

Why Field Reversed Configurations (FRC's)?

- Superior Reactor Potential:

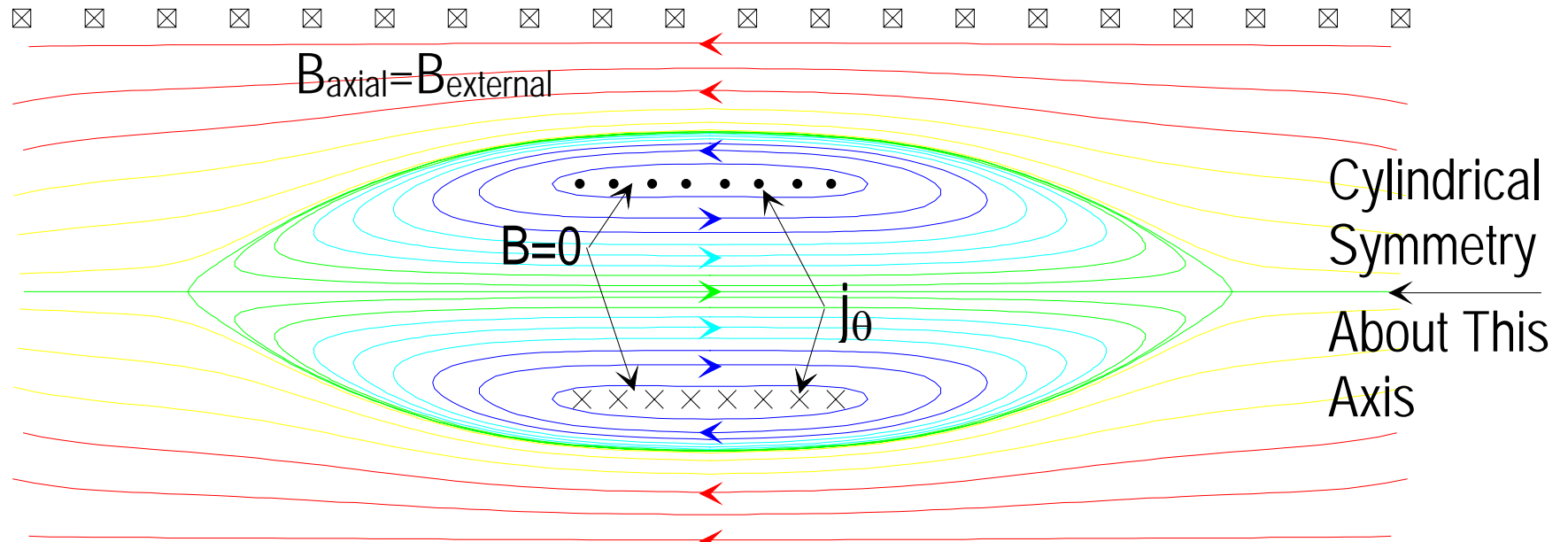
- High β ($.5 < \langle \beta \rangle < 1$, $\langle \beta \rangle = (nkT)_{\text{null}} / 2\mu_0 B_{\text{ext}}^2$)
- CAN BURN ADVANCED FUELS ($D+^3\text{He} \rightarrow p+^4\text{He}$)
- Simple Device Geometry
- Lower Cost Path to Development
- Natural Diverter

- Possible Space Applications:

- Advanced Fuels Produce Ions, Not Neutrons
- Direct Conversion of Ion Energy to Electrical Energy
- Space Propulsion, Rocket of 10 MeV Ions (chemical~1eV)

What Is a Field Reversed Configuration (FRC)?

