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3rd International Conference and Exhibition on
Mechanical & Aerospace Engineering
October 05-07, 2015 San Francisco, USA

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Radar Screening using Weekly Ionized Plasmas

Jonathan Blackledge

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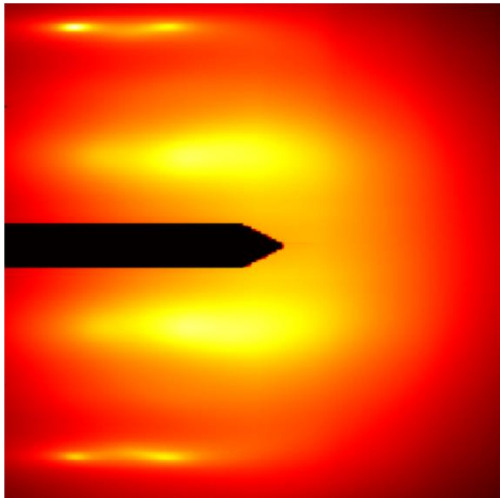
Tuesday, 6 October, 2015 @ 12:15 - 12:35



Contents

Stealth Planes

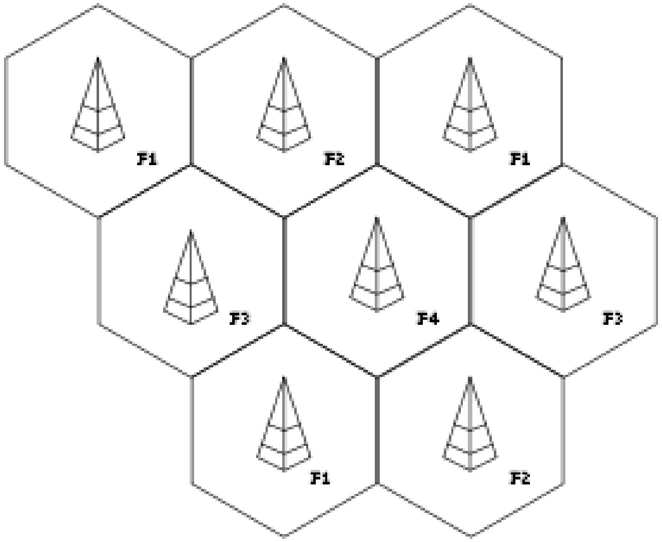
- Horton brothers develop first flying wing concept in 1930s
- Observe that the radar cross section is significantly reduced

Stealth Planes are not Invulnerable

March 27, 1999, 250th Serbian Air Deference Brigade shoot down an American F-117 Nighthawk for the first and only time (to-date).

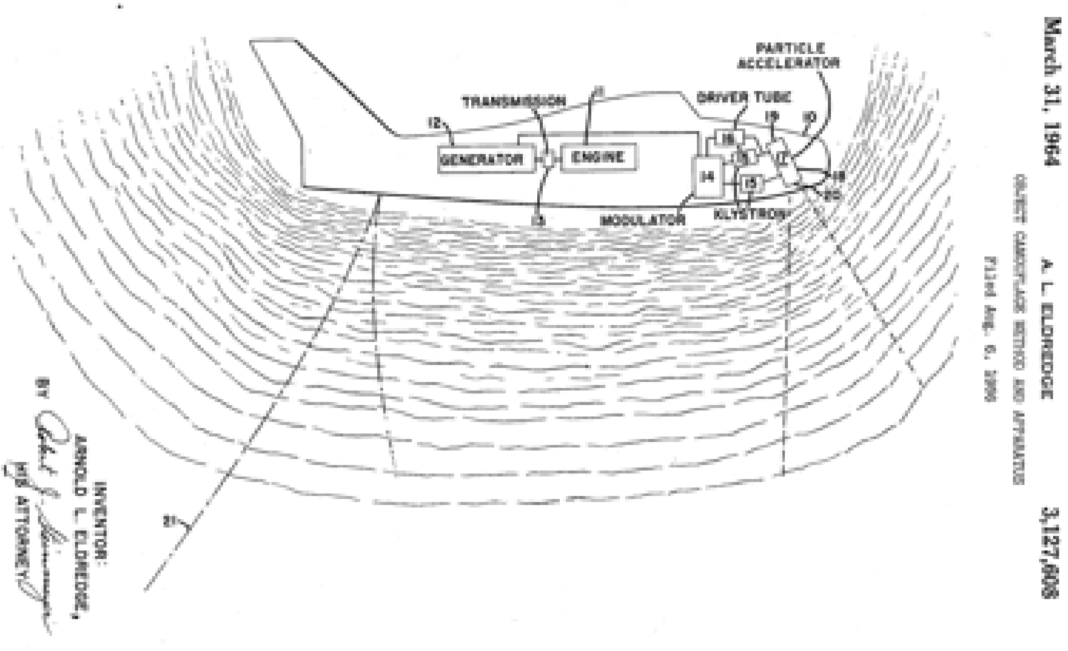
How did they do it?

First application of Cellular Networks for air defense against stealth planes!!



