A Status report of E-driven ILC Positron Source

LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

ALCW2018 at Fukuoka, Japan

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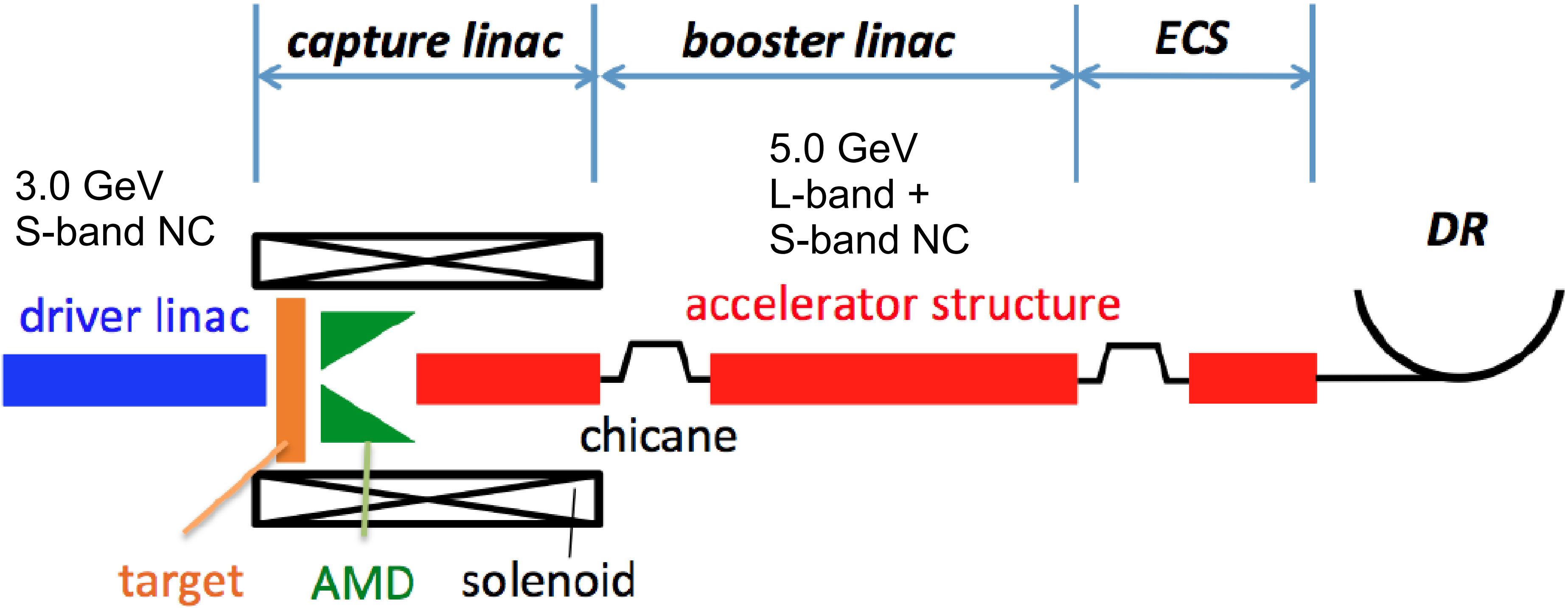
Introduction

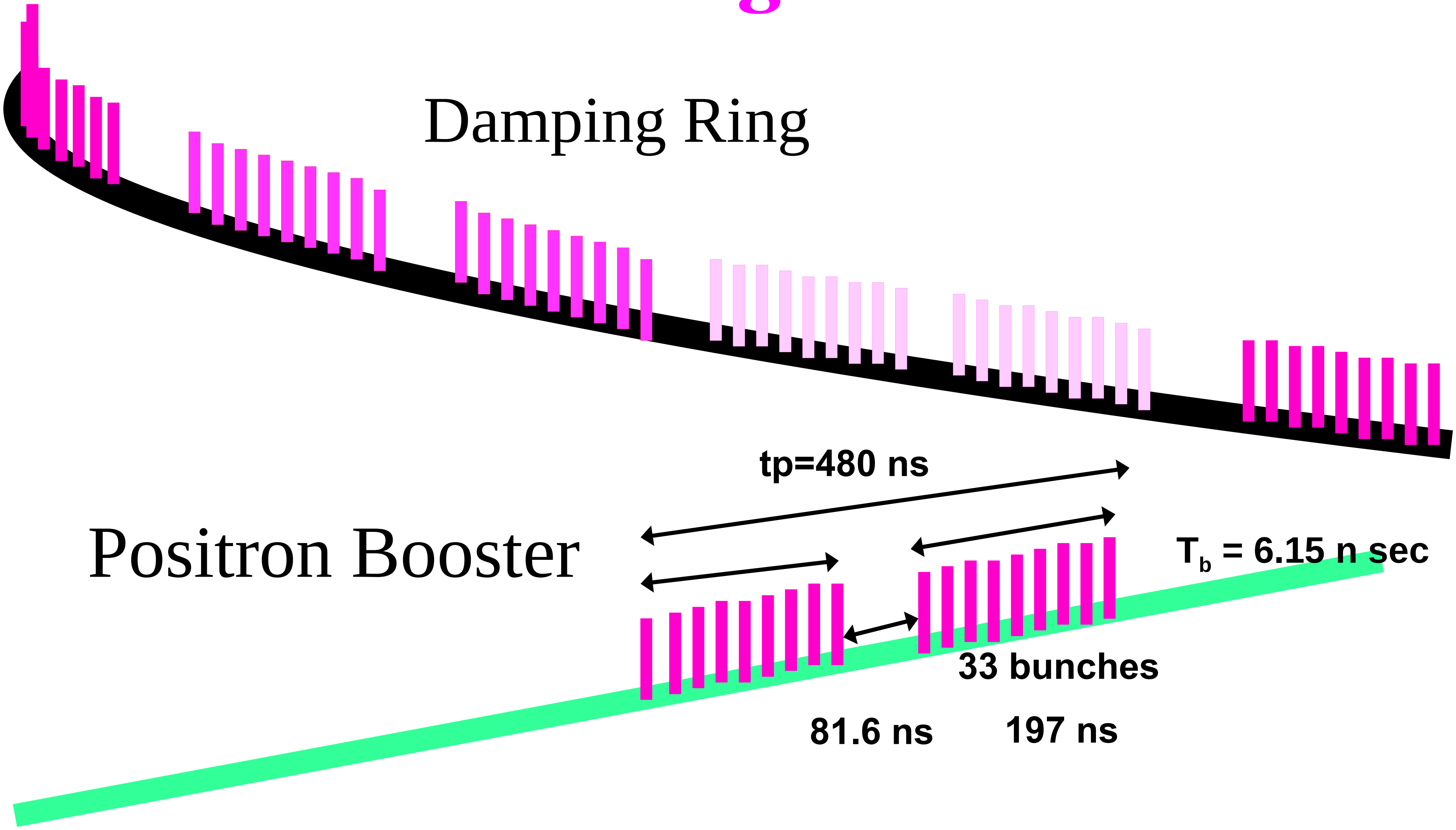
- The design of the ILC positron source based on off-the-shelf components has been established.
- Optimization for 250 GeV parameter as
  - Small beam size on target for better yield. (3.5 2.0 mm rms)
  - Lower drive beam energy for less cost. (4.8 3.0 GeV)
  - Consider only the nominal parameter.
- A margin for the booster energy is now reserved.

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.

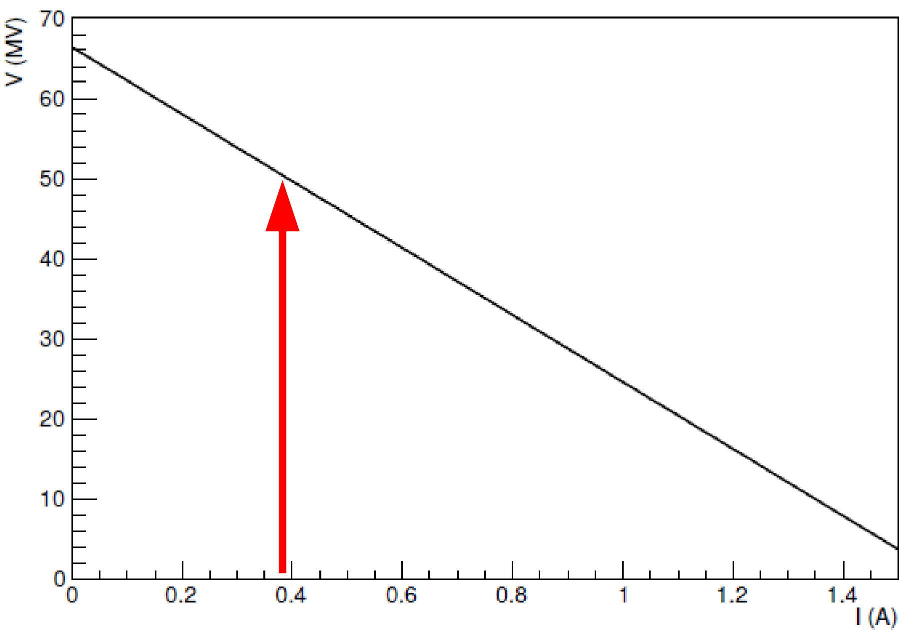
The beam handling and format



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



KEK CONCEPT DESIGN 80MW S-band RF & Solid State Modulator PARAMETERS

Fig: *K400-platform*

Main Parameters	Value	Unit
RF Frequency	2600	MHz
RF Peak Power	80	MW
RF Average Power	0.2 (12)[1]	kW
Mod. Peak Power	143	MW
Mod. Average Power	1.4 (86)[1]	kW
Klystron Voltage	382	kV
Klystron Current	375	A
RF Pulse width (top)	0.5	μs
Pulse Repetition Rate	5 (300)	Hz
Pulse-to-Pulse stability	<15	ppm

[1] *Corresponding to 300Hz operation*

OPTIONS: Integration of …

- Solenoid Power Supply
- Ion Pump Power Supply
- RF Drive amplifier
- Cooling of Klystron (Collector, Body), Solenoid
- All diagnostics and interlocks

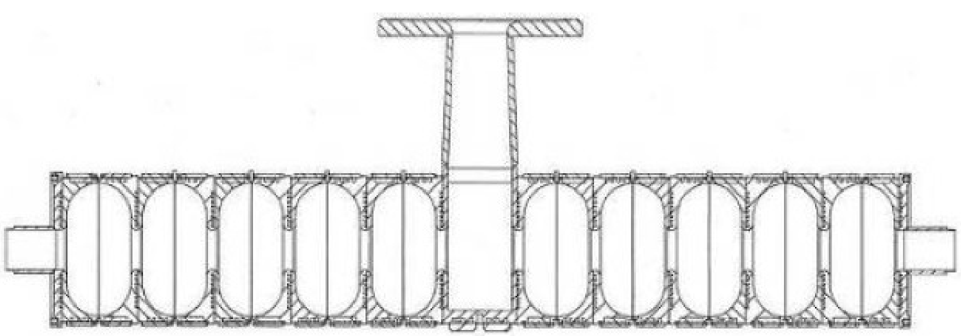
- 60 + 4 (spare) of 3m S-band TW structures for the acceleration. The energy is 3.2 GeV.
- The lattice design was based on ATF linac, 4Q + 2RF(S) up to 600 MeV, 4Q+4RF(S) for other.

