

Mode Switching in Relativistic Magnetrons and Hysteresis

Edl Schamiloglu
Gardner-Zemke Professor of ECE
University of New Mexico

March 16, 2011



...in collaboration with

- Mikhail Fuks (Research Professor)
- C. Jerald Buchenauer (Research Professor)
- Sarita Prasad (Post Doc)
- Christopher Leach (Ph.D. student)
- Cedric Michel (M.S. student, Montpellier University of Sciences, France, interned at UNM Summer 2008)
- Meiqin Liu (Ph.D. student, Jiaotong University, Xi'an, China, performing internship at UNM 2009-2011)
- Marvin Roybal (M.S. student on pulsed power)

OUTLINE

- A Little Bit About UNM's Applied EM Group
- Why the DoD (AFOSR/ONR*) is Interested in High Power Microwave (HPM) Sources
- A6 Magnetron with Radial Extraction – Transparent Cathode
- A6 Magnetron with Axial Extraction – RF Mode Switching and Hysteresis
- How this Relates to Pulsars
- Concluding Remarks

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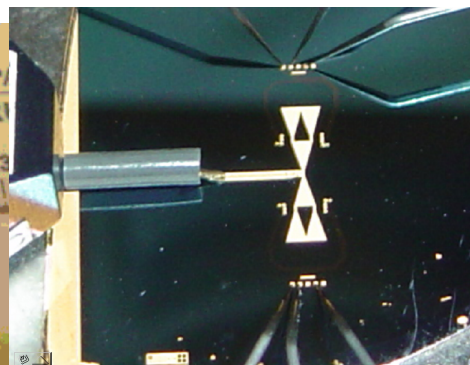
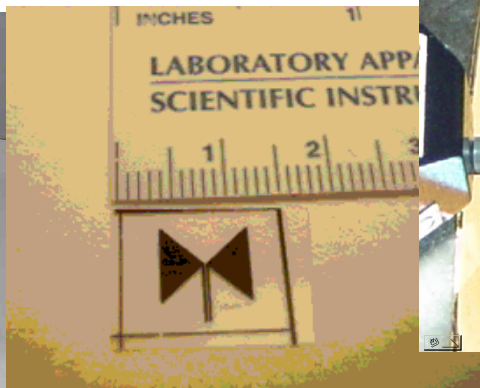
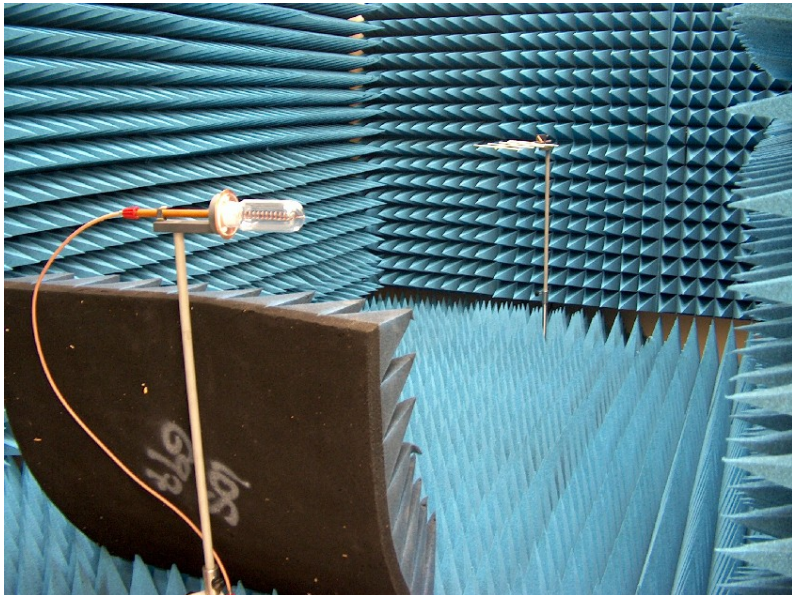
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PROFESSOR CHRISTOS CHRISTODOULOU

Antennas

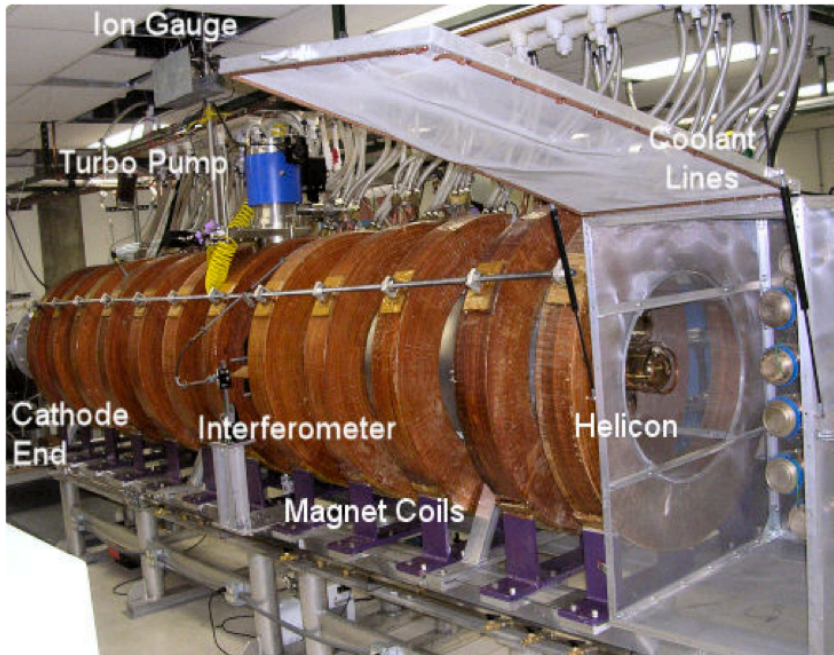


PROFESSOR MARK GILMORE

UNM Plasma and Fusion Science Group

The HelCat (Helicon-Cathode) Plasma Device at UNM

Mark Gilmore, *Associate Professor*
Alan Lynn, *Research Assistant Professor*



- Length: 4 m
- Diameter: 50 cm
- $B_z \leq 0.22$ Tesla
- Plasma Sources: Cathode & RF Helicon

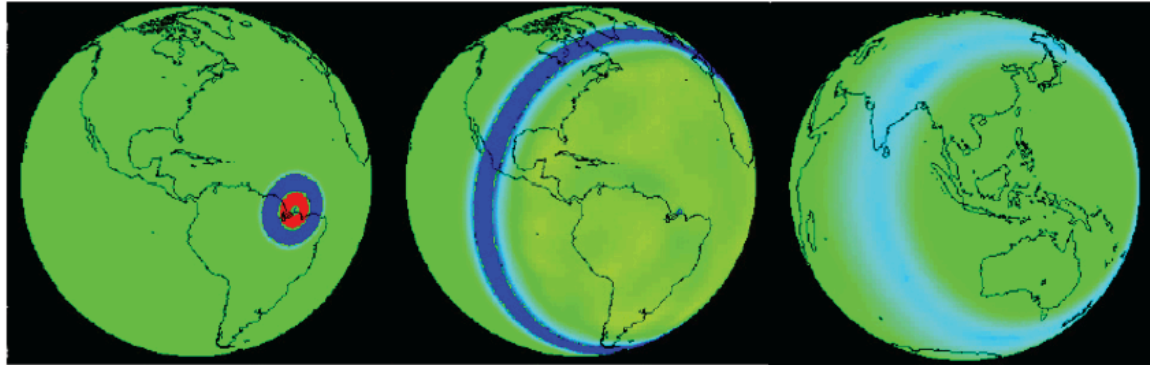
Current Research Scope:

- **At UNM:** Basic Plasma Physics relevant to magnetic fusion, space plasmas and astrophysics, spacecraft thrusters
 - Turbulence and transport
 - Flows, flow shear, flow control
 - Boundary physics
 - Magnetic relaxation
 - Helicons in B-field gradients
- **Off site collaborations:**
 - Magneto-inertial fusion (MIF) physics
 - Diagnostics for MIF and other Innovative Confinement Concept experiments

PROFESSOR JAMESINA SIMPSON

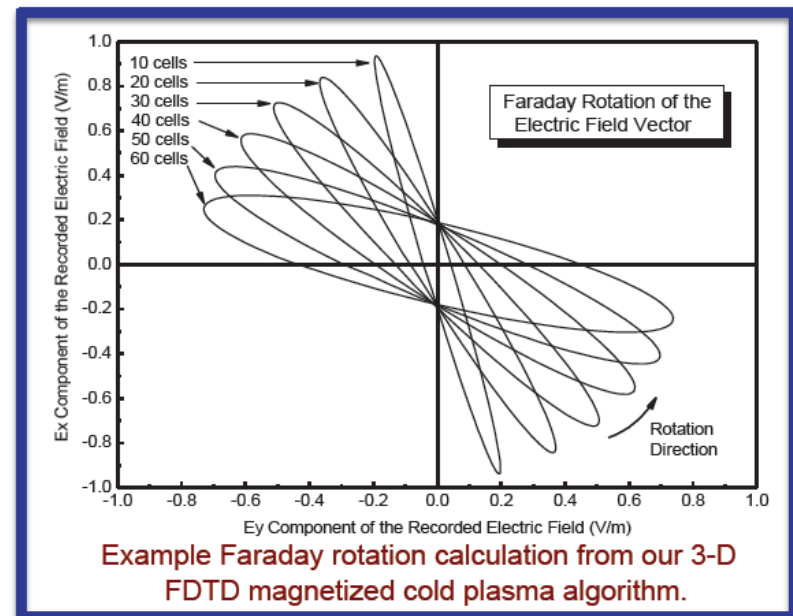
FDTD Computation

3-D Maxwell's Equations Models of the Global Earth-Ionosphere System



Employing the finite-difference time-domain (FDTD) method, these models account for:

- 1) EM wave propagation dynamics within ± 400 km of the Earth's surface;
- 2) Earth's topography/bathymetry;
- 3) Variability of the lithosphere composition;
- 4) Geomagnetic field;
- 5) Anisotropic magnetized ionospheric plasma.



Prof. Simpson was awarded a 2010 NSF CAREER to support her work in this area.

Email: simpson@ece.unm.edu; Website: www.ece.unm.edu/~simpson

UNM IS LOCATED AT THE HUB OF PULSED POWER-DRIVEN PHYSICAL SCIENCES RESEARCH IN THE US



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IEEE
SPECTRUM
Nov. 2003

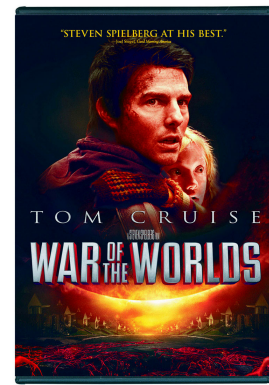
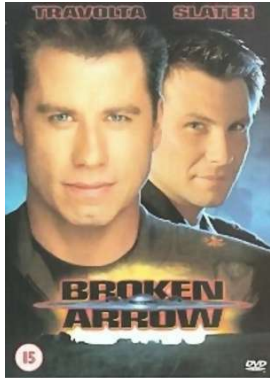
MILITARY

The Dawn of E-BOMB

For the wired world, the allure and the danger of high-power microwave weapons are both very real By Michael Abrams

10/58

“High Power Microwaves (HPM)” in Hollywood....



and many more...

From “Futurama” Season 2, Episode 20...



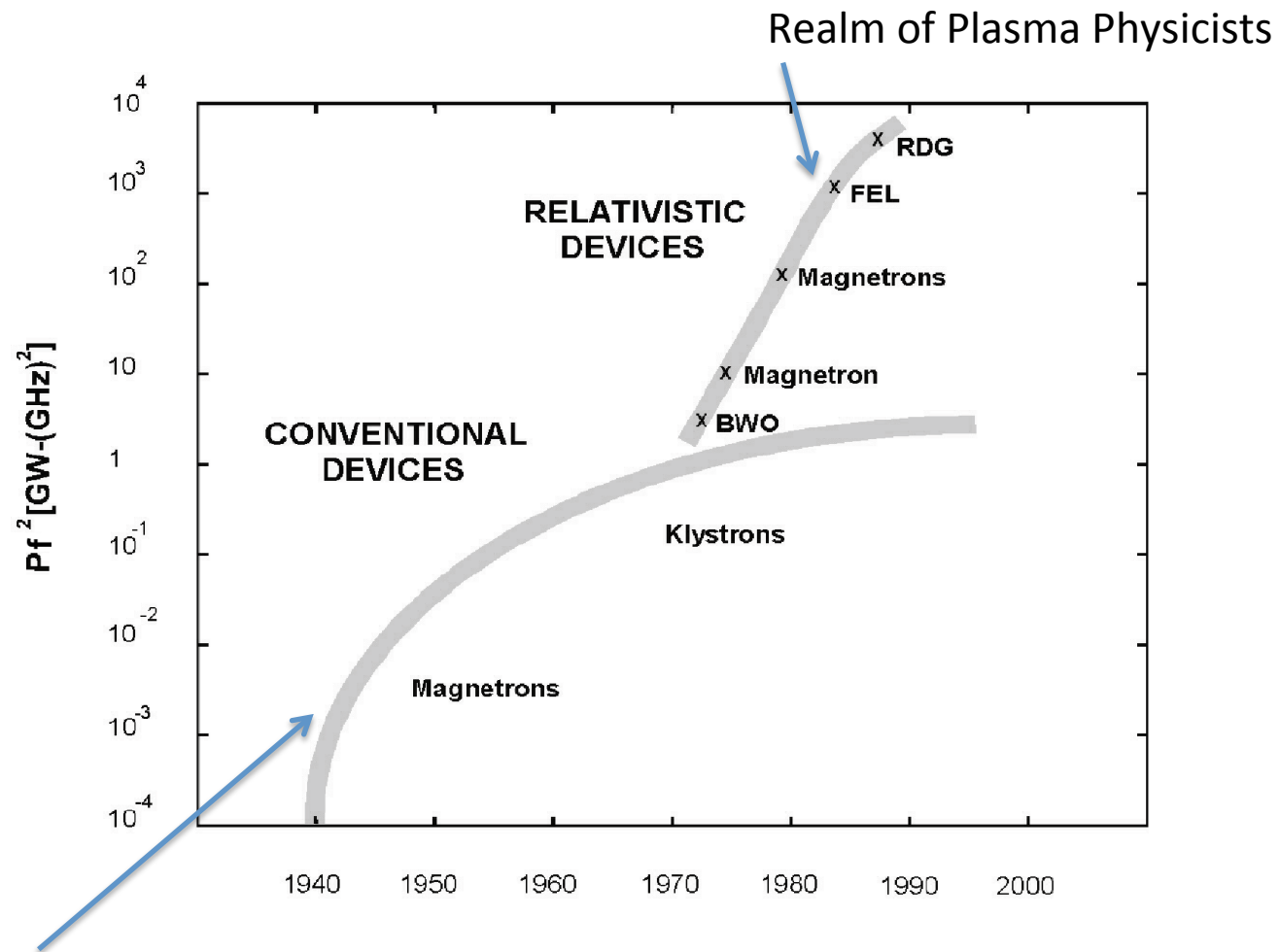
HISTORY OF HPM LINKED TO HISTORY OF PULSED POWER

High Power Microwaves “born” in late 1960’s and early 1970’s – Prof. John Nation (Cornell University - retired) and Drs. Petelin, Kovalev (Institute of Applied Physics, Gorky (Nizhny Novgorod), USSR, in collaboration with group in Moscow).

Pulsed Power – “modern pulsed power” attributed to Charlie Martin (deceased) and colleagues at AWRE, Aldermaston in England in 1960’s. Group interested in radiography had to use pulsed power to increase x-ray fluence.

