Final Beam Transport Issues

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1 Final HIB Transport
- Key issues

/ deliver HIBs to Target

2 My question
- Practically possible to control HIB focus point in each shot?

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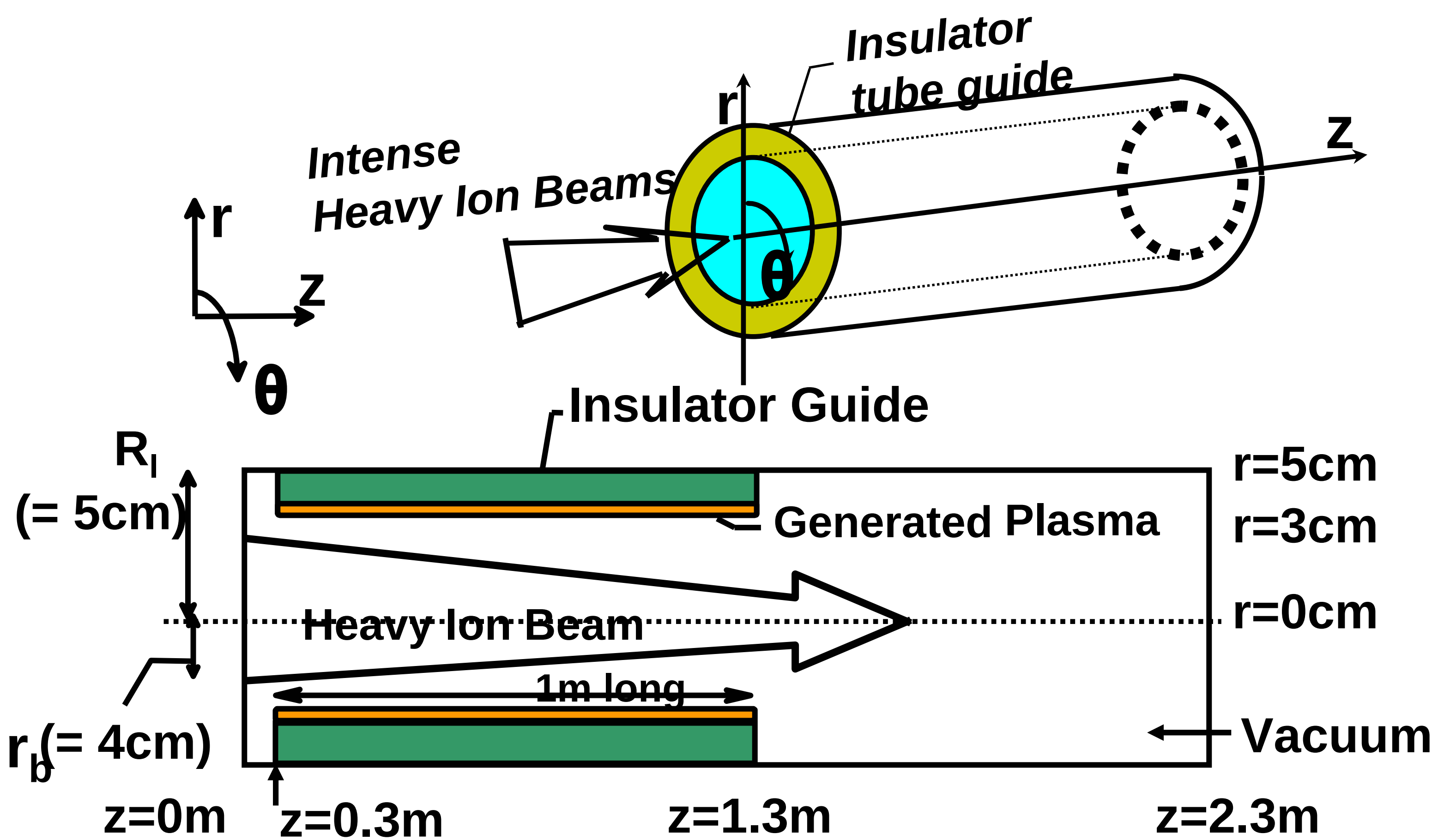
At US-Japan workshop 2004

HIB transport through a tube liner

Ceramics guide: S.Kawata, T.Kikuchi, T.Someya, et al.

