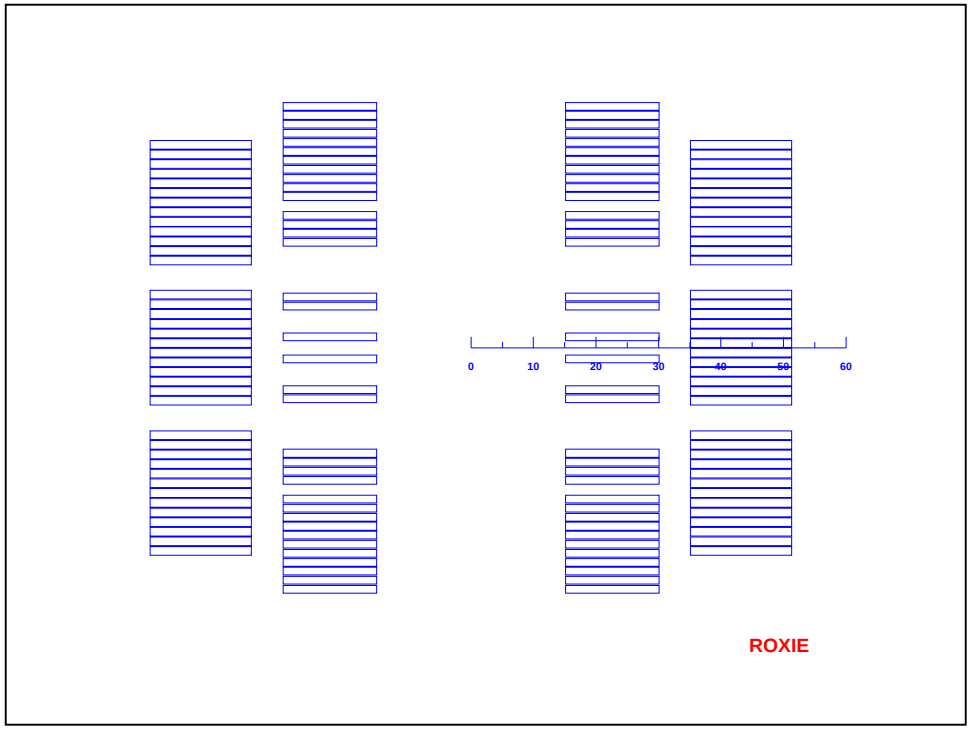
Nb_3Sn: $J_c(12T, 4.2K)$ = 2 [A] - 3 [B] kA/mm^2 (-10% degr.)
NbTi: $J_c(7T,4.2K)$ = 1.8 kA/mm^2 (-5% degr.)
T_{op} = 4.3 K
J_{cu} (I_{ss})= 2 [A] - 1.8 [B] kA/mm^2

Nb_3Sn cost = 10 [A] - 5 [B] \$/mm^2/m
NbTi cost = 1.2 [A] - 1 [B] \$/mm^2/m
(All Cu in SC strand [A] - Cu/Sc = 0.75 in SC strand [B])

Short sample calculations include iron saturation effect
Inductance ratios R_{ind} are estimates from 1-aperture models

2-layer, 30 mm bore, hybrid
B_{ss} = 11.0 - 11.5 T





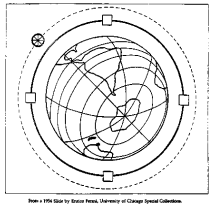
Parameter	Unit	A	B
B_{ss}	T	11.0	11.5
I_{ss}	kA	15.4	16.1
L	mH/m	5.4	
d_{bore}	mm	30	
ΔB_{ss}	T	0	0
R_{cond}		1	1

