# RF Catalyzed MHD Power Generation

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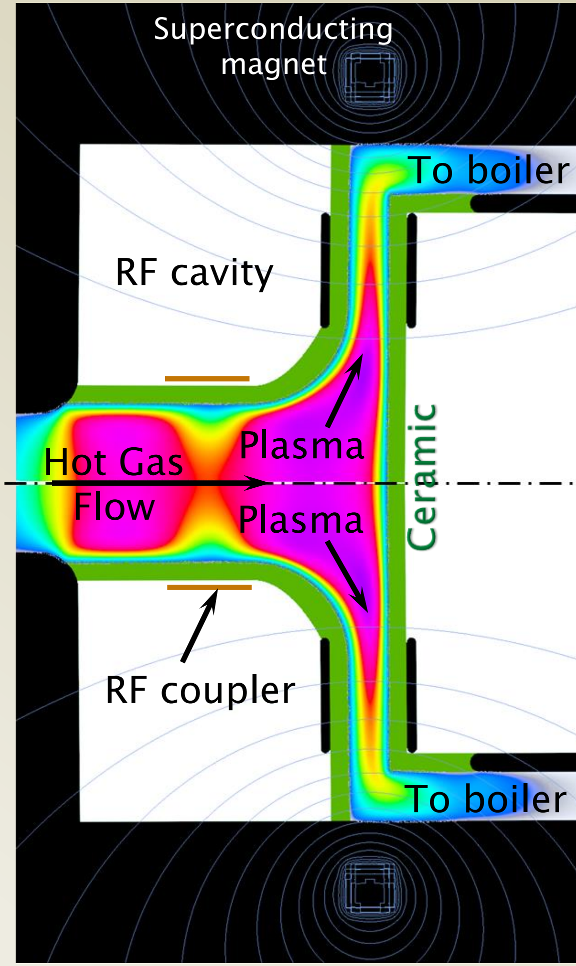
# Concept

- Radio Frequency (RF) power injection just upstream of the MHD power generator can ionize gas to enhance conductivity right where needed
  - RF creates a non-equilibrium electron energy distribution for electron impact ionization
  - Relatively uniform volumetric ionization
  - Magnetic fields allow industrial radio (near FM band) to couple to high-harmonic fast waves (helicon-like modes)
- Plasma flows across a strong magnetic field for MHD generation before recombination can occur
  - Joule heating by MHD currents may also prolong the plasma state
- DC electrode pickup with continuous RF power
- Or, RF power pulses can modulate MHD currents to allow inductive pickup without electrodes in plasma

# RF pulse train for MHD inductive pickup

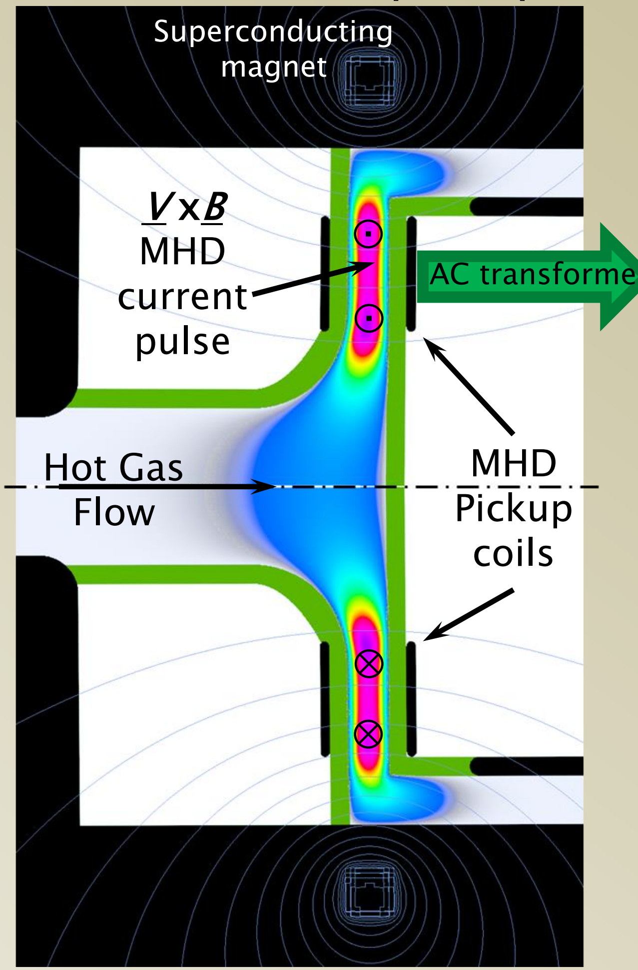
- RF power upstream of the magnet can generate a pulse of plasma (<1% ionized) with high electrical conductivity (~100s of S/m)
- Pedersen current (~MA/$m^2$) can be picked up as AC pulses when plasma passes between pickup coils in high magnetic field region

