Analytical and Numerical Studies of Ion Beam Plasma Interaction for Heavy Ion Driven Inertial Fusion

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Talk Outline

- Basics
  - Why do Heavy Ion Fusion?
  - What do we have to do?
  - A bit about the accelerator and the beams
- Program
  - Past Accomplishments
  - Present Program
  - Future Plans
- Physics of Ion Beam Plasma Interaction
  - Degree of charge and current neutralization
  - Self electric and magnetic fields

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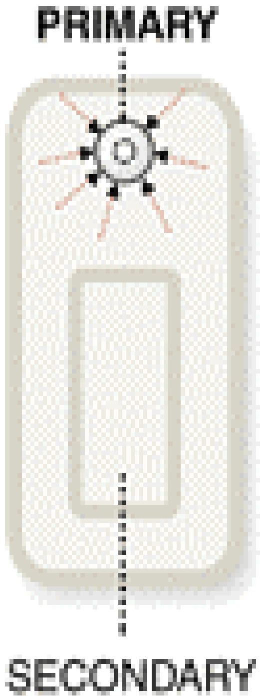
Introduction to Heavy Ion Fusion

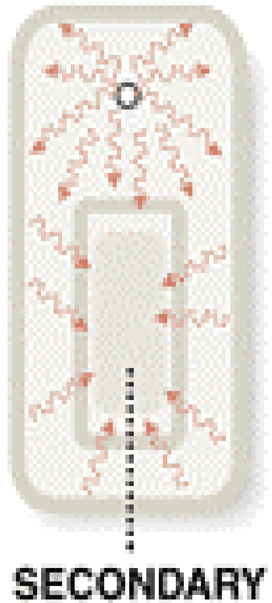
- **Inertial fusion is based on H-bomb design**

- **Who built the h-bomb? Debate revives**
- **By WILLIAM J. BROAD, April 24, 2001**

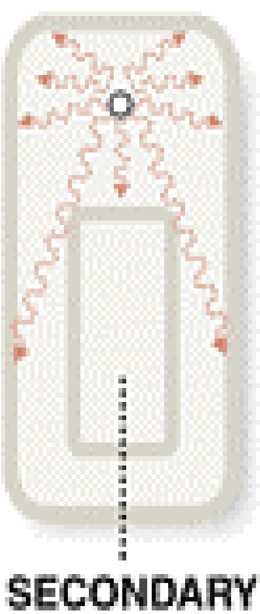
Bomb Basics



Conventional explosives compress plutonium in the primary, creating a critical mass in which atoms begin to split apart and release nuclear energy.



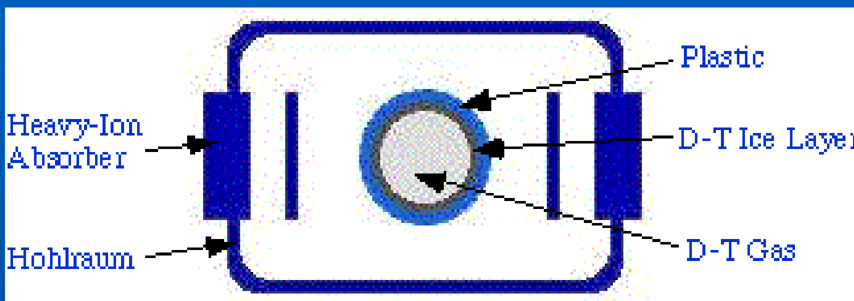
The radiation vaporizes the lining of the casing and radiates back toward the secondary, compressing it and heating it to fusion temperature.

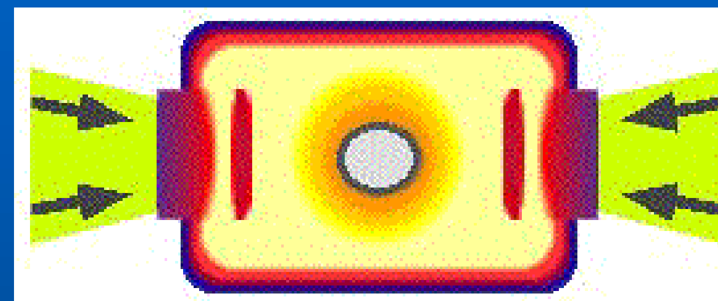


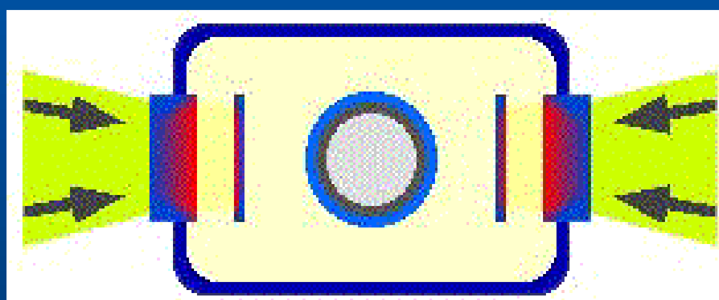
Radiation from the primary flows down the length of the bomb casing ahead of the primary blast.

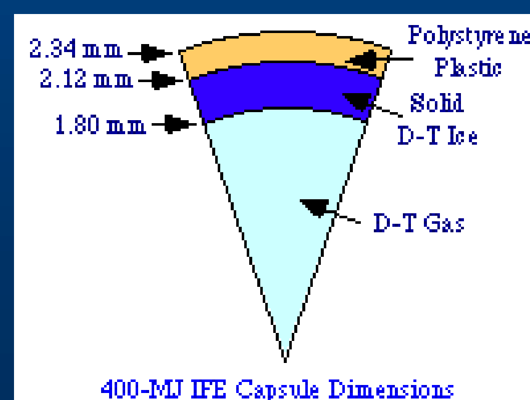
Heavy Ion Fusion Concept

How IFE Targets Work









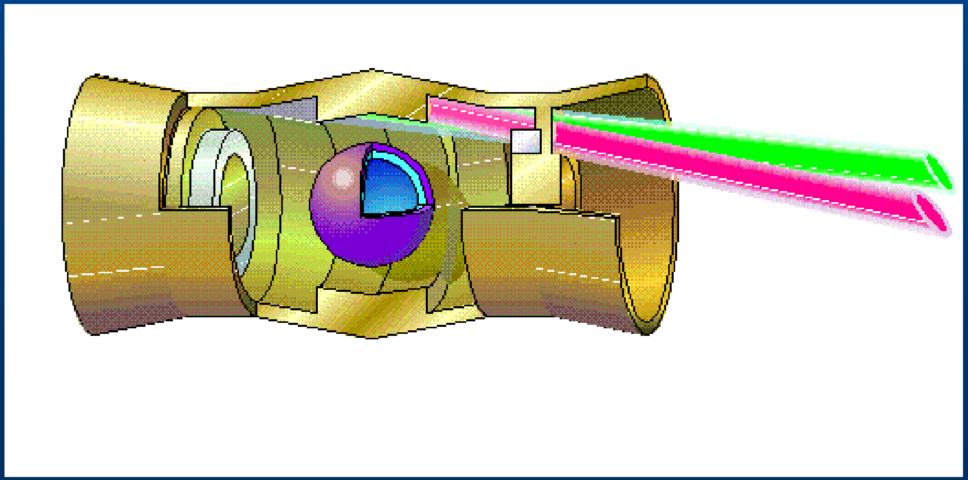
Heavy Ion Fusion Requirements

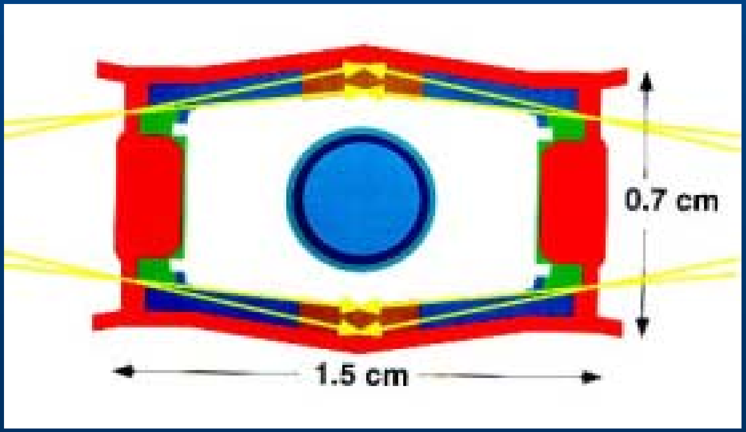
Target requirements

3 - 7 MJ x ~ 10 ns ⇒ *~ 500 Terawatts*

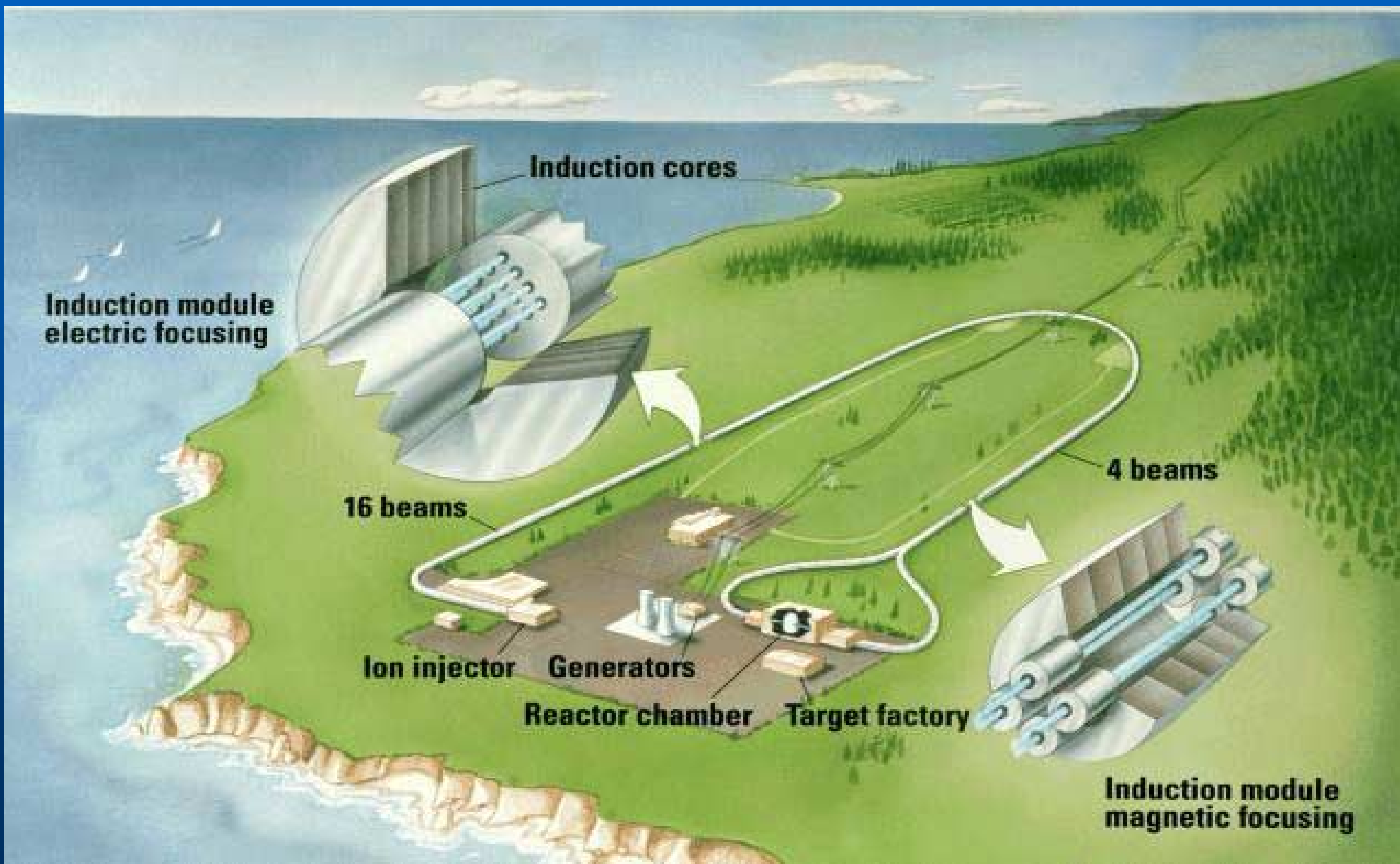
(*hand grenade*) (*Forty times the averaged world-wide electric power consumption*)

Ion Range: 0.02 - 0.2 g/cm^2 ⇒ *1- 10 GeV*





Peaceful Power -- An Artist's Conception of a HIF Power Plant



Why Heavy Ion Fusion?