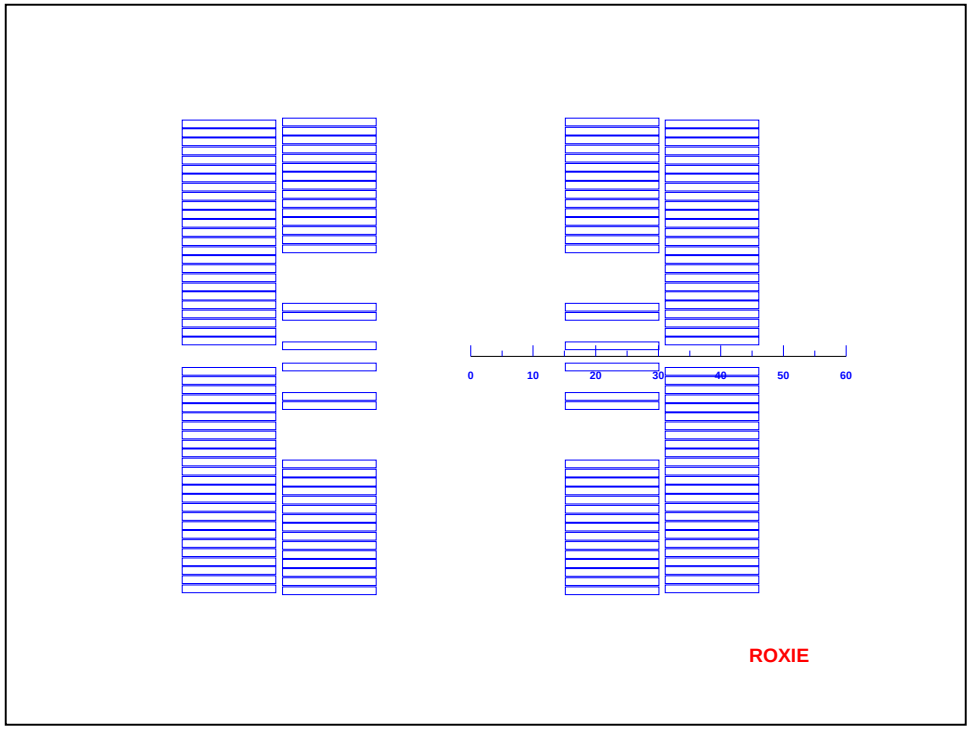
Parameter	Unit	I.L.	O.L
Strand diam.	mm	0.7	0.8
No. strands		40	40
Cable width	mm	15.0	16.2
$N_t^{(quad, 1ap)}$		18	19
$A^{(quad, 1 ap)}$	cm^2	2.8	3.9
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	9.9	3.0
$F_y^{(quad, 1ap)}$		-2.2	-2.6

Geom. harm. (r_0 = 10 mm)

b_3	b_5	b_7	b_9	b_{11}
0.0	-0.1	0.4	-0.3	0.2

2-layer, 30 mm bore, one cable
B_{ss} = 11.7 - 12.4 T





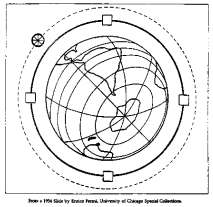
Parameter	Unit	A	B
B_{ss}	T	11.7	12.4
I_{ss}	kA	13.7	14.6
R_L		1.4	
Δ_{bore}	mm	0	
R_{cond}		2.0	1.9
ΔB_{ss}	T	0.7	0.9

