Microwave Plasma Confinement

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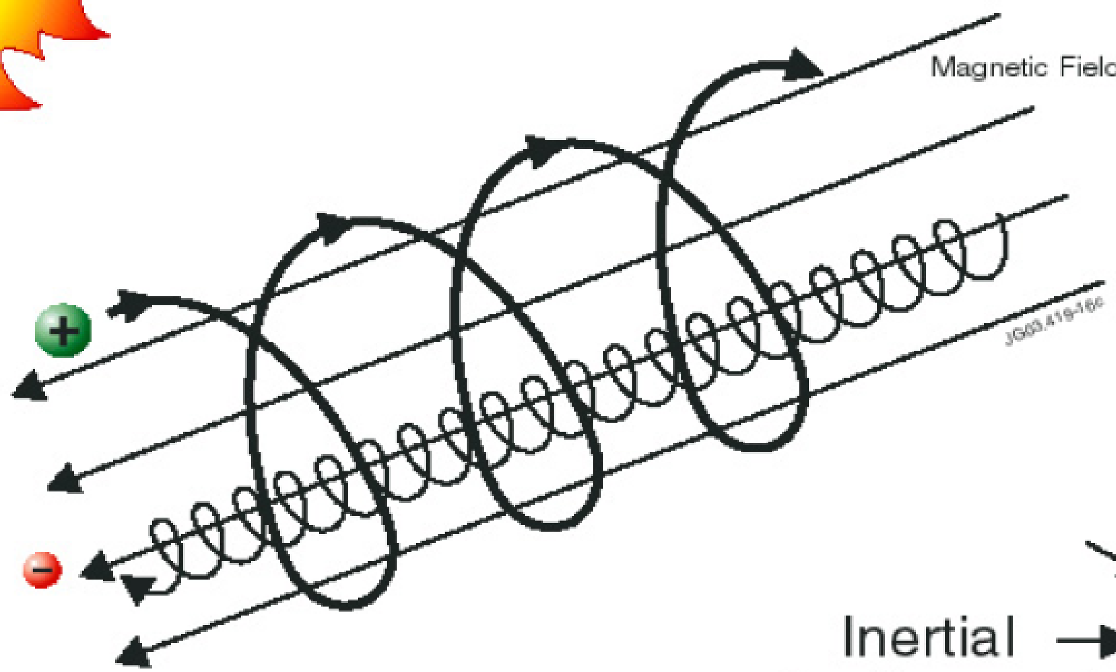
Outline

- **Fusion Reactor Concept**
- **Motivation for Microwave Plasma Confinement**
- **Microwave Confined Plasma Equilibrium**
- **Particle-in-Cell Simulation**
- **Ion Heating due to Parametric Decay**
- **Conclusions**