Beam-pipe electron trapping: W.B. Herrmannsfeldt

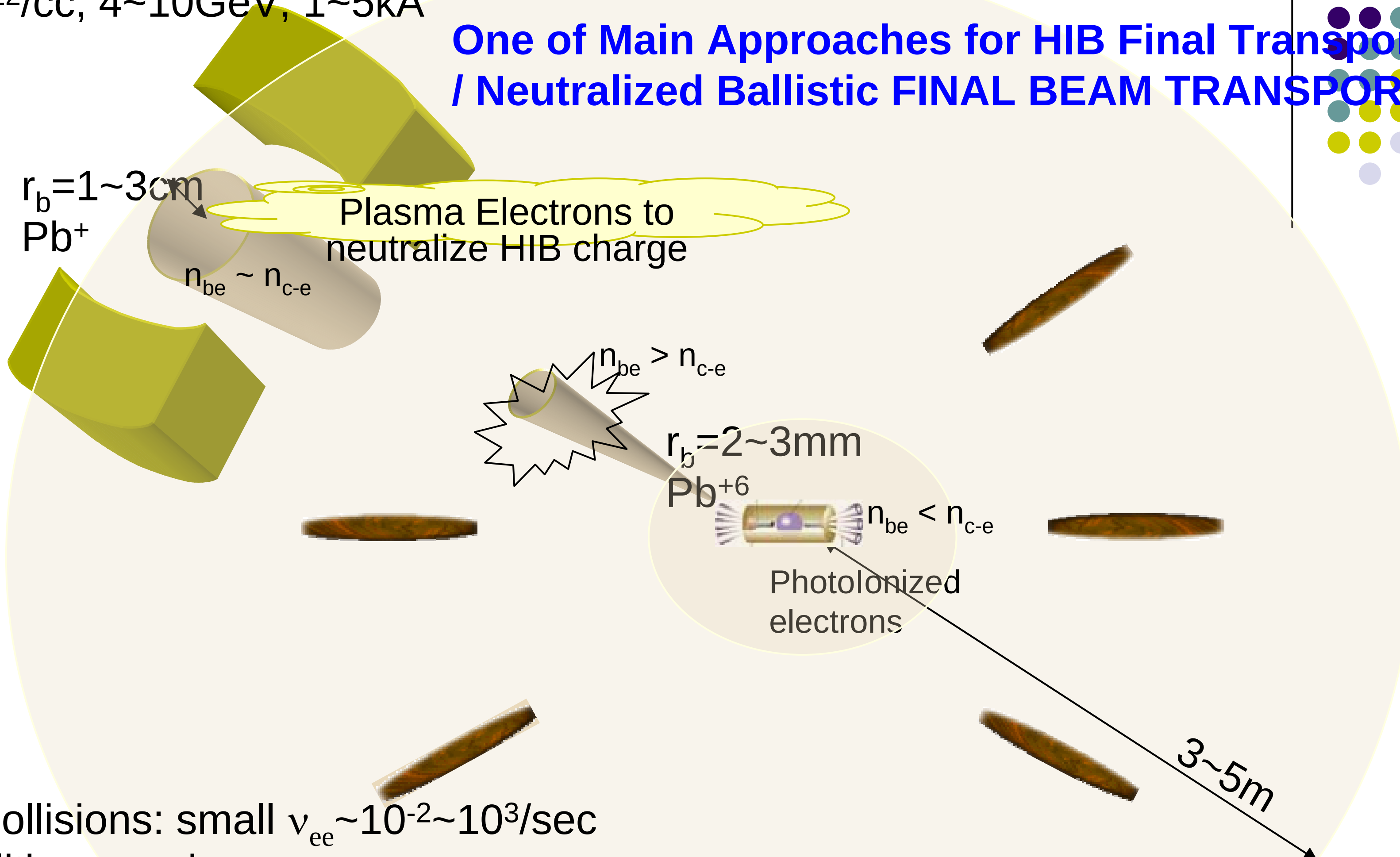
Neutralization of beam space charge



Bunched beam ~ a few 10 nsec

n_{b0}~10^{12}/cc, 4~10GeV, 1~5kA

One of Main Approaches for HIB Final Transport:
/ Neutralized Ballistic FINAL BEAM TRANSPORT



/e-e Collisions: small ν_{ee}~10^{-2}~10^3/sec

/Stabilities: e-e, b-e

/Neutralized beam dynamics at the middle & very end

-> r_b=1~3cm => r_b=2-3mm

-> n_{b0}~10^{12}/cc => n_b~10^{14}/cc >> n_{ce}~10^{11}~10^{12}/cc

-> may induce ambipolar field beam expansion

$n_{c\_neutral}$~10^{14}/cc

n_{ce}~10^{11}~10^{12}/cc

$\tau_{transport}$~30~80nsec

Neutralized Ballistic FINAL BEAM TRANSPORT

/Neutralized beam dynamics at the very end

-> r_b=1~3cm => r_b=2-3mm

It makes Te high: Te~10~100keV <- Te~Te0x$(r_{b0}/r_b)^{4/3}$~22xTe0

-> n_{b0}~10^{12}/cc => n_b~10^{14}/cc >> $n_{chamber-e}$~10^{11}~10^{12}/cc

-> λ_{Le} >> r_b, $\lambda_{Debye-e}$~0.1mm~0.3mm~ 10% of beam radius

-> may induce **ambipolar field** beam expansion

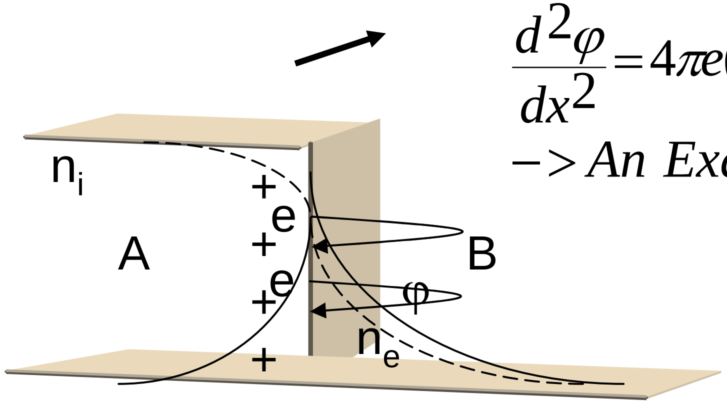
$$\frac{d^2\varphi}{dx^2} = 4\pi e(n_e - n_i) \approx 4\pi n_0 e(e^{\frac{e\varphi}{T}} - 1) \quad \textit{for Region A}$$

Here we can assume $n_e \sim n_i$ *in A*

$$\frac{d^2\varphi}{dx^2} = 4\pi e(n_e) \approx 4\pi n_0 e(e^{\frac{e\varphi}{T}}) \quad \textit{for Region B}$$

$(r > r_b)$

$->$ *An Exact solution for this nonlinear Eq.:*



$$e\varphi = T[1-2\ ln\{1+\sqrt{\frac{\exp}{2}}k_{De}r\}]$$

$$-> qE = Z_b T k_{De}\left[\frac{2\sqrt{\exp/2}}{1+\sqrt{\exp/2}(k_{De}r)}\right] \quad \text{for } r > r_b$$

At the beam surface

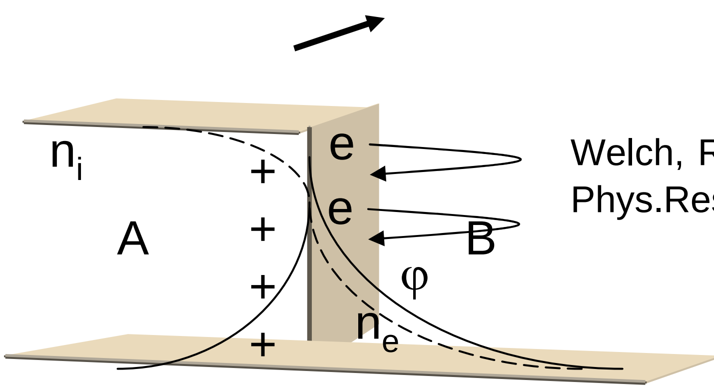
$Z_b eE$[eV/cm]~1.35×10^{-3}Zb$(n_e T_e)^{1/2}$[eV]~(2MeV/cm~10MeV/cm)

At the middle stage

$\theta = V_\perp / V_{//} \sim \sqrt{\varepsilon_\perp / \varepsilon_{//}} \sim$ [(3~100**keV**)/(4–10**GeV**)]$^{1/2}$~(0.001~0.005)

for 100cm transport δr ~ 1~5mm Increase in r_{bf}

-> may be serious.



