Pulsed Quadrupoles for a Heavy Ion Fusion Neutralized Beam Transport Experiment

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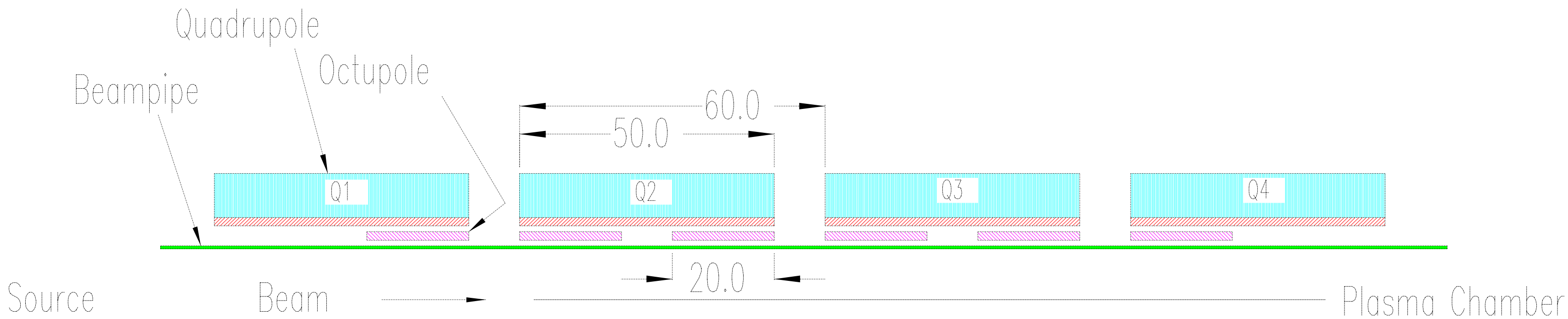
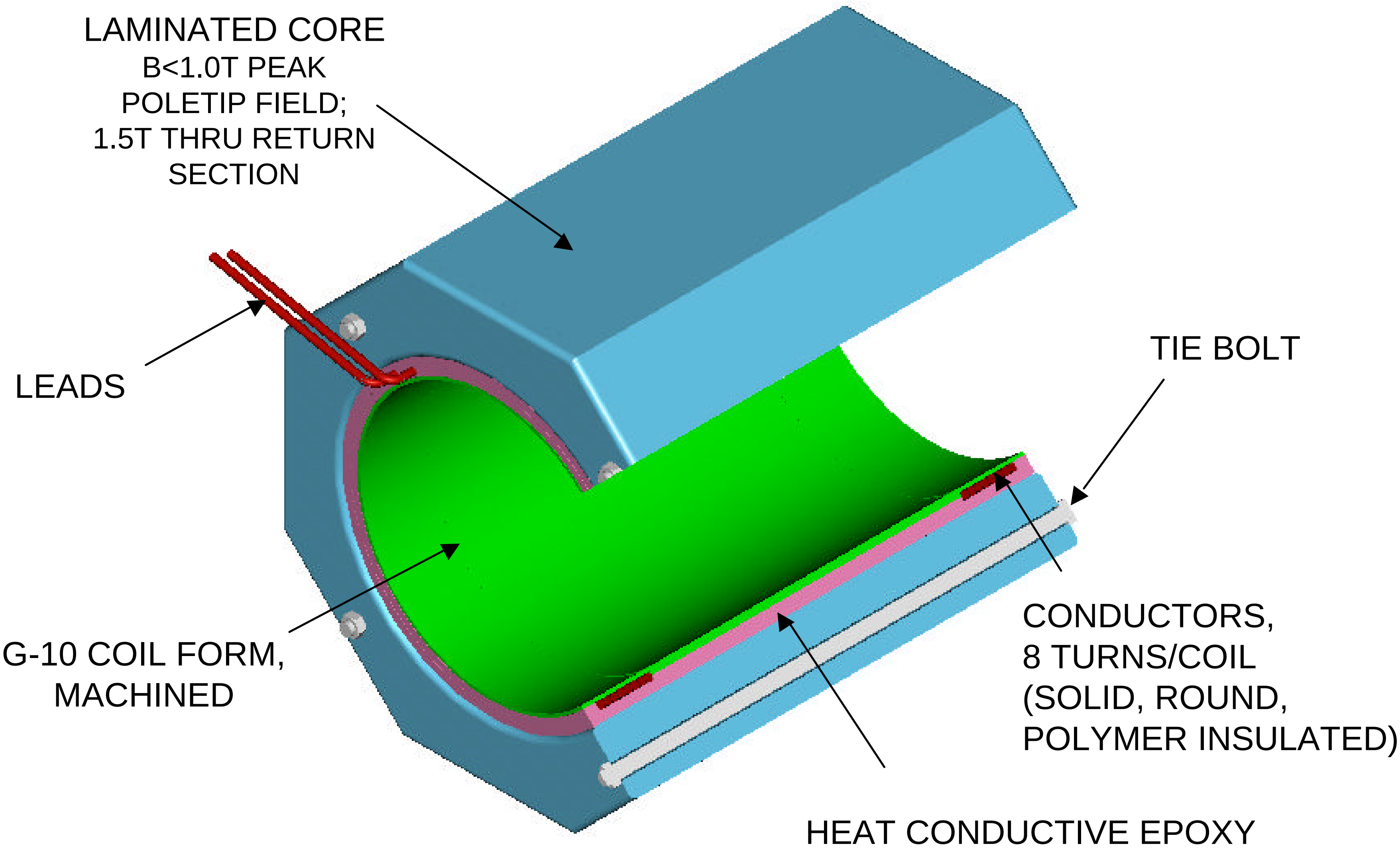
NTX Requirements for Quadrupoles

