Pulsed Normal Quadrupoles for a Heavy Ion Fusion Driver Final Focus Section

D. Shuman , S. S. Yu , LBNL

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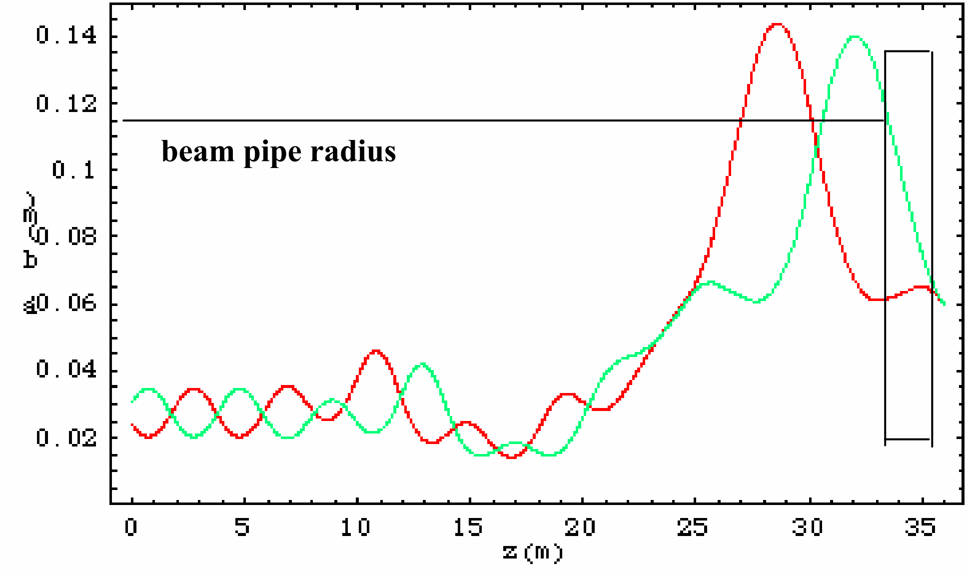
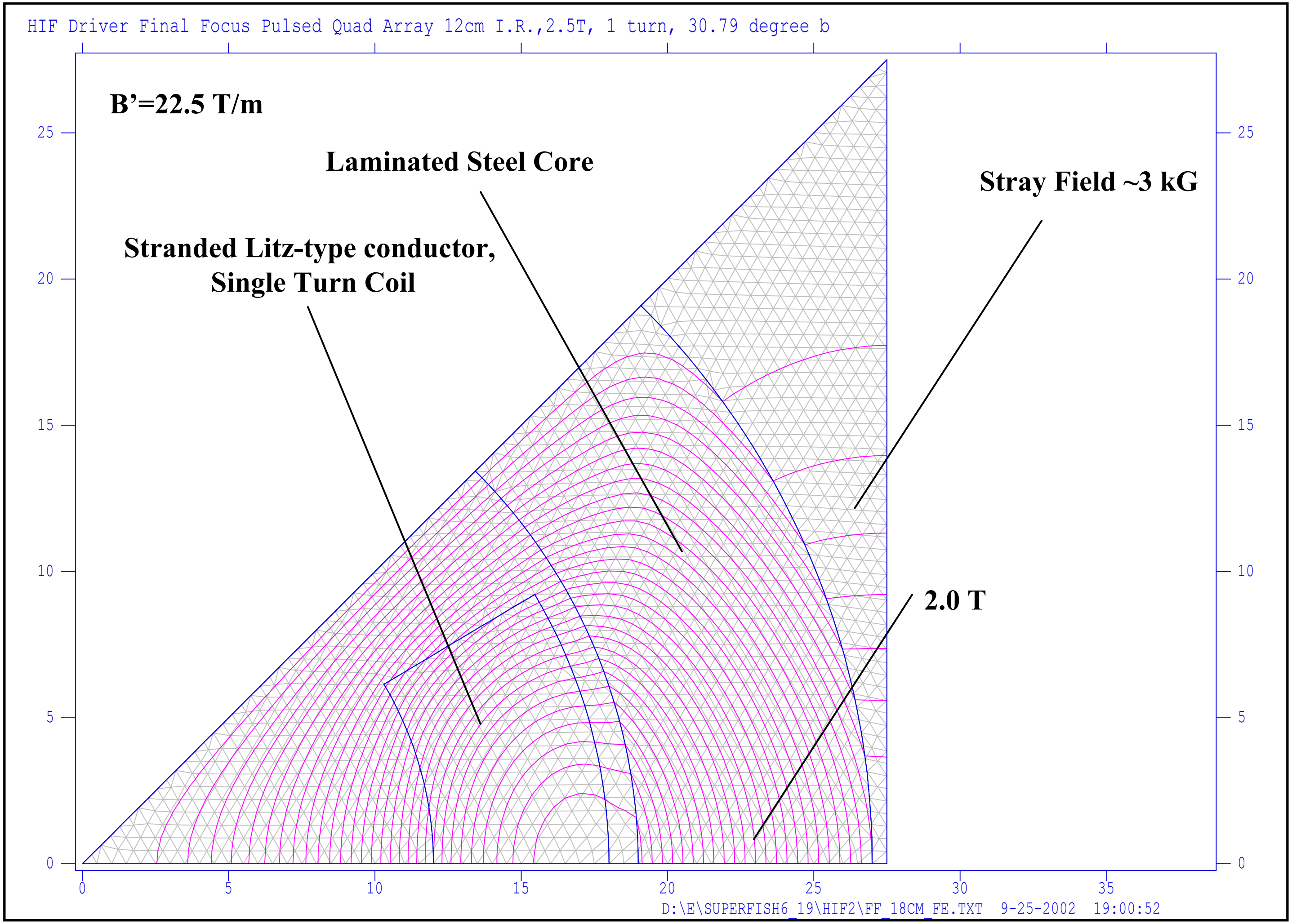
Design is for Last Quadrupole (facing target chamber)