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

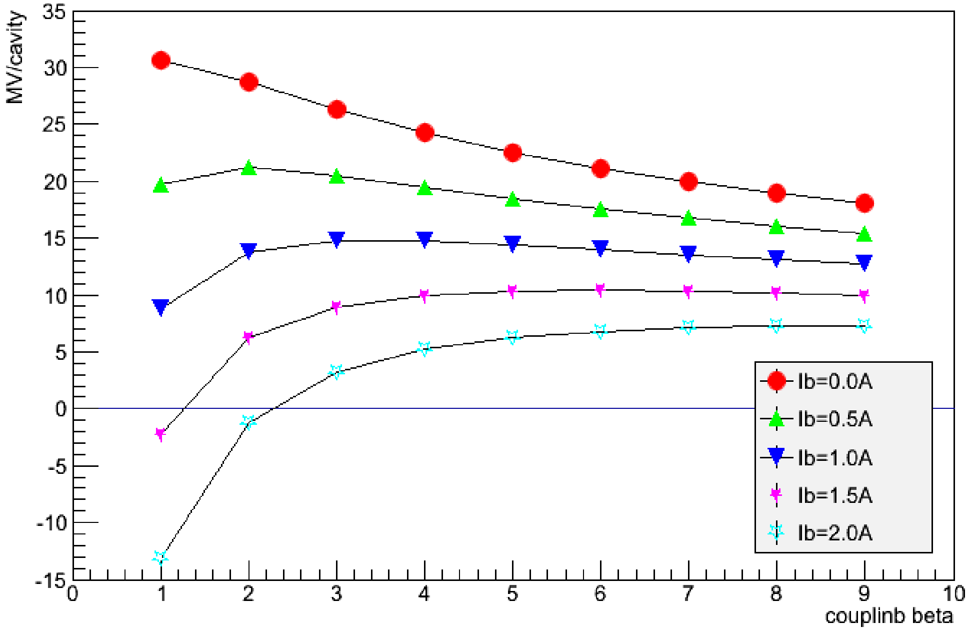
- 36 L-band SW structures designed by J. Wang (SLAC) for the undulator capture section is employed.
- Two structures are driven by one 50 MW klystron.
- Surrounded by 0.5 T solenoid field.

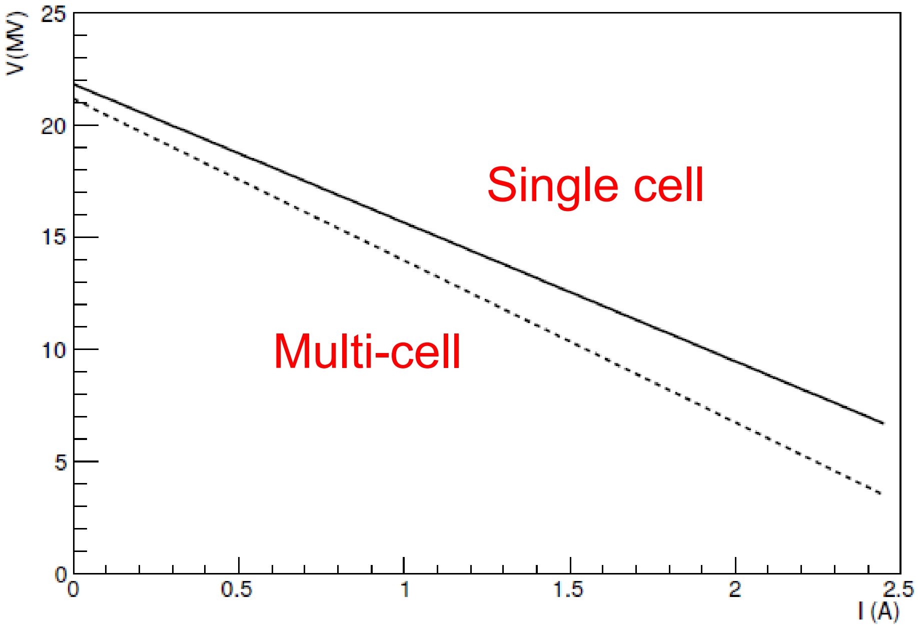


Structure Type	Simple π Mode
Cell Number	11
Aperture 2a	60 mm
Q	29700
Shunt impedance r	34.3 MΩ/m
E_0 (8.6 MW input)	15.2 MV/m

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.





KEK CONCEPT DESIGN 50MW L-band RF & Solid State Modulator PARAMETERS

October 6, 2017

Fig: *K300-platform*

Main Parameters	Value	Unit
RF Frequency	1300	MHz
RF Peak Power	50	MW
RF Average Power	0.125 (7.5)[1]	kW
Mod. Peak Power	76	MW
Mod. Average Power	0.7 (42)[1]	kW
Klystron Voltage	271.7	kV
Klystron Current	282	A
RF Pulse width (top)	0.5	μs
Pulse Repetition Rate	5 (300)	Hz
Pulse-to-Pulse stability	<20	ppm

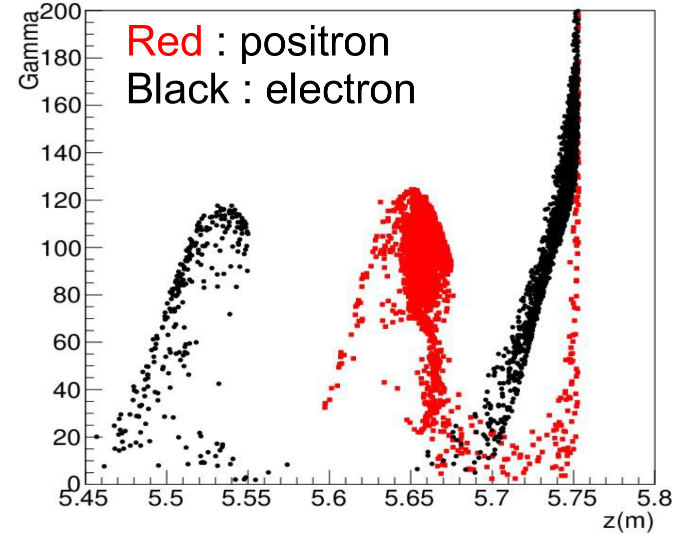
[1] *Corresponding to 300Hz operation*

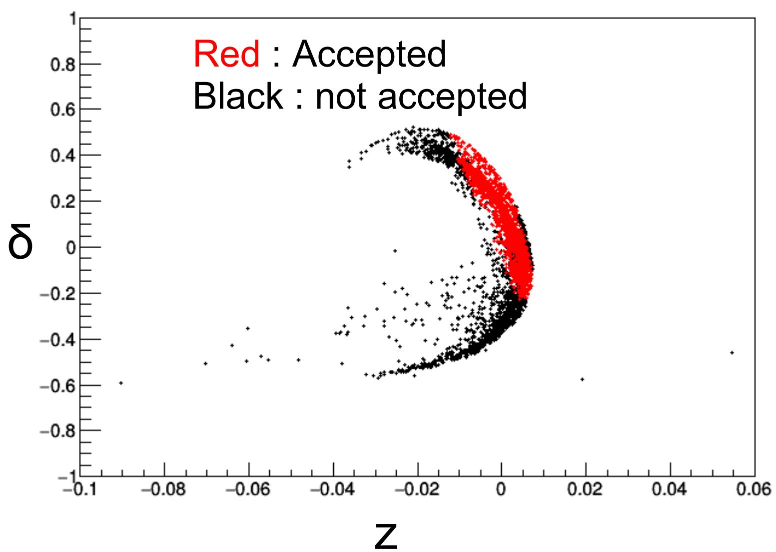
OPTIONS: Integration of …

- Solenoid Power Supply
- Ion Pump Power Supply
- RF Drive amplifier
- Cooling of Klystron (Collector, Body), Solenoid
- All diagnostics and interlocks

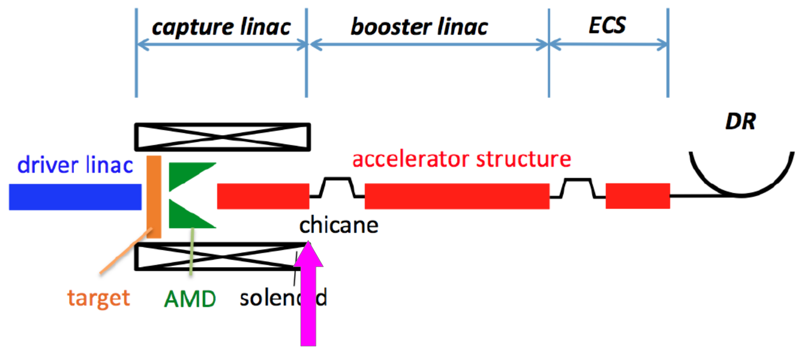
Capture Simulation

- 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, because the energy is determined by booster.
- The energy after the capture have less effect on the capture.
- The beam loading current is typically ~1.5 A, which is much less than the NLC design.

