ILC電子ビームドライブ陽電子源におけるoff-crest加速条件でのビームローディング補償

Compensation of the transient beam-loading effect in the capture linac of E-Driven positron source

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Outline

- Linear collider requires a large amount of electron and positron comparing to ring collider.
- In ILC E-Driven positron source, the positron is generated in a multi-bunch format, 66 bunches with 6.15 ns spacing.
- Positron rides initially on the deceleration phase and slips to the acceleration phase.
- The phase of the heavy beam loading is moving from cos(π) to cos(0). It causes the voltage and phase variation of acceleration field.

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Overview of the Capture Linac

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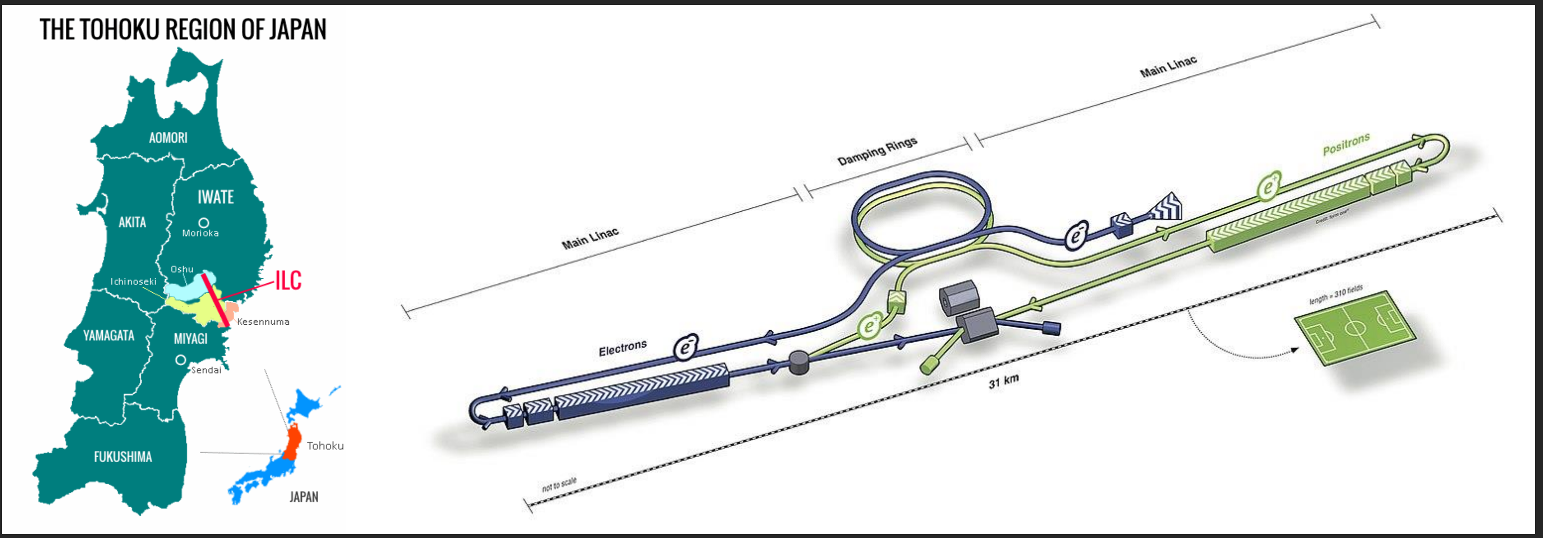
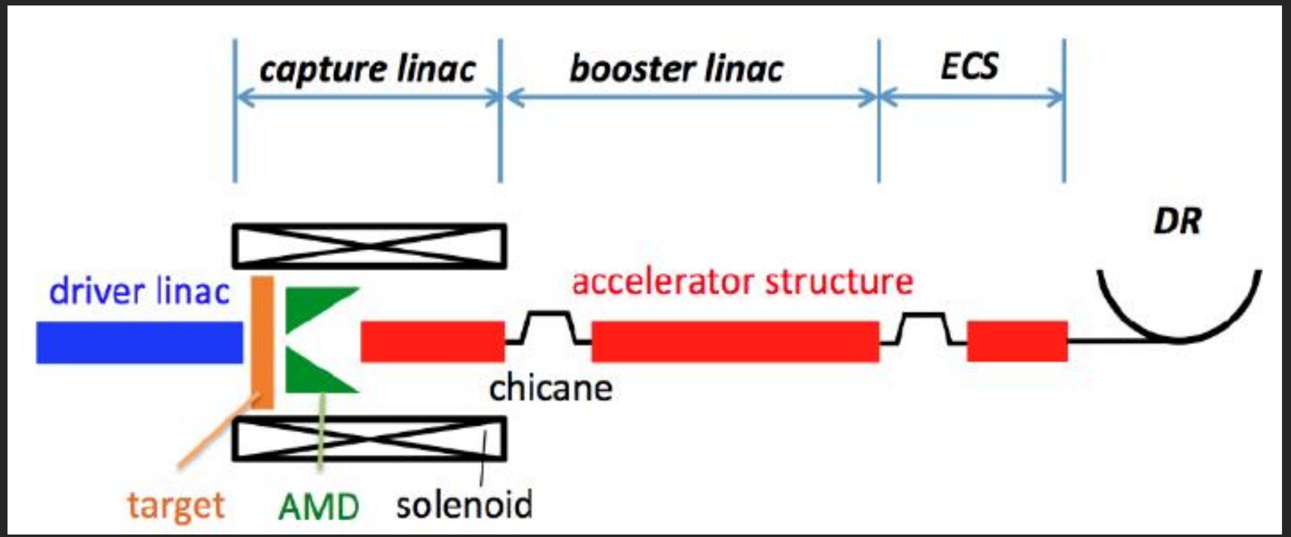


3 GeV 4.0 nC electron driver
19 mm W-Re rotating Target
37of L-Band SW (11cell APS) Linac
Chicane to remove electron
Booster : L and S-Band TW Linac
ECS (Energy Compressor Section)



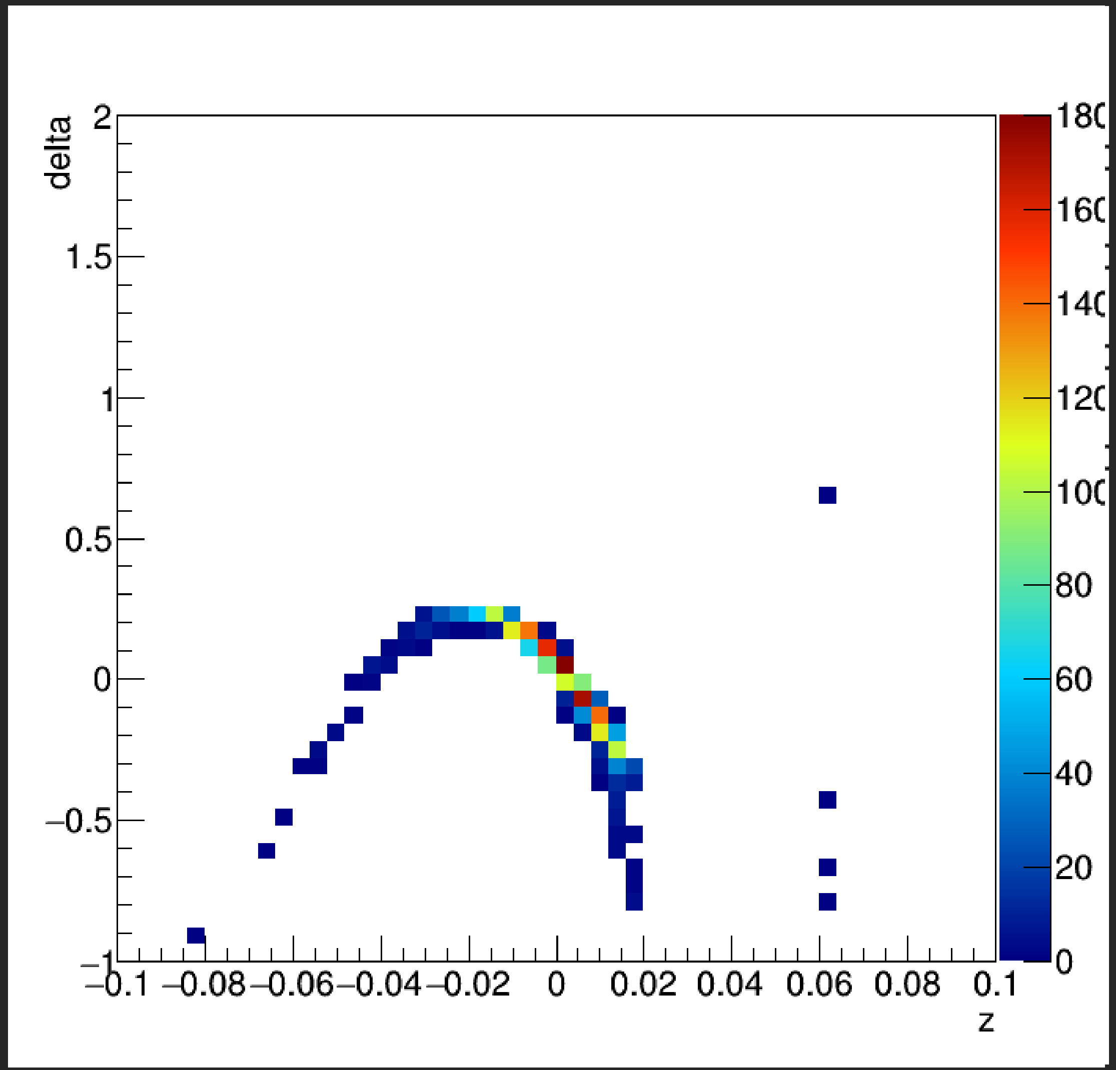
Parameter	**Number**	**Unit**
Frequency	1300	MHz
Shunt Impedance	31.5	MΩ/m
Aperture (2a)	60	mm
Q Value	24970	
Length	1.27	m
RF power	22.5	MW

Positrons are placed at the deceleration phase and captured at the acceleration phase by slippage.

Positrons are handled as 66 multi-bunch format with 6.15 ns spacing.

