長岡技術科学大学
Nagaoka University of Technology

Nagaoka University of Technology
PLASMA LABORATORY

Study on Beam Dynamics during Longitudinal Bunch Compression using Compact Simulator Supported by Theoretical and Numerical Approaches for Heavy Ion Inertial Fusion

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Nagaoka University of Technology

19th International Symposium on Heavy Ion Inertial Fusion,
August 12-17, 2012, Berkeley, CA, USA

Topics

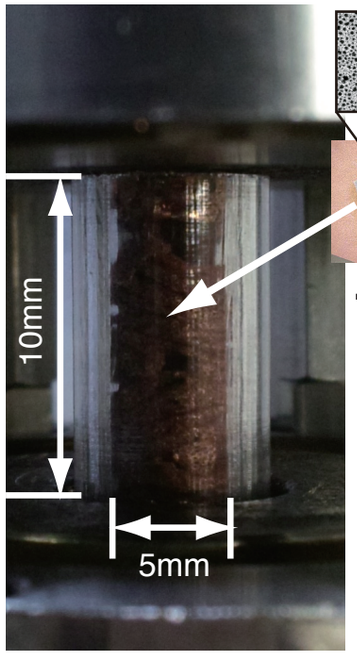
Researches in Heavy Ion Inertial Fusion & High Energy Density Laboratory Physics in Nagaoka University of Tech.

Beam Dynamics Study during Longitudinal Bunch Compression using Compact Simulator

+ Electron Beam Compact Simulator Device in Tokyo Tech.
+ Numerical Simulation of Beam Dynamics
+ Beam Parameters in Compact Simulator

Experimental setup for isochoric heating of WDM and evaluating WDM electrical conductivity

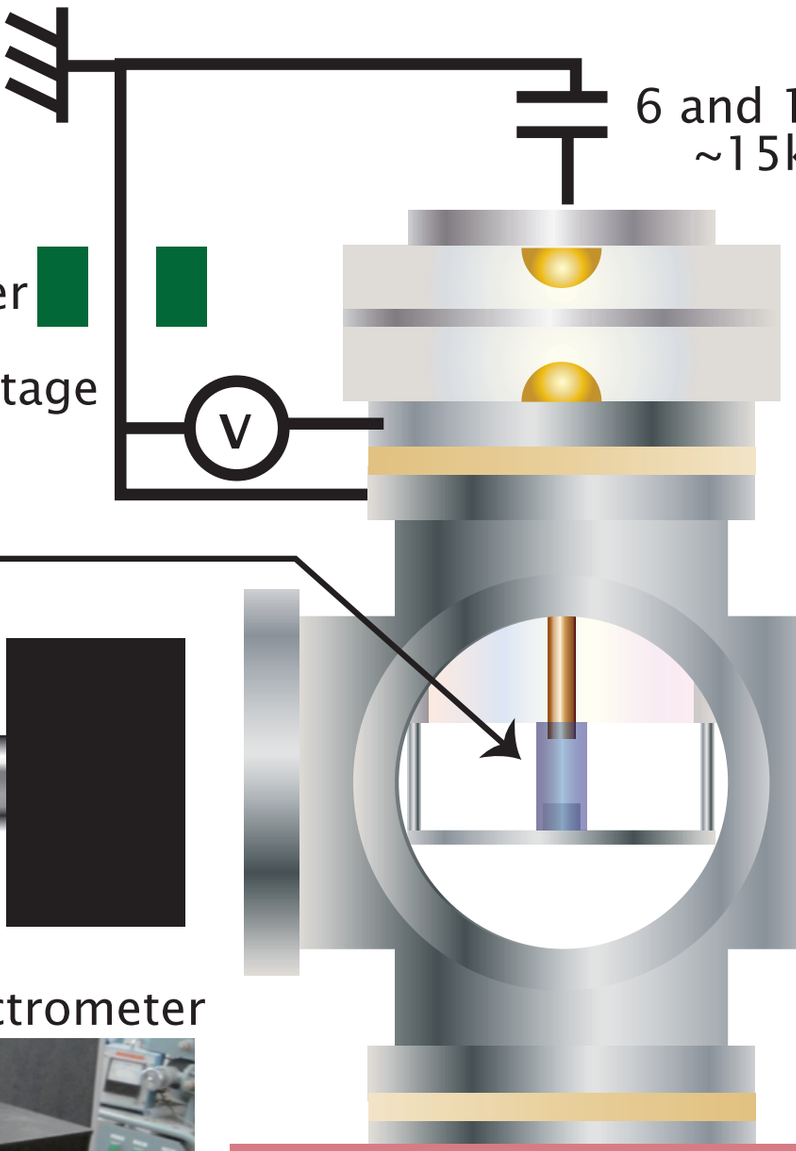
Foam materials confined by Sapphire Capirary



Current Transformer

High Voltage Probe

6 and 12μF ~15kV

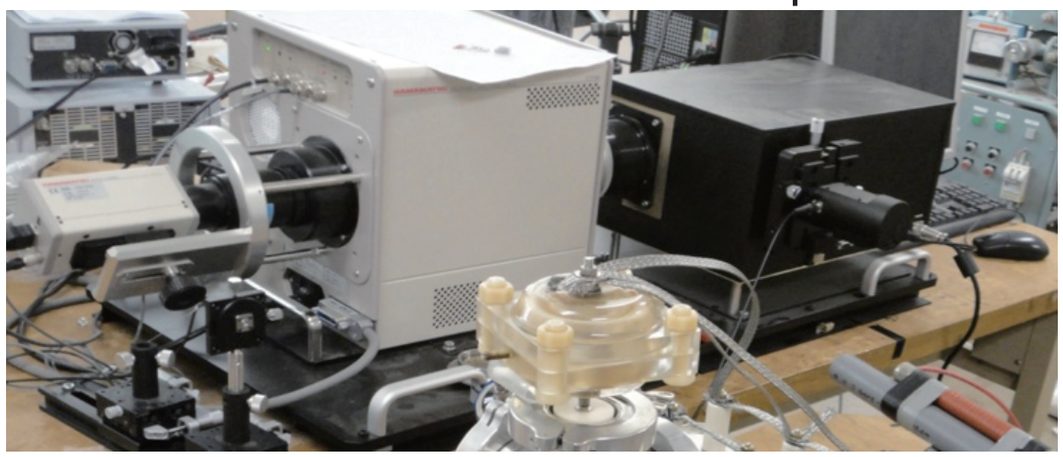


Y. Amano, et. al., to be published RSI, 83 (2012)

Streak Camera

Framing Camera
(Ultra Neo: Nac Imaging Tec.)

Spectrometer

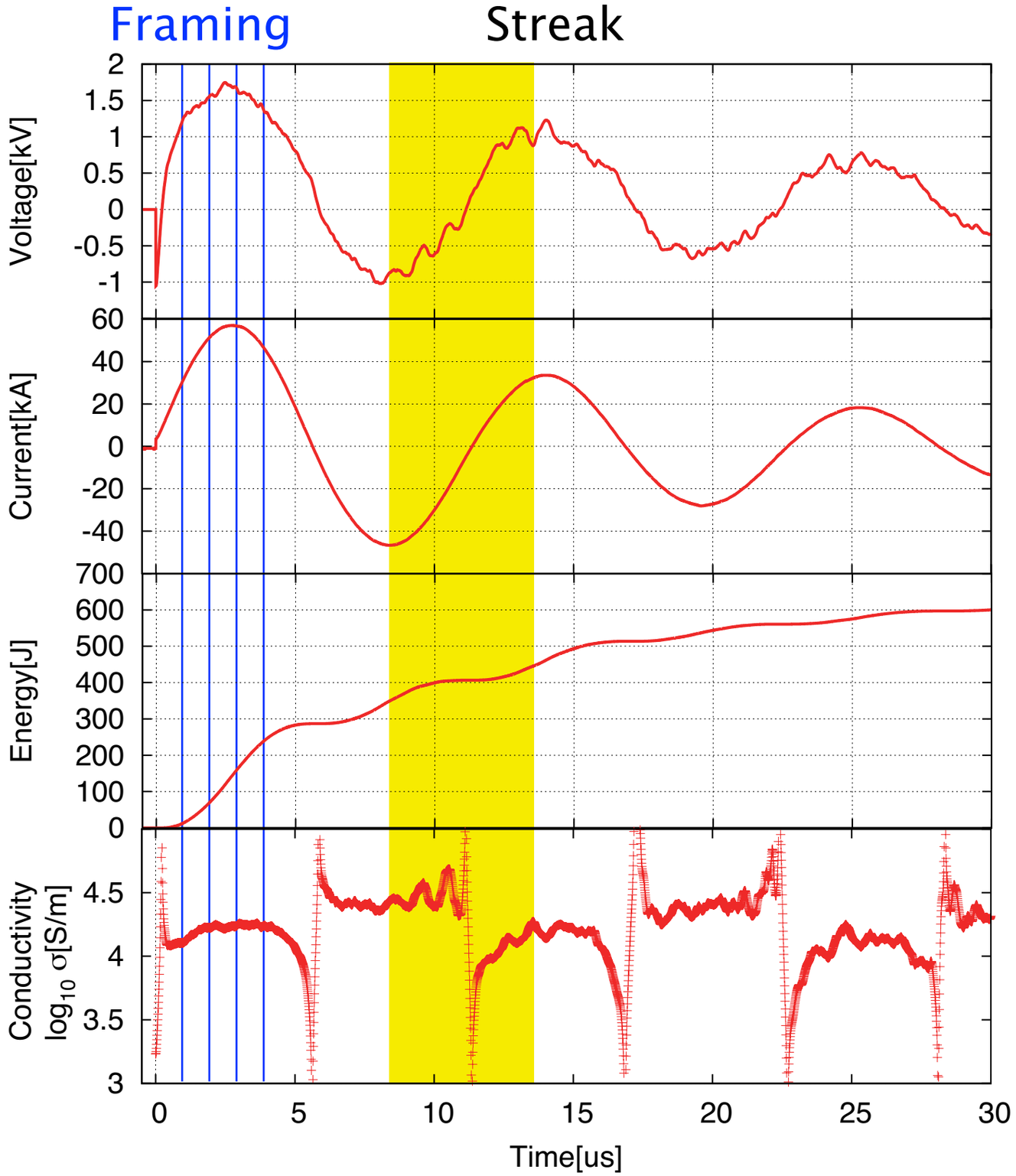


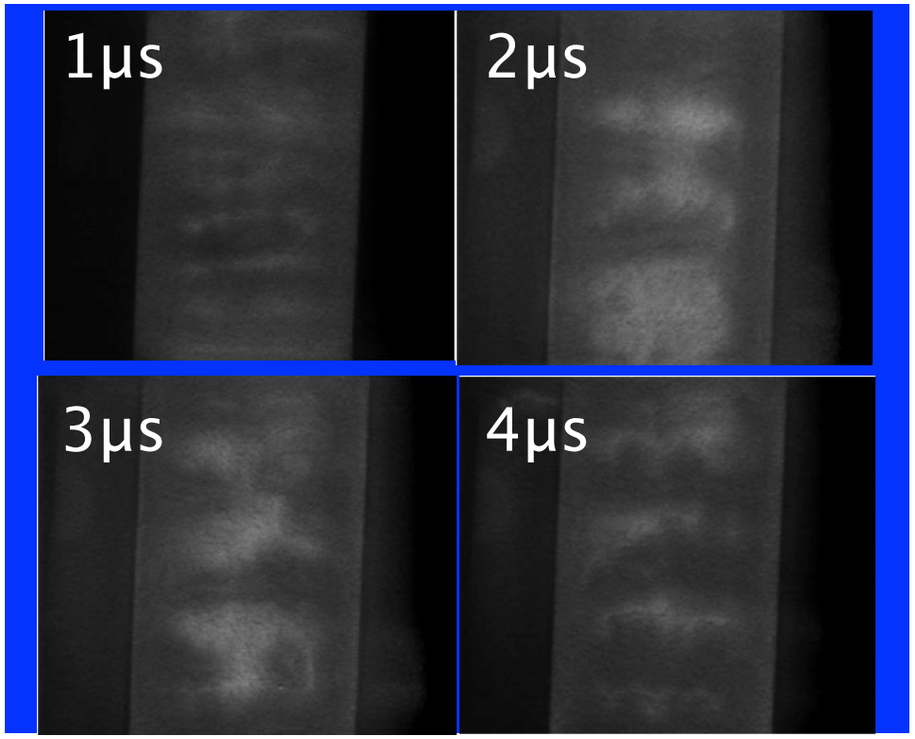
Rotary and
Tubo Molecular Pumps (~10^{-3}Pa)

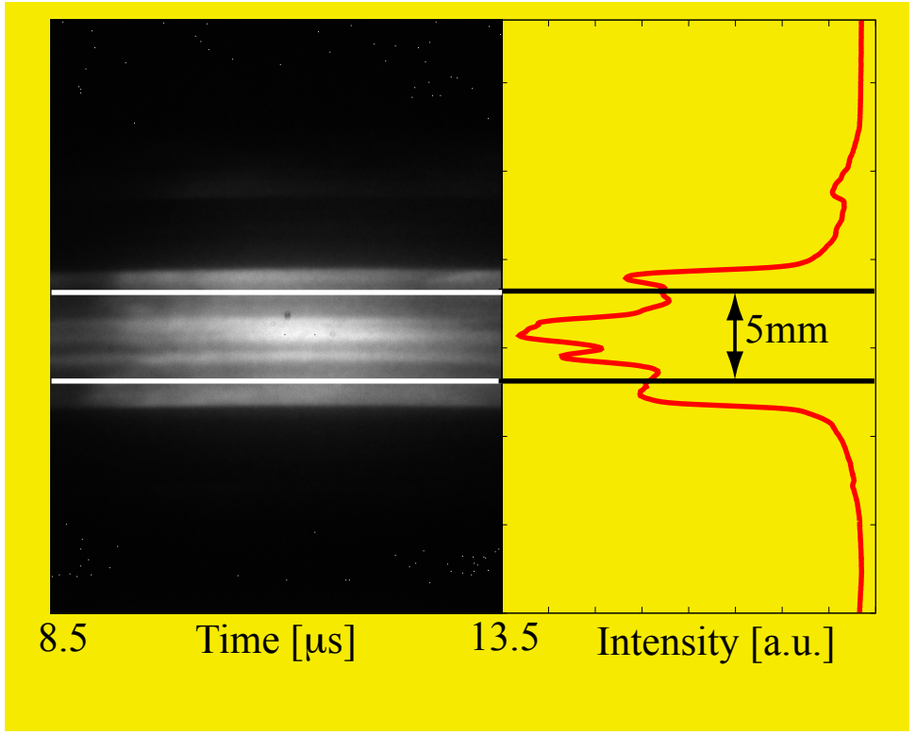
Y. Miki, et. al., in this conference, Poster 102

T. Sasaki, et. al., in this conference, Talk 75

WDM is confined by the sapphire capillary (0.1ρ_s@Copper)

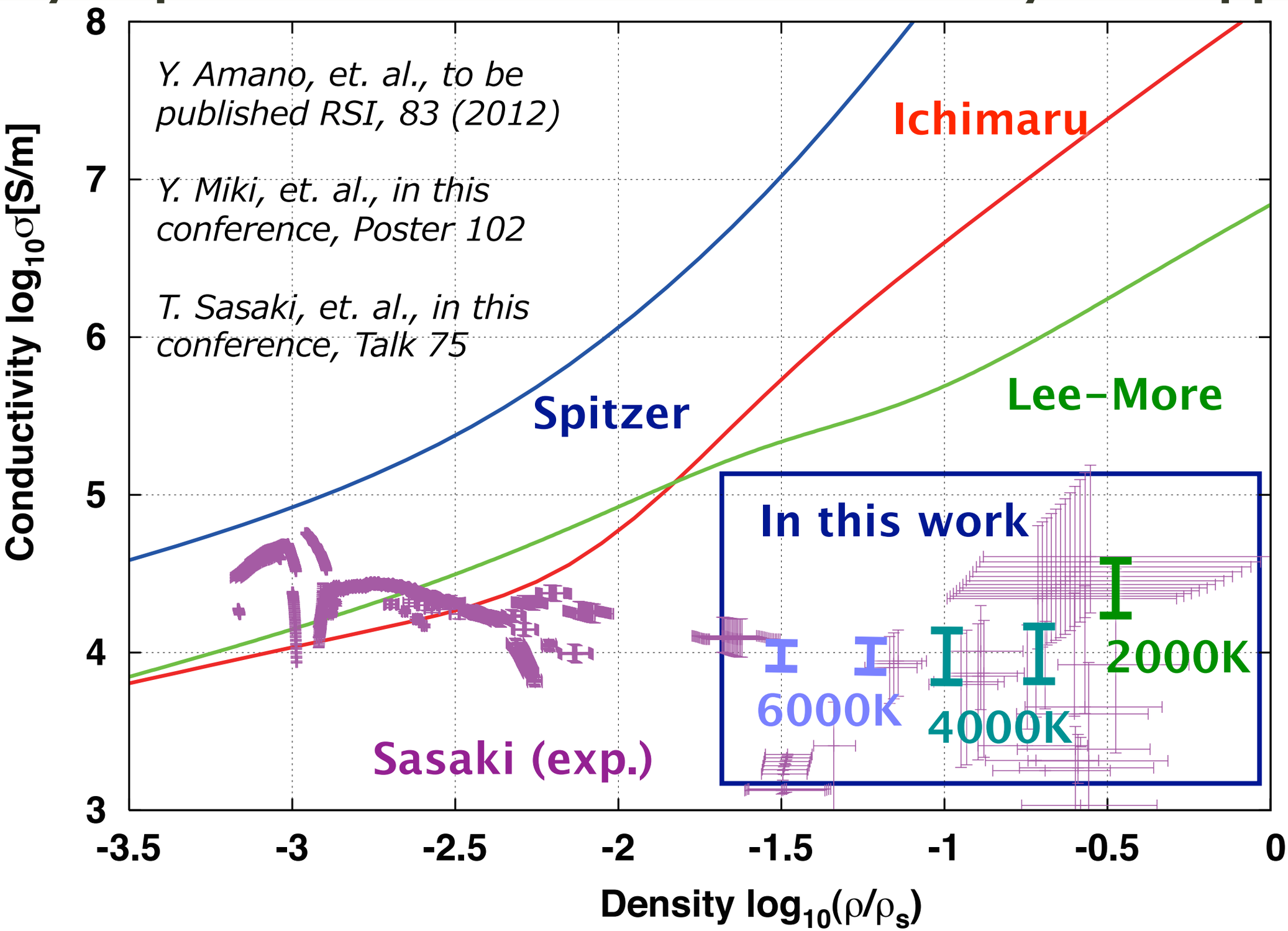






Y. Amano, et. al., to be published RSI, 83 (2012); Y. Miki, et. al., in this conference, Poster 102

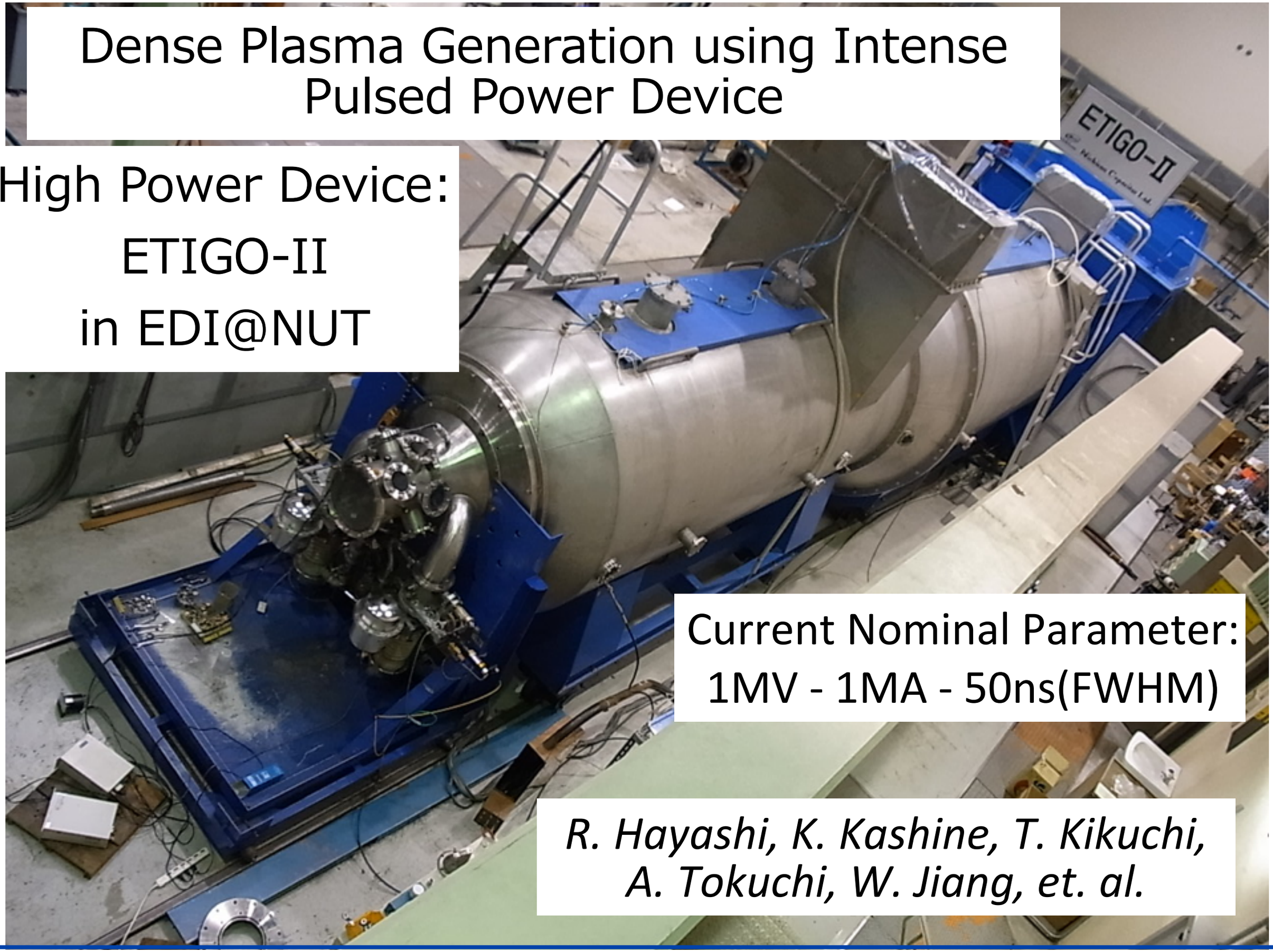
Density dependence of electrical conductivity for copper



Observed electrical conductivity dependence on density is similar for previous experimental results.

