Beam Physics Studies at Tokyo Tech

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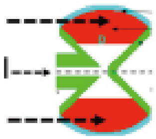
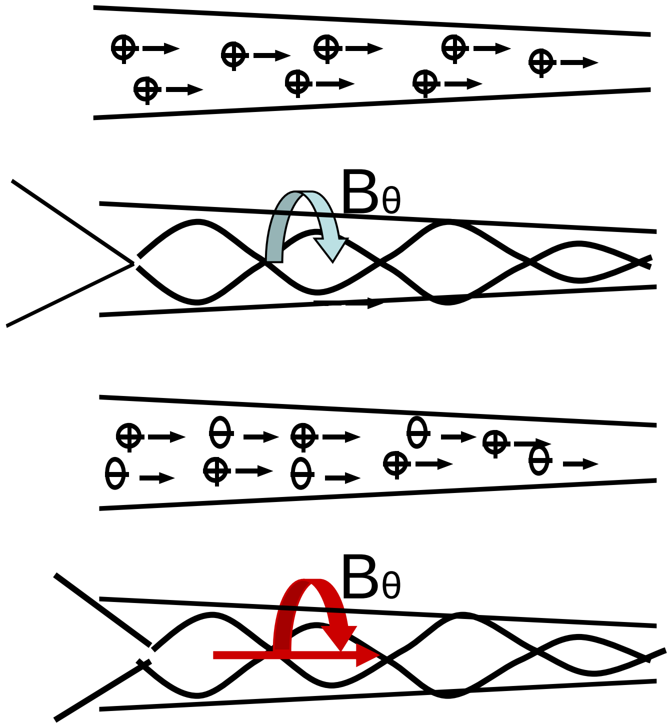
HIF-targets cover a wide range of designs which request a variety of beam parameters

	Features	Issues
Indirect drive – *HS ign.* 	• Integrated 2D designs exist • Ablation/burn physics on NIF • Natural two-sided geometry	• Lower drive efficiency • Lower gains, high driver energies
Direct drive X-target – *Fast ign.* 	• Inherent one-sided drive • High coupling efficiencies • Reduced stability issues • Potential for high yields (~GJ) and gains	• High gains require high densities under quasi-3D compression • Higher ion kinetic energies • High power, small focal spot beams needed for fast ignition • Driver concepts immature
Direct (+indirect) drive, tamped – *Shock ign.* 	• High coupling efficiencies (tamped ablation) • Simple targets • High gains consistent with low ion-kinetic-energies (~2-10GeV)	• Optimum ion species and energy • Two-sided (polar) geometry to be established** • High power beams needed for shock ignition • Stability to be confirmed
Direct drive, cylindrical compression – *Fast ign.* 	• Inherent one-sided drive • High coupling efficiencies • Simple targets	• Low gains, high driver energies • High ion kinetic energies • High power. small focal spot beams needed for fast ignition • Driver concepts immature • No U.S target design interest

**Will leverage present NIF PDD studies

Ed. by P.A.Seidel and J.Barnard : Summary report of workshop on accelerators for Heavy Ion Fusion, LBL (2011)

Beam transport scheme from final focus to the target is also an important issue



- Ballistic Transport
- Self-pinched Transport
- Ballistic with Electrons
- In pre-formed Plasma Channel

Possible chamber transport scheme depends on beam current and energy

HIF-Accelerator system and target designs must be correlated closely

- Allows various target designs and chamber transport scheme
  - Direct or indirect
  - Cylindrical, spherical and X-targets
  - Chamber transport scheme

- Optimum ion species, its energy and beam number are still non-fixed

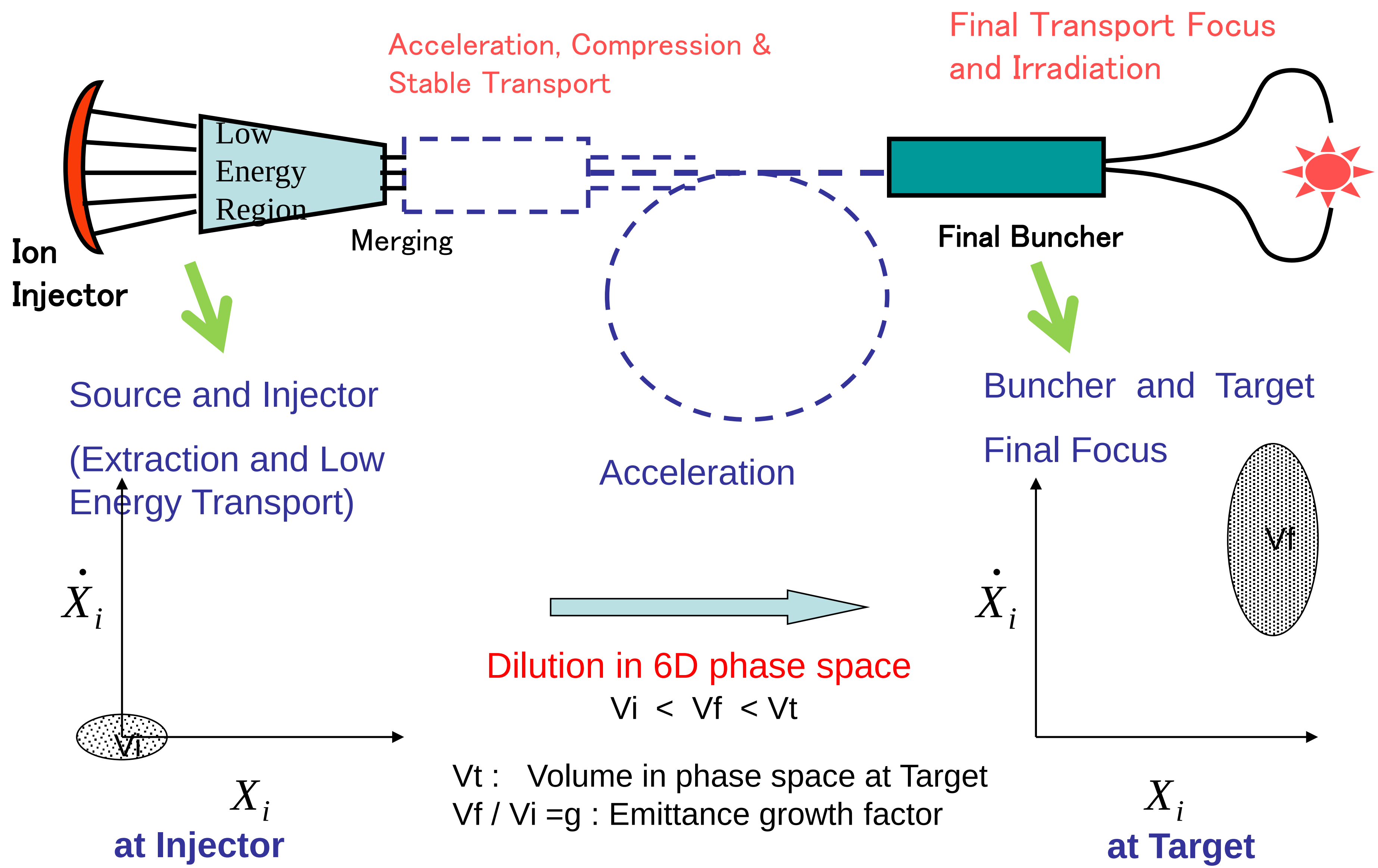
- We have to consider a rational accelerator scheme in the multidimensional parameter space

We can standardize the problems with discussion of particles in the phase space

- Necessary requirement that all of driver scheme must be met is;
  - The phase space density of particles must be less than the achievable phase density at the injector

- Goals of beam physics studies at Tokyo Tech are;
  - Quest for high-flux and low emittance injector
  - Investigate the phase density dilution (emittance growth) process from the injector to the target chamber
  - Discuss those beam dynamics in high power accelerators with laboratory-scale devices

There are strong space charge issues in the ion injector and the final stage of high power ion accelerators



We need a breakthrough for HIF injector

High-flux (∼10^{-4} A・sec (10^{15} particles), and low emittance (Vi < Vt / g))

Ion Extraction from Non-Stationary Moving Plasmas

Expanding plasma

- Laser ablation plasma through strong axial field
- Plasma acceleration and gas-dynamic cooling
- Low temperature and high flux

