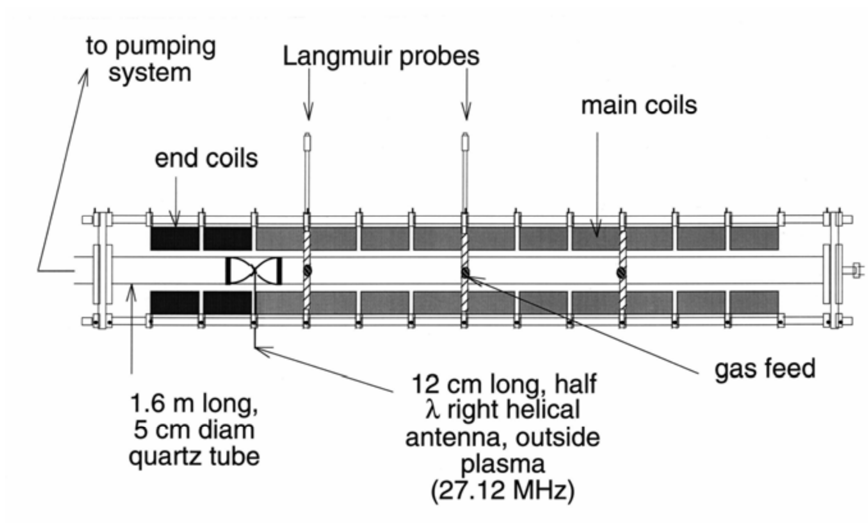
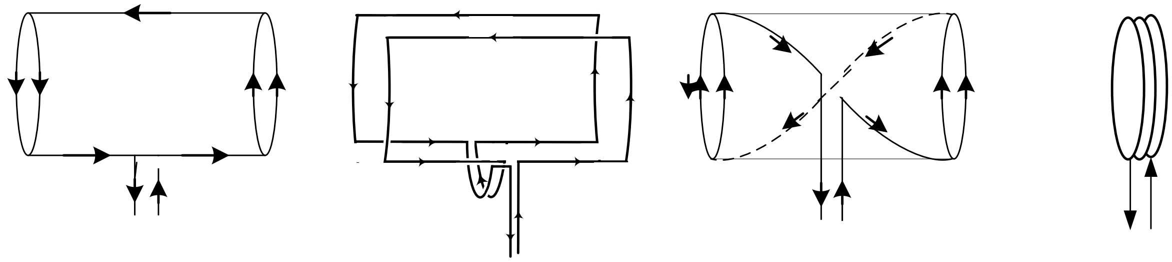
Use of permanent magnets for laboratory and industrial plasmas

Francis F. Chen, UCLA

Helicon discharges are usually in long glass tubes inside a uniform B-field created by coils.

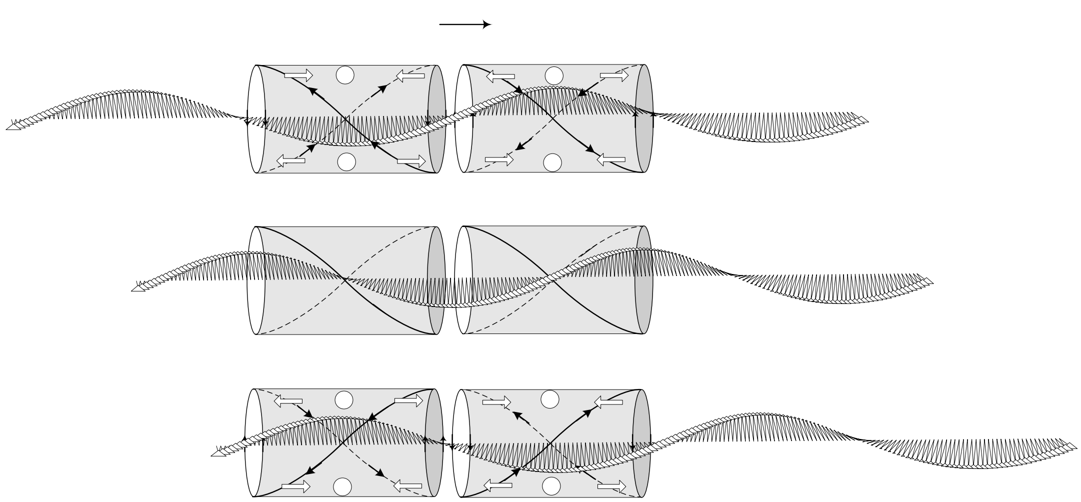


These are the common types of antennas:

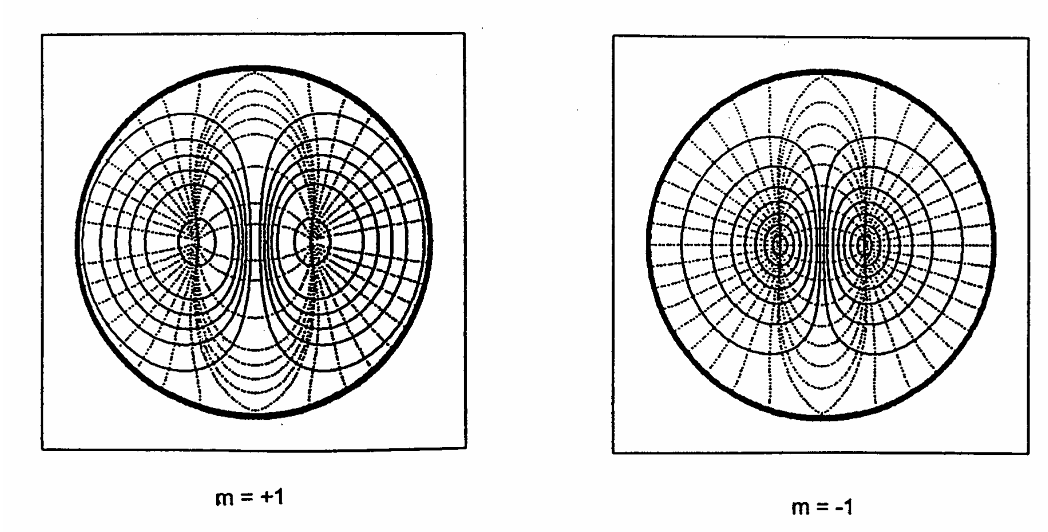


Nagoya Type III | Boswell type | RH helical | Loop

The antenna excites a helicon wave which propagates out.