Dense Plasma Generation using Intense Pulsed Power Device

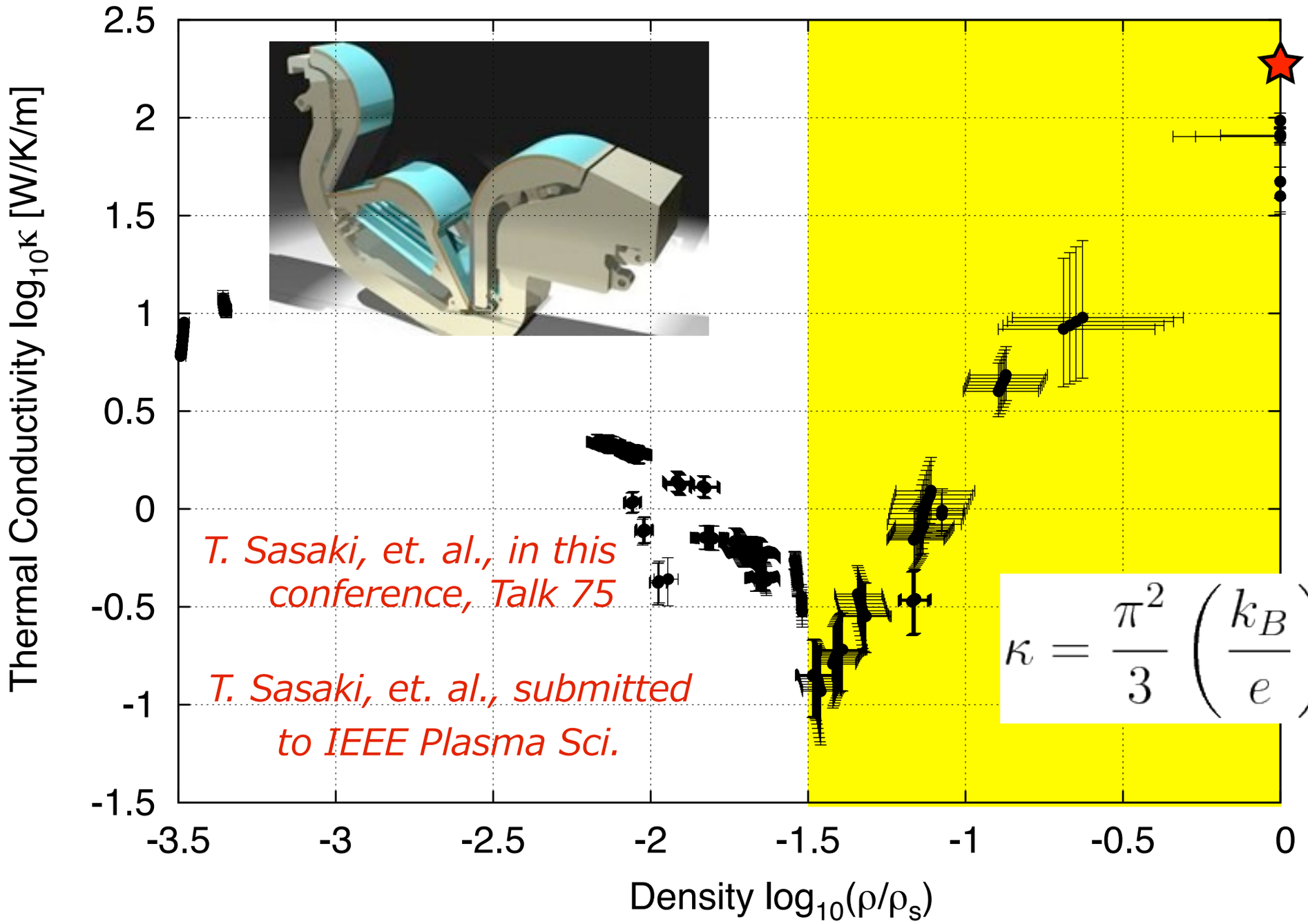
High Power Device:
ETIGO-II
in EDI@NUT



Current Nominal Parameter:
1MV - 1MA - 50ns(FWHM)

R. Hayashi, K. Kashine, T. Kikuchi,
A. Tokuchi, W. Jiang, et. al.

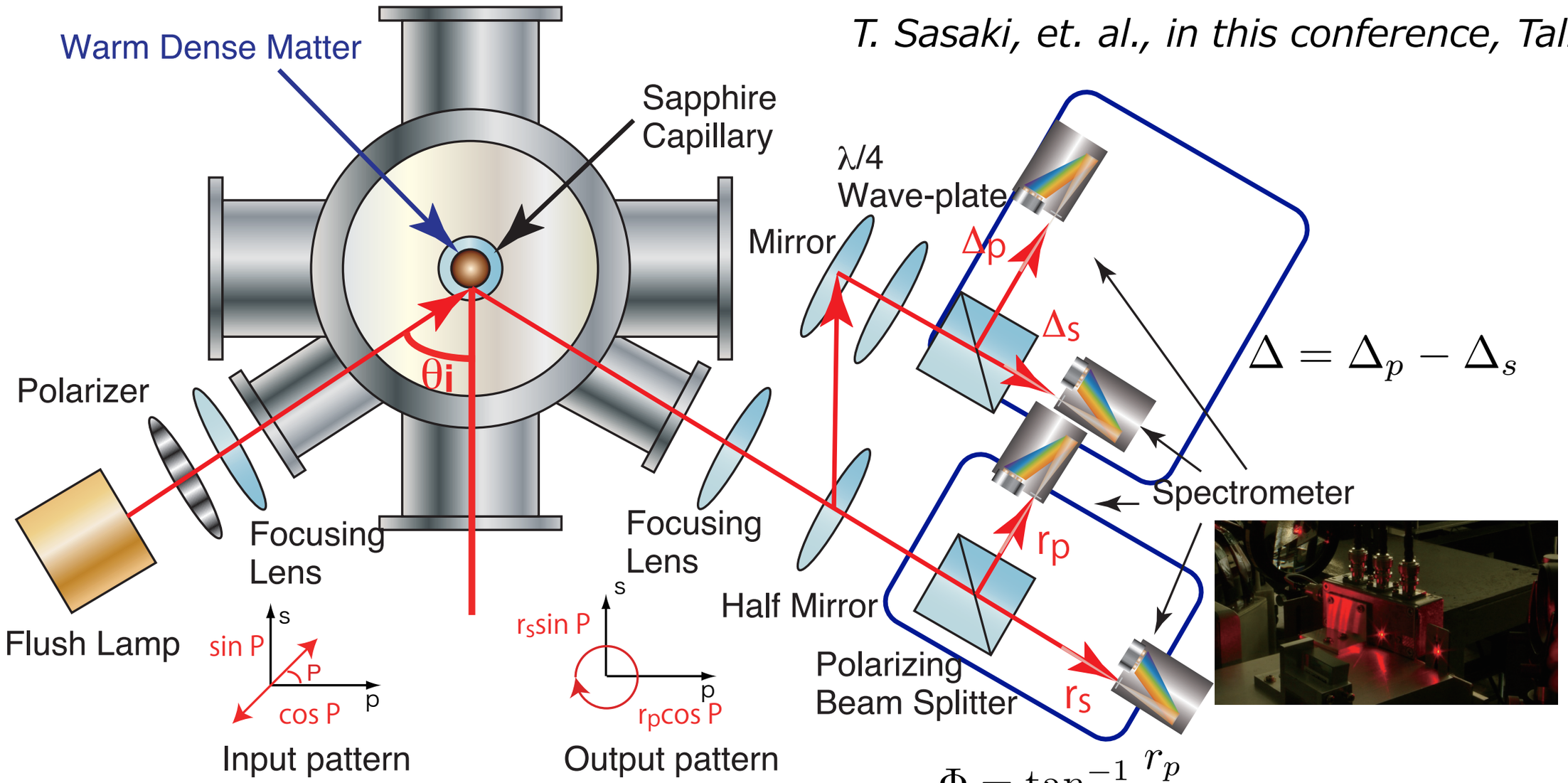
Thermal conductivity for WDM are semi-empirically evaluated by the electrical conductivity



Thermal conductivity of dense tungsten plasma is estimated to be 0.1 W/K/m at 0.03ρ_s. => For predicting lifetime of divetor for MCF.

Opacity measurement for visible wavelength observed by using fast ellipsometry is started

T. Sasaki, et. al., in this conference, Talk 75



$$\Delta = \Delta_p - \Delta_s$$

$$\Phi = \tan^{-1}\frac{r_p}{r_s}$$

$$n^2 - k^2 = \sin^2\theta_i\left\{1 + \frac{\tan^2\theta_i\left(\cos^2 2\Phi - \sin^2 2\Phi\sin^2\Delta\right)}{\left(1+\sin 2\Phi\cos\Delta\right)^2}\right\}$$

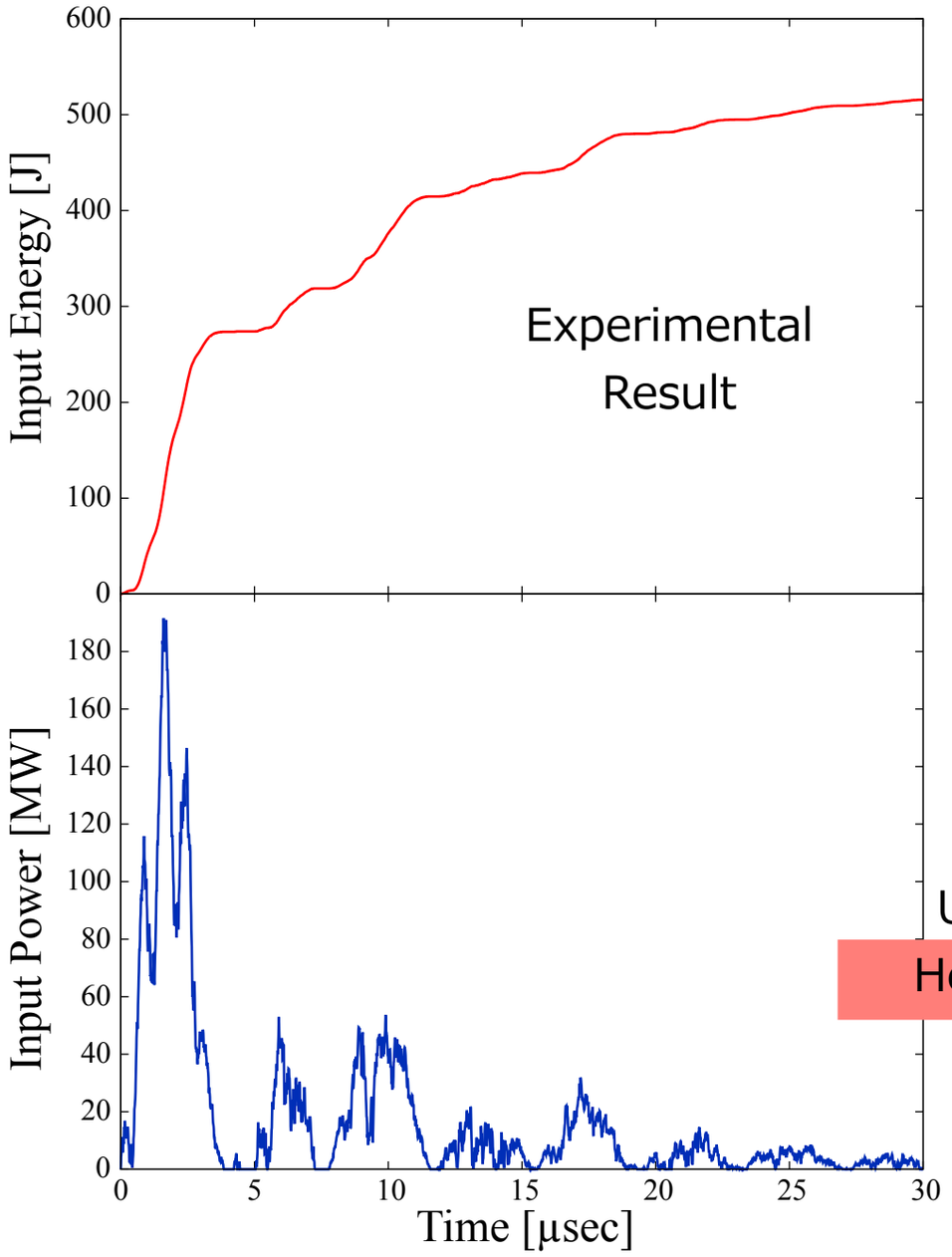
$$2nk = \frac{\sin^2\theta_i\tan^2\theta_i\sin 4\Phi\sin\Delta}{\left(1+\sin 2\Phi\cos\Delta\right)^2}$$