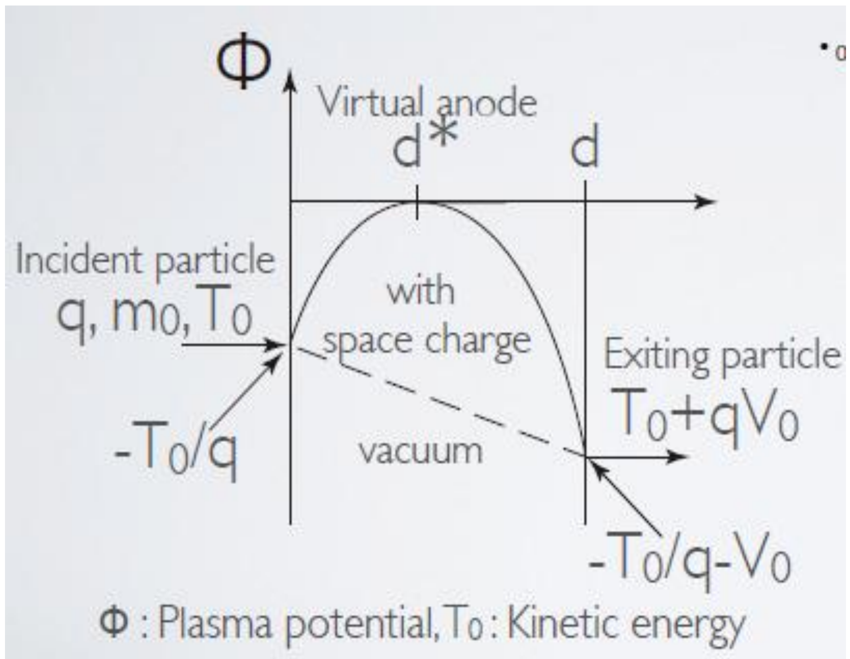
Achievable beam flux and emittance (Phase space density)

Beam Dynamics during Ion Extraction from Moving Plasma

Plasma Injection

n_i, v_i, T_i, J_p

Acceleration Gap



Emission Surface d*

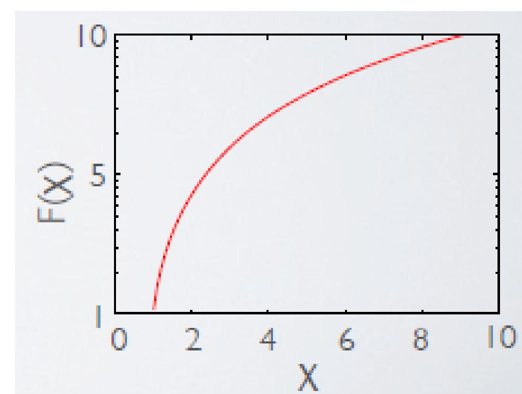
Potential Hump φ_h

Enhancement F(χ)

Beam Extraction

J_i, ΔE_i, ε_i

$$Ji \propto J_{CL} \bullet F(\chi)$$



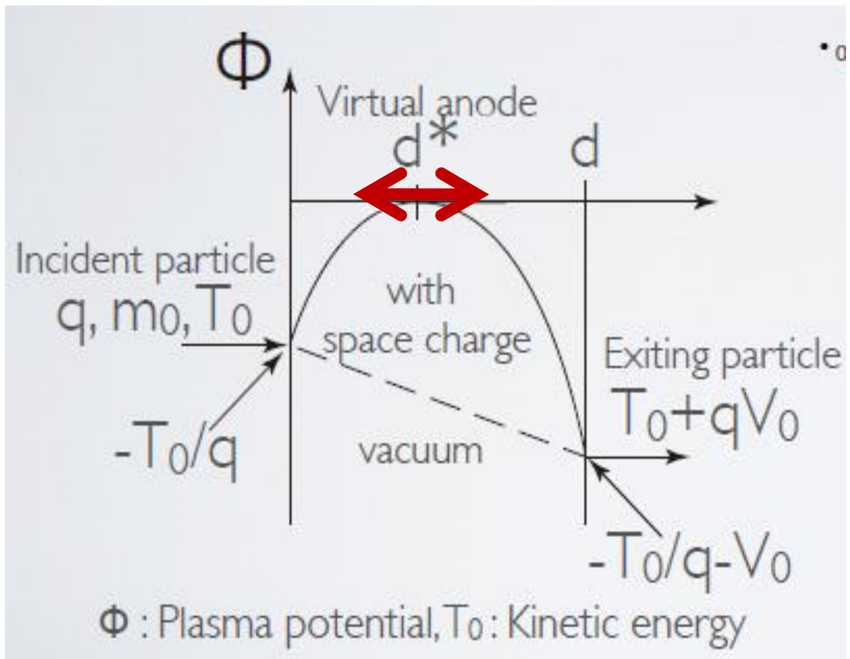
Enhancement Factor

Beam Dynamics during Ion Extraction from Moving Plasma

Plasma Injection

n_i, v_i, T_i, $\underline{J_p}$

Acceleration Gap



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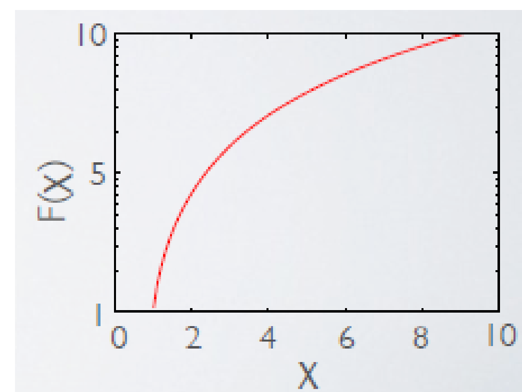
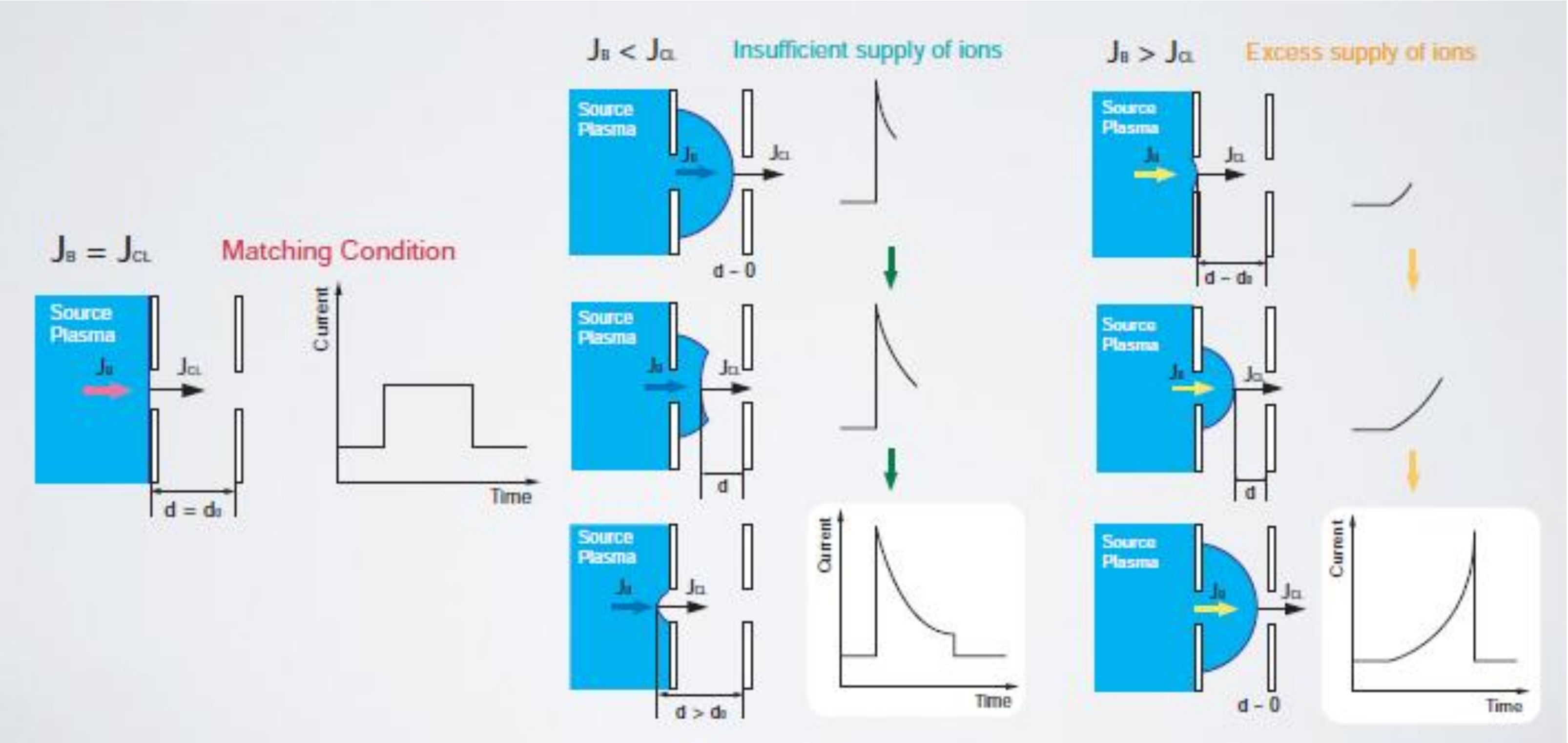