Advantages of Heavy Ion Fusion Approach

- **Driver is separate from the fusion chamber**

  $\Rightarrow$ accelerator not exposed to fusion environment

  $\Rightarrow$ can protect 1st wall

- **High electrical efficiency**

- **Takes advantage of decades of worldwide investment in accelerators & defense-funded target design**

Heavy Ion Accelerators are a Good Choice for a Fusion Driver

High Energy Physics accelerators already have:

Long life

High pulse repetition rates

High efficiency (~ 30%)

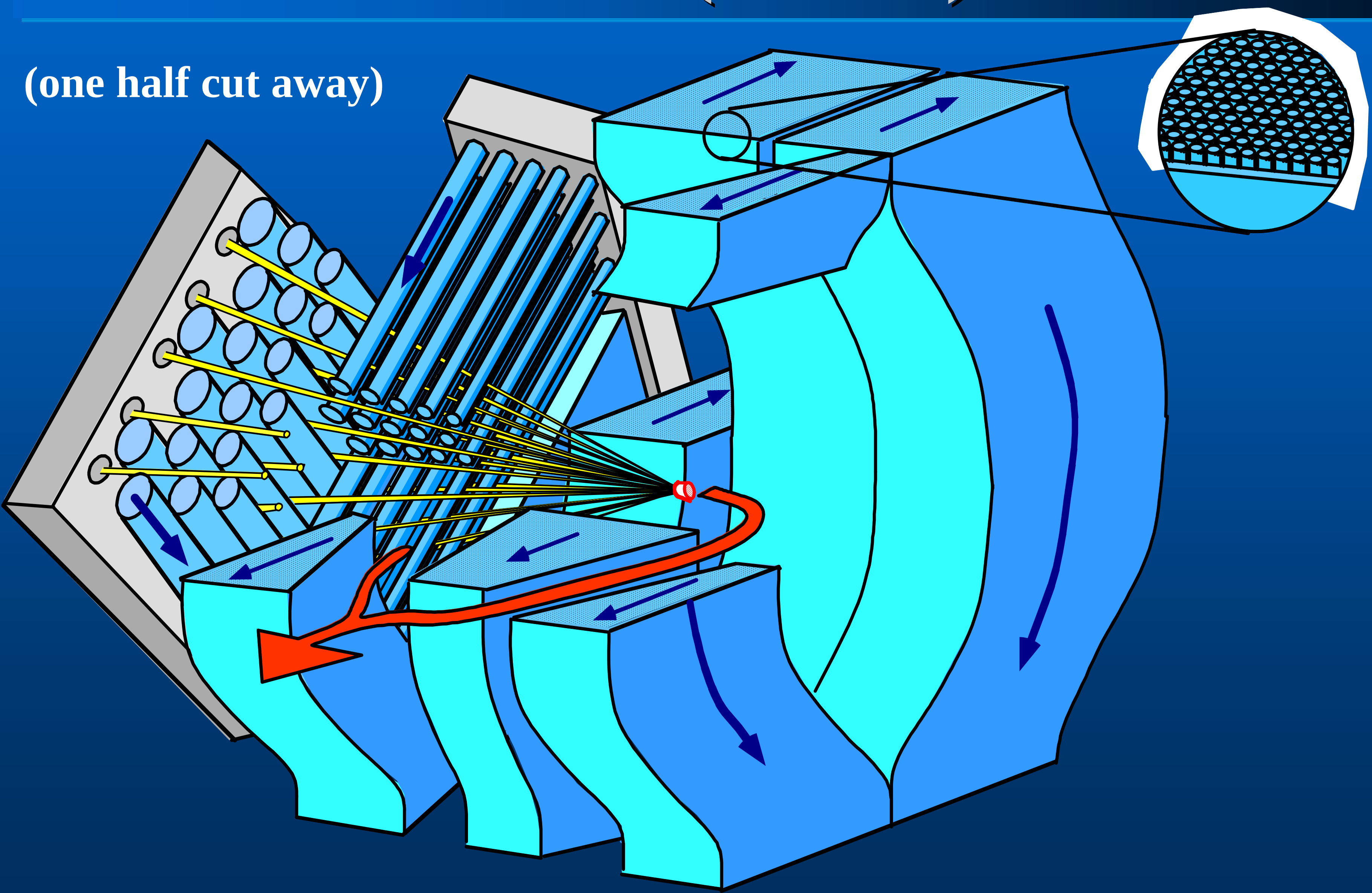
Present systems comparable to requirements in:

complexity
cost
ion energy

But: **much higher charge-per-unit-length is needed.**
induction is not used in HEP accelerators

The First Wall is Protected by Neutron-thick Molten Salt (FLiBe)

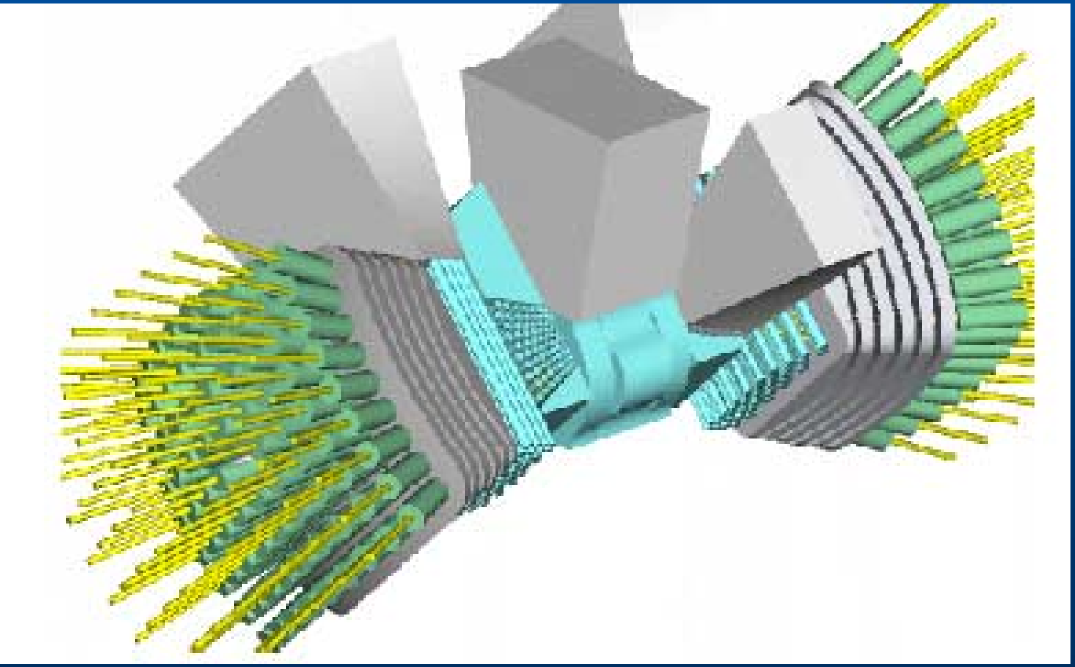
(one half cut away)

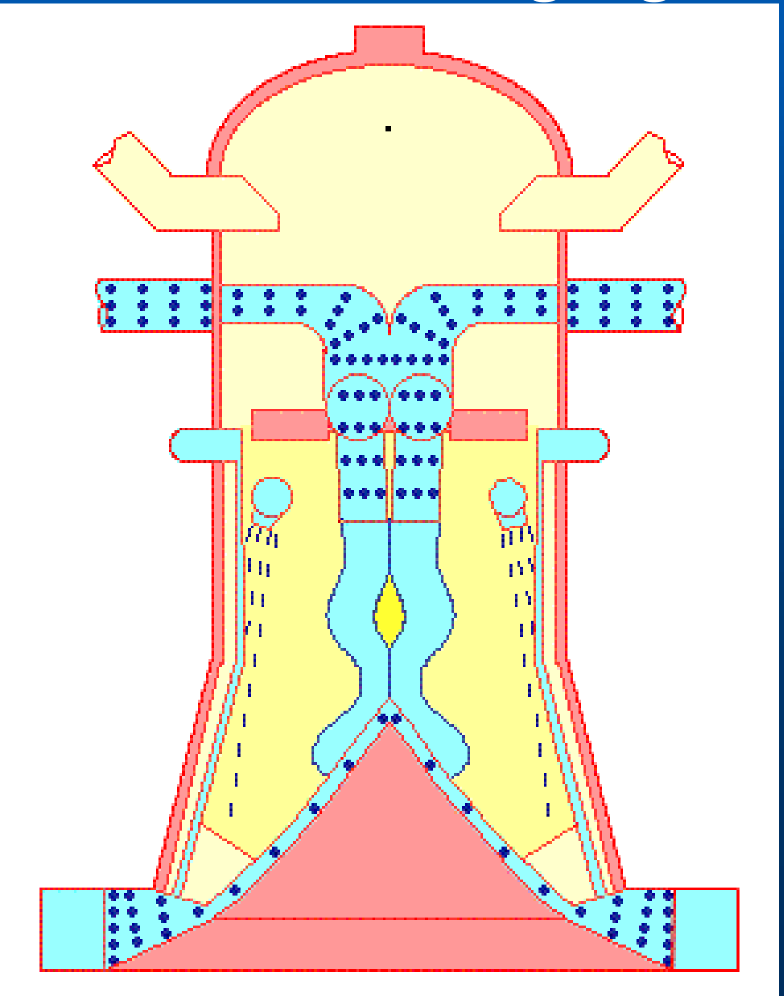


Fusion Pocket Formed by Liquid Jets

Flibe (Li_2BeF_4), is a molten salt with twice the density of water, and roughly the same viscosity, desired for making high-pressure steam for driving turbines.

Flibe absorbs neutrons.





Why Not Laser Drivers?

Lasers:

- Easy to focus
- Much more money in program
- Easier development path

but:

- Problem protecting final optics
- Problem protecting first wall
- Target gets damaged (hot)

} All

- Low repetition rate (a few/day)
- Low electrical efficiency (a few - 10%)

} Glass

Features of the Accelerator

3 - 7 MJ / *1- 10 GeV ions ⇒ ~ 10^{16} ions / 100 beams*

⇒ *1-2 kA / beam* =>Space-charge-dominated beams (non-neutral plasma)

For accelerator design:

Focusability ⇒ Multiple beams

Efficiency ⇒ Induction acceleration

Stability ⇒ Linear accelerator

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Present Experiments

Present experiments – higher current (larger radius)
similar to the driver at low energy
⇒ **high space charge potential**.

0.1 - 0.5 A, 0.4 - 1 MeV, space charge potential ~ few kV

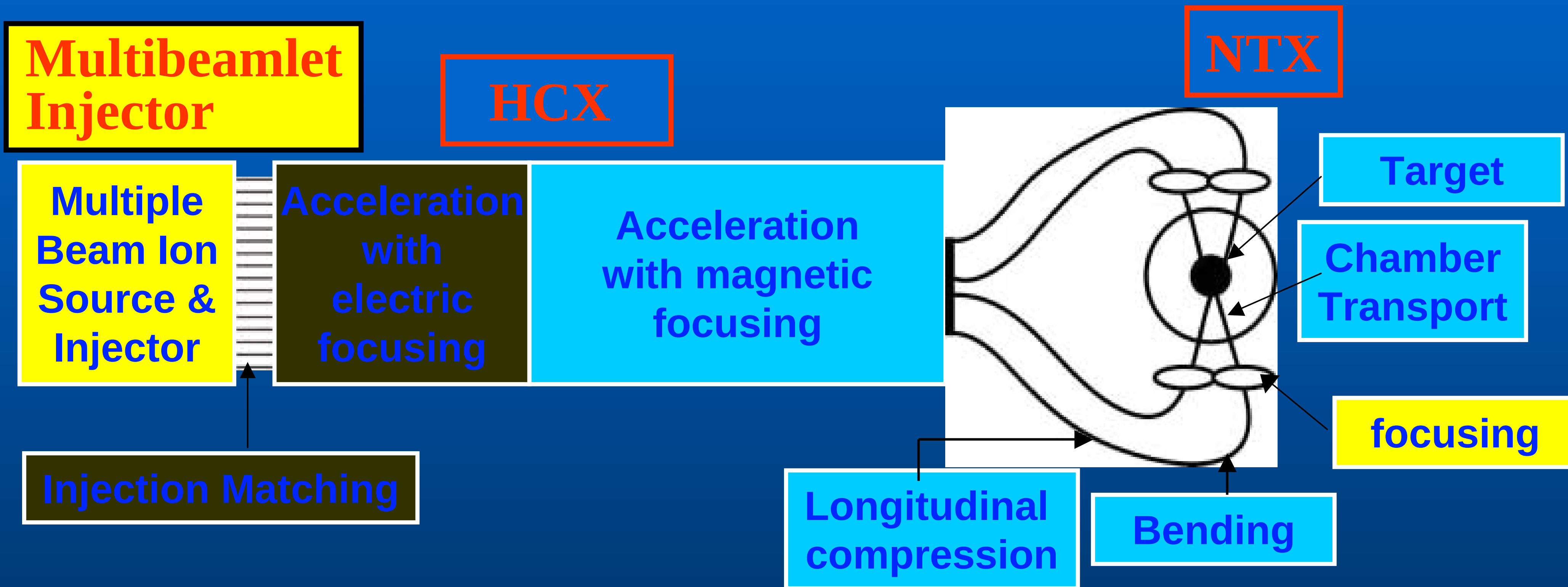
High Current Experiment (HCX) –

how much beam can be transported?

Neutralized Transport Experiment (NTX) –

neutralization by plasmas after the final focus

The Present Experimental Program:
HCX and NTX experiments



Many, but not all, issues experimentally explored

Very complete experimental understanding

The High Current Experiment HCX)

Issues to be resolved:

How much beam can be transported?