Context

Original Idea



- First proposed in 1956 by A. Eldredge while working for General Electric

- US patent* granted in 1964

- Proposed using a particle accelerator in an aircraft to create a cloud of ionised gas that would ‘...absorb incident radar beams'

*A. Eldredge, *Object Camouflage Method and Apparatus*,
US Patent No. 3127608, August 6, 1956; Issued on March 31, 1964.

What do we need to understand?

Principles of Radar

Principles of Fluid Dynamics

Principles of Plasma Physics

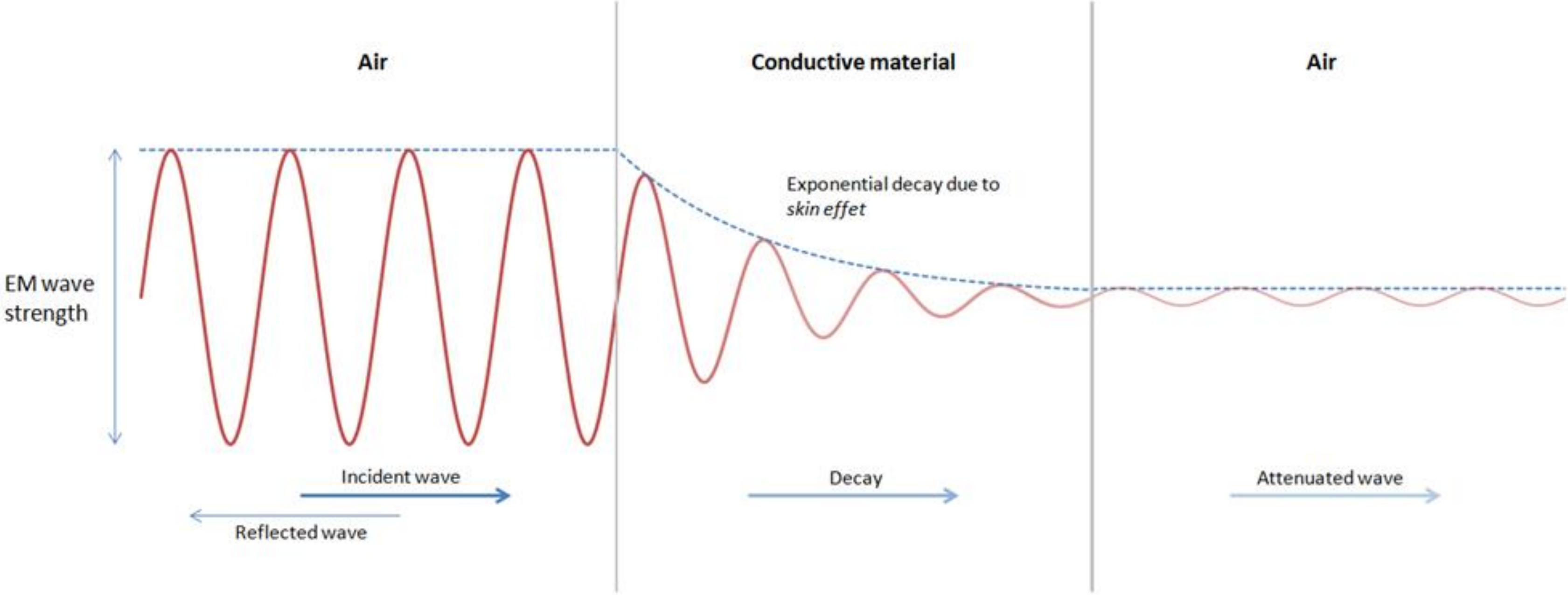
Defining the (Active) ‘Stealth Problem’

Given Maxwell’s equations, find functions of space for the permittivity and **conductivity** **which can ‘fly’** such that the reflected microwave energy is effectively zero.

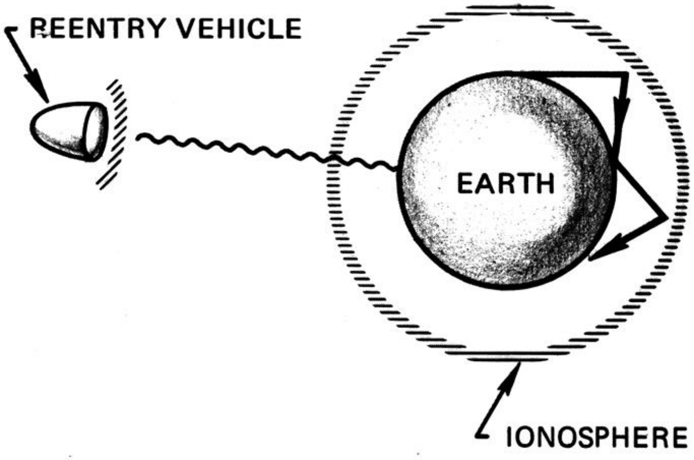
Generic Approaches

- Consider functions which reflect energy away from transmitter
- **Consider materials that absorb microwave radiation**

Conductors and EM waves



Skin Depth $$\delta = \left(\frac{2}{k z_0 \sigma} \right)^{\frac{1}{2}}$$



Plasma Screening Model

Impulse Response Function for a weakly conductive plasma is

$$f(t) = -z_0 \frac{d}{dt}[\sigma(t) \exp(-\sigma_0 t/\epsilon_0)]$$

- For a weakly ionized plasma, the electron number density determines its conductivity.