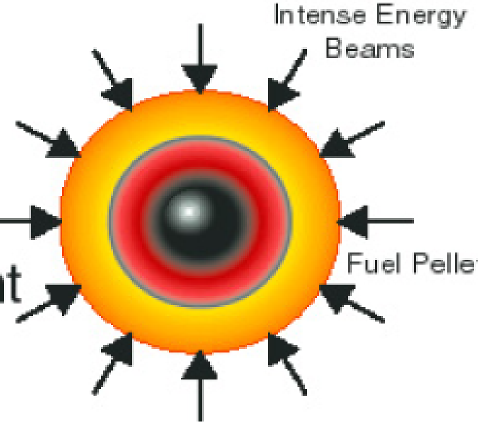
Fusion Plasma Confinement

Gravitational
Confinement

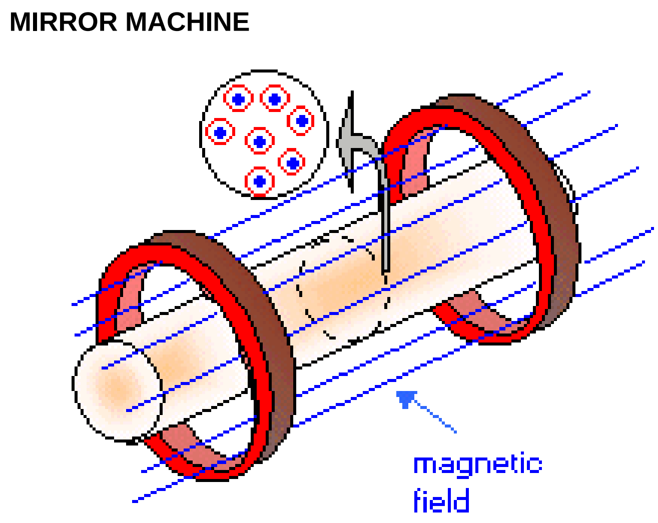
Magnetic Confinement

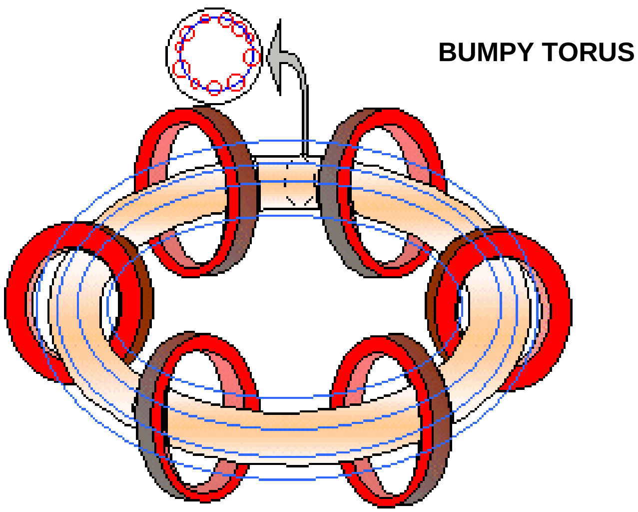


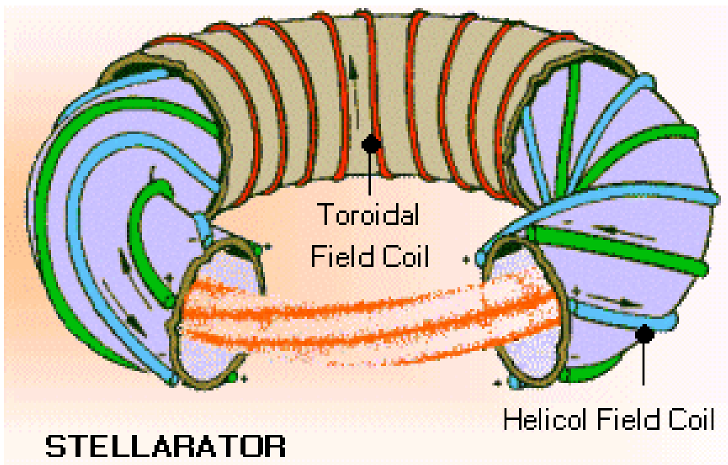
Inertial
Confinement

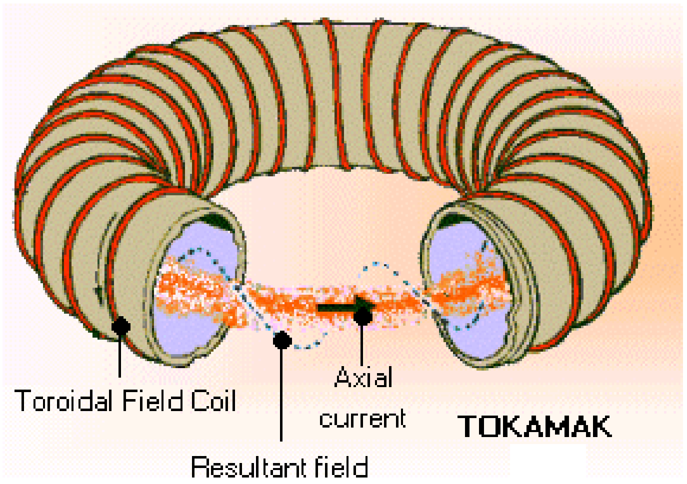


Varieties in Magnetic Confinement







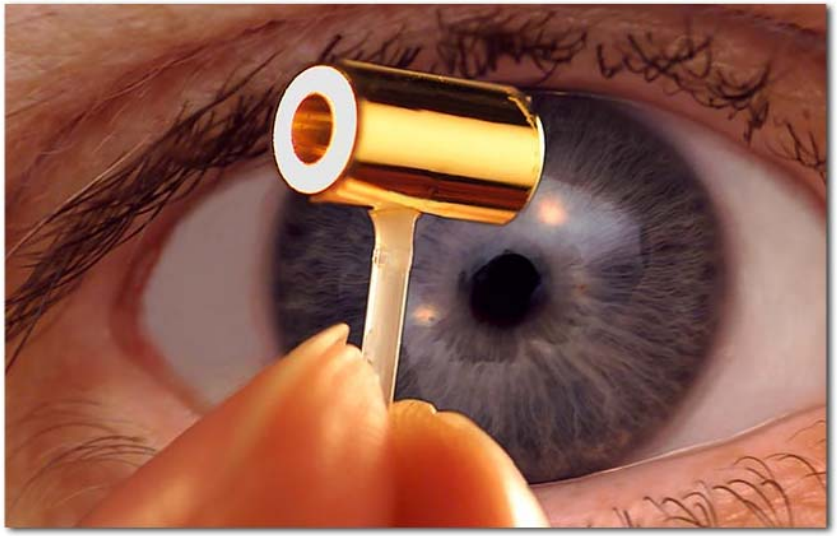


Tokamak Concept

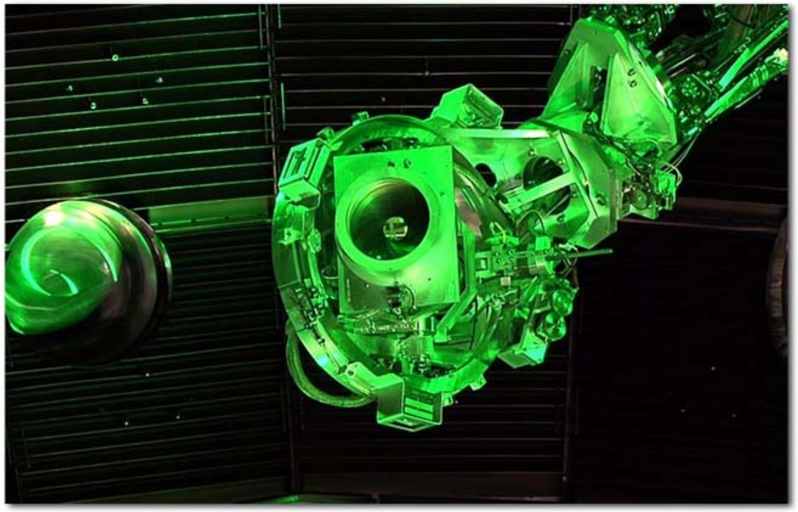
- **Toroidal current makes confinement easy but causes major disruption, a problem for a fusion reactor.**
- **Ignition takes major investment, not supposedly to be reused if truly steady-state.**
- **Magnetic confinement brings the wall close to the plasma and causes impurity radiation.**
- **A marriage of 4 Kelvin superconductor with the hundreds of million degree plasma in close proximity, awkward situation.**
- **Rich country's caviar: Euro$11 b 35Yrs**

National Ignition Facility (NIF)-Laser Fusion

The 10-meter-diameter target chamber, installed in June 1999, weighs 287,000 pounds. The spherical vacuum vessel was assembled from 18 four-inch-thick aluminum sections fabricated by Pitt-Des Moines, Inc., of Pittsburgh, Pennsylvania, and was installed with one of the largest cranes in the world.



A NIF hohlraum. The hohlraum cylinder, which contains the NIF fusion fuel capsule, is just a few millimeters wide, about the size of a pencil eraser, with beam entrance holes at either end. The fuel capsule is the size of a small pea.



NIF's final optics inspection system, when extended into the target chamber from a diagnostic instrument manipulator, can produce images of all 192 beamline final optics assemblies.

Lawrence Livermore National Laboratory is located in Livermore, California, about 40 miles east of San Francisco in southern Alameda County. The National Ignition Facility is in the northeast corner of the Laboratory, at the bottom right corner in the photo.

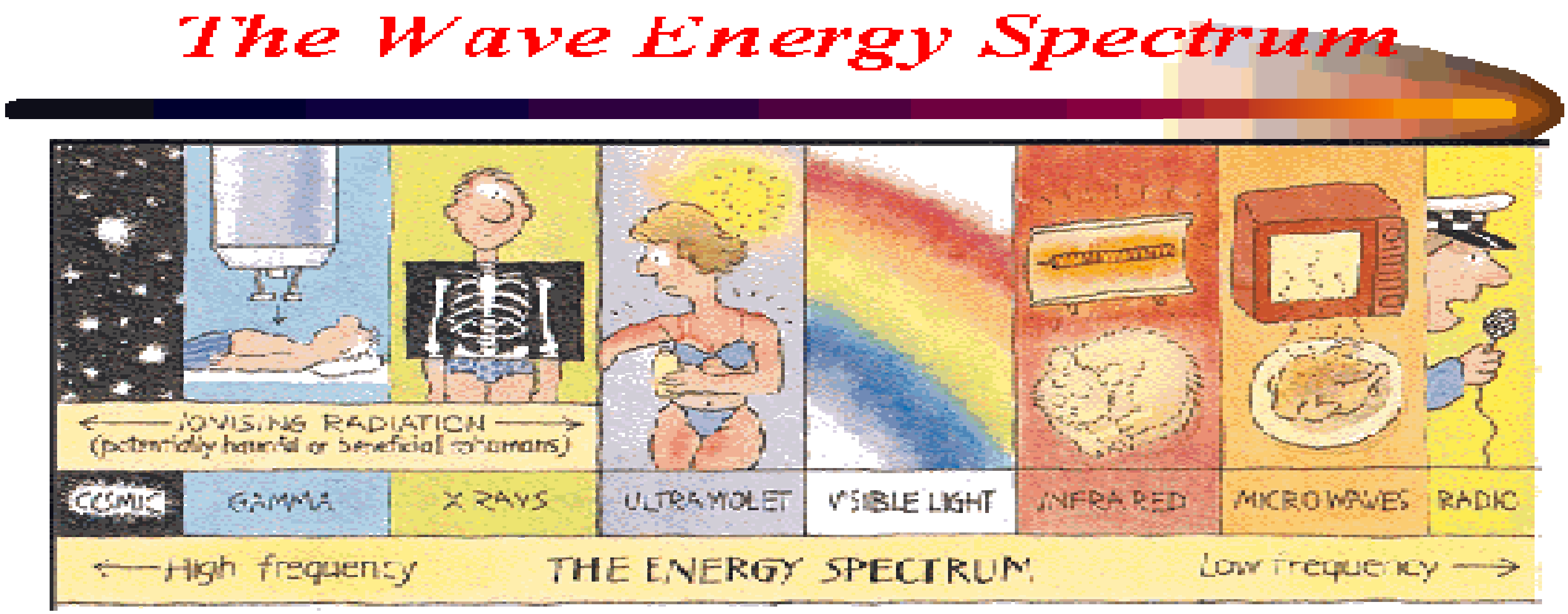
Laser Fusion Inertia Confinement

- 2~3 KeV ions 2 nanosecond confinement
- A military exercise ground, astrophysics
- Quarter density parametric decay
- Expensive and extremely difficult micro pellet
- Q=>1: The fusion energy gain factor, usually expressed with the symbol Q, is the ratio of fusion power produced in a nuclear fusion reactor to the power required to maintain the plasma in steady state.

