A Positron Capture Simulation for the E-driven ILC Positron Source

LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

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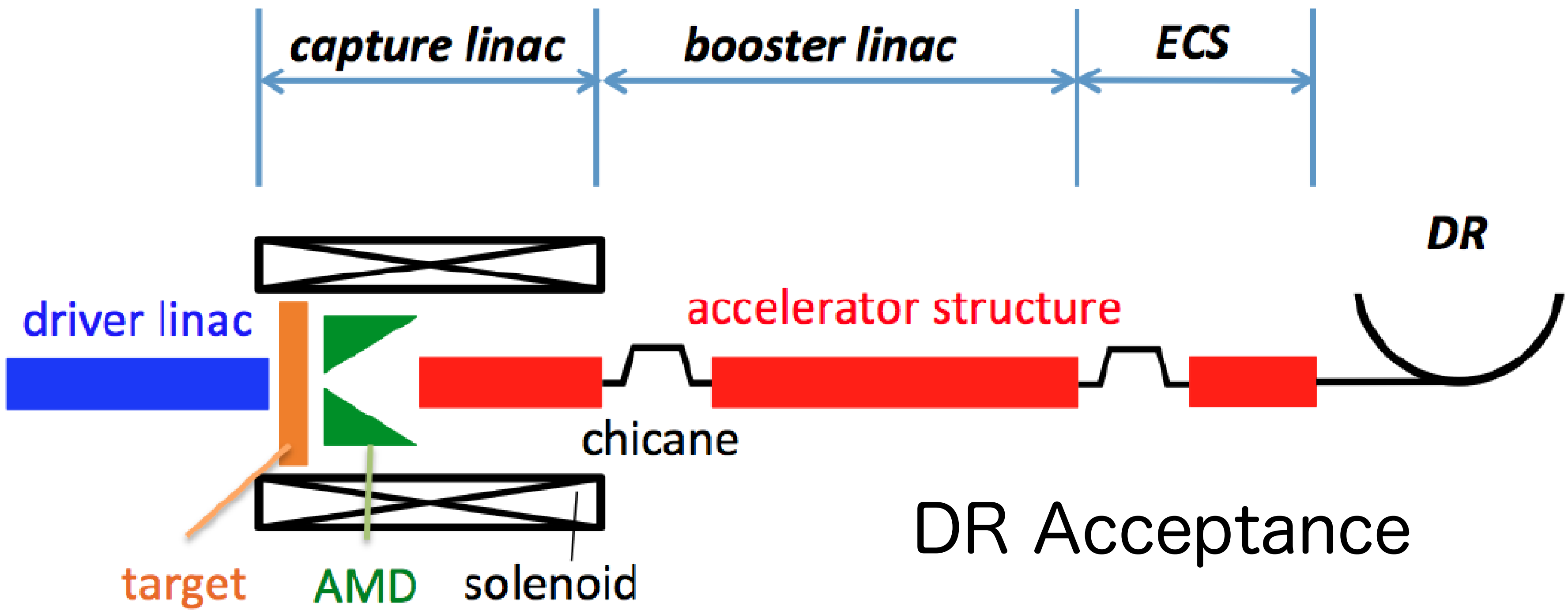
Introduction

- Electron driven ILC Positron Source is considered to be a technical backup of the undulator ILC Positron source.
- It is designed based on NC accelerators operated in 300Hz.
- The first simulation by T. Omori, T. Tahakashi, et al.
  - Positron generation was simulated with GEANT4.
  - The positron yield was evaluated only with the capture linac up to 250 MeV.
  - Constant gradient 20MV/m is assumed and the beam-loading effect is not considered at all.

- The second simulation was done by Y. Seimiya, M. Kuriki,et al.
  - It was a start to end simulation including chicane, booster, ECS, etc.
  - The lattice for each sections was designed.
  - The gradient is constant and the beam loading is not considered at all.
  - In the capture Linac (up to 250 MeV), SW L-band (2a=40mm, E_0=25MV/m) has been assumed.
- In the current study, the capture efficiency is re-evaluated assuming a realistic and conservative RF configuration including the beam loading effect.

The Positron Yield



DR Acceptance

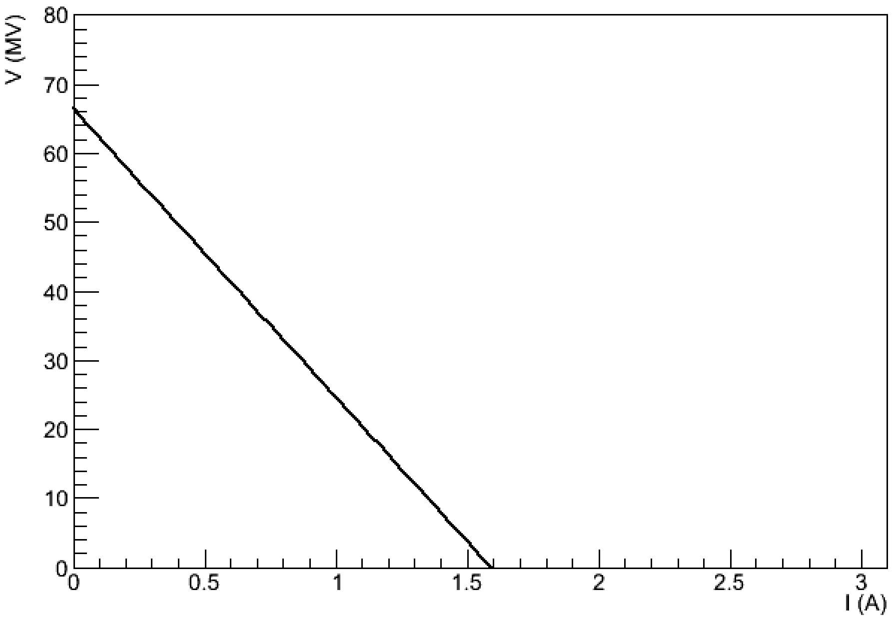
- The positron yield is defined by DR dynamic aperture.
- The beam intensity is normalized giving 3.0e+10 (150% of design) positron in the aperture.

