Plasma Technologies for Aerospace Applications

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Outline

- ***Plasmas***
- ***Main Thrust for Plasma Research: Fusion Energy***
- ***Aerospace Applications***
- ***Research at UHCL***

Plasmas

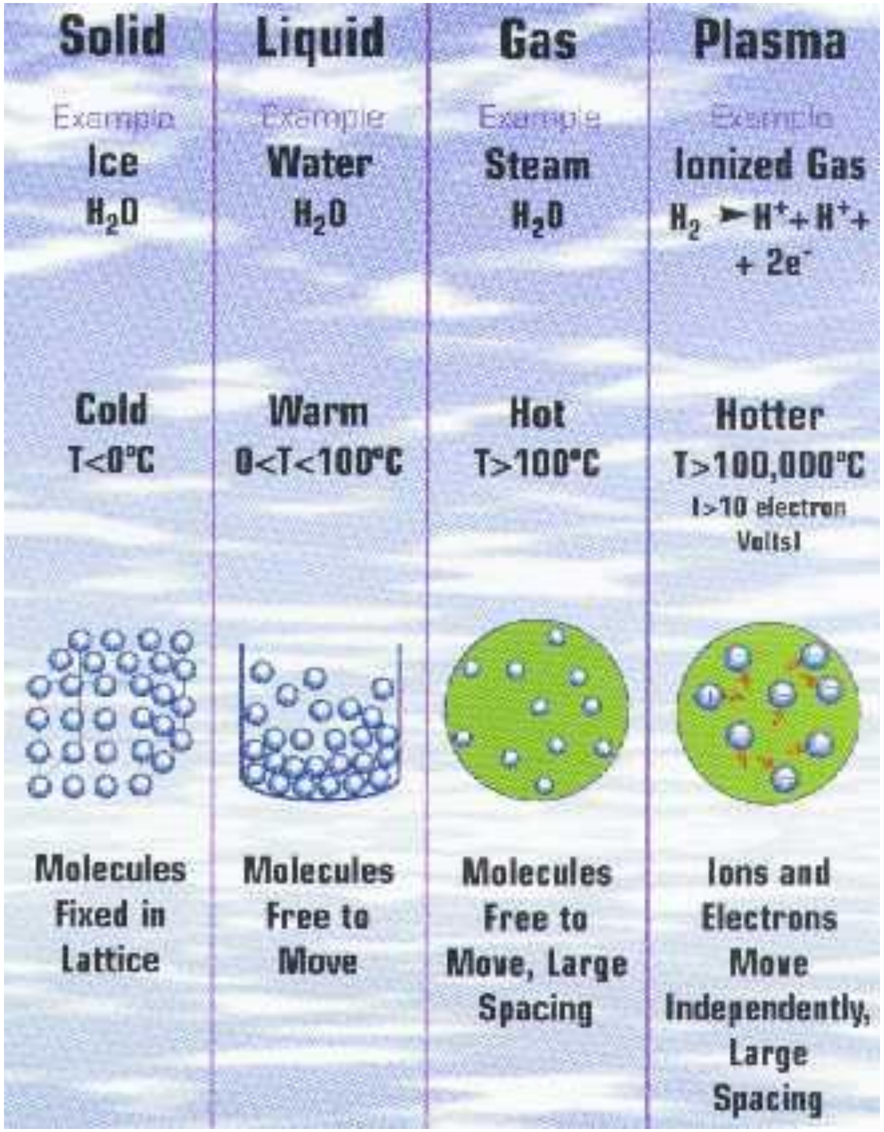
The “Fourth State” of the Matter

- The matter in “ordinary” conditions presents itself in three fundamental states of aggregation: solid, liquid and gas.
- These different states are characterized by different levels of bonding among the molecules.
- In general, by increasing the temperature (=average molecular kinetic energy) a phase transition occurs, from solid, to liquid, to gas.
- A further increase of temperature increases the collisional rate and then the degree of ionization of the gas.

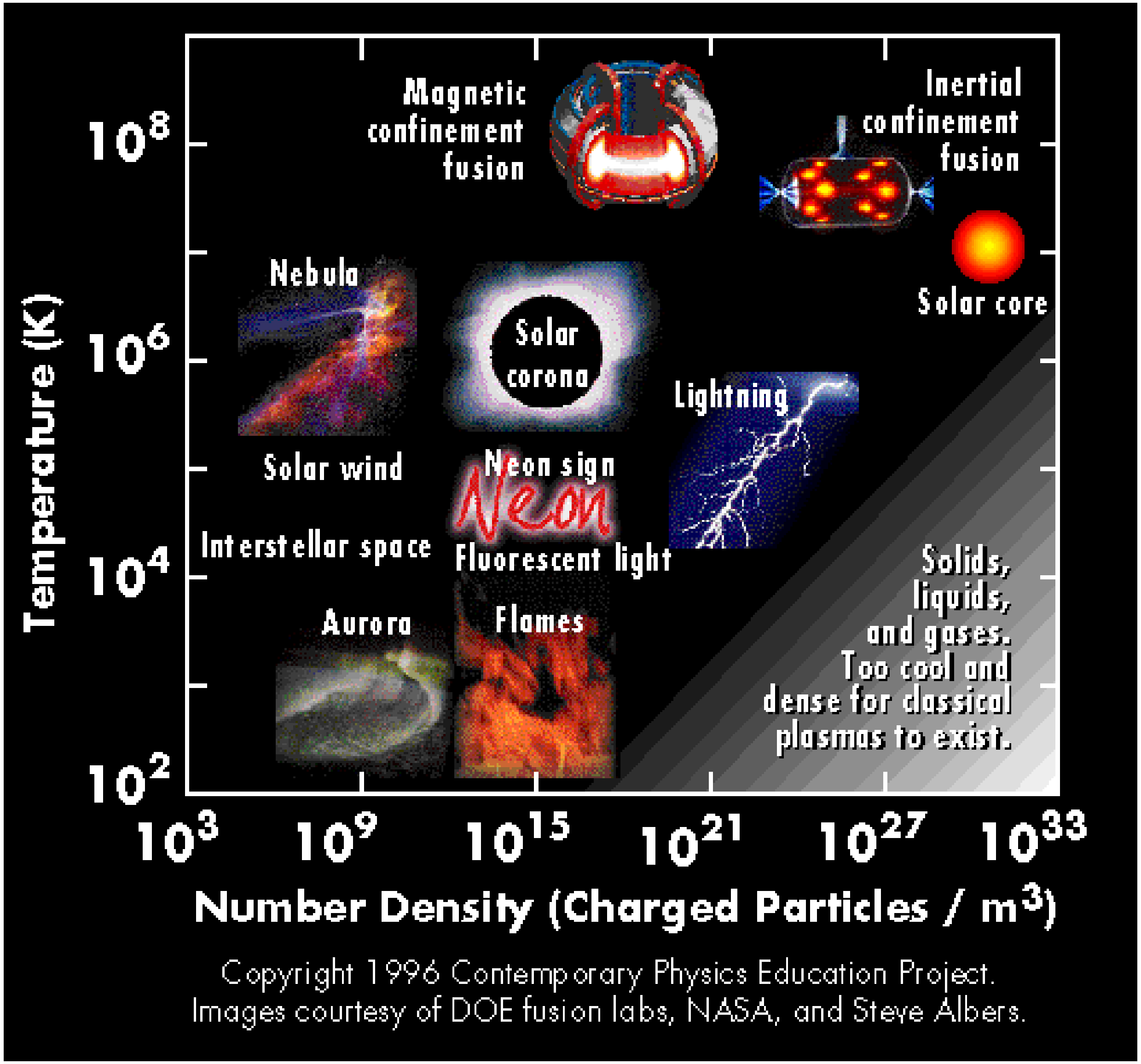
The “Fourth State” of the Matter (II)

- The ionized gas could then become a plasma if the proper conditions for density, temperature and characteristic length are met (quasineutrality, collective behavior).
- The plasma state does not exhibit a different state of aggregation but it is characterized by a different behavior when subjected to electromagnetic fields.

The "Fourth State" of the Matter (III)



Plasmas (V)



Magnetic confinement fusion
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^2
10^4
10^6
10^8
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)
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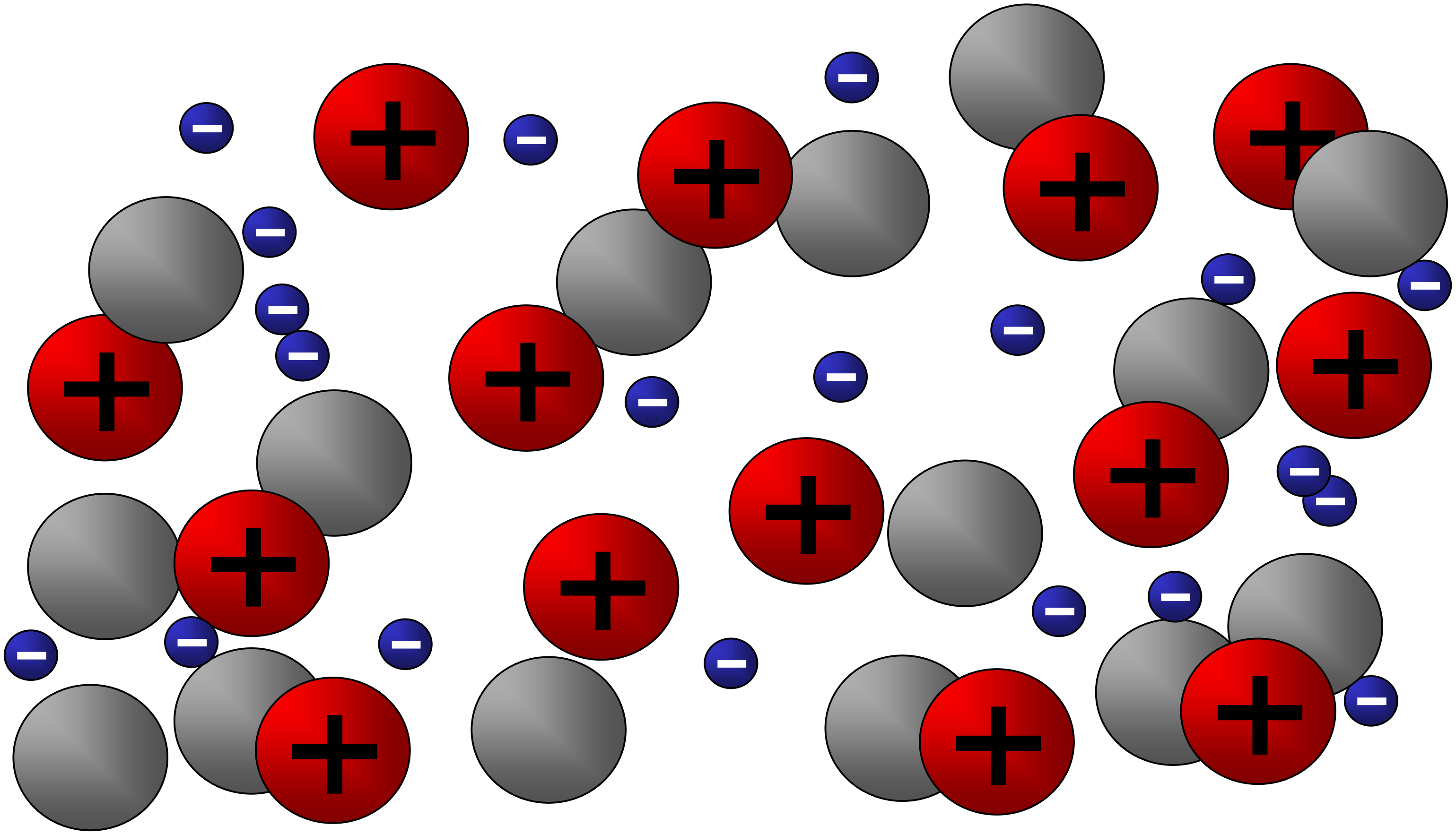
Images courtesy of DOE fusion labs, NASA, and Steve Albers.

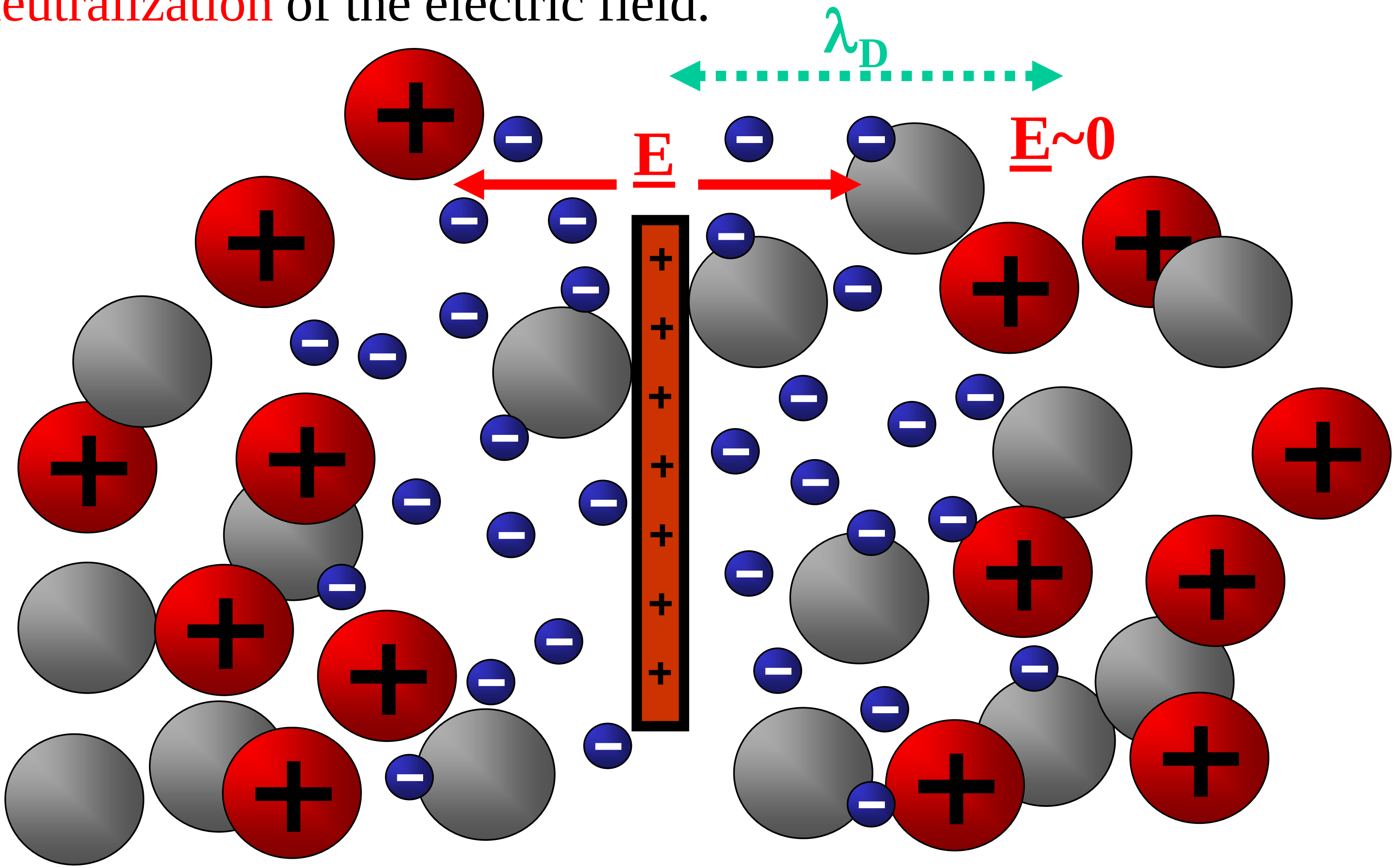
Debye Shielding

- An ionized gas has a certain amount of free charges that can move in presence of electric forces



Debye Shielding (II)

- Shielding effect: the free charges move towards a perturbing charge to produce, at a large enough distance λ_D, (almost) a neutralization of the electric field.



Debye Shielding (IV)

- The quantity

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T}{n q_e^2}}$$

  is called the (electron) Debye length of the plasma

- The Debye length is a measure of the effective shielding length beyond which the electron motions are shielding charge density fluctuations in the plasma

Debye Shielding (IV)

- Typical values of the Debye Length under different conditions:

	n [m^{-3}]	T[eV]	Debye Length [m]
Interstellar	10^6	10^{-1}	1
Solar Wind	10^7	10	10
Solar Corona	10^{12}	10^2	10^{-1}
Solar atmosphere	10^{20}	1	10^{-6}
Magnetosphere	10^7	10^3	10^2
Ionosphere	10^{12}	10^{-1}	10^{-3}

From Ionized Gas to Plasma

- An ionized gas is characterized, in general, by a mixture of neutrals, (positive) ions and electrons.
- For a gas in thermal equilibrium the Saha equation gives the expected amount of ionization:

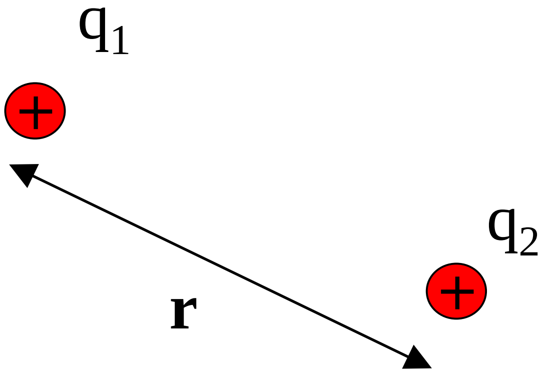
$$n_i^2 \cong 2.4 \cdot 10^{21} n_n T^{3/2} e^{-U_i / k_B T}$$

- The Saha equation describes an equilibrium situation between ionization and (ion-electron) recombination rates.

From Ionized Gas to Plasma (II)

- (Long range) Coulomb force between two charged particles q_1 and q_2 at distance r:

$$F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$



From Ionized Gas to Plasma (III)

- (Short range) force between two neutral atoms (*e.g.* from Lenard-Jones interatomic potential model)

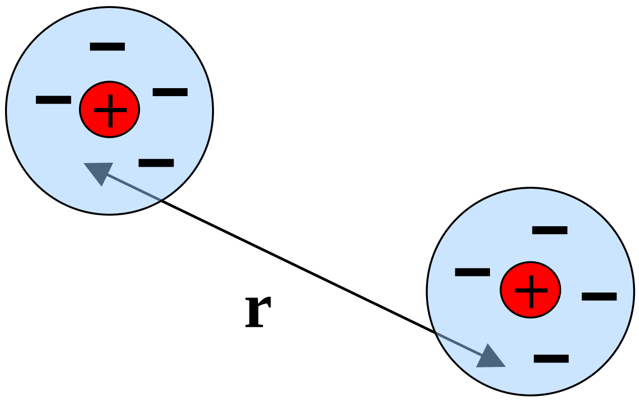
$$U = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$

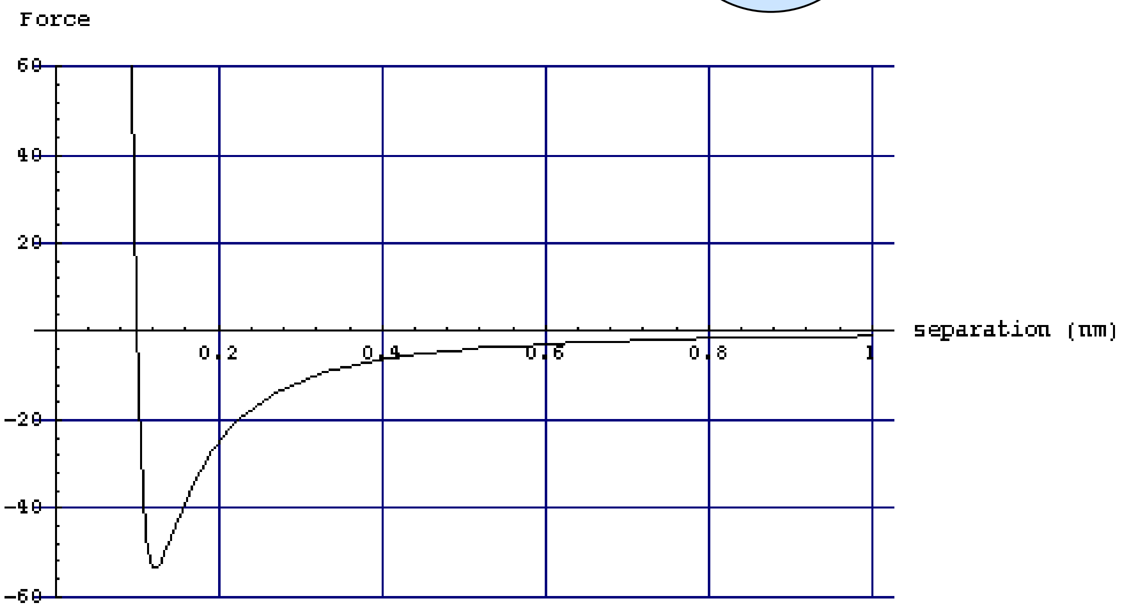
$$\mathbf{F} = -\nabla \mathbf{U}$$

$$\mathbf{F} = 4\varepsilon\left[12\left(\frac{\sigma}{r}\right)^{12} - 6\left(\frac{\sigma}{r}\right)^{6}\right]\frac{\hat{\mathbf{r}}}{r^2}$$

repulsive

attractive





From Ionized Gas to Plasma

- If L is the typical dimension of the ionized gas, a condition for an ionized gas to be "quasineutral" is:

$$\lambda_D << L$$

- The "collective effects" are dominant in an ionized gas if the number of particles in a volume of characteristic length equal to the Debye length (Debye sphere) is large:

$$N_D = n\frac{4}{3}\pi\lambda_D^3 >> 1$$

- N_D is called "plasma parameter"

From Ionized Gas to Plasma (II)

- A plasma is an ionized gas that is "quasineutral" and is dominated by "collective effects" is called a plasma:

$$\lambda_D << L$$

$$N_D = n\frac{4}{3}\pi\lambda_D^3 >> 1$$

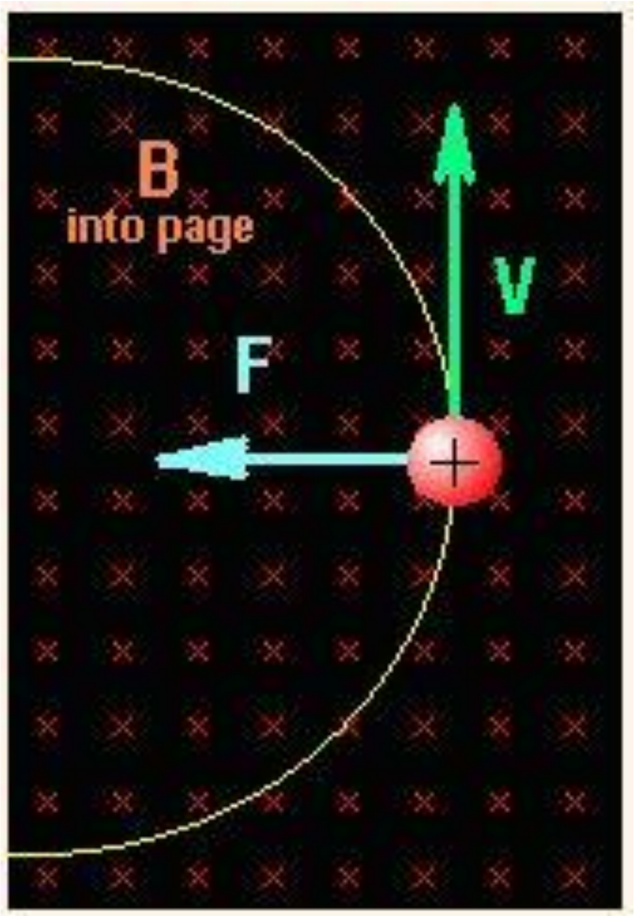
From Ionized Gas to Plasma (III)

- An ionized gas is not necessarily a plasma
- An ionized gas can exhibit a "collective behavior" when the long-range electric forces are sufficient to maintain overall neutrality
- An ionized gas could appear quasineutral if the charge density fluctuations are contained in a limited region of space
- A plasma is an ionized gas that exhibits a collective behavior and is quasineutral

Plasma Confinement: the Lorentz Force

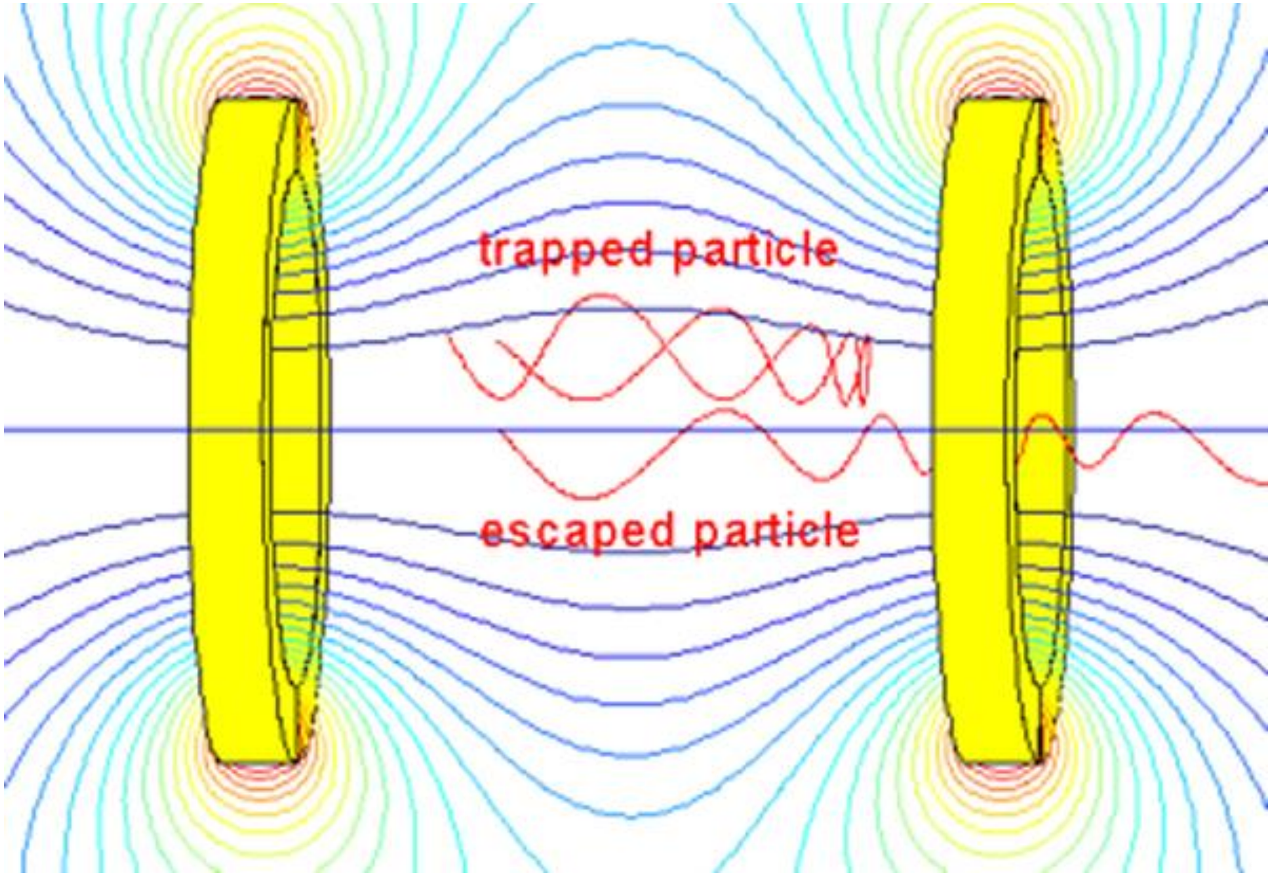
Force on a charged particle in a magnetic field

$\underline{\mathbf{F}} = q\,\underline{\mathbf{v}} \times \underline{\mathbf{B}}$



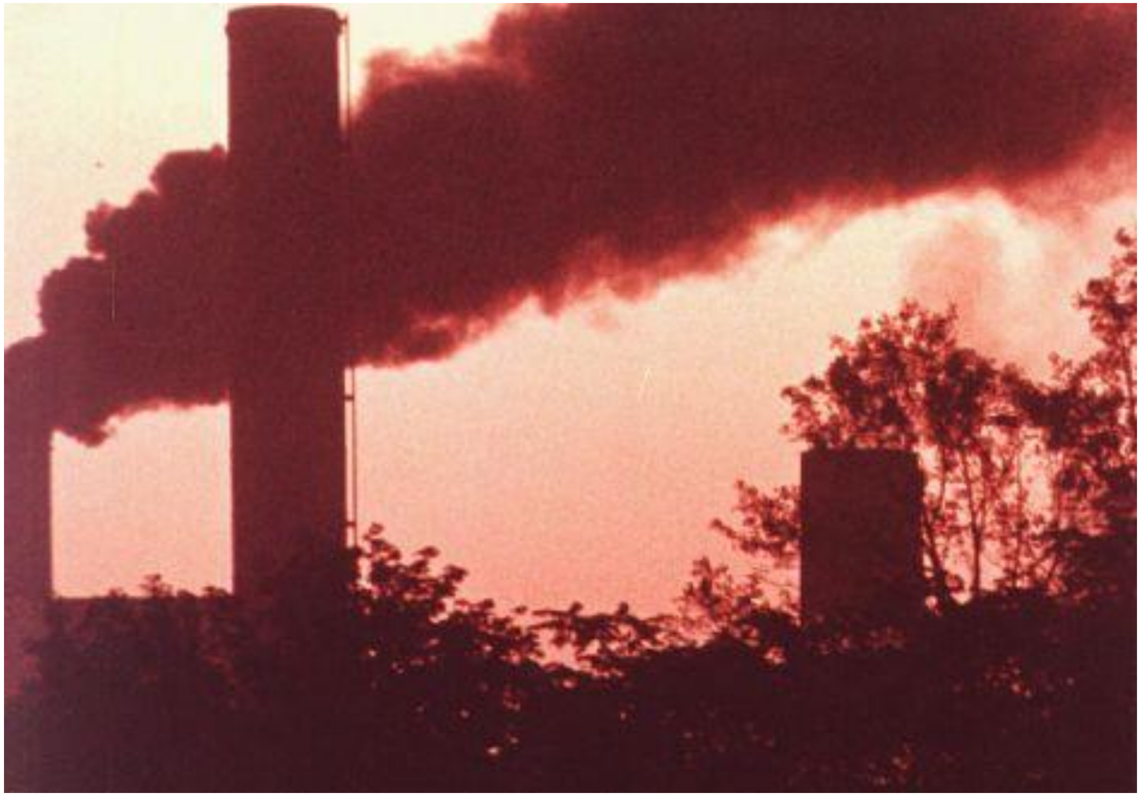
Plasma Confinement: the Magnetic Mirror

Magnetic Mirror: charged particles (protons and electrons) move in helical orbits at their cyclotron frequency

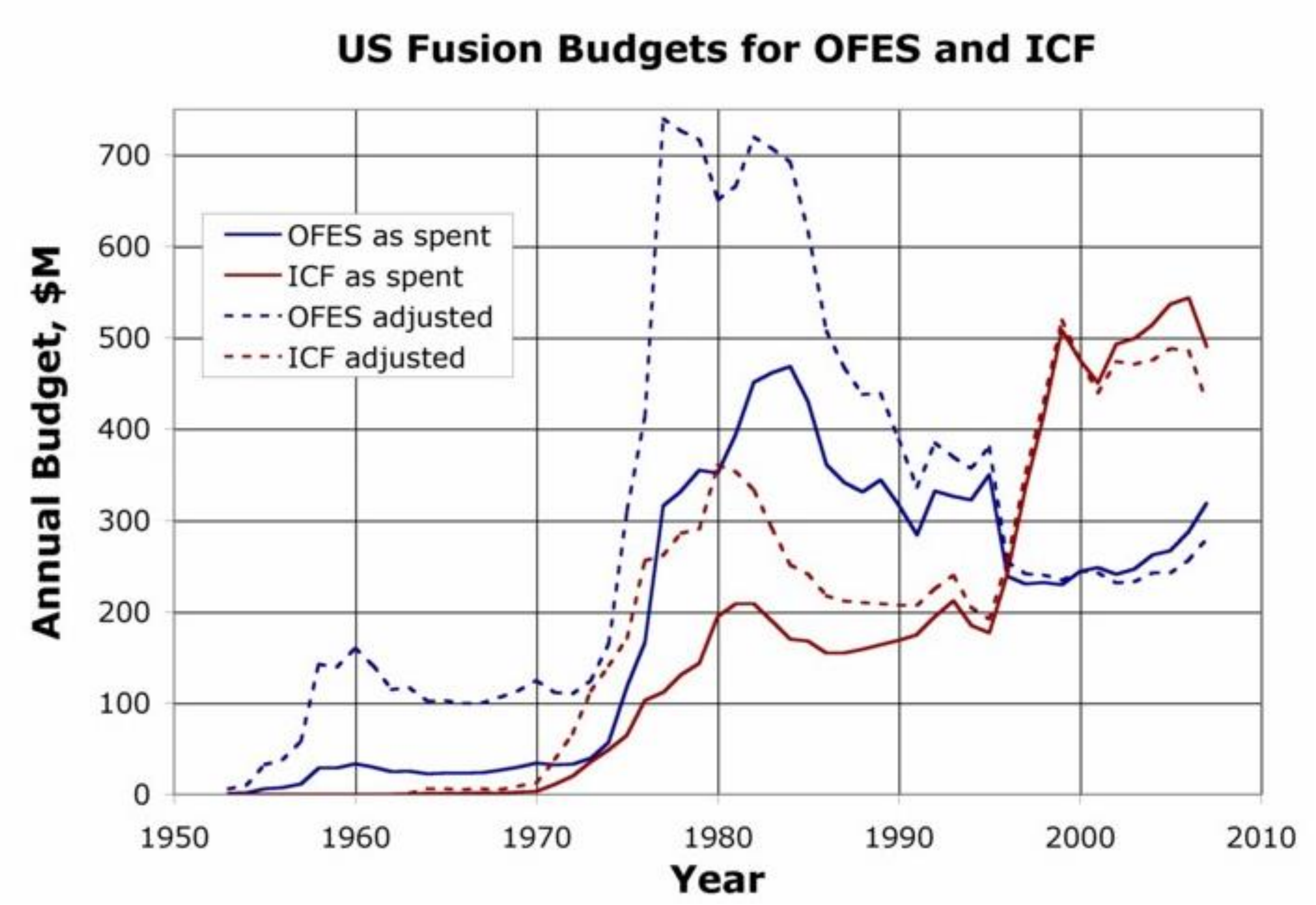


Main Thrust for Plasma Research: Fusion Energy

The Bad Stuff

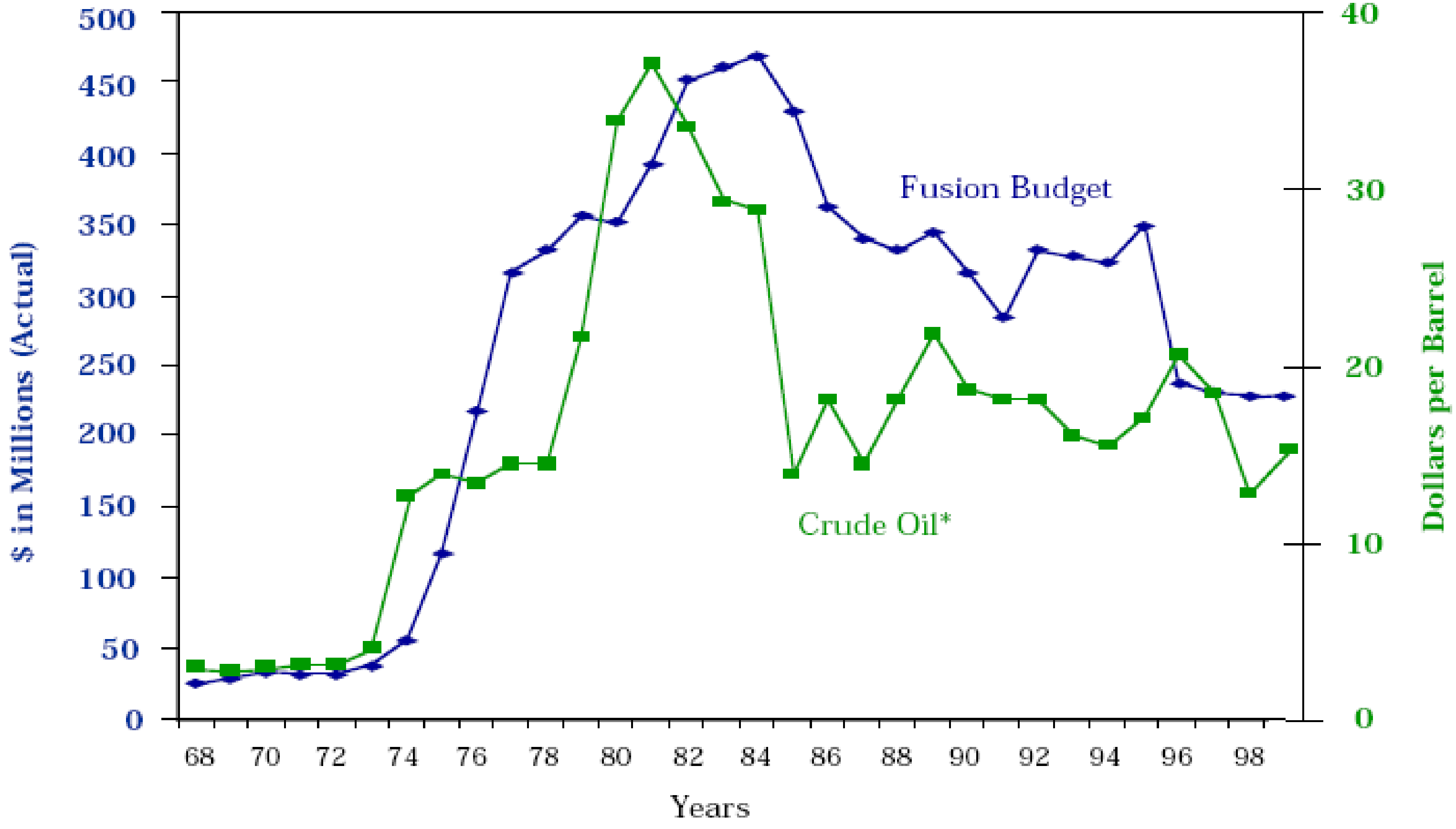


The Bad Stuff



[Ref: Fusion Power Associates, http://fusionpower.org]