Detail of the capture simulation: H. Nagoshi, et al., NIMA(953)163134(2020)

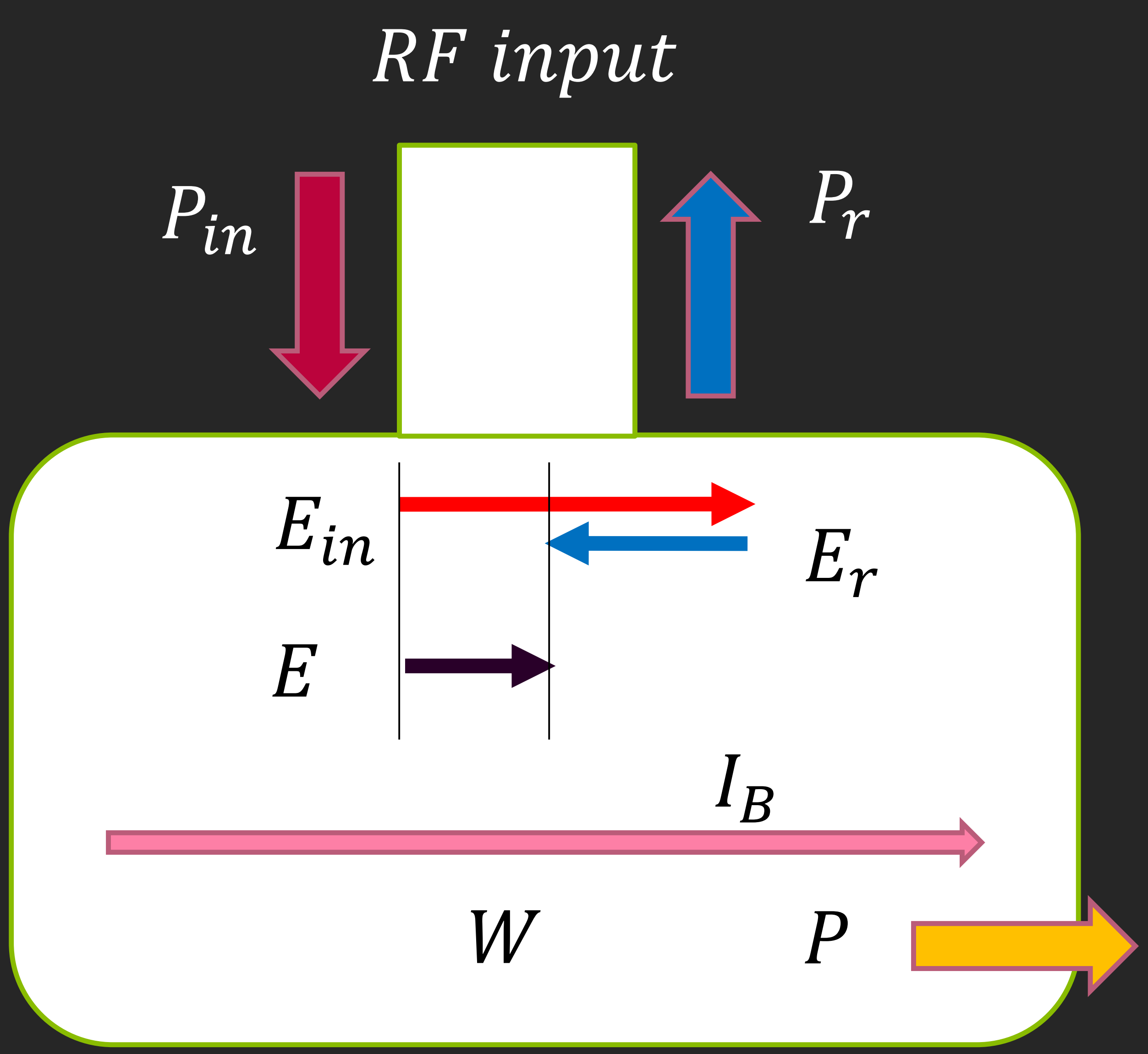
APS cavity property : Next talk by S. Konno



Beam Loading Compensation

Transient property of SW cavity (Single cell model)

Acceleration field by RF input



$$V = EL$$

Energy Conservation

$$\frac{dW}{dt} = P_{in} - P_r - P - IV$$

By voltage,

$$W = \frac{Q}{\omega R} V^2, \qquad P = \frac{V^2}{R}$$

$$P_{in} = \frac{\beta V^2}{R}, P_r = \frac{\beta (V_{in} - V)^2}{R}$$

$$\frac{dV}{dt} = -\frac{(1+\beta)\omega}{2Q} V + \frac{\omega}{Q}\sqrt{\beta R P}$$

$V(t=0) = 0, P = P_o u(t)$, $\mathrm{I} = I_0 u(t - t_b)$,
$u(t)$: step function

$$V(t) = \frac{2\sqrt{\beta P_o R}}{1+\beta}\left(1 - e^{-\frac{t}{\tau}}\right) - \frac{R I_B}{1+\beta}\left(1 - e^{-\frac{t-t_b}{\tau}}\right)$$