MOQUI (2-D nonlinear resistive MHD code) generated



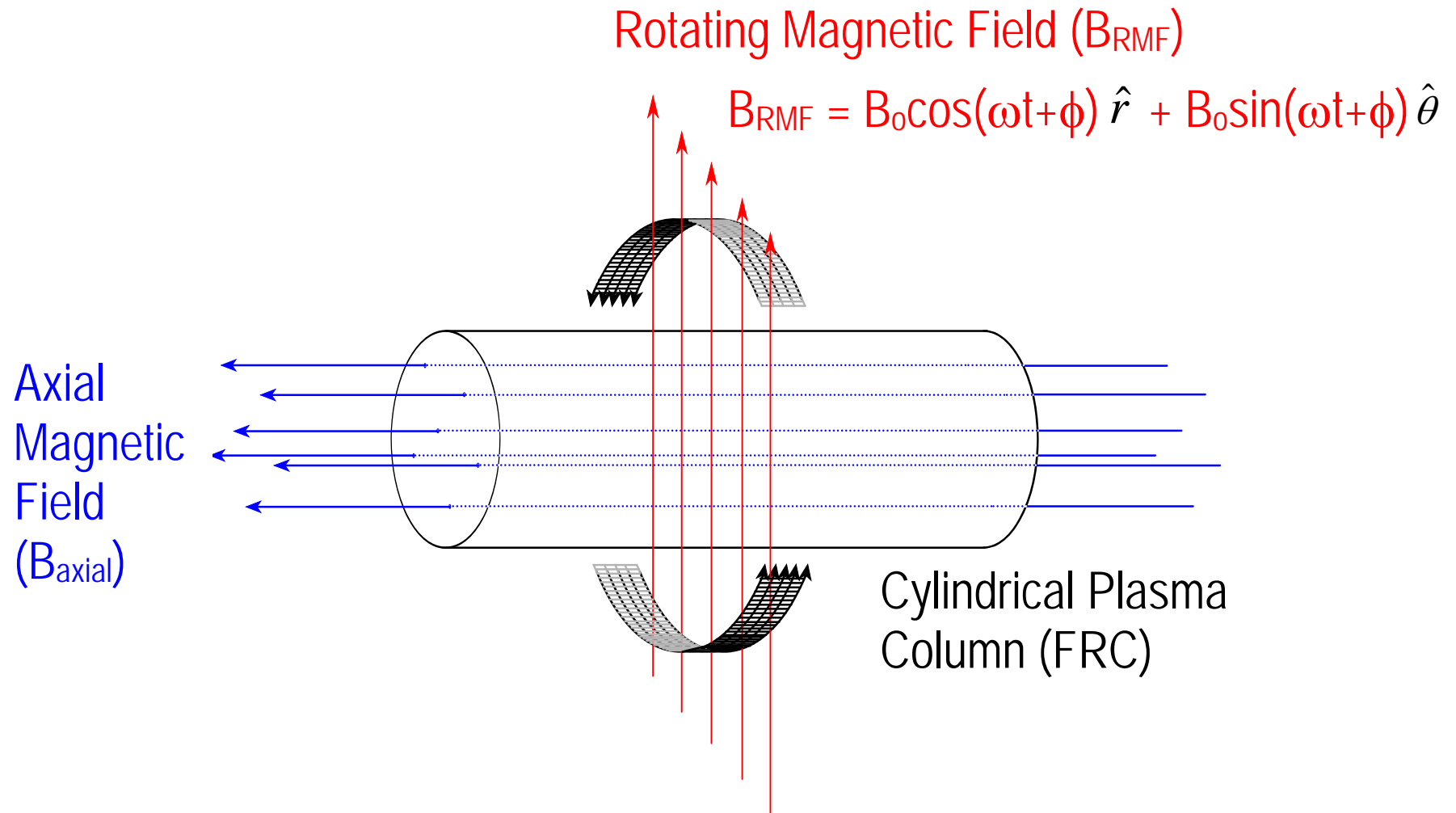
Theta Pinch Coils

Closed Contours Are Flux Surfaces

$$P_{interior(B=0)} \approx (B_{external})^2 / 2\mu_0$$

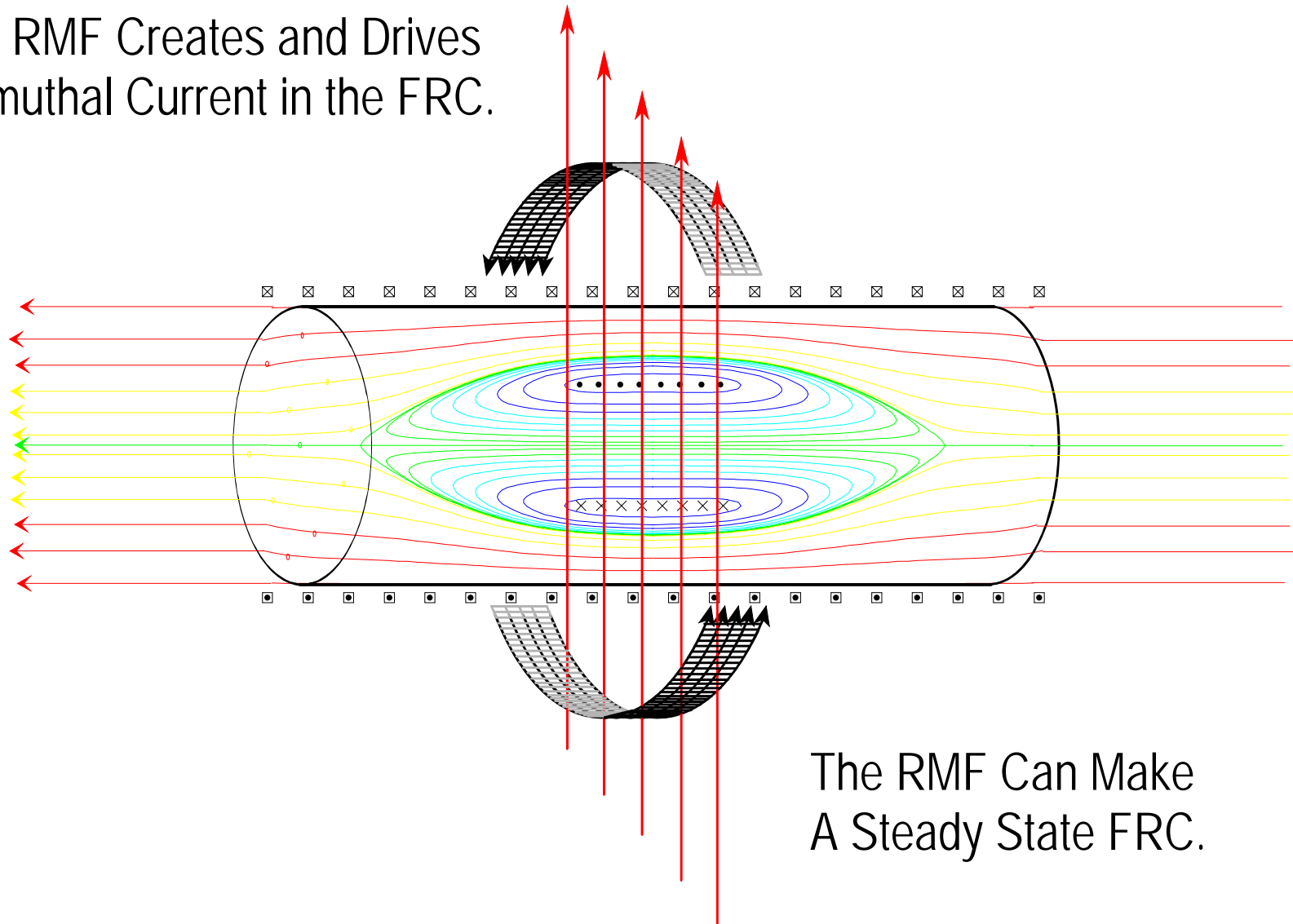
$$\beta \approx 1$$

What Rotating Magnetic Field Are We Using?



