LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

# A Simulation Study of E-driven ILC Positron Source

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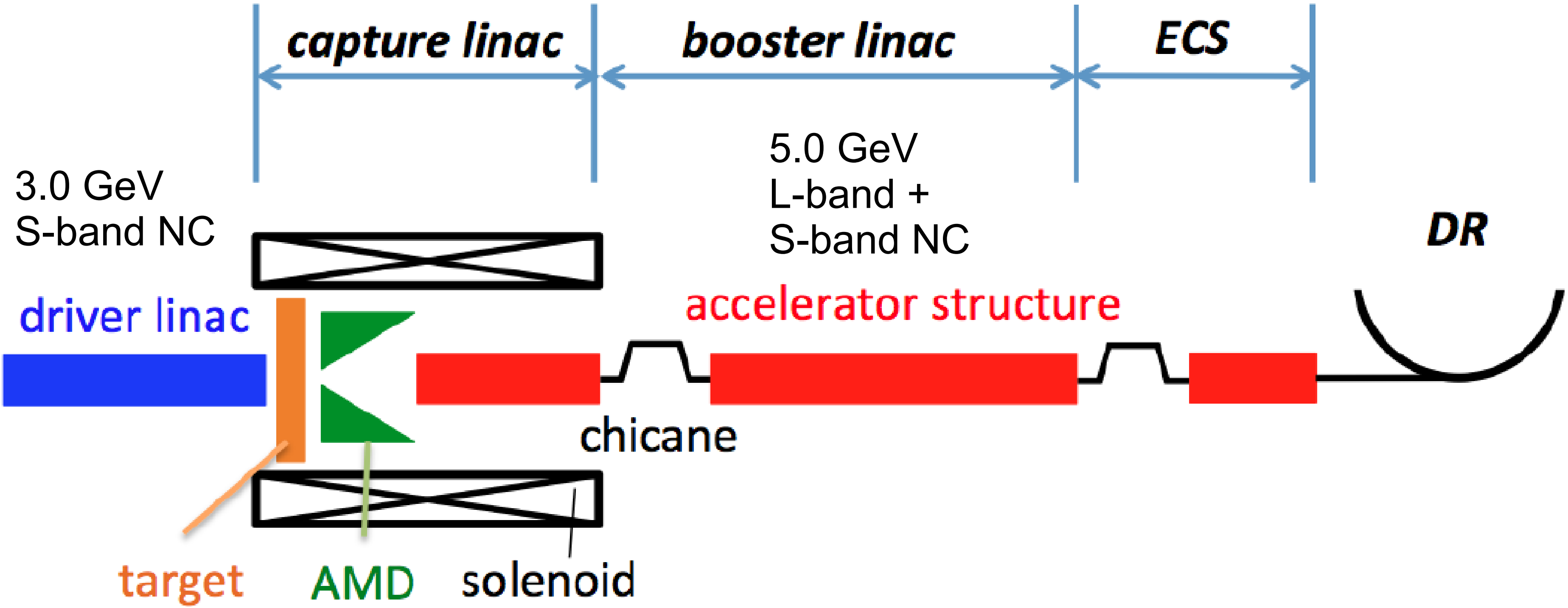
# Introduction

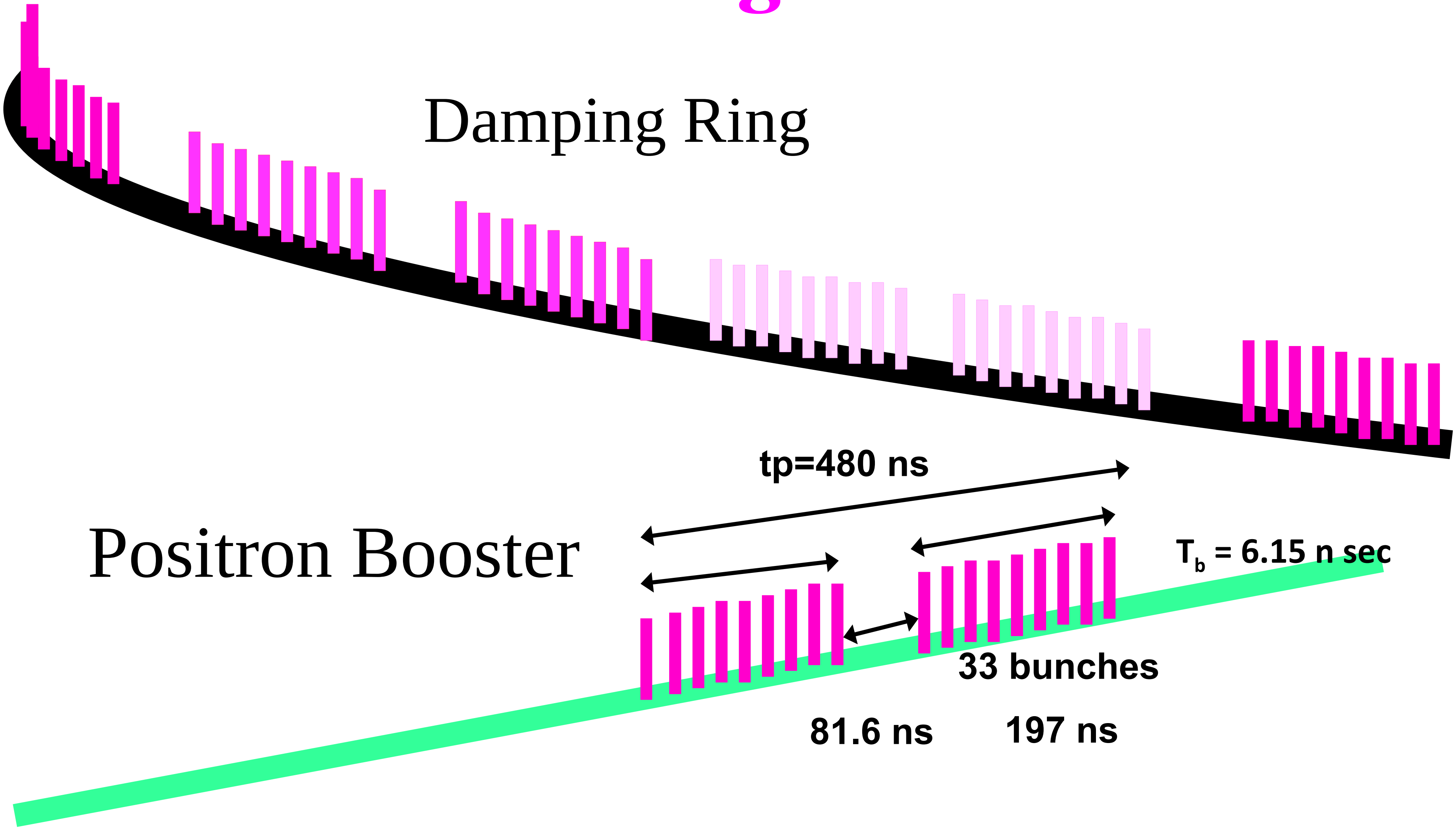
- The design of the ILC positron source based on off-the-shelf components has been established.
- Further optimization was made to improve the performance and optimize the cost-effective system by,
  - Small beam size on target for better yield. (3.5  2.0 mm rms)
  - Lower drive beam energy for less cost. (4.8  3.0 GeV)
  - Consider only the nominal parameter.
- Booster configuration (lattice) is modified to make the consistency.

# E-driven ILC Positron Source




- 20 of 0.48us pulses are handled with NC linacs operated in 300Hz.
- 100 of 300 pulses are actually fired.

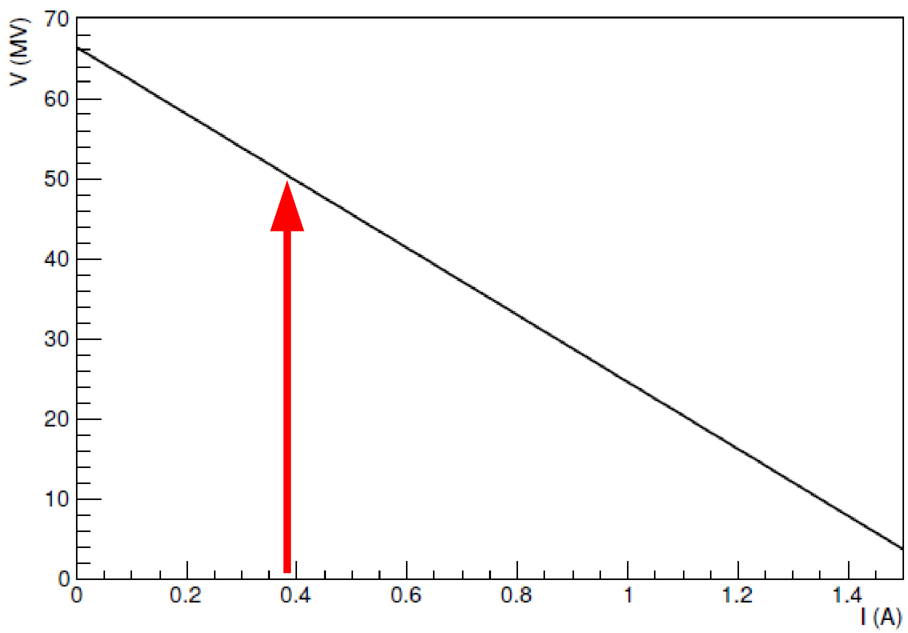
# The beam handling and format



# Electron Driver

- 3.0 GeV Electron beam with 2.0 mm RMS beam size at the target.
- 2.4 nC bunch charge is giving 0.39 A beam loading.
- S-band Photo-cathode RF gun for the beam generation.
- 80 MW klystron-modulator drives 2 structures.
- The effective input power for each tube is 36 MW. 50 MV/tube.

| Parameter | Number | unit |
|---|---|---|
| Frequency | 2856 | MHz |
| Shunt Impedance | 60.0 | MΩ/m |
| Aperture (2a) | 25.3 - 18.4 | mm |
| Group velocity | 2.04 - 0.65 | % of c |
| Filling time | 0.83 | μs |
| Attenuation | 0.57 | |
| Q value | 13000 | |
| Length | 3.0 | m |



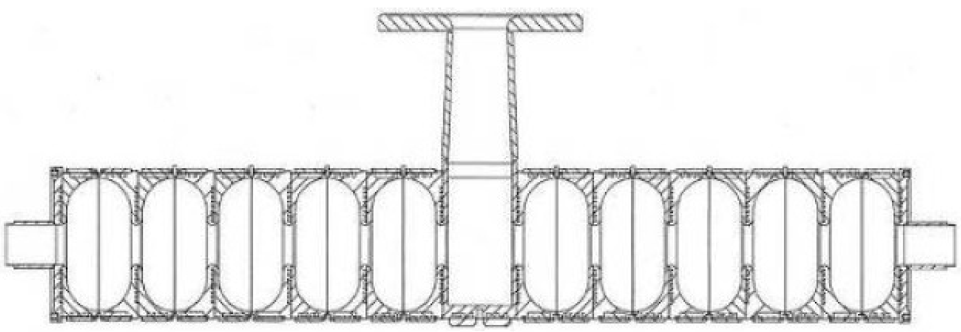
- 60 + 4 (spare) of 3m S-band TW structures for the acceleration. The energy is 3.2 GeV.
- The lattice design was based on ATF linac, 4Q + 2RF(S) up to 600 MeV, 4Q+4RF(S) for other.

| Lattice | # of cell | Cell length(m) | Section length(m) |
|---|---|---|---|
| 4Q+2S | 6 | 8.0 | 48.0 |
| 4Q+4S | 13 | 14.4 | 172.8 |

- The total length is 235.2 + 20 m (RF gun + matching section).