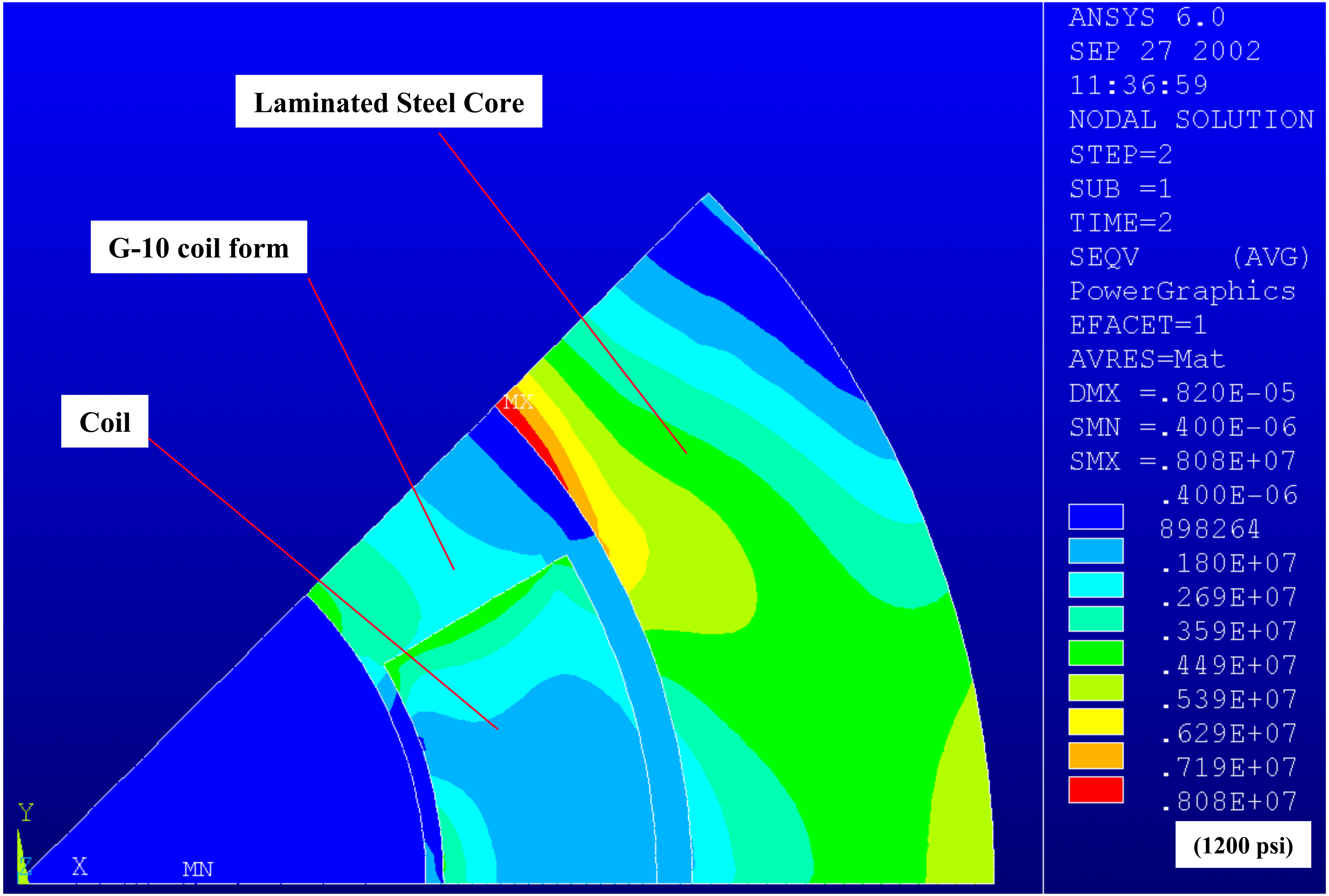
- **Minimize Power Loss**
- **Be Highly Radiation Resistant (particularly insulation)**
- **Must not create High Level Radioactive Waste Products (activation of niobium in SC magnets a HLW problem)**