Beam Aperture Radius, R_a	14.9	cm
Maximum Focusing Power	2.0	T
Desired Magnetic length, L_m	46	cm
Maximum Total Length, L_t	60	cm
Max. Beam Passage Time (flat top)	5	μs
Max. Flat top field variation, $\Delta B/B_{max}$	<0.1	%
Operating Pulse Rate	0.1	Hz
(2D) Field Quality @ R_m=12cm ($\Sigma\|B_n\|$, n>2)	<0.1	$\%B_2$

•Quadrupoles must accommodate addition of tunable and moveable (in Z) octupoles (2kG@12cm radius)



NTX Low Field, Large Bore Pulsed Quad Design



NTX Current Dominated Pulsed Magnet Choice

•Tunable and movable octupole requirements for Phase II require a circular iron boundary (current dominated design).

•DC design requires inordinately large water cooled conductors (50 cm^2/octant), and high power requirements for supplies.

•>>CAVEAT: Eddy currents must be understood and managed with pulsed design.

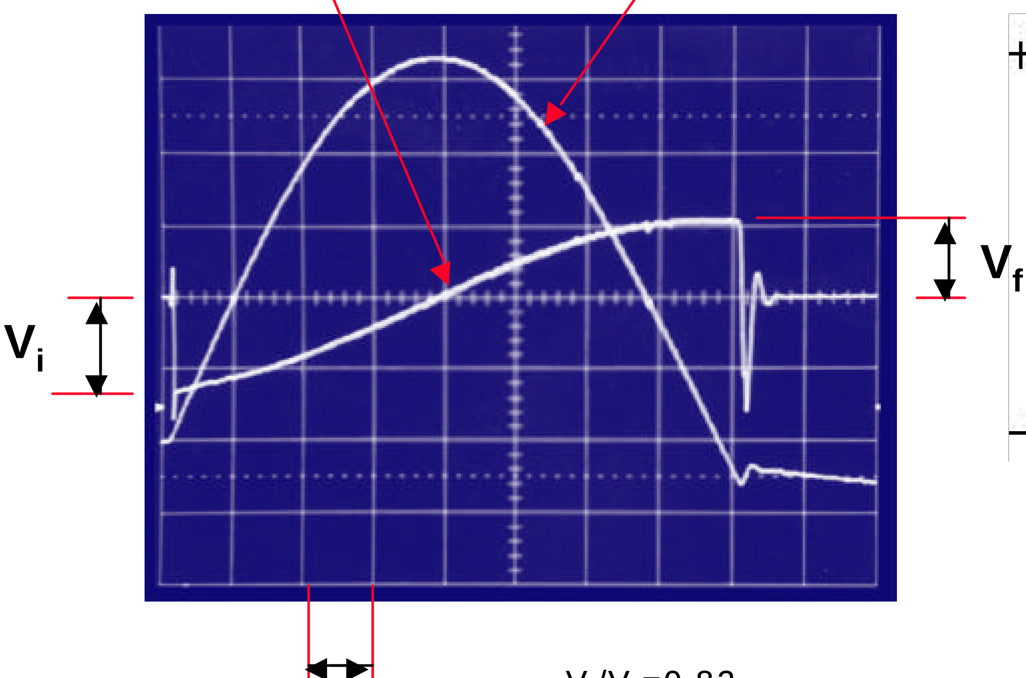
- •Beampipe
- •Flux Return Core (2D; 3D)
- •Conductors
- •Vacuum Flanges