# Positron Capture Linac

- 36 L-band SW structures designed by J. Wang (SLAC) for the undulator capture section is employed.
- Two structures are driven by one 50 MW klystron.
- Surrounded by 0.5 T solenoid field.



| | |
|---|---|
| Structure Type | Simple π Mode |
| Cell Number | 11 |
| Aperture 2a | 60 mm |
| Q | 29700 |
| Shunt impedance r | 34.3 MΩ/m |
| $E_0$ (8.6 MW input) | 15.2 MV/m |

# Beam Loading in SW Linac

## Single Cell Model : Simple, but not realistic

- The field in SW accelerator

$$V(t)=\frac{2\sqrt{\beta P_0 r L}}{1+\beta}\left(1-e^{-\frac{t}{T_0}}\right)-\frac{rIL}{1+\beta}\left(1-e^{-\frac{t-t_b}{T_0}}\right) \qquad T_0=\frac{2Q}{\omega(1+\beta)}$$

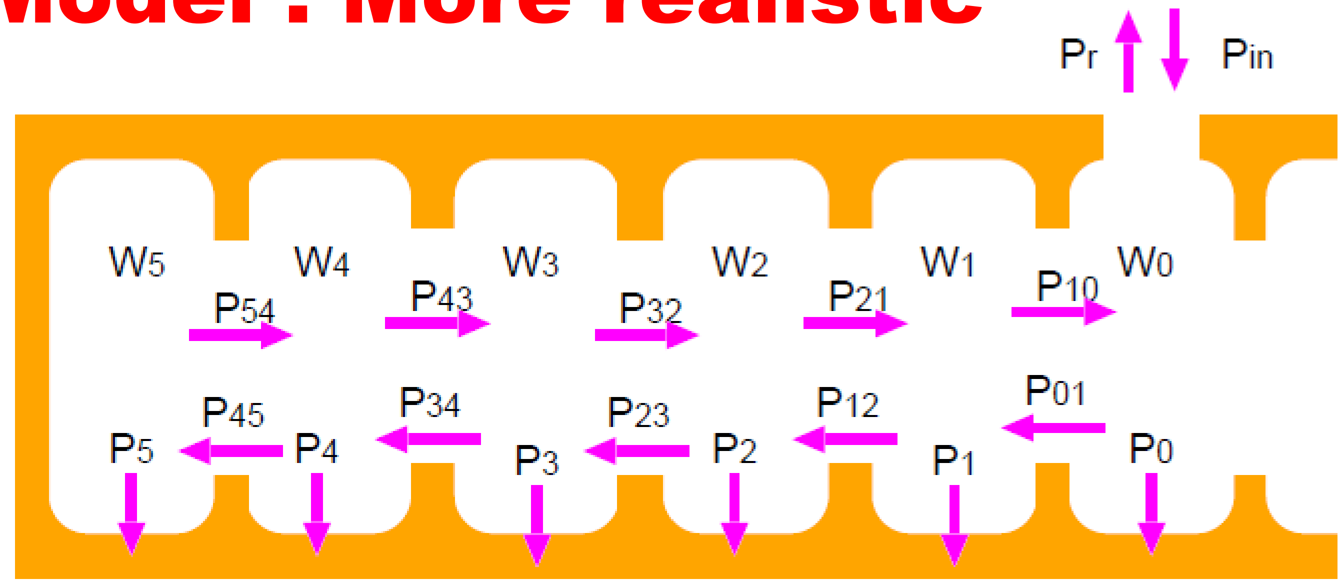
RF (first term) — Beam Loading (second term)

- The voltage becomes constant if

$$t_b=-T_0\ln\left(\frac{I}{2}\sqrt{\frac{rL}{\beta P_0}}\right)$$

$$V_0=\frac{2\sqrt{\beta P_0 r L}}{1+\beta}\left(1-\frac{I}{2}\sqrt{\frac{rL}{\beta P_0}}\right)$$

# Multi-Cell Model : More realistic




***Time differential of the energy of the center cell,***

$$\frac{dW_0}{dt} = -GV_0^2 - 2kQGV_0^2 + 2kQGV_1^2 + G_{wg}V_{in}^2 - G_{wg}(V_{in} - NV_0)^2 - IV_0,$$

*Power flow to next cells*

*Input Power*

*Beam loading*

*Power loss*

*Power flow from next cells*

*WG loss*

***Time differential of the voltage***

$$\frac{dV_0}{dt} = -\left[\frac{(1+N\beta)\omega}{2Q} + k\omega\right] V_0 + k\omega V_1 + \frac{\omega\beta}{Q} V_{in} - \frac{\omega RI}{2Q}.$$

***For the intermediate cells,***

$$\frac{dV_1}{dt} = k\omega V_0 - \left(\frac{\omega}{Q} + 2k\omega\right) V_1 + k\omega V_2 - \frac{\omega RI}{Q}.$$

***For the end cells,***

$$\frac{dV_5}{dt} = k\omega V_4 - \left(\frac{\omega}{Q} + k\omega\right) V_5 - \frac{\omega RI}{Q}.$$

# 11 linear simultaneous differential equations

$$\frac{dt\mathbf{V}}{dt} = \mathbf{AV} + \mathbf{C},$$

$$\frac{d}{dt}\begin{pmatrix} \cdots \\ V_{-1} \\ V_0 \\ V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{pmatrix} = \begin{pmatrix} & & & \cdots & & & & \\ & a & \alpha & 0 & 0 & 0 & 0 & 0 \\ & \alpha & a_0 & \alpha & 0 & 0 & 0 & 0 \\ & 0 & \alpha & a & \alpha & 0 & 0 & 0 \\ \cdots & 0 & 0 & \alpha & a & \alpha & 0 & 0 \\ & 0 & 0 & 0 & \alpha & a & \alpha & 0 \\ & 0 & 0 & 0 & 0 & \alpha & a & \alpha \\ & 0 & 0 & 0 & 0 & 0 & \alpha & a_5 \end{pmatrix}\begin{pmatrix} \cdots \\ V_{-1} \\ V_0 \\ V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{pmatrix} + \begin{pmatrix} \cdots \\ -\frac{\omega RI}{Q} \\ \frac{\omega\beta}{Q}V_{in} - \frac{\omega RI}{2Q} \\ -\frac{\omega RI}{Q} \\ -\frac{\omega RI}{Q} \\ -\frac{\omega RI}{Q} \\ -\frac{\omega RI}{Q} \\ -\frac{\omega RI}{Q} \end{pmatrix}$$

$$a_0 = -\frac{(1+N\beta)\omega}{2Q} - k\omega \qquad a_5 = -\frac{\omega}{2Q} - \frac{1}{2}k\omega$$

$$a = -\frac{\omega}{2Q} - k\omega \qquad \alpha = \frac{1}{2}k\omega$$

*$\boldsymbol{A}$ can be diagonalized with a orthgonal matrix $\boldsymbol{R}$ as*

$$\mathbf{R}^{\mathrm{T}}\mathbf{A}\mathbf{R} = \mathbf{B} = \begin{pmatrix} \lambda_{-5} & & & & \\ & \dots & & 0 & \\ & & \lambda_0 & & \\ & 0 & & \dots & \\ & & & & \lambda_5 \end{pmatrix}$$

$$\frac{dt\mathbf{R}^{\mathrm{T}}\mathbf{V}}{dt} = \mathbf{R}^{\mathrm{T}}\mathbf{A}\mathbf{R}\mathbf{R}^{\mathrm{T}}\mathbf{V} + \mathbf{R}^{\mathrm{T}}\mathbf{C}.$$

$$\frac{dt\mathbf{V}'}{dt} = \mathbf{B}\mathbf{V}' + \mathbf{C}',$$

*Because $\boldsymbol{B}$ is diagonal, the equations for V' are 11 independent linear differential equations,*

$$\frac{dV_i'}{dt} = \lambda_i V_i' + C_i',$$

*The solution for V′ is*

$$V_i'(t) = \tau_i C_i' \left(1 - e^{-\frac{t}{\tau_i}}\right),$$

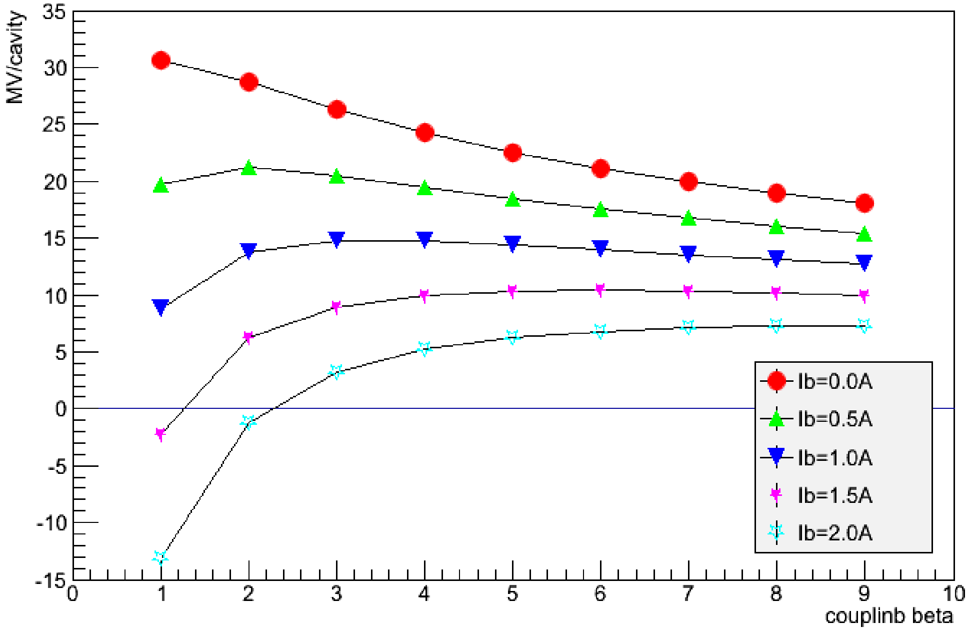
*The solution for V is expressed as a linear sum of the solution for V′*

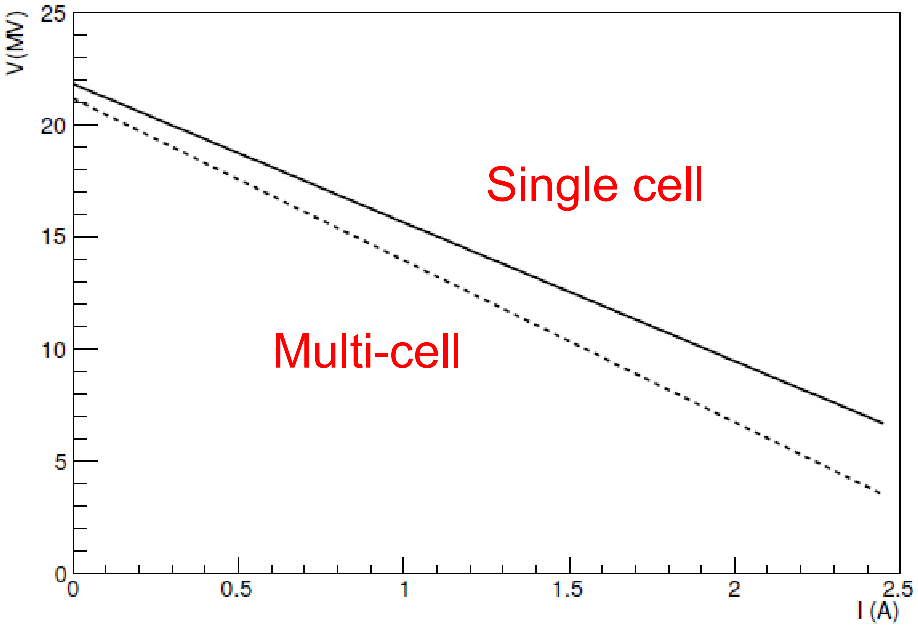
$$\mathbf{V} = \mathbf{R}\mathbf{V}'.$$

$$V_i(t) = \sum_{j=0}^{5} R_{ij}\tau_j C_j'(1 - e^{-\frac{t}{\tau_j}}).$$

# Acceleration Field

- L=1.27 m (11 cells, L-band SW)
- R=34e+6 Ohm/m
- $P_0$=22.5 MW (50MW at klystron, 5MW wave guide loss).
- 10.36 MV/tube with beta=6.0.