Beam Aperture Radius, R_a	11.5	cm
Transverse Quad Spacing	55	cm
Maximum Gradient, B’	22.4	T/m
Magnetic length, L_m	1.33	m
Maximum Total Length, L_t	<2.75	m
Max. Beam Passage Time (flat top)	20	nS
Max. Flat top field variation, $\Delta B/B_{max}$	<0.1	%
Operating Pulse Rate	5-10	Hz
(2D) Field Quality @ R_m=10cm ($\Sigma\lvert B_n\rvert$, n>2)	<?1?	$\%B_2$

HIF Final Focus Driver Quadrupole Field Plot



HIF FF Quad Stress (Von Mises) Plot (Pa)



HIF Driver Final Focus Pulsed Quad Design Parameters

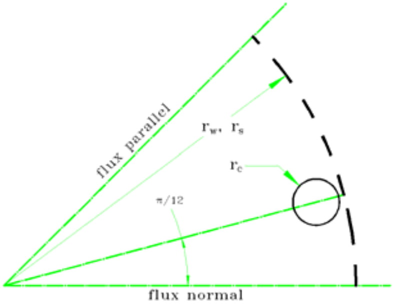
Beam Aperture Radius, R_b	11.5	cm
Coil Inner Winding Radius, R_w	12	cm
Magnet Coil Radial Thickness	6.0	cm
Steel Inner Radius , R_i	19.0	cm
Steel Outer Radius , R_o	27.0	cm
Magnetic Length, L_m	1.33	cm
Operating Field Gradient, B’	22.4	T/m
Maximum Field, B	2.24	T, @10cm
Number of turns, N	1	Turns/coil
2D H.O. Multipole Field Sum ($\Sigma n\|A_n\|/2A_2$, $n>2$)	<2	%, @10cm
Magnet Current, I	280	kA
Magnet Resistance, R	88	μΩ
Magnet Inductance, L	6.4	μH
Pulse energy, U	254	kJ
Est. Pulser Volume (from NIF flashlamp pulser, 3.6 J/in^3)	1.1	m^3
Est. Pulser cost (from NIF flashlamp pulser, $0.13/J)	33	k$ (2002)
Pulse length (full half sine), t	0.1	mS
Capacitance Required, C	157	μF
Magnet Voltage, V	57 (+/- 27)	kV