Enhancement Factor

Example of Ion Extraction Process from a Moving Plasma

Moving and quasi-stationary source plasma $$\frac{mv^2}{2q} << V_0$$

Behavior of the extraction gap is dominated by the parameter of source plasma



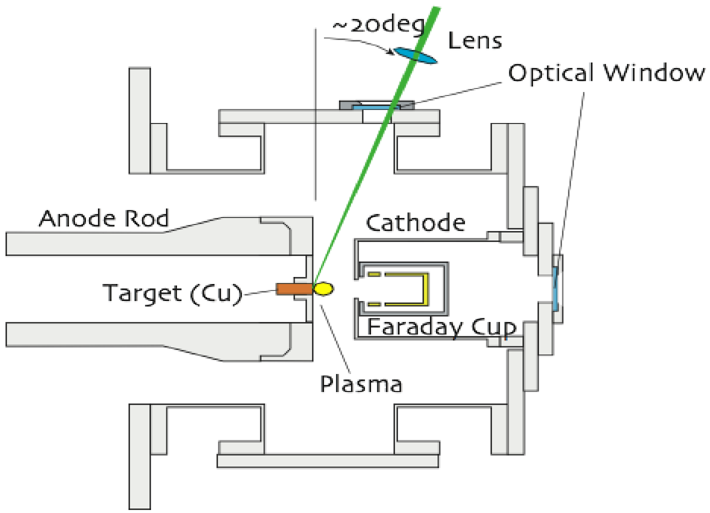
High flux Ions are directly extracted from laser ablation plasma

Direct ion extraction from drifting plasma

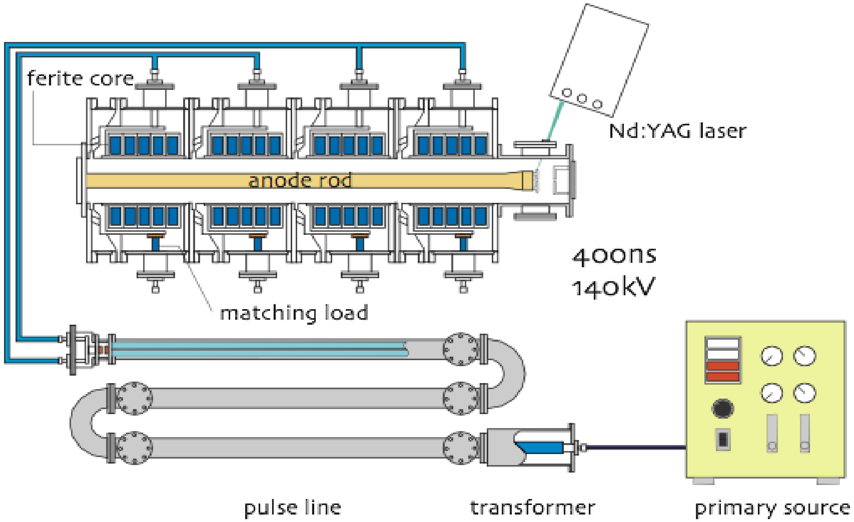
Cu Ions are extracted from 20mm gap

Beam current → Faraday Cup

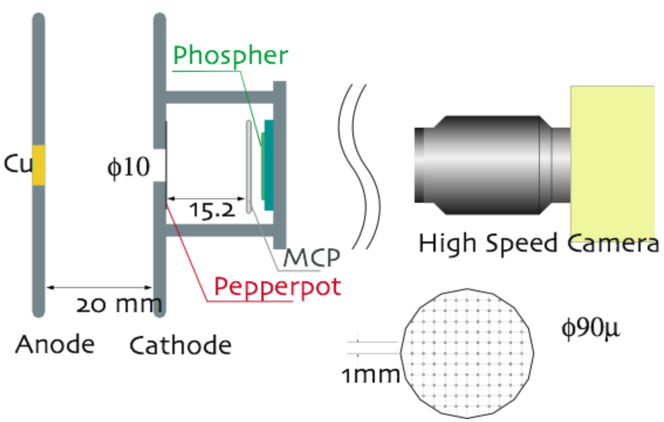
Beam emitance → Peper-pot image



A schematic view of laser ion source



Pepper-pot Emiitance Measurement



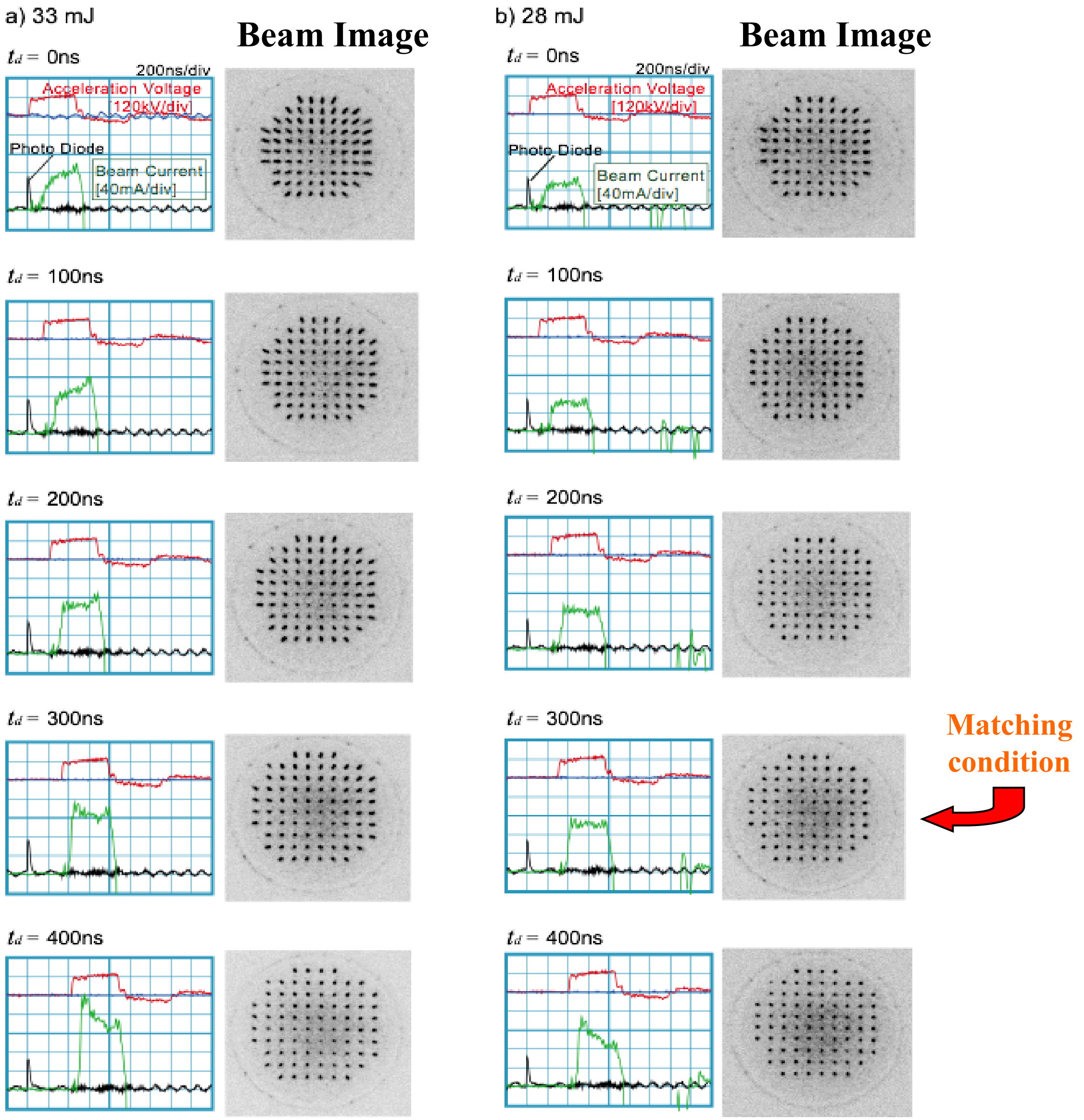
M.Nakajima, K.Horioka, et.al., NIFS-Proc. (2004)