$$\left(\frac{z}{0.035}\right)^2+\left(\frac{\delta}{0.0075}\right)^2<1$$

$$\gamma A_x+\gamma A_y<0.07$$

Electron Driver

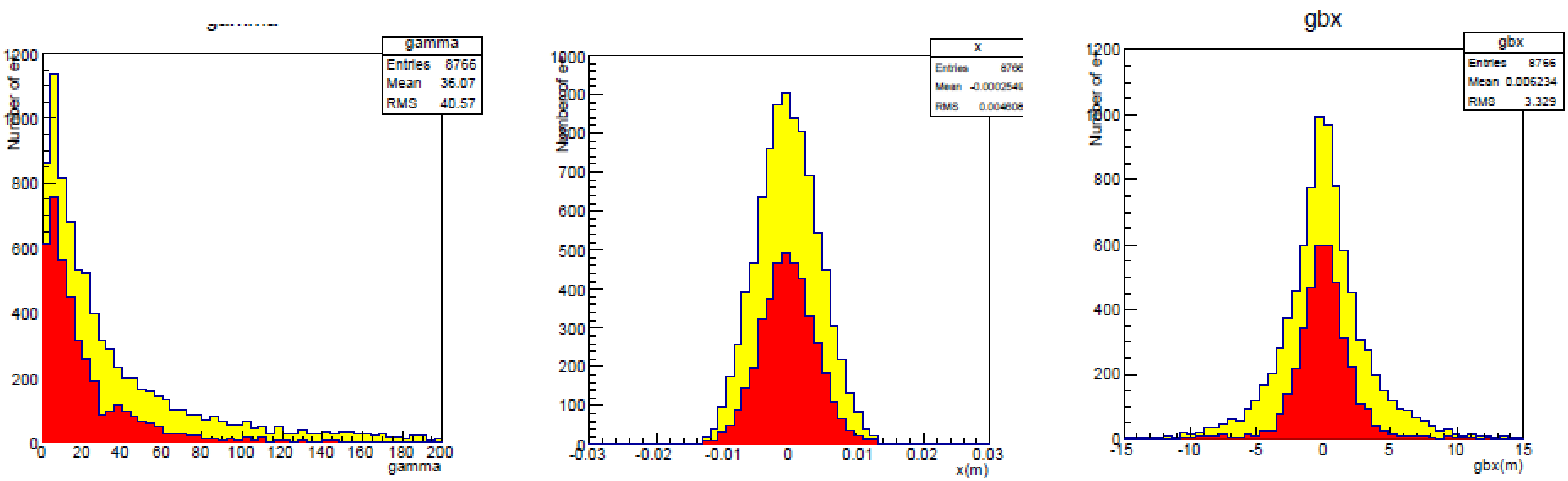
- 4.8 GeV Electron beam in the format with 3.8 nC bunch charge.
- S-band Photo-cathode RF gun for the beam generation.
- 120 of 3m S-band TW structures for the acceleration.
- 80 MW klystron-modulator drives 2 structures giving 40.1 MV/3m with 0.6A beam loading.



Lattice configuration	Number of cells	cell length	section length	Section energy
4Q + 2S	6	8.0 m	48.0 m	481 MeV
4Q + 4S	27	14.4 m	388.8 m	4330 MeV