- Dynamic aperture (usable aperture set by dynamics)
- Halo production
- Effect of desorbed gas on tail
- Electron production & orbits (magnetic transport)
- Mismatch, misalignment

Parameters:

K^+ or Cs^+

~ 0.2 - 0.5 Amp

1 - 1.7 MeV

4.5 - 7 μs

Quadrupoles:

10 (30-40 later) electrostatic

4 pulsed normal magnetic

a few superconducting

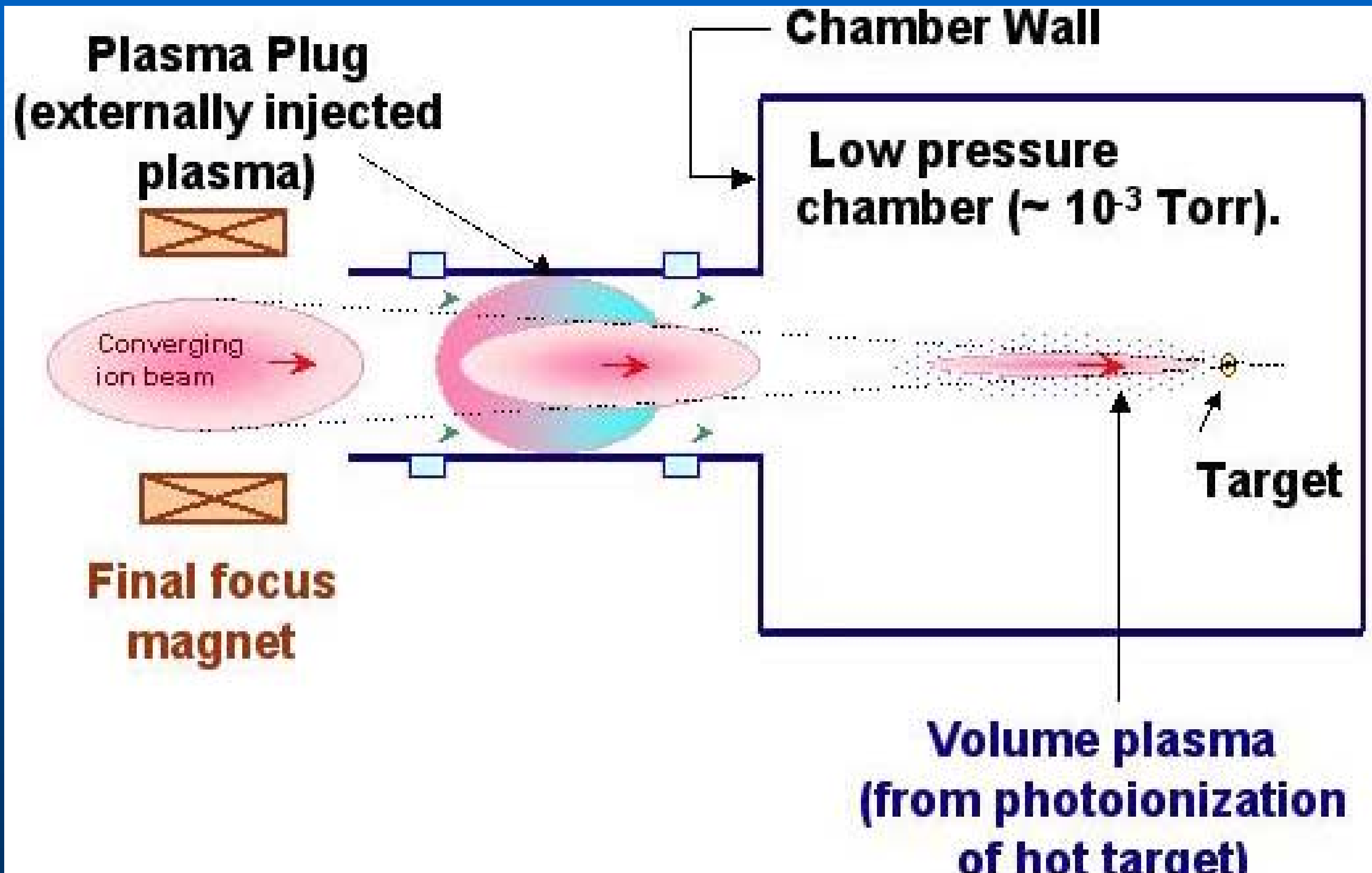
High Current Experiment (HCX)
operation since January, 2002

Transport

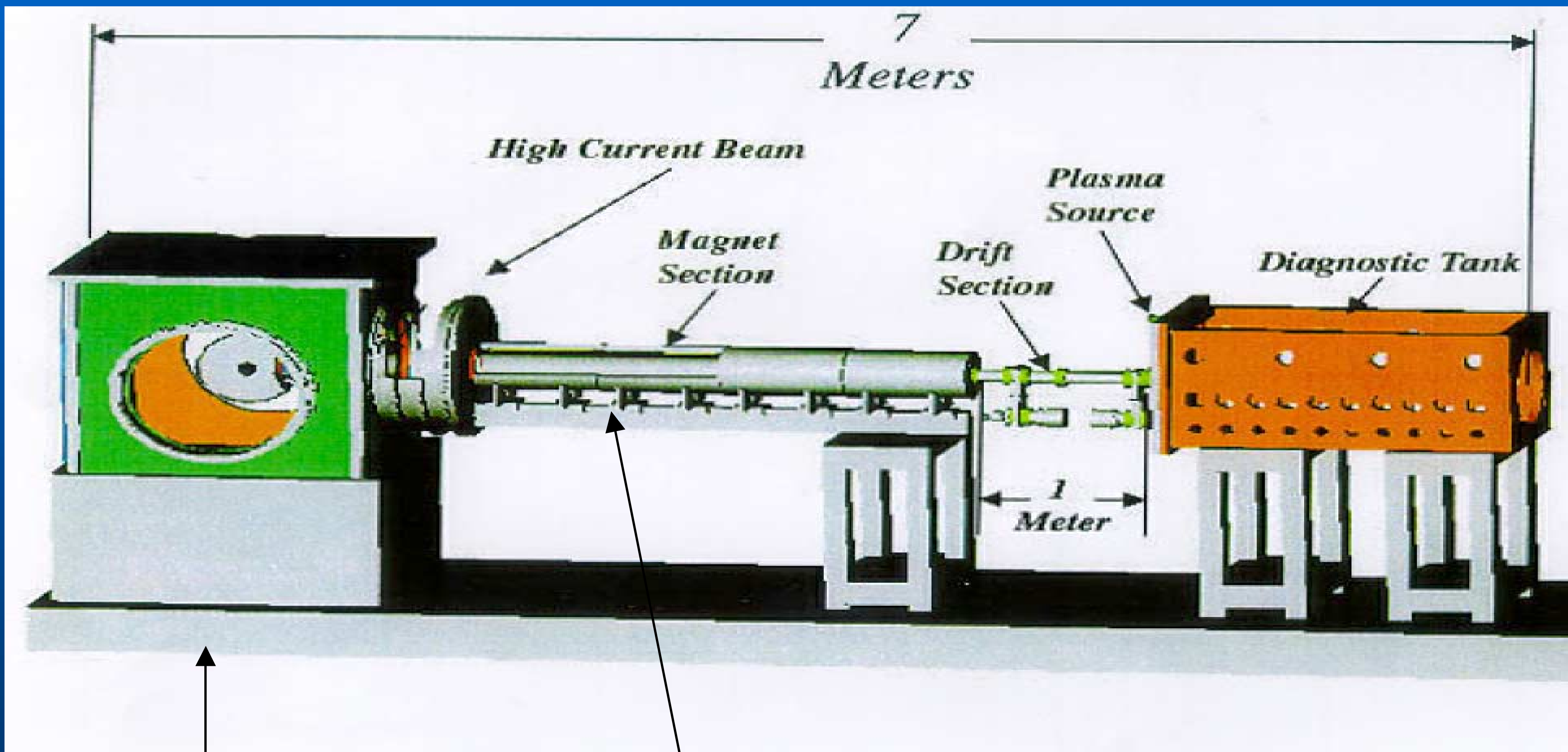
- aperture limits
- electrons
- gas effects
- halo formation
- steering

Chamber Transport

Neutralization competes with stripping in the target chamber



Neutralized Transport Experiment

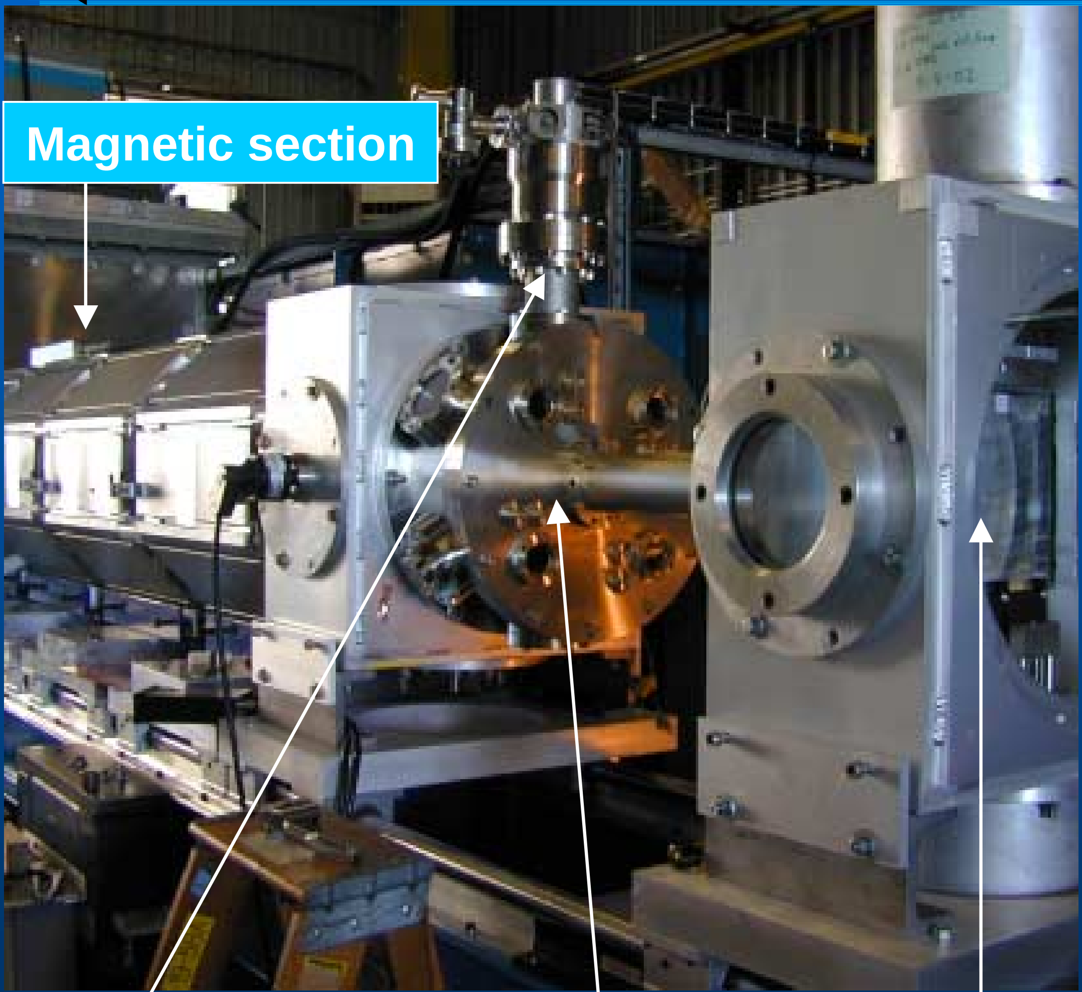


400 kV injector

Final-focusing optical system

FY02: characterize ion & plasma sources
FY03: study beam aberrations
FY04: complete initial neutralization experiments

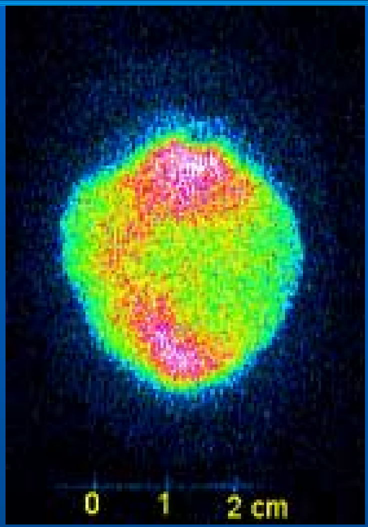
Beam Focusing with Plasma Plug
(operation since September, 2002)