The m = 1 antennas create these magnetic field patterns:



The m = 0 mode goes from electromagnetic to electrostatic in each half-cycle:

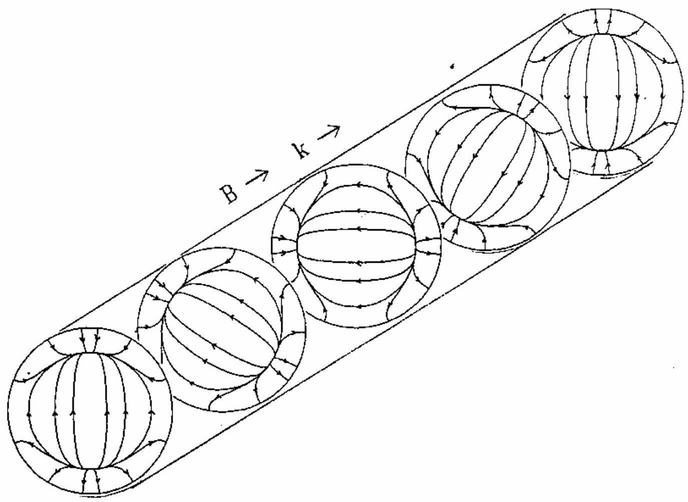


Figure 3. Instantaneous electric field pattern for an m = +1 helicon wave in space (Ref. 27).

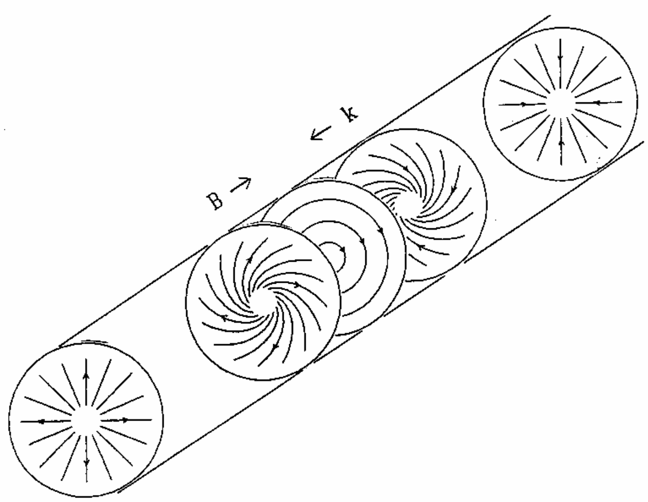
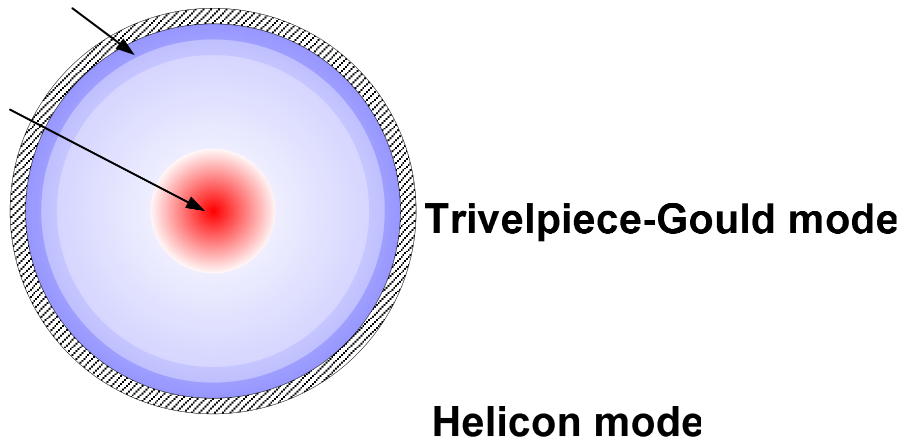


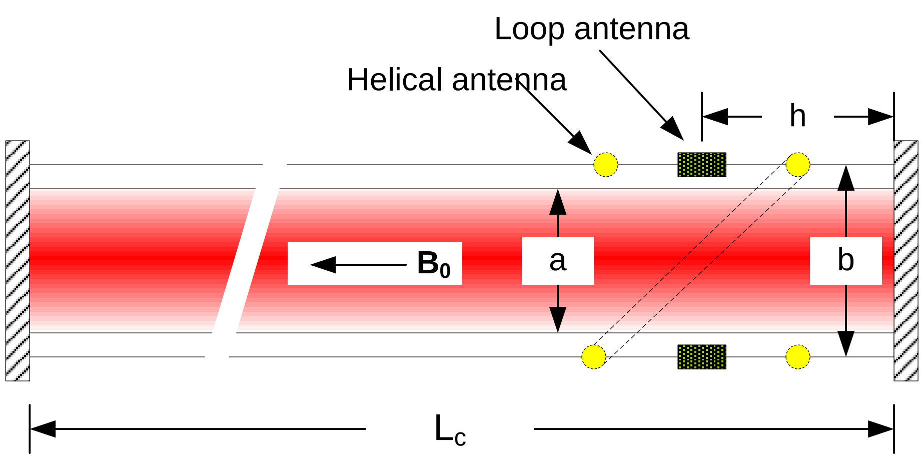
Figure 4. Instantaneous electric field pattern for an m = 0 helicon wave in space (Ref. 27).

We have to use the m = 0 mode with permanent magnets, as we shall see.