NTX Pulser

Magnet voltage and current

Voltage, V
scale: 2.4kV/div

Current, I
scale: 800A/div

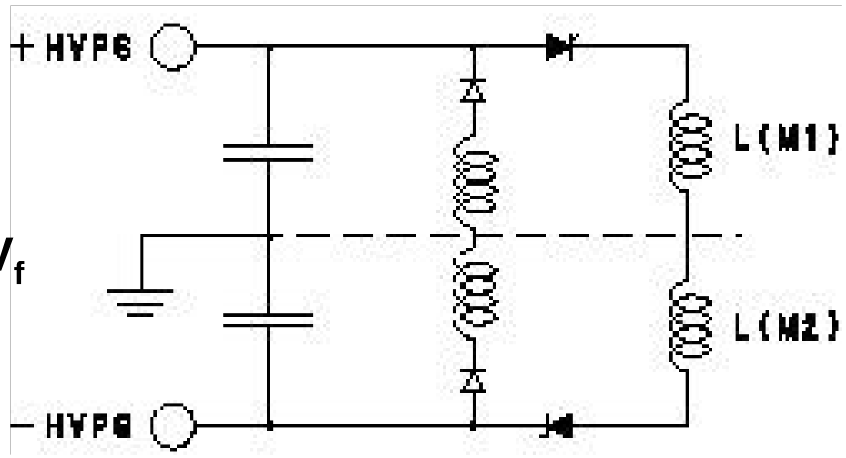


0.1mS

V_f/V_r=0.82

Energy recovery ratio, (initial)
$E_f/E_i=(V_f/V_i)^2=.67$

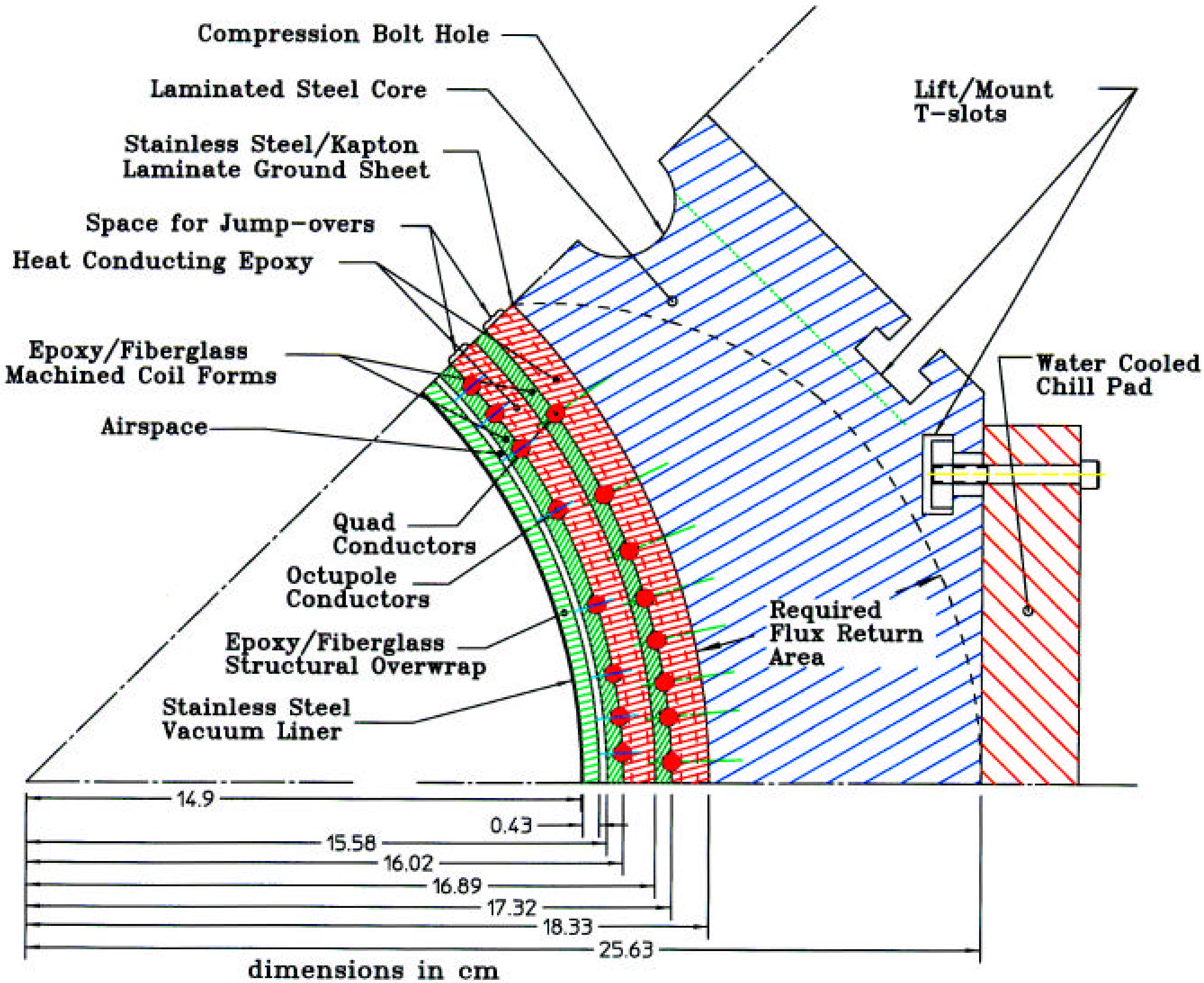
Charging supply | **Capacitor bank** | **Energy recovery inductor (optional)** | **SCR switch** | **Magnet(s)**



NTX Pulsed Quad Parameters

Beam Aperture Radius, R_b	14.9	cm
Magnet Winding Radius, R_w	17.32	cm
Steel Inner Radius, R_{si}	18.32	cm
Steel Outer Radius, R_{so}	25.63	cm
Mag., Total Lengths, L_m, L_o	46, 51	cm
Magnet to magnet spacing	60	cm (ctr.-ctr.)
Operating Field Gradient, B'	2-5	T/m
Maximum Field, B	0.6	T, @ 12cm
Number of turns, N	8	Turns/coil
2D Field Coeffs., B_n ($\Sigma n\|A_n\|/2A_2$, $n>2$)	$6\text{x}10^{-4}$	T/T, @ 12cm
Conductor diameter, d_c	4.6	mm
Magnet Current, I_{min}, - I_{max}	3.3- 8.2	kA
Magnet Resistance, R	.036	Ω
Magnet Inductance, L	232	μH
Pulse length (full half sine), t	1.6	ms
Magnet Voltage, @ 5T/m, V	4.0 [+/-2.0]	kV
Pulse energy, @ 5T/m, U	7.9	kJ
Energy loss/pulse, @ 5T/m, Q_t	2.0	kJ
Resistive conductor losses/pulse	2.0	kJ
Eddy current conductor loss/pulse	16	J
Max., Operating Pulse Rates	0.5, 0.1	Hz
Operating Temp. Rise, steady state	5	°C,