Welch, Rose, et al., NIM in Phys.Res.A 464(2001)134

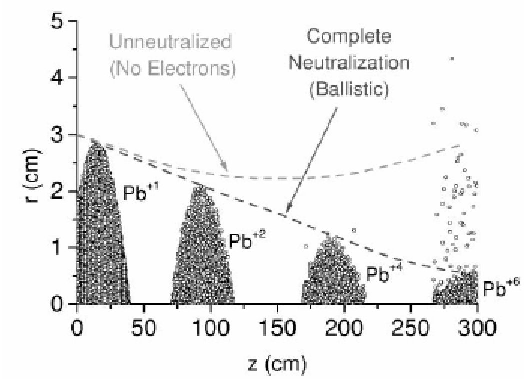


Fig. 3. Beam ions at four different times are plotted for case 2. At each time, the dominant beam charge state is shown. Curves for the peak beam radius as a function of distance are shown for a ballistic simulation and one without electron sources.

$$e\varphi = T[1-2\,ln\{1+\sqrt{\frac{\exp}{2}}k_{De}r\}]$$

$$-> qE = Z_b T k_{De}\left[\frac{2\sqrt{\exp/2}}{1+\sqrt{\exp/2}(k_{De}r)}\right] \quad \text{for } r > r_b$$

After integration of qE between r_b and $r_b+\lambda_{De}$

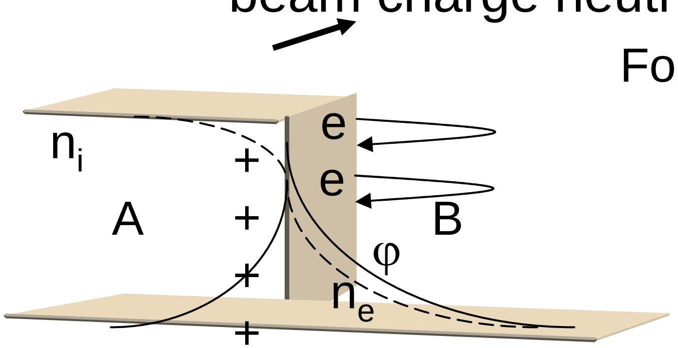
->

$$\varepsilon_\perp \propto Z_b \sqrt{\frac{1}{N_{be}}\frac{T_e^{1.5}}{r_b}} \quad \text{for } \lambda_{Debye\text{-}e} < r$$

-> $\varepsilon_\perp / \varepsilon_{//}$ ~ (3~100keV)/(4-10GeV)

If $n_{be} << n_{chamber\text{-}e}$, NO problem for the ambipolar expansion.

Mainly chamber background electrons contribute beam charge neutralization.

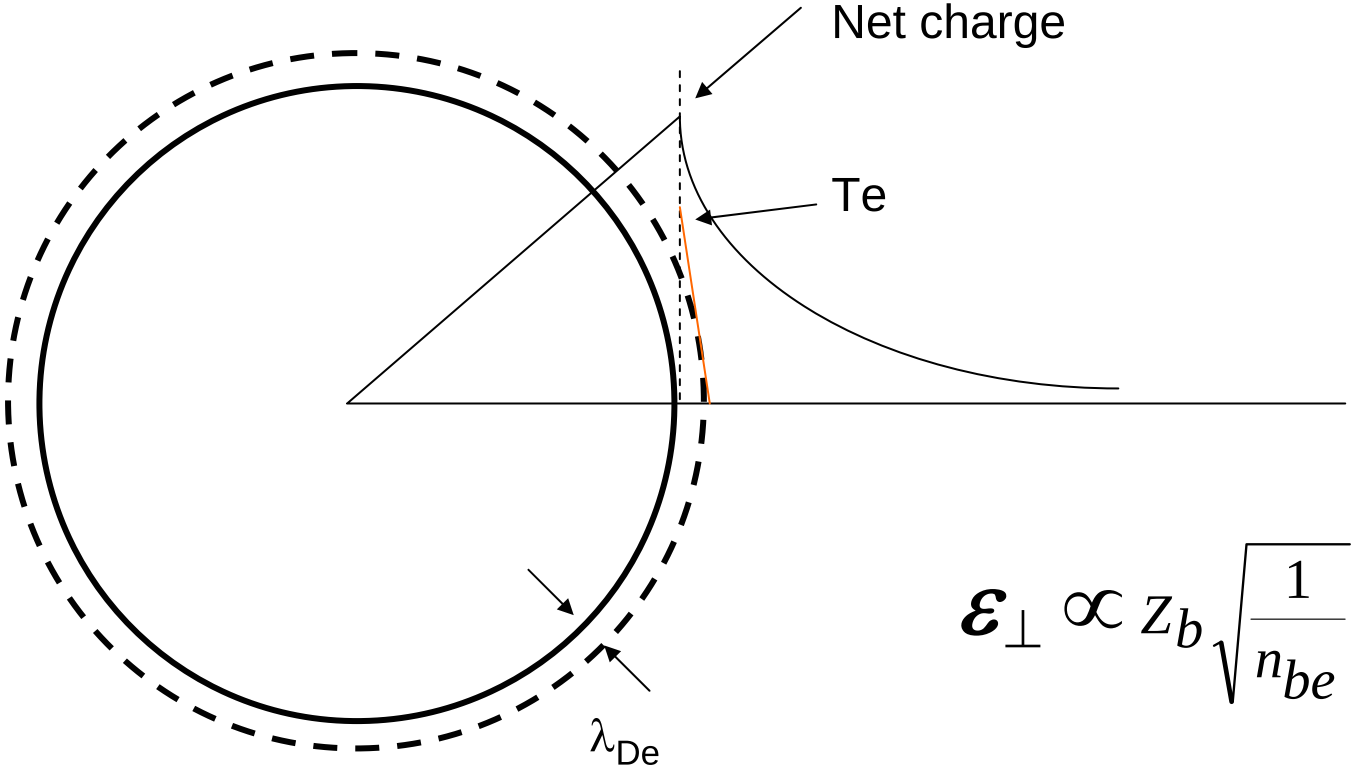


For example: T_e=10eV, n_e=10^{14}/cc, Z_b=5

λ_{De} ~1.4x10^{-4}cm

$\varepsilon_\perp$ ~0.05eV Well neutralized!

Difference between Coulomb divergence & Ambipolar divergence



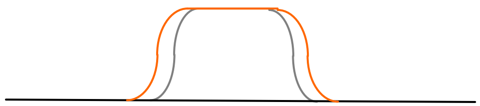
$$\varepsilon_\perp \propto z_b \sqrt{\frac{1}{n_{be}}} \frac{T_e^{1.5}}{r_b}$$

If we have low-*T*e electrons together with high-*T*e neutralizing electrons, low-*T*e electrons dominates the charge neutralization.

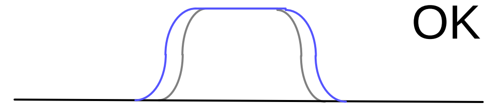
$$\varepsilon_{\perp} \propto z_b \sqrt{\frac{1}{n_{be}} \frac{T_e^{1.5}}{r_b}}$$

$$T_{effective} = \frac{1}{\frac{1}{T_{low}} + \frac{1}{T_{high}}} \approx T_{low}$$ for $N_{\mathbf{e\_hot}} \sim N_{\mathbf{e\_low}}$

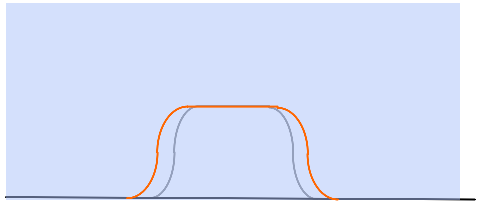
Therefore if HIB is surrounded by low-temperature electrons,
NO PROBLEM!