# RF Mode and Beam Loading Mode

- *The total acceleration voltage is given as sum of the RF mode and the Beam-loading mode.*
- *They are not identical, but the dominant mode is common (tau=1.22 us).*
- *The RF mode has the second dominant mode, but nothing for BL. This gives the imperfection on the BL compensation, but the effect is not large.*

RF mode

| $\tau$ | 0.020 | 0.006 | 0.011 | 0.068 | 1.22 |
|---|---|---|---|---|---|
| cell -5 | 0.063 | -0.003 | -0.026 | -0.232 | 2.078 |
| cell -4 | -0.013 | 0.010 | 0.034 | -0.149 | 2.043 |
| cell -3 | -0.074 | -0.016 | 0.015 | -0.013 | 1.975 |
| cell -2 | -0.045 | 0.021 | -0.039 | 0.127 | 1.873 |
| cell -1 | 0.038 | -0.026 | -0.002 | 0.222 | 1.740 |
| cell 0 | 0.075 | 0.030 | 0.040 | 0.238 | 1.578 |
| cell 1 | 0.038 | -0.026 | -0.002 | 0.222 | 1.740 |
| cell 2 | -0.045 | 0.021 | -0.039 | 0.127 | 1.873 |
| cell 3 | -0.074 | -0.016 | 0.015 | -0.013 | 1.975 |
| cell 4 | -0.013 | 0.010 | 0.034 | -0.149 | 2.043 |
| cell 5 | 0.063 | -0.003 | -0.026 | -0.232 | 2.078 |

BL mode

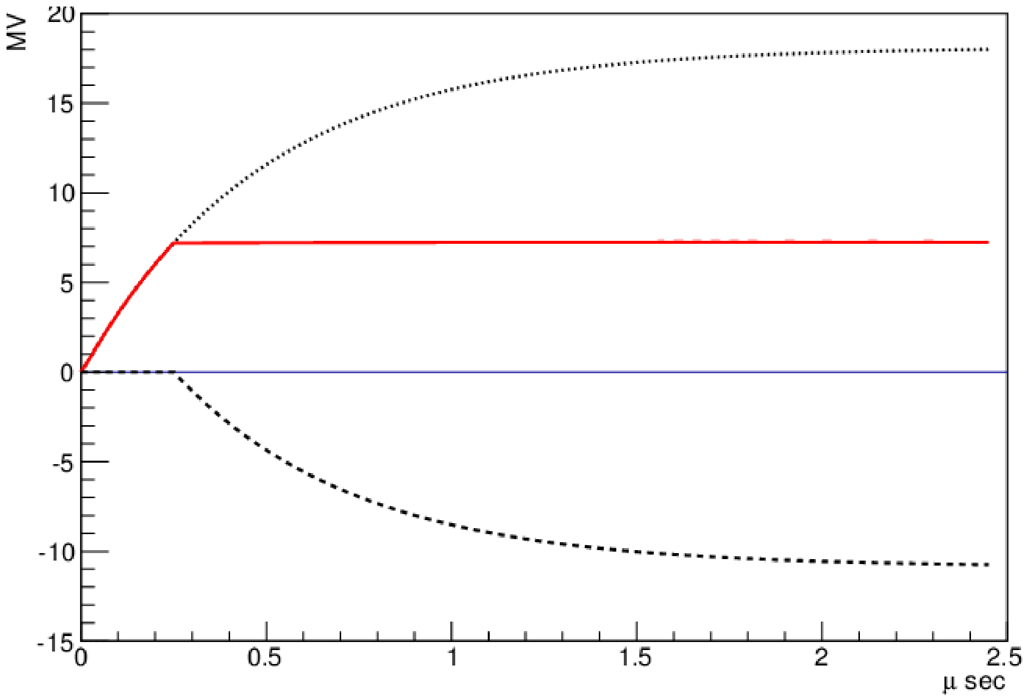
| $\tau$ | 0.020 | 0.006 | 0.011 | 0.068 | 1.22 |
|---|---|---|---|---|---|
| cell 0 | -0.000 | 0.000 | 0.000 | 0.004 | -0.710 |
| cell 1 | 0.000 | -0.000 | -0.000 | 0.002 | -0.698 |
| cell 2 | -0.000 | 0.000 | -0.000 | 0.000 | -0.674 |
| cell 3 | 0.000 | -0.000 | 0.000 | -0.002 | -0.639 |
| cell 4 | -0.000 | 0.000 | 0.000 | -0.004 | -0.594 |
| cell 5 | -0.000 | -0.000 | -0.000 | -0.004 | -0.539 |
| cell 6 | -0.000 | 0.000 | 0.000 | -0.004 | -0.594 |
| cell 7 | 0.00 | -0.000 | 0.000 | -0.002 | -0.639 |
| cell 8 | 0.000 | 0.000 | -0.000 | 0.000 | -0.674 |
| cell 9 | 0.000 | -0.000 | -0.000 | 0.002 | -0.698 |
| cell 10 | -0.000 | 0.000 | 0.000 | 0.004 | -0.710 |

# Beam Loading Compensation

*No big difference on the no-load voltage, but 30 % less on the heavyly loaded voltage,*

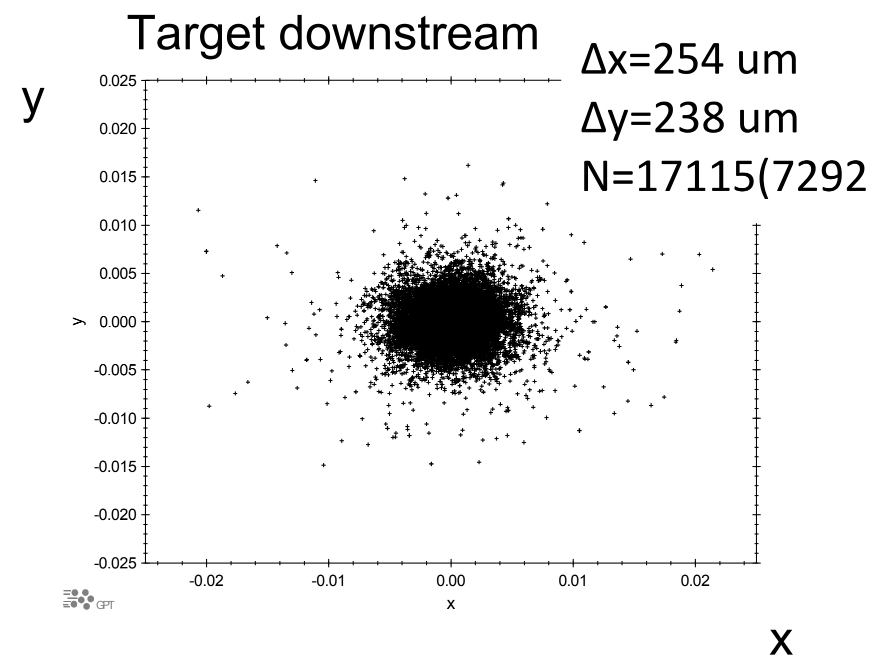
| Voltage (MV) | One cell model | Multi-cell model | difference |
|---|---|---|---|
| No load | 18.7 | 18.0 | -0.7 |
| Beam Loading (2.0A) | -8.6 | -10.8 | -2.2 |
| Total | 10.1 | 7.2 | -2.9 |

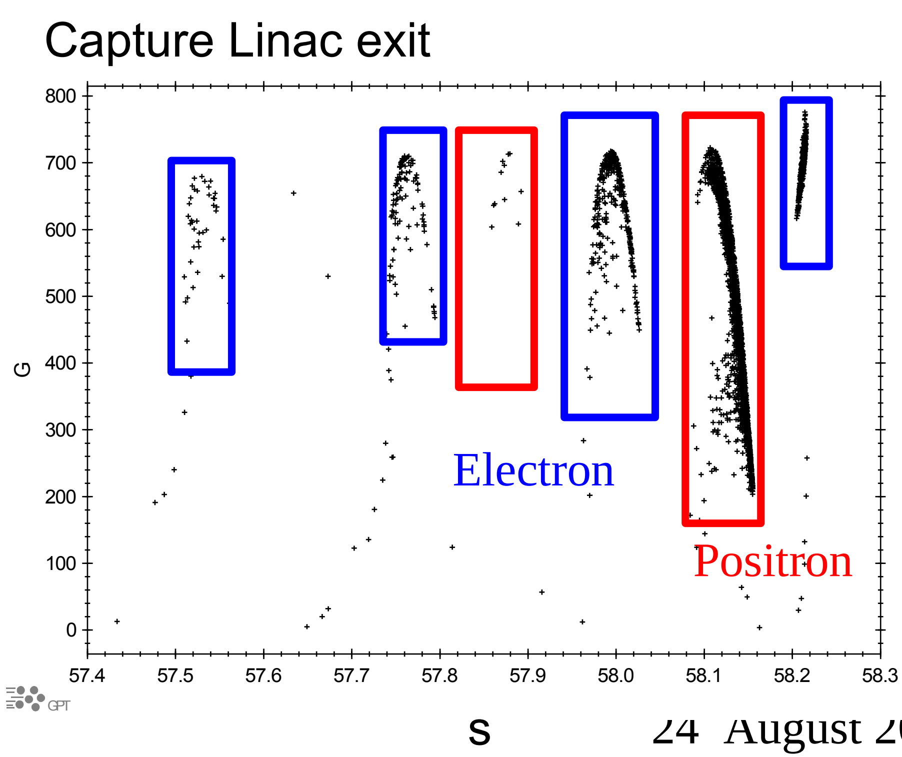
*The beam loading compensation works well. Flatness is less than 0.1%.*

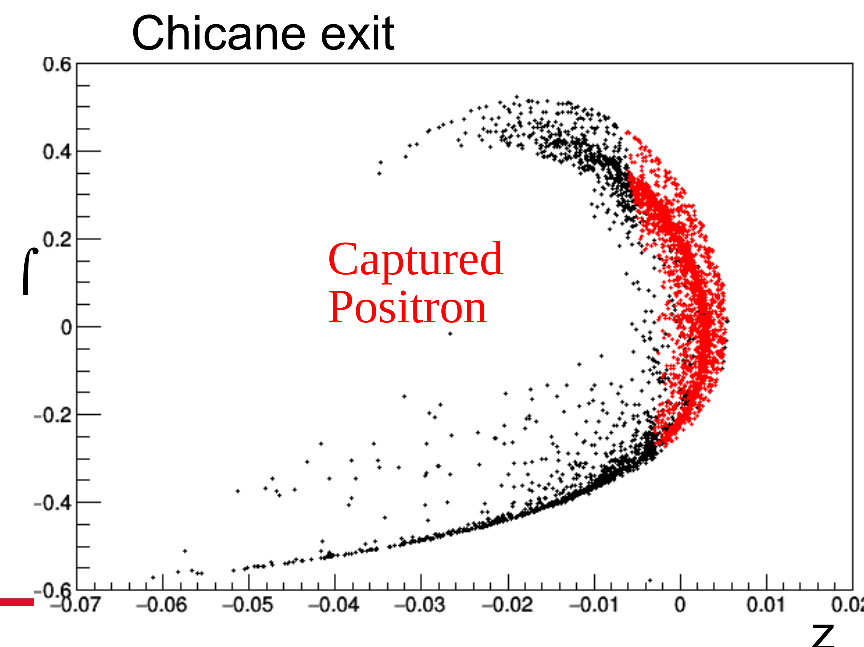


# Capture Simulation

- 1000 electrons on target by GEANT 4.
- The positron is decelerated and bunched at the acceleration phase by phase-slipping.
- Positrons with a large z (longitudinal position) are not captured by the final acceptance. This is not the case for δ.



