Final Beam Transport and Target Illumination

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1 Final HIB Transport
- Brief summary for final Transport
- Ambipolar HIB expansion & Transport window

2 HIBs illumination 3-D code
3 Conclusions

Relating presentations:
Thursday Morning, June 10: T. Kikuchi, et al., "Beam Dynamics …Bunching in HIF …"
Wednesday Afternoon, June 9, T. Someya, et al., "HIB Illumination on a Target…"

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We would like to express our appreciations to Colleagues in
VNL, USA & Japan.

1 Final HIB Transport

/ Brief summary for HIB Final Transport (A part)

D.A. Callahan: Fusion Eng. & Design (1996), UCRL-JC-121279(1995)
"Chamber Transport Physics"
E. Lee – Divergence analyses + Solenoidal Transport
/ Unneutralized ballistic transport in vacuum: sensitive to HIB charge state

/ Preformed plasma Sheet & Column:
- Good performance, require an plasma generation device
- Near the target, hot electrons can not be focused, as HIB is.
  -> Autoionizing target -> a target with a plastic

/ Pinched scheme: 100% charge & 99% current Neutralization
- small hole at the reactor wall & cost effective
- stability in pinch position & beam dynamics

/Channel transport
- External magnetic field and Z-discharged plasma
- channel formation & expansion

J.L.Vay & C. Deutsch: PoP (1998), more….
“Charge compensated HIB propagation”

/ Koshkarev Scheme: Pt+ & Pt- -> combined to compensate charge

/ 3D PIC simulations: BPIC

C.L. Olson: NIM A464(2001), …
“Camber Transport”

/ Detail comparison among various transport schemes
/ Transport issues are well summarized

R.R.Peterson & M.E. Sawan: UWFDM-1040(1997), more….
"Preformed plasma channel"

/ Channel Formation
/ static & filamentation instabilities
/ Channel expansion
/ Energy loss

-> Transportable window through the plasma ~5mm channel

W.M. Sharp, et al.: PoP, Fusion Sci. & Tech. 43, 393(2003), …
Bangerter, Langdon, et al., …for Photoionization
/ Precise HIB final transport LSP simulations
including electron emission from wall, photoionization by target radiation, preneutralization by a plasma, …
/ Foot pulse transport
-> Plasma neutralization is effective. …

S. Yu、Roy, et al: PoP, 11(2004)2890, et al.
"NTX Experiments Charge compensated HIB propagation"
/ Beautiful suppression of beam divergence by a plasma

Stability problems

R.L. Davidson, H.Qin, et al.
S.M. Lund, et al.
T.Kikuchi, T.Katayama, K.Horioka, et al.

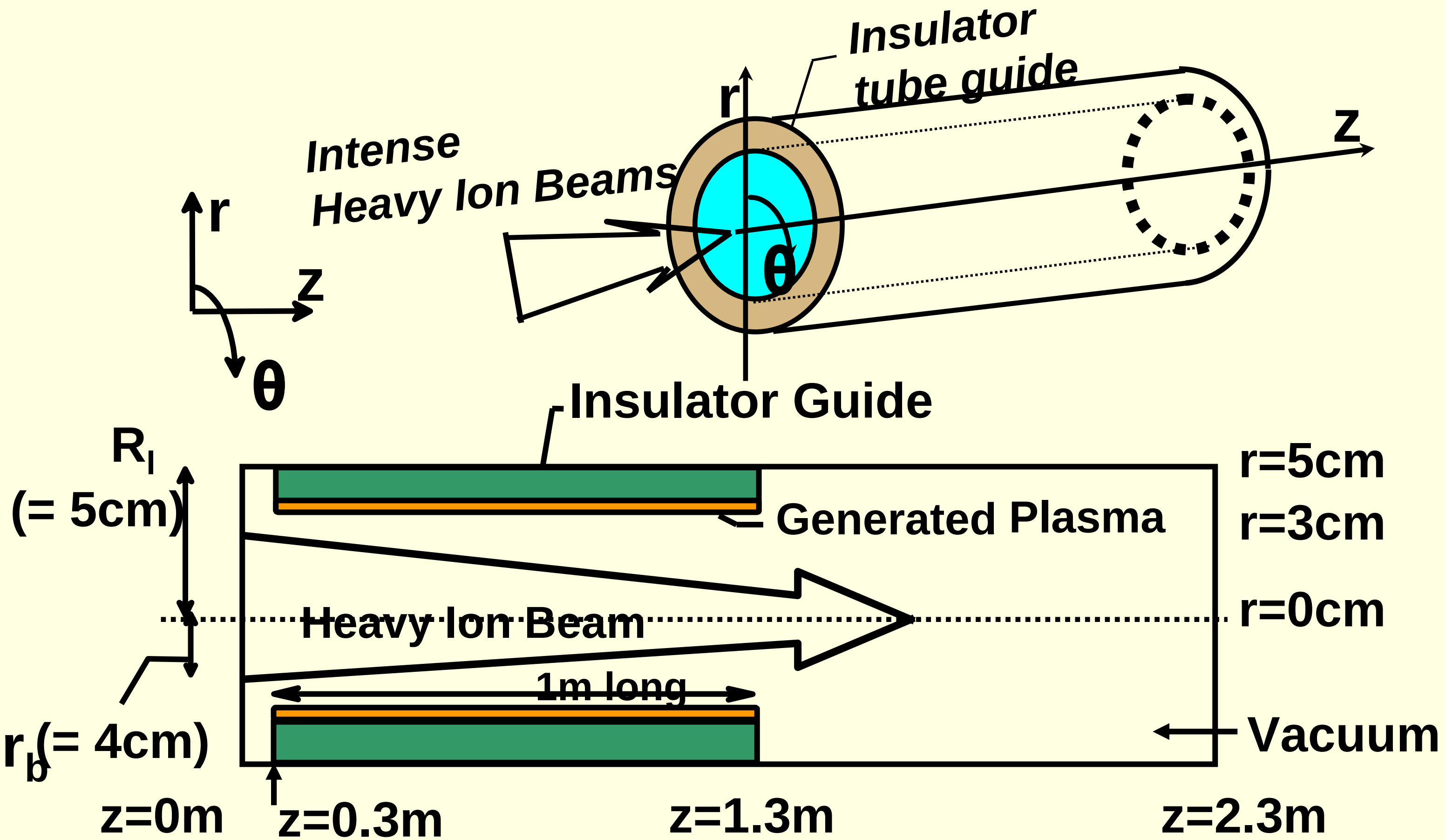
D.R.Welch: LSP code
A.Friedman, D.P. Grote et al, WARP code

W.B. Herrmannsfeldt: Beam-pipe electron trapping
S. Kawata, T. Kikuchi, T. Someya, S.Kato, et al.:
"Insulator guide transport"

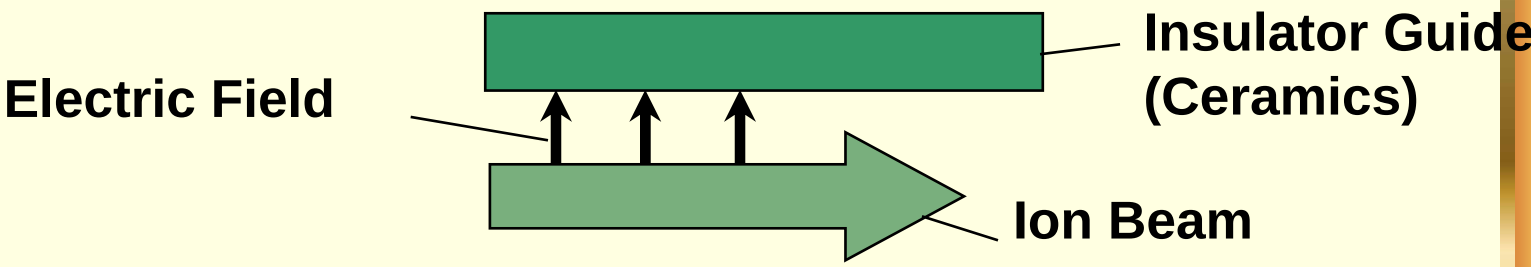
/ electron supply by a surface plasma at the ceramics wall
-> - at the final 10-20cm near the target at the chamber center?
- collisions
-> - simple & no additional plasma generation device