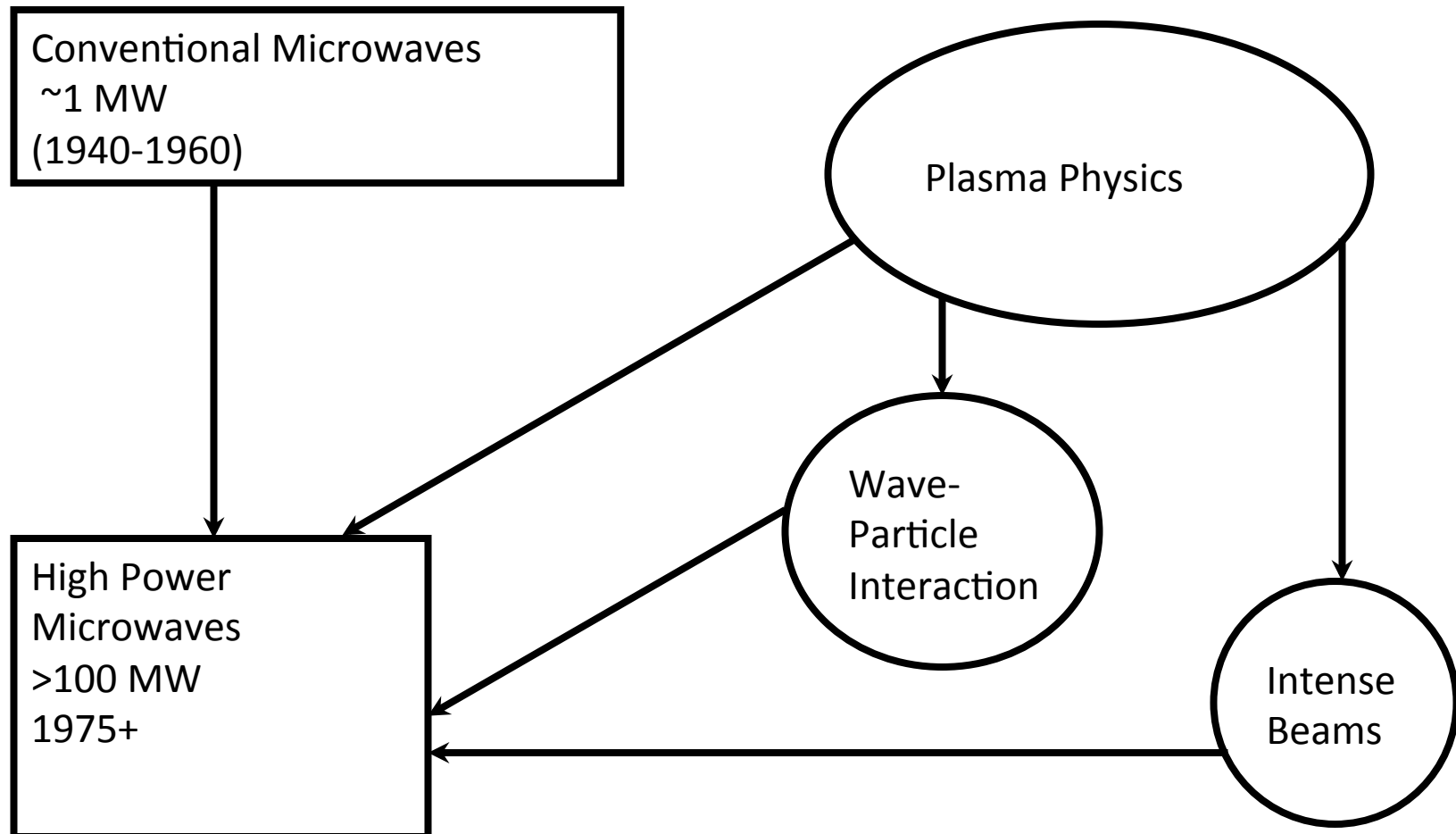
Initial HPM sources revisited traditional microwave tubes, except used intense beams to drive them.

HISTORICAL DEVELOPMENT OF HPM



Realms of Electrical Engineers

HISTORICAL DEVELOPMENT OF HPM



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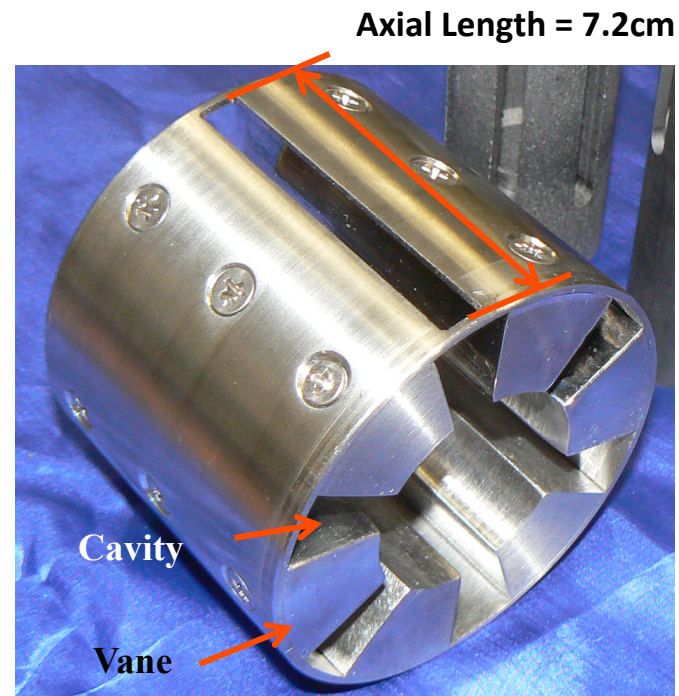
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A6 MAGNETRON WITH RADIAL EXTRACTION – TRANSPARENT CATHODE

Radius of the Vane = 2.11 cm

Radius of the Cavity = 4.11 cm

Radius of the Cathode = 1.58 cm



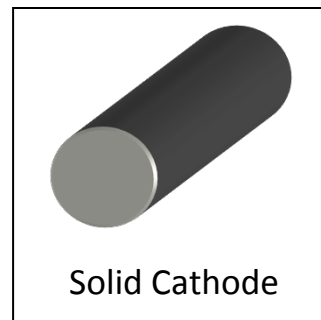
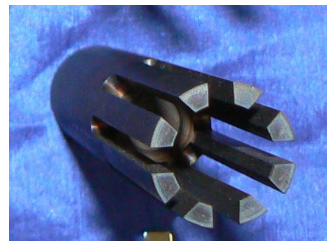
**UNM's reproduction of MIT's
A6 Magnetron**

THE TRANSPARENT CATHODE

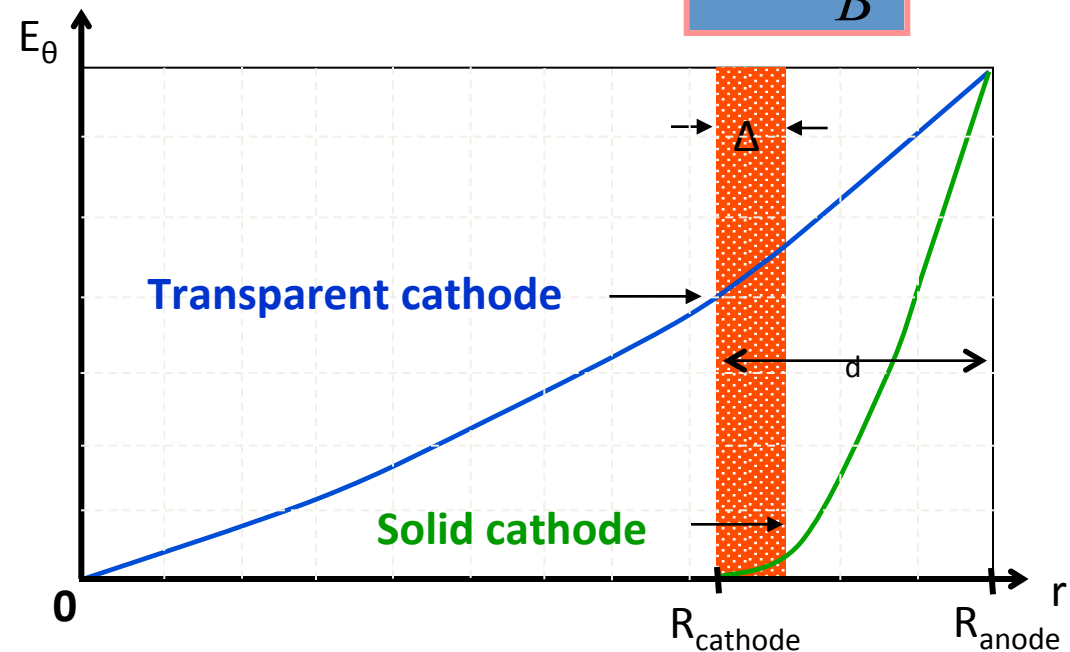
Genesis of the Idea:¹

The rate of energy transfer from the electrons to the RF field

$$v_r = \frac{E_\theta}{B}$$



Solid Cathode

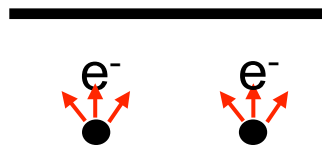


Azimuthal Electric Field Distribution

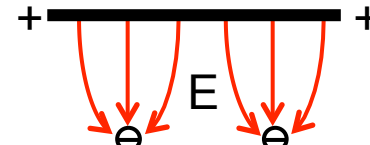
¹ M.I. Fuks and E. Schamiloglu, "Rapid Start of Oscillations in a Magnetron with a "Transparent Cathode", " *Phys. Rev. Lett.* vol. 95, 205101-1-4 (2005).

The Transparent Cathode: Achieves 3 priming methods self-consistently w/o requiring additional hardware!

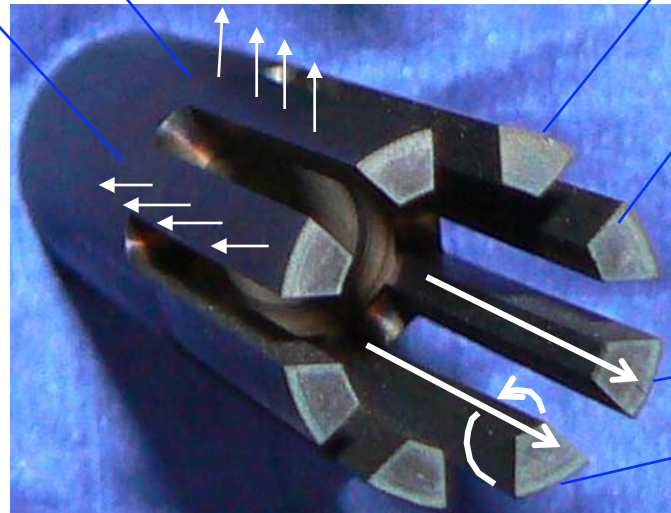
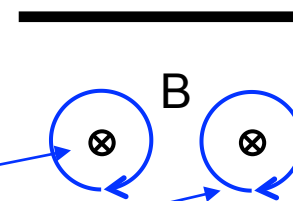
Cathode Priming



Electric Priming



Magnetic Priming



INITIAL PATENT ISSUED APRIL 2010



US007696696B2

(12) **United States Patent**
Fuks et al.

(10) **Patent No.:** **US 7,696,696 B2**
(45) **Date of Patent:** **Apr. 13, 2010**

(54) **MAGNETRON HAVING A TRANSPARENT CATHODE AND RELATED METHODS OF GENERATING HIGH POWER MICROWAVES**

(75) Inventors: **Mikhail Fuks**, Albuquerque, NM (US);
Edl Schamiloglu, Albuquerque, NM (US)

(73) Assignee: **STC.UNM**, Albuquerque, NM (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 838 days.

(21) Appl. No.: **11/462,561**

(22) Filed: **Aug. 4, 2006**

(65) **Prior Publication Data**

US 2007/0030088 A1 Feb. 8, 2007

Related U.S. Application Data

(60) Provisional application No. 60/705,169, filed on Aug. 4, 2005.

(51) **Int. Cl.**
H01J 25/50 (2006.01)

(52) **U.S. Cl.** **315/39.51**

(58) **Field of Classification Search** 315/39.51,
315/39.57, 39.63, 39.67, 39.71, 39.75; 204/298.19,
204/298.21, 298.22

6,538,386 B2 3/2003 Small
6,872,929 B2 3/2005 Neculaes et al.
6,921,980 B2 7/2005 Nakanishi et al.
2004/0026240 A1* 2/2004 Shidoji et al. 204/298.03
2004/0206751 A1 10/2004 Neculaes et al.
2004/0206754 A1 10/2004 Neculaes et al.

OTHER PUBLICATIONS

Fuks et al., "Operation of a Relativistic Magnetron with a 'Cut Cathode'," Abstract from *IEEE Conference Record-Abstracts, The 31st IEEE International Conference on Plasma Science*, Jun. 28-Jul. 1, 2004, Baltimore, MD, 4P7, p. 277.
Fuks et al., "Improvement of the Output Characteristics of Relativistic Magnetrons," *The Papers of Joint Technical Meeting on Plasma Science and Technology and Pulsed Power Technology, IEEE Japan*, Aug. 5-6, 2004, Maui, HI, pp. 71-76.
Schamiloglu, "Relativistic Magnetron Powered Using a Transparent Cathode," Presentation given at 2005 IEEE International Pulsed Power Conference, Jun. 14, 2005, Monterey, CA, (21 pages).
Fuks et al., "Rapid Onset Of Oscillations In A Magnetron with a Transparent Cathode," Abstract from *IEEE Conference Record-Abstracts, 2005 IEEE International Conference on Plasma Science*, Jun. 20-23, 2005, Monterey, CA, 2P21, p. 206.