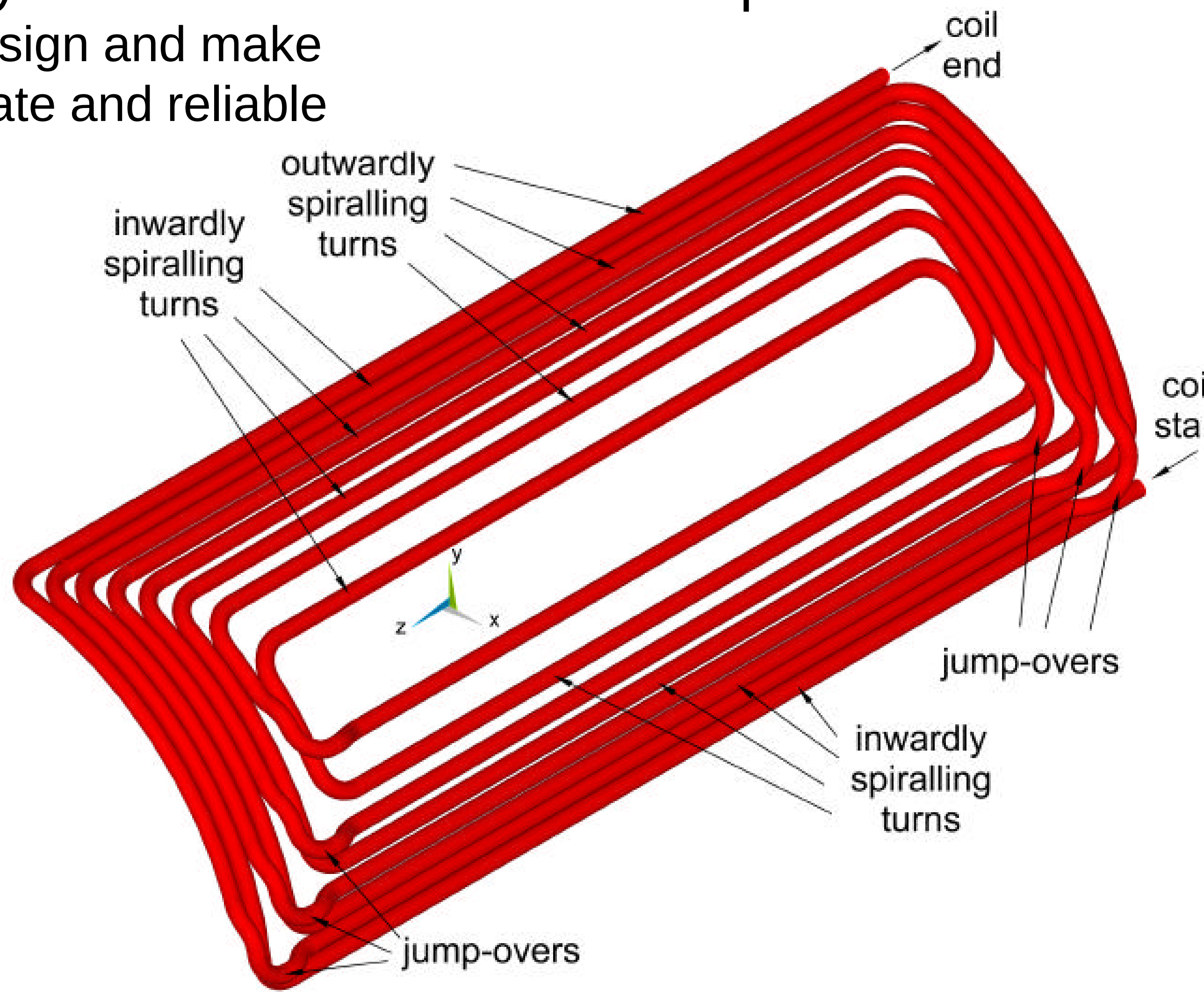
NTX Pulsed Quad Cross-section (XY)



NTX Pulsed Quad Coil Design

"Single Layer/Double Pancake" Concept

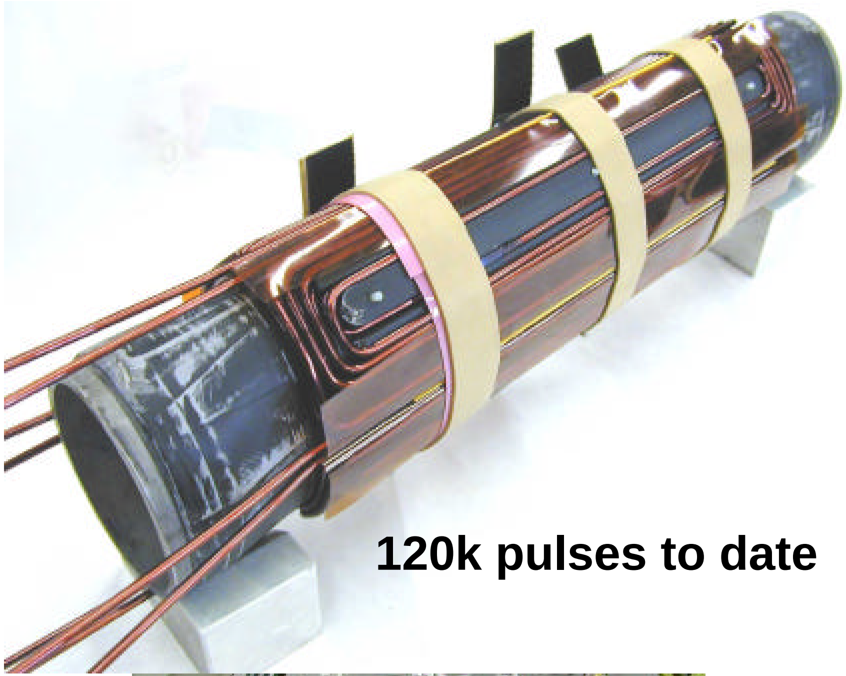
•easier to design and make
•more accurate and reliable