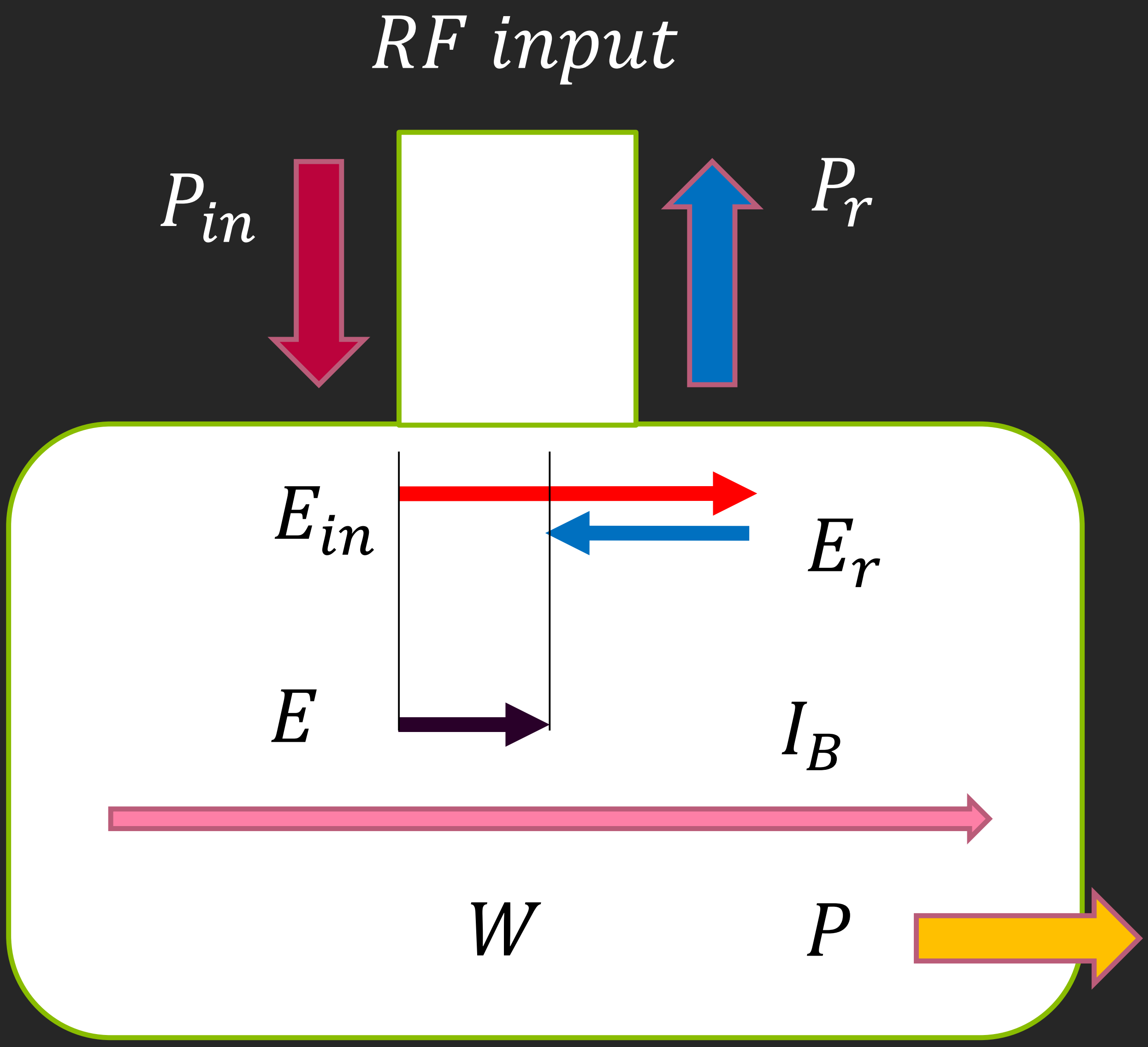
$$\tau = 2Q/(1+\beta)\omega$$

Beam Loading Compensation

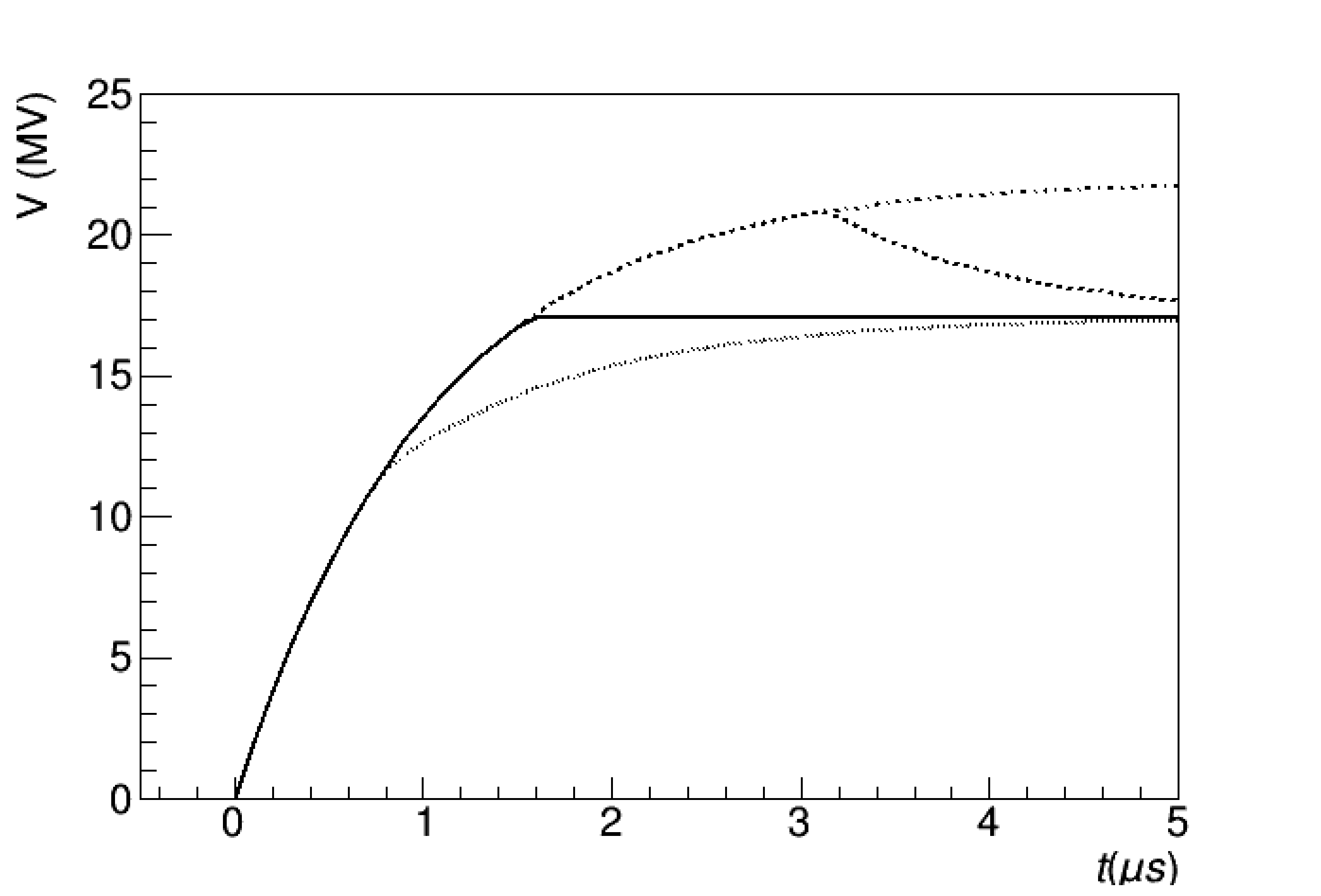
On crest acceleration

$$V(t) = \frac{2\sqrt{\beta P_o R}}{1+\beta}\left(1 - e^{-\frac{t}{\tau}}\right)e^{\iota\omega t} - \frac{\omega R I_{B0}}{1+\beta}\left(1 - e^{-\frac{t-t_b}{\tau}}\right)e^{\iota\omega t}$$

Voltage is uniform, if $t_b = -\tau ln\left(\frac{I_{B0}}{2}\sqrt{\frac{RL}{BP_0}}\right)$



