Electrically Small Antennas

Project Objective
Development of an electrically small antenna, capable of ~ 1 MW cw power output, tunable from ~ 3 to 10 MHz

Accomplishments / Progress
• Experimental verification of antenna concept and tuning capability at 100 MHz (30 MHz to 100 MHz)
• Experimental demonstration of full size antenna at 10 MHz (limited tuning range from 9.5 to 10 MHz)
• Verified conventional antenna drive (sinusoidal source through 50 Ohm coax)
• Verified direct drive approach
• Radiated ~ 500 W at 10 MHz with approx. 90% efficiency (relative to DC power input)
• Transportable “HAARP” scale-up
Electrically Small Antenna

- An electrically small, inductively coupled antenna design
  - \( k \cdot a < 0.5 \)
- Highly resonant structure
  - Provides natural match to 50 Ohm source
- Up to 98% efficient
- Small Loop Antenna (SLA) inductively couples to Capacitively Loaded Loop (CLL)

Antenna Concept Verified

Early 100 MHz ESA antenna

CAD Drawing

Built Antenna

dielectric tuner
Tuning with Dielectric Insertion

Experimental results of capacitive tuning only

- Resonant frequency adjusted by changing capacitance of CLL
  - e.g. inserting a dielectric
- Eccostock HiK
  - $\varepsilon_r = 15$, $\tan\delta = 2 \cdot 10^{-3}$
  - 45-100 MHz
- Teflon
  - $\varepsilon_r = 2.1$, $\tan\delta = 2 \cdot 10^{-4}$
  - 83 – 100 MHz

Resulting antenna: 5 – 10 times smaller than dipole
• E/H-Plane Gain Pattern
  - f = 99.35 MHz (No dielectric inserted)
  - Peak Gain = 2.82 dBi
  - 3 dB Beamwidth = 158°
10 MHz Antenna Pattern

- Small ground plane over soil (4.8 x 4.8 m)
- Gain: 1.9 dBi
- 124.5° HPBW
- High losses into soil

- Extended ground plane (9.7 x 7.2 m) (E x H direction)
- Gain: 5.8 dBi
- 114.4° HPBW
Horizontal Gap

- University of Maryland suggested modification
- Larger gap possible due to increased capacitive area
- Tunable by adjusting area of overlap – air tuning possible
- Increased dielectric requirement for breakdown mitigation

*(large volume, high quality dielectric needed)*
Horizontal Gap

Horizontal Gap

With Rollers

S-Parameter [Magnitude in dB]

Frequency / MHz

S1,1 : -24.262416

S1,1 : -24.104054

[Graphs showing frequency response with and without rollers]

[Heat maps displaying ionospheric modification with and without rollers]
Ferrite Tuning

- \( \tan \delta = 0.0065, \mu = 50 \), 2 cm slabs
  - 85.6% radiation efficiency
  - 13.9% loss into ferrite
  - 81% Accepted Power
  - 69% Total efficiency

Low matching quality is observed
Horizontal Gap Max Power (10 MHz)

- Limited by
  - Air Breakdown
    - > 30 kV/cm at 50 MW
    - Assumes adequate insulation at feed point.
  - Teflon* Melting (2 MW input power)
    - Loss tangent: $2 \times 10^{-4}$, 68.4 min at 9.4% loss (188 kW)
    - Loss tangent: $2 \times 10^{-3}$, 18.8 min at 34.2% loss (684 kW)
  - Loss of original properties
    - Ferrites
      - Permeability changes with temperature, dependent on individual composition of soft ferrites (NiZn)
      - Typical loss at 2 MW excitation: 278 kW (2 cm thick slabs)

→ 1 to 2 MW should be feasible, air tuning preferred (6 kV/cm)

* Teflon sheet: 15 cm thick, 200 x 300 cm approx.
Full Size ESA

10 MHz ESA

![Diagram of 10 MHz ESA](image)