(Continued)

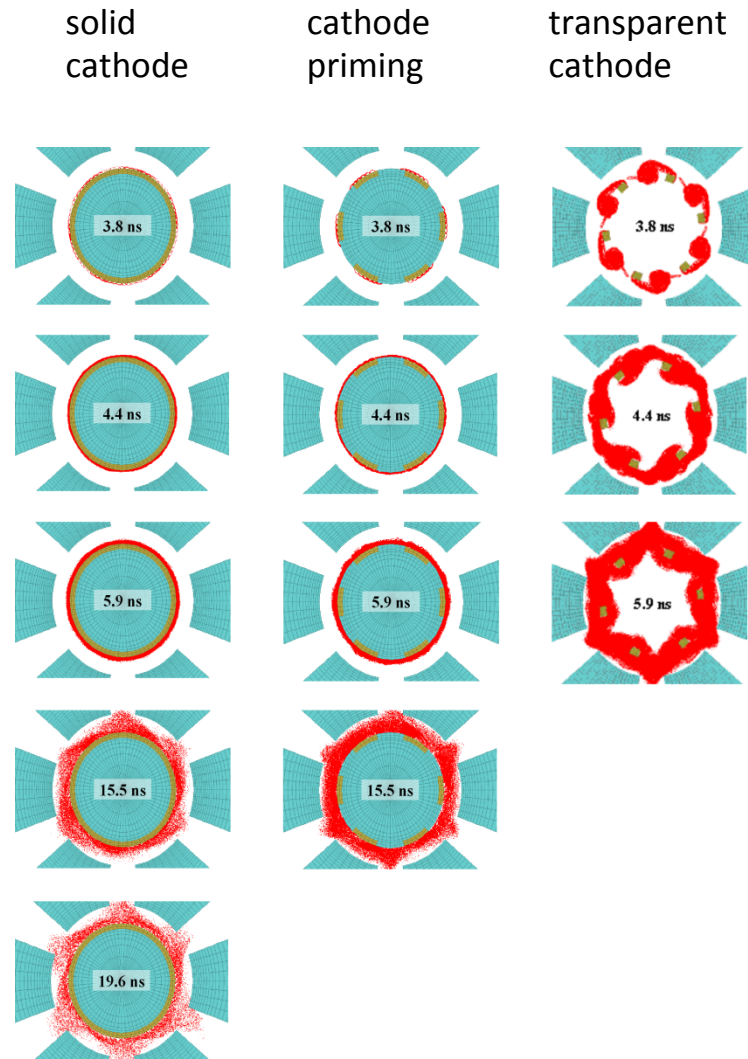
Primary Examiner—Douglas W Owens
Assistant Examiner—Minh D A
(74) Attorney, Agent, or Firm—MH2 Technology Law Group

(57) **ABSTRACT**

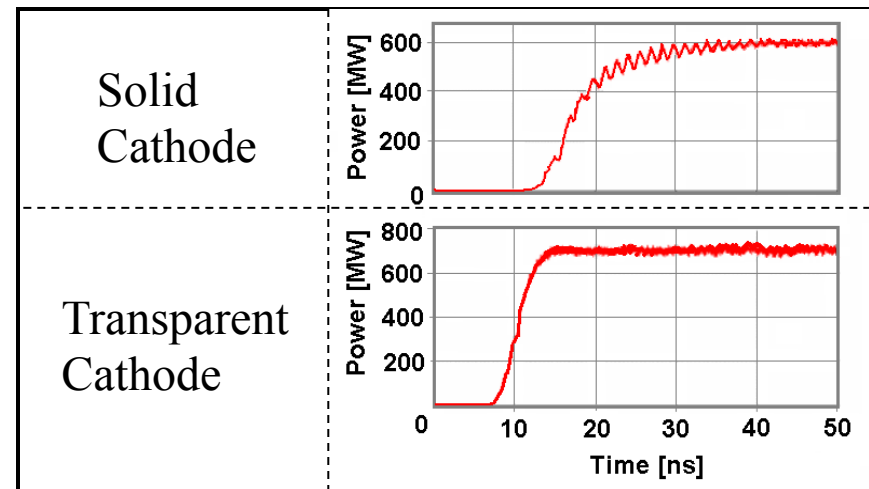
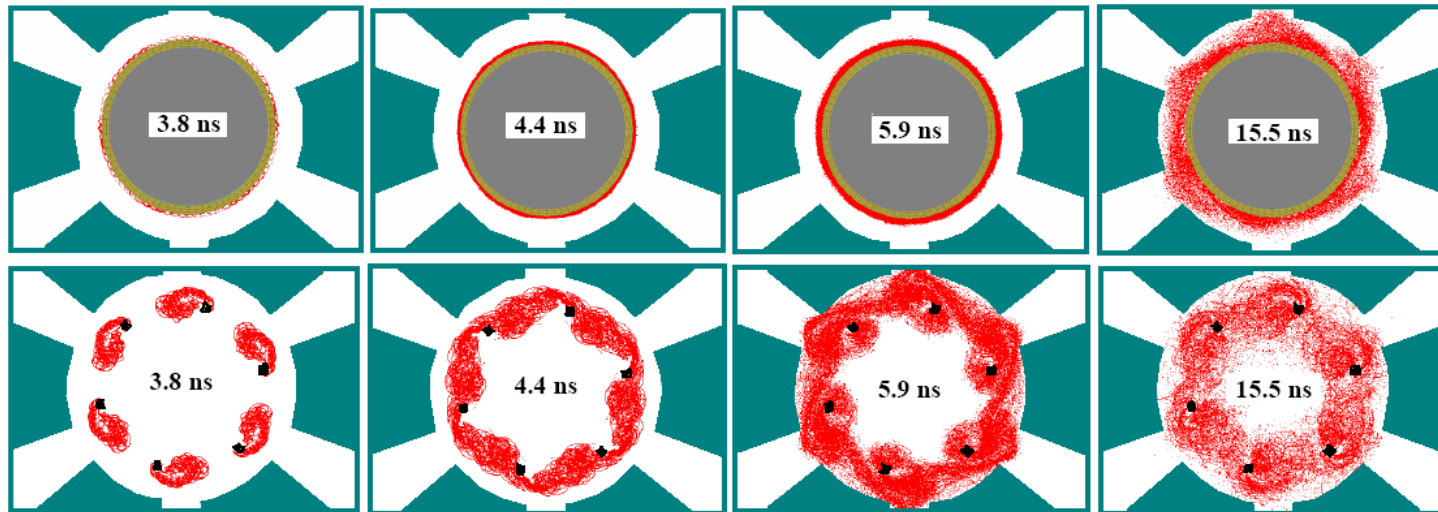
Second Patent Just Issued (US Patent #7,893,621 – “Eggbeater Transparent Cathode for Magnetrons and Ubitrons and Related Methods of Generation of High Power Microwaves” – Fuks, Schamiloglu, Bosman, and Prasad)

MAGIC 3D PIC SIMULATIONS

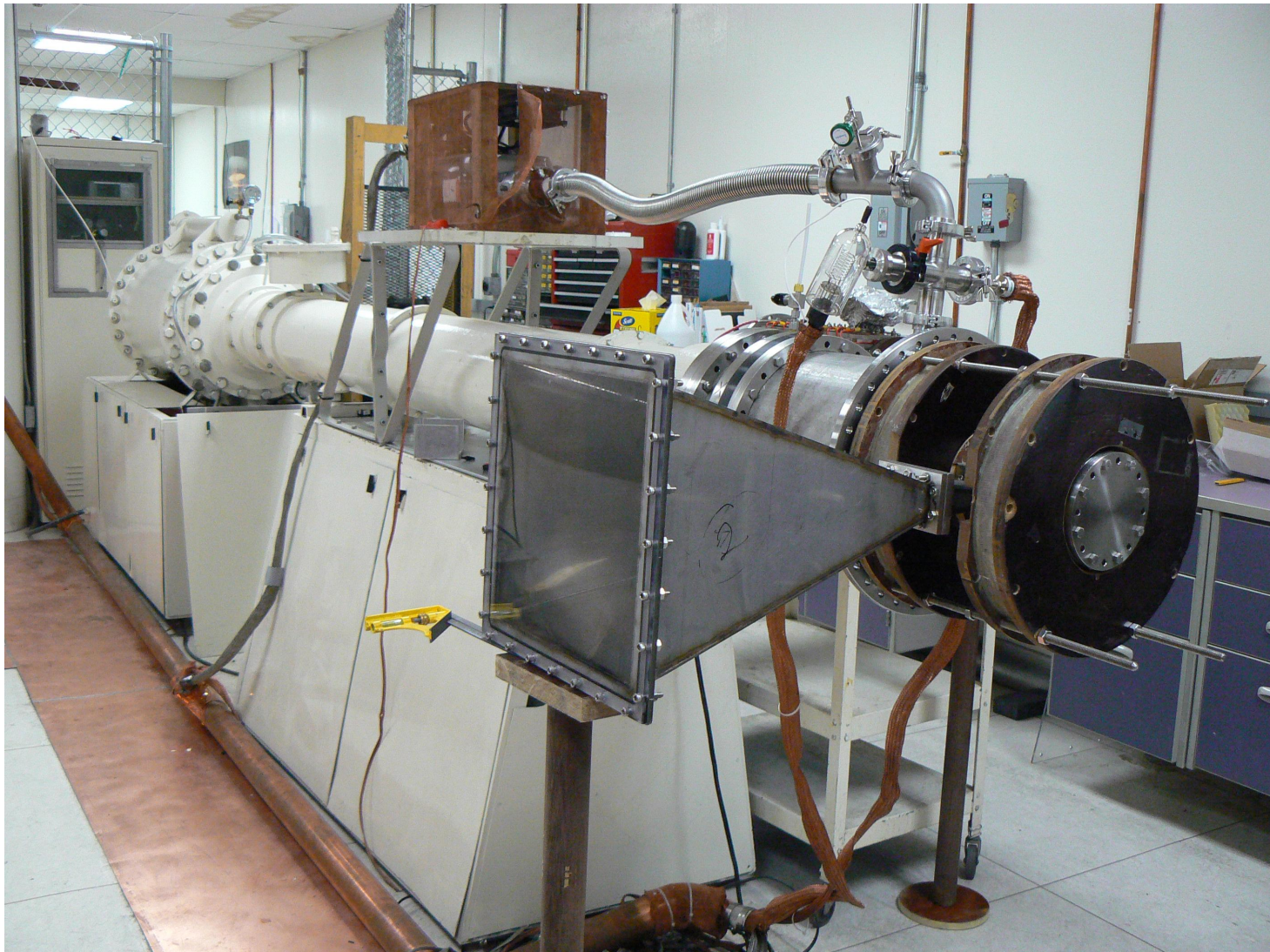
Comparison of electron spoke formation time for three different cathodes in an A6 magnetron.