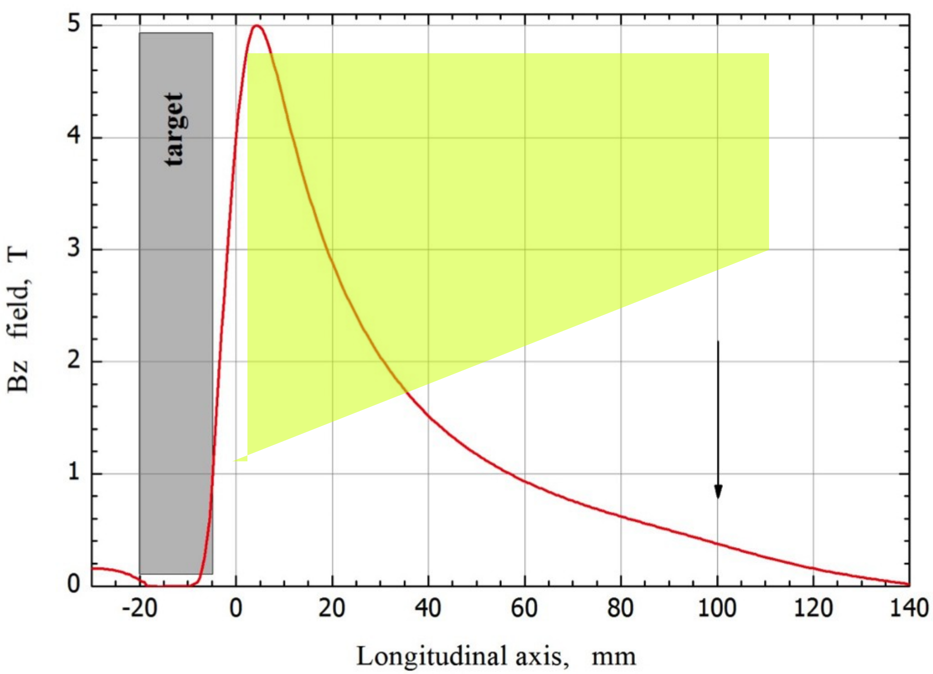
Positron Generation

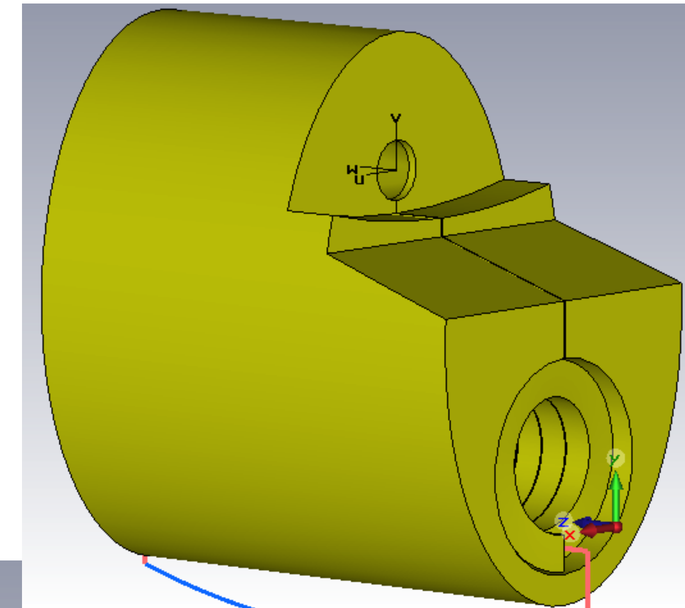
- Positron generation was simulated by GEANT 4 with 1000 incident electrons (macro particle) on the target.
- Electron Driver : 4.8GeV with s=3.5mm
- Target : t=16mm

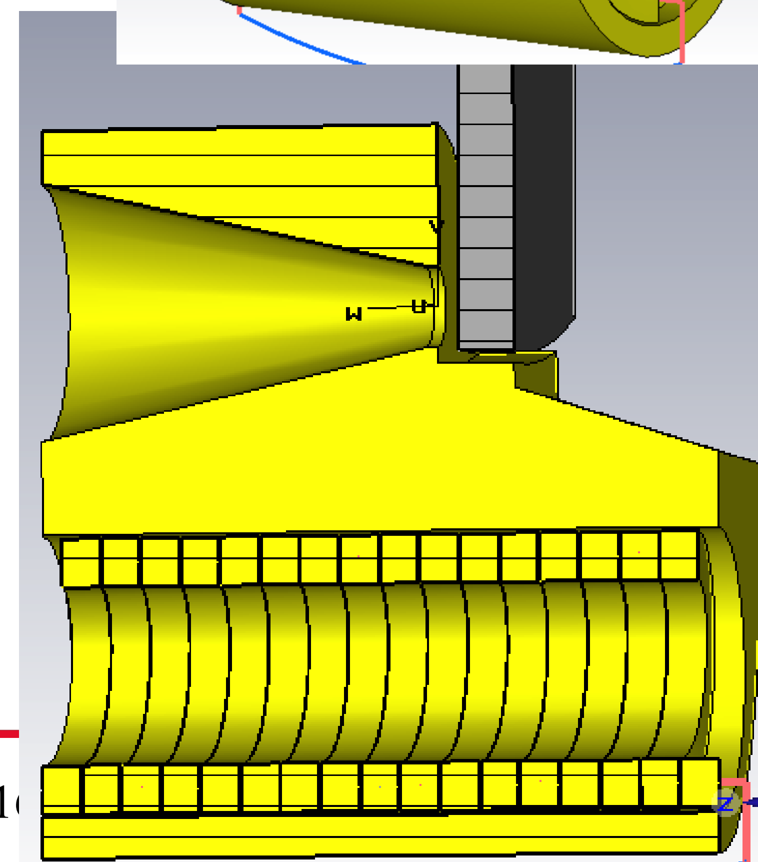


Flux Concentrator
(P. Martyshkin)

- Flux Concentrator for AMD (Adiabatic Matching Device)
- 16 mm aperture, 5mm clearance.
- 5 Tesla Peak field, 40mT trans.
- 25 kW ohmic loss.
- B_t is not accounted in the simulation.





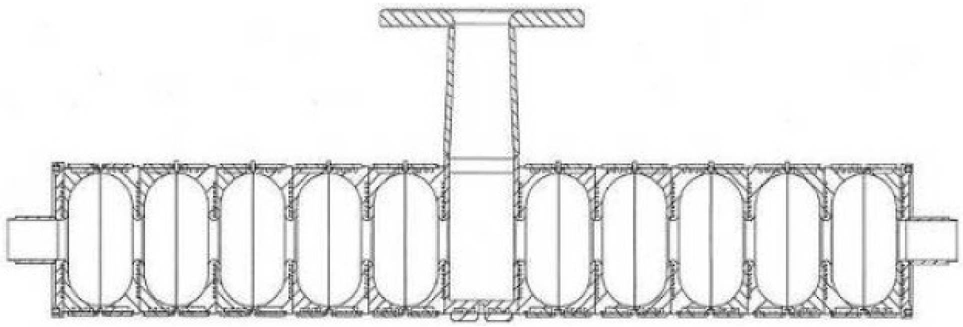


- The capture linac (-250 MeV) was simulated with GPT tracking code.
- AMD (5T peak) followed by solenoid (0.5 T) for focusing.
- SW L-band (2a=60mm) capture the positron in an RF bucket.