A Missing Regime

Cosmic Gamma X-ray Ultraviolet Visible Infrared Microwave Radio

Laser ---------- ↓ ----------- DC

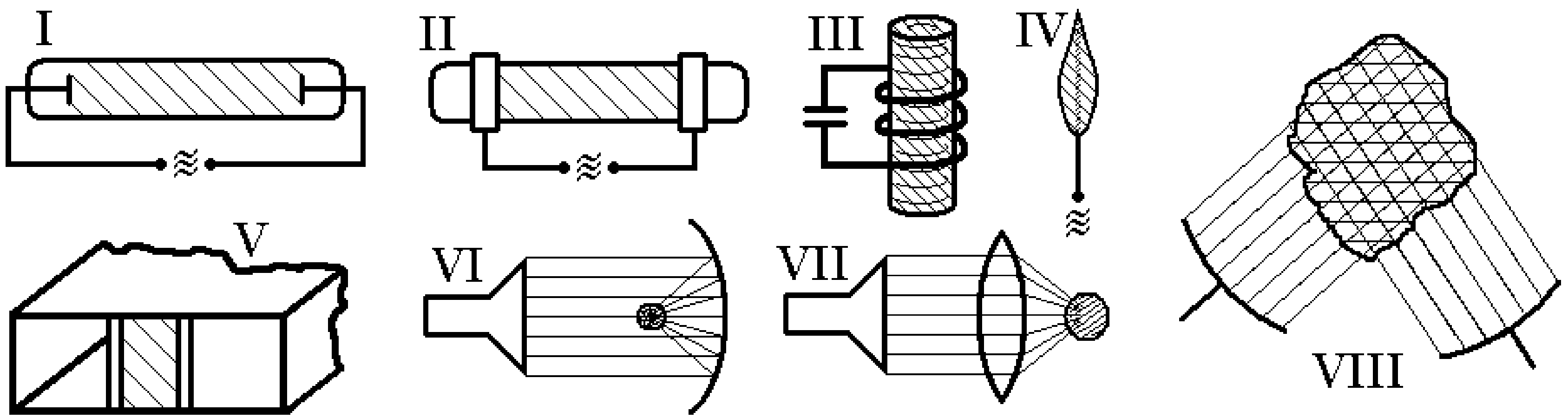


Microwave radiation

Wavelength: 10-1 m – 1-0.1 mm

Frequency: .03-.3 GHz – 0.3-3 THz

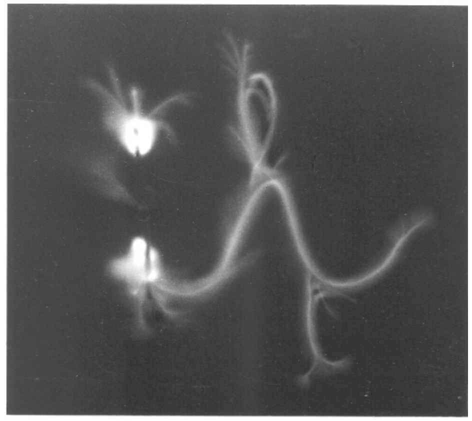
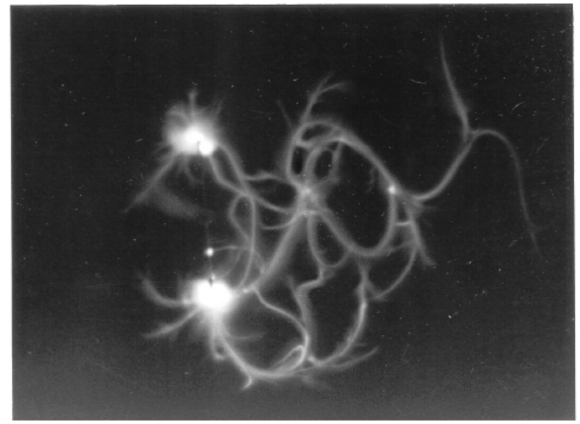
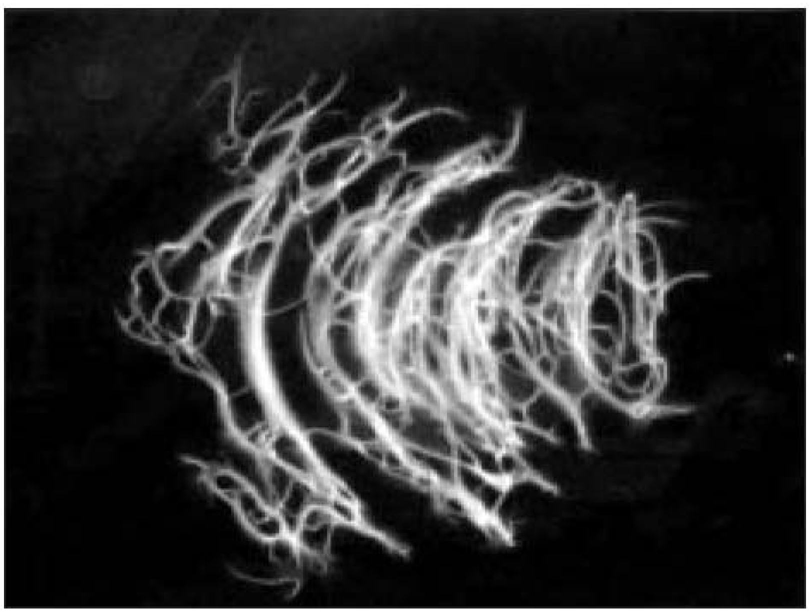
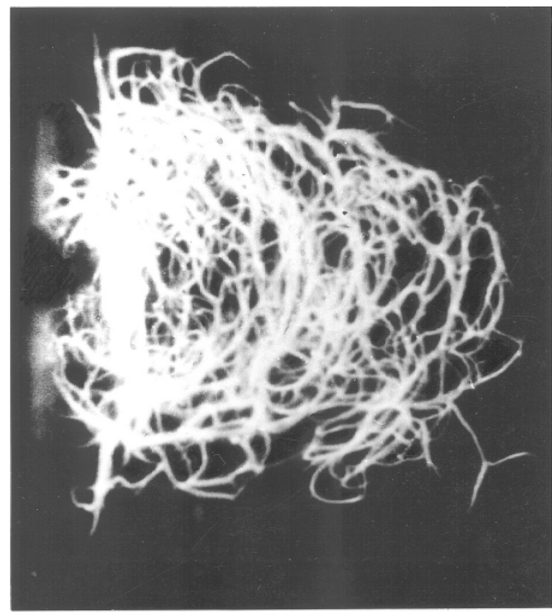
Power can be effectively deposited in needed region.



I – electrodes; II – outer rings; III – inductive current; IV – single electrode;
V – waveguide; VI, VII – beam focused by mirror or lens; VII – two-beam intersection

A. P. Ershov, G. S. Solntsev "Interaction of Electromagnetic Waves with a Plasma and Microwave Discharges". MSU, Moscow, 1990.

Microwave Discharge in Wave Beams

"Make everything as simple as possible, but not simpler." -- Albert Einstein

Try simple but nontrivial solutions.

Motivation

- **Theoretical:**
- Single mechanism to achieve heating, confinement, and MHD stability.
- Desktop Fusion Reactor.

  Too good to be true?

- **Experimental :**

  Two Mirror Resonator, Microwave confinement.

  Kapitsa

Pyotr Kapitsa's Nobel Lecture

Nobelprize.org

NOBEL PRIZES | ALFRED NOBEL | PRIZE AWARDERS | NOMINATION | PRIZE ANNOUNCEMENTS | AWARD CEREMON

By Year | **Nobel Prize in Physics** | Nobel Prize in Chemistry | Nobel Prize in Medicine | Nobel Prize in Literature

Physics

Pyotr Kapitsa
The Nobel Prize in Physics 1978

Nobel Lecture

Nobel Lecture, December 8, 1978

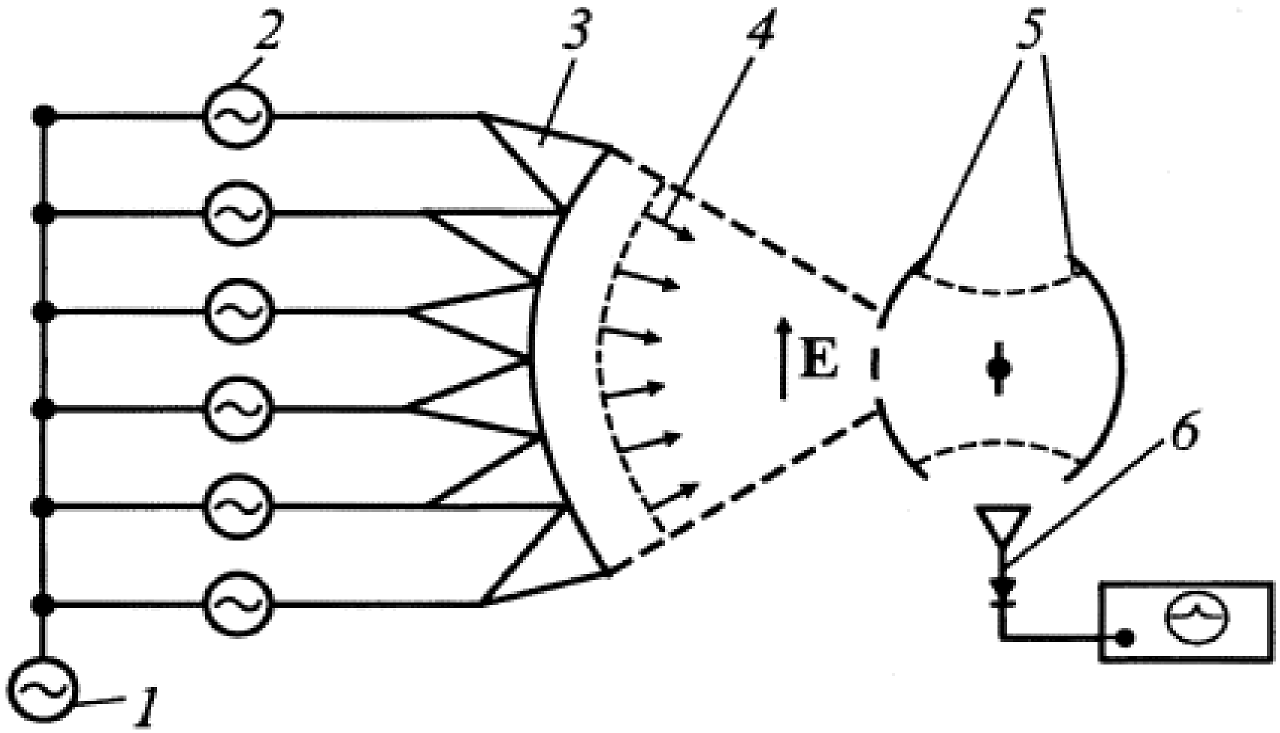
Plasma and the Controlled Thermonuclear Reaction