$$k(\lambda) = \frac{4\pi}{d}$$

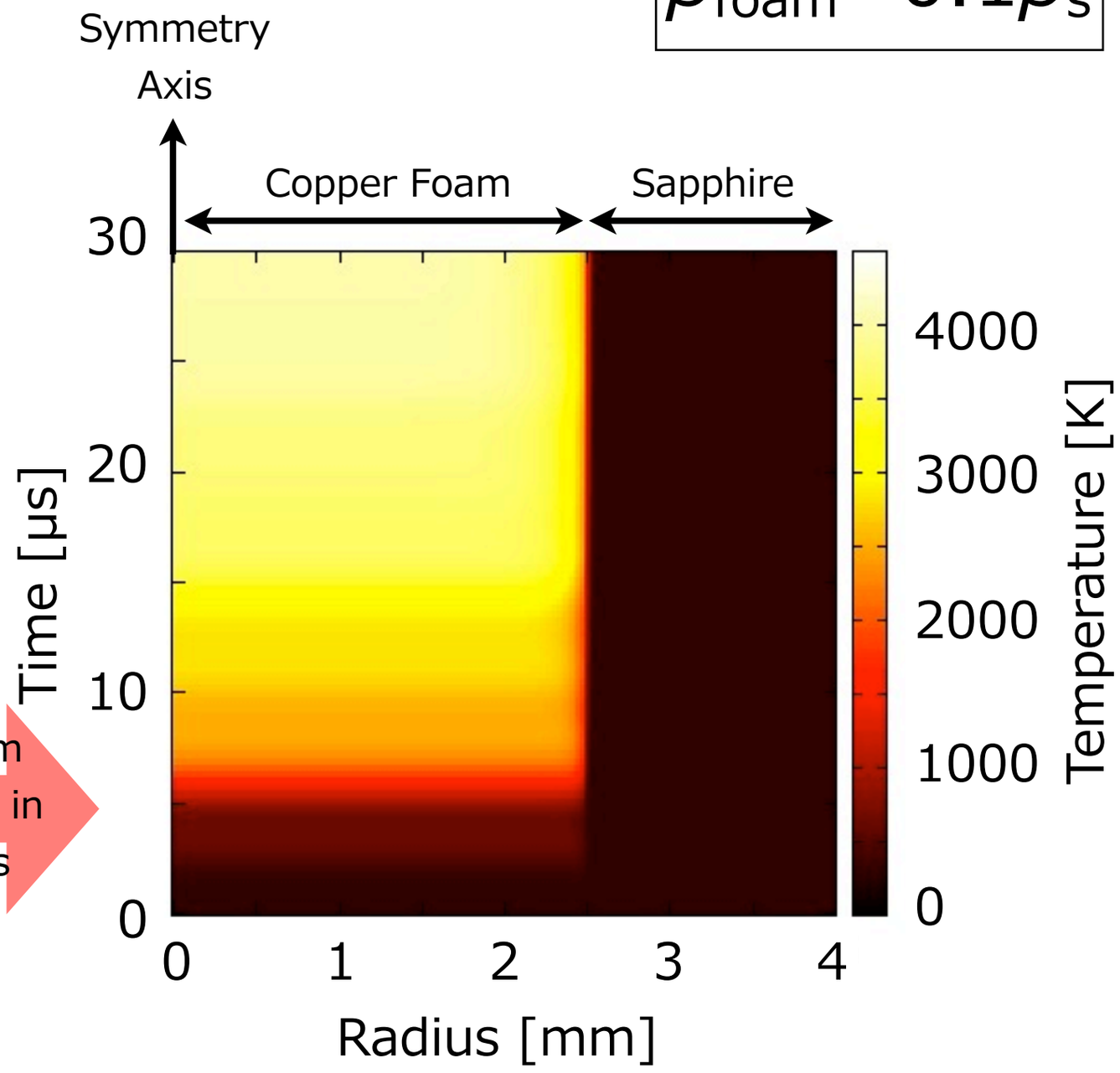
d:Optical Depth

Calculation Result of Thermal Diffusion

$\rho_{foam}=0.1\rho_s$



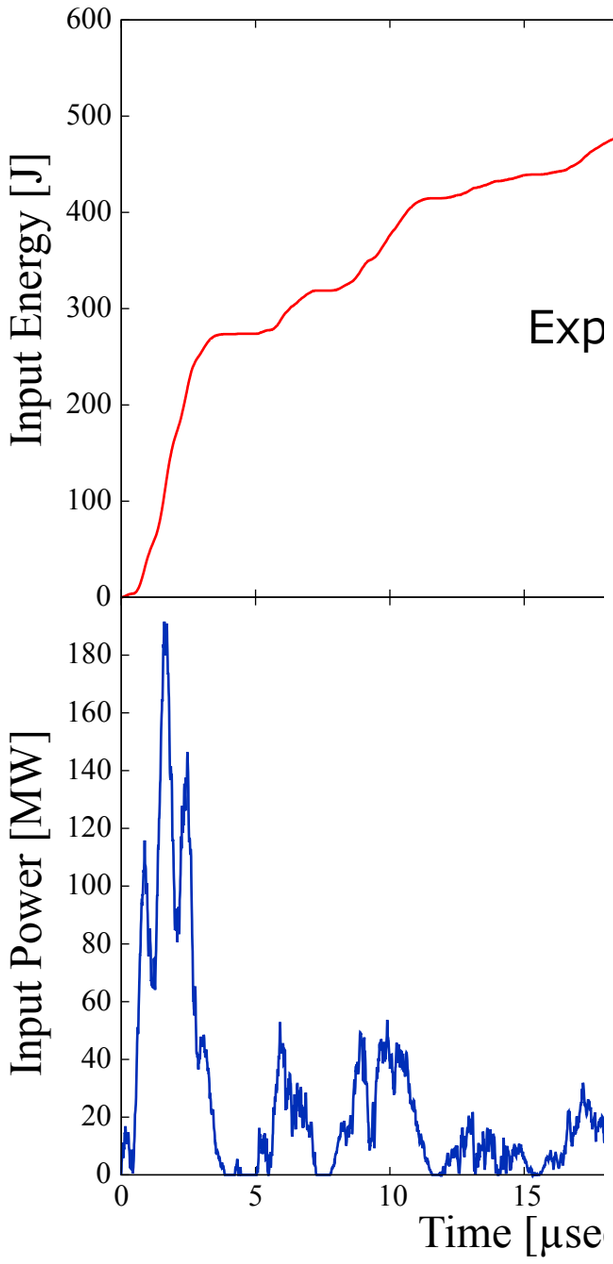
Uniform Heating in Radius

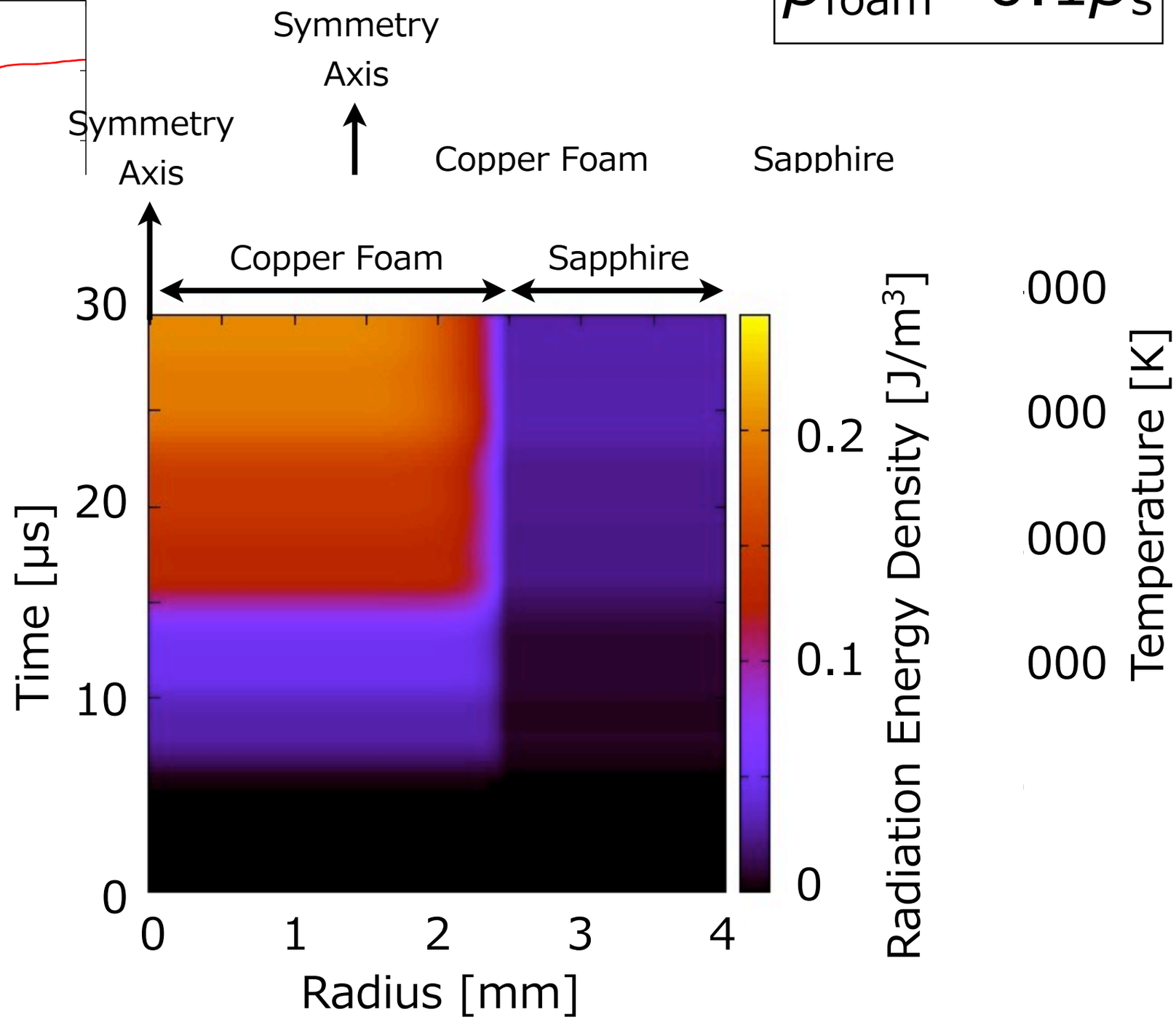


T. Kikuchi, et. al., to be published in NIFS-Proc.

Calculation Result of Thermal Diffusion

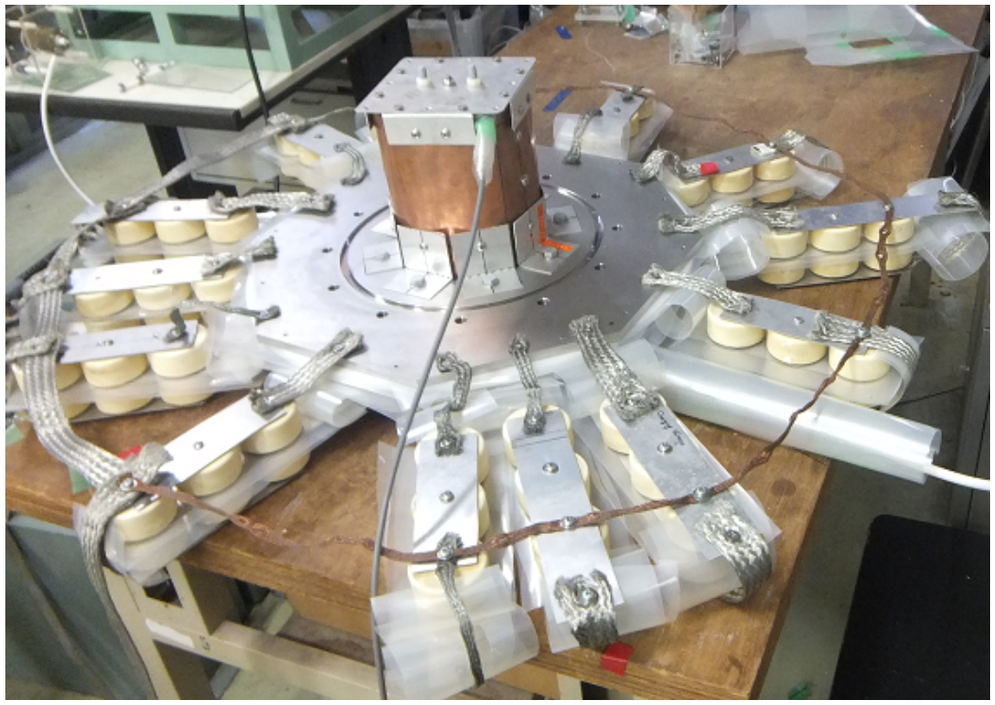
$\rho_{foam}=0.1\rho_s$

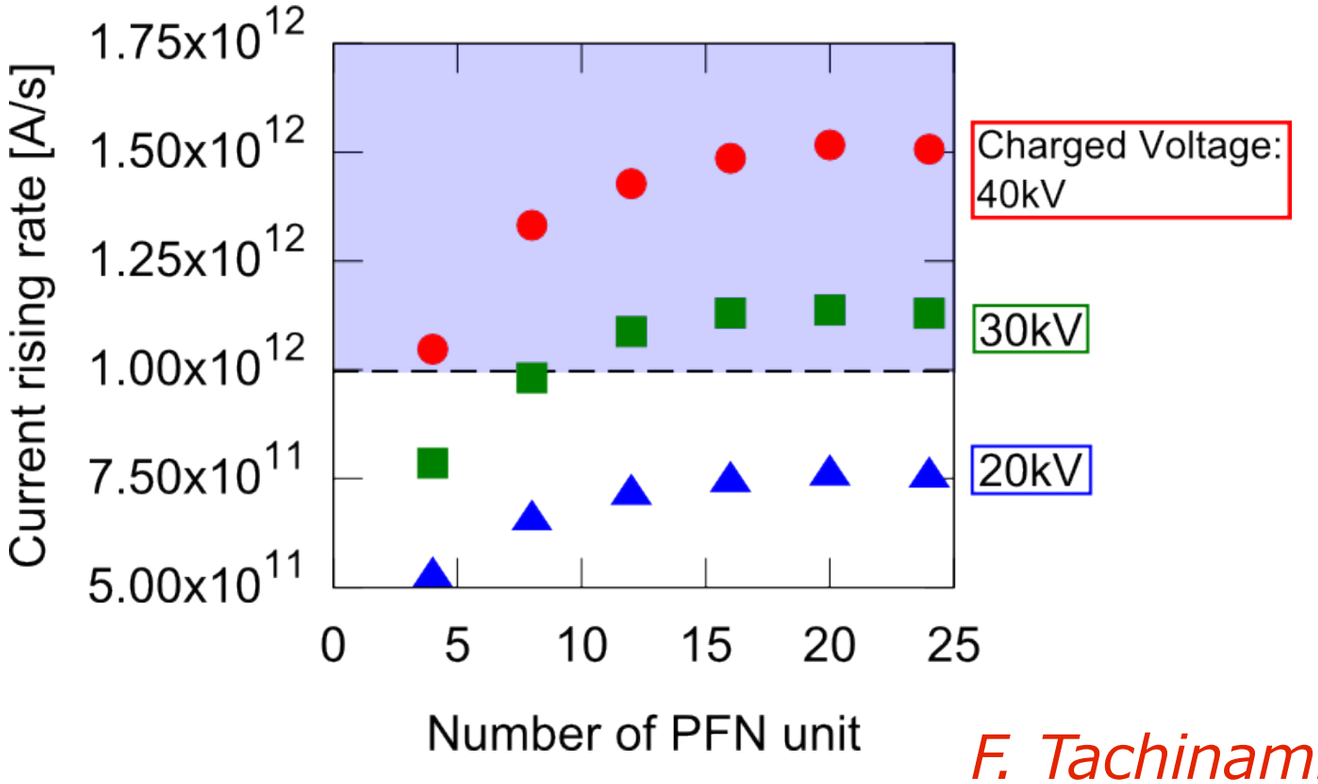


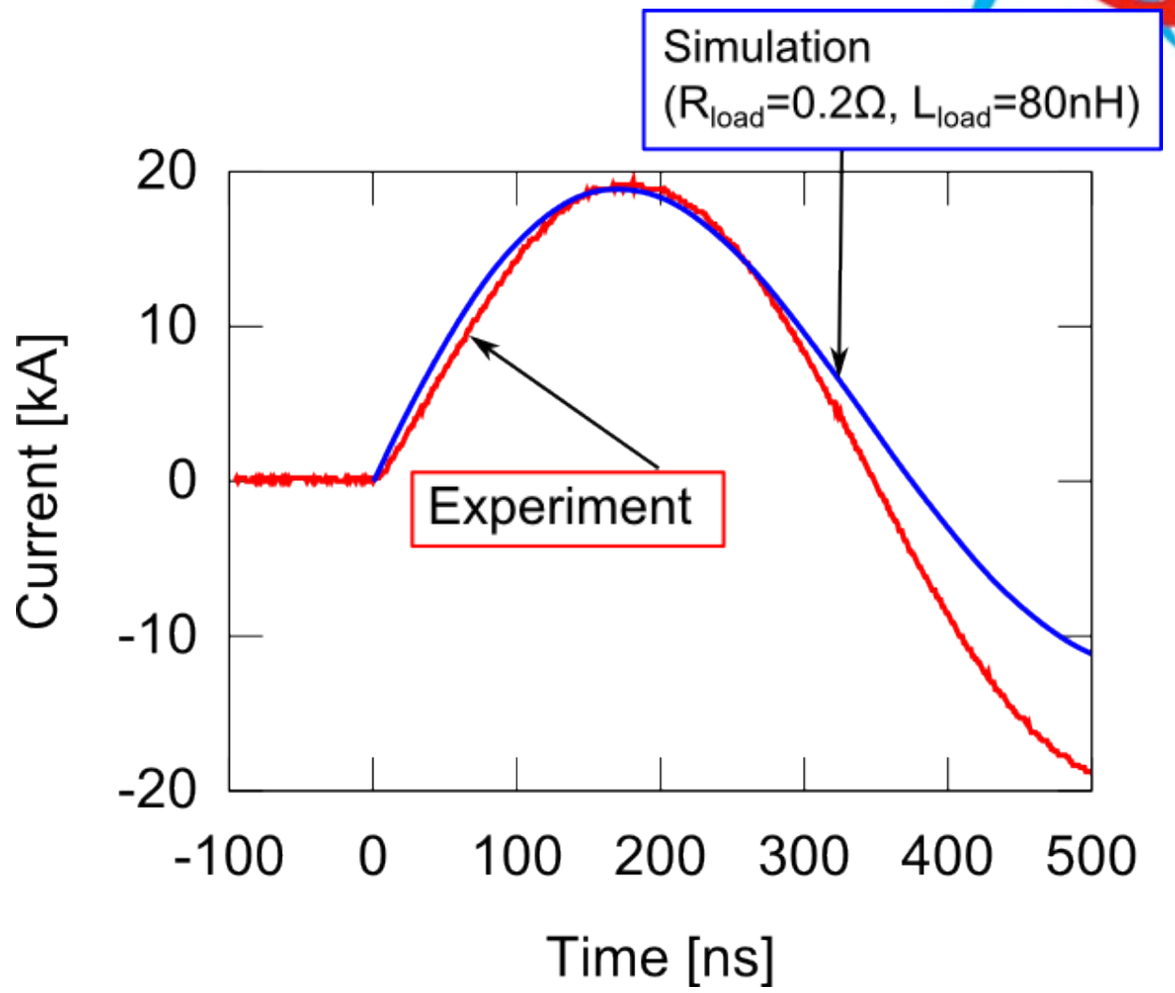


T. Kikuchi, et. al., to be published in NIFS-Proc.

Pulsed-power Generator toward intense X-ray source from X-pinch emission







The pulsed-power generator toward intense X-ray source from X-pinch emission is constructed.

Required voltage can be reduced about 30 kV.

F. Tachinami, et. al., in this conference, Poster 104

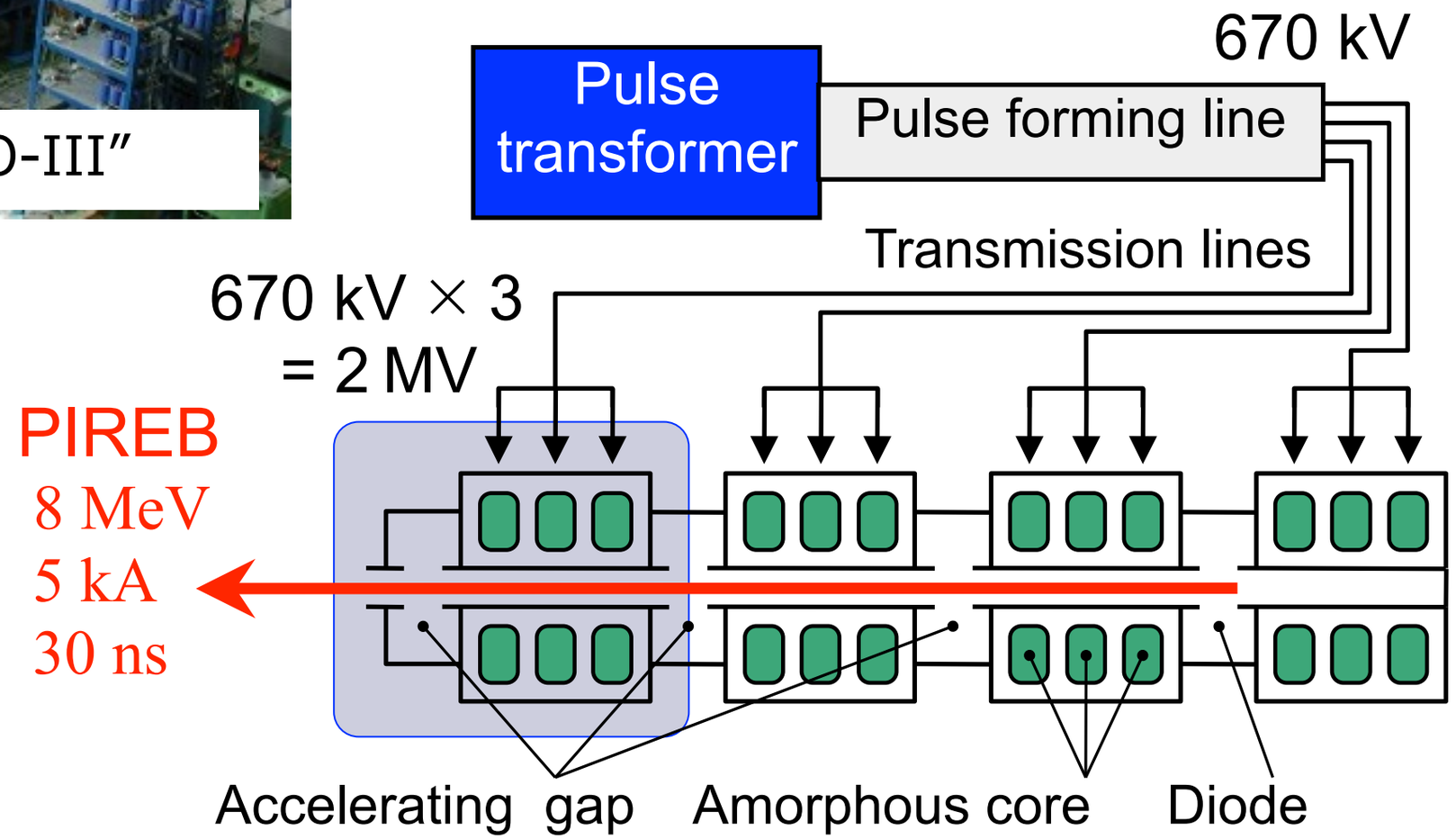
Pulsed Intense Relativistic Electron Beam Generator "ETIGO-III"

Induction LINAC "ETIGO-III"

Intense Beam Applications :

- *G. Imada and K. Yatsui, IEEE Trans. Plasma Sci. 31 (2003) 295*
- *H. Kondo, et al., Plasma Fusion Res. 5 (2010) 036*
- *G. Imada, IEEJ Trans. 6 (2011) 88*
- *T. Kikuchi, et al., Plasma Fusion Res. 6 (2011) 1206021*

Design Value of ETIGO-III
@ 1 cell
Input Current : 15 kA
Input Voltage : 670 kV
Output Current : 5 kA
Output Voltage : 2 MV



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Beam Dynamics Study during Longitudinal Bunch Compression using Compact Simulator

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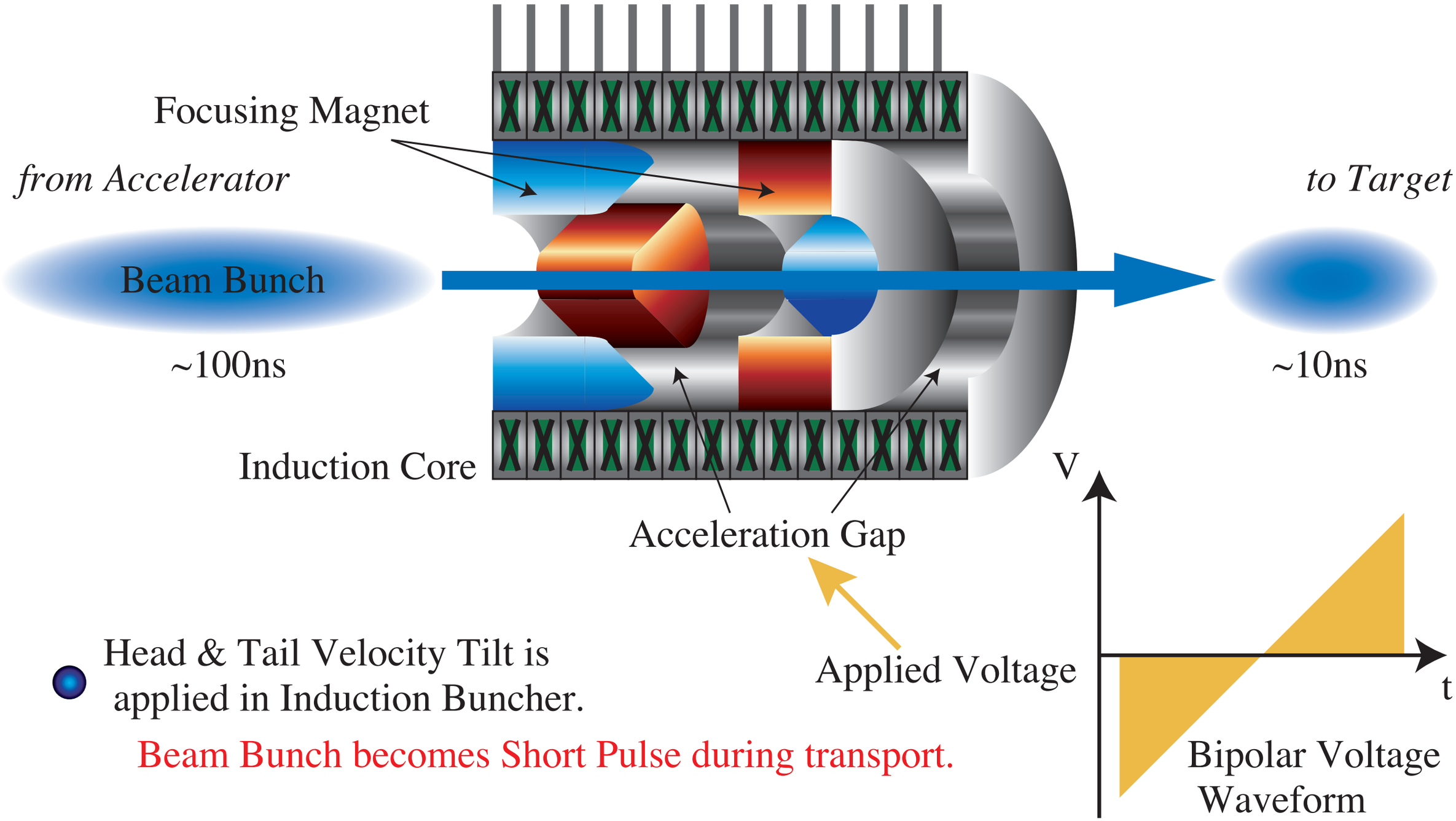
+ Beam Parameters in Compact Simulator

Bunch Compression using Induction Modulator

Induction buncher consists of periodic lattice



- Head & Tail Velocity Tilt is applied in Induction Buncher.

Beam Bunch becomes Short Pulse during transport.