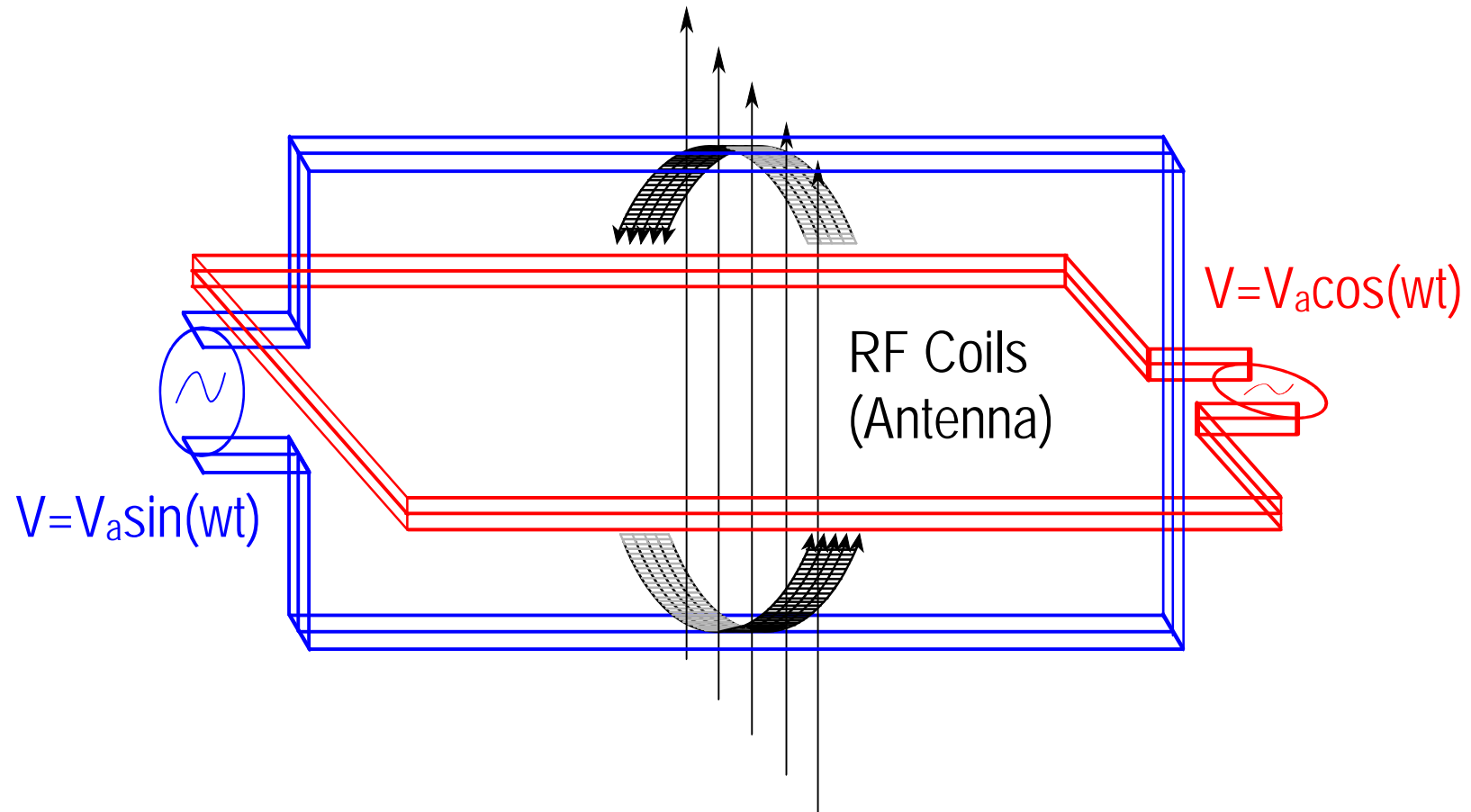
Why is a Rotating Magnetic Field (RMF) Useful?

The RMF Creates and Drives
Azimuthal Current in the FRC.



The RMF Can Make
A Steady State FRC.

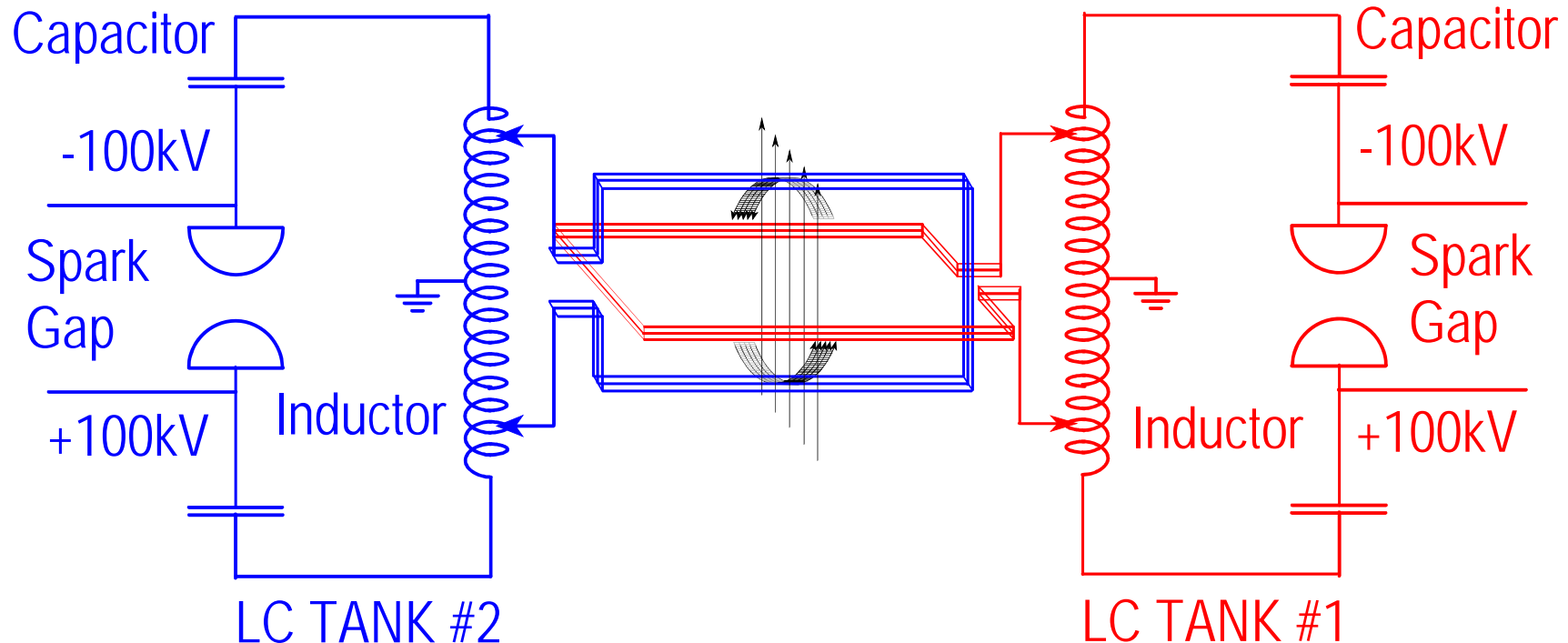
How is the Rotating Magnetic Field Generated?