The Lecture in Text Format
Pdf 124 kB »

From *Nobel Lectures*, *Physics 1971-1980*, Editor Stig Lundqvist, World Scientific Publishing Co., Singapore, 1992

In order to read the text you need Acrobat Reader.

Two Mirror Resonator

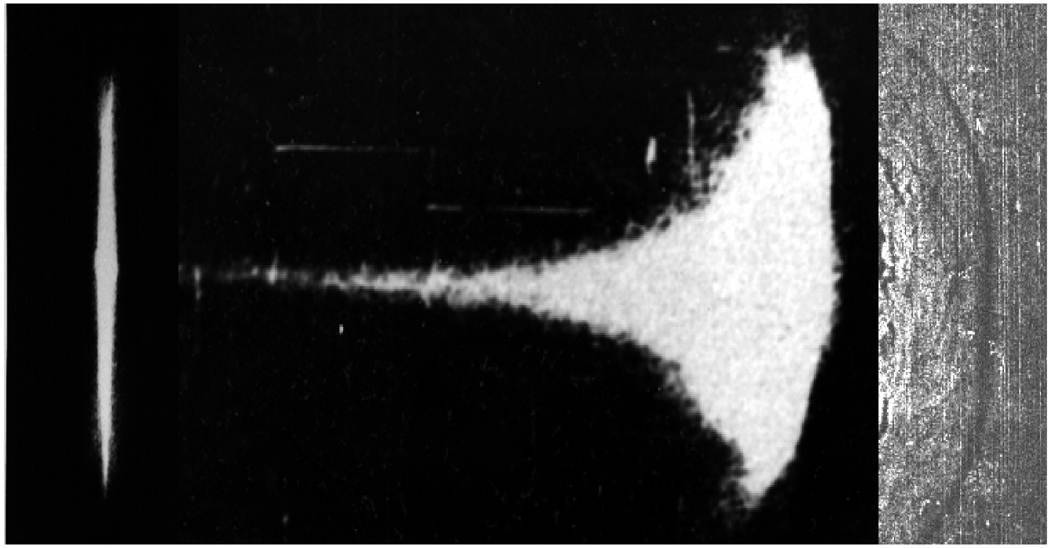


1 – master oscillator
2 – amplifying klystrons
3 – emitting horns

4 – MW beam,
5 – open resonator,
6 – measuring circuit

K.V. Aleksandrov, Technical Physics, Vol48, No.1, 2003

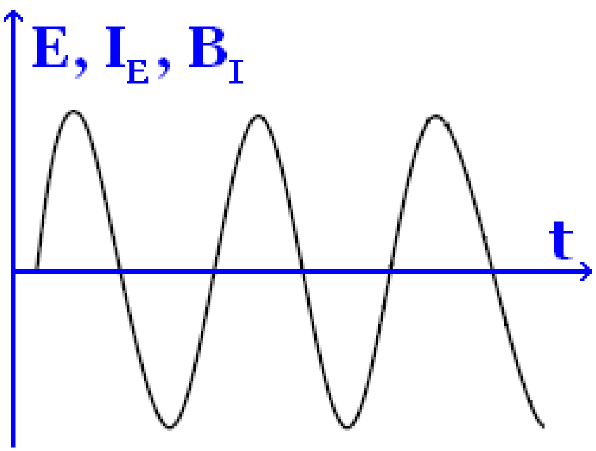
Two Mirror Resonator

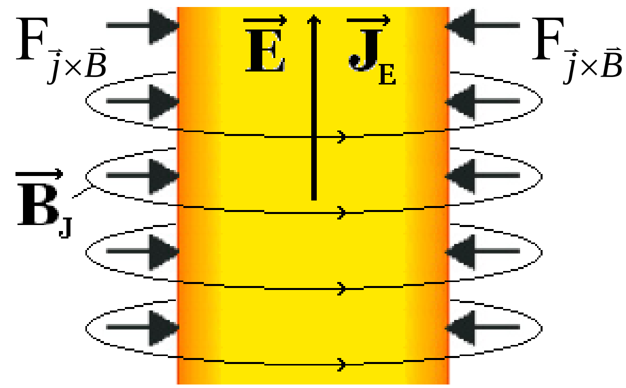


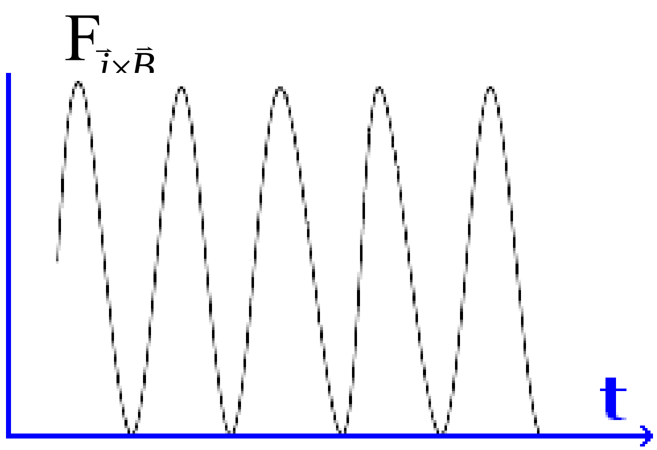
a. b. c.

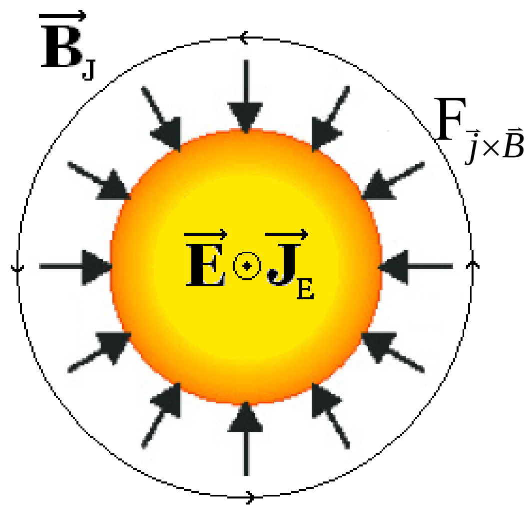
a. **photo with the permanent exposition (length= λ /2)**
b. **time resolution photo (duration – 100 ns)**
   (electrons avalanche- stretch along E field-
   length= λ /2 -E field break down-streamer explode)
c. **shadow photo of streamer explosion**

Microwave Plasma Confinement (MWPC)









Inward pinch despite the ac current switches direction.
At zero current the plasma is inertia confined.