The Bad Stuff



U.S. Fusion Budget Vs. the Price of Crude Oil

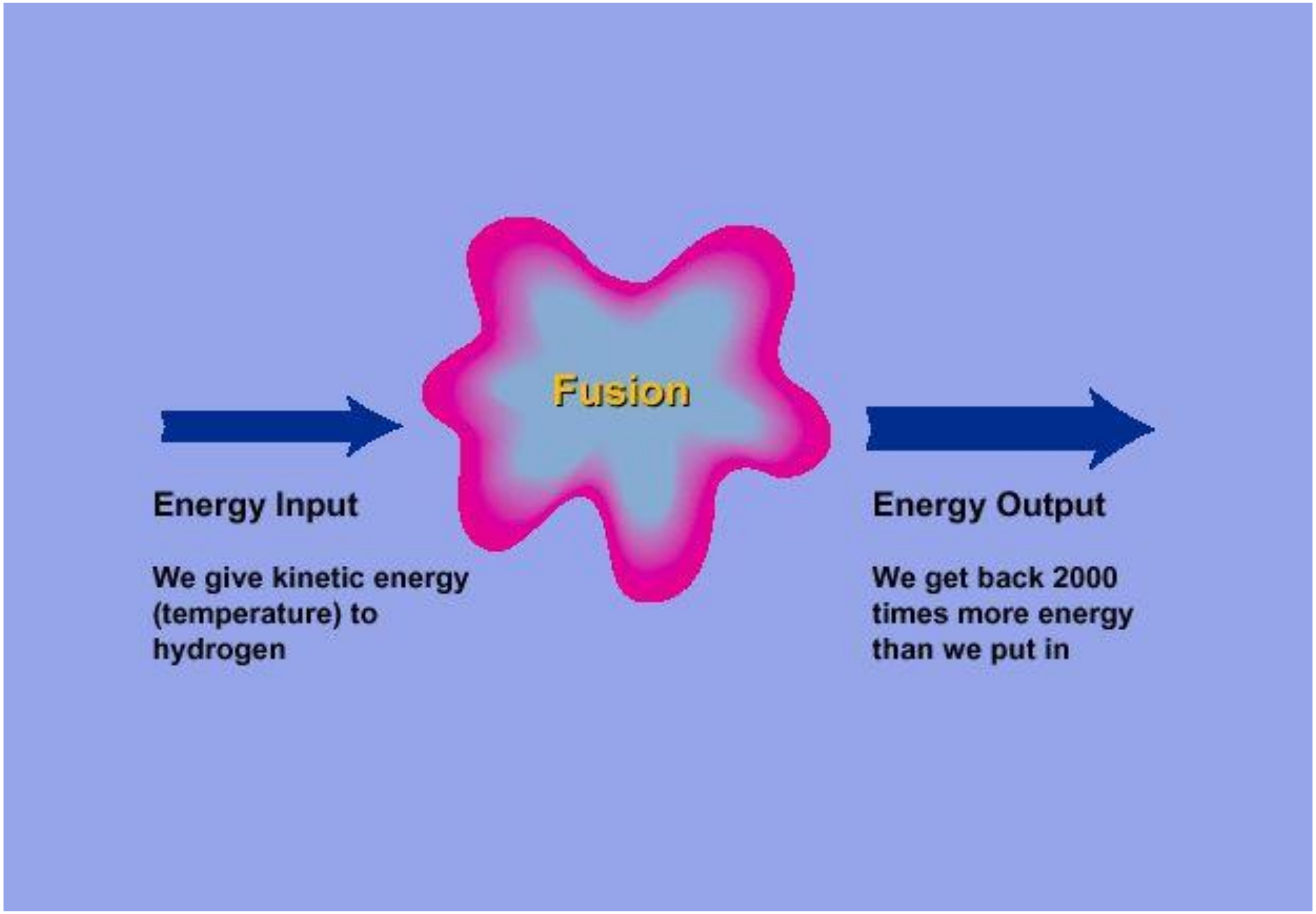
[Ref: US DoE, 1999]

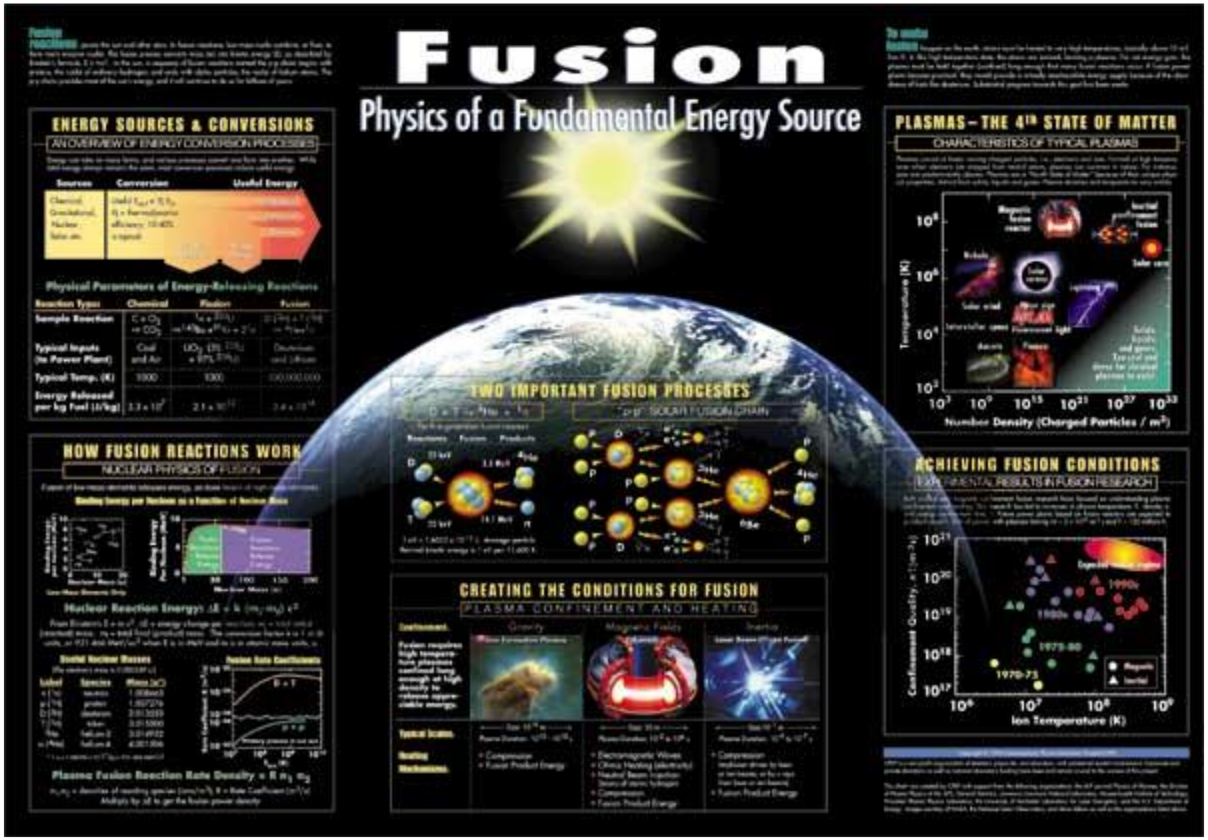
The Bad Stuff

World Magnetic Fusion Effort (1999)

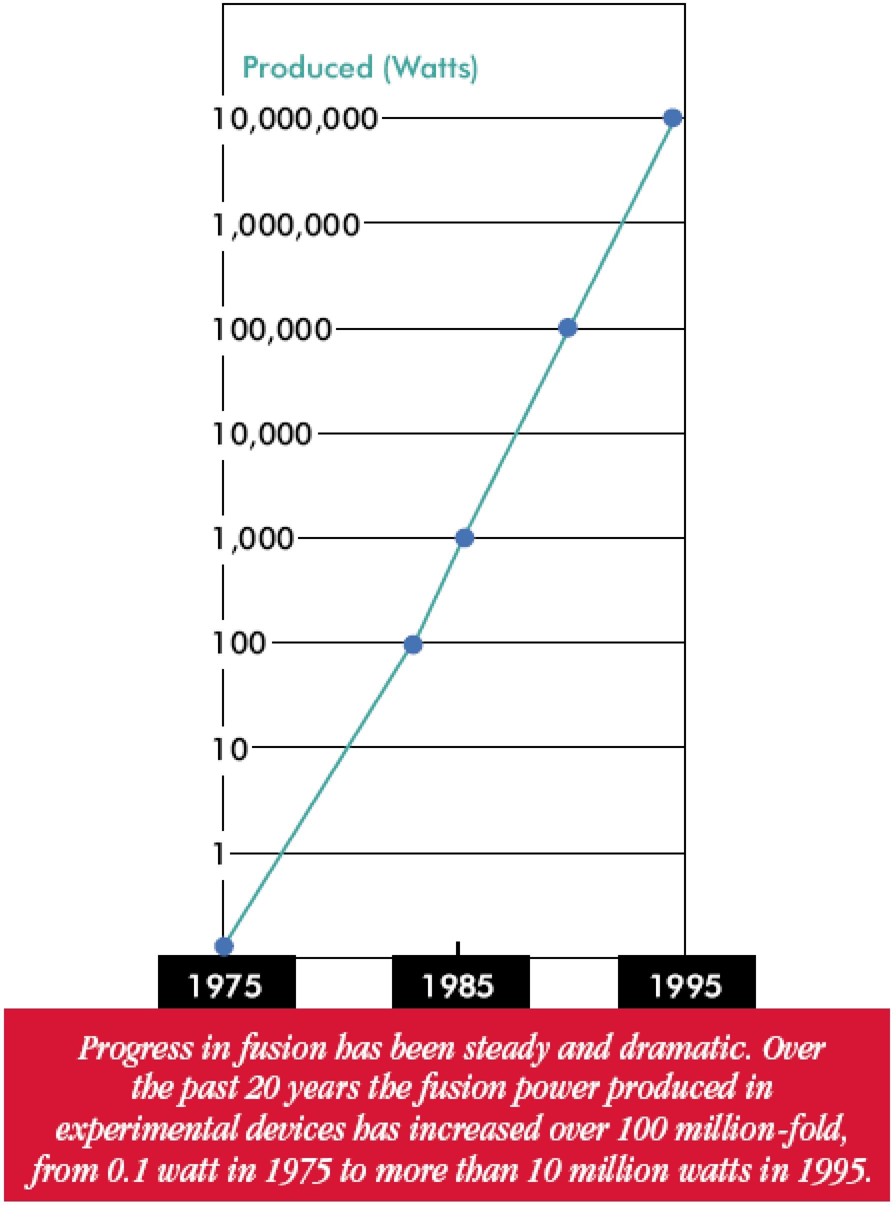
[Ref: US DoE, 1999]

The Fusion Energy Hope



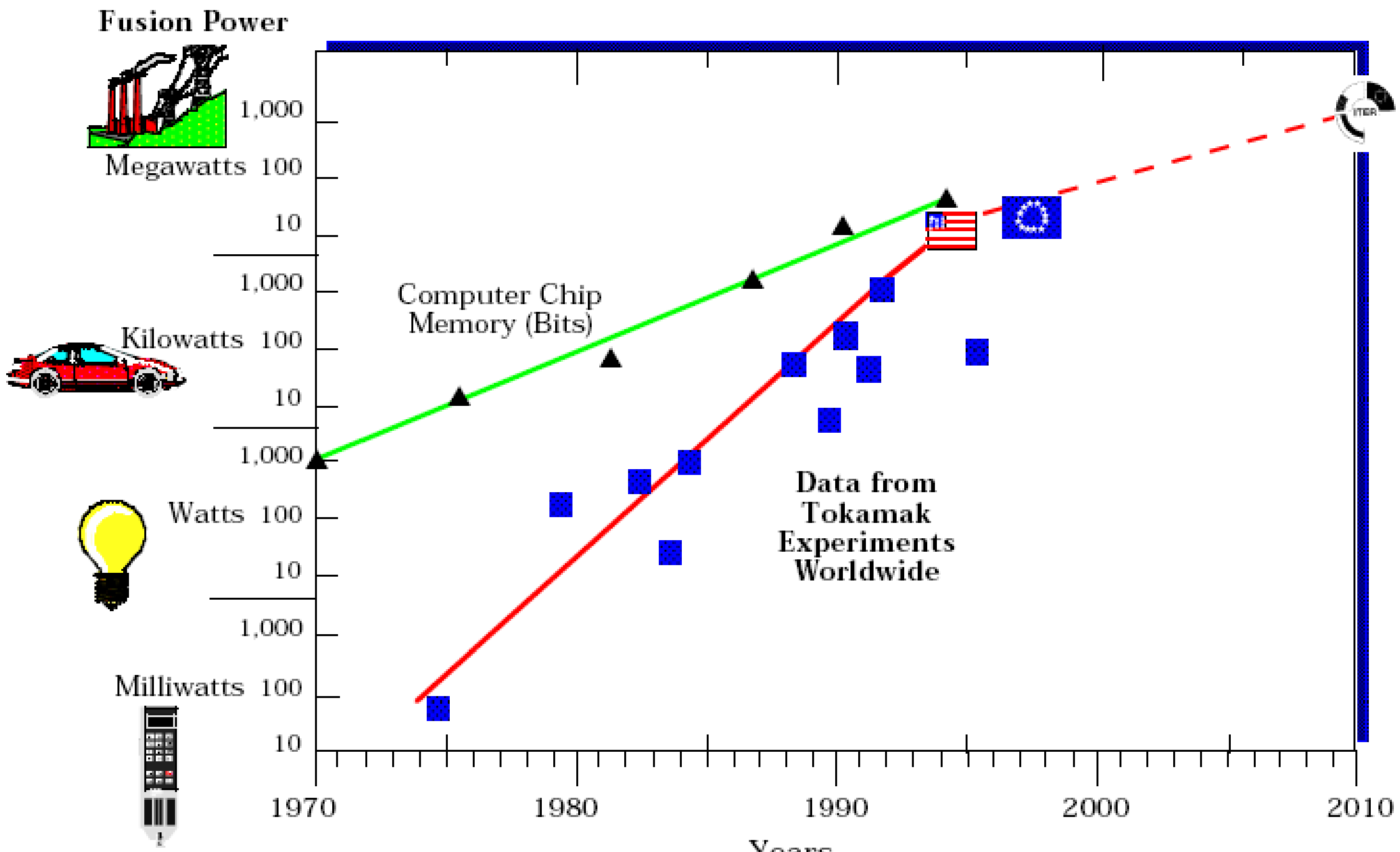

Fusion
Physics of a Fundamental Energy Source
ENERGY SOURCES & CONVERSIONS
AN OVERVIEW OF ENERGY CONVERSION PROCESSES
HOW FUSION REACTIONS WORK
NUCLEAR PHYSICS OF FUSION
TWO IMPORTANT FUSION PROCESSES
CREATING THE CONDITIONS FOR FUSION
PLASMA CONFINEMENT AND HEATING
PLASMAS – THE 4TH STATE OF MATTER
CHARACTERISTICS OF TYPICAL PLASMAS
ACHIEVING FUSION CONDITIONS
EXPERIMENTAL RESULTS IN FUSION RESEARCH

The Fusion Energy Hope



[Ref: Fusion Power Associates, http://fusionpower.org]

The Fusion Energy Hope



[Ref: US DoE, 1999]

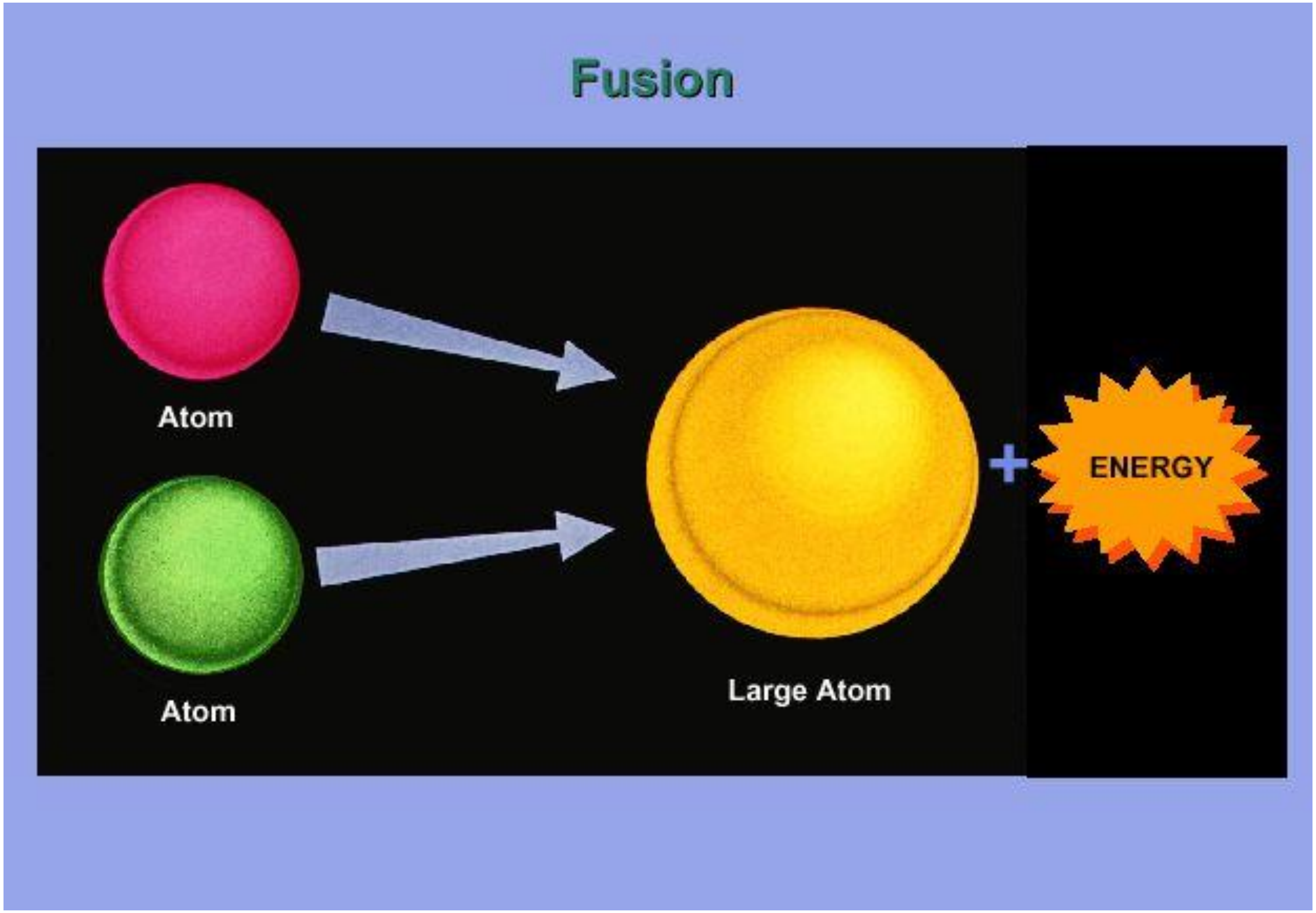
The Advantages of Fusion Energy

Reduced Waste Products

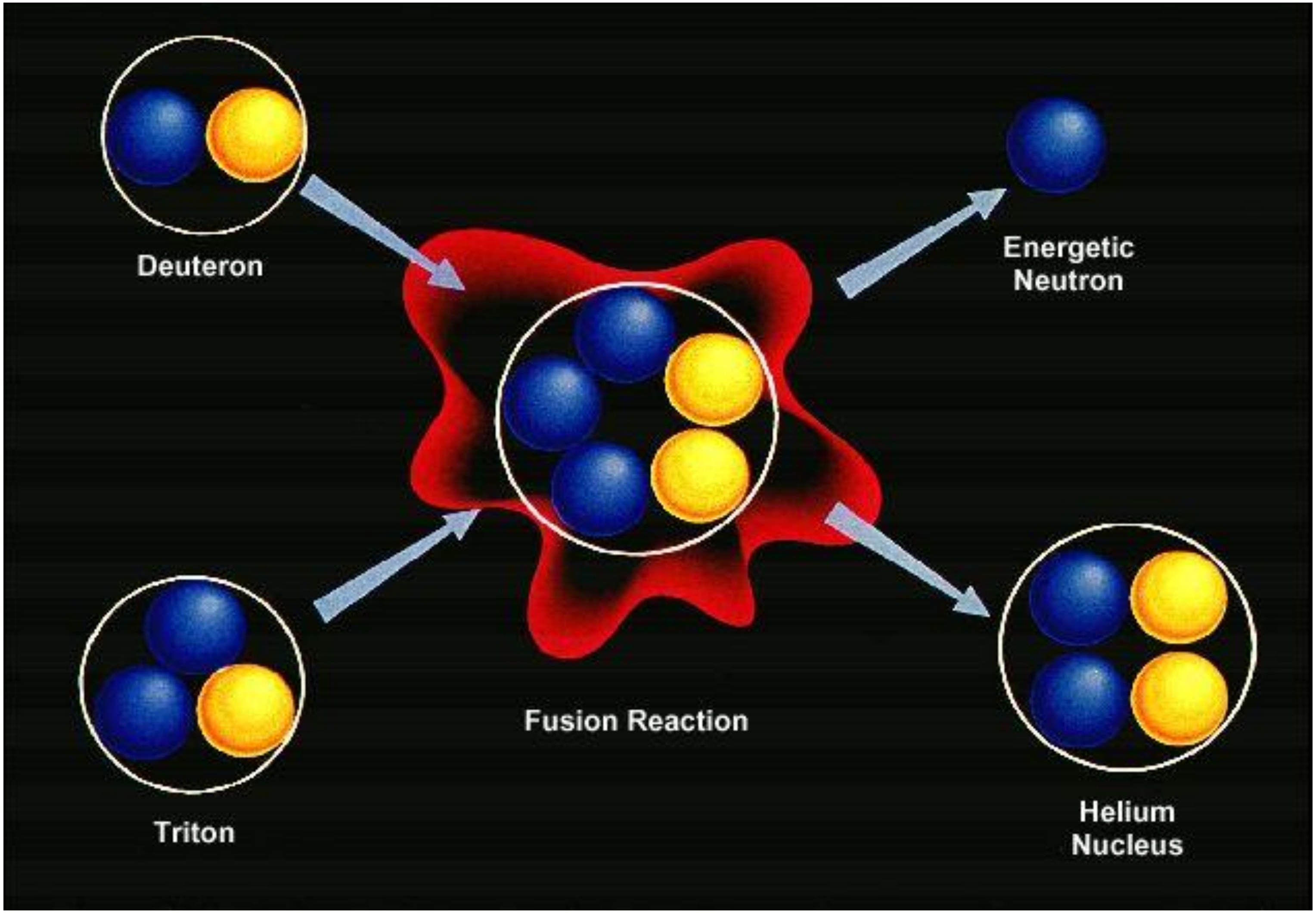
Power Source	Total Waste (cubic meters)	High-Level RAD Waste
Coal	10,000 (ashes)	0
Fission	440	120
Fusion:		
Today's Materials	2000	30
Advanced Materials	2000	0