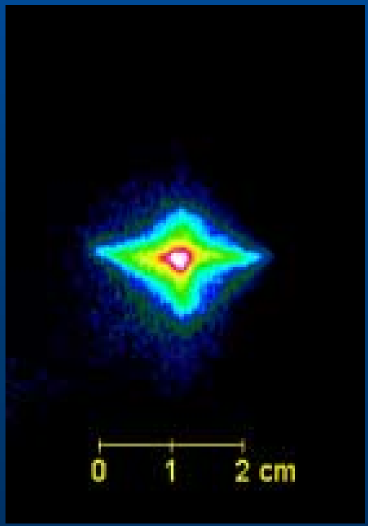
Pulsed arc plasma source

Drift tube

Scintillating glass

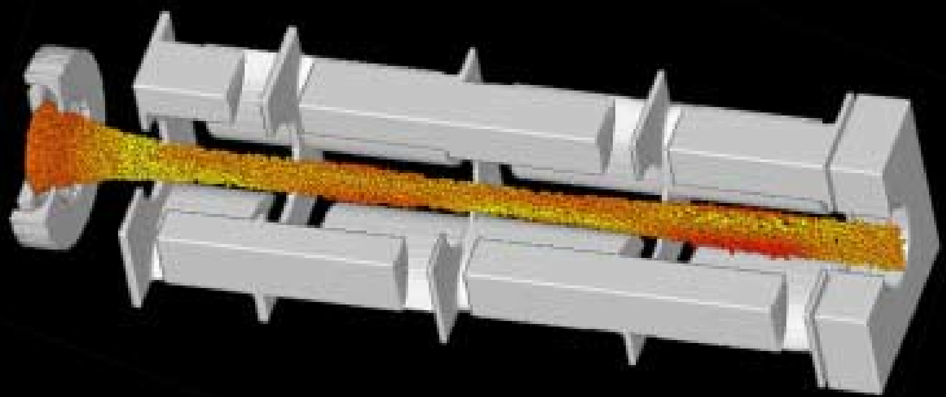


Without Plasma

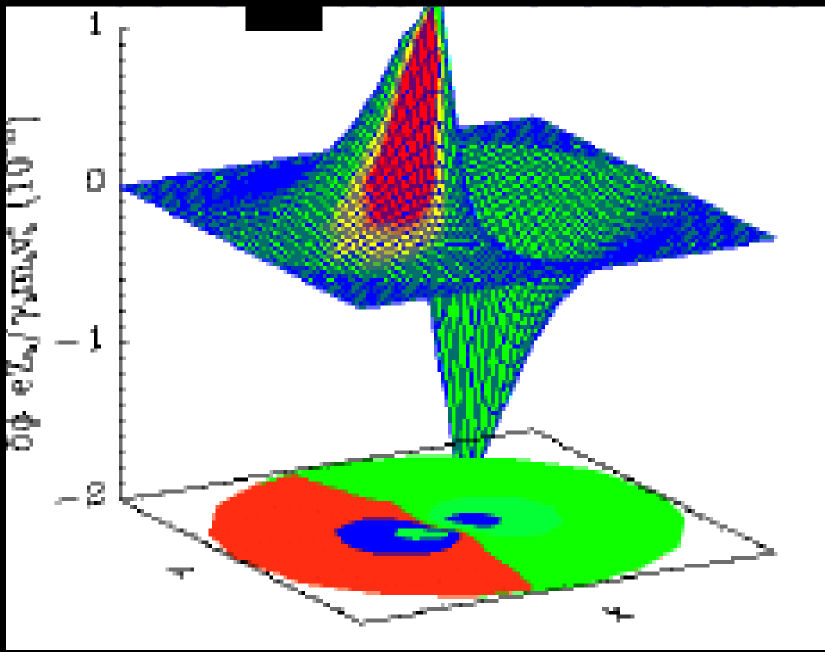


With Plasma

Beam simulations and theory span a variety of processes

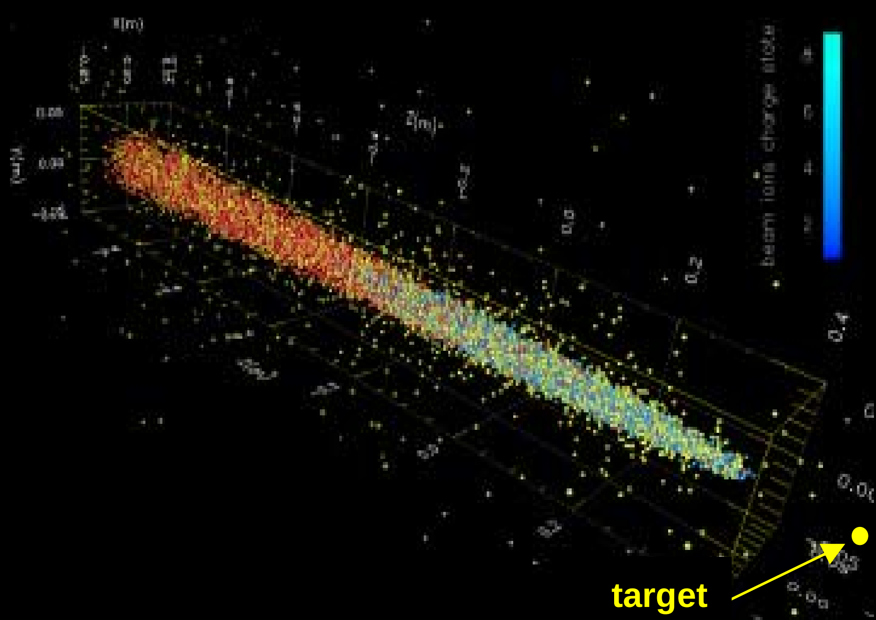


acceleration in 3-D structure

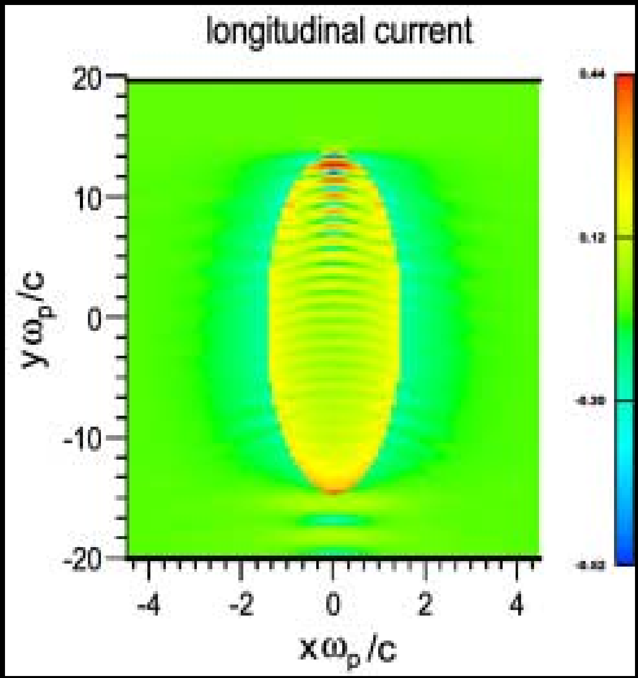


two-stream instability

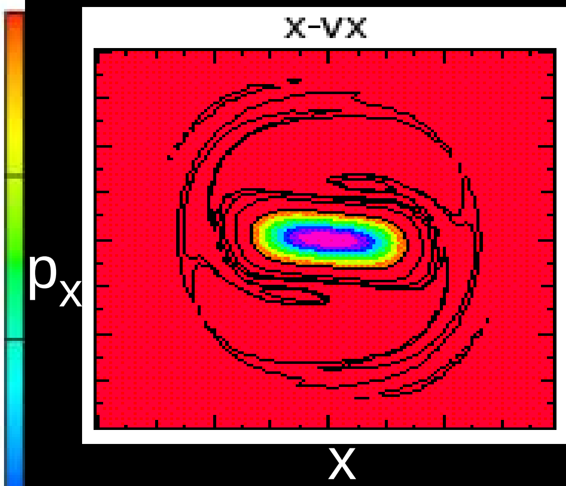
beam ions Flibe ions electrons



chamber propagation

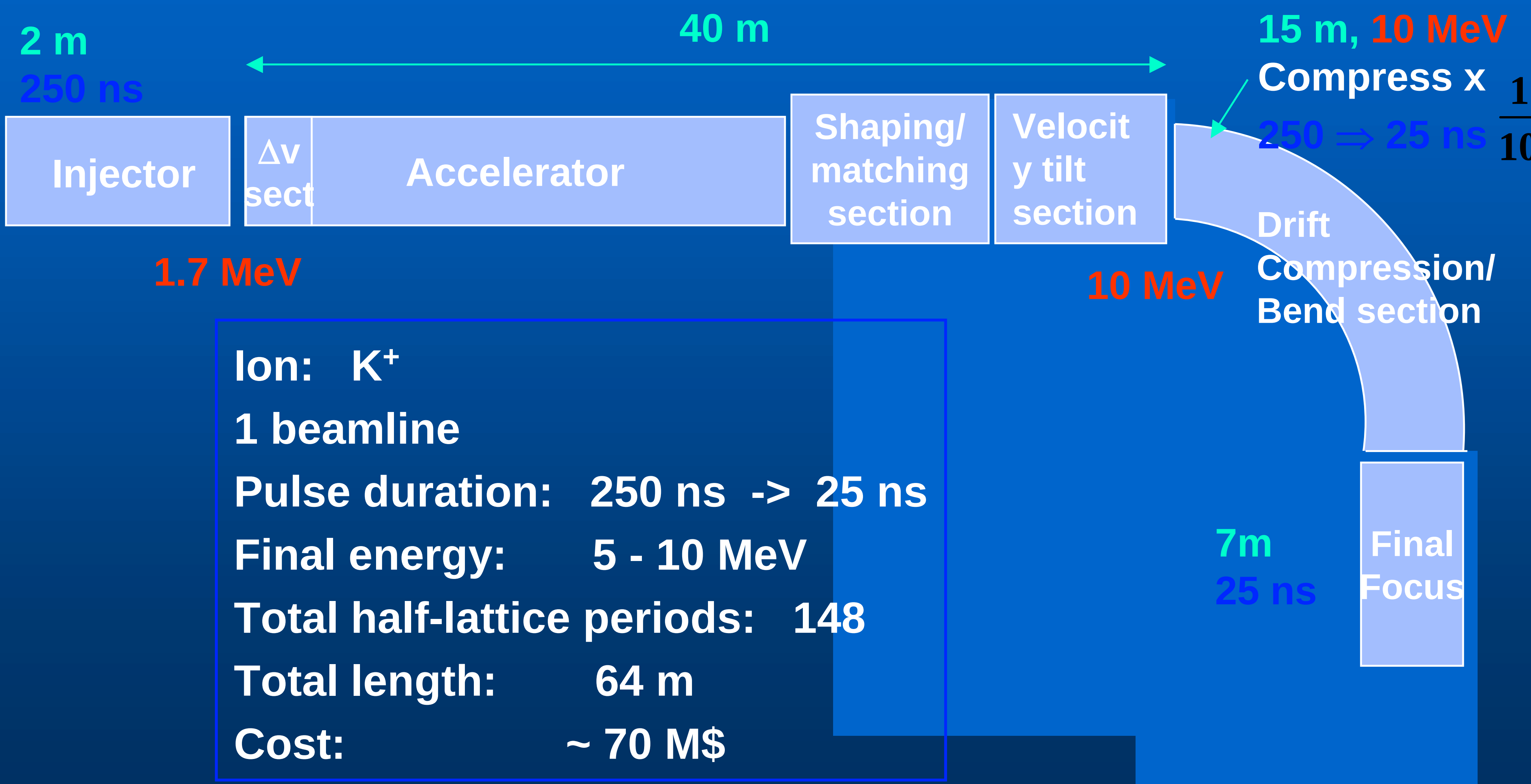


electrons during neutralization



halo generation

Integrated Beam eXperiment Short-Pulse Source-to-Focus Experiment



Ion: K^+

1 beamline

Pulse duration: 250 ns -> 25 ns

Final energy: 5 - 10 MeV

Total half-lattice periods: 148

Total length: 64 m

Cost: ~ 70 M$

$50 - 70 M TEC over 5 yrs + $15 M R&D

Heavy Ion Fusion Summary

- Because of the separation of accelerator from fusion chamber, the heavy ion fusion concept is able to protect the 1st wall, and the driver, from fusion products.
- HIF benefits from large U.S. and worldwide investments in accelerators and defense-funded target research.
- Past and present experiments have demonstrated production, acceleration, compression, and focusing of beams at lower energy and current.
- The Integrated Beam Experiment would be a proof-of-principle experiment with a rich physics mission: to explore longitudinal physics and test integrated source-to-focus transport.

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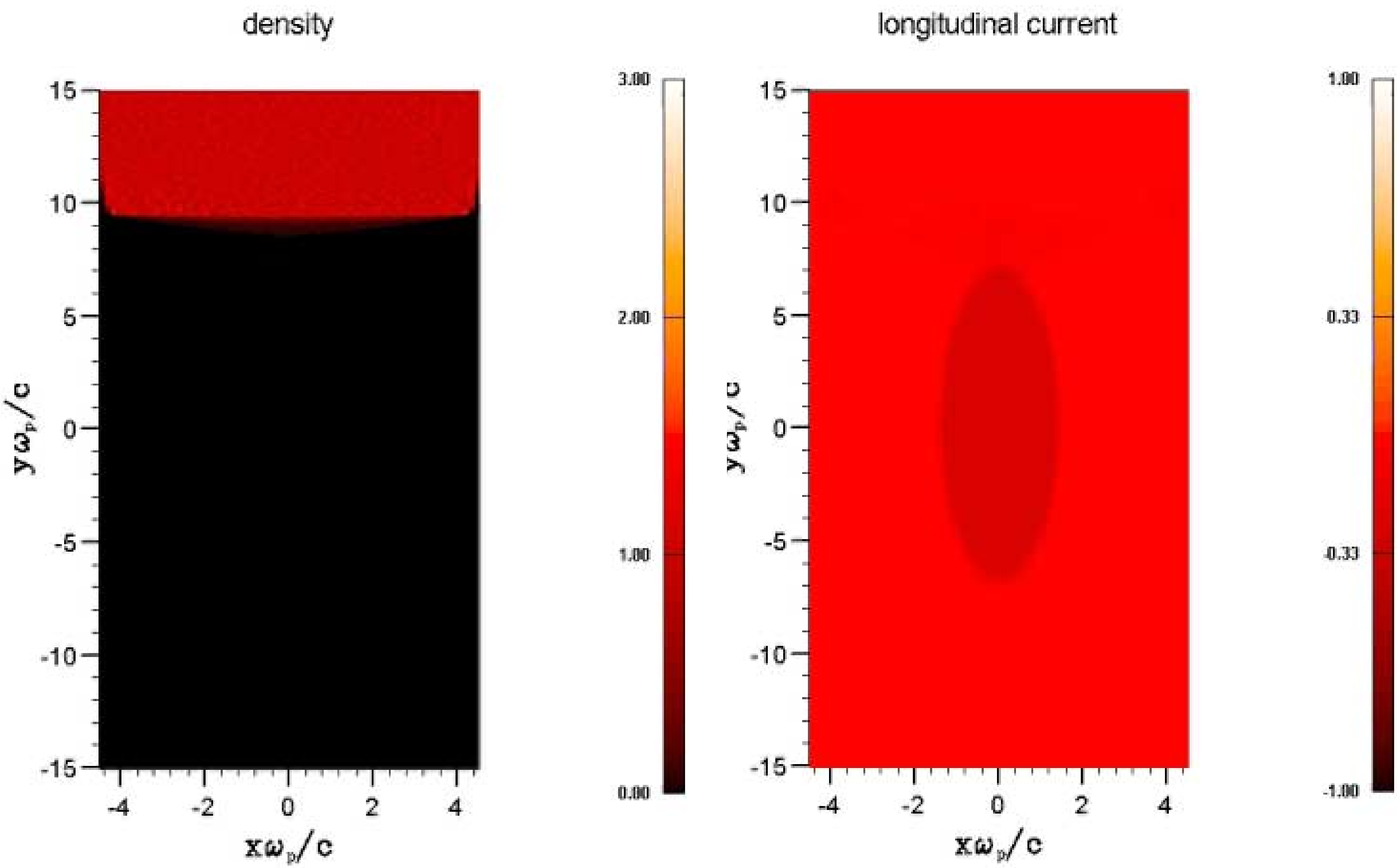
Means of Investigation

- Nonlinear theory
- Numerical simulation:
  - Particle in cell
  - Fluid
- Neutralization experiment (VNL)

Results of 2D PIC-MC Code

- **Beam propagation in the y-direction,**
- **beam length 7.5 c/ω_p;**
- **beam radius 1.5 c/ω_p;**
- **beam density equal to the half of the plasma density;**
- **beam velocity $c/2$.**