**Diagram Details**
- **Dimensions:**
  - Width: 3.1 m
  - Height: 2.44 m
- **Components:**
  - $L_0$, $L_1$, $L_2$, $C_1$, $C_2$, $R$,
  - 50 Ohm load
- **Frequency Range:**
  - 3 - 10 MHz

---

**Image 654x475 to 718x539**

**Image 12x471 to 60x534**

**Image 180x58 to 590x180**

**Image 24x205 to 294x408**

**Image 325x220 to 709x409**

---

2/10/2016

COLLABORATIVE RESEARCH ON NOVEL HIGH POWER SOURCES FOR AND PHYSICS OF IONOSPHERIC MODIFICATION
Antenna Drive Methods

Conventional (Freq. –domain)

Direct (Freq.– domain)

Direct (Time – domain)

10 MHz values: \( L_1 = 1 \ \mu\text{H}, \ L_2 = 2 \ \mu\text{H}, \ k = 0.154, \ C_2 = 126 \ \text{pF}, \ R = 1.6 \ \Omega, \ (L_0 \sim 20 \ \text{nH}, \ C_1 \sim 20 \ \text{pF}) \)
Freq. Domain Analysis

- Analytical Solutions for standard drive

Ladder network impedance

S11 with 50 Ohm coaxial cable drive
Freq. Domain Analysis

Compared to direct drive frequency domain (6 kV rms drive)

- Black: 50 Ohm, Red: Direct drive
- Dotted/Dashed: Reactive power

Mutual Inductance adjusted to maximize direct drive

- Increasing $k$ by 40% changes the mutual inductance from to 0.34 to 0.48 $\mu$H. (freq. shift by 120 kHz)
Freq. Domain Analysis

Compared to 3.3 MHz operation (only capacitive tuning)

Mutual Inductance adjusted to reduce reactive component (60% increase)

Increased power output in direct drive (20 kVrms source). Power and matching in standard drive (50 Ohm) also improved.
Spice Analysis, Freq. domain

PARAMETERS:
Cap = 15pF

COUPLING = 0.145
L1 = L1
L2 = L1
C3

Place voltage probe between R8 and R9
E.g. DB(V(R8:1)) will give S11 in dB

Tune this capacitor
Freq. Domain Comparison

stray only (~10 pF)

15 pF cap + stray

130 pF cap + stray
Direct Drive / Time Domain

- 10 MHz ESA
  - 3 x 2.5 x 1.2 m
  - 4.8 m square ground plane, extended with steel wire mesh
- Tunable via:
  - Dielectric insertion (polymer dielectric limits duration due to Joule heating)
  - Gap adjustment
- ~ 4.7 dBi Gain
- ~ 1 MW Breakdown Strength (air, 30 kV/cm)
- Excited with square pulse train

Dial in square pulse period from S11 frequency
COLLABORATIVE RESEARCH ON NOVEL HIGH POWER SOURCES FOR AND PHYSICS OF IONOSPHERIC MODIFICATION

**Experimental Setup**

- HV PSU
- Signal Gen
- Oscilloscope
- Switcher
- Voltage Probe
- Current Monitor
- Instrument Bench
- Magnetic Loop
- 50 – 250V
- 3... 10 MHz
- 15m above antenna plane
Implementation with 1,200 V SiC MOSFET, mimicking PCSS for “low” voltage.
Excitation

- 1,200 V MOSFET switch
- Antenna effectively filters out unwanted harmonics
- Driving voltage: 100 V (50…250 V)
- Magnetic loop placed 15 m centered above antenna

- Approx. 500 W Radiated for 200V DC input
- Approx. 90% efficiency
Measured vs. Simulated

- Current through exciting loop
- Current through load R2
- Received antenna signal
10 MHz small scale model

Adjust $d_{coil}$ to tune mutual inductance, i.e $k$

~ 5 cm diameter
Parameter Optimization

10 MHz tuning

- Current (A)
- Load Current (A)
- Time (μs)
- Power as MSA
- Frequency (MHz)