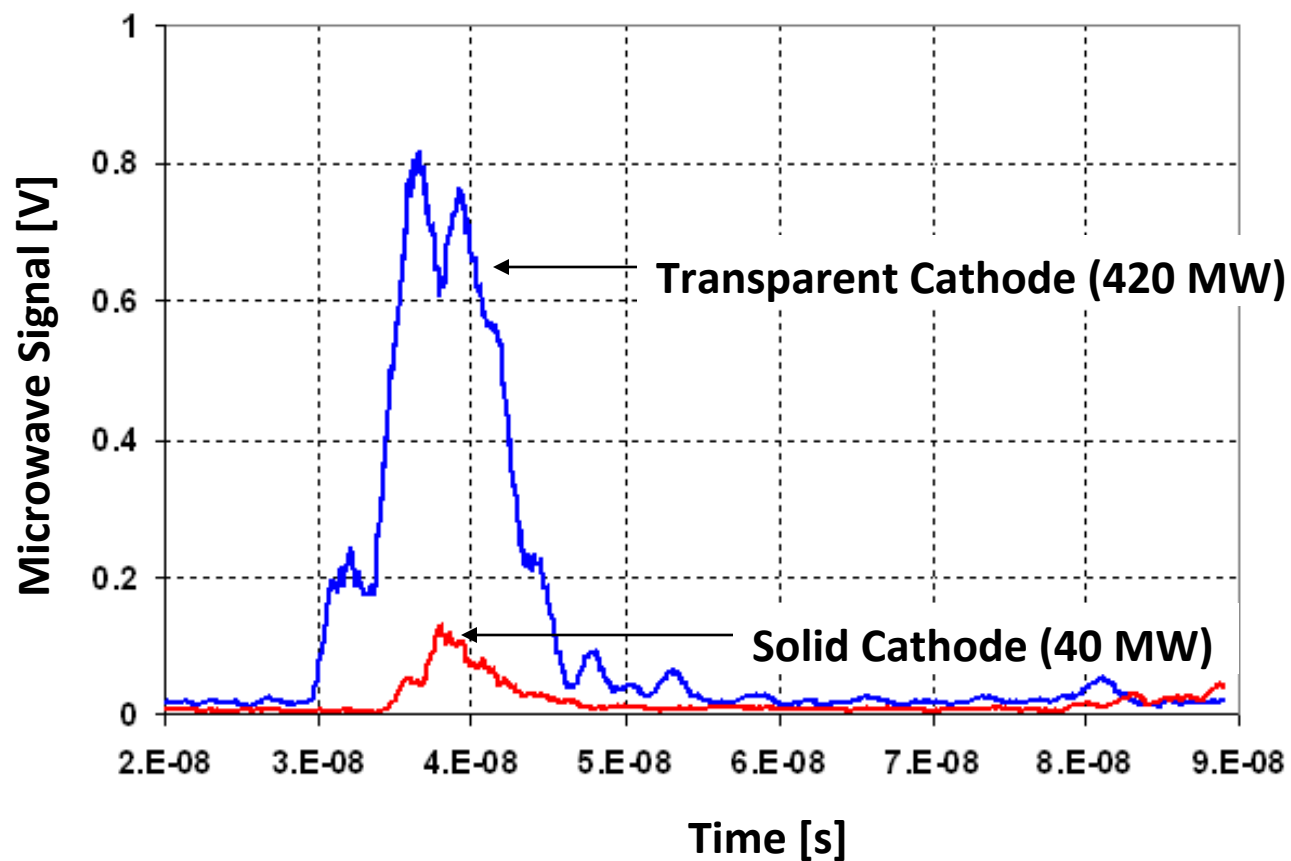
MAGIC 3D PIC SIMULATIONS



OUR EXPERIMENT

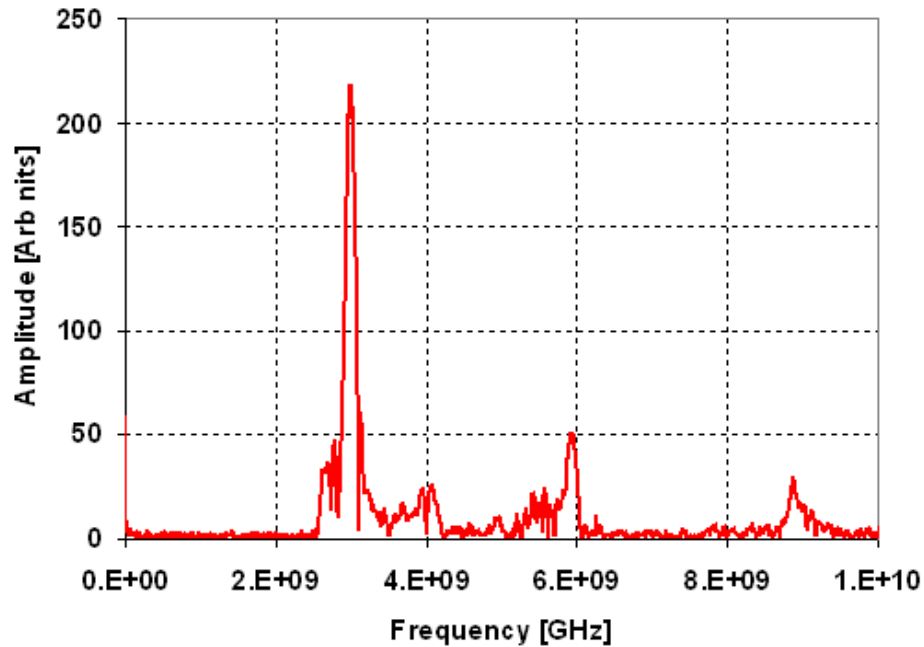


EXPERIMENTAL DATA



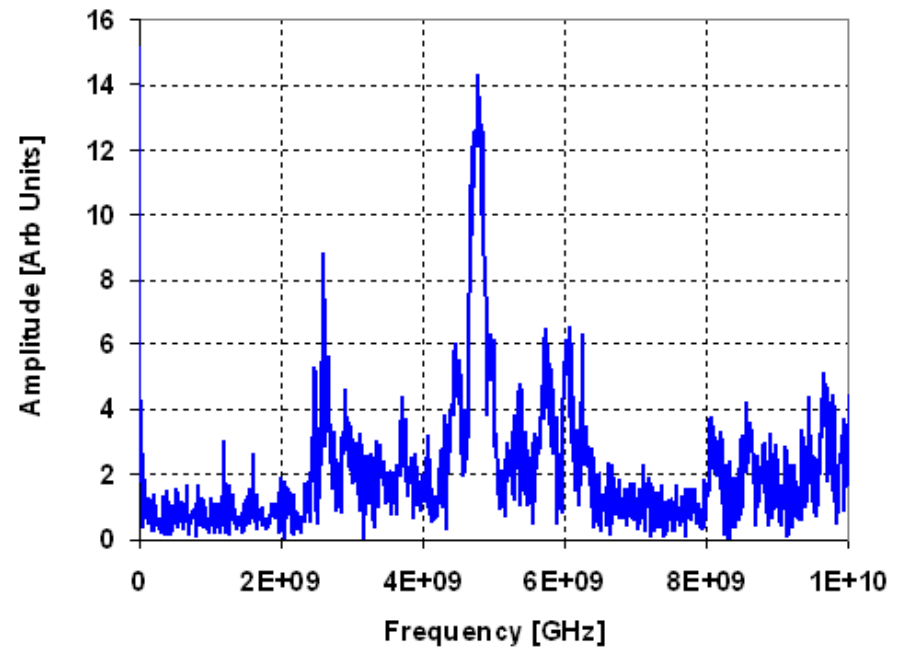
EXPERIMENTAL DATA

Transparent Cathode



Frequency = 2.9 GHz
 π -mode

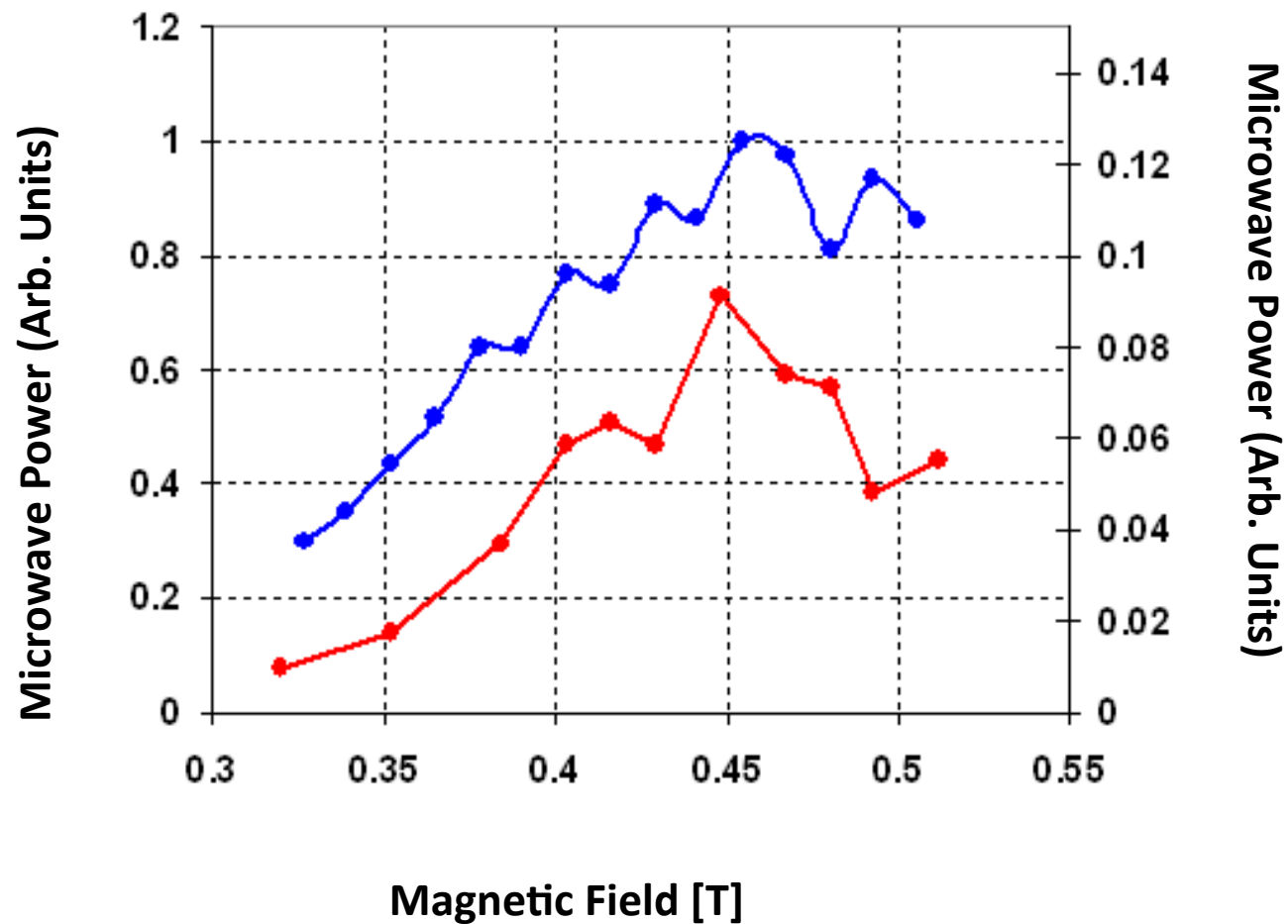
Solid Cathode



Frequency = 4.8 GHz
 $4\pi/3$ -mode

EXPERIMENTAL DATA

Microwave Power Dependence on Magnetic Field



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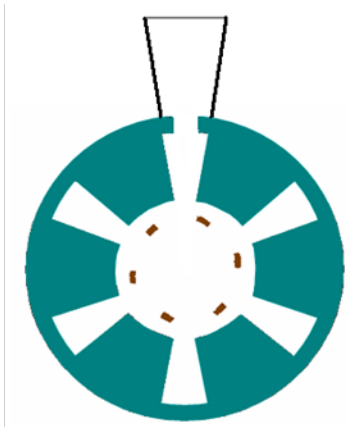
A6 MAGNETRON WITH AXIAL EXTRACTION – RF MODE SWITCHING AND HYSTERESIS

In the 1980's Mikhail Fuks (at the Institute of Applied Physics, Gorky, USSR) and colleagues had designed and tested a 3 GW X-band magnetron with *axial extraction* (as opposed to the traditional radial extraction). This was eventually dropped because efficiency was low, 7% or so.



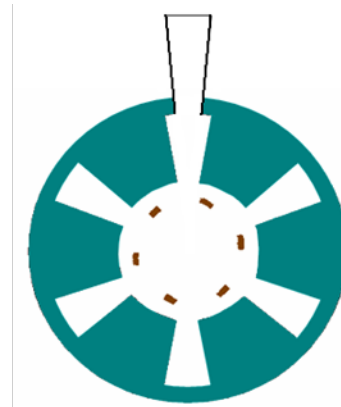
³ M. Fuks and E. Schamiloglu, "Optimization of the Parameters of a Relativistic Magnetron with Diffraction Output," *Intense Microwave Pulses IX, SPIE* (Orlando, FL, April 2002), p. 18-27.

20° Extractor

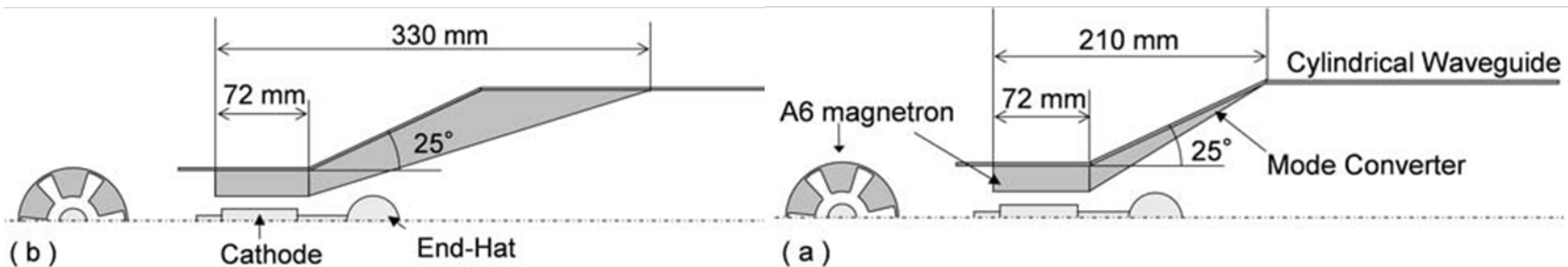


Initial Configuration

10° Extractor



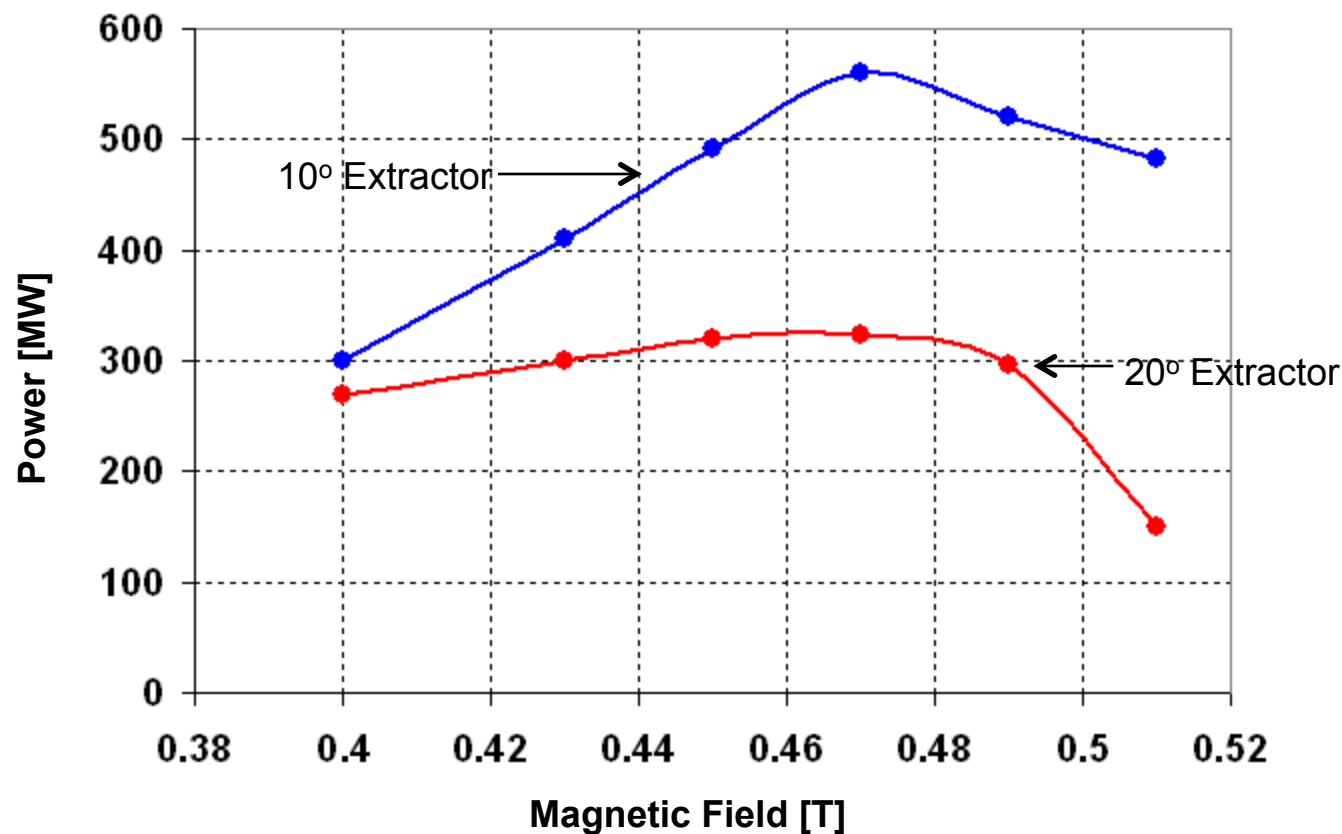
Modified Configuration



Improved Axial Extraction

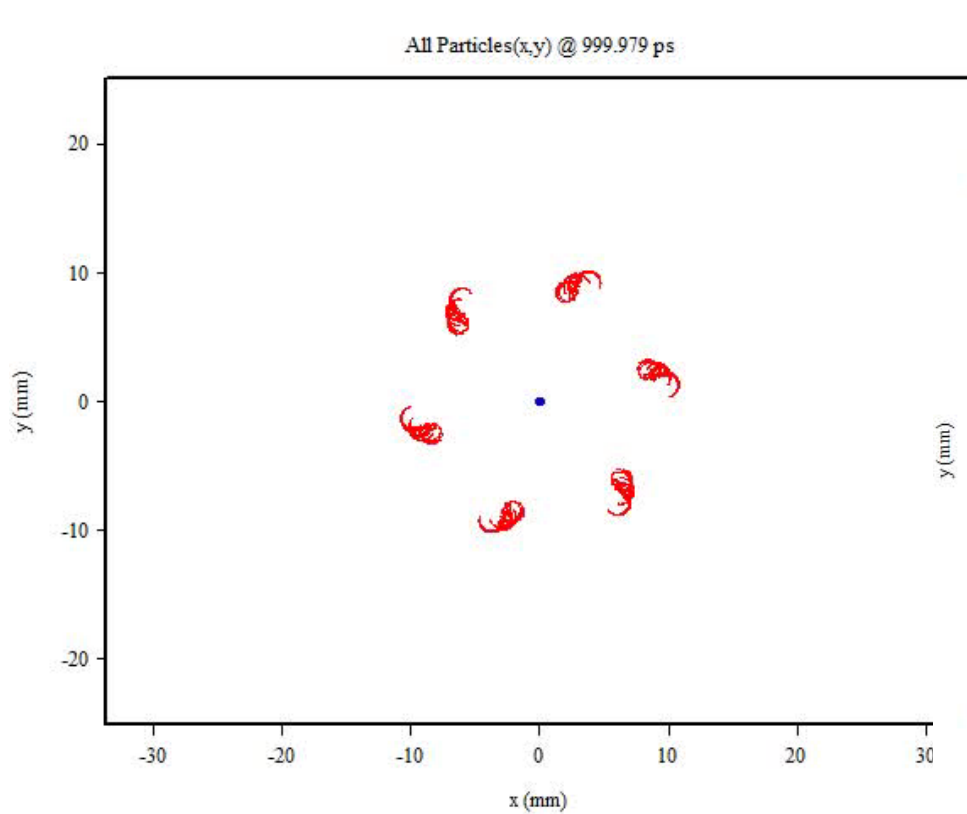
Two recent 2007 Applied Physics Letters by Jiang *et al.* (Nagaoka, Japan) revisited this idea and obtained efficiency increase from 7% to 37%. Upon seeing this we also studied this modification.

OPTIMIZATION OF THE MICROWAVE EXTRACTOR: SIMULATION RESULTS

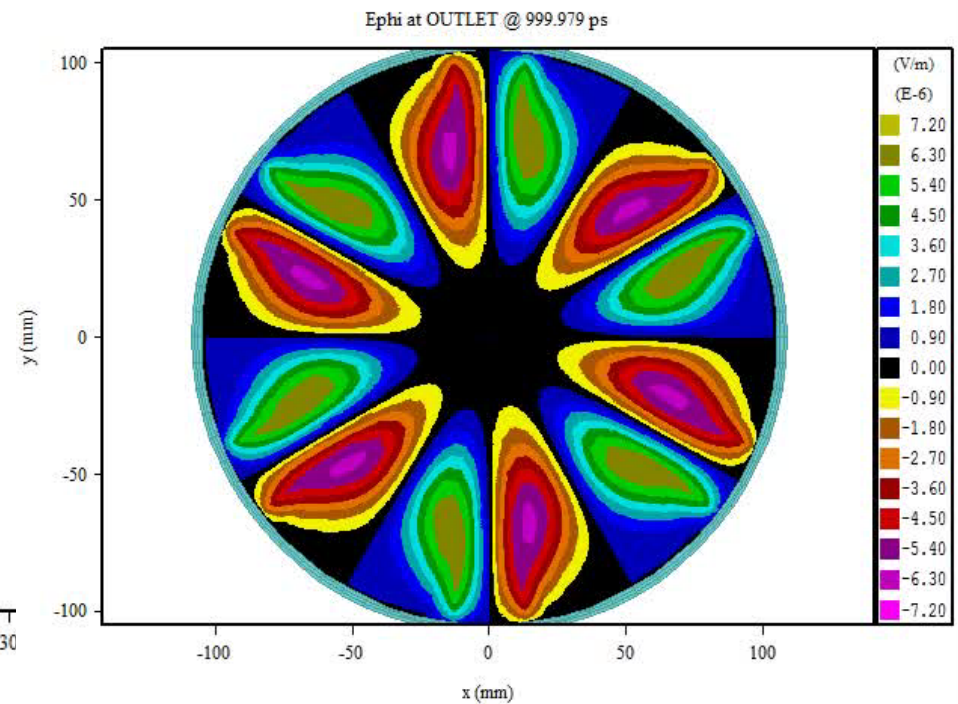


Efficiency was improved from 11% to 20% - Most recent result demonstrated ~70% efficiency with transparent cathode at UNM!