1000 MW(e) Power Plant - 30 year Lifetime

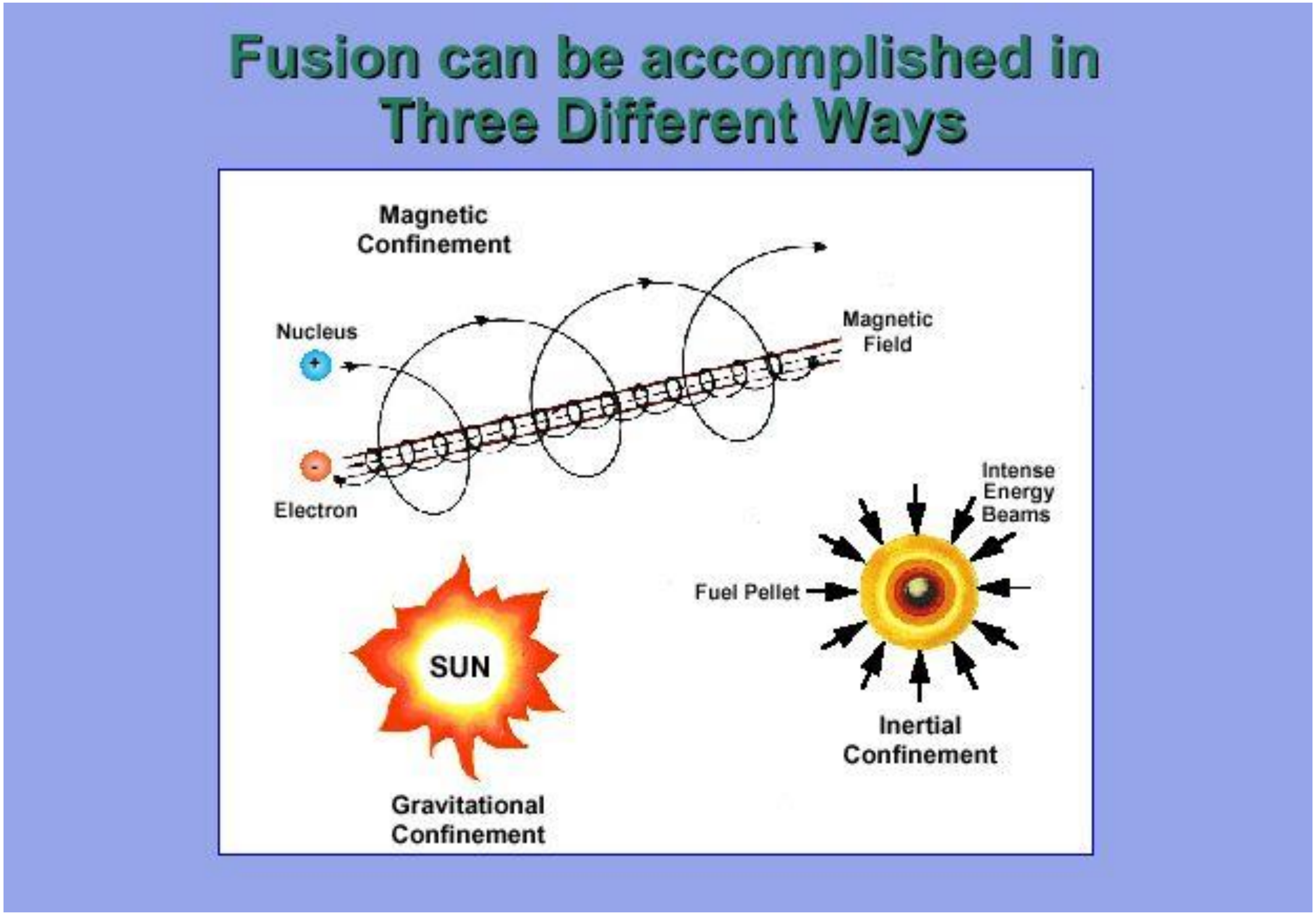
The Fusion Process



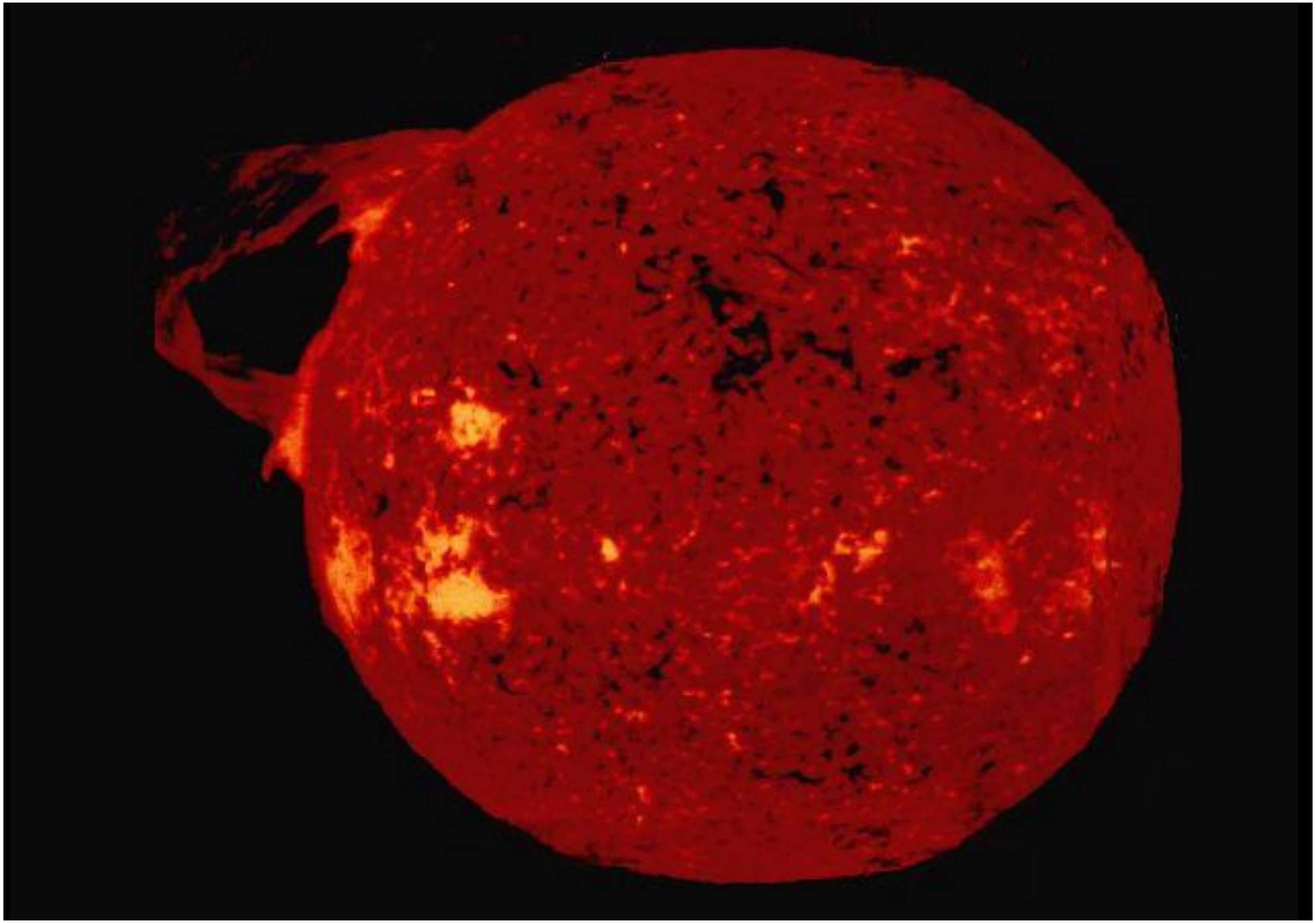
Deuterium Tritium Fusion



How to Achieve Nuclear Fusion



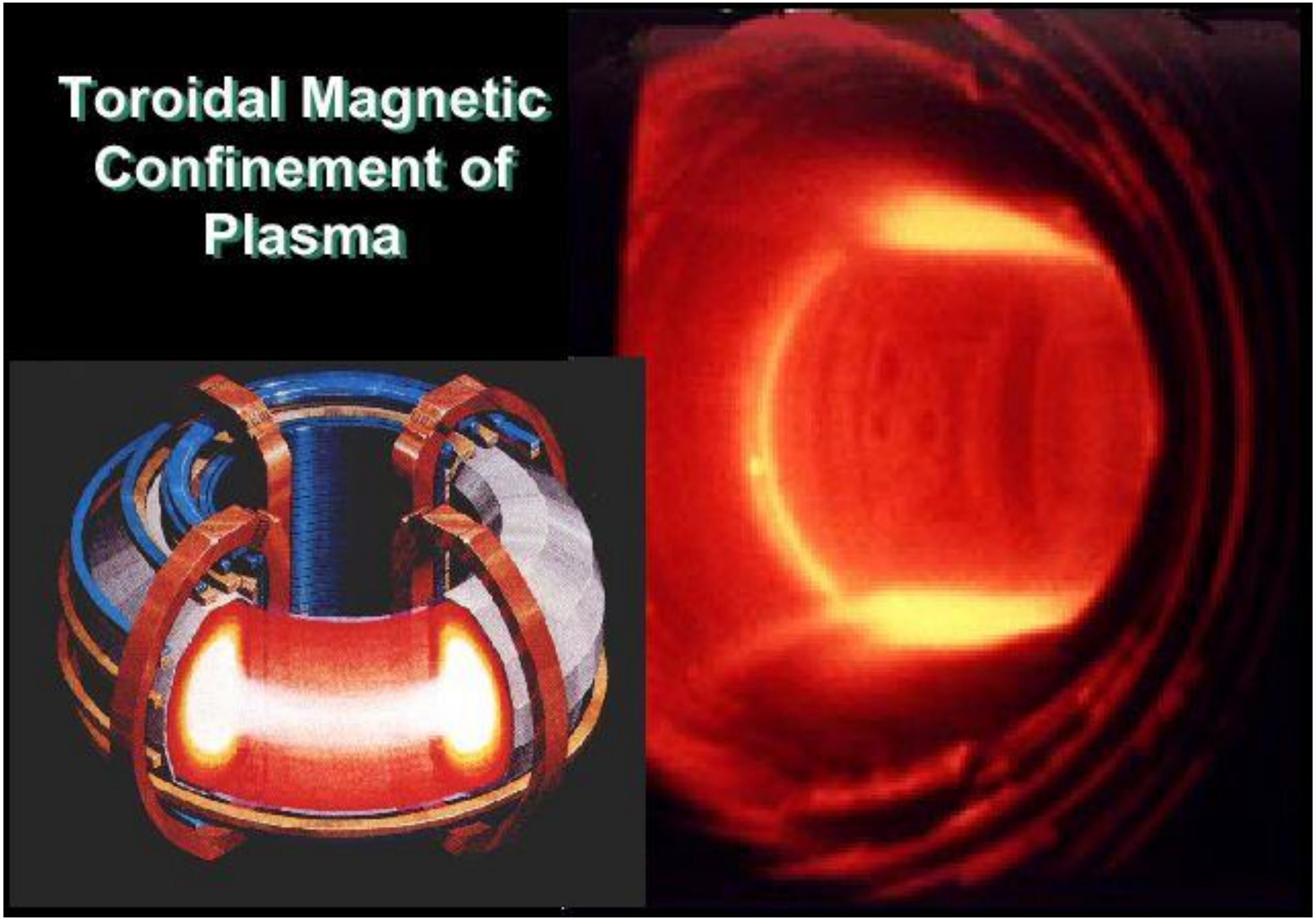
Fusion Works



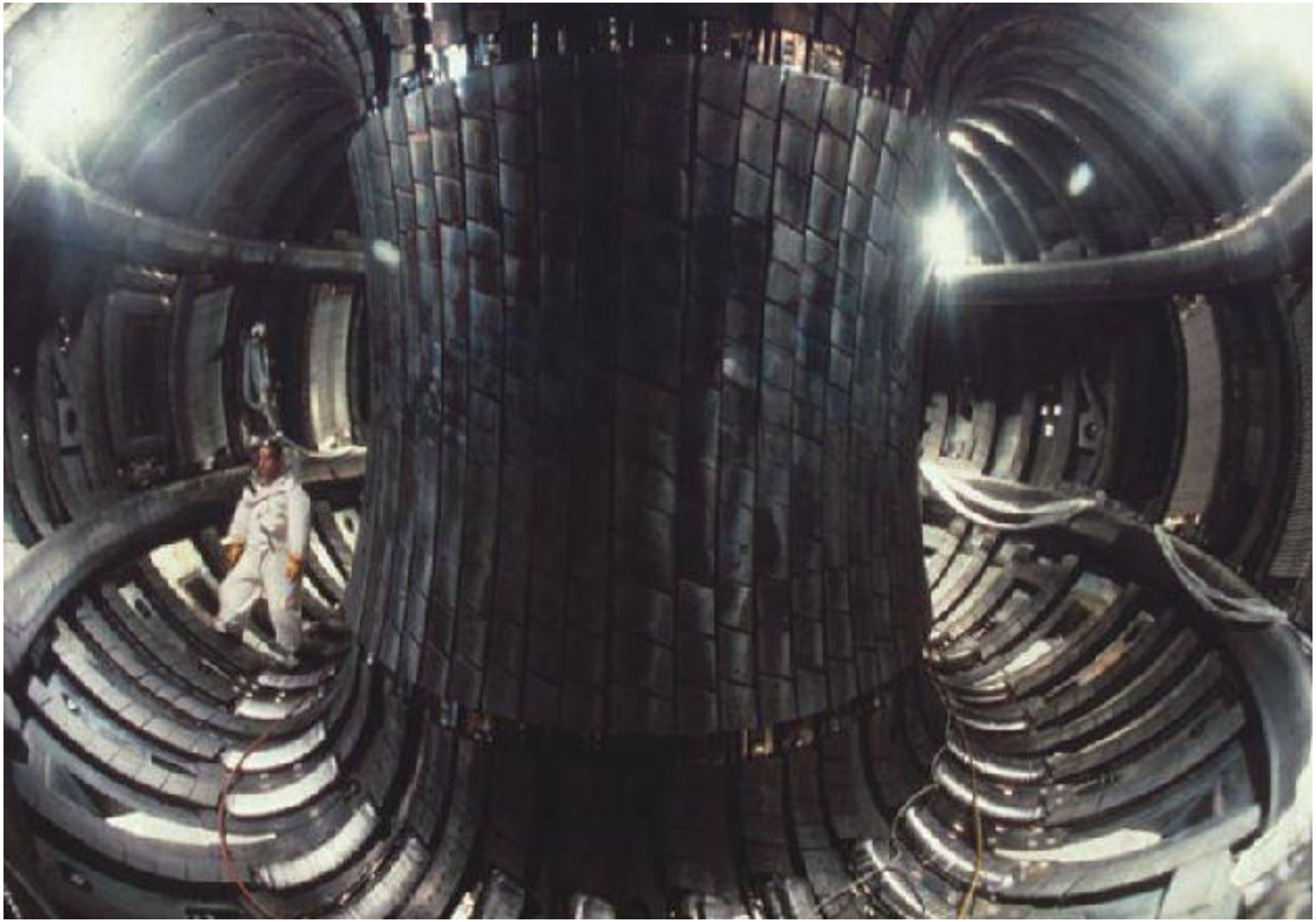
The Sun: a very old fusion reactor

Fusion Works

Controlled Fusion Experiments

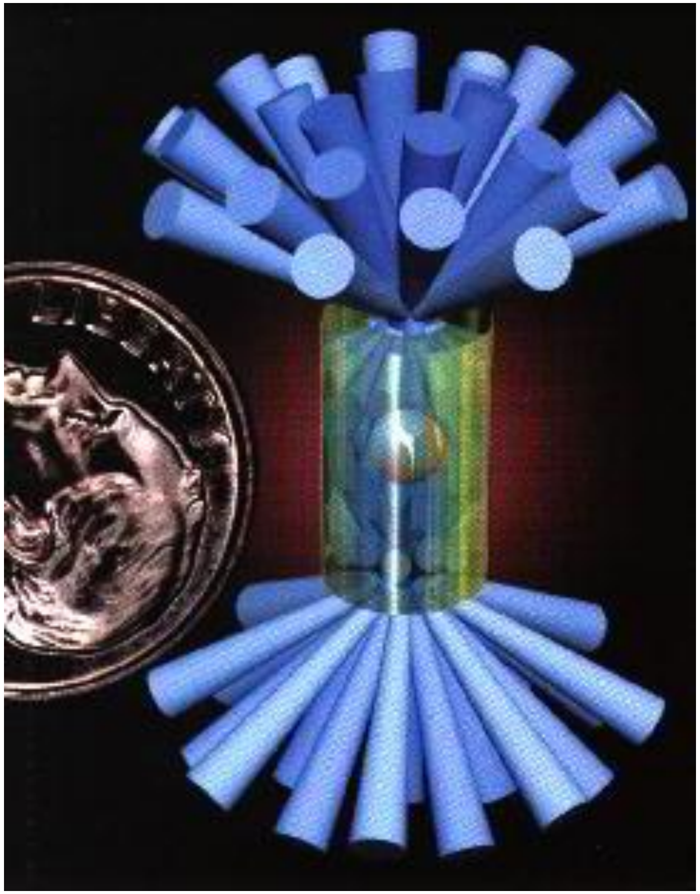


Controlled Fusion Experiments



Joint European Torus (JET), Culham, UK

Controlled Fusion Experiments



Inertial confinement: the 192 laser beams in the National Ignition Facility (LLNL) heat the inside surface of a *hohlraum* with high uniformity

Controlled Fusion Experiments

Inertial confinement: the target chamber in the National Ignition Facility (LLNL)

Aerospace Applications

- *Lightning Protection*
- *Airfoils for Super/Hypersonic Flight*
- *MHD/Chemical Plasma Propulsion*
- *Plasma Spacecraft Interactions*
- *Electric Propulsion*

Lightning Plasma Channel

Lightning Plasma Channel

- Lightning affect spacecrafts:

Apollo 12

Space Shuttle

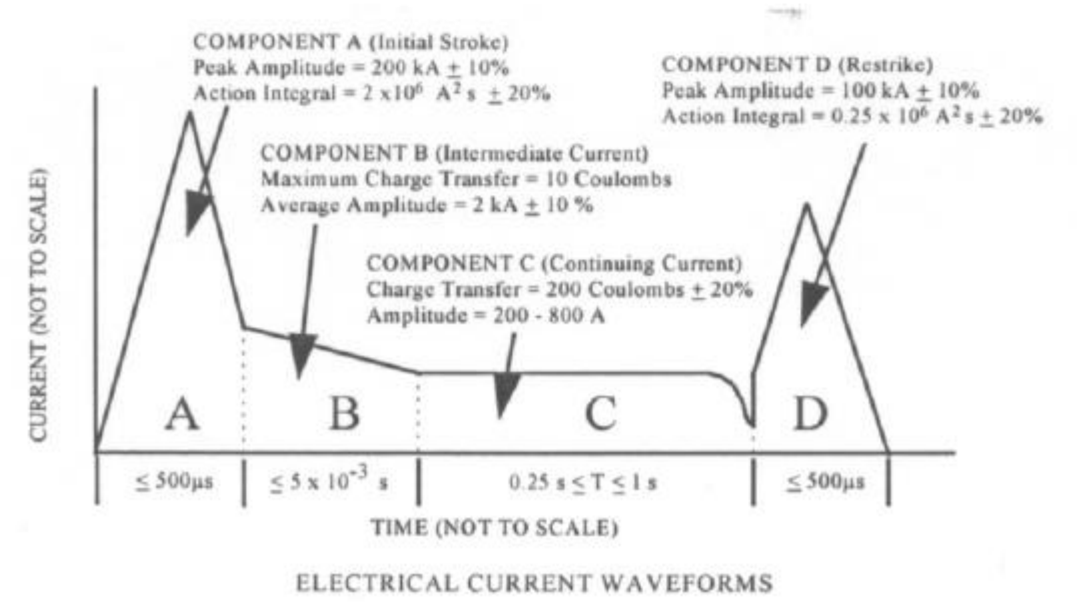
Lightning Plasma Channel (II)

- Objective: improve current fluid dynamic models [1-3] with prescribed current waveforms to a self-consistent plasma channel in a neutral background

[1] S. I. Braginskii, Sov. Phys. JETP **7** , 1068 (1958).

[2] M. N. Plooster, Phys. Fluids **14**, 2111 (1971)

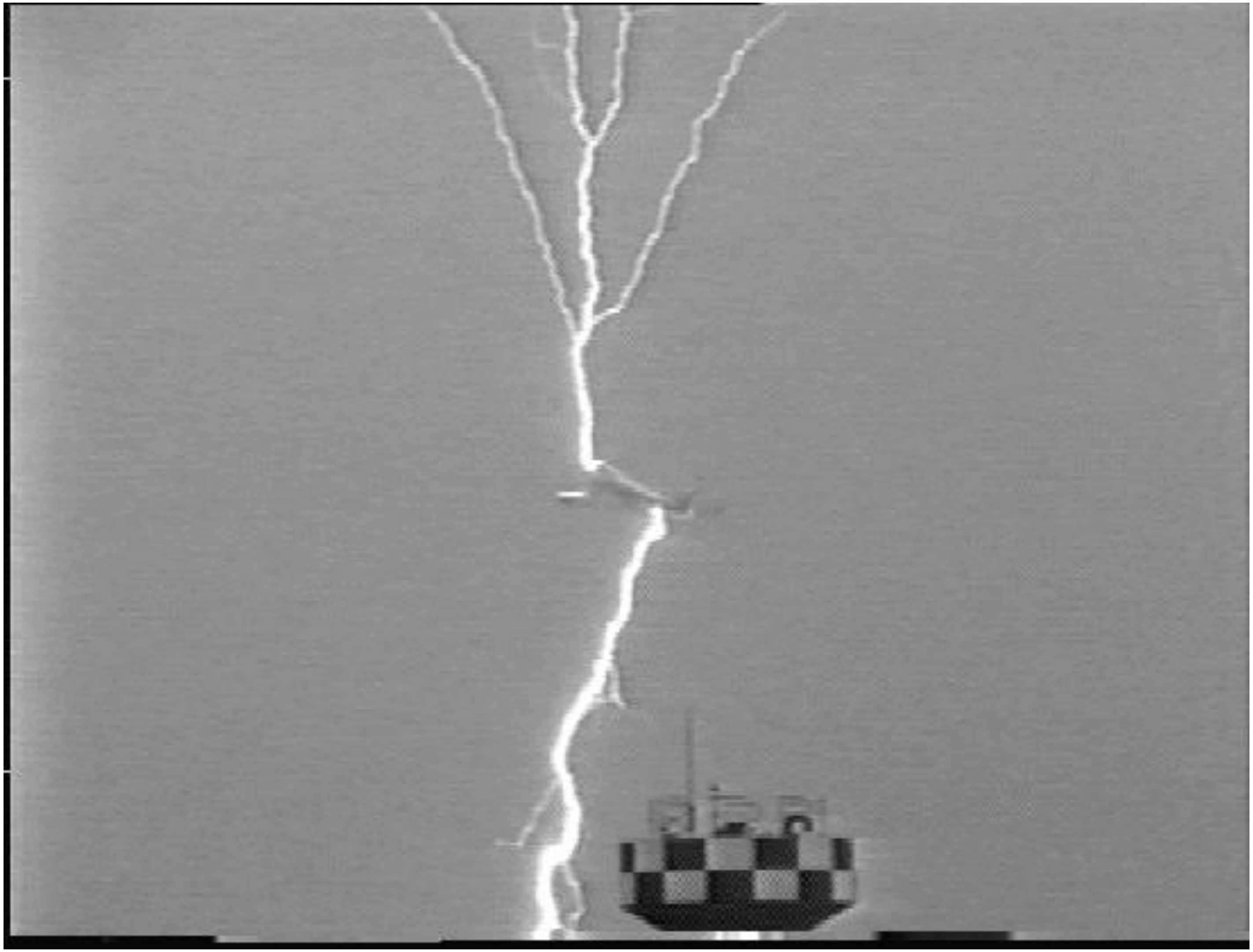
[3] A. H. Paxton, R. L. Gardner, and L. Baker, Phys. Fluids **29**, 2736 (1986)



Idealized lightning current waveform

Lightning Plasma Channel (III)

“Stuff” happens:

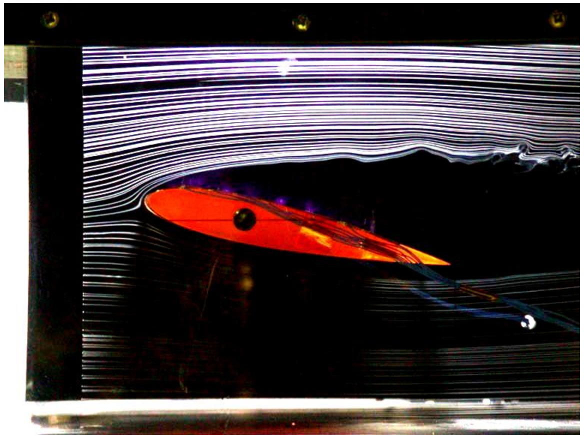


Lightning Plasma Channel (IV)

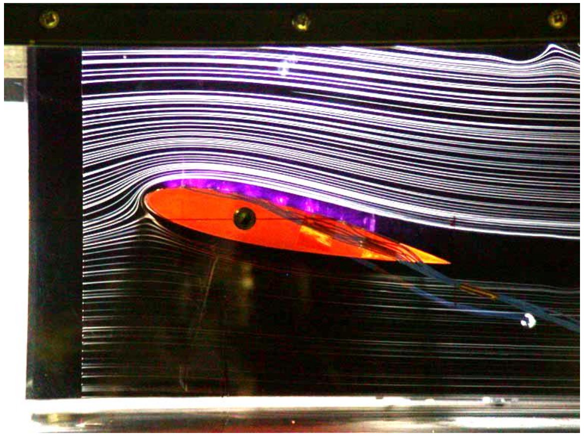
Current Interest: Constellation Program Lightning Protection Design

Plasma Airfoils for Super/Hypersonic Flight

Plasma Airfoils/Actuators



a) Plasma off.

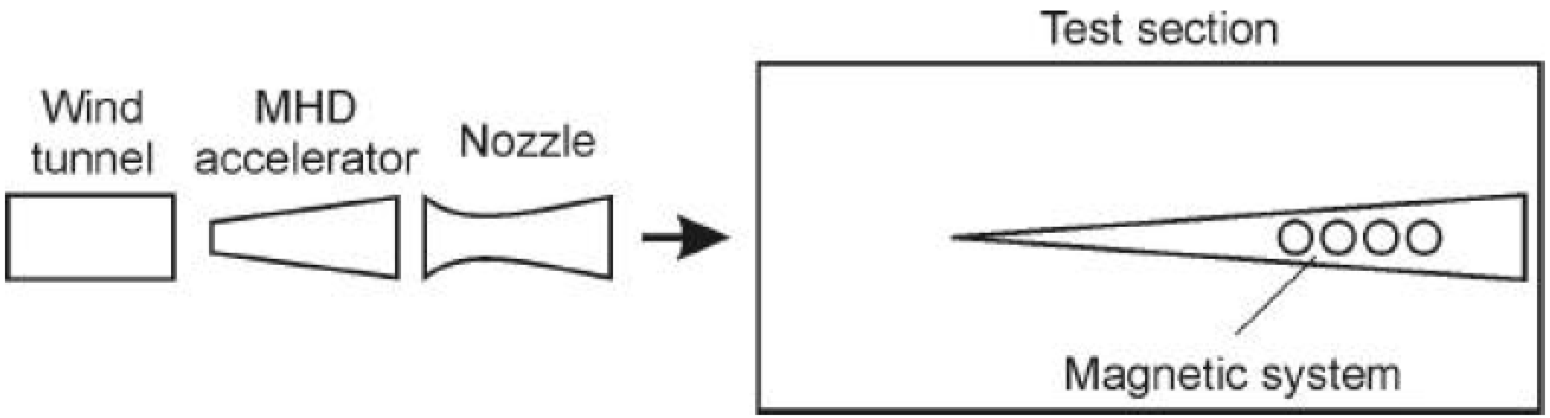


b) Plasma on

Subsonic Plasma Aerodynamics for Flight Control of Aircraft: Surface plasma induced flow re-attachment of an airfoil at an angle to the oncoming free-stream (University of Tennessee).

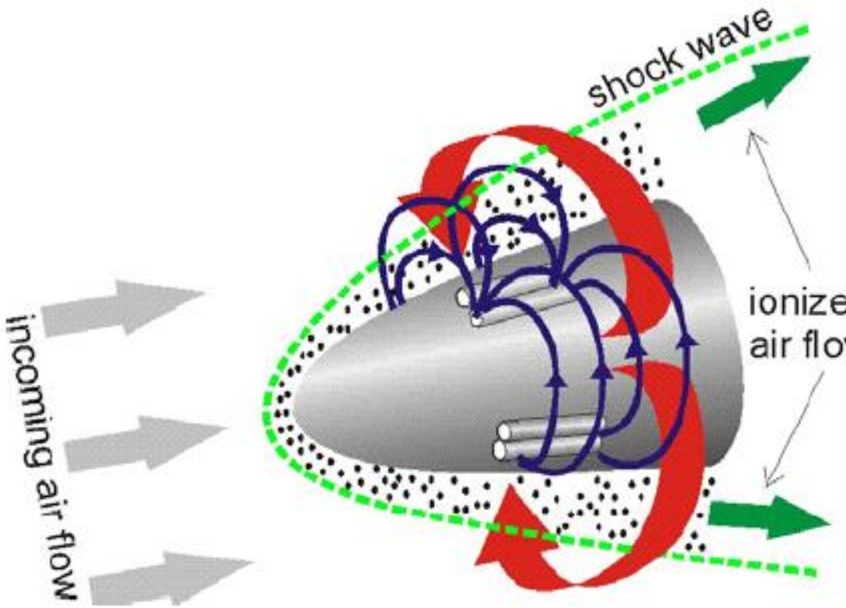
Plasma Airfoils/Actuators

MHD HYPERSONIC FLOW CONTROL (Russian Academy of Sciences, Moscow, Russia



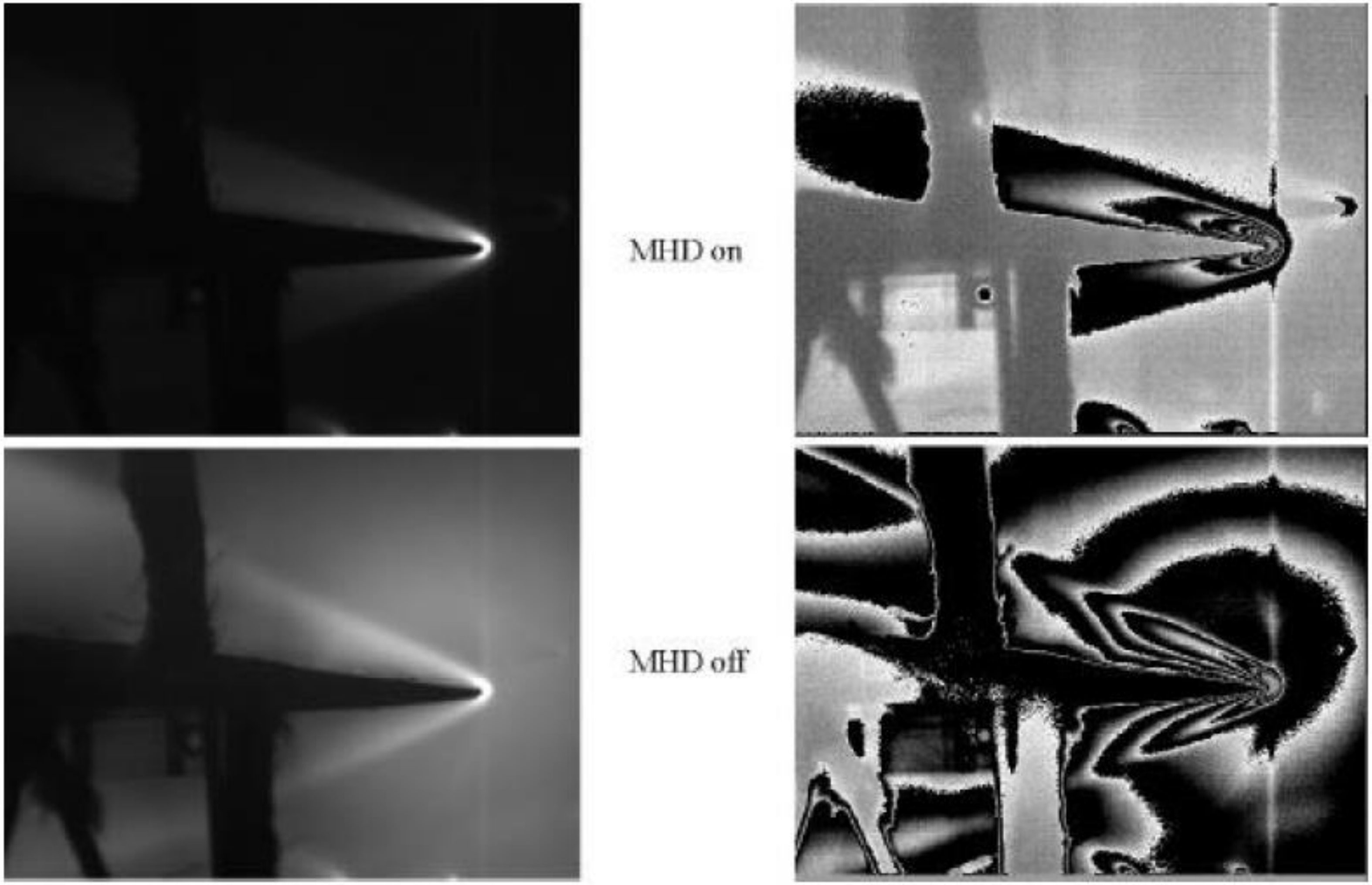
General Test Bed Arrangement for Wedge Model MHD Flow Interaction Experiments

Plasma Airfoils/Actuators



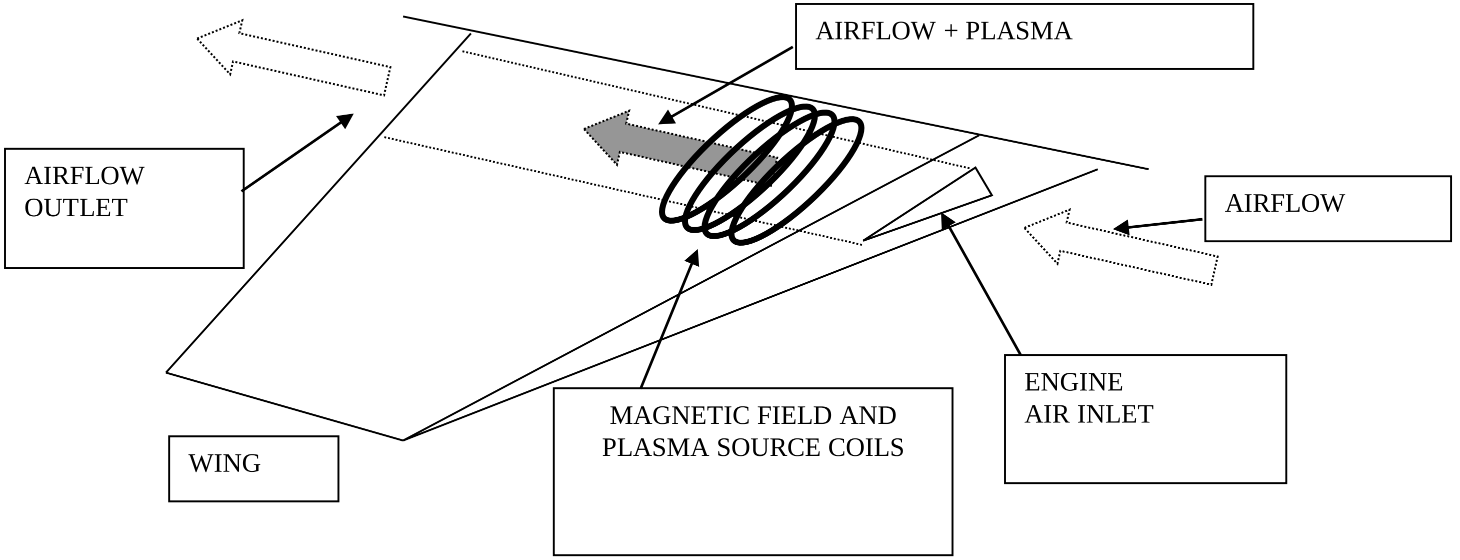
A concept of On-Board surface MHD Generator on a Re-Entry vehicle.

Plasma Airfoils/Actuators



Experimental Photographs of Wedge Model Test *(Right Side Photo Images – Left Side Spectral Enhanced Images)*

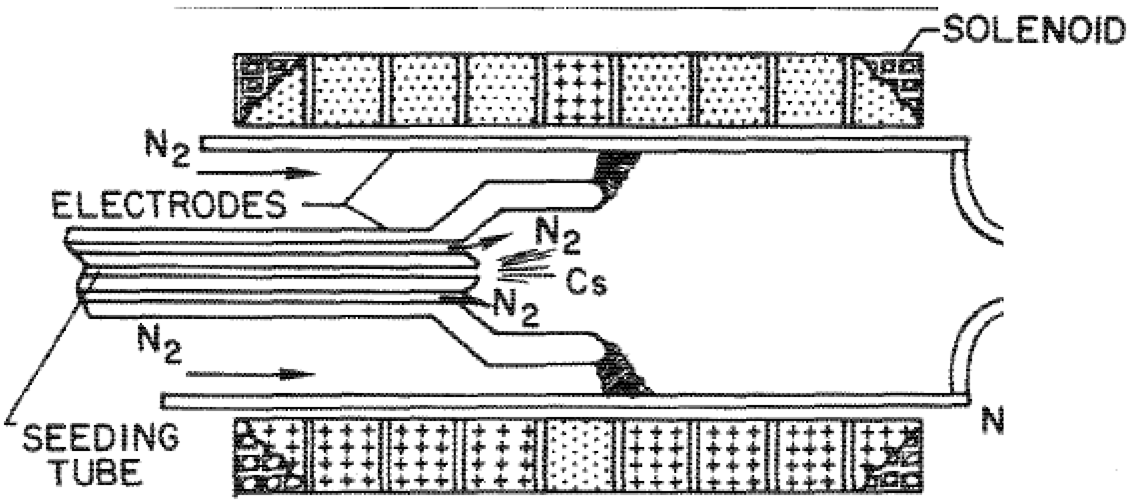
Plasma Actuators for Super/Hypersonic Flight

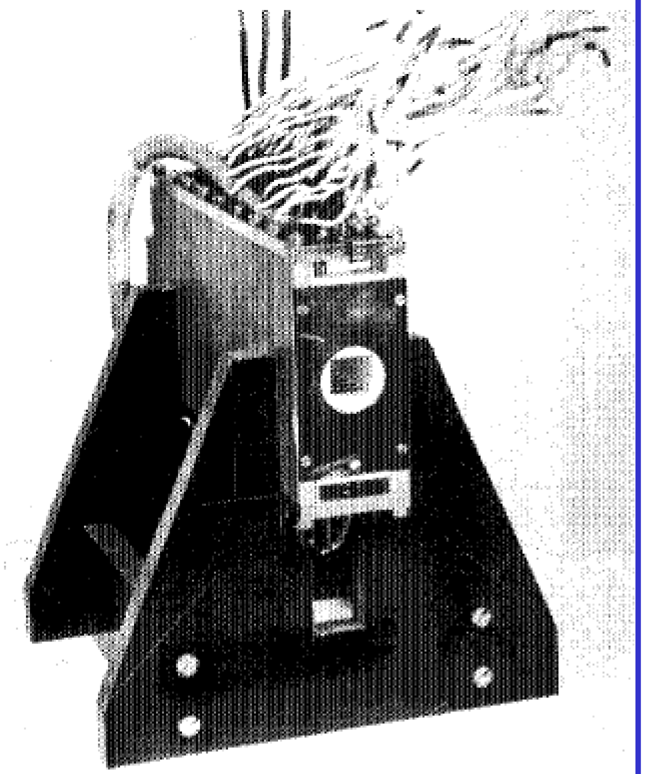


Conceptual Scheme of Airframe Embedded Magnetized Plasma Actuator

MHD/Chemical Plasma Propulsion

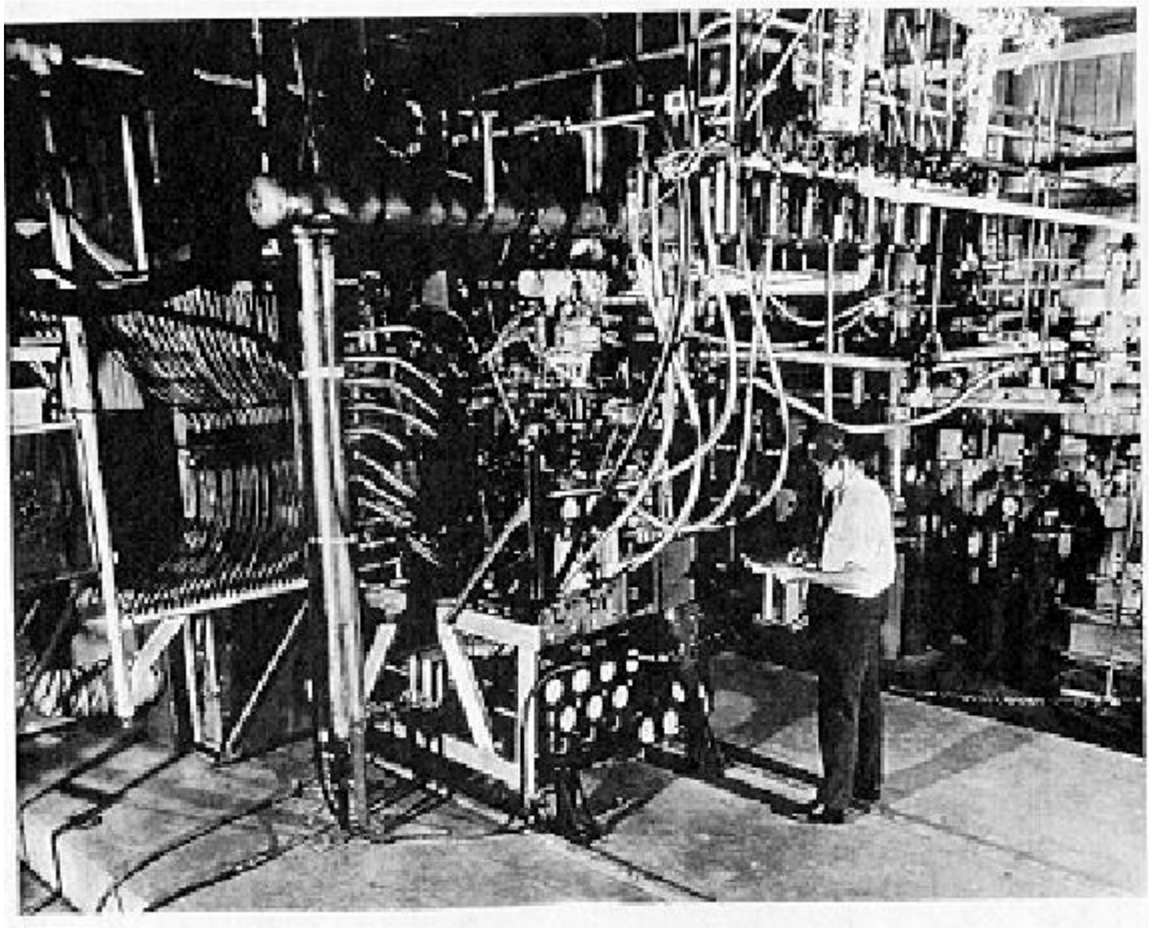
MHD/Chemical Plasma Propulsion





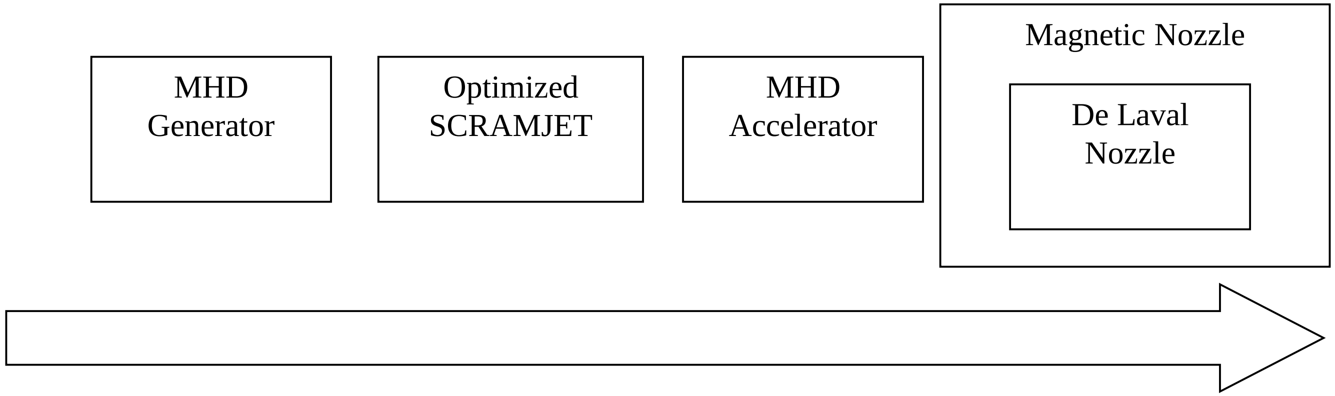
NASA-Langley Seeded Plasma Accelerator for enhanced propulsion experiment (1965)