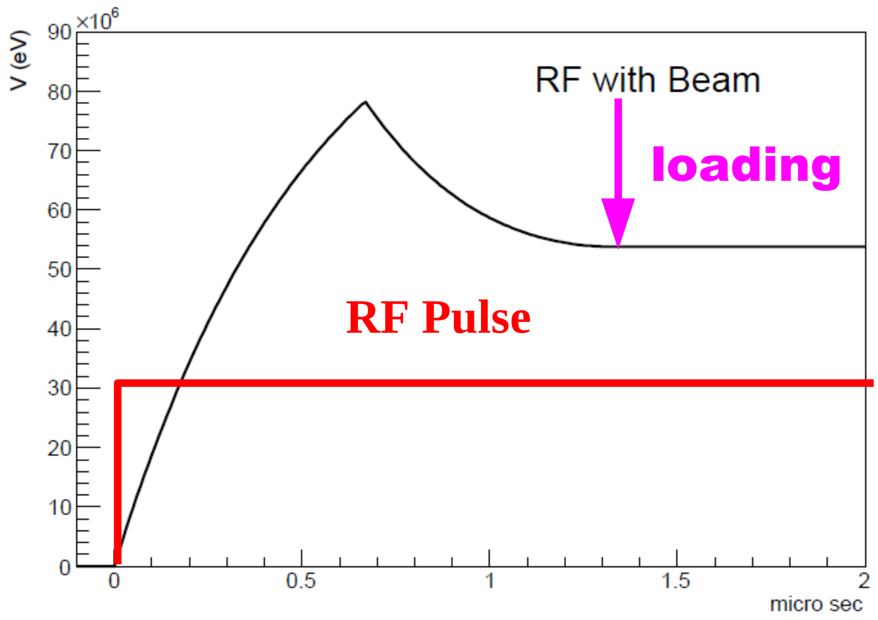
# Booster

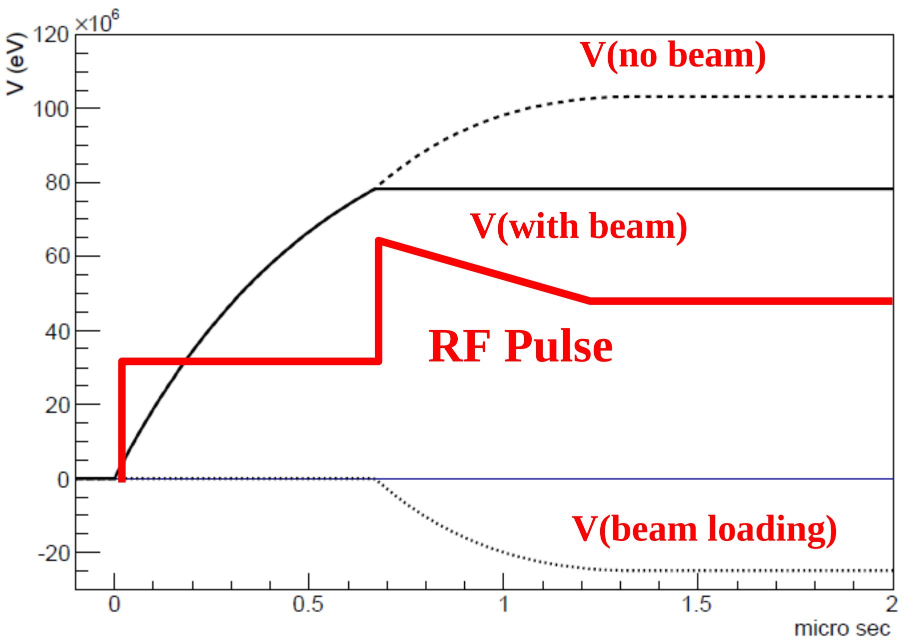
- A first half is implemented by L-band acc. and the last half is by S-band.
- 50MW L-band Klystron drives two L-band acc. (2a = 34 mm).
- 80MW S-band Klystron drives two S-band acc. (2a = 20 mm).
- The gradient at 0.78 A (4.8nC/bunch) beam loading is assumed.
- The beam loading compensation and its accuracy determine the accelerator gradient.

# Beam-loading in TW Linac

- Transient beam-loading is compensated by Amplitude Modulation.
- Acceleration voltage by a flat RF,

$$V(t) = E_0 L + \frac{r_0 L I_0}{2(1-e^{-2\tau})}\left[\frac{\omega}{Q}e^{-2\tau}(t-t_f) - 1 + e^{2\tau - \frac{\omega}{Q}t}\right].$$



# Beam Loading Compensation with AM

Laplace transformation of TW accelerator voltage V(s) is

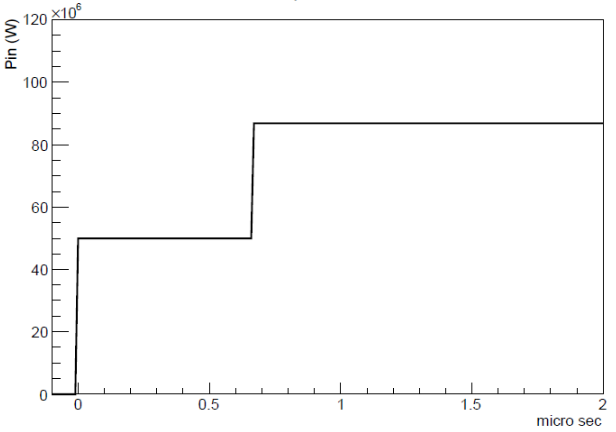
$$V(s) = \frac{\omega L}{Q(1-e^{-2\tau})}\frac{1}{s+\omega/Q}E(s)\left(1-e^{-(s+\omega/Q)t_f}\right)$$
$$-\frac{\omega r_0 L}{2Q(1-e^{-2\tau})}\frac{I_0}{s^2}e^{-st_f}\left[1-e^{-\frac{\omega}{Q}t_f}-\frac{\omega(1-e^{-st_f-2\tau})}{Q(s+\omega/Q)}\right],$$

where E(s) is the Laplace transformation of applied voltage (power).
E(s) is determined to cancel s (t) dependence of V(s or t).

# Step Modulation

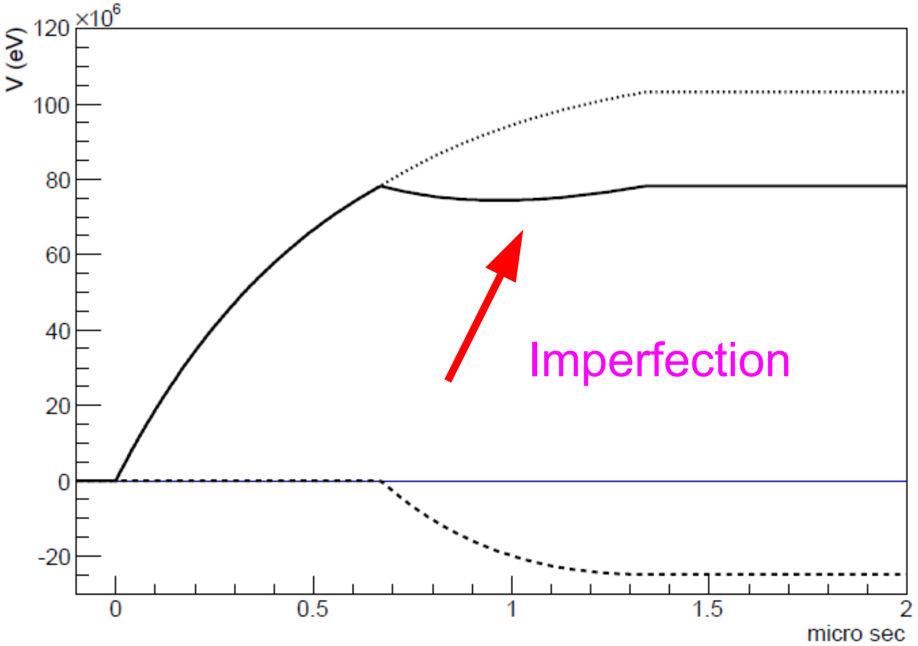
$$E(t) = E_0 U(t) + E_1 U(t - t_f),$$

$$E(s) = \frac{E_0}{s} + \frac{E_1}{s} e^{-st_f},$$




$$V(t) = E_0 L + \frac{LE_1}{1-e^{-2\tau}}\left(1 - e^{-\frac{\omega}{Q}(t-t_f)}\right) - \frac{r_0 L I_0}{2(1-e^{-2\tau})}\left[-\frac{\omega}{Q} e^{-2\tau}(t - t_f) + 1 - e^{-\frac{\omega}{Q}(t-t_f)}\right]$$

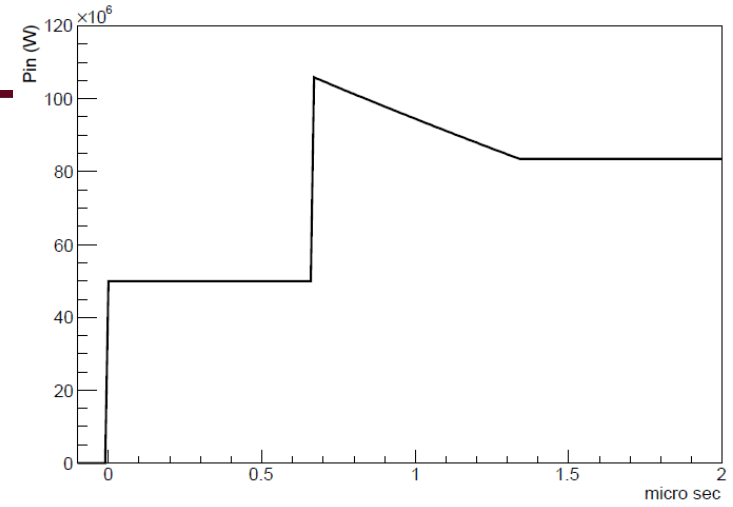
$$E_1 = \frac{r_0 I_0}{2}\left(\frac{2\tau e^{-2\tau}}{1-e^{-2\tau}} - 1\right)$$