Dangerous

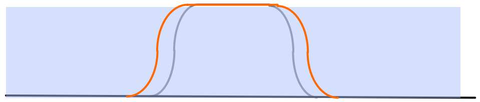


OK

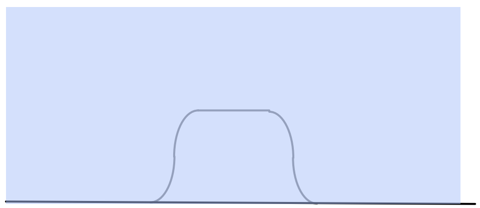


OK

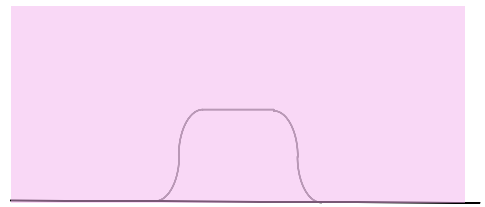
$$\varepsilon_\perp \propto Z_b \sqrt{\frac{1}{n_{be}}}\,\frac{T_e^{1.5}}{r_b}$$



OK

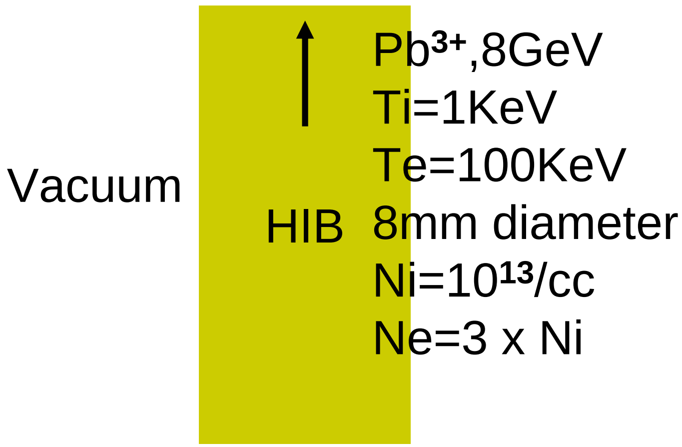


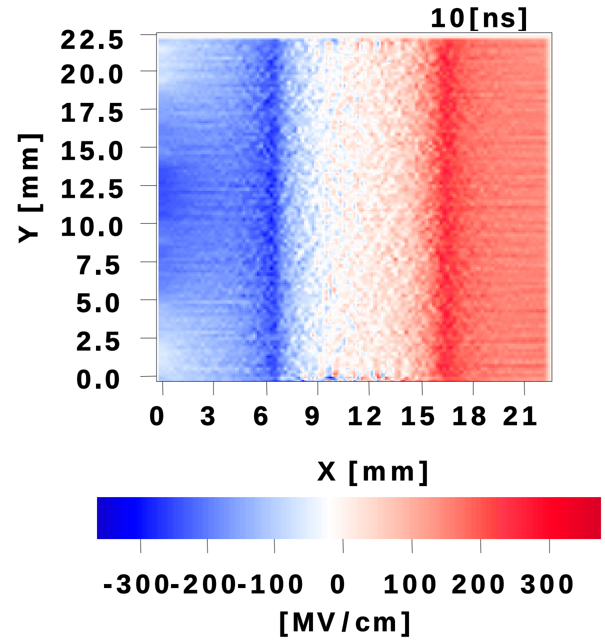
OK

