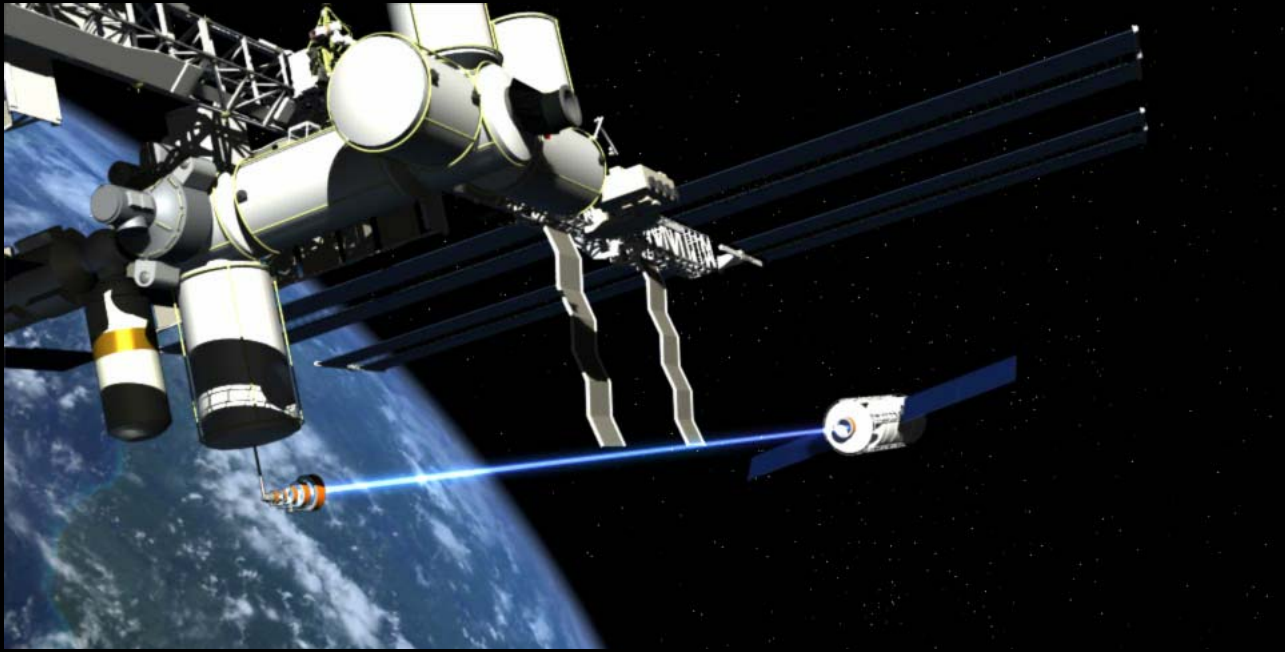
MagBeam:



R. Winglee, T. Ziemba, J. Prager, B. Roberson, J Carscadden

- **Coherent Beaming of Plasma**
- **Separation of Power/Fuel from Payload**
- **Fast, cost-efficient propulsion for multiple missions**

Plasma Propulsion

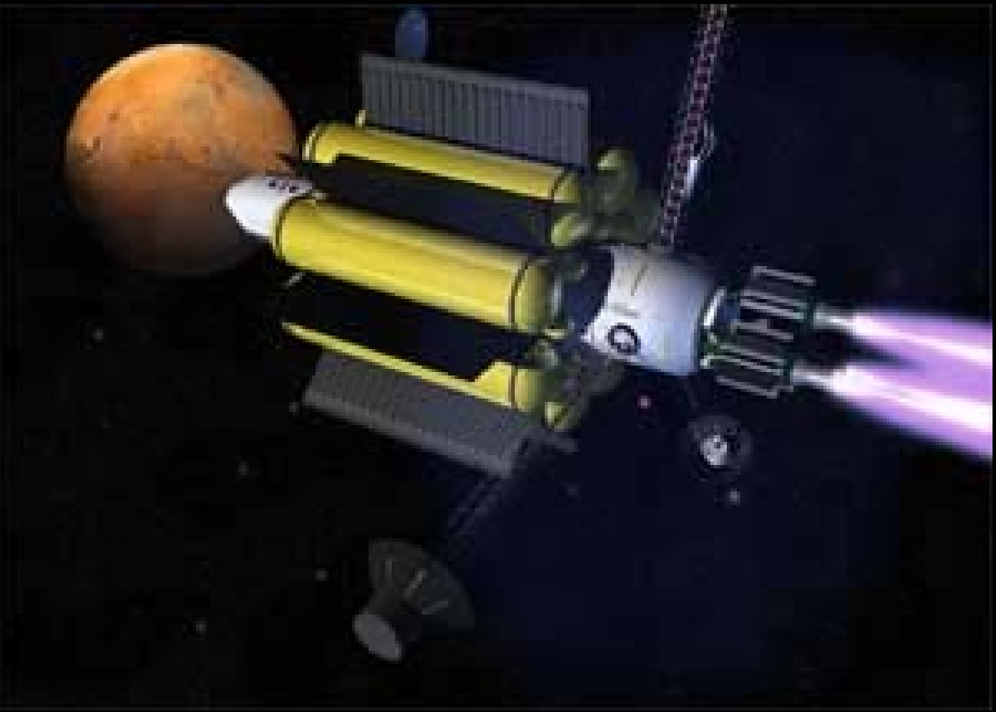
Major Savings in Mass through higher energy/speed plasma systems

Inherently low thrust systems:
very low acceleration

Solar electric ~1×10^{-4} m/s/s

Plasma Propulsion

VASIMR



Major Savings in Mass through higher energy/speed plasma systems

Inherently low thrust systems:
very low acceleration

Solar electric ~1 × 10^{-4} m/s/s

Nuclear electric ~1 × 10^{-3} m/s/s

Long duration and/or costly dedicated power units for single missions

MagBeam: Focused Beaming of Plasma Power

Separation of Power and Payload for High Thrust/Low Propellant Usage

Beam Propagation

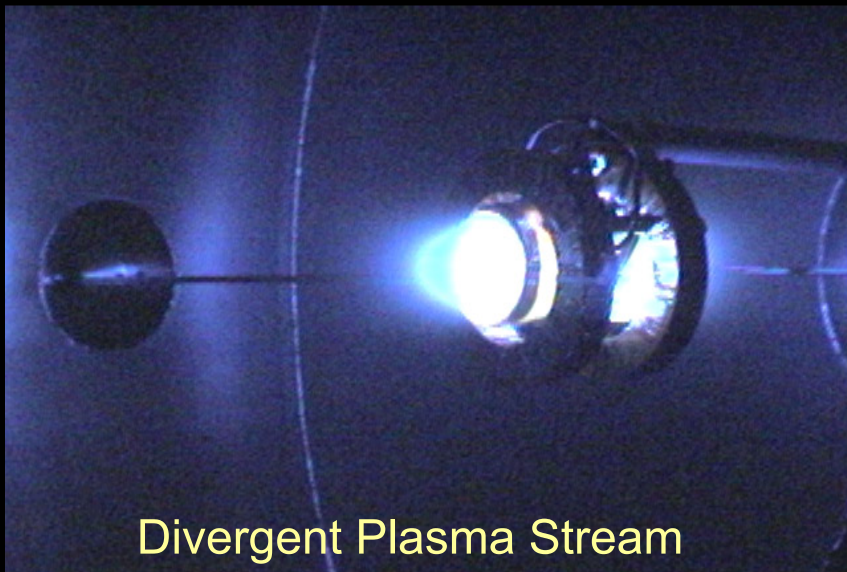
Beam Expansion will reduce the efficiency of any beamed energy system

Nature regularly propagates plasma beams over 10's km to 10's of Earth radii

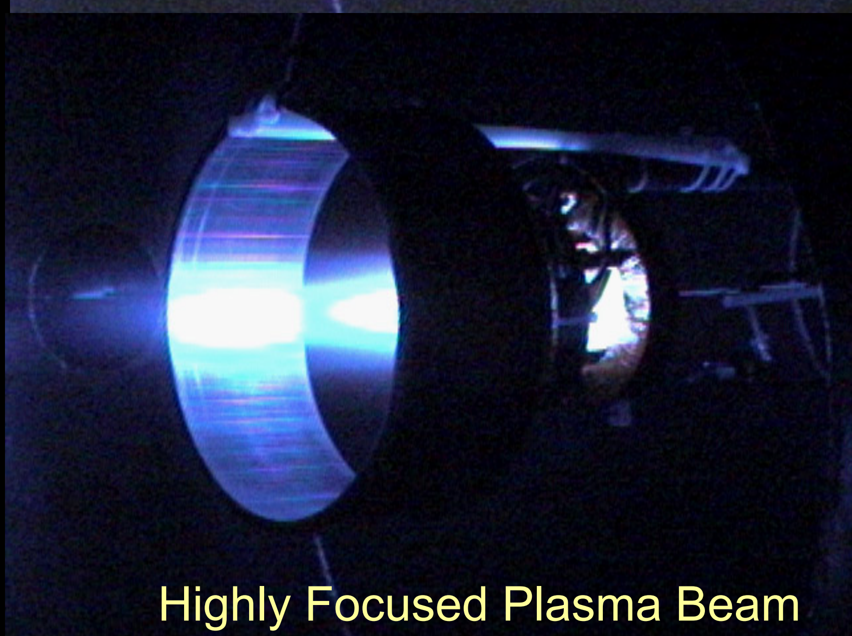
Able to do so by using collective behavior of plasmas

MagBeam uses these same collective processes to minimize beam dispersion

Importance of MagBeam



Divergent Plasma Stream



Highly Focused Plasma Beam

Benefit 1:

By studying focusing techniques obtain Higher Efficiency Plasma Thrusters

Can yield increases by factors of 50% performance

Importance of MagBeam

Benefit 2:

Compact electrodeless thrusters

Able to take high power operation without degradation

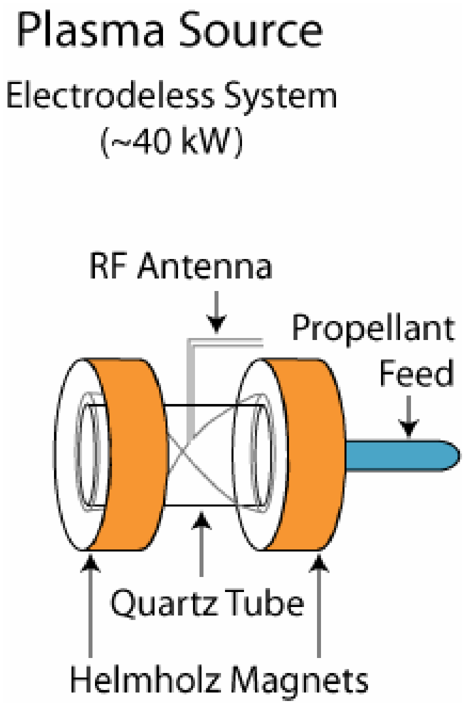
Means consider orbital transfers for large systems like Space Station

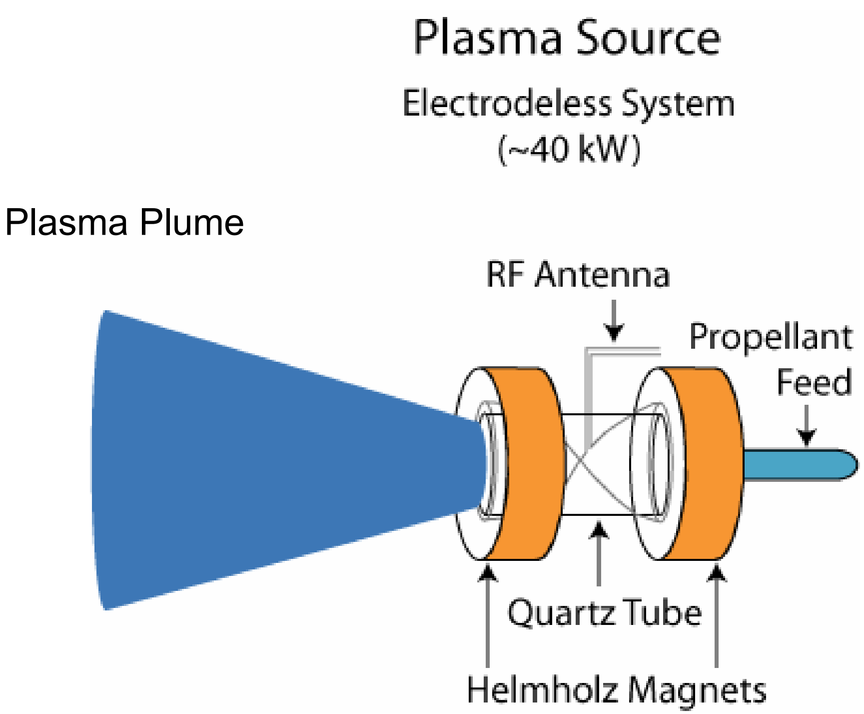
Importance of MagBeam

Benefit 3:

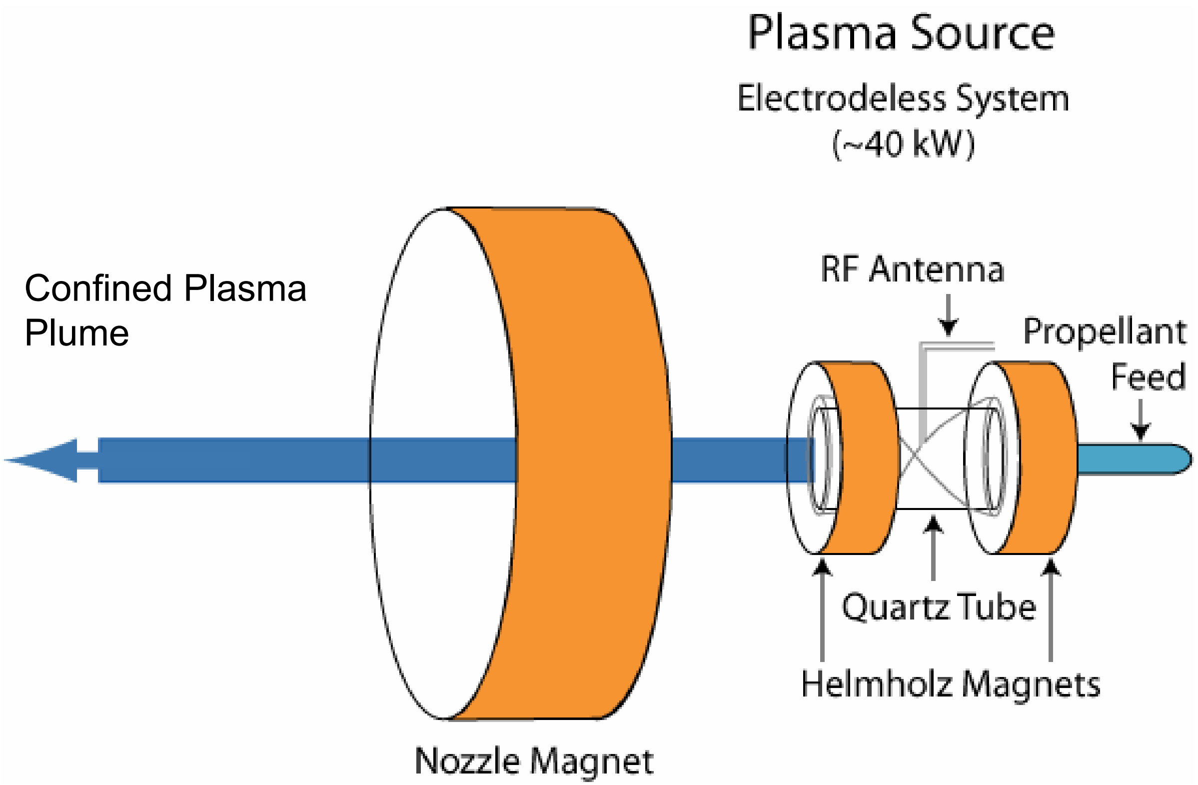
- Modify spacecraft orbits (raise or lower)
- Planetary/lunar transfer orbital for multiple payloads
- Reduced cost due to reusable nature of system

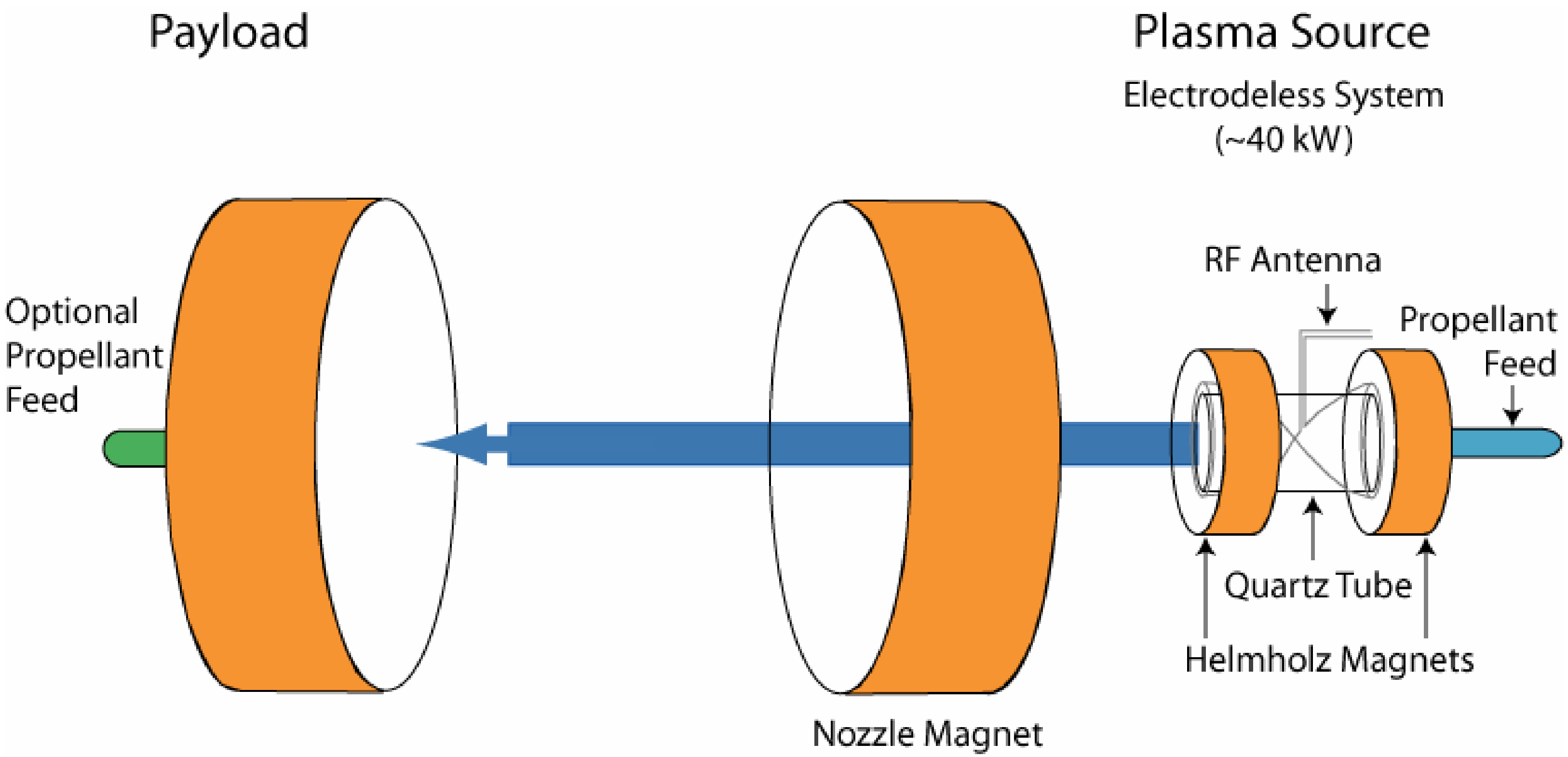
Full up system would facilitate human exploration to the Moon, Mars and Beyond


Plasma Source
Electrodeless System
(~40 kW)
RF Antenna
Propellant
Feed
Quartz Tube
Helmholz Magnets