Neutralized vs. Un-Neutralized Compression

Compression Ratio

Neutralized

Un-Neutralized

Transverse Focusing

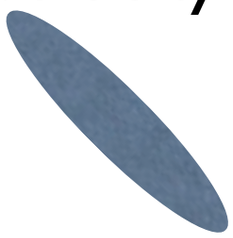
Neutralized

Un-Neutralized

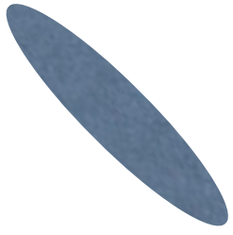
Momentum Spread

velocity tilt

Neutralized



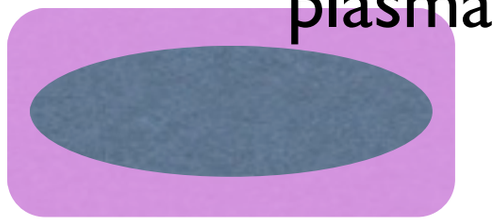
Un-Neutralized



Neutralized vs. Un-Neutralized Compression

Compression Ratio

Neutralized



Un-Neutralized

Transverse Focusing

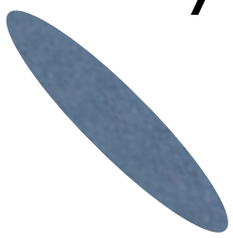
Neutralized

Un-Neutralized

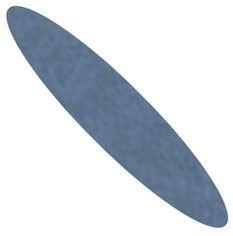
Momentum Spread

velocity tilt

Neutralized



Un-Neutralized

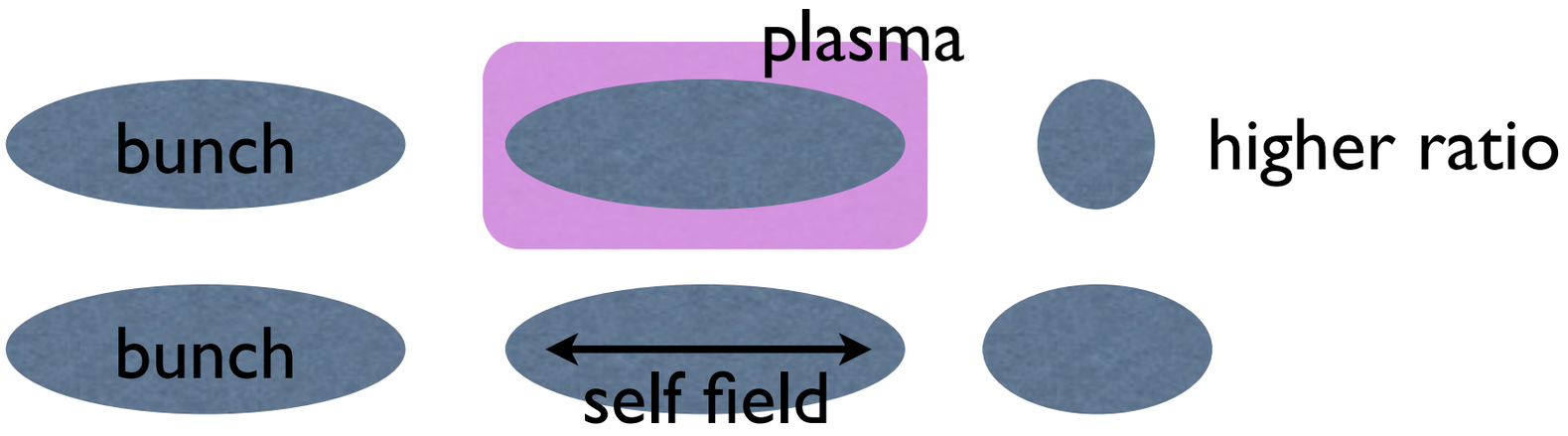


Neutralized vs. Un-Neutralized Compression

Compression Ratio

Neutralized

Un-Neutralized



Transverse Focusing

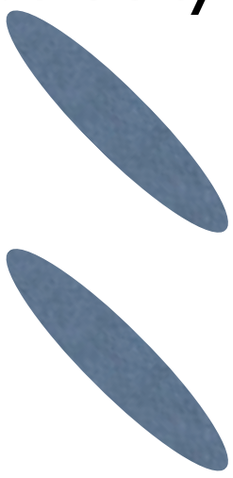
Neutralized

Un-Neutralized

Momentum Spread

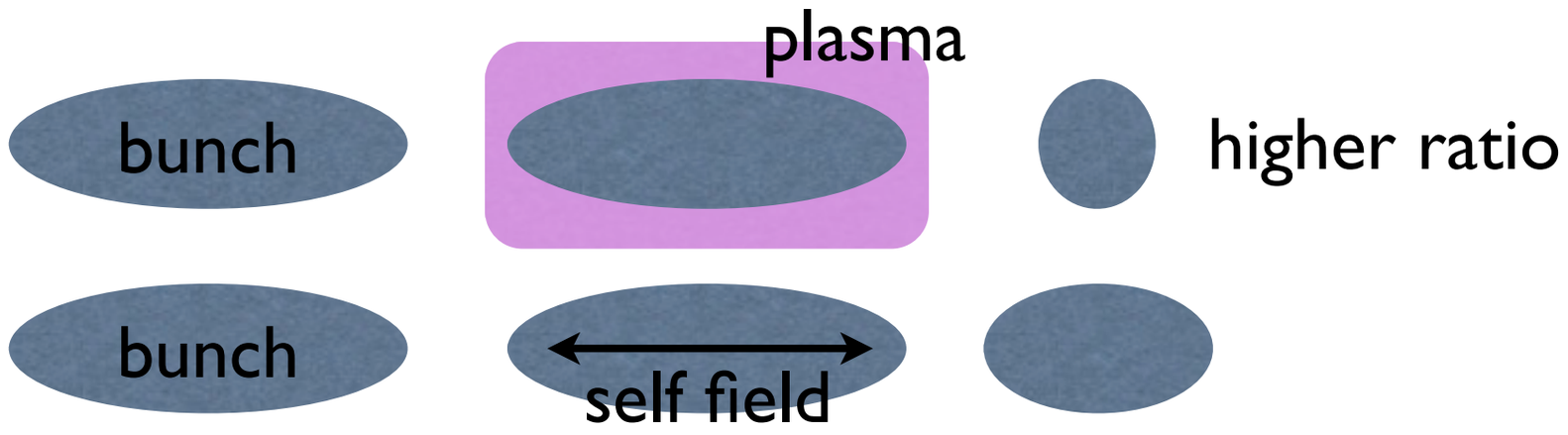
Neutralized

Un-Neutralized



Neutralized vs. Un-Neutralized Compression

Compression Ratio



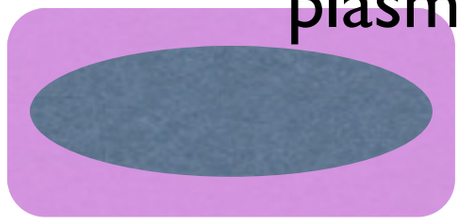
Transverse Focusing

Momentum Spread

Neutralized vs. Un-Neutralized Compression

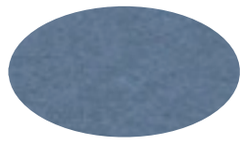
Compression Ratio

Neutralized



higher ratio

Un-Neutralized



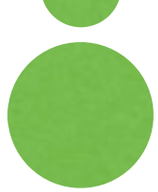
Transverse Focusing

spot size

Neutralized

smaller size

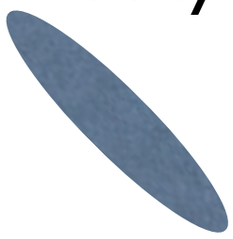
Un-Neutralized

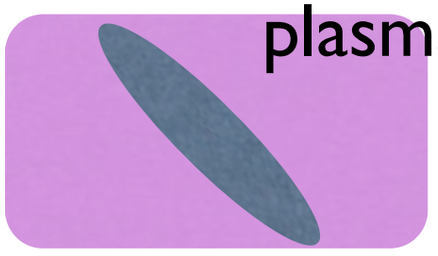


Momentum Spread

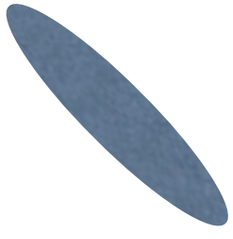
velocity tilt

Neutralized



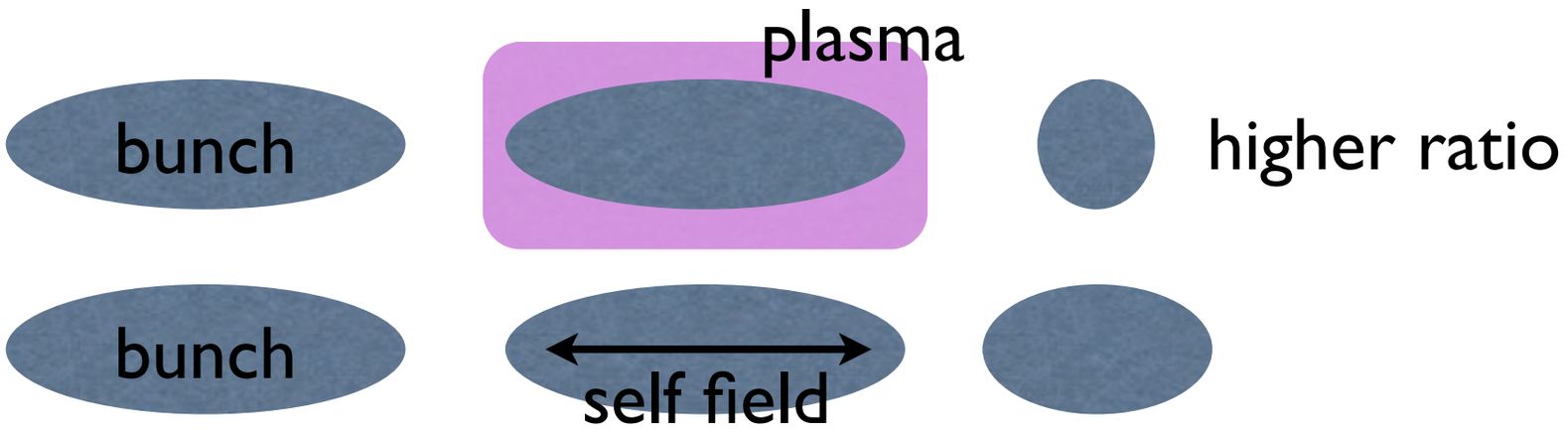


Un-Neutralized

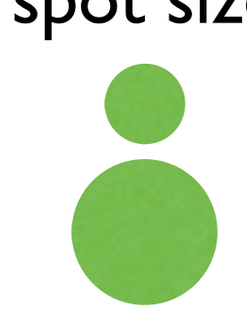


Neutralized vs. Un-Neutralized Compression

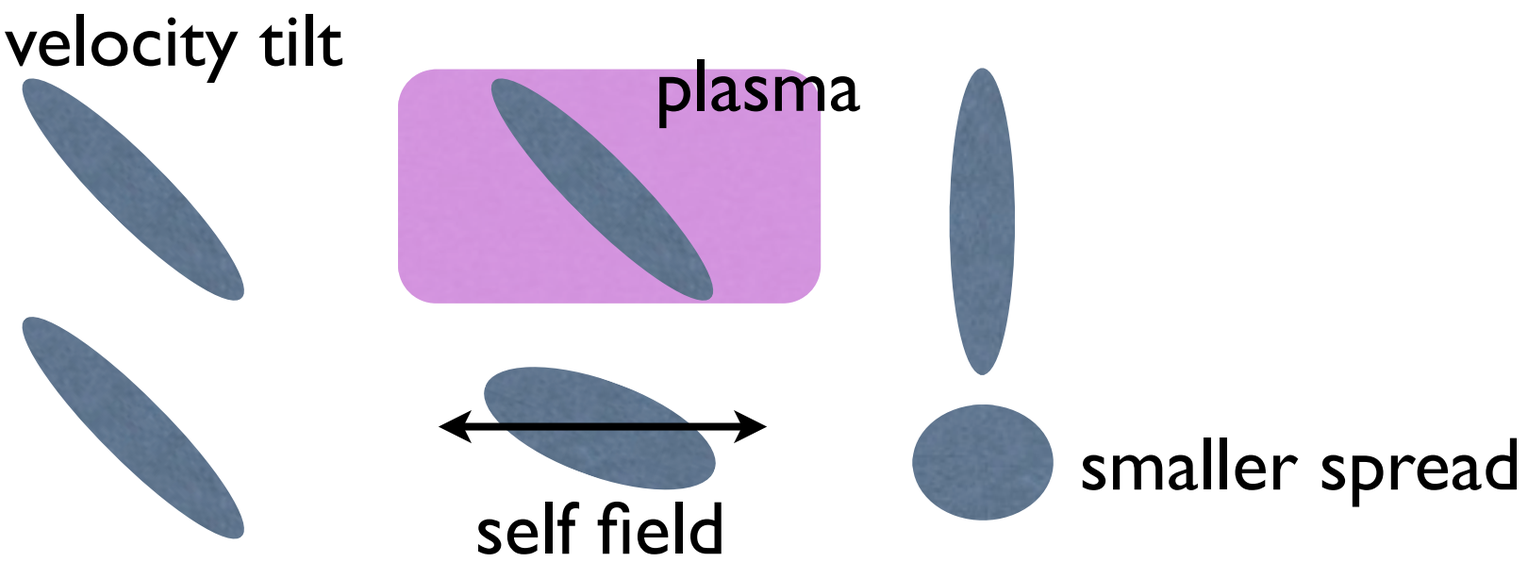
Compression Ratio



Transverse Focusing

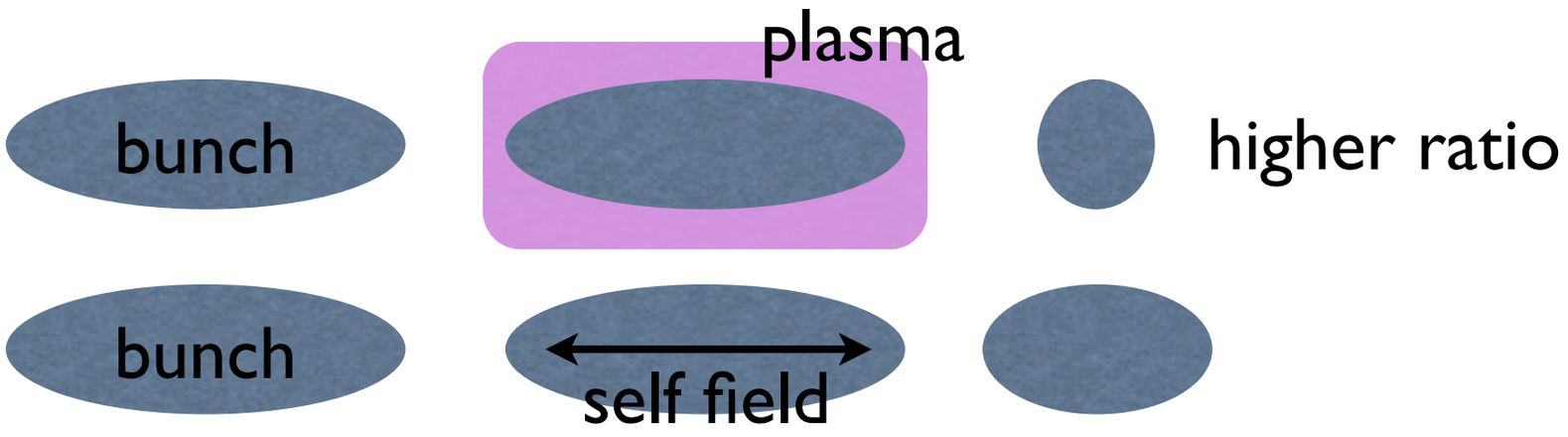


Momentum Spread

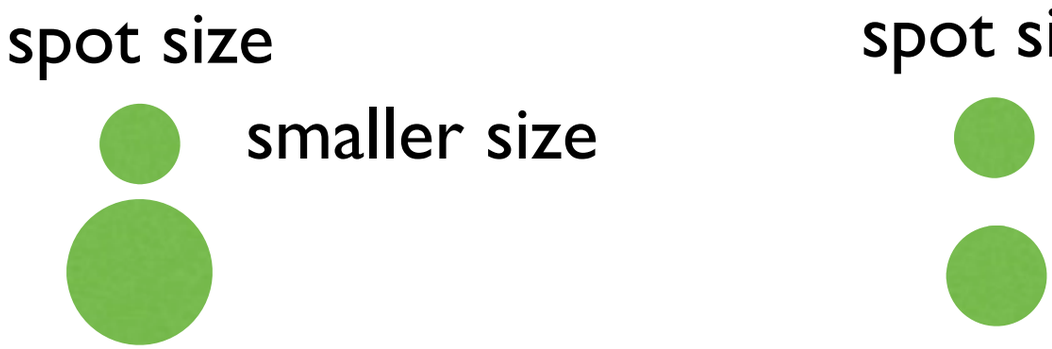


Neutralized vs. Un-Neutralized Compression

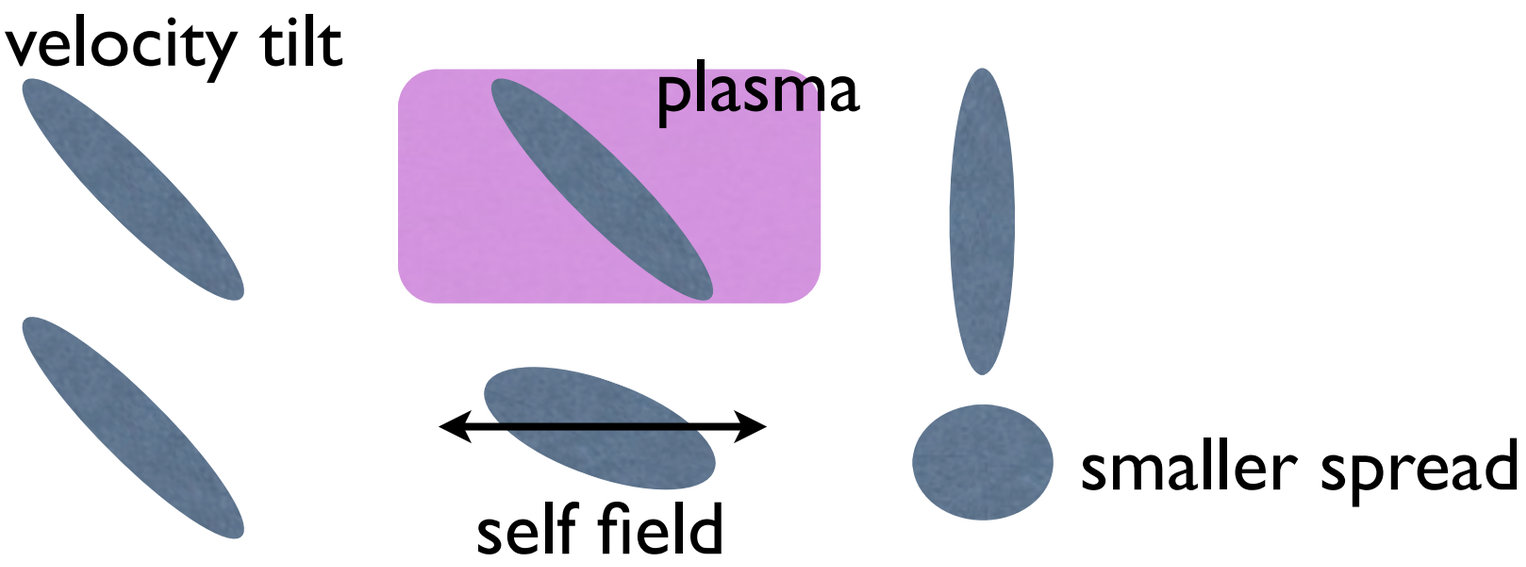
Compression Ratio



Transverse Focusing



Momentum Spread



Purpose

Bunch Compression is key issue for effective heavy ion inertial fusion energy

- final compression ratio
- beam quality (emittance)
- pulse shape control

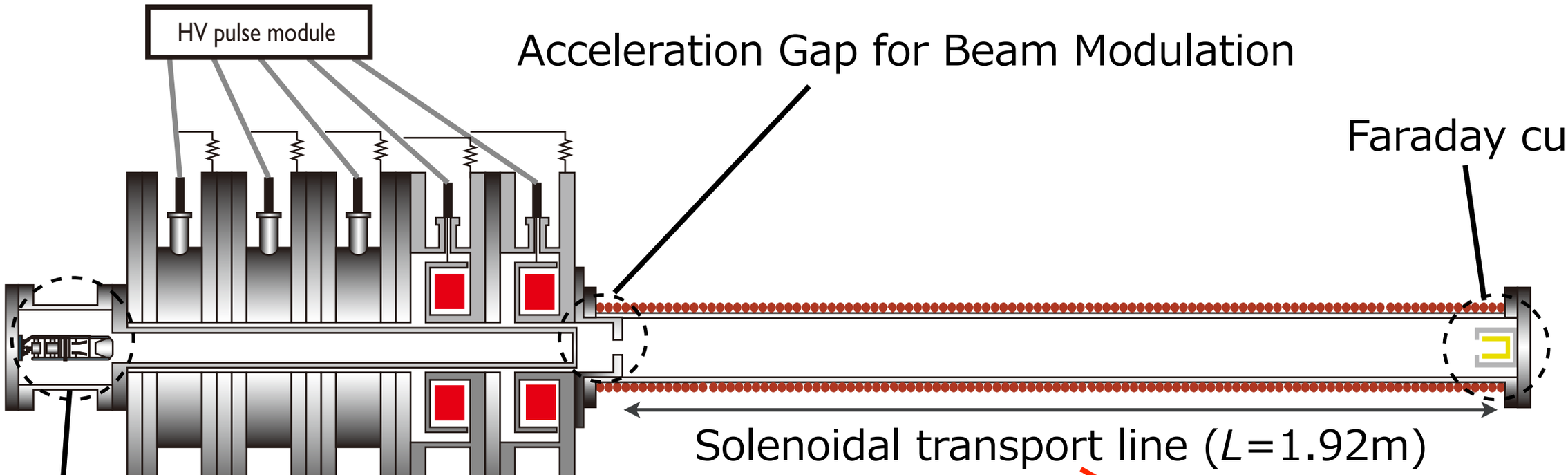
Using Compact Simulator by Electron Beam

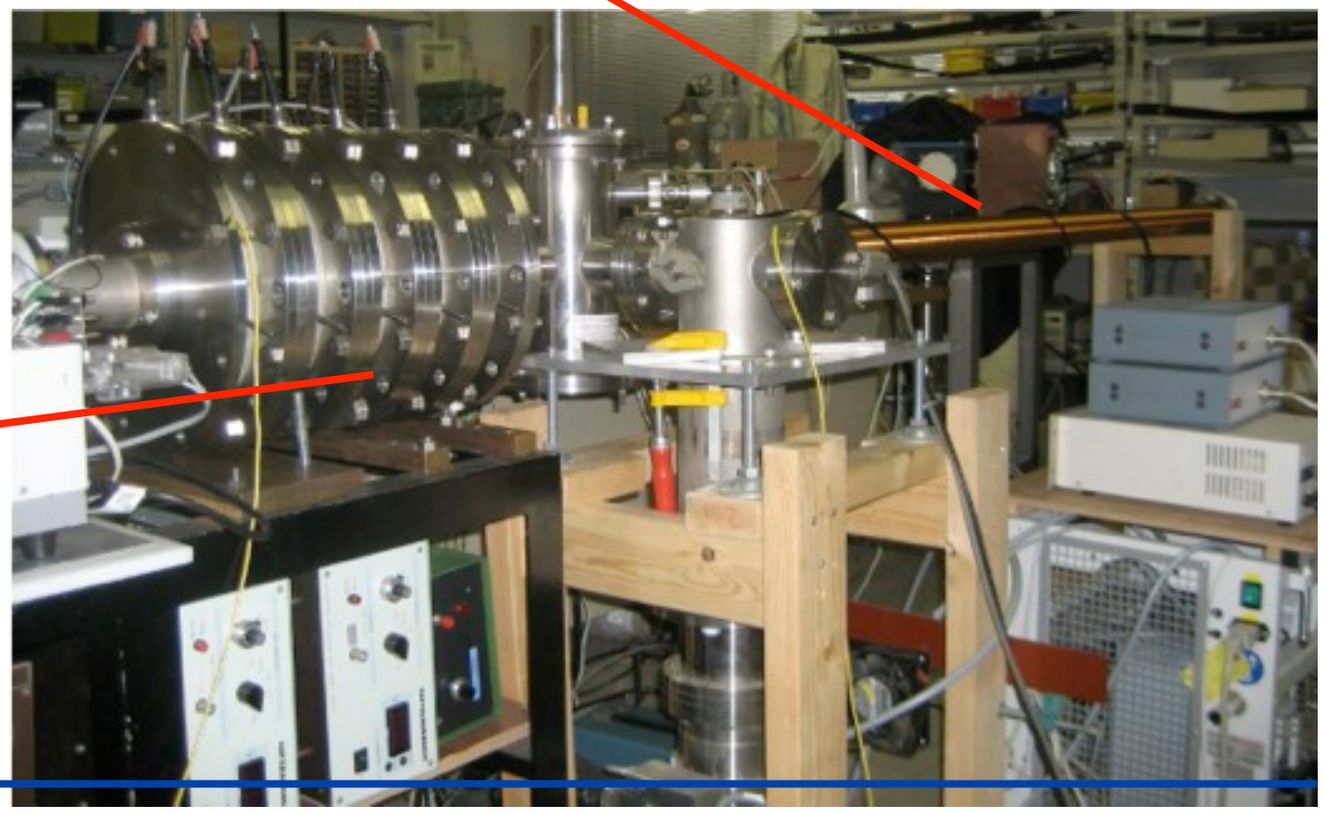
Beam Dynamics Analysis in Extreme Pulse Compression using Electron Beam Compact Simulator

Research Topics: Key violation issues for extreme pulse compression

- applied voltage errors
- space charge effect
- thermal effect
- mismatch transport
- finite gap length

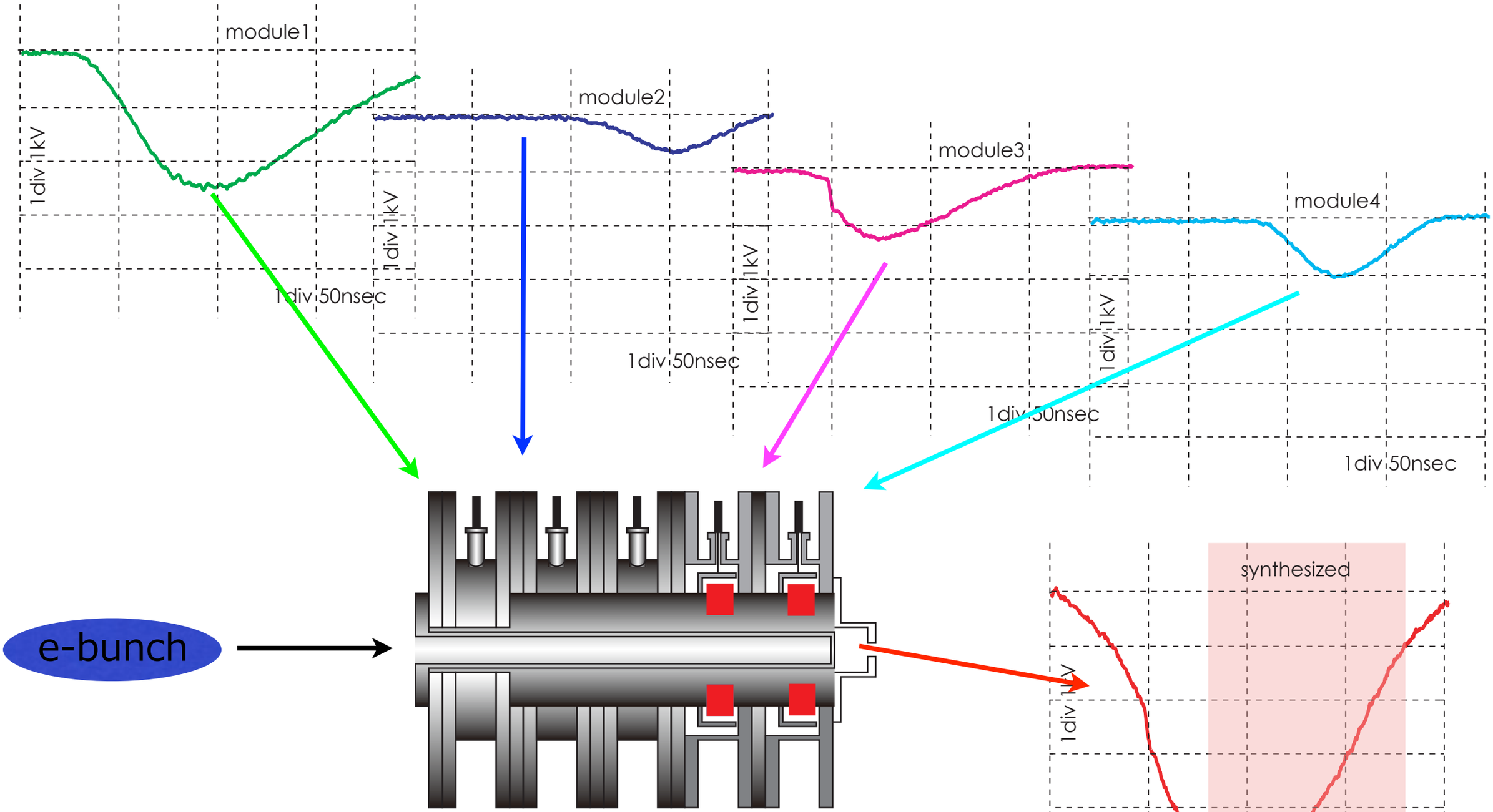
Experimental Arrangement in Tokyo Tech.





Y. Sakai, et. al., in this conference, Poster 109

Multi-Pulse -> 1 Gap

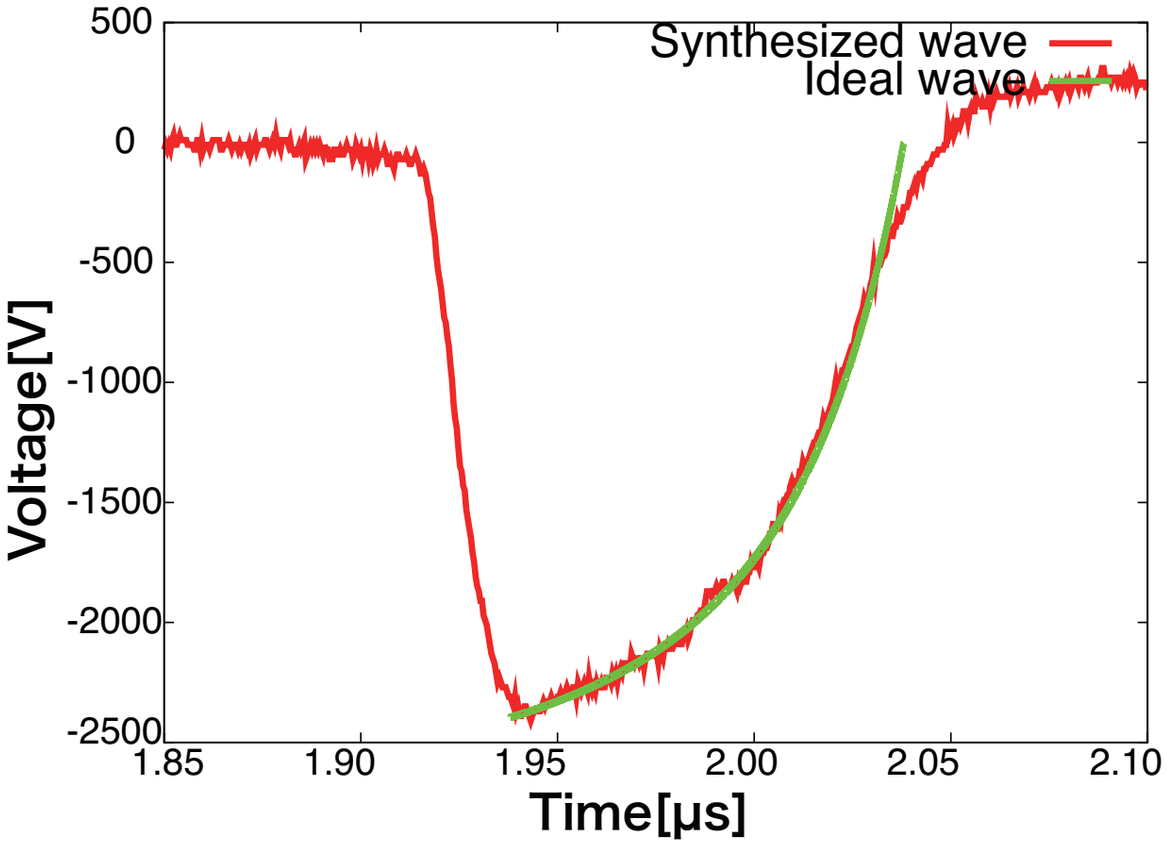


Various Multi-Voltage Pulses are applied into one gap.

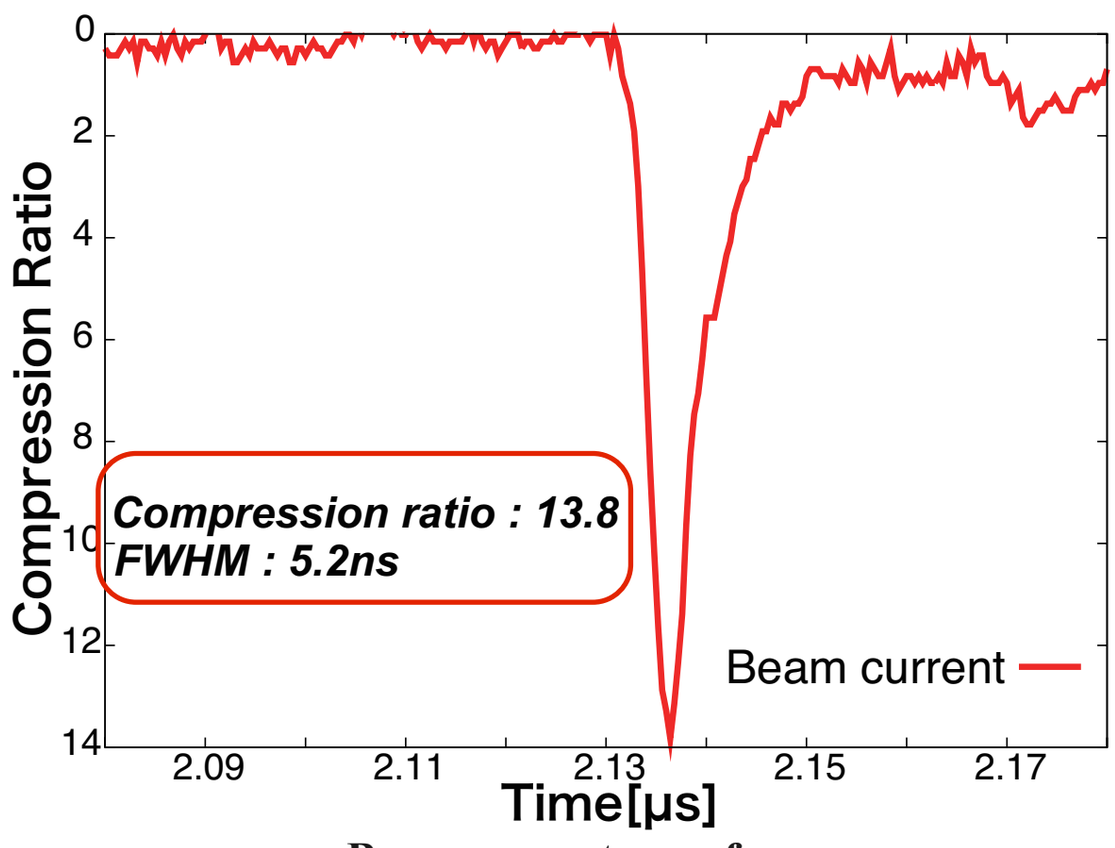
-> Synthesized voltage pulse can compress electron beam bunch.