A6 MAGNETRON WITH AXIAL EXTRACTION



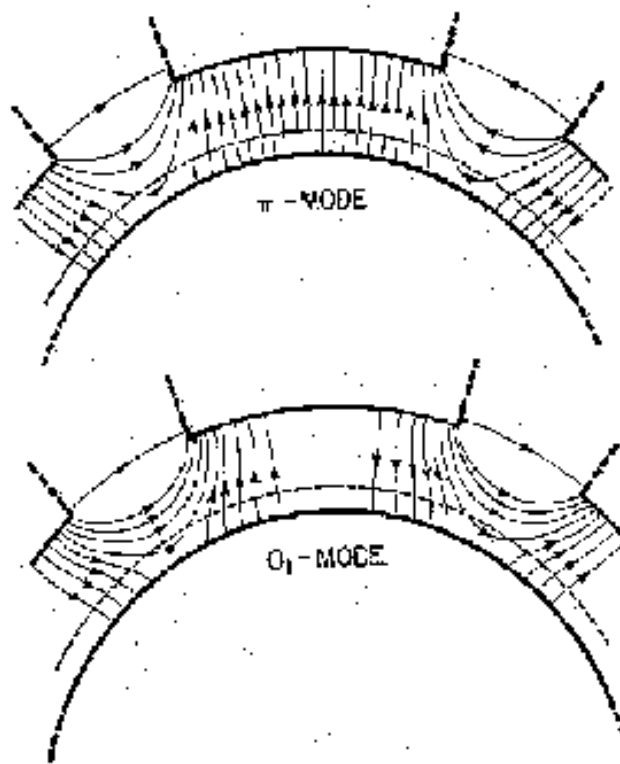
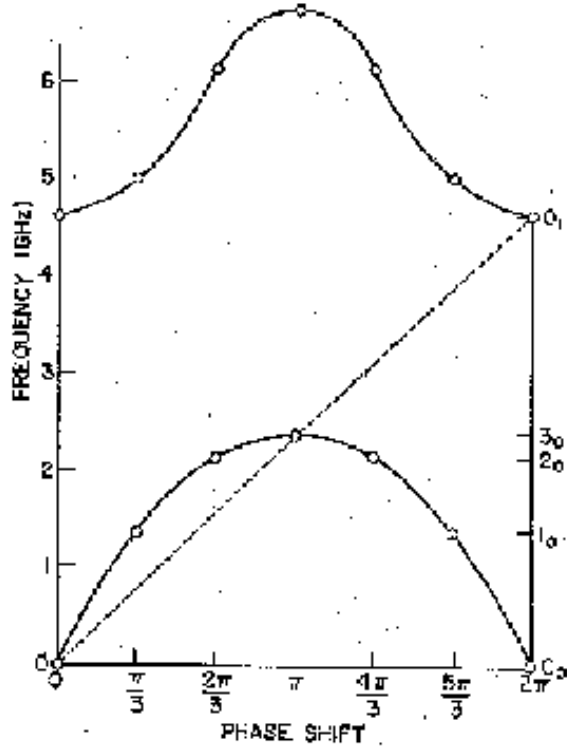
Particle Plot



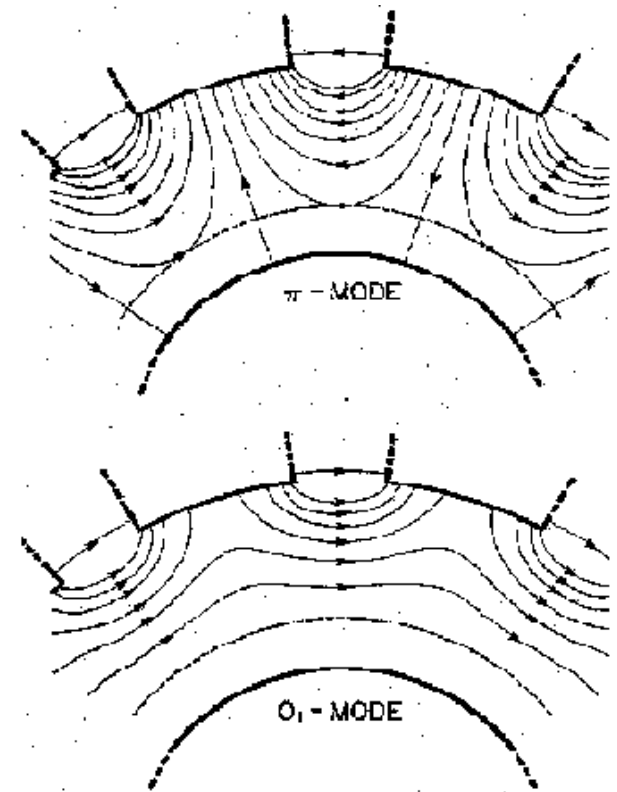
Azimuthal Electric Field Contours

MOST RECENT RESULTS: RF MODE SWITCHING IN A6 MAGNETRON WITH DIFFRACTION OUTPUT

E-FIELD STRUCTURES IN THE A6 MAGNETRON



NARROW GAP
 $R_c = 1.58$ CM

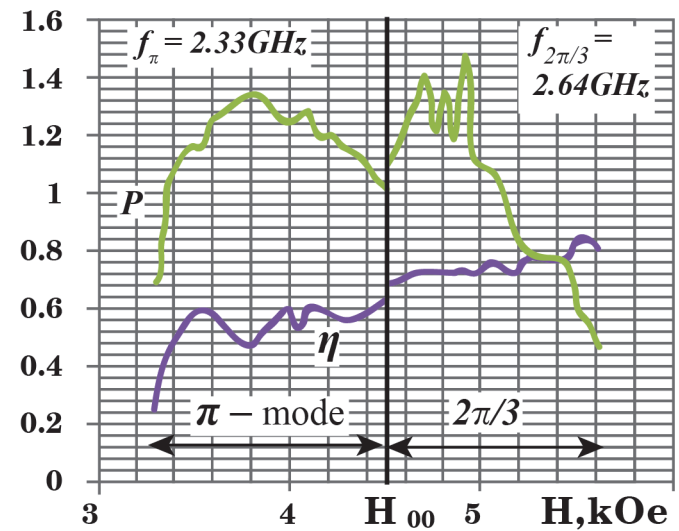
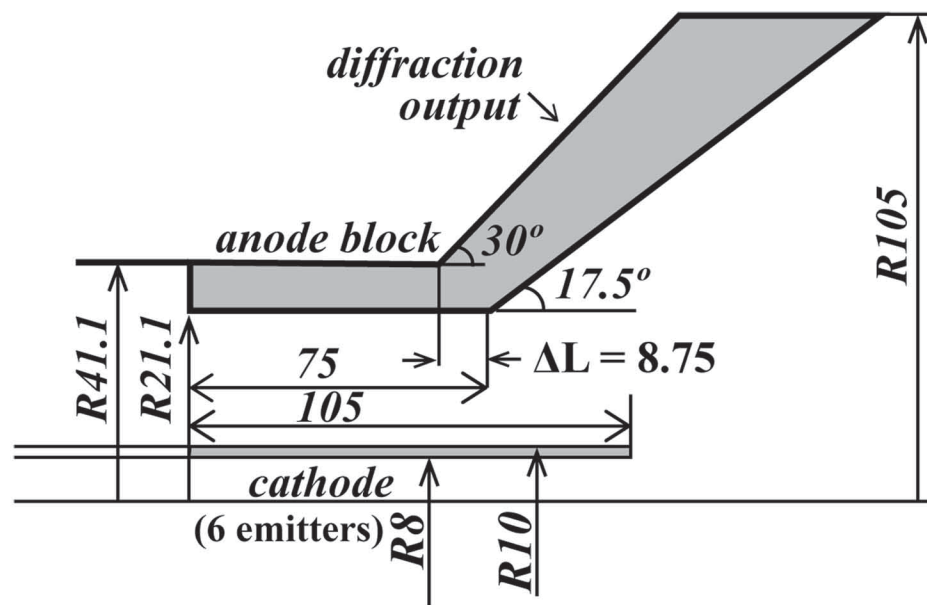


WIDE GAP
 $R_c = 1.0$ CM

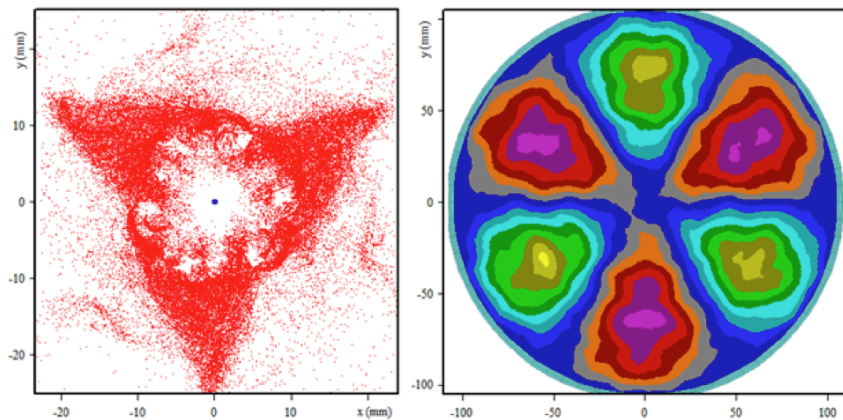
MODE SWITCHING IN THE CONVENTIONAL A6 MAGNETRON

In magnetrons of the conventional design, *i.e.*, with asymmetric output only non-degenerate modes can be used as operating ones, *viz. the* π -mode or 2π -mode. Mode hopping to neighboring modes leads to magnetron operation with unloaded modes, resulting in overheating and erosion of electrodes.

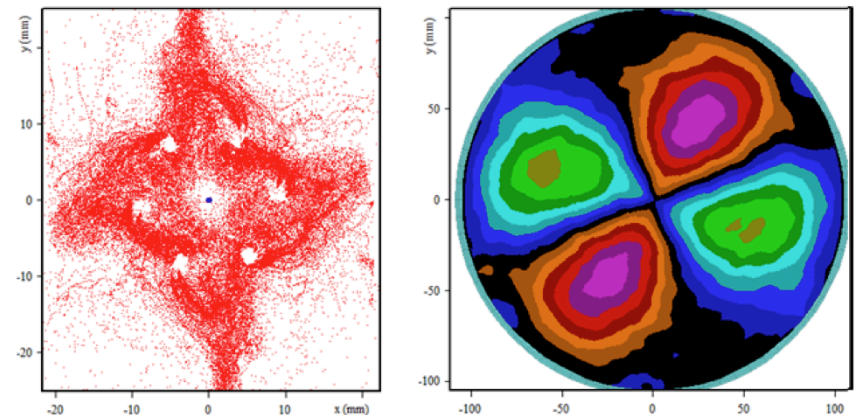
- Solid cathode – mode competition when $1.0 < R_c \text{ (cm)} < 1.58$, for mode switching $P_{in \text{ min}} = 200 \text{ MW}$ ($R_c = 1.4 \text{ cm}$) (Cedric Michel - UNM)
- Transparent cathode – mode competition when $1.4 < R_c \text{ (cm)} < 1.58$, for mode switching $P_{in \text{ min}} = 30 \text{ MW}$ ($R_c = 1.5 \text{ cm}$) (Meiqin Liu – UNM)



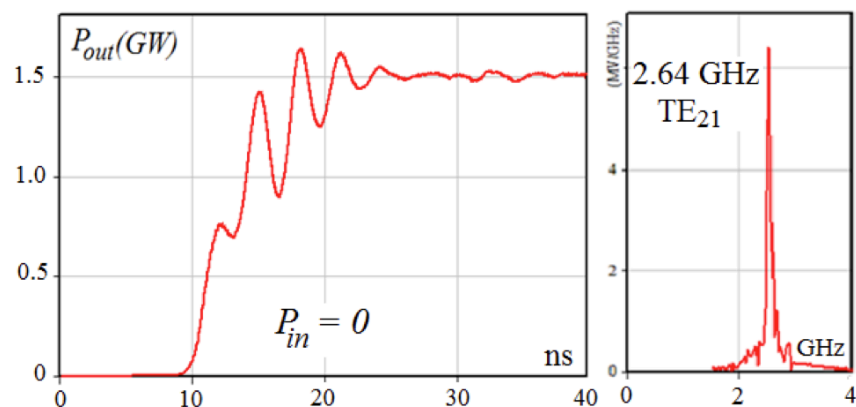
The dependences of radiation power (1,2) and efficiency (1',2') on the axial magnetic field for the π mode and the $2\pi/3$ mode for the optimized A6 MDO with short (1,1') and long (2,2') transparent cathodes.



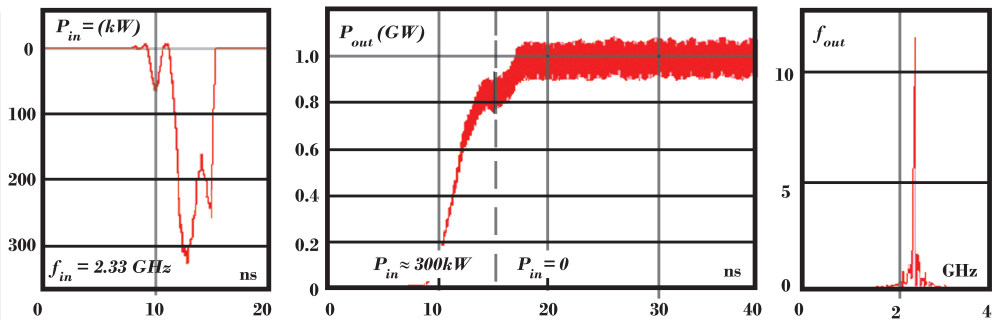
Electron spokes synchronous with the fundamental harmonic of the mode (left) and structure of the output radiation when the axial magnetic field $H_{0z} < H_{00}$ (right).



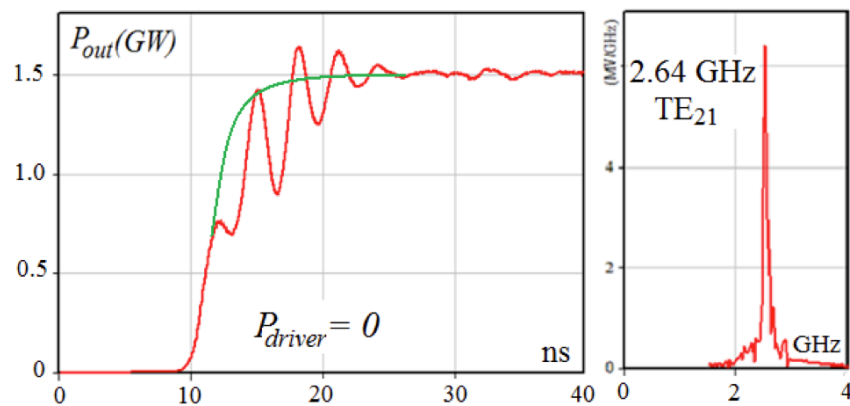
Electron spokes synchronous with the (-1st) spatial harmonic of the $2\pi/3$ mode (left) and structure of the output radiation when the axial magnetic field $H_{0z} > H_{00}$ (right).