RMF is generated by driving two mutually perpendicular antenna coils 90 degrees out of phase.

How is the Rotating Magnetic Field Powered?

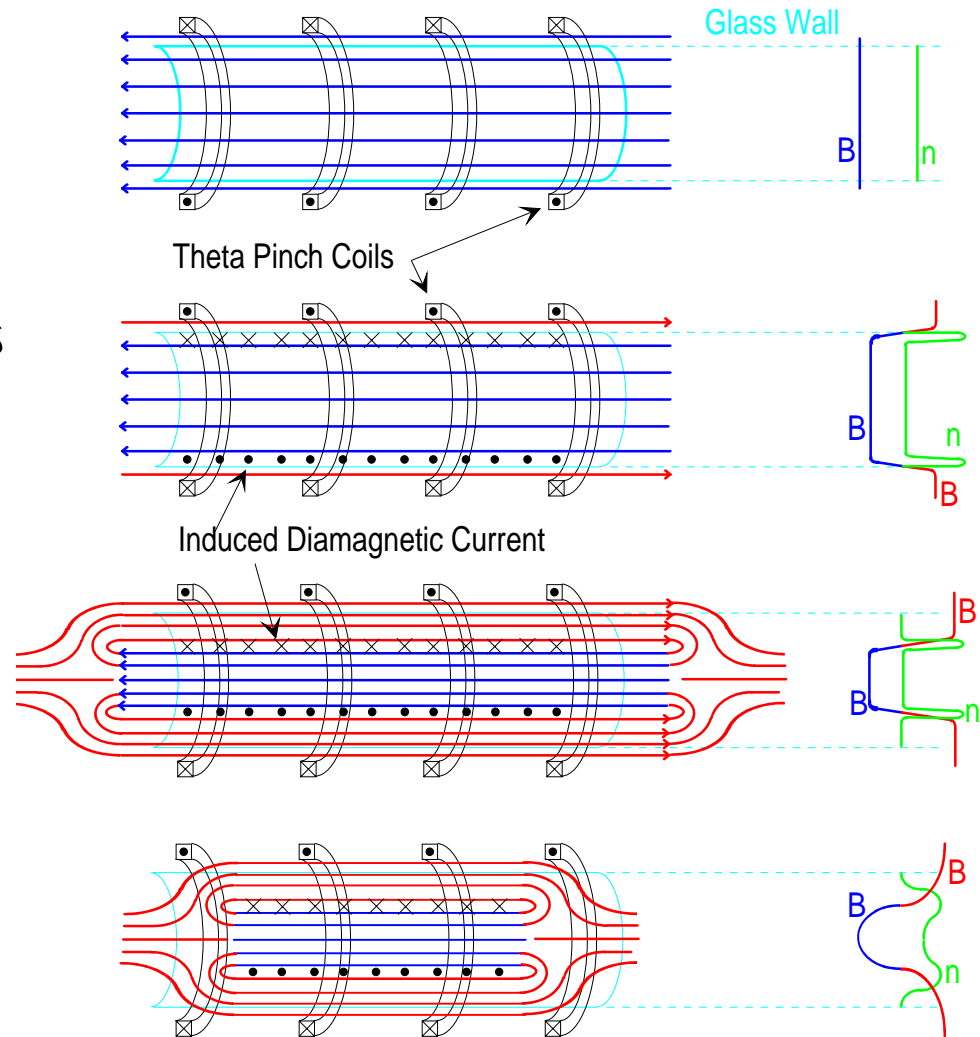
$P_{\text{circulating}}$ in LC Tank Must Be Much Greater than $P_{\text{delivered}}$ to Antenna.



Each antenna coil will be powered by a decaying L-C resonant circuit, (LC tank). The capacitors will be charged to $\pm 100\text{kV}$ and then the spark gap fired in order to start the resonant oscillation.

Conventional FRC Startup:

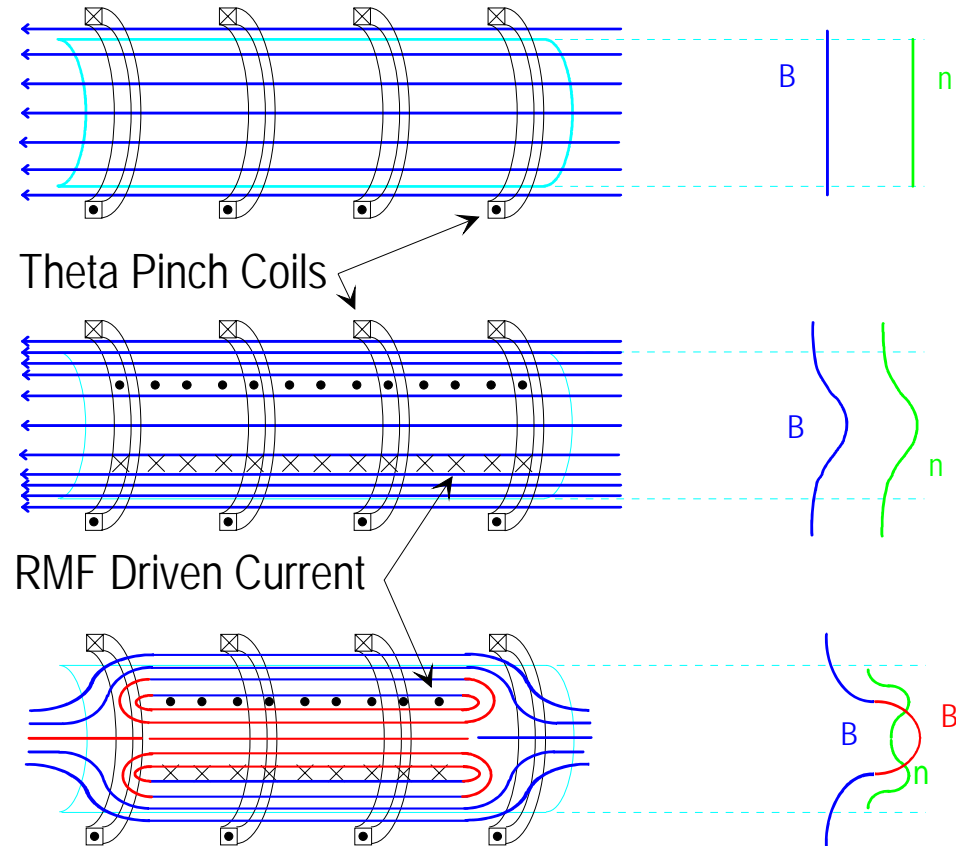
- 1) Start with uniform B in magnetized plasma.
- 2) Reverse B. Plasma slams up against wall. Induced current flows due to gradient in B.
- 3) Radial compression. Plasma pushed off wall.
- 4) Equilibrium.



One Generates a Field Gradient ΔB and Gets a Diamagnetic Current I_θ .
 No Sustainment $\rightarrow I_\theta$ Decays Resistively \rightarrow Life Determined by Trapped Flux.

RMF FRC Startup:

- 1) Start with Uniform B in partially magnetized plasma.
- 2) Turn the RMF on. It drives I_θ . I_θ digs a hole in the axial magnetic field.
- 3) I_θ reverses the axial magnetic field. An FRC is formed.



Now one Generates an I_θ and Gets a Field Gradient ΔB .
Advantage: Can drive I_θ indefinitely, Plasma Stays Off Wall.

RMF's, Existing FRC's and Plasma Ionization:

- An RMF can be used to drive current in an existing FRC. This has not been tried. There are penetration issues since the plasma is hot. On what time scale will the RMF diffuse into the FRC?

$$\tau_{\text{penetration}} \sim R_{\text{plasma}}^2 / \eta_{\parallel}$$

If $\eta_{\parallel} \sim \eta_{\text{FRC decay}} = \eta_{\text{anomalous}} \rightarrow$ Possible FRC penetration and sustainment

If $\eta_{\parallel} \sim \eta_{\text{classical}} \gg \eta_{\text{anomalous}} \rightarrow$ FRC decays before RMF penetrates

- One can start with a partially ionized Plasma. We will focus on this. If the plasma is fully ionized then the RMF takes too long to penetrate, especially with no preexisting magnetic confinement. Some relevant issues are:

FRC energetics (ionization losses, ion heating, radiation losses)

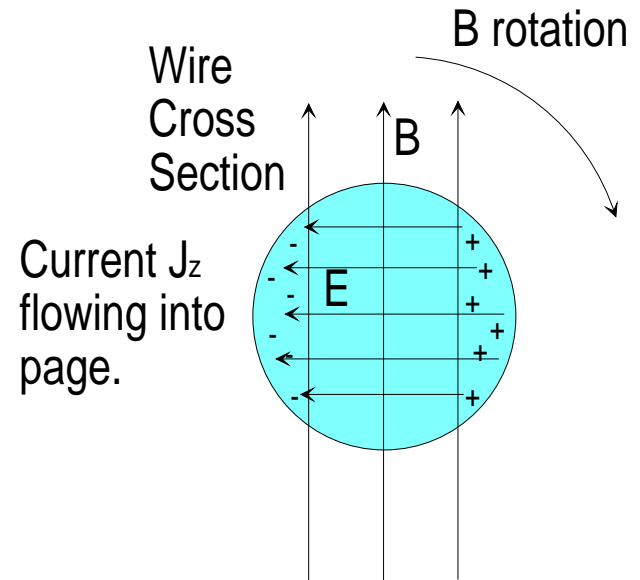
RMF exclusion

FRC dynamics

Describing the RMF; A Physical Picture

- Compare what the RMF does to an FRC to what a transverse magnetic field does to a current carrying wire.

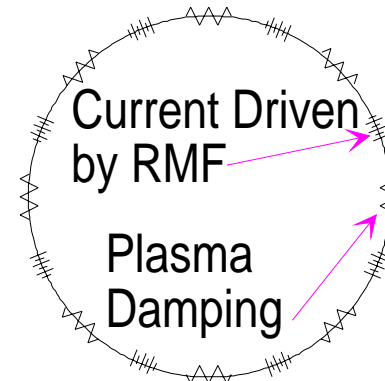
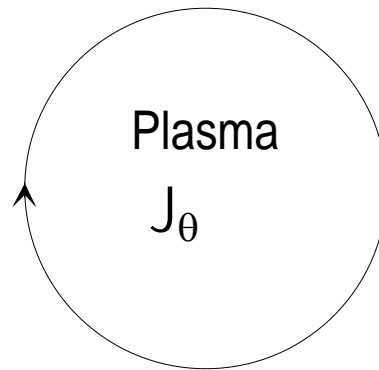
In accordance with the Lorentz force law, $\mathbf{F}=q(\mathbf{E}+\mathbf{v}\times\mathbf{B})$, a static magnetic field transverse to a current carrying wire produces a charge separation and a transverse electric field. Now, if \mathbf{B} were rotated as indicated to the right, the electrons would rotate around with it due to the Lorentz force. This would result in an azimuthal current in the wire in addition to the initial axial current J_z .