With properly adjusting the operating condition, high flux & low emittance ion beam can be extracted from ablation plasma

Can overcome the Bohm limit

Matching problem is overcome by controlling the ion supply close to the space charge limitting current of effective gap

Beam bunch of Cu ions with 100mA/cm2 level with emitance of 0.25π mm・mrad and flat-top waveform was obtained



Correlation between beam current and emittance for moving plasma source

- Flux from plasma source

$$j \propto Zen_i u$$

$$\varepsilon \propto T_i^{\frac{1}{2}}$$

- Stationary plasma

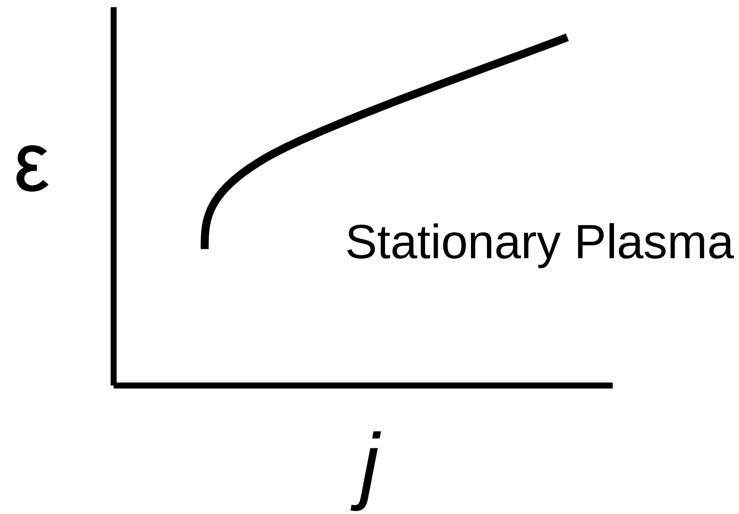
$$u \geq \left(\frac{kT_e}{m_i} \right)^{\frac{1}{2}}$$

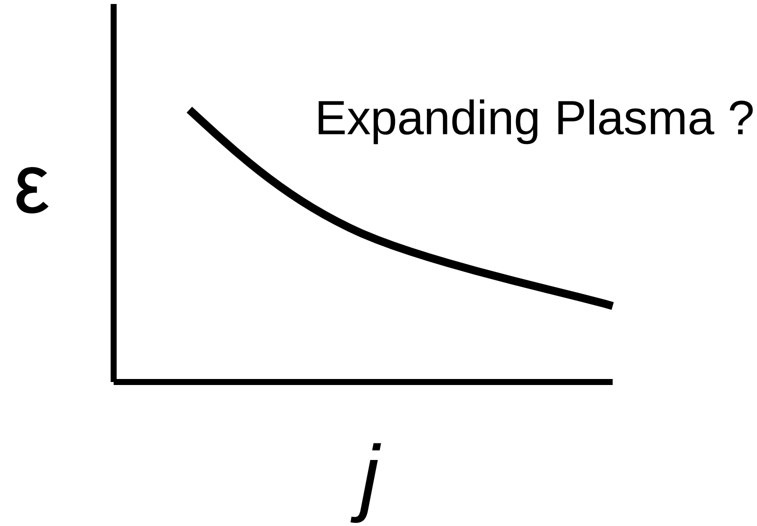
$$j_B = en_s v_0 = 0.6en_0 \sqrt{\frac{\kappa Te}{m_i}} \quad \propto \quad \sqrt{T_e}$$

- Expanding plasma

$$u^2 = \frac{2\gamma R}{\gamma - 1} (T_0 - T_i)$$

$$j \quad \propto \quad \sqrt{(T_0 - T_i)}$$





Moving (expanding) plasma source can increase the phase space density

Conventional injector (by J.Barnard)

$$\frac{dN}{dU_6} = \frac{N}{\Delta P_x \Delta P_y \Delta P_z \Delta x \Delta y \Delta z} = \frac{I}{q\gamma\beta^2 m^3 c^4 \varepsilon_{nx}\varepsilon_{ny}\left(\Delta P_z / \ P_z\right)} = \frac{\pi\varepsilon_0}{2^{\frac{1}{2}}9}\left(\frac{V_0}{m^3 q^3}\right)^{\frac{1}{2}} \frac{1}{kT_s\left(\Delta P_z / \ P_z\right)\alpha_B (1cm)^2}$$

Injector based on expanding plasma

$$\frac{dN}{dU_6} = \frac{I}{q\gamma\beta^2 m^3 c^4 \varepsilon_{nx}\varepsilon_{ny}\left(\Delta P_z / \ P_z\right)} = \frac{qnv_d A}{q\frac{2qV_0}{m} m^3 \left(\frac{kT_s}{m}\right)\left(\Delta P_z / \ P_z\right)} = \frac{A}{2qkmV_0}\frac{nv_d}{\left(\Delta P_z / \ P_z\right)T_s} \propto \frac{\left(T_0 - T\right)^{\frac{1}{2}}}{\left(\Delta P_z / \ P_z\right)T^{\frac{\gamma-2}{\gamma-1}}}$$

$$n \propto cT^{\frac{1}{\gamma-1}}, \quad v_d \propto \left(\frac{\gamma}{\gamma-1}R\left(T_0 - T\right)\right)$$

Expansion (cooling & acceleration) → High-flux and high phase space density

Summary of the injector study

Summary

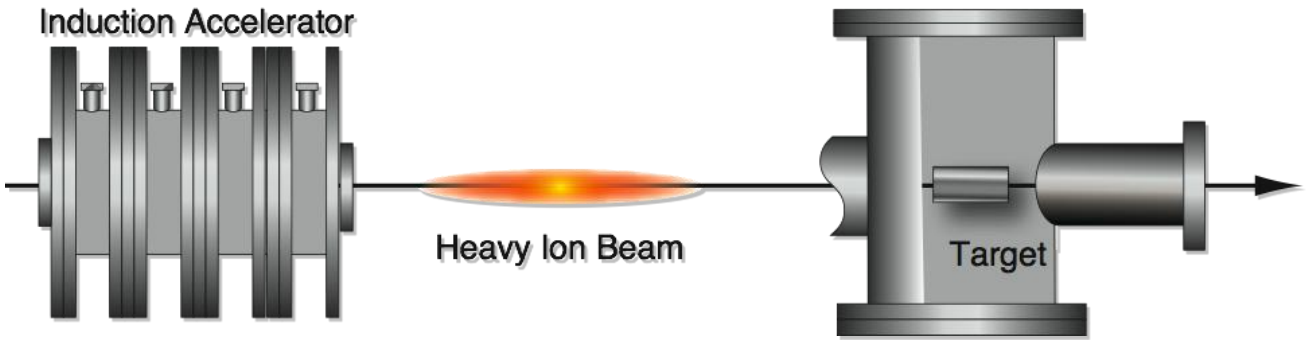
- We discussed ;
  - Ion extraction process from laser ablation (moving) plasma
  - Behavior of laser ablation plasma through axial magnetic field