$V = EL$

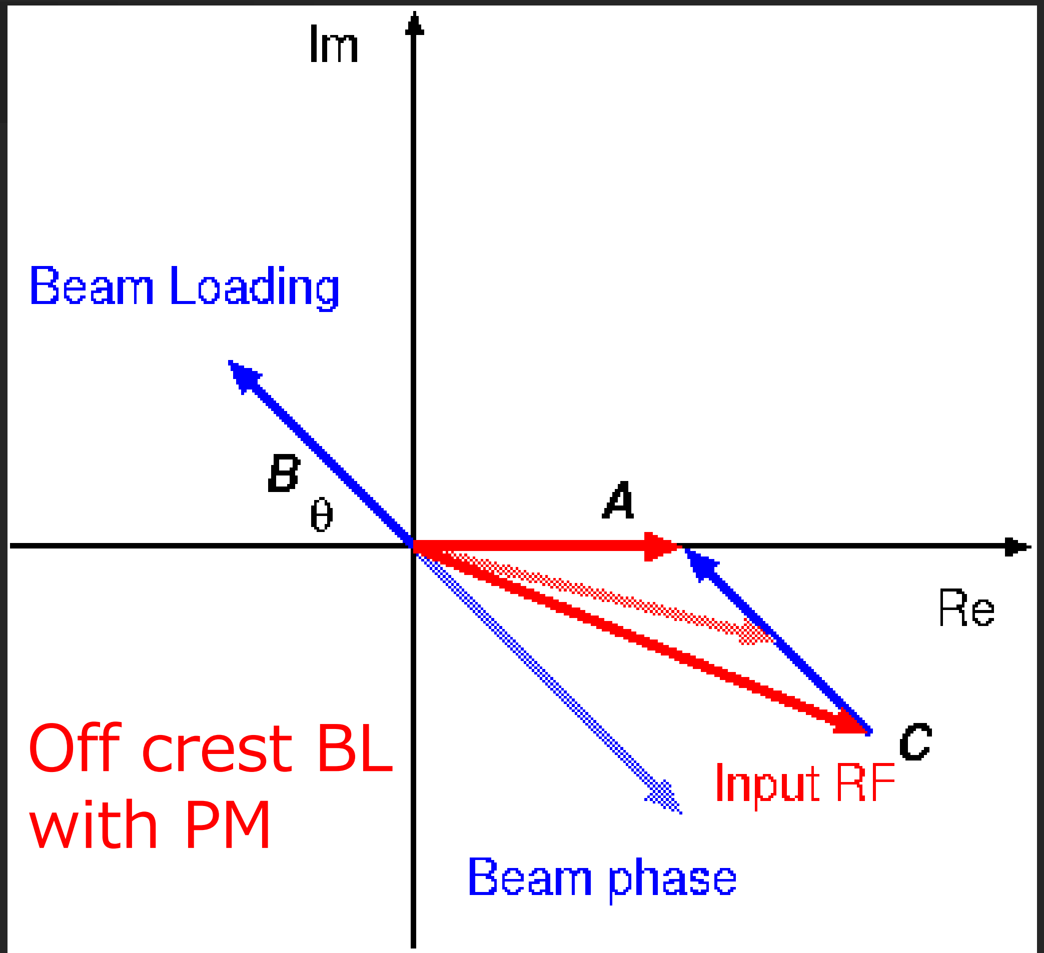


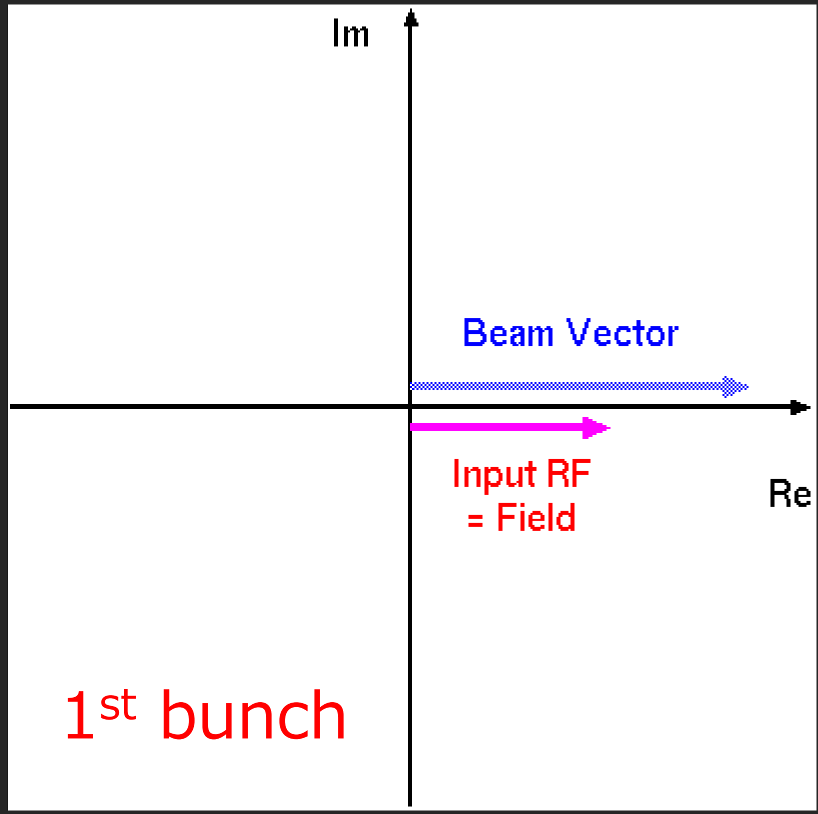
Beam Loading Compensataion : Off crest

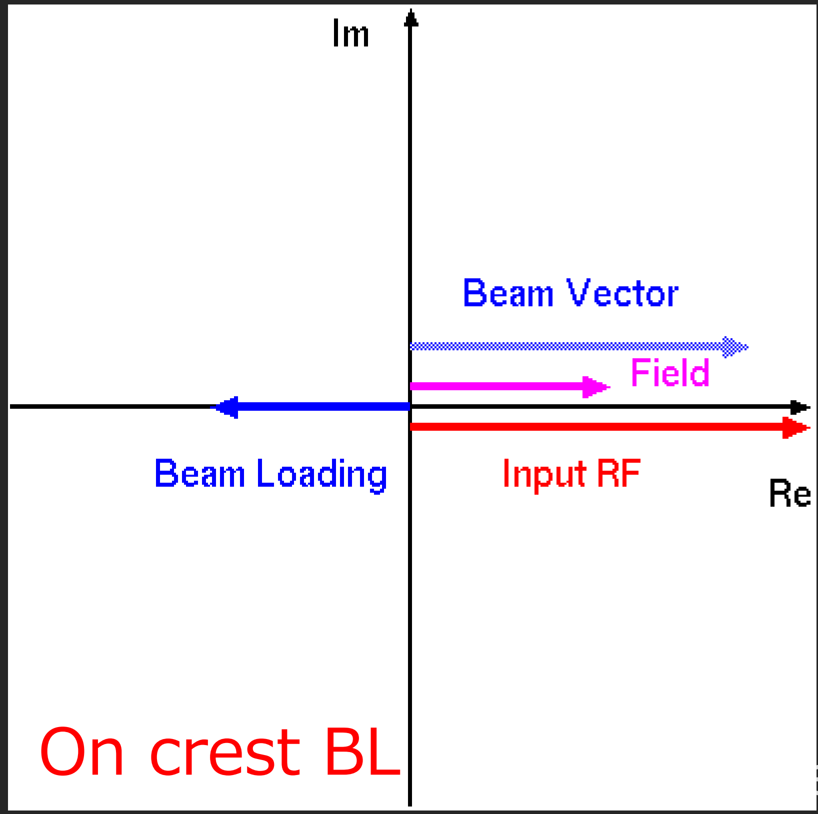
Off crest acceleration with a phase θ,

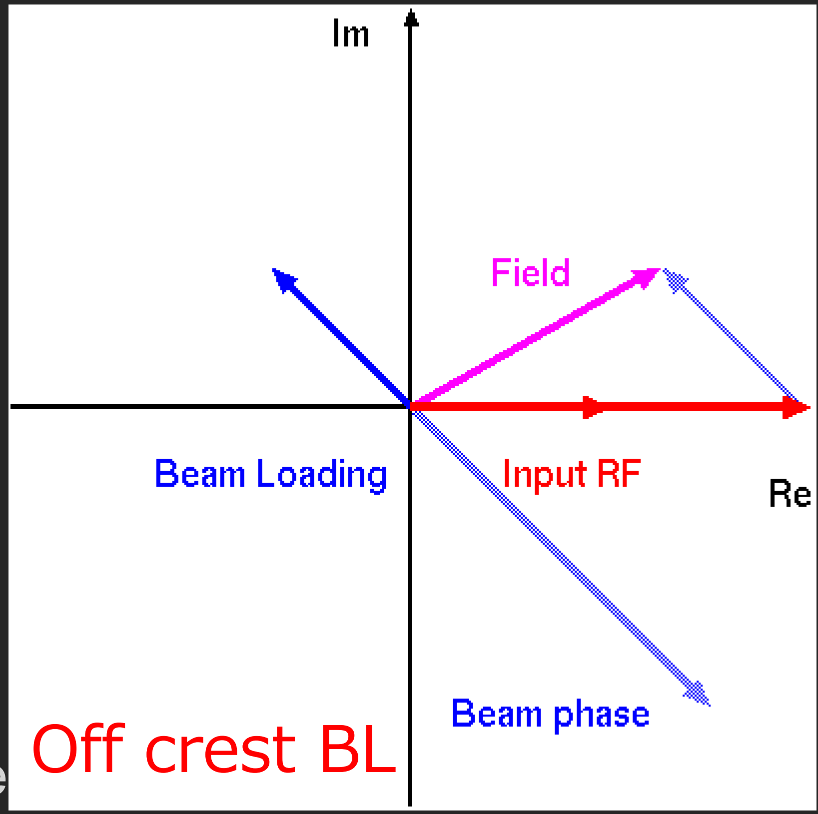
$$V(t) = \frac{2\sqrt{\beta P r L}}{1+\beta}\left(1 - e^{-\frac{t}{T}}\right)e^{\iota\omega t} - \frac{IrL}{1+\beta}\left(1 - e^{-\frac{t-t_b}{T}}\right)e^{\iota(\omega t+\theta)}$$

The phase is varied over the pulse. The phase should be controlled for the compensation.









RF input Phase Modulation

Acceleration voltage of the off-crest acceleration with phase q,

$$\boldsymbol{V}(\boldsymbol{t}) = V_0\left(1 - e^{-\frac{t}{\tau}}\right)\cos\omega t - V_{b0}\left(1 - e^{-\frac{t-t_b}{\tau}}\right)\cos(\omega t + \theta)$$

The voltage and phase are varied, even the envelope is matched. To cancel the beam loading voltage, the RF input voltage has to be,

$$V_{RF}(t) = V_{10}\cos\omega t + V_{b0}\left(1 - e^{-\frac{t-t_b}{\tau}}\right)\cos(\omega t + \theta)$$

In this case, $\mathrm{V}(t) = V_{10}\cos\omega t$. $V_{RF}(t)$ is rewritten as

$$V_{RF}(t) = \sqrt{\mathrm{A}^2 + B^2}\cos(\omega t + \varsigma)$$

$$V_2 = V_{b0}\left(1 - e^{-\frac{t-t_b}{\tau}}\right)$$

$$A = V_{10} + V_2\cos\theta$$

$$\mathrm{B} = V_2\sin\theta$$

$$\varsigma = \tan^{-1} B/A$$

$$V(t) = \sqrt{\mathrm{A}^2 + B^2}\cos(\omega t + \varsigma)$$

The asymptotic value of the envelope has to be equal to the envelope of the input RF as

$$\lim_{t\to\infty}\sqrt{\mathrm{A}^2 + B^2} = \frac{2\sqrt{\beta P_o R}}{1+\beta} = V_0$$

V_{10} (Voltage at the first bunch) is obtained as

$$V_{10}^2 + 2V_{b0}\cos\theta\, V_{10} + V_{b0}^2 - V_0^2 = 0$$

$$V_{10} = -V_{b0}\cos\theta + \sqrt{V_0^2 + V_{b0}^2(\cos\theta^2 - 1)}$$

Time to start the beam acceleration t_b is

$$t_b = -T_0\ln\left(1 - \frac{V_{10}}{V_0}\right)$$

$$\boldsymbol{V(t)} = V_0\left(1 - e^{-\frac{t}{\tau}}\right)\cos(\omega t + \varsigma)$$

$$\varsigma = \begin{cases} 0\ (t < t_b) \\ \tan^{-1}\frac{V_2\sin\theta}{V_{10}+V_2\cos\theta}\ (t > t_b) \end{cases}$$