The helicon wave excites another wave, the Trivelpiece-Gould (TG) mode, due to matching conditions at the boundary: The TG mode causes most of the ionization.

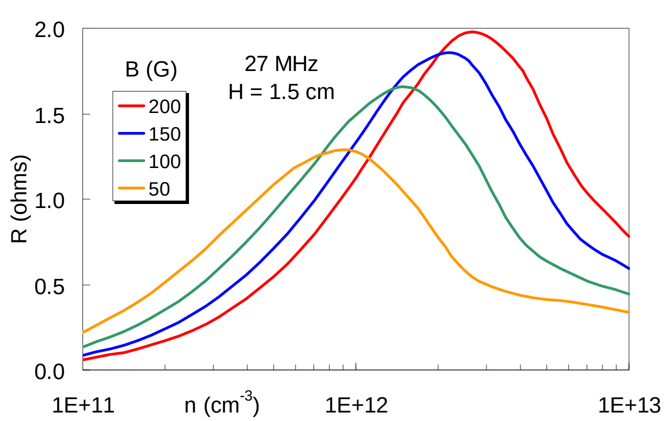


To design a helicon discharge, we use the HELIC code written by Don Arnush, who died in 2003.



The code calculates the **E** and **B** fields everywhere, and also where the energy is deposited. Most useful is the quantity R, the plasma resistance, which tells how well the RF energy is absorbed.

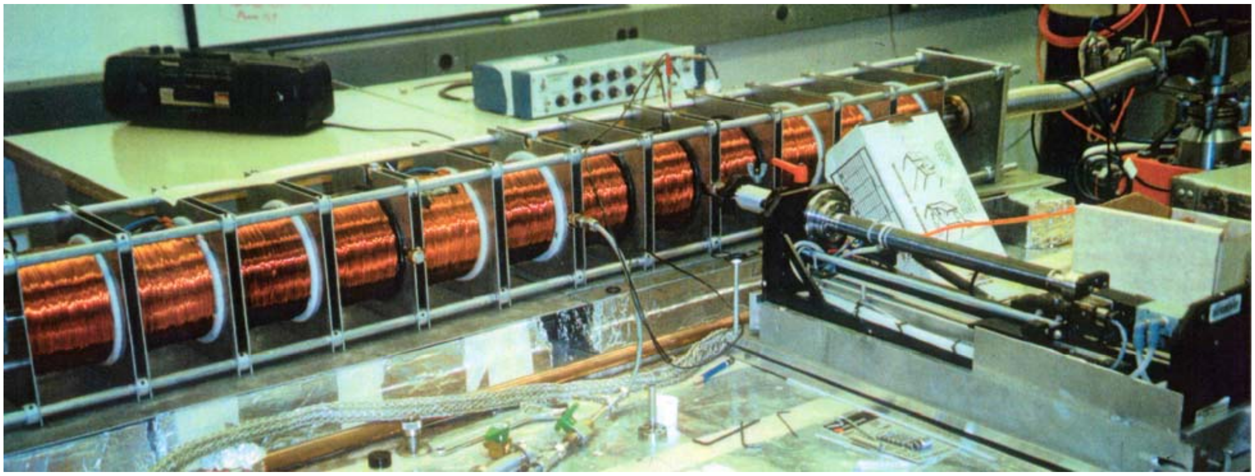
To design a system, we need to get $R >> R_c$, where R_c is the loss to circuitry. It is not easy to get $R >> 1\Omega$. HELIC calculates RnB, curves of R vs. density n and B-field B. For example:



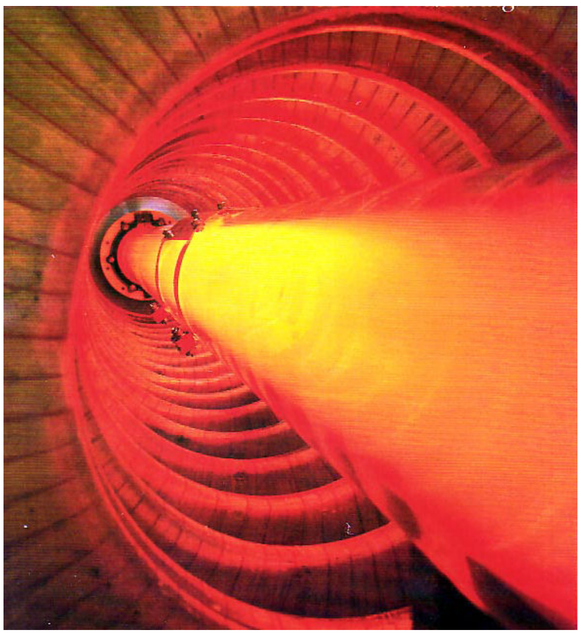
For each point on this graph, HELIC solves two coupled differential equations for hundreds of values of axial wave number k. Such a graph takes about two hours.

We need to choose n and B somewhere past the peak for a stable operating point.

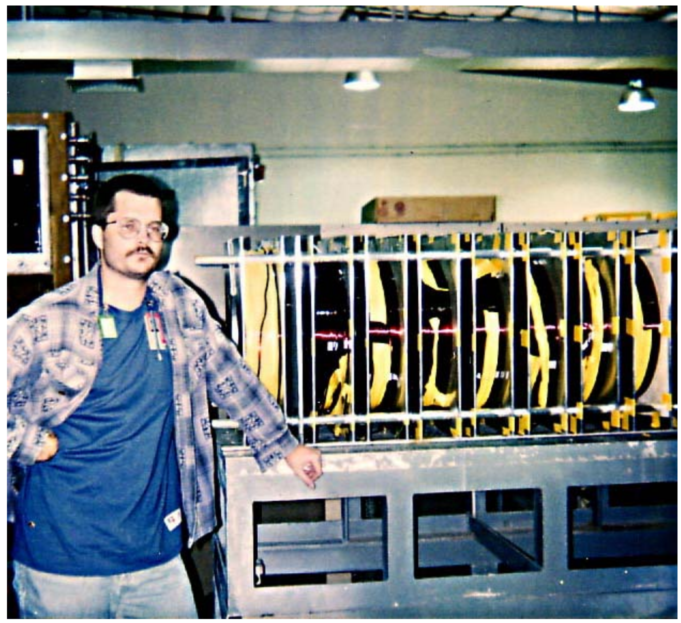
Previous helicon sources were either long solenoids for experimentation, like these:



My original machine (UCLA)

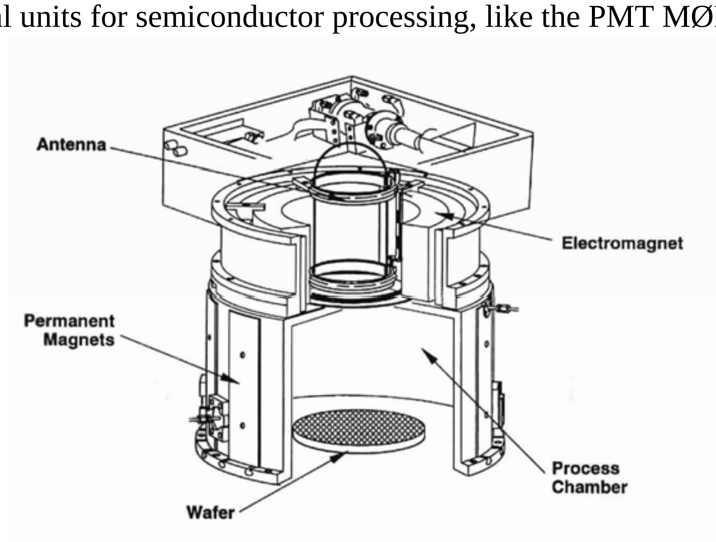


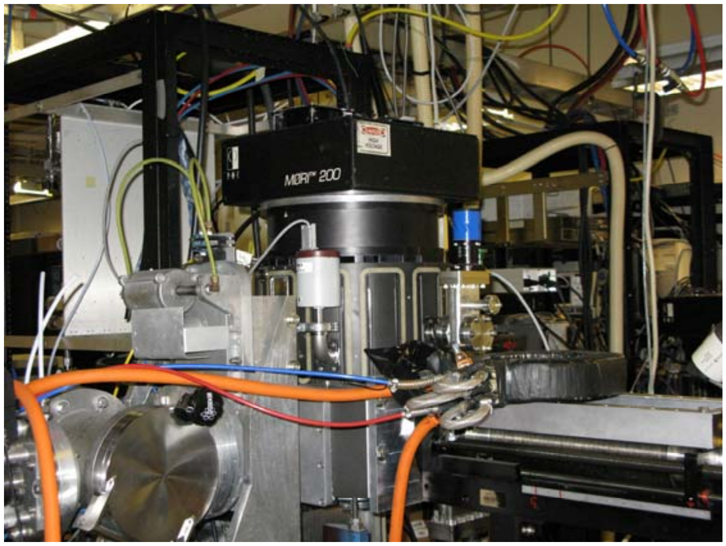
Wisconsin (Hershkowitz)



Max Light at Los Alamos

…or they were commercial units for semiconductor processing, like the PMT MØRI source:





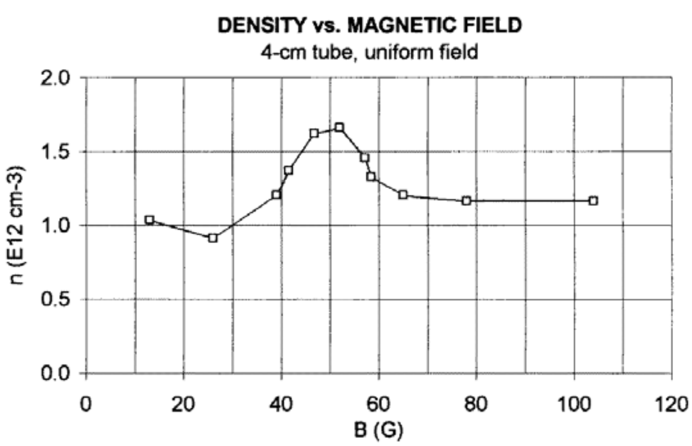
This source was sold by Plasma Materials Technologies, a company started by Bob Conn and his student Greg Campbell, after I brought the idea from Boswell in Australia. The source was designed by Tatsuo Shoji and me. It was very popular with semiconductor companies who tried it, but the company was closed by a bad business decision. My research was delayed by 10 years as a result.

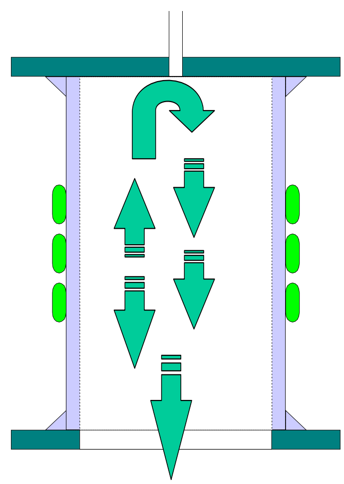
The source required two heavy electromagnets and their power supply. I have replaced them with a 5-inch permanent magnet weighing maybe two pounds.

The new permanent-magnet (PM) helicon source involves TWO INVENTIONS:

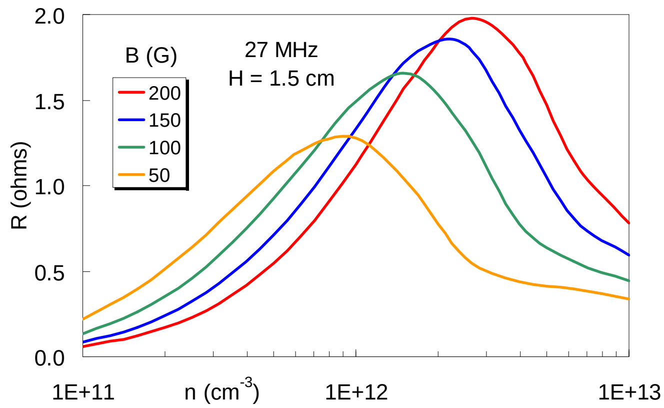
1. Use of the "Low-Field Peak" effect.
2. Use of the remote, reverse field of a ring magnet.