- In terms of this result, there are two principal factors affecting the performance of a practical radar plasma screening system:

- maximizing the electron number density of the plasma;

- maximizing the thickness of the screen.

Radar Screening Skin Depth

- For 1 cm wavelength microwaves, the weakly conductive plasma condition gives

$$\sigma_0 << 17$$

- Skin depth is

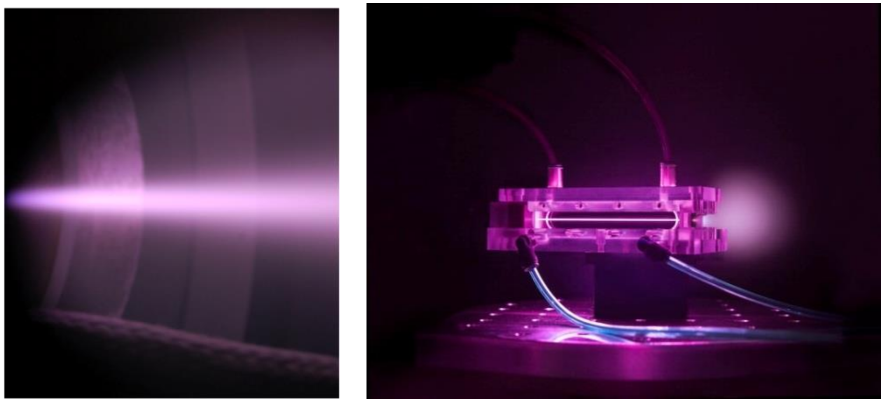
$$\delta = \frac{10^{-3}}{\sqrt{\sigma_0}}$$

- For plasma with conductivity of 1 siemens/meter, the skin depth is 1mm, i.e. electric field strength decays by 63% over 1mm penetration into plasma sheath.

The Rate Equation

- For a weakly ionized plasma the **conductivity is proportional to the electron number density**

- Required to simulate the electron number density generated for a plasma screening system



- Rate equation is

$$\frac{\partial n}{\partial t} = D\nabla^2 n + In + B - Rn^2$$

Diffusion + Ionization + Beam + Recombination

Plasma Flow: Sub-sonic Case

- For a moving aerospace vehicle with velocity **v** the plasma density conforms to the conservation equation

$$\frac{\partial n}{\partial t} = \nabla \cdot (n\mathbf{v})$$

- Required to solve the steady state equation

$$D\nabla^2 n + B + In - Rn^2 - \nabla \cdot (n\nabla u) = 0$$

where u is the velocity potential obtained by solving

$$\nabla^2 u = 0$$

Incompressible Flow

Iterative Solution

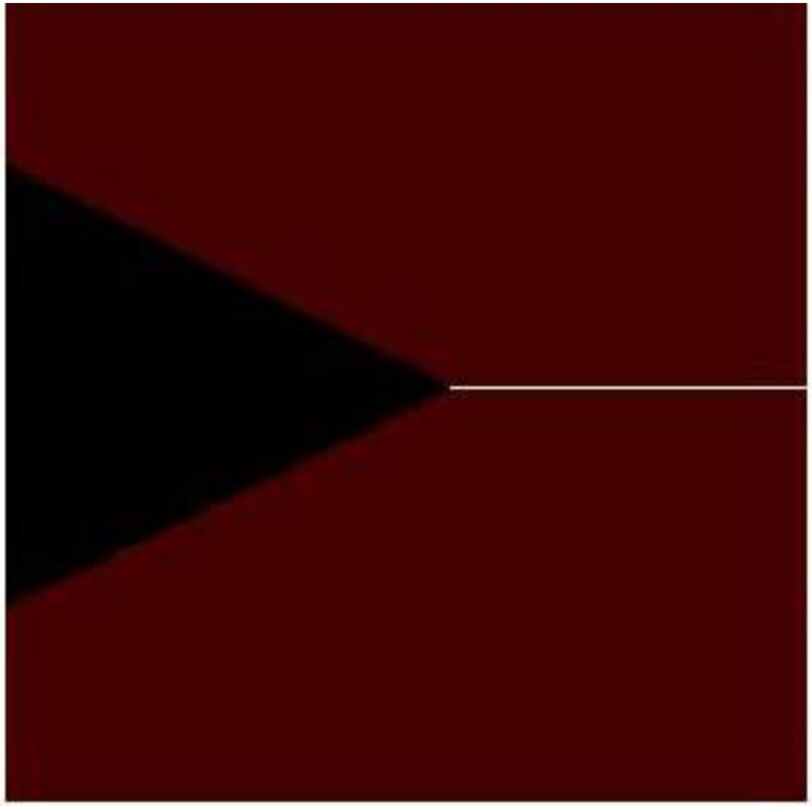
For $\nabla \cdot (u \nabla n) = 0$

$$n = \frac{1}{4\pi r} \otimes \left(\frac{B}{u+D} + \frac{In}{u+D} - \frac{Rn^2}{u+D} \right)$$