2/10/2016
Parameter Optimization

6 MHz tuning

$C_2$ increased from 126 to 313 pF
$k$ changed from 0.129 to 0.093 (non-optimized)
Parameter Optimization

Circuit values (200 Vdc drive)

- 6.36 MHz: $k = 0.093$, $C_2 = 313$ pF, increase in load power until $k = 0.12$, then beats starting to show up

- 10.075 MHz: $k = 0.129$, $C_2 = 126.2$ pF, increase in load power until $k = 0.15$, then lower
  - 0.129 – 1.6 kW peak power in load
  - 0.14 – 2.2 kW
  - 0.15 – 2.4 kW (← optimum)
  - 0.16 – 2.19 kW
  - 0.17 / 0.18 – obvious beats

- Experimentally verified

6 MHz Waveform with beats, $k = 0.15$
For given $L_1$ and $L_2$, the following allows tuning to about 90% efficiency (switching losses) over the frequency range from 3 to 10 MHz:

- Adjusting the capacitance $C_2$ sets the approximate frequency
- Tuning the mutual inductance enables adjustments for
  - Changes in effective resistance with frequency
  - Maximizing efficiency (reducing reactive portion)
- Mutual inductance will also fine-tune the frequency
- Setting the matching capacitance $C_1$ to roughly 50 pF keeps switch voltages at reasonable level (roughly 2.5 times the DC voltage)
Scaling to High Power

Idealized PCSS switch model
System Scaling

- 6.6 kV DC input supply
- Approx. 1 MW output power
- About 1 to 2ns switch rise time (doesn’t matter much)
- 1 Ohm on-state resistance
System Scaling

6.6 kV DC input

Note:
Changing the coupling coefficient slightly changes resonant frequency as well. At the very high coupling coefficients, around 0.3, the efficiency will increase again, however, the absolute power is very low.
Scaling

Switch parameter study: increasing rise/fall time…
(the non-varied time is kept at 1 ns)

Power Efficiency (%)

Rise Time (ns)

Dashed: fall time
Solid: rise time
Physical Implementation

Requirements:
• Adjust capacitance from 100 pF to about 1.3 nF for full 2 to 10 MHz range
• Adjust mutual inductance, coupling coefficient from 0.15 to 0.09
• Handle 1 MW power, support fields up to 20 kV/cm

Challenges:
• Capacitance adjustment technique with low loss
  - Air gap tuning
  - Dielectric tuning
  - Magnetic tuning
• Adjusting mutual inductance will affect the driving loop inductance
  - Take coupling between $L_1$ and $k$ into account for tuning
Alternative Tuning Methods

Horizontal Gap
- Larger gap allows for higher power before breakdown
  - >2 MW with air
- Tuning without use of dielectric possible
  - Tuning via mutual inductance also possible

Ferrite
- Tuning via inductance
- High losses for soft ferrites
- Unstable permeability with temperature

Ferrite slabs:

61 Material Characteristics:

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Permeability @ B &lt; 10 gauss</td>
<td>gauss</td>
<td>(\mu_1)</td>
<td>125</td>
</tr>
<tr>
<td>Flex Density @ Field Strength</td>
<td>gauss</td>
<td>B</td>
<td>2350</td>
</tr>
<tr>
<td>Residual Flux Density</td>
<td>gauss</td>
<td>(B_r)</td>
<td>1200</td>
</tr>
<tr>
<td>Coercive Force</td>
<td>oersted</td>
<td>(H_c)</td>
<td>1.8</td>
</tr>
<tr>
<td>Loss Factor @ Frequency</td>
<td>(10^{-6}) MHz</td>
<td>(\tan \delta)</td>
<td>30</td>
</tr>
<tr>
<td>Temperature Coefficient of Initial Permeability (20-70°C)</td>
<td>%/°C</td>
<td>(T_p)</td>
<td>0.10</td>
</tr>
<tr>
<td>Curie Temperature</td>
<td>°C</td>
<td>(T_c)</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Resistivity</td>
<td>(\Omega) cm</td>
<td>(\rho)</td>
<td>1 x 10^4</td>
</tr>
</tbody>
</table>

http://www.fair-rite.com/newfair/materials61.htm
Scaling / Comparison with HAARP

- High Frequency Active Auroral Research Program
  - Studies the effects of high power HF on the ionosphere
  - Operating frequency: 2.8-10 MHz
  - Single element 21 m wide, 16 m tall
  - Occupies 33 acres
  - Located in Alaska