1. The Low-Field Peak was seen in early experiments:

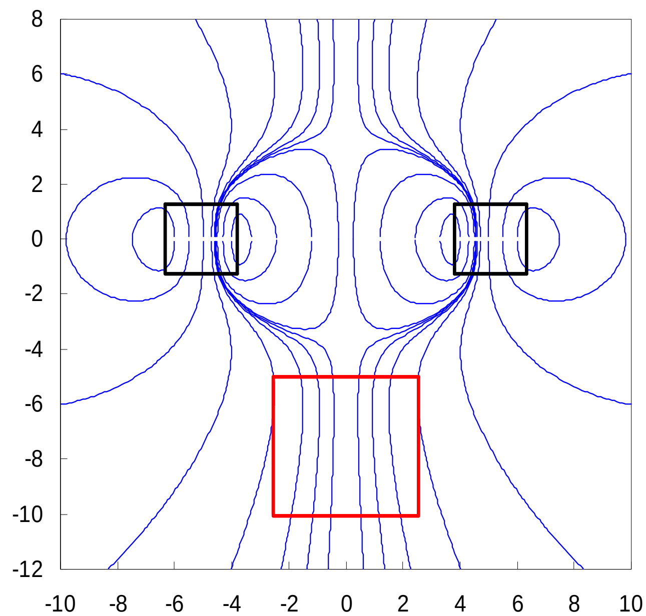




This is due to reflection of the backward wave from the back plate, which is placed so that the reflected wave adds constructively to the forward wave. This is confirmed by HELIC calculations. Since the wavelength depends on *n* and *B*, the peak depends on these, as shown in the previous plot:



2. The remote field of a ring magnet:



Design of the tube:

MATRIX A: Magnet position

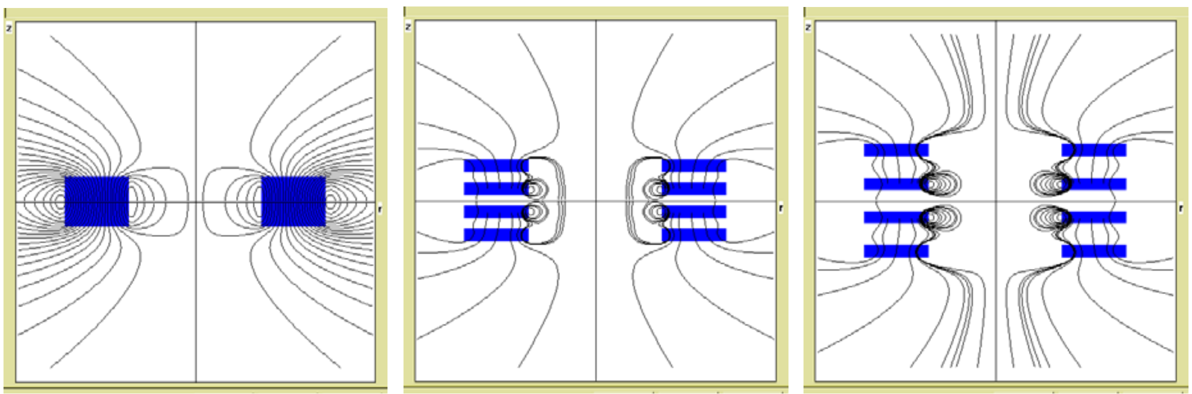
	1 mTorr, ei = -1			
	D = 7.4"	D = 11"	D = 13"	D = 0
100W	Folder D7W100	Folder D11W100	Folder D13W100	Folder D0W100
300W	Folder D7W300	Folder D11W300	Folder D13W300	Folder D0W300
500W	Folder D7W500	Folder D11W500	Folder D13W500	Folder D0W500

Matrices of parameters to be calculated were formulated. HELIC calculations were made for each case. We varied tube diameter, tube height, pressure, *B*-field, etc.

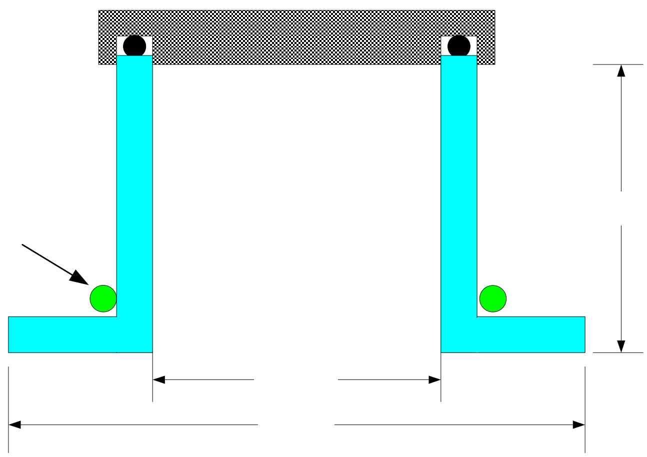
MATRIX B: Pressure

	300W, ei = -1			
	D = 7.4"	D = 11"	D = 13"	D = 0
1 mTorr	Folder D7P1	Folder D11P1	Folder D13P1	Folder D0P1
10 mTorr	Folder D7P10	Folder D11P10	Folder D13P10	Folder D0P10