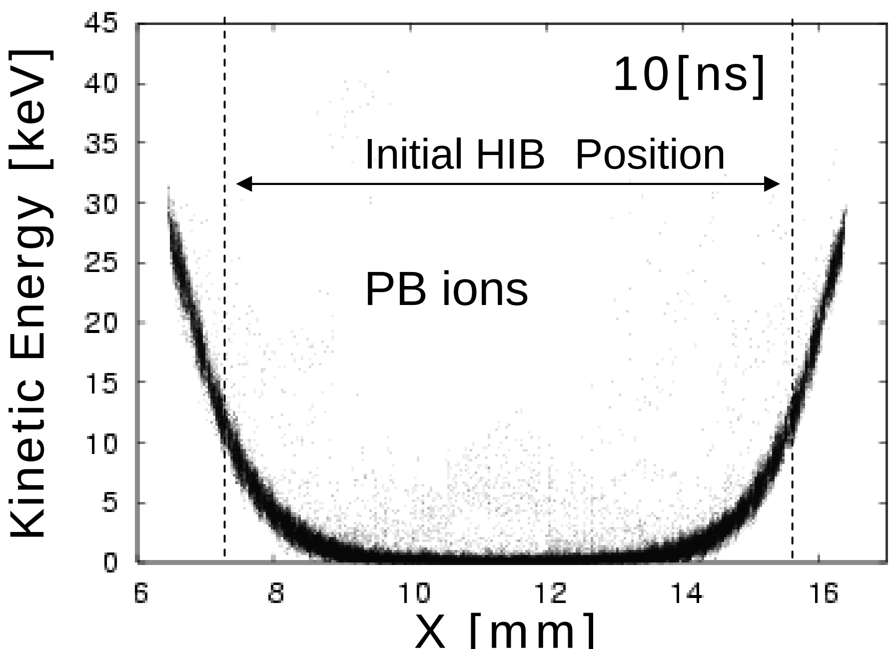


OK

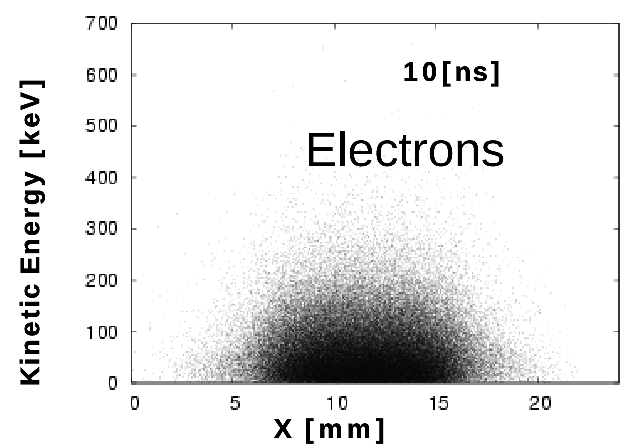
PIC Simulation

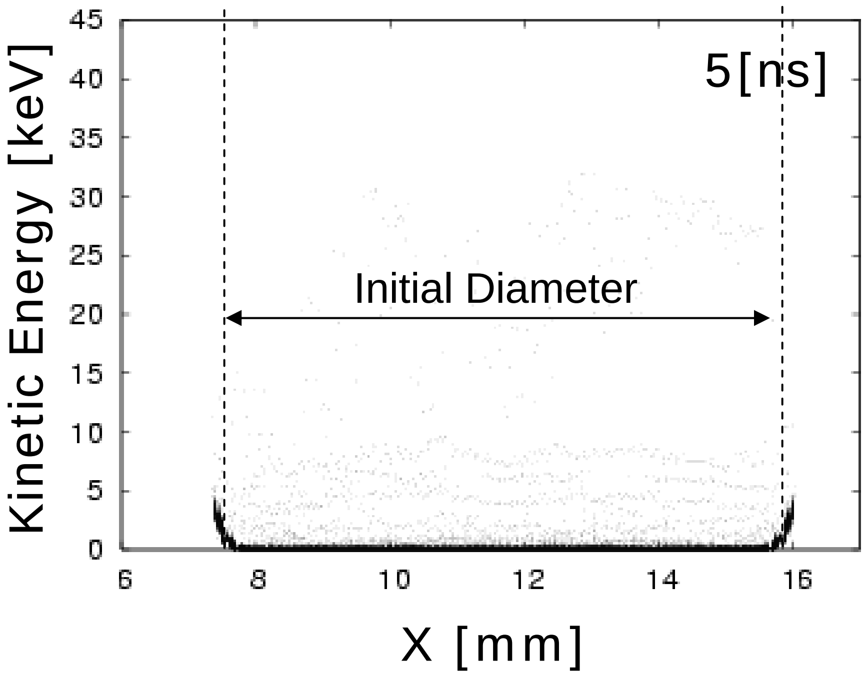


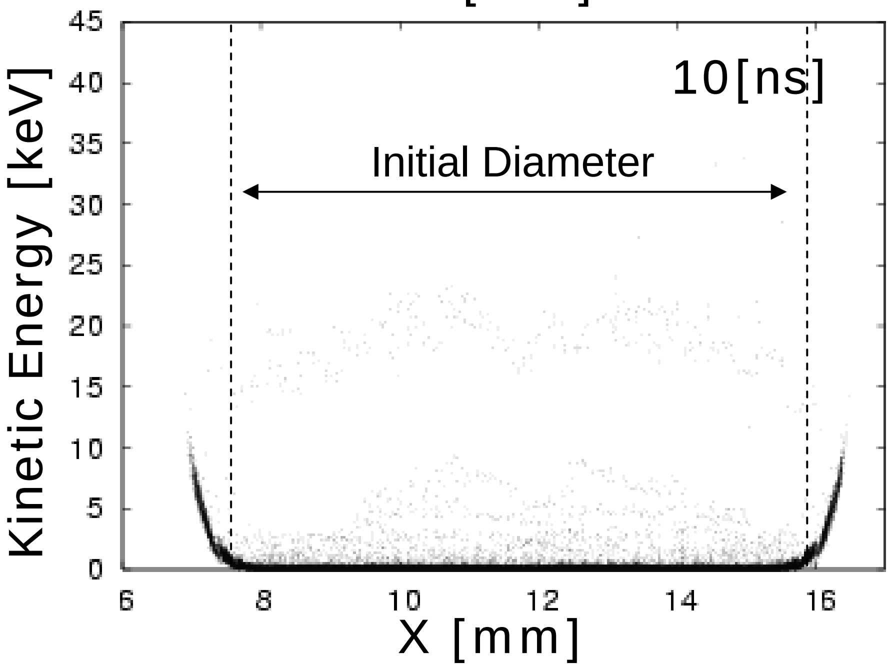




Strong E-field
generated by high-T electrons
pulls Pb ions out!

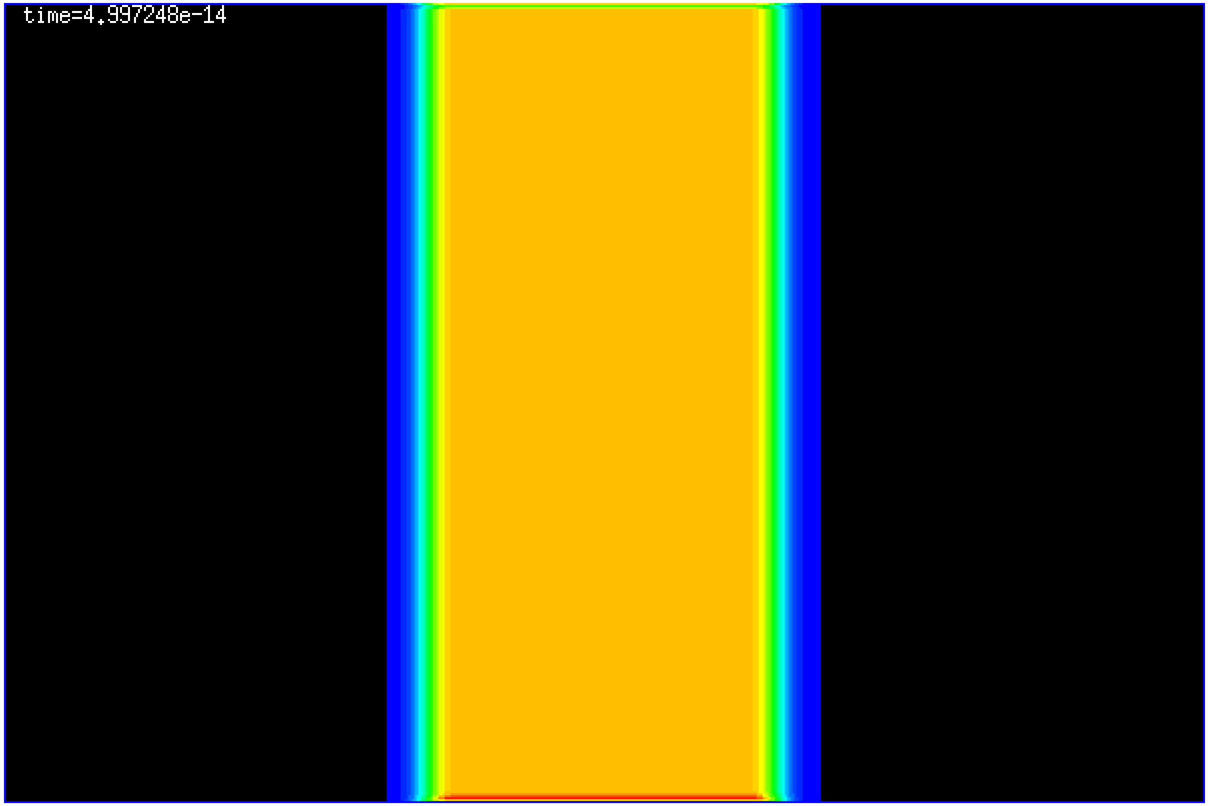



5[ns]
Initial Diameter
Kinetic Energy [keV]
X [mm]