Design presents both difficulties and opportunities

- Use of steel cores allows high degree of flux isolation. No special edge coils will be needed at array periphery to provide proper boundary.
- Pulsed steering correctors may be incorporated into each magnet for individual beam alignment. Timing of correctors might allow real time target tracking (fire on ramp as pulser voltage is hard to adjust quickly).
- Large drift distance upstream minimizes stray field penetration into neighboring SC quads. Space will be needed for large leads, however.
- Solid conductors of previous pulsed designs would have either high resistive or high eddy current losses; large stranded litz-type cable conductors must be used to minimize both.
- Single turn coils are essentially mandatory to minimize inductance.
- Short pulse times (~0.1 mS) are needed to avoid excessive conductor size. A 1 μS pulse will give 20 nS flat-top of 0.1% with very small conductors, HOWEVER:
- Inductive voltage sets a limit on minimum pulse width. A 1 μS pulse will require 5 MV of inductive voltage for a single turn/coil quad! Practical voltage limitation will be likely be around 100kV.

Power Losses for Multistrand Quadrupoles

For a single turn quadrupole coil operating at a gradient of B', of insulated multistrand cable of a circular cross section with radius r_c, strand radius r_s, packing fraction F_p, winding and steel (unsat) radius r_w, coil total conductor length l_c, resistivity ρ, average field factor K_f in the conductor (fraction of maximum), subject to a pulse width (half sine) Coil eddy current losses, q_e per unit length of conductor scale to the square of either the conductor and/or strand diameter:



$$q_e = \frac{F_p (K_f \pi r_c r_s r_w B')^2}{8 \rho t}$$

Total coil eddy current losses Q_e are: $$Q_e = 4 q_e l_c$$

while total coil resistive losses Q_r, fall as the square of the conductor diameter:

$$Q_r = \tfrac{1}{2} I^2 R t \qquad R = \text{total magnet resistance} \qquad Q_r = \tfrac{1}{2} I^2 \frac{4 \rho l_c}{F_p \pi r_c^2} t$$

An optimum conductor radius, r_{copt} can be found which produces a minimum total loss $Q_t = Q_e + Q_r$:

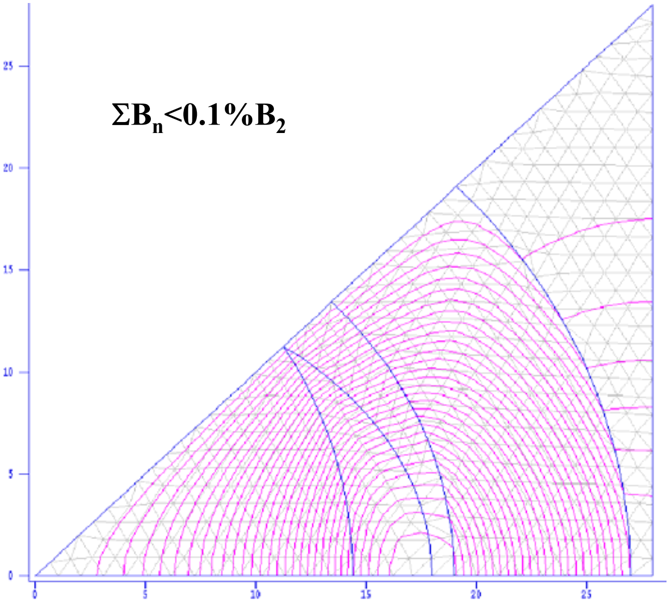
$$r_{c_{opt}} = \sqrt{\frac{2 t r_w \rho}{r_s \mu_0 \pi^{3/2} K_f F_p^{1/2}}}$$

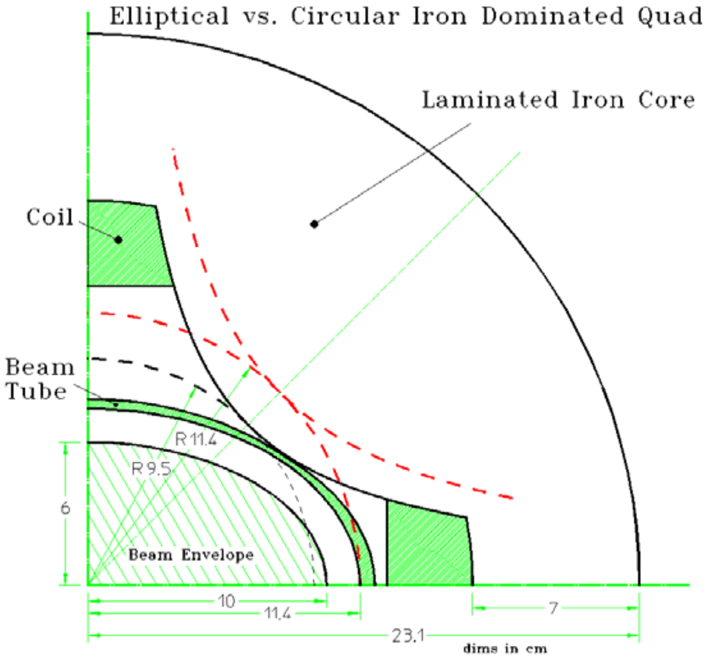
Applying this to the above formulas yields an expression for the total energy loss Q_t:

$$Q_t = \frac{r_s r_w^3 l_c B'^2 \pi^{1/2}}{\mu_0 F_p^{1/2}} \left(1 + \frac{K_f}{4}\right)$$

Power Loss Scaling

- For a given strand diameter, winding radius, material conductivity, and pulse width there is an optimum cable diameter (or coil cross-section area) which minimizes total power loss.
- Optimized cable diameter is proportional to the square root of the pulse width.
- Total coil power loss then becomes a linear function of strand diameter only (for optimized cable cable diameter). Smaller strand size requires larger cross sectional areas to be effective.
- Total power loss is proportional to the cube of the winding radius. Designs which minimize radius (specially shaped conductors or pole tips) will show significant loss reductions.

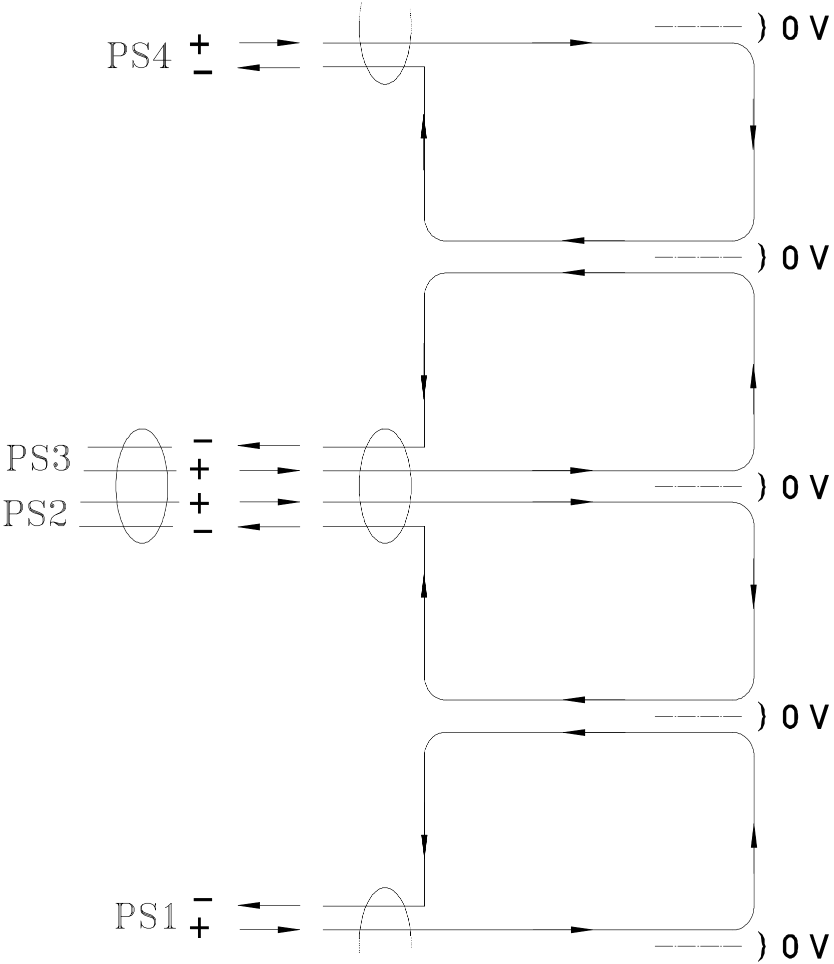




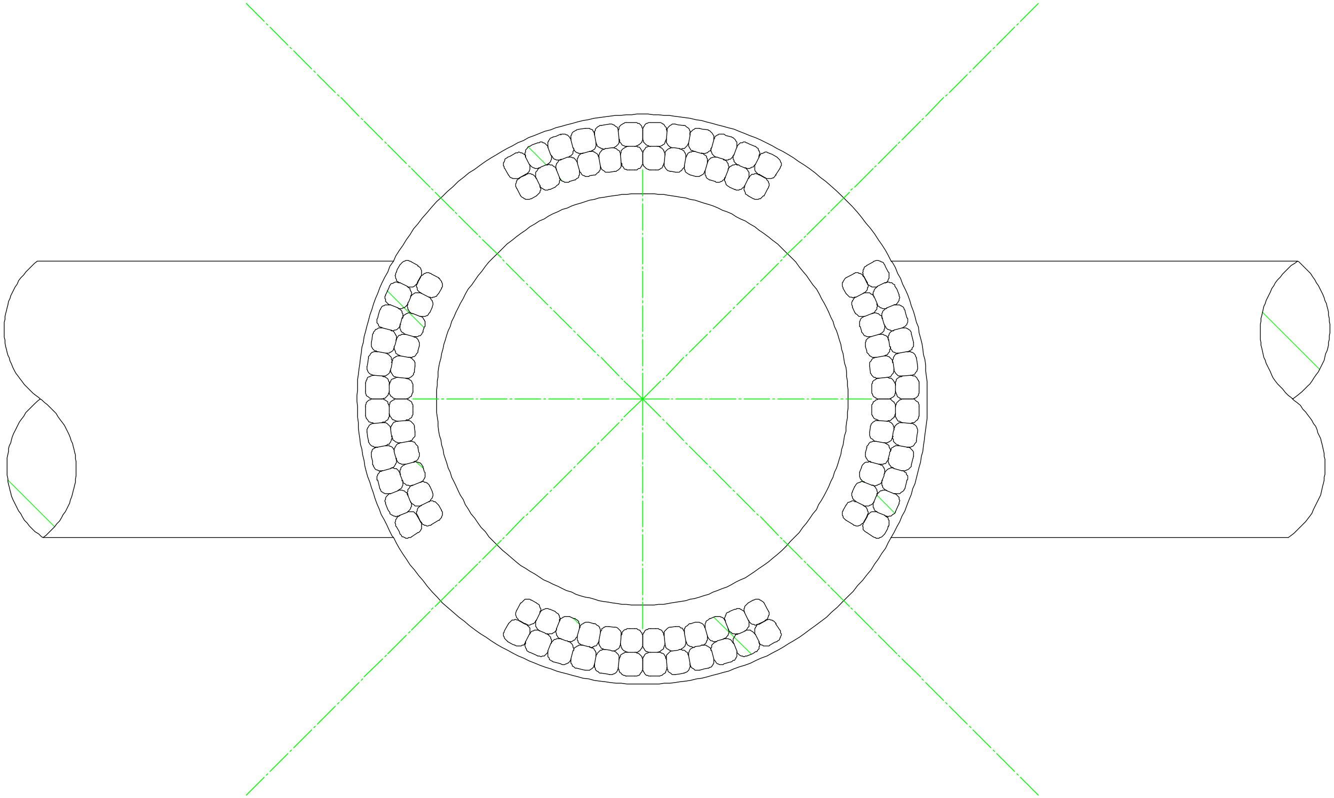
HIF Driver F. F. Pulsed Quad Operating Parameters

Pulse length (full half sine), t	0.1	mS
Capacitance Required	157	μF
Magnet Voltage, @ 22.4 T/m, V	57 [+/-29]	kV
Conductor Strand radius, r_s	0.05	mm
Resistive conductor losses/pulse	350	J
Eddy current conductor loss/pulse	60	J
Coil Energy loss/pulse, @ 22.4 T/m, Q_t	410	J
Coil Temp. Rise/pulse	0.0024	°C
Core loss/pulse (.003” lamination thk.)	20	J
Lead loss/pulse, (est. equal to magnet)	400	J
Switch loss/pulse (typ. IGBT @max V, I rating)	400	J
Capacitor loss/pulse (est. 0.1% U)	250	J
Total Magnet Channel Energy loss/pulse	1.5	kJ
Array Power requirement @ 6Hz , 120 beams	1100	kW