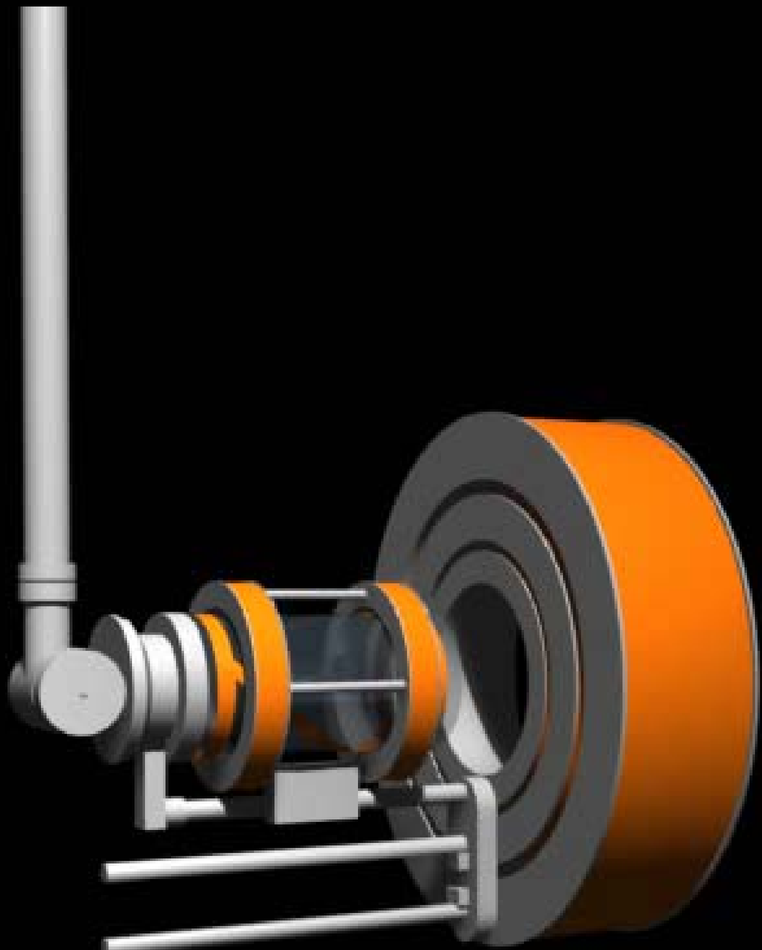


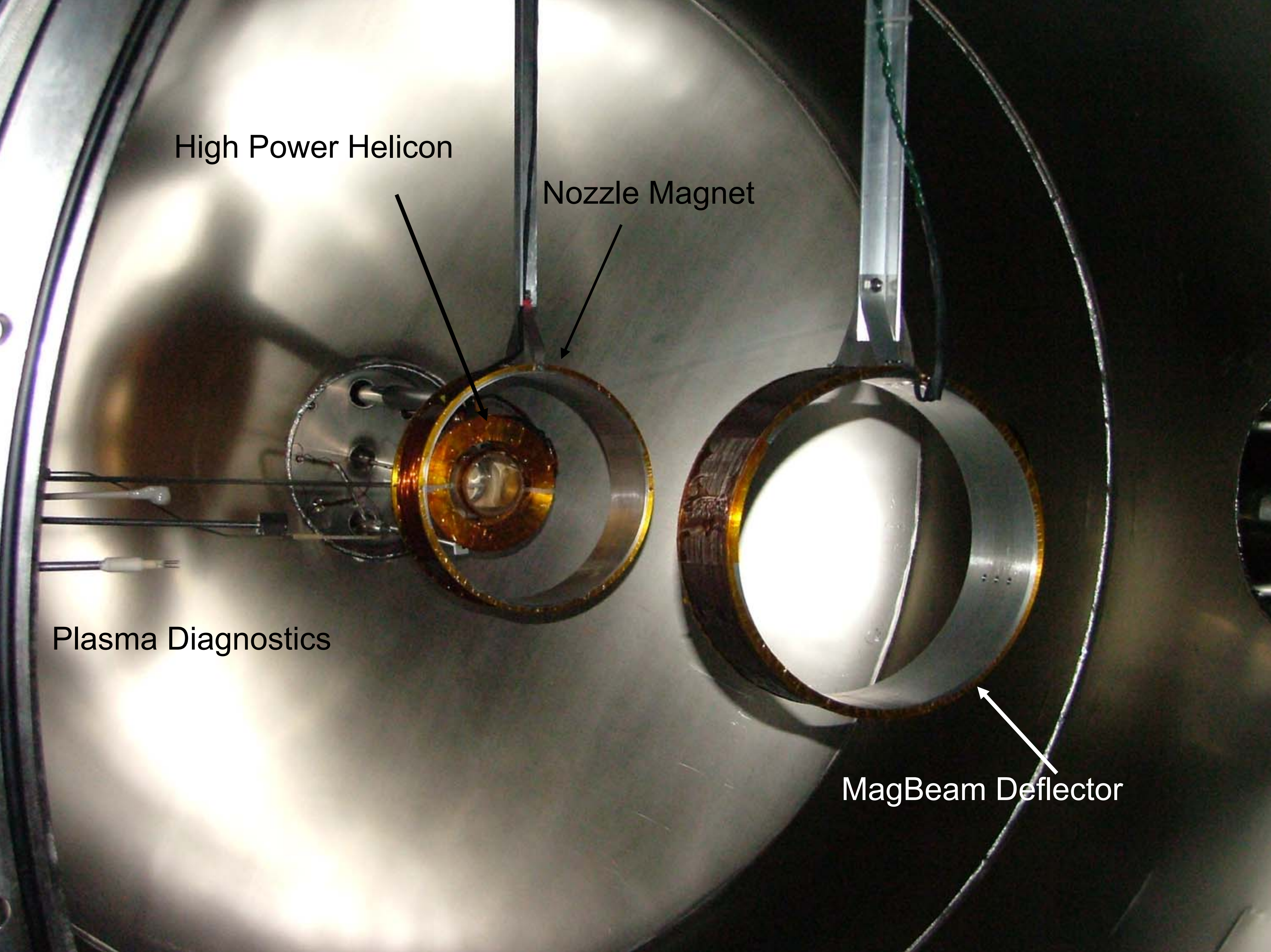
Plasma Source
Electrodeless System
(~40 kW)
Plasma Plume
RF Antenna
Propellant
Feed
Quartz Tube
Helmholz Magnets

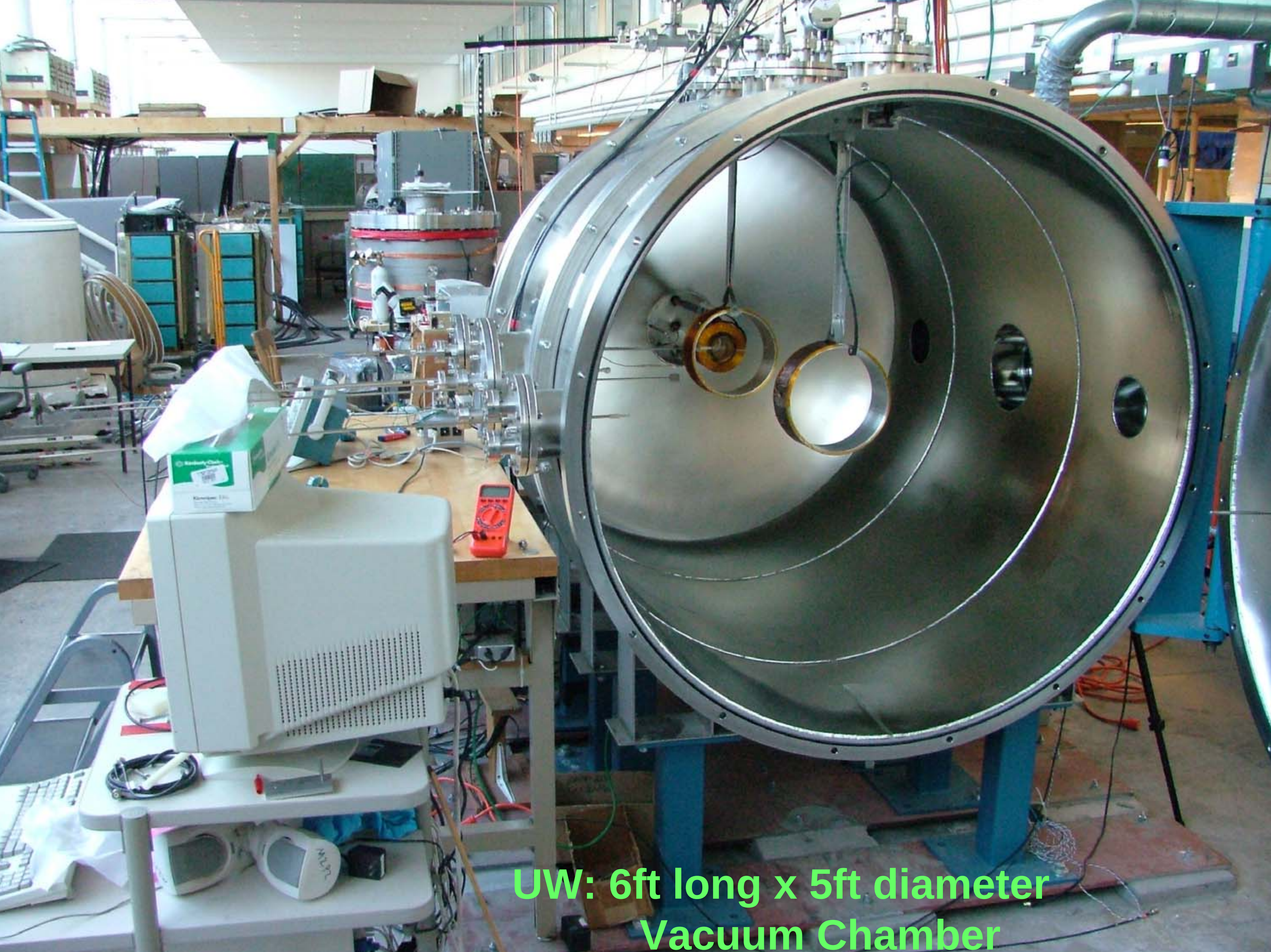

Plasma Source
Electrodeless System
(~40 kW)
Confined Plasma
Plume
RF Antenna
Propellant
Feed
Quartz Tube
Helmholz Magnets
Nozzle Magnet


Payload
Plasma Source
Electrodeless System
(~40 kW)
RF Antenna
Optional
Propellant
Feed
Propellant
Feed
Quartz Tube
Helmholz Magnets
Nozzle Magnet

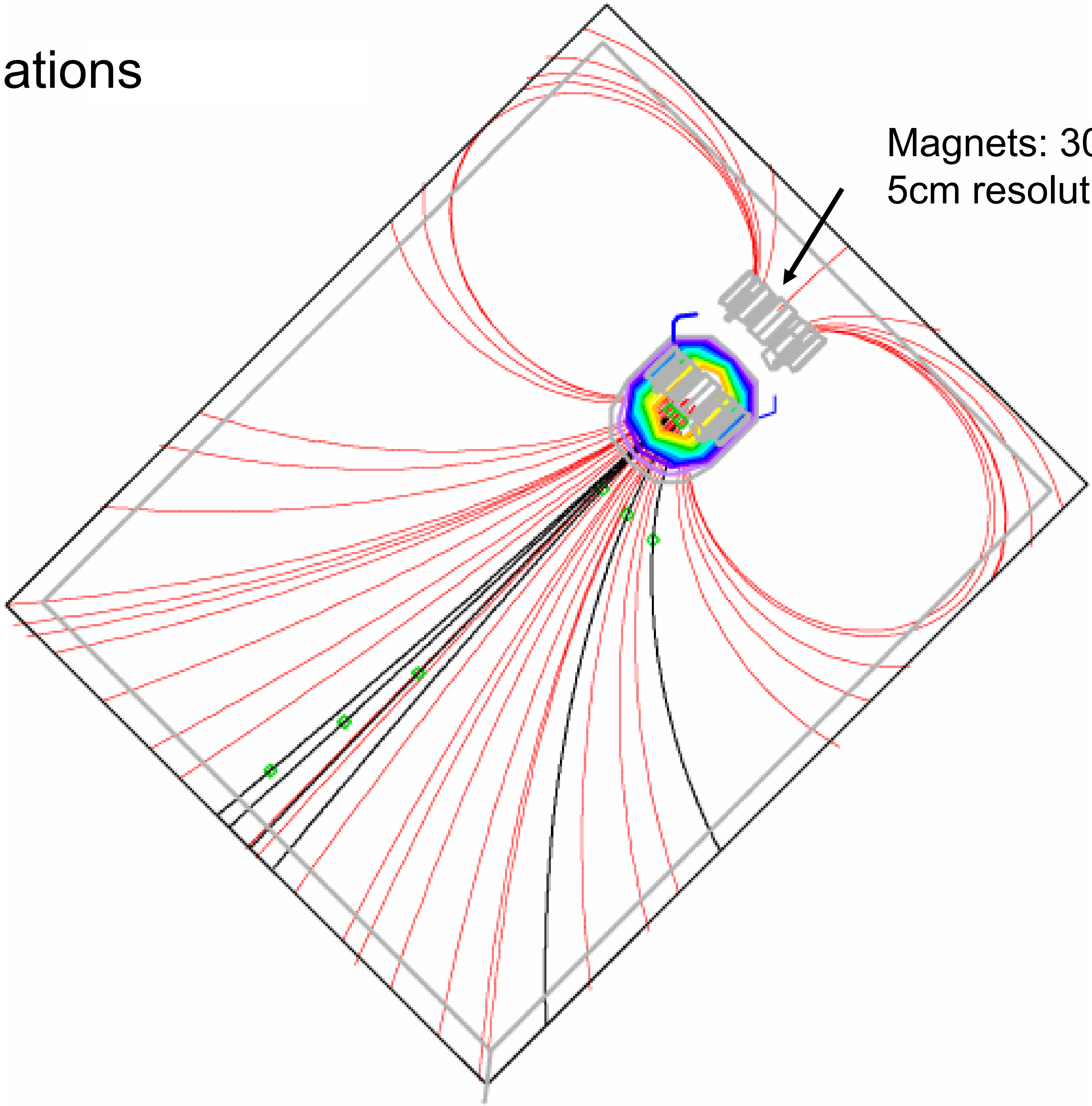
Implementation of Magnetic Nozzle System




High Power Helicon
Nozzle Magnet
Plasma Diagnostics
MagBeam Deflector


UW: 6ft long x 5ft diameter
Vacuum Chamber

Simulations



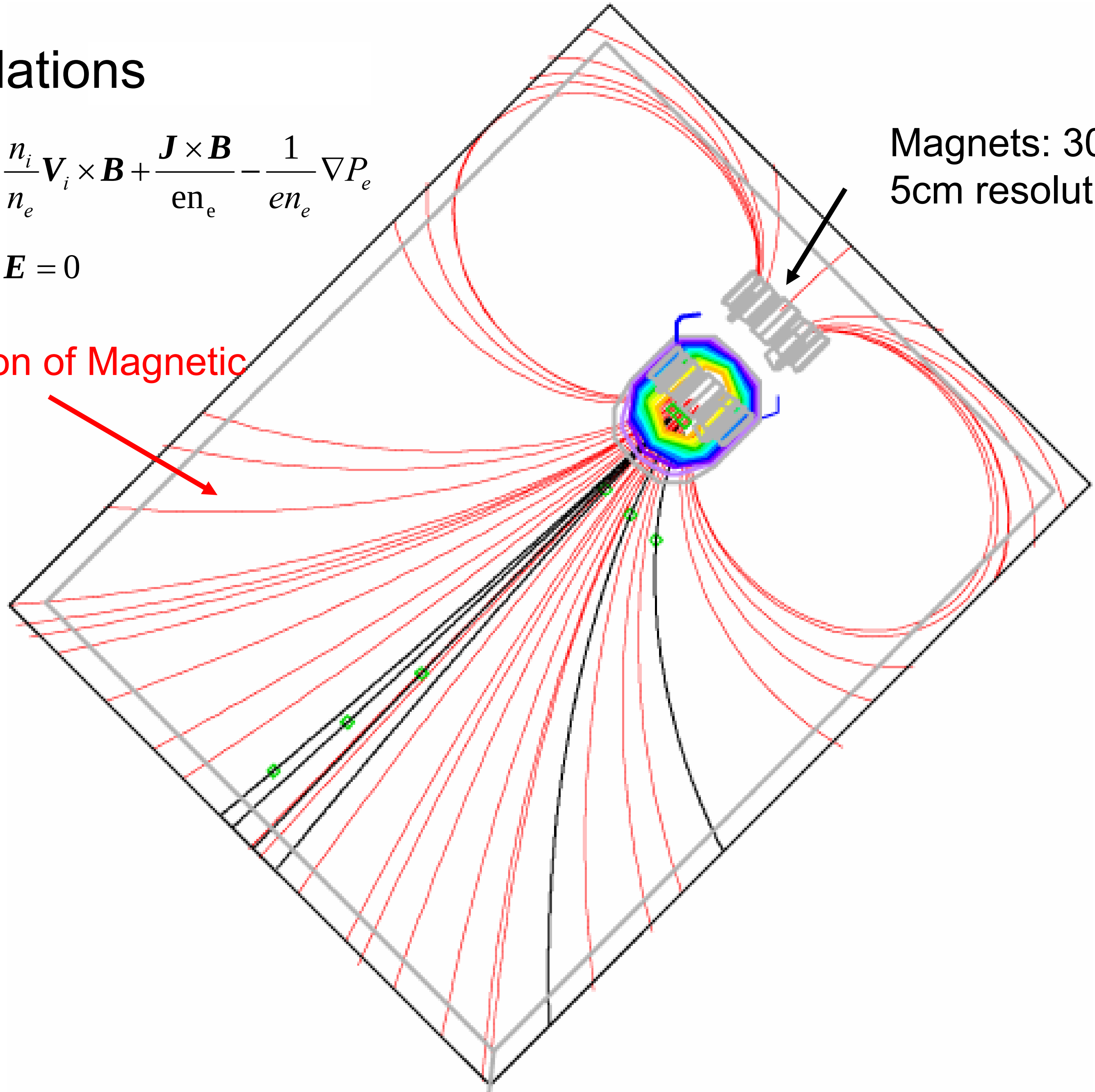
Simulations

$$\boldsymbol{E} = -\sum_i \frac{n_i}{n_e}\boldsymbol{V}_i \times \boldsymbol{B} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{\mathrm{en_e}} - \frac{1}{en_e}\nabla P_e$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0$$

Evolution of Magnetic Field

Magnets: 30 cm; 5cm resolution



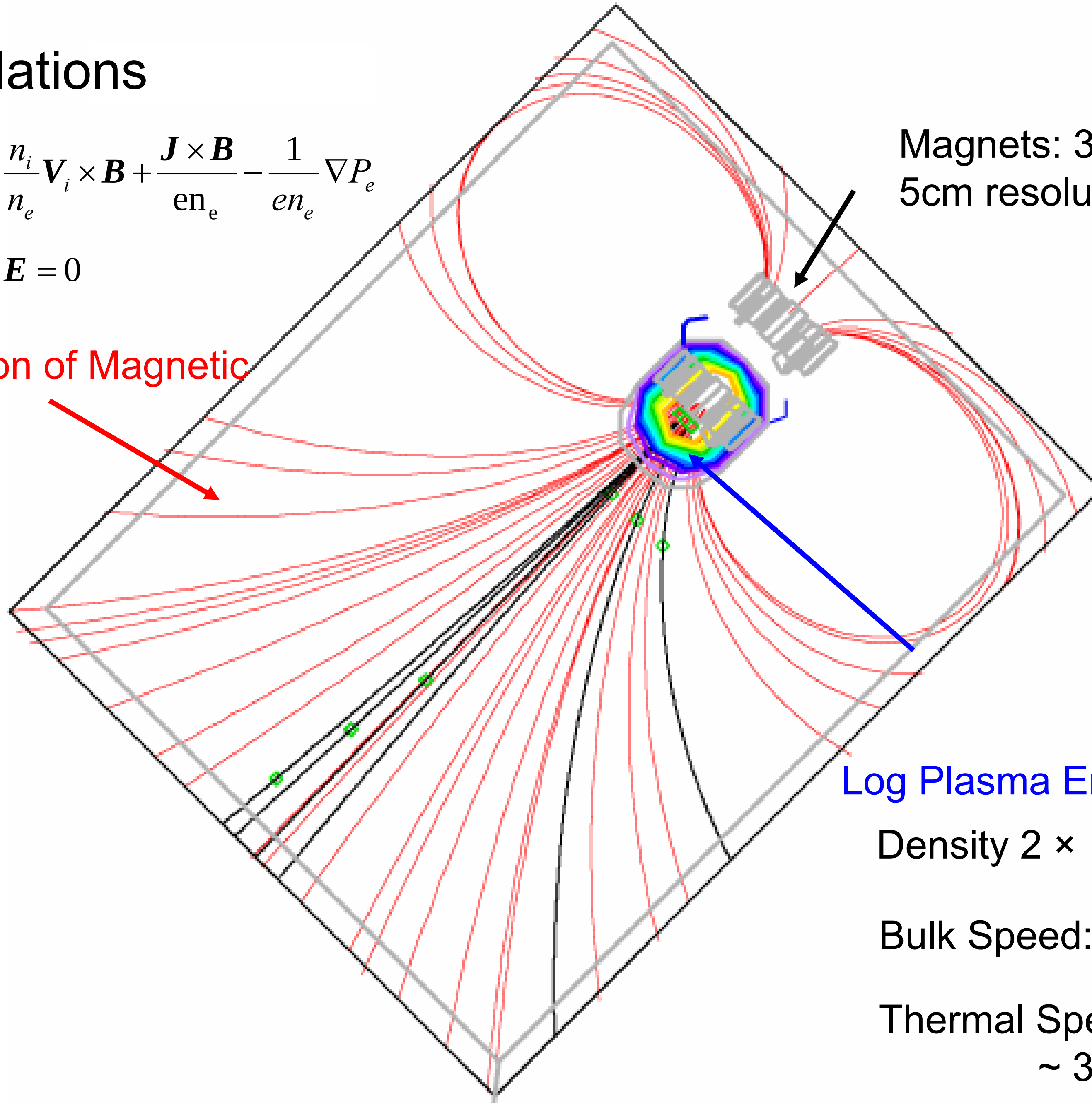
Simulations

$$E = -\sum_i \frac{n_i}{n_e} V_i \times B + \frac{J \times B}{\mathrm{en_e}} - \frac{1}{en_e} \nabla P_e$$

$$\frac{\partial B}{\partial t} + \nabla \times E = 0$$

Evolution of Magnetic Field

Magnets: 30 cm;
5cm resolution



Log Plasma Energy Density

Density 2×10^{13} cm^{-3}

Bulk Speed: 30 km/s

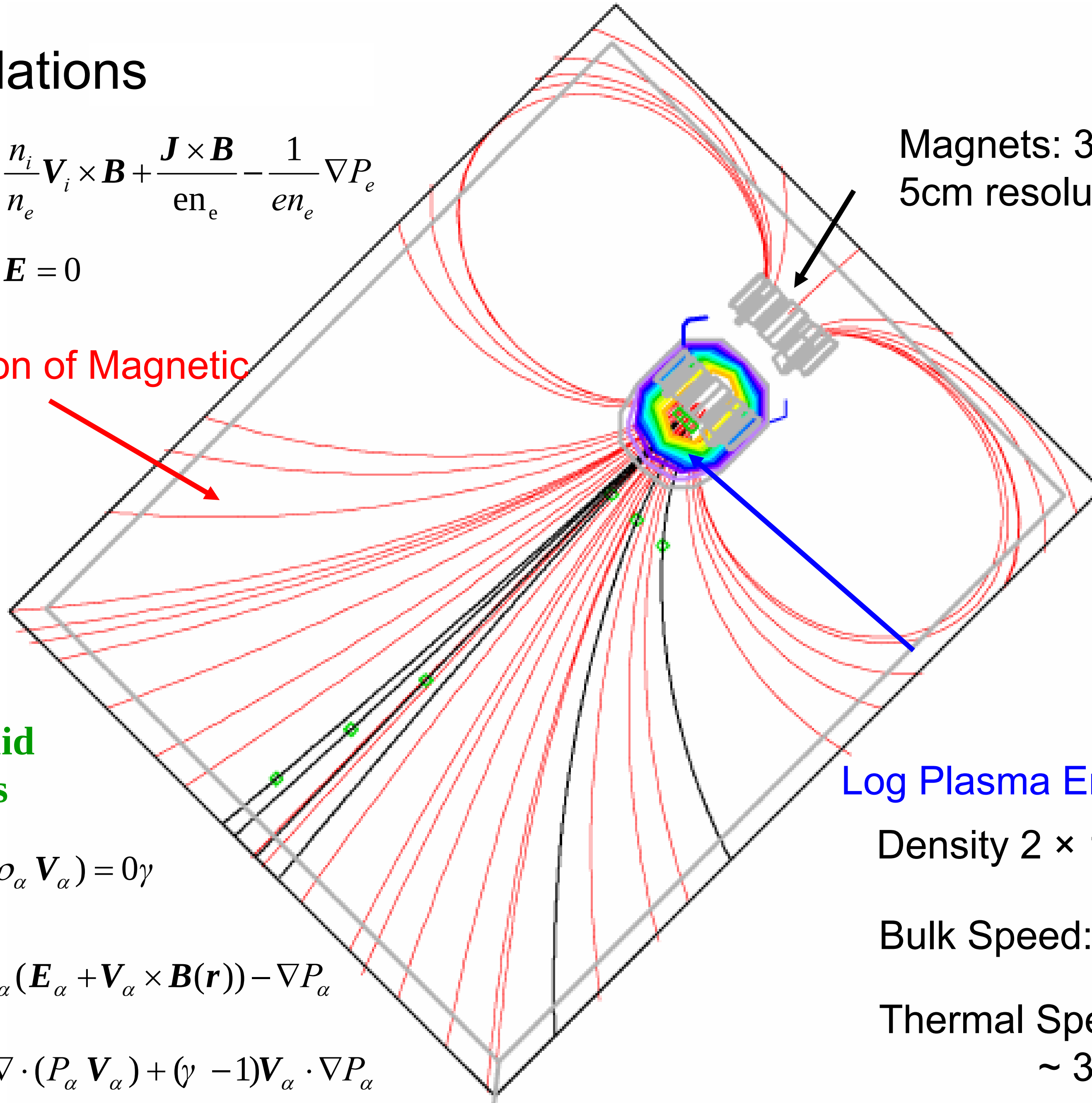
Thermal Speed:
~ 30 km/s

Simulations

$$\boldsymbol{E} = -\sum_i \frac{n_i}{n_e}\boldsymbol{V}_i \times \boldsymbol{B} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{\mathrm{e}n_e} - \frac{1}{en_e}\nabla P_e$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0$$