- The RMF does the same thing to the electrons in an FRC. In accordance with Faraday's law, an oscillating transverse magnetic field produces an axial electric field which in turn produces an axial current (the equivalent of J_z above). Then, as above, the Lorentz force induces a charge separation which is spun around by the RMF, producing an azimuthal current.

Describing the RMF; Another Physical Picture

- Start with Ohm's Law $\mathbf{E} = \eta\mathbf{j} + \mathbf{j}\times\mathbf{B}/ne$. If the Hall term $\mathbf{j}\times\mathbf{B}/ne$ is negligible (i.e. the plasma is unmagnetized), then $E_\theta = \eta j_\theta > 0$. From Faraday's law, $\int \mathbf{E}\cdot d\mathbf{l} = -d\Phi/dt$, flux is leaving the FRC ($d\Phi/dt < 0$), and it is decaying.
- The Inclusion of the RMF Hall term Compensates. Now, $E_\theta = \eta j_z + j_z\times B_r/ne \leq 0$. From Faraday's law, $d\Phi/dt$ is positive. Thus flux is entering the FRC and it is growing.
- The RMF is simply a distributed driving term that overcomes the plasma's resistive damping of j_θ .



Constraints on the Rotating Magnetic Field:

- Pick ω such that $\omega > \omega_{ci} = qB/m_i$. One wants the ions to be unmagnetized. A large ω ensures this.
- Pick B such that $\omega_{ce} = qB/m_e \gg v_{ei}$. One wants the electrons magnetized. This means that the Hall term will be significant and that the electrons will be tied to the RMF. A large B ensures this.
- The RMF must be able to penetrate the plasma. A large B ensures this.
$$\delta_{\text{RMF}} \approx (\omega_{ce}/v_{ei})\delta_{\text{classical}} = (\omega_{ce}/v_{ei})(2\eta/\mu_0\omega)^{1/2} \sim R_{\text{plasma}}$$
- One wants the RMF to last as long as possible so that it has time to form the FRC. Also, one wants to be prepared for unforeseen contingencies. Current experimental time scale are on the order of $200\mu\text{sec}$.

Practical Consideration #1:

Circulating power on antenna.

- One is not free to pick any RMF that satisfies the above constraints. Expressing these constraints in terms of the required circulating power on the antenna give the following:

$$P_{\text{circulating}} = c_1 M L_a R_a^2 B^3$$

$$N \equiv \omega_{ce}/v_{ei}, \quad M \equiv \omega/\omega_{ci},$$

$$P_{\text{circulating}} = c_2 M^{-2} L_a R_a^2 \omega^3$$

$$R_a = \text{Antenna Radius}$$

$$P_{\text{circulating}} = c_3 L_a R_a^2 n^3 M N^3 T_e^{-9/2}$$

$$L_a = \text{Antenna inductance}$$

$$(P_{\text{circulating}} = IV/2, V=IR, R=\omega L_a, I=\pi R_a B/\mu_0, \omega=M\omega_{ci}=MqB/m_i, B=m_e N v_{ei}/q, v_{ei}=q^{5/2} n \ln \lambda / 16 \pi m_e^{1/2} \epsilon_0^2 T_e^{3/2})$$

$$(c_1=q\pi^2/2m_i\mu_0^2, c_2=\pi^2m_i^2/2q^2\mu_0^2, c_3=m_e^{3/2}q^{11/2}(\ln\lambda)^3/8192\pi m_i\epsilon_0^6\mu_0^2)$$

- Idealizing these leads to unattainable power levels. If one selects $M=N=10$, then $P_{\text{circulating}} = 100\text{GW}$. ($R_a=.4\text{m}$, $T_e=2\text{eV}$, $L_a=2.5\mu\text{H}$, $n=10^{20}\text{m}^{-3}$)
- This is most restrictive at $t=0$, when the plasma is cold. If $T_e=20\text{eV}$ then $P_{\text{circulating}} = 3\text{MW}$. Things get MUCH MUCH better as the plasma warms.

Practical Consideration #2:

Real power delivered by tank circuit.

- This consists of:
 - Plasma damping of RMF (e- heating)
 - Resistivity in Antenna and Leads
 - Losses in the tank circuit
- The real power delivered by the tank circuit scales as $P_{\text{circulating}}$ (sort of).
If 5% of $P_{\text{circulating}}$, $P_{\text{delivered}} = 5\text{GW} = 5$ to 10 power plants. If run at this level for $200\mu\text{sec}$, $E_{\text{delivered}} = 1\text{MJ} = 5000$ 3-Musketeers bars/sec.
- It is this consideration that Directly determines duration of RMF. One can only have so much stored energy.