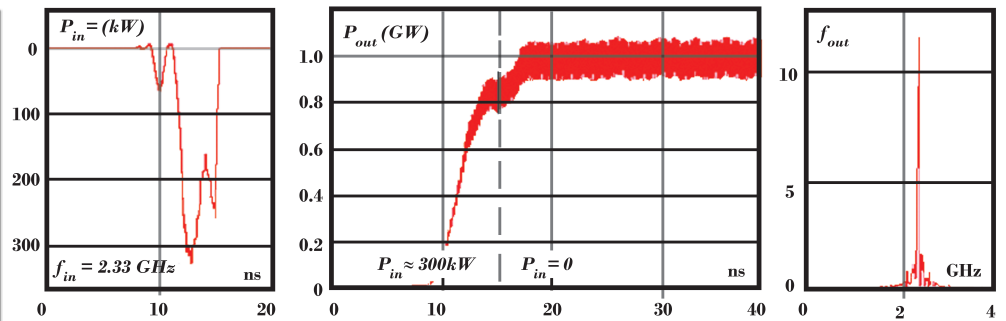
Radiation power and frequency of the $2\pi/3$ mode when $H_{0z} = 4.6$ kOe and $P_{in} = 0$.



Left: Input signal power. Middle: Radiation power. Right: radiation frequency.



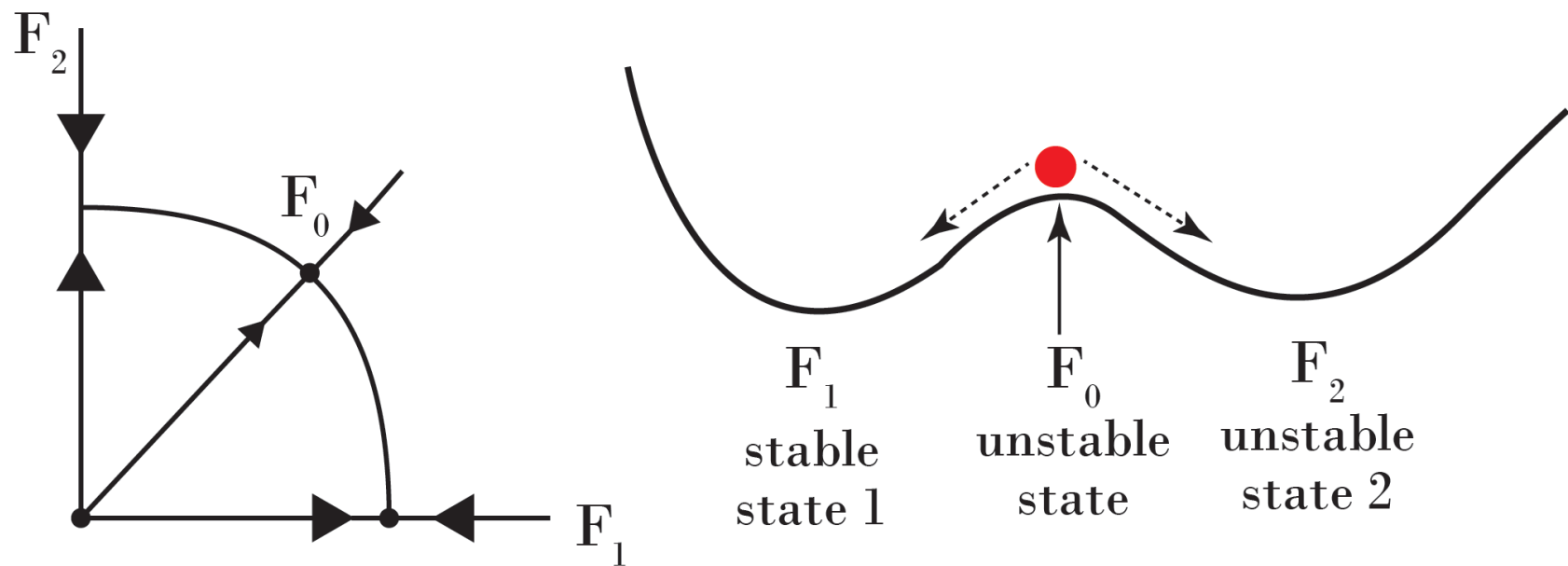
The curve in green represents the $2\pi/3$ mode with an input signal of the same mode.



Left: Input signal power. Middle: Radiation power. Right: radiation frequency.

OUR VIEW OF THIS PROBLEM

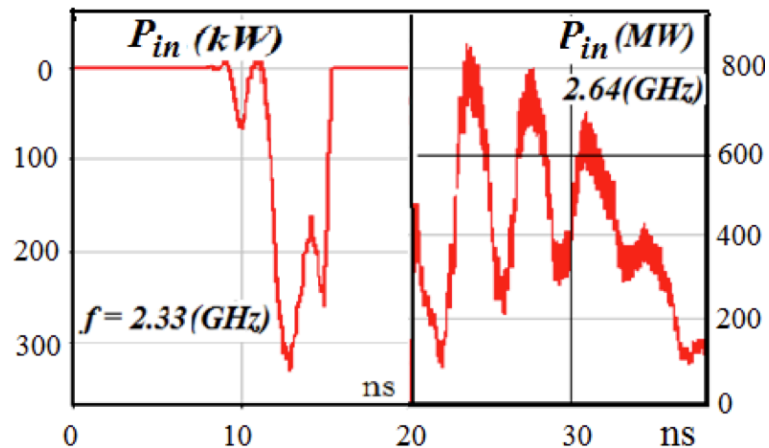
(Buridan's Ass Parable in Philosophy/Mathematics)



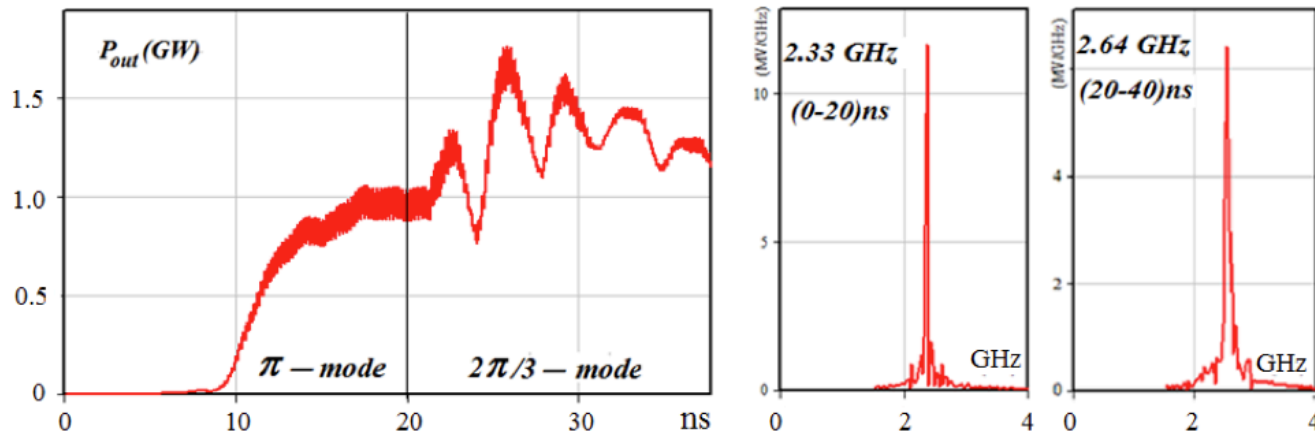
Van der Pol diagram.

B. Van der Pol, "The nonlinear theory of electric oscillations," *Proc. IRE*, vol. 22, pp. 1051-1086 (1934).

HIGH POWER RF SWITCHING

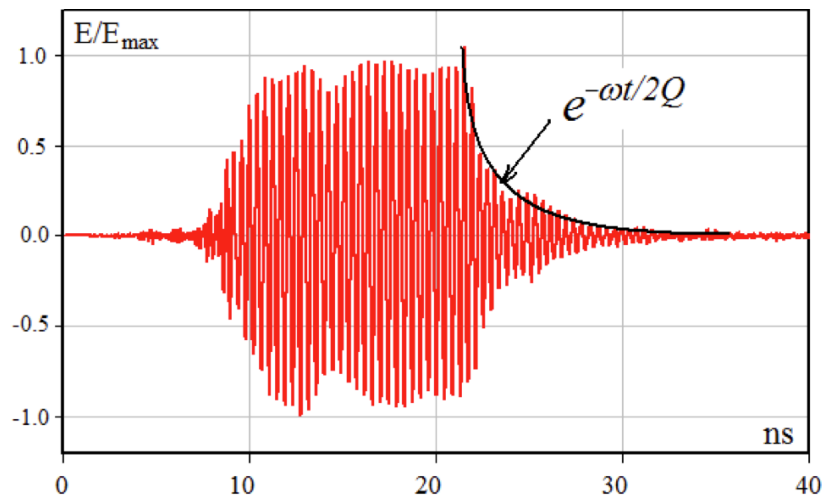


Left: Input signal power to generate the π mode. Right: Input signal power to switch the π mode to the $2\pi/3$ mode.

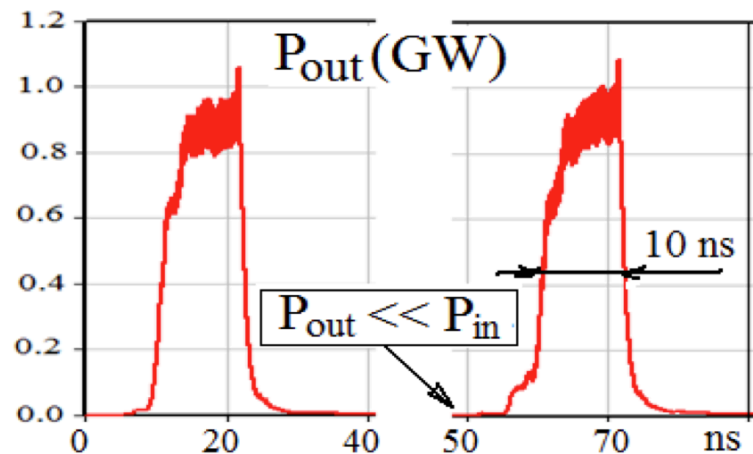


Radiation power and frequency for π mode generation switched by the input power 300 kW and for switching the π mode to the $2\pi/3$ mode.

HIGH REPETITION RATE OPERATION

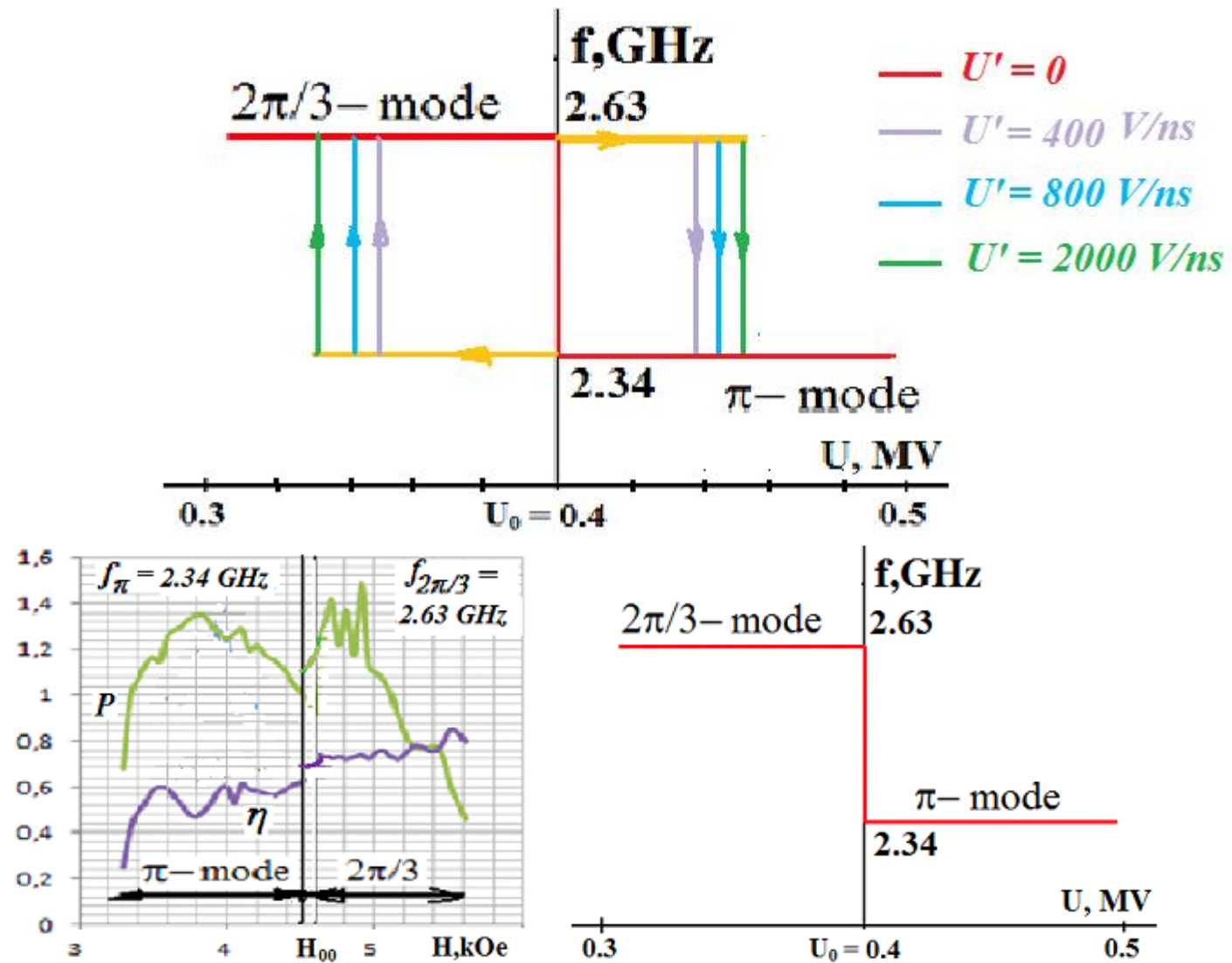


Output electric field of one microwave pulse.



A series of microwave pulses with different modes generated (the first pulse with the π mode, the second pulse with the $2\pi/3$ mode).