Evolution of Magnetic Field



Magnets: 30 cm; 5cm resolution

Log Plasma Energy Density

Multi-Fluid Equations

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla\cdot(\rho_\alpha \boldsymbol{V}_\alpha) = 0\gamma$$

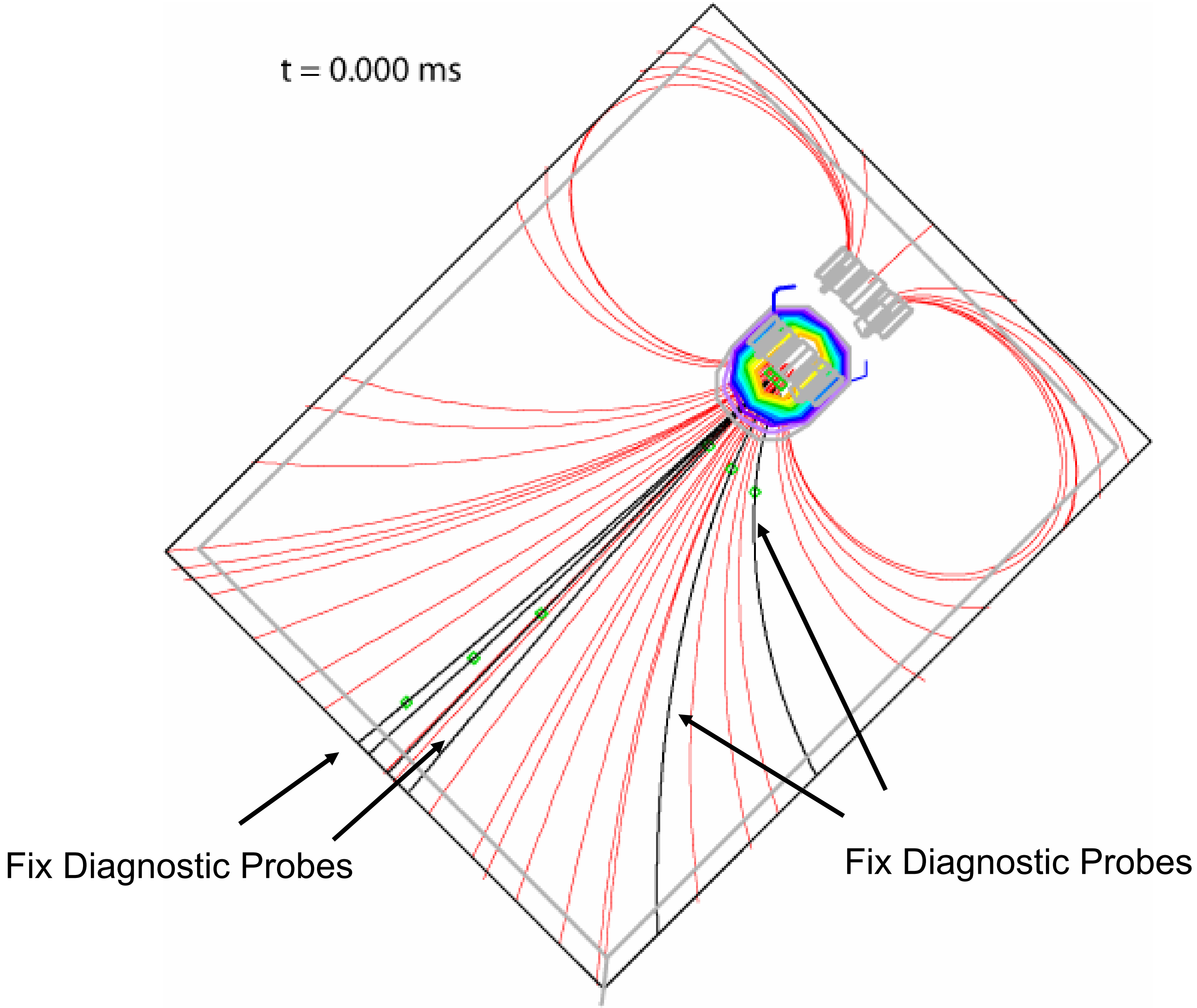
$$\rho_\alpha \frac{d\boldsymbol{V}_\alpha}{dt} = q_\alpha n_\alpha (\boldsymbol{E}_\alpha + \boldsymbol{V}_\alpha \times \boldsymbol{B}(\boldsymbol{r})) - \nabla P_\alpha$$

$$\frac{\partial P_\alpha}{\partial t} = -\gamma\ \nabla\cdot(P_\alpha \boldsymbol{V}_\alpha) + (\gamma\ -1)\boldsymbol{V}_\alpha\cdot\nabla P_\alpha$$