# Saw Modulation

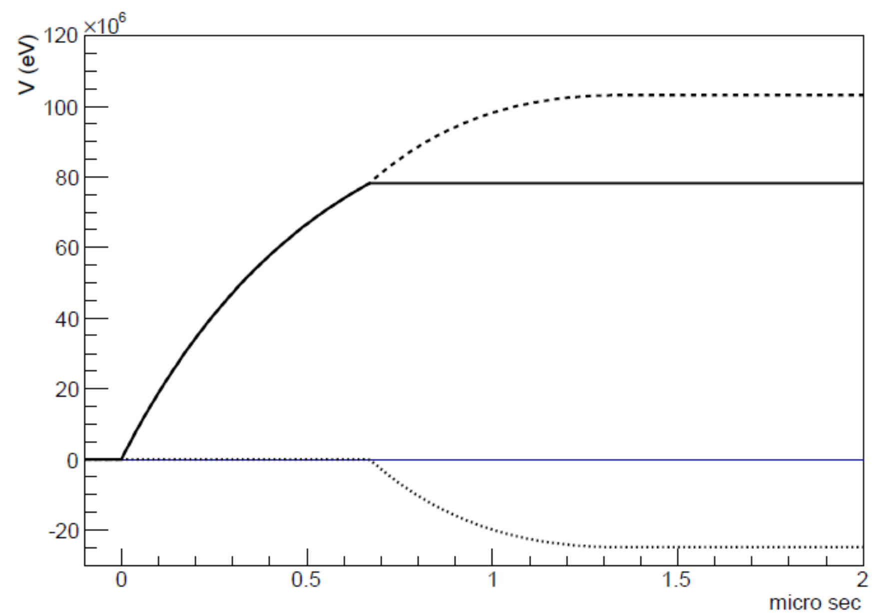
$$E(t)=E_0U(t)+E_{1U}(t-t_f)+\frac{E_2}{t_f}(t-t_f)U(t-t_f)$$

$$E(s)=\frac{E_0}{s}+\frac{E_1}{s}e^{-st_f}+\frac{E_2}{t_f s^2}e^{-st_f}$$




$$\begin{aligned} V(t) &= E_0L+\frac{L}{1-e^{-2\tau}}\left(E_1-\frac{Q}{\omega}E_2\right)\left(1-e^{-\frac{\omega}{Q}(t-t_f)}\right)+\frac{Le^{-2\tau}}{1-e^{-2\tau}}E_2(t-t_f) \\ &\quad -\frac{r_0LI_0}{2(1-e^{-2\tau})}\left[-\frac{\omega}{Q}e^{-2\tau}(t-t_f)+1-e^{-\frac{\omega}{Q}(t-t_f)}\right], \end{aligned}$$

$$\begin{aligned} E_1 &= \frac{r_0I_0}{2}(1-e^{-2\tau}), \\ E_2 &= -\frac{r_0I_0}{2}\frac{\omega}{Q}e^{-2\tau}, \end{aligned}$$



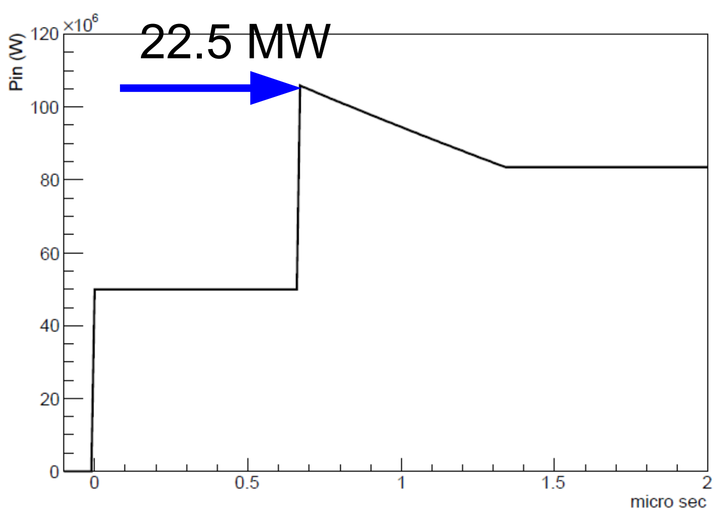
# Actual Compensation (Trade off)

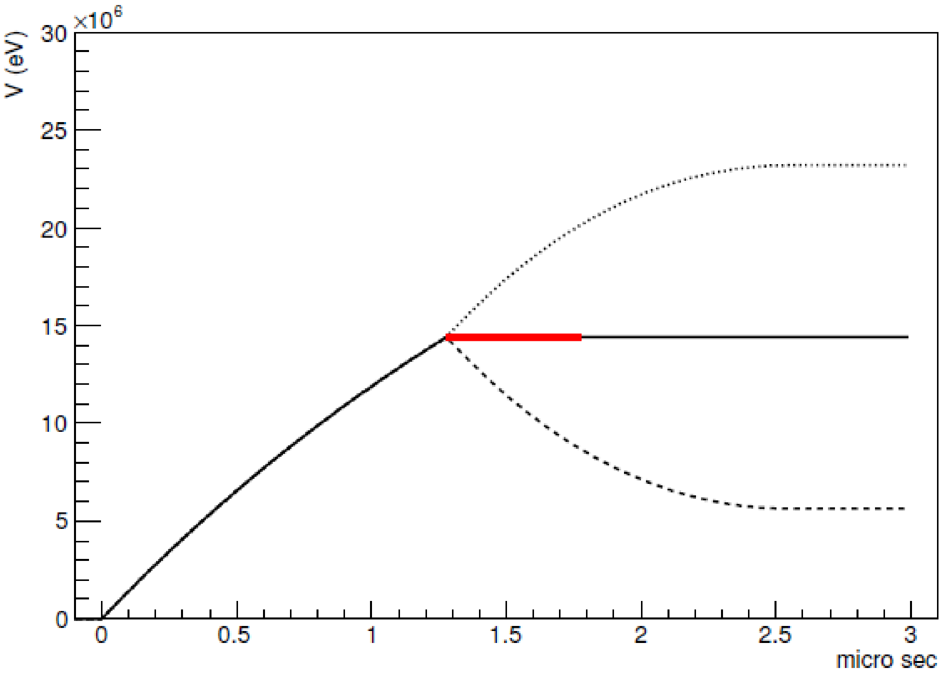
- Saw modulation is ideal, but it requires a high peak power.
- Step modulation is a replacement, but it has an imperfection (energy spread).
- If $t_p << t_f$, an optimization for $P_0$ gives smaller energy spread.

# 2m L-band TW structure (Positron Booster)

- 2m L-band (1298 MHz) designed for KEKB injector.
- Saw modulation:22.5 MW input with 0.78 A BL gives 14.41 MV/tube (2m)
- The energy spread is zero (ideal), but the voltage is very limited.

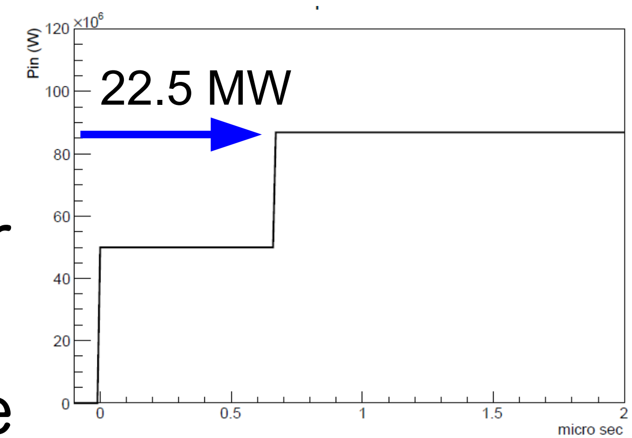
| Parameter | Number | unit |
|---|---|---|
| Frequency | 1298 | MHz |
| Shunt Impedance | 47.2 | MΩ/m |
| Aperture (2a) | 39.4 - 35.0 | mm |
| Group velocity | 0.61 - 0.39 | % of c |
| Filling time | 1.32 | μs |
| Attenuation | 0.261 | |
| Q value | 20000 | |
| Length | 2.0 | m |

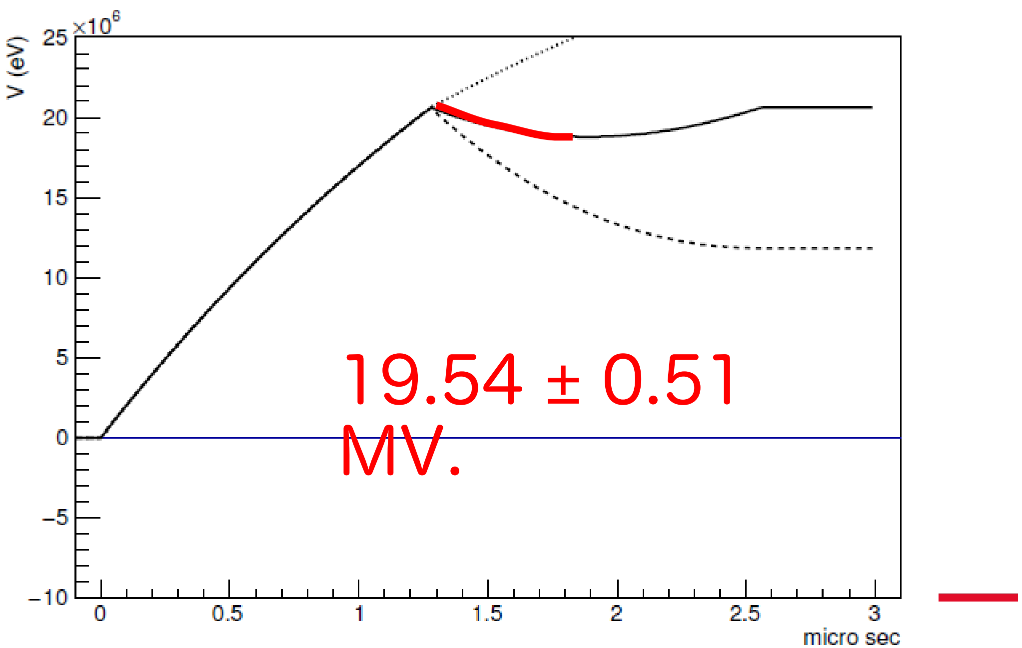


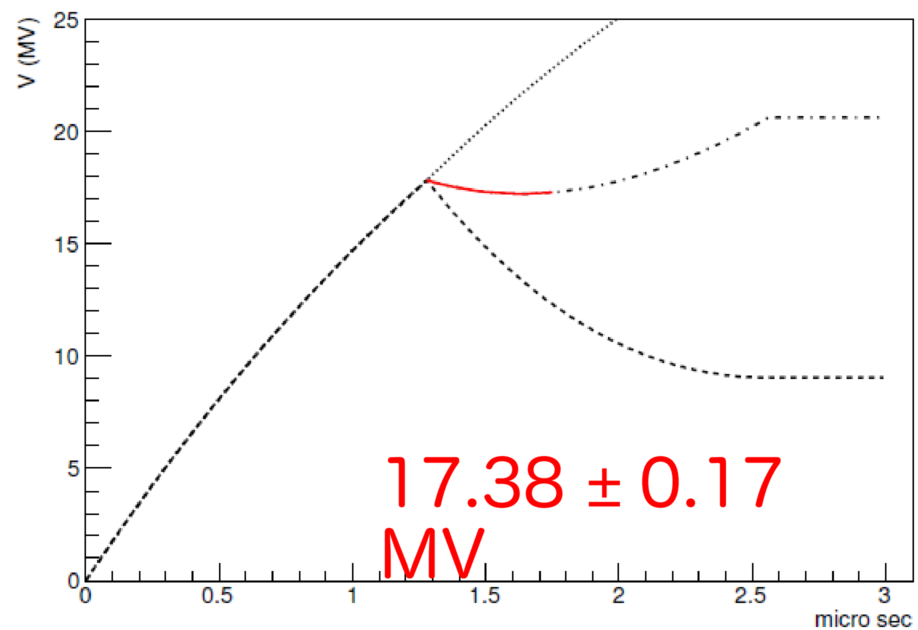



# Step Modulation

- Step modulation: 19.54 ± 0.51 MV.
- If $P_0$ is optimized (lowered) for lower energy spread, 17.38 ± 0.17 MV.
- The gradient depends on acceptable energy spread and we took 17.38 MV as our working assumption.