MHD/Chemical Plasma Propulsion



MHD Plasma Accelerator for wind tunnel experiment (USAF, 1999)

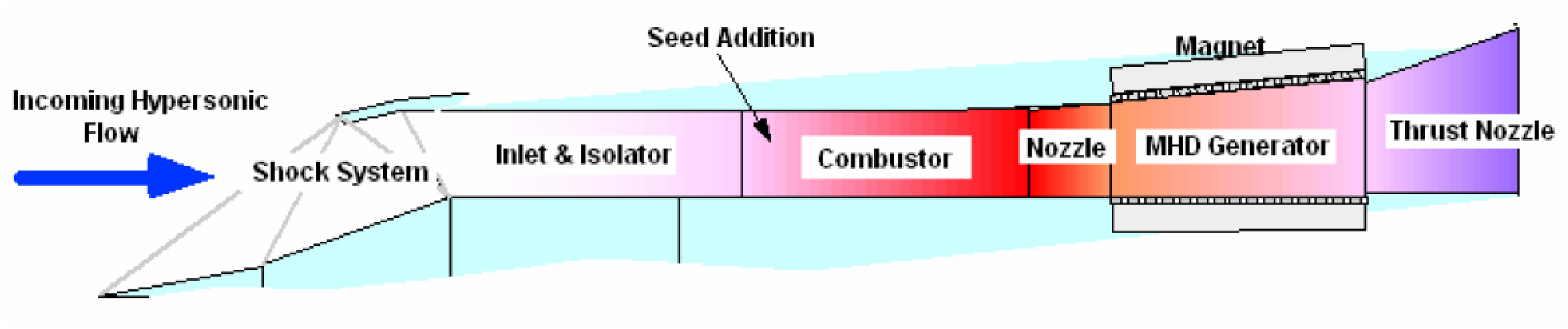
MHD/Chemical Plasma Propulsion



General scheme of an MHD Augmented propulsion system

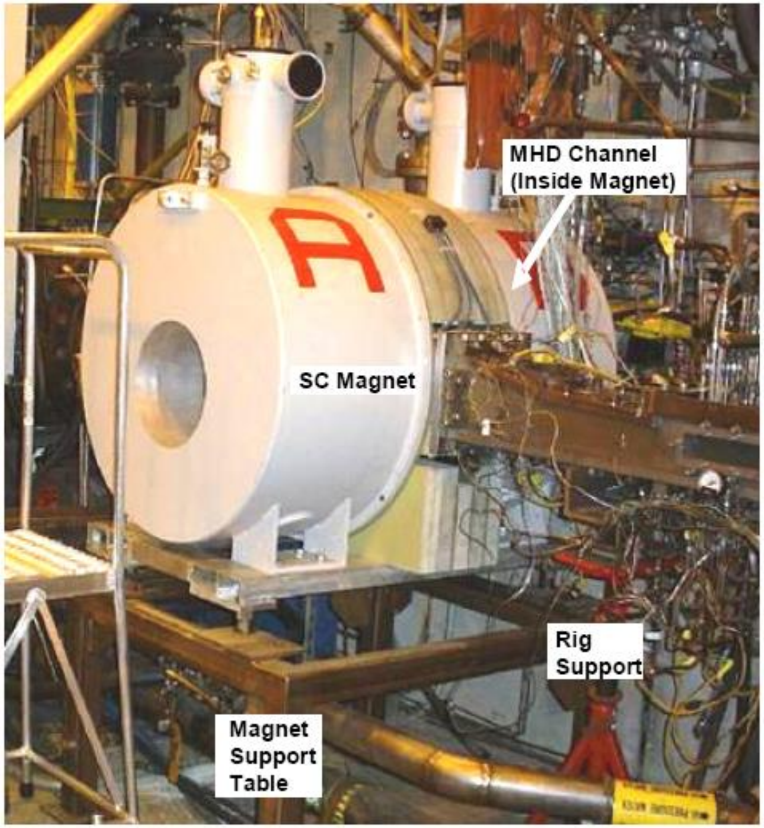
System study on the efficiency of an MHD Augmented Atmospheric Propulsion System

MHD/Chemical Plasma Propulsion

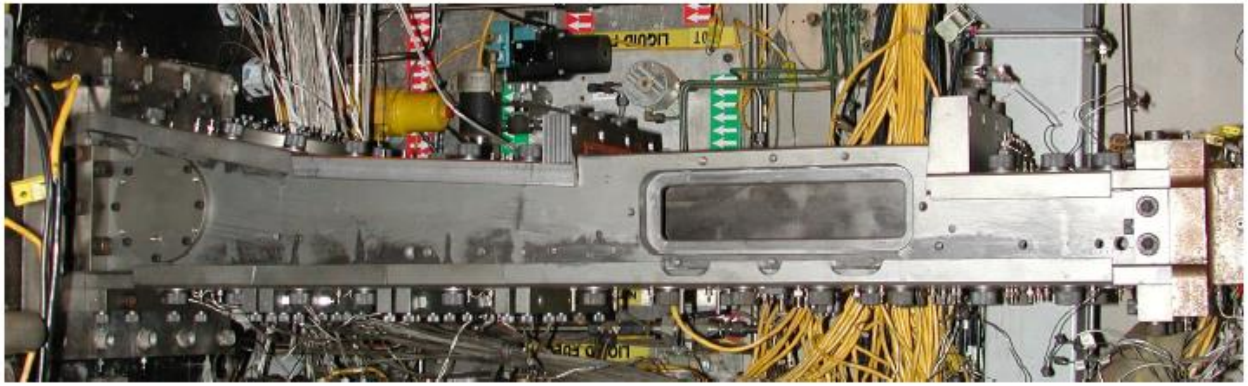


Scramjet-Driven Air Borne MHD Generator Concept (US Air Force)

MHD/Chemical Plasma Propulsion

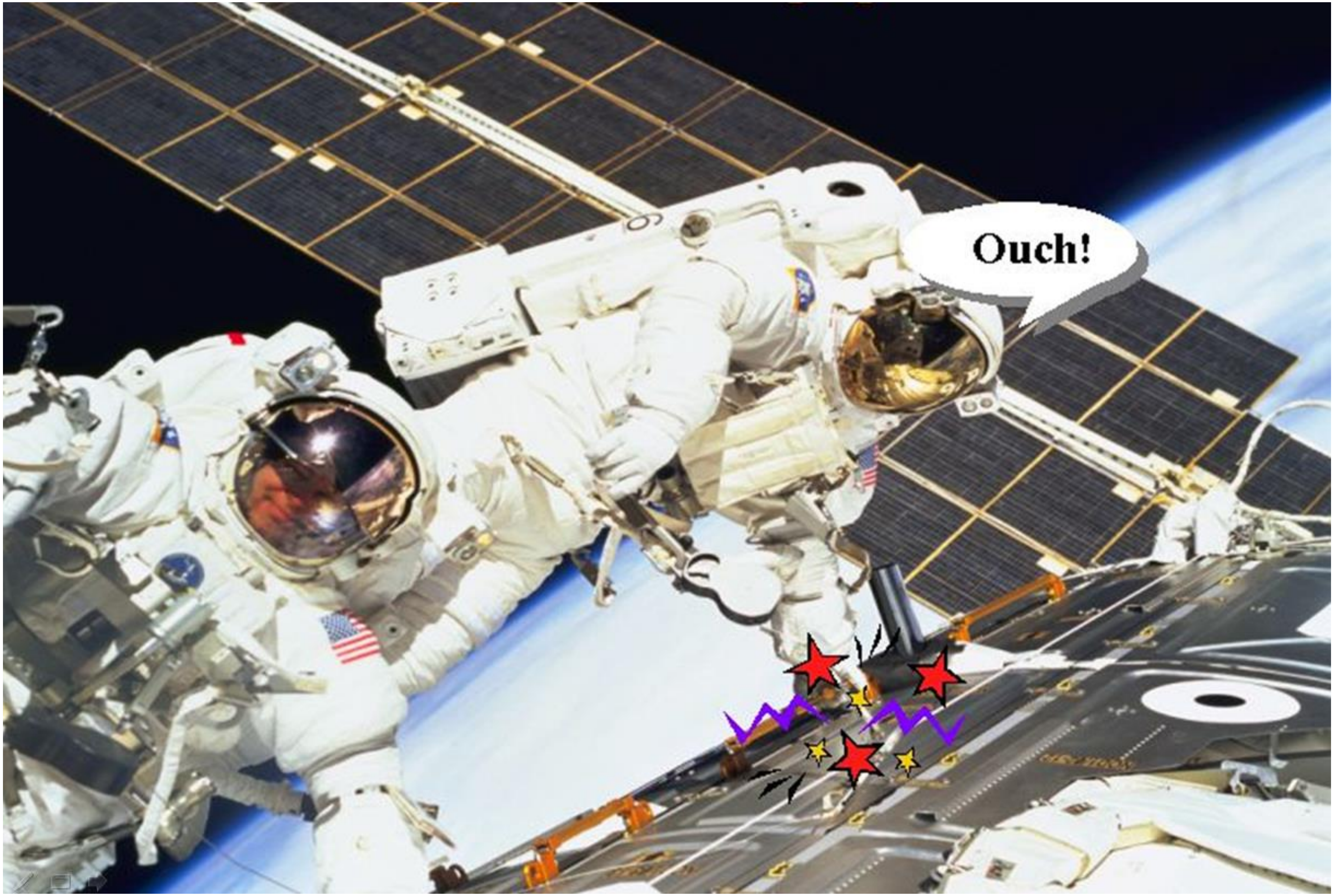


Assembled Scramjet MHD Test Bed



Plasma-Spacecraft Interactions

Spacecraft Charging Hazard



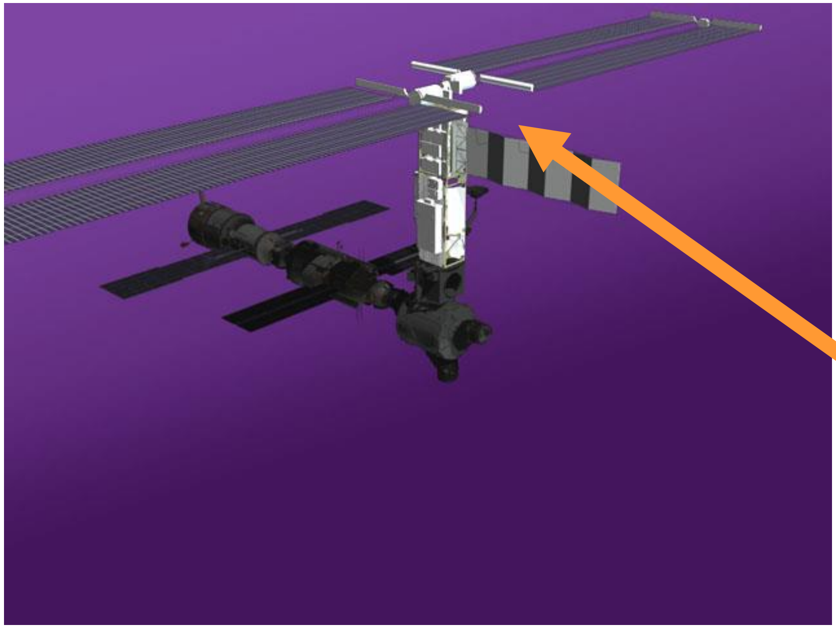
Spacecraft Charging Hazard (II)

- The ISS has large surfaces (MMOD shields) covered by a thin (1.3 mm) anodized aluminum as a dielectric insulator
- Voltages as low as 70 V have been found to produce arcing on the dielectric coating
- Long-term exposure of the dielectric surface to the space environment can produce local damages (due to micro-meteorites or debris) of the dielectric and enable arcing at even lower voltages

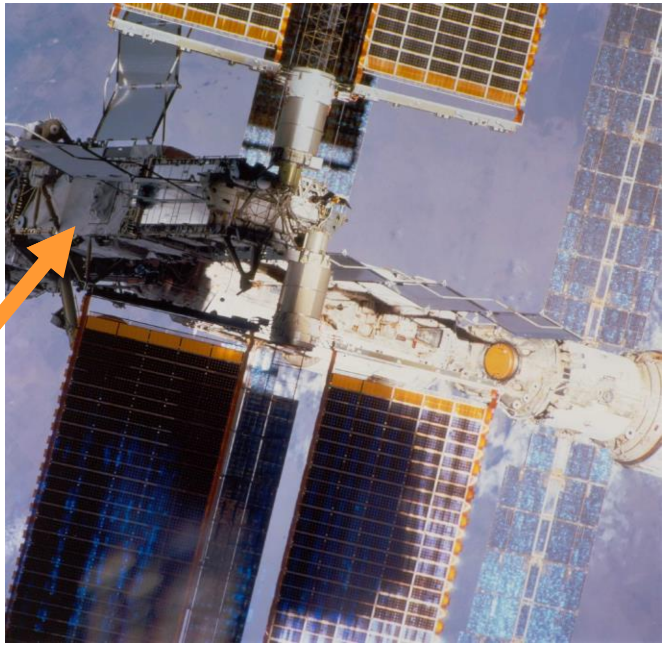
Spacecraft Plasma Hazard (III)

- EVA space suits have a safety threshold of 40 V (Marshall Space Flight Center test showed arcing through the suit at 68 V with new fabric)
- Beyond the 40 V value it is possible that a circuit close through the astronaut's thorax cavity with a current in excess of 1 mA
- This current limit is generally accepted as safety threshold to prevent heart fibrillation.

Spacecraft Plasma Hazard (IV)



FPP



ISS Floating Potential Probe

Plasma Contactors

- Plasma contactors are devices that allow to control the maximum floating potential of a spacecraft by providing a discharge path to the ionosphere for the excess electrons
- Essentially, the plasma contactor is a plasma source that establishes an electrically conducting path (the plasma) between the spacecraft ground and the ionosphere.
- The floating potential of the spacecraft is then “clamped down” to safe values (in the order of -10 V for the current ISS implementation)
- ISS plasma contactors are Xenon sources (hollow-cathode design, maximum current of 4 A, much larger than the present requirements)

Plasma Contactors

- In steady-state conditions a plasma sheath is formed between the contactor plasma and the spacecraft conducting surface
- For large values of the spacecraft floating potential the current in the sheath can be computed through the Child law and is independent on the spacecraft floating potential
- Corrections to the Child law can be introduced for collisional sheaths: in this case there is a dependence of the current on the potential.
- For example a (ion) plasma current of about 12 A can be sustained in a Hydrogen plasma with density of 10^{18} and temperature of 1 eV with a plasma radius of 5 cm.

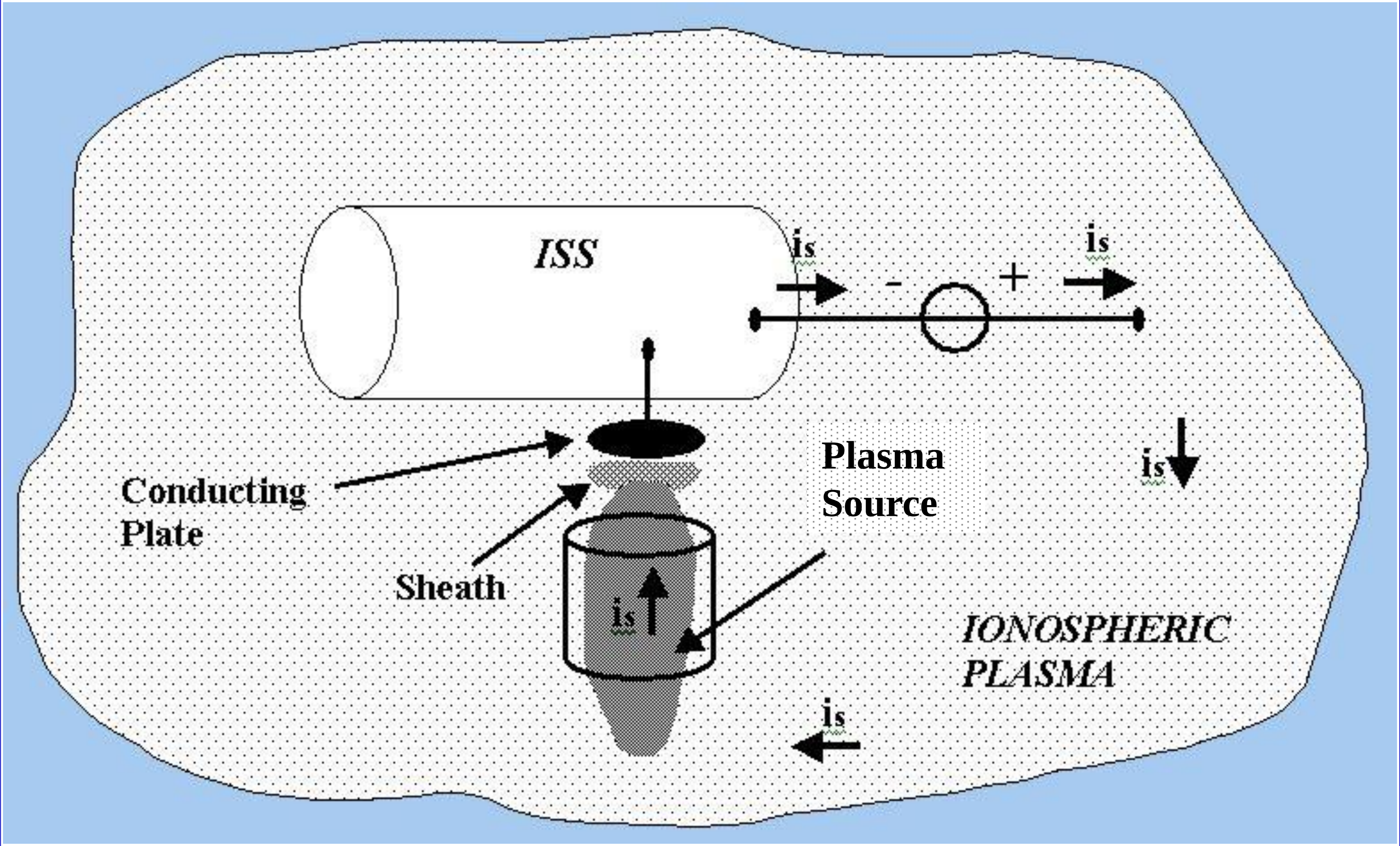
Plasma Contactors

- If transients occur (for example a sudden variation of the spacecraft potential at orbital sunrise) the sheath thickness adjust itself to new the value of the potential causing variations of the current that are also dependent on the potential.
- If the plasma contactor is effectively lowering the floating potential to small values (compared to the ionospheric plasma temperature) the sheath becomes much smaller (few Debye lengths) and a calculation of the equilibrium conditions according to the Bohm sheath criterion should be performed.

Plasma Contactors

- If a high-density plasma is produced near a conducting surface of a spacecraft in the Earth orbit an additional current path to the ionosphere will be established (in addition to the path represented by the interface between the ionospheric plasma and the spacecraft exposed conducting surfaces).
- On the ISS, the charging due to the solar panels produces an electron excess on the station structure and brings it to a potential energy that is significantly larger than the thermal energy of the ionospheric plasma.
- This is often expressed in less rigorous terms by saying that the “floating potential is much higher than the plasma temperature”.

Plasma Contactors



i_s: current through the sheath supported by the ISS floating potential that discharges plasma electrons to the ionosphere

Outline

- *Plasmas*
- *Main Thrust for Plasma Research: Fusion Energy*
- *Aerospace Applications*

  - Airfoils for Super/Hypersonic Flight

  - MHD/Chemical Plasma Propulsion

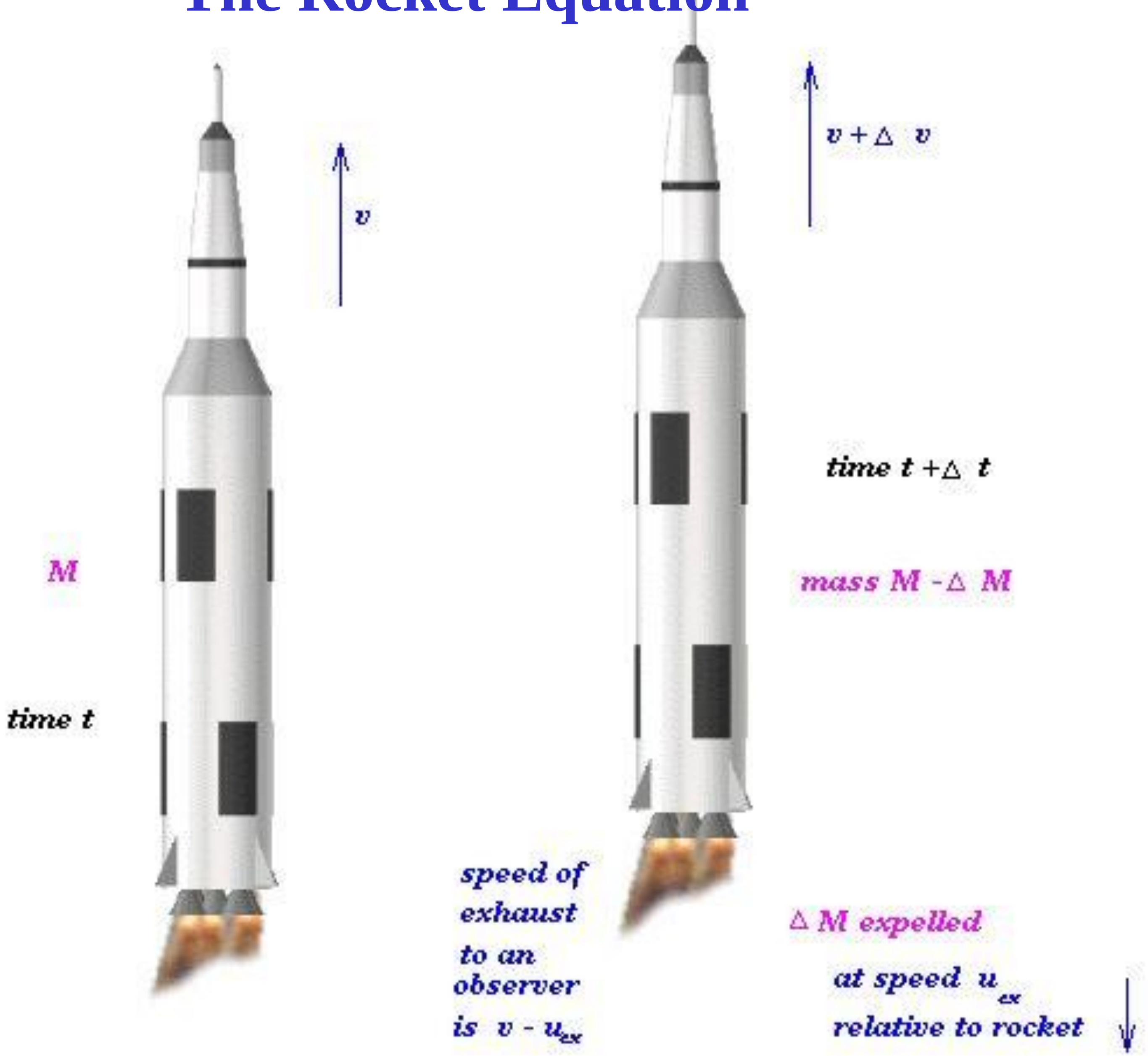
  - Plasma Contactors

  - Electric Propulsion

Limitations of Chemical Rockets

- Chemical rocket: exhaust ejection velocity intrinsically limited by the propellant-oxidizer reaction
- Larger velocity increment of the spacecraft could be obtained only with a larger ejected mass flow.
- Mission practical limitation: exceedingly large amount of propellant that needs to be stored aboard

The Rocket Equation



Understanding the motion of a spacecraft

The Rocket Equation (II)

- The rocket equation links the mass of exhausted propellant ΔM, the relative exhaust velocity u_{ex} and the velocity increment of the spacecraft Δv:

$$\Delta m = M_0 \left[1 - \exp\left(-\frac{\Delta v}{u_{ex}} \right) \right]$$

- For a given Δv, the larger u_{ex}, the smaller ΔM, and viceversa
- A large ΔM requires the storage of a large amount of propellant on board, reducing the useful payload

Advanced (Electric) Propulsion

The Concept:

- Definition - Electric propulsion: A way to accelerate a propellant through electro(magnetic) fields
- There is no intrinsic limitation (other than the relativistic one) to the speed to which the propellant can be accelerated
- Energy available on board is the only practical limitation

Advanced (Electric) Propulsion *(II)*

Understanding what's behind it:

- Tradeoff 1: more energy available, less propellant mass required
- Tradeoff 2: more time allowed for a maneuver, less power needed

Advanced (Electric) Propulsion *(III)*

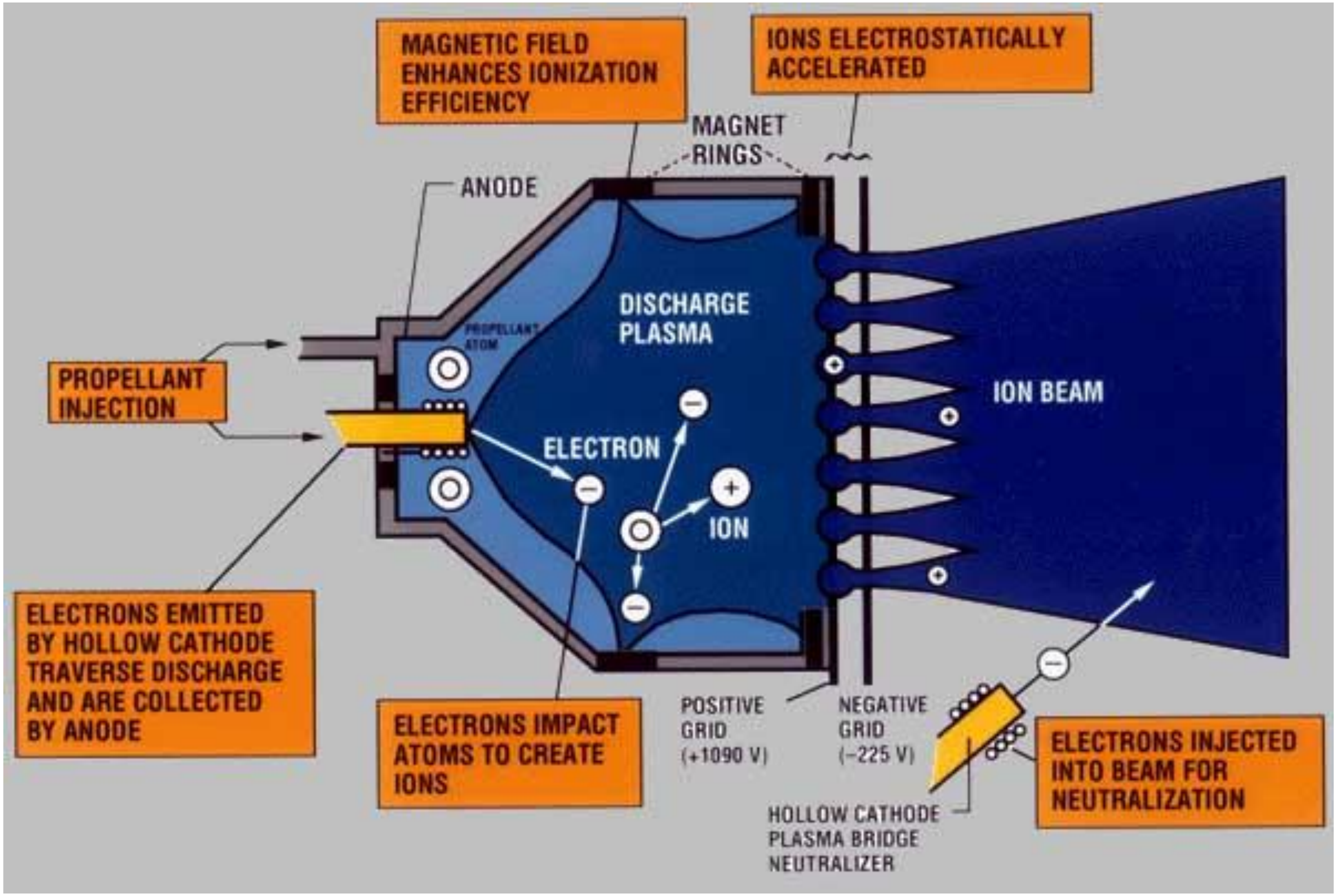
Features:

- High exhaust speed (*i.e.* high specific impulse), much greater than in conventional (chemical) rockets
- Much less propellant consumption (much higher efficiency in the fuel utilization)
- Continuous propulsion: apply a smaller thrust for a longer time
- Mission flexibility (Interplanetary travel, defense)
- Endurance (commercial satellites)

Electric Propulsion Concepts

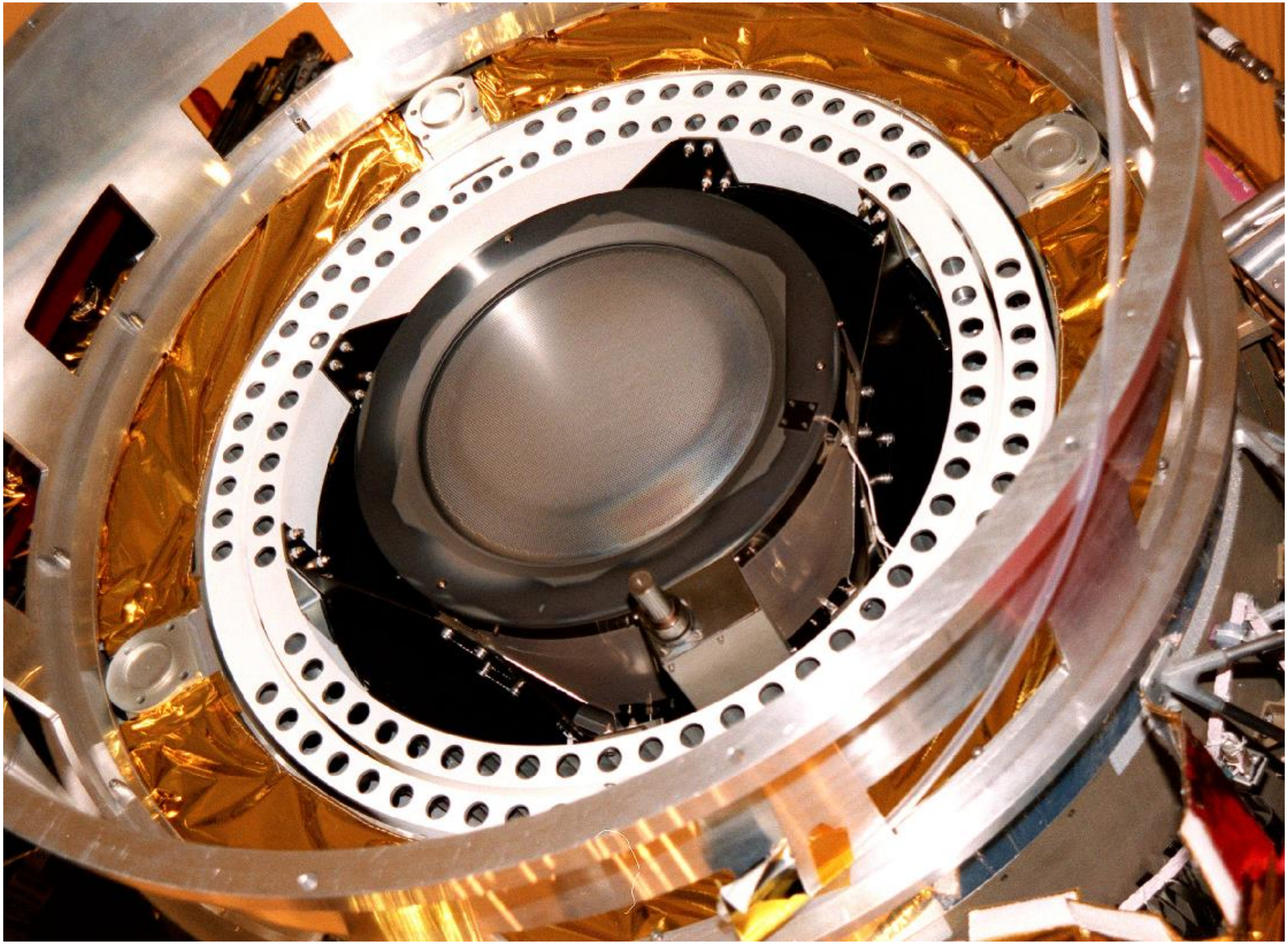
- Variety of designs to accelerate ions or plasmas
- Most concepts utilize grids or electrodes: power and endurance limitations
- Ion Engine
- Hall Thruster
- RF Plasma Thrusters (ECR, VASIMR, Helicon Double Layer)
- Magnetoplasma Dynamic (MPD) Thrusters
- Plasmoid Accelerated Thrusters

Ion Engine



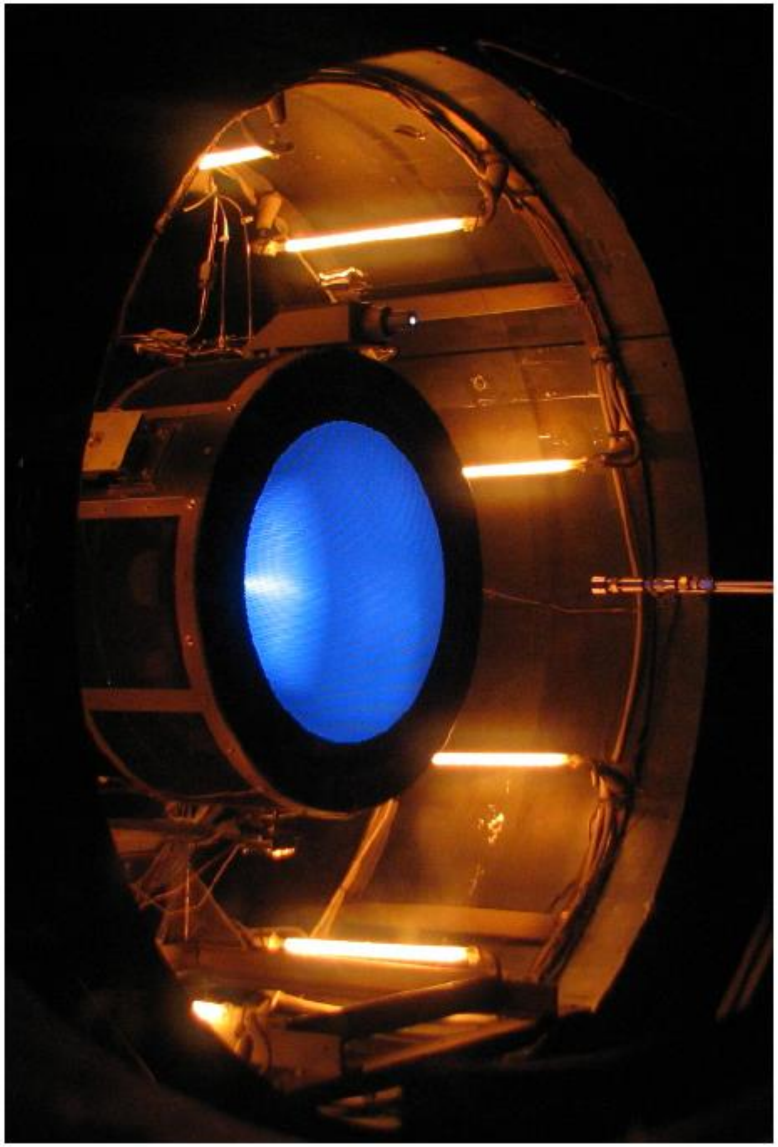
- Scheme of a gridded ion engine with neutralization