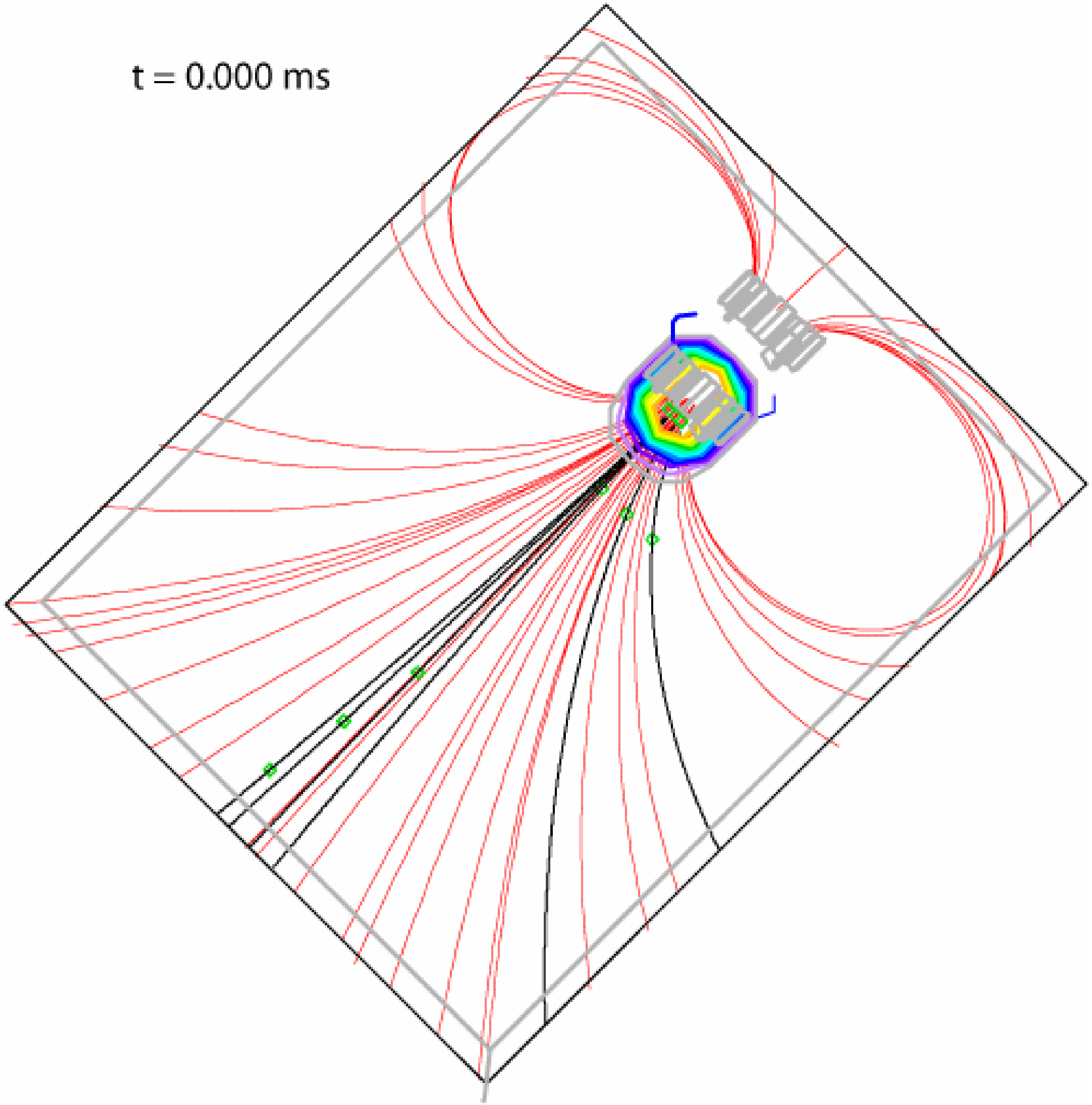
Density 2 × 10^{13} cm^{-3}

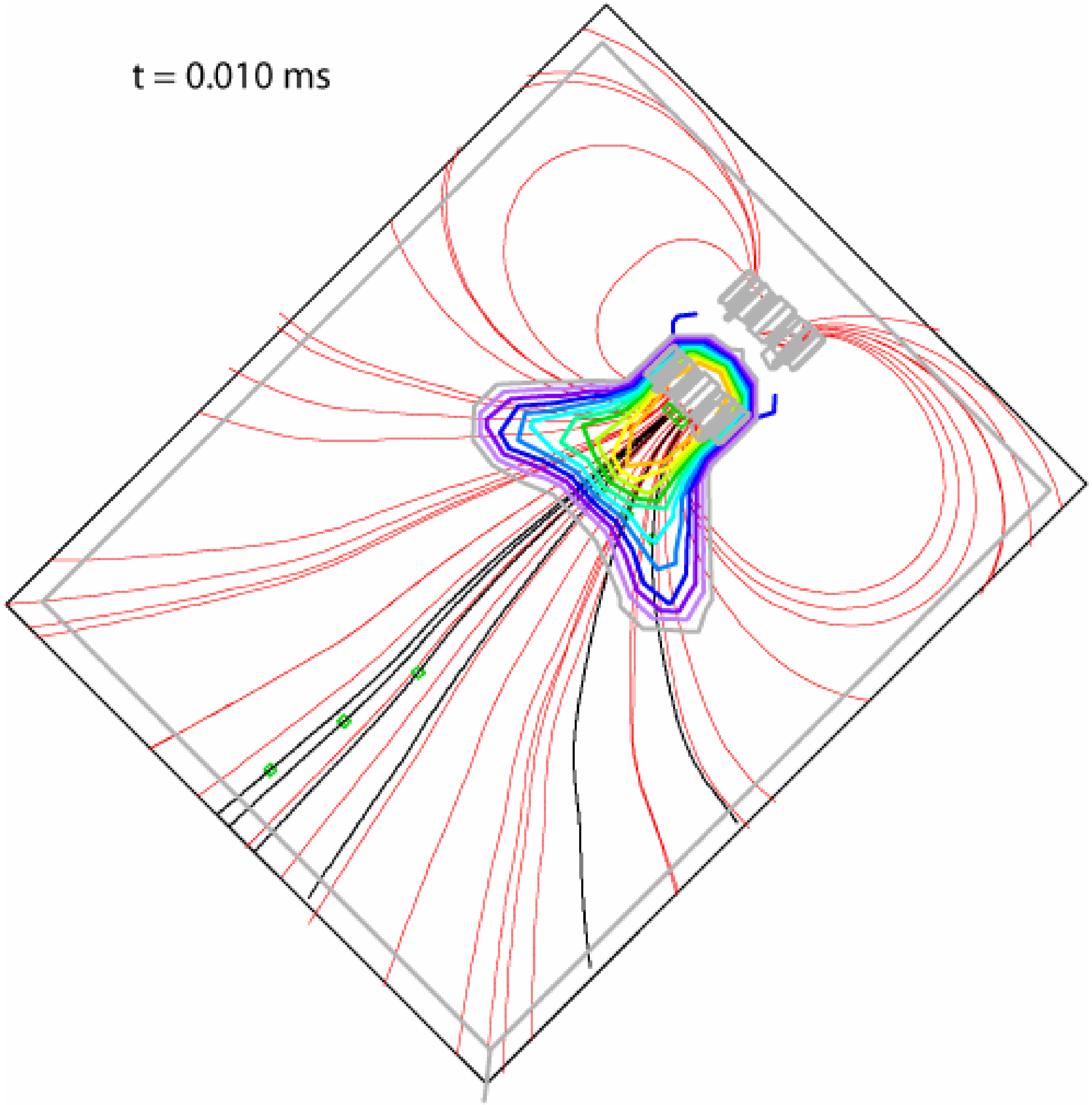
Bulk Speed: 30 km/s

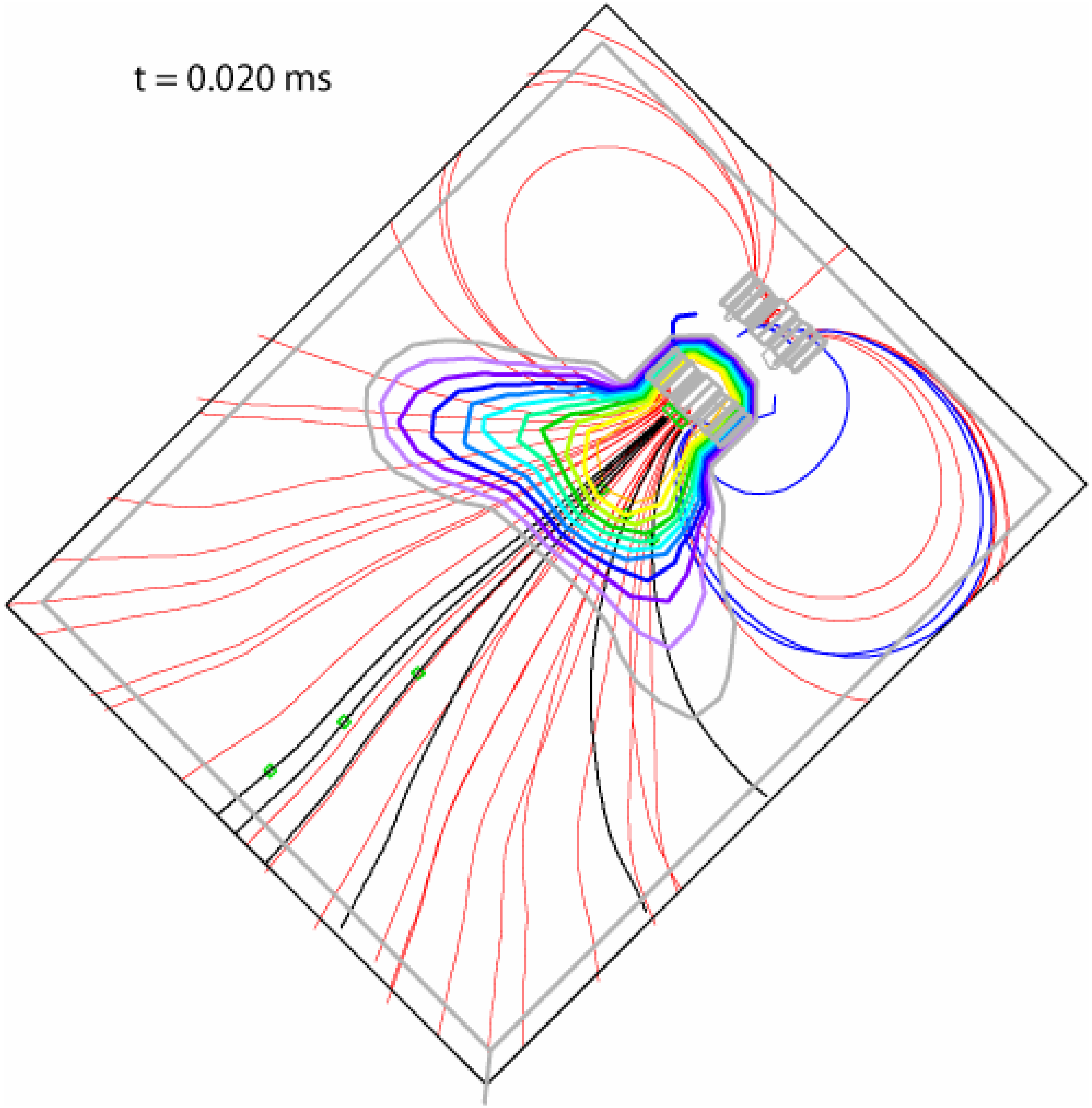
Thermal Speed: ~ 30 km/s

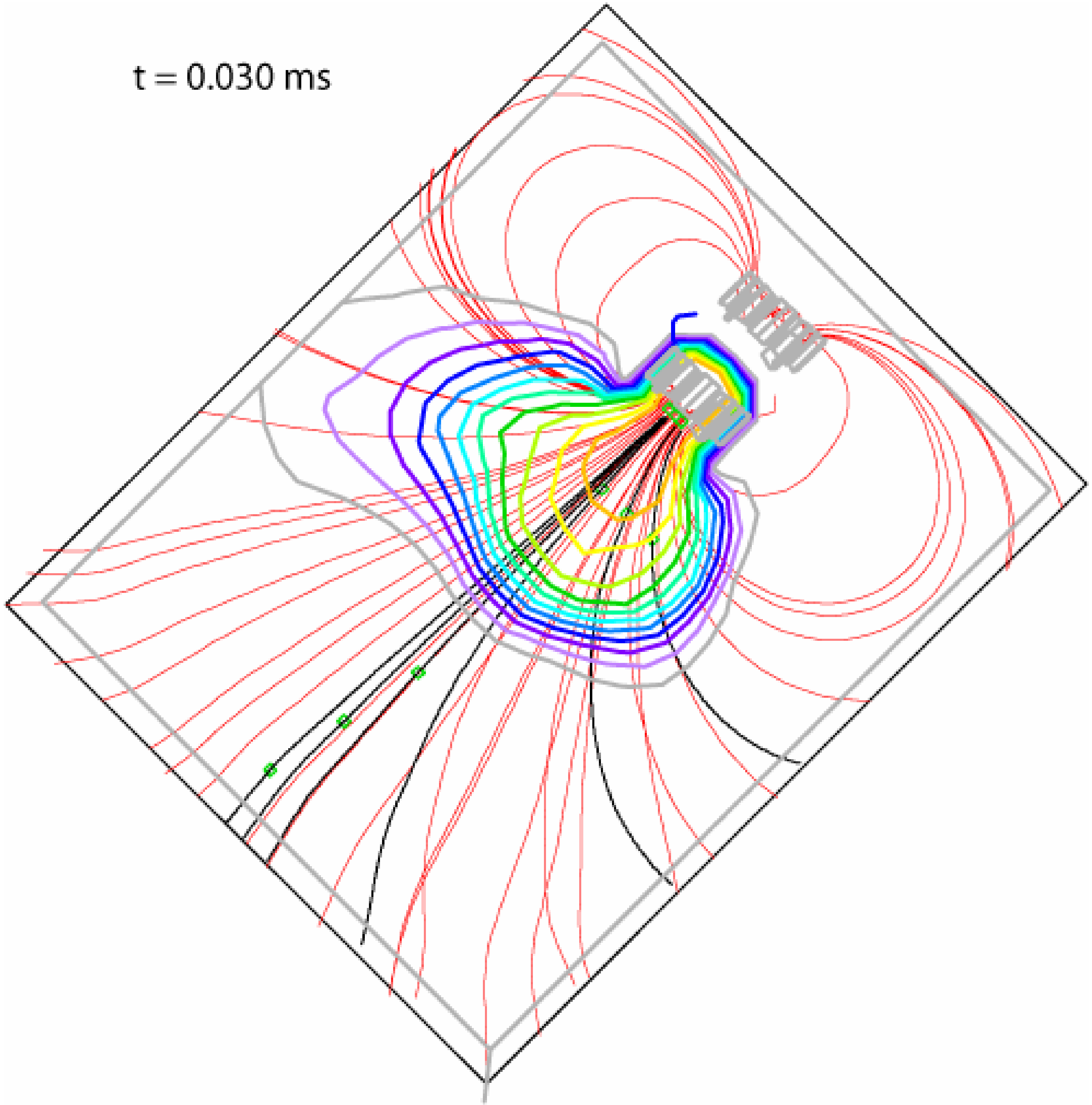


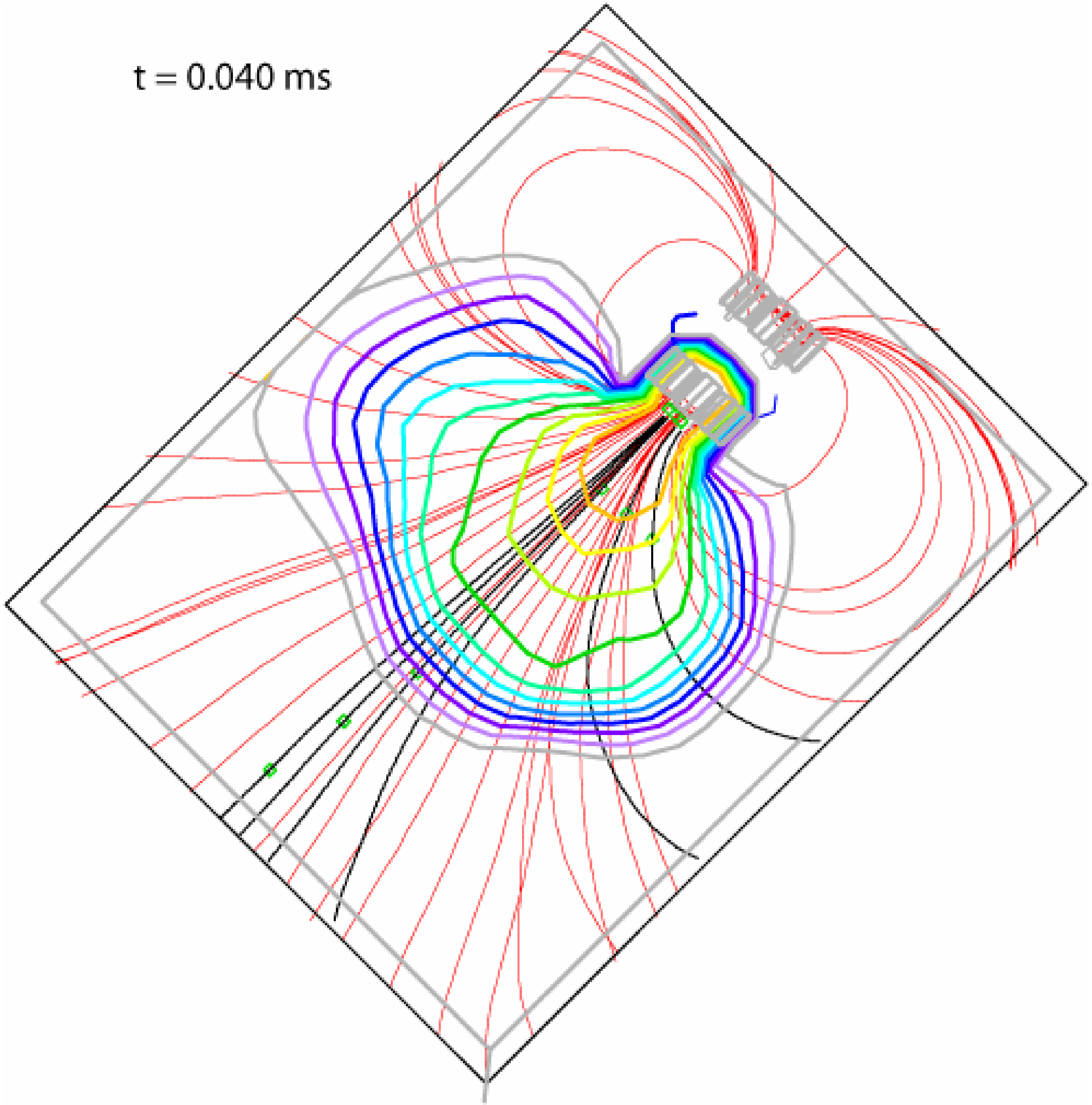
t = 0.000 ms
Fix Diagnostic Probes
Fix Diagnostic Probes