HIB transport through a tube liner

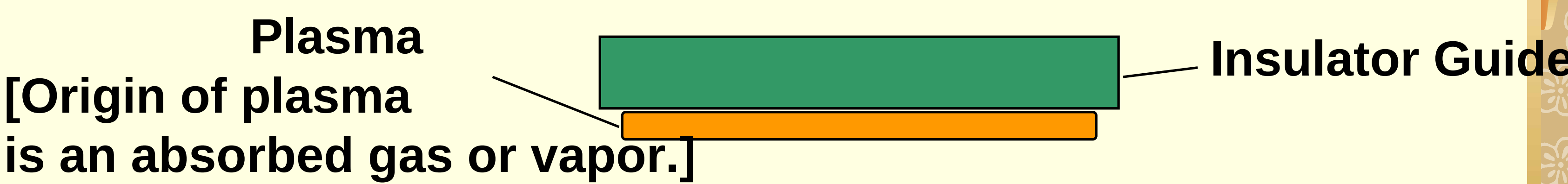
Neutralization of beam space charge



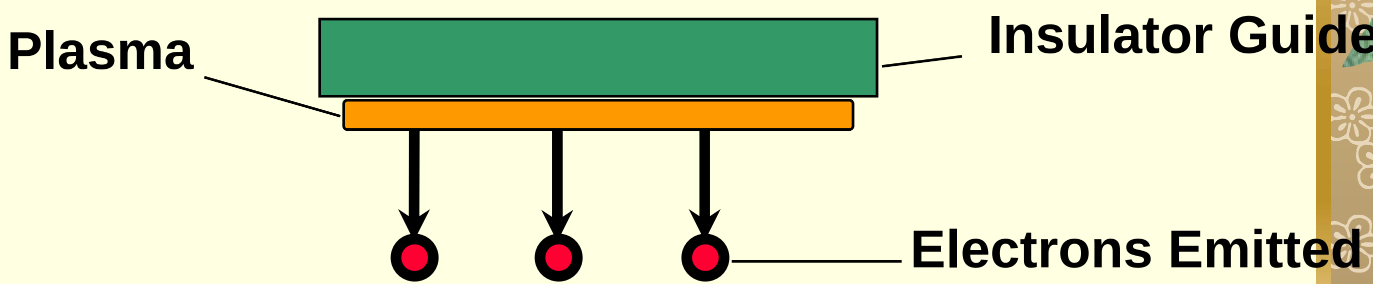
Physical Mechanism for the Insulator Guide-based HIF Transport