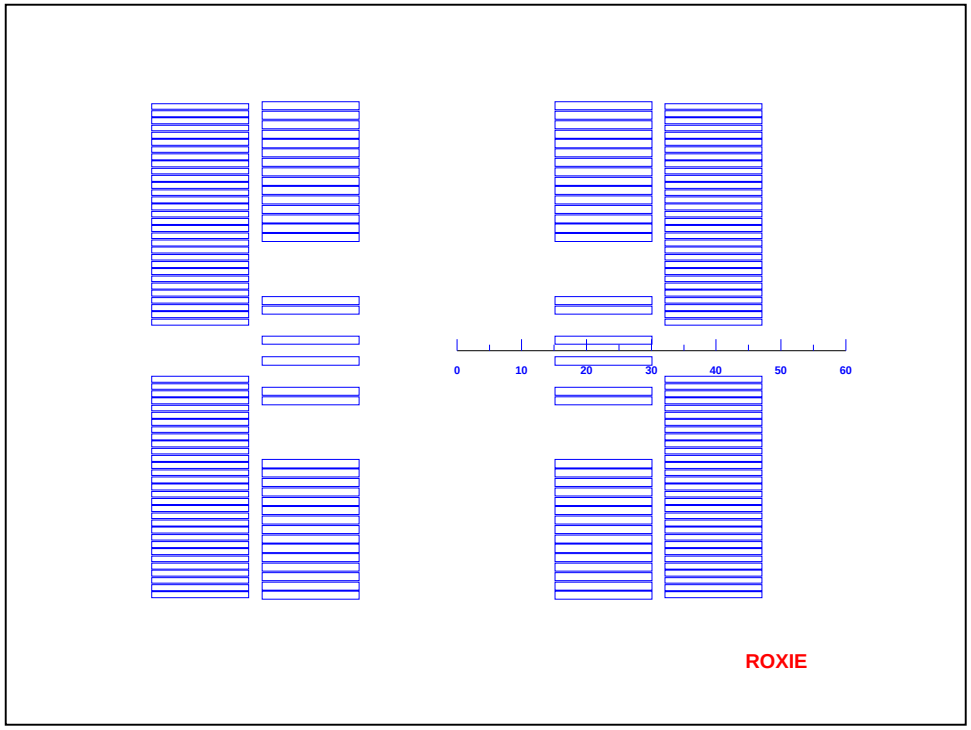
Parameter	Unit	I.L.	O.L
Strand diam.	mm	0.7	
No. strands		40	
Cable width	mm	15.0	
$N_t^{(quad, 1ap)}$		18	25
$A^{(quad, 1 ap)}$	cm^2	2.8	3.8
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	12.4	5.0
$F_y^{(quad, 1ap)}$		-2.5	-3.7

Geom. harm. (r_0 = 10 mm)

b_3	b_5	b_7	b_9	b_{11}
0.0	-0.3	0.6	-0.5	0.1

2-layer, 30 mm bore, graded
B_{ss} = 12.0 - 12.8 T





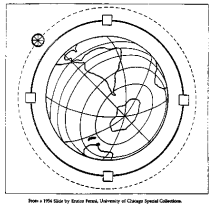
Parameter	Unit	A	B
B_{ss}	T	12.0	12.8
I_{ss}	kA	12.9	13.7
R_L		1.8	
Δ_{bore}	mm	0	
ΔB_{ss}	T	1.0	1.3
R_{cond}		1.9	1.4

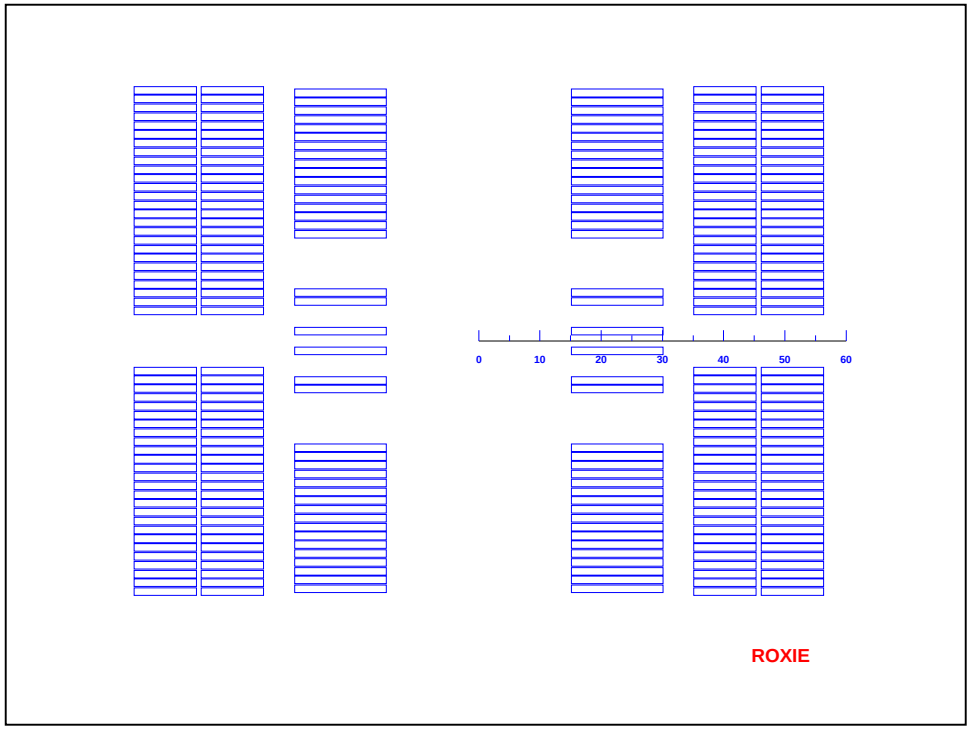
Parameter	Unit	I.L.	O.L
Strand diam.	mm	0.7	0.5
No. strands		40	56
Cable width	mm	15.0	15.0
$N_t^{(quad, 1ap)}$		18	31
$A^{(quad, 1 ap)}$	cm^2	2.8	3.4
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	14.6	8.0
$F_y^{(quad, 1ap)}$		-2.7	-5.0