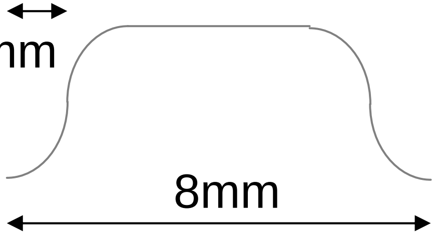

10[ns]
Initial Diameter
Kinetic Energy [keV]
X [mm]

for Te=10KeV

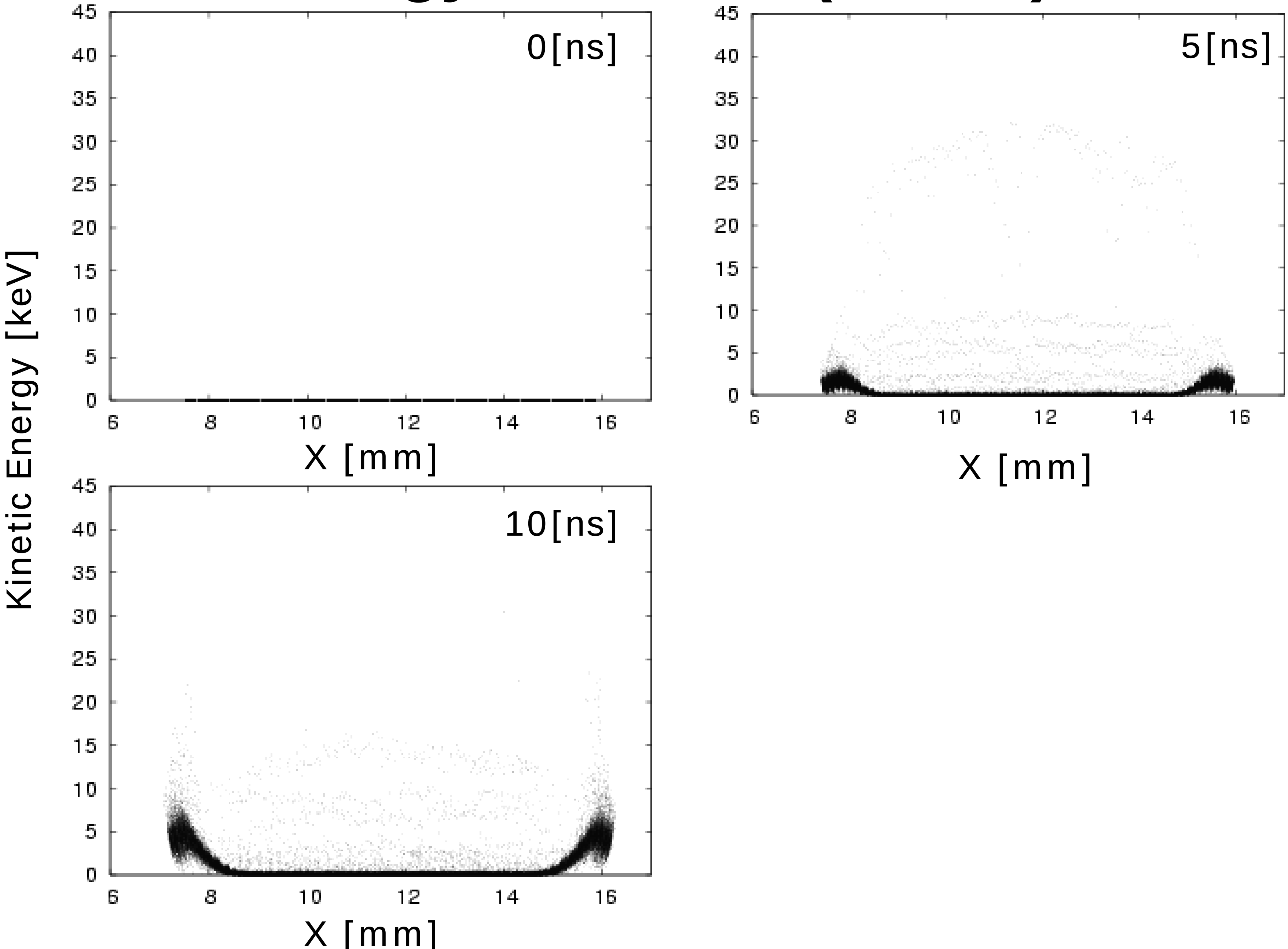
Initial Density Distribution (10keV)



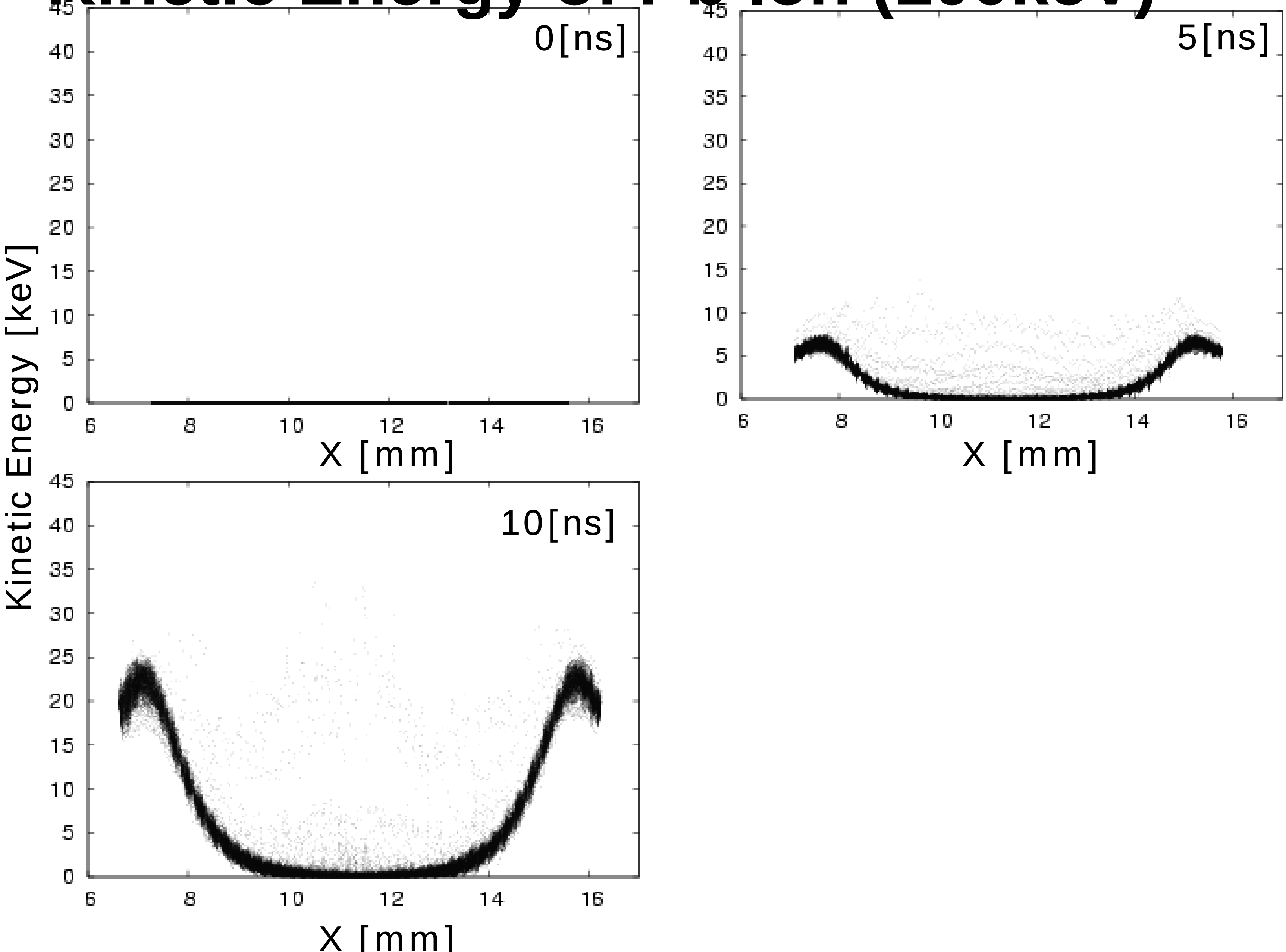
Pb^{3+},8GeV
Ti=1KeV
Te=100KeV
8mm diameter
Ni=10^{13}/cc
Ne=3 x Ni