Experimental Result: Waveforms of Applied Voltage & Beam Current

Injection 2.8keV, Pulsed Beam T=100ns, L=1.92m



Compression voltage waveform



Beam current waveform

Temperature corresponding to initial emittance is estimated to be 3000~5000K.

Y. Sakai, et. al., in this conference, Poster 109

A. Nakayama, et. al., "Longitudinal bunch compression study with induction voltage modulator", 7th Conf. Inertial Fusion Sci. Appl. (IFSA2011), 2011, P.We_105.

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Numerical Simulation

Assumptions for Numerical Simulation:

- 1D electrostatic particle-in-cell method
- long wave approximation for electric field

$$E_z = -\frac{g}{4\pi\varepsilon_0}\frac{d\lambda}{dz}$$

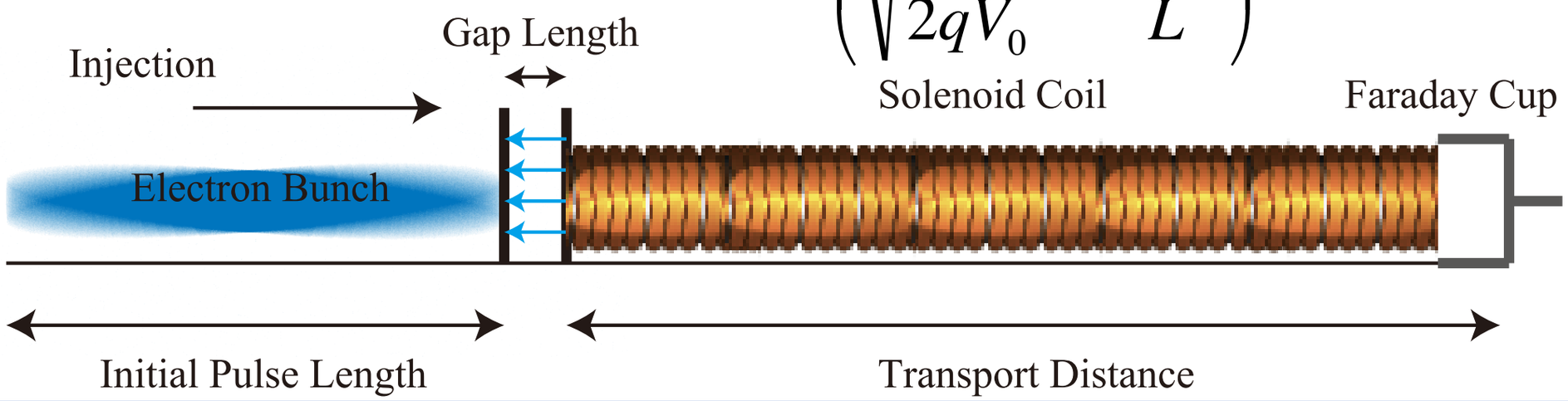
g: geometry factor = 2

λ: line-charge density

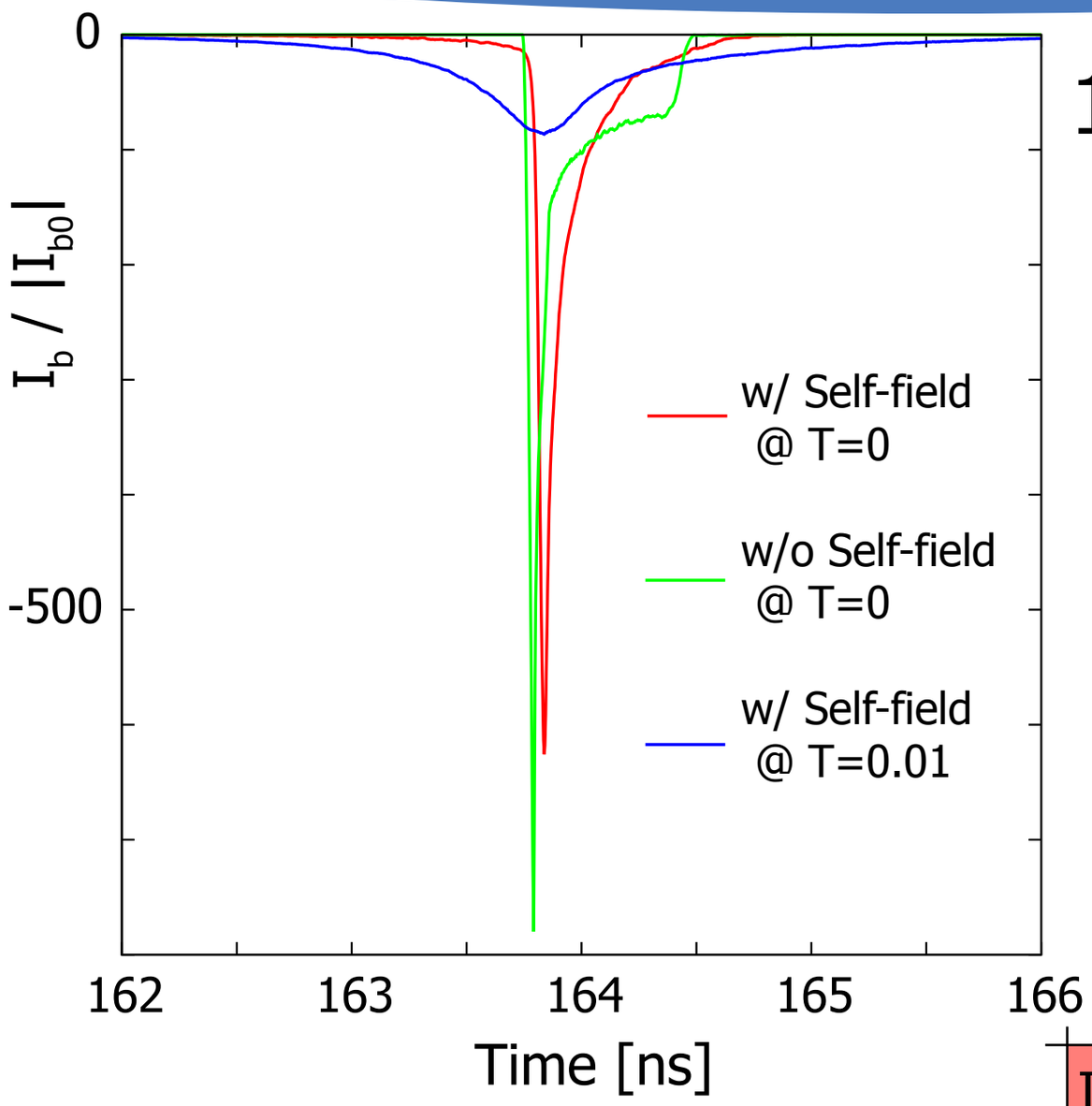
- Initial thermal velocity is applied by $v_{th} = \sqrt{\frac{k_B T_e}{m_e}}$
- Bunch compression voltage at gap is applied by

$$V_{dec}(t) = \frac{m_e}{2q}\frac{1}{\left(\sqrt{\frac{m_e}{2qV_0}} + \frac{T-t}{L}\right)^2} - V_0$$

V_0=2.8kV @ L=1.92m, T=100ns



Limitation for Pulse Compression



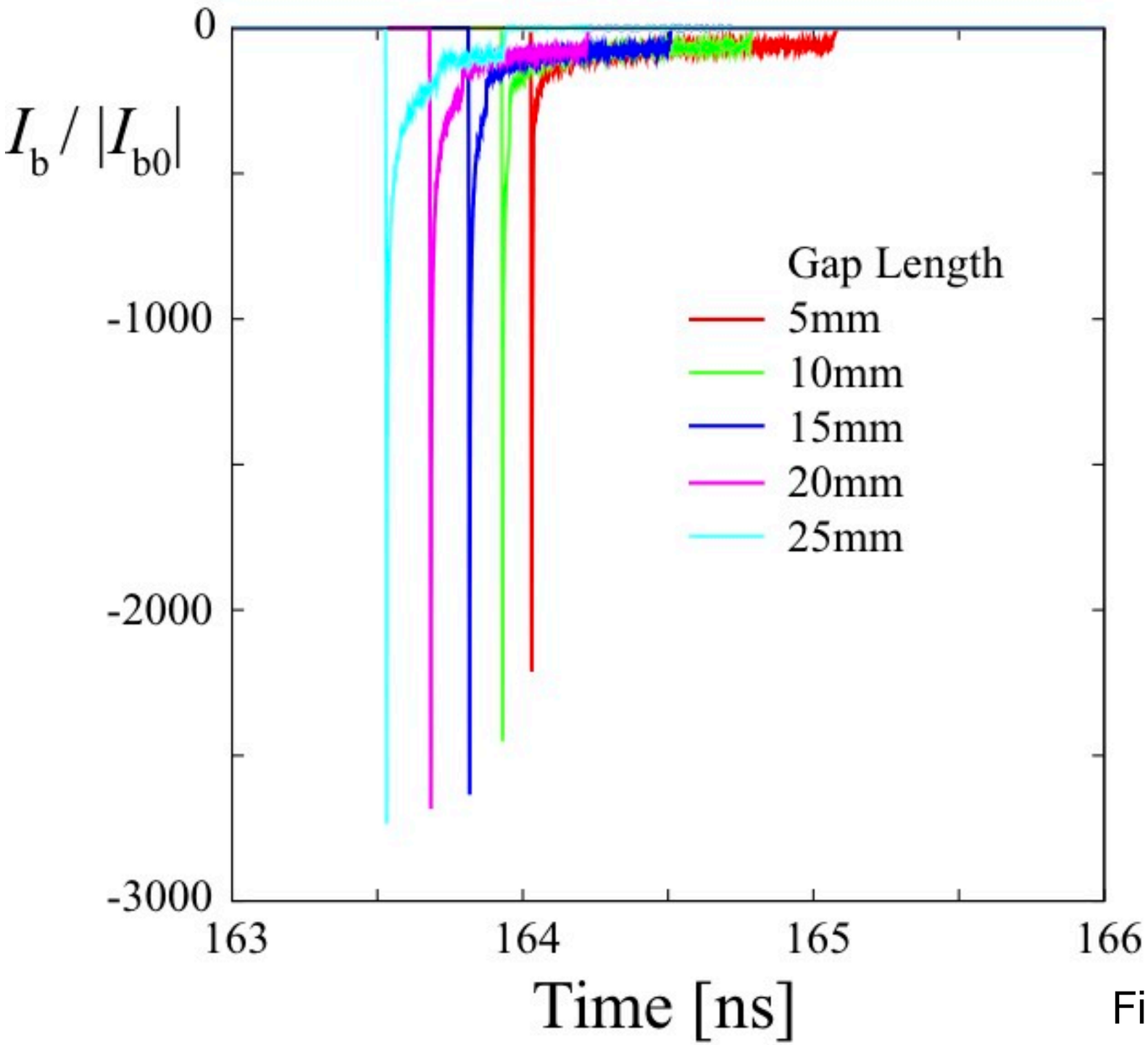
1D PIC result

Applied voltage for the pulse compression is good enough for the operation.

Space charge effect & initial temperature of electron bunch can interfere extreme pulse compression.

In this experimental condition, initial temperature of electron bunch is main issue of interference for extreme pulse compression.

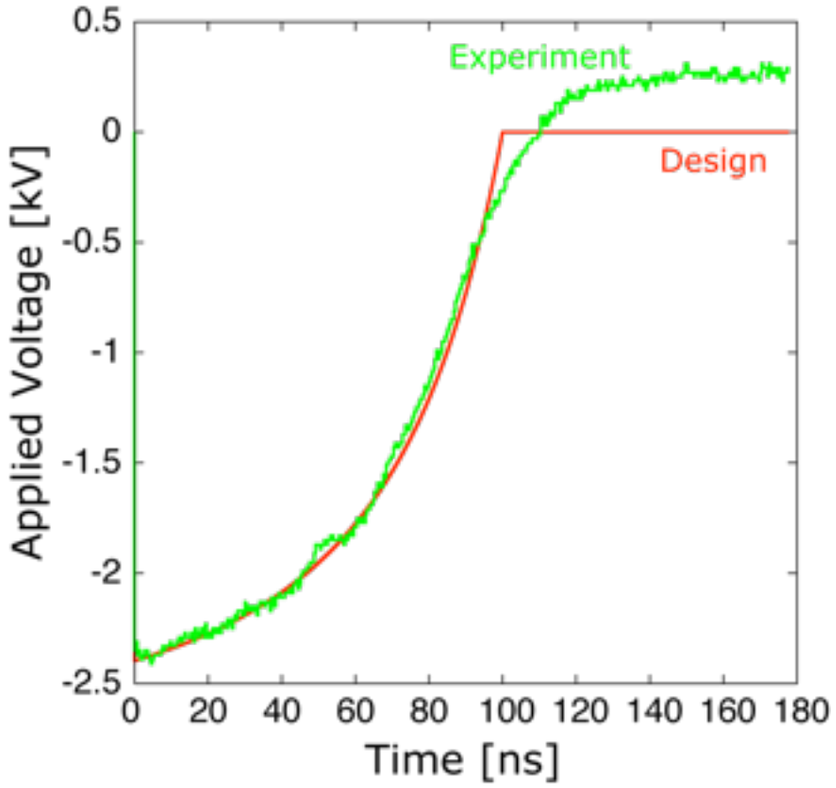
Beam current profile at each Gap Length



I_{b0} =100 μA, τ_{b0} =100 ns,
$k_B T_L$ =0 eV,
without space charge effect

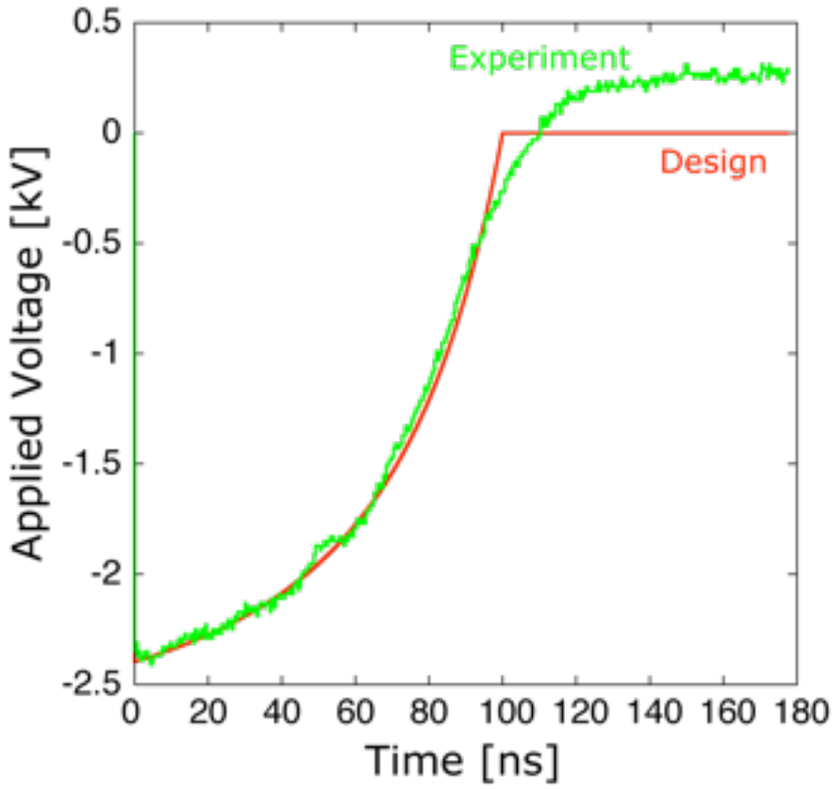
Finite Gap Length influences Final Compression.

1D PIC Results by Applied Voltage with "Experiment"

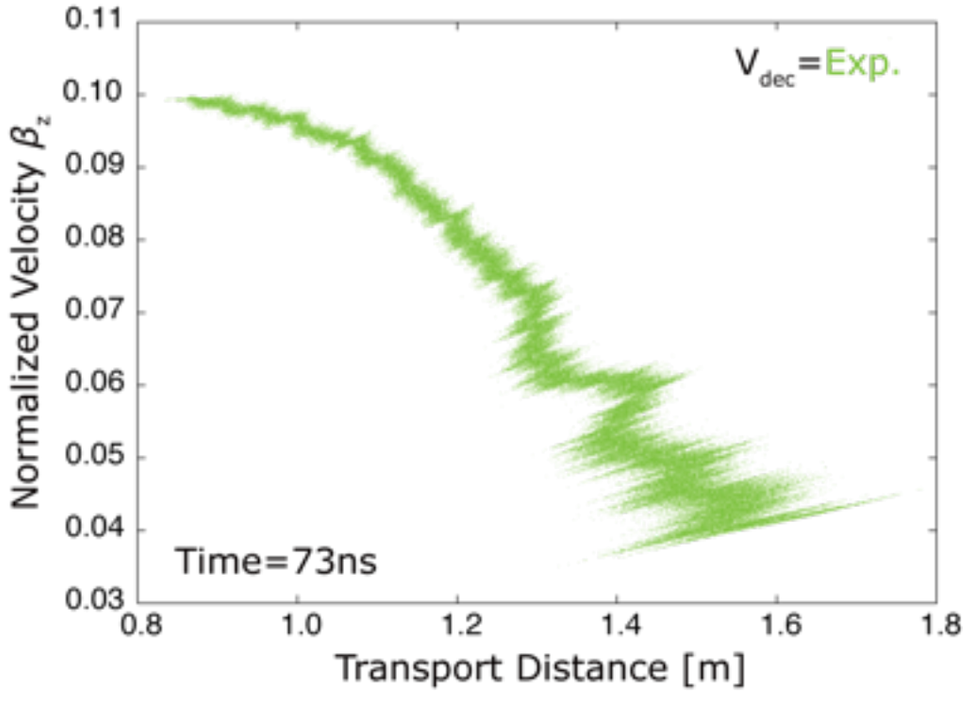


Experimental data is used for applied Voltage.

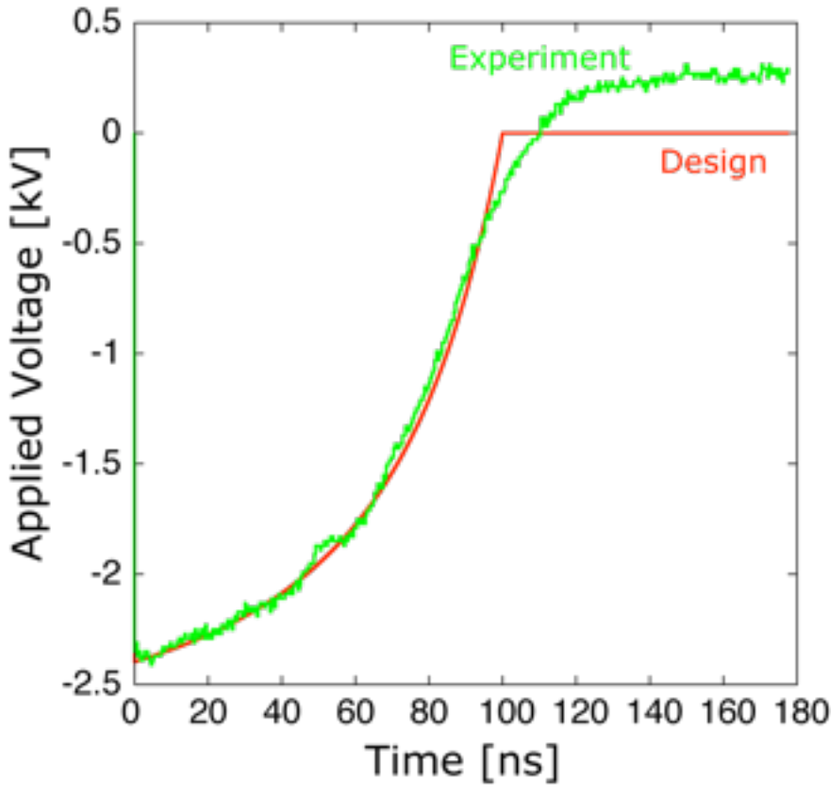
1D PIC Results by Applied Voltage with "Experiment"

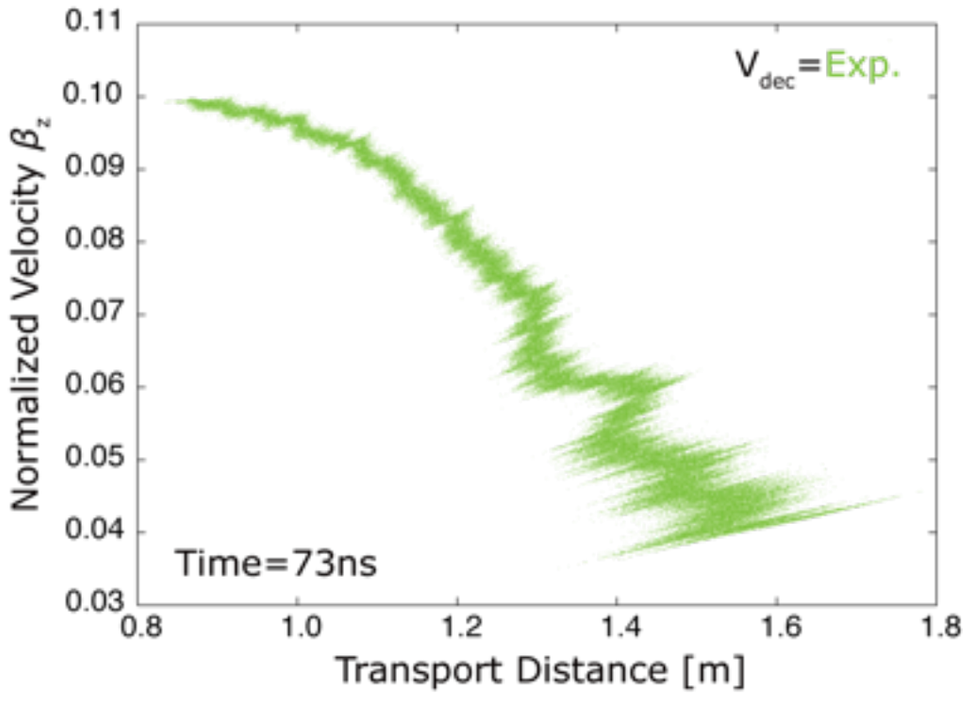


Experimental data is used for applied Voltage.