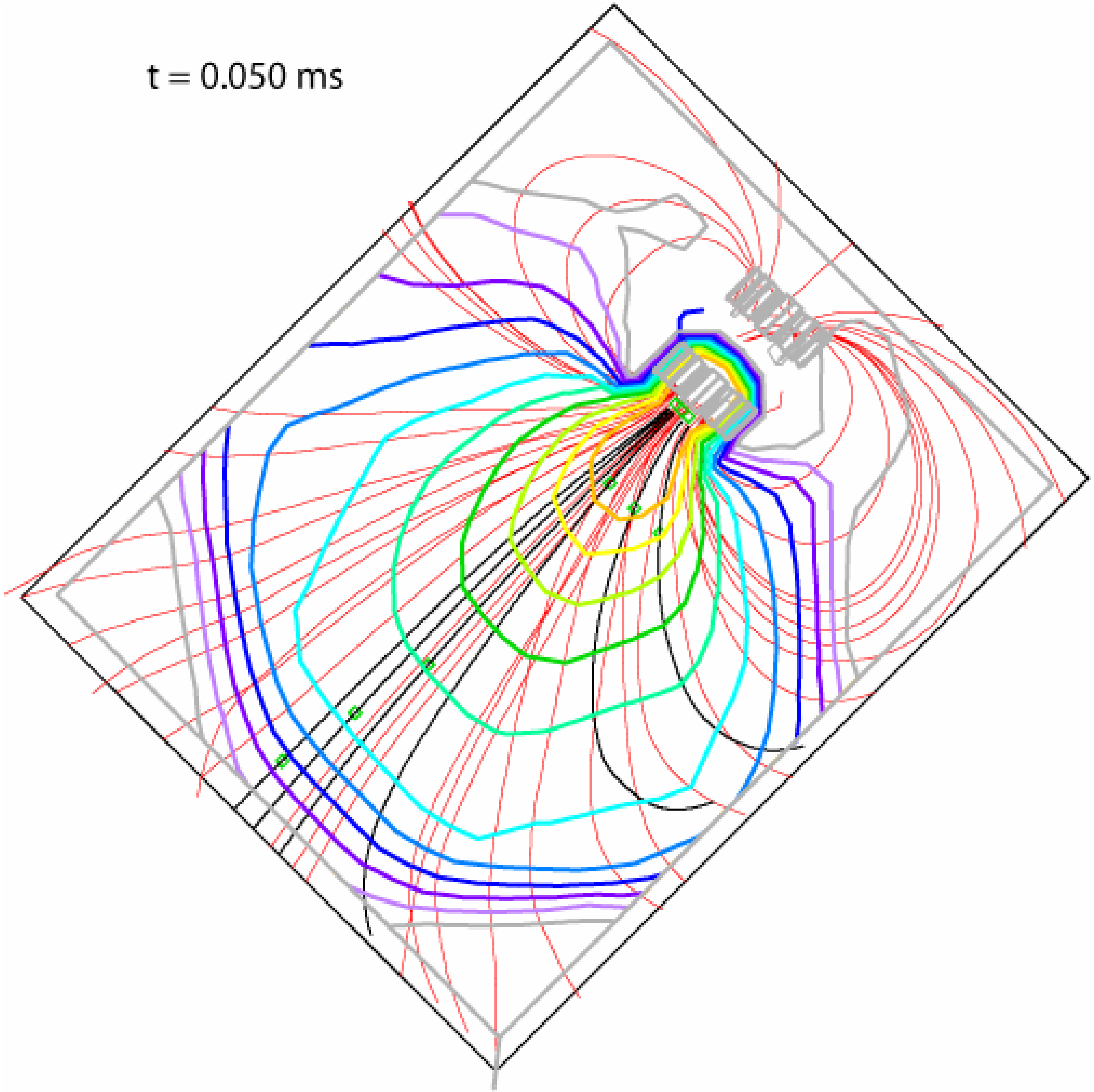

t = 0.000 ms

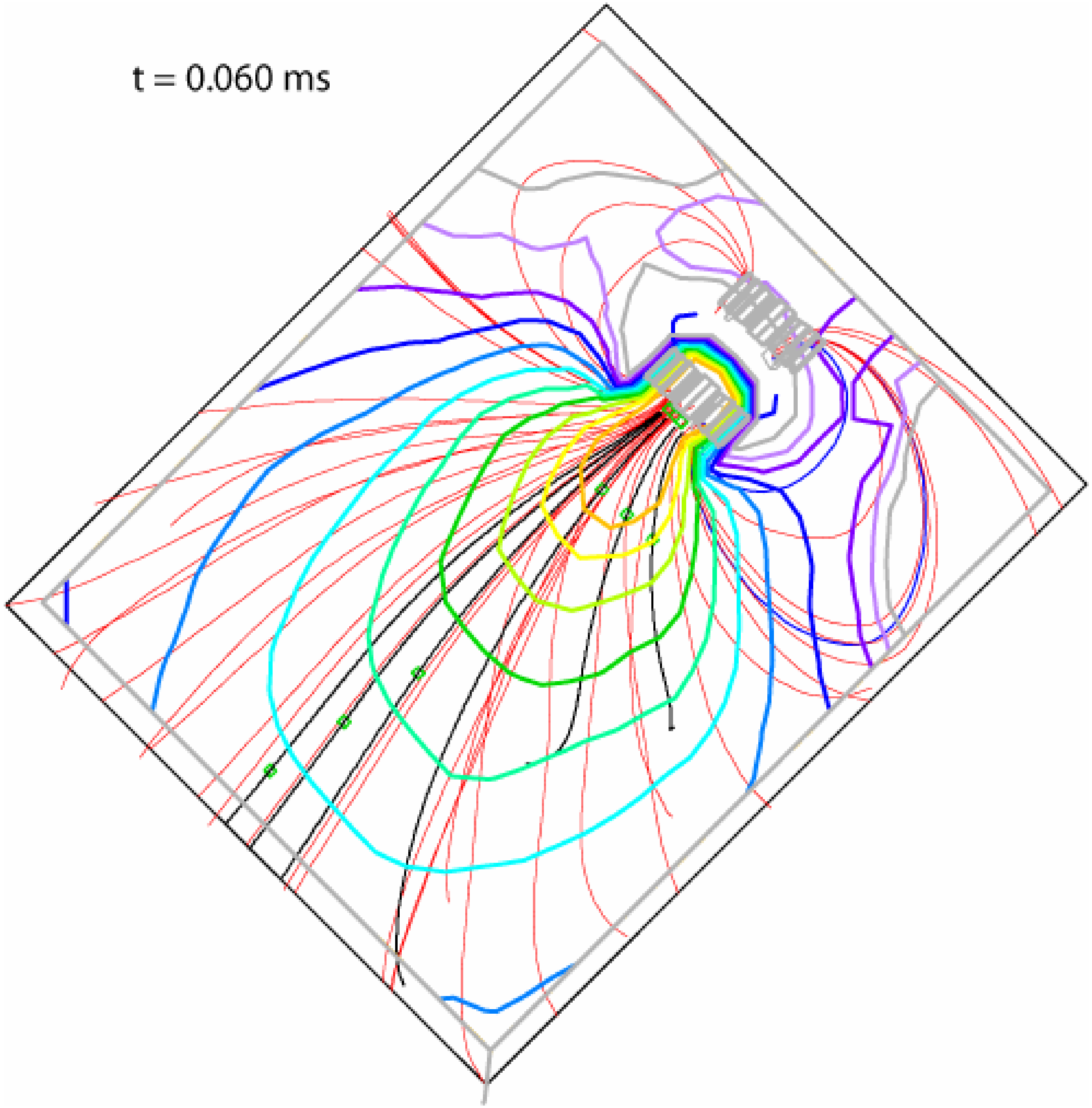

t = 0.010 ms

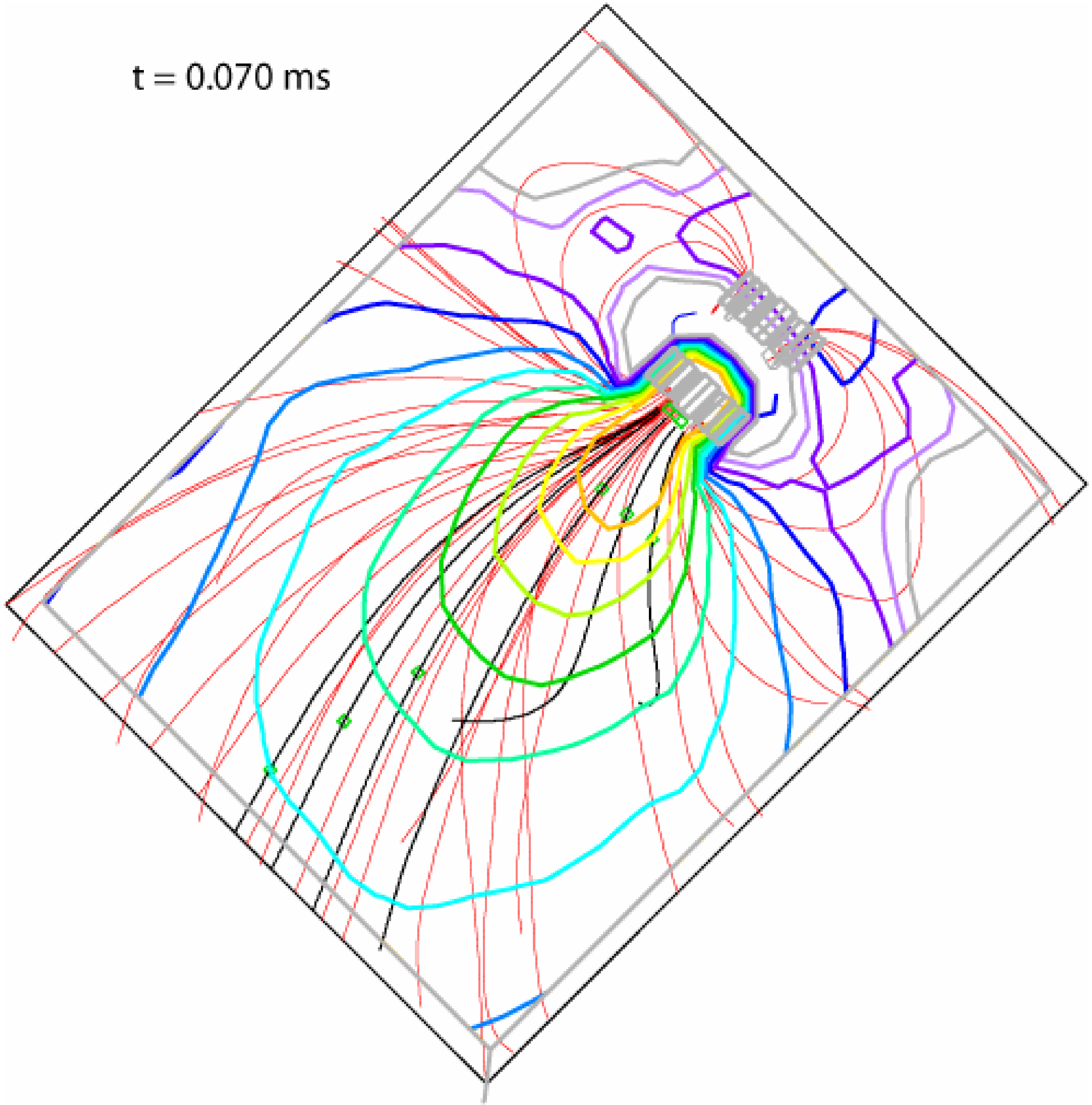

t = 0.020 ms

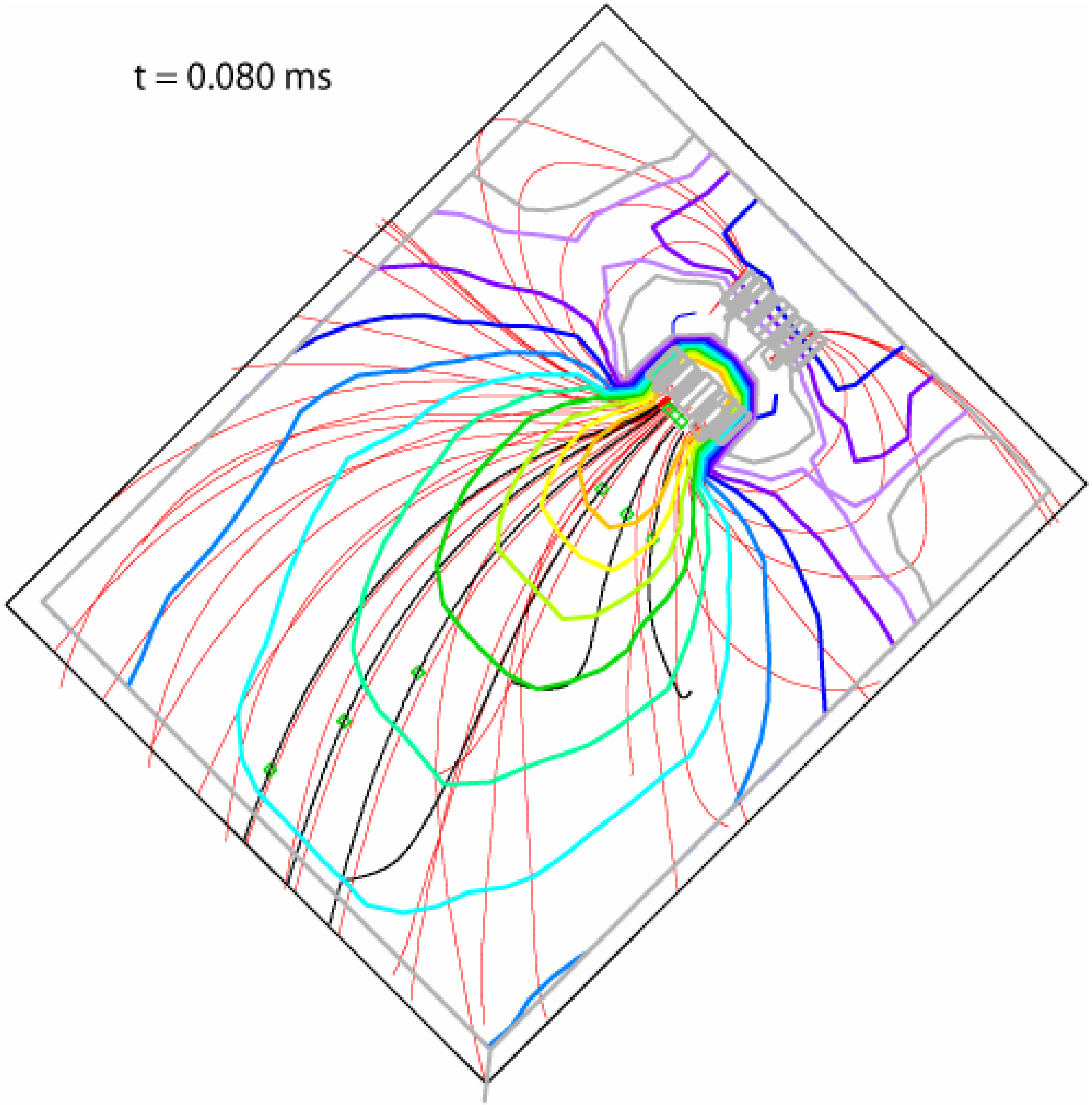

t = 0.030 ms


t = 0.040 ms

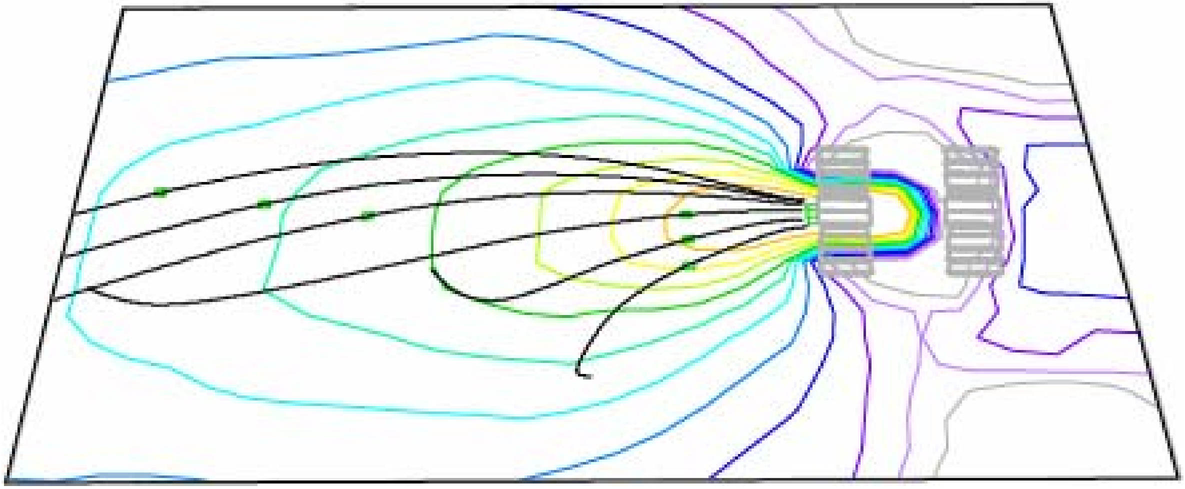

t = 0.050 ms


t = 0.060 ms


t = 0.070 ms

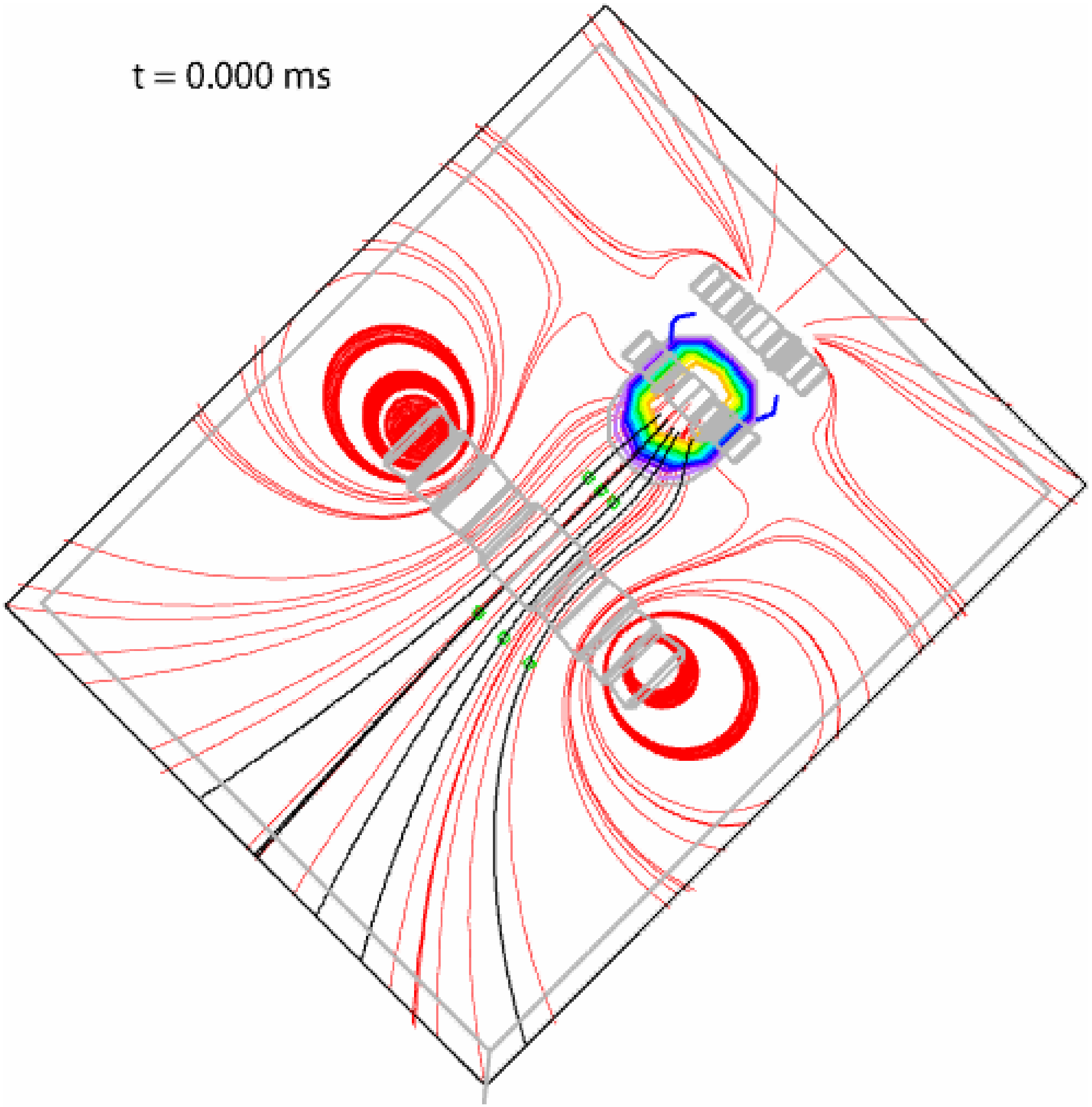

t = 0.080 ms

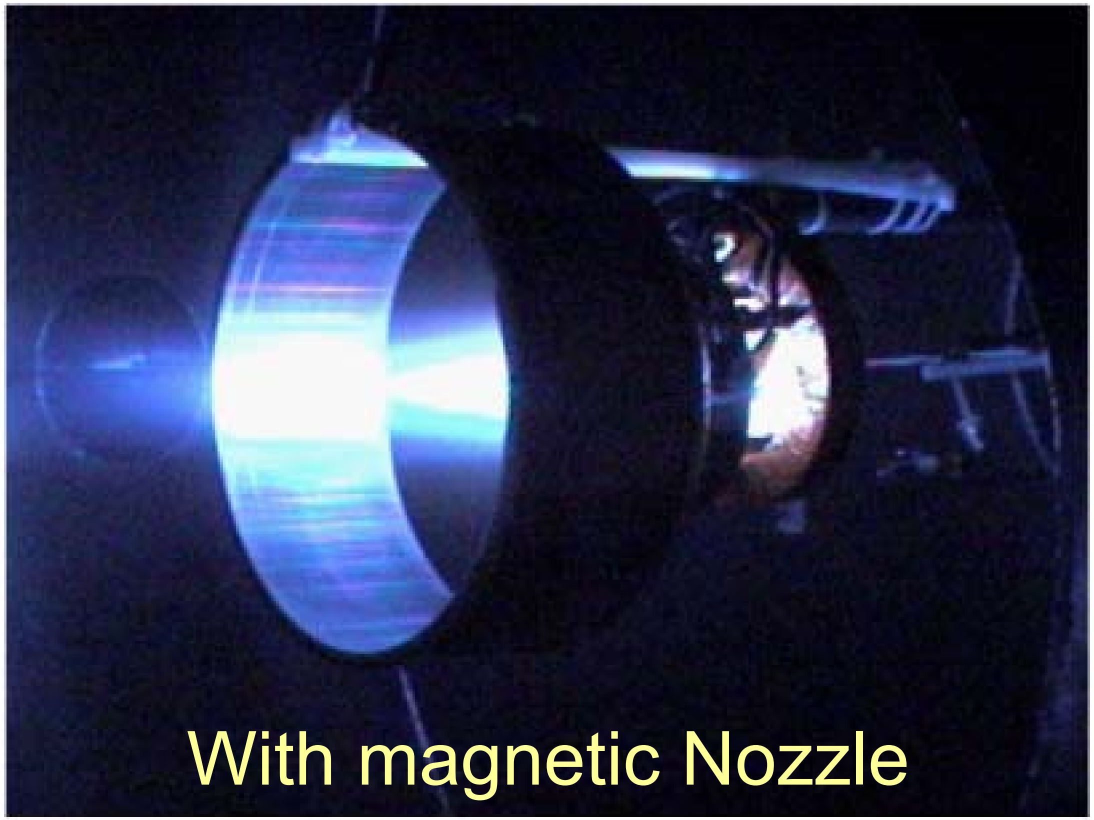

No Nozzle Configuration

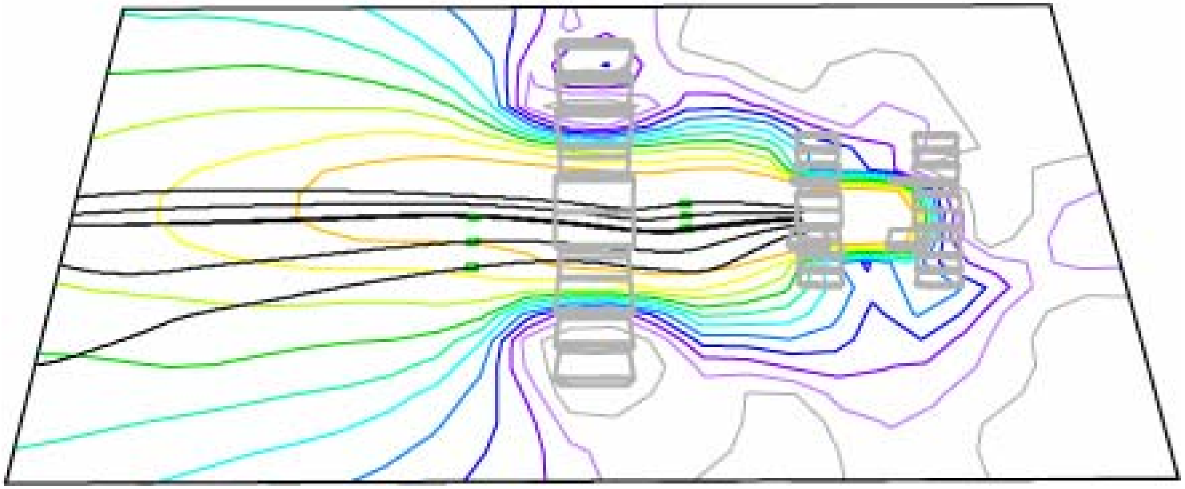


High Power Helicon: No Magnetic Nozzle

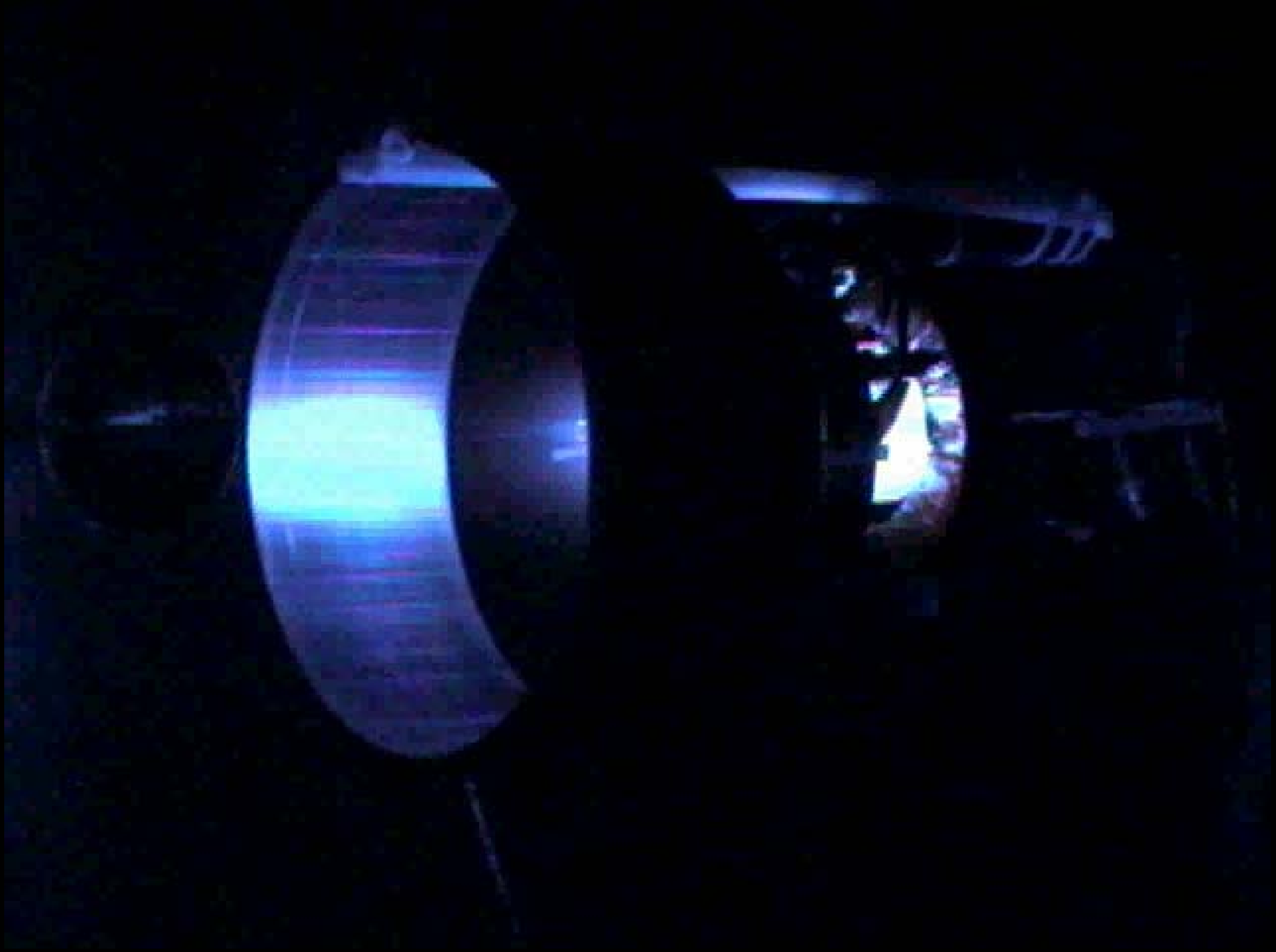
Improved Performance with Magnetic Nozzle



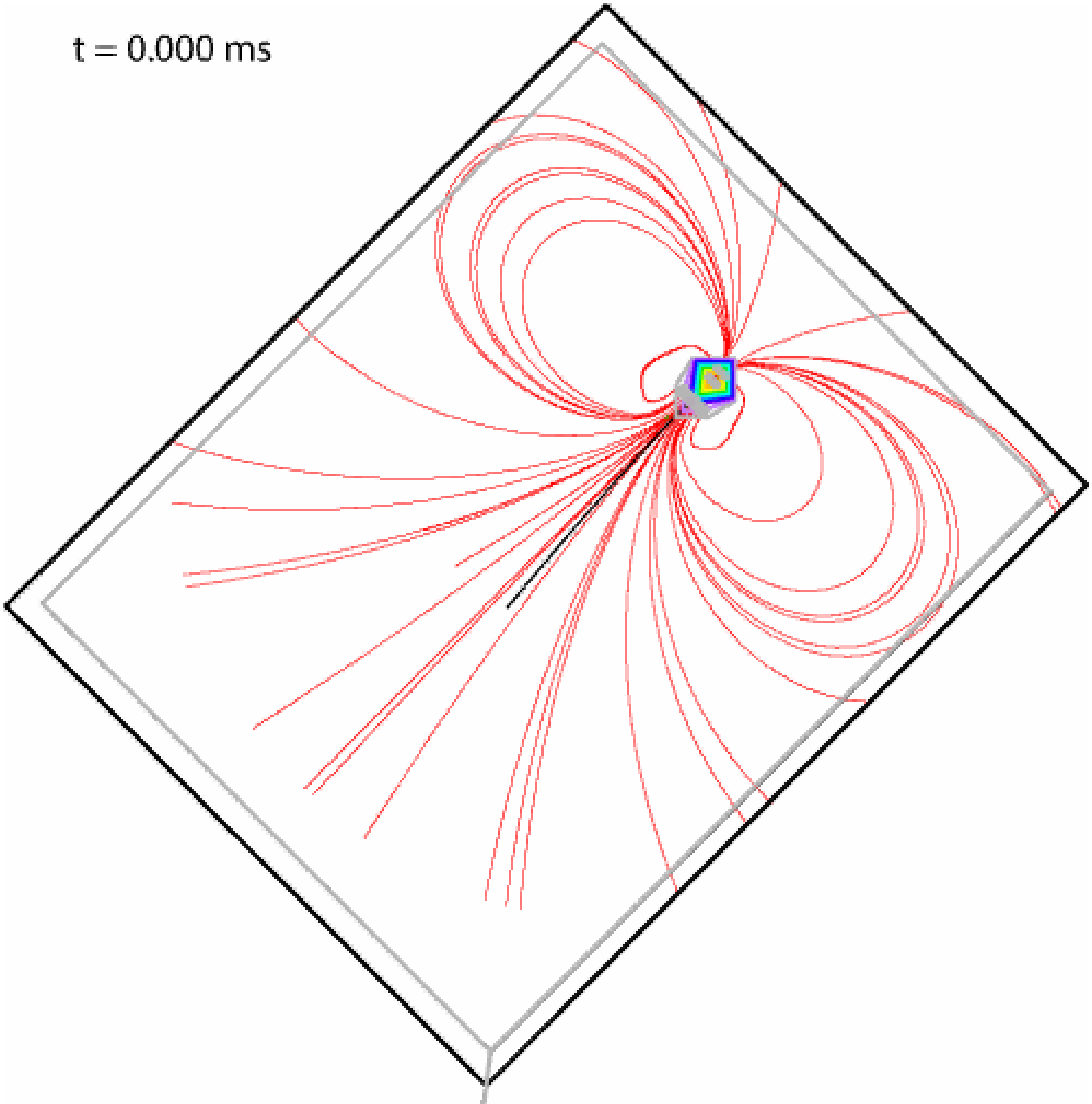

With magnetic Nozzle

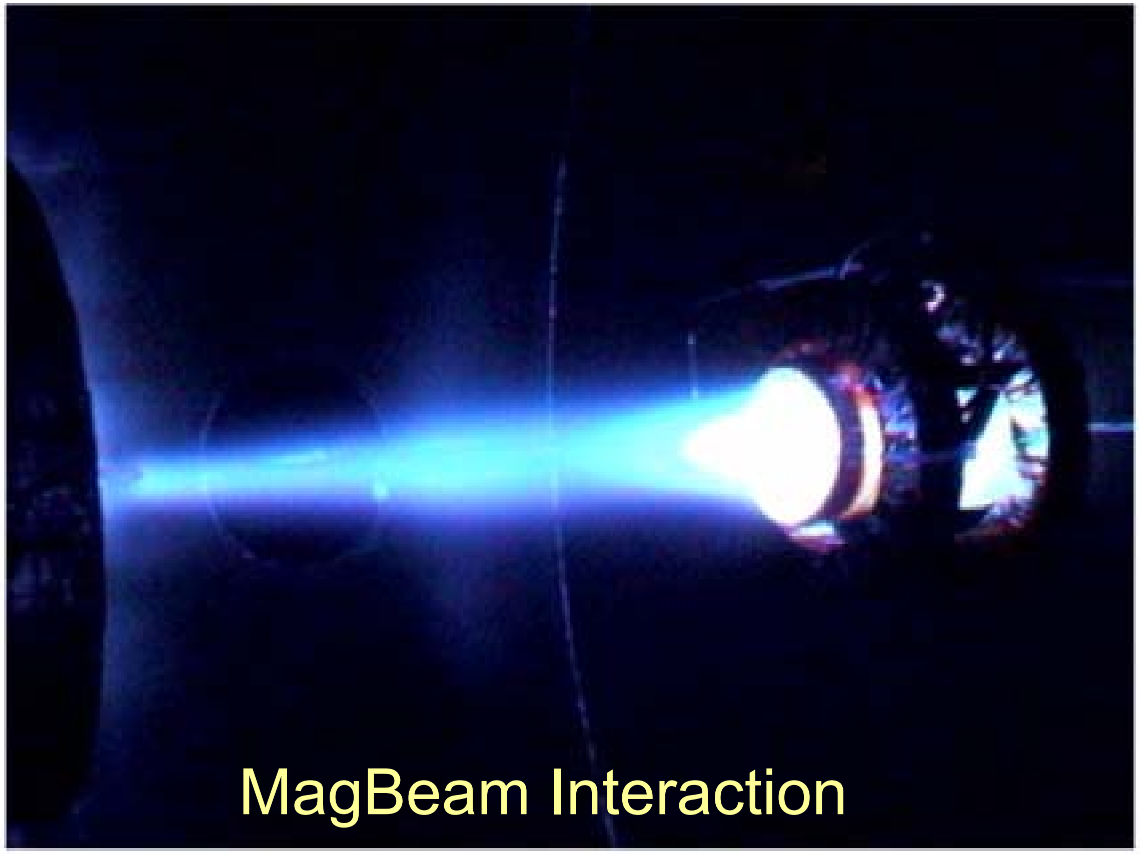


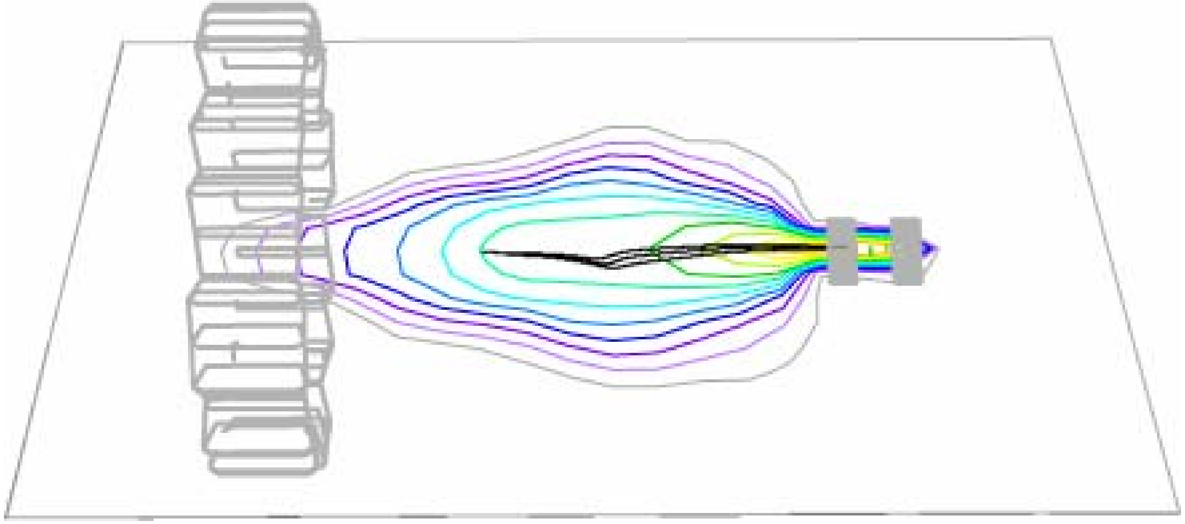
High Power Helicon: With Magnetic Nozzle