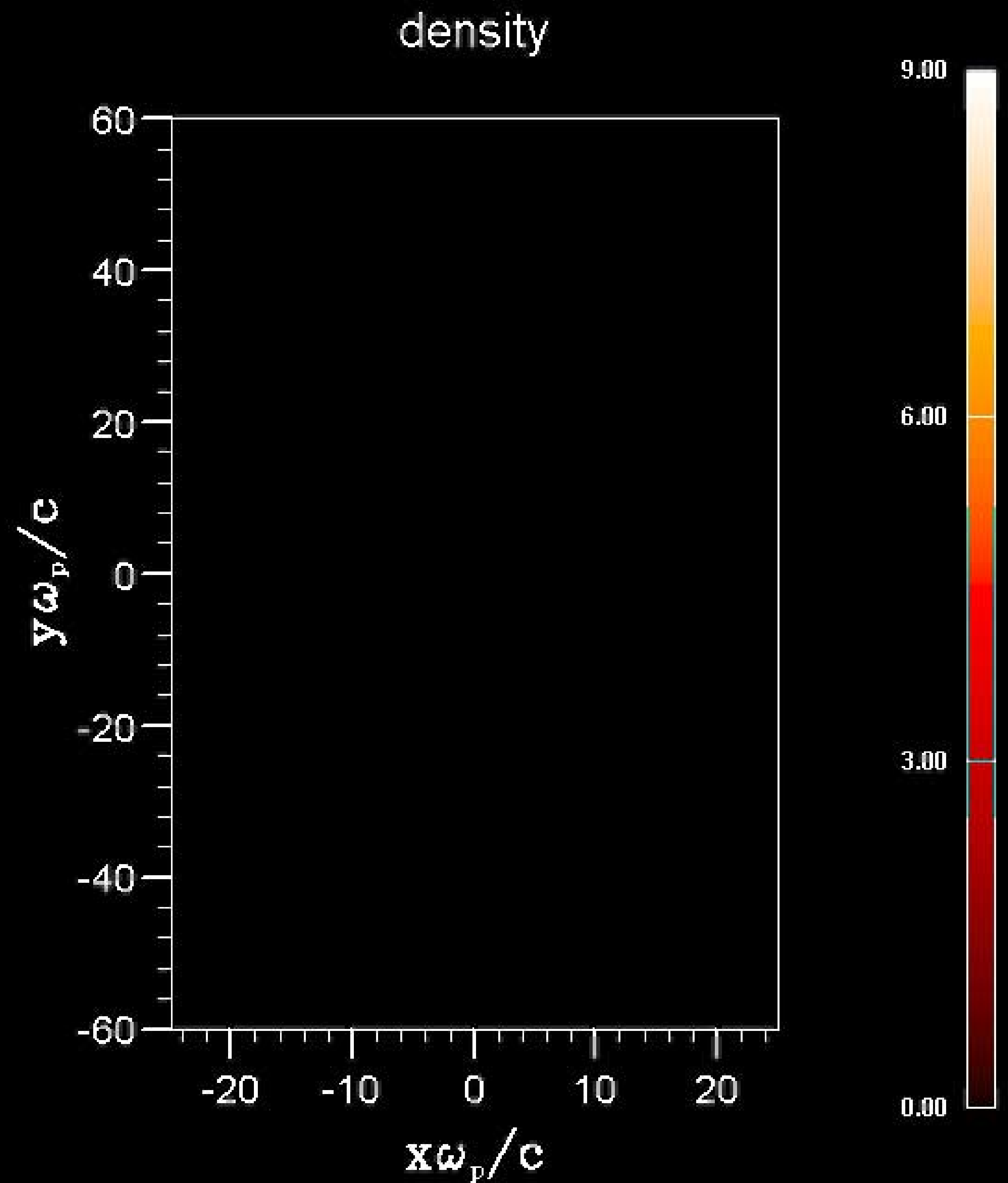
- **Shown are electron density and the current.**


density
longitudinal current
15
10
5
0
-5
-10
-15
-4
-2
0
2
4
$y\omega_p/c$
$x\omega_p/c$
3.00
2.00
1.00
0.00
1.00
0.33
-0.33
-1.00

beam length 30. c/ω_p; beam radius 0.5 c/ω_p;

•beam density is 5 of plasma density;

•beam velocity 0.5c.



System of Equations

$$\frac{\partial n_e}{\partial t} + \nabla \bullet \left(n_e \vec{V}_e \right) = 0,$$

$$\frac{\partial \vec{p}_e}{\partial t} + (\vec{V}_e \bullet \nabla)\vec{p}_e = -\frac{e}{m}(\vec{E} + \frac{1}{c}\vec{V}_e \times \vec{B}),$$

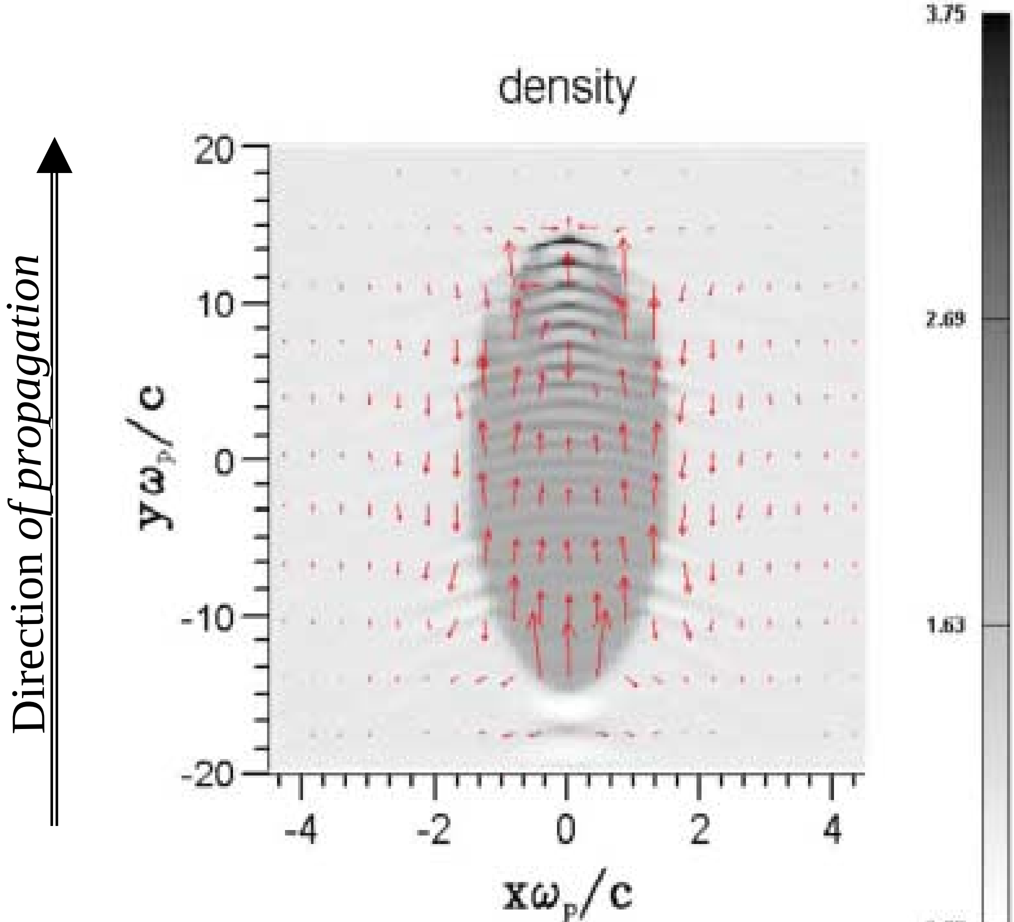
$$\nabla \times \vec{B} = \frac{4\pi e}{c}\left(Z_b n_b V_{bz} - n_e V_{ez} \right) + \frac{1}{c}\frac{\partial \vec{E}}{\partial t},$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}.$$

Steady- State Results (current flow)

Beam propagates in the y-direction, beam half length l_b=15 c/ω_p ; beam radius r_b =1.5 c/ω_p ; beam density n_b is equal to the background plasma density n_p; beam velocity $V_b=c/2$.

Shown are the normalized electron density n_e/n_p and the vector fields for the current.



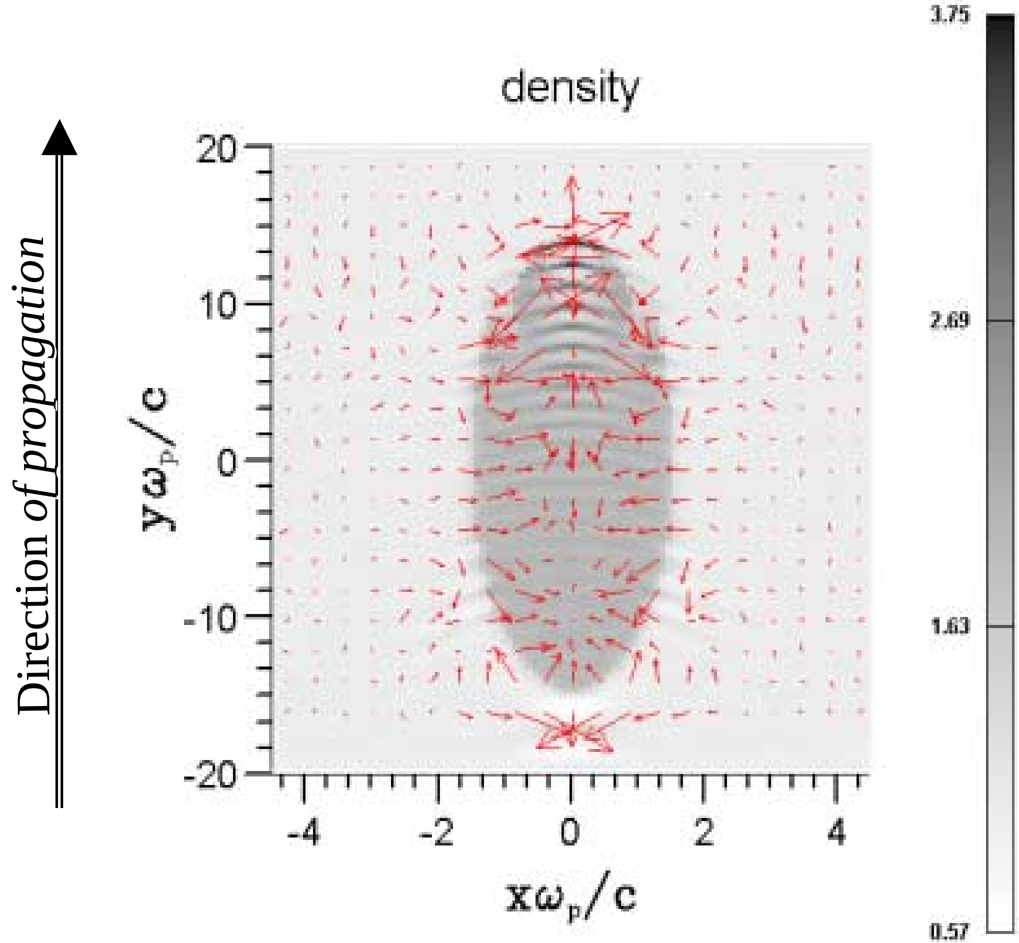
FOR MORE INFO...

http://hifnews.lbl.gov/hifweb08.html

Steady- State Results (electric field)

Beam propagates in the y-direction,
l_b**=15** c/ω_p **;**
r_b **=1.5**c/ω_p **;**
$n_b = n_p$**;**
V_b**=**$c/2$**.**

Shown are the normalized electron density n_e/n_p **and the vector fields for the electric force on electrons.**



FOR MORE INFO...