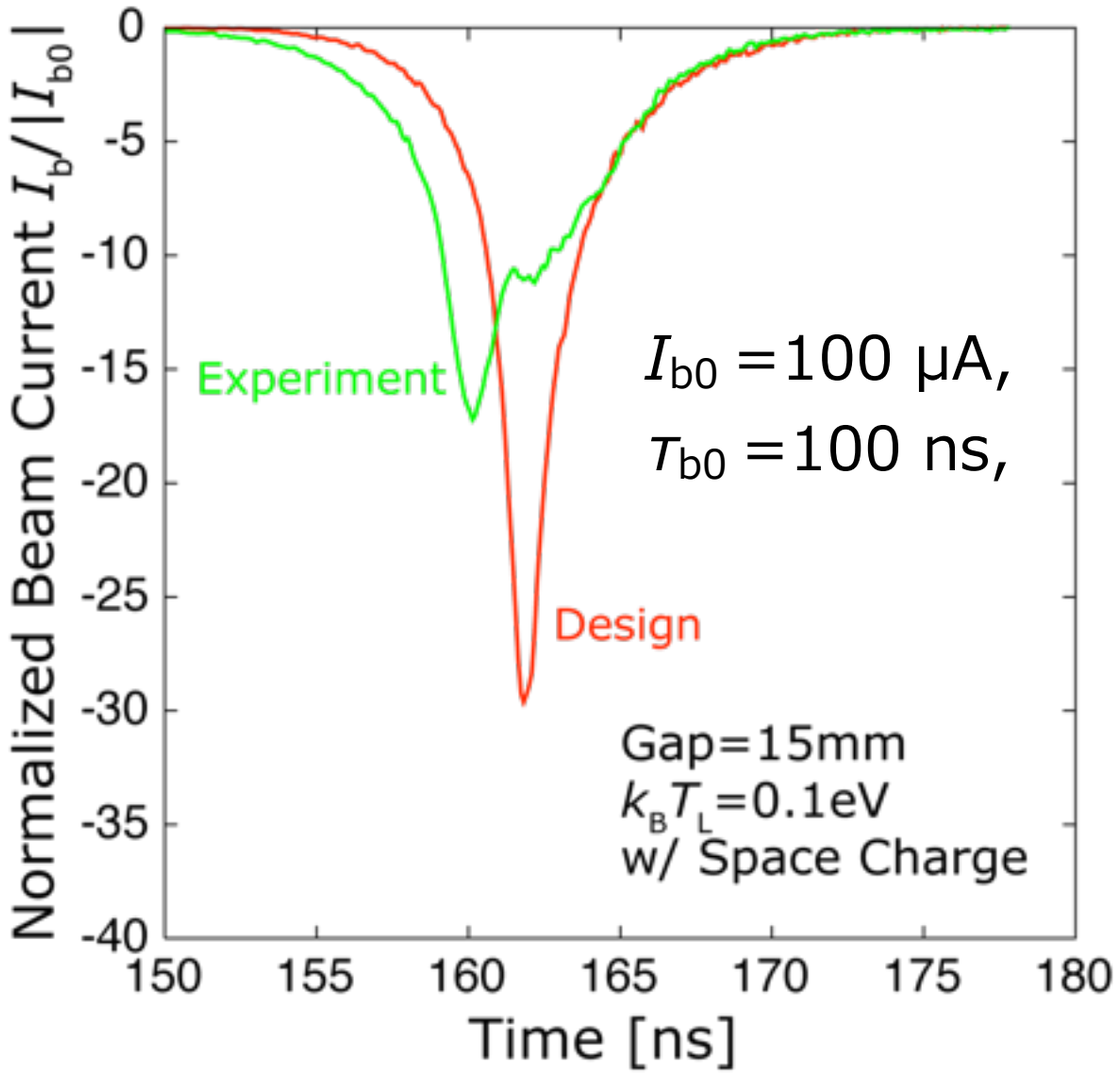


1D PIC Results by Applied Voltage with "Experiment"





Experimental data is used for applied Voltage.



Summary (numerical simulation)

Numerical Study for Electron Beam Dynamics in Compact Simulator for Heavy Ion Inertial Fusion

Research Topics: Key violation issues for extreme pulse compression

- applied voltage errors
- space charge effect
- thermal effect
- mismatch transport
- finite gap length

In this experimental condition, from comparison with experimental & numerical simulation results:

- Applied voltage for the pulse compression is good enough for the operation.
- Space charge effect & initial temperature of electron bunch can interfere extreme pulse compression.
- Initial temperature of electron bunch is main issue of interference for extreme pulse compression.
- Applied voltage errors with higher frequency are not influential.

Topics

Researches in Heavy Ion Inertial Fusion & High Energy Density Laboratory Physics in Nagaoka University of Tech.

Beam Dynamics Study during Longitudinal Bunch Compression using Compact Simulator

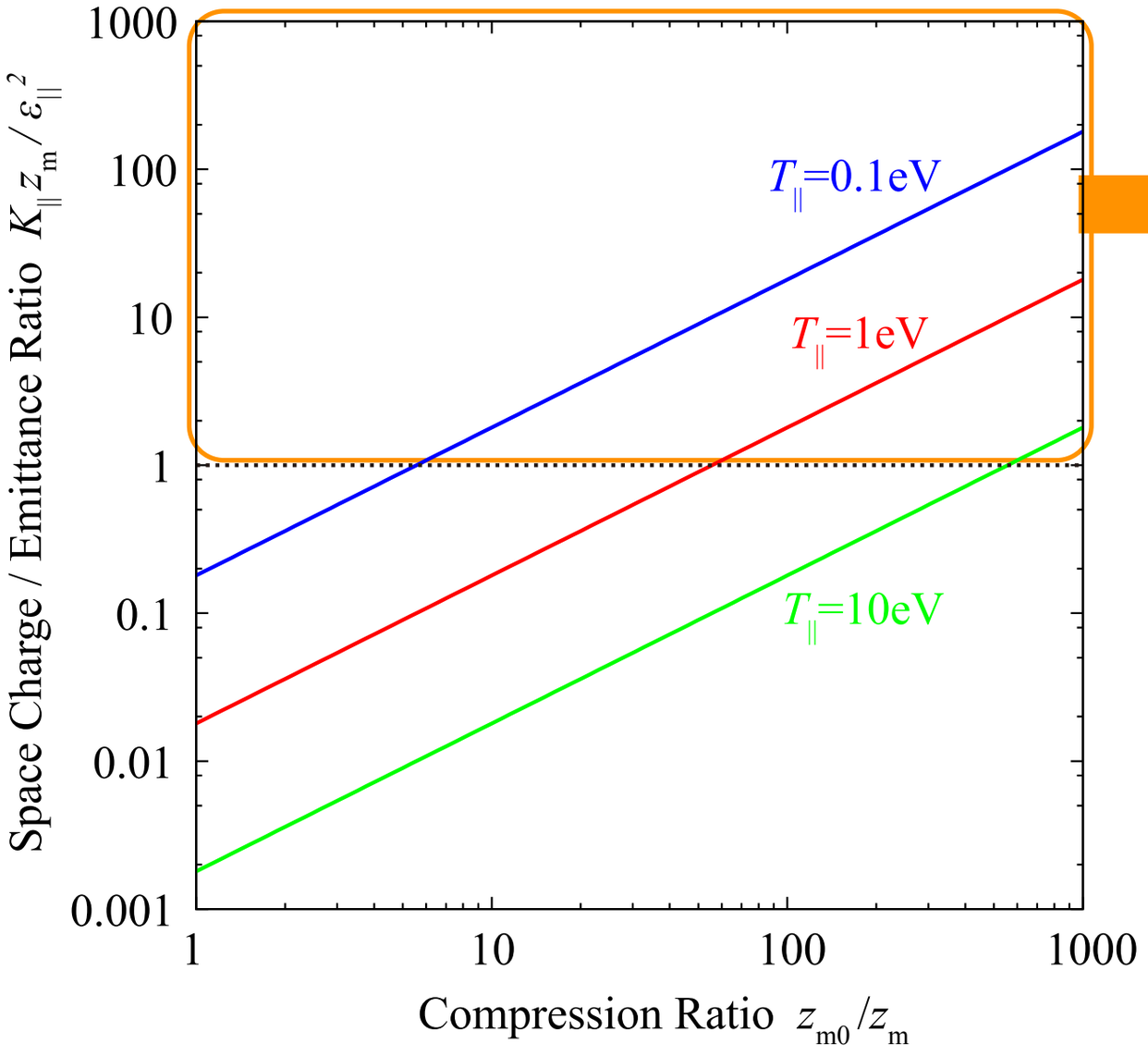
+ Electron Beam Compact Simulator Device in Tokyo Tech.
+ Numerical Simulation of Beam Dynamics
+ Beam Parameters in Compact Simulator

Estimation for Space Charge Dominated Condition in Longitudinal Direction

$$z_m'' + k_{\parallel} z_m - \frac{K_{\parallel}}{z_m^2} - \frac{\varepsilon_{\parallel}^2}{z_m^3} = 0$$

$$\frac{K_{\parallel}\, z_m}{\varepsilon_{\parallel}^2} = \frac{3\, e\, g\, I_{b0} \tau_{b0}}{40\, \pi\, \epsilon_0 z_m k_B T_{\parallel}}$$

longitudinal direction



Space Charge Dominated

for experimental condition

I_{b0} =100 μA, τ_{b0} =100 ns, g= 2,

$k_B T$ = 0.1 eV

$$T_{\perp} = T_{\parallel}$$

Pulse compression of x6~

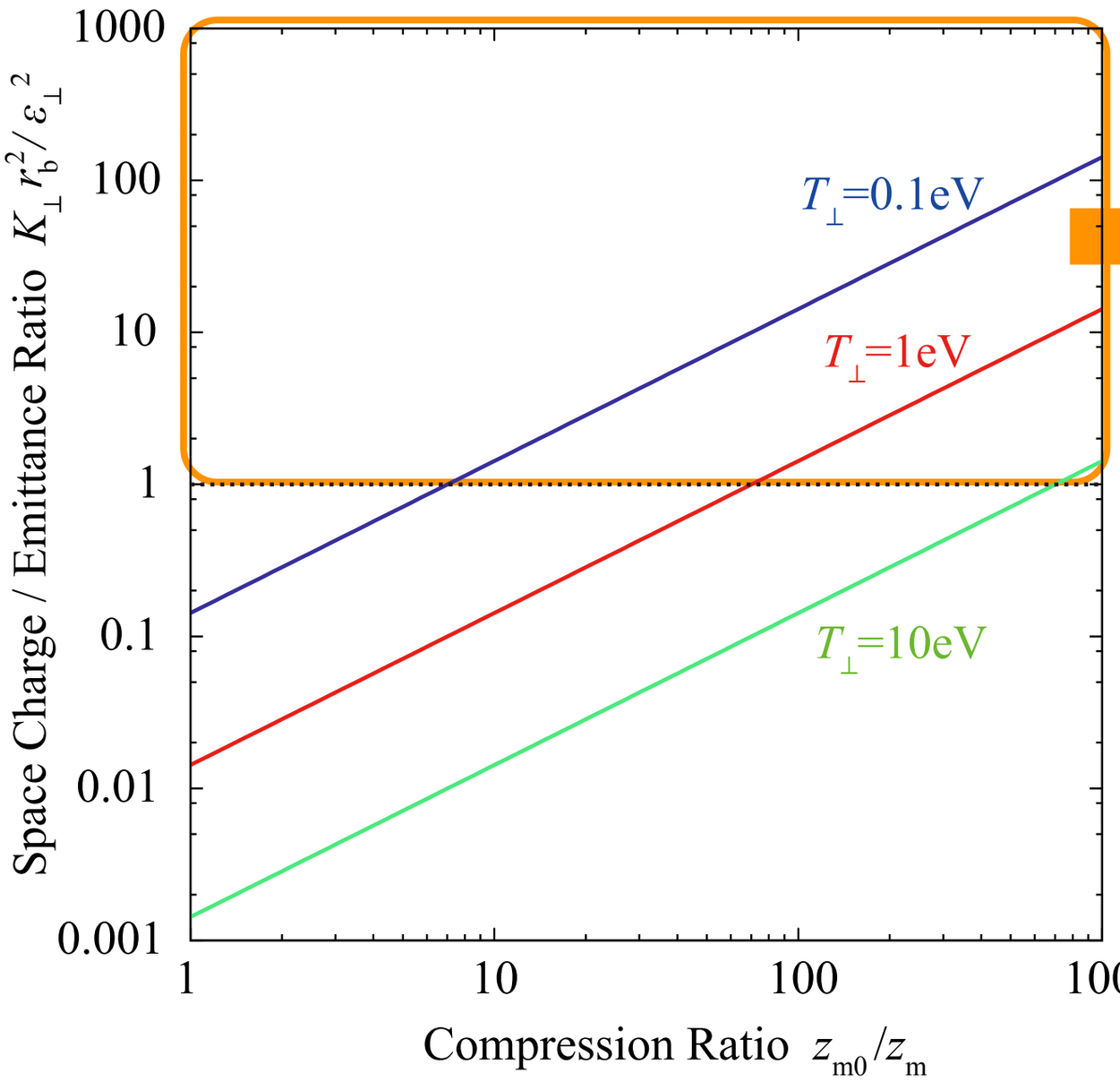
- T. Kikuchi, et. al., 7th Conf. Inertial Fusion Sci. Appl. (IFSA2011), 2011, P.We_104
- T. Kikuchi, et. al., Plasma 2011 (Kanazawa, Nov. 2011) 23P165-B.

Estimation for Space Charge Dominated Condition in Transverse Direction

$$r_b'' + k_\perp^2 r_b - \frac{K_\perp}{r_b} - \frac{\varepsilon_\perp^2}{r_b^3} = 0$$

$$\frac{K_\perp r_b^2}{\varepsilon_\perp^2} = \frac{e\, I_{b0}}{8\pi\,\epsilon_0 v_z \gamma_b^2\, k_B T_\perp} \frac{z_m}{z_{m0}}$$

transverse direction



Space Charge Dominated

for experimental condition

I_{b0} =100μA, τ_{b0} =100ns, g=2,

$k_B T$ = 0.1 eV

$$T_\perp = T_\parallel$$

Pulse compression of x7~

Estimation of Tune Depression

Tune Depression* $$\frac{\sigma}{\sigma_0} = \sqrt{1 - \frac{K_\perp}{k_\beta^2 r_b^2}}$$

*S.M. Lund, T. Kikuchi, R.C. Davidson, PRSTAB 12 (2009) 114801

Estimation of Tune Depression

Tune Depression* $$\frac{\sigma}{\sigma_0} = \sqrt{1 - \frac{K_\perp}{k_\beta^2 r_b^2}}$$

Transverse Perveance

$$K_\perp \propto I_\mathrm{b} \propto 1/z_\mathrm{m}$$

*S.M. Lund, T. Kikuchi, R.C. Davidson, PRSTAB 12 (2009) 114801

Estimation of Tune Depression

Tune Depression* $$\frac{\sigma}{\sigma_0} = \sqrt{1 - \frac{K_\perp}{k_\beta^2 r_b^2}}$$

Transverse Perveance

$$K_\perp \propto I_\mathrm{b} \propto 1/z_\mathrm{m}$$

*S.M. Lund, T. Kikuchi, R.C. Davidson, PRSTAB 12 (2009) 114801

by solenoidal transport line

$$k_\beta = \omega_\mathrm{c}/v_\mathrm{z} = eB_\mathrm{z}v_\mathrm{z}/m_\mathrm{e}$$

⇧

cyclotron frequency

Estimation of Tune Depression

Tune Depression* $\frac{\sigma}{\sigma_0} = \sqrt{1 - \frac{K_\perp}{k_\beta^2 r_b^2}}$

Transverse Perveance

$K_\perp \propto I_b \propto 1/z_m$

*S.M. Lund, T. Kikuchi, R.C. Davidson, PRSTAB 12 (2009) 114801

by solenoidal transport line

$k_\beta = \omega_c / v_z = eB_z v_z / m_e$

⇧

cyclotron frequency

beam radius

$r_b \sim 0.5\text{mm}$

(experiment)

Estimation of Tune Depression

Tune Depression* $\frac{\sigma}{\sigma_0} = \sqrt{1 - \frac{K_\perp}{k_\beta^2 r_b^2}}$

Transverse Perveance

$K_\perp \propto I_b \propto 1/z_m$

*S.M. Lund, T. Kikuchi, R.C. Davidson, PRSTAB 12 (2009) 114801

by solenoidal transport line

$k_\beta = \omega_c / v_z = eB_z v_z / m_e$

⇧

cyclotron frequency

beam radius

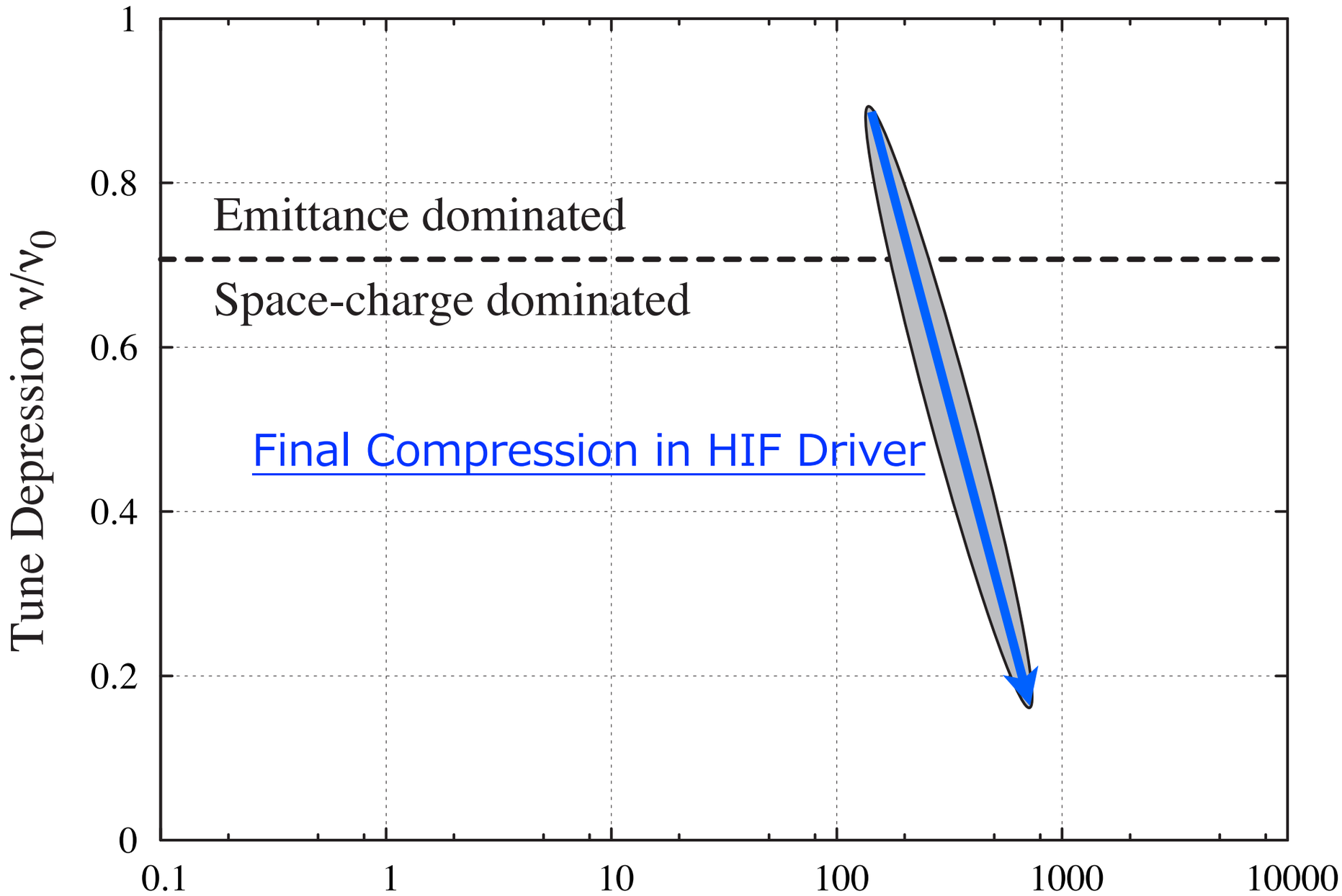
$r_b \sim 0.5\text{mm}$

(experiment)

$\sigma/\sigma_0 = 0.996 \sim 0.915$

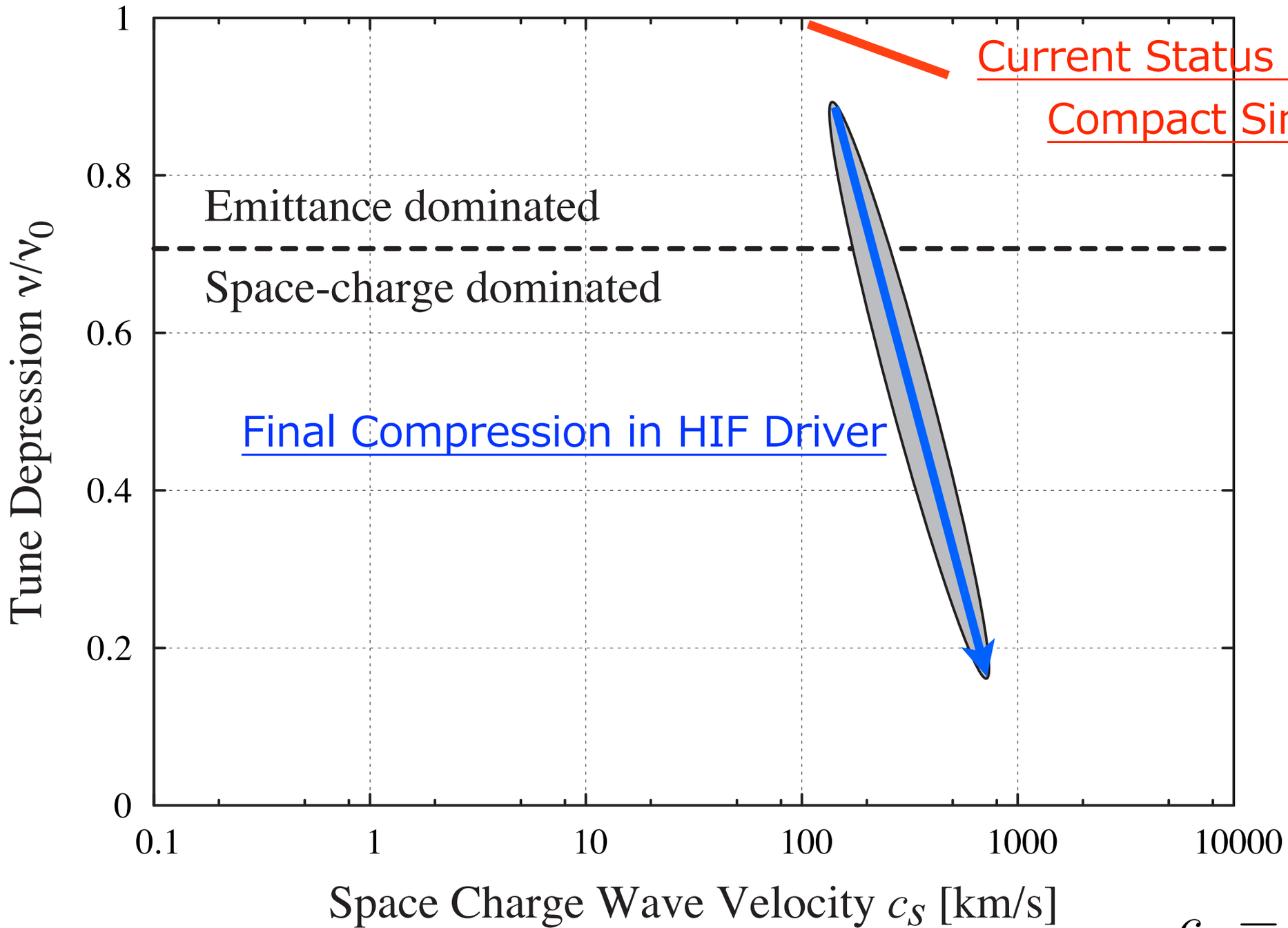
⇧ initial ⇧ x20 compression

Tune Depression - Space Charge Wave Diagram



$$c_s = \left(\frac{g c^2 I_b}{\beta \gamma^5 I_0} \right)^{1/2},$$

Tune Depression - Space Charge Wave Diagram



$$c_s = \left(\frac{g c^2 I_b}{\beta \gamma^5 I_0} \right)^{1/2},$$

Summary

Researches in Heavy Ion Inertial Fusion & High Energy Density Laboratory Physics in Nagaoka University of Tech.

-> *T. Sasaki, et. al., in this conference, Talk 75*
Y. Miki, et. al., in this conference, Poster 102
F. Tachinami, et. al., in this conference, Poster 104

Beam Dynamics Study during Longitudinal Bunch Compression using Compact Simulator

+ Electron Beam Compact Simulator Device in Tokyo Tech.

+ Numerical Simulation of Beam Dynamics

+ Beam Parameters in Compact Simulator

in progress

Y. Sakai, et. al., in this conference, Poster 109

Colleagues & Acknowledgment

<u>for HIF & HEDLP+WDM Researches in Nagaoka Univ. Tech.</u>

Staff: Nob. Harada (MHD), T. Sasaki, W. Jiang@EDI (pulse power), K. Kashine@YNCMT, T. Aso (radiation therapy), A. Tokuchi@PPJ+EDI (pulse power), G. Imada@NIIT+EDI (ETIGO-III), et. al.