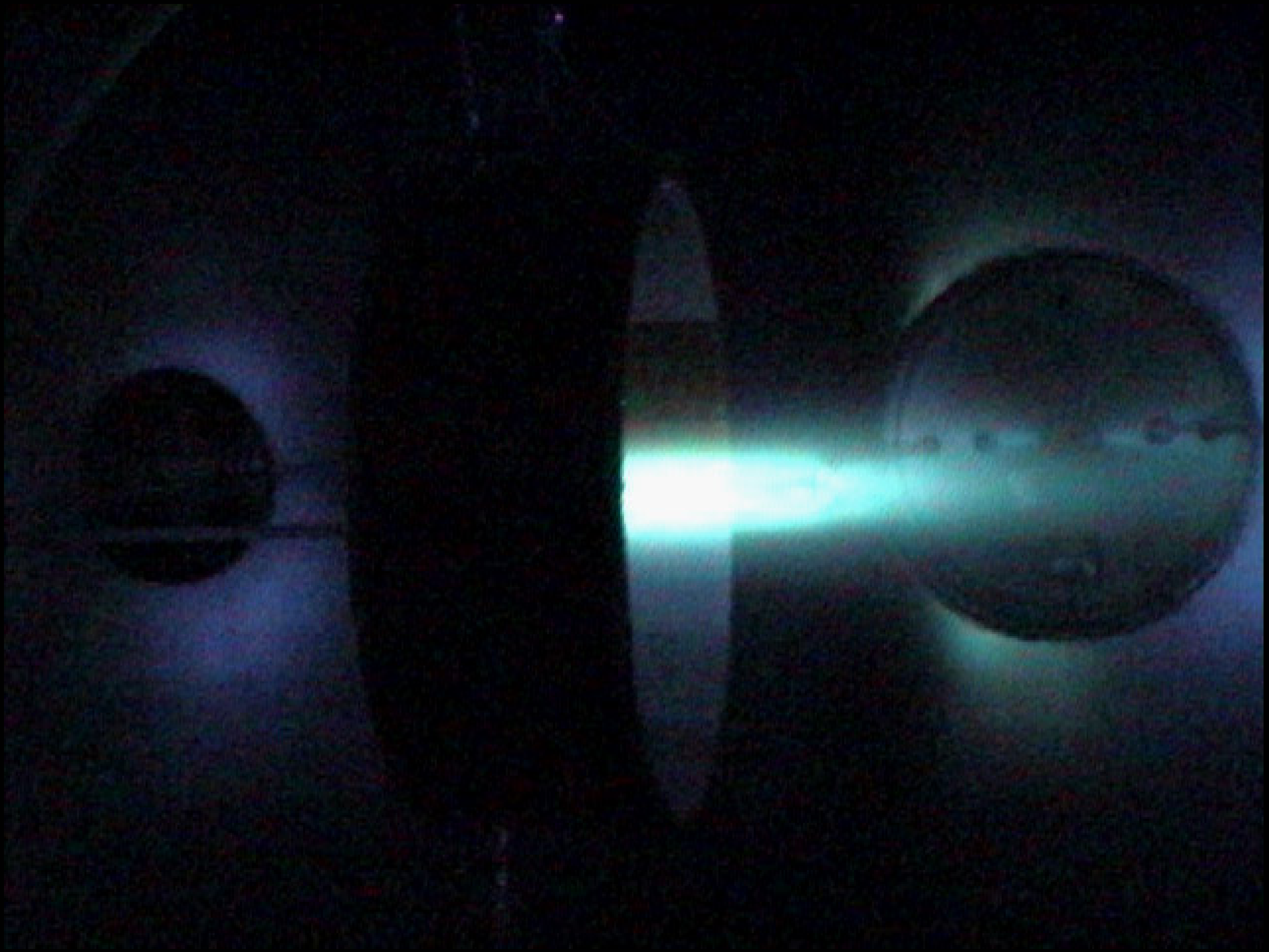
Far Field View of Beamed Plasma



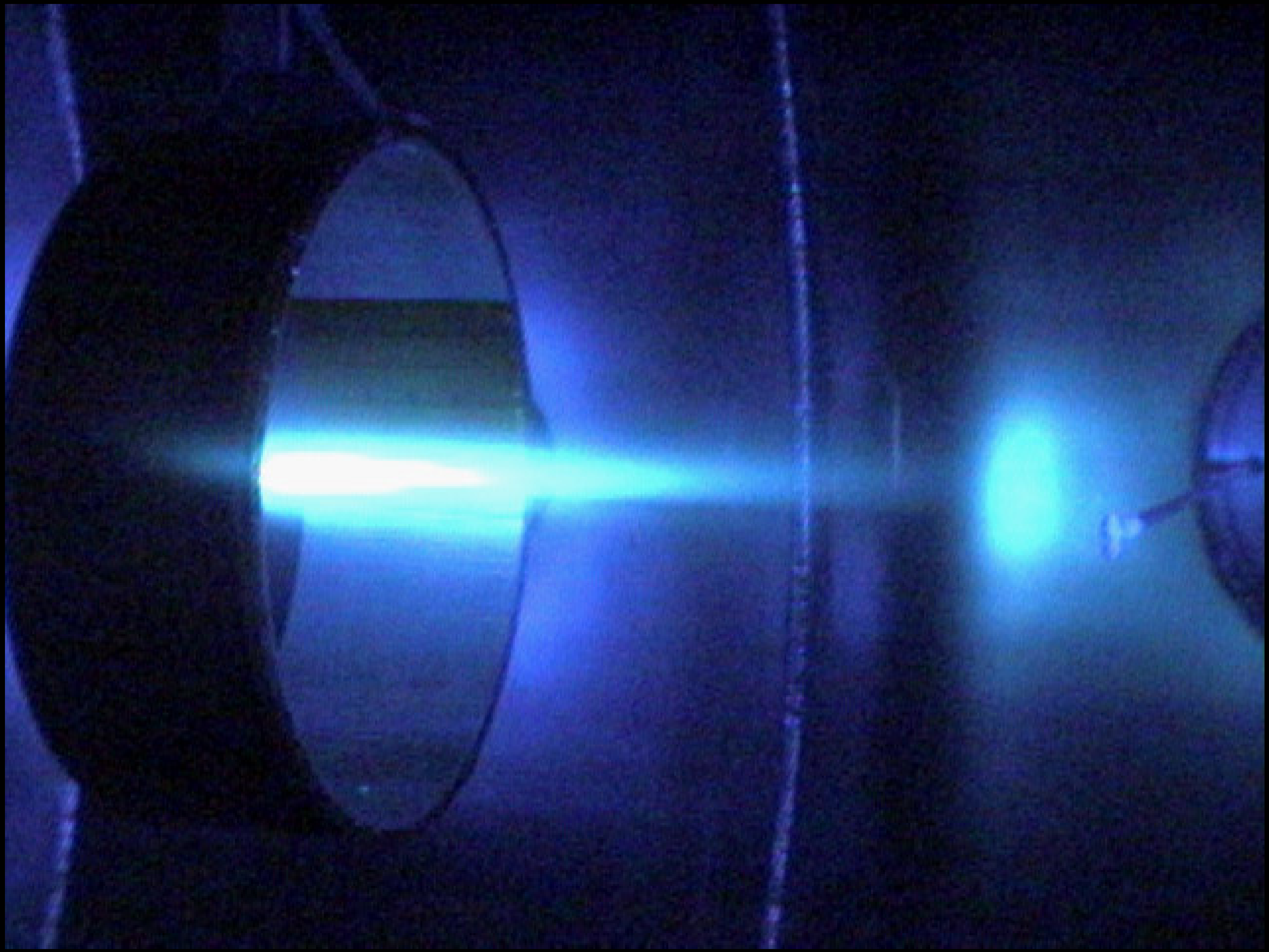

MagBeam Interaction



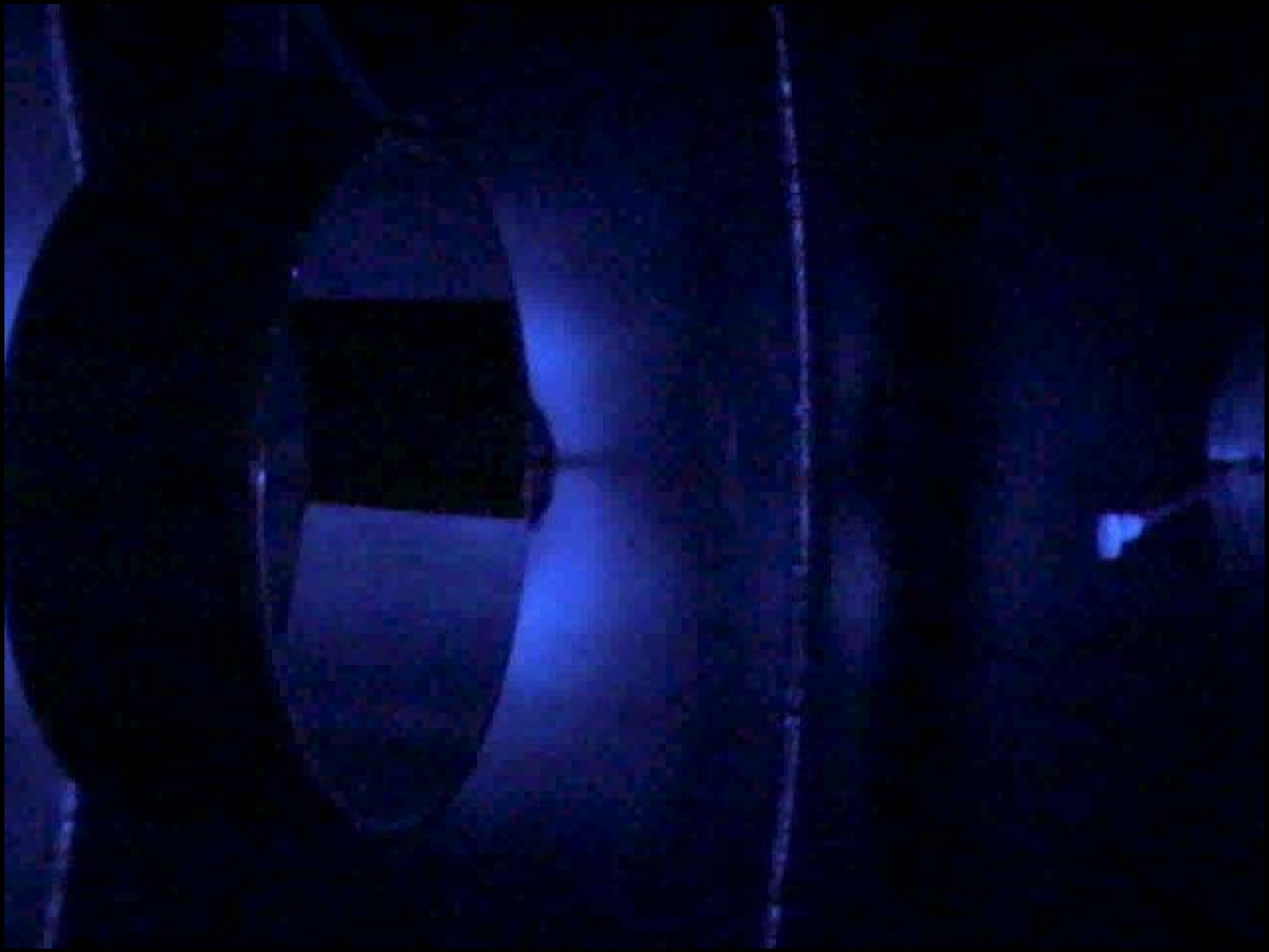
MagBeam: Middle of Chamber

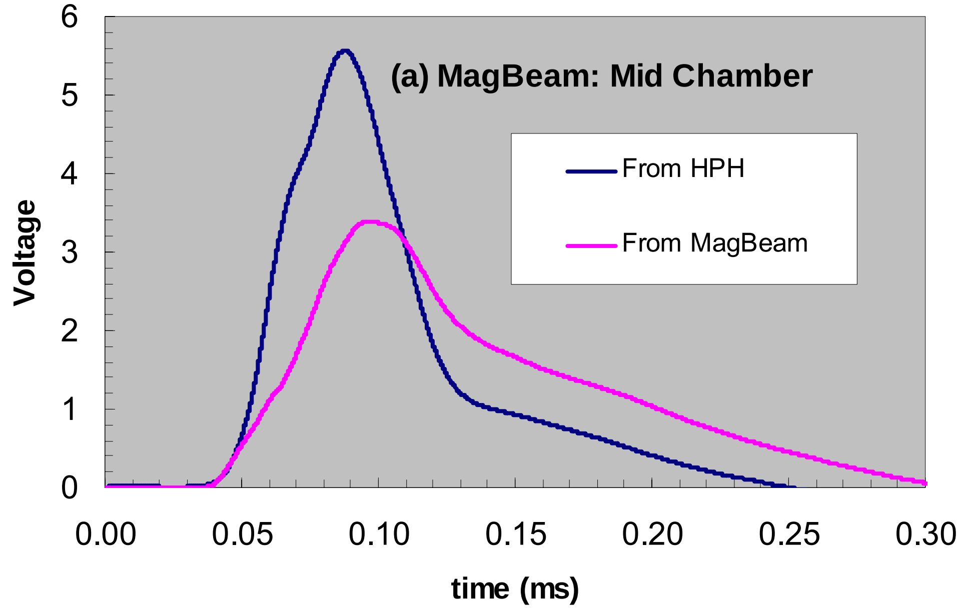


MagBeam: End of Chamber

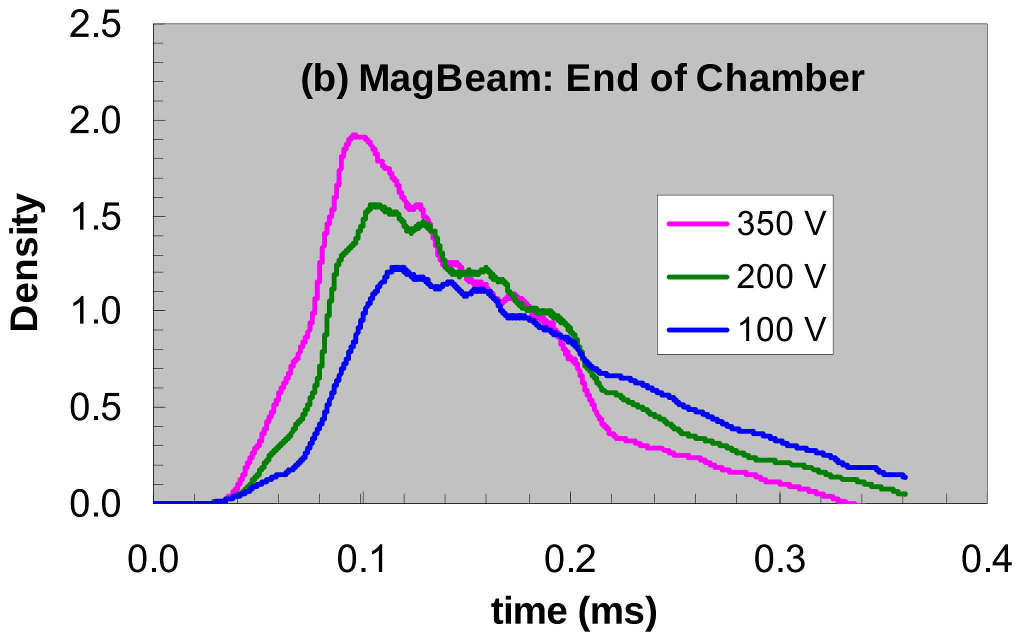


MagBeam: Hitting the Target





(a) MagBeam: Mid Chamber
From HPH
From MagBeam
Voltage
time (ms)
0
1
2
3
4
5
6
0.00
0.05
0.10
0.15
0.20
0.25
0.30



(b) MagBeam: End of Chamber
350 V
200 V
100 V
Density
time (ms)
0.0
0.5
1.0
1.5
2.0
2.5
0.0
0.1
0.2
0.3
0.4

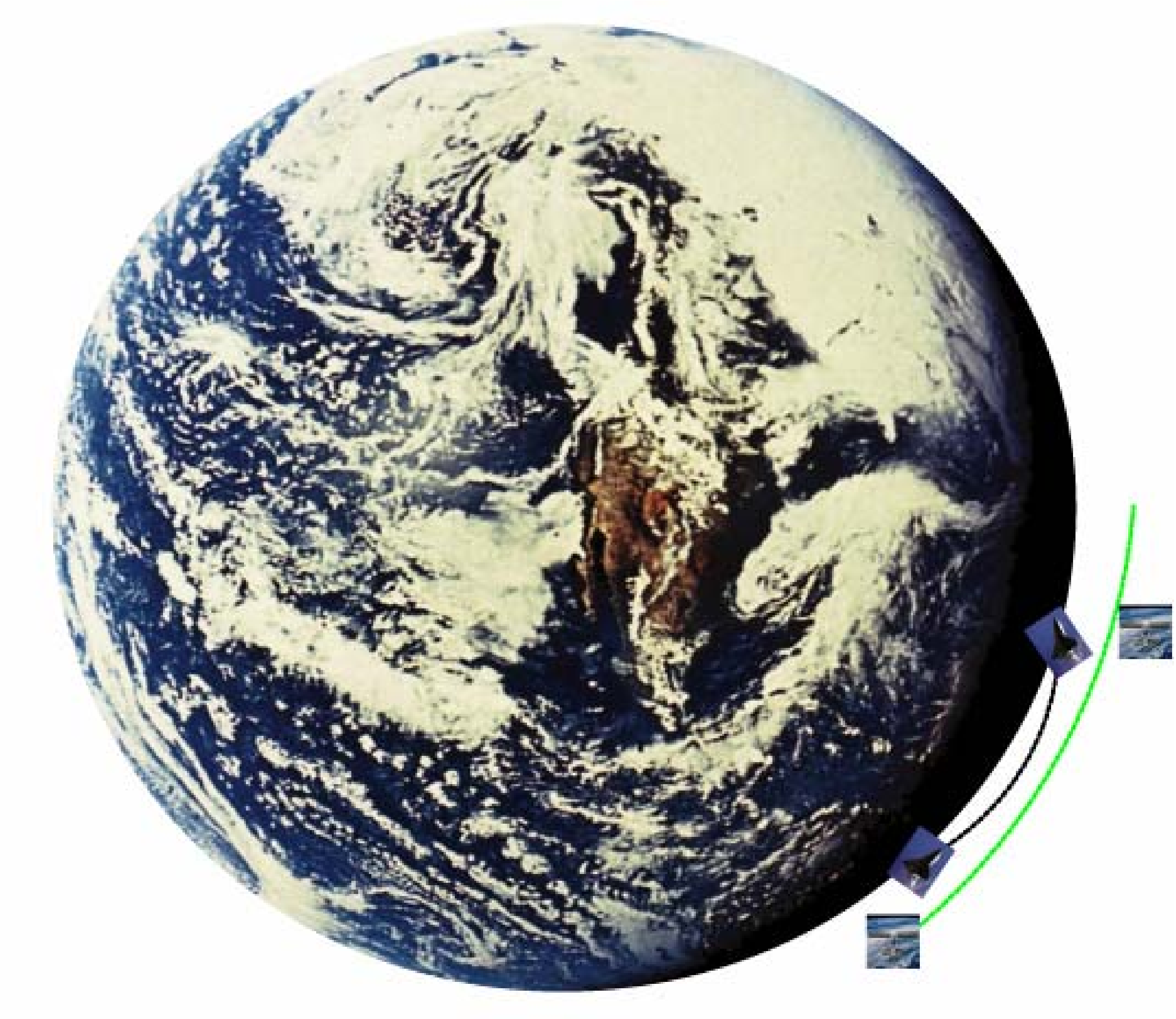
Power System Requirements

- Fast Discharge Rates (associated with LEO and Geo)
  - Best supplied by Batteries/Fuel Cells (recharge between missions)
  - Present day capabilities is 400 W hrs/kg (1.5 MJ/kg)
  - Expectation in the next decade might be 600 W hrs/kg
- Charging: - Solar Electric
  - Space Station presently yields 100 kW using 6% efficiency
  - Present day triple junction systems yield nearly 30% efficiency

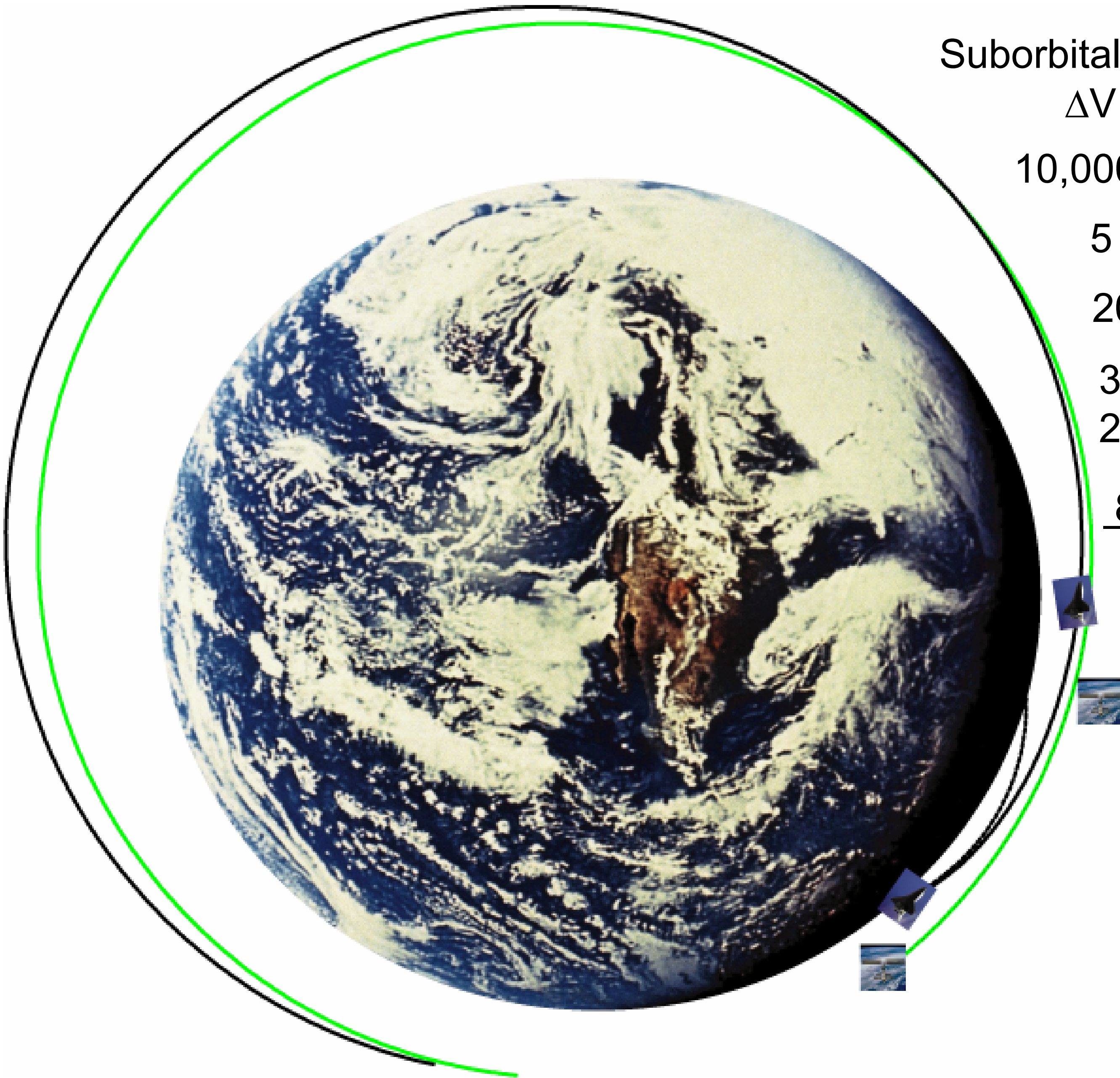
  - Nuclear Electric
    - Present day capabilities is 20 kg/kW
    - Expectation in the next decade 5 kg/kW