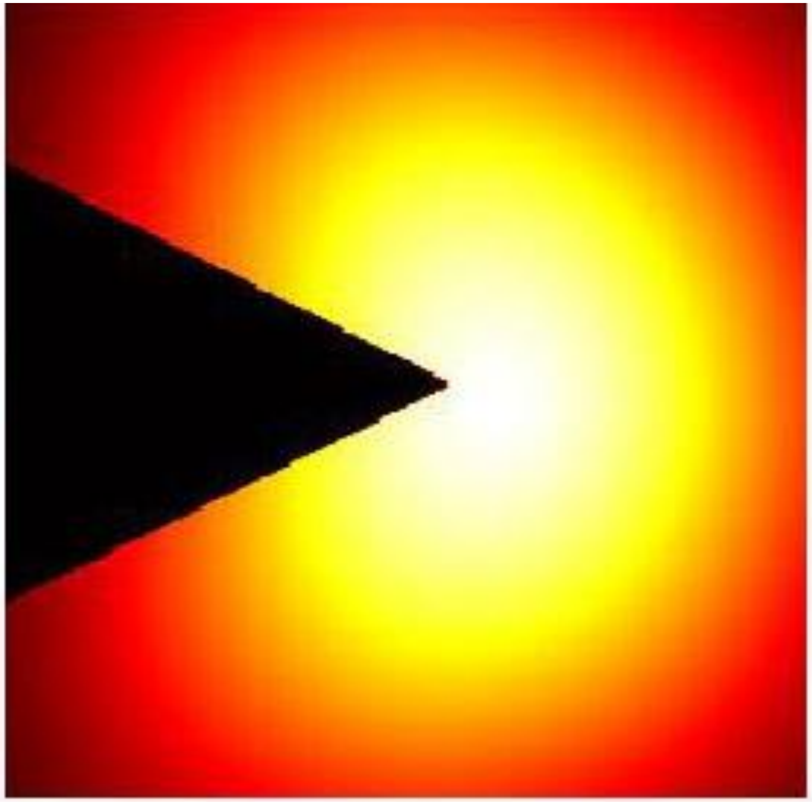
Fundamental equation with no frills

- Electron generation $$n_1 = \frac{1}{4\pi r} \otimes \frac{B}{u+D}$$
- Ionization $$n_2 = n_1 + \frac{1}{4\pi r} \otimes \frac{In_1}{u+D}$$
- Recombination $$n_3 = n_1 + n_2 - \frac{1}{4\pi r} \otimes \frac{Rn_2^2}{u+D}$$

2D simulation of an e-beam induced plasma sheath for the subsonic case



Electron Beam



Electron Number Density

Compressible Flow Regime

What is the effect of a plasma screen generated at super-sonic velocities?

- Number Density Equation

$$n = \frac{1}{4\pi r} \otimes \left(\frac{B}{u+D} + \frac{In}{u+D} - \frac{Rn^2}{u+D} \right)$$

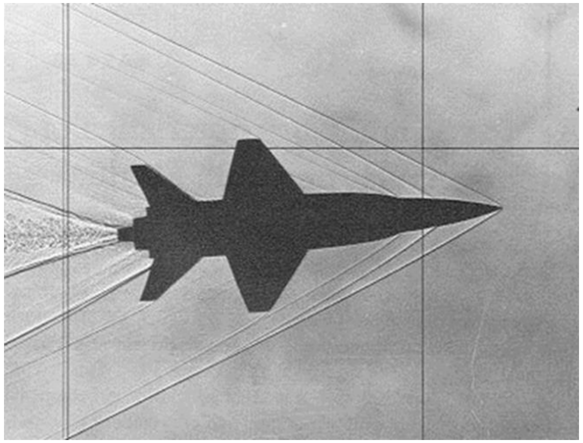
- Velocity Potential is the solution of

$$\left((1 - M^2)\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) u(x, y, z) = 0$$

where *M* is the Mach number of the incoming free stream

Incorporating Shock Waves

- **Wave Velocity Potential** given by the solution of the wave equation (for sound speed *c*)



$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) u = s$$

where *s* is the source function (surface of aerofoil)

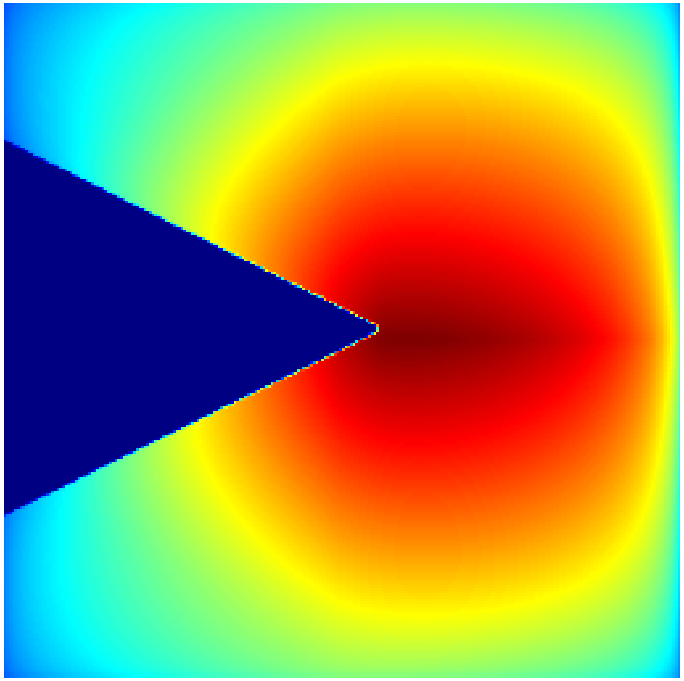
- **2D Fresnel Zone** (for frequency *f* and distance from source *L*)

$$u(\mathbf{r}) \sim \frac{1}{4\pi L} \mid \exp(i\alpha r^2) \otimes s(\mathbf{r}) \mid, \quad \alpha = \frac{\pi f}{cL}$$