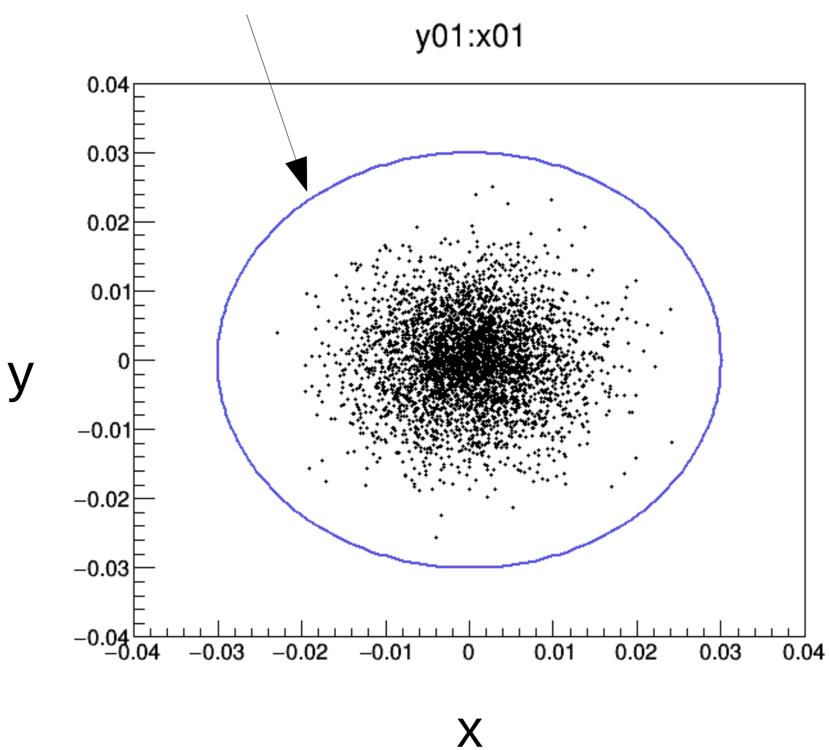


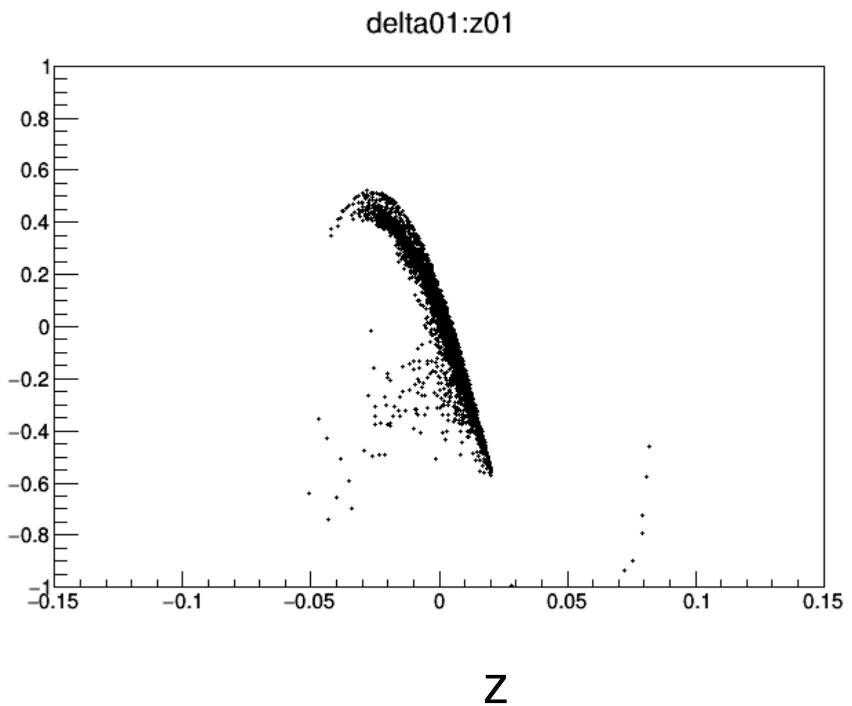


At the end of capture linac



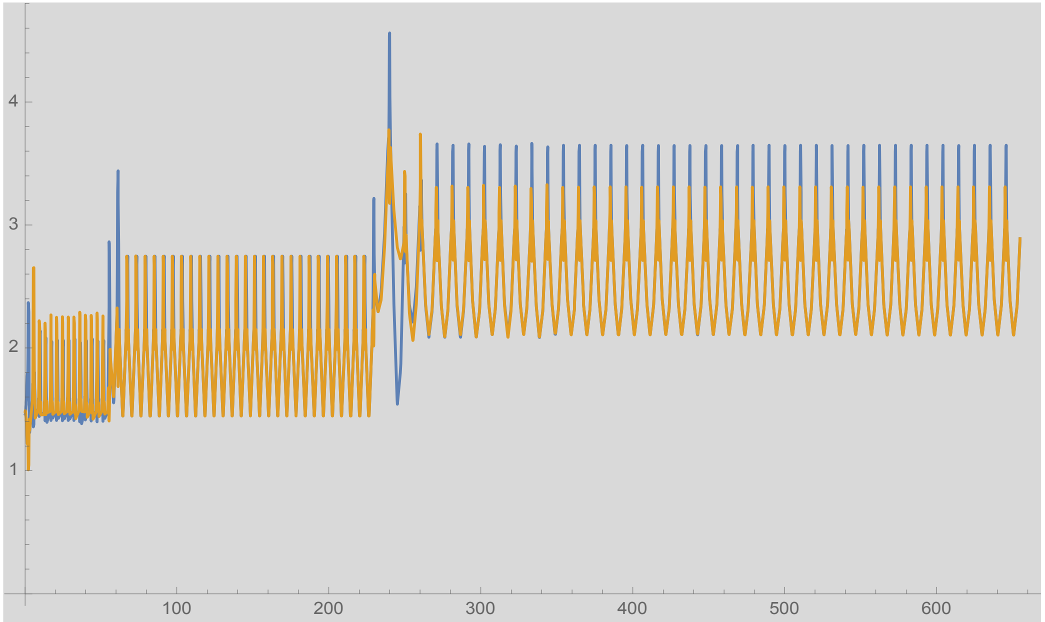
Accelerator Aperture





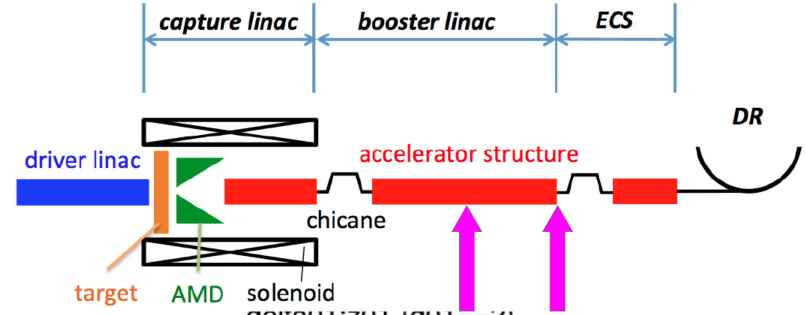
Booster

- 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).

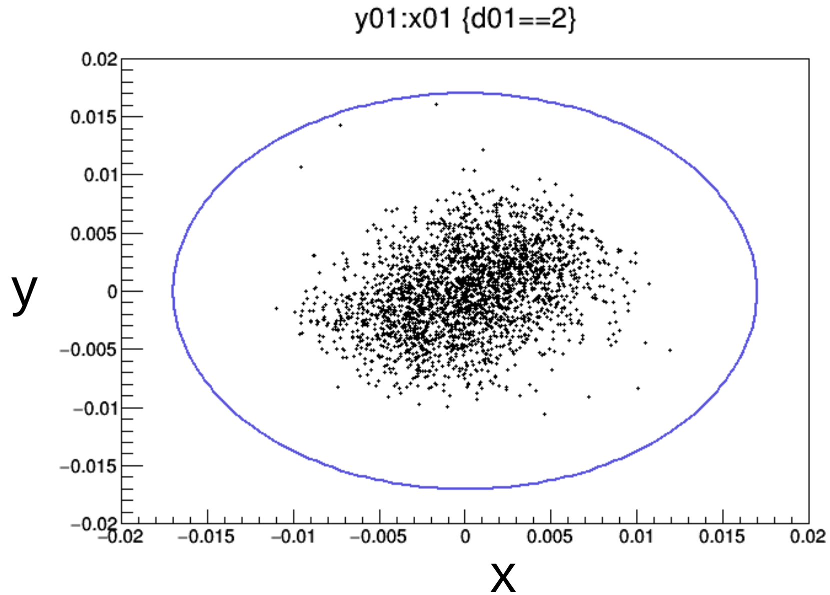


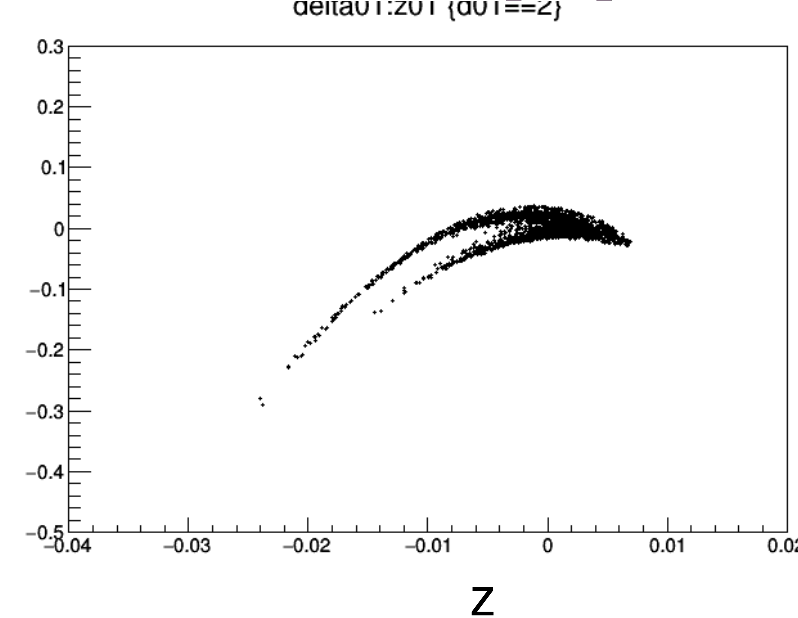
Lattice config.	N. of cells	Acc. energy	Energy at the exit	cell length	section length
4Q + 1L	14	243 MeV	493 MeV	3.8 m	53.2 m
4Q + 2L	29	1009 MeV	1502 MeV	6.0 m	174 m
4Q + 4L	18	1252 MeV	2754 MeV	10.4 m	187.2 m
4Q + 4S	26	2345 MeV	5099 MeV	10.4 m	270.4 m