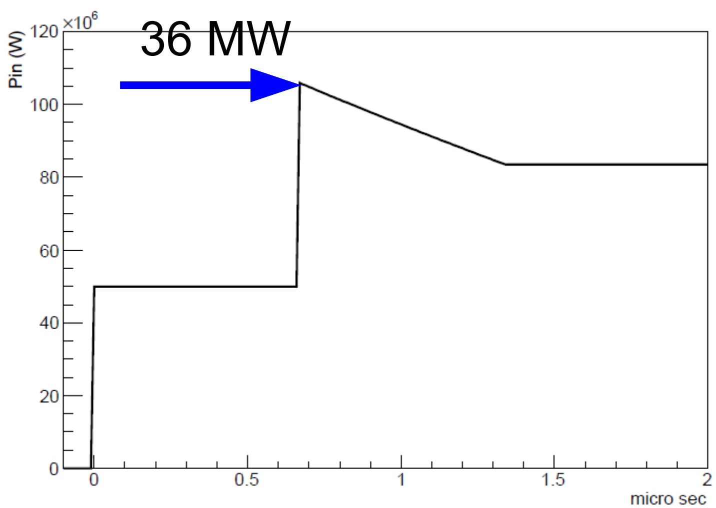



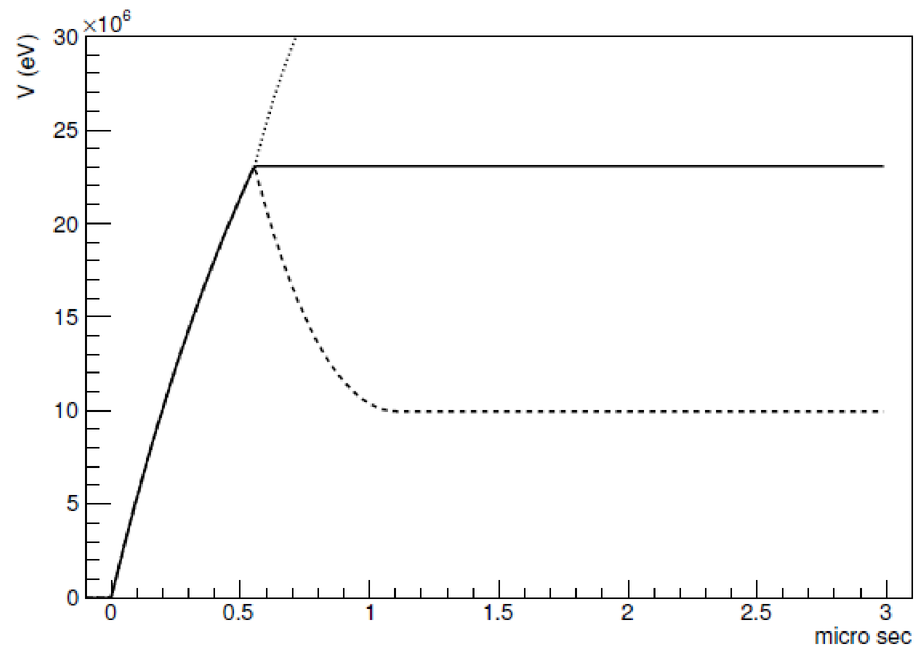



# S-band TW accelerator (Positron Booster)

- 2m S-band (2856MHz) accelerator designed for KEKB injector.
- Saw modulation:22.5 MW input with 0.78 A BL gives 23.03 MV/tube (2m)
- Step modulation gives 29.42 ± 0.69 MV.

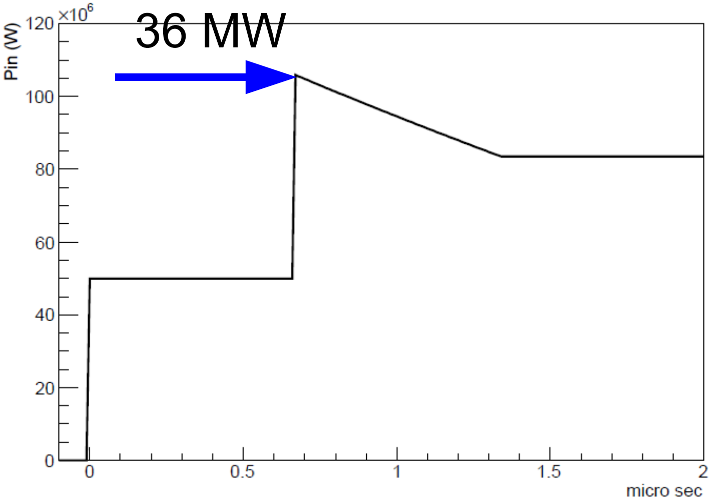
| Parameter | Number | unit |
|---|---|---|
| Frequency | 2856 | MHz |
| Shunt Impedance | 57.8 | MΩ/m |
| Aperture (2a) | 24.28 - 20.3 | mm |
| Group velocity | 1.24 (av) | % of c |
| Filling time | 0.507 | $\mu$s |
| Attenuation | 0.333 | |
| Length | 1.959 | m |

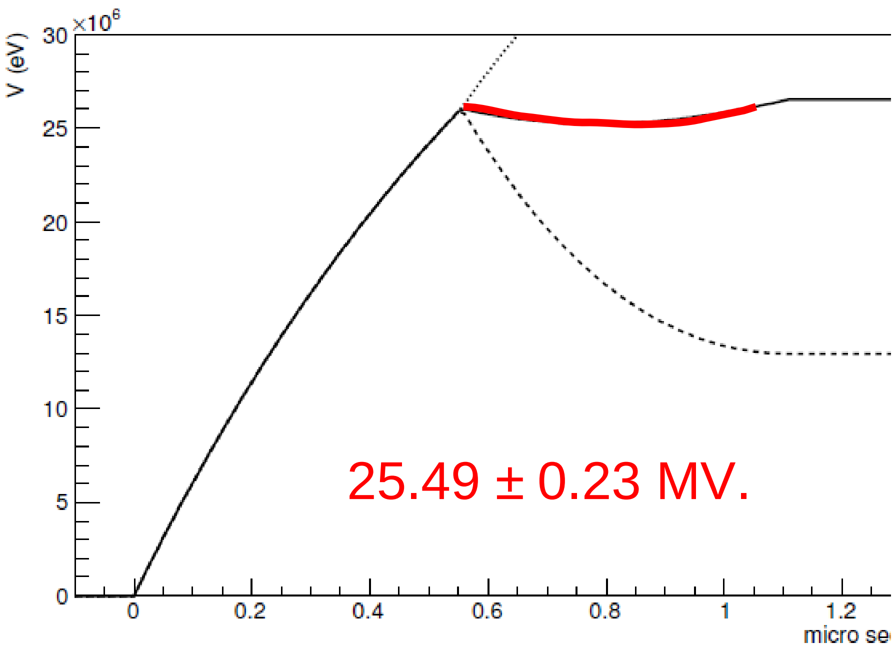


# Optimization

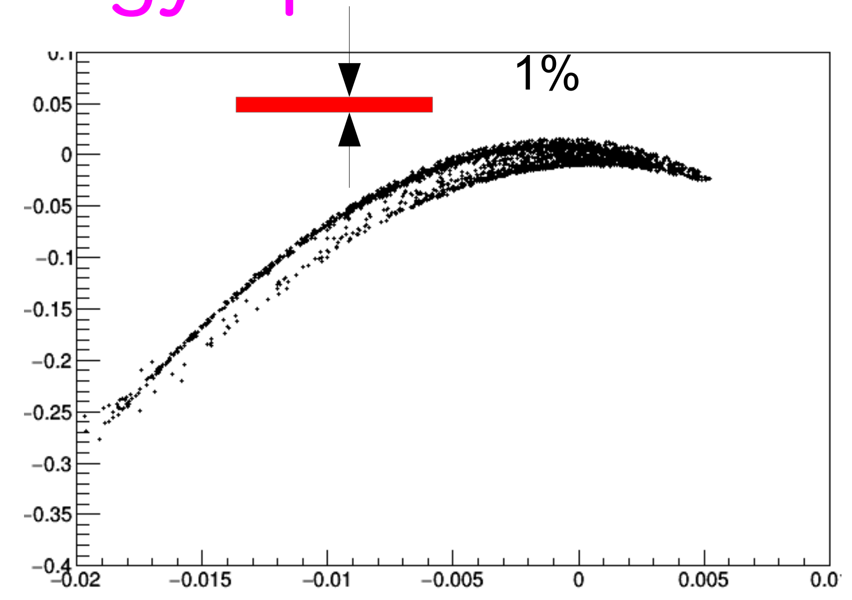
- Step modulation gives 29.42 ± 0.69 MV.
- P0 optimization does not work, because tf~tp.
- Instead, semi-Step-saw modulation was made with the peak power which is less than that for the perfect compensation.
- The accelerator voltage is determined by the acceptable energy spread.

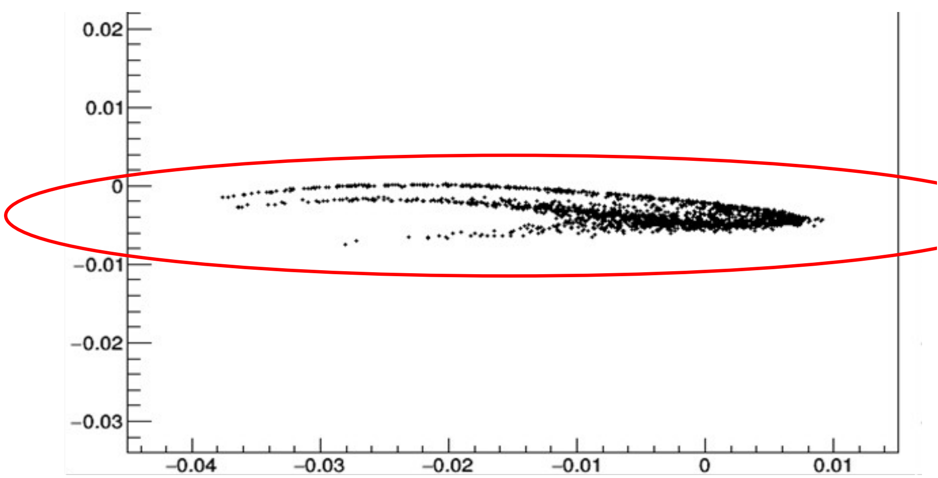


# What is the acceptable energy spread?

- z -d phase space distribution after booster has a larger energy spread by RF curvature.
- Imperfection of the compensation gives additional energy spread.
- The effect is not expected large, because the energy spread is compensated by ECS further.
- As our working assumption, 1% additional energy spread does not affect the yield.
- If larger energy spread is acceptable, the accelerator voltage is gained.