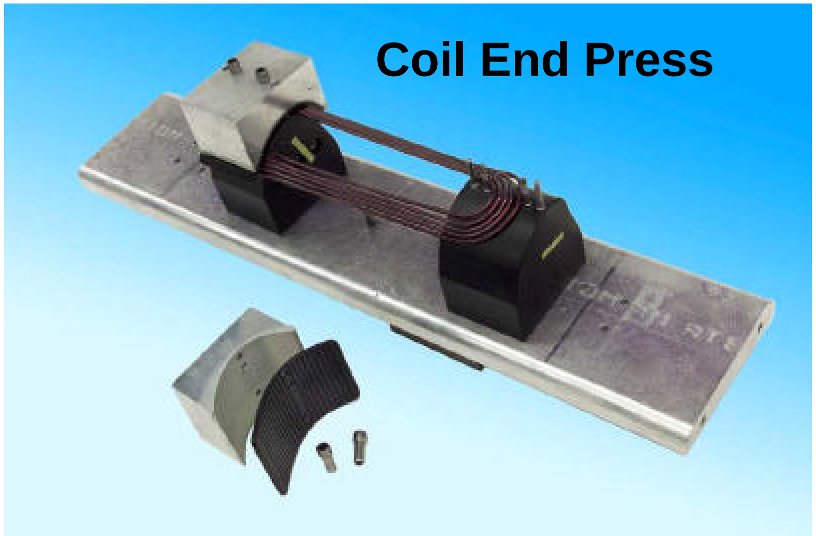


NTX Pulsed Quad Fabrication Design

- Coils wound and stretched to form straight and accurate conductor runs.
- Ends pressed circular with forming press. No pressure applied to jump-overs.
- Machined wire grooves in cylindrical fiberglass or phenolic coil form to hold wires in position.
- Quasi-single layer conductor layout (topologically still a two layer winding scheme); simplifies assembly adds reliability and accuracy. Jump-over bends required.
- Coils potted to laminated iron cores with heat conducting epoxy; cores cooled externally with water cooled chill bars.