In Booster

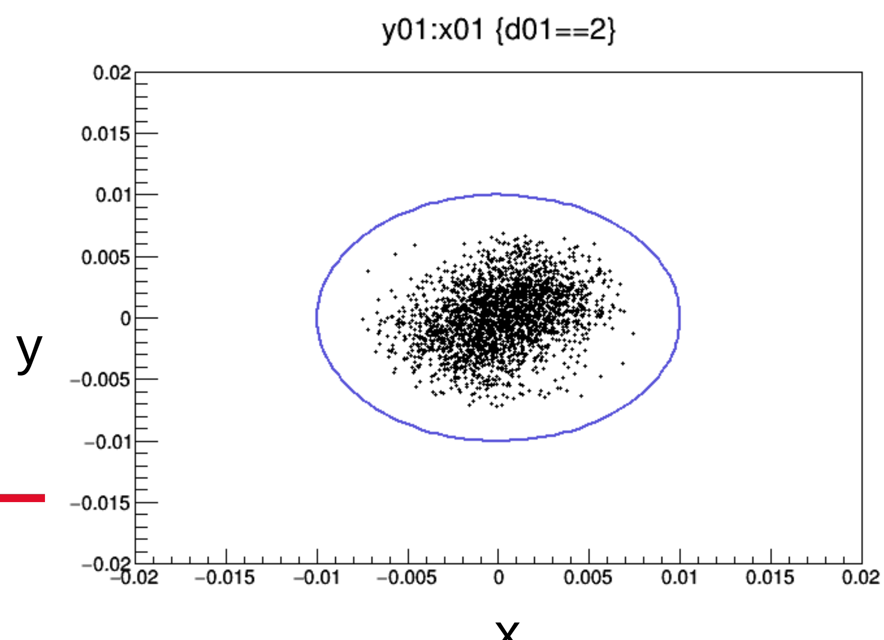


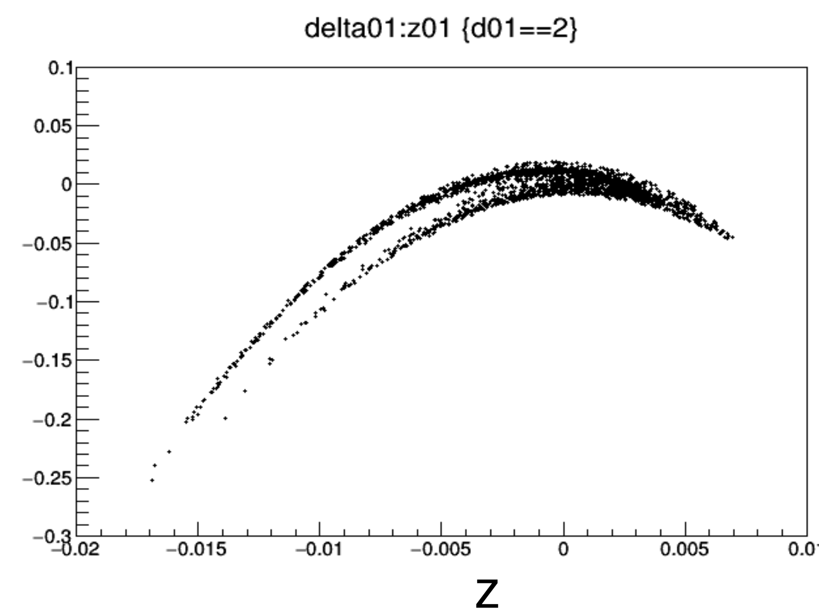
Middle





End

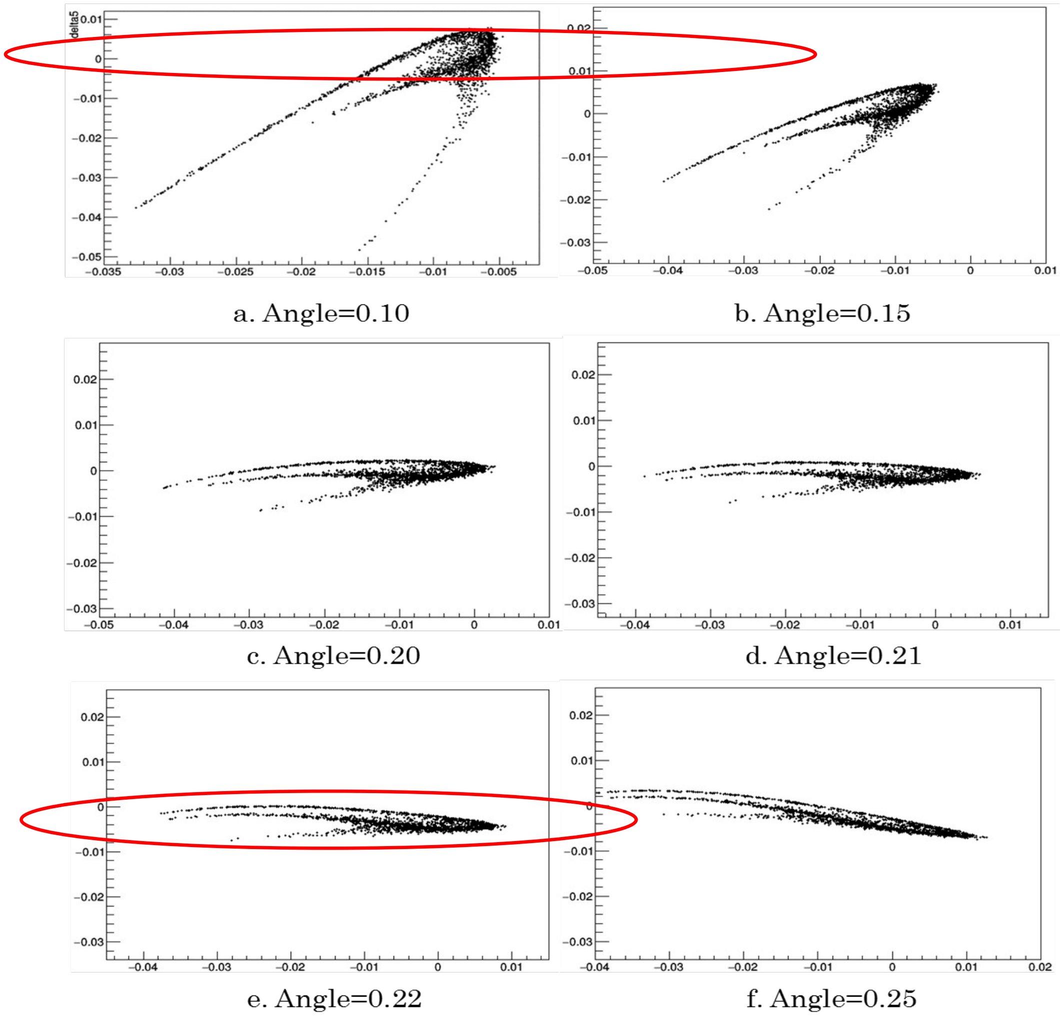




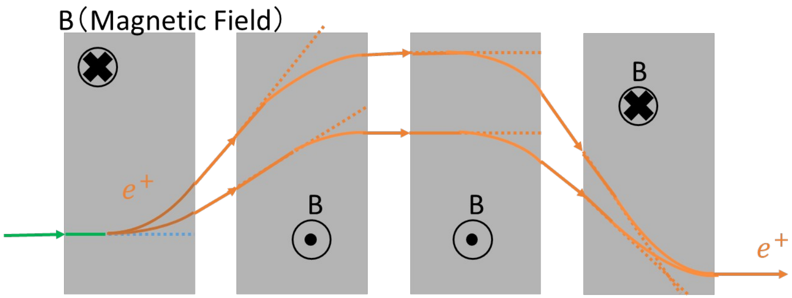
ECS Section

- ECS design R_{56}=1.2m and R_{65}=-0.8.
- Required voltage is 122 MeV, 3 tubes are enough.
- We need an additional RF to compensate the beam loading.

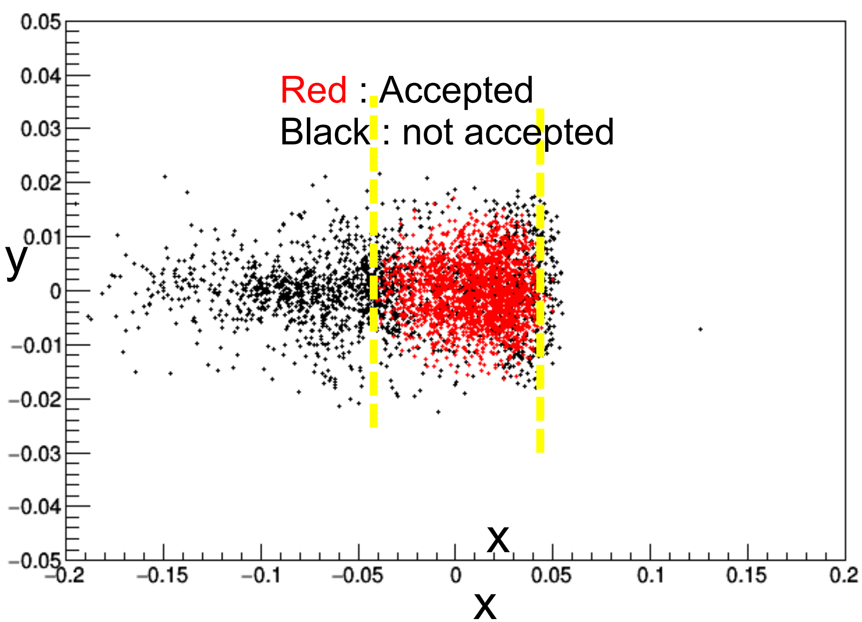
ECS optimization



Limit the current



- Removing "rude positrons" by collimation in the capture section (22mm rad.) and in the chicane (100 mm width) was studied.
- The rude positrons are decreased 15% with 7% less yield.

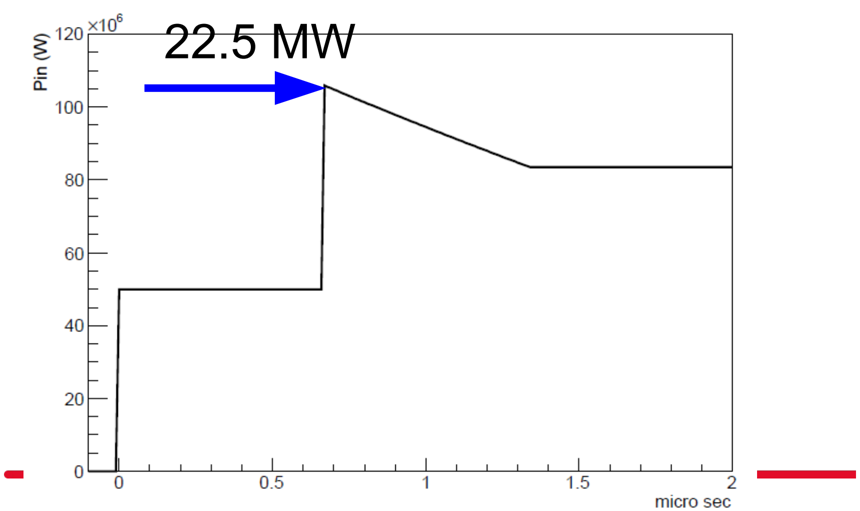


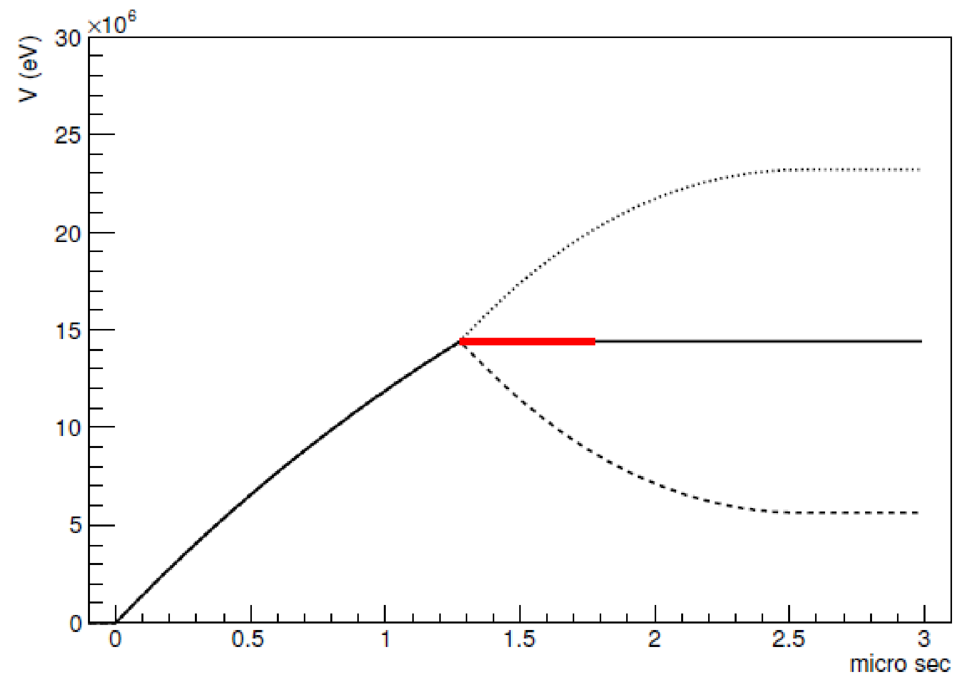
Config.	I_{blcap}(A)	I_{blbstr}(A)	Yield
No cut	1.71	0.96	2.06
Cap.	1.56	0.93	2.04
Chic.	1.71	0.93	2.04
Cap. + Chic.	1.56	0.90	2.02

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 limited.