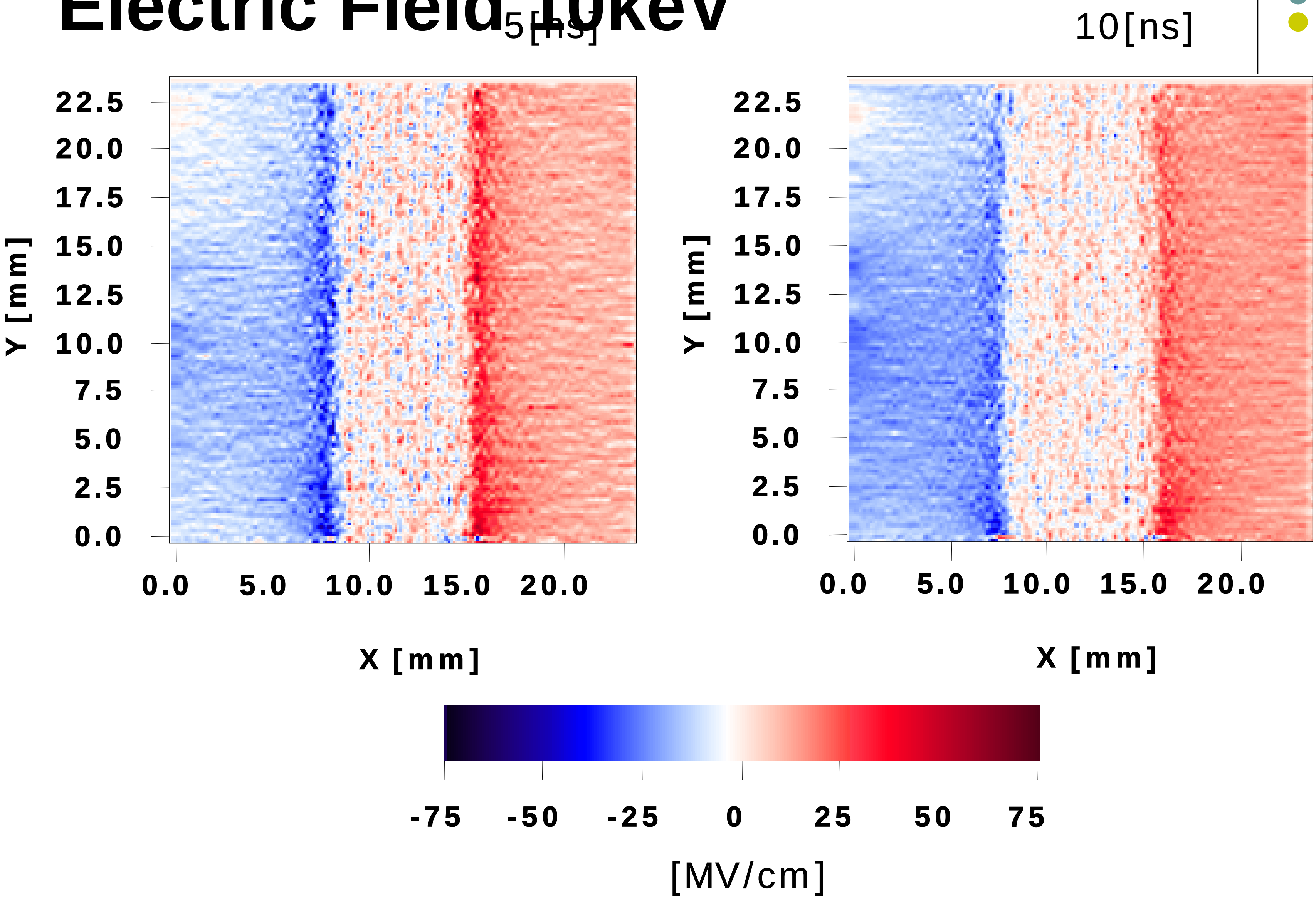
Kinetic Energy of Pb Ion (10keV)