1. Local electric field creation



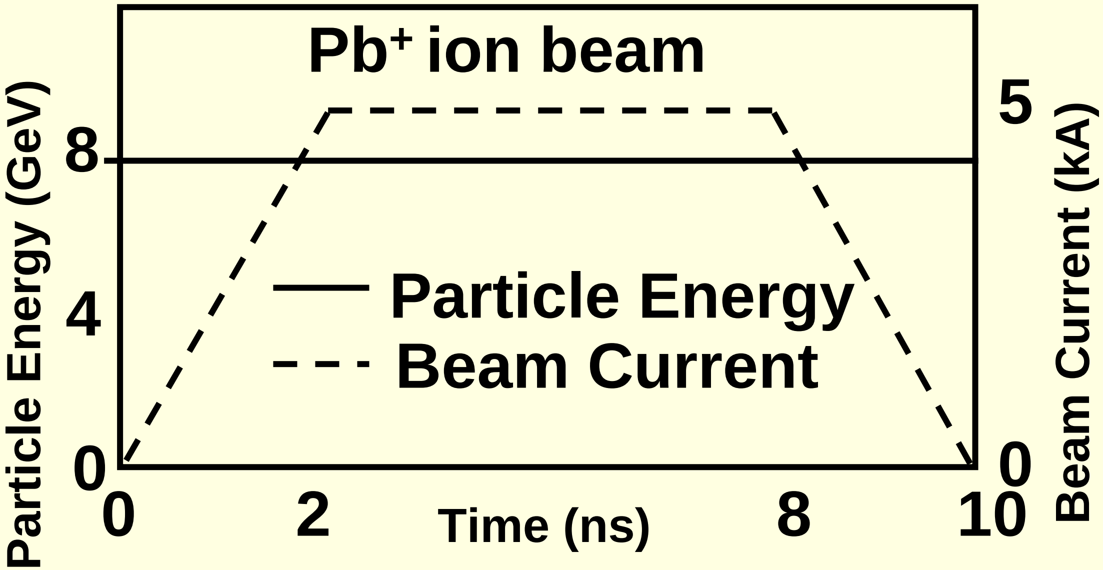
2. Discharges and plasma production



3. Electron extraction

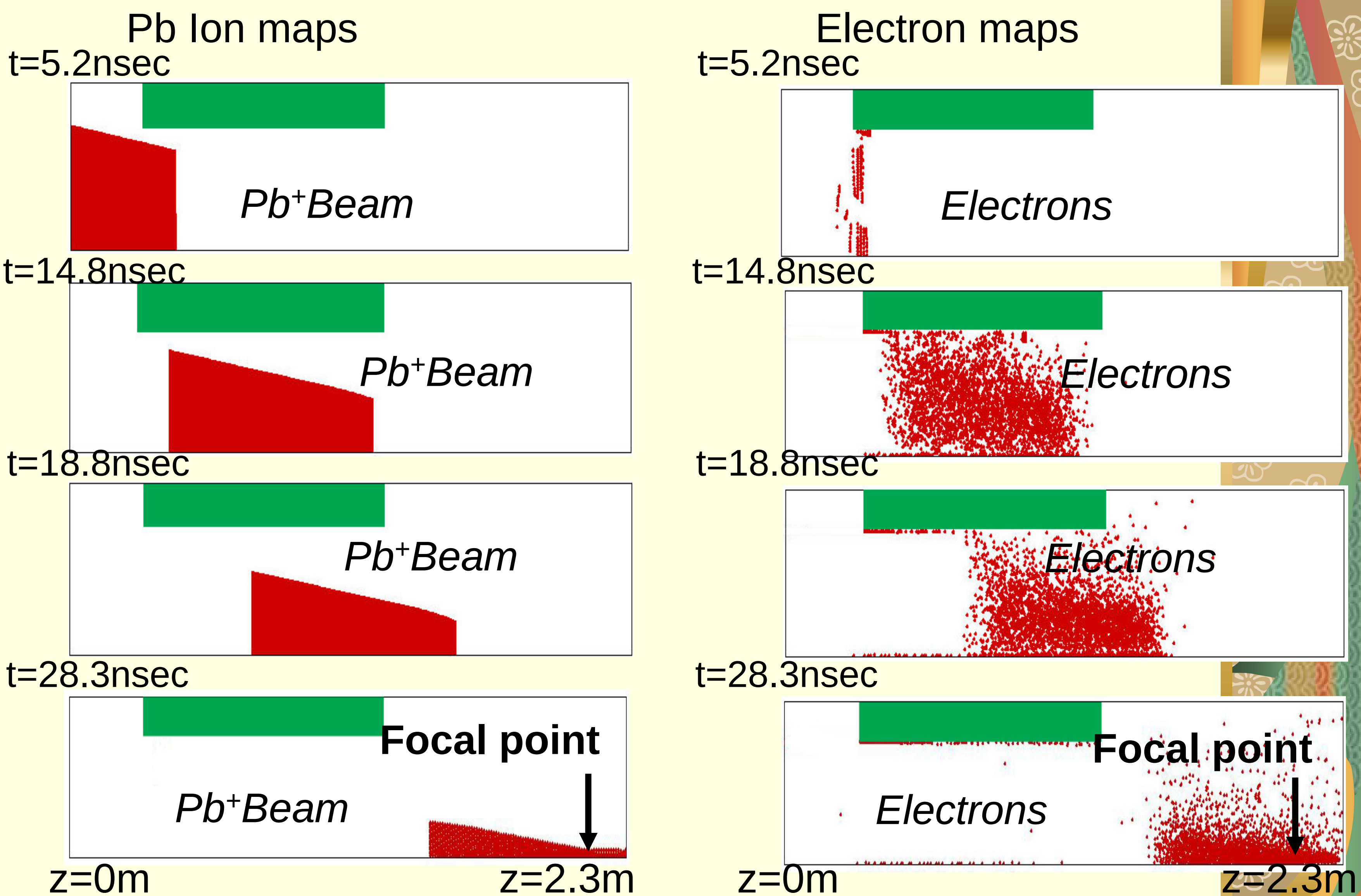
Input Pb^+ Ion Beam Waveform

- Max of beam current: 5 kA
- Particle energy: 8 GeV
- Pulse width: 10 nsec
- Beam particle temperature: 10 eV



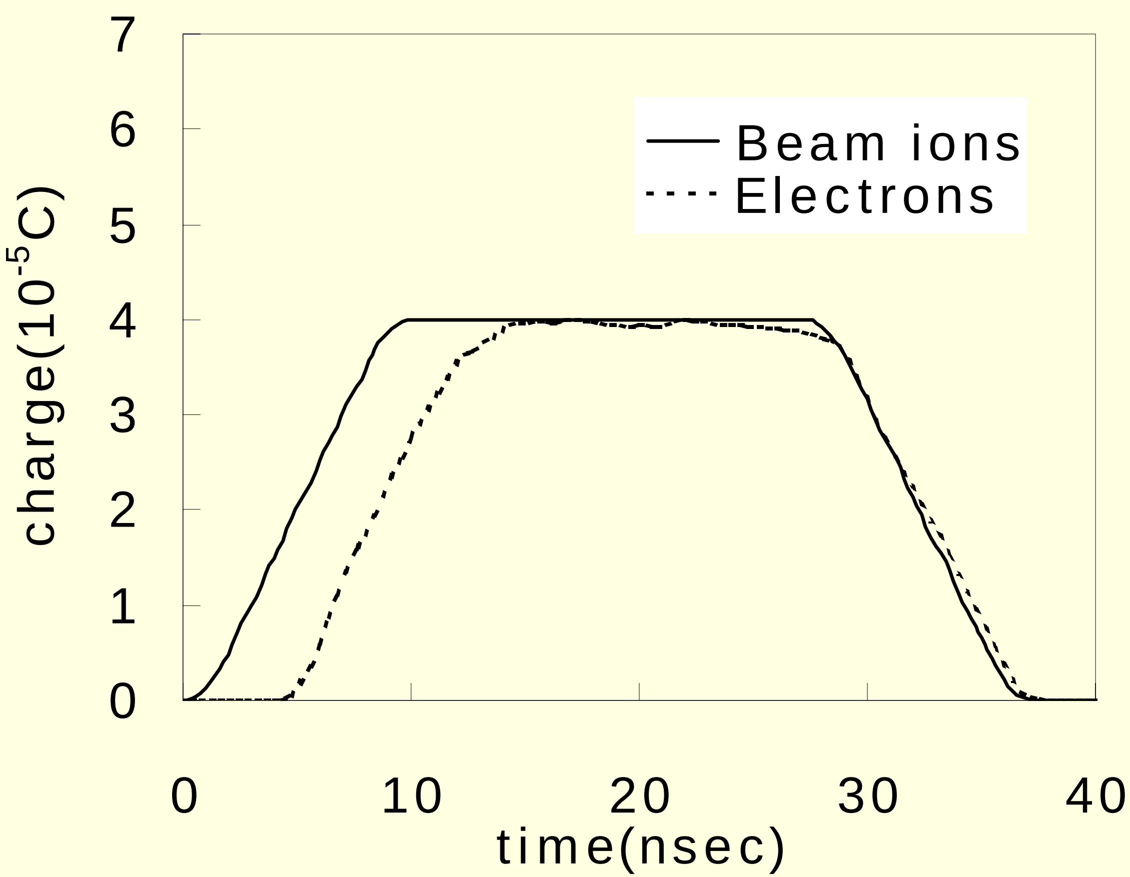
Ion beam waveform

Simulation Results(With insulator guide)