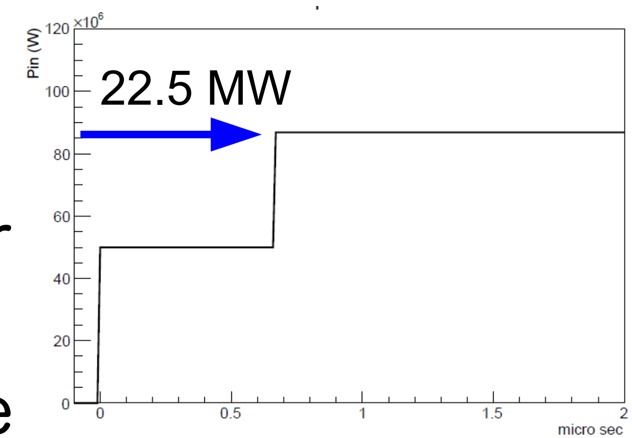
Parameter	Number	unit
Frequency	1298	MHz
Shunt Impedance	47.2	MΩ/m
Aperture (2a)	39.4 - 35.0	mm
Group velocity	0.61 - 0.39	% of c
Filling time	1.32	μs
Attenuation	0.261	
Q value	20000	
Length	2.0	m

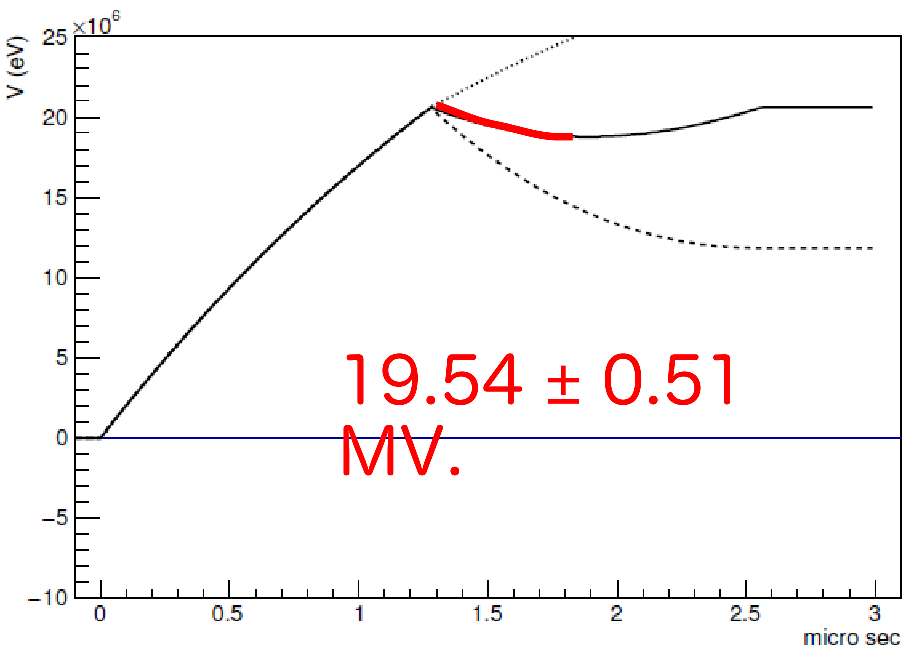


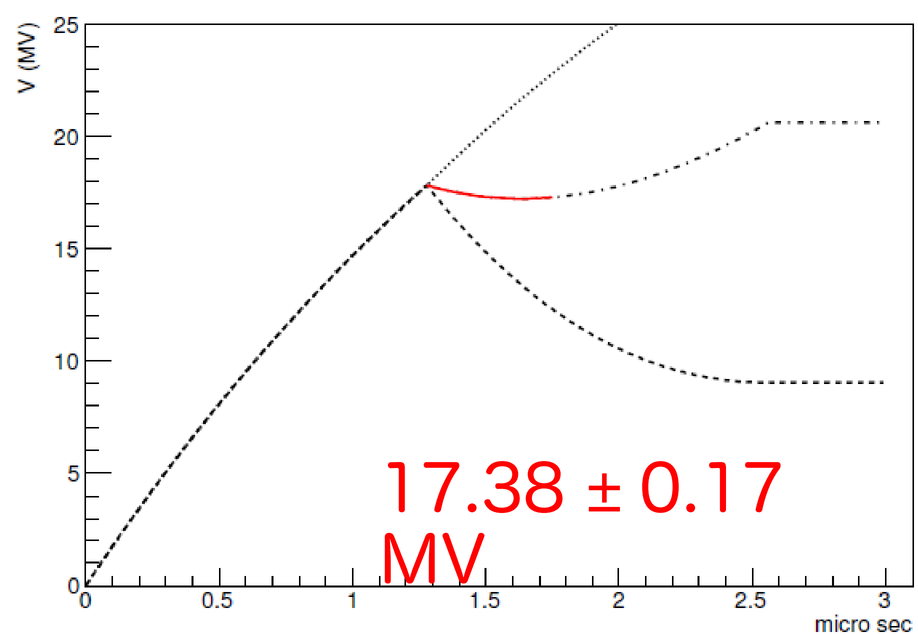


Step Modulation

- 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.



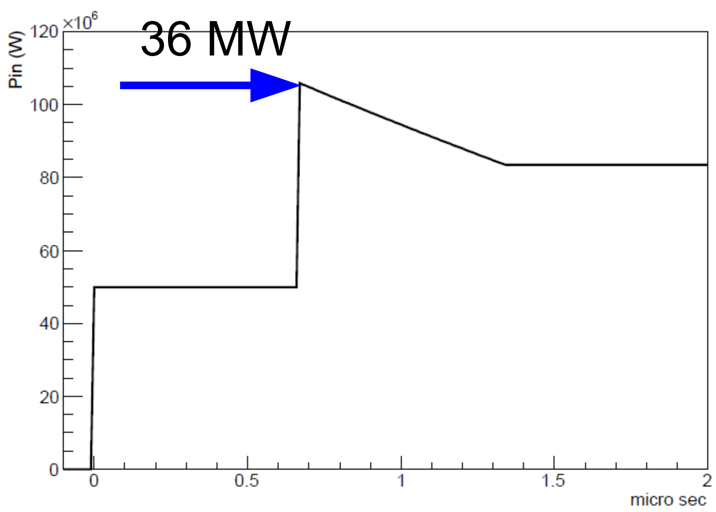


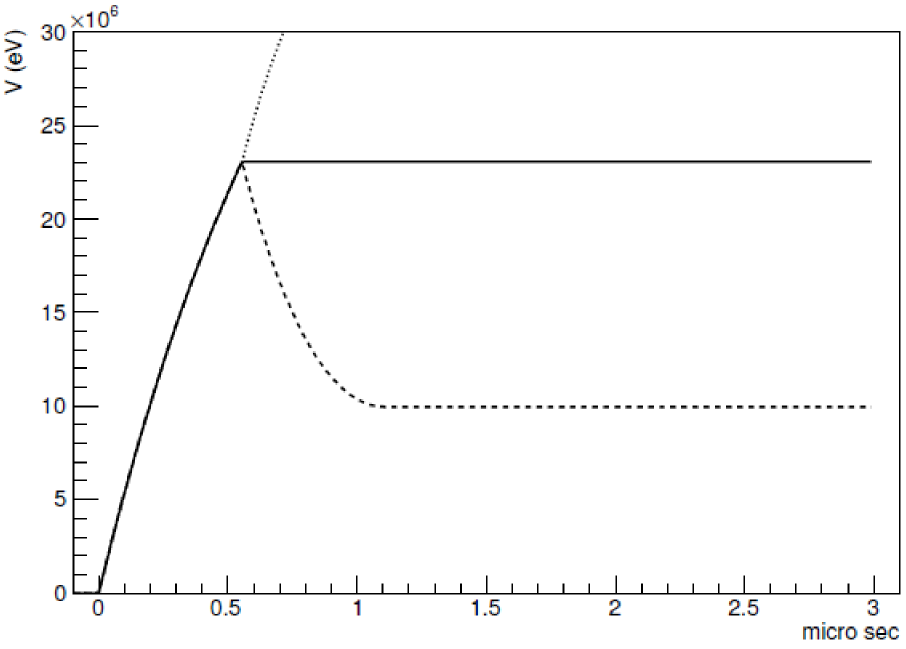


S-band TW accelerator (Positron Booster)

- 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.

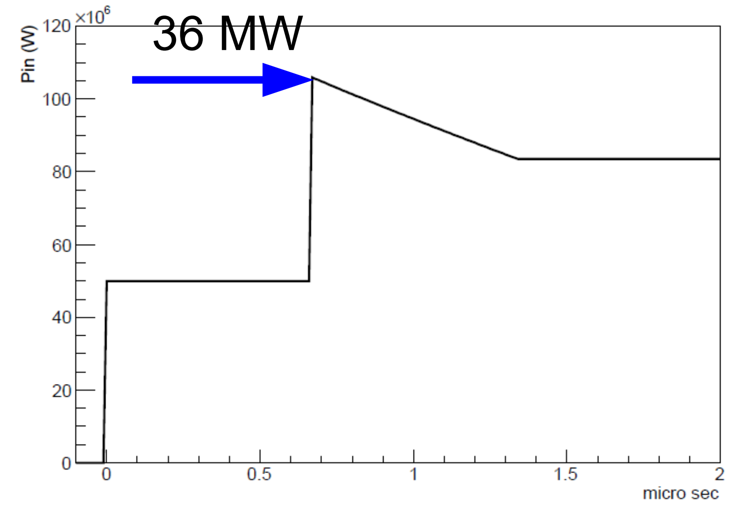
Parameter	Number	unit
Frequency	2856	MHz
Shunt Impedance	57.8	MΩ/m
Aperture (2a)	24.28 - 20.3	mm
Group velocity	1.24 (av)	% of c
Filling time	0.507	μs
Attenuation	0.333	
Length	1.959	m

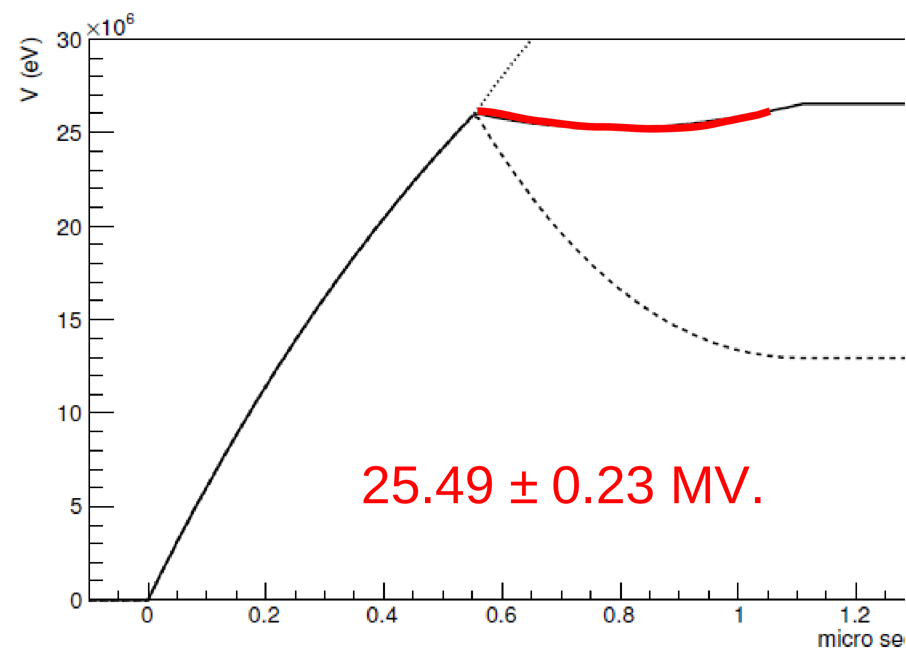




Optimization

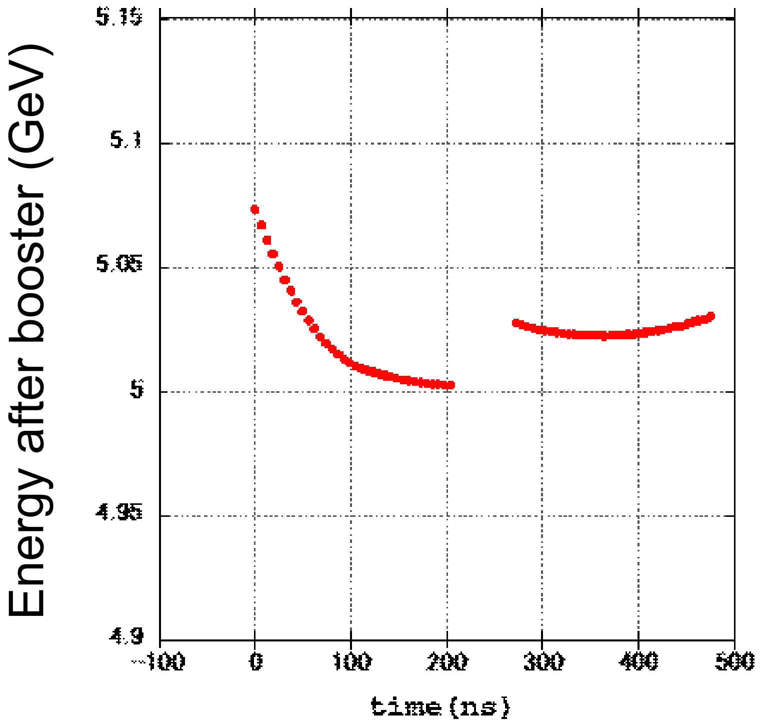
- Step modulation gives 29.42 ± 0.69 MV, the spread is more than 2%.
- P0 optimization does not work, because tf~tp.
- Instead, semi-Step-saw modulation was made with the peak power which is less than that for the perfect compensation.
- An example is 25.49 ± 0.23 MV.
- The accelerator voltage is determined by the acceptable energy spread.