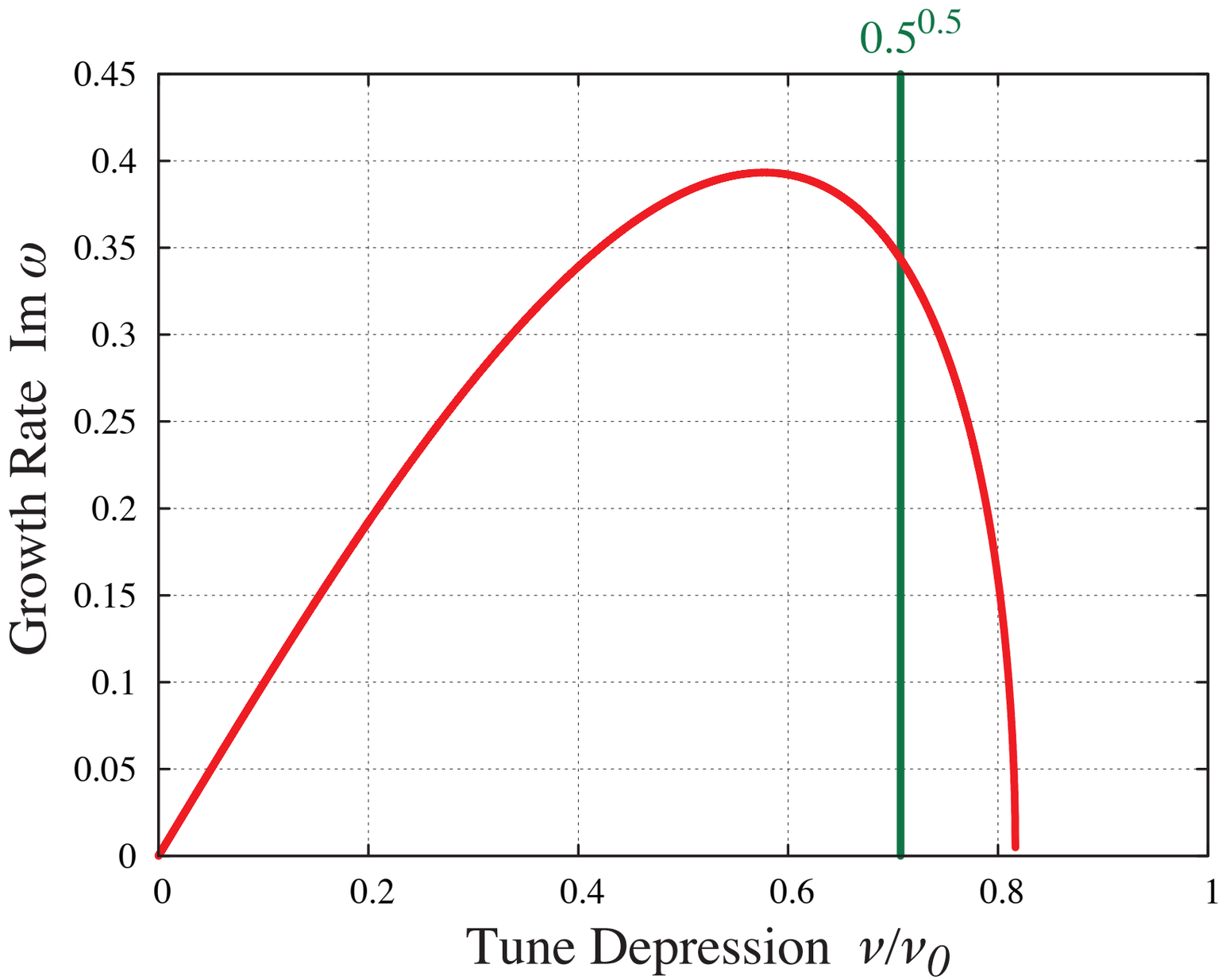
Student: F. Tachinami, Y. Miki, H. Saito, R. Hayashi, S. Izumi, T. Kazeto, et. al.

EDI = Extreme Energy Density Institute, Nagaoka Univ. Tech.
YNCMT = Yuge National College of Maritime Technology
PPJ = Pulsed Power Japan Laboratory Ltd.
NIIT = Niigata Institute of Technology

<u>for Beam Dynamics Study by Compact Simulator</u>

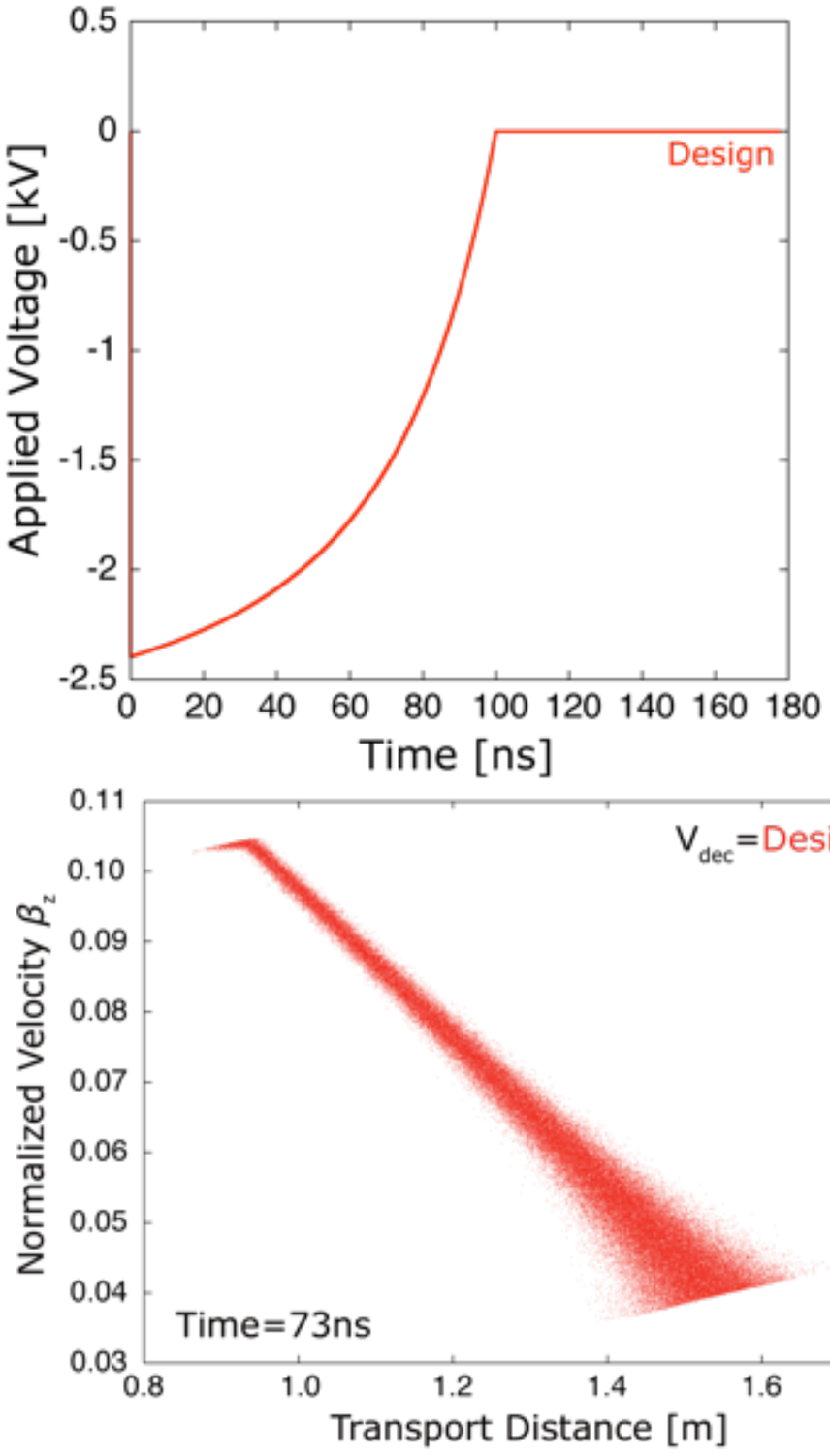
K. Horioka, M. Nakajima, J. Hasegawa, Y. Sakai, A. Nakayama, et. al.
@ Tokyo Tech.

Instability in Longitudinal-Transverse Coupling Motion

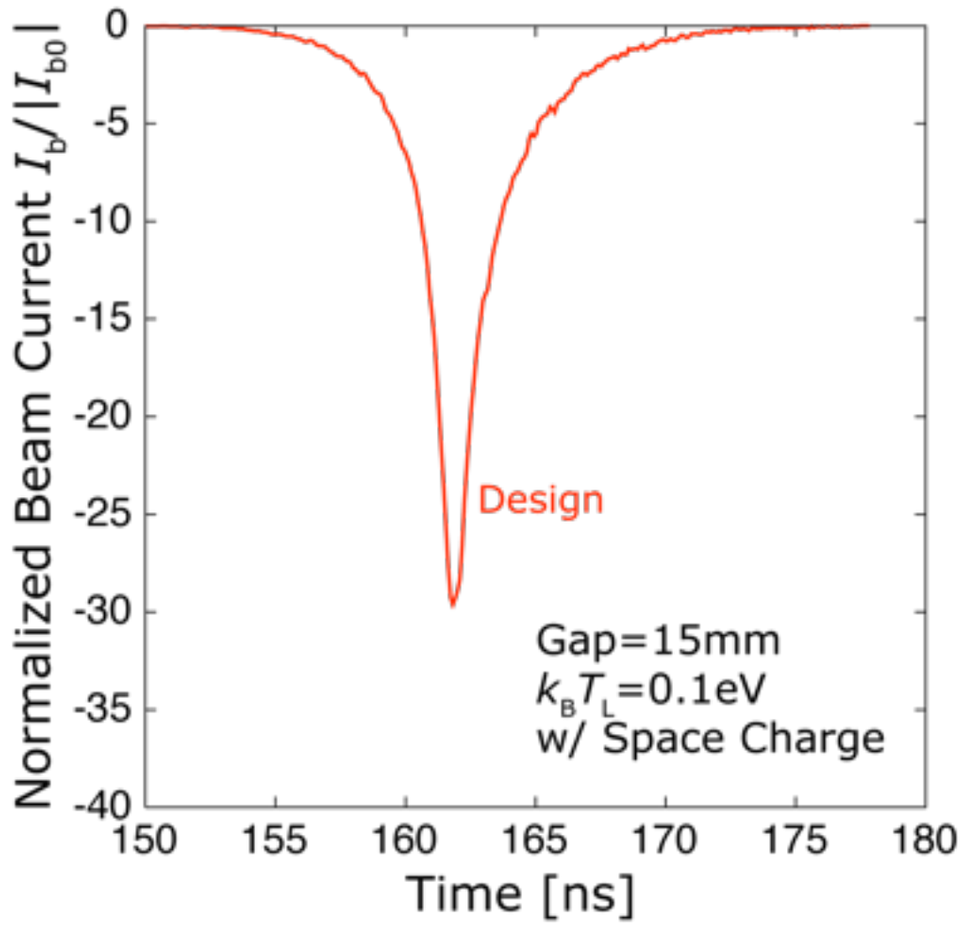


E.A. Startsev, R.C. Davidson, H. Qing, NIMA 544 (2005) 125.

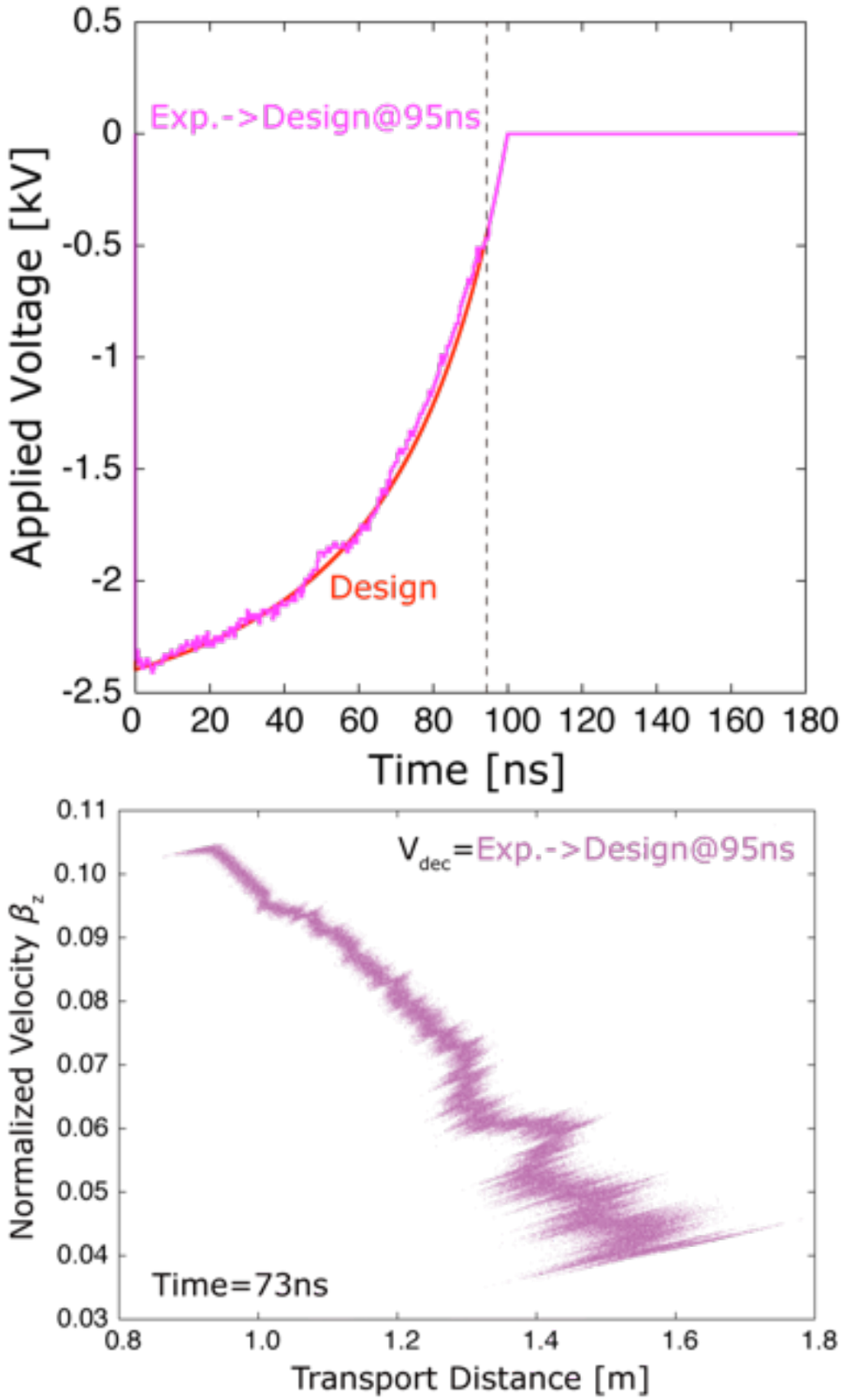
1D PIC Results by Applied Voltage with "Design"



I_{b0} =100 μA,
τ_{b0} =100 ns,



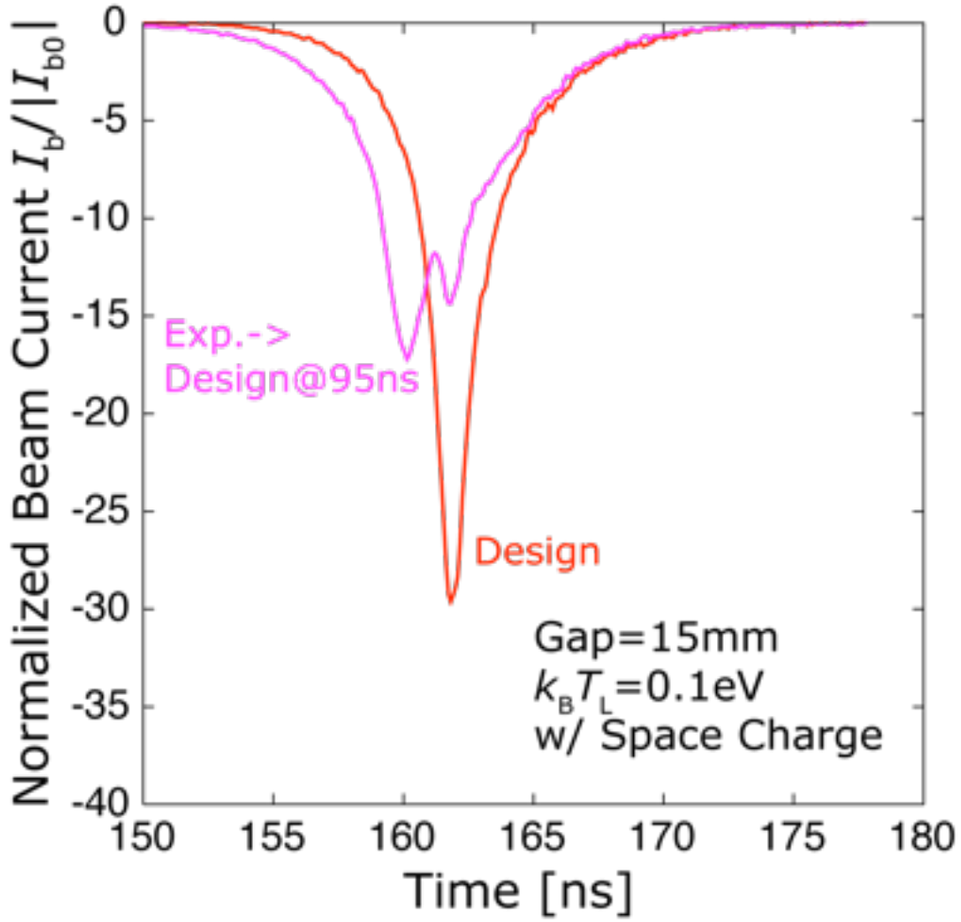
1D PIC Results by Applied Voltage with "Exp.->Design@95ns"



Applied Voltage is switched from experimental data to design value at 95ns.

I_{b0} =100 μA,

τ_{b0} =100 ns,

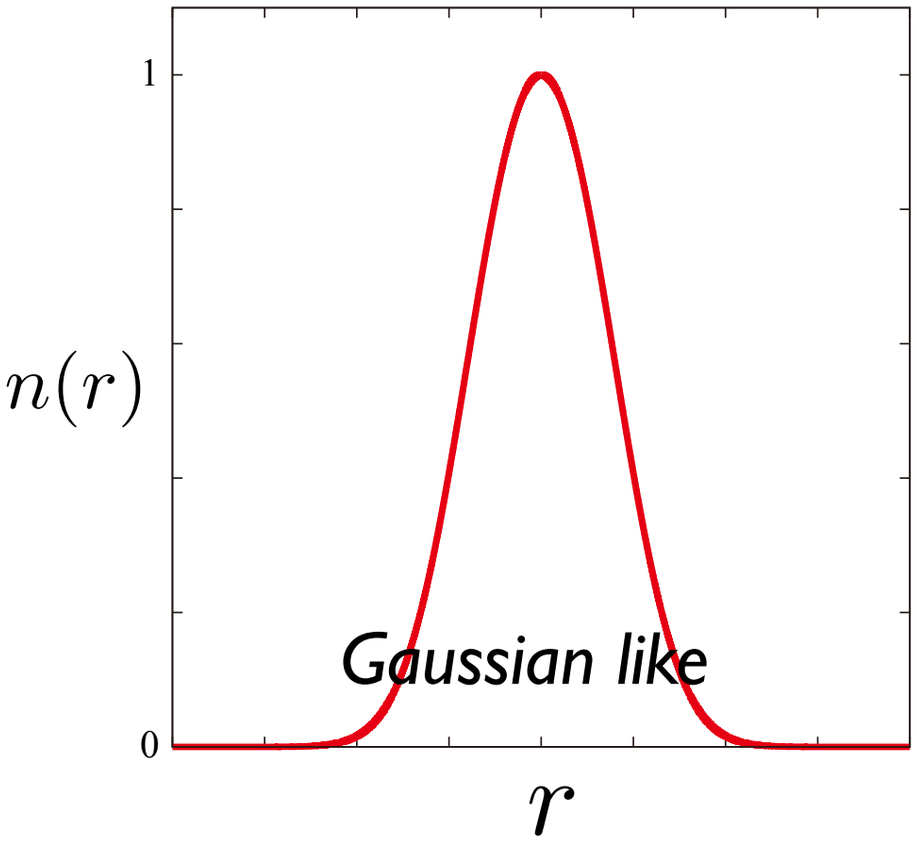


Thermal Equilibrium (=Maxwell-Boltzmann) Distribution

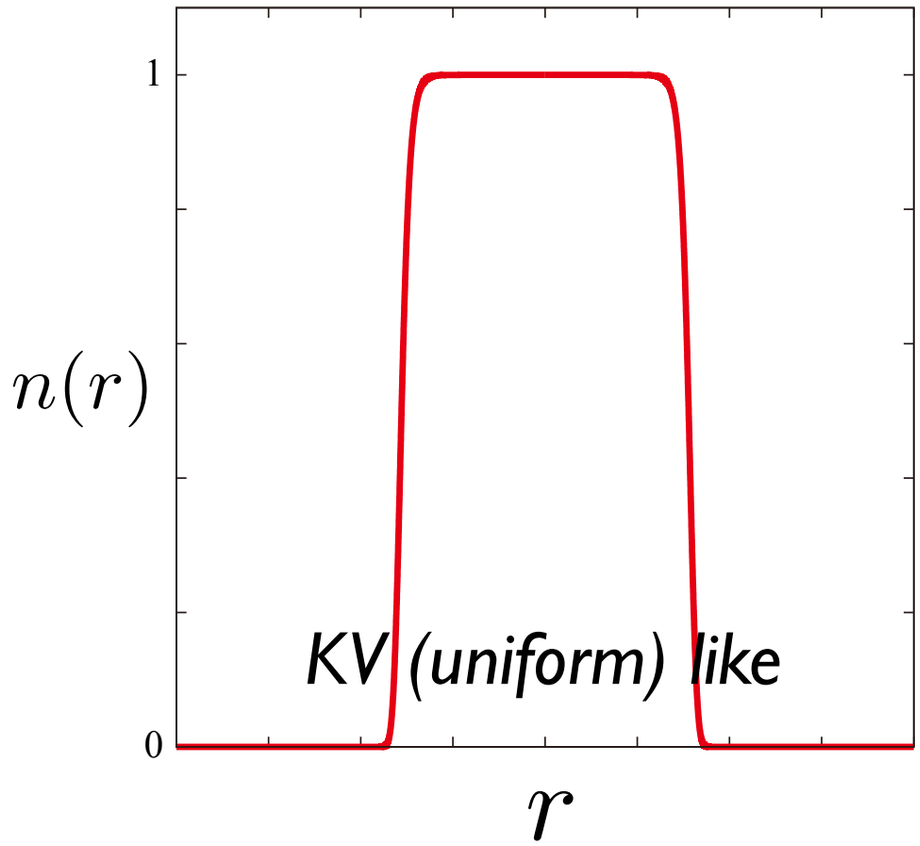
Particle Distribution in Real Space for Thermal Equilibrium (TE)

$$n(r) = \hat{n} \exp\left[-\frac{\gamma_b m \beta_b^2 c^2 k_{\beta 0}^2}{2 k_B T} r^2 - \frac{1}{\gamma_b^2} \frac{q\phi(r)}{k_B T} \right]$$

$\sigma/\sigma_0 = 0.9$



$\sigma/\sigma_0 = 0.1$



Space Charge Effect

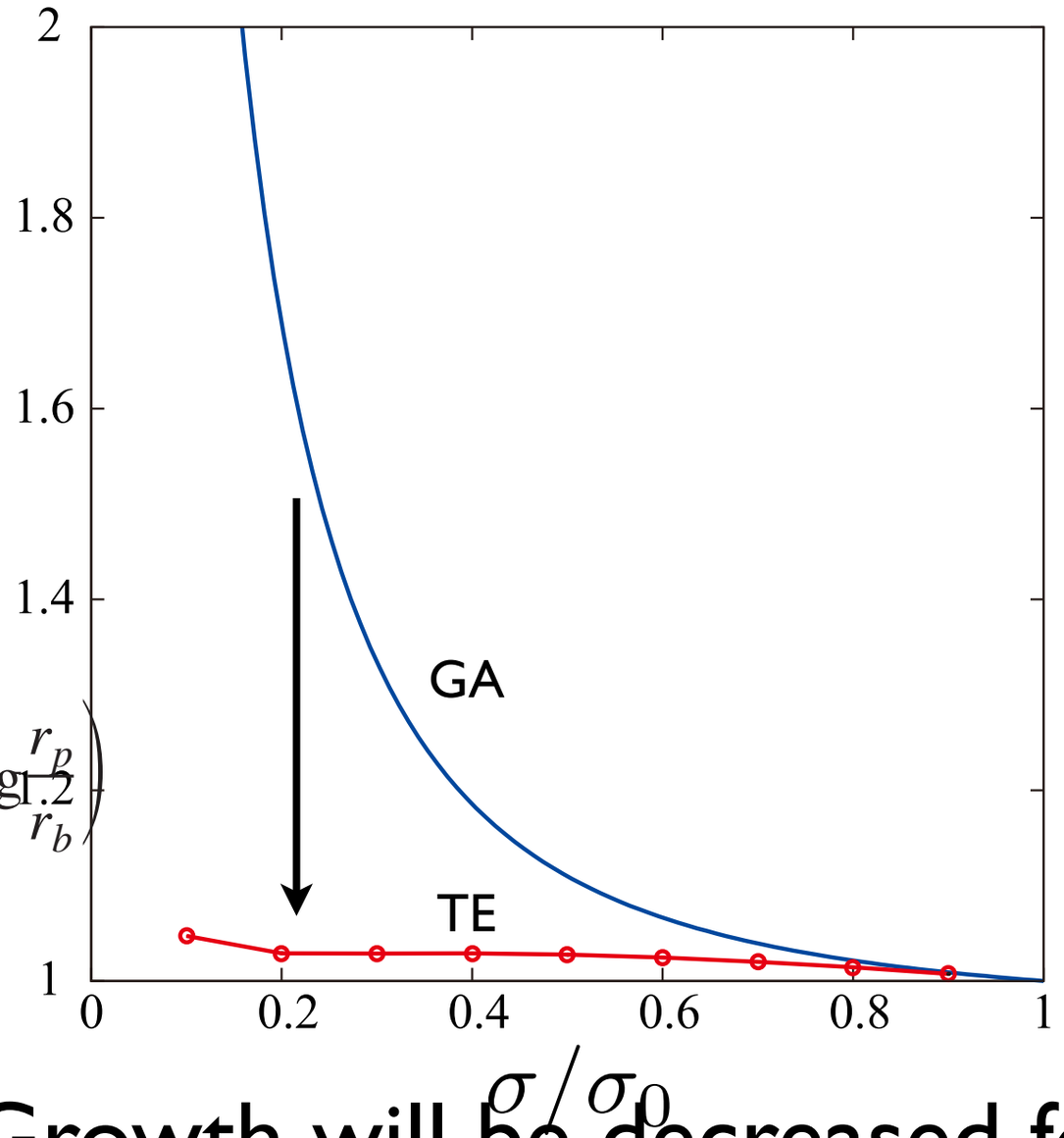
weak ⟶ strong

Possible Emittance Growth for TE Distribution

T. Kikuchi, K. Horioka, Phys. Plasmas 16 (2009) 050703

$$\frac{\epsilon_f}{\epsilon_i} = \left[1 + \frac{1}{2}\left(\frac{1}{\sigma^2/\sigma_0^2} - 1\right)\frac{U}{w_0}\right]^{1/2}$$

$$\frac{U}{w_0} = \frac{4}{(\int_0^\infty \tilde{n} r dr)^2}\int_0^{r_p} \tilde{E}^2 r dr - \left(1 + 4\log\frac{r_p}{r_b}\right)$$



Possible Emittance Growth will be decreased for TE Distribution, dramatically!