Future Plans

- Modify the drifted-Maxwellian particle distribution

- Discuss the achievable flux, phase space density and pulse length of the ion injectors

Issues for Longitudinal Bunch Compression Experiments



- Bunch Compression Experiments using Induction Voltage Modulator
- Emittance Growth accompanied by the Beam Manipulation
- Coupling Effects between Longitudinal and Transverse Modes
- Collective Effects during the Bunch Compression

Influence Factors of Compression Ratio (Emittance Growth)

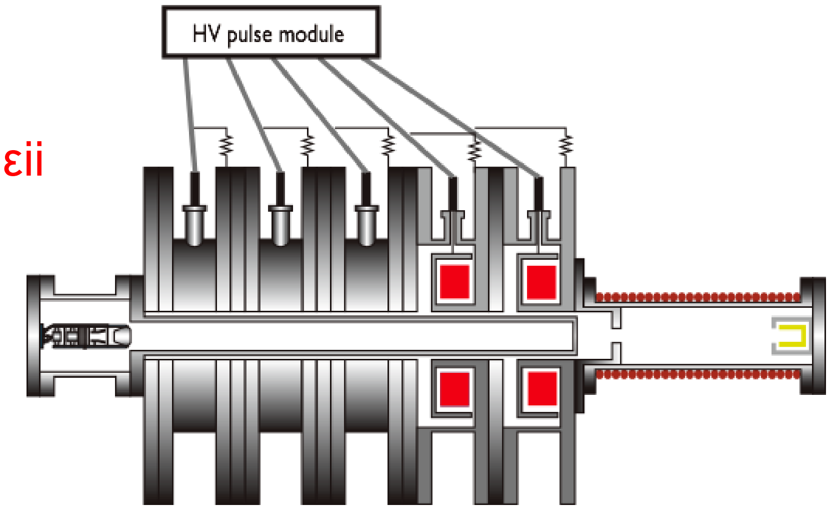
- Accuracy of Modulation Voltage
- Longitudinal Emittance at Injector
- Space Charge Effect
- Collective Effect

Beam Dynamics during Bunch Compression in the Final Stage

Beam Injection

E_i, ΔE_{if}, J_{ii}, T_{ii}, ε_{ii}

Beam Bunching and Transport



Space Charge Field

Collective Effect

Longitudinal-Transverse Coupling

Beam Extraction

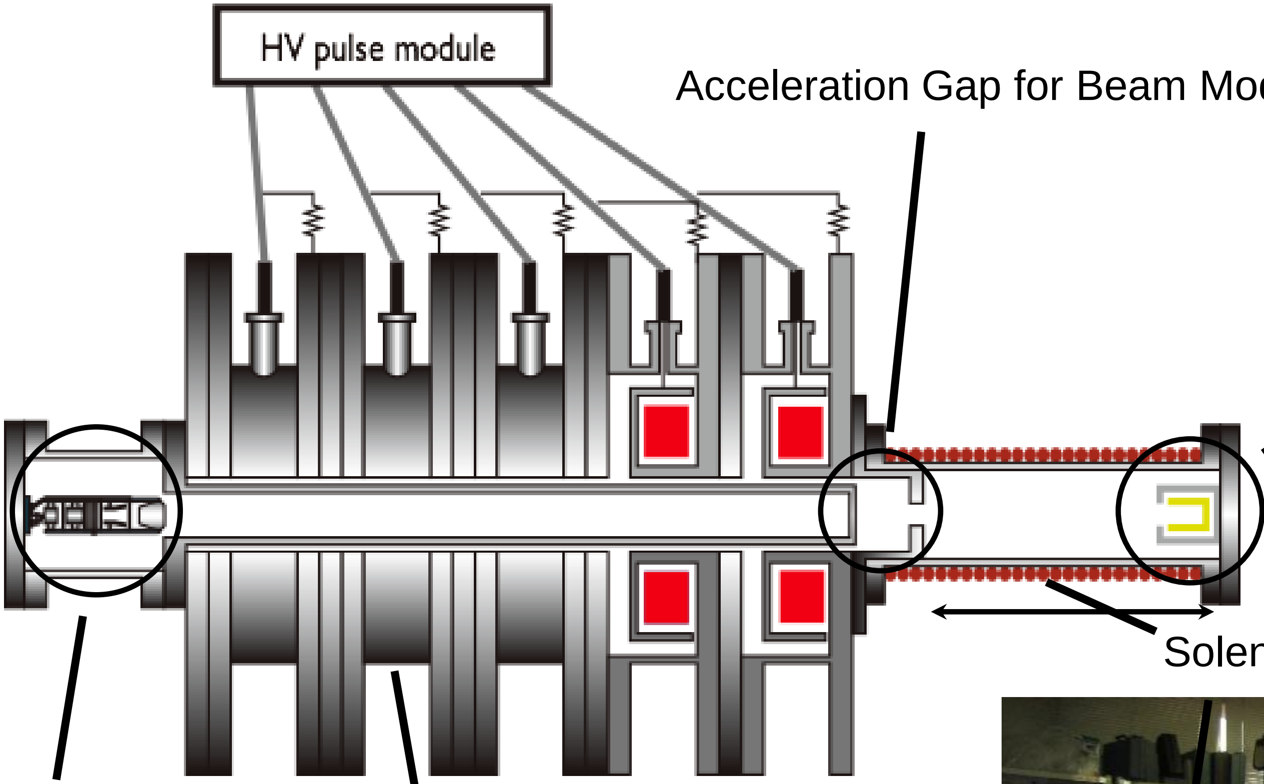
E_{if}, ΔE_{if}, T_{if}, J_{if}, ε_{if}

$$F(\chi)=\frac{J_{if}}{J_{ii}} \propto f(\varepsilon_{if})$$

Emittance Growth

Compression Ratio

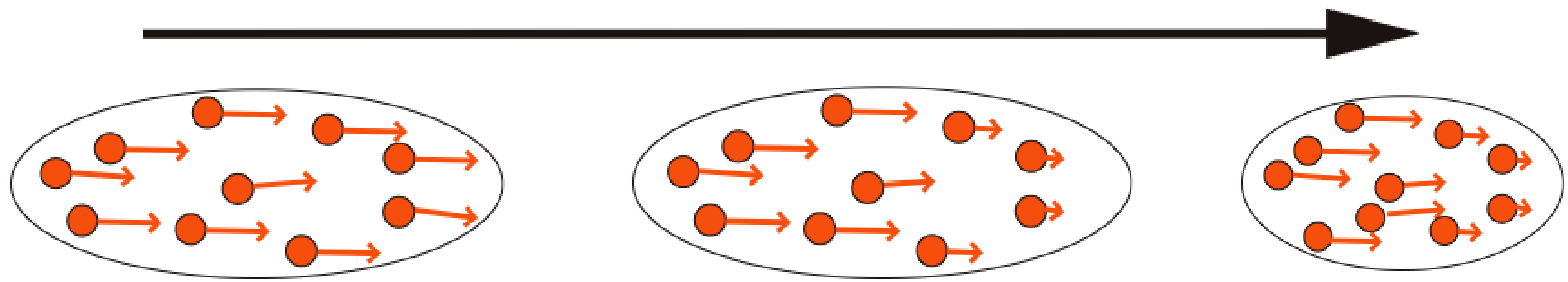
Arrangement for Bunch Compression Experiments