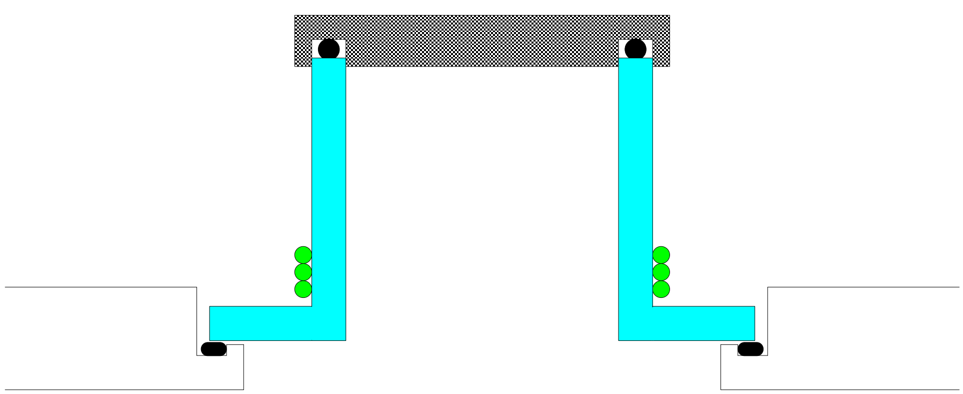
Design of the magnet:

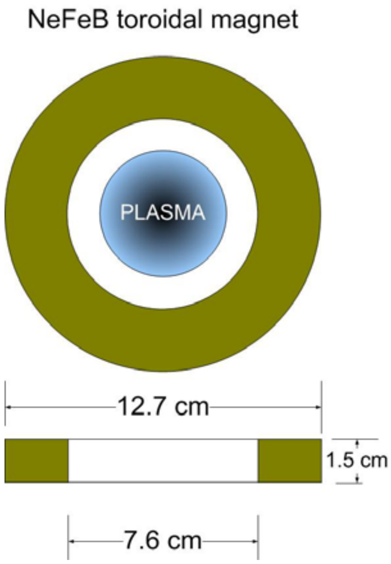


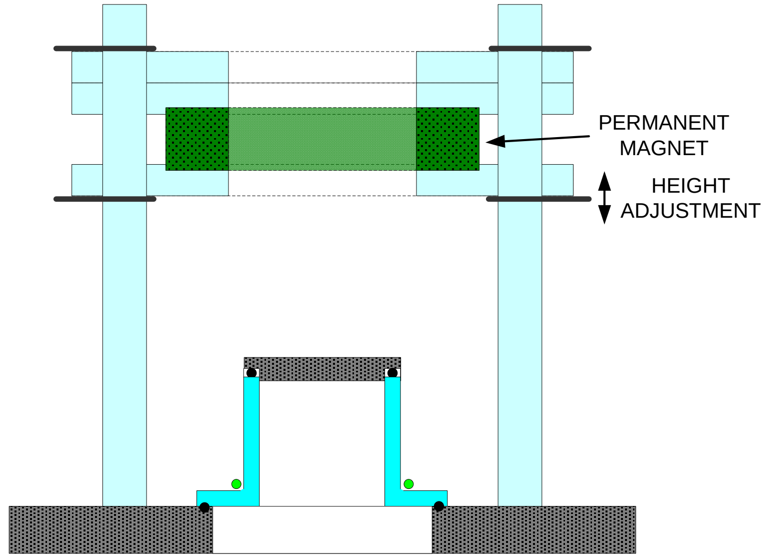
The resulting design:



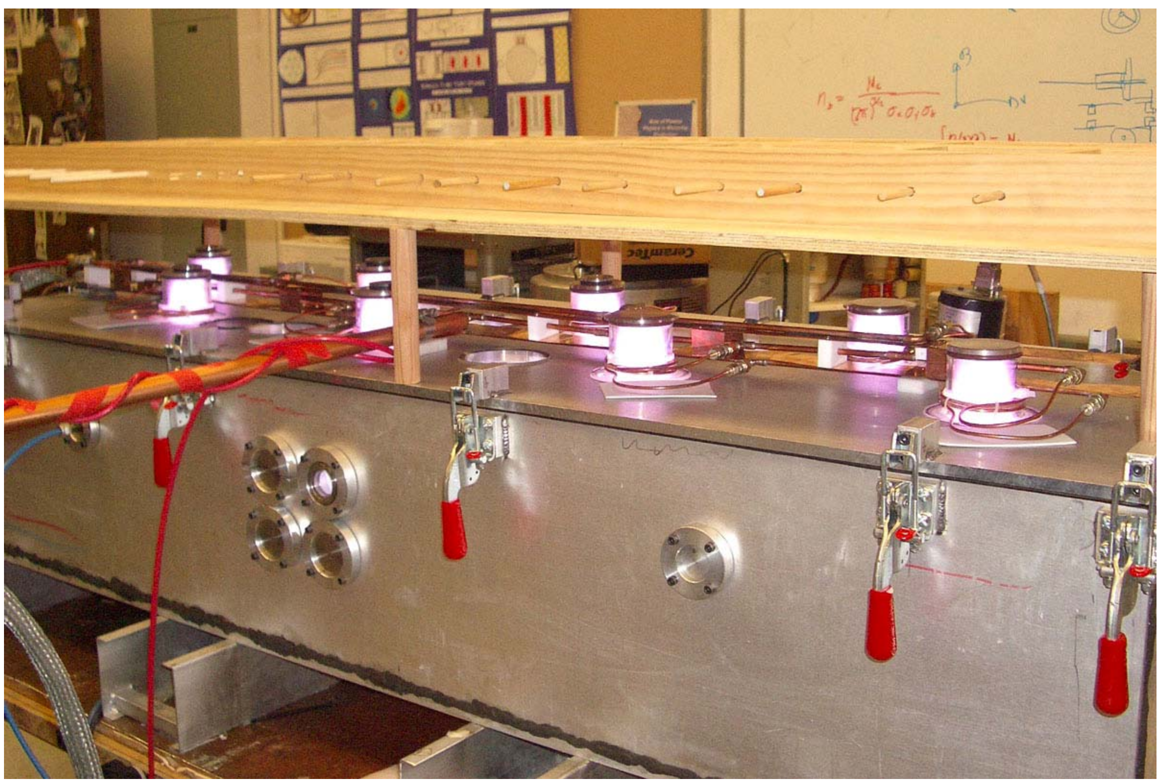
Note the “skirt” to get antenna away from flange. 3-turn antenna for 13 MHz, 1 turn for 27 MHz.