Parameter	Value	Unit
Drive Beam Energy	4.8	GeV
Target material	W-Re	
Target thicknesss	16	mm
Beam Size (rms)	3.5	mm
AMD peak field	5.0	T
R_{AMD} (smallest aperture of AMD, 2a)	16.0	mm
Average gradient (MV/m)	6.4 – 27.8	MV/m
Accelerator Aperture (2a)	60	mm
Solenoid	0.5	T
Booster	Hybrid (L-band + S-band)	

L-band SW structure

- The L-band SW structure designed by J. Wang (SLAC) for the undulator capture section is used.
- 2 of 1.27 m 11 cells L-band TW driven by 50 MW RF unit (10% loss by WG).
- It has a large aperture (2a=60mm) which is optimized for the positron capture.



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 Compensation

- The beam-loading decreases the accelerator gradient which is proportional to the beam current.
- It is quite serious in the capture section because both electron and positron contribute to the loading.
- Static beam-loading : the field is decreased. We need more input power to recover it, otherwise, we have to be patient with the low-field.
- Transient beam-loading : the field is gradually decreased by the effect during the pulse. It causes the energy spread.

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 becomes constant if

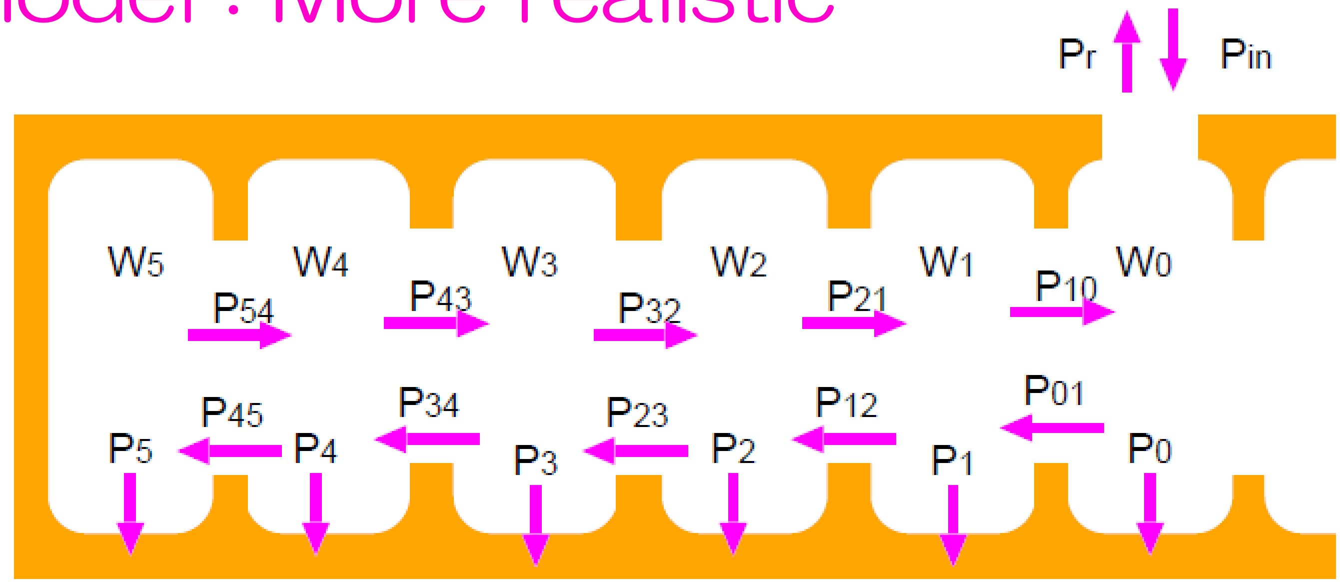
$$t_b = -T_0 \ln\left(\frac{I}{2}\sqrt{\frac{rL}{\beta P_0}}\right)$$

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

Single Cell Model : Simple, but not realistic

- The beam loading is completely corrected by adjusting the beam timing in the single cell model.
- It is not true for our real world, where the field is a linear sum of modes with different time constants.
- Because the real tube is a multi-cell, the gradient and the beam loading compensation should be examined with this model.

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

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

For the intermediate cells,

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

For the end cells,

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

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

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

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

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

*Because **B** is diagonal, the equation for V' is simply expressed as 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′

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

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

Amplitude for each modes and cells; two modes are dominant

cell	$\tau = 0.038$	τ	.004	$\tau = 0.489$
0	0.299		10	1.278
1	0.253		19	1.462
2	0.126		09	1.613
3	-0.041		10	1.730
4	-0.195		19	1.809
5	-0.287		09	1.849

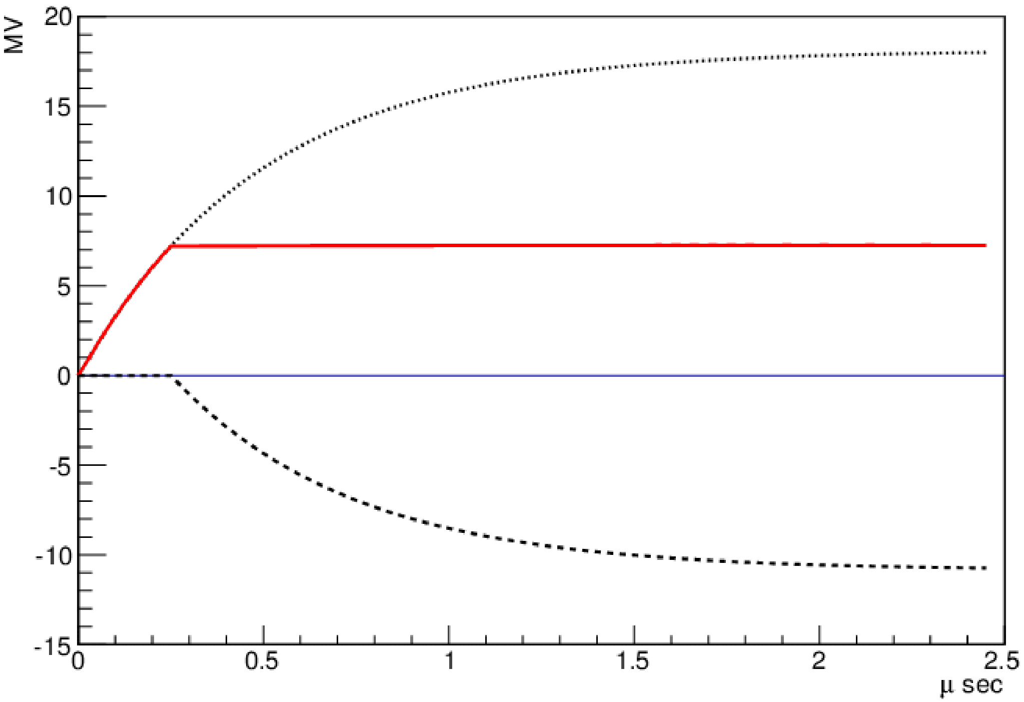
(beta=9)