APS cavity

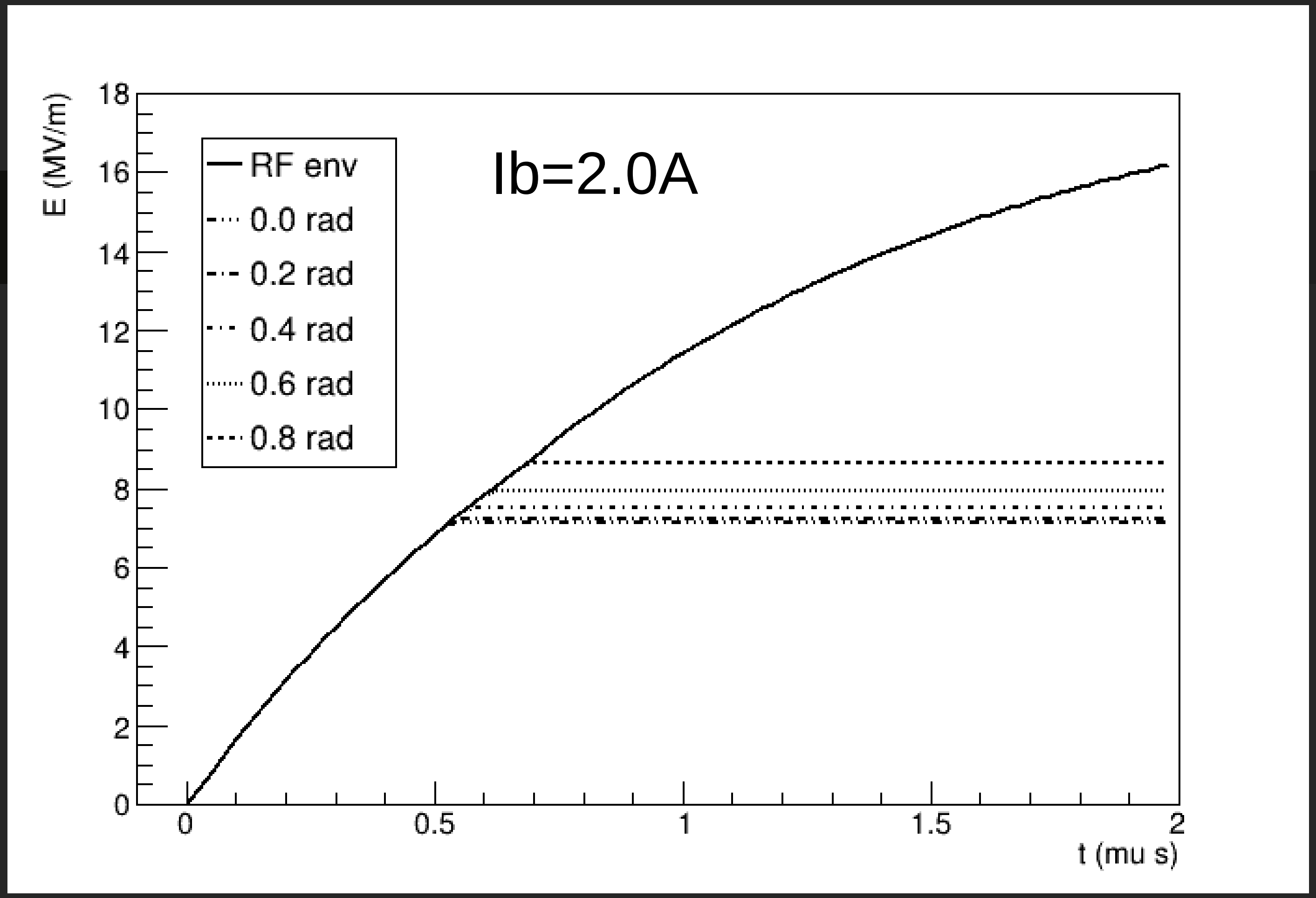
π/2 mode SW

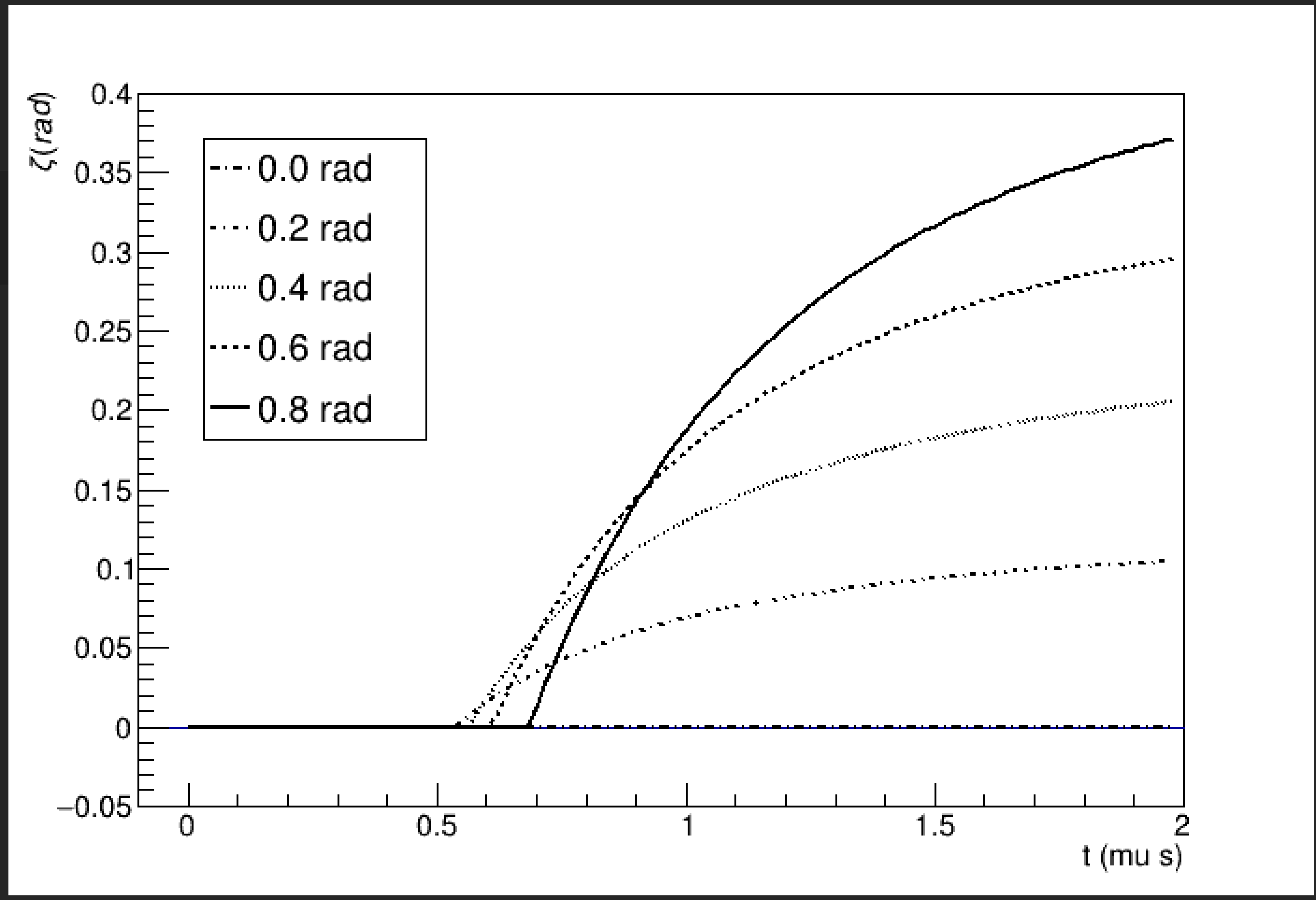
$$r_{sh} = 31.5 \frac{M\Omega}{m}$$

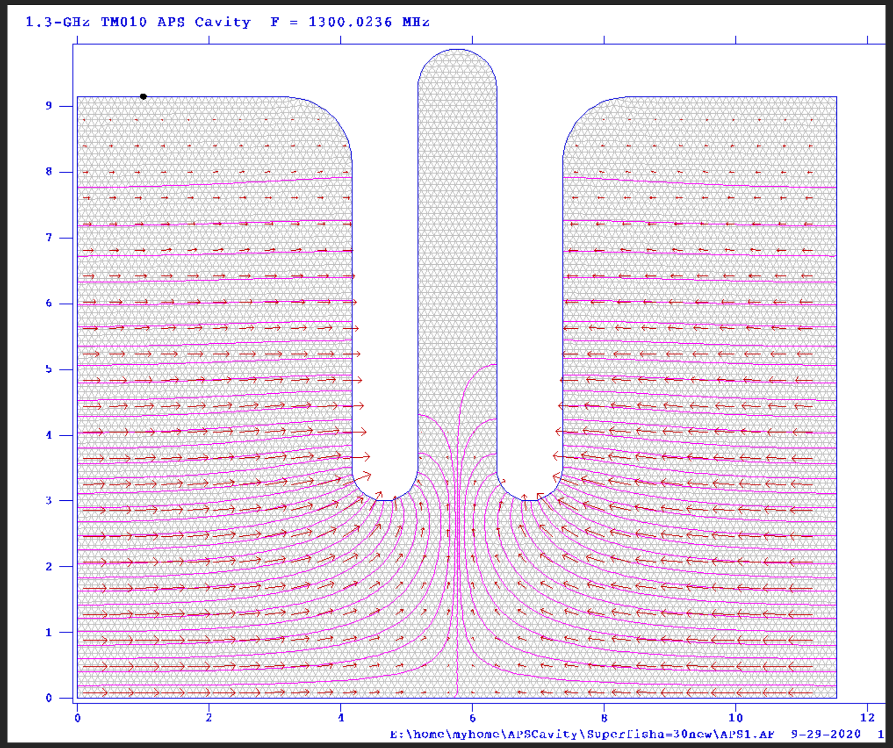
$$Q_0 = 25000$$

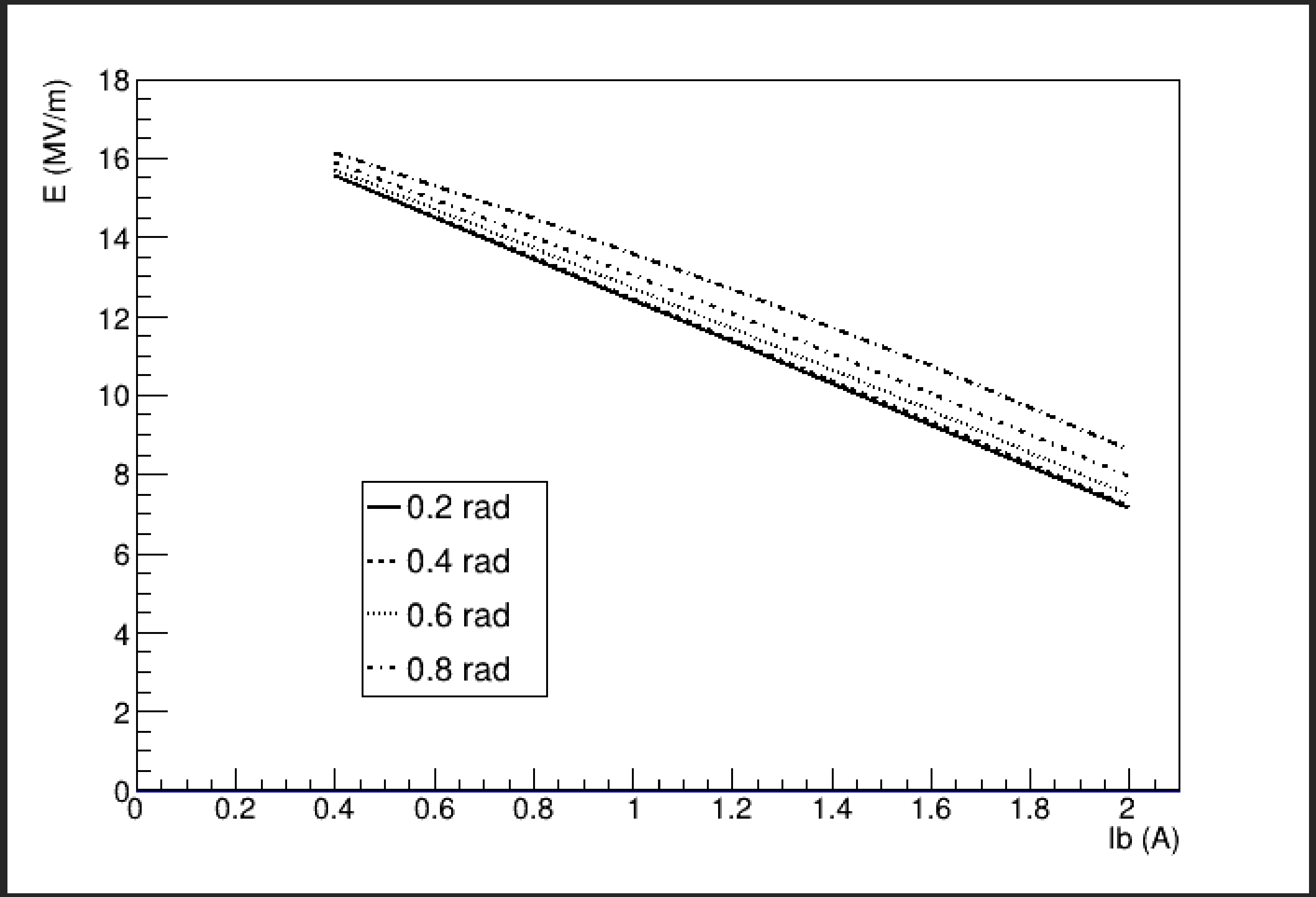
$$\beta = 5.0$$

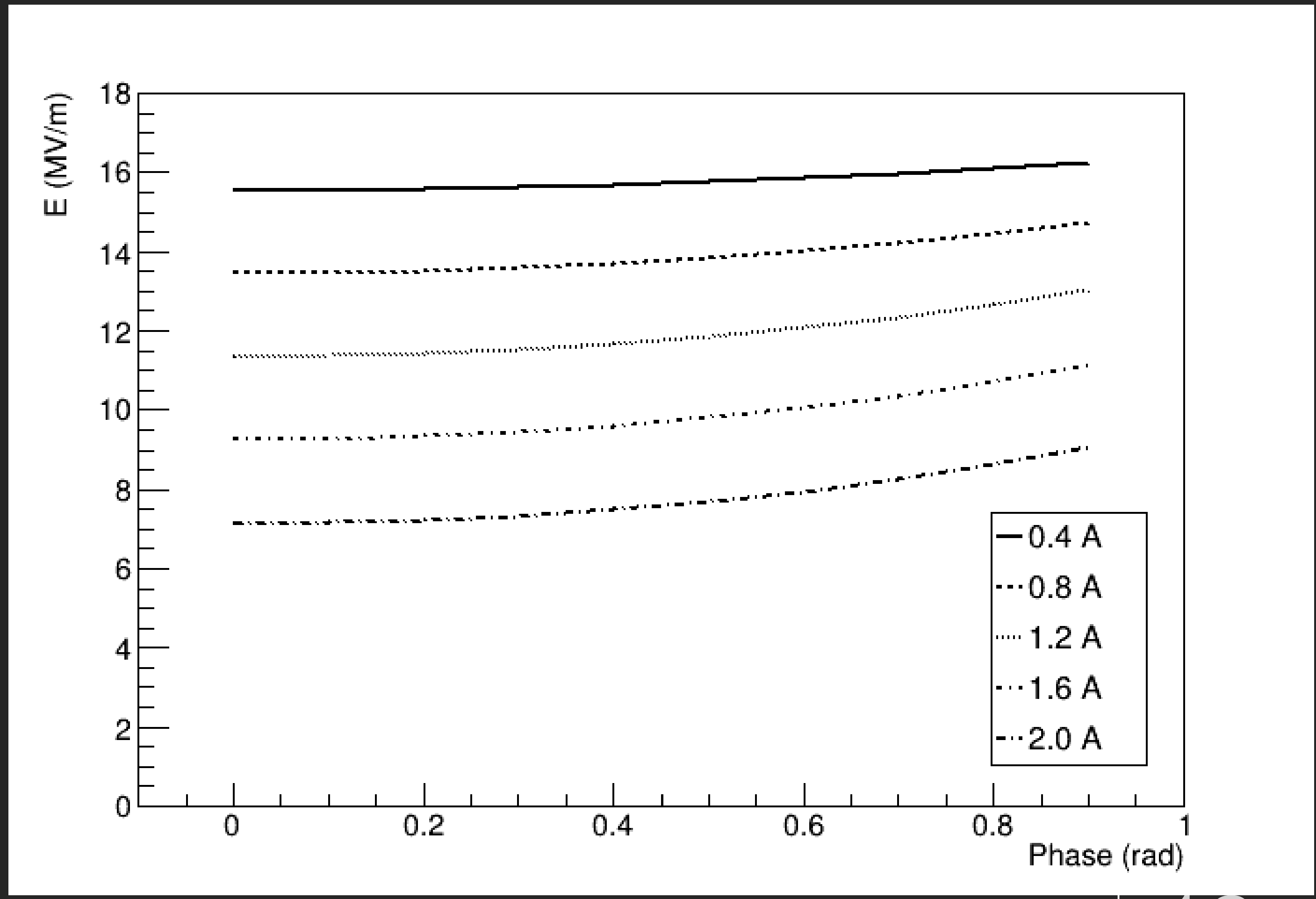
P_{RF}=22.5 MW







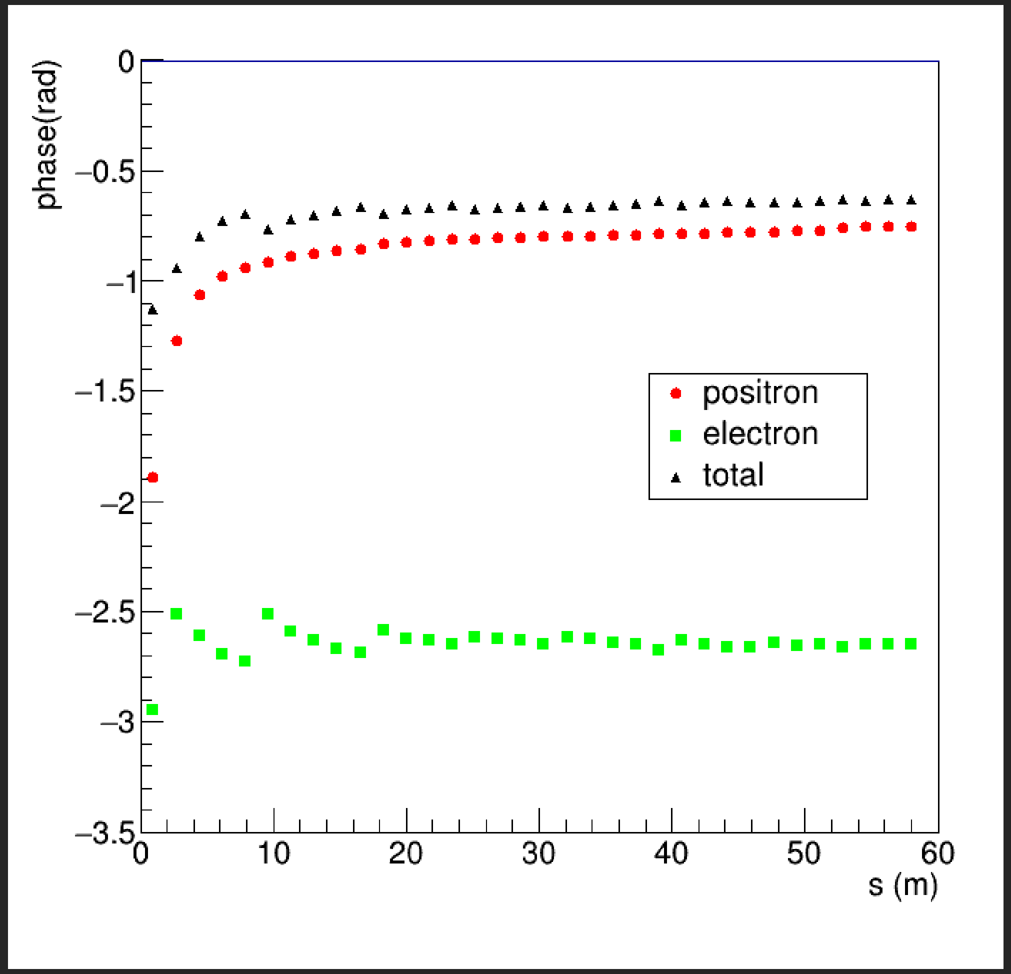


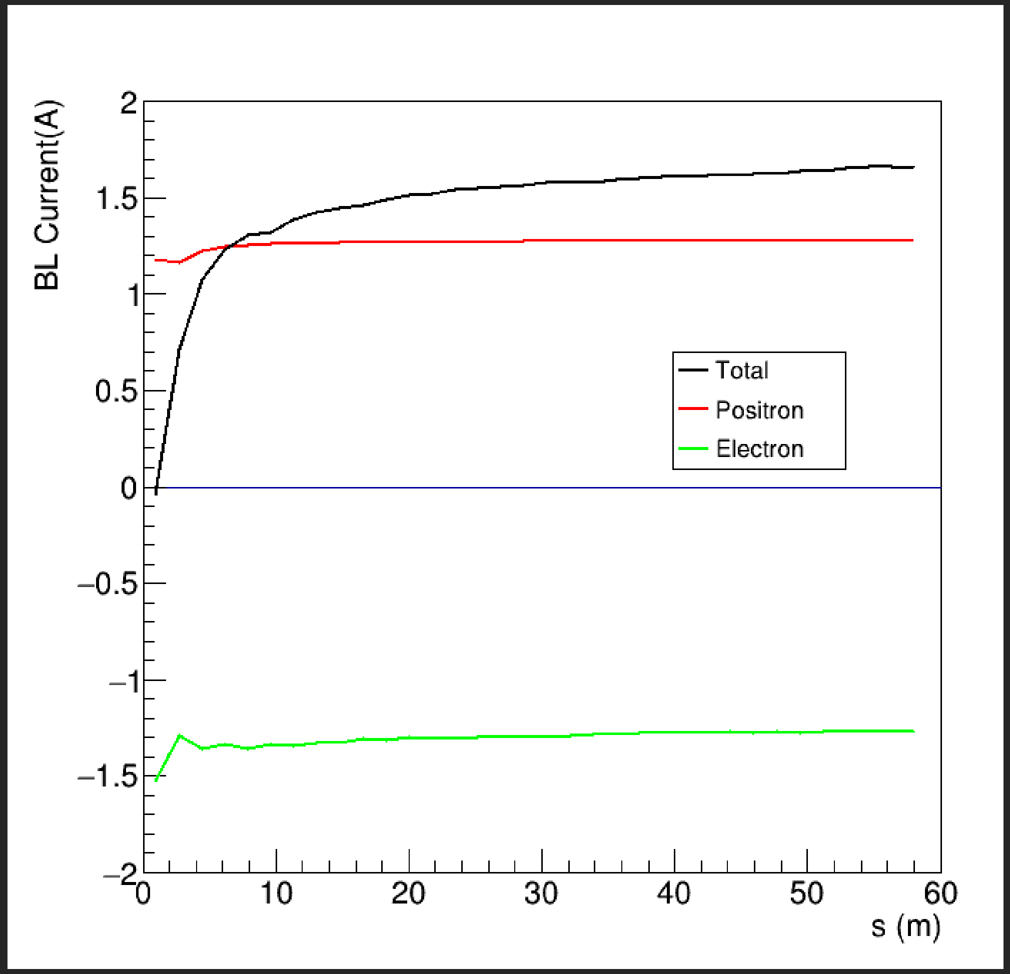


