AFOSR Annual Review

Creating Space Plasma from the Ground

Jan 15, 2015
Figure 1. Hierarchy of Heater Thresholds.
1993 Quantitative Prediction Confirmed in 2009

Daytime ISR at EISCAT; Nighttime HAARP multiple instr.


**Arecibo (to compliment HAARP)**

2014 (Carlson and Jensen)

**HAARP**

2009 (Pedersen et al)
To Create Artificial Ionospheres ~ Sun has opened a new thrust of HF activity

- Here we 1st summarize why 1 GW ERP ~ Sun (HF accelerated electrons must exceed ~20 eV)
- Then we decompose problem into:
  - Propagation of energy to acceleration region(s)
  - HF to electron energy conversion; electron acceleration mechanisms/high-energy cutoff (Kinetic theory)
  - Electron transport (optically thin/thick)
  - Elastic/inelastic collisions & energy spectrum
- Concl: challenge continues to be to channel energy among competing instabil/thresholds/resp-times
Why Expect Artificial Ionospheres (~Sun) when HF Facilities approach ~1 GW ERP

Without Aeronomy there’d be no HF Artificial Ionosphere

Experiment shown here: Carlson et al, 1982

- **Q1:** Can HF facilities produce ionization?
- **A1:** Must. Left Plasma Line direct proof $e^- > 20eV$; Right optical support
- **Theory in agreement:** Multiple $e^-$ crossings accel region: Carlson et al, 1982; Detailed Theory Vas’’kov et al, 1983; Gurevich et al, 2004 Full Kinetic Theory
Quantify why Artificial Ionospheres ~ Sun when HF Facilities approach ~1 GW ERP

(Carlson, 1993)

- **Q2:** Can HF ionization be **SIGNIFICANT** fraction of **SUN**
- **A2a:** Quantify **SUN:** Electron prod. rate by sun (for SS# 60) is $10^3 \text{ cm}^{-3} \text{ s}^{-1}$
- Spread over 2 atomic O scale hts (~100 km) is ~ $10^{10}$ ionizations cm$^{-2}$ s$^{-1}$
- At ~30 eV per ionization by electron-impact, $3 \times 10^{11} \text{ eV cm}^{-2} \text{ sec}^{-1} = 4 \times 10^{-8} \text{ Watt cm}^{-2}$. [Production rates and **Production power densities**]
- **A2b:** Quantify **HF Facility: 1 GW ERP** delivers to 250 km ~ $1.3 \times 10^{-7}$ Watts cm$^{-2}$
- **EFFICIENCY** convert HF energy to electrons accelerated > ioniz. threshold
  - Only Experimental estimate (Carlson et al., 1982): ~15% at ~ 140MW ERP.
  - **Predicted** (1993) ~ 1 GW ERP ~ ½ **Overhead Sun** if maintain **15%** efficiency.
  - **Observed** (2009) HAARP March 17, 2009 (Pedersen et al, 2010) Observed an HF production rate ~$2.6 \times \text{ cm}^{-3} \text{ s}^{-1}$ at 150 km (1/2 overhead sun for a SS# of 60)
EISCAT enhanced Daytime Ne(h) ~25%
Magn Zenith, 3 x elec gyro freq, 20% of 1 GW ERP
[Blue: HF off; Red: HF on] (Blagoveshchenskaya et al, 2009)
HAARP in 1\textsuperscript{st} campaign \(\sim 1\)GW, confirmed (mag zen) artificial ioniz Nighttime \(\sim\) Sun

(Pedersen et al, 2009, 2010)
HAARP HF accel-electron-produced ionization
(Estimated from ionosonde)
Left: HF off, Center: HF on, derived Ne “layers”
Pedersen et al, 2009, 2010
To Create Artificial Ionospheres has opened a new thrust of HF activity

• Here we 1st summarize why 1 GW ERP ~ Sun
  (HF accelerated electrons must exceed ~20 eV)

• Update framework- decompose problem into:
  – Propagation of energy to acceleration region(s)
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HF Fractional Trapping