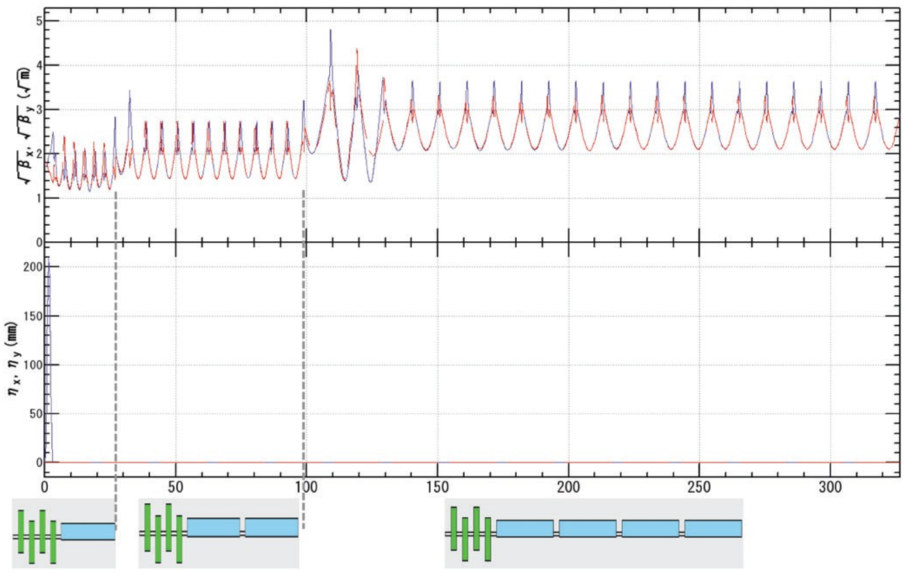



e. Angle=0.22

# Booster Configuration

- Lattice design was made by Y. Seimiya, but the accelerator voltage was larger than our assumptions.
- We change the cell number for each section giving a close energy at the section end.



Seimiya's design

| Lattice configuration | Number of lattice cells | Accelerating energy | energy at the exit |
|---|---|---|---|
| 4Q + 1L | 6 | 240 MeV | 490 MeV |
| 4Q + 2L | 12 | 960 MeV | 1450 MeV |
| 4Q + 4L | 8 | 1280 MeV | 2730 MeV |
| 4Q + 4S | 14 | 2240 MeV | 4970 MeV |

Scaled design

| Lattice configuration | Number of lattice cells | Accelerating energy | energy at the exit |
|---|---|---|---|
| 4Q + 1L | 14 | 243 MeV | 493 MeV |
| 4Q + 2L | 28 | 974 MeV | 1467 MeV |
| 4Q + 4L | 19 | 1321 MeV | 2788 MeV |
| 4Q + 4S | 23 | 2345 MeV | 5133 MeV |

# Booster Configuration (large dE)

If 3% energy spread is acceptable (no significant impact on yield), the configuration is

| Lattice configuration | Number of lattice cells | Accelerating energy | energy at the exit |
|---|---|---|---|
| 4Q + 1L | 12 | 234 MeV | 484 MeV |
| 4Q + 2L | 24 | 936 MeV | 1420 MeV |
| 4Q + 4L | 17 | 1326 MeV | 2746 MeV |
| 4Q + 4S | 20 | 2352 MeV | 5098 MeV |

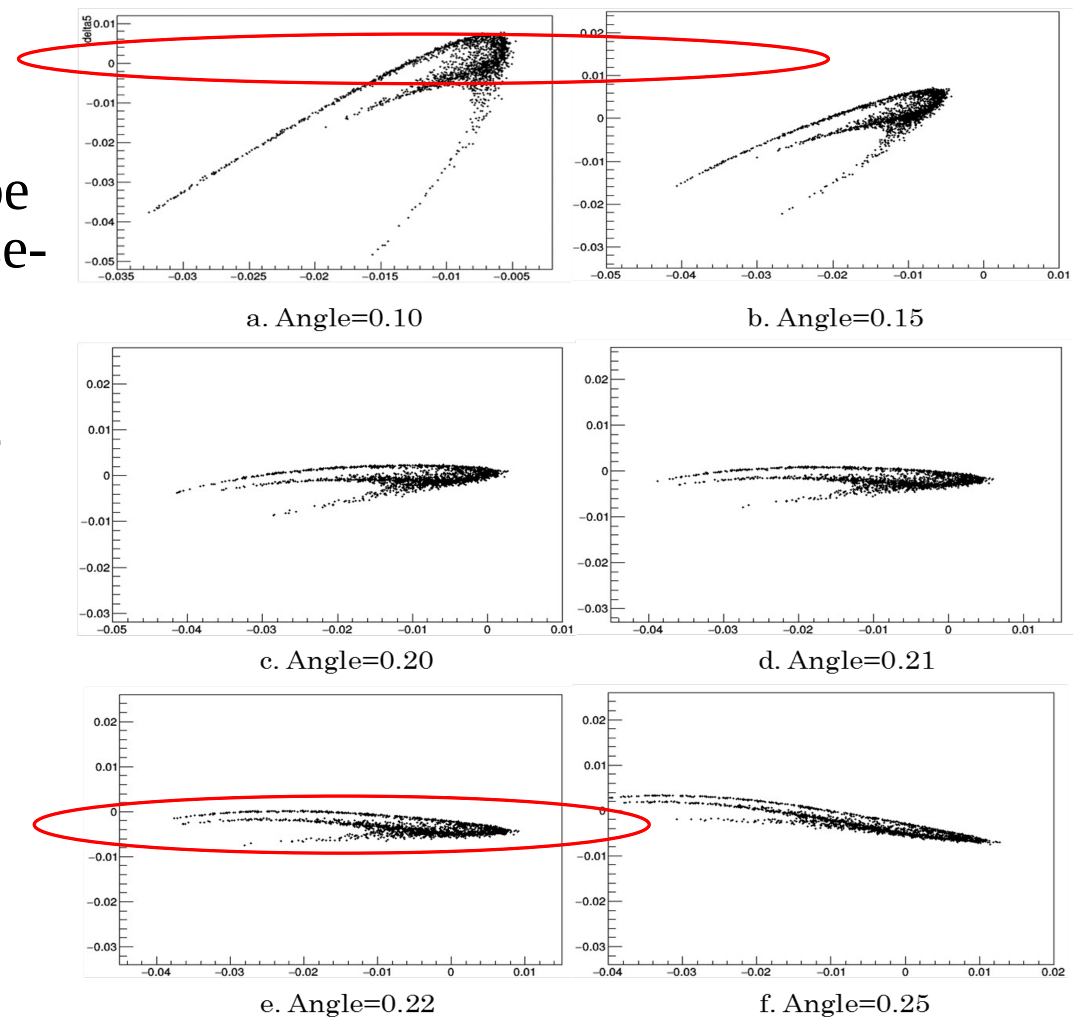
| Lattice config. | cell length | number of cells | section length |
|---|---|---|---|
| 4Q + 1L | 3.8 m | 12 | 45.6 m |
| 4Q + 2L | 6.0 m | 24 | 144 m |
| 4Q + 4L | 10.4 m | 17 | 177 m |
| 4Q + 4S | 10.4 m | 20 | 208 m |

Table 11: Section length of the booster givng 574.4 m total.

# ECS Section

- ECS design $R_{56}$=1.2m and $R_{65}$=-0.8.
- Required voltage is 122 MeV, 3 tubes are enough.
- Beam-loading (phase-shift) can be compensated by an artificial phase-shift of drive RF.
- If it does not work, we need an additional RF for compensate the phase shift., 4 tubes.

ECS optimization



# Impact of Lattice Modification

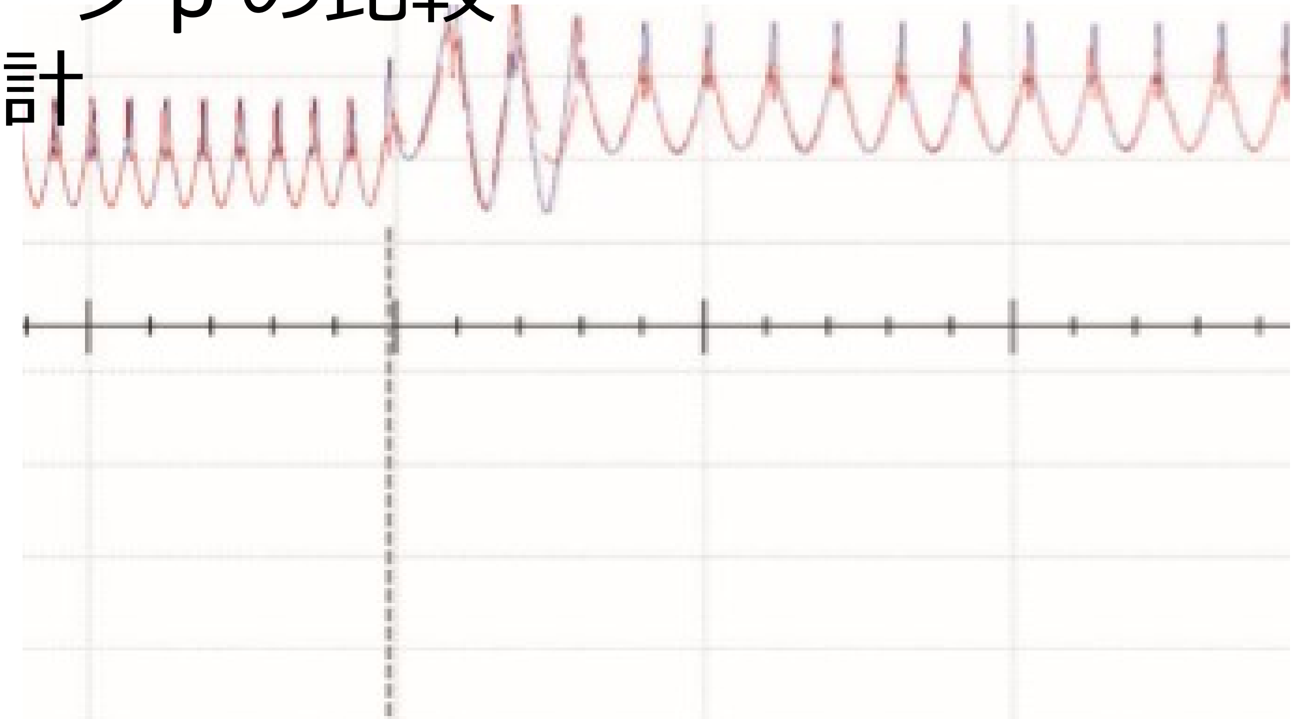
- The booster configuration (acceleration field andlattice) are modified.
- The yield is re-evaulated with the modified booster configur ation.

| | Seimiya | New |
|---|---|---|
| # of RF (L-band) | 62 | 144 |
| # of RF (S-band) | 56 | 92 |
| Voltage (L-Band) | 40(MV/tube) | 17.38(MV/tube) |
| Voltage (S-Band) | 40(MV/tube) | 25.49(MV/tube) |
| Booster Length | 323.6(m) | 653.6 (m) |