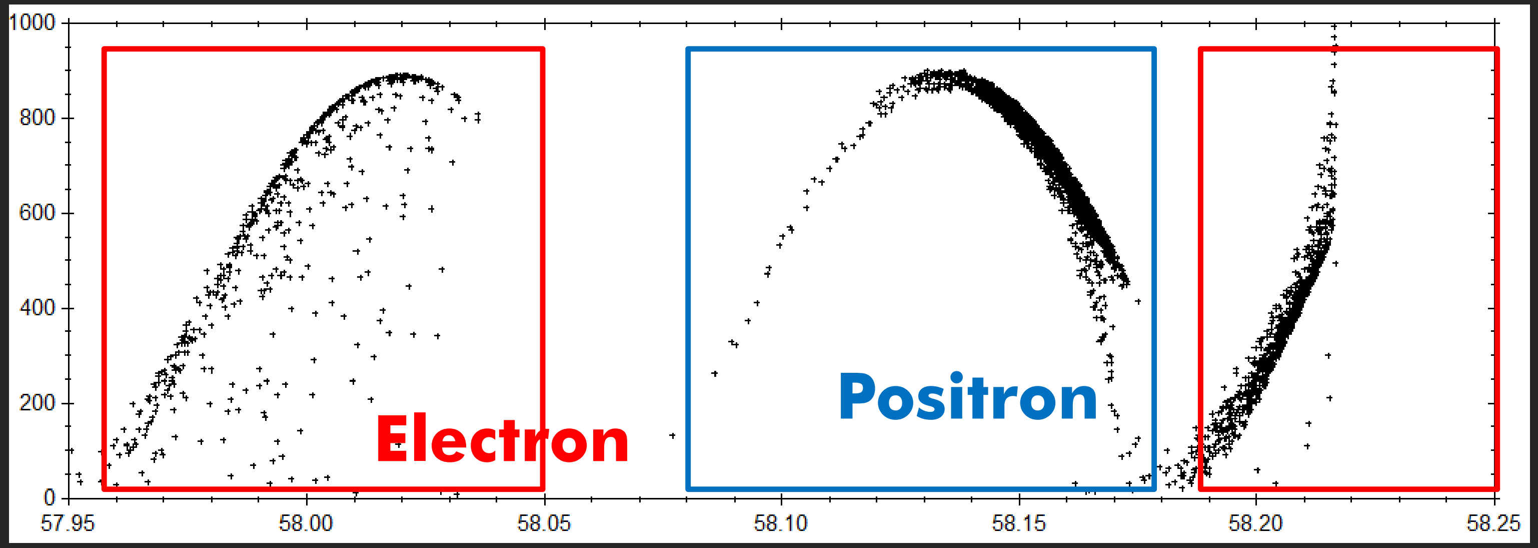
Linac Tuning

Beam profile at the capture linac

- Positrons and electrons are initially placed at cos(-p), Ez<0 phase.
- Positrons moved to the acceleration phase by slippage.
- Beamloading current is initially zero, and increased up to <2A.
- GEANT for particle generation (Bremsstralung + pair-creation) , GPT for particle tracking in the capture linac, BL is evaluated by a C program.