Ion beam and electrons from insulator guide

History of the Total Space Charge

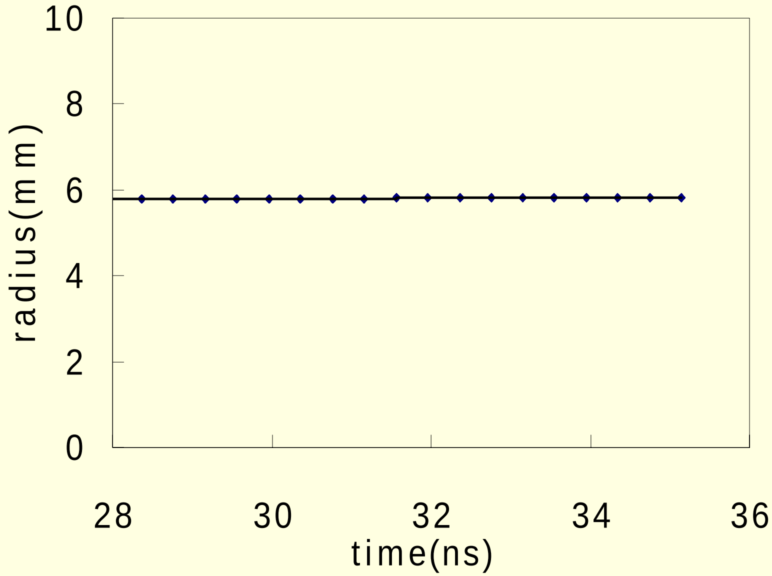


Total space charge

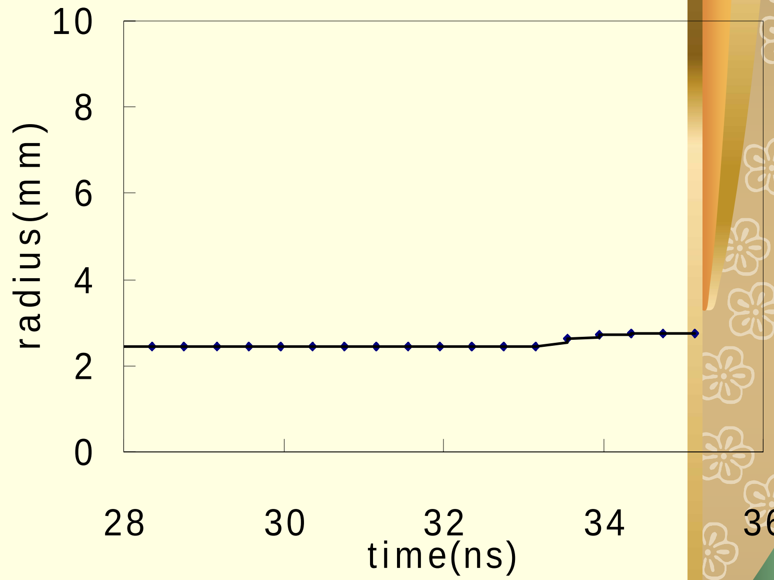
Charge neutralization is self-regulated

Improvement of Focusing

Change of radius at Z=210cm

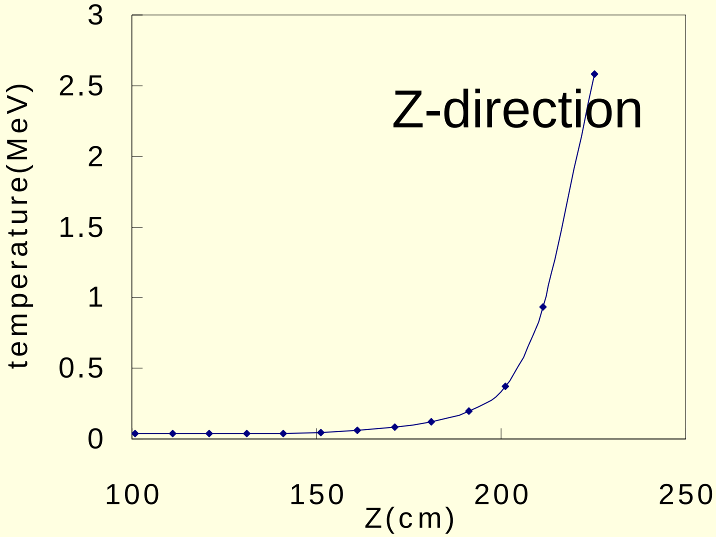


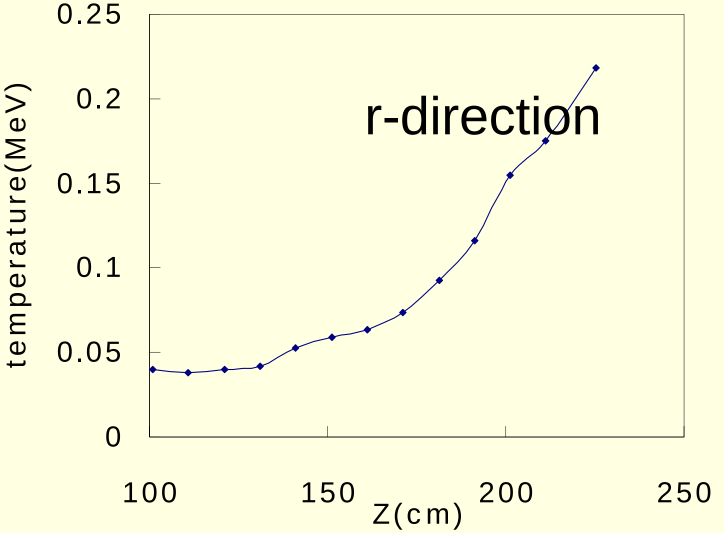
Without insulator guide



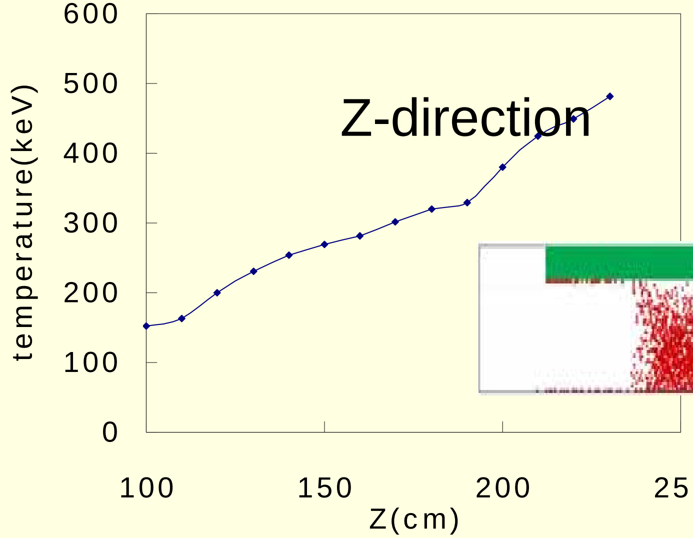
With insulator guide

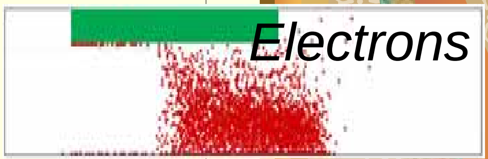
Temperature

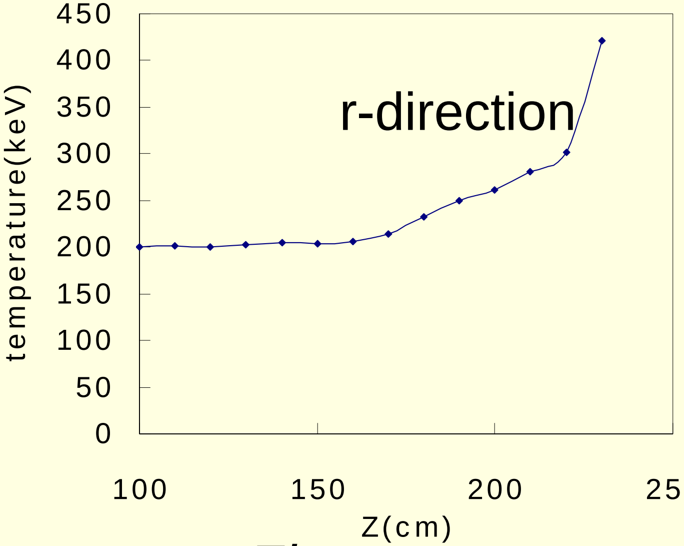




Beam Ion temperature





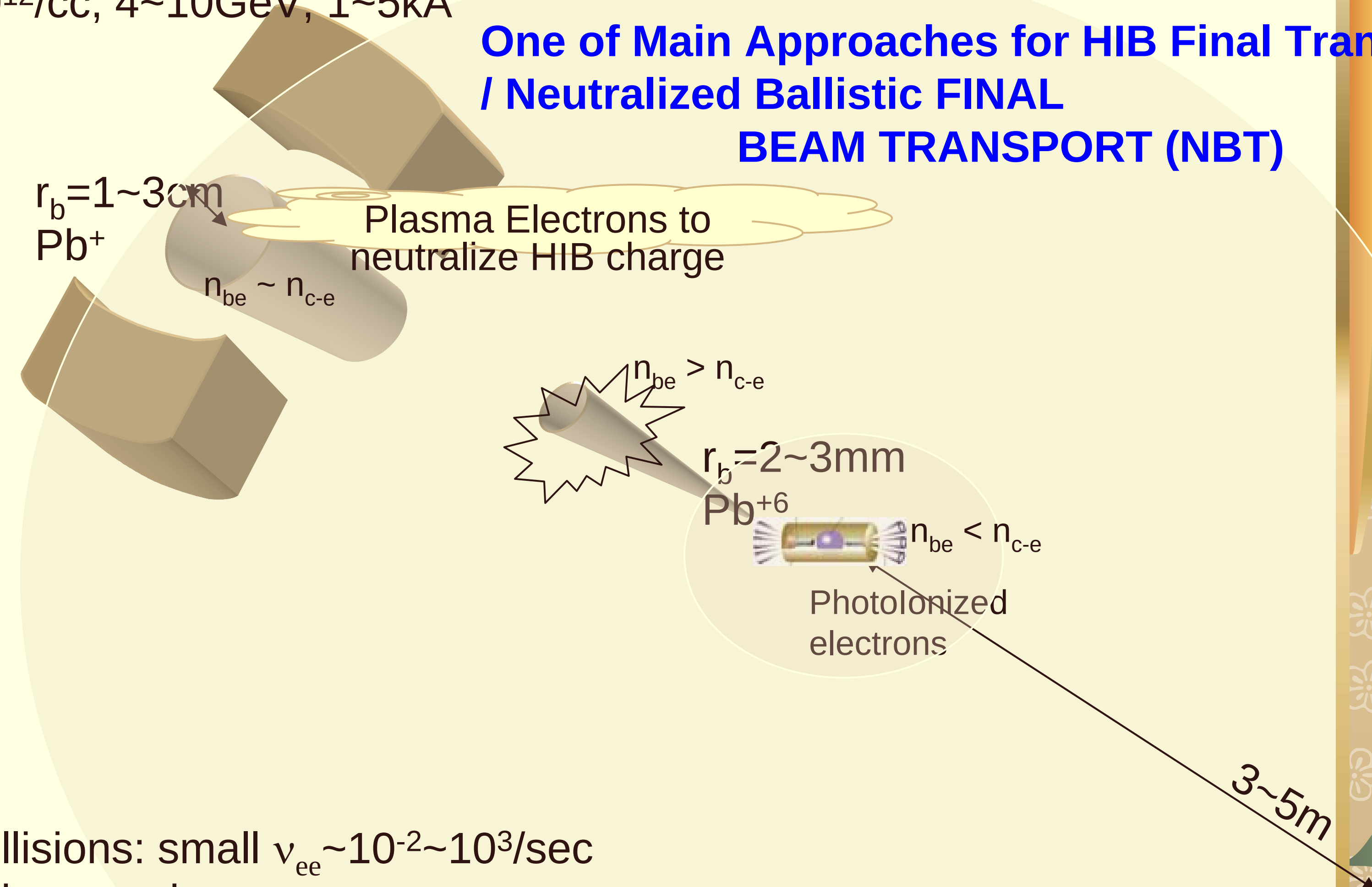


Electron temperature

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 (NBT)



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

/Stabilities: e-e, b-e

/Neutralized beam dynamics at the middle

-> r_b=5-10mm

-> n_b~10^{13}/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 <- $Te \sim Te0 \times (r_{b0}/r_b)^{4/3} \sim 22 \times Te0$

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

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

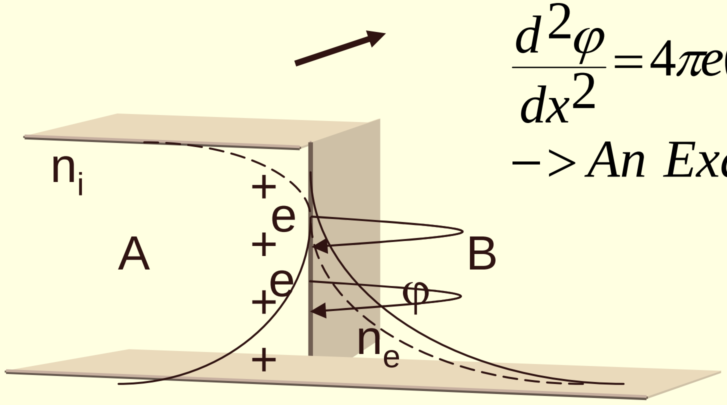
-> may induce **ambipolar field** beam expansion