Model Comparison

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

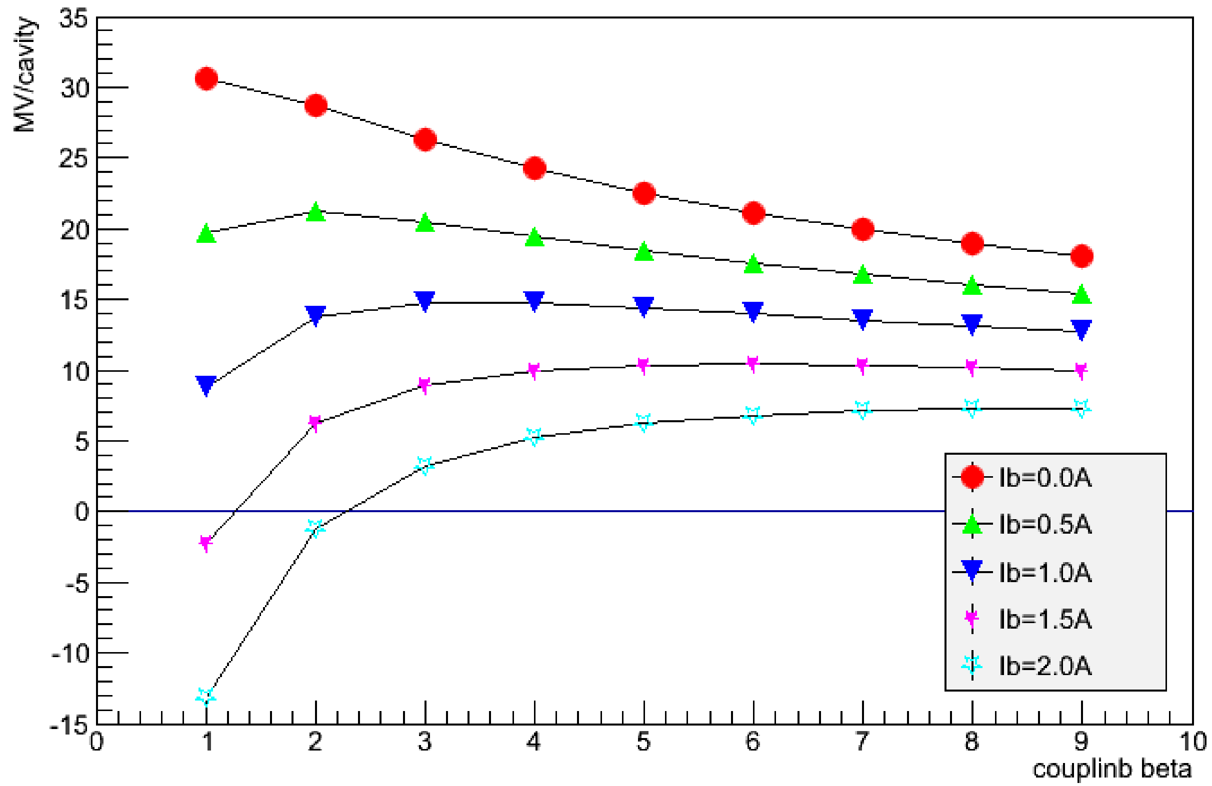
The beam loading compensation works well, because only a few modes contribute.



Accelerating Voltage

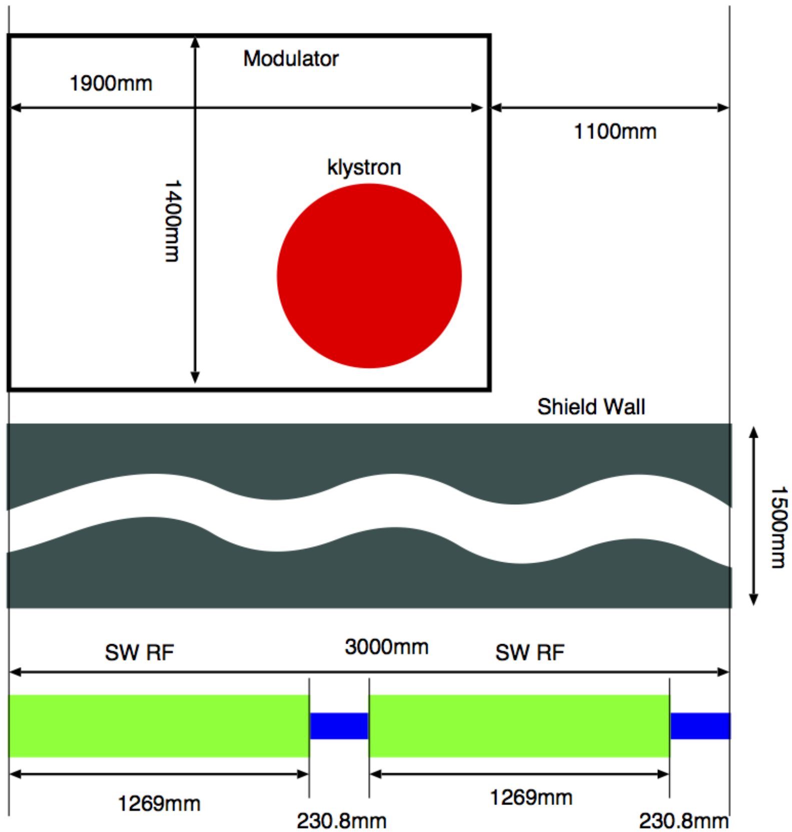
- **The voltage is obtained by assuming**
  - L=1.27 m (11 cells, L-band SW)
  - R=34e+6 Ohm/m
  - P_0=22.5 MW (50MW at klystron, 5MW wave guide loss)