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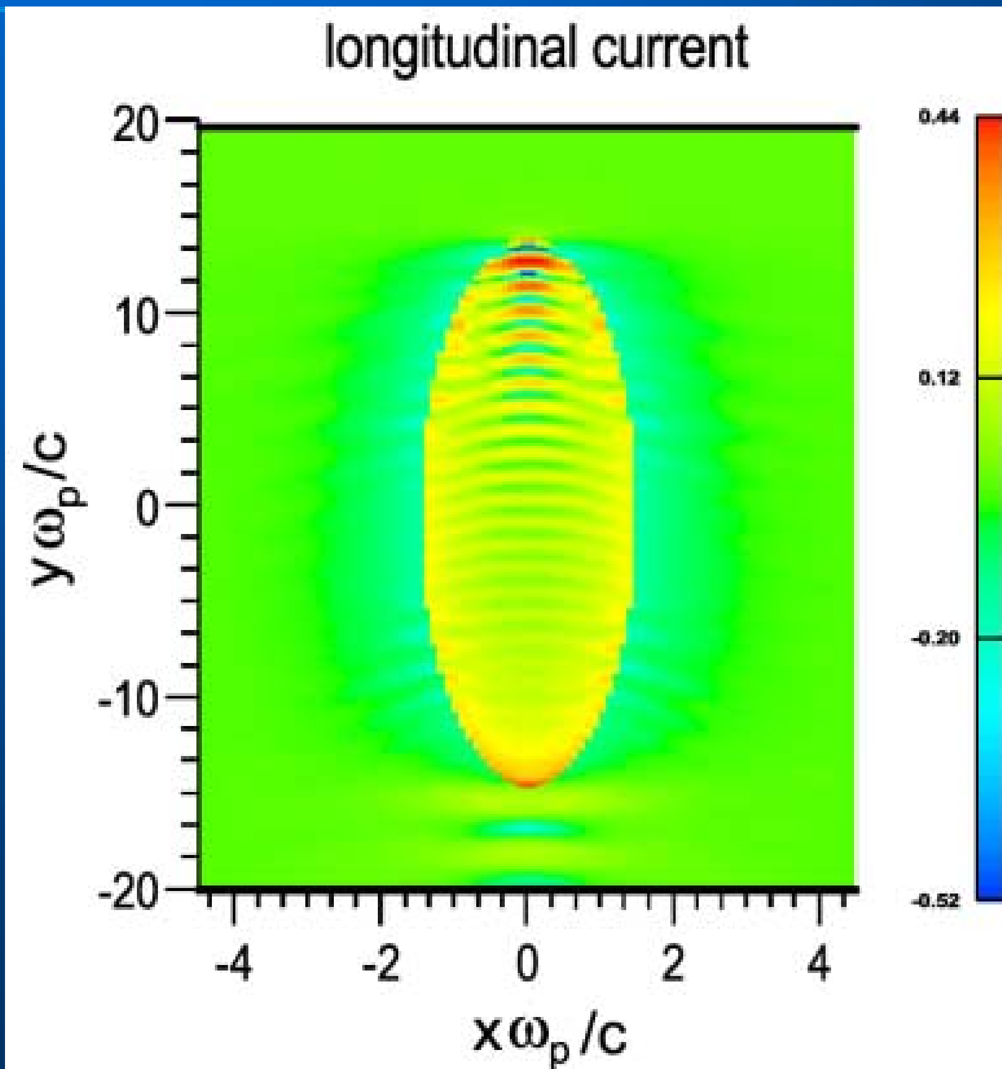
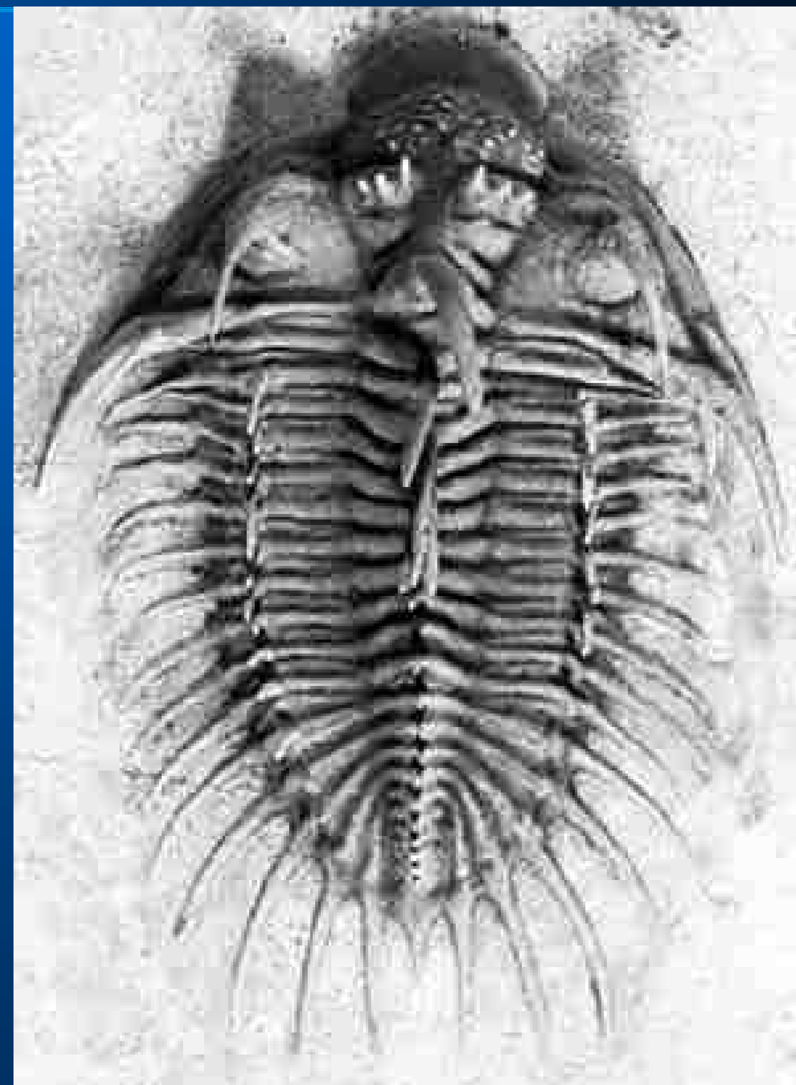
Steady- State Results

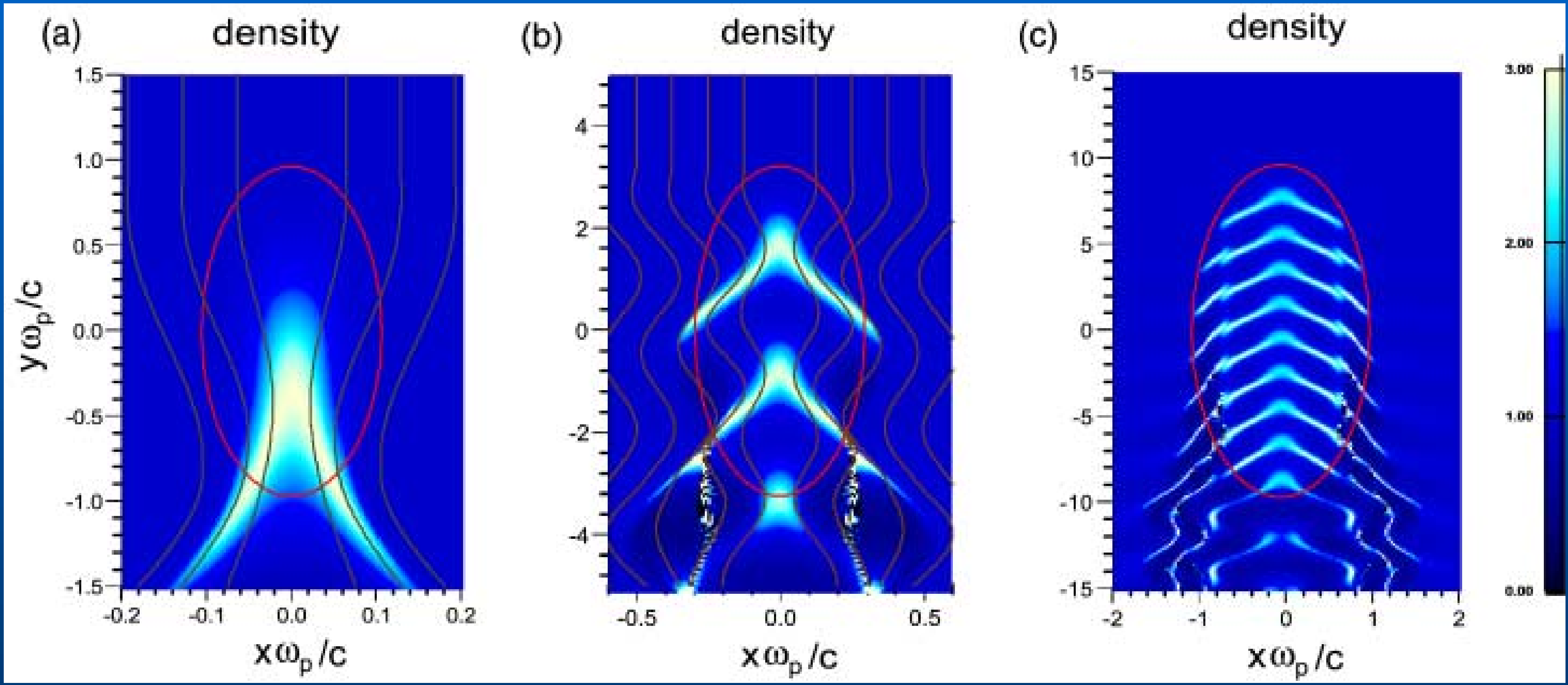




normalized electron current $j_y/(ecn_p)$

http://www.trilobites.com

Analytic theory of chamber transport: excitation of plasma waves by beam depends on bunch length



β_b=0.5, l_b/r_b =10, n_b/n_p=0.5 a) l_b= $2V_b/\omega_p$, b) l_b= $6V_b/\omega_p$, c) l_b= $20V_b/\omega_p$.

Red line: ion beam size, brown lines: electron trajectory in beam frame

Nonlinear Theory

If you would like to experience delicious taste, bite in small pieces.

- Important issues:
  - Finite length of the beam pulse,
  - Arbitrary value of n_b/n_p ($n_b >> n_p$),
  - *2D.*
- *Approximations:*
  - *Fluid approach,*
  - *Conservation of generalized vorticity,*
  - *Long dense beams* $l_b >> r_b$, V_b/ω_p.
- Exact analytical solution.

Conservation of Generalized Vorticity

$$\vec{\Omega}_e = \nabla \times \vec{p}_e - e\vec{B}/c,$$

$$\frac{\partial \vec{\Omega}_e}{\partial t} - \nabla \times (\vec{V}_e \times \vec{\Omega}_e) = 0,$$

$$\oiint \vec{\Omega}_e \cdot d\vec{S} = \oint (\vec{p}_e - \frac{e}{c}\vec{A}) \cdot \delta \vec{r} = const.,$$

$$\vec{\Omega}_e = 0 \Rightarrow \nabla \times \vec{p}_e = e\vec{B}/c.$$

FOR MORE INFO... I. Kaganovich, *et.al*, Physics of Plasmas 8, 4180 (2001).

Approximate System of Equations

$$l_b >> r_b,$$

$$(V_{ey} - V_b)\frac{\partial n_e}{\partial y} + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_e V_{er}\right) = 0,$$

$$\nabla \times \vec{\mathbf{p}}_e = \frac{e}{c}\vec{\mathbf{B}},$$

$$\frac{1}{r}\frac{\partial}{\partial r}E_r = 4\pi e(Z_b n_b + n_p - n_e),$$

$$K_e = m_e \vec{V}_e^{\,2} / 2,$$

$$(V_{ey} - V_b)\frac{\partial p_{er}}{\partial y} + \frac{\partial K_e}{\partial r} = -eE_r,$$

$$-\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} p_{ey} = \frac{4\pi e}{c}\left(Z_b n_b V_{by} - n_e V_{ey}\right).$$

Simplified Code

- Approximation of long beams:
  - Beam length is much longer than beam radius;
  - Therefore, beam can be described by a number of weakly interacting slices.
  - The electric field is found from radial Poisson's equation.
  - As a result of the simplification the second code is hundreds times faster than the first one and can be used for most cases, while the first code provides benchmarking for the second.

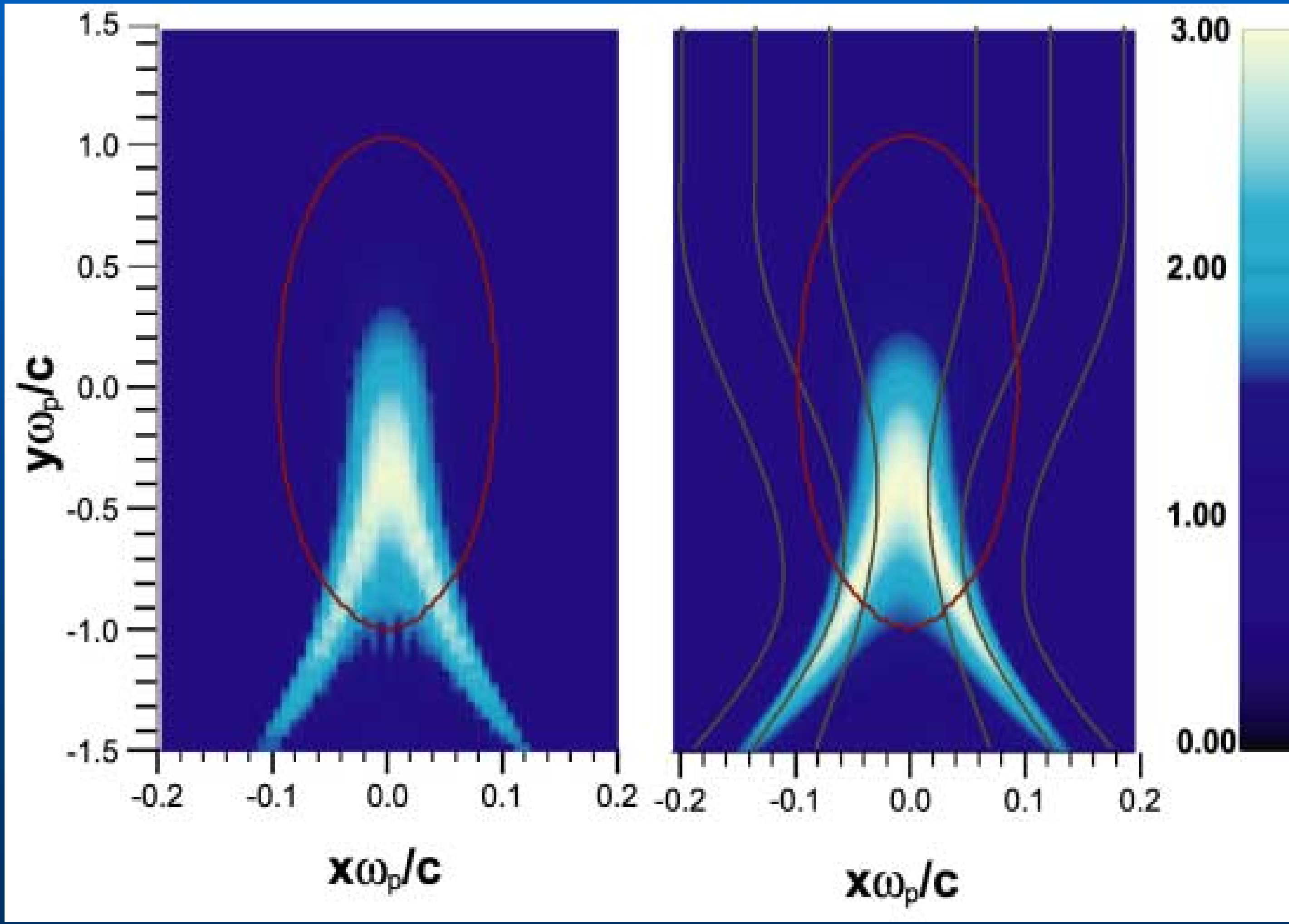
Comparison of Theory and Simulation: Electron Density

Electron density
Left – PIC,
Right - fluid

$l_b = 1c/\omega_p$, $r_b = 0.1c/\omega_p$
$n_b = 0.5n_p$, $V_b = 0.5c$

Brown lines: electron trajectory in the beam frame.

Red line: ion beam size.



FOR MORE INFO...