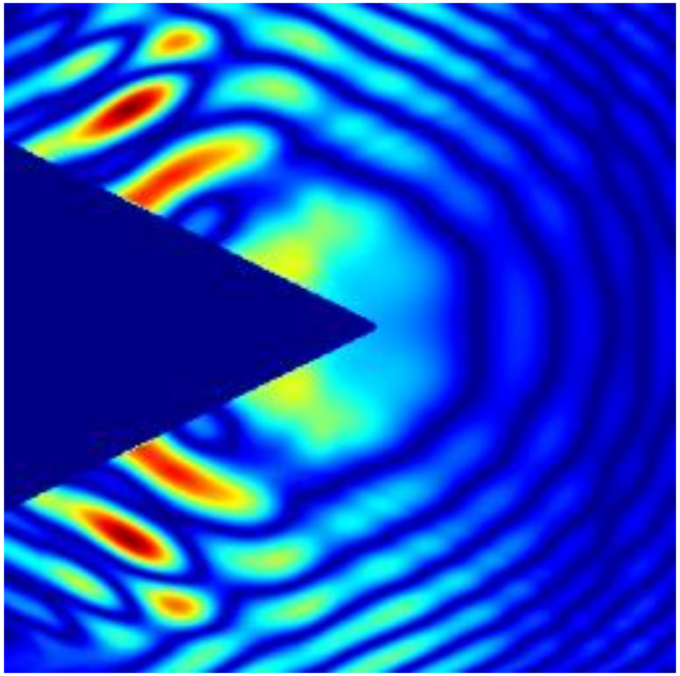
Combined Potential Flow in 2D

Combined velocity potential is given by

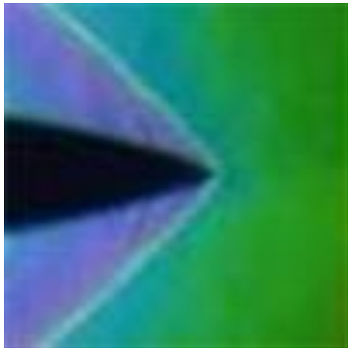
Compressible Velocity Potential + Wave Velocity Potential