MWPC Equilibrium

Electric field $\vec{E}_0 = \hat{\mathbf{e}}_z E_0 \cos(\omega_0 t)$ $n_c \equiv m\omega_0^2 / 4\pi e^2$ (critical density)

Current $\vec{j}_0 = \hat{\mathbf{e}}_z j_0(r)\sin(\omega_0 t)$ $j_0(r) \approx n_0(r) e^2 E_0 / m\omega_0$

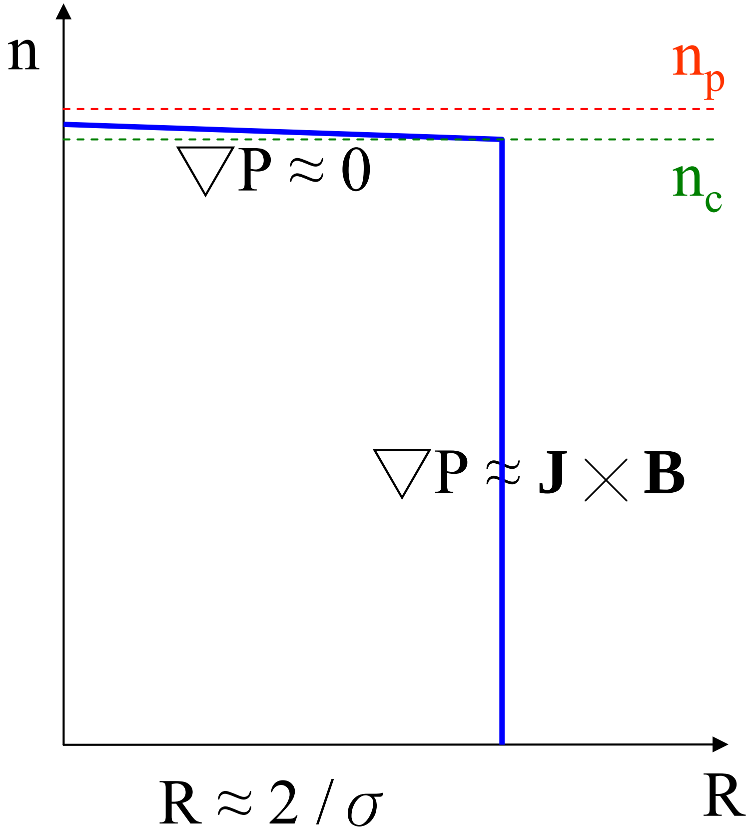
Magnetic field $\vec{B}_0 \approx \hat{e}_\theta \dfrac{\omega_0}{rc}\int_0^r r'dr'[\dfrac{n_0(r')}{n_c} - 1]E_0 \sin(\omega_0 t)$

Momentum equation

$$M\frac{d\vec{V}}{dt} = -\hat{e}_r \frac{e^2}{mrc^2}\int_0^r r'dr'(\frac{n_0(r')}{n_c} - 1)E_0^2 \sin^2(\omega_0 t) - k_B T \nabla \ln n_0(r)$$

Plasma density must be higher than the critical density for inward pinch and plasma confinement

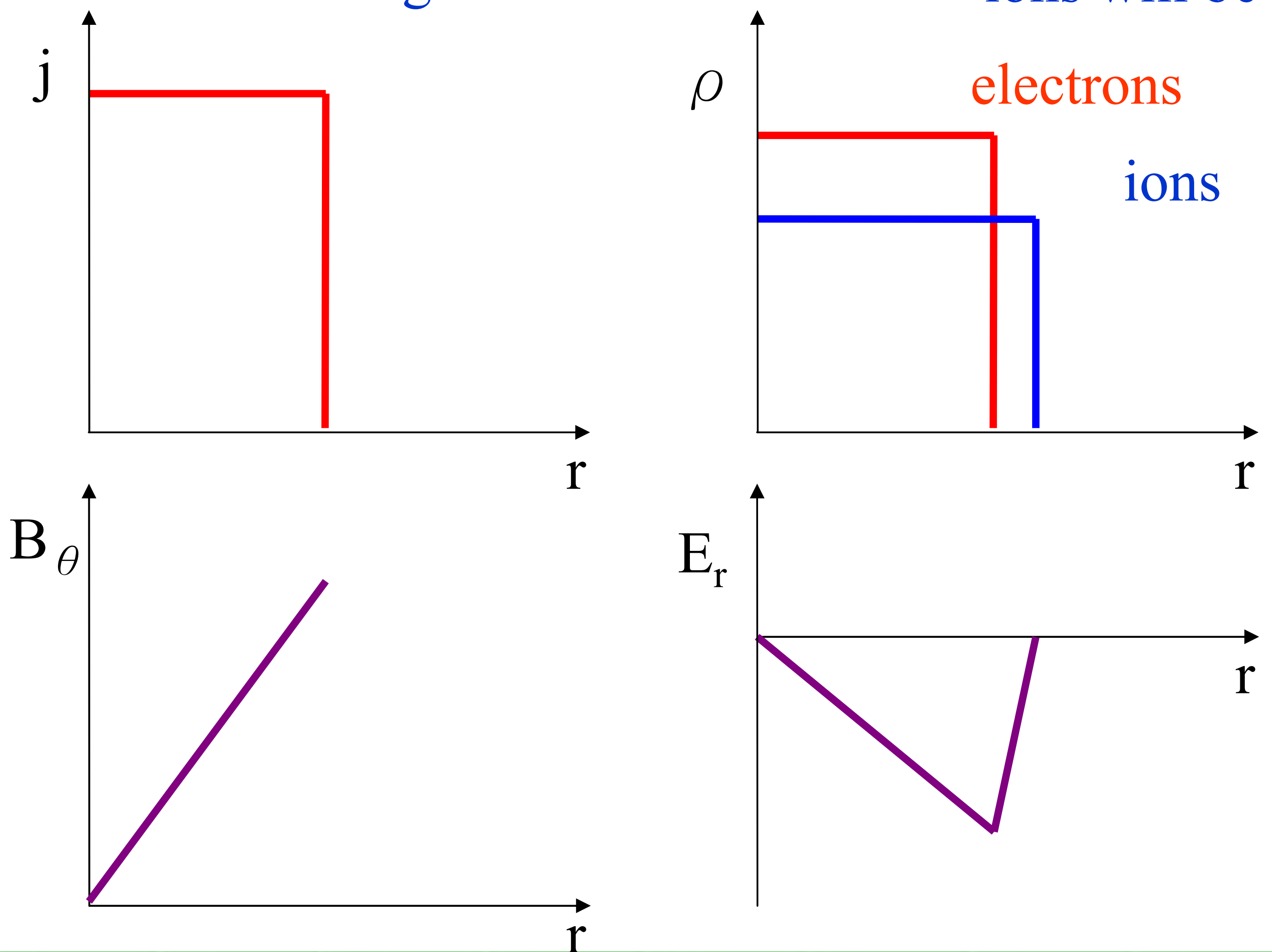
$\sigma \to 0$


n
n_p
$\nabla P \approx 0$
n_c
$\nabla P \approx \mathbf{J} \times \mathbf{B}$
$R \approx 2/\sigma$
R

Confinement Mechanisms

electrons build magnetic fields

ions will be pulled back



Summary Remarks on MWPC Equilibrium

- MWPC agrees with our daily experience - the florescent light.
- Compact and lower cost is expected.
- Far away from physical wall – impurity issue is reduced or totally alleviated.
- Encapsulation is easy and self-organized.
- 100GHz to 1THz will be the best frequency range
- Ion heating?

Particle in Cell (PIC) Simulation

Advancing particles by the leapfrog algorithm

$$\frac{d\vec{v}_j}{dt} = \frac{\vec{F}\left(\vec{r}_j, t\right)}{m_j}$$

$$\frac{d\vec{r}_j}{dt} = \vec{v}_j$$

Charge and Current are loaded onto grids to solve for electromagnetic force

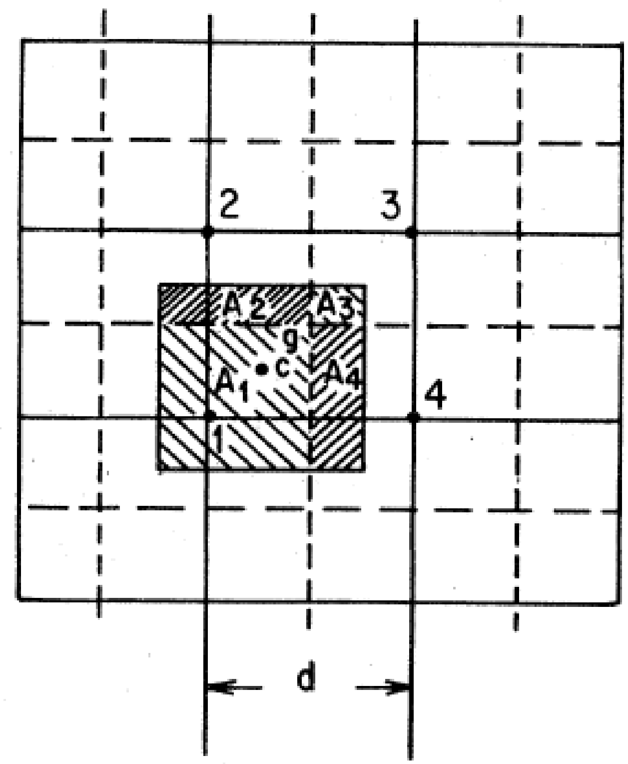


FIG. 5. Area-weighting method for charge sharing.