Ion Engine



NASA's Deep Space One Ion Engine

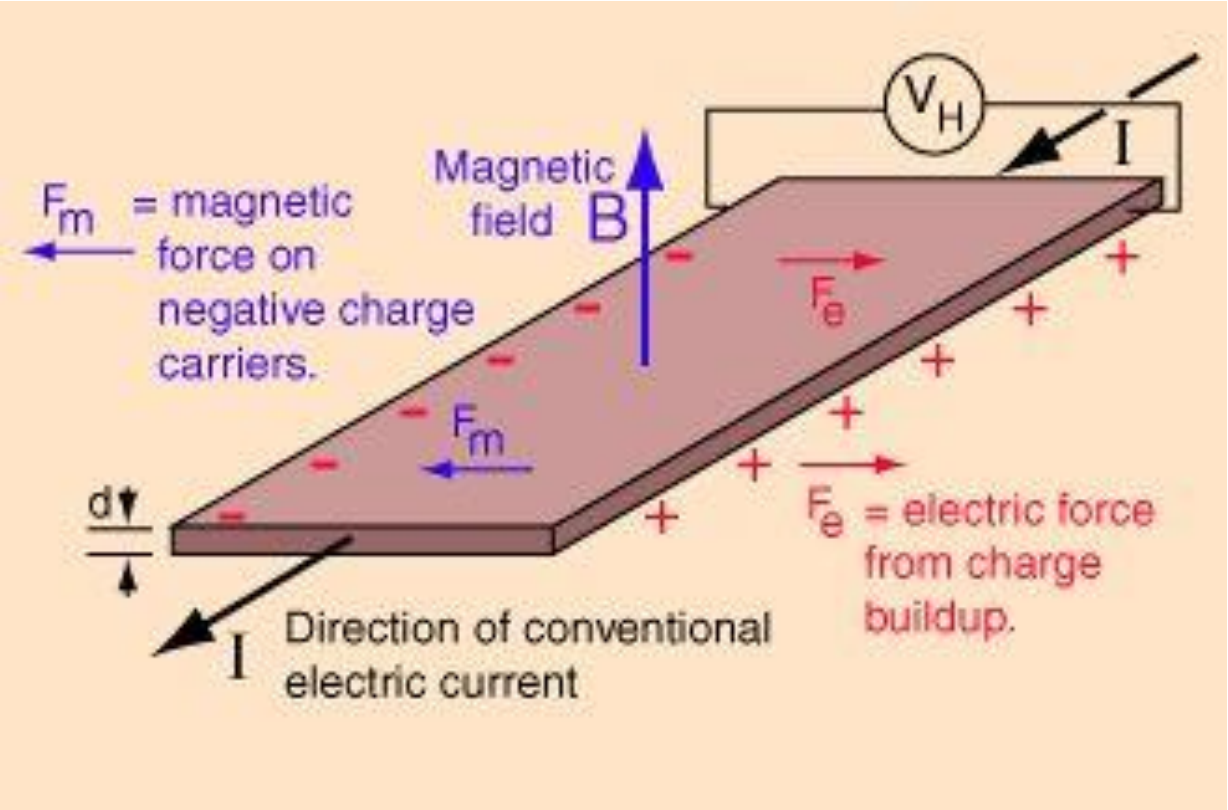
Ion Engine



Characteristic	NEXT
Thruster Power Range, kW	0.5-6.9
Throttle Ratio	> 12:1
Max. Specific Impulse, sec	>4100
Max. Thrust, mN	236
Max. Thruster Efficiency	>70%
Max. PPU Efficiency	94%
Propellant Throughput, kg	> 300
Specific Mass, kg/kW	1.8
PPU Specific Mass, kg/kW	4.8
PMS Single-String Mass, kg	5.0
PMS Unusable Propellant Residual	1.00%

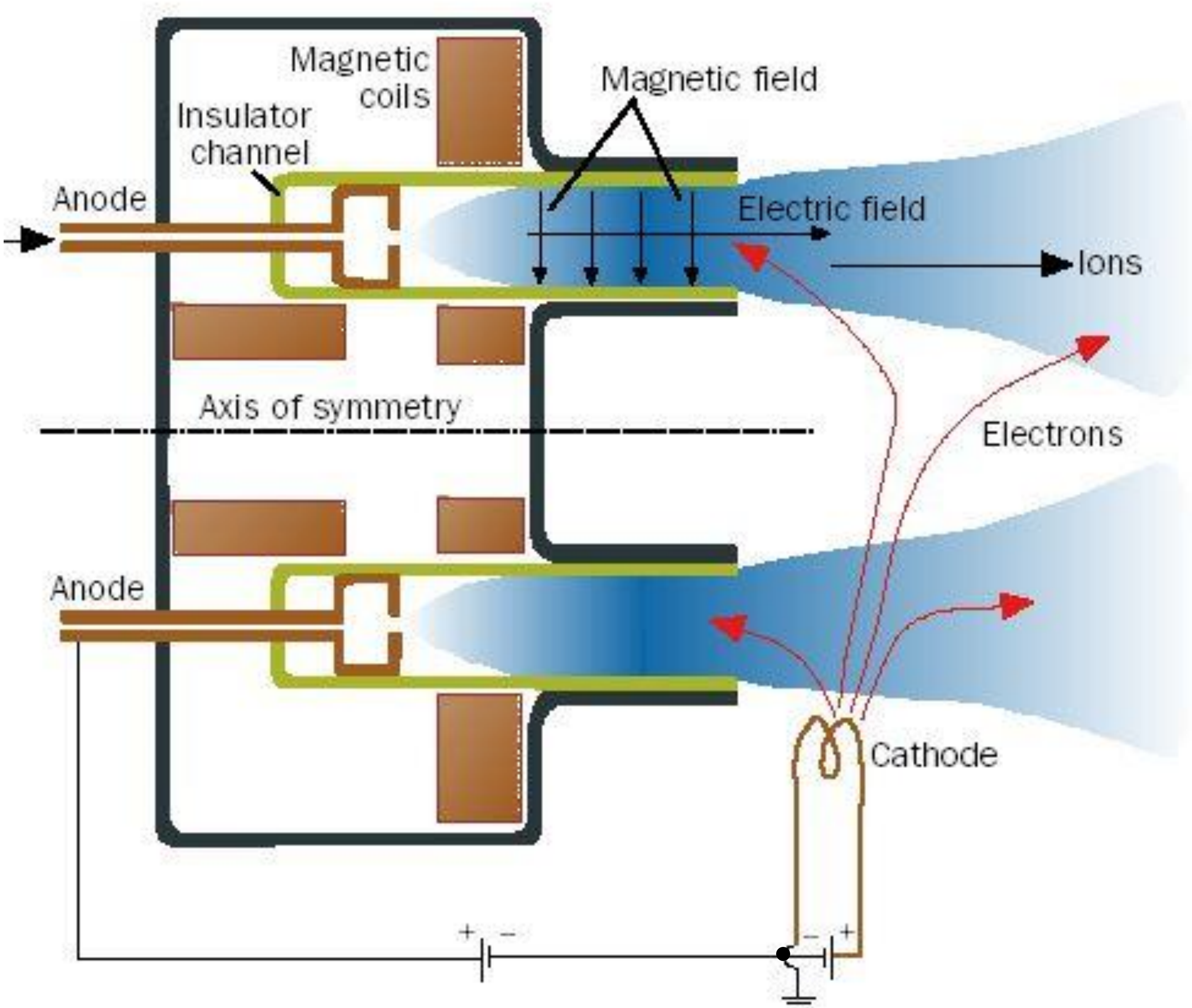
NASA's Evolutionary Xenon Thruster (NEXT) at NASA's JPL

Hall Thruster



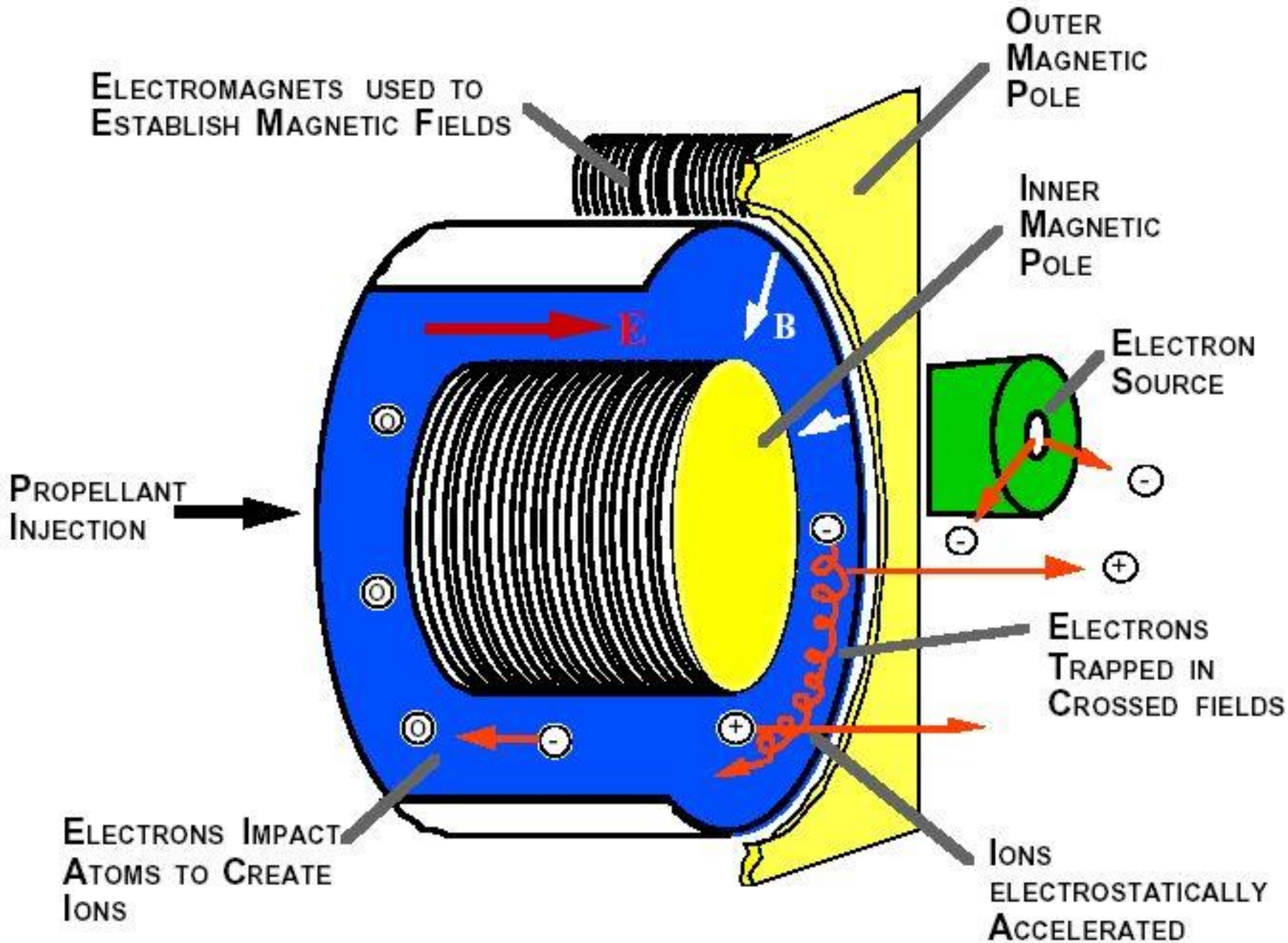
The Hall effect

Hall Thruster (II)



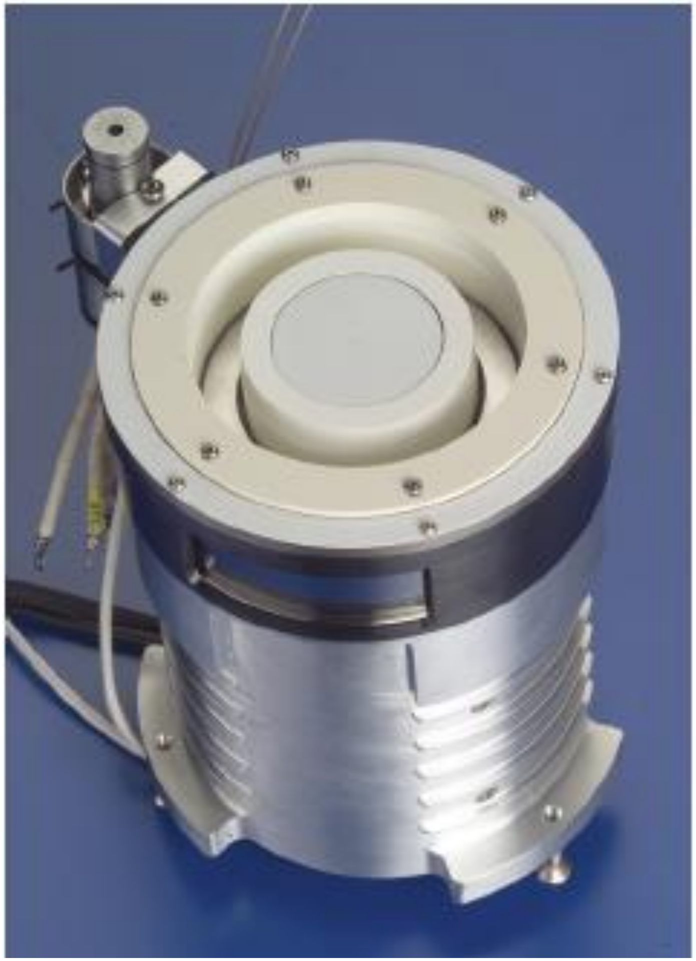
The Hall thruster scheme

Hall Thruster (III)



The Hall thruster: the Hall effect confines electrons

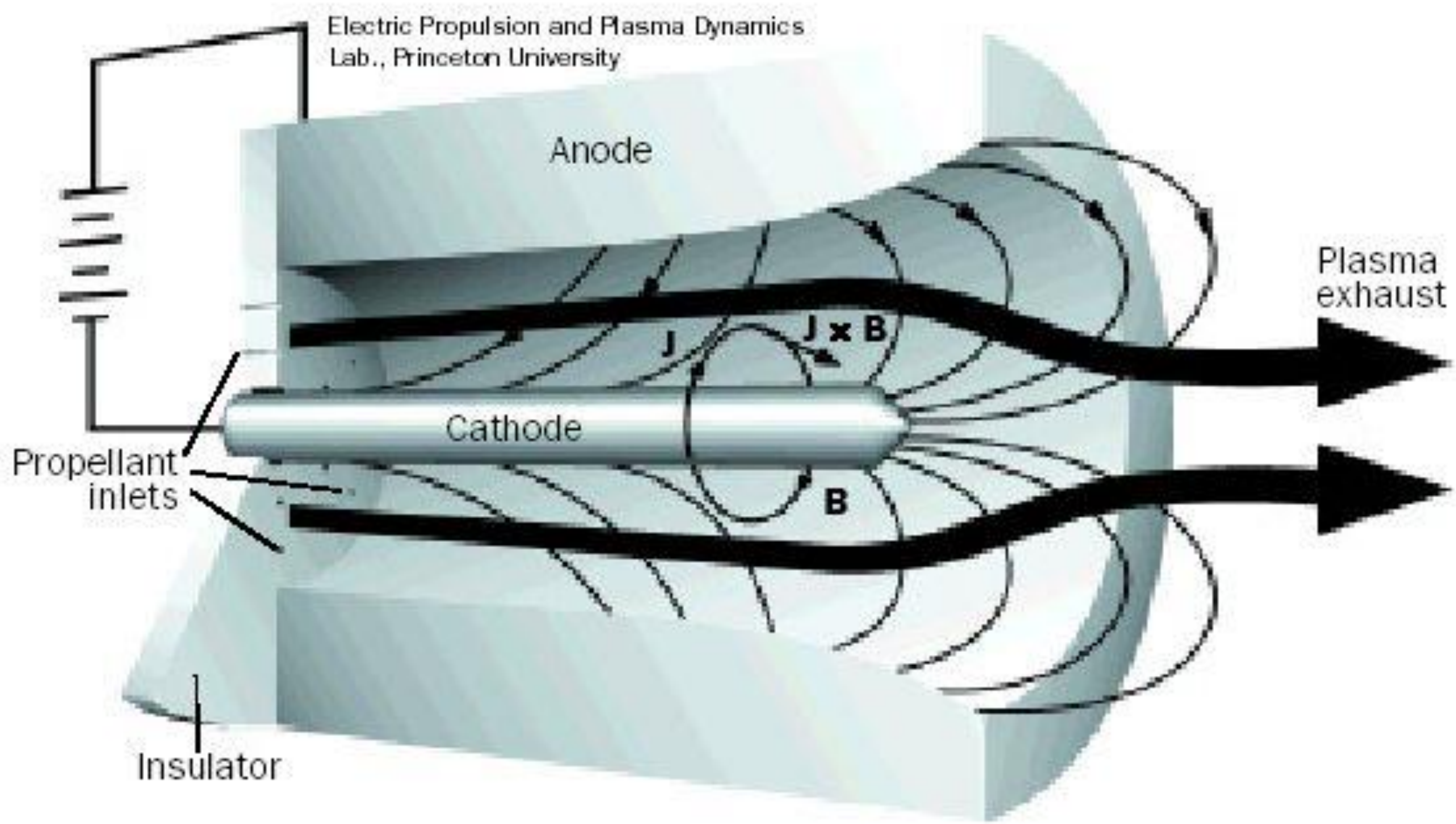
Hall Thruster (III)



Characteristic	HiVHAC
Thruster Power Range, kW	0.3 - 3.6
Throttle Ratio	12:1
Operating Voltage, V	200 – 700
Specific Impulse, s	1000 – 2800
Thrust, mN	24 – 150
Thruster Alpha, kg/kW	1.5
Propellant Throughput, kg	300

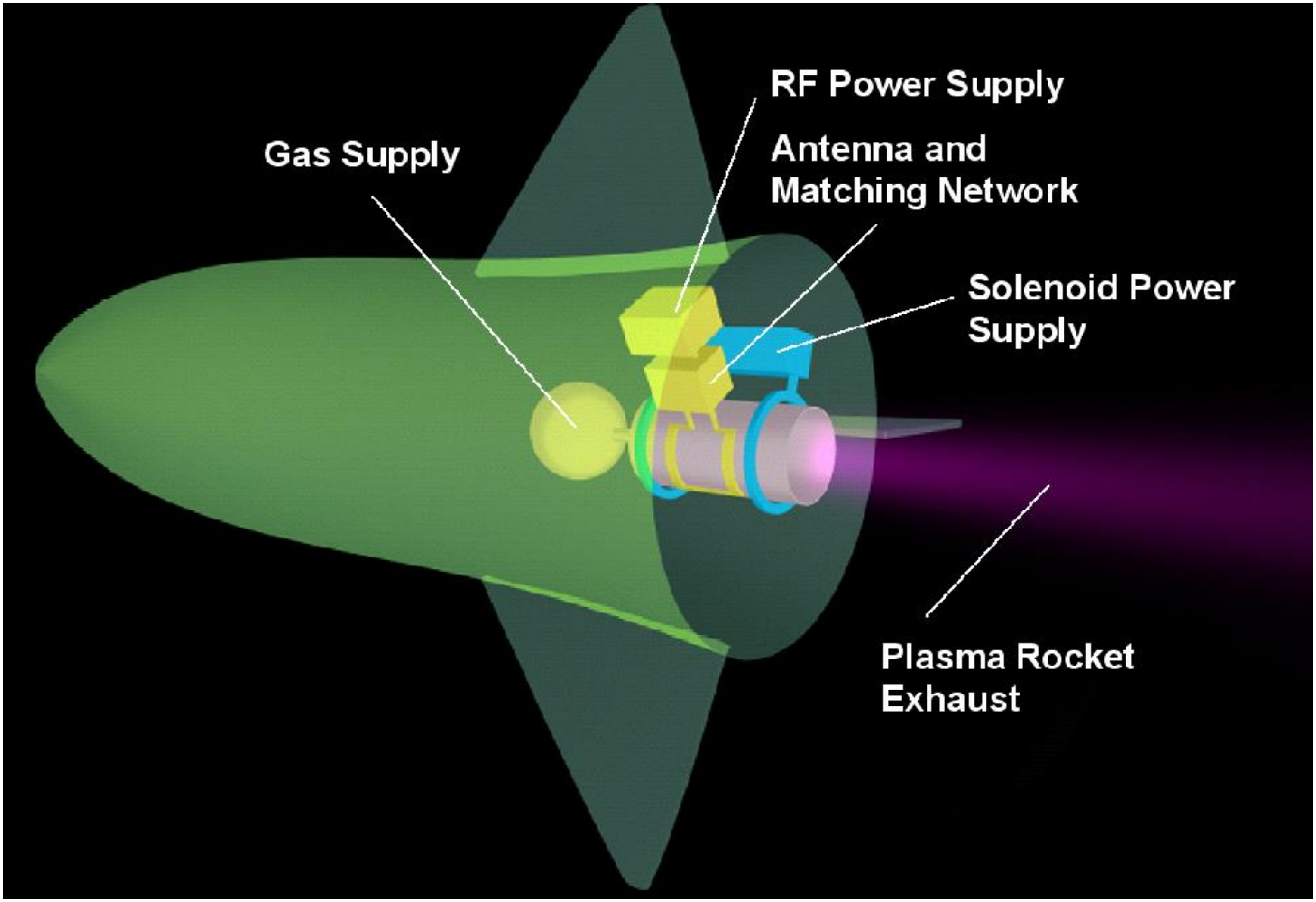
High Voltage Hall Accelerator (HiVHAC) Thruster - Hall Thruster (NASA Glenn R.C.)

MagnetoPlasma Dynamic Thruster



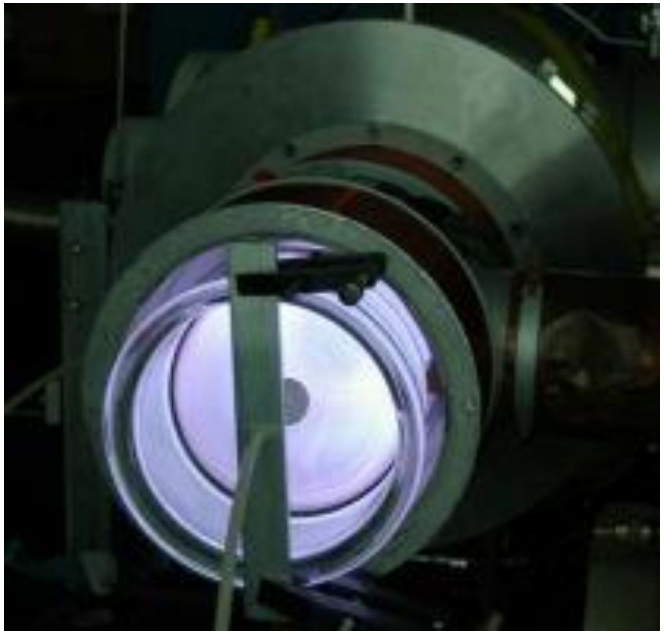
The MPD thruster

Helicon Double Layer Thruster Experiment

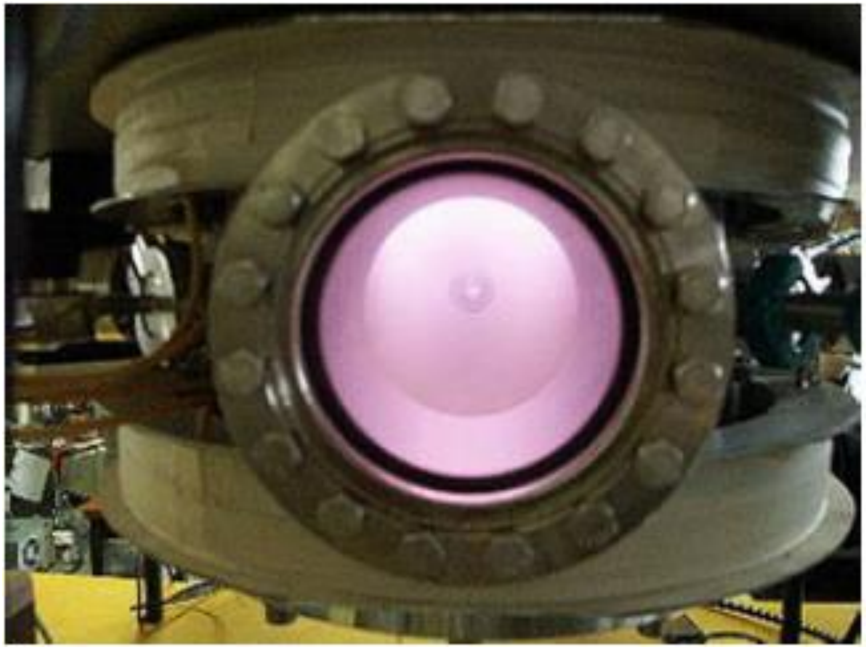


Artists rendering of a Helicon Double Layer Thruster concept (Australian National University)

Helicon Double Layer Thruster Experiment

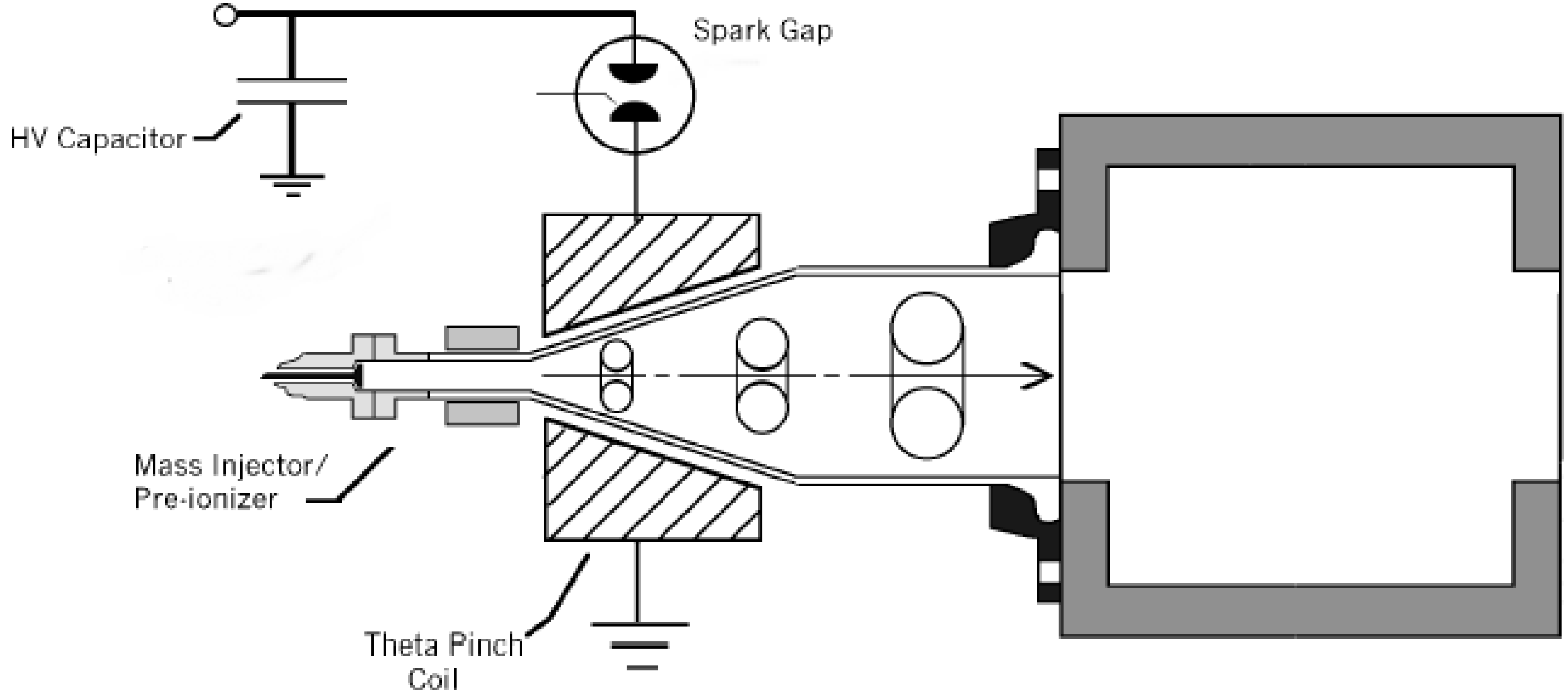


2003 Helicon Double Layer Thruster Experiment (Australian National University)



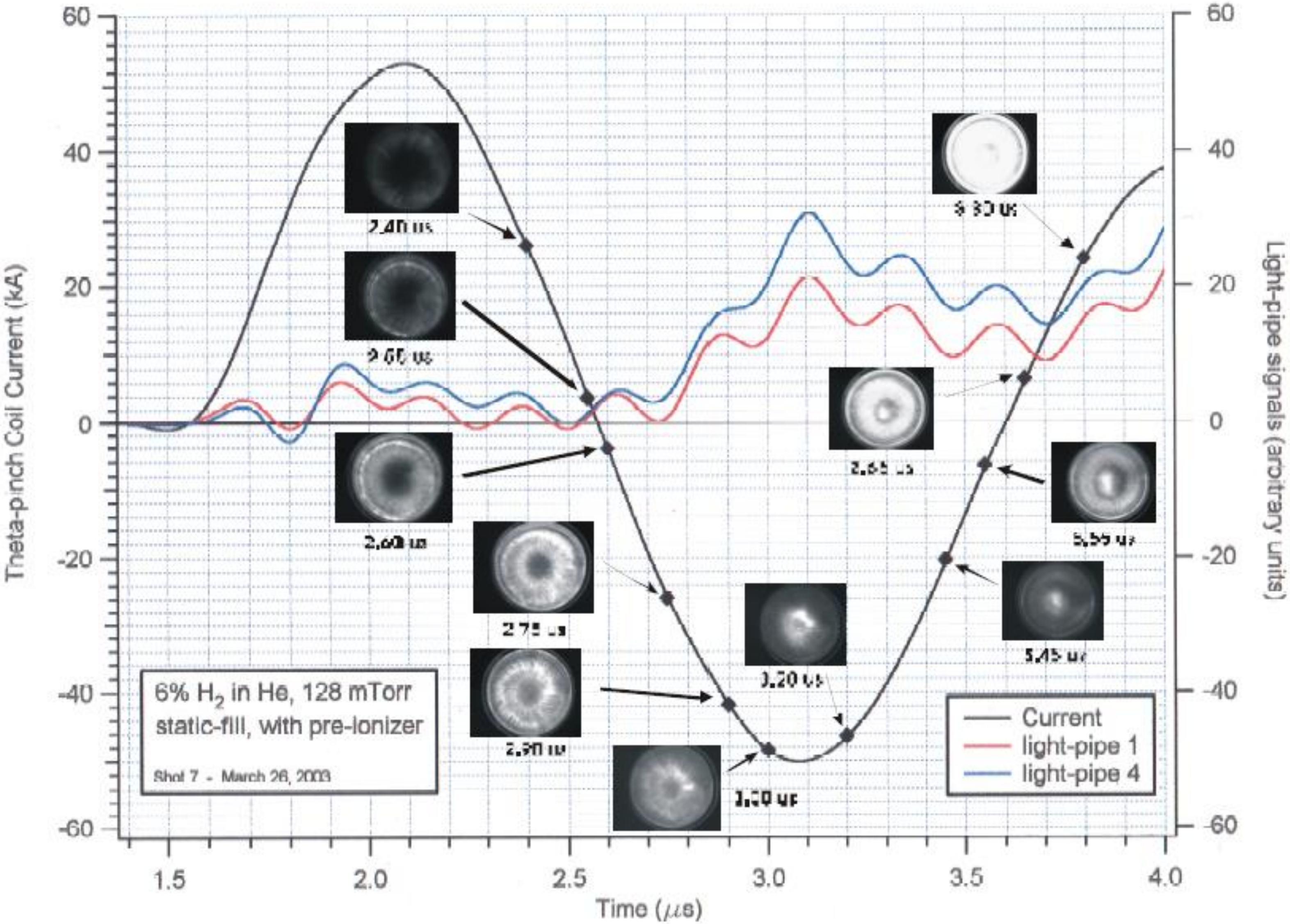
2005 Helicon Double Layer Thruster Experiment (European Space Agency, EPFL, Switzerland)

Plasmoid Thruster Experiment (PTX)



PTX Schematic (NASA MSFC/U. Alabama)

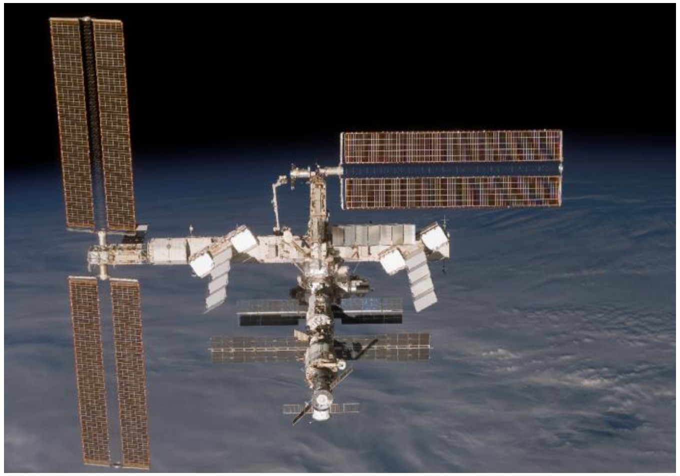
Plasmoid Thruster Experiment (PTX)



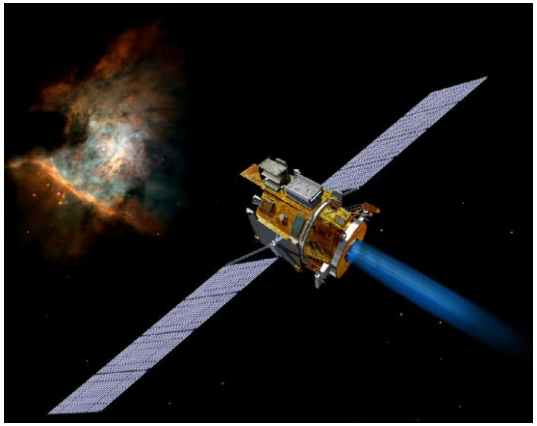
PTX Plasmoid Images with Coil Current

Electric Propulsion Applications

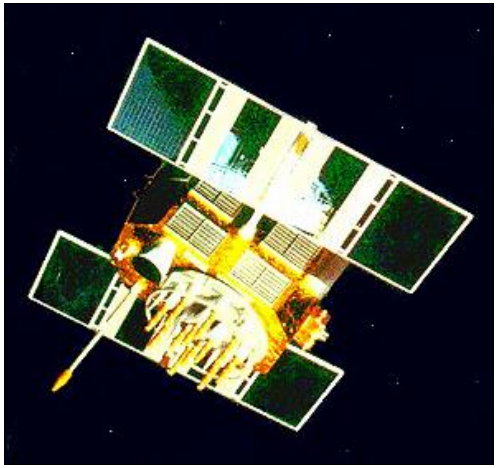
1. ***ISS***



2. ***Interplanetary Missions***



3. ***Commercial/Defense***



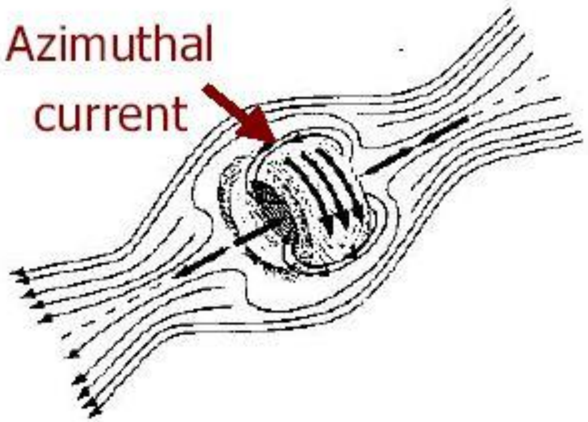
ISS Electric Propulsion Boosting

- ISS meeds drag compensation
- Currently ISS is “reboosted” periodically
- Presently Shuttle (or Soyuz) perform this operation
- Very high cost: 9000 lbs/yr propellant at $5,000/lbs = 45M$/yr!