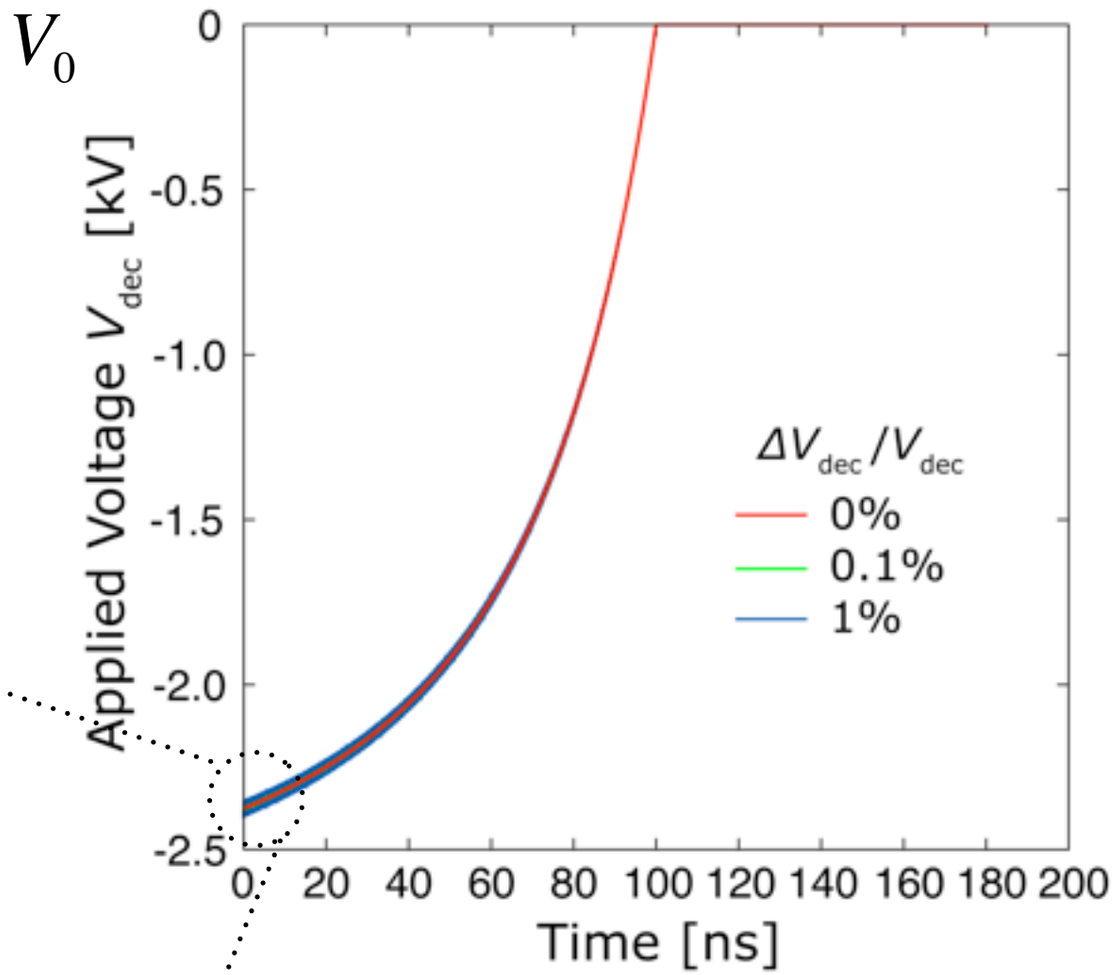
Compression Voltage Model with Error

- Bunch compression voltage at gap is applied by

$$V_{dec}(t) = \frac{m_e}{2q}\frac{1}{\left(\sqrt{\frac{m_e}{2qV_0}} + \frac{T-t}{L}\right)^2} - V_0$$

- with Error

$$+\frac{\Delta V_{dec}}{V_{dec}(t)}\sin\left(\frac{2\pi}{\tau_n}t\right)$$



Compression Voltage Model with Error

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- with Error

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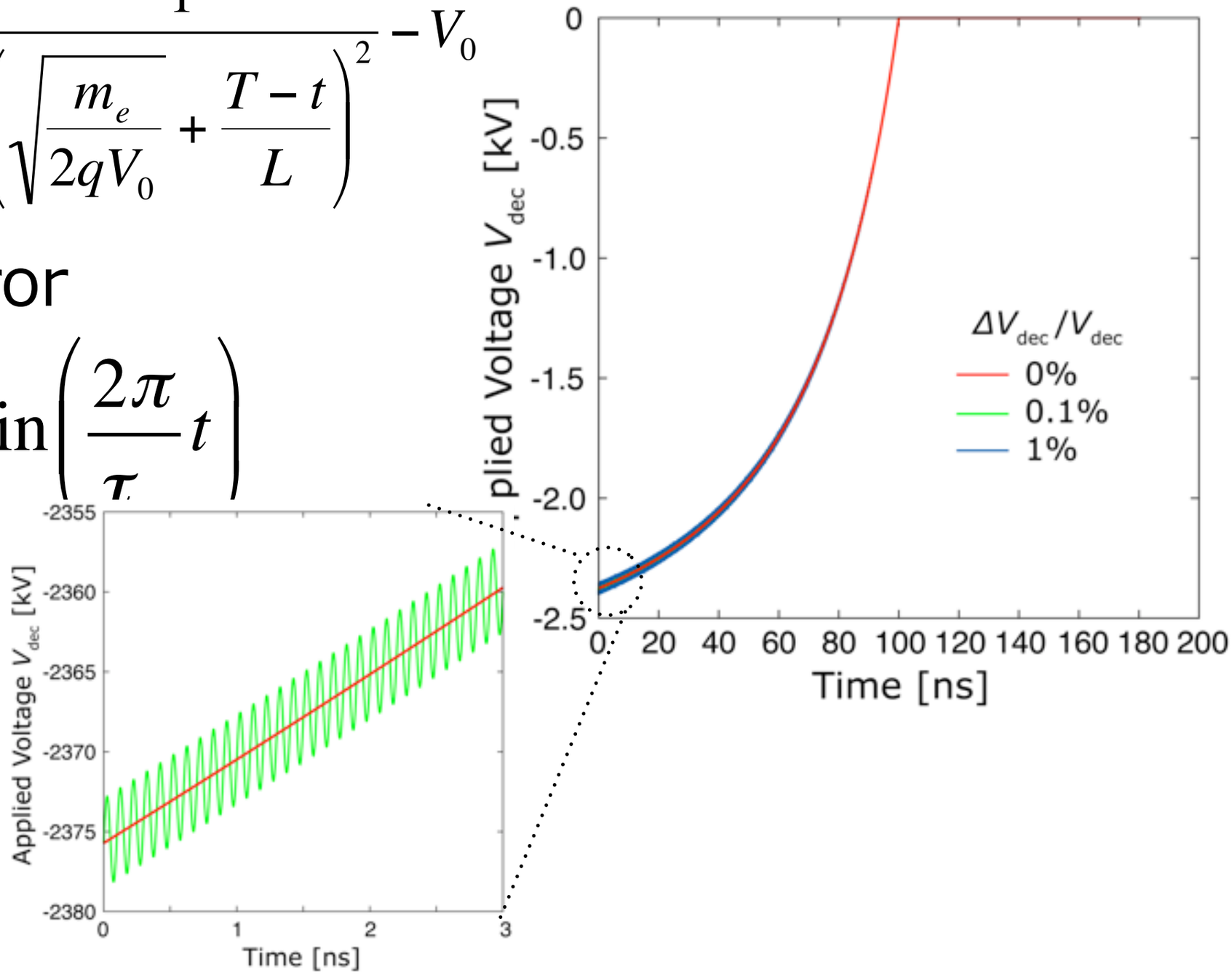
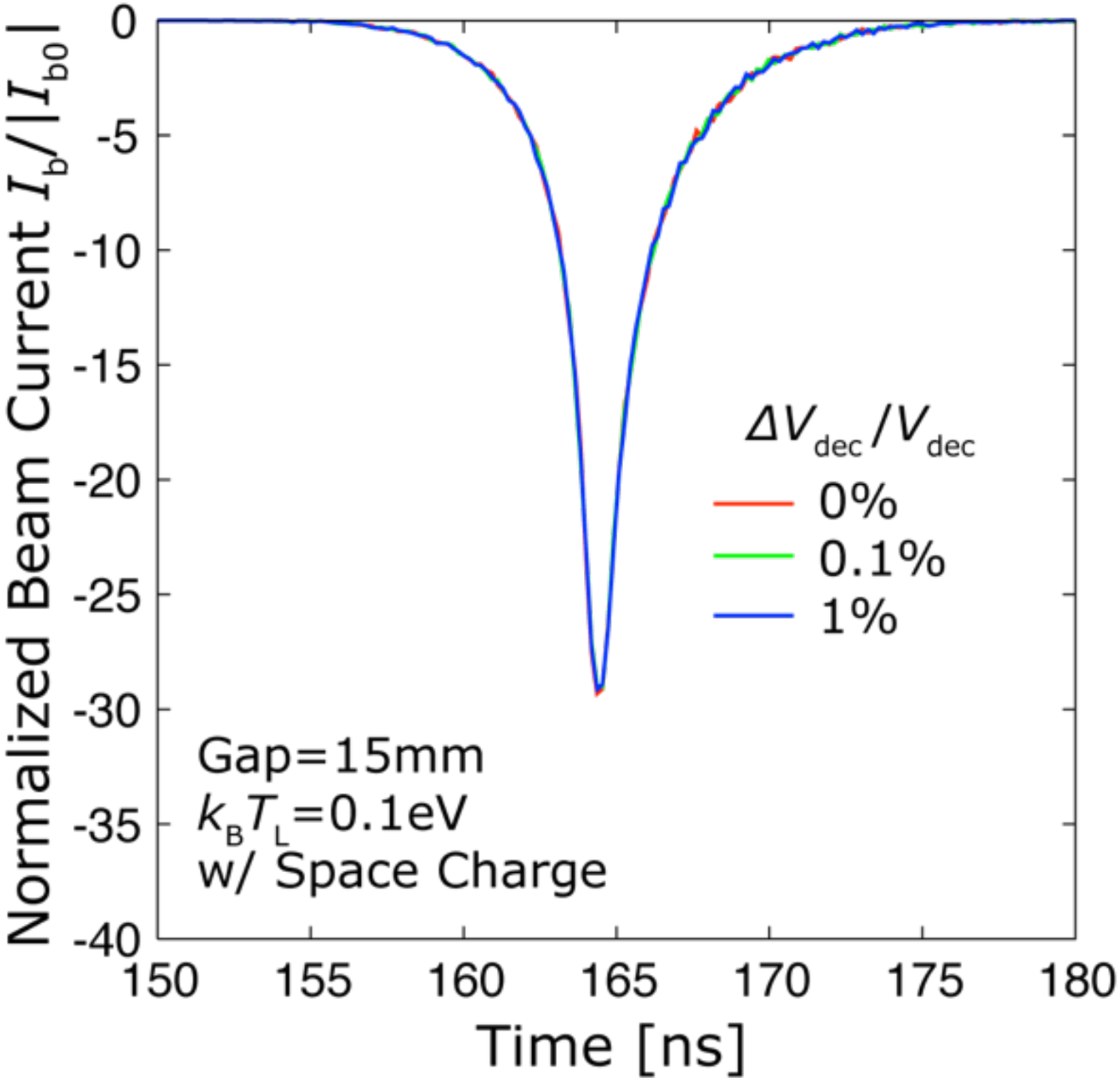


Final Beam Current Profile with Voltage Error Model

1D PIC result

I_{b0} =100 μA

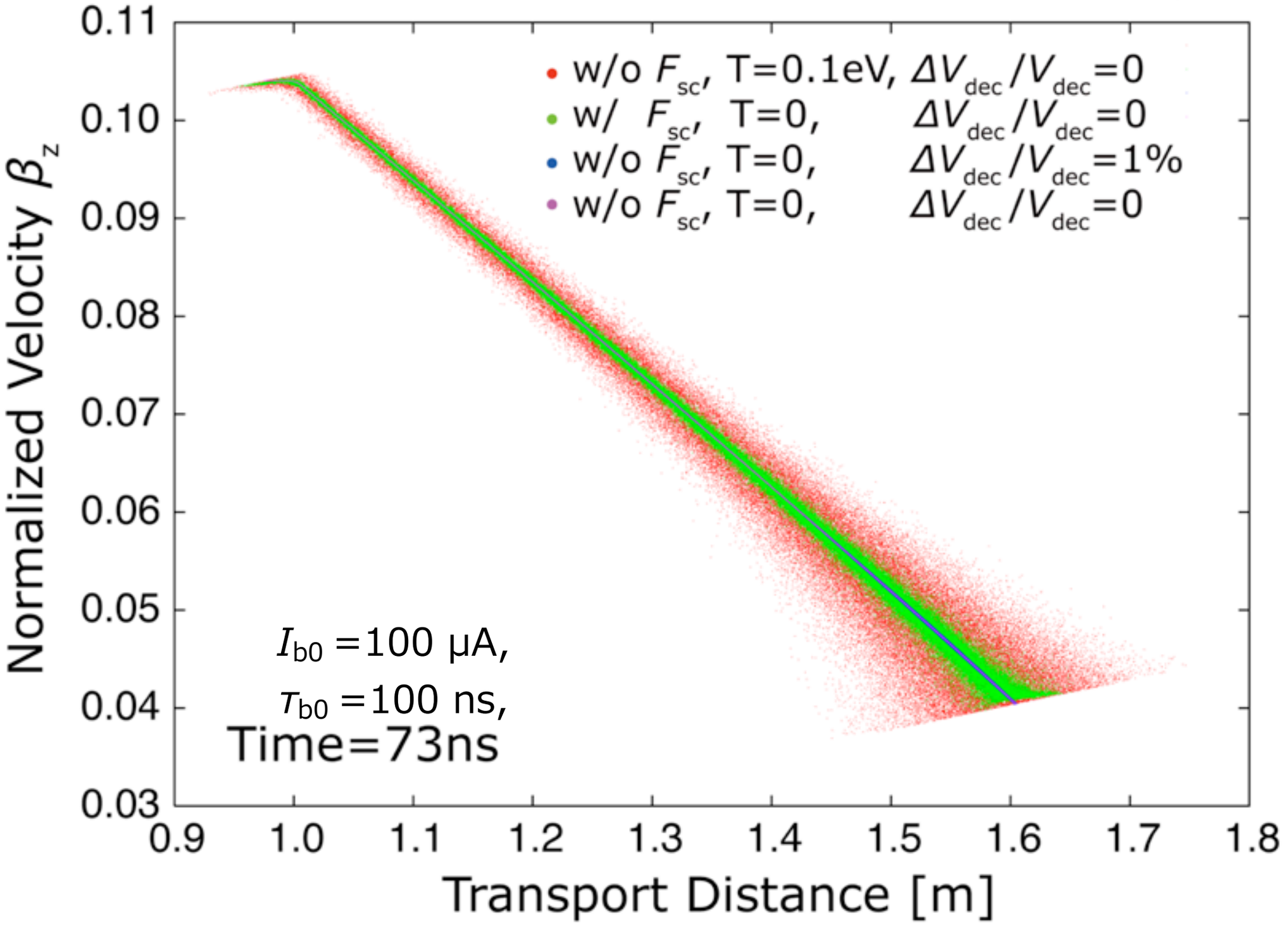
τ_{b0} =100 ns



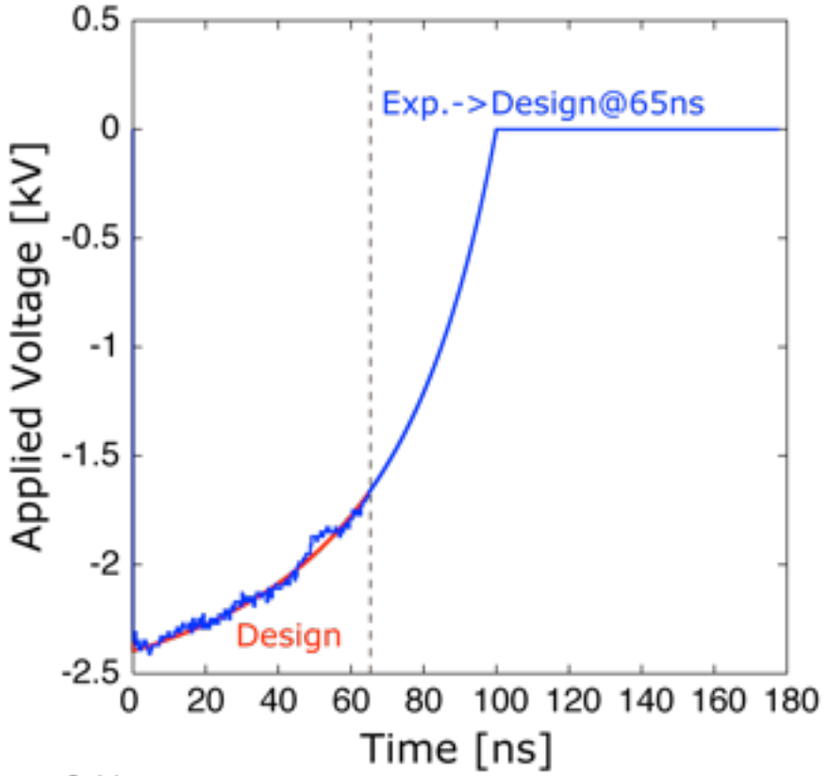
+Sin Noise

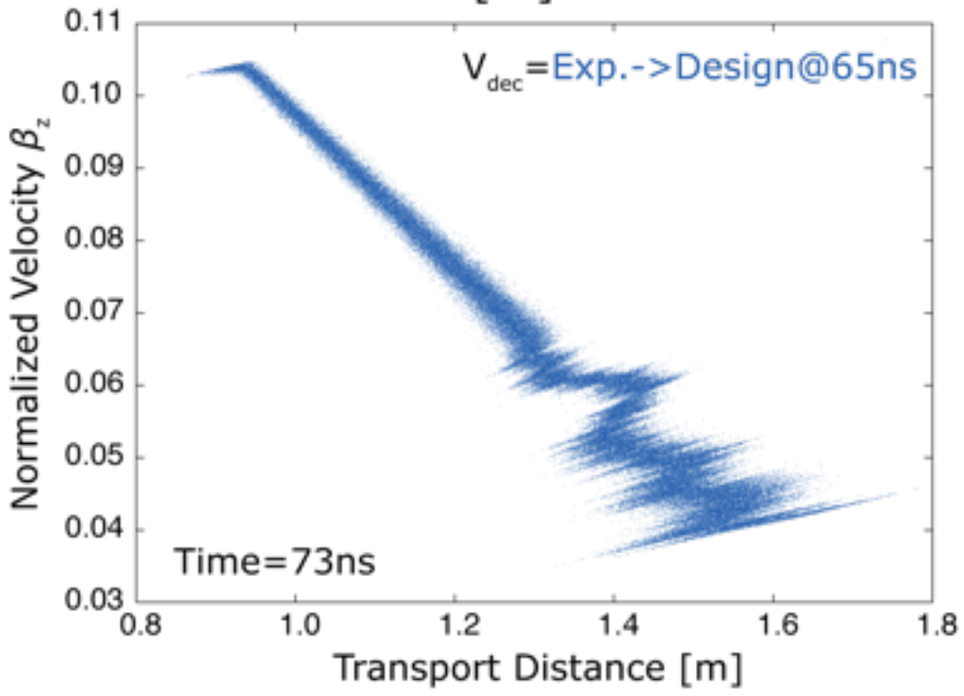
Particle Map in Longitudinal Phase Space

1D PIC result

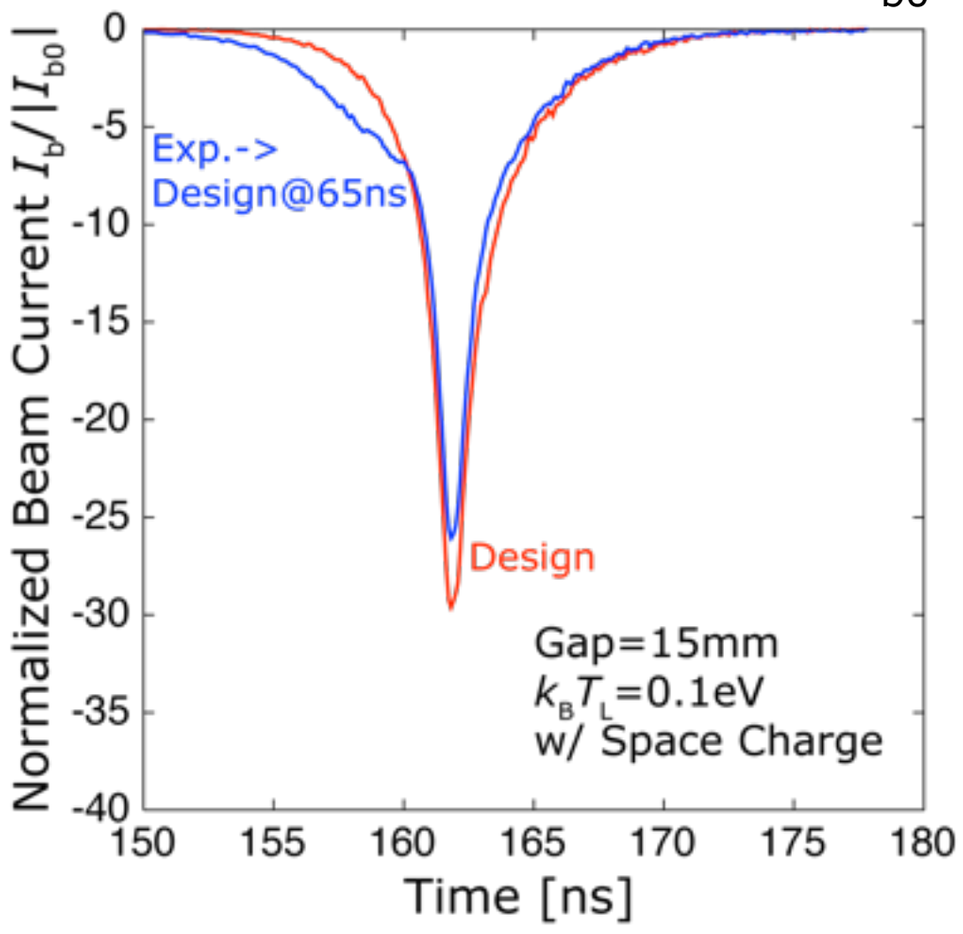


1D PIC Results by Applied Voltage with "Exp.->Design@65ns"





Applied Voltage is switched from experimental data to design value at 65ns.

I_{b0} =100 μA,

τ_{b0} =100 ns,