HYSTERESIS EFFECT IS OBSERVED IN SIMULATIONS



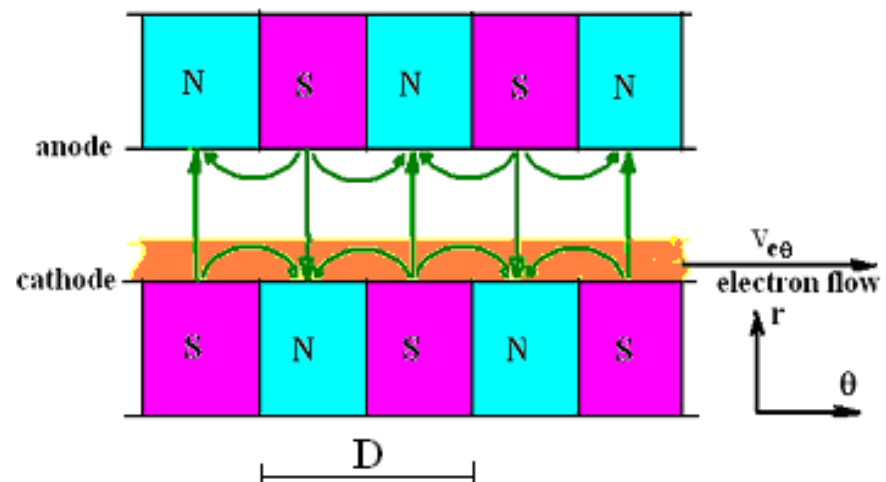
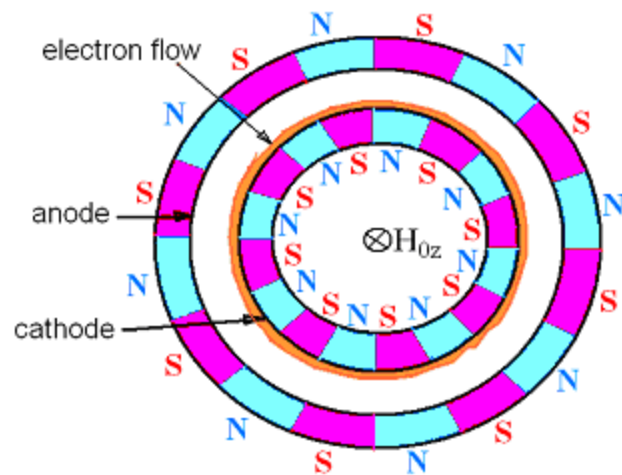
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- Concluding Remarks

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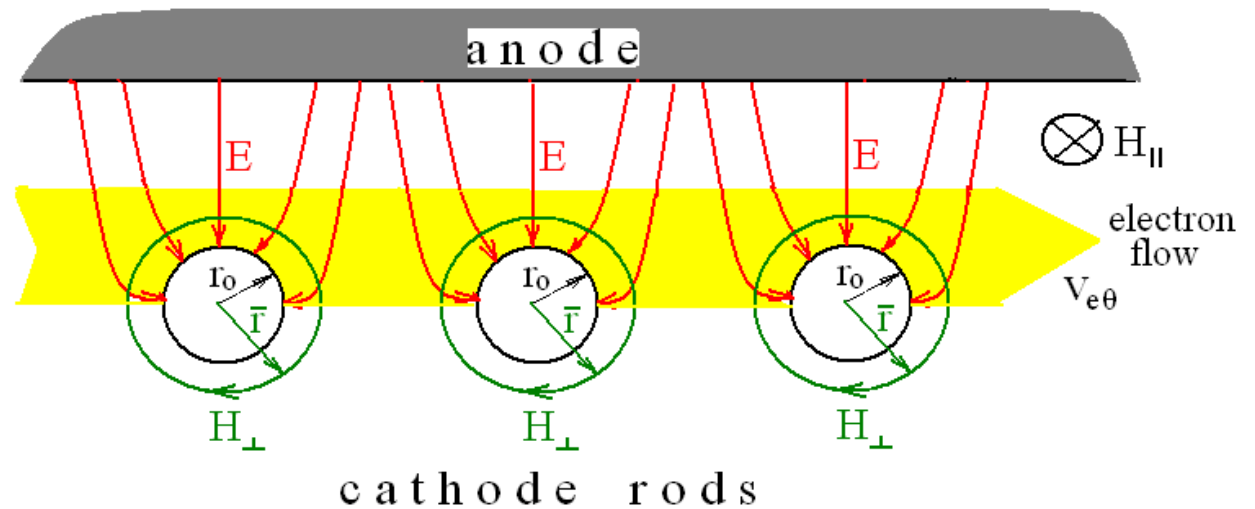
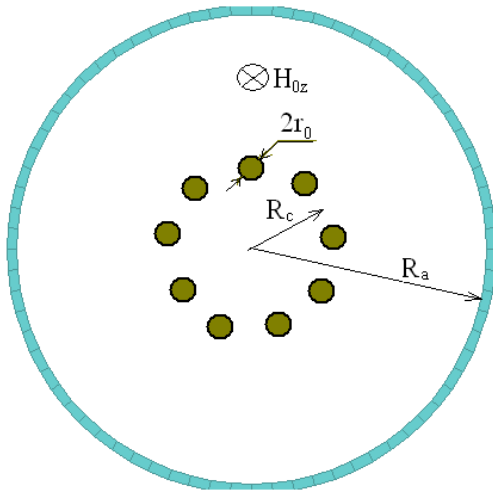
RIPPLED-FIELD MAGNETRON (RFM)

G. Bekefi, Appl. Phys. Lett. 40, 578-580, 1982



1. Complicated wiggler.
2. Generates a large useless axial current from this magnetically insulated diode because of the narrow gap between electrodes, which is necessary to provide a detectable periodic radial magnetic field (otherwise the magnetic field will basically be concentrated between adjacent magnets).

UNM's SIMPLEST UBITRON



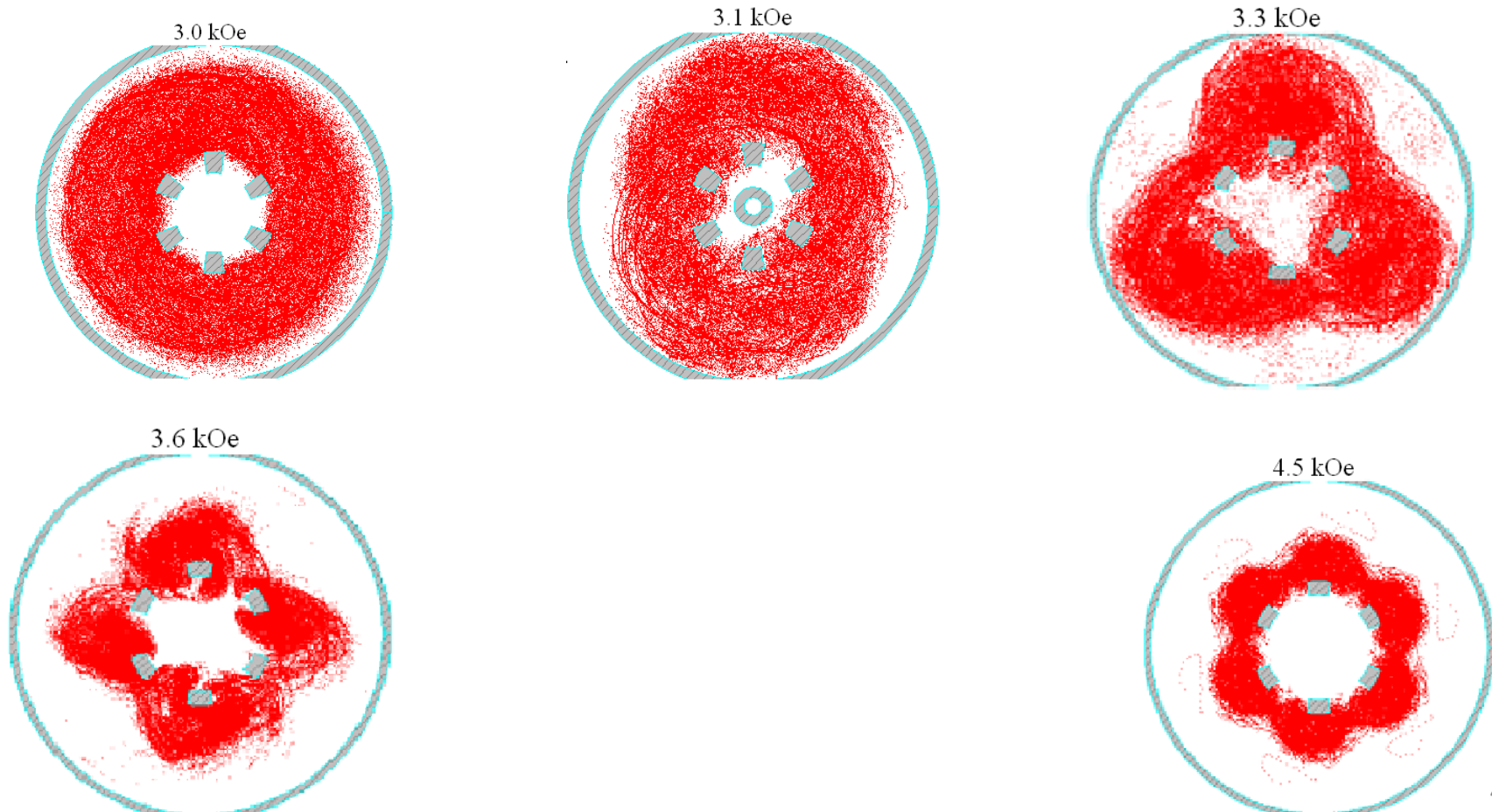
- The ubitron is a magnetically insulated coaxial diode with a cathode in the form of N individual longitudinal metal emitters periodically arranged on an imaginary cylindrical surface. The configuration of cross-section of these emitters is arbitrary.
- The cathode radius can be selected to provide a suitable electron current.

Electron Waves $\omega = (h_\theta + m\bar{h})v_e$

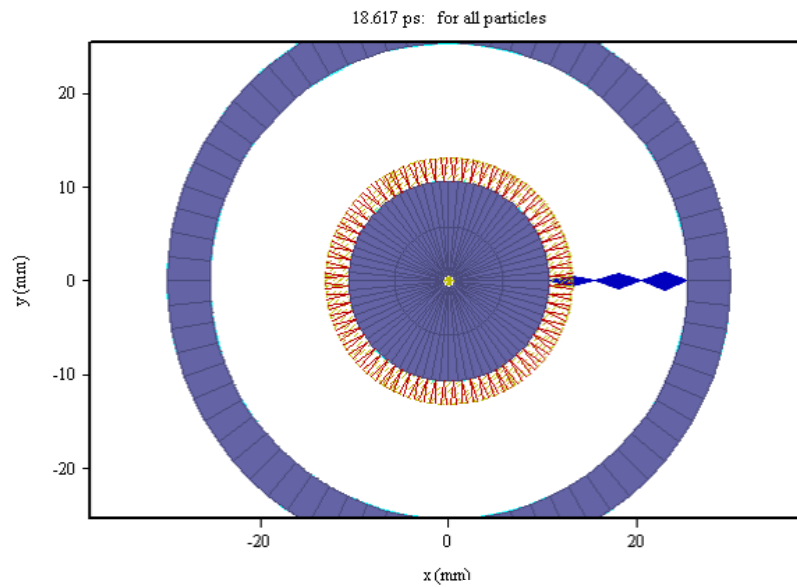
$$h_\theta = \frac{n}{r}; \quad \bar{h} = \frac{2\pi}{D} = \frac{N}{r}; \quad v_{e\theta} = c \frac{[\vec{E} \times \vec{H}]_\theta}{H^2};$$

$$m = 0, \pm 1, \pm 2, \dots; \quad r \sim R_{cathode};$$

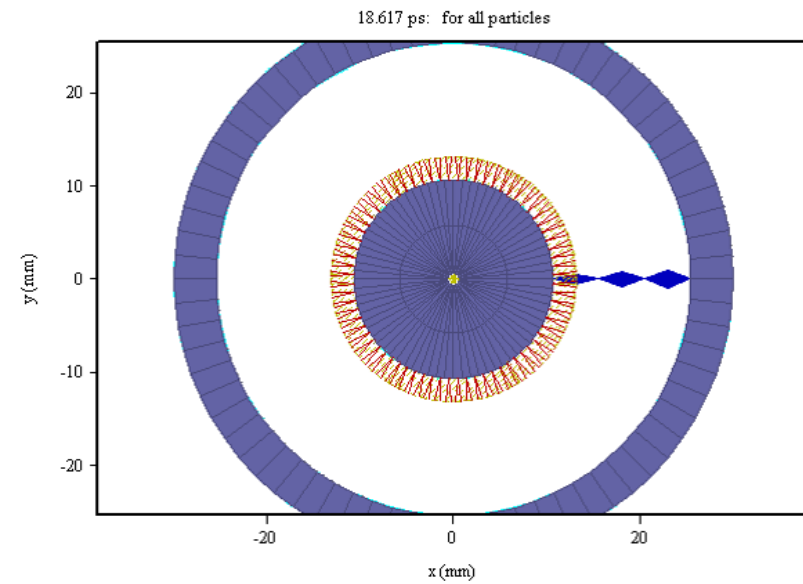
D – wiggler period; N – the number of cathode strips



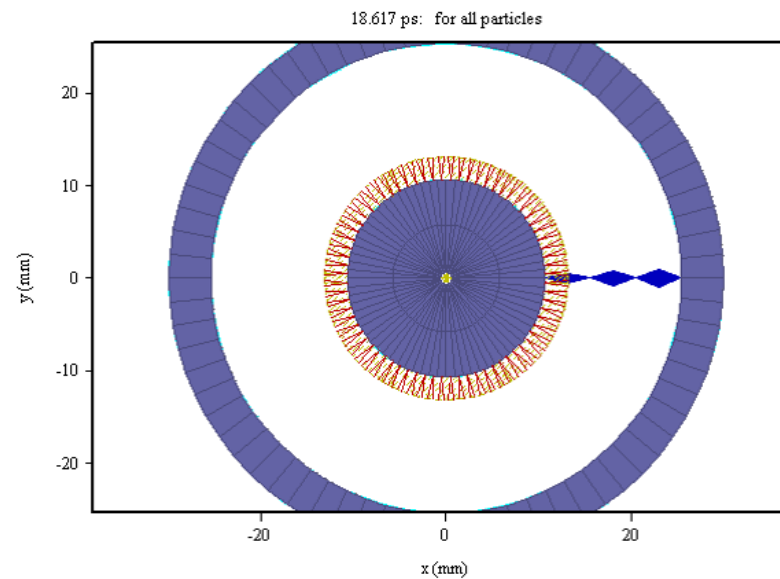
SOME SIMULATION RESULTS



0.35 kOe



0.36 kOe



0.375 kOe

PULSAR DISCOVERED IN 1967



Jocelyn Bell

Reprinted from Nature, February 24, 1968

Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
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University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

PETRI, 2008

<http://arxiv.org/pdf/0711.2416v1>

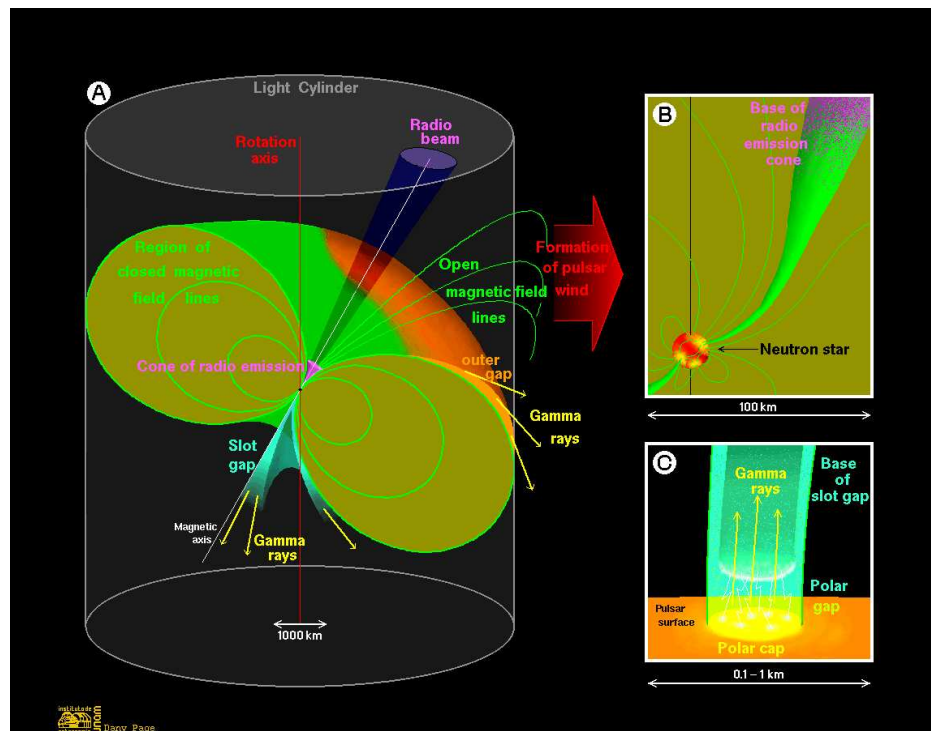
Astronomy & Astrophysics manuscript no. ms8442
February 2, 2008

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The magnetron instability in a pulsar's cylindrical electrosphere.