Selecting a Rotating Magnetic Field:

- Using the above constraints and practical considerations, we have selected the following optimized RMF:

$$\text{Frequency} = \pi \times 10^6 \text{ rad/sec}$$

$$\text{Field Strength} = .01 \text{ T}$$

$$\text{Duration} = 200 \mu\text{sec}$$

$$E_{\text{delivered}} = 1200 \text{ J}$$

- This sets some of the other parameters as follows:

$$N = \omega_{ce}/v_{ei} = 2 \quad (N = 60 \text{ if } T_e = 20 \text{ eV})$$

$$M = \omega/\omega_{ci} = 6$$

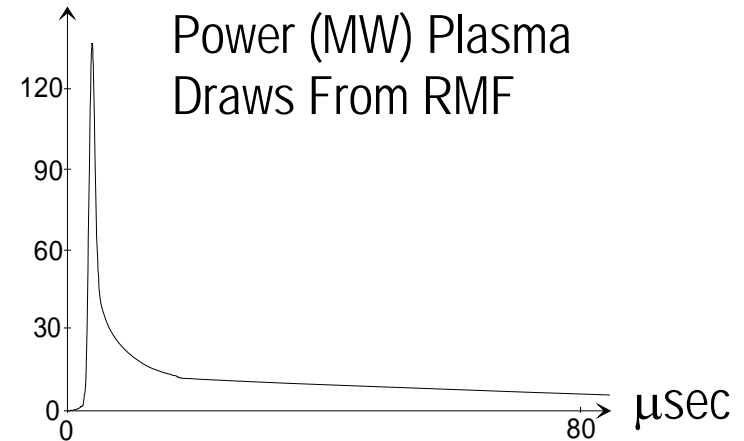
$$P_{\text{circulating antenna}} = 400 \text{ MW}$$

$$P_{\text{avg delivered}} \equiv 6 \text{ MW} = 1200 \text{ J} / 200 \mu\text{sec}$$

$$(R_a = .4 \text{ m}, T_e = 2 \text{ eV}, L_a = 2.5 \mu\text{H}, n = 10^{20} \text{ m}^{-3})$$

Designing the RMF Supply:

- The graph to the right is illustrative of the power the tank will have to deliver to the RMF. This is too much power to draw from the grid, so we will need an energy storage system. 6MW for 200 μ sec is 1200 J of stored energy.



- $\omega = \pi \times 10^6$. This is too fast for solid state devices at the 400 MW level. We will use an L-C resonant tank circuit. A tank circuit has its highest power output when it is first turned on, making it well suited to deliver the sort of power curve shown above.
- $t = 200 \mu$ sec. At .5 MHz, the tank will have to oscillate through 100 cycles before decaying away. Thus the tank circuit must be high Q.

$$Q = 2\pi \frac{\text{energystored}}{\text{energylostpercycle}} = \omega \frac{L_{\text{circuit}}}{R_{\text{circuit}}} = 630$$

Selecting Tank L C and V:

- To achieve 100 oscillations, tank losses must be minimized. Practically, the Q requirement of 630 is most restrictive. We will build a tank where tank losses equal the power delivered to the RMF.
- The Constraints on the tank parameters are:
$$\omega = \sqrt{LC}^{-1} = \pi \times 10^6$$
$$.5CV^2 = 1200$$
$$Q = \omega L / R_{\text{tank}} = 630$$
- The optimization procedure is as follows (to maximize tank Q):
 - 1) Make L as big as possible to allow for realistic R_{tank} .
 - 2) A big L means a small C to satisfy the ω requirement.
 - 3) A small C means a big V to satisfy the energy storage requirement

Tank Parameters:

$$V = 200 \text{ kV}$$

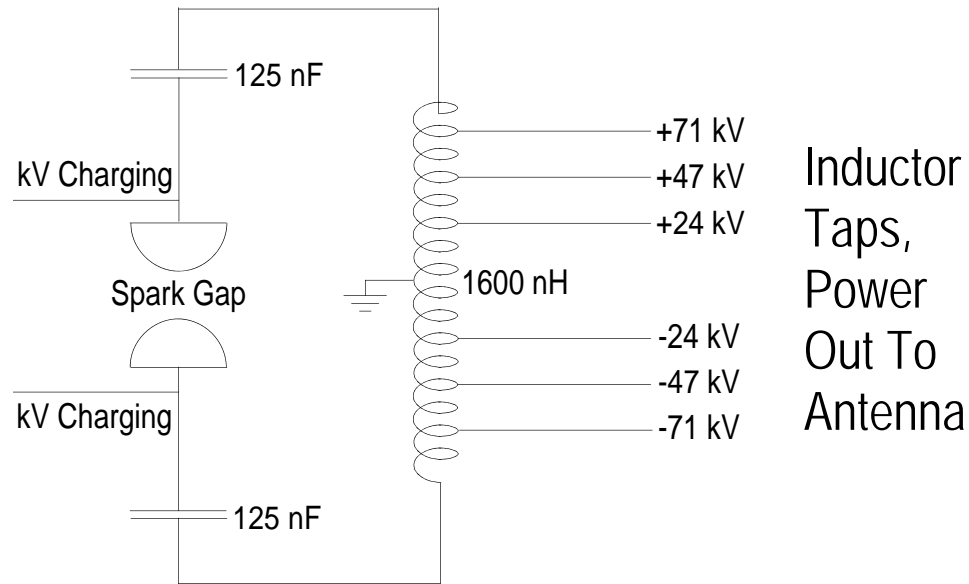
$$C = 62.5 \text{ nF}$$

$$L = 1600 \text{ nH}$$

- The upper limit on the tank voltage is the practical constraint that limits the maximum size of Q and thus the maximum allowable tank resistance. To achieve a Q of 630, the tank resistance must be less than $8\text{m}\Omega$.

Tank Circuit Design:

$V_{\text{charge}} = 200 \text{ kV}$
 $C = 62.5 \text{ nF}$
 $L = 1600 \text{ nH}$
 $Q = 630$
 $R_{\text{internal}} = 8 \text{ m}\Omega$
 $P_{\text{circulating}} = 4 \text{ GW}$



$$R_{\text{dielectric}} = \omega L(\text{dielectric power dissipation factor}) = 1.5 \text{ m}\Omega$$

$$R_{\text{conductors}} = \rho l/A = 1.5 \text{ m}\Omega \text{ (conductor length} \sim \text{twice conductor perimeter, no thin wires)}$$

$$R_{\text{spark gap}} = 600 \text{ fC}(V-150)/I^2 = 5 \text{ m}\Omega$$

Two capacitors in series are used so that we only need to deal with half the voltage with respect to ground. The tank is fired by shorting the positive side of one capacitor to the negative side of the other capacitor. Doing this lets us use one spark gap instead of two which helps to keep R_{internal} down. Also, it keeps the antenna and inductor at ground except when the circuit is actually fired.