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

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.:*



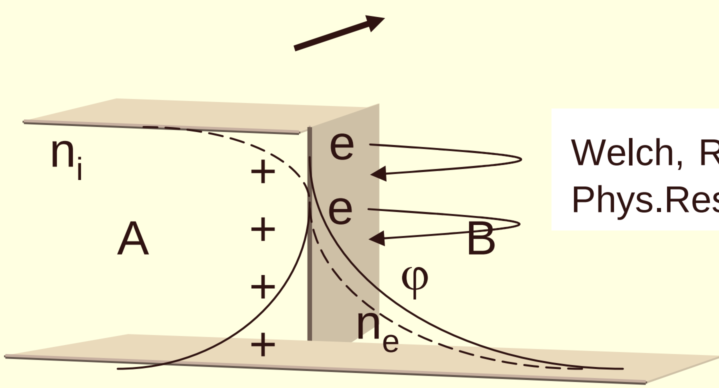
$$\frac{d^2\varphi}{dx^2} = 4\pi e(n_e) \approx 4\pi n_0 e(e^{\frac{e\varphi}{T}}) \quad \textit{for Region B}$$

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

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

At the beam surface & at the middle stage

$Z_b eE$[eV/cm]~$1.35\times10^{-3} Zb(n_e T_e)^{1/2}$[eV]~(2MeV/cm~10MeV/cm)



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

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

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

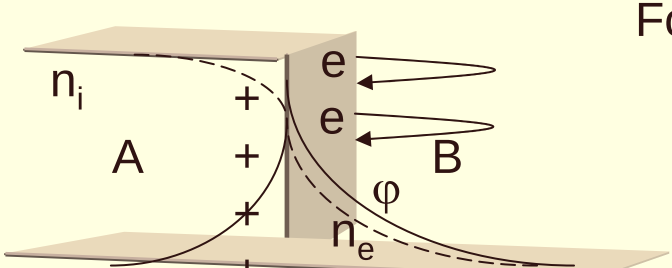
After integration of qE between r_b and $r_b+\lambda_{De}$
->

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

-> $\varepsilon_{\perp}/\varepsilon_{//}$ ~ (3~100keV)/(4-10GeV)
for 100cm transport dr ~ 1~5mm Increase in rbf
-> may be serious.

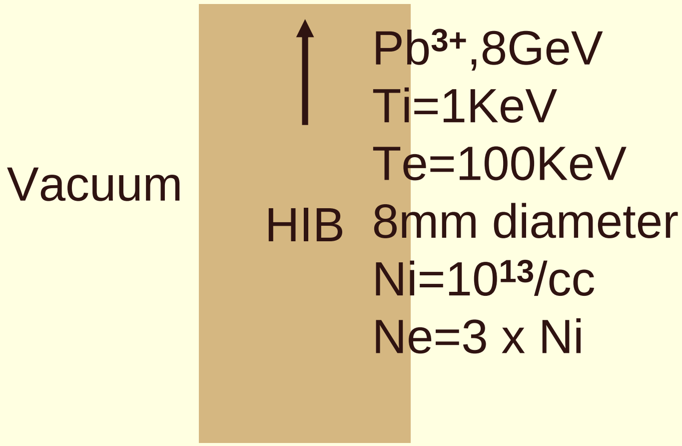
On the other hand

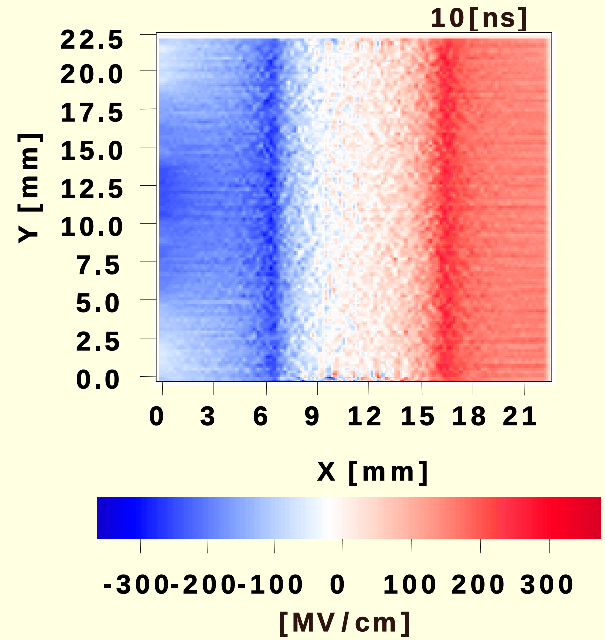
If $n_{be} << n_{chamber\text{-}e}$, NO problem for the ambipolar expansion.
Mainly chamber background electrons contribute beam charge neutralization.