Geom. harm. (r_0 = 10 mm)

b_3	b_5	b_7	b_9	b_{11}
0.0	-0.2	0.6	-0.4	0.1

3-layer, 30 mm aperture, graded
B_{ss} = 13.0 - 14.0 T





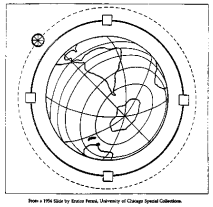
Parameter	Unit	A	B
B_{ss}	T	13.0	14.0
I_{ss}	kA	10.9	11.7
R_L		4.1	
Δ_{bore}	mm	0	
ΔB_{ss}	T	2.0	2.5
R_{cond}		2.6	2.3

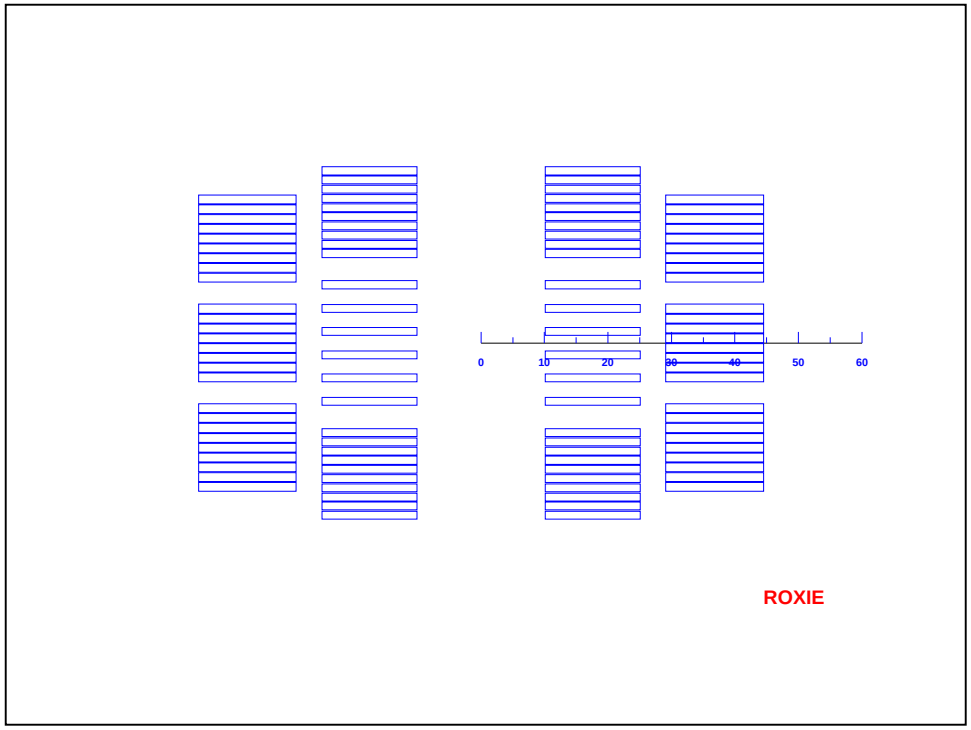
Parameter	Unit	I.L.	O.L
Strand diam.	mm	0.7	0.7
No. strands		40	26
Cable width	mm	15.0	10.2
$N_t^{(quad, 1ap)}$		20	52
$A^{(quad, 1 ap)}$	cm^2	3.1	5.2
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	22.3	21.4
$F_y^{(quad, 1ap)}$		-3.5	-12.