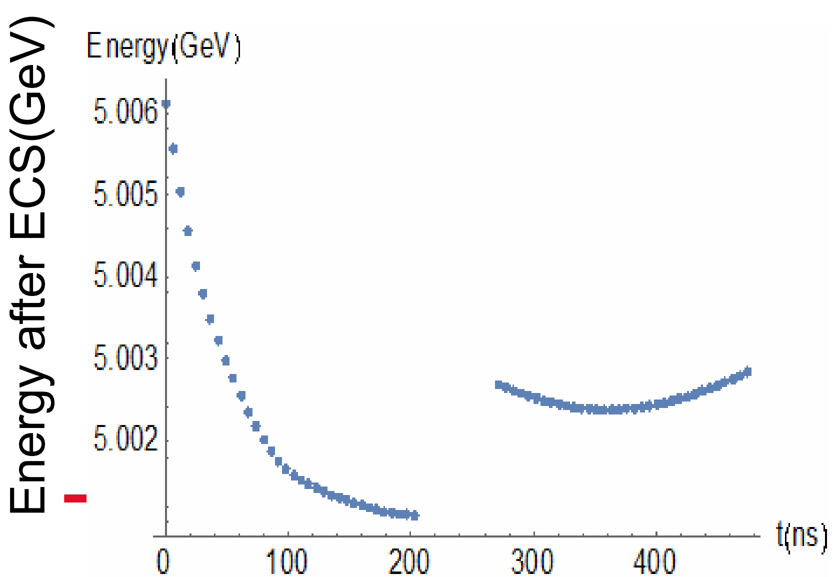




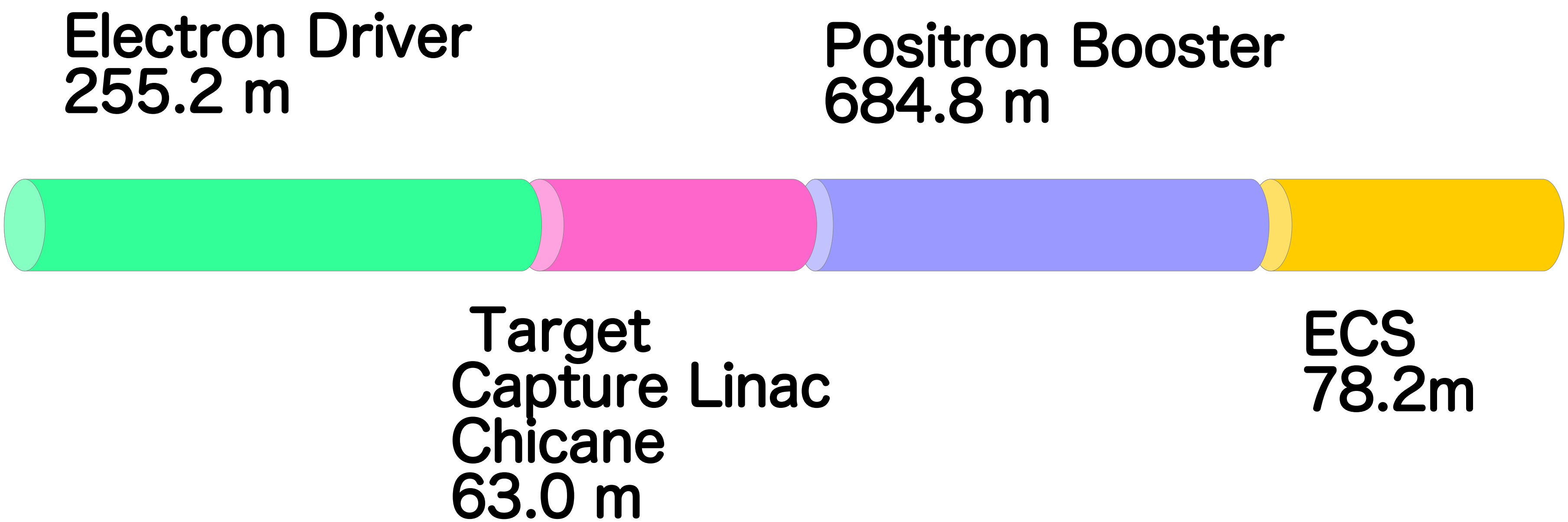
Yield variation in a pulse

- By employing the quasi-perfect BL compensation, energy for each bunch in a pulse will be varied.
- The positron yield variation by the energy variation was studied.
- The bunch energy is varied 1.2% in a pulse, that corresponds to 0.1 % after ECS.