RF plasma pulse




AdAstraRF code

MHD transient pickup




Qualitative only

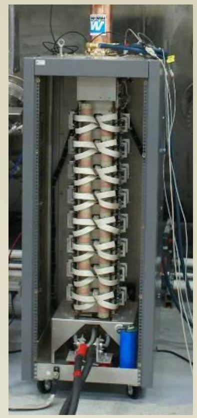
# Relevant Ad Astra work

- United States Patent No – 8593064 B2, “Plasma Source Improved with an RF Coupling System,” November 26, 2013
- VX-200 experimental operation at 2 Tesla and up to 200 kW RF with over 10,000 shots fired (2010 to 2012)
  - Conduction-cooled superconducting magnet has no liquid cryogens
  - Rarefied argon injection pressure ~ 0.01 bar (room temp)
  - Source startup to ~100% ionization of flowing argon stream in ~ 10 ms (neutral gas oscillations in transition to full ionization)
  - Plasma density ~ mid $10^{20}$ $m^{-3}$ with argon at 40 kW
  - An additional ~160 kW of ion cyclotron power is added to achieve argon ion energies up to ~500 eV
  - RF power density is on the order of 30 $MW/m^3$
- Complex ceramic manufacturing and seals with custom silicon nitride parts from 3M (formerly Ceradyne)
- Metal-to-ceramic and ceramic-to-ceramic seals for over 1000 C in support of plasma source development
- High-temperature superconducting magnet designs with Stirling cycle conduction cooling (liquid-free) in collaboration with SuperPower, Inc., Schenectady, NY

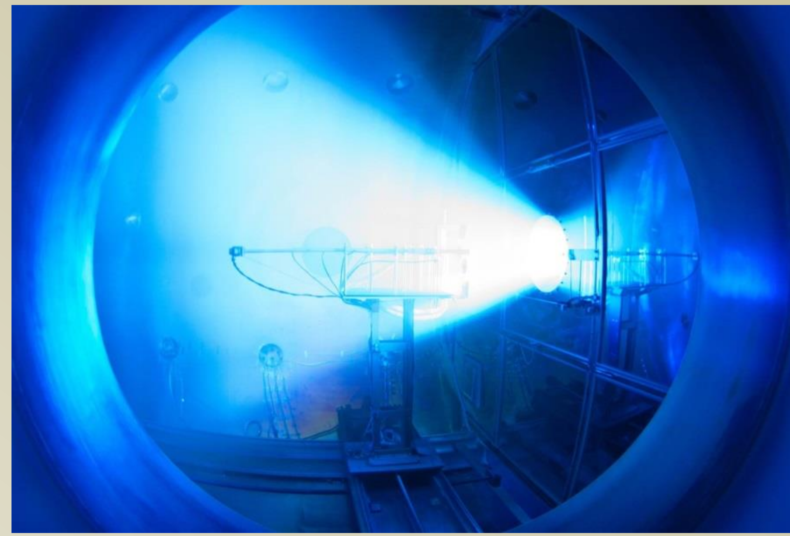
# VX-200 basics

Niobium-Titanium superconducting magnet

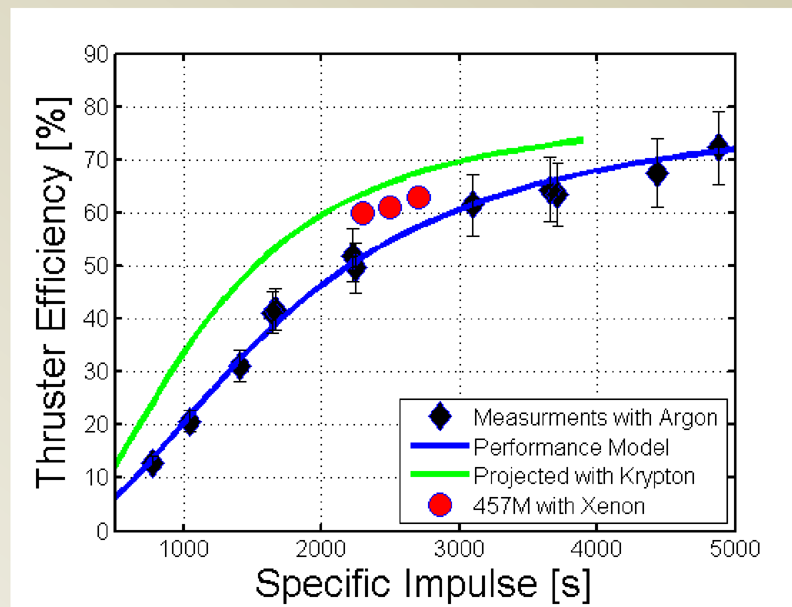
ICH booster PPU
170 kW
(98% efficient)