Bootstrapping into Space

Suborbital + LEO Space Station



Bootstrapping into Space



Suborbital + LEO Space Station

$\Delta V \sim 3$ km/s

10,000 kg payload

5 min interaction time

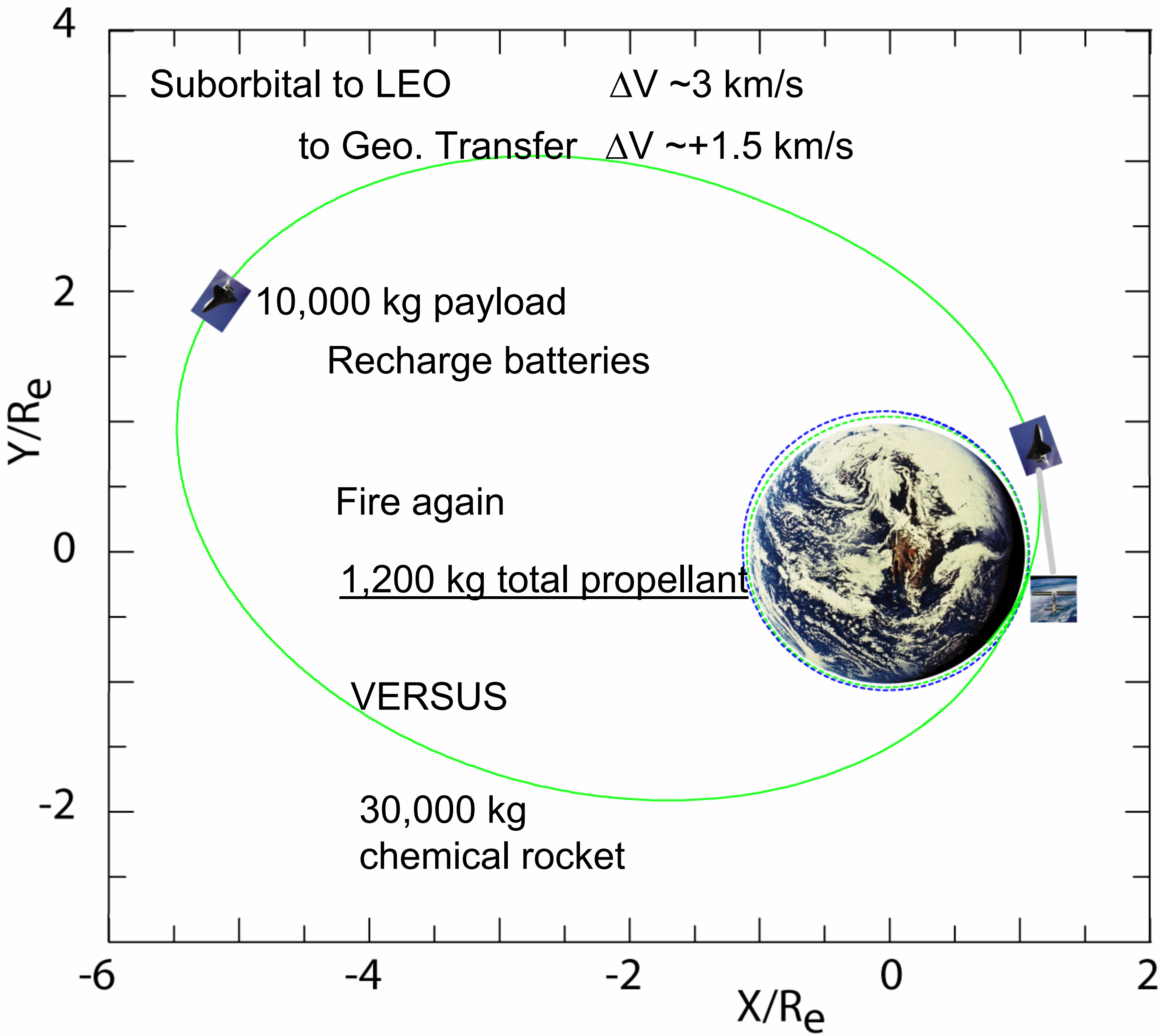
200,000 kg batteries

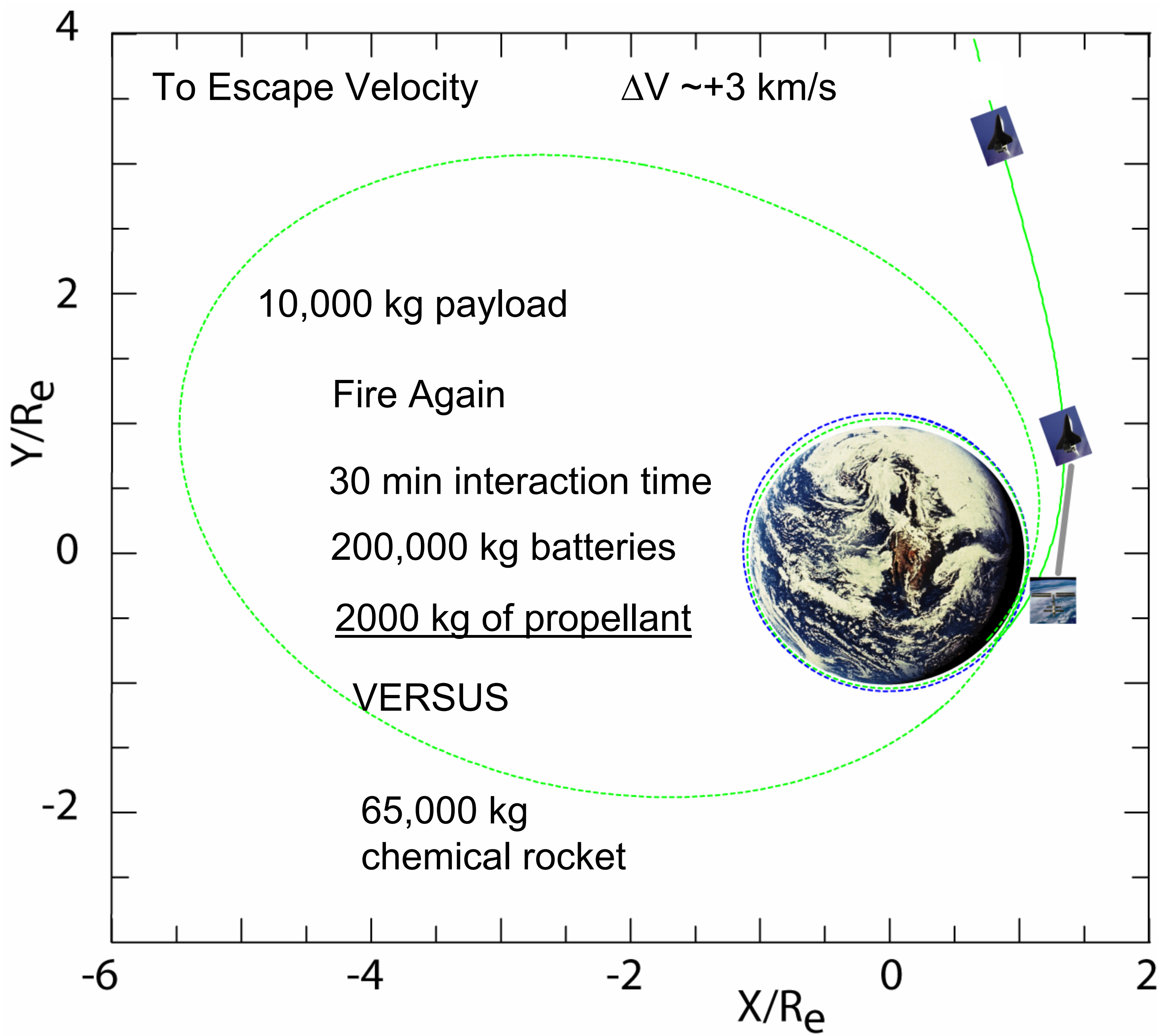
300 MW thruster,
2000s Isp

<u>800 kg of propellant</u>

VERSUS

20,000 kg
chemical rocket

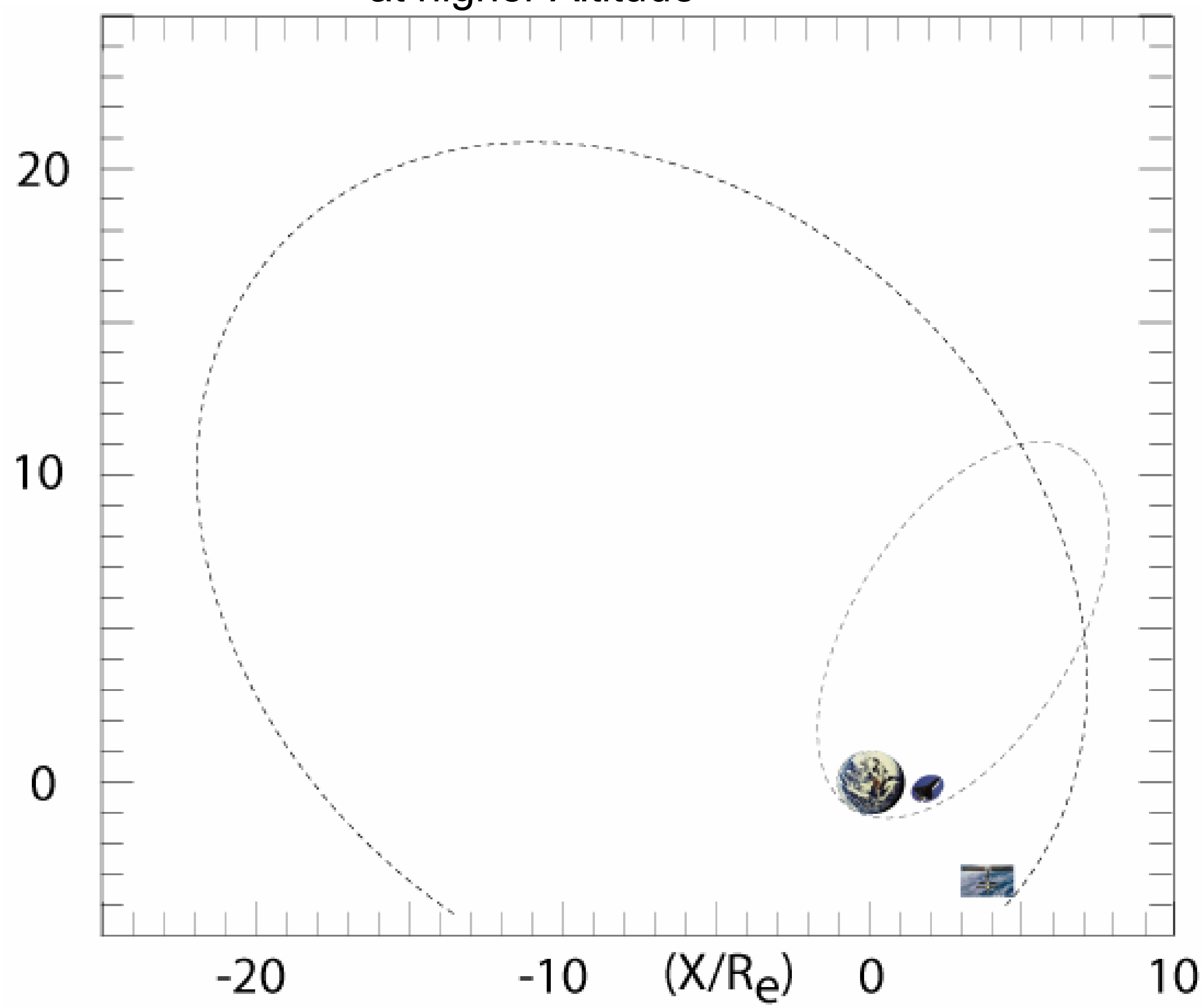

Suborbital to LEO
ΔV ~3 km/s
to Geo. Transfer
ΔV ~+1.5 km/s
10,000 kg payload
Recharge batteries
Fire again
1,200 kg total propellant
VERSUS
30,000 kg
chemical rocket
Y/Re
X/Re
4
2
0
-2
-6
-4
-2
0
2



To Escape Velocity
ΔV ~+3 km/s
10,000 kg payload
Fire Again
30 min interaction time
200,000 kg batteries
2000 kg of propellant
VERSUS
65,000 kg
chemical rocket
Y/Re
X/Re
4
2
0
-2
-6
-4
-2
0
2