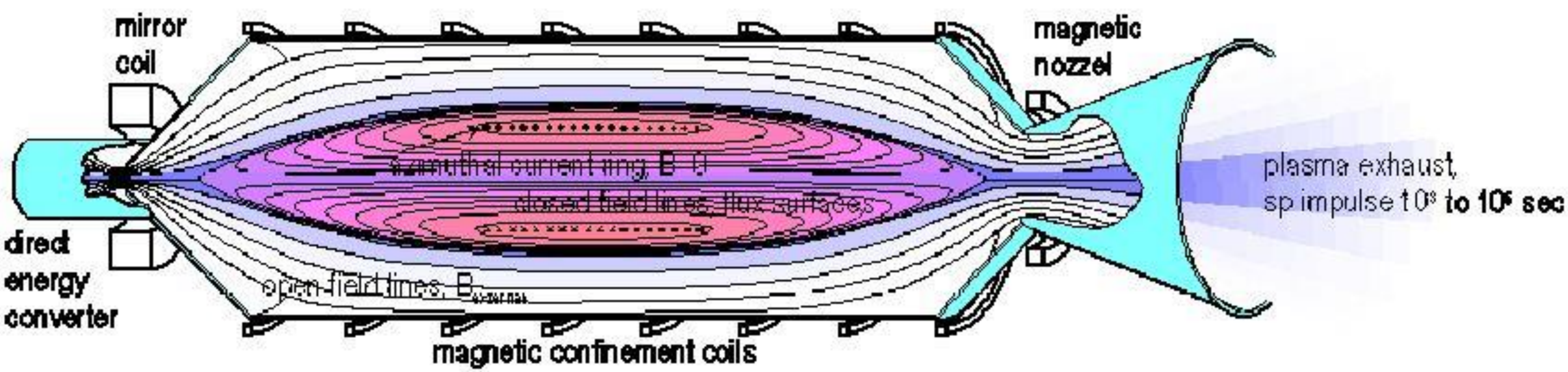
Future Perspectives: *Fusion Propulsion*

Fusion Propulsion

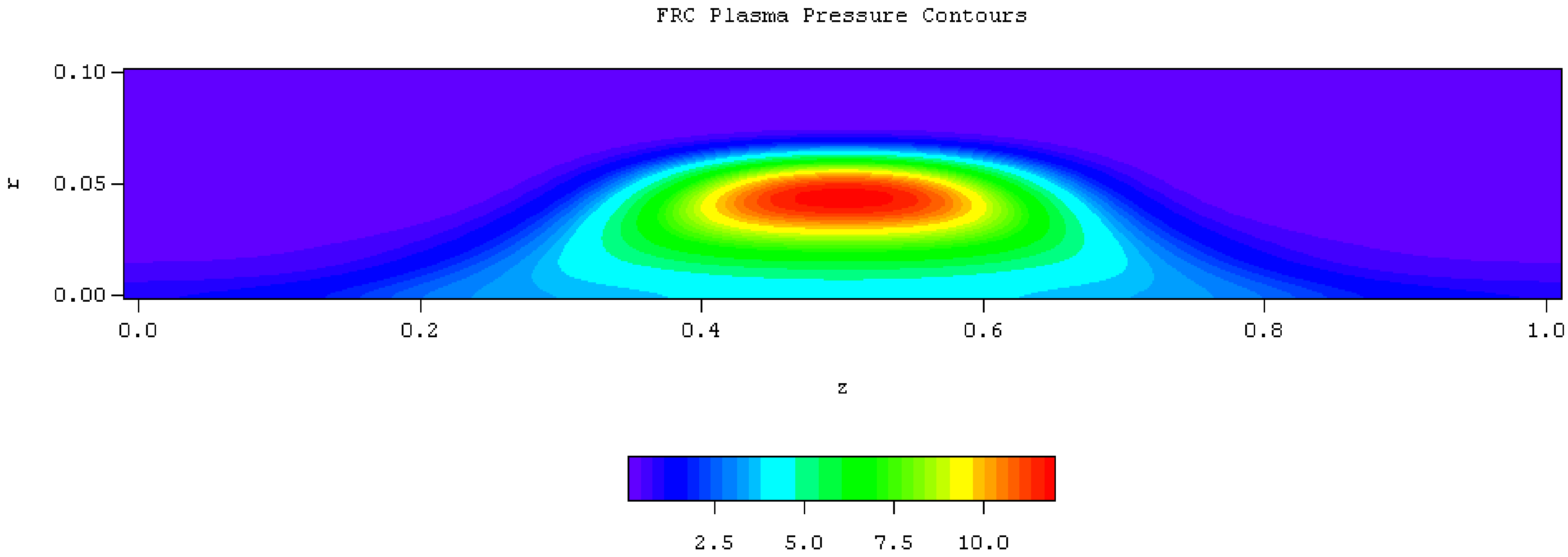
The **F**ield **R**eversed **C**onfiguration is a plasma confinement scheme very appealing also for propulsion applications



- High $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- RMF current drive

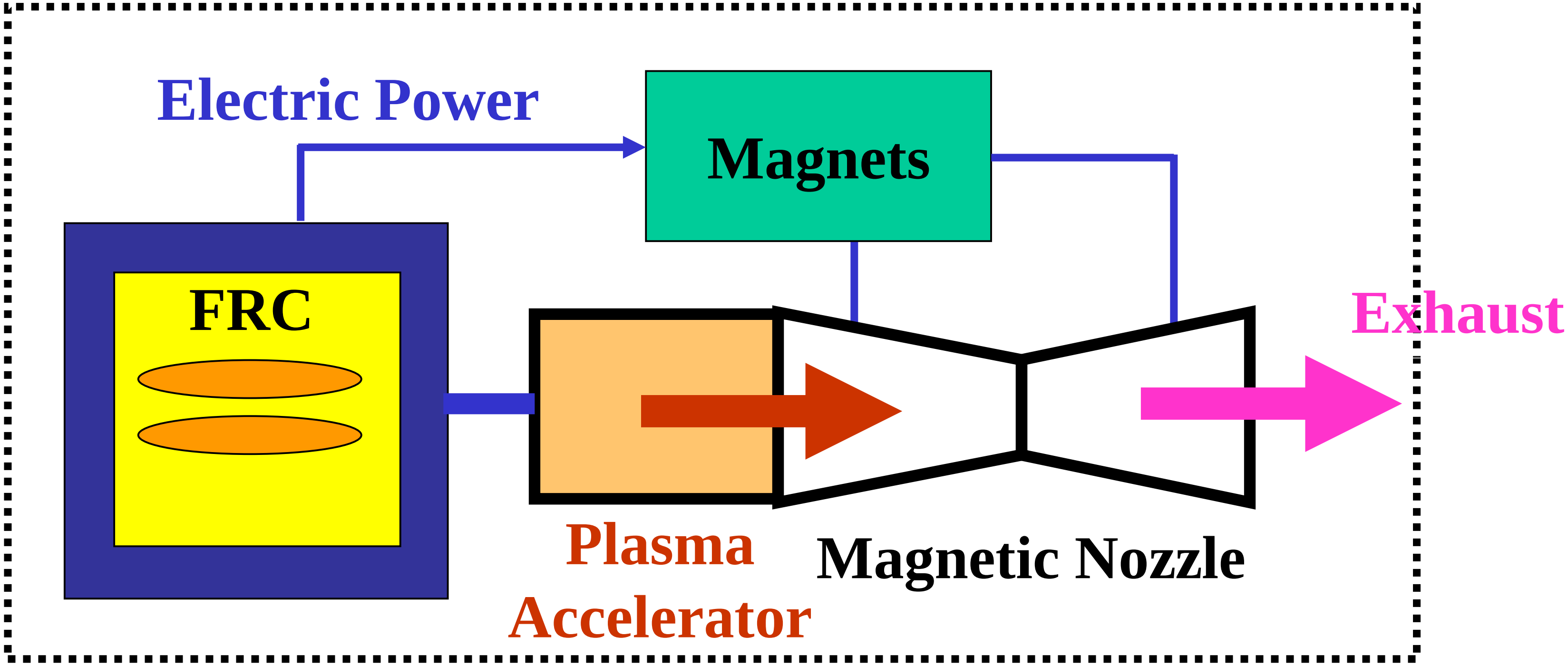


Fusion Propulsion



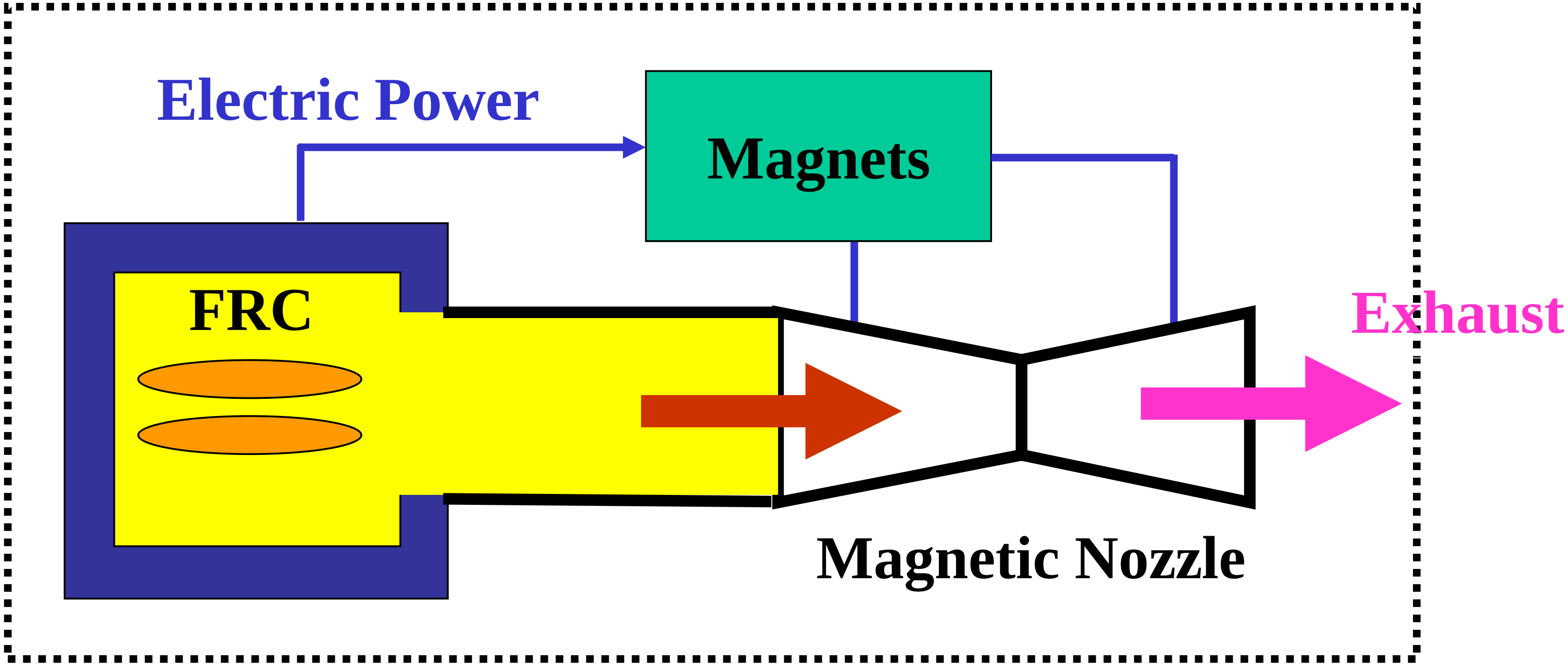
FRC plasma simulated with the MHD-2 Fluid *NIMROD* code

Fusion Propulsion



Plasma and power production scheme for a FRC fusion (still to be demonstrated…) indirect propulsion rocket

Fusion Propulsion



Plasma and power production scheme for a FRC fusion (still to be demonstrated…) direct propulsion rocket

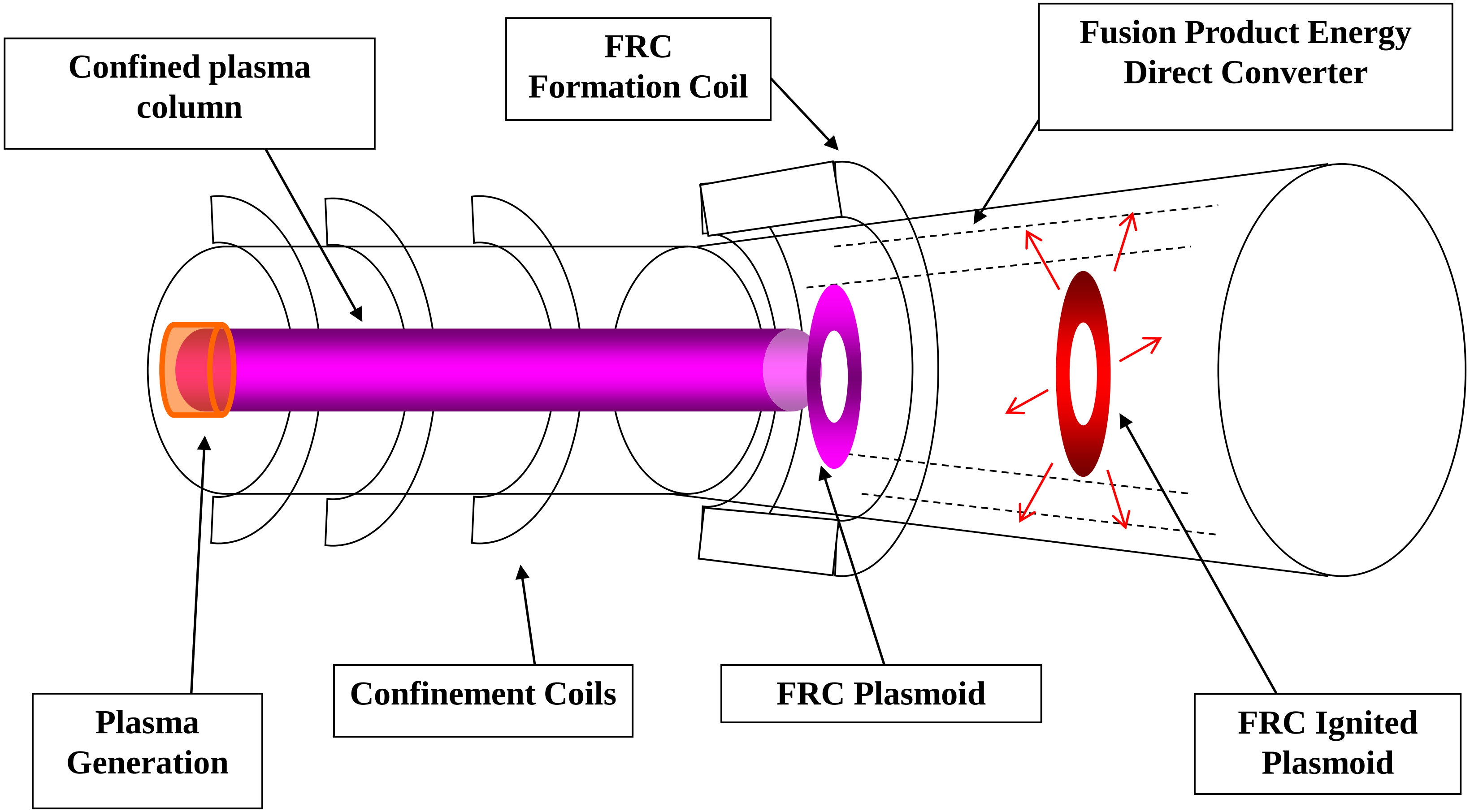
FRC Direct Propulsion

- The Field Reversed Configuration (FRC) is an attractive concept for plasma propulsion because its intrinsically high plasma *beta* and the formation of magnetically detached plasmoids.
- Direct FRC fusion-propulsion schemes (that is, besides the basic concept of a reactor producing electricity to power a thruster) have been previously discussed (*e.g.* [1]), with the plasma exhaust accelerated directly from the fusion core or collected from the FRC scrape-off layer and channeled through a magnetic nozzle

[1] M.J. Schaffer, *Proc. NASA Advanced Propulsion Workshop in Fusion Propulsion*, Huntsville, AL, Nov. 2000 and *General Atomics report* GA-A23579, Dec. 2000

FRC Fusion Plasma Thruster Concept

- The plasma detachment in the nozzle is then induced in a controlled way, through the formation of a sequence of FRC plasmoids



Short-term: Sub-critical FRC's

- The case of a sub-critical (without fusion yield) FRC is also interesting for the possibility of increasing the overall nozzle performance via a controlled detachment and of implementing plasmoid pre-acceleration schemes.

Long-term: FRC Fusion Propulsion

- For an FRC plasmoid able to sustain fusion conditions, the energy of the fusion products can be collected in the nozzle, while the plasmoid is leaving the rocket (ideally via direct conversion from neutron-free reactions) with transit time in the nozzle longer than the ignited FRC life time.
- Only the fusion products that are escaping radially the detached plasma (plasmoid) are interacting with the rocket and are not expected to produce appreciable net back-thrust.

Long-term: FRC Fusion Propulsion (II)

- Assuming that the plasmoids are formed in a *1ms* and have the lifetime of *100 μs* and that they travel at $5 \cdot 10^4$ *m/s* the direct conversion system should be *5 m* long (if the fusion conditions are maintained for the lifetime of the FRC).
- The fusion power can be collected in the nozzle during the lifetime of the plasmoid.
- A *D-T* plasmoid with density of $1 \cdot 10^{20}$ and $T=10$ *keV* will produce a power density of about $3 MW/m^3$. For plasmoids of a $1\ m^3$ volume, *e.g.*, $r=0.22\ m$, $R=1\ m$, $P=3\ MW$
- The mass of one of these plasmoids will be:

$$m_{pmd}=2 \cdot 10^{20} \cdot 2.5 \cdot 1.67 \cdot 10^{-27} = 8.77 \cdot 10^{-7}\ kg$$

- The thrust for 1 plasmoid per *ms* ejected at $5 \cdot 10^4$ *m/s* will be $T=5 \cdot 10^4\ (m/s) \cdot 8.77 \cdot 10^{-7}\ kg/(1 \cdot 10 \cdot 10^{-3}\ s)=43\ N$ and the specific impulse will be about *5000 s*.

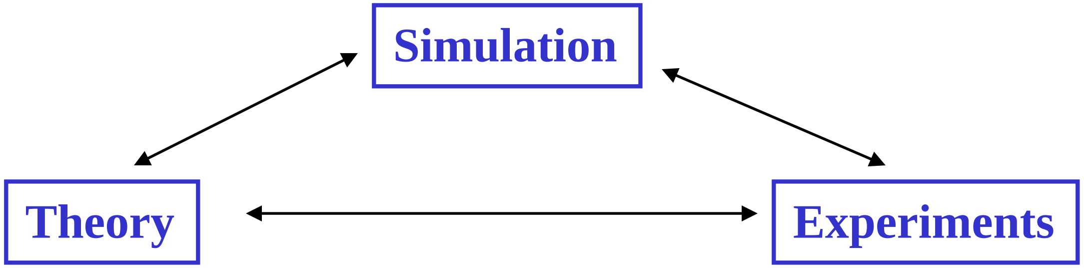
Research at UHCL

- Current Application Focus
  - MHD Augmented Propulsion (UHCL)
  - RF Magnetized Plasma Sources, Atmospheric Plasma Torches (Propulsion, Re-entry plasma) (UHCL/JSC)
  - Plasma Actuator/Airfoil for Hypersonic Flight (UHCL)
  - FRC-based Electric Propulsion (Fusion/Propulsion)
  - Lightning Stroke Simulation (JSC)
  - Magnetic Reconnection (UHCL)

- Some applications require neutrals:
  - Development 0-D Plasma-Neutral model

Simulation Studies

1. *Fluid (MHD) Plasma Simulation*
2. *Particle Simulation*
3. *Computer Science: Massively Parallel Processing*



MHD Plasma Simulation

1. **Pre-Maxwell Equations:** $\mathbf{j}_p \Rightarrow \mathbf{E}\ ,\mathbf{B}_p$

2. **Continuity Equation:** $n, \mathbf{u} \Rightarrow \dfrac{\partial n}{\partial t}$

3. **Momentum Equation** $\mathbf{j}, \mathbf{B}, \nabla p\ , \nu, \rho, \mathbf{u}, \nabla \mathbf{u} \Rightarrow \dfrac{\partial \mathbf{u}}{\partial t}$

4. **Energy Equation** $n, \nabla T, p, \mathbf{u}, \mathbf{q}, Q \Rightarrow \dfrac{\partial T}{\partial t}$

5. **Ohm's Law (resistive MHD)** $\mathbf{u}, \mathbf{B}, \eta, \mathbf{j}_\mathbf{p} \Rightarrow \mathbf{E}$

MHD Plasma Simulation

1. **Pre-Maxwell Equations:** $\dfrac{\partial \mathbf{B}_p}{\partial t} = -\nabla \times \mathbf{E}$, $\nabla \times \mathbf{B}_p = \mu_0 \mathbf{j}_p$

2. **Continuity Equation:** $\dfrac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0$

3. **Momentum Equation:** $\rho\left(\dfrac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = \mathbf{j} \times \mathbf{B} - \nabla p - \nabla \cdot (\nu\rho\nabla\mathbf{u})$

4. **Energy Equation:** $\dfrac{n}{\gamma - 1}\left(\dfrac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = p\nabla \cdot \mathbf{u} - \nabla \cdot \mathbf{q} + Q$

5. **Ohm's Law (resistive MHD):** $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{j}_\mathbf{p}, \mathbf{B} = \mathbf{B}_0 + \mathbf{B}_p$

MHD Plasma Simulation

Physical Model:

Legenda

$\nu = m_e/m_i$ is the mass ratio

μ_0 and ε_0 are the permeability and permittivity of free space

n is the number density

ρ is the mass density

v is the center of mass velocity

B is the magnetic flux density

E is the electric field

J is the current density

p is the scalar pressure

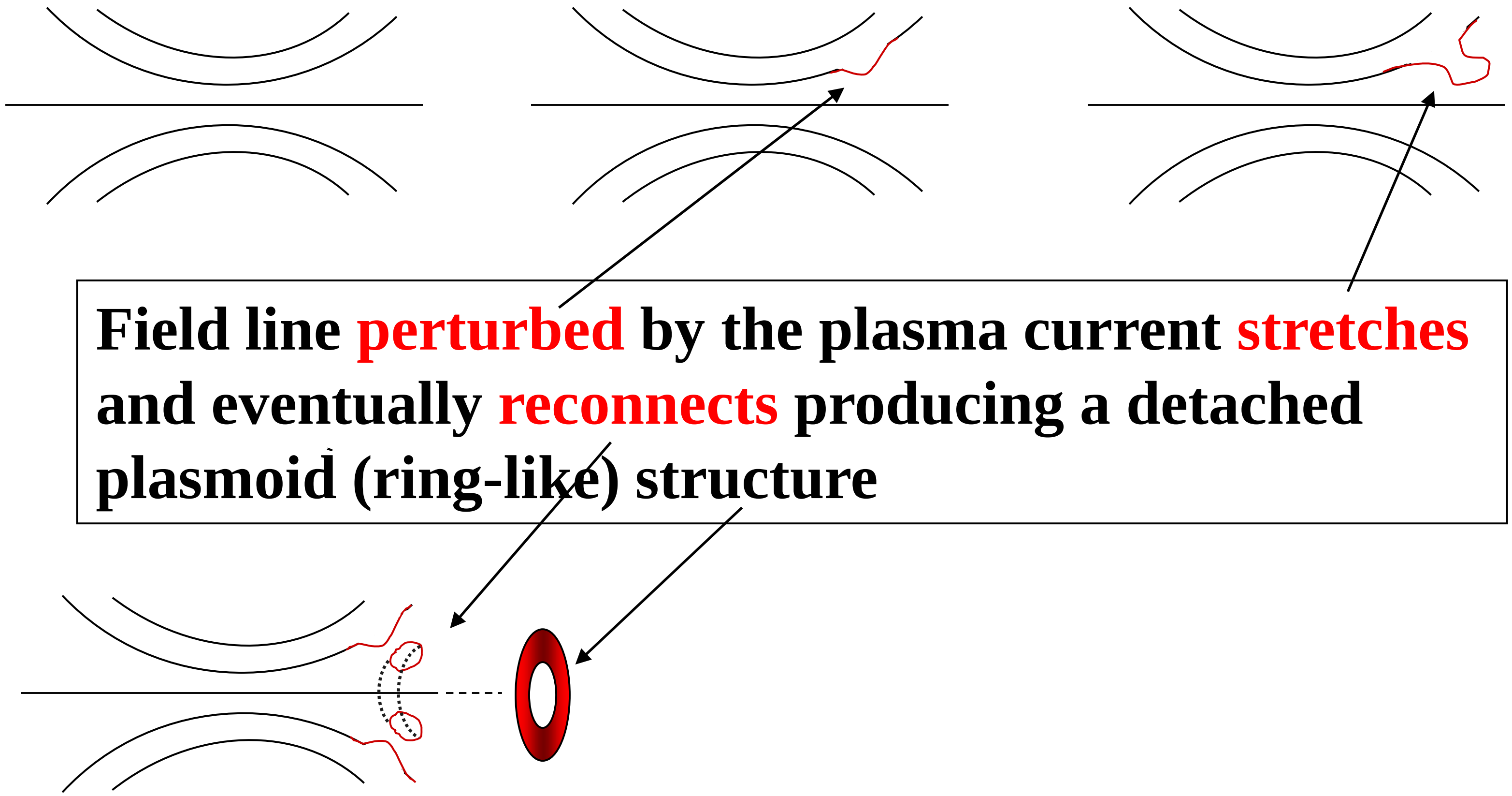
Q is the heat flux

η is the electrical resistivity

$\mathbf{P}' = p\mathbf{I} + \mathbf{\Pi}$, **I** is the unit tensor

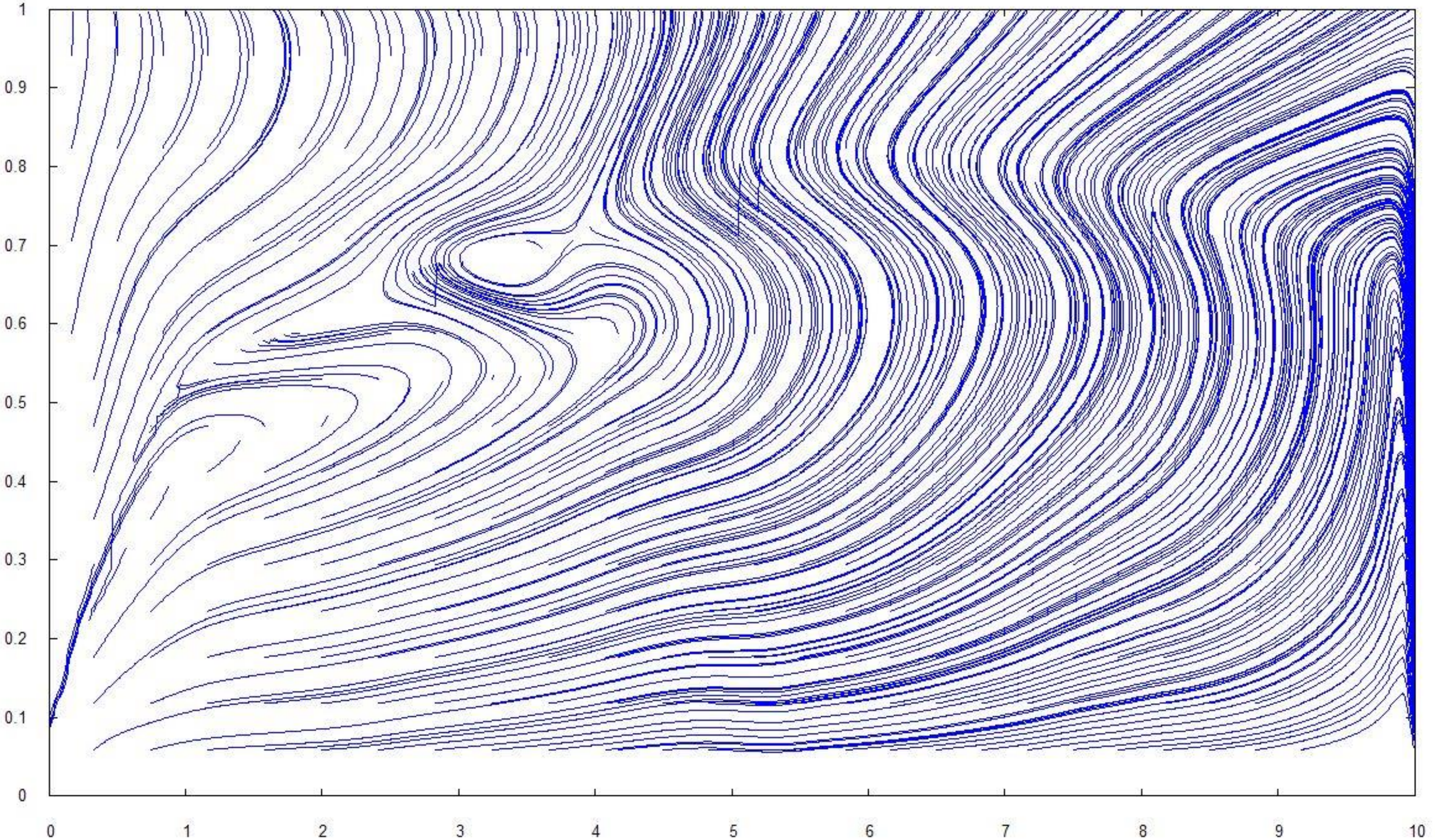
$\mathbf{\Pi}$ is the symmetric, traceless part of the stress tensor

Magnetic Reconnection Leading to Detachment



Field line perturbed by the plasma current stretches and eventually reconnects producing a detached plasmoid (ring-like) structure

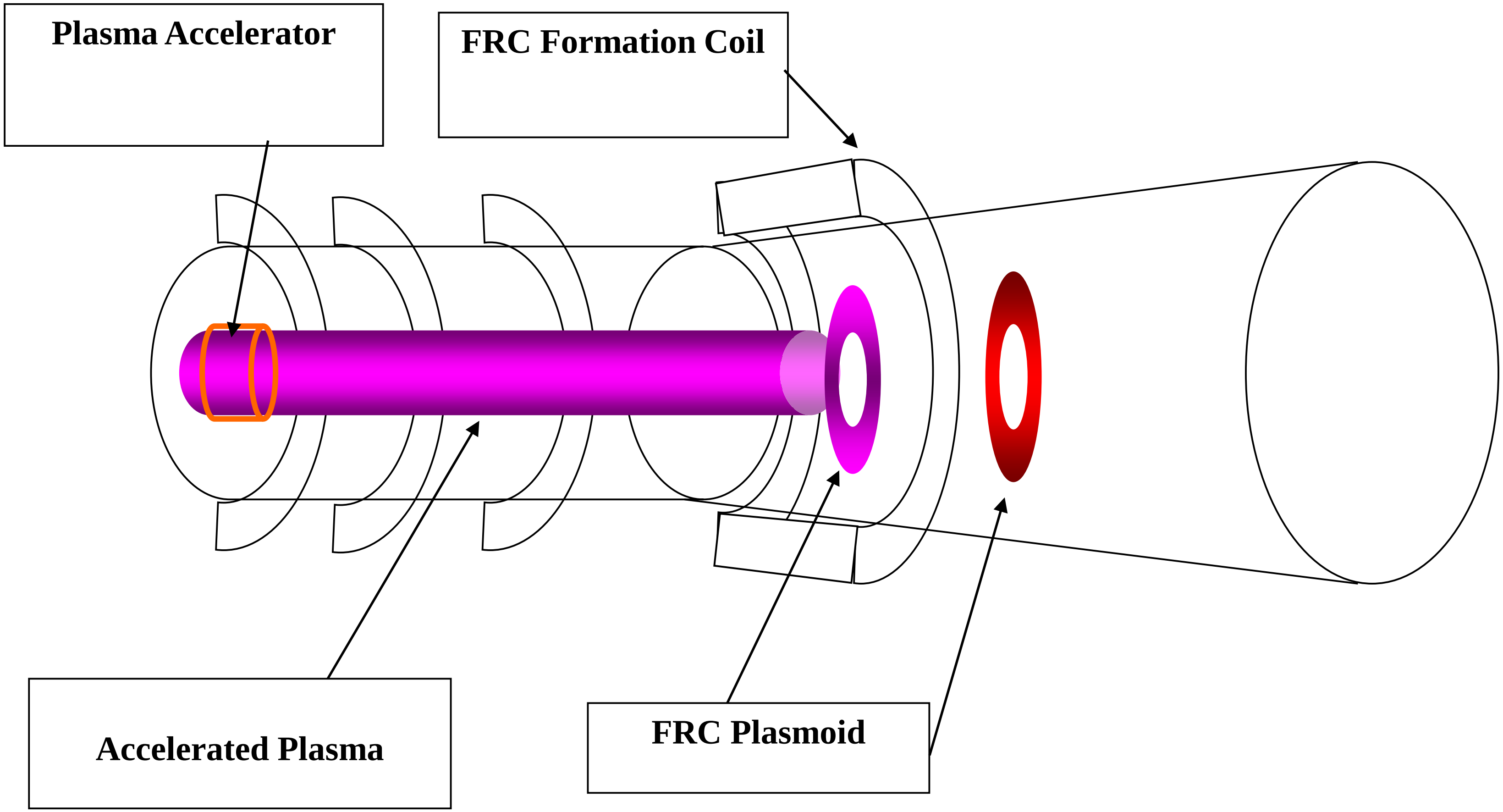
Reconnection Studies: Magnetic Nozzle Perturbation



NIMROD MHD Simulation: Step 450000 = 425 μs

FRC-based Plasma Thruster

- The plasma detachment in the nozzle is induced in a controlled way, through the formation of a sequence of FRC plasmoids.