Finite-Sized Particles

if the particles are of finite size,
 their charge is smeared out over a finite regions smaller than the size of a particle cannot be resolved.

this implies that in making
 calculations we may divide the space into cells which are about the size of a particle.

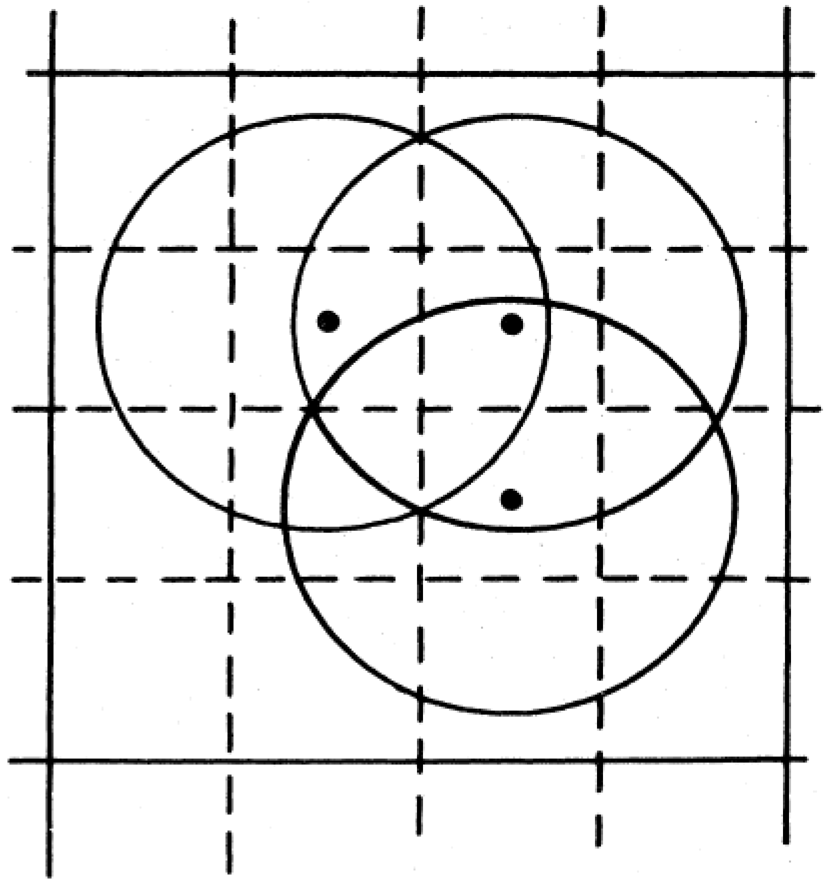
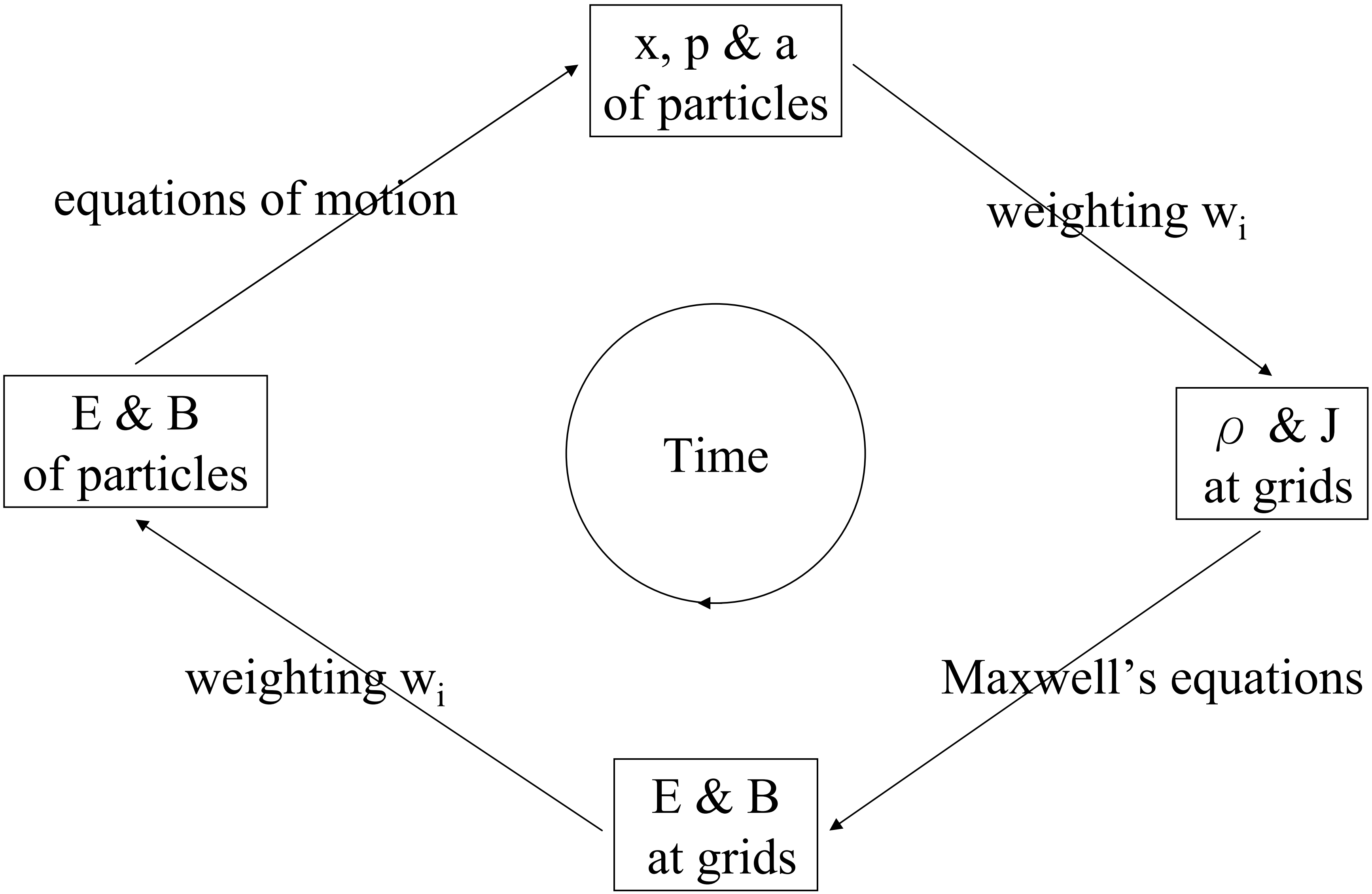


FIG. 3. Finite-sized particles and discrete grid used for calculating the force.