# Twiss パラメータ β の比較

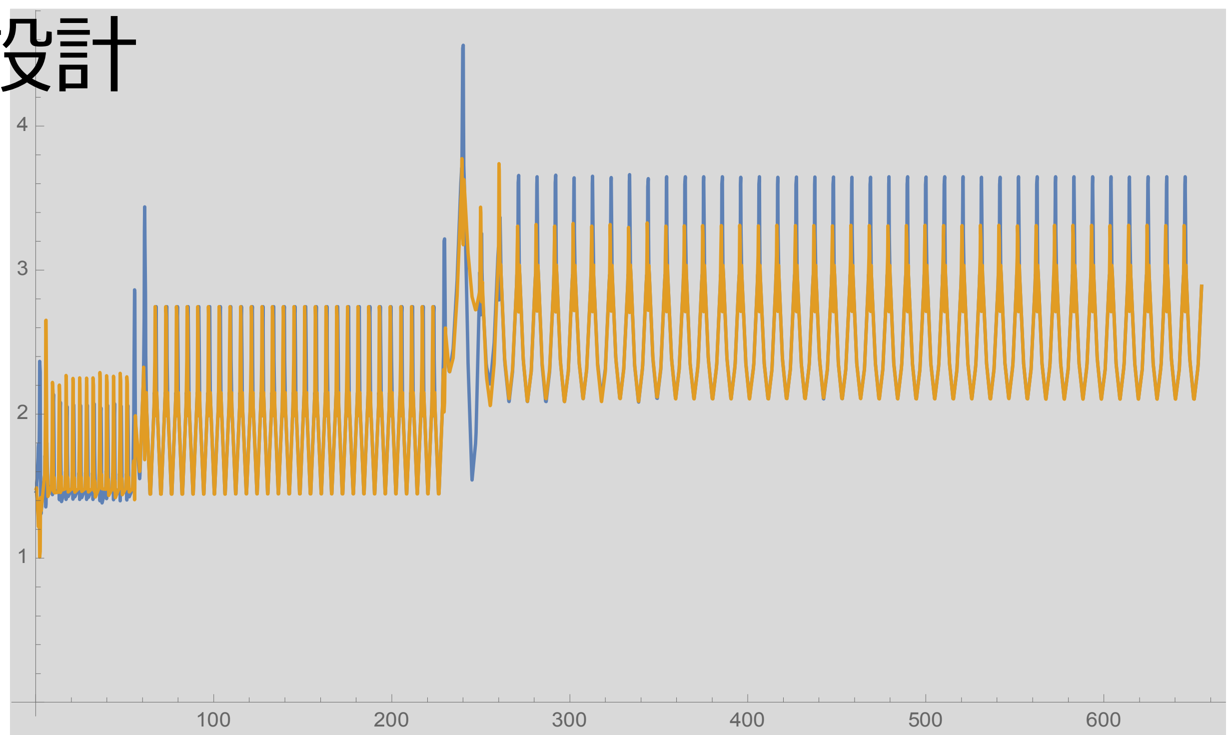
PTEP Positron capture simulation for the ILC electron-driven positron source
Yuji Seimiya　P7　より引用

# 清宮さんの設計



$\sqrt{\beta_x}$: 青
$\sqrt{\beta_y}$: 赤

# 今回変更した設計



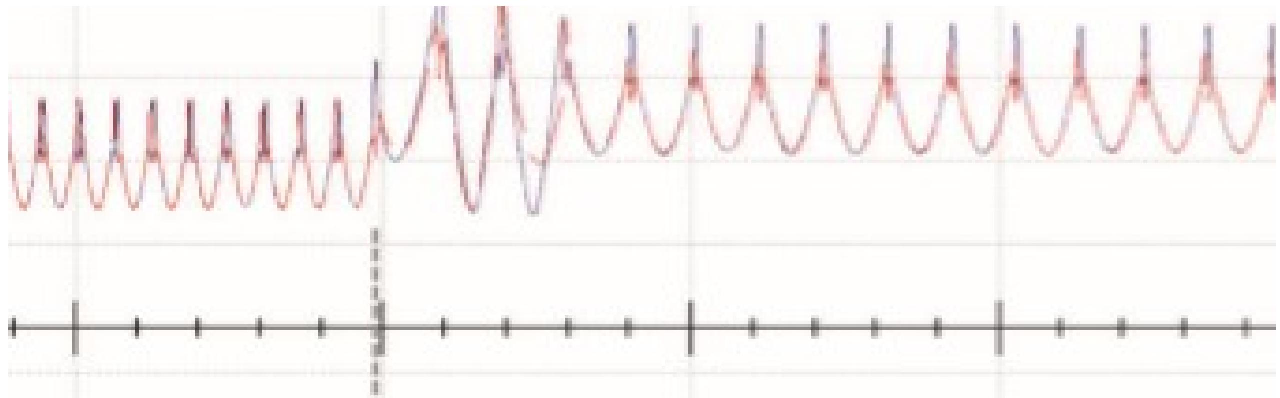

$\sqrt{\beta_x}$: 青
$\sqrt{\beta_y}$: 黄

# Twiss Parameter

PTEP Positron capture simulation for the ILC electron-driven positron source
Yuji Seimiya　P7　より引用

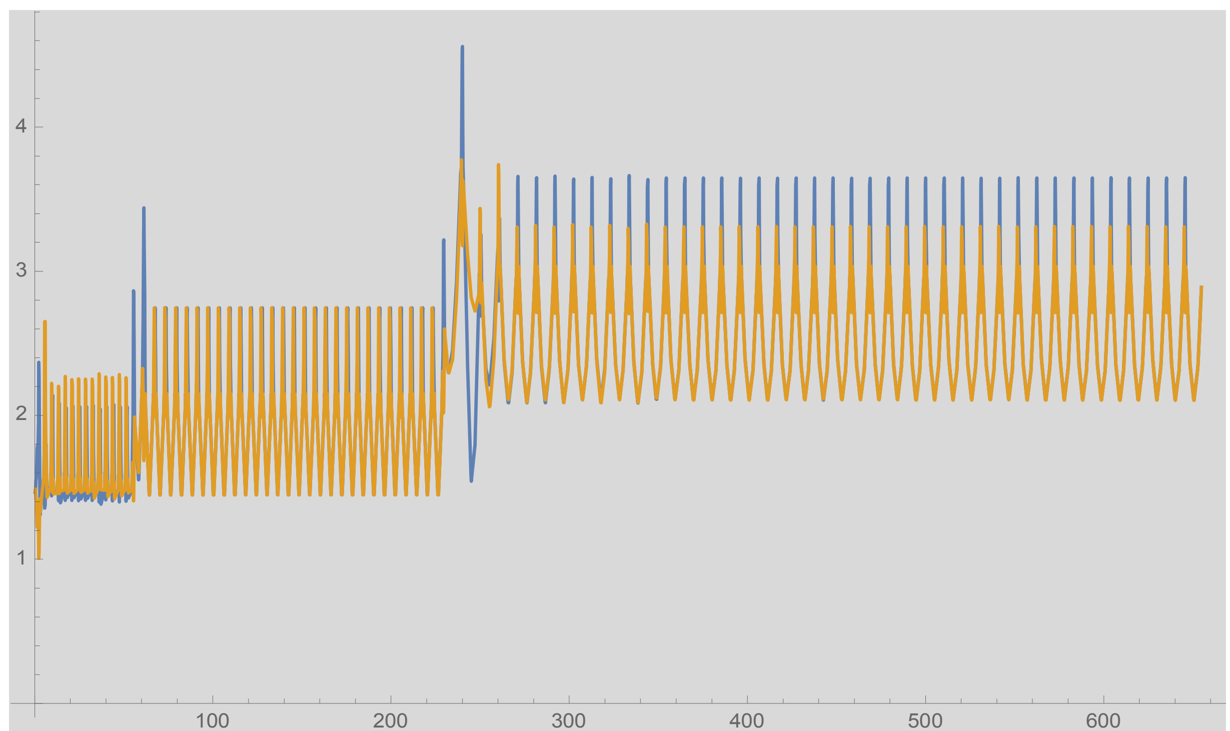
## Seimiya's

$\sqrt{\beta_x}$: 青
$\sqrt{\beta_y}$: 赤



## New

$\sqrt{\beta_x}$: 青
$\sqrt{\beta_y}$: 黄



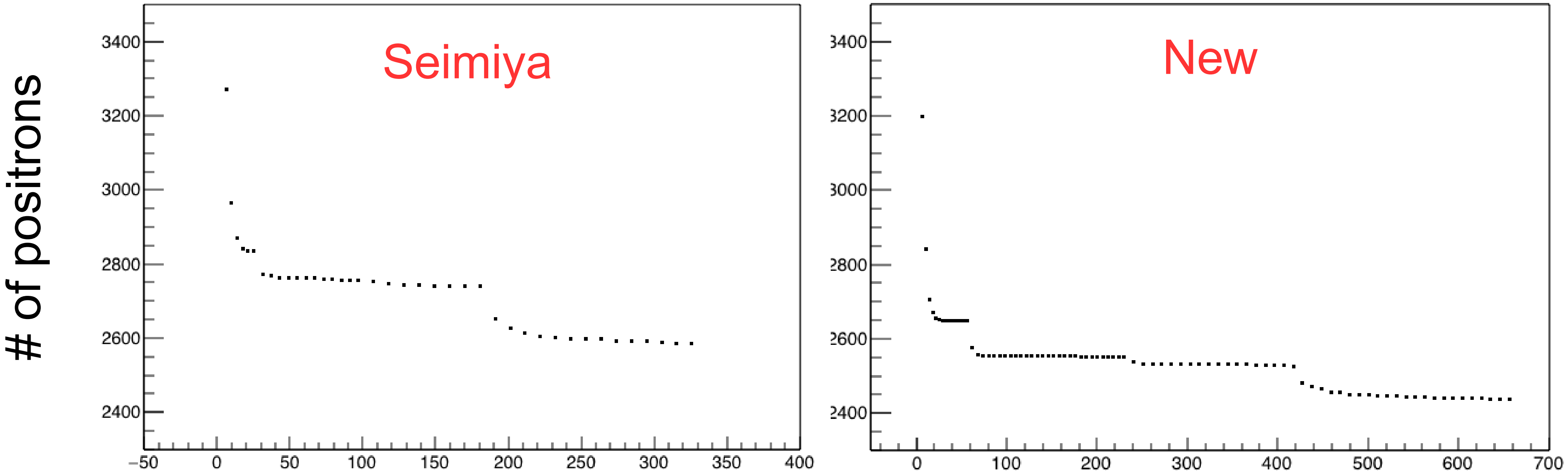
# Imapct on Yield

| | 変更前 | 変更後 |
|---|---|---|
| Yield | 2.1 | 2.0 |
| Total Energy | 5.0070(GeV) | 5.0917(GeV) |

- Yield is decreased by 5%.
- The reason is now under investigation, but it might be a pseudo effect.
- The aperture is set at the end of tubes. The low gradient and the long booster increased the density of checkpoints.

- The total energy is increased. (We set the margin)

# The Gospel?




- The yield is decreased by 5%, but the number of positrons in booster is decreased by 10% giving a low beam loading.
- Further optimization might be possible.

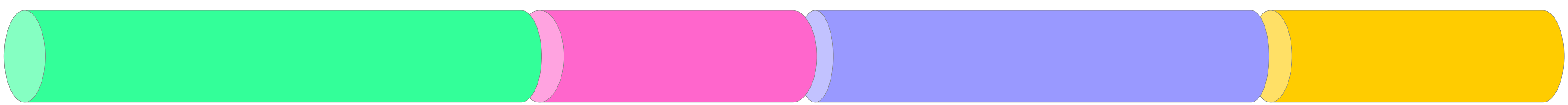
# Summary

- E-driven ILC positron source is optimized for nominal parameter (staging).
- RF configuration is modified based on a realistic RF source design.
- The beam loading compensation for SW and TW were studied.
- For SW, it works effectively well.
- For TW, semi-perfect methods for L-band and S-band are considered.
- Lattice is re-designed giving 2.0 yield. The change is not considered real.

# Total Length

Electron Driver
255.2 m

Positron Booster
658 (574m)



Target
Capture Linac
Chicane
59m

ECS
75.2m

## Total : 1047(963) m