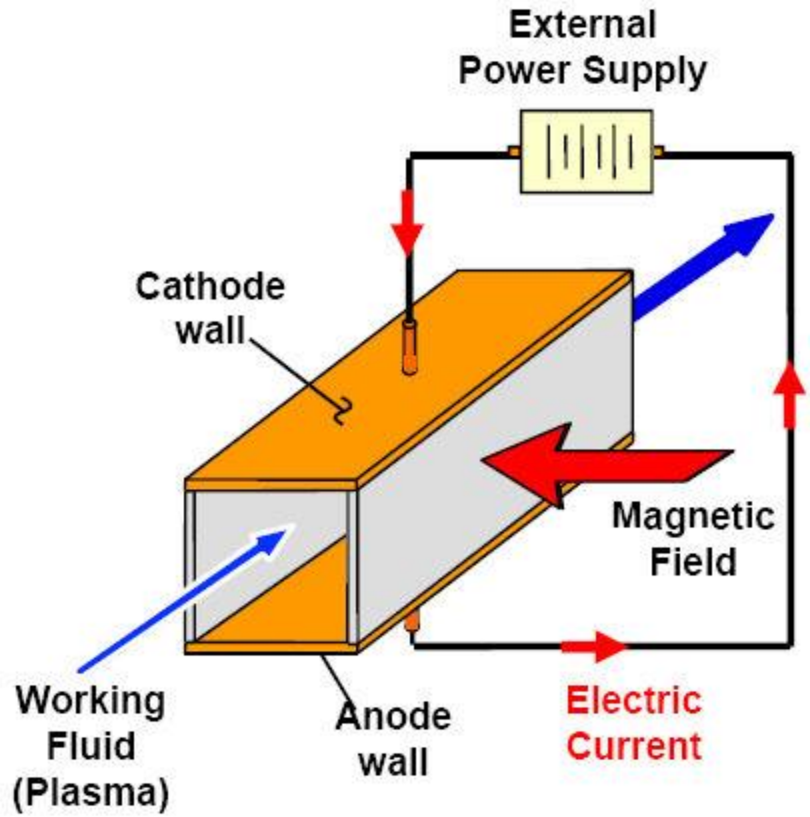
Simulation Hardware

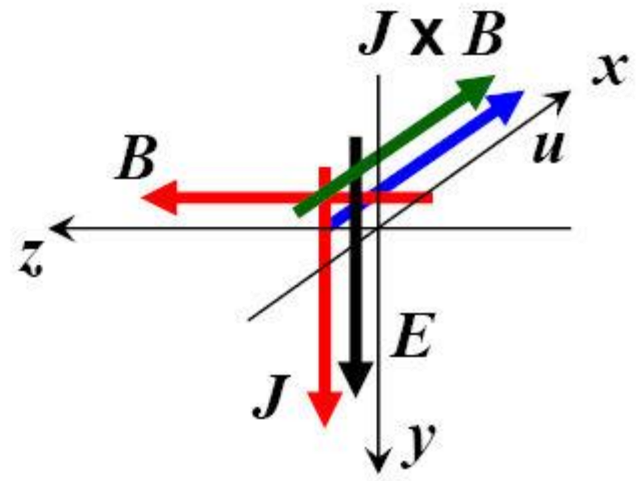
- "Columbia" at NASA-Ames: 20 SGI® Altix™ 3700 superclusters, each with 512 Itaniunm processors = 10240 processors

- In-house Linux Clusters

MHD Accelerator

Operating Principle for MHD Accelerator





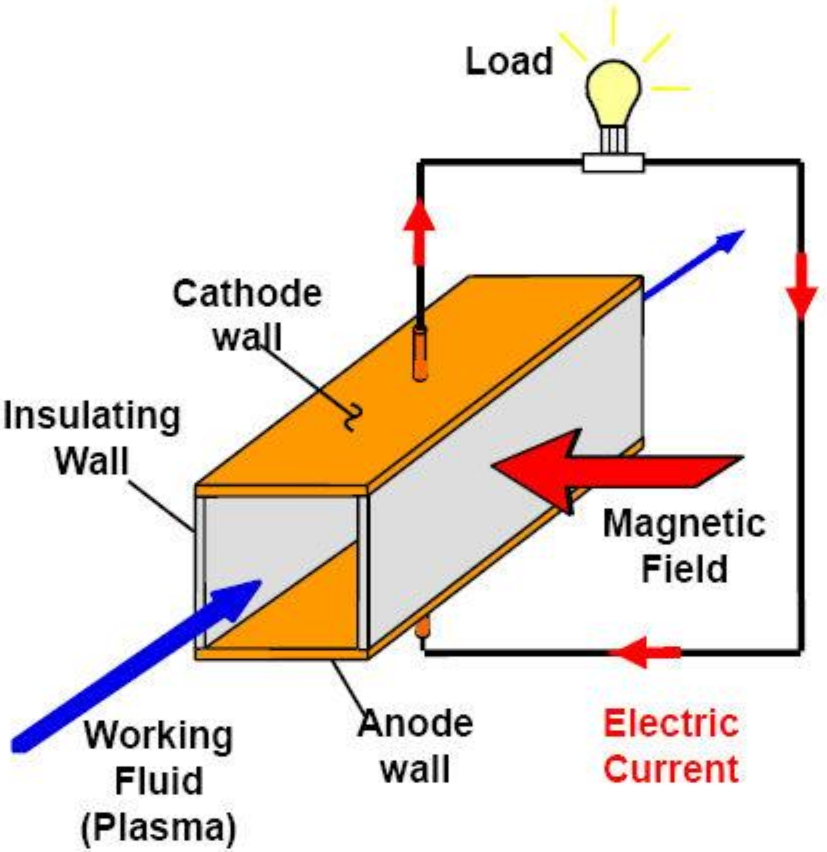
Elec. Power in : $P = J \cdot E$

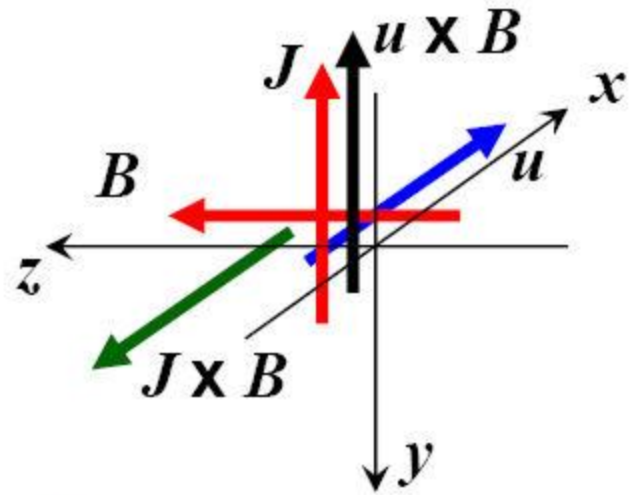
Increase of : Gas velocity
or Gas Pressure

Lorentz Force: $F = J \times B$

MHD Generator

Operating Principle for MHD Generator



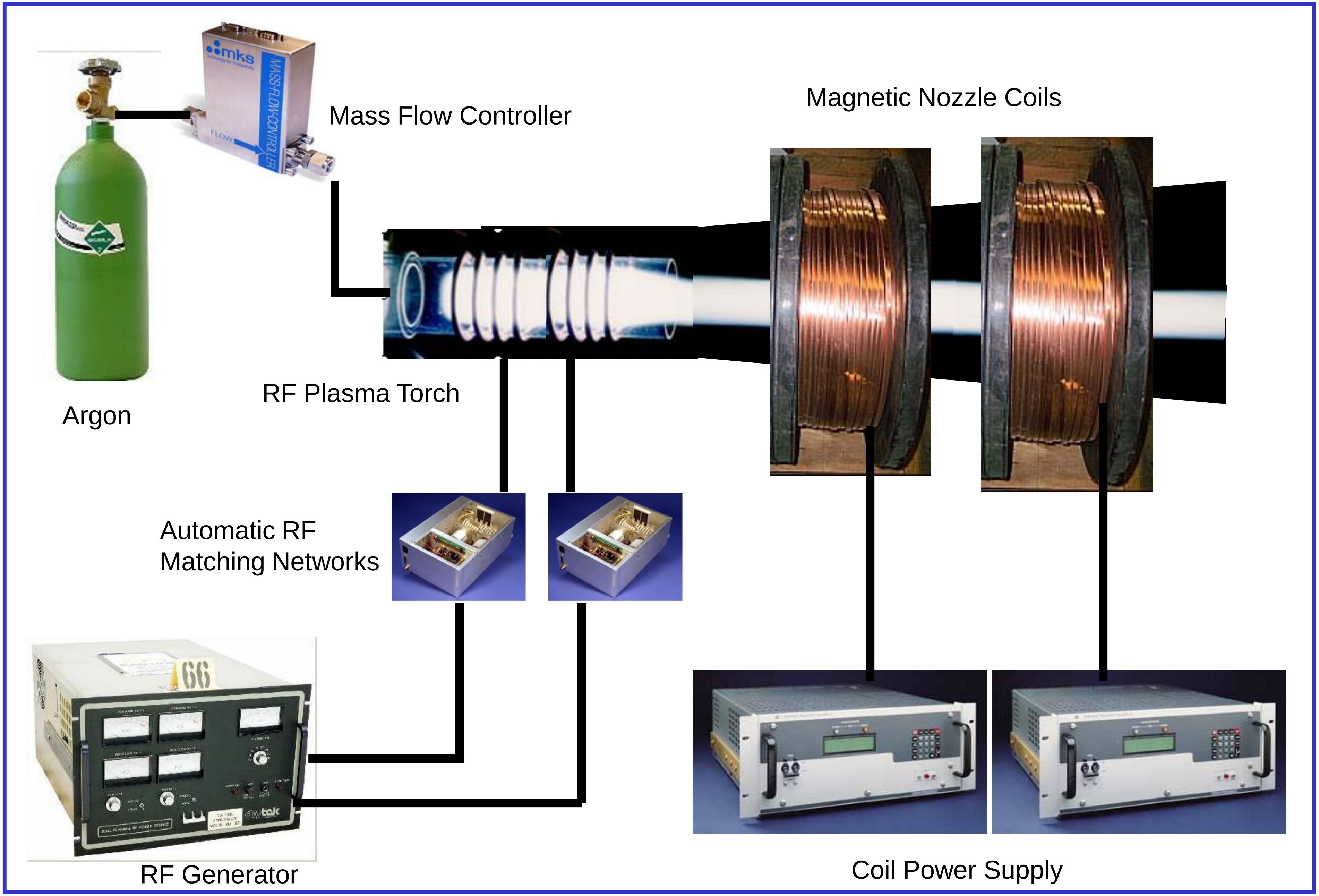


- MHD Generator is energy conversion machine

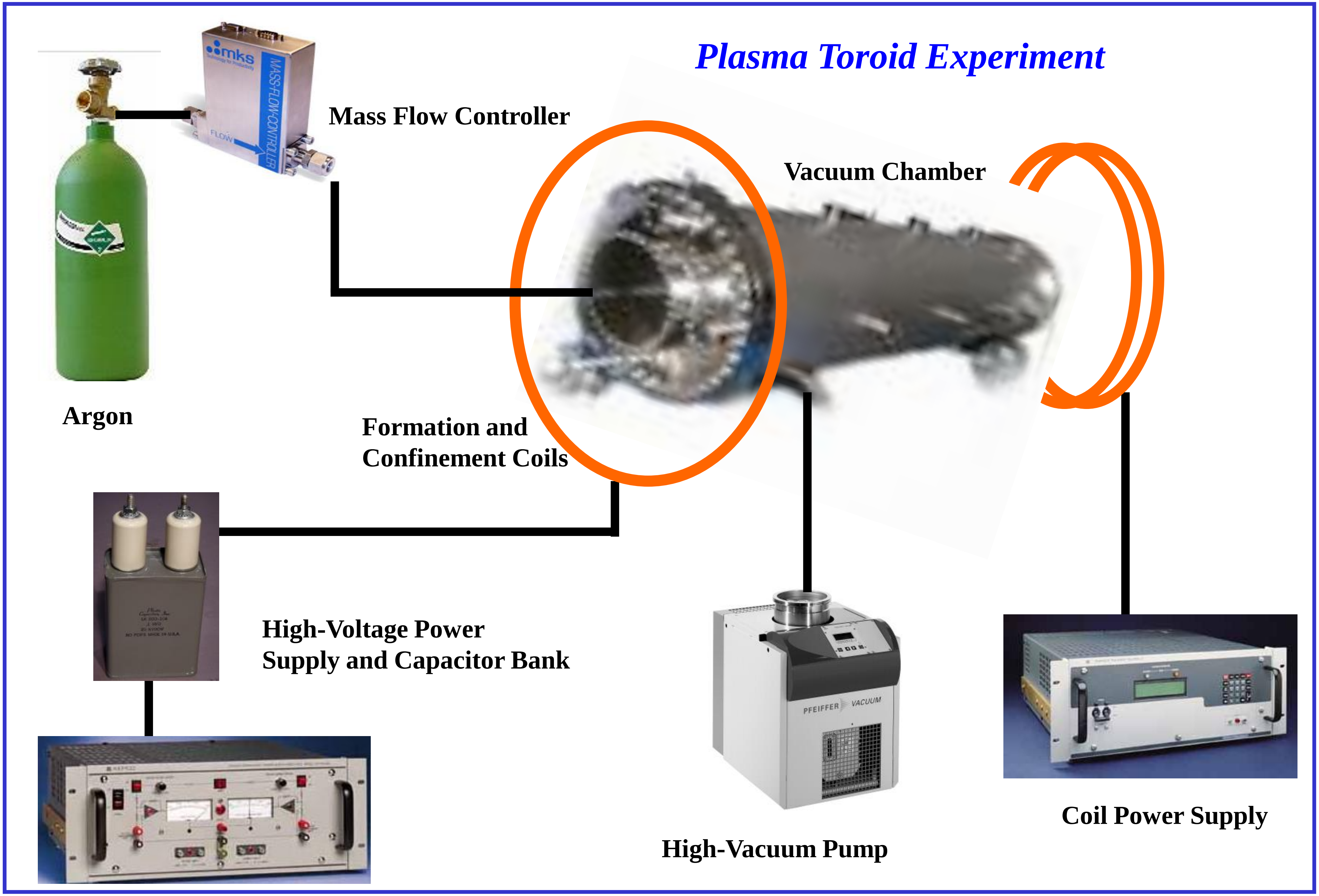
Lost enthalpy : $\Delta h = \boldsymbol{u} \cdot \boldsymbol{J} \times \boldsymbol{B}$

Elec. Power out : $P = \boldsymbol{J} \cdot \boldsymbol{E}$

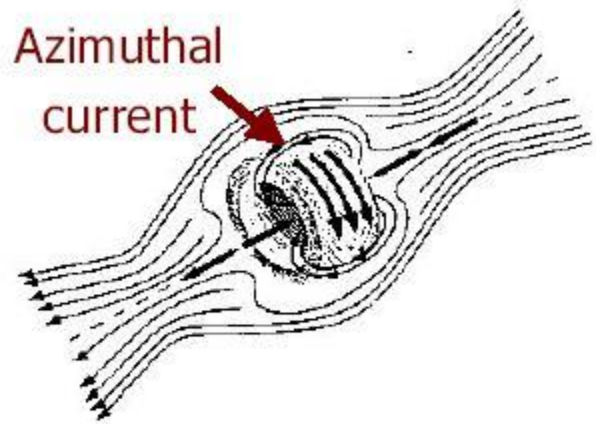
Building the UHCL Plasma Lab



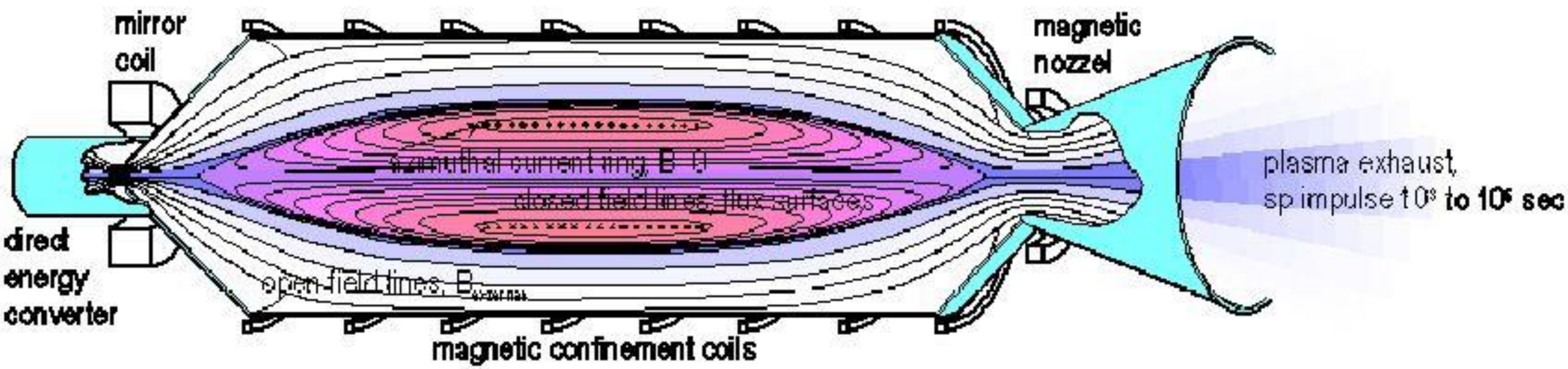
Building the UHCL Plasma Lab



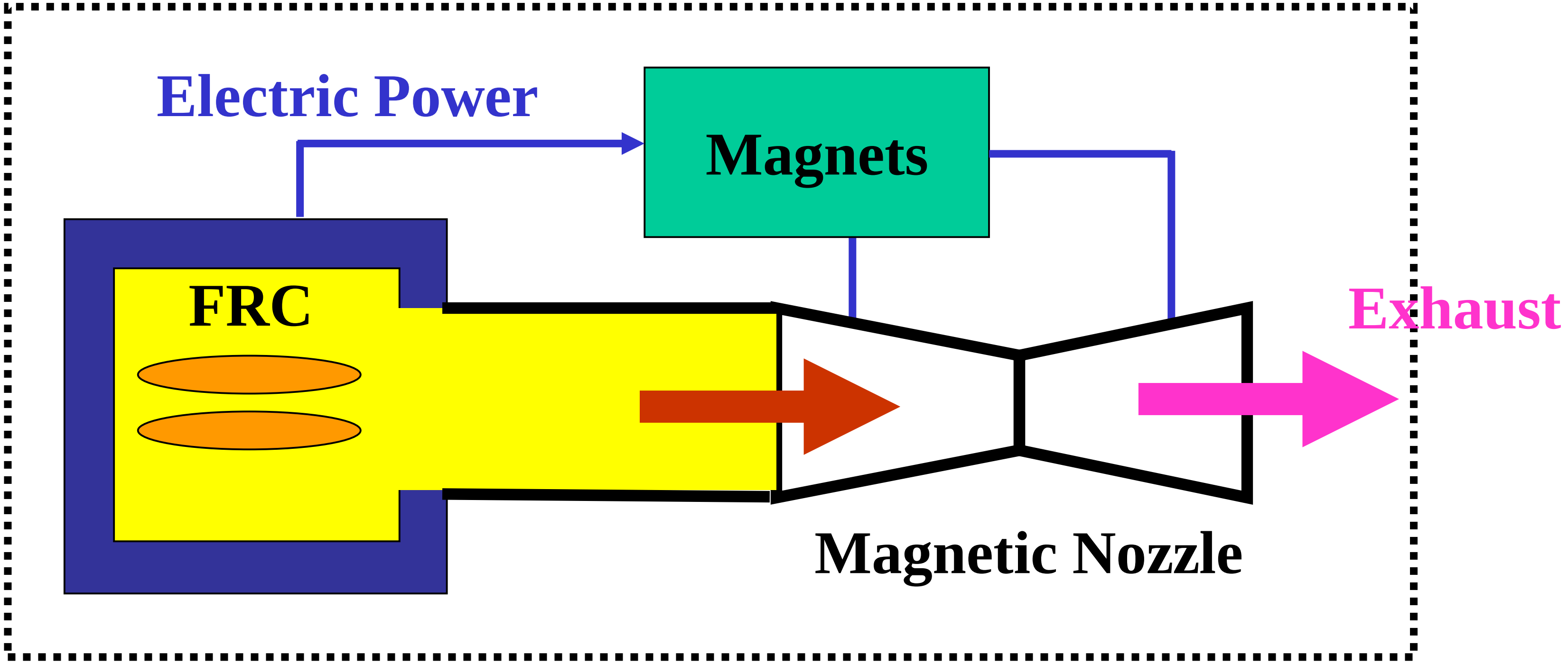
The **Field Reversed Configuration** (FRC) is a well studied plasma confinement scheme that is very appealing also for propulsion applications



- High $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- RMF current drive



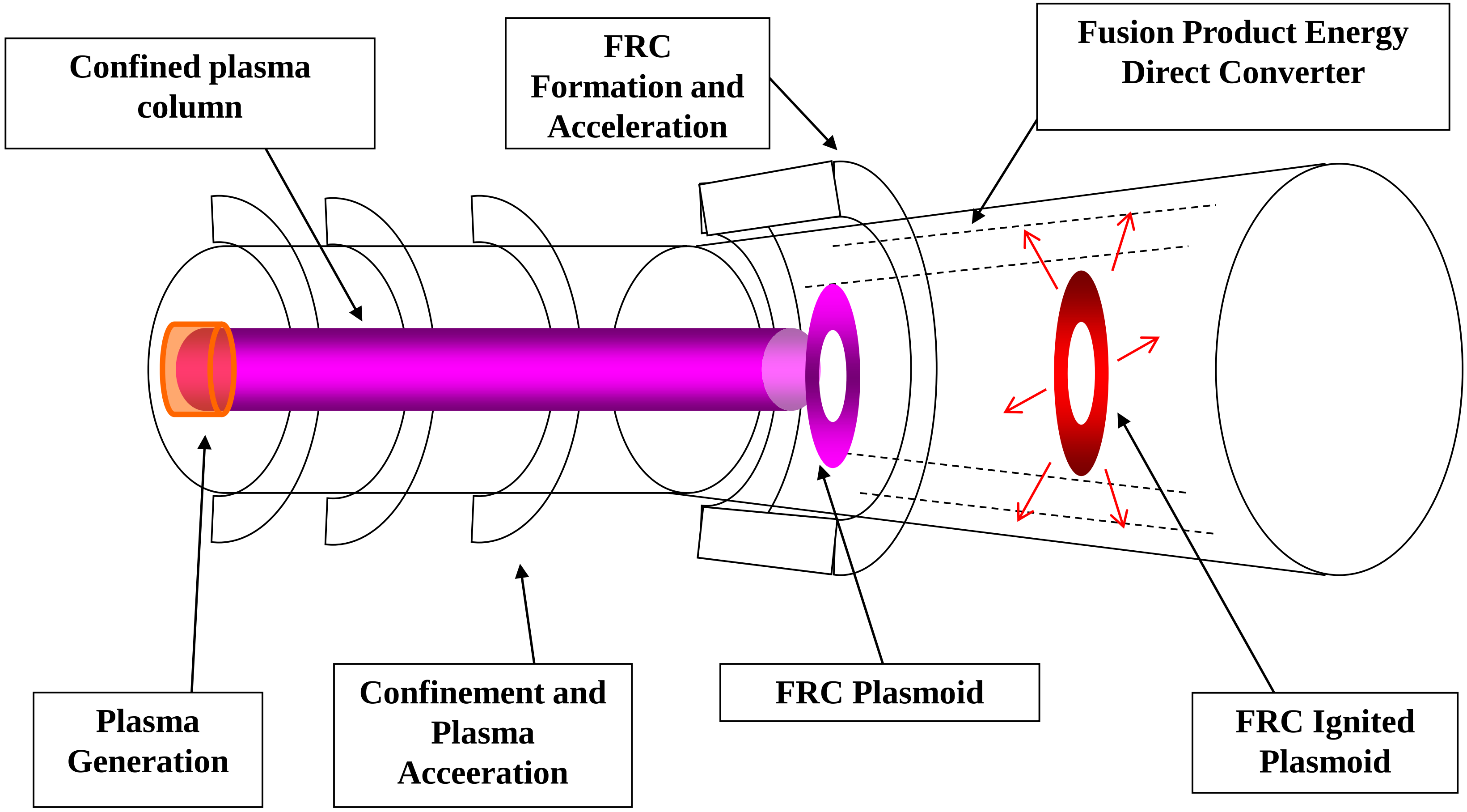
A conceptual scheme for a FRC Rocket



Plasma and power production scheme for a FRC fusion (still to be demonstrated…) direct propulsion rocket

FRC Plasmoid Fusion-Propulsion Concept

A sequence of FRC plasmoids is formed from an accelerated plasma column



APPENDIX A

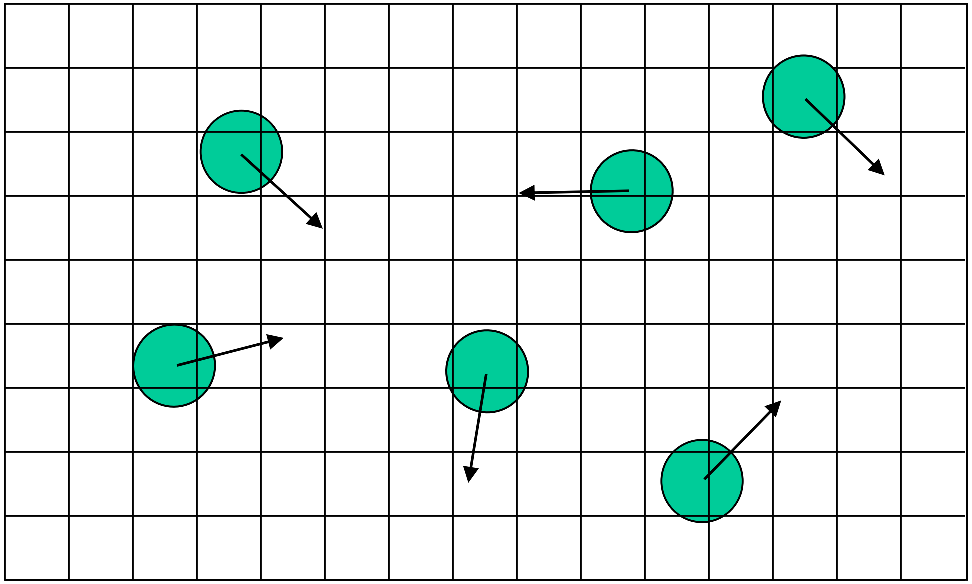
Particle Simulation

- The computer "particles" are elementary (at some level) constituents of a complex system
  - Examples:

System	Particles
Galaxies	Stars
Biological Systems	Macromolecules
Materials, Fluids, Gases	Molecules, Atoms
Plasmas	(Aggregates of) Electron, ions

Particle Simulation

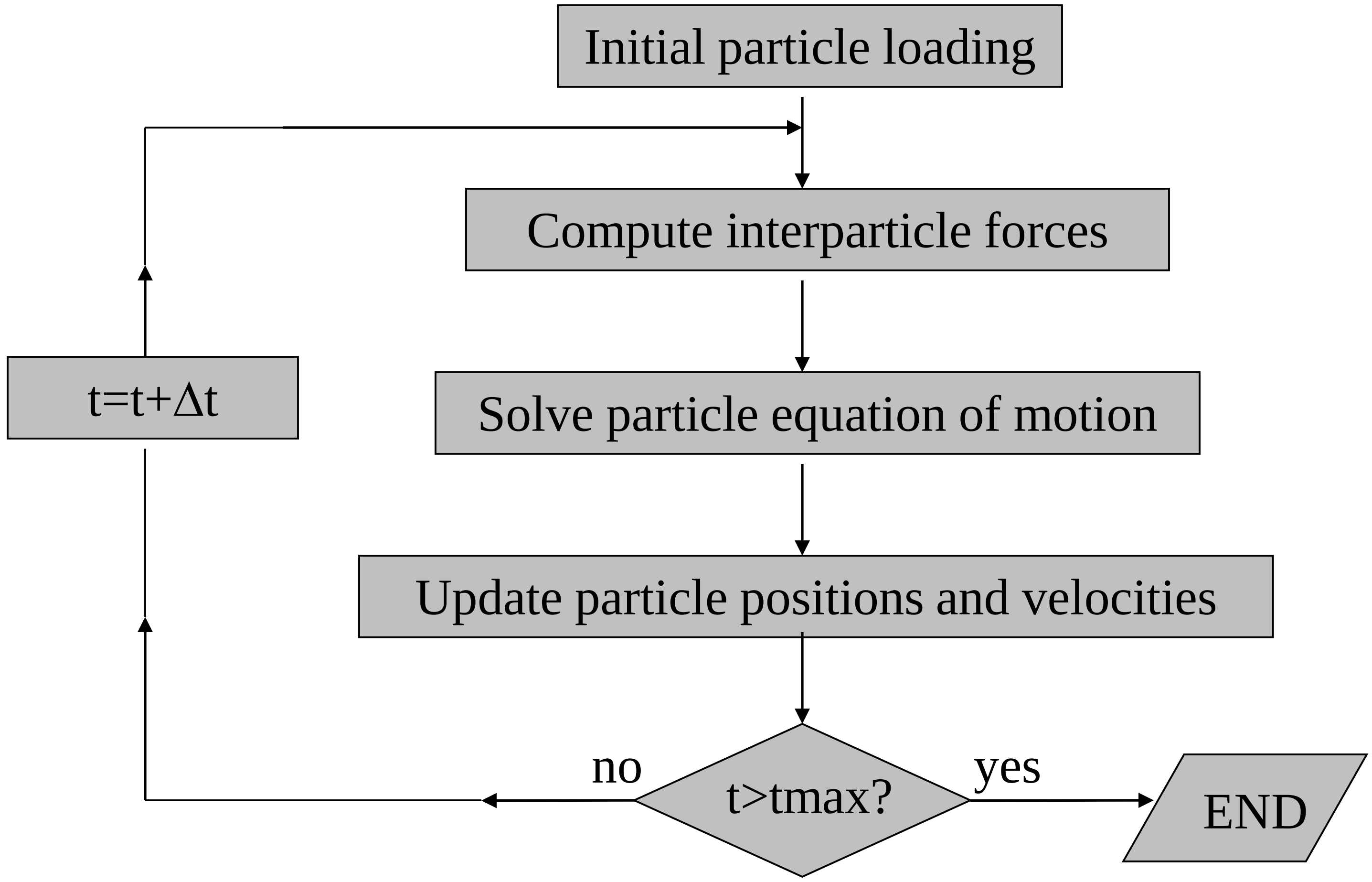
- A discretization grid is introduced to compute quantities like density, temperature, electromagnetic fields



Discretization of a 2D domain. In reality many particles per cell are typically considered

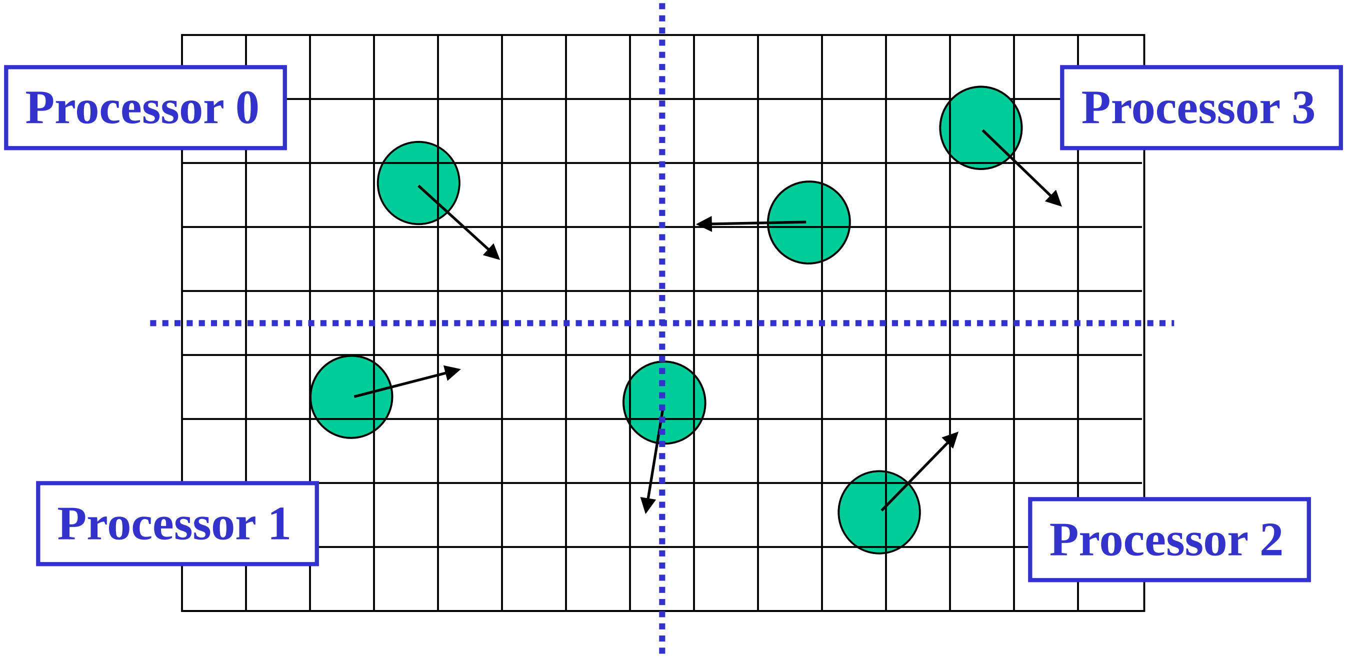
Particle Simulation

Basic Algorithm Summary



Massively Parallel Processing

- Parallel Computing: many "chips" (processors) working on the same problem at the same time



Massively Parallel Processing

- Parallel Computing cannot defeat the causality principle: only operations within the same time step can be performed simultaneously
- The "parallelization" must not add significant overhead.