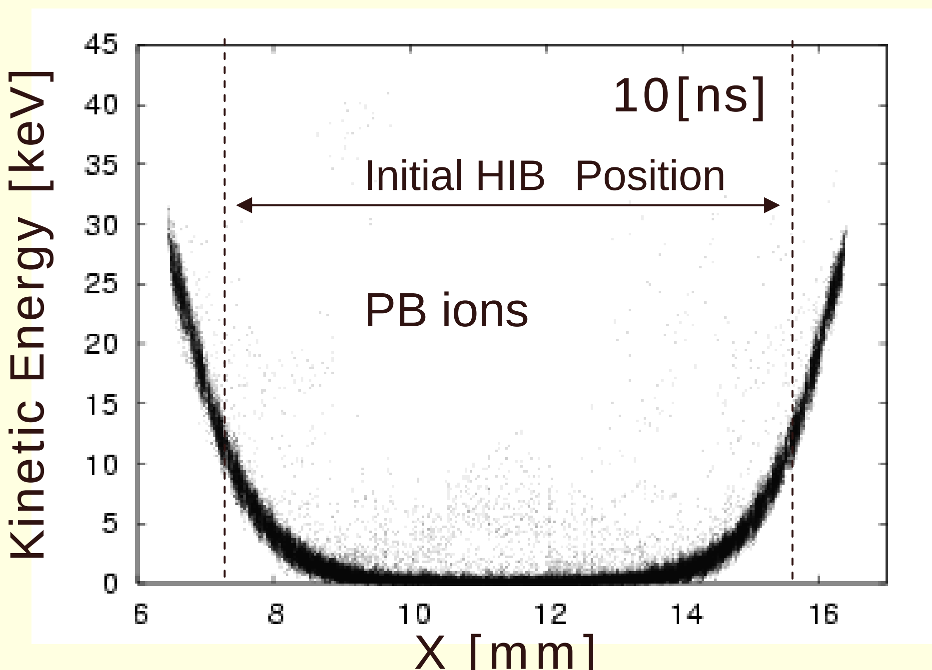


For example: T_e=10eV, n_e=10^{14}/cc, Z_b=5
λ_{De} ~$1.4\text{x}10^{-4}$cm
$\varepsilon_{\perp}$ ~0.05eV Well neutralized!

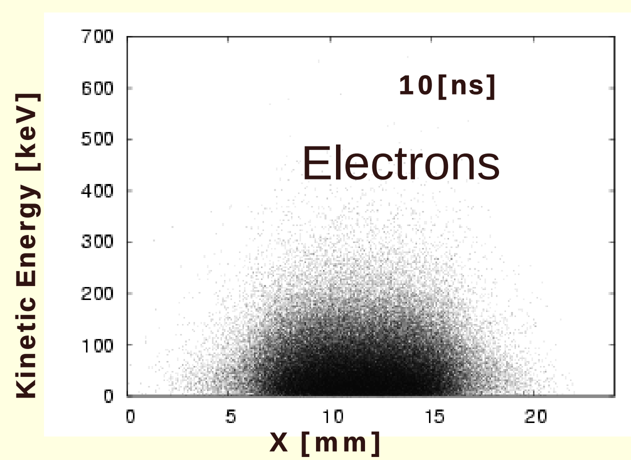
PIC Simulation

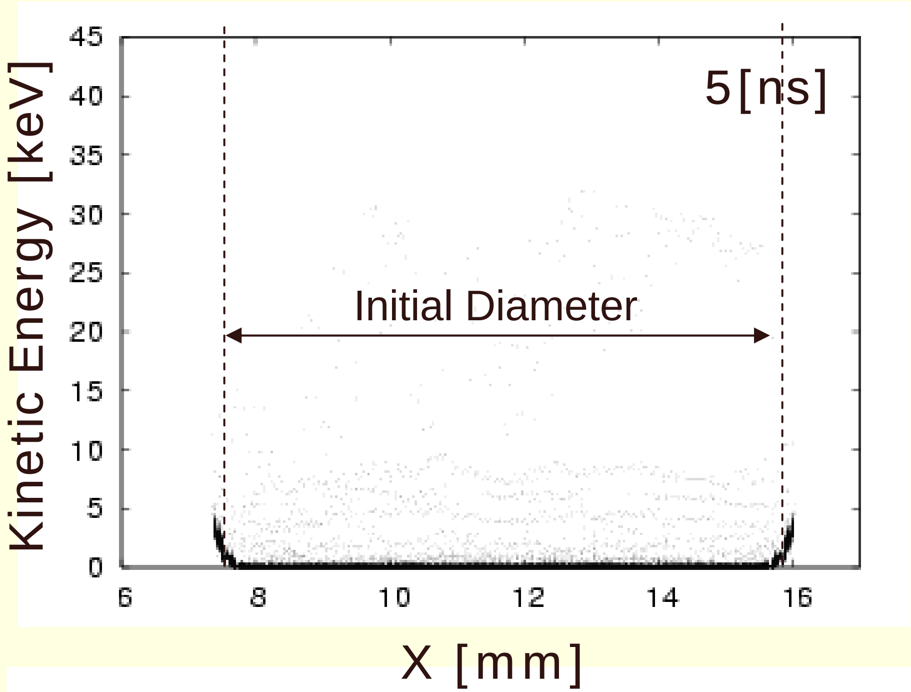


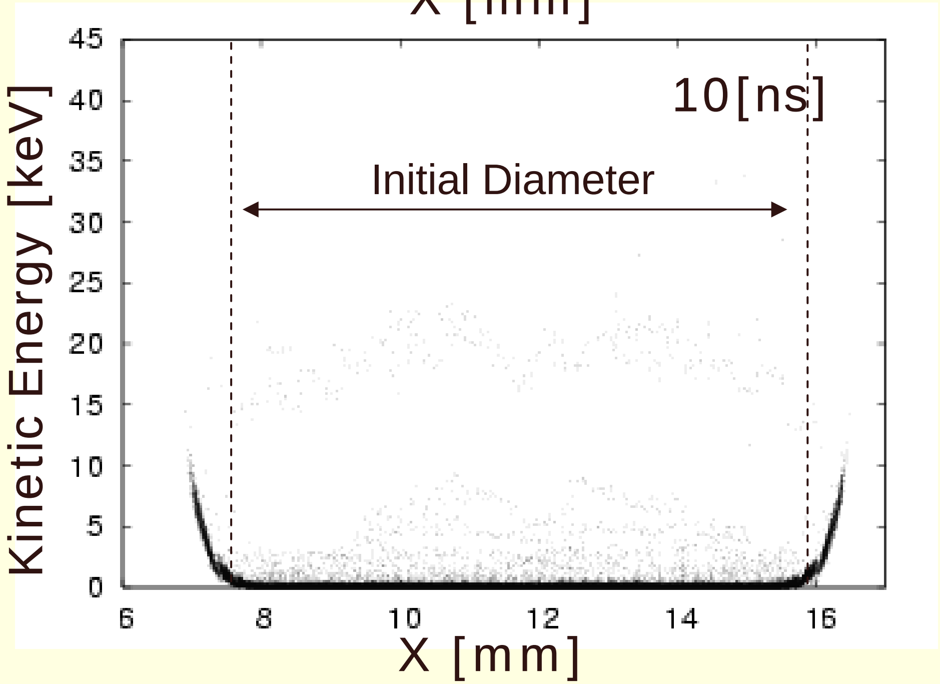




Strong E-field
generated by high-T electrons
pulls Pb ions out!