30.6MV for 0A (b=1)
21.2MV for 0.5A(b=2)
14.7MV for 1.0A(b=3)
10.4MV for 1.5A(b=6)
7.3MV for 2.0A(b=9)



Capture Linac Configuration

- Two L-band SW accelerators are driven by one RF unit.
- 14 units (28 tubes) for 250 MeV acceleration.
- High density power unit array along the capture linac.



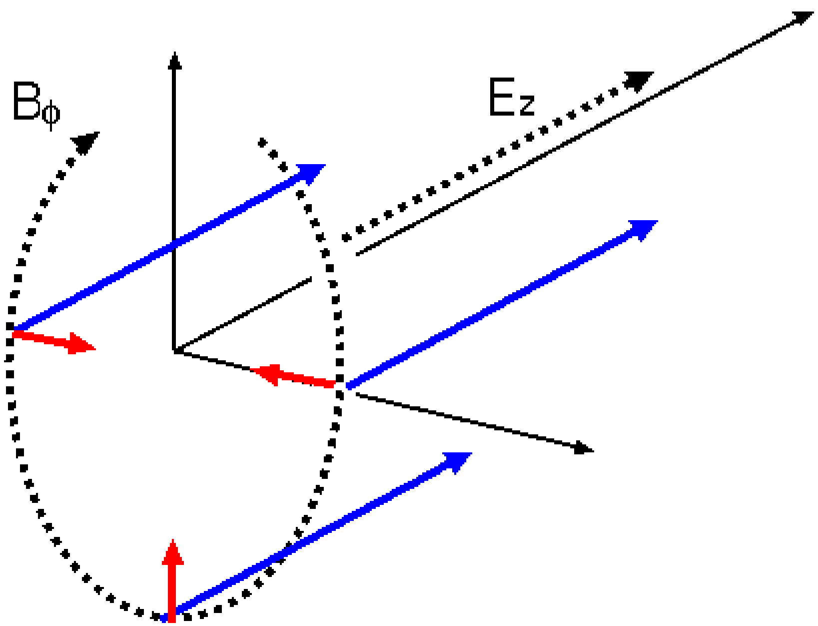
RF field function and the phase

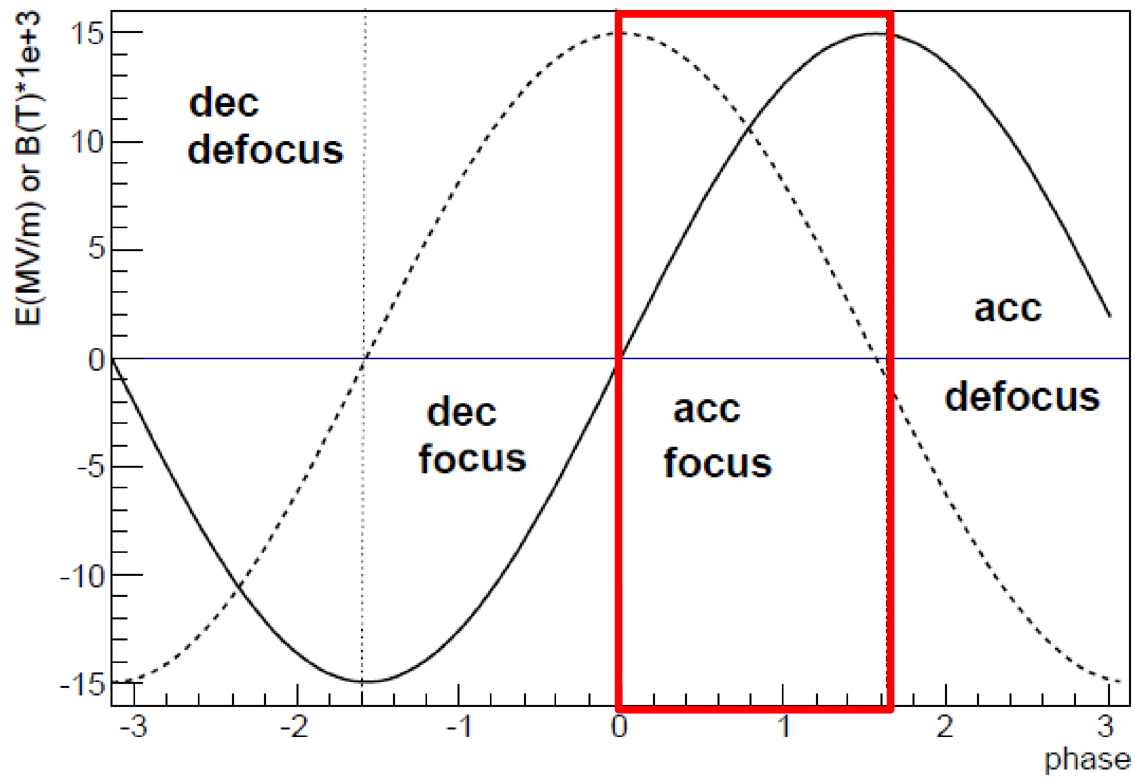
Acceleration and deceleration

$$E_z(t) = E_0 J_0\left(\chi_{01}\frac{r}{b}\right)\sin(\omega t + \phi_0)$$

Focusing and defocusing

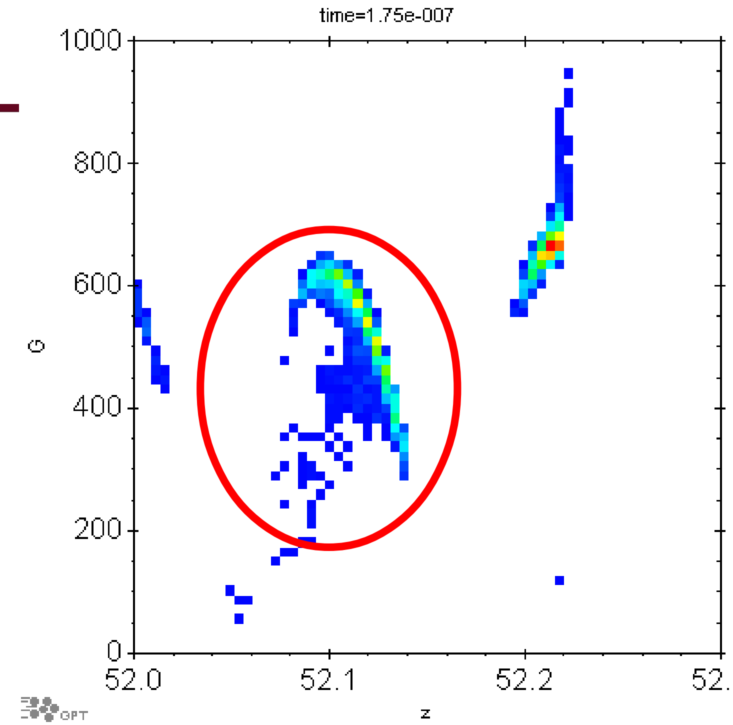
$$B_\theta(t) = \frac{E_0}{c} J_1\left(\chi_{01}\frac{r}{b}\right)\cos(\omega t + \phi_0)$$