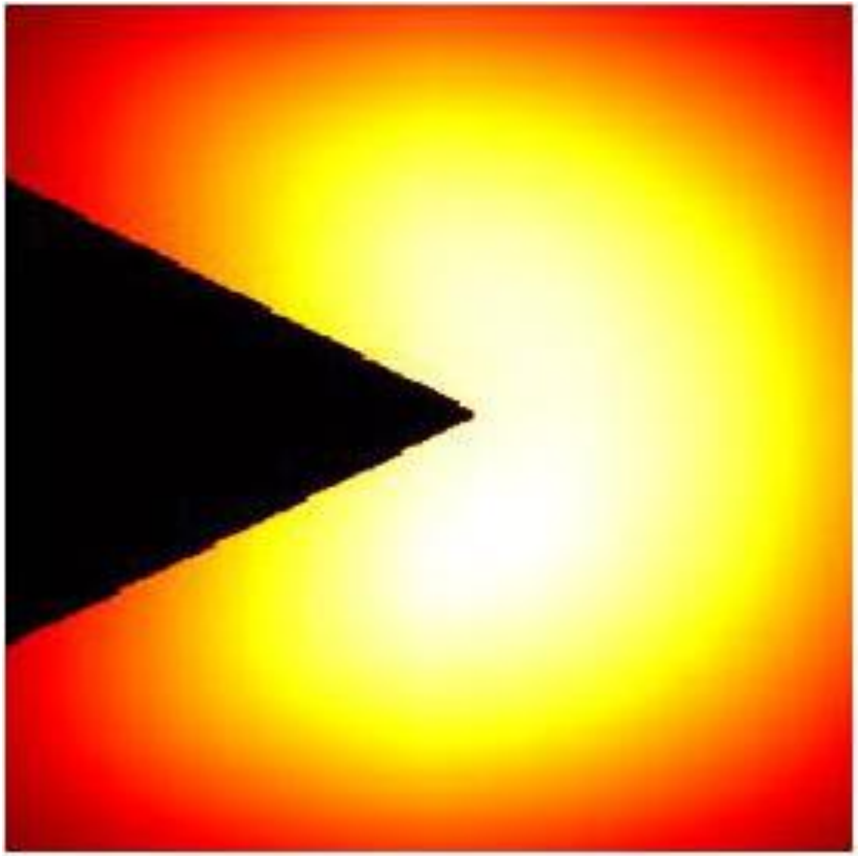
Compressible
Flow Velocity Potential



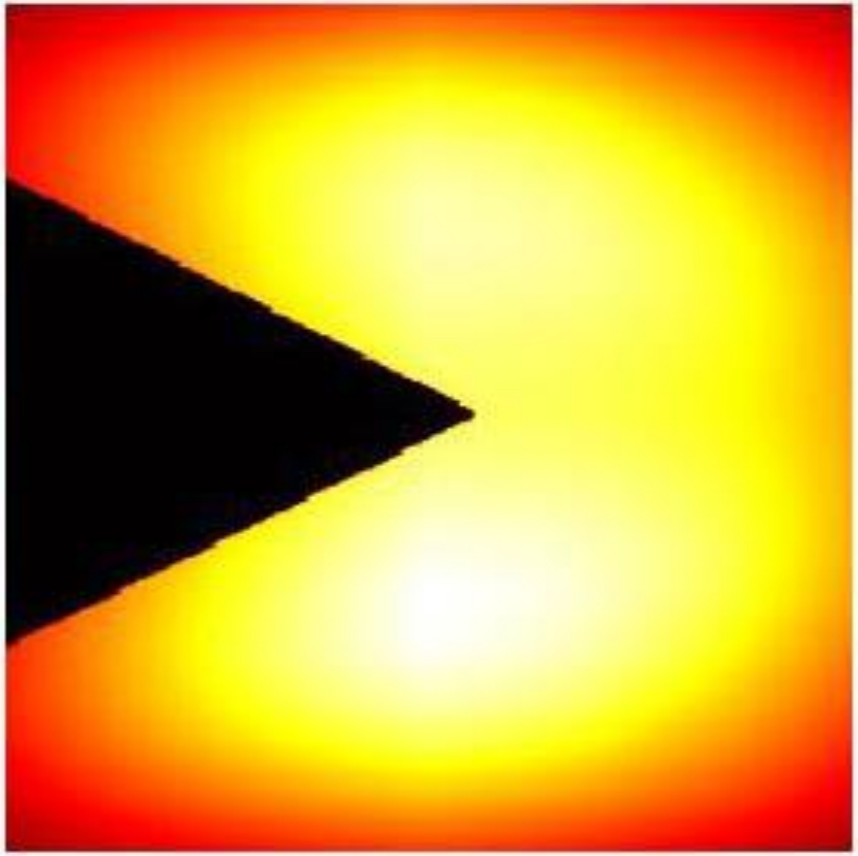
Wave Velocity Potential



2D simulation of an e-beam induced plasma sheath for the supersonic case

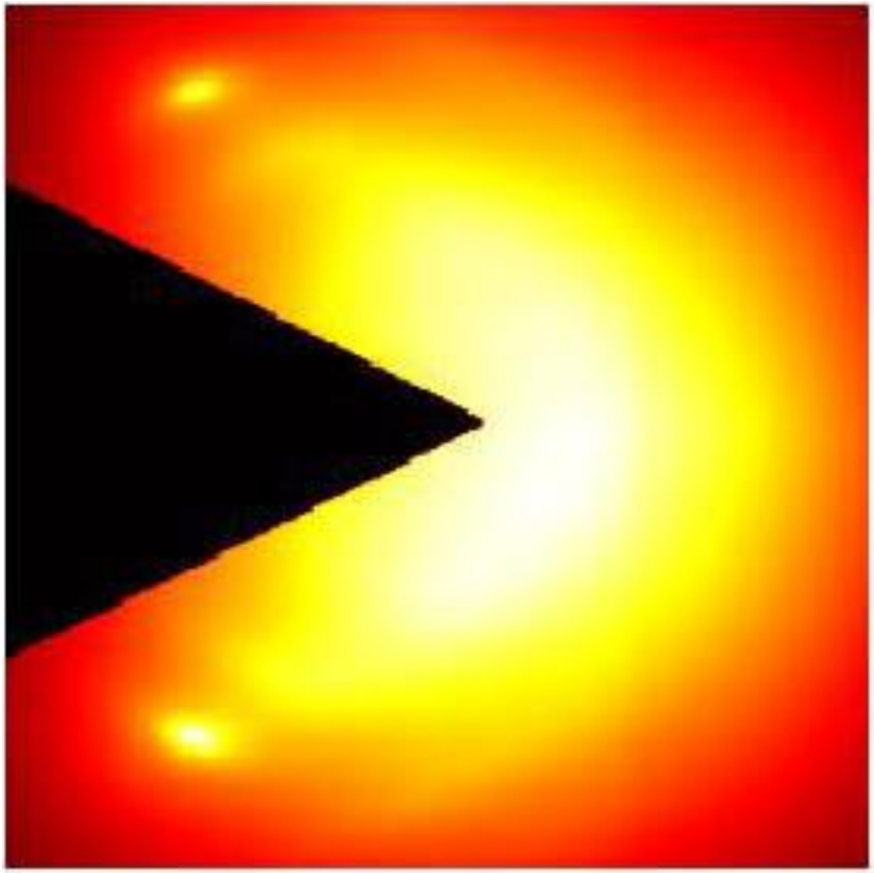


Electron Number Density for M=2

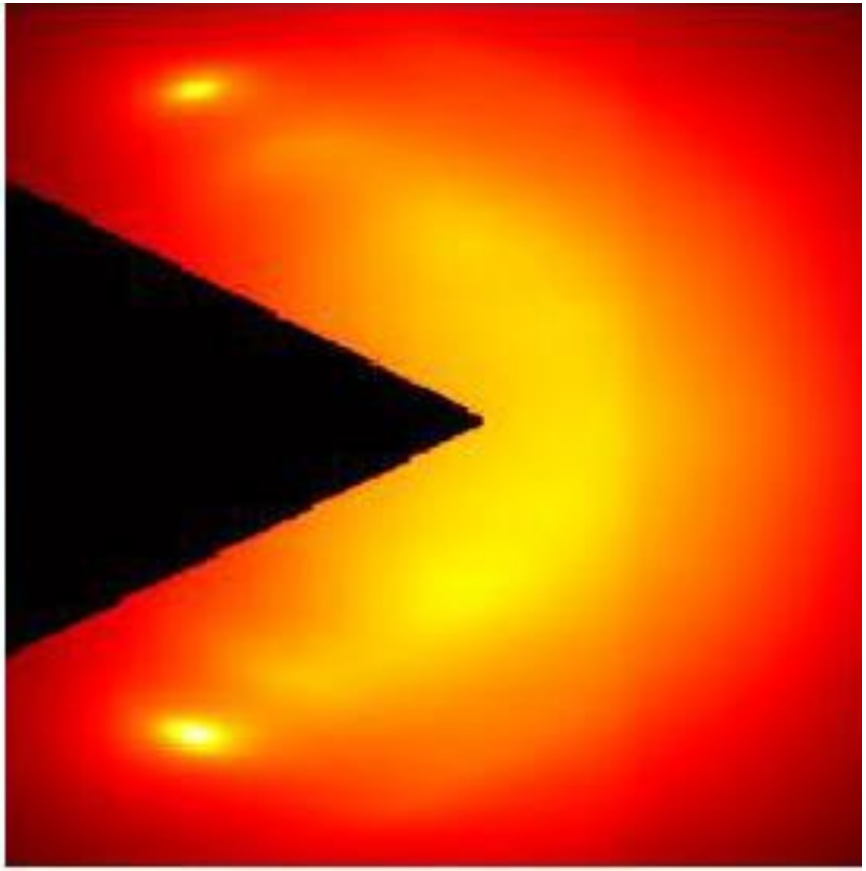


Electron Number Density for M=3

Q3D Simulation of an e-beam induced plasma sheath for the supersonic case

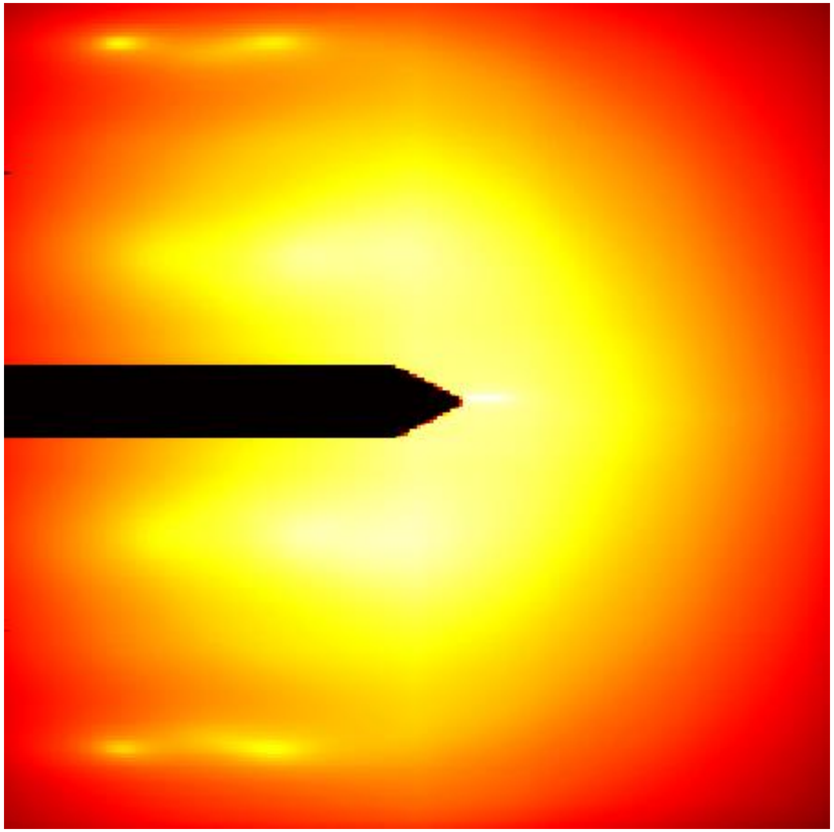


Electron Number Density for M=2

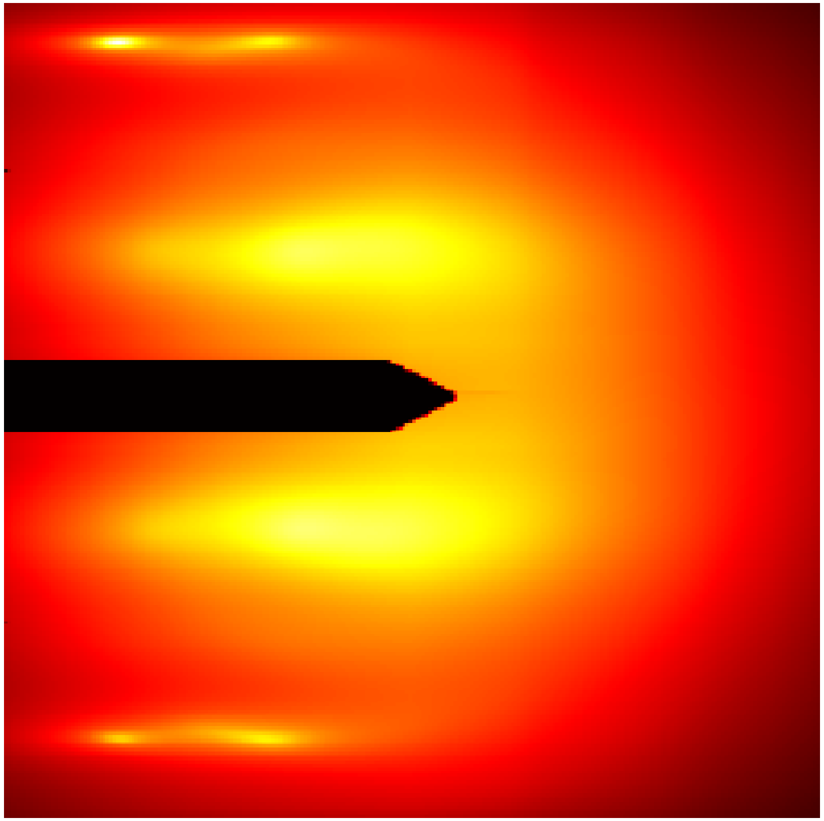