NTX Quad Based on IRE Pulsed Elliptical Quad

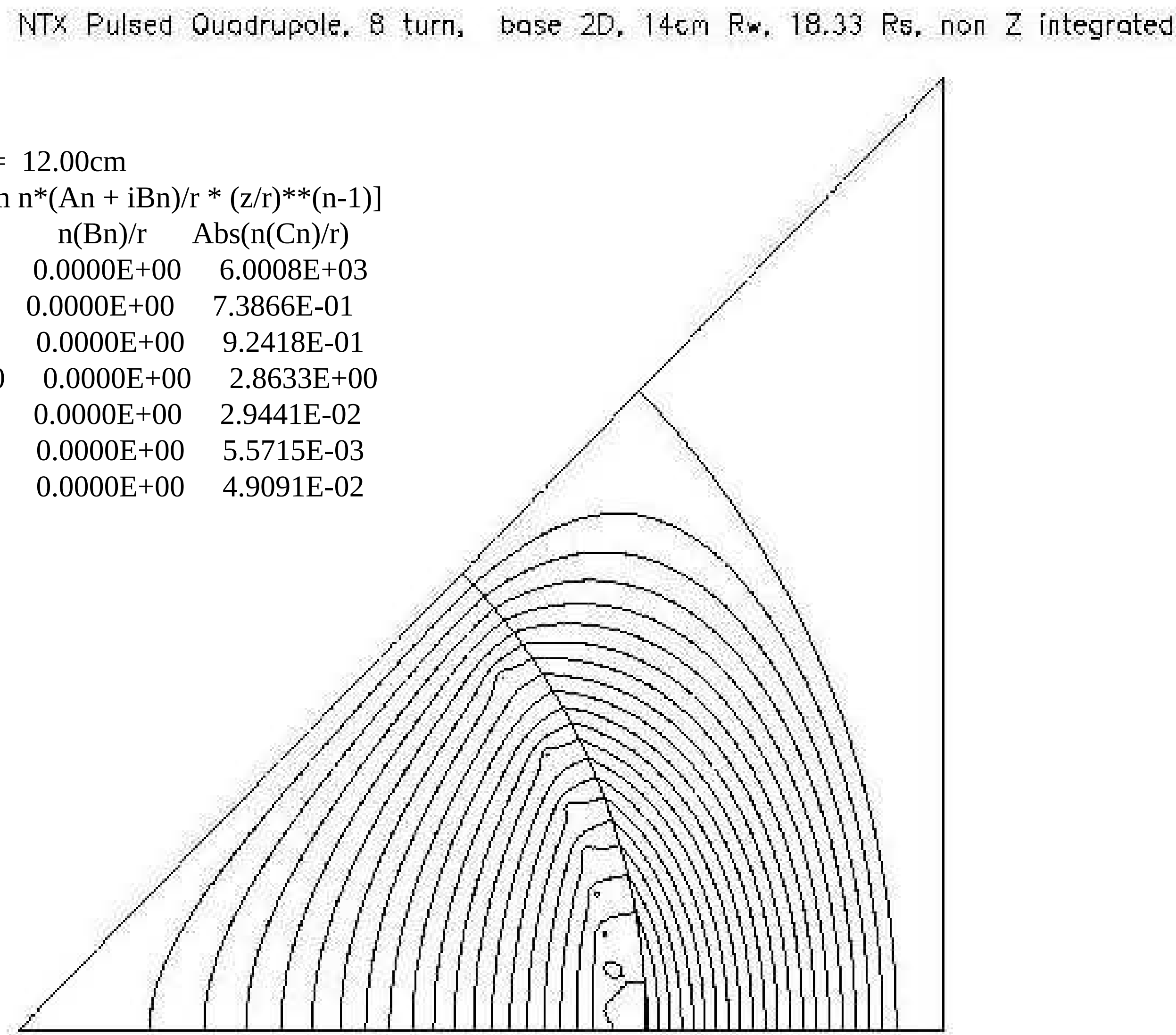




NTX Magnetic Transport Vacuum System

- Single, long composite S.S./ epoxy/fiberglass beamtube, separate from magnets.
  - No thick flanges in high field regions near beam.
  - .020” stainless steel vacuum liner easily penetrated by fields.
  - Internal end flanges allow beamtube to be easily inserted through magnet bores.
- Beamtube supported on end flanges (light and stiff).
- Magnets supported on external rail; easily pre-aligned on surface plate, and re-aligned in place. Quad positions adjustable in Z (if needed).
- Phase IIb octupoles inserted either inside quad bores, or onto beamtube.

NTX 2D Magnetic Model, 5 T/m (PANDIRA)