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(2002b). The status of models of the pulsar magnetospheres, or electrospheres, has recently been critically reviewed by Michel (2005). A solution with vacuum gaps has the peculiar property that those parts of the magnetosphere that are separated from the star's surface by a vacuum region are not corotating and so suffer differential rotation, an essential ingredient that will lead to non-neutral plasma instabilities in the closed magnetosphere, a process never addressed in detail.

This raises the question of the stability of such a charged plasma flow in the pulsar magnetosphere. The differential rotation in the equatorial, non-neutral disk induces a non-neutral plasma instability that is well known to plasma physicists (O'Neil 1980; Davidson 1990; O'Neil & Smith 1992). Their good confinement properties (trapped particles can remain on an almost unperturbed trajectory for thousands of gyro-periods) makes them a valuable tool for studying plasmas in laboratory, by using for instance Penning traps. In the magnetosphere of a pulsar, far from the light cylinder and close to the neutron star surface, the instability reduces to its non-relativistic and electrostatic form, the diocotron instability. The linear development of this insta-

PULSAR DISCOVERED IN 1967

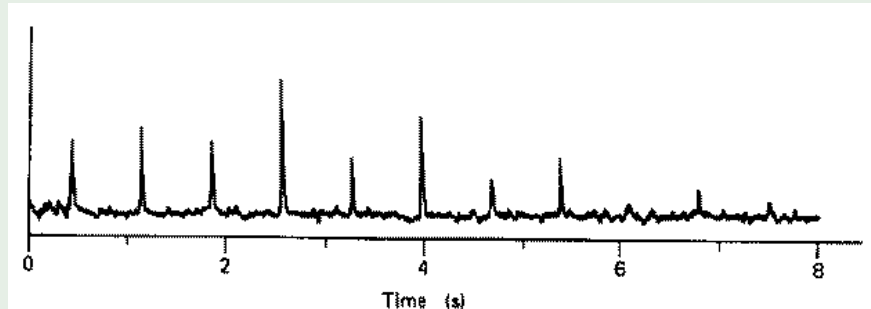
The first pulsar

discovered fortuitously at Cambridge Observatory (UK) in 1967 at radio-frequencies

- signal made of a series of pulses separated by a period $P = 1.337$ s
- pulse profile changes randomly but arrival time stable
- duration of a pulse $\Delta t \approx 16$ ms
 - ⇒ size of the emitting region : $L \leq c \Delta t \approx 4800$ km
 - ⇒ evidence for a compact object

Radio signal measured from PSR1919+21

(Bell & Hewish, 1968) (already 40 years ago)



Basic assumption

Pulsar = strongly magnetised rotating neutron star

(from J. Petri presentation)

WHAT IS THE ELECTROSPHERE?

ELECTROSPHERE

=

PART OF THE MAGNETOSPHERE

FILLED WITH PLASMA

The relativistic magnetron regime

Assumptions

- electric drift replaced by Lorentz force

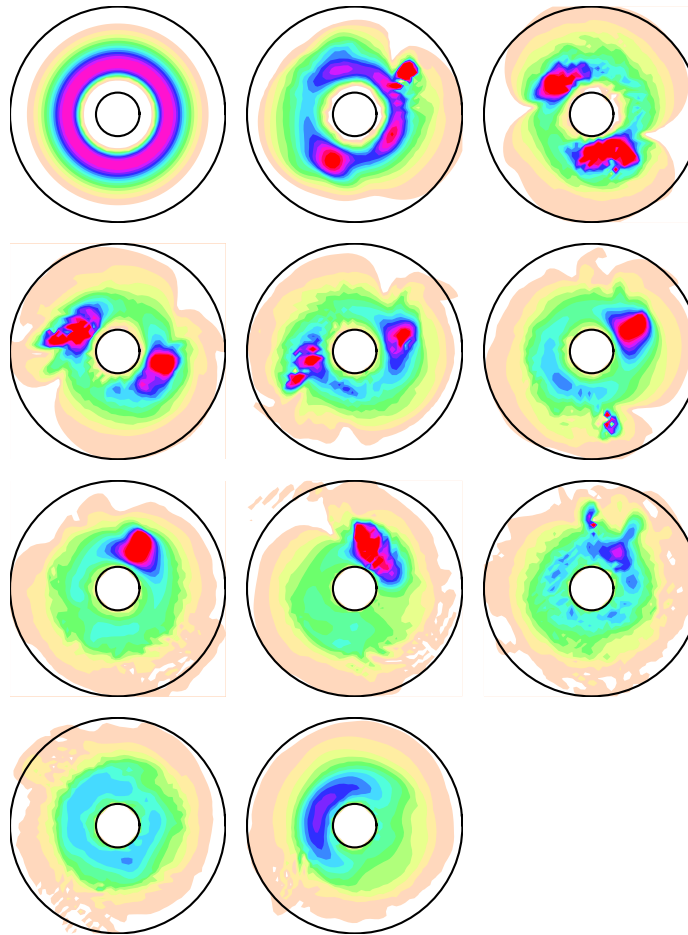
$$\frac{D\vec{p}}{Dt} = \left(\frac{\partial}{\partial t} + \vec{v} \cdot \frac{\partial}{\partial \vec{r}} \right) (\gamma m \vec{v}) = q (\vec{E} + \vec{v} \wedge \vec{B})$$

therefore particle inertia m included

- full set of Maxwell equations taken into account
⇒ possibility of electromagnetic wave radiation
- relativistic regime

(from J. Petri presentation)

Non linear evolution : disk feded with a source of charges



(from J. Petri presentation)

Non-linear evolution of the diocotron instability in a pulsar electrosphere: two-dimensional particle-in-cell simulations

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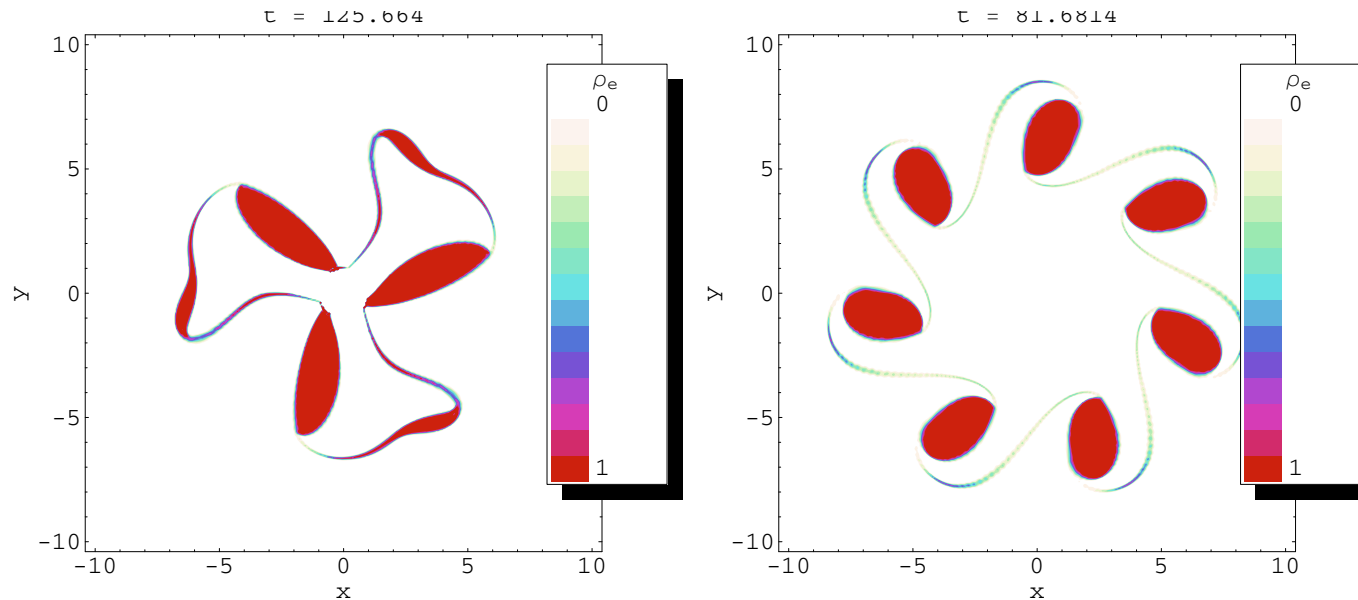
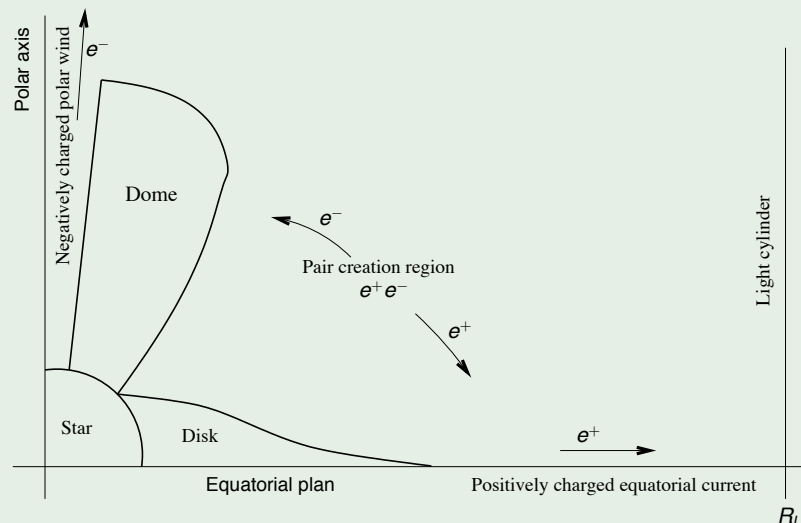


Fig. 2. Snapshot of the charge density in the plasma column showing the $m = 3$ pattern (on the left) and the $m = 7$ pattern (on the right). The chosen time corresponds to the transition between the linear phase and the beginning of the non-linear regime, associated with the total electrostatic energy curves discussed in Fig. 1.

Conclusions & Perspectives

My pulsar model : a trap for non-neutral astrophysical electron-positron plasmas



Properties

- electrosphere do exist, finite in extension and in electrostatic equilibrium
- **non-neutral plasma instabilities** (diocotron & magnetron) develop
⇒ **particle diffusion** across the magnetic field lines
- numerical simulations have shown the formation of an **equatorial current** carrying a net flux of charges towards the light cylinder

(from J. Petri presentation)

Physics of pulsars : everything remains to be done !

Apart from the obvious need of

- general relativity
 - neutron star equation of state
 - gravitational waves
 - electromagnetic field enhancement by frame dragging effect
- quantum electrodynamics ($e^\pm$ pair creation)

Physics of pulsar needs two essential ingredients

- 1 **non neutral plasma** physics
 - trapping of particles in special traps
 - stability properties of the plasma configuration
 - instabilities like diocotron and magnetron
- 2 **plasma distribution** does not overlap with the magnetosphere
⇒ **large vacuum gaps** and thus “electrospheric solution” and **NOT** magnetospheric one.

(from J. Petri presentation)

CONCLUDING REMARKS – THE LIKELY BEGINNINGS OF AN UNLIKELY COLLABORATION

“Our subjects seem far from each other but I think that there are some common techniques and tools to apply *to* both fields. Non-neutral plasmas are not well known *in* the *astrophysics* community because they do not happen very often in this context.

Nevertheless, pulsars or strongly magnetized rotating neutron stars are probably places where non-neutral plasma can be confined on a large scale, dipolar magnetic field and quadrupolar electric field, a kind of terella or so. My aim is to study these plasmas (mostly electron/positron pairs) in such a configuration, charge transport across magnetic field lines and also the (coherent?) radio emission properties.”

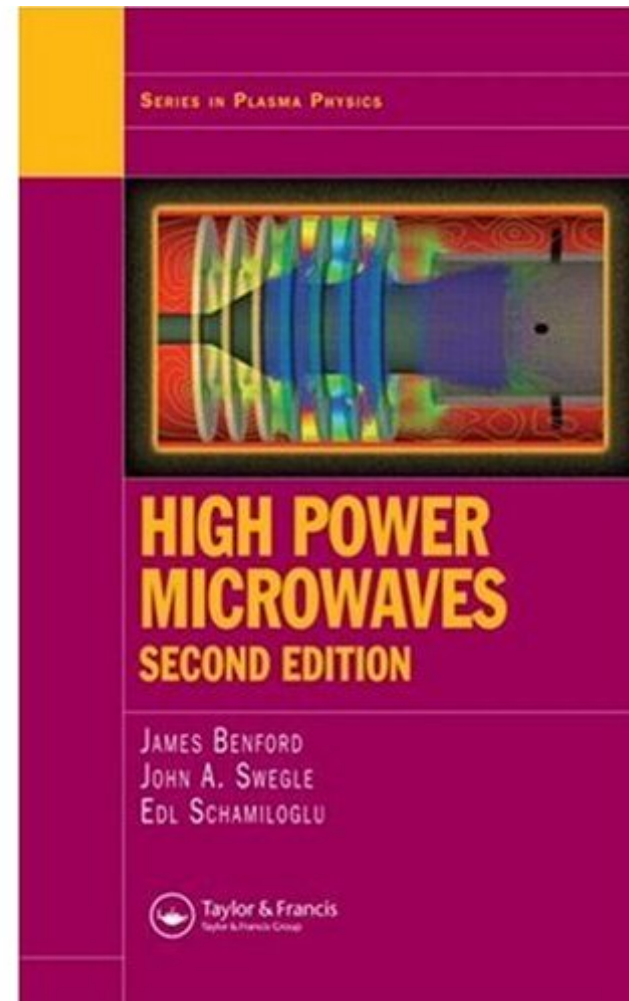
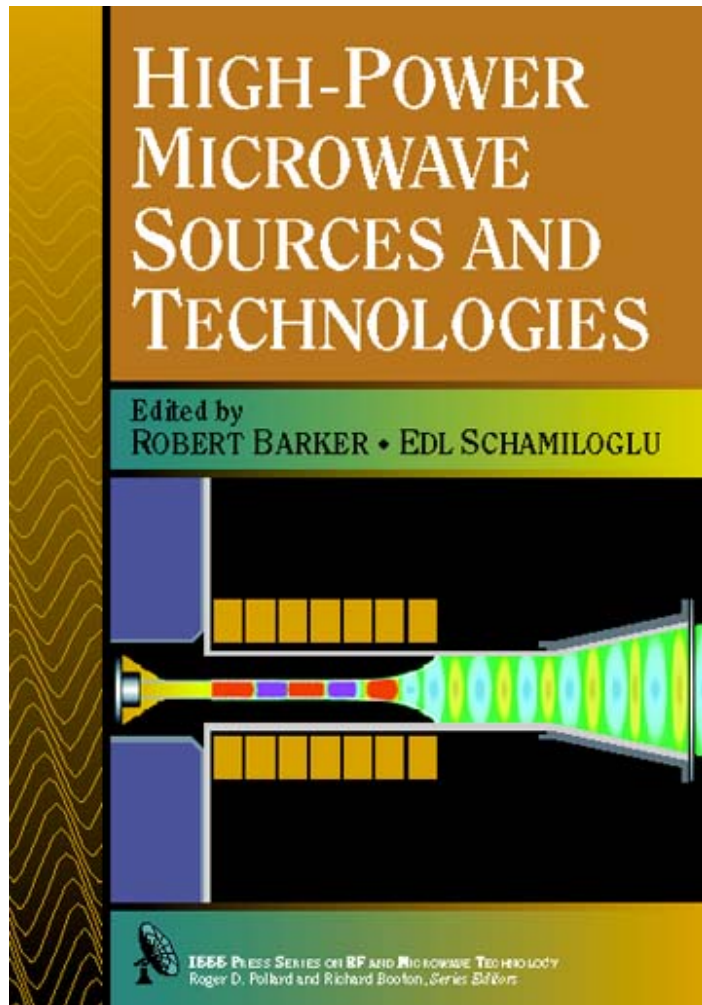
(e-mail from Jerome Petri to Edl Schamiloglu, 3/11/11)

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