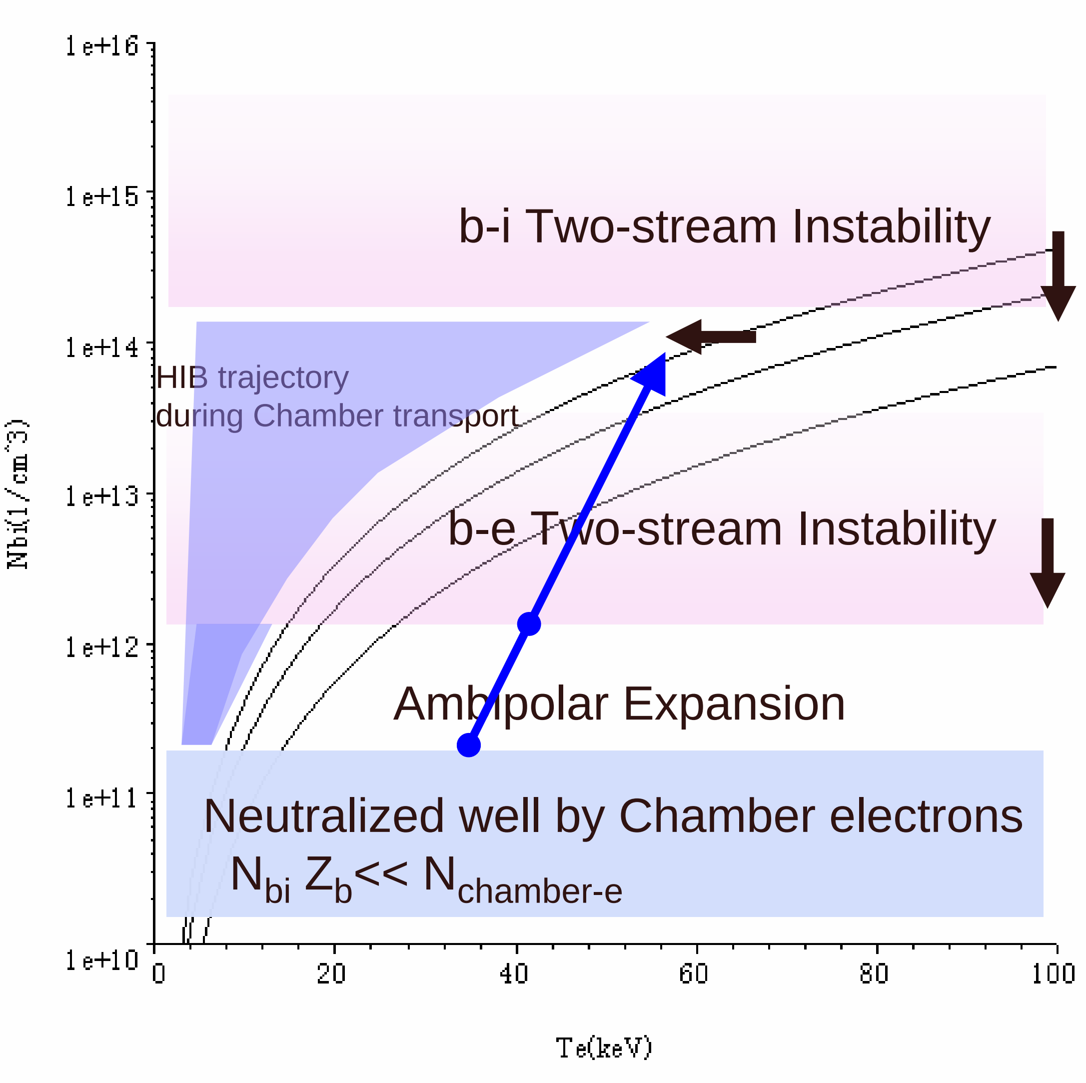



5[ns]
Initial Diameter
Kinetic Energy [keV]
X [mm]


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

for Te=10KeV

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



8GeV
Zb=3,
r_b=0.5 cm
0.7cm
1 cm

For NBT

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 $N_{e\_hot} \sim N_{e\_low}$

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

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
   $N\text{be}|_{\textbf{cold}} > N\text{ce}|_{\textbf{hot}}$ 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, …

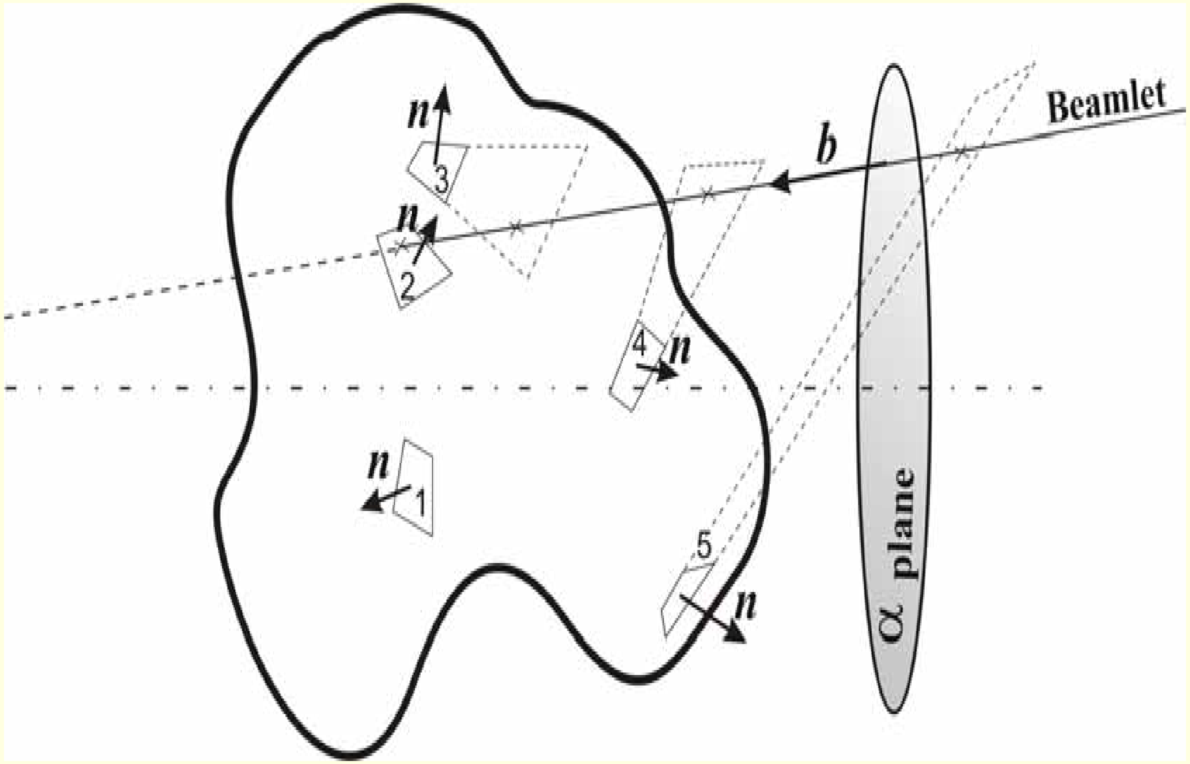
2. HIBs illumination Nonuniformity on a pellet