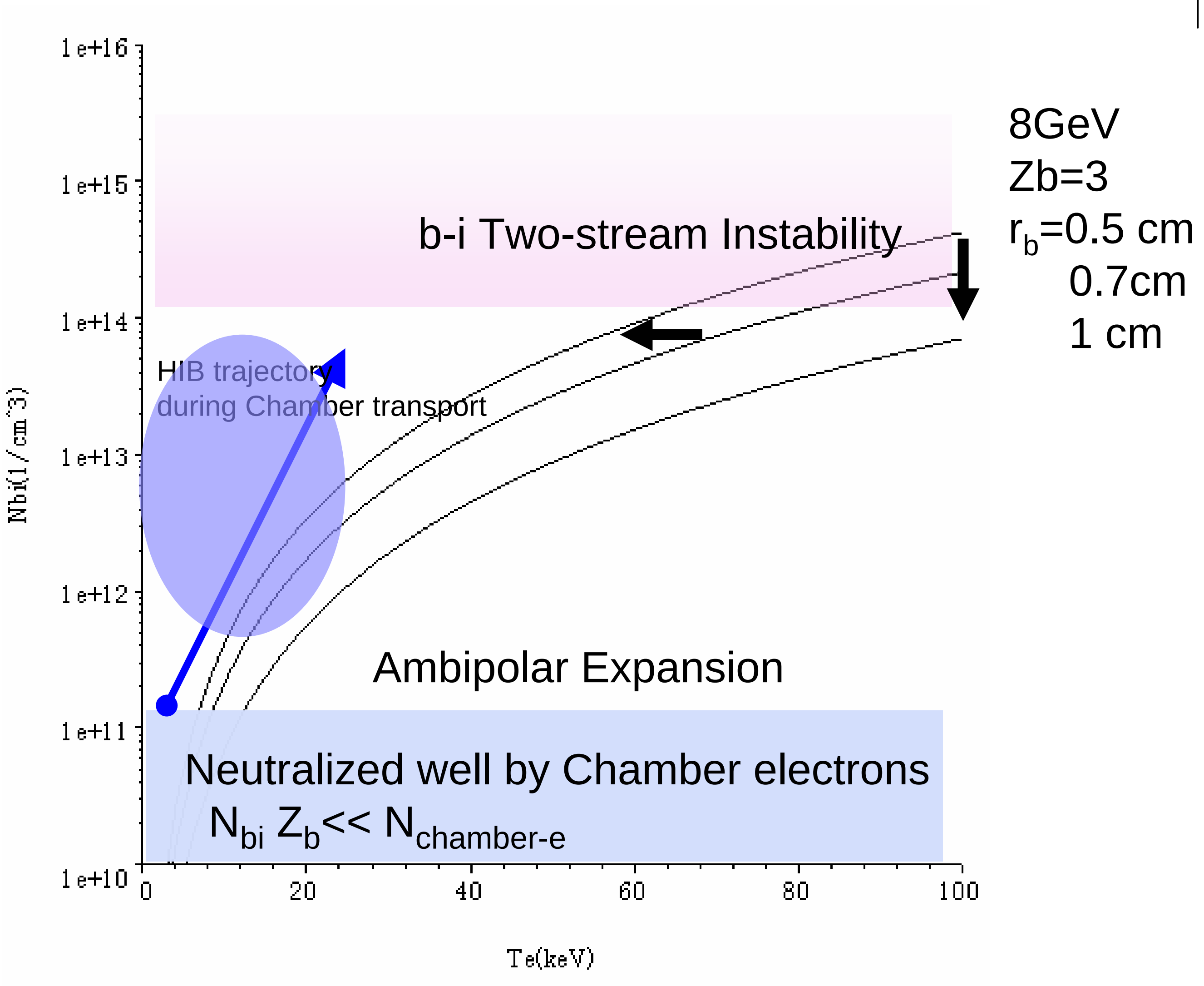
Kinetic Energy of Pb Ion (100keV)



Electric Field 10keV



Transport Window in Neutralized Ballistic Transport (NBT) against Ambipolar-Field Expansion & Beam-Chamber Electron Two-stream Instability



Possible solutions:

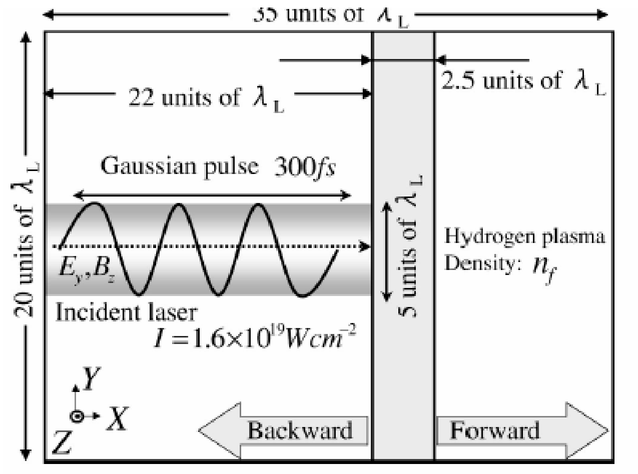
1) Neutralized ballistic transport
with careful chamber density control and
with careful beam co-moving electron temperature control

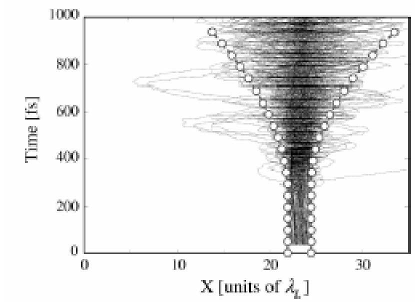
/ Lower electron temperature -> T -> Cool electron supply
*N*be$|_{\mathbf{cold}}$> *N*ce$|_{\mathbf{hot}}$ at the middle stage!

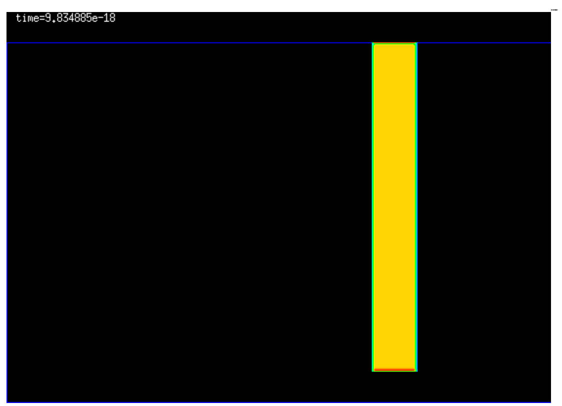
/ Suppress charge stripping & Low I_b ->
Z_b, n_{be} -> Low chamber gas density / pressure
But high enough for charge neutralization

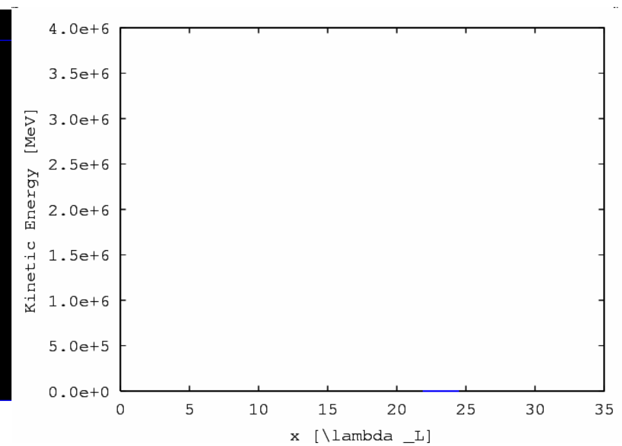
2) Through High density chamber plasma $n_{be} < n_{chamber\text{-}e}$
for all region

/ can avoid ambipolar field expansion
/ instability analyses
/ blast wave interactions with a liquid wall, …


35 units of λ L
22 units of λ L
2.5 units of λ L
20 units of λ L
Gaussian pulse 300fs
5 units of λ L
Hydrogen plasma
Density: n_f
E_y, B_z
Incident laser
$I = 1.6\times10^{19} Wcm^{-2}$
Y
X
Z
Backward
Forward


1000
800
600
400
200
0
Time [fs]
0
10
20
30
X [units of λ_L]


time=9.834885e-18


4.0e+6
3.5e+6
3.0e+6
2.5e+6
2.0e+6
1.5e+6
1.0e+6
5.0e+5
0.0e+0
Kinetic Energy [MeV]
0
5
10
15
20
25
30
35
x [\lambda _L]

Conclusions:

1. Deliver HIBs to a furel target!

2. My question
   - Practically possible to control HIB focus point in each shot?

Acknowledgements:

This work was partly supported by JSPS & MEXT, Japan.
We would like to express our appreciations to Colleagues & Friends in VNL, USA & Japan.