Geom. harm. (r_0 = 10 mm)

b_3	b_5	b_7	b_9	b_{11}
0.0	-0.3	0.4	-0.3	0.1

2-layer, 20 mm bore, hybrid
B_{ss} = 10.8 - 11.4 T





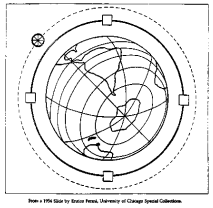
Parameter	Unit	A	B
B_{ss}	T	10.8	11.4
I_{ss}	kA	16.2	17.0
R_L		0.5	
Δ_{bore}	mm	-10	
ΔB_{ss}	T	-0.2	-0.1
R_{cond}		0.7	0.7

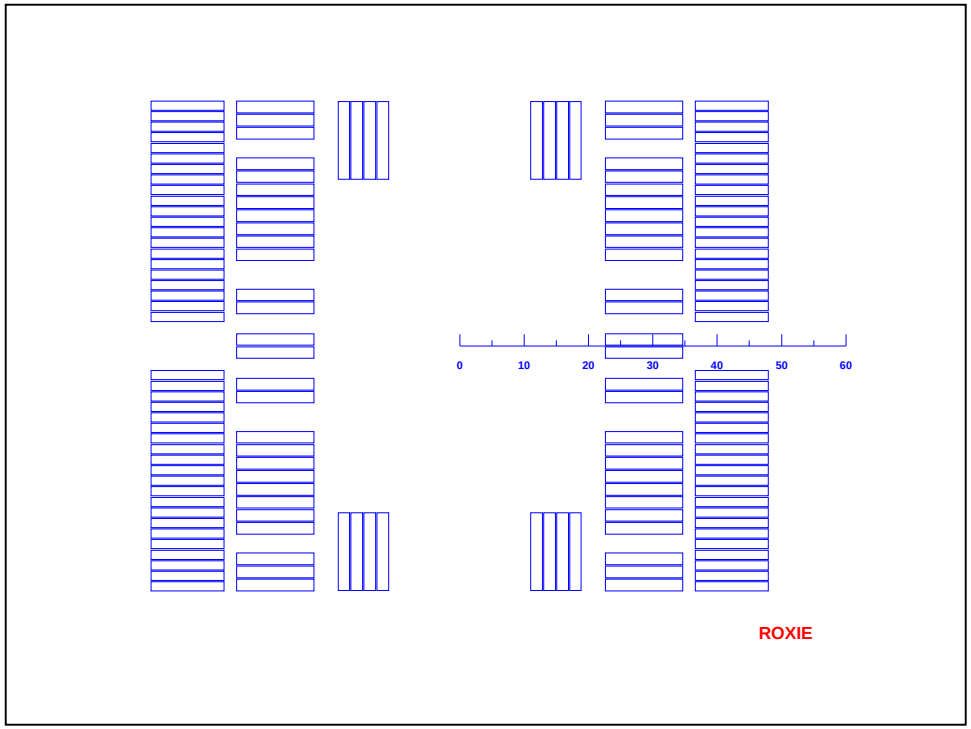
Parameter	Unit	I.L.	O.L
Strand diam.	mm	0.7	0.5
No. strands		40	38
Cable width	mm	15.0	15.4
$N_t^{(quad, 1ap)}$		13	13
$A^{(quad, 1 ap)}$	cm^2	2.0	2.5
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	6.1	1.3
$F_y^{(quad, 1ap)}$		-1.4	-1.8

Geom. harm. (r_0 = 7 mm)

b_3	b_5	b_7	b_9	b_{11}
0.0	-0.6	0.6	-0.2	-0.1

2-layer + aux coils, 45 mm bore, graded
B_{ss} = 11.9 - 12.6 T





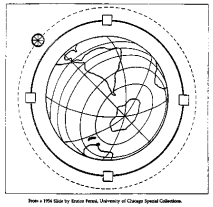
Parameter	Unit	A	B
B_{ss}	T	11.9	12.6
I_{ss}	kA	16.8	17.8
R_L		1.1	
Δ_{bore}	mm	+15	
ΔB_{ss}	T	0.9	1.1
R_{cond}		1.9	1.5