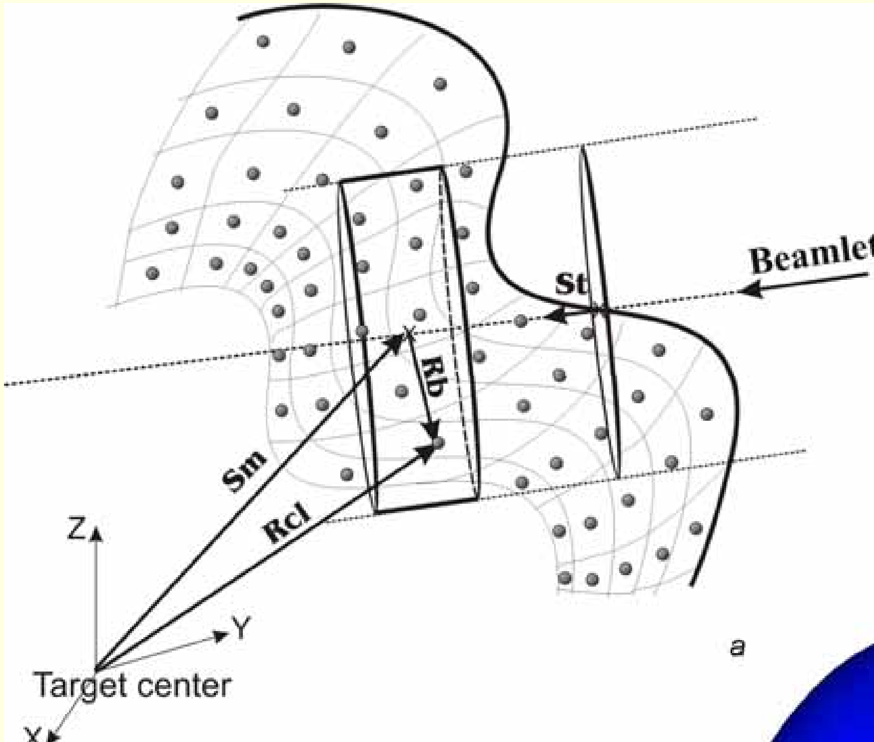
Assumptions:

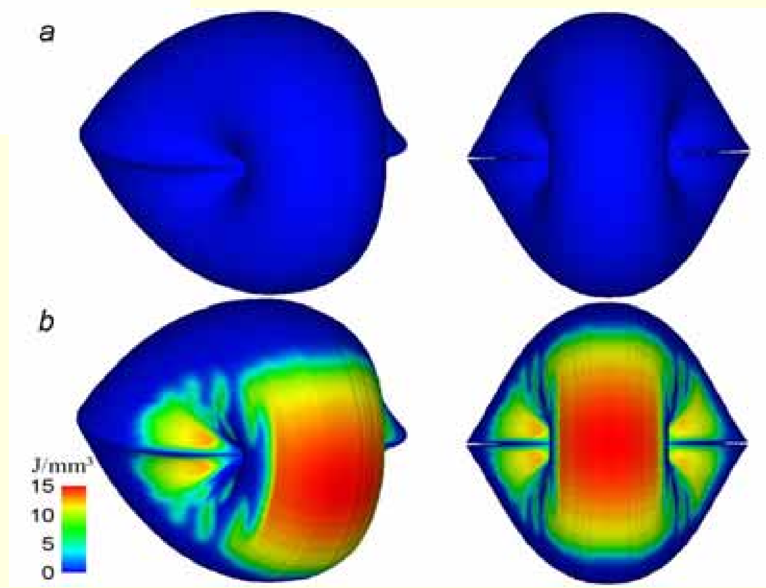
/ Ballistic transport inside the target

/ Each beam is divided into beamlets, for example 316 beamlets

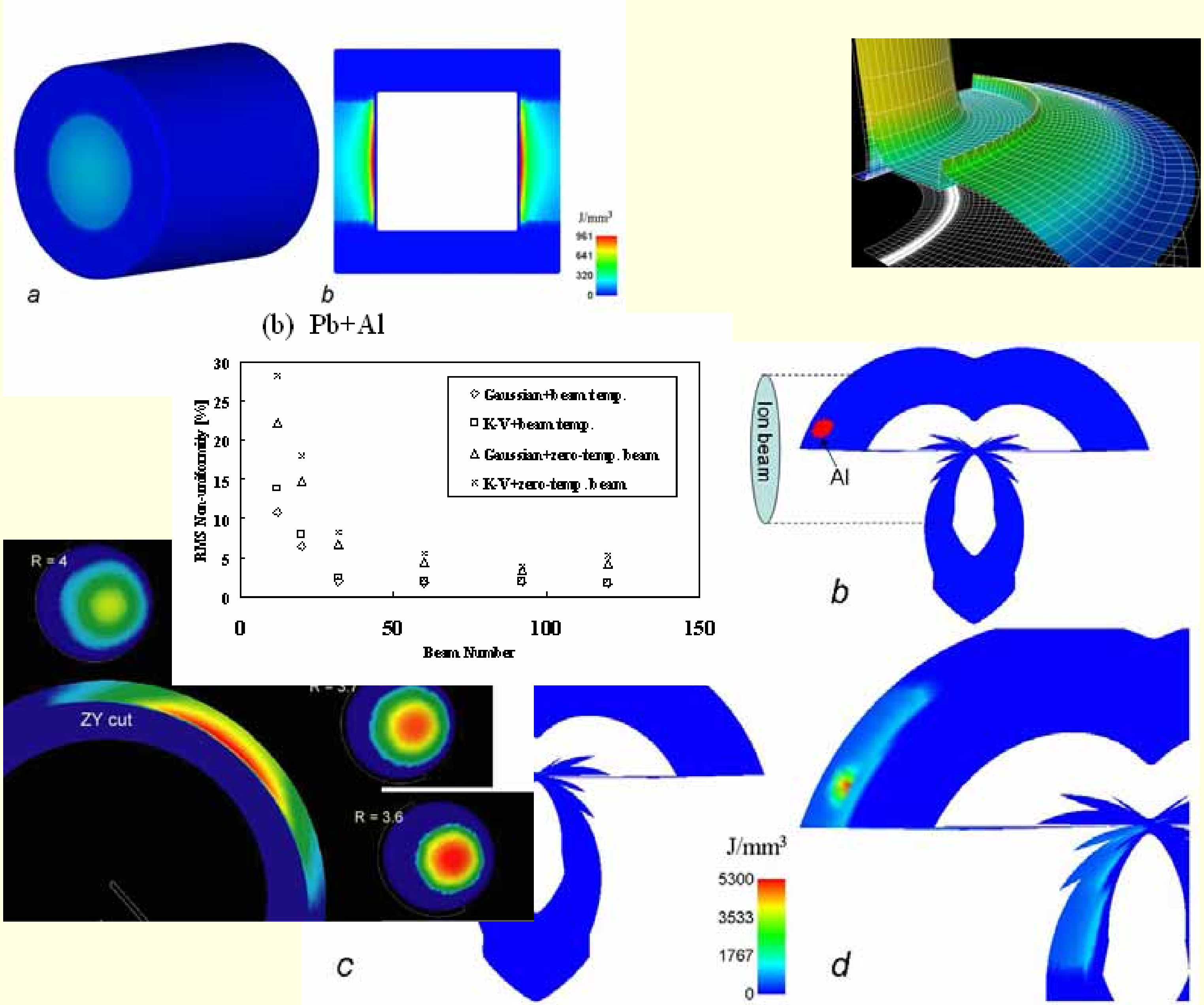
/ perfect charge neutralization




Beamlet
St
Rb
Sm
Rcl
Z
Y
X
Target center


a
b
J/mm³
15
10
5
0

Wednesday Afternoon, June 9, T. Someya, et al., “HIB Illumination on a Target…”



Conclusions:

1. Ambipolar field HIB expansion is pointed out.

    - Its physics is clarified
    - Possible solutions are presented
    - Transport window is also presented

2. 3-D HIB illumination code was developed

    - A Hydro code is now under reconstruction
    - will be coupled to our 3-D HIB illumination code

Acknowledgements:

This work was partly supported by JSPS & MEXT, Japan.
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