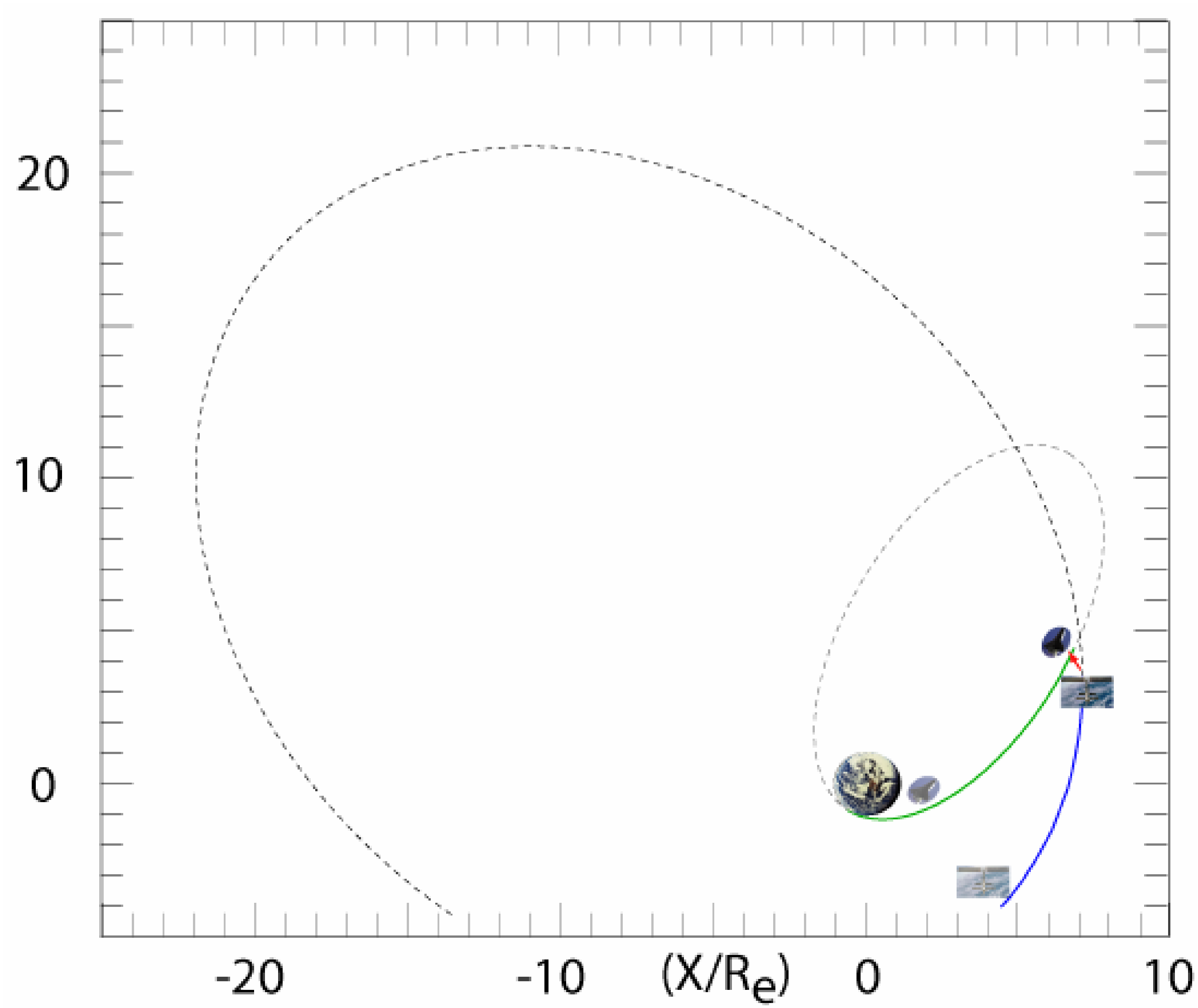
Fast Trip to Mars: ΔV ~20 km/s

Longer Acceleration Period: Need to Start with Space Station at higher Altitude

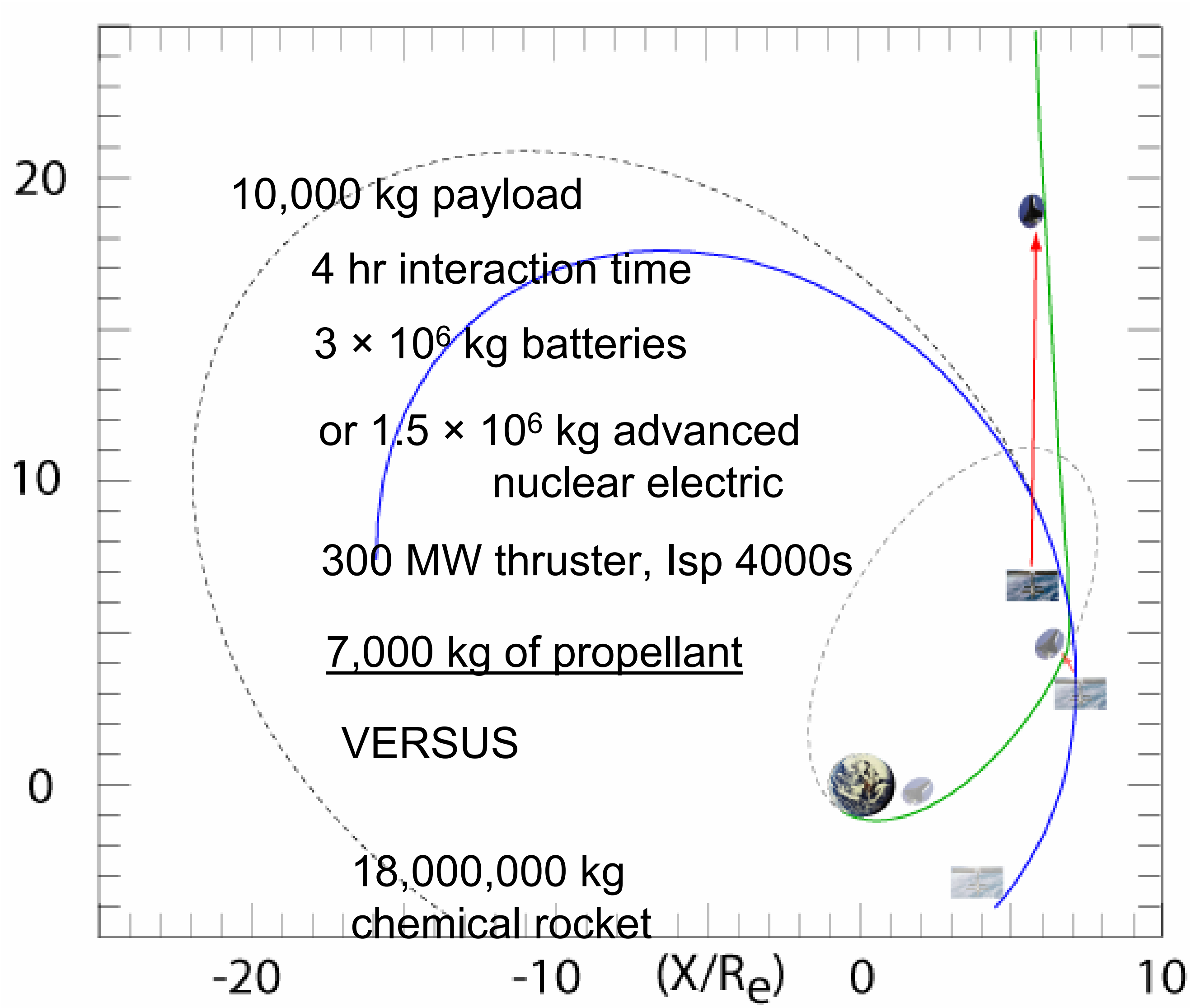


Fast Trip to Mars: ΔV ~20 km/s

Rendezvous using geosynchronous-like transfer

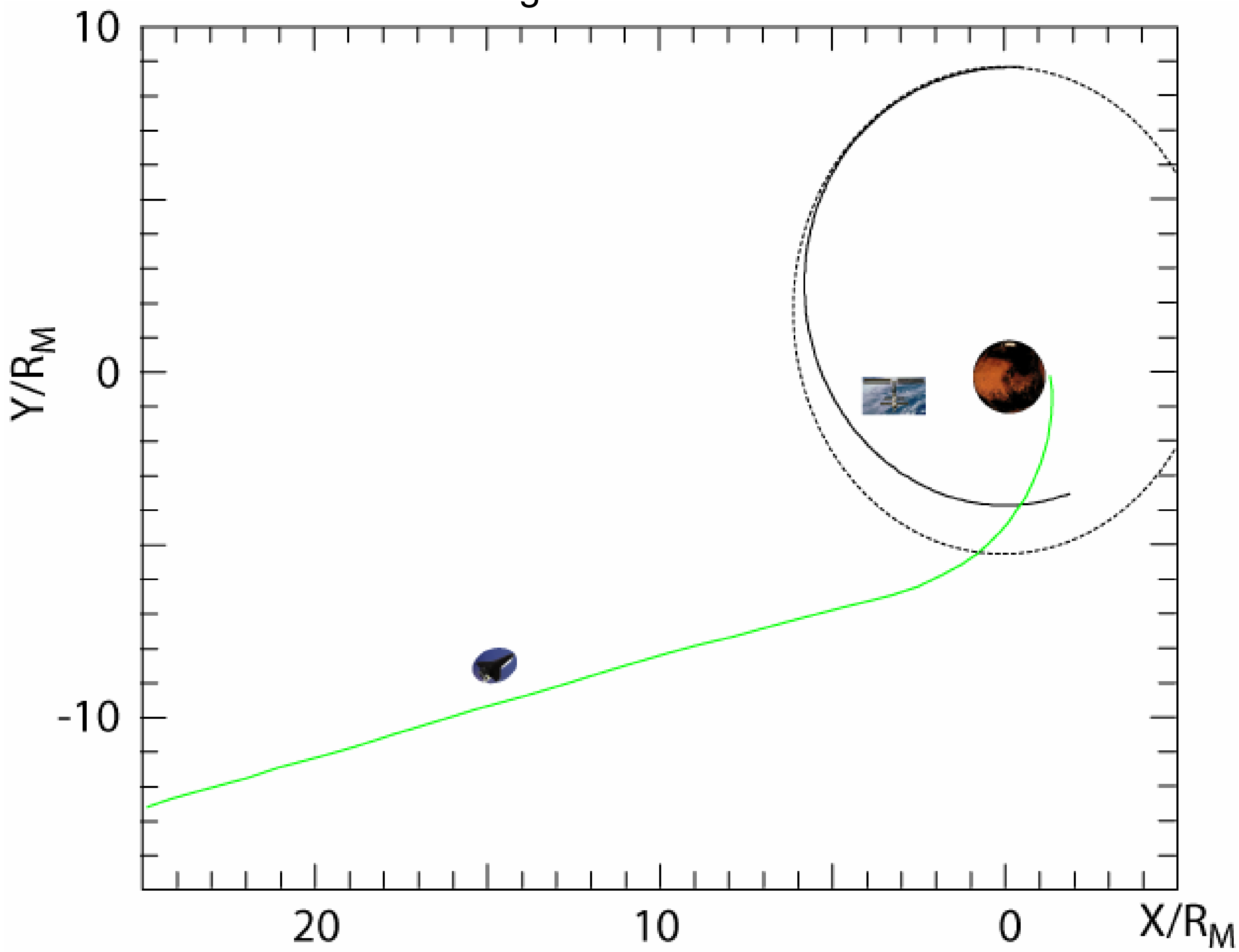


Fast Trip to Mars: ΔV ~20 km/s

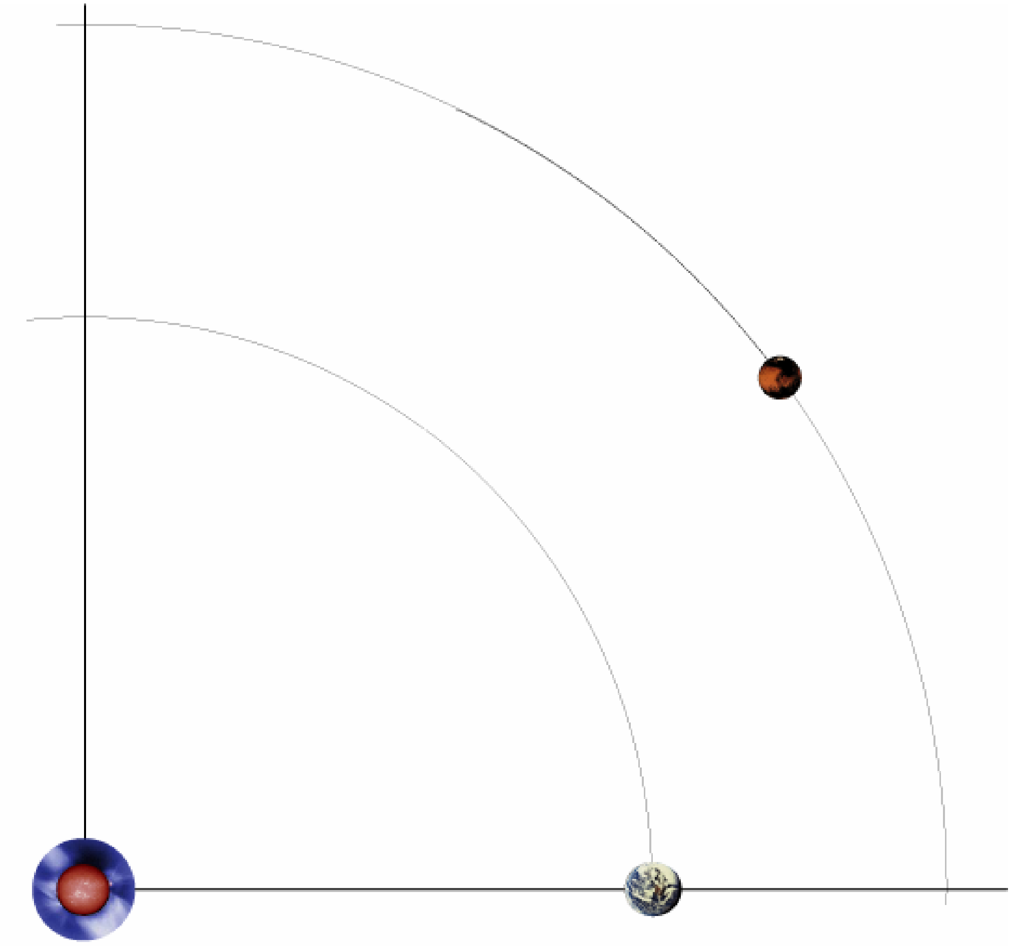


Mars Station Provides Braking: ΔV ~25 km/s

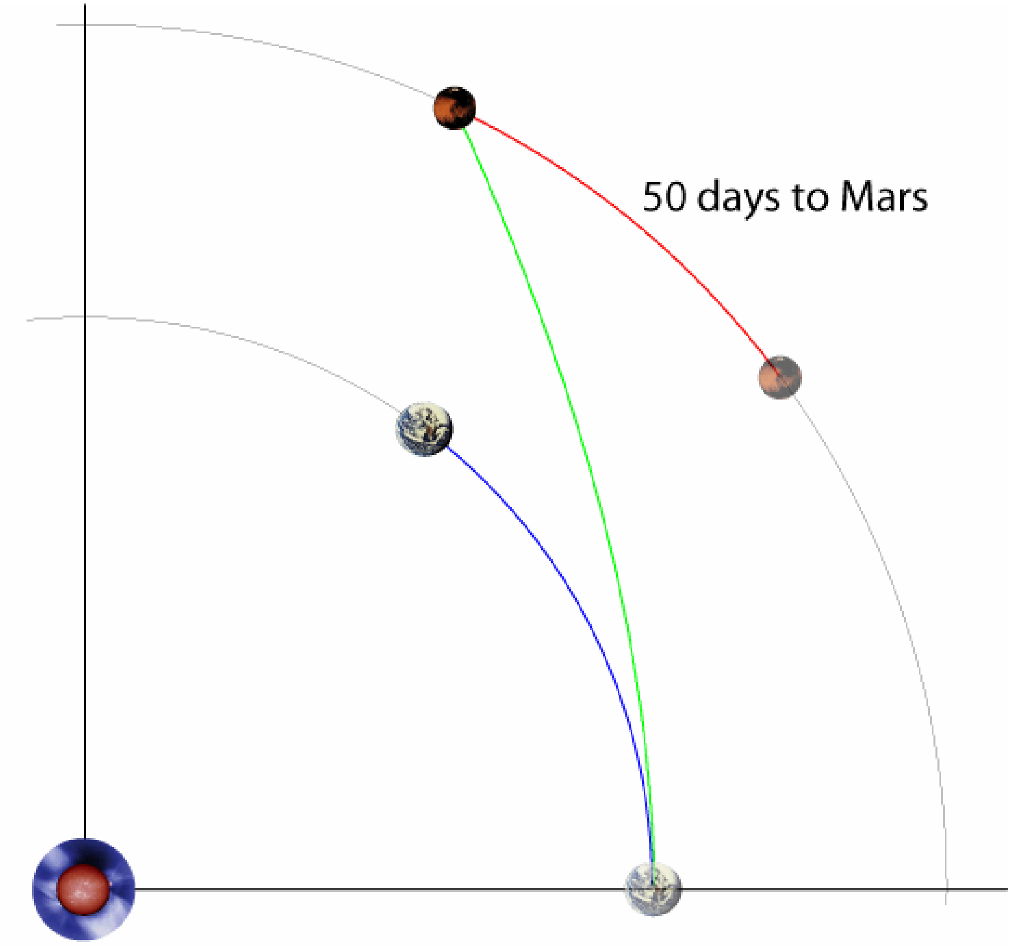
- ΔV ~ 7 km/s right at surface



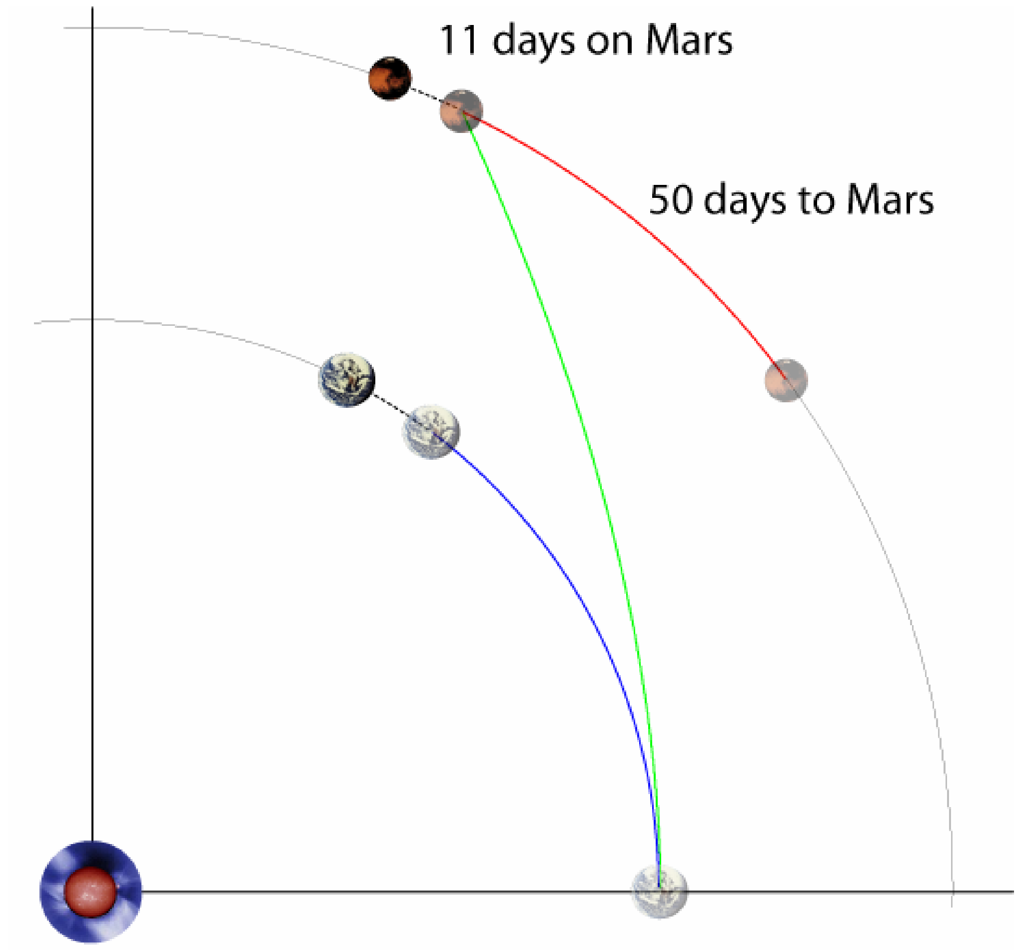
Total Trip Time: 0 Day - Start



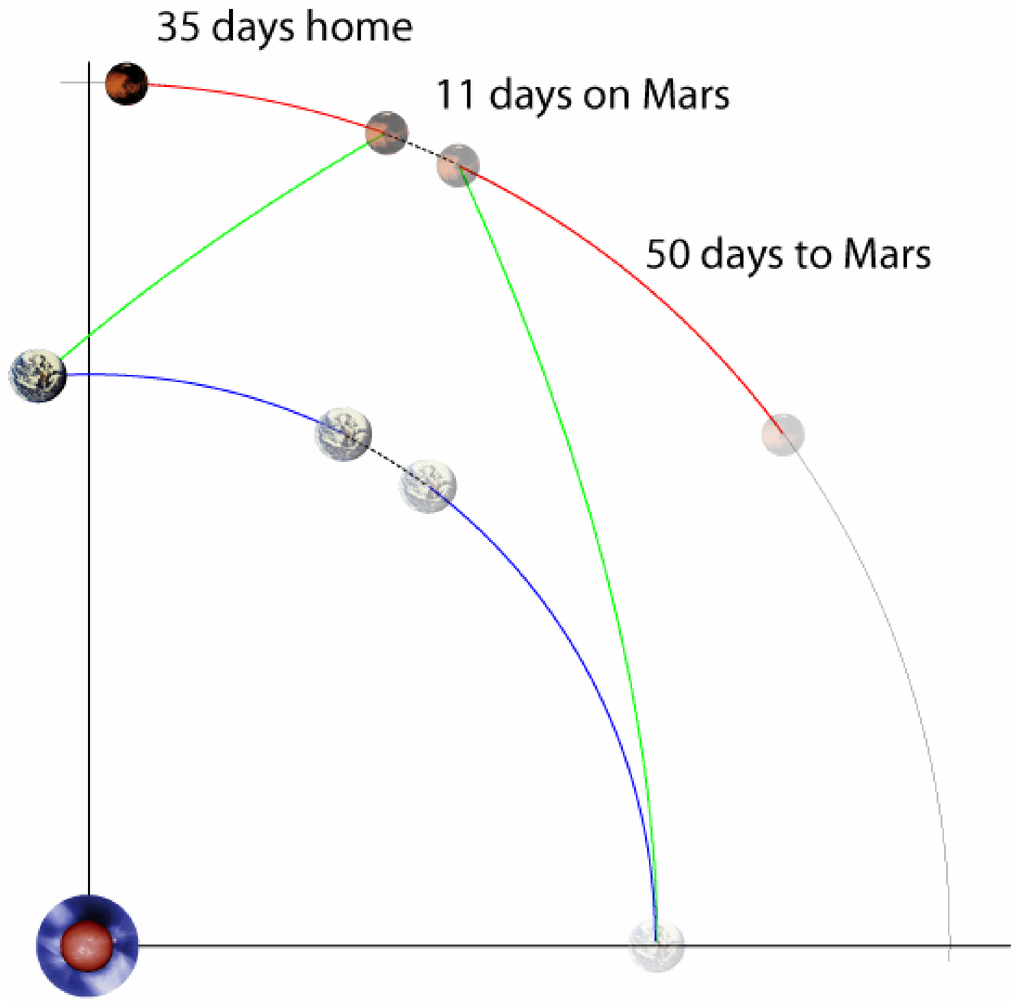
Total Trip Time: 50 Day - Arrive at Mars



Total Trip Time: 61 Day - Leave Mars



Total Trip Time: 96 Day - Arrive Eath

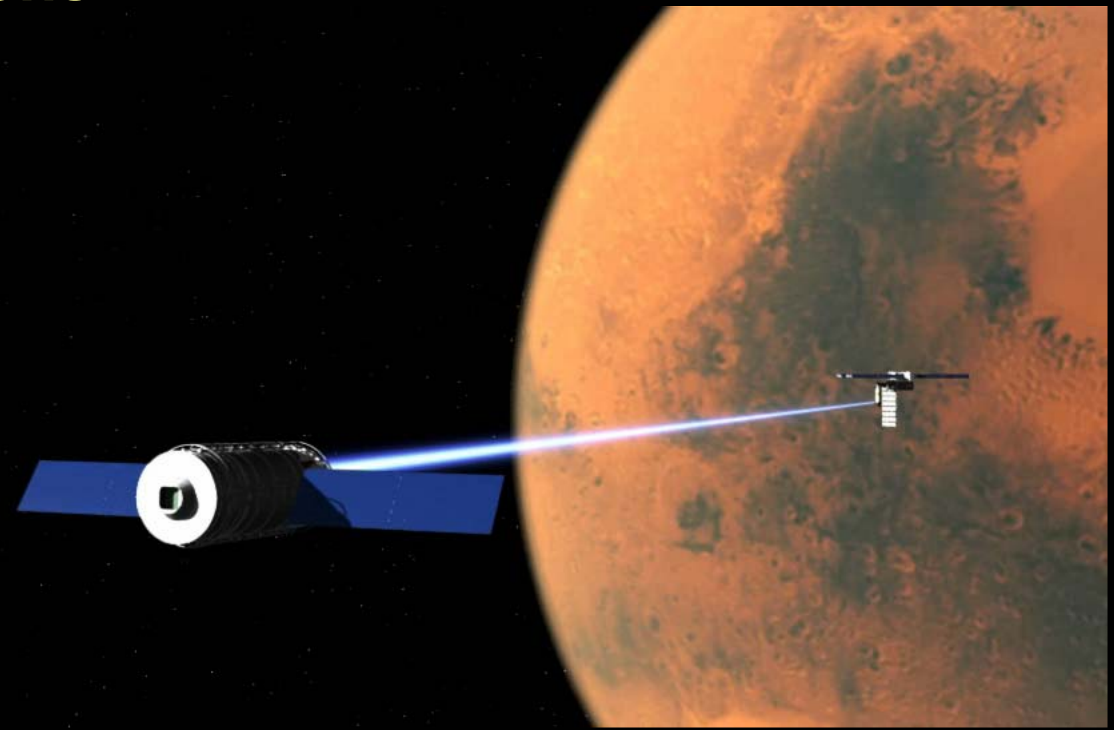


MagBeam:

Model/lab results demonstrating performance

Beamed Plasma System ⇨ Fast Missions

Reusable system & eliminates large power units for each new mission ⇨ cost effective solution for multiple missions



Roadmap:

Phase II –

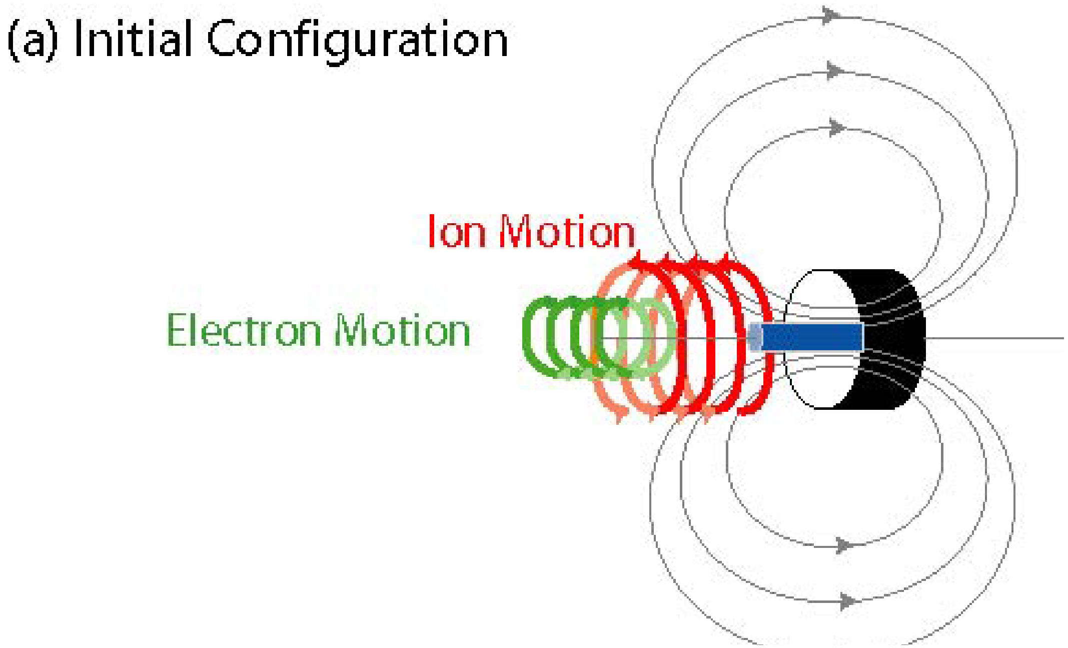
- Demonstrate beam coherence in expanded UW chamber (to 9 ft)
- Comparative model/lab studies in larger chambers (help from NASA centers to perform studies to 30 ft)
- Demonstrate performance of higher power thrusters and develop scaling laws for large systems

Further work

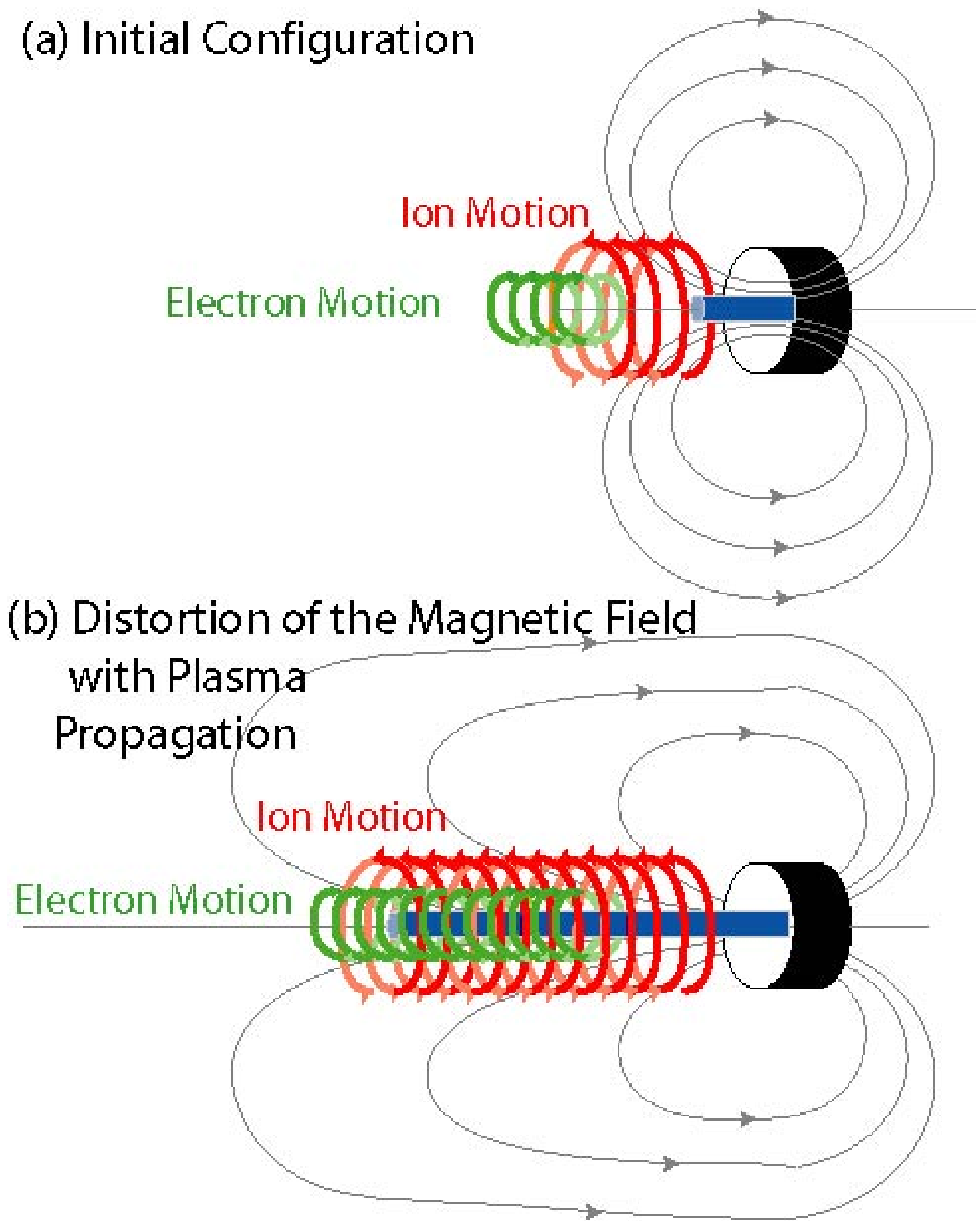
– demonstrate km range using sounding rocket experiment

- orbital demonstration

Still Finds the Target Even if Deflector Misaligned



Differential motion between the ions and electrons are generated currents and electric fields such that the magnetic field in which the plasma is born stays with the plasma.



Magnetic Field is essentially the transmission wire of space for plasma and power