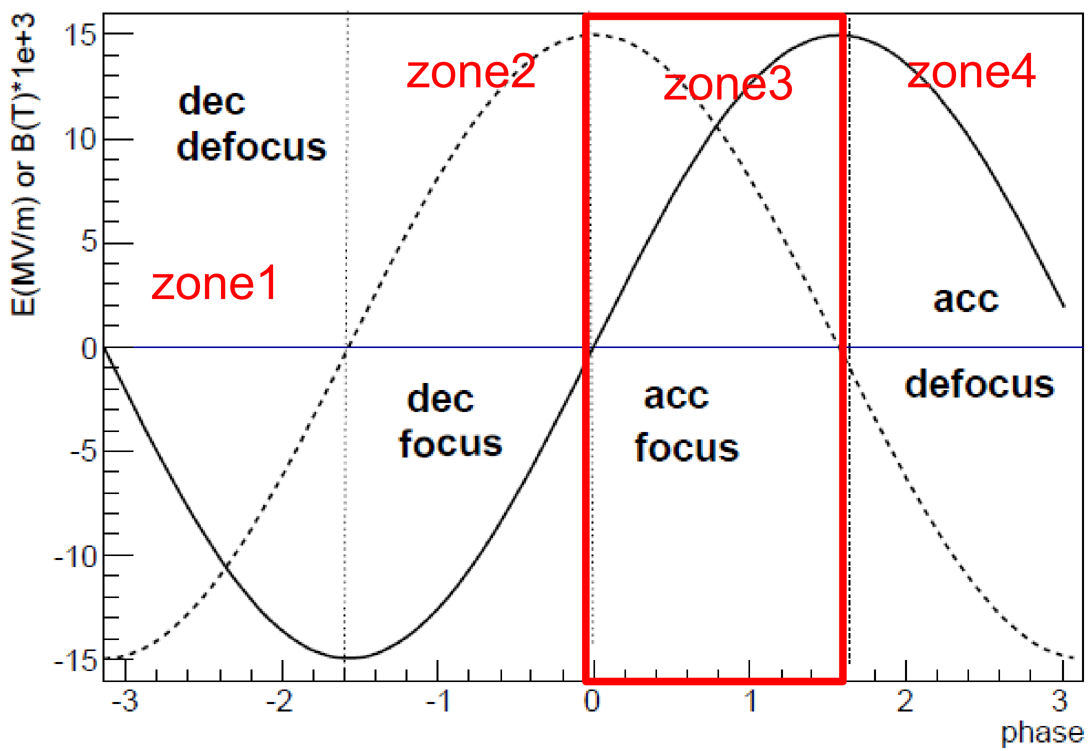


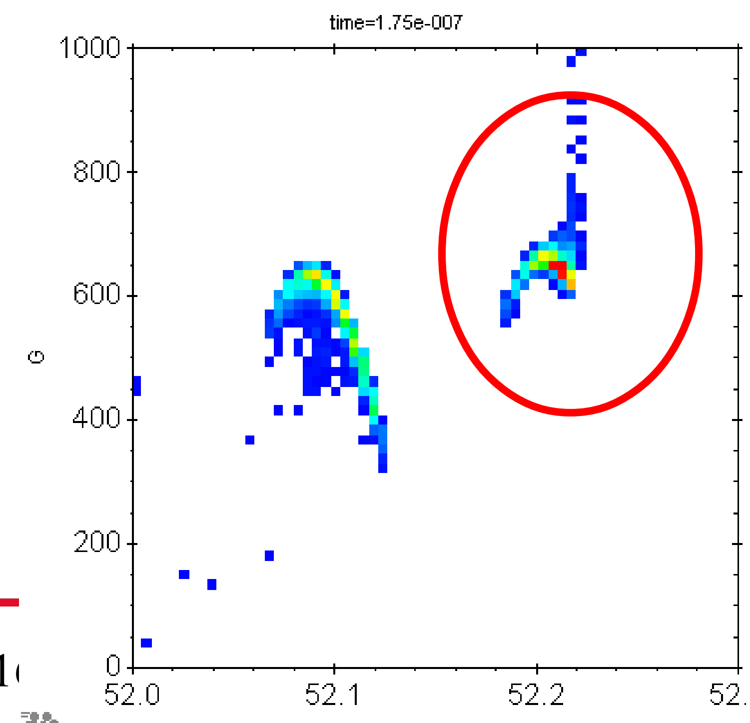


Capture Strategy

- **Deceleration Capture**
  - Start at zone 2 (dec. + focus).
  - Capture at zone 3. (acc. + focus).
- **Acceleration Capture**
  - Start and capture at zone 3. (acc. + focus)





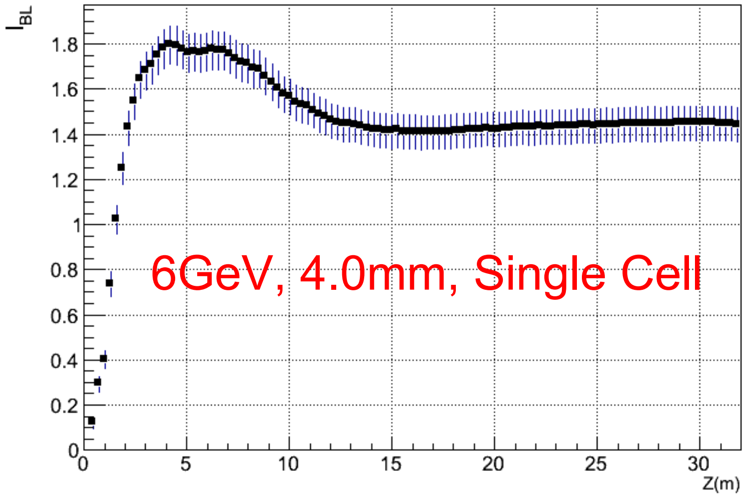


Beam Loading Current

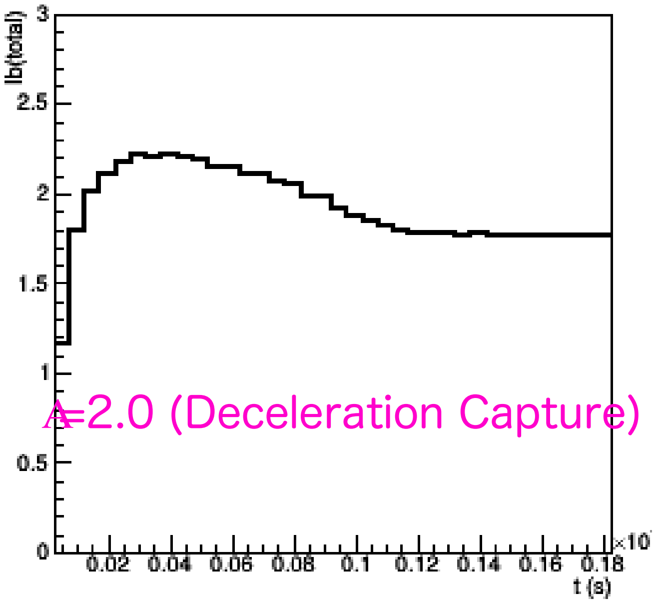