J. M. Dawson, Particle Simulation of Plasma, **Reviews of Modern Physics,** 55, p403 (1983)

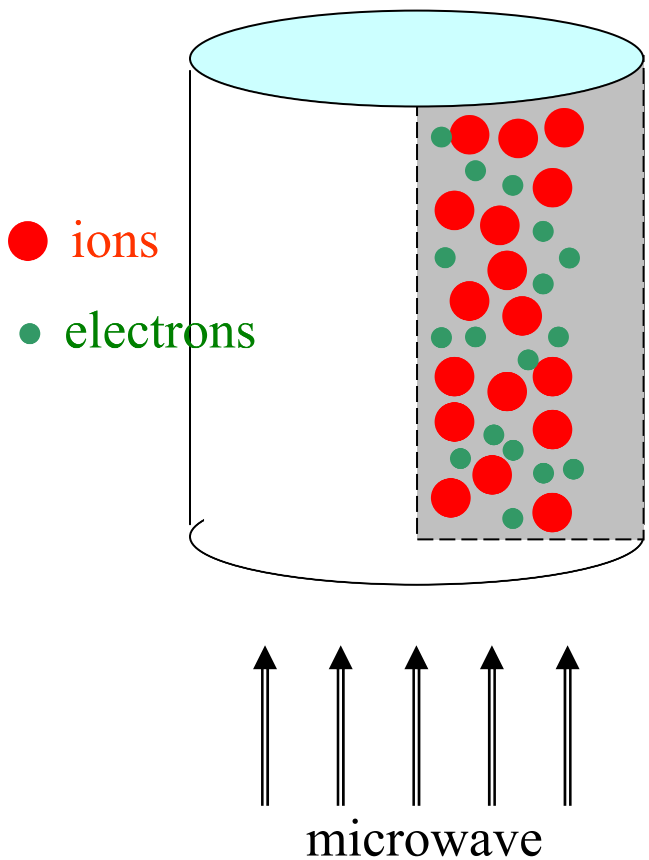
Flow Chart

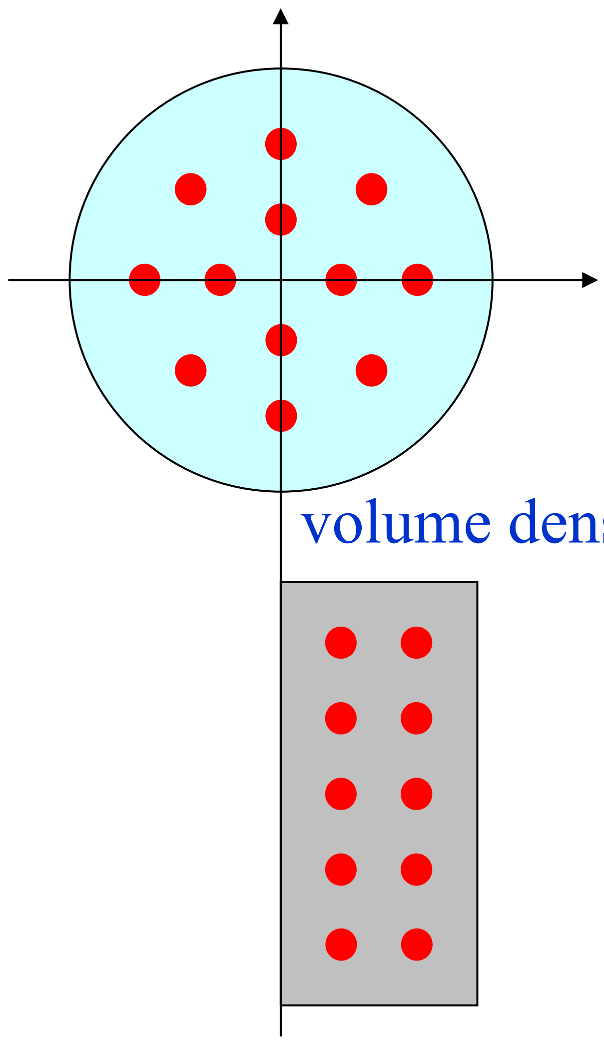


x, p & a of particles
weighting w_i
ρ & J at grids
Maxwell's equations
E & B at grids
weighting w_i
E & B of particles
equations of motion
Time

Particle-in-Cell Simulation

cylindrical model





volume densities = area densities

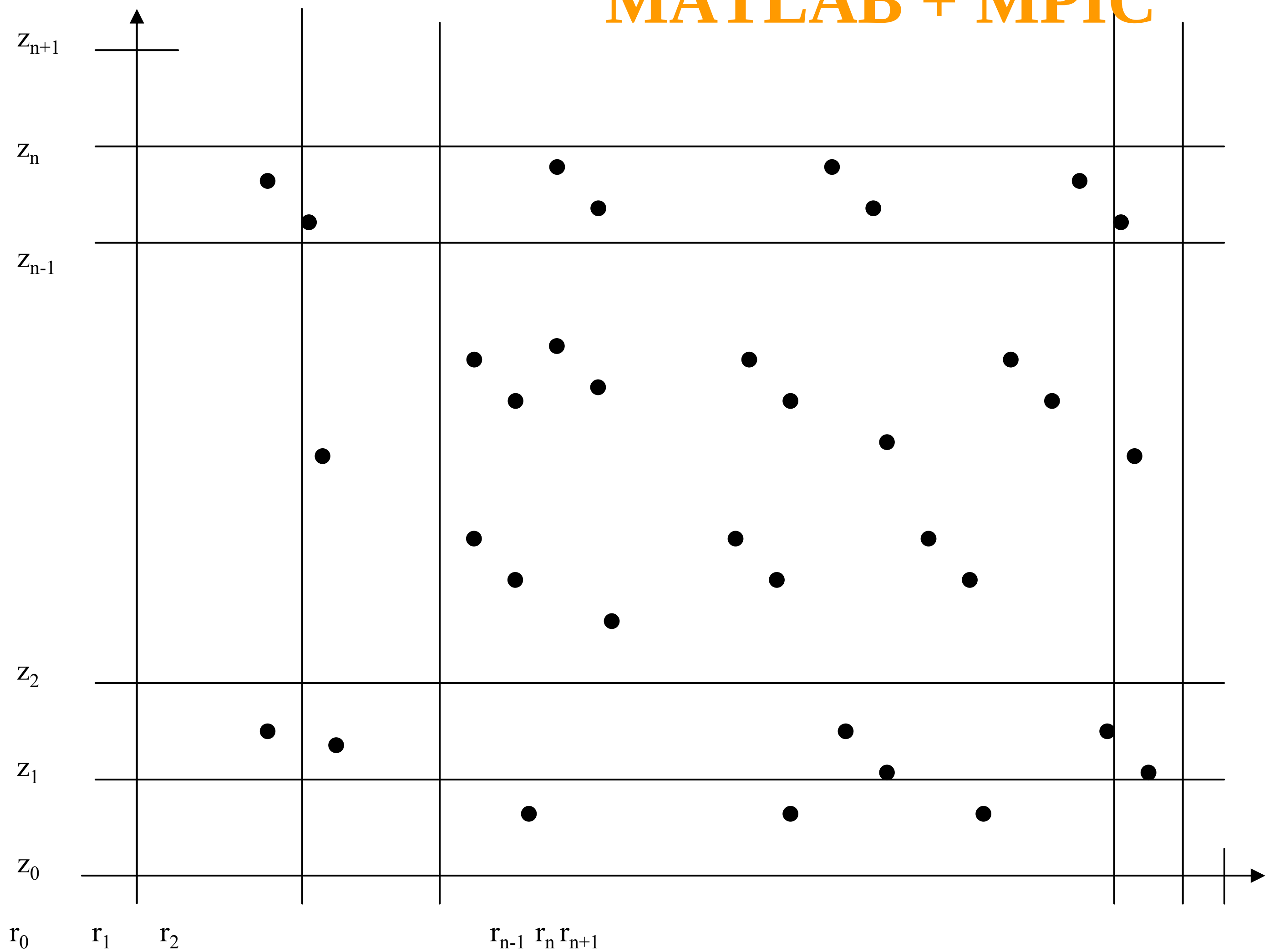
no θ variations

θ is ignorable

reduce to r-z coordinate problems

Simulation Model

MATLAB + MPIC



a delta theta thickness

Parametric Decay

Besides the high frequency pump wave to produce ac electron current to confine plasma, it has the possibility of parametric decay to ion sound to potentially heat the ions.

$$\omega_0 \approx \omega_1 + \omega_2$$

$$\vec{k}_0 \approx \vec{k}_1 + \vec{k}_2$$

Ion Sound Instability

Wave equation with σ - expansion to leading order

$$\frac{\partial^2 \psi}{\partial \tau_A^2} \approx \frac{n_0}{n_c}\psi + \frac{\lambda_D^2}{\sigma^2}\nabla^2\psi \qquad \psi \equiv \nabla \cdot n_0 \delta \vec{V}_l$$

Local approximation: $\gamma_A^2 \approx n_0 / n_c - k_z^2 \lambda_D^2 / \sigma^2$