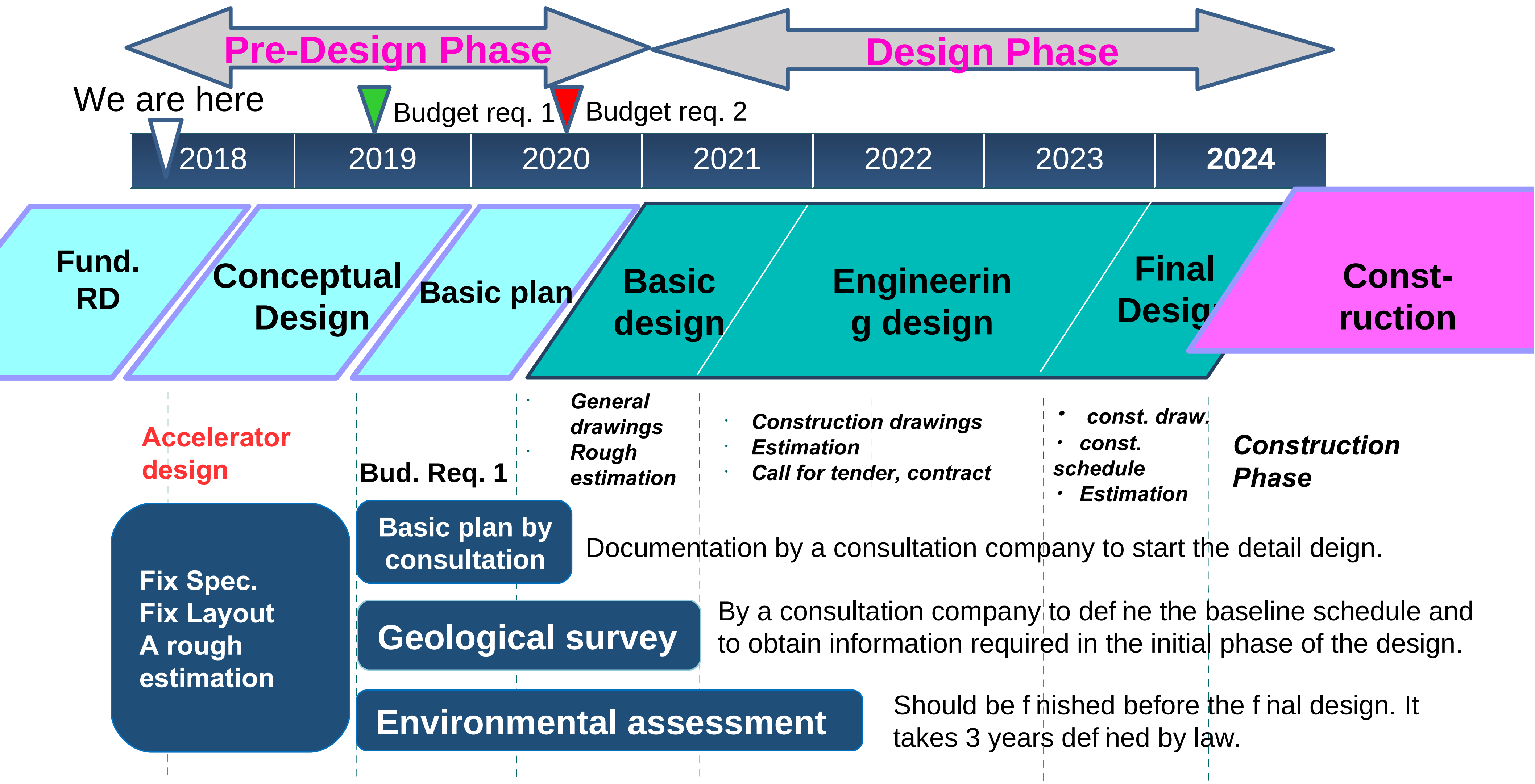


Total Length



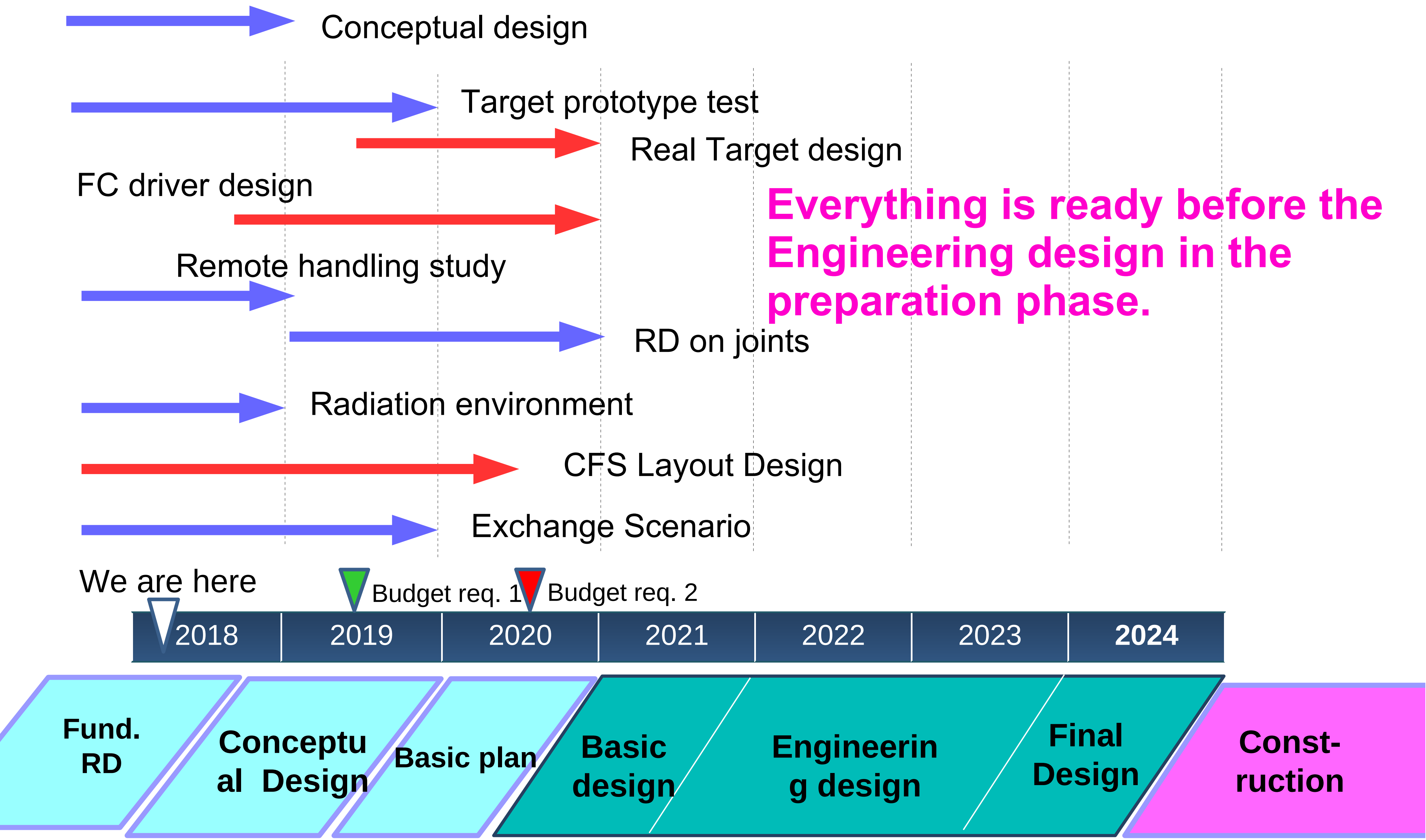
Total : 1081.2 m

An Expected Schedule on Pre- and Design Phase



English translation by M. Kuriki
The slide is originally made by Y. Miyahara (CFS Group).

An Expected Schedule on Positron Source Design



Summary

- E-driven ILC positron source is optimized for 250 GeV ILC.
- Collimation at chicane (after capture linac) and cut by iris in the capture are effective to decrease the beam loading.
- The energy variation by the positron booster is evaluated with the quasi-perfect BL compensation.
- The yield variation due to the energy variation is 6% in full-width.
- The conceptual design should be fixed in this year.
- Everything can be ready before the engineering design in the preparation phase.

LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

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

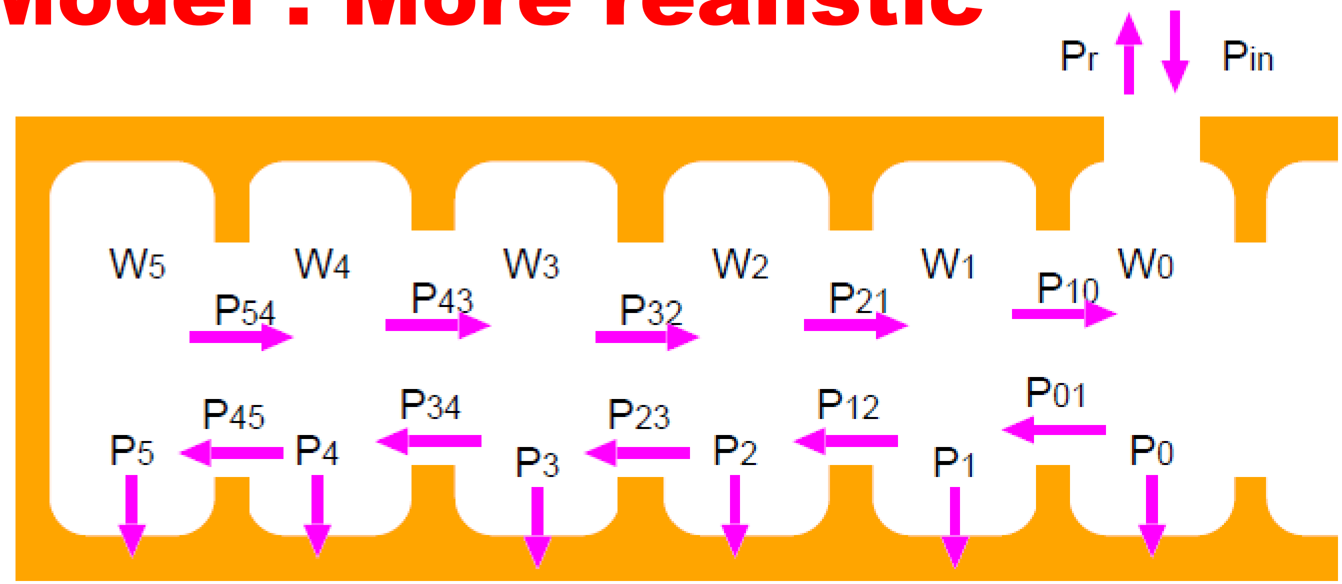
Beam Loading

- The voltage … es cons

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

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

Multi-Cell Model : More realistic



Time differential of the energy of the center cell,

Power flow to next cells

Input Power

Beam loading

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

Power 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

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

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

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

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

***A** can be diagonalized with a orthgonal matrix **R** as*

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

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

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

*Because **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'

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

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

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

τ	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

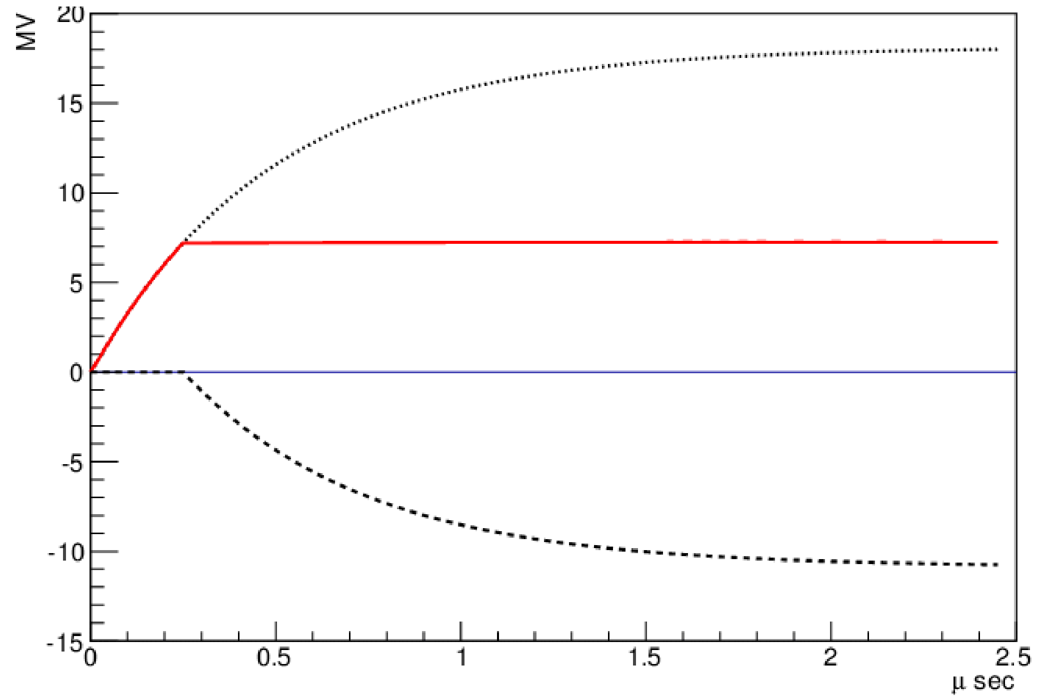
τ	0.020	0.006	0.011	0.068	1.22
cell 0	-0.000	0.000	0.000	0.004	-0.710
cell 1	0.000	-0.000	-0.000	0.002	-0.698
cell 2	-0.000	0.000	-0.000	0.000	-0.674
cell 3	0.000	-0.000	0.000	-0.002	-0.639
cell 4	-0.000	0.000	0.000	-0.004	-0.594
cell 5	-0.000	-0.000	-0.000	-0.004	-0.539
cell 6	-0.000	0.000	0.000	-0.004	-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

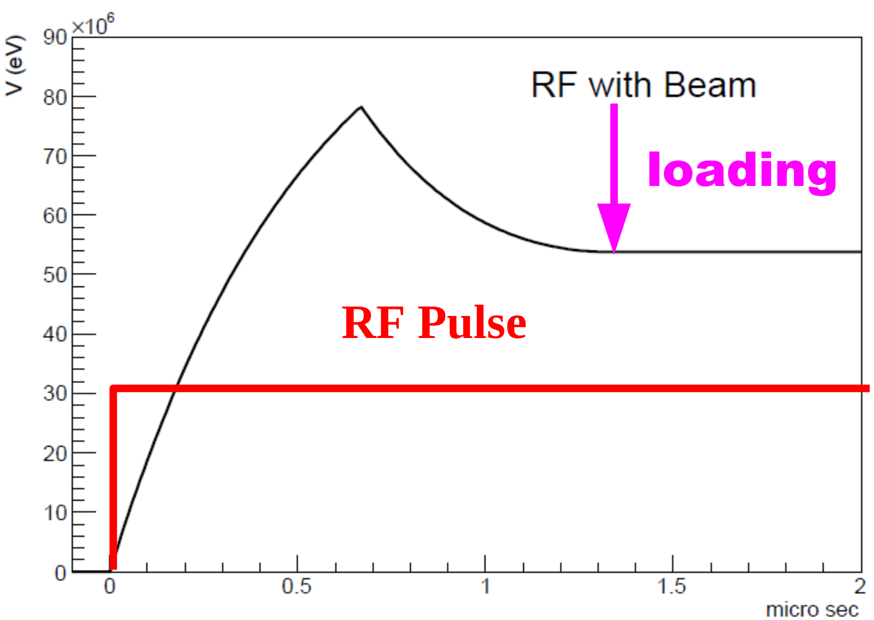
The beam loading compensation works well. Flatness is less than 0.1%.