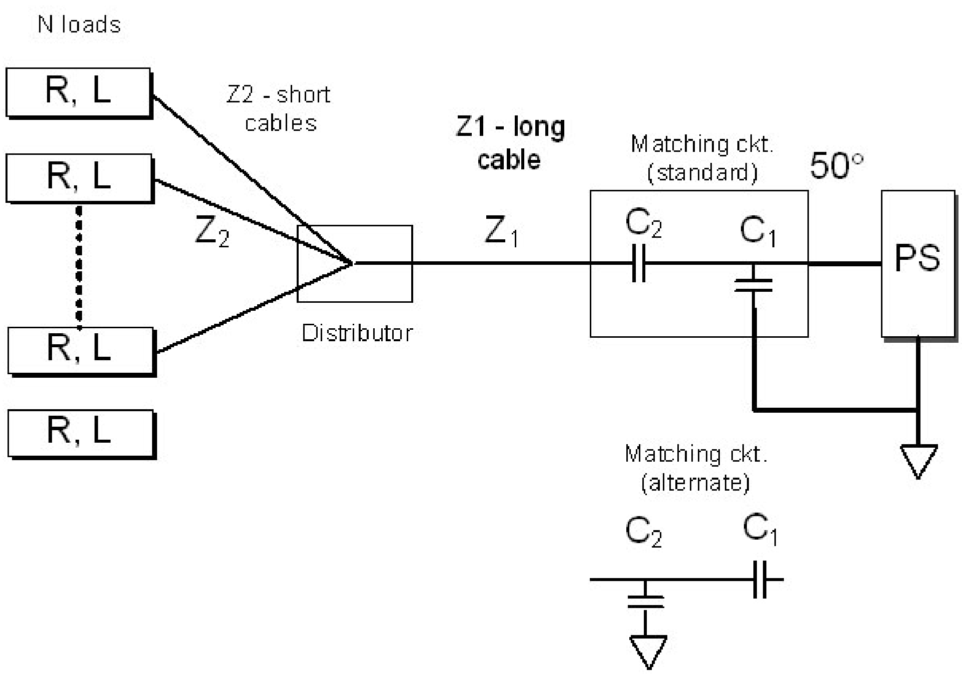




Medusa 2: an 8-tube array of these sources:



Antenna matching



Standard circuit:

$$C_1 = \left[1-(1-2R)^2\right]^{1/2}/2R$$
$$C_2 = \left[X-(1-R)/C_1\right]^{-1}$$

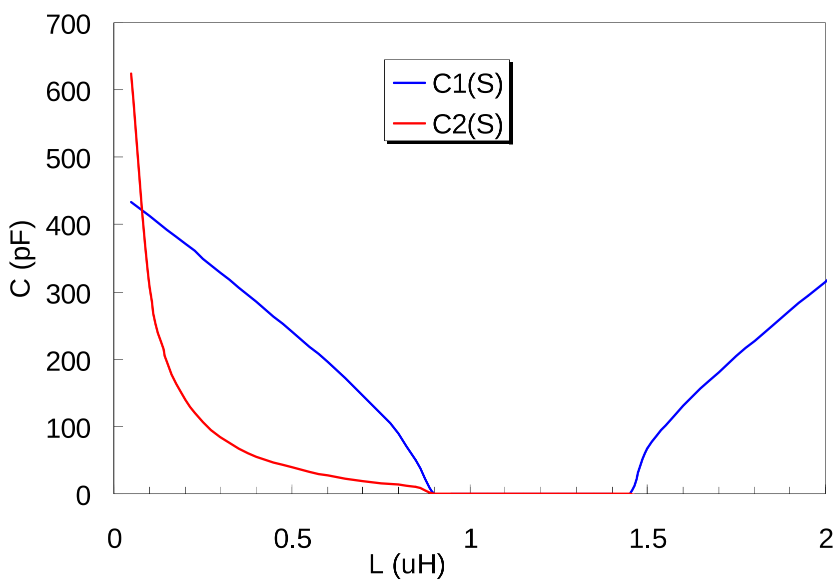
Alternate circuit:

$$C_1 = R/B\ , \qquad C_2 = (X-B)/T^2$$
$$T^2 \equiv R^2+X^2$$
$$B^2 \equiv R(T^2-R)$$

No direct match is possible for a capacitive load $(X<0)$. However, if impedances are transformed by a line of length kz, R and X above should be replaced by

$$R = R_L/D\ , \qquad D \equiv (\cos kz - X_L \sin kz)^2 + R_L^2 \sin^2 kz$$
$$X = \left\{\left[1-\left(R_L^2+X_L^2\right)\right]\sin kz \cos kz + X_L(cos^2 kz - \sin^2 kz)\right\}/D \quad ,$$