I. Kaganovich *et.al*, http://pacwebserver.fnal.gov/papers/Tuesday/PM_Poster/TPPH317.pdf

Comparison of Theory and Simulation: Electron Density

Key parameter $\omega_p\, l_b/V_b$,

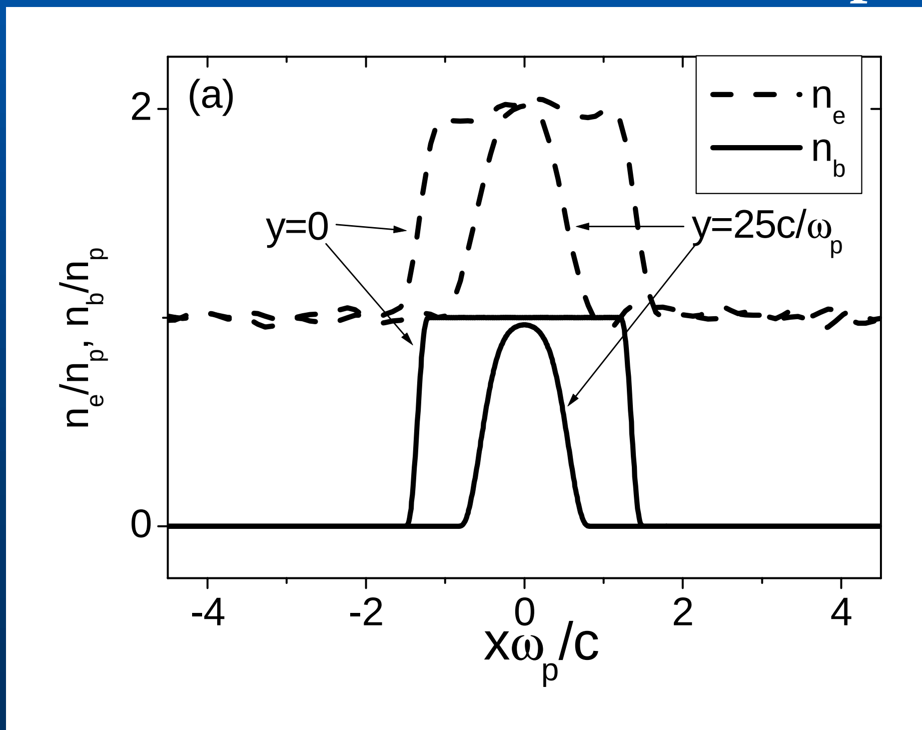
Quasineutrality $l_b >> V_b/\omega_p$.

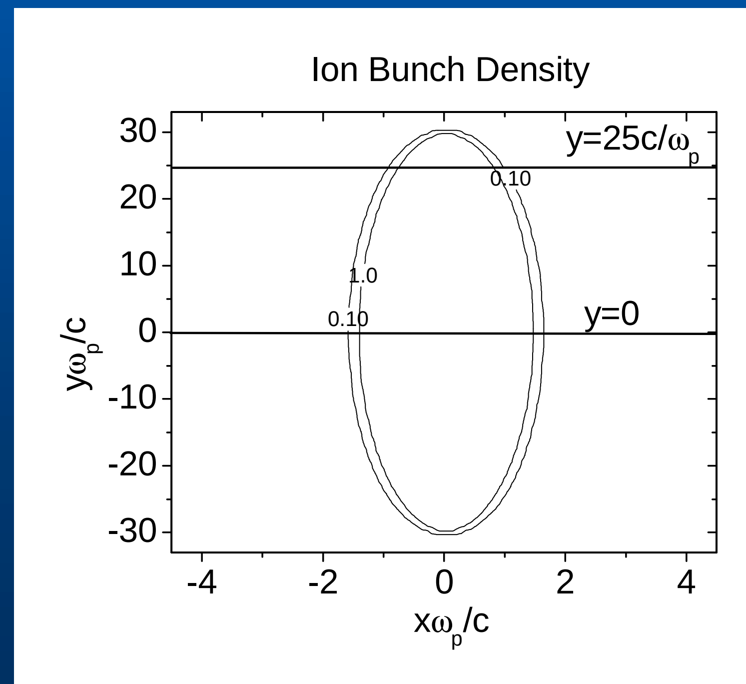
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega_p$

$n_p = n_b$

$V_b = 0.5c$





Comparison of Theory and Simulation: Current Neutralization

Key parameter $\omega_p r_b/c$,

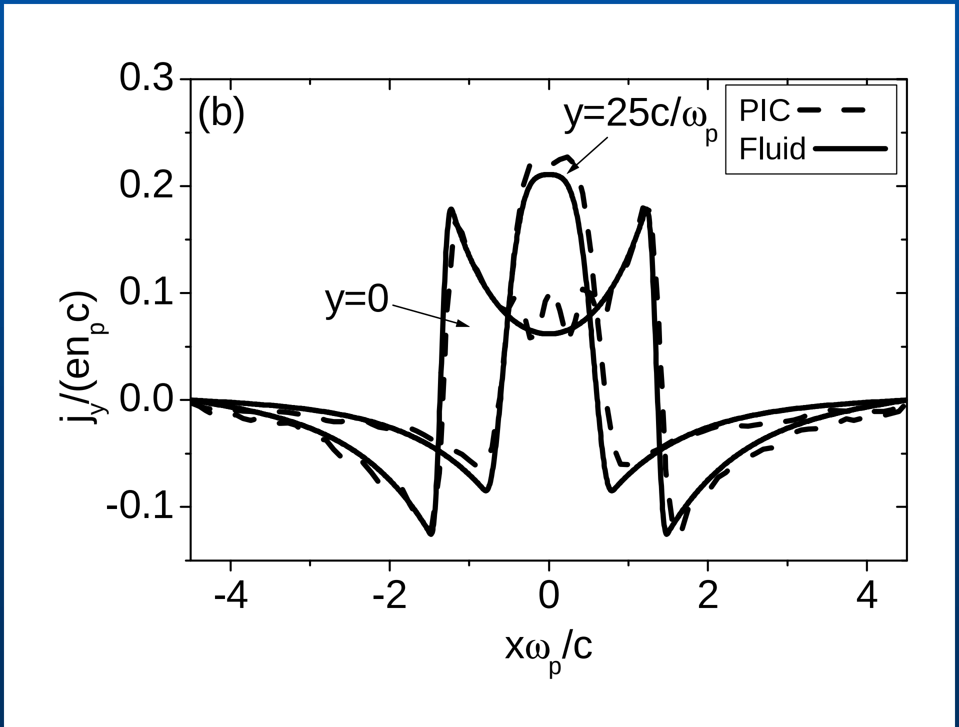
Current neutralization $r_b >> c/\omega_p$.

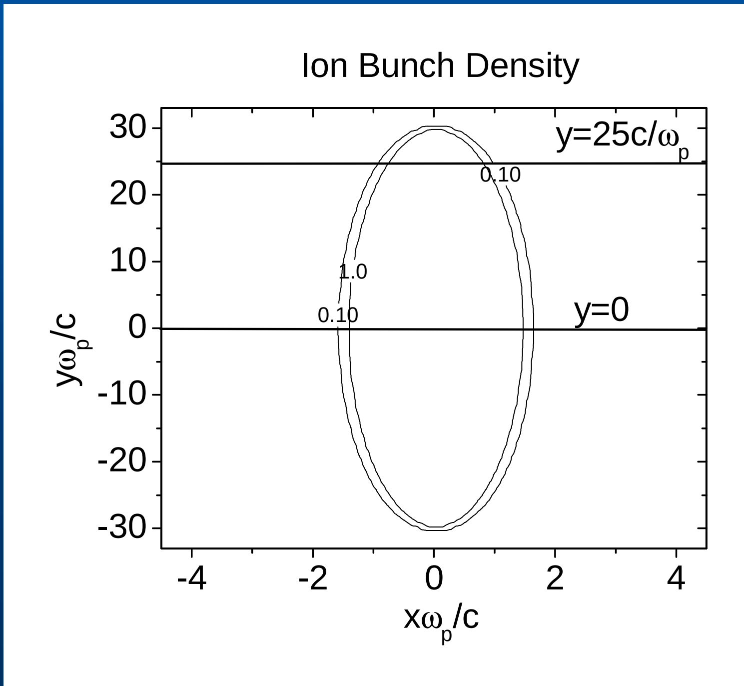
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega_p$

$n_p = n_b$

$V_b = 0.5c$





Comparison of Theory and Simulation: Magnetic Field

Key parameter $\omega_p r_b/c$,

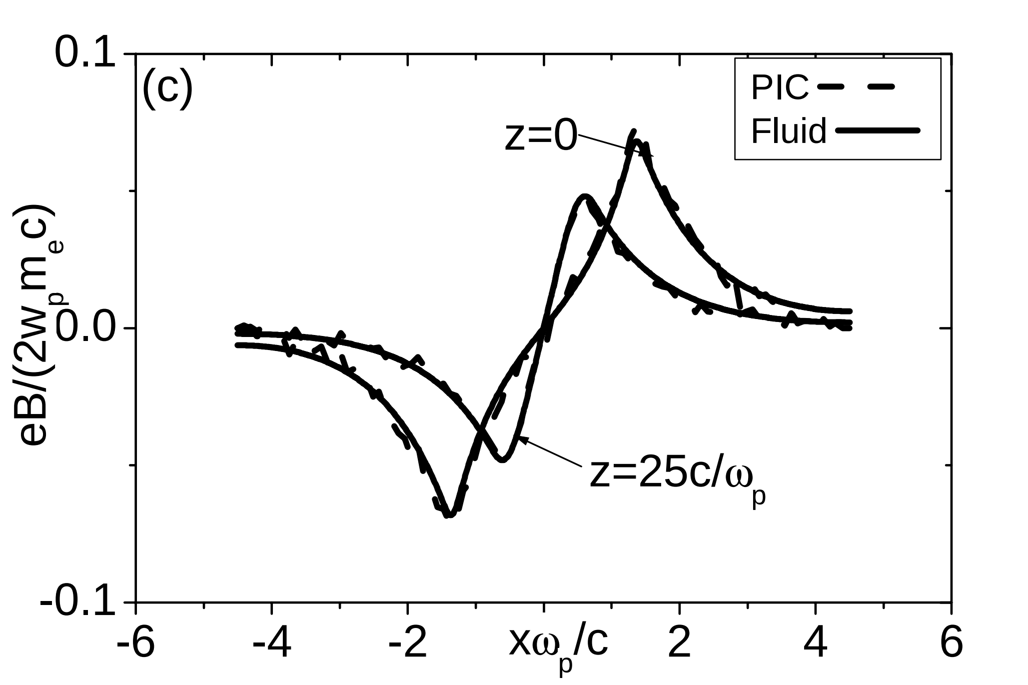
Magnetic field neutralization $r_b >> c/\omega_p$.

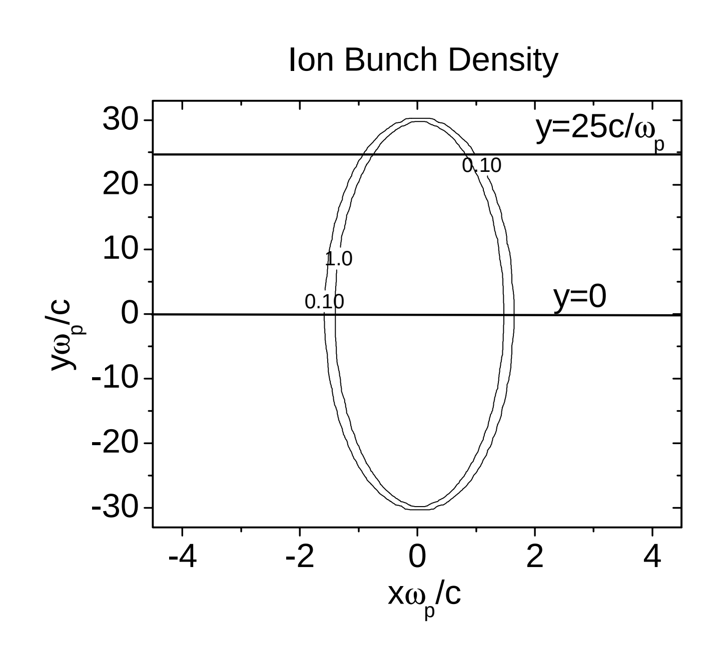
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega_p$

$n_p = n_b$

$V_b = 0.5c$





FOR MORE INFO... I. Kaganovich, *et.al*, Physics of Plasmas 8, 4180 (2001).