![Antenna Element Components](image_url)

- 180 of these
- approx. 25 football fields
- 3.6 GW ERP
HAARP

- High-Frequency Active Auroral Research Program
- Studies effects of high power HF on ionosphere
  - 180 x 2 element array on 30.5 acres
    - Each element: pair of dipoles, 10 kW transmitter each
- Max Array Gain: 32.2 dBi
- Expected Gain: \(~34\ldots35\) dBi
  (array plus dipole)
- Roughly 2 to 3 dB difference between expected and published gain
  - Losses in efficiency of transmitters, matching, antenna crosstalk?
- ERP: 3.6 GW (95.5 dBW)
  - EIRP: 5.9 GW (97.7 dBW)

HAARP Array

- Array Size: 1280 x 1040 ft
- Spacing ~ 0.82 λ
- Calculated array directivity given isotropic radiators: 30.91 dBi
  - With dipole: ~38 dBi
Matching HAARP ERP

- Commercially available barge*: 120 x 32.2 m
- Two barges fits a 6 x 4 array with 0.75 \( \lambda \) spacing: 112.5 x 67.5 m
- Array directivity: 20.94 dBi
  - With ESA Gain: 25.64
- 30 to 40° beam width
- Power required:
  - 16.1 MW array
  - 0.67 MW per element

Two Barge Array

Compare HAARP: 33 acres, equivalent to 365 m x 365 m (factor 17 reduced footprint area)
Sea deployment

- ESA on steel barge submerged in sea water
- Frequency: 9.903 MHz
- Peak Gain: 7.13 dBi
  (compared to 5.16 dBi on land)
- Angular Width: 62.3°
80 dBW ELF Array

- 4x4 array on barge:
  - 0.75 λ spacing
  - Gain: 20.5 dBi
  - Power Needed: 1.46 MW
    - 366 kW per element
  - Beam width: 16.7°
  - Slightly better performance with 0.82 λ spacing

- 20.5 dBi @ 9.903 MHz
- 16.7° Beam Width
HAARP dipole vs. ESA

- Single HAARP antenna limited to ~ 10 kW power
  - Primarily limited due to electric breakdown in matching network
- ESA antenna roughly limited to ~ 1 MW power
  - Matching network moved into large scale antenna
  - Approx. factor 10 larger physical size of matching enables factor 100 higher power
- ESA antenna highly resonant
  - Requires active adjustment of parameters for even small frequency changes (~ 10 kHz)
- ESA antenna may be driven by
  - Conventional (IOT)
  - Direct drive sinusoidal
  - Direct drive, square switcher
- HAARP radiation efficiency: ~ 55 to 75 %
- ESA system efficiency: ~ 90%
• HAARP: 700 km² of F-layer
  – Beam width: 4.5 to 5.8°
  – $2 \times 10^{-6}:1$ of Earth’s ionosphere

• Two Barge: 20,000 km²
  – Beam width: 30 to 40°
  – $4 \times 10^{-5}:1$ of Earth’s ionosphere
Future Plans

- Verify tuning methods that worked in 3 to 10 MHz mockup with full-size antenna
- Verify matching approach with full size antenna
- Develop practical mutual inductance tuning
- Find optimum capacitive gap geometry
- Evaluate array performance at shorter spacing (antenna cross-talk)
- Drive antenna mockup with PCSS
- Evaluate antenna geometry for 10 MHz breakdown limits (several MW cw)
- Drive antenna with IOT or similar mock source