Plasma plume during tests with thrust target and other plasma diagnostics



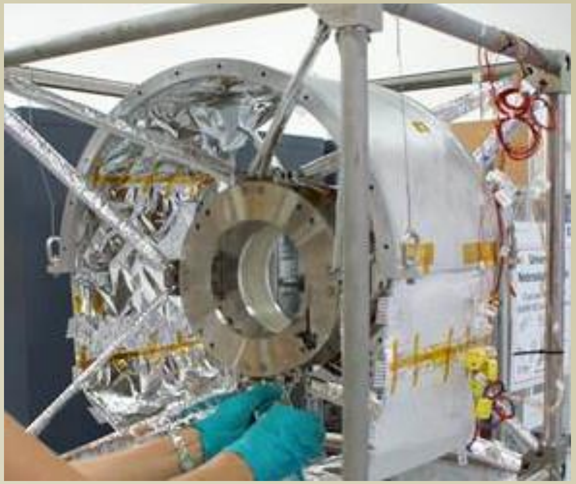
Integrated magnet and rocket core in test bus ready for vacuum and plasma performance testing

# Long duration VX-200 "shot"

# Superconducting magnet manufacturing and cryo-cooler tests

- High-temperature superconducting (HTS) magnet coil prototype development and testing completed in 2007 (Creare, Tai Yang) to TRL-5
- Preliminary design of proto-flight coils complete in 2008 (continuing refinements as HTS product performance improves)
  - 2nd generation HTS vendor is Superpower, Inc (Schenectady, NY)
  - Three vendors have expressed interest in critical design and manufacturing
- Cryocooler baseline model and placement finalized in 2013 preliminary design (Sunpower GT)



# Advantages and applications of RF catalyzed MHD

- RF analogous to MHD plasma “turbocharger”
  - High conductivity with lower gas temperatures
  - No impurity addition
- Electrode-less AC extraction is possible
  - Pulsed ionization for reasonably uniform conductivity
- Efficiency enhancement for open cycles
  - Can be added as a topping cycle
  - Coal flue gas from conventional or oxy-fuel
  - Brayton cycles such as natural gas or jet fuel
- Efficiency enhancement for closed cycles
  - Gas cooled nuclear reactors
  - Low mass electrical power generation in space

# Key design considerations

- Collisionality plays a strong role in:
  - RF absorption
  - Plasma diffusion and confinement
  - Conductivity characteristics (Hall or Pedersen)
- High conductivity is necessary for good gain
  - Plasma current is proportional to ionization fraction
  - Volumetric and surface recombination limit the maximum ionization fraction
- Gain ($Q_{rf} \equiv P_{mhd}/P_{rf}$)
  - RF power is recovered as heat, but conventional electrical conversion back to coupled RF is likely ~ 30%
  - $Q_{rf}$ must be ~ 10 and the bigger the $Q_{rf}$ the better
  - Preliminary estimates indicate that gains ~100 may be possible with electrode-less power extraction
- Self-consistent MHD currents and fields

# Hall or Pedersen?

- Scale lengths are on the order of 1 m
- Practical magnetic fields of this size are ~ 5 T using today's HTS technology
  - Electron cyclotron frequency less than 150 GHz
- Neutral density at a few bar and 1000 C is on the order of $10^{25}$ per cubic meter
- Pedersen conductivity is likely to be higher than Hall, but methods to exploit both phenomenon should be considered self-consistently
- Disk geometries may allow inductive pickup of Pedersen currents
- Self-consistent MHD currents and geometry

# Key development considerations

- RF power levels must be technologically feasible on a power plant scale
  - $P_{rf}$ on the order of hundreds of kW to a few MWs
  - Broadcast radio power technology is adequate
  - RF coupler configurations in a relevant environment are challenging, but doable with modern ceramics
- Large ceramic parts are becoming readily available but manufacturing is expensive
  - Silicon nitride is a good candidate for this app
  - High-level skill set needed for machining and seals
- Superconducting magnets of appropriate size and field strength must be thermally isolated
  - High temperature superconductors with cryocoolers are available but expensive

# Questions to consider

- What are the ionization properties of hot flue gas?
  - Oxy-fuel $CO_2$ stream from coal, hotter is better
  - Geometry to obtain proper expansion and flow
  - Turbulent flow may increase surface recombination rate
- What RF frequency is best?
  - RF injection power and voltage are affected by the RF frequency and geometry at the RF injection location
- What RF coupler geometries are best?
  - Wave accessibility for best power deposition and location
  - Manufacturability and thermal management of the coupler and cavity
- Should MHD power generation by DC or AC be emphasized?
  - DC extraction has significant experience but electrode difficulties
  - AC extraction eliminates electrode arcing in plasma, but little experience, so more experimentation will be needed
  - AC circuit/transformer design for MHD power extraction
- Can large ceramic parts and seals be manufactured?
  - Straight ceramic tubes for RF injection are straightforward (DC or AC)
  - Disk shapes for AC inductive power extraction are difficult but doable
- Will MHD instabilities affect the design?
  - Self-consistent magnetic field geometry