Gurevich, Carlson, Kelley, Hagfors, Karashtin and Zybin, 1999)
Magnetic Zenith Effect

Important: Sura, EISCAT, HAARP

Left: (Gurevich, Carlson, Zybin, 2001)
Right: Extend from 2 to 3 dimensions (Gurevich, Carlson, Pedersen, Zybin, 2001)
Confirmation of Magnetic Zenith Prediction
Left: Observed 630.0 nm emission at HAARP
Right: Ray tracing for HF propagation
Prediction: Gurevich et al, 2001; Confirmation of theory: Pedersen and Carlson, 2001,
Magnetic Zenith Striation Area

Left: Optical emissions from HF accelerated e-

Right: Predicted Striation area (pred match obs) (obs.) Left: Pedersen et al, 2009; (pred) Right: Gurevich et al, 2001
Multiples of electron gyro freq $f_{ce}$

**Double Resonance**

- $f_{HF}$ at integer multiples or electron gyro freq $f_{ce}$
- For frequency matching condition

$$f_{HF} = n f_{ce} = f_{UH} = \left[ f_{pe}^2 + f_{ce}^2 \right]^{1/2}$$

Where $f_{UH}$ and $f_{pe}$ are the frequency of the upper hybrid oscillations and the local plasma frequency.

- Platteville 2-10 m irreg tenfold increase near $2f_{ce}$
- EISCAT 10 m irreg (and O(1D) minimum near $3f_{ce}$
- Strong airglow (incl suprath) all $n f_{ce}$
- Important: Sura, EISCAT, HAARP
High vs. Low Latitude (electron acceleration has essential differences)
Thermal plus suprathermal electrons

HAARP (Djuth et al, 2004), Boulder (Mantas and Carlson, 1996)

Below HAARP Suprath only magn. zen. +/- 4°

below, suprathermal electrons also contribute to the excitation of 630.0 nm and 557.7 nm airglow.

**FIG. 2 (color).** CCD image of 557.7 nm emissions acquired immediately after HF turn-on during the period 0617:30–0618:00 UT on 20 March 2004.

**FIG. 3.** CCD image of 630.0 nm emissions acquired during the period 0617:36.0–0617:43.5 UT on 20 March 2004. The full field of view is 16° centered on the geomagnetic zenith.
Arecibo Low Latitude Physics
Electron Energization 10s%
Fill HF Beam
Arecibo: Transport in Optically thin and thick

Right axis: HF reflection height km (supra e\textsuperscript{-} source)

Left Axis: Obs … 630.0 nm lifetime seconds
Calc - - - 630.0 nm lifetime for 3 values of T_{ex}

OCT.13, 1972 ARECIBO
Platteville also saw optically thin & thick Triangulation for airglow separation from HF refl. ht.
Haslett and Megill, 1974

- HF excited layer separates ~ same neutral press. level
- 557.7 nm is evidence for non-Maxwellian HF electrons
- HF impact airglow filled HF beam (~100 km) (48.4° Mlat)
Left: Arecibo 630.0, 557.7, 777.4 nm obs. Emissions excited by HF accelerated electrons (alt. - lat.)
Right: electron impact excitation cross-sections [O]
To test obs. against electron flux transport model
(Carlson and Jensen, 2014)
557.7(h), 777.4(h), O+(h) (e⁻ transport) for optically thick accelerated electron source height

Carlson and Jensen, 2014
Find 557.7 nm intensities relative to 777.4 nm can be in error by factor of 3 if \textbf{Ne(h)} omitted (Electron flux degradation < 10 eV important)

Figure 6: (a) (left) Differential particle fluxes obtained by degrading the experimental spectrum shown in Abreu and Carlson (1975) Figures 5a and 8b at 1.0 \times 10^{13} \text{ cm}^{-2} using the Schunk and Hays [1971] energy loss expression; (b) (right) The observed differential particle fluxes for matched conditions.
Generalize: Optical Constraints on HF electron spectra remain as good a concept as ever, but: must revisit electron flux transport; track optically thin/thick Ne(h)