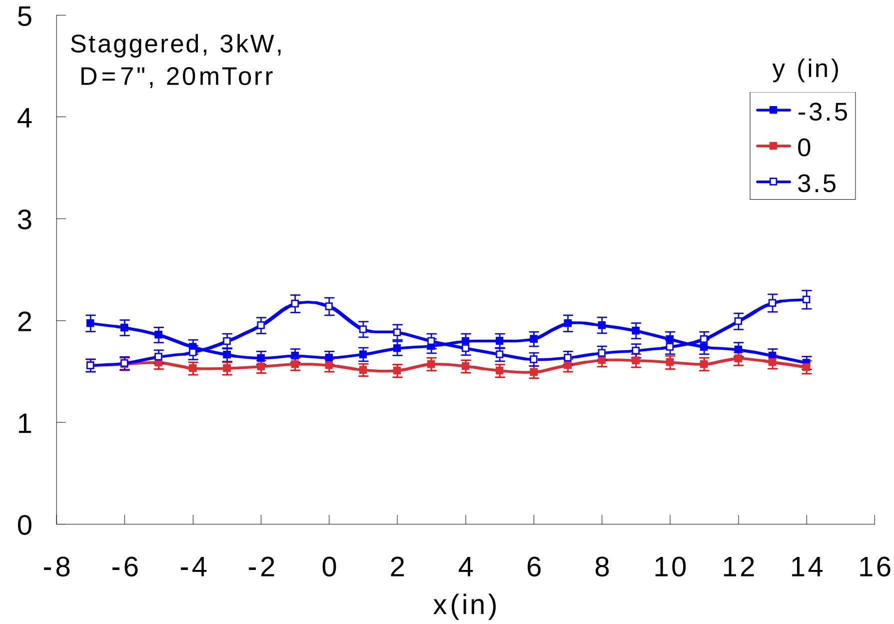
where the actual load is $R_L + jX_L$.

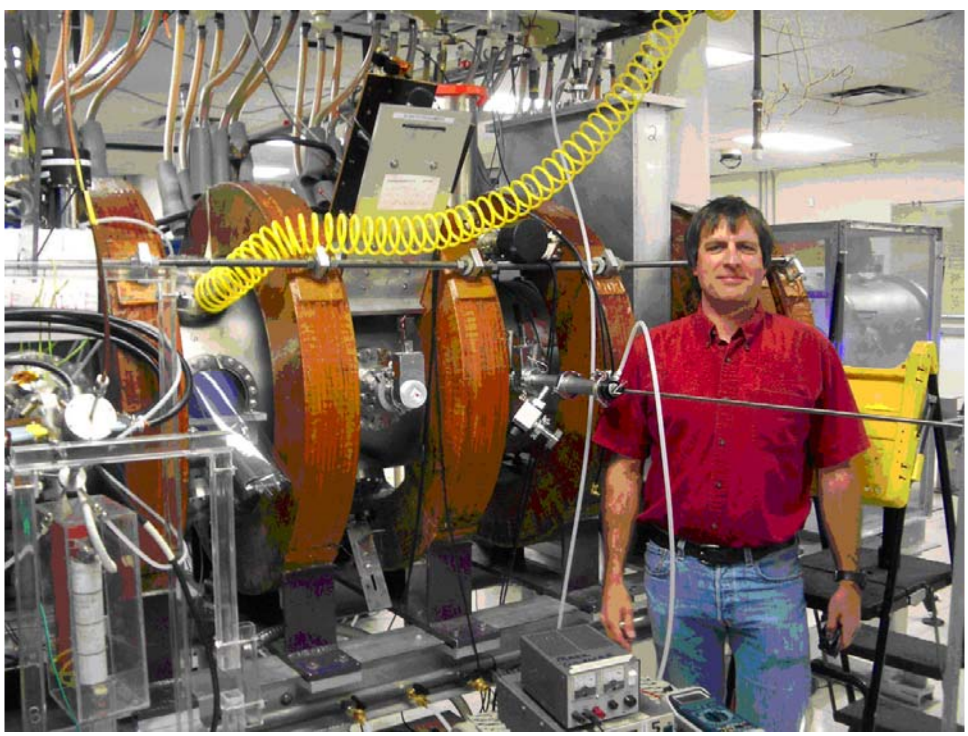


There are restrictions on the antenna inductance. At 13 MHz, we can use three turns of *m* = 0. At 27 MHz, we can use only one turn.

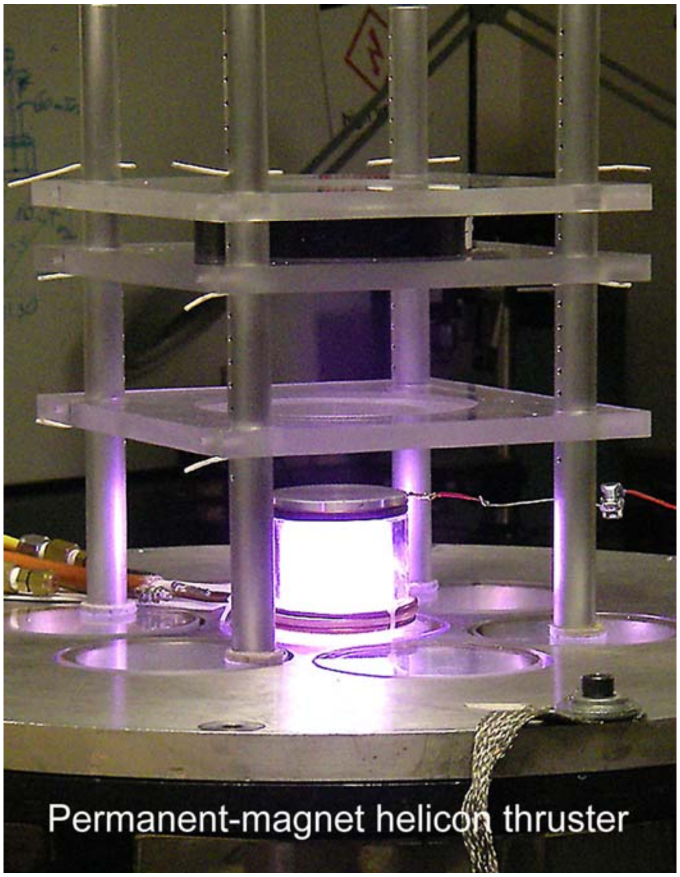
A 50-ohm rectangular transmission line

Data by Humberto Torreblanca





Mark Gilmore and his helicon machine, U. New Mexico



My current machine

Excel and HELIC programs for design are on the Low Temperature Plasma Technology (LTPTL) website: www.ee.ucla.edu/~ltptl

ffchen@ee.ucla.edu   www.ee.ucla.edu/~ffchen

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