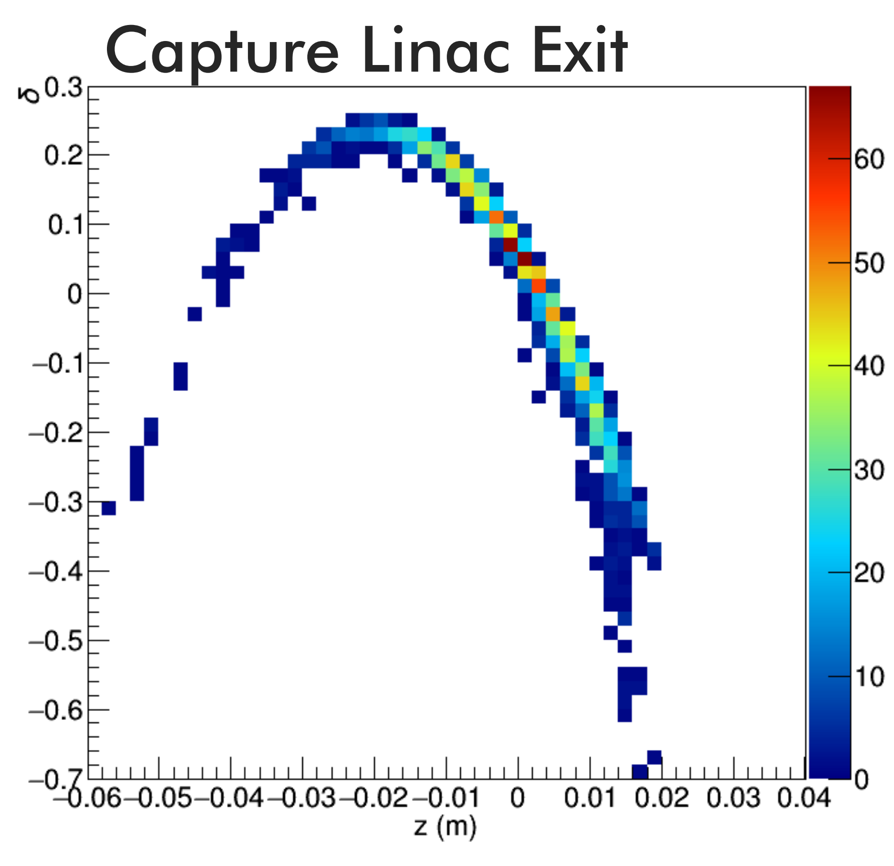
Positron yield evaluation

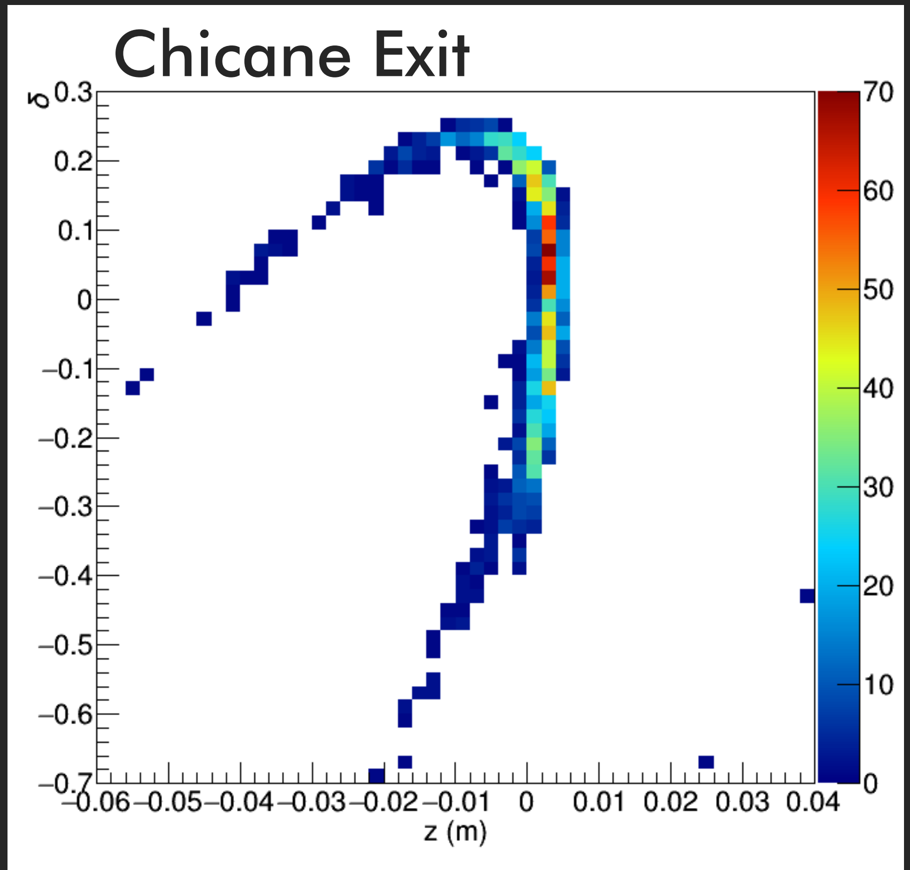
- After the capture linac, chicane, booster, and ECS are simulated as a linear transformation.
- Chicane (R_{56}=0.053)、Booster (L and S-band acceleration)、ECS (R_{56} =-0.90, R_{56}=1.14).
- Phase space distribution (z, δ) is examined with the dynamic aperture of DR as

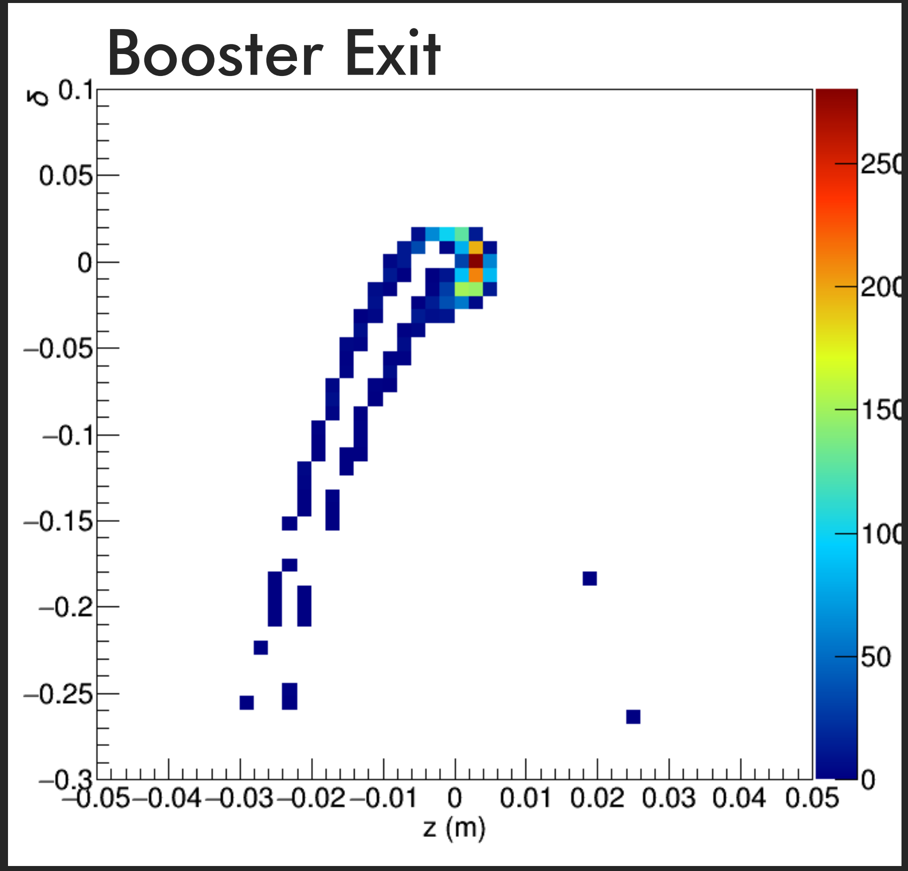
$$\frac{z^2}{0.035^2}+\frac{\delta^2}{0.0075^2}<1$$

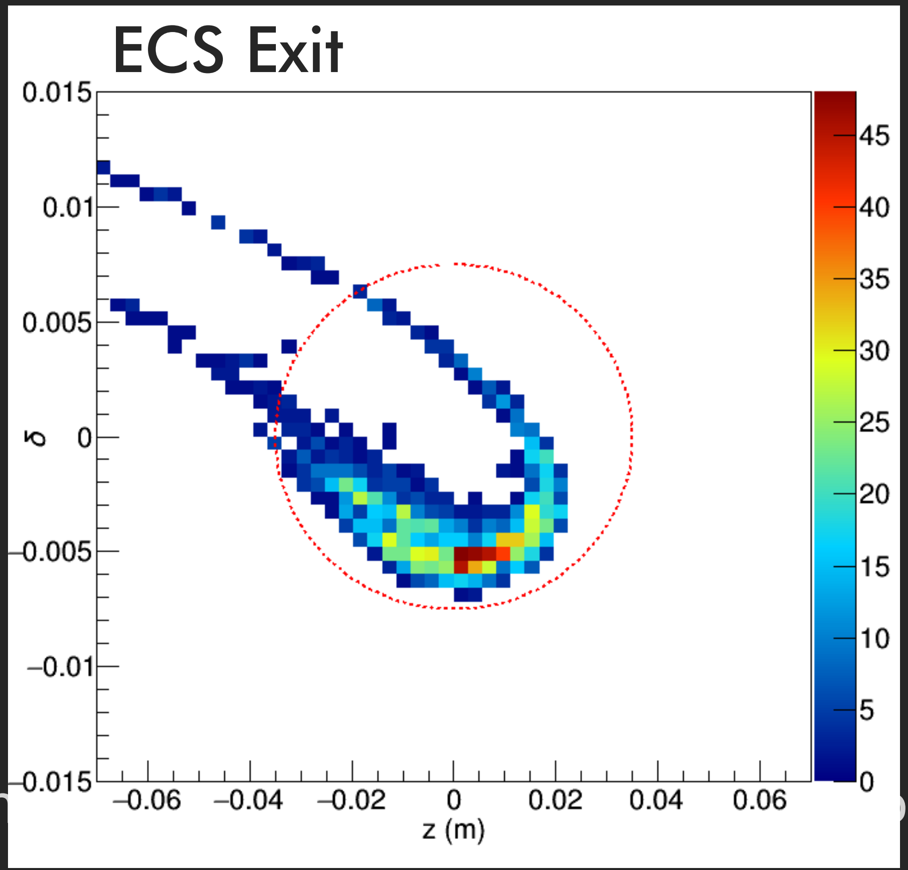
$$\eta=\frac{\#\ of\ e+in\ aperture}{\#\ \ of\ electron\ on\ target\ (1000)}$$

Transverse acceptance, beam loss after the chicane is not considered.