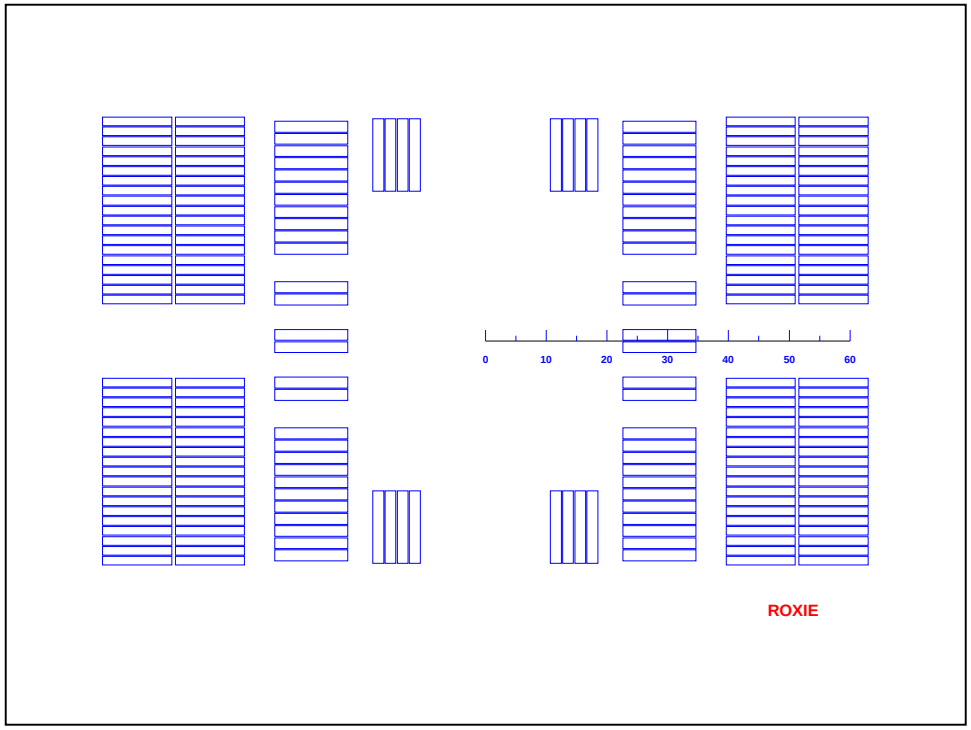
Parameter	Unit	I.L.	O.L
Strand diam.	mm	1.0	0.8
No. strands		24	26
Cable width	mm	12.0	11.3
$N_t^{(quad, 1ap)}$		18	21
$A^{(quad, 1 ap)}$	cm^2	3.4	2.7
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	10.2	2.4
$F_y^{(quad, 1ap)}$		-2.2	-3.1

Geom. harm. (r_0 = 15 mm)

b_3	b_5	b_7	b_9	b_{11}
0.0	0.0	0.1	-0.1	0.4

3-layer + aux coils, 45 mm bore, graded
B_{ss} = 12.6 - 13.6 T





Parameter	Unit	A	B
B_{ss}	T	12.6	13.6
I_{ss}	kA	14.3	15.4
R_L		2.7	
Δ_{bore}	mm	+15	
ΔB_{ss}	T	1.6	2.1
R_{cond}		2.6	2.3

Parameter	Unit	I.L.	O.L
Strand diam.	mm	1.0	0.8
No. strands		24	26
Cable width	mm	12.0	11.3
$N_t^{(quad, 1ap)}$		18	38
$A^{(quad, 1 ap)}$	cm^2	3.4	5.0
$F_x^{(quad, 1ap)}$	kN/ m/kA^2	15.3	10.8
$F_y^{(quad, 1ap)}$		-2.6	-7.6

Geom. harm. (r_0 = 15 mm)

b_3	b_5	b_7	b_9	b_{11}
0.1	0.1	0.1	-0.7	0.4