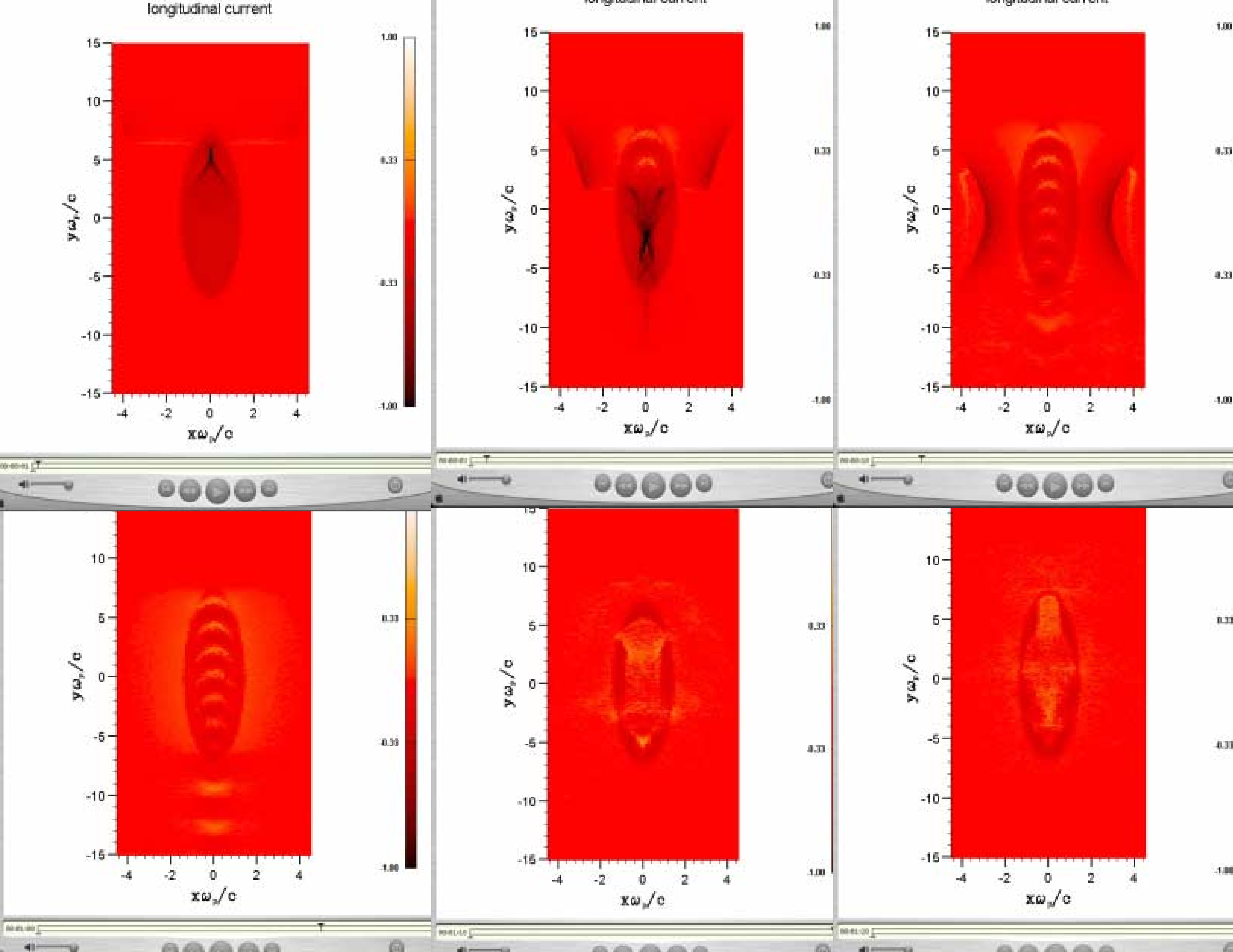
Results and Conclusions

- Developed a nonlinear fluid theory for the quasi-steady-state propagation of an intense ion beam pulse in a background plasma under the assumption of a long beams $l_b >> r_b$.
  - The analytical formulas can provide an important benchmark for numerical codes.
  - The analytical solutions form the basis of a hybrid semi-analytical approach, used for calculations of beam propagation in the target chamber.
- The simulations of current and charge neutralization performed for conditions relevant to heavy ion fusion showed:
  - very good charge neutralization: key parameter $\omega_p l_b/V_b$,
  - very good current neutralization: key parameter $\omega_p r_b/c$.
- Plasma wave breaking heats electrons $n_b > n_p$.

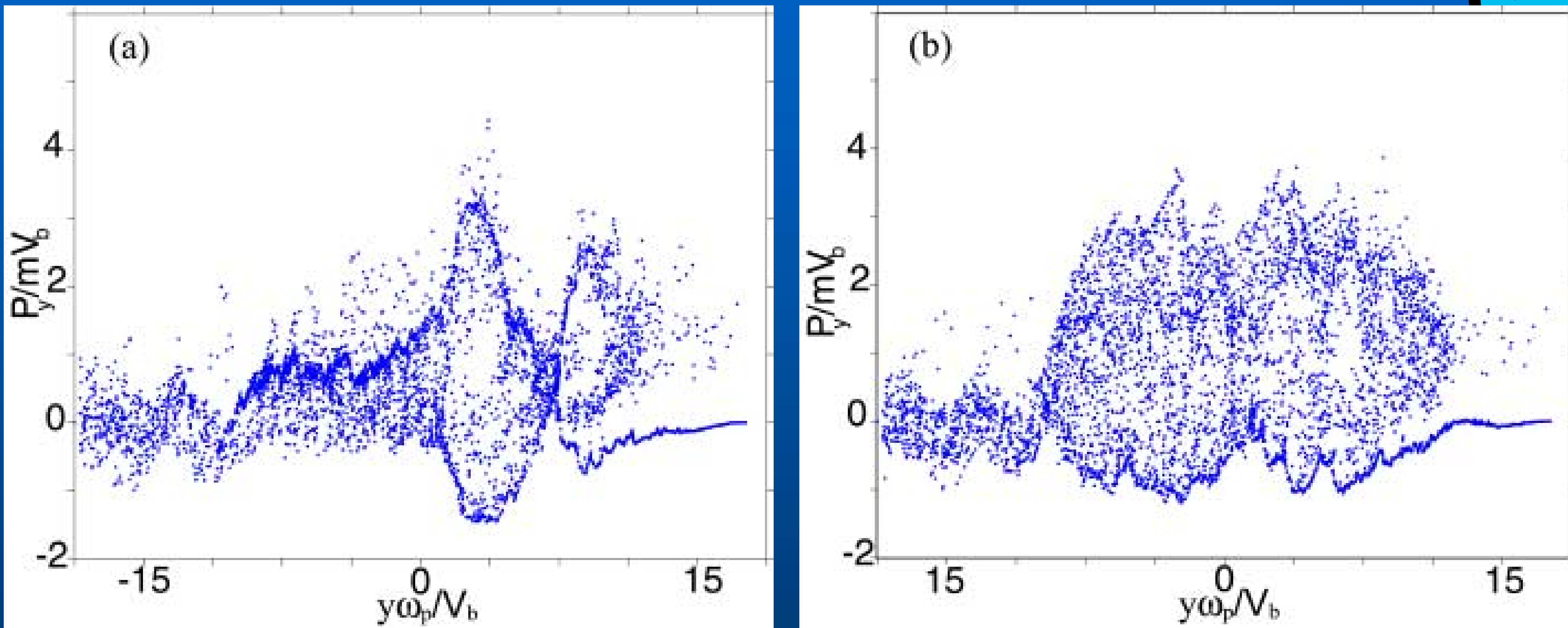
Results of 2D PIC-MC Code

- Beam propagation in the y-direction,
- beam half length 7.5 c/ω_p;
- beam radius 1.5 c/ω_p;
- beam density equal to the half of the plasma; density;
- beam velocity $c/2$.

- Shown is the electron current.

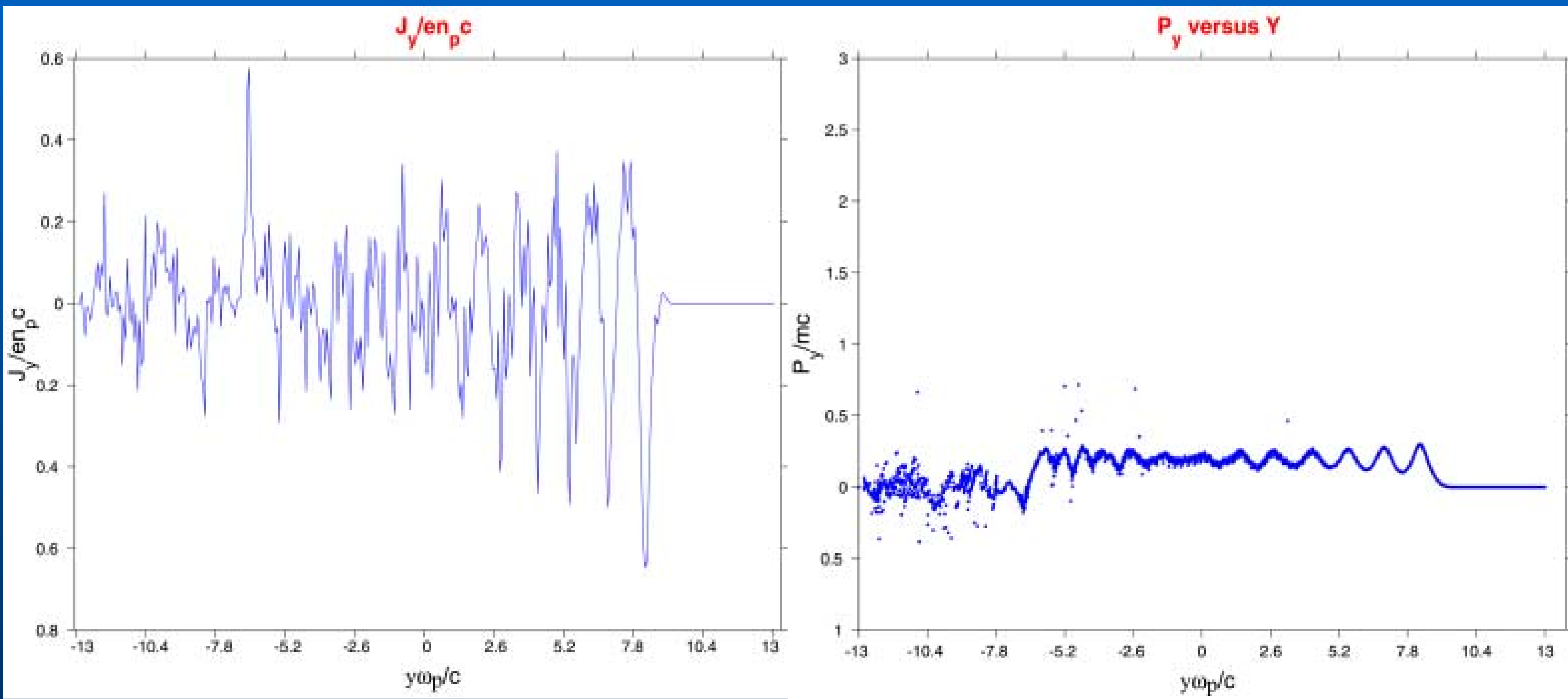

longitudinal current
yω_p/c
xω_p/c
1.00
0.33
-0.33
-1.00

Plasma Wave Breaking Heats the Electrons when $n_b > n_p$



Electron phase space shown for l_b=30V_b/ω_p; $n_b = 2n_p$.
Times after entering the plasma plug are: (a) 113 $/\omega_p$, and (b) $245/\omega_p$.

Fluid approximation is good for $n_b \le n_p$

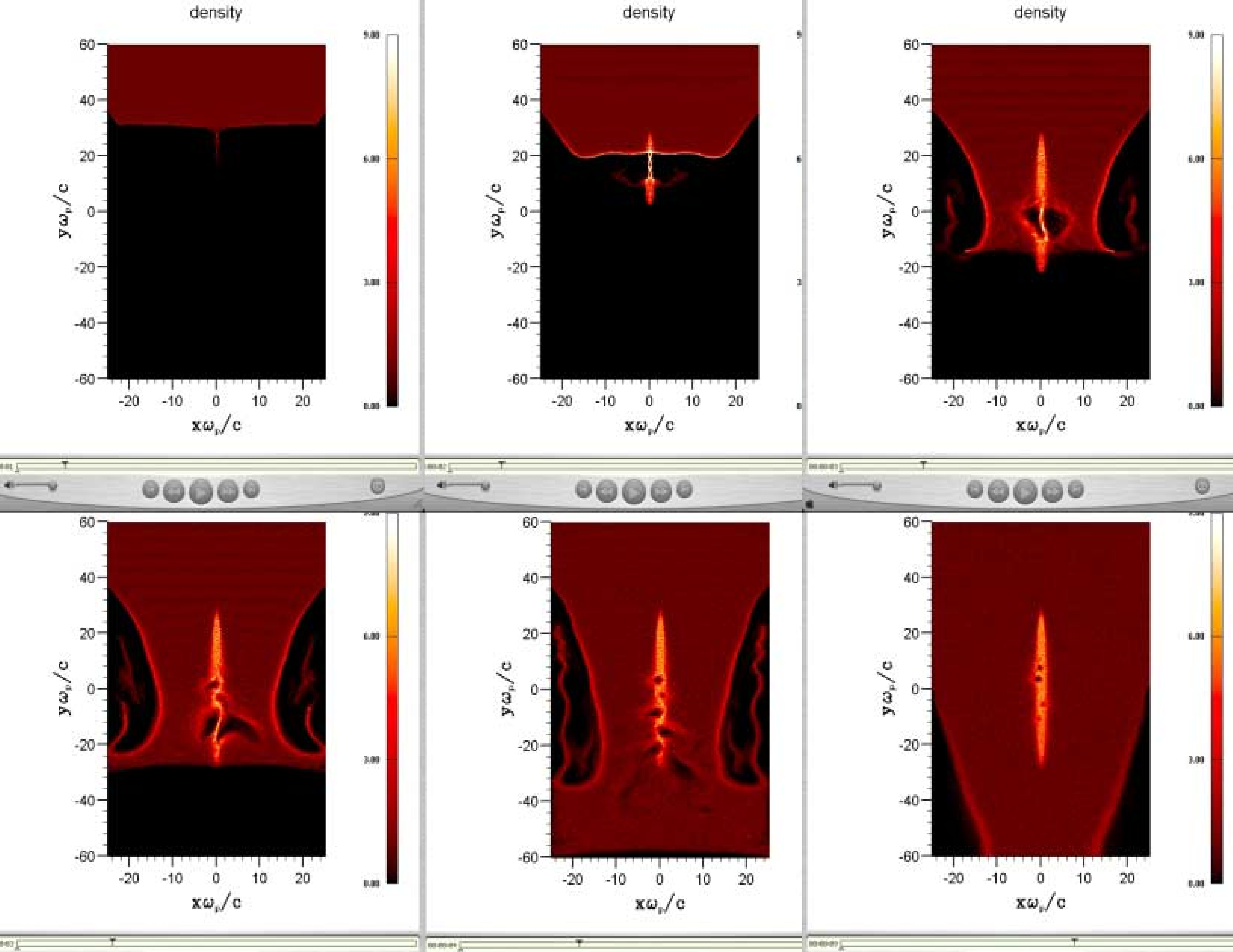


Electron current and phase space l_b=15c/ω_p; $n_b = n_p$; $V_b = c/2$.

Results of 2D PIC-MC Code

- Beam propagation in the y-direction,
- beam half length 30 c/ω_p;
- beam radius 0.5 c/ω_p;
- beam density is equal to 5 of the plasma density;
- beam velocity $c/2$.

- Shown is the electron density.


density
density
density
$y\omega_p/c$
$x\omega_p/c$
60
40
20
0
-20
-40
-60
-20
-10
0
10
20