The instability occurs in a long and slim plasma due to the

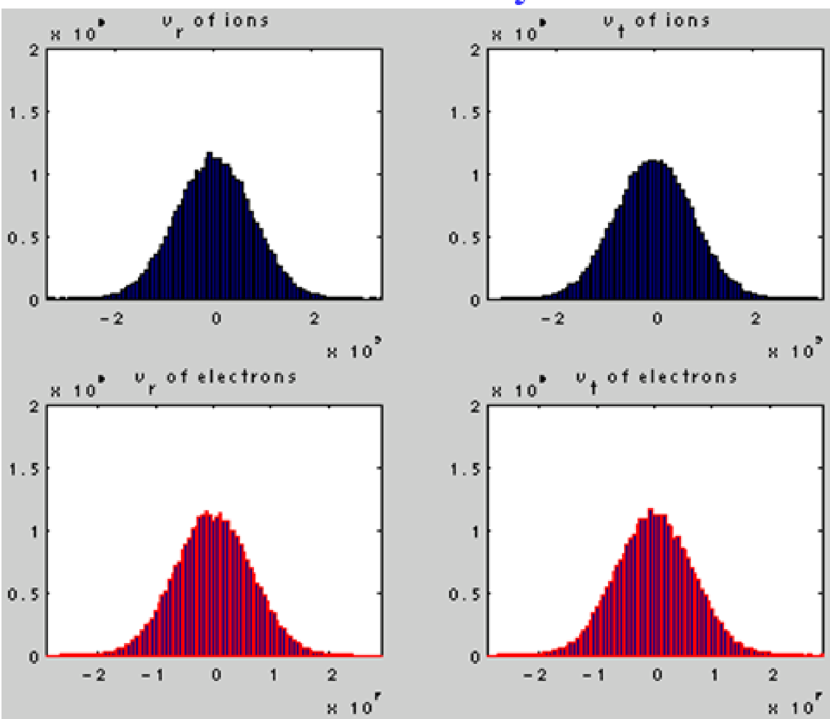
$$\vec{j}_0 \times \delta \vec{B}_h$$

the pump current and the high frequency azimuthal magnetic field to result in the low frequency density perturbation.

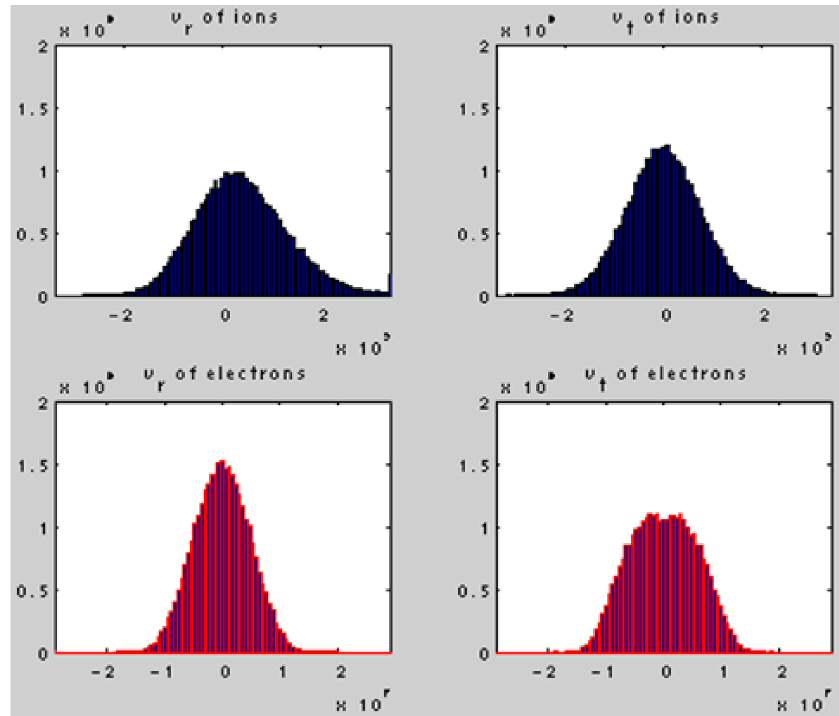
The growth rate is on the time scale of $1/\sigma\omega_{pi}$ and has ion sound characteristics.

Electron and Ion Velocity Distribution

initially



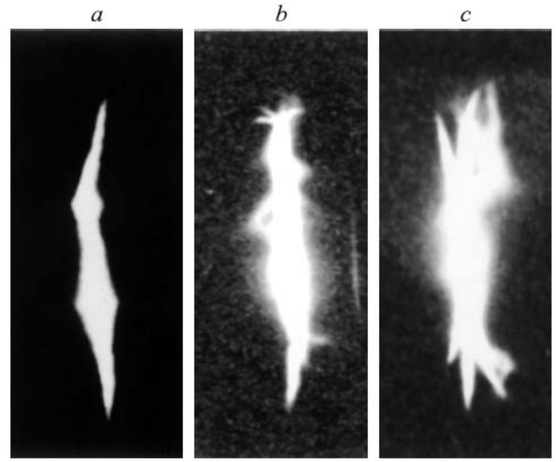
after 0.8 μs



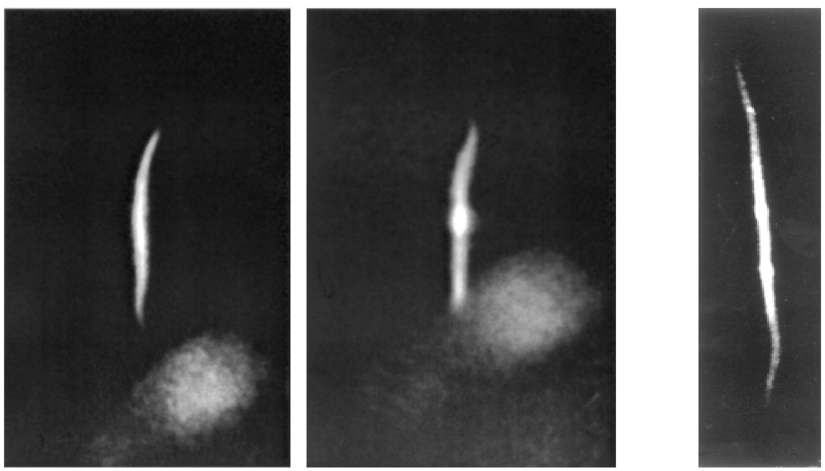
MHD Instabilities

L. P. Grachev, I. I. Esakov, K. V. Khodataev "Magnetohydrodynamic instabilities of a pinch resonant streamer microwave discharge". Technical Physics Vol. 48, No. 5, p.557, May 2003.

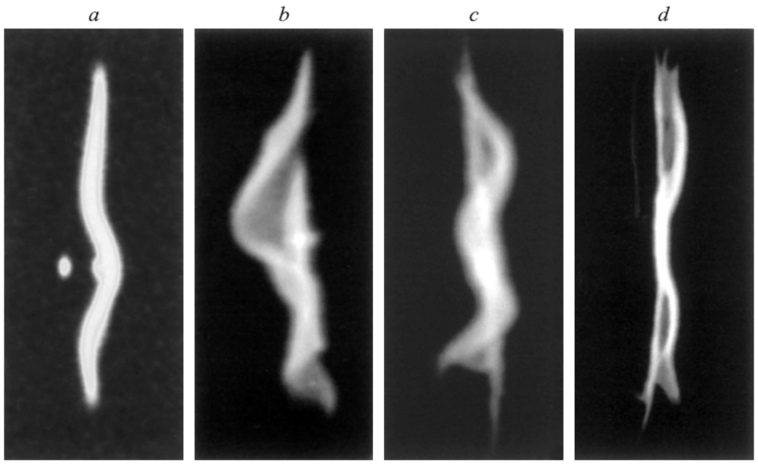
V. S. Barashenkov, L. P. Grachev, I. I. Esakov, B. F. Kostenko, K. V. Khodataev, M. Z. Yurev "Threshold of a cumulative resonant microwave streamer discharge in a high-pressure gas" Technical Physics, Vol. 45, No. 11, Nov. 2000.



Air: a – 1.5 atm, b – 2.5 atm; c – 3 atm



Air, 1 atm: with & without core; H_2, 1 atm: 2 cores



H_2: a – 2.5 atm, b – 4 atm; c – 5 atm; d – 8 atm

Conclusions

- **We set to find out whether a single mechanism to achieve plasma confinement and ion heating is feasible.**
- **MWPC equilibrium can reach microsecond confinement time and beyond, much longer than the experimental result.**
- **PIC simulation shows agreement with the prediction from the MHD equilibrium equation.**
- **Ion sound instability can be a good thing. No simulation result so far, however.**