  Linear scaling: doubling the number of processors reduces computing time in half
- Particle models can often be considered "embarassingly parallel" as their computational performances depend linearly on the number of particles
- Present day massively parallel computers can run simulations in the 100 million particle range (fusion plasma applications)

Massively Parallel Processing

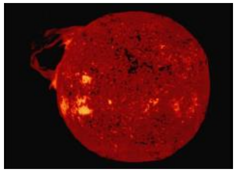
- ~Past: access to NASA and NERSC supercomputers (not so efficient anymore…)
- Present: Linux Cluster (in continuous evolution)
- Future: waiting for availability of cheaper 64-bit clusters

APPENDIX B

NIMROD MHD SIMULATION:

Fluid Modeling of Plasma Flow in a Magnetic Nozzle

Fluid Modeling of Plasma Flow in a Magnetic Nozzle

- Resistive (3D) MHD evolution of plasma profile in the magnetic nozzle: quantitative picture
- Effect of anisotropic conductivity on temperature and directed kinetic energy profiles
- Showing a case of plasma detachment (besides )
- Reconnection in the detaching plasma
- Electron temperature effects: two-fluid simulation
- 3D plasma exhaust stability analysis
- Magnetic nozzle efficiency

The tool: *NIMROD* Fluid Simulation Code

- NIMROD [3] DOE Multi-Institution Project
- MHD and two-fluid (ions and electron temperature)
- 3D (r-z-φ), nonlinear, time-implicit code
- General geometries (toroidal, cylindrical), non-orthogonal grid
- Finite element formulation
- Parallel code (supercomputers, Linux clusters)

[3] http://www.nimrodteam.org

NIMROD Equations

1. **Pre-Maxwell Equations:** $\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$, $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$

2. **Continuity Equation:** $\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0$

3. **Momentum Equation:** $\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = \mathbf{j} \times \mathbf{B} - \nabla p + \nabla \cdot (\nu \rho \nabla \mathbf{u})$

4. **Energy Equation:** $\frac{n}{\gamma - 1}\left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = -p\nabla \cdot \mathbf{u} - \nabla \cdot \mathbf{q} + Q$

$$\mathbf{q} = -n\left[\chi_{//}\hat{\mathbf{b}}\hat{\mathbf{b}} + \chi_{\perp}\left(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}\right)\right] \cdot \nabla T$$

$$Q = \eta \mathbf{J}^2 + \nu_{vis} \rho \nabla \mathbf{V}^T : \nabla \mathbf{V}$$

NIMROD Equations (II)

5. Generalized Ohm's law:

$$\mathbf{E} = -\underbrace{\mathbf{u}\times\mathbf{B}}_{\textit{Ideal MHD}} + \underbrace{\eta\mathbf{J}}_{\textit{Resistive MHD}} + \underbrace{\frac{1}{ne}\frac{1-\nu}{1+\nu}\mathbf{J}\times\mathbf{B}}_{\textit{Hall Effect}}$$

$$-\underbrace{\frac{1}{ne(1+\nu)}\nabla\cdot\left(\mathbf{P}_e' - \nu\mathbf{P}_i'\right)}_{\textit{Diamagnetic Effects and Neo-classical Closures}} + \underbrace{\frac{1}{\varepsilon_0\omega_{pe}^2(1+\nu)}\left[\frac{\partial\mathbf{J}}{\partial t} + \nabla\cdot\left(\mathbf{uJ}+\mathbf{Ju}\right)\right]}_{\textit{Electron Inertia}}$$

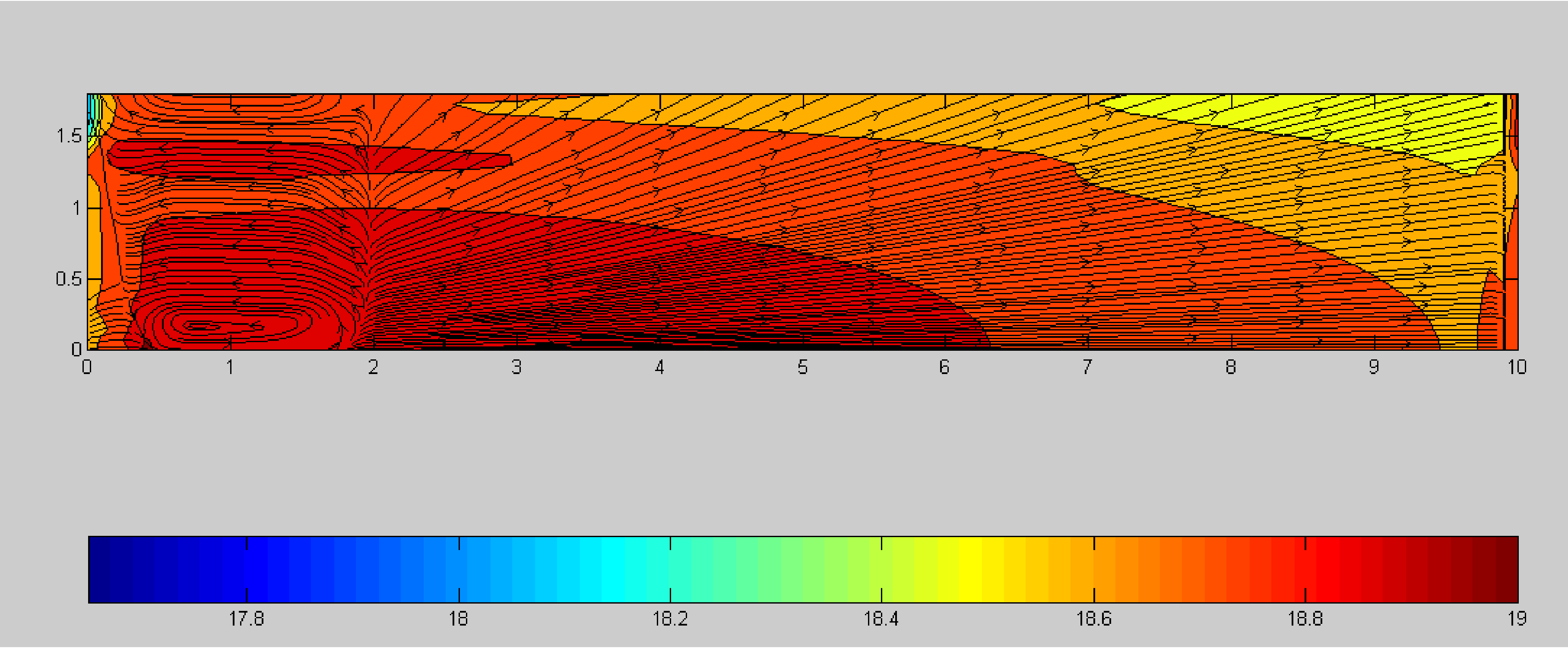
$$\mathbf{P}_\alpha' = p_\alpha\mathbf{I} + \mathbf{\Pi}_\alpha$$

$$\nu = m_e / m_i$$

Bounded Plasma Flow: Density Evolution

NIMROD Movie Clip

Simulation of Plasmoid Formation in the Nozzle



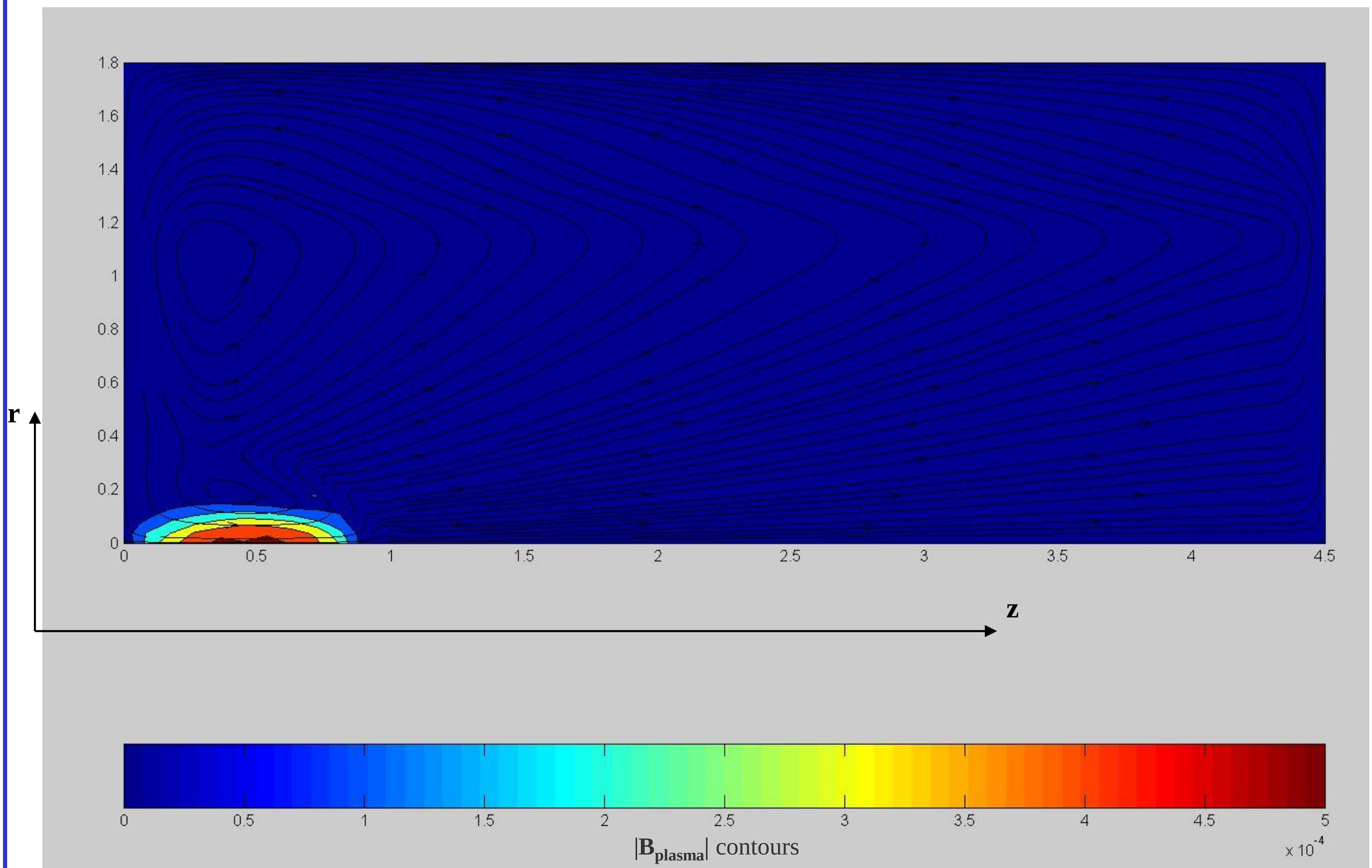
NIMROD Simulation: density contours and field lines with induced translating plasmoid in a 10 m long magnetic nozzle

“Open” Plasma Flow: Density Evolution

NIMROD Movie Clip

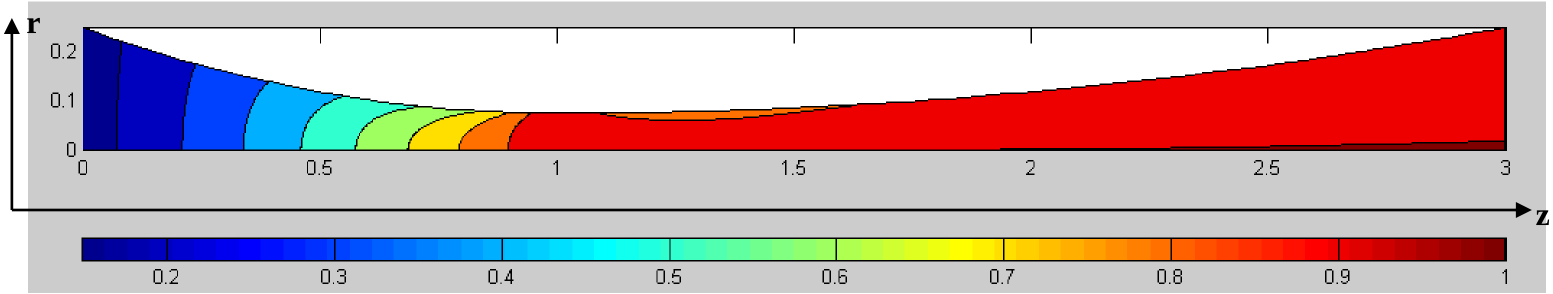
Plasma Magnetic Field

t=6μs

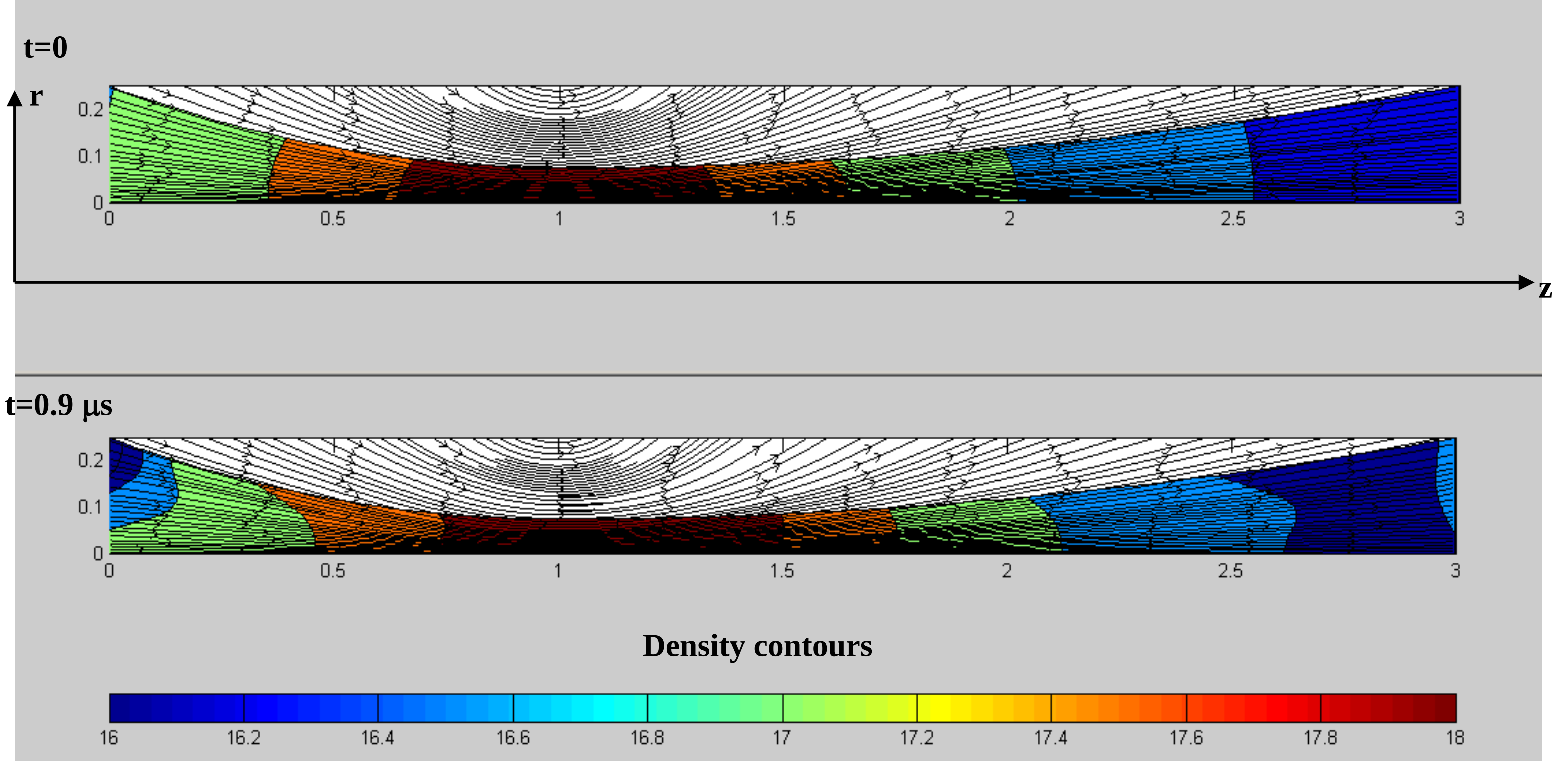


$|\mathbf{B}_{plasma}|$ contours

De Laval Magnetic Nozzle *NIMROD* Simulation

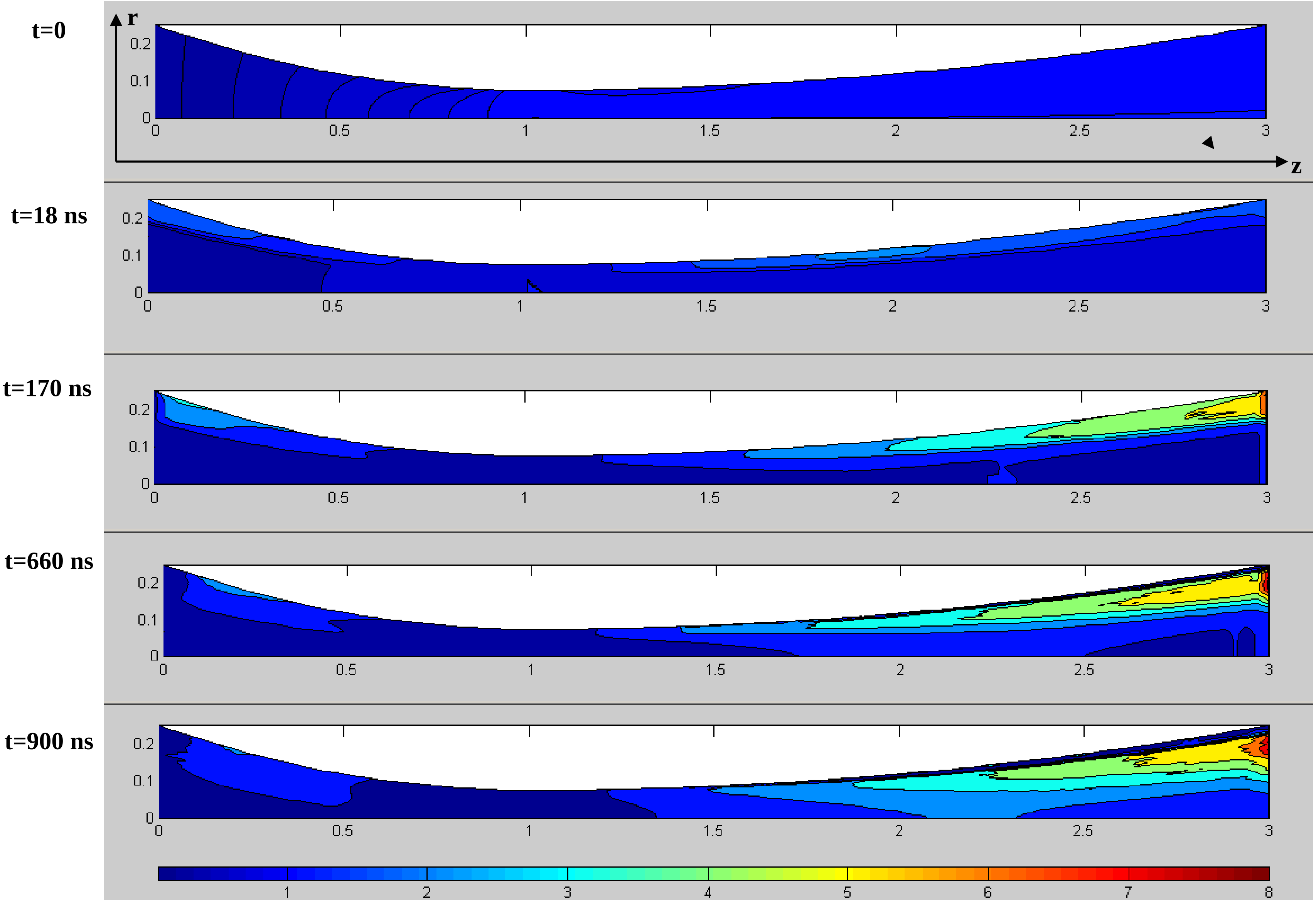


Mach # contours in t=0



Density contours

De Laval Magnetic Nozzle *NIMROD* Simulation



Time evolution of Mach # contours

NIMROD Simulation: Next Steps

- Fluid simulation with "strong" flows is not easy…
- Work in progress on improved matrix solver and open-end boundary conditions

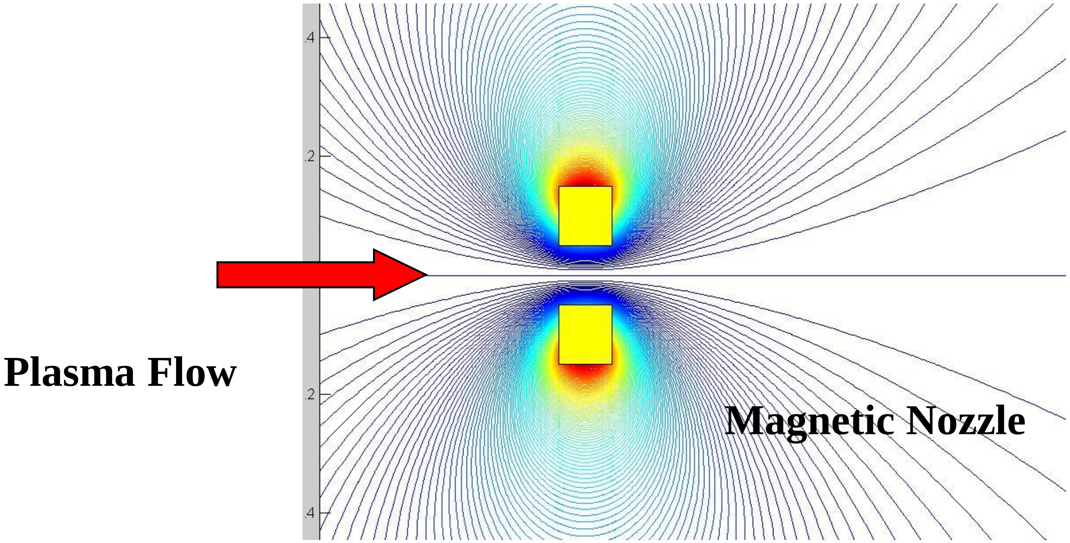
APPENDIX C

MHD Plasma Simulation

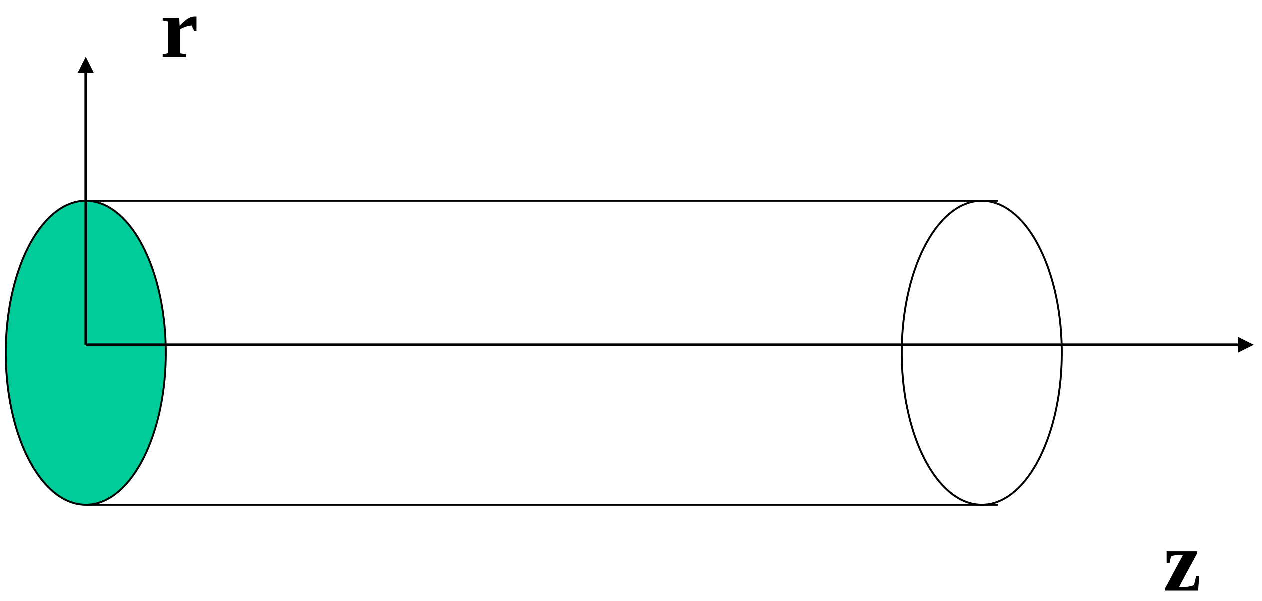
- Fluid, 3D code for magnetized plasma available in the public domain (US Dept. of Energy):
- No development from scratch, upgrades only
- Modeling 3D plasma plume dynamics in the magnetic field
- Studying the plasma exhaust detaching from the nozzle: computing useful thrust
- Magnetic nozzle design optimization for the maximum efficiency.

Theory of Plasma Flow in Magnetic Nozzle

- The plasma currents in the nozzle: physical analysis and estimates
- Perturbation of the external magnetic field: qualitative picture
- Reconnection patterns and detachment: physical picture

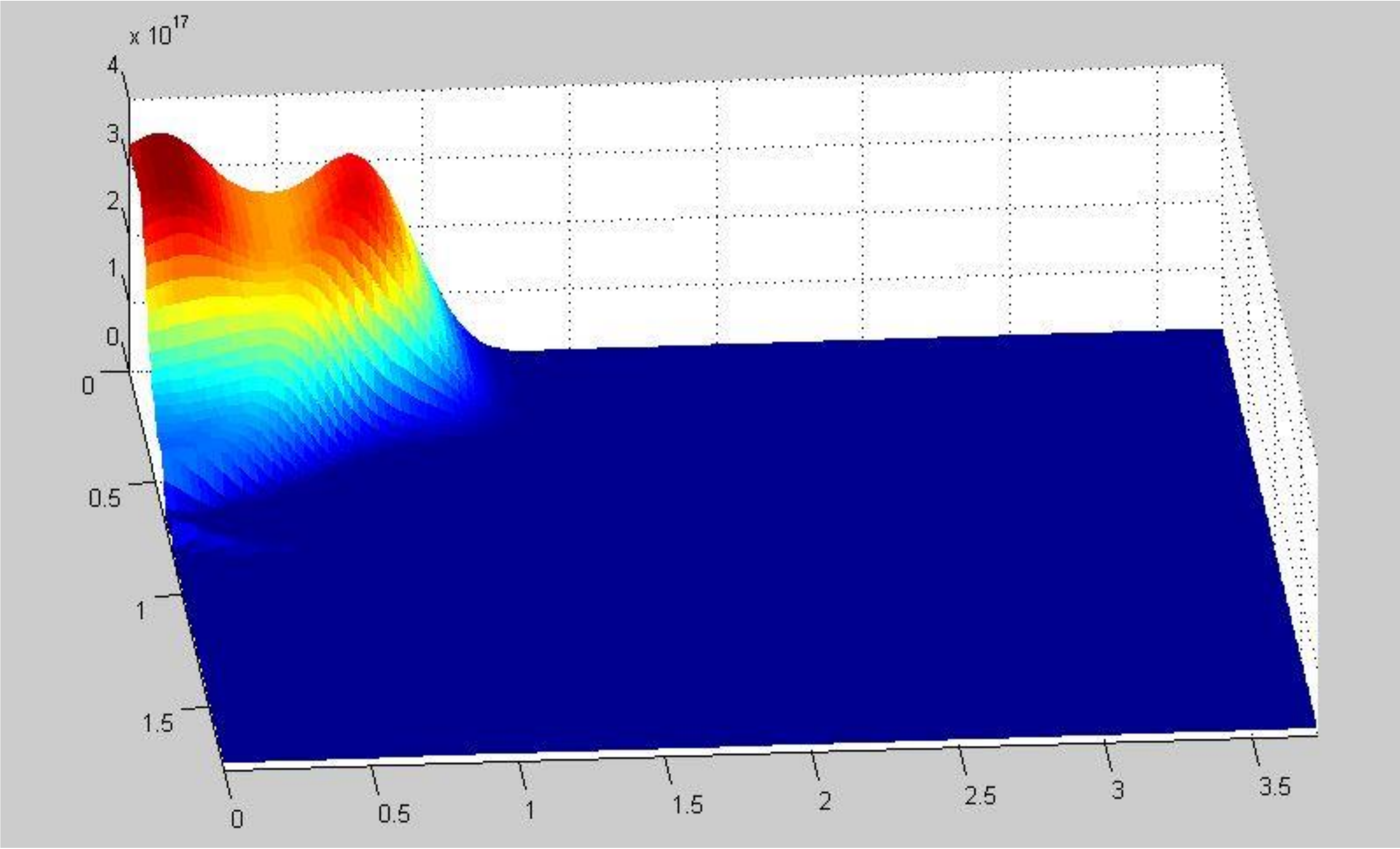


MHD Plasma Simulation



Model Geometry

MHD Plasma Simulation



Currents in the Exhaust Plasma

- Diamagnetic current

$$\mathbf{j}_D = -\frac{\nabla p \times \mathbf{B}}{B^2}$$

- Grad-B current

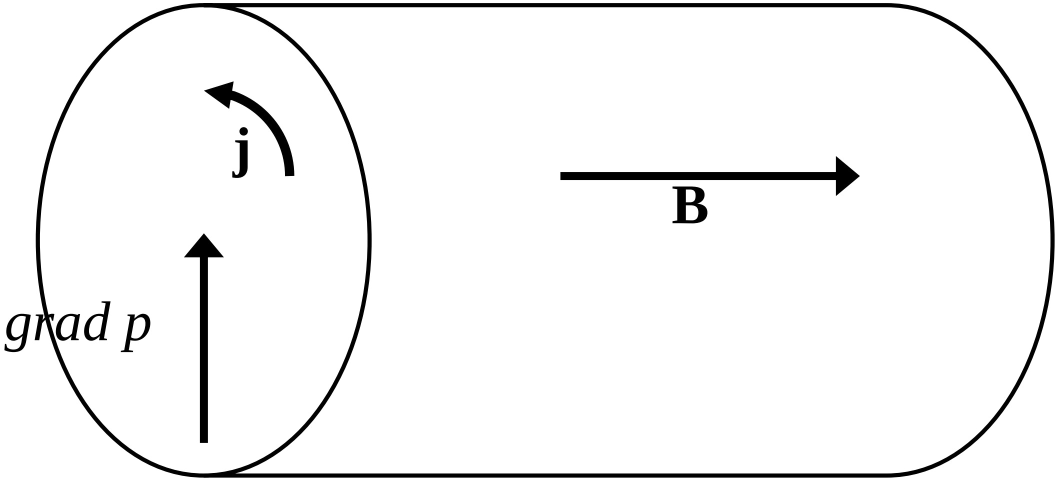
$$\mathbf{j}_{cf} = -nmv_{\parallel}^2 \frac{\mathbf{R_c} \times \mathbf{B}}{R_c^2 B^2}$$

- B-Curvature current

$$\mathbf{j}_{\nabla B} = -nq\frac{1}{2}v_{\perp} r_L \frac{\mathbf{B} \times \nabla \mathbf{B}}{B^2} = -nm\frac{v_{\perp}^2}{2}\frac{\mathbf{R_c} \times \mathbf{B}}{R_c^2 B^2}$$

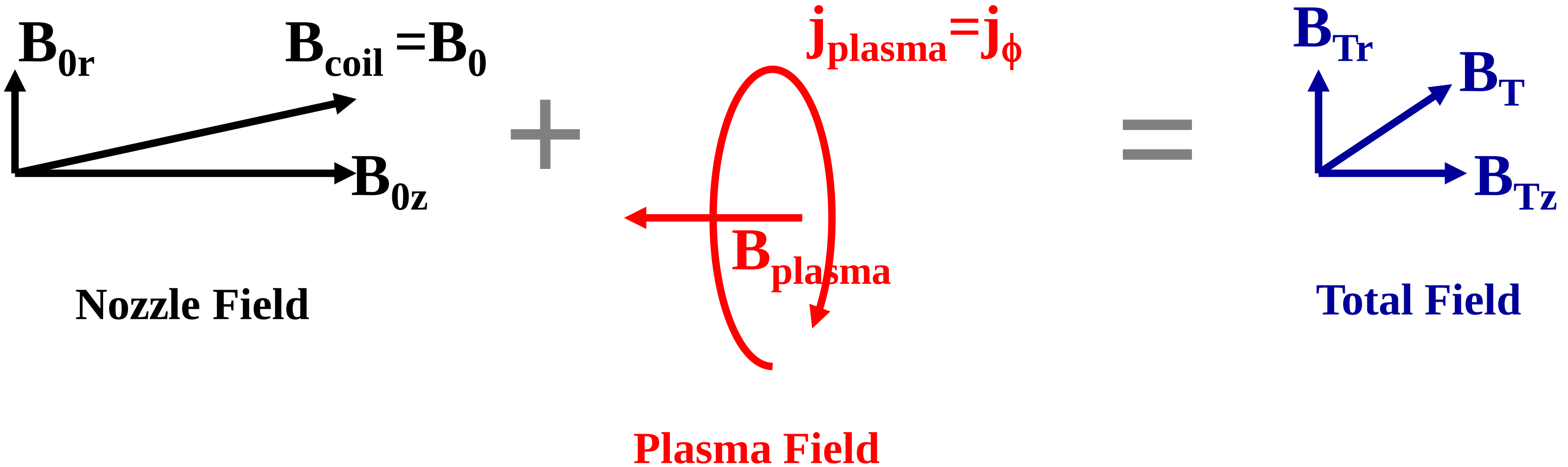
Diamagnetic Current: Physical Picture

- Diamagnetic current produced by the pressure gradient

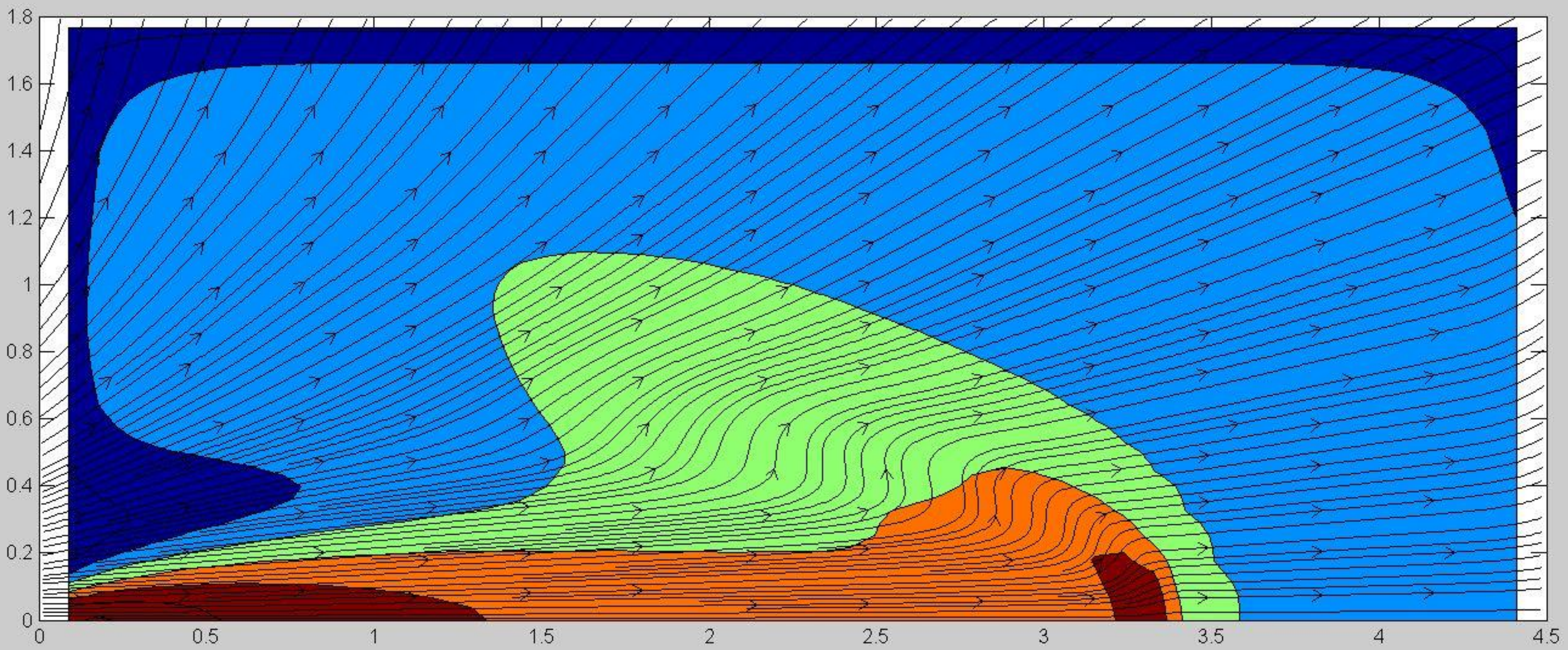


$$\mathbf{j} = \frac{\mathbf{B} \times \nabla p}{B^2} = \frac{\mathbf{B} \times \nabla [n(k_B T_i + k_B T_e)]}{B^2}$$

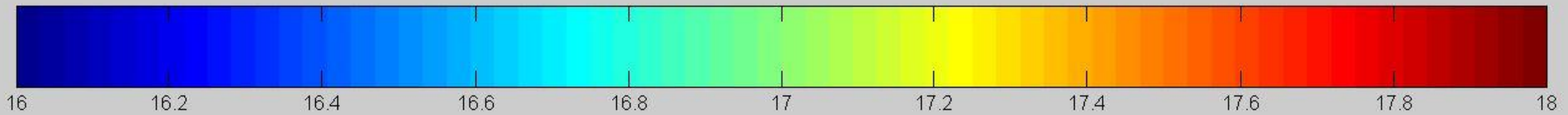
Magnetic Nozzle Perturbation



Magnetic Nozzle Perturbation: MHD Simulation



NIMROD MHD simulation: snapshot showing a plasma transient propagating while perturbing the magnetic nozzle field



Log(density) contours