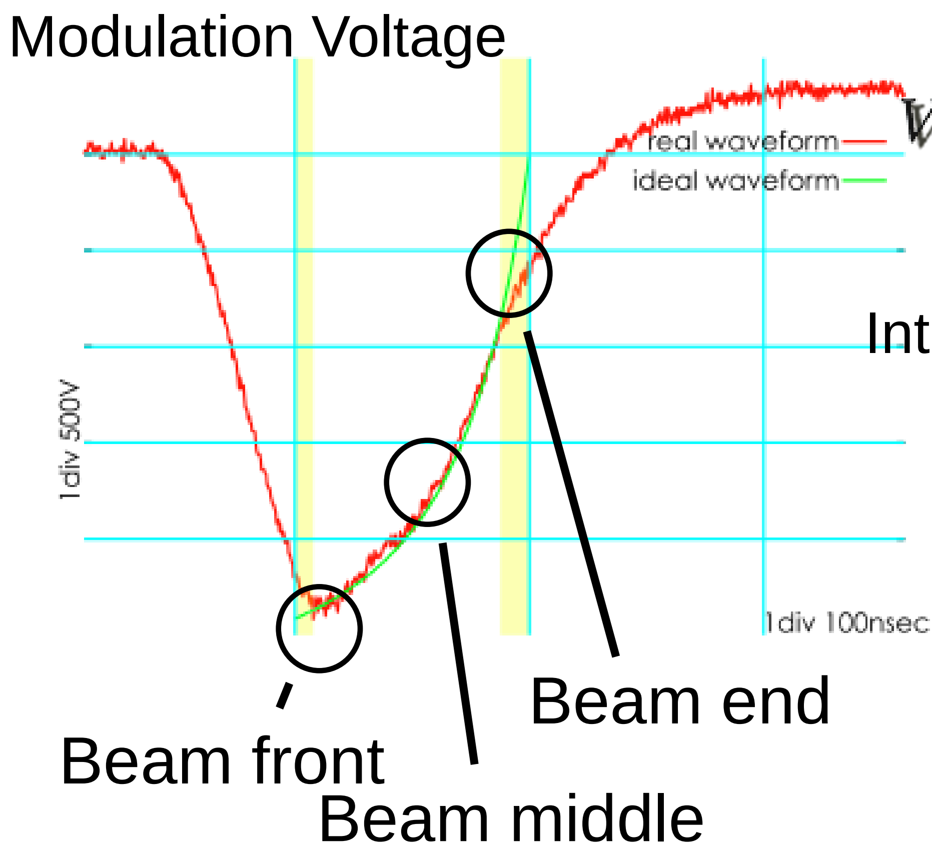


Strategy

- FET-based voltage driver for Induction Adder
- E-beam using Grid-controlled e-gun
- Solenoidal transport line

Analytically Derived Manipulation-Voltage for Longitudinal Compression





$$V_{dec}(t) = \frac{m_e}{2q_e} \cdot \frac{1}{\left(\sqrt{\frac{m_e}{2q_e V_0}} + \frac{T-t}{L}\right)^2} - V_0$$

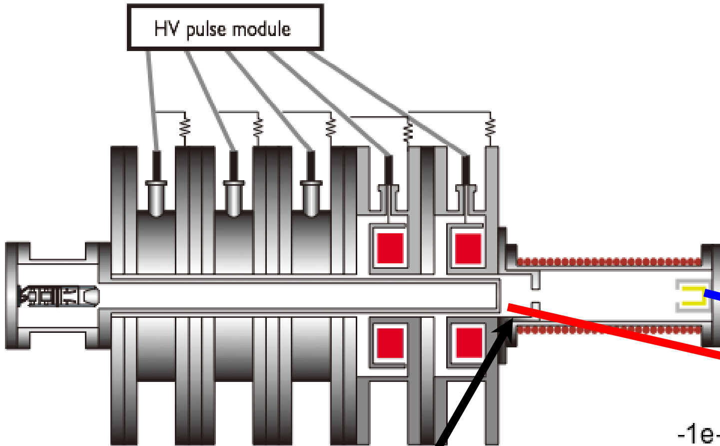
Intended Voltage at Beam buncher

V_0 : Initial Beam-Voltage

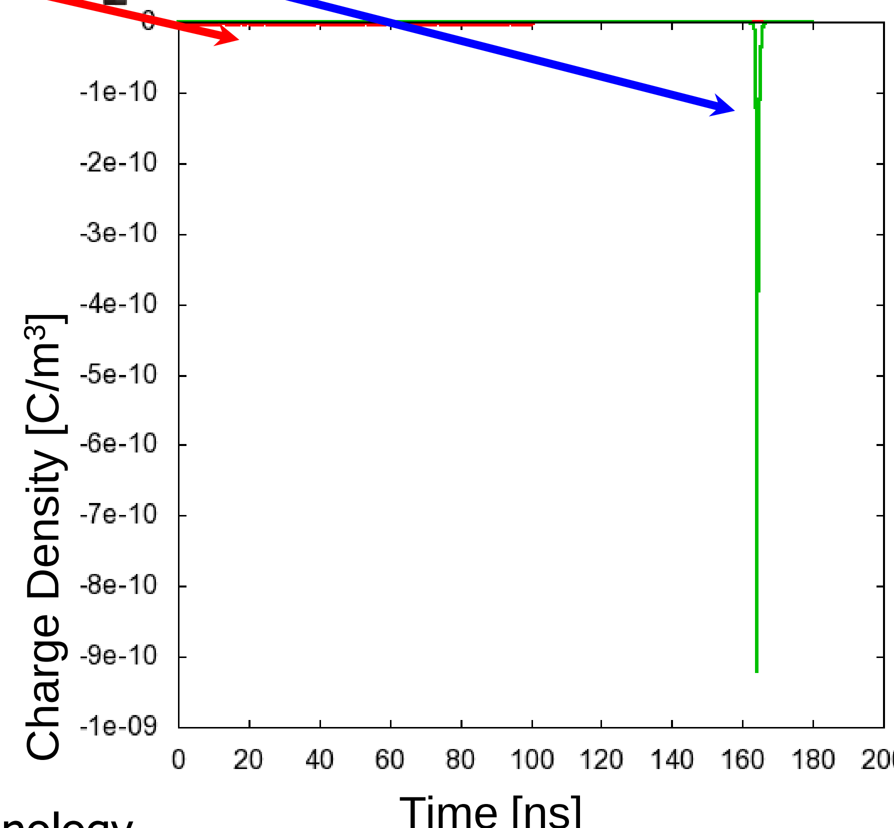
T : Initial Pulse Width

L : Transport Distance

Typical Result of PIC Simulation of the e-Beam Transport



1D PIC Calculation



Applied Voltage

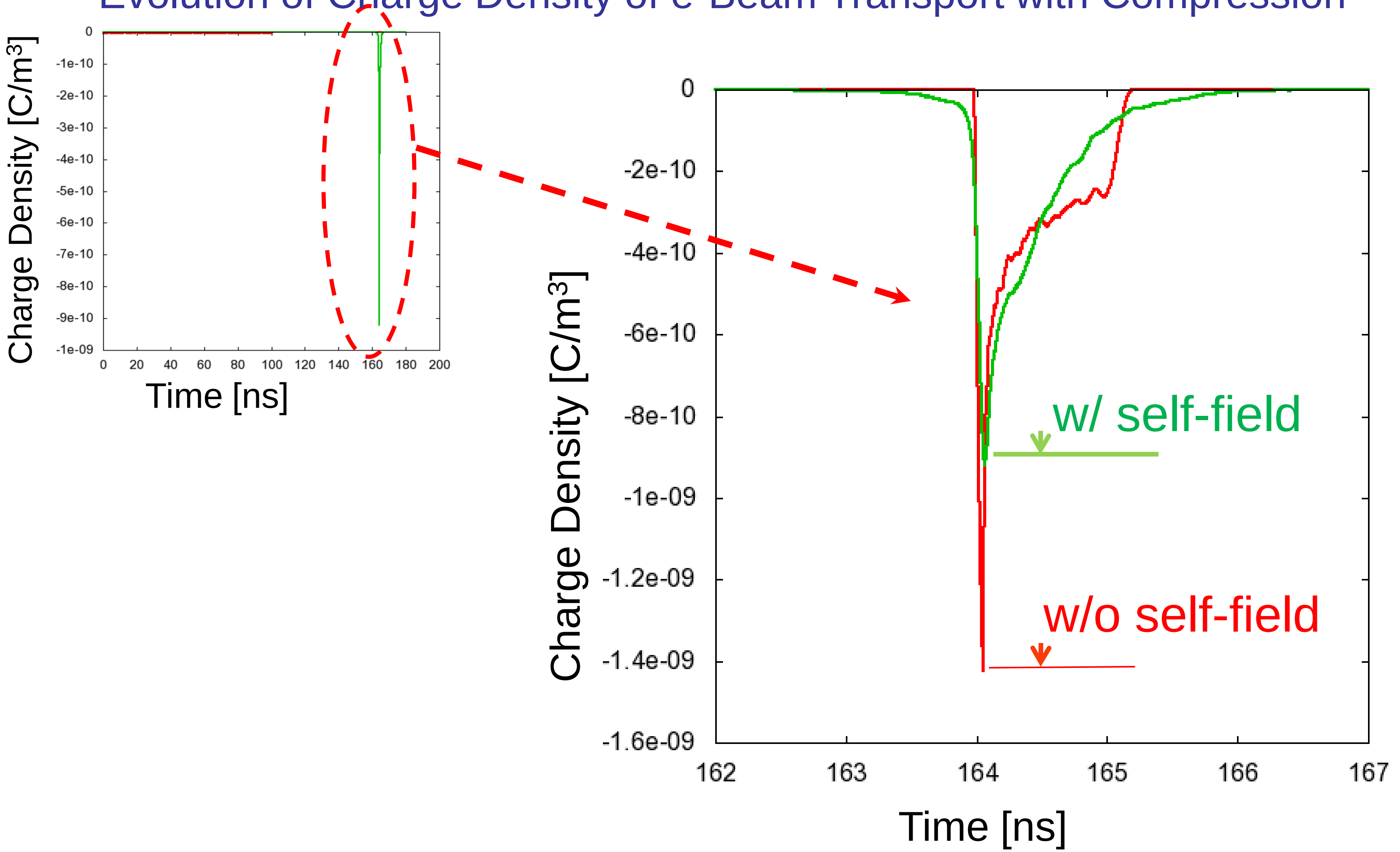
$$V_{dec}(t) = \frac{m_e}{2q_e} \cdot \frac{1}{\left(\sqrt{\frac{m_e}{2q_e V_0}} + \frac{T-t}{L}\right)^2} - V_0$$