Electron Number Density for M=3

Q3D Simulation of an e-beam induced plasma sheath for the hypersonic case



Electron Number Density for M=3



Electron Number Density for M=6

Summary

- The ***Radar Cross Section*** can be significantly reduced with weakly ionized plasmas for which the ***Impulse Response Function*** (IRF) is

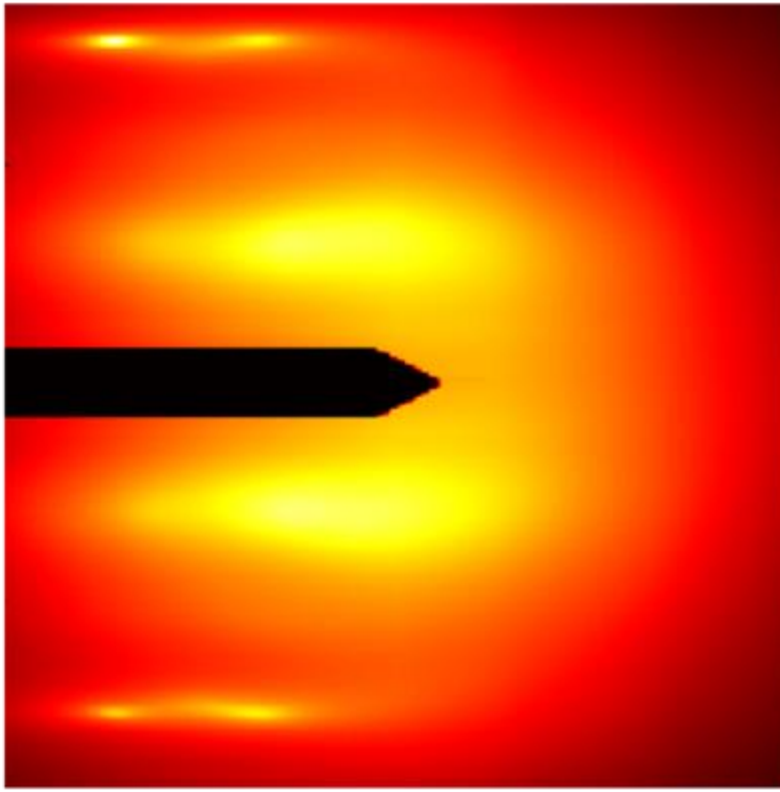
$$\frac{d}{dt}\left[\sigma(t)\exp(-\sigma_0 t/\epsilon_0)\right]$$

- The IRF is characterised by a negative exponential determined by the conductivity of the plasma sheath

- For a weakly ionized plasma, the conductivity is proportional to the electron number density which is computed by solving the equation

$$n = \frac{1}{4\pi r} \otimes \left(\frac{B}{u+D} + \frac{In}{u+D} - \frac{Rn^2}{u+D}\right)$$

Q & A



Publication:

J M Blackledge and A Kawalec
Steady State Solutions for a Weakly Ionised Plasma in a Sub- and Super-Sonic Axial Flow
MATHEMATICA AETERNA, Vol. 4, No. 2, 143 - 162, 2014.
http://www.e-hilaris.com/MA/2014/MA4_2_7.pdf

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