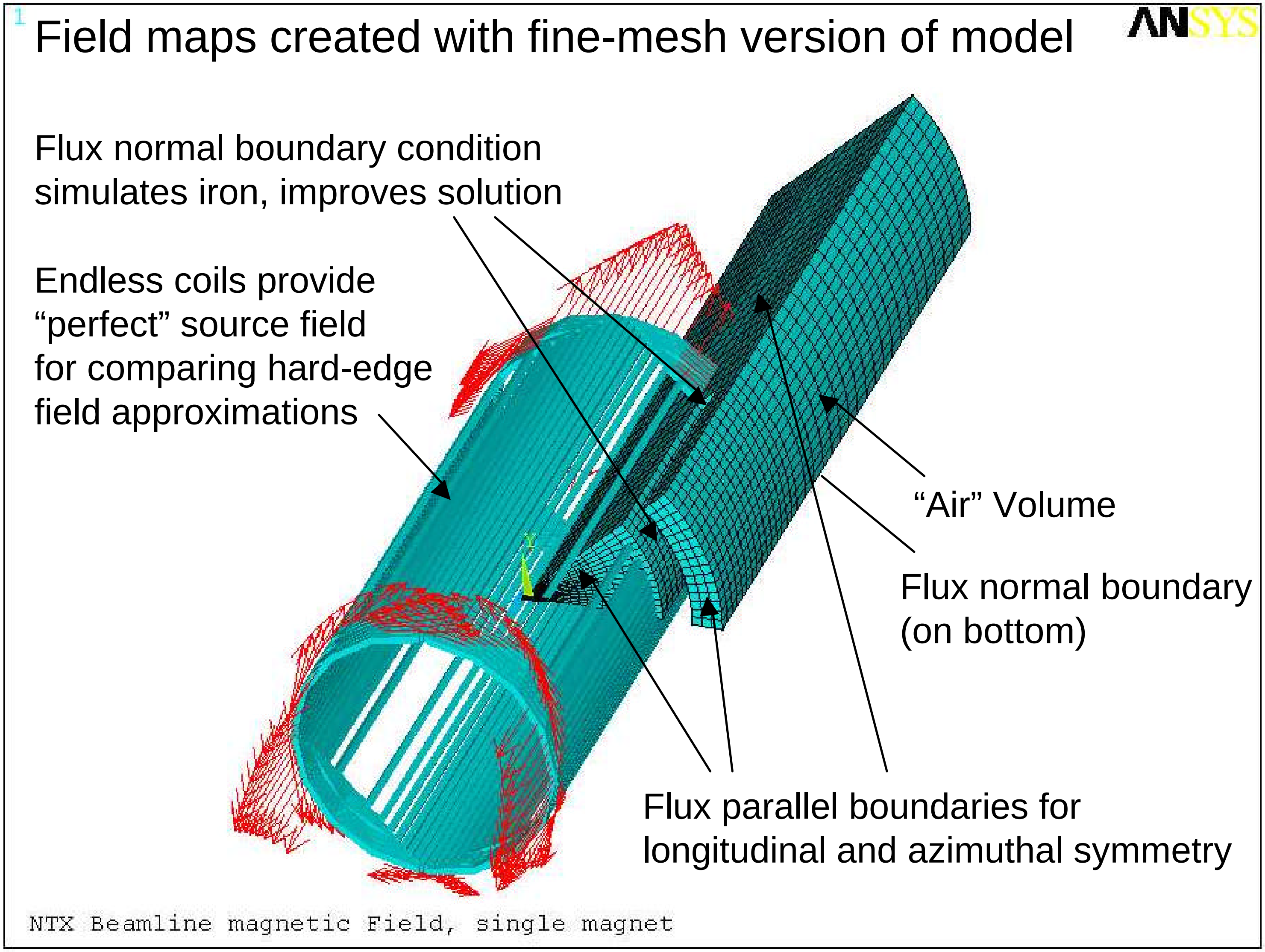
Field coefficients

Normalization radius = 12.00cm

(Bx - iBy) = i[sum n*(An + iBn)/r * (z/r)**(n-1)]

n	n(An)/r	n(Bn)/r	Abs(n(Cn)/r)
2	6.0008E+03	0.0000E+00	6.0008E+03
6	7.3866E-01	0.0000E+00	7.3866E-01
10	-9.2418E-01	0.0000E+00	9.2418E-01
14	-2.8633E+00	0.0000E+00	2.8633E+00
18	2.9441E-02	0.0000E+00	2.9441E-02
22	-5.5715E-03	0.0000E+00	5.5715E-03
26	-4.9091E-02	0.0000E+00	4.9091E-02

NTX 3D Magnetic Finite Element Modeling



NTX Magnetic Modeling to be performed

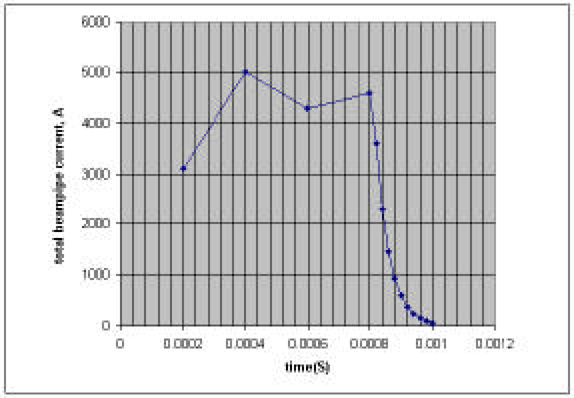
- TOSCA 3D model with iron for final accurate comparison to non-iron (infinite permeability iron) models.
- Coil asymmetries and lead effects.
- Multiple quad field maps (non-superposed fields; mutual inductance).
- Octupole and combined quad/octupole field maps.
- Magnetic shielding of source and plasma regions.
- Transient analysis of eddy currents in flanges.

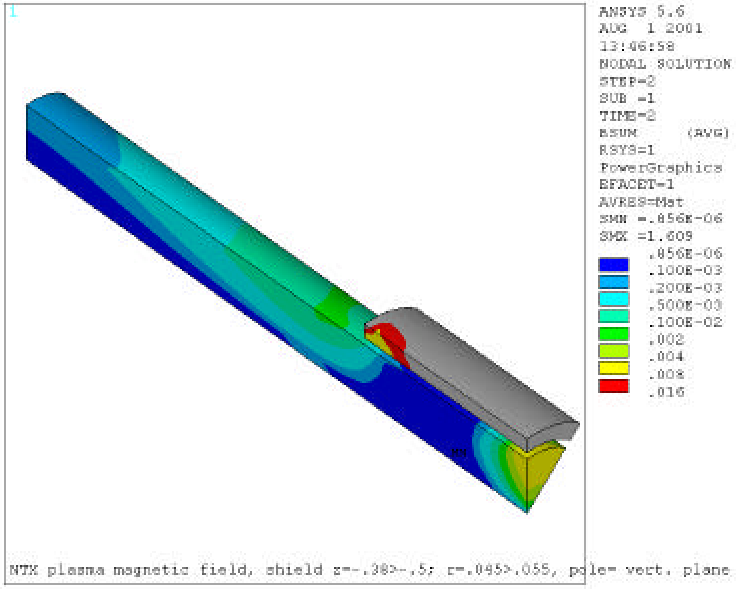
NTX Eddy Currents and Magnetic Shielding Modeling

- Eddy currents can be present in four areas:
  - Beampipe: main field bucked by “2nd quad”, of 1/15 main field amplitude, 86 deg. out of phase (34 μs calculated decay time constant)
  - Conductors: small power loss (scales as r^4); negligible slight shift of centroids
  - Laminated core: negligible losses; negligible heating or drop in efficiency of flux return
  - Flanges: possibly some heating, end fields possibly perturbed at large radius (however, beam is small at flanges)