V_0=2.8kV @ L=2m during T=100ns

by T. Kikuchi, Nagaoka University of Technology,

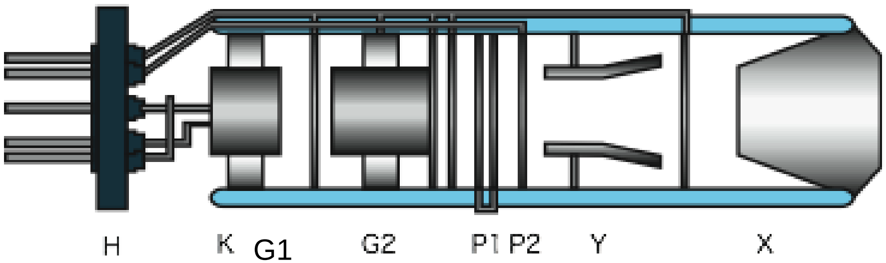
PIC Simulation indicates an Effect of Space Charge Field on the Bunch Compression in Our Experimental Condition

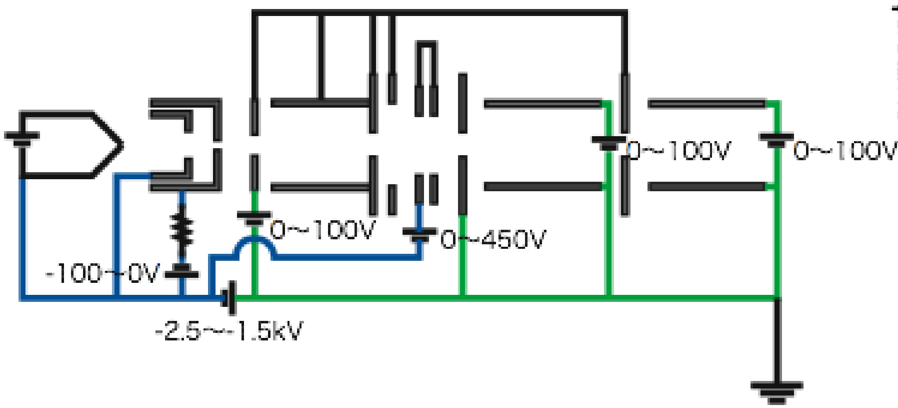
Evolution of Charge Density of e-Beam Transport with Compression

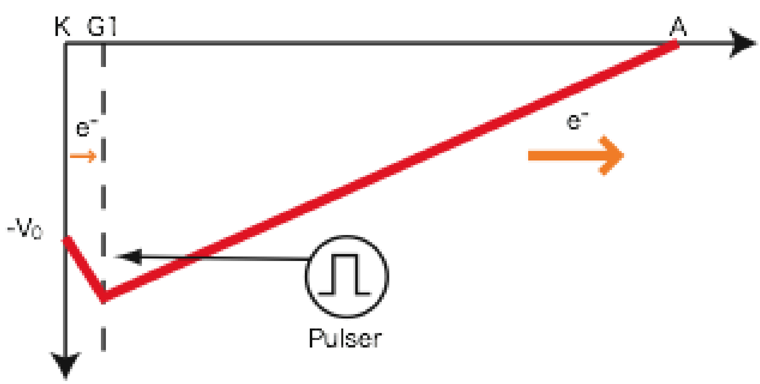


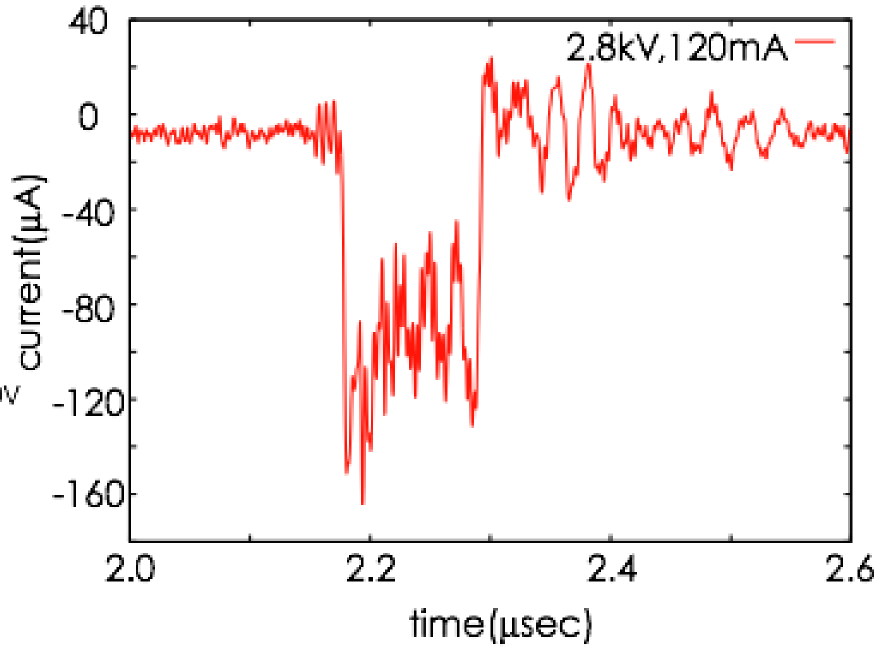
by T. Kikuchi, Nagaoka University of Technology,