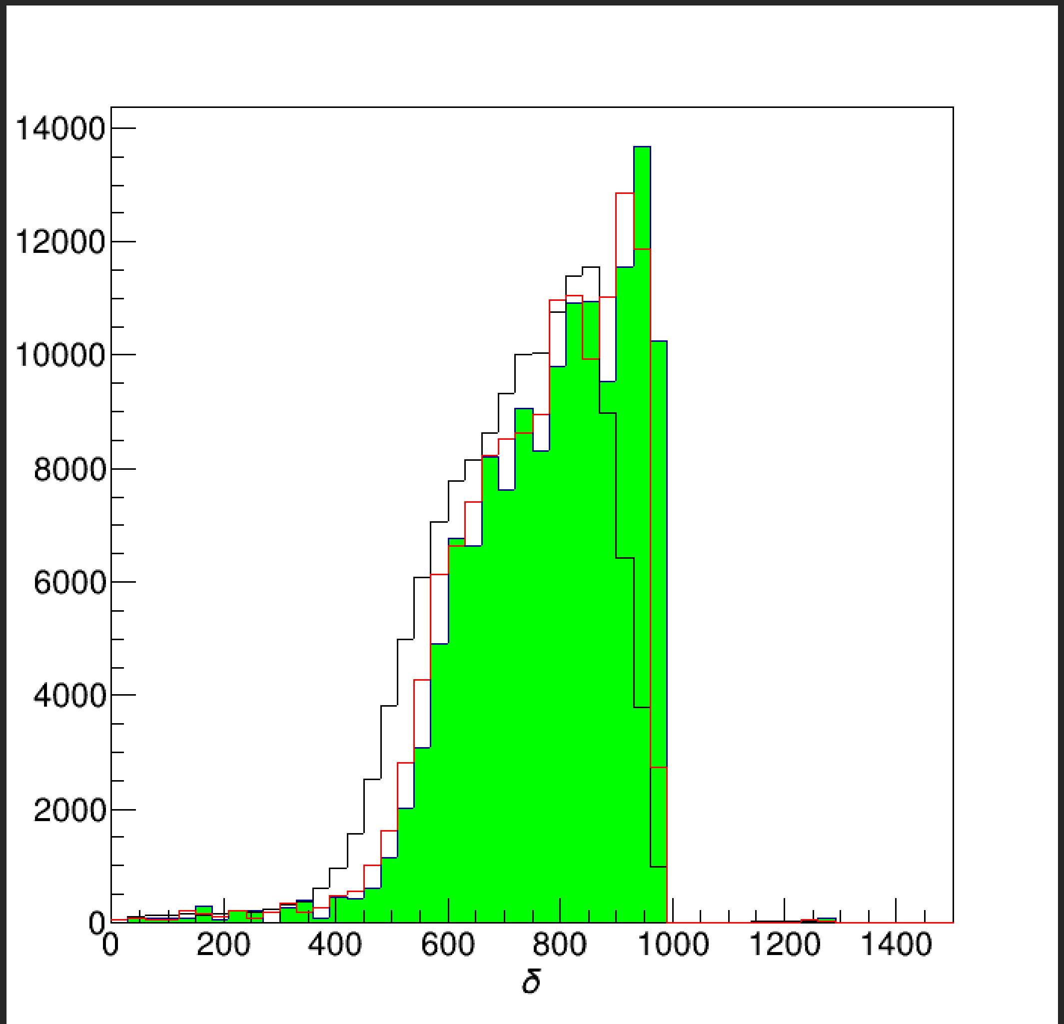


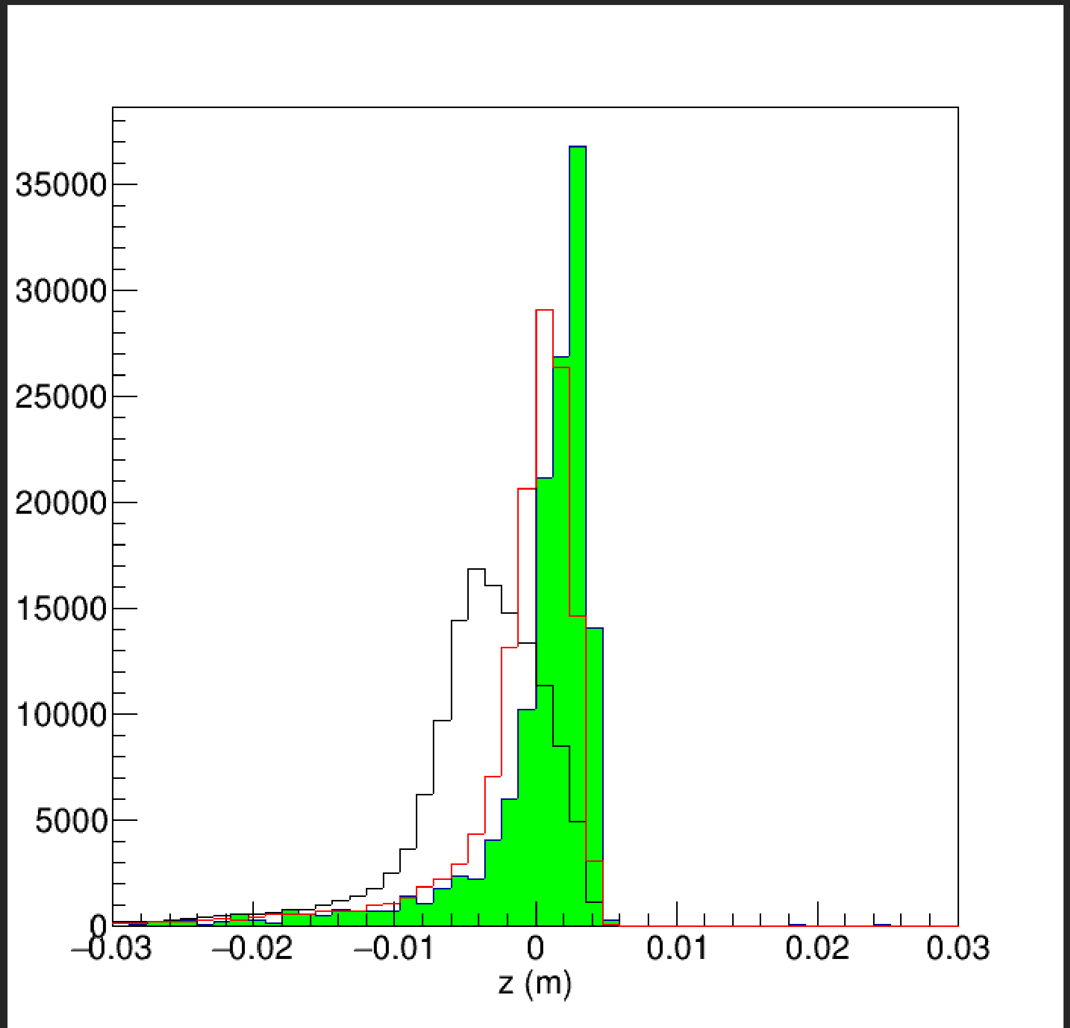


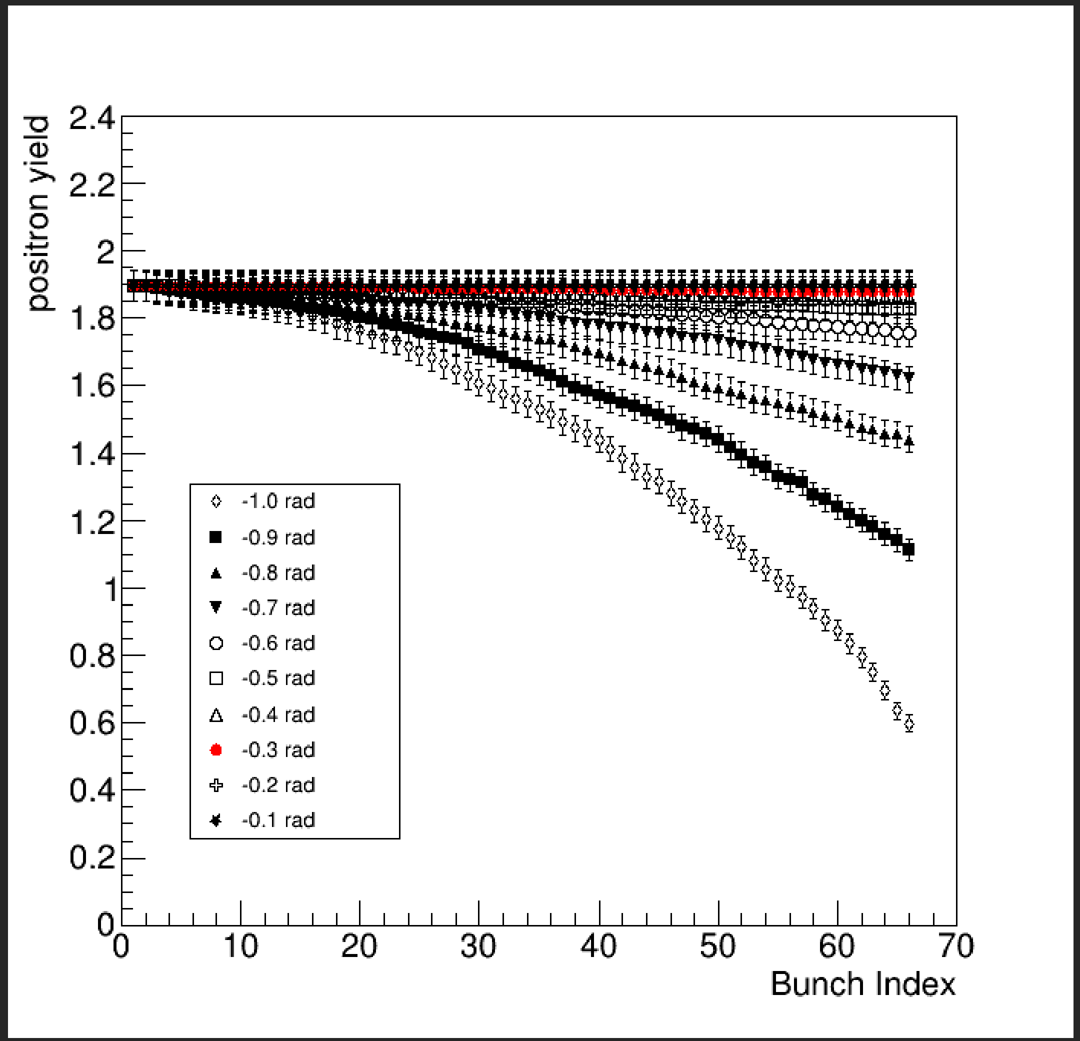


Global phase modulation

- Assumptions
  - Beam loading current is average over the linac.
  - We assume a global phase.
- δ and σ_z are improved.
- The yield over the pulse (66 bunches) is uniform with the optimum phase modulation.
- The tuning parameters for the beam loading compensations are only two: phase and current.







Summary

- Beam loading compensation for the off-crest acceleration of SW cavity is considered.
- A simple envelop adjustment by the timing does not work.
- The timing adjustment with PM works well.
- The linac tuning for the beam loading compensation is possible only with a couple of global parameters, current and phase.
- In this method, we treat the cavity as a single cell.
- Effect of the cell couplings is discussed in the next Konno’s presentation.

THANK YOU!

Any Questions?