Single coil per power supply reduces voltage 75%

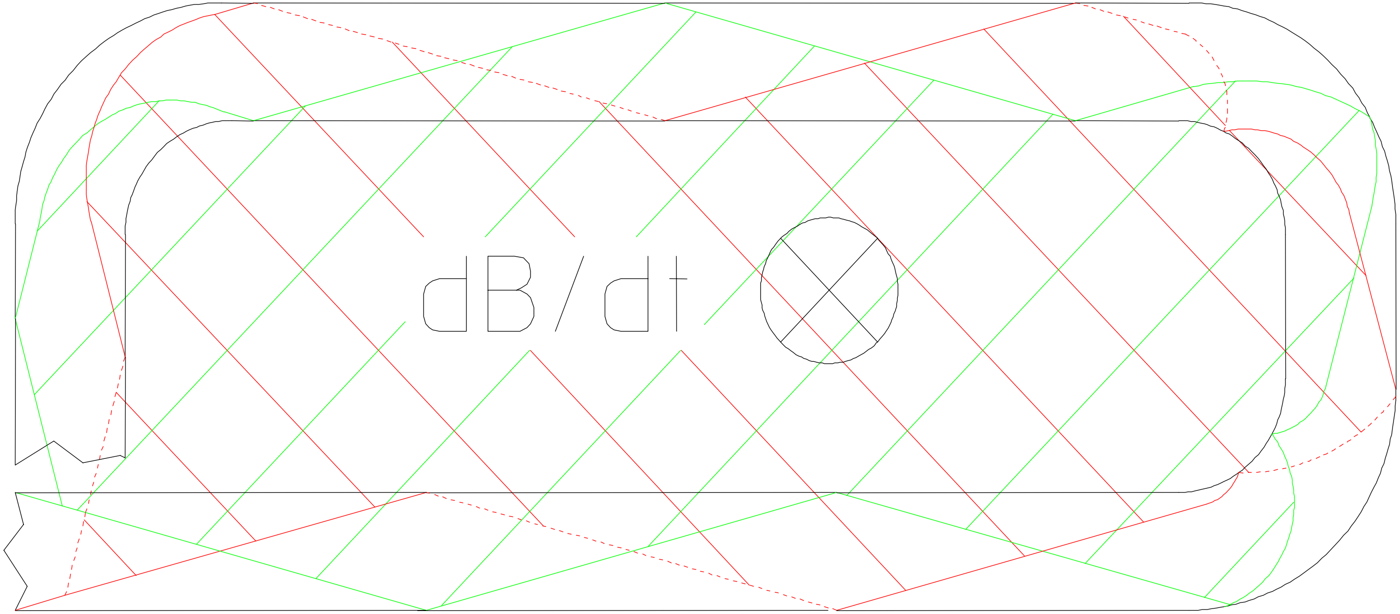


Magnet end view showing relative size of leads

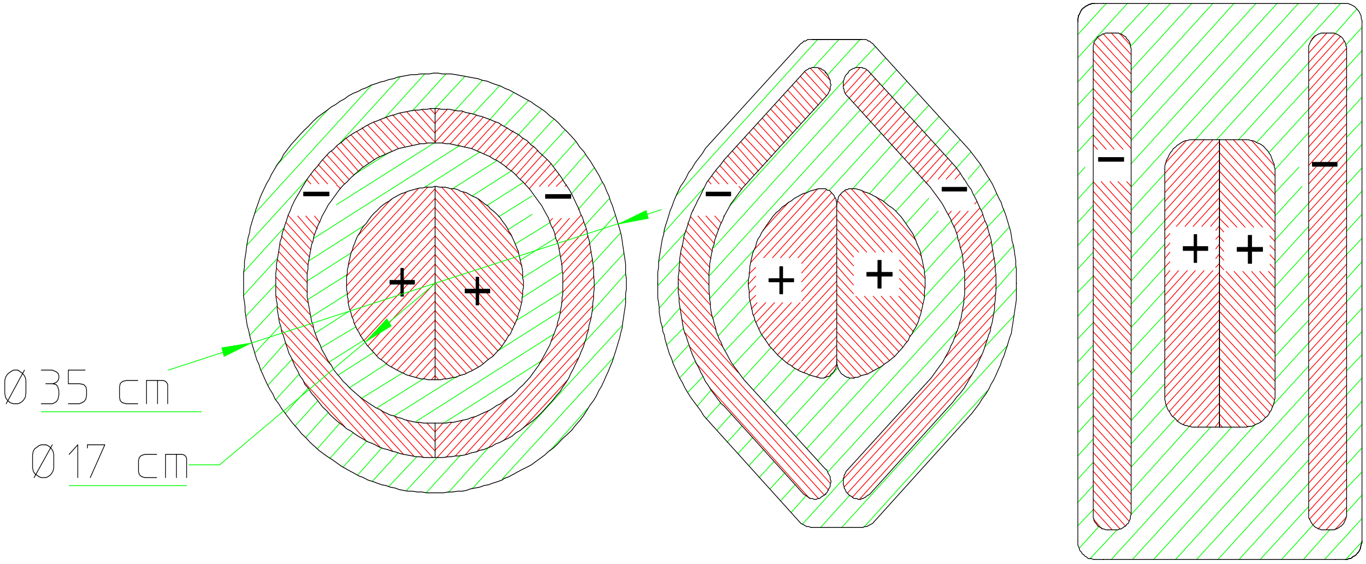


Single Turn Helical Litz-type Coil Feasibility

- Each strand forms a loop connected in parallel with all others.
- Strand helicity is needed to equalize loop inductances (to equalize strand currents).
- Furthermore, for small residual strand current imbalances, helicity serves to minimize their effect on overall magnetic field quality.



Coaxial Cable Transition into Coil



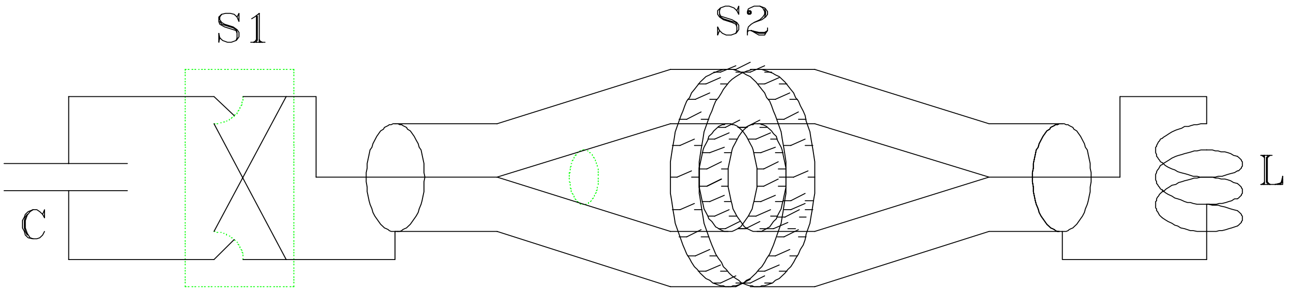
Further Feasibility Studies

- Lead routing in an array. Is there space for stacked leads?
- Pulser arrangement and configuration (is there room? how long must leads be? What is the added inductance?)
- Determine power losses in steel, beamtubes, flanges, and pulsers.
- Determine candidate insulation and support materials.
- Perform optimization of insulation thickness vs. conductor thickness.
- Verify that current strands and bundles can be inductance matched to the necessary tolerance.
- Verify that the proposed field quality is acceptable.

Possible R&D efforts

- Radiation resistant insulation (inorganic impregnant?)
- Optimization and improvement of Litz type conductor
    - Thinner strand insulation
    - Intermediate bundle configuration
    - Impregnation techniques
    - Characterize strand to strand voltage
- Lead to coil transitions.
- High strength coaxial leads (to avoid magnetostrictive degradation)
- Coil forming techniques.
- Compact low loss switching for pulser.
- Configuration of low inductance pulser circuit.

Low Inductance, Coaxial Pulser Topology



- Large switch area (S2) required to minimize losses; to equal coil losses:
  - Switch area required: 3.5 m^2 (typical hi-power IGBT module)
  - 43 switch modules in parallel, 17 banks in series= 7.5k total per magnet!
- Switch S1 avoids losses from recirculating, by providing "flip-flop" operation (switched under open circuit conditions only).