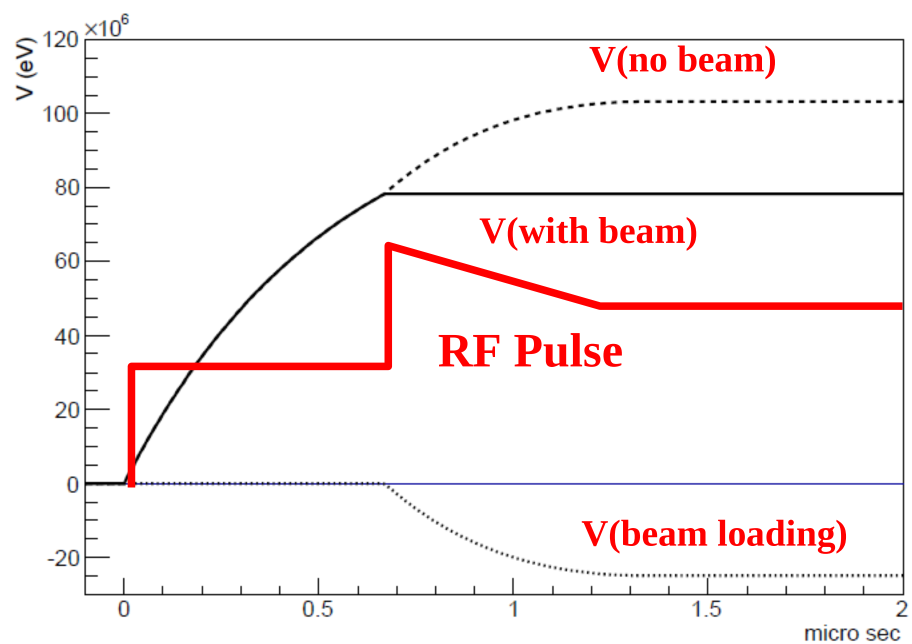


Beam-loading in TW Linac

- 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

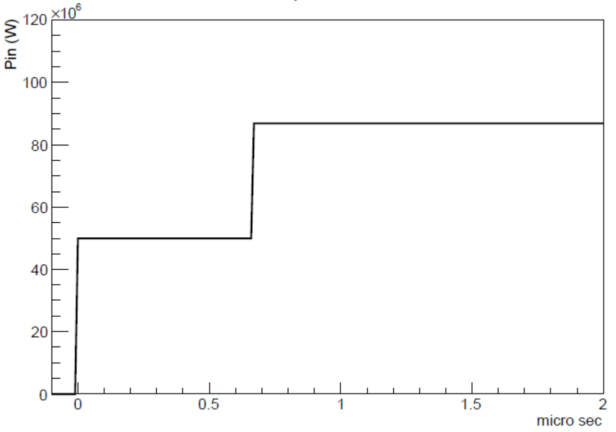
$$V(s) = \frac{\omega L}{Q(1-e^{-2\tau})}\frac{1}{s+\omega/Q}E(s)\left(1-e^{-(s+\omega/Q)t_f}\right)$$
$$-\frac{\omega r_0 L}{2Q(1-e^{-2\tau})}\frac{I_0}{s^2}e^{-st_f}\left[1-e^{-\frac{\omega}{Q}t_f}-\frac{\omega(1-e^{-st_f-2\tau})}{Q(s+\omega/Q)}\right],$$

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

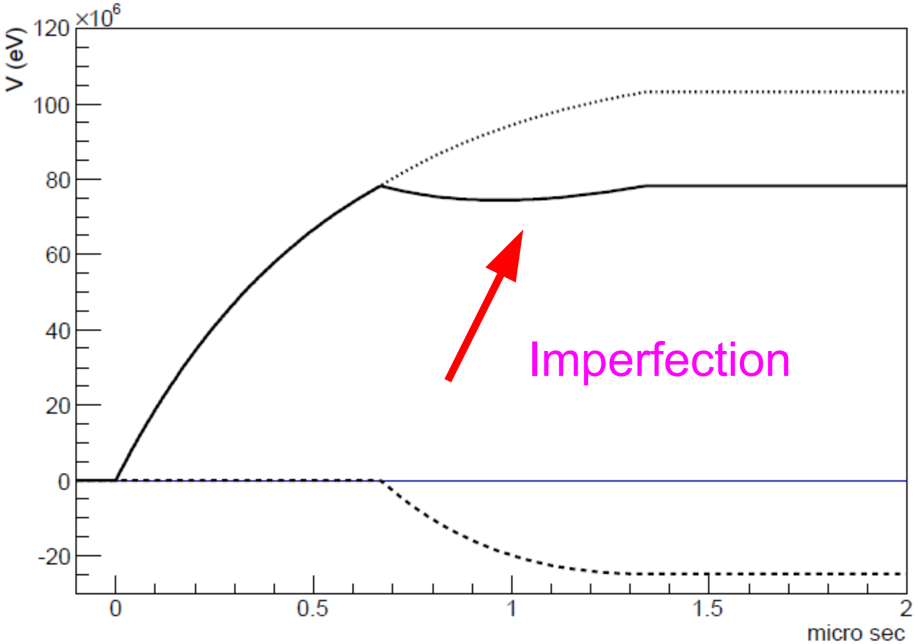
$$E(t) = E_0 U(t) + E_1 U(t - t_f),$$

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

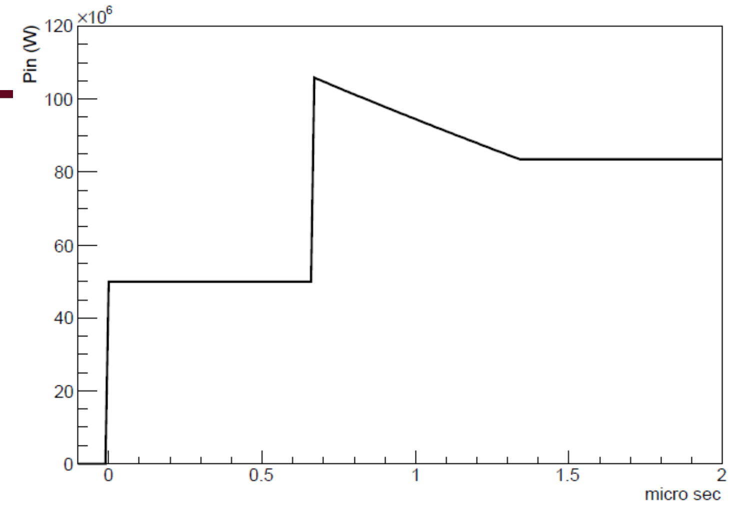


$$V(t) = E_0 L + \frac{LE_1}{1 - e^{-2\tau}} \left(1 - e^{-\frac{\omega}{Q}(t - t_f)}\right) - \frac{r_0 L I_0}{2(1 - e^{-2\tau})} \left[-\frac{\omega}{Q} e^{-2\tau} (t - t_f) + 1 - e^{-\frac{\omega}{Q}(t - t_f)}\right]$$

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



Saw Modulation



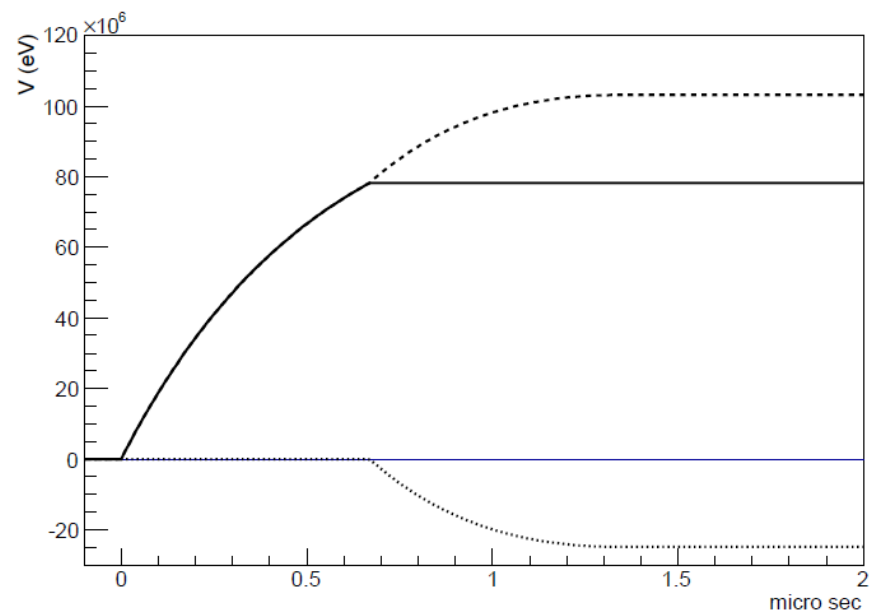
$$E(t)=E_0 U(t)+E_{1U}(t-t_f)+\frac{E_2}{t_f}(t-t_f)U(t-t_f)$$

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

$$V(t) = E_0 L + \frac{L}{1-e^{-2\tau}}\left(E_1 - \frac{Q}{\omega}E_2\right)\left(1-e^{-\frac{\omega}{Q}(t-t_f)}\right) + \frac{Le^{-2\tau}}{1-e^{-2\tau}}E_2(t-t_f) - \frac{r_0 L I_0}{2(1-e^{-2\tau})}\left[-\frac{\omega}{Q}e^{-2\tau}(t-t_f)+1-e^{-\frac{\omega}{Q}(t-t_f)}\right],$$

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

$$E_2 = -\frac{r_0 I_0}{2}\frac{\omega}{Q}e^{-2\tau},$$

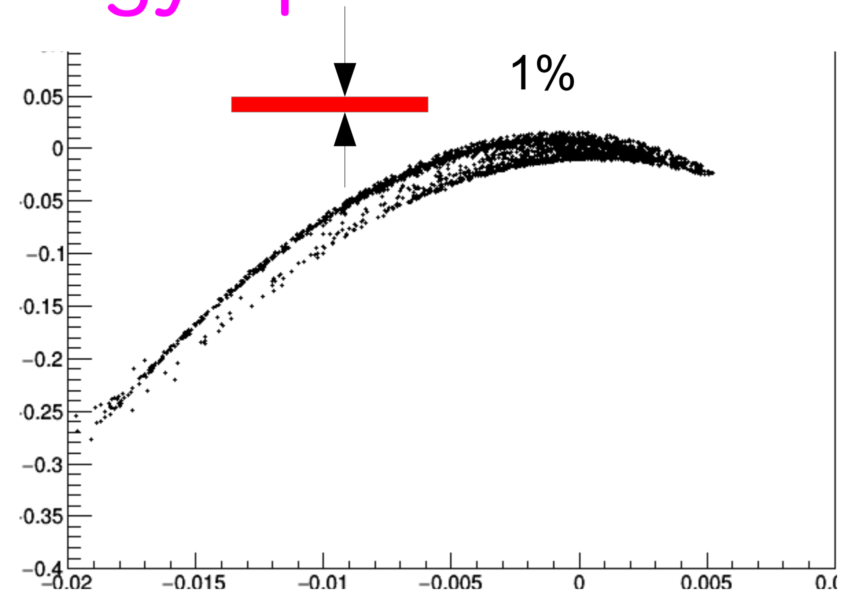


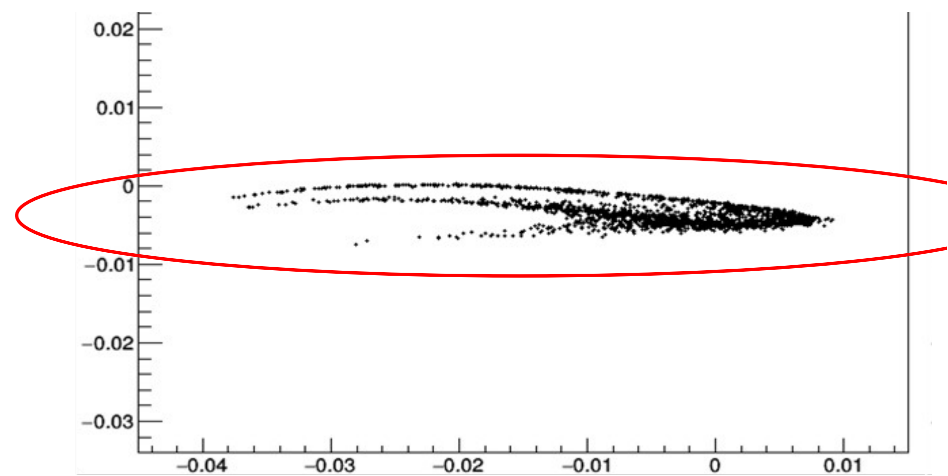
Actual Compensation (Trade off)

- 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.

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.





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