Grid-controlled Electron Gun for Low Temperature Beam Formation







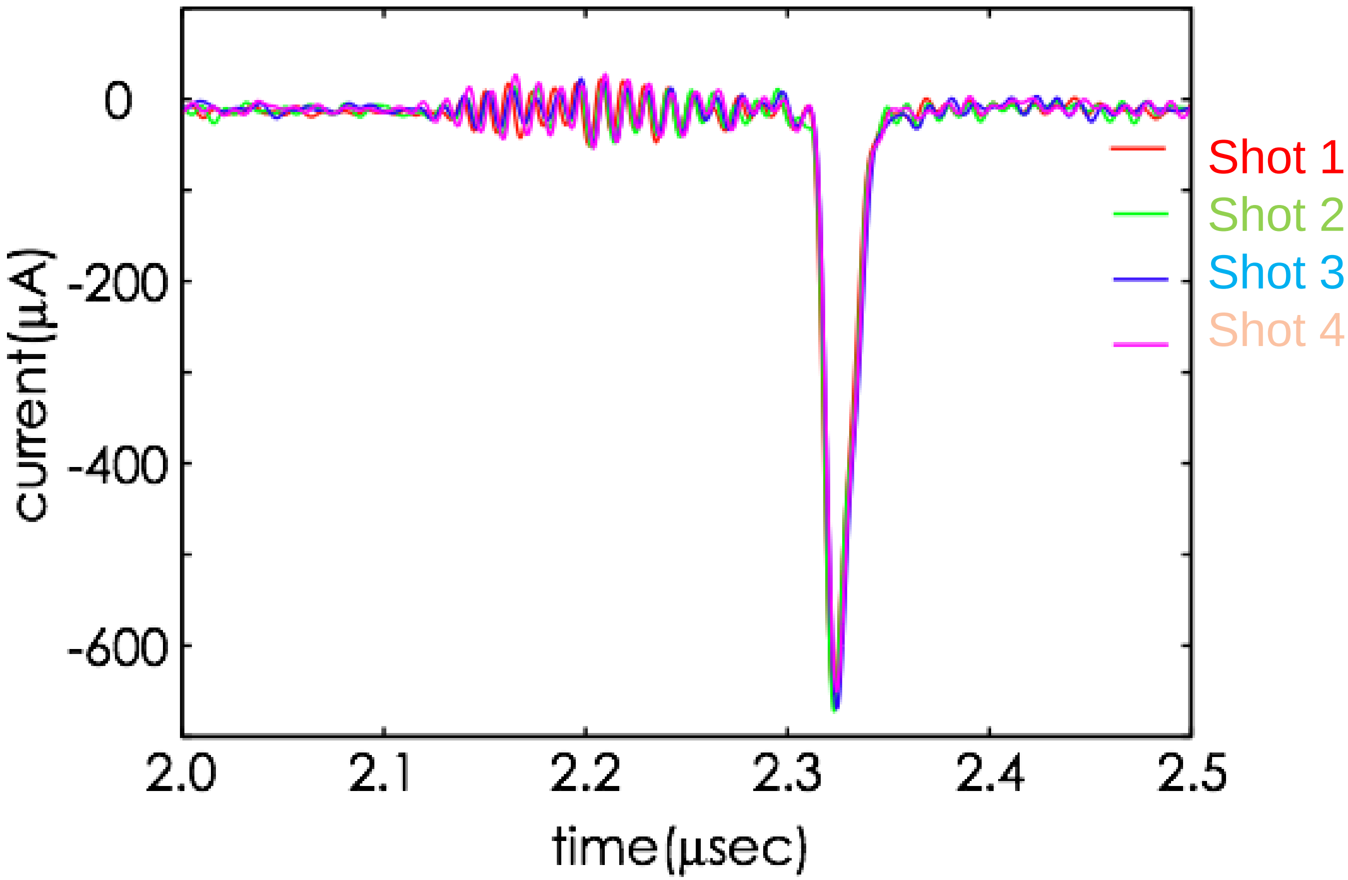


Typical Waveform of e-Injector Current

Electron Gun

- Thermo-electric Emission
- Statically Biased Electrodes
- Grid-controlled

Reproducibility of the Compressed Waveform

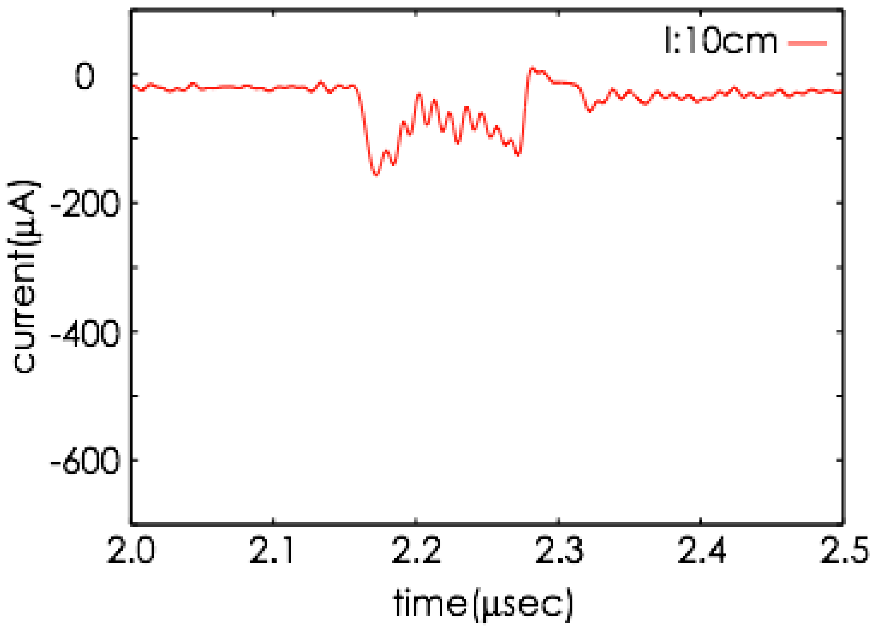


Successive 4-shots traces were overlapped

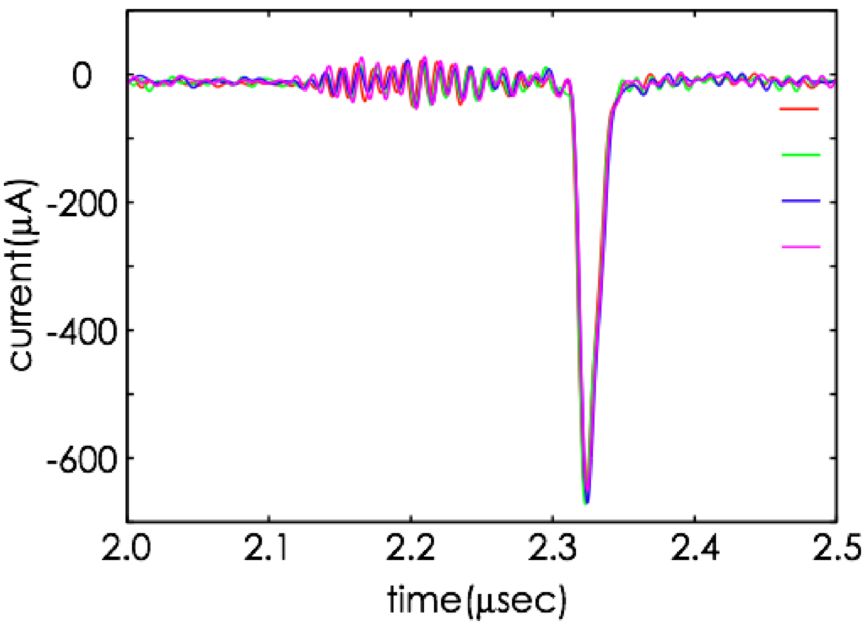
Reproducibility was vastly improved by the Grid-controlled electron gun and FET voltage modulator

Waveforms of Beam Current at Injection and at the Destination

Injection 2.8keV, Pulsed Beam T=100ns, $\boldsymbol{B} \simeq 0.03T$



Current at beam injector



Beam current at destination (L=2m)
Successive 4-shots were over lapped

$$I_{peak} \approx 100\mu A$$

$$\Delta t \approx 100nsec$$

$$J \approx 3.2mA/cm^2$$

→

$$I_{peak} \approx 670\mu A$$

$$\Delta t \approx 15nsec$$

$$J \approx 21mA/cm^2$$

Summary and Future Plans of the Beam Compression Experiments

Summary

- We developed ;
  - FET-driven voltage adder for longitudinal bunch compression
  - Grid-controlled quasi-static electron gun
  - 2m solenoidal transport line
- Beam bunch was compressed with factor 6-7 and the process has good reproducibility

Future Plans

- Faster FET switch for more precise modulation waveform
- Stronger magnetic field for suppresion of transverse beam motion
- Discuss transverse-longitudinal coupling and/or collective effects on the emittance growth

Concluding Remarks

- HIF and/or HED drivers need beam manipulation in strongly space charge dominated region, in particular, in the ion injector and the final stage of the accelerator

- For high-flux and low emittaance ion extraction:
  - We are investigating ion extraction processes from moving plasma

- For study on the bunching-beam dynamics:
  - We have started a scaled experiment using a controllable/reproducible device composed of grid-controlled e-beam source and FET-driven induction buncher

- Goal of our beam physics studies is to know the margin of emittance growth from the injector to the target