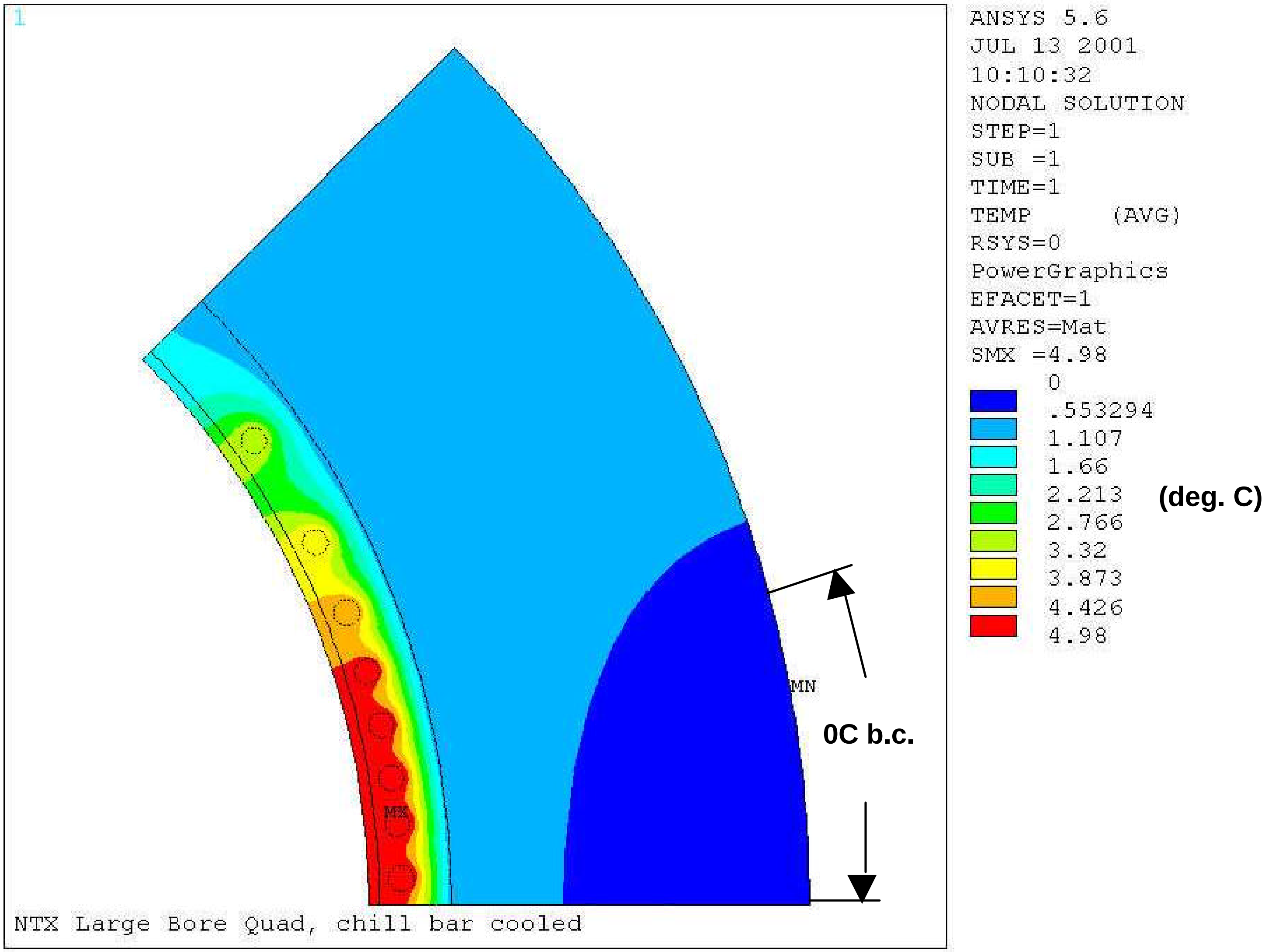
- Magnetic Shielding may be required at:
  - Source area where beam energy is low
  - Plasma volume downstream (Bmax~1G)

ANSYS 2D finite element transient analysis showing ~30μs decay time constant (response to step input where dB/dt goes to 0 @ t=.0008s)





NTX Pulsed Quad 2D FE Thermal Model, equil.



NTX Pulsed Quadrupole plus Octupole Modeling

Field coefficients from nt_q_o+.opn (positive octupole)
Normalization radius = 12.00000cm
(Bx - iBy) = i[sum n*(An + iBn)/r * (z/r)**(n-1)]

n	n(An)/r	n(Bn)/r	Abs(n(Cn)/r)
2	5.9613E+03	0.0000E+00	5.9613E+03
4	2.0044E+03	0.0000E+00	2.0044E+03
6	3.4416E-01	0.0000E+00	3.4416E-01
8	-1.1531E+00	0.0000E+00	1.1531E+00
10	-9.6456E-01	0.0000E+00	9.6456E-01
12	-2.0029E+01	0.0000E+00	2.0029E+01
14	-2.8390E+00	0.0000E+00	2.8390E+00

Field coefficients from nt_q_o-.opn (negative octupole)
Normalization radius = 12.00000cm
(Bx - iBy) = i[sum n*(An + iBn)/r * (z/r)**(n-1)]

n	n(An)/r	n(Bn)/r	Abs(n(Cn)/r)
2	5.9614E+03	0.0000E+00	5.9614E+03
4	-2.0039E+03	0.0000E+00	2.0039E+03
6	3.0062E-02	0.0000E+00	3.0062E-02
8	1.0328E+00	0.0000E+00	1.0328E+00
10	-6.5909E-01	0.0000E+00	6.5909E-01
12	1.9690E+01	0.0000E+00	1.9690E+01
14	-2.8517E+00	0.0000E+00	2.8517E+00