Electron temperature (~0.3 eV)

Gustavsson, Kosch et al., 2005
Electron Distribution Function (EDF) 
Strong Langmuir Turbulence, Kinetic solution 
Near HF reflection height (Gurevich et al, 2004)

Fig. 5. EDF at the times $t = 0$ (diamonds), 300 (circles), 1000 (crosses), and 3000 (triangles).
Because repeated accel of initial population

- $\text{Te} \sim 3000 \text{ K} \rightarrow$ stronger ioniz. flux than $\text{Te} \sim 1000 \text{ K}$
- Any pre-existing supra-thermal tail enhances ioniz.
- Photoelectrons* should quick-start, amplify daytime ionization produced [eg Sergeev, Grach, et al, 2013]
With KINETIC THEORY replacing Hydrodynamic and Phenomenological theory (Gurevich et al., 2004)

- In Kinetic Theory, fast electrons stabilize cavitons.
- Cavitons vs. collapse, instead evolve into quasi-steady finite-amplitude ion-acoustic wave with HF enhanced plasma oscillations balanced by fast electron absorption.
- The high energy tail so produced transfers HF energy in Langmuir turbulence into accelerated electrons.
  - Conservation laws not satisfied before (old power law accel electrons drained energy flux too fast for HF input).
  - Fast electrons are accelerated until their energy gained equals their energy lost in collisions.
Conclusions re significant ionization by HF accelerated electrons

• We Know:
  – There’s enough energy density to compete with Sun
  – Hi Lat: double resonances/magnetic zenith important
  – Low Lat: Langmuir Turbulence at refl. ht. is enough
  – Kinetic Theory best estimate yet for energy spectrum

• Prominent Challenges:
  – Role of plasma wave propagation/mode conversion
  – Role of UH waves in electron acceleration
  – Excitement over X mode production of ionization
    [Blagoveshchenskaya et al., (2013)]

• Challenge continues to be to channel energy among competing instabil/thresholds/resp-times
2015 Experiment
HF ionization production [Plasma Line]
QUANTIFY EFFICIENCY  Test & Extend to Higher HF Powers
Arecibo HF ENHANCED PL INTENSITIES
DAYTIME PL 13 July, 1992  NIGHTTIME PL 20 May, 1972
Thank you
Derive differential electron flux from ISR Plasma Line spectra

The energy in the plasma waves is given in terms of an apparent plasma temperature $T_p(E\phi)$ or intensity $kT_p(E\phi)$:

$$kT_p = kT_e \frac{f_m(E\phi) + f_p(E\phi) + \chi}{f_m(E\phi) - kT_e \frac{df_p(E\phi)}{dE\phi} + \chi}$$  \hspace{1cm} (1)

where $f_p$ is the one-dimensional velocity distribution of the photoelectrons along the radar wave vector; $f_m$ a modified one-dim. Maxwellian vel. distrib of ambient electrons; Chi provides for excitation and damping of plasma waves by the collective effects of ion-electron collisions.
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(Carlson, 1993)

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• **Q2:** Can HF ionization be **significant** fraction of SUN

• **A2b:** HF Facility 1 GW ERP HF delivers to 250 km, ~ $1.3 \times 10^{-7}$ Watts cm$^{-2}$

• **Efficiency** convert HF energy to electrons accelerated $>$ ioniz. threshold
  
  – Only Experimental estimate (Carlson et al., 1982): ~15% at ~ 140MW ERP.
  
  – **Predict** (1993)~ 1 GW ERP $\sim \frac{1}{2}$ Overhead Sun if maintain **15%** efficiency.

  – **Observed** (2009) HAARP March 17, 2009 (Pedersen et al, 2010) Observed an HF production rate $\sim 2.6 \times \text{cm}^{-3} \text{s}^{-1}$ at 150 km (correcting for geometry this is within a factor of 2 of an overhead sun for a SS# of 60)

  – **Prediction** (1993) = **Observed** (2009) = $\sim 1/2$ Sun