Antenna Design:

- Requirements:
 - 1) 800 MW circulating power to generate .01T RMF, (400 MW in each antenna coil set).
 - 2) RMF of constant magnitude and direction over plasma volume.
- Parameter Selection:
 - 1) To satisfy circulating power requirement:
 $V_a = \omega I_a L_a = +/-40 \text{ kV}$, $L_a = 2.5 \mu\text{H}$, $I_a = \pi B R_a / \mu_0 = 10 \text{ kA}$
 - 2) To satisfy the field uniformity requirement, take each antenna coil and separate it into 2 parallel coils. Thus one will have 2 mutually perpendicular coil sets. Next, determine the spacing between the parallel coils by doing an "Helmholtz" minimization. This gives a coil separation of $2R_a / \sqrt{3}$ to produce the most uniform field for the selected geometry. We select $R_a = .4\text{m}$ to get a 10% field magnitude variation over the 20 cm plasma radius

RMF Antenna:

$$V_a = +/-40 \text{ kV}$$

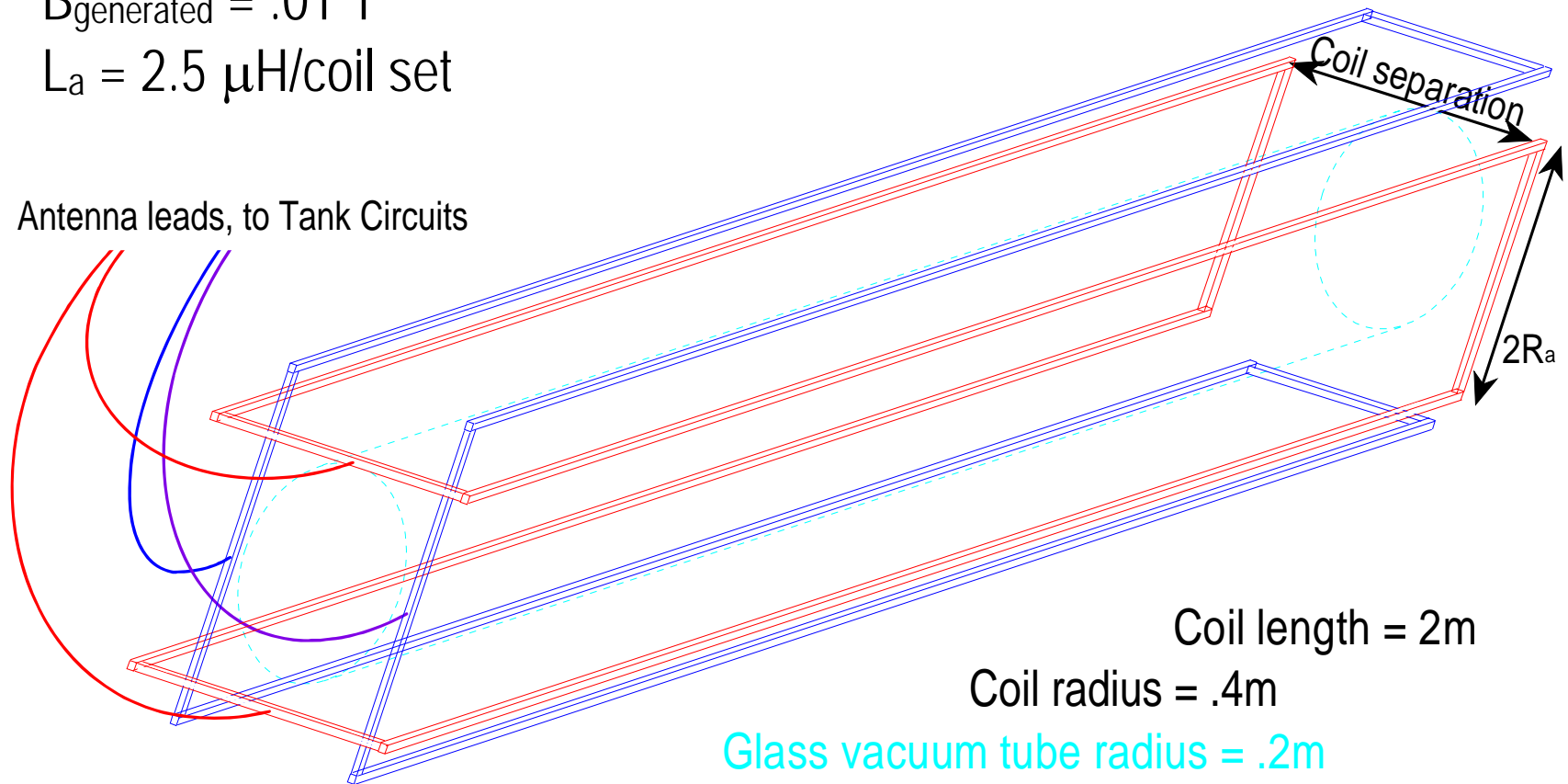
$$I_a = 10 \text{ kA/coil set}$$

$$P_{\text{circulating}} = 400 \text{ MW/coil set}$$

$$B_{\text{generated}} = .01 \text{ T}$$

$$L_a = 2.5 \mu\text{H/coil set}$$

Antenna leads, to Tank Circuits



Coil length = 2m

Coil radius = .4m

Glass vacuum tube radius = .2m

What's Next:

- Build Ion heater
 - will use $m=0$ Alfvén mode generated with existing θ -pinch coils.
 - will drive FRC above natural resonant frequency of .5 MHz.
- Build preionizer
 - need a few percent preionization.
 - will use an helicon wave and or an axial discharge.
- Plasma diagnostics to see effects of RMF
 - plasma emission tomography
 - interferometry
 - Doppler broadening
 - spectrometry
 - Thompson scattering
 - neutron emission