- Beam loading current

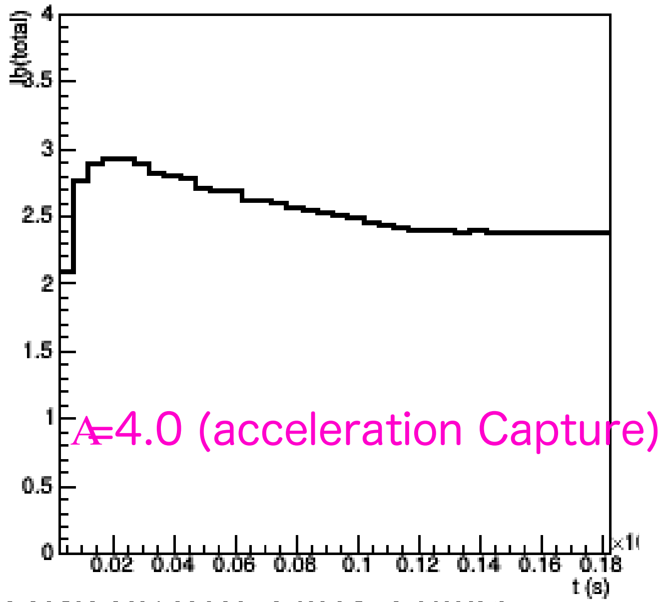
$$I_{BL}=\frac{1}{t_b}\sum q_i \cos\left(\omega t_i - k z_i\right)$$

- In the simulation, the beam loading current is given according to the preceding simulation.
- In the current simulation, it is up to 1.8 A.
- The real current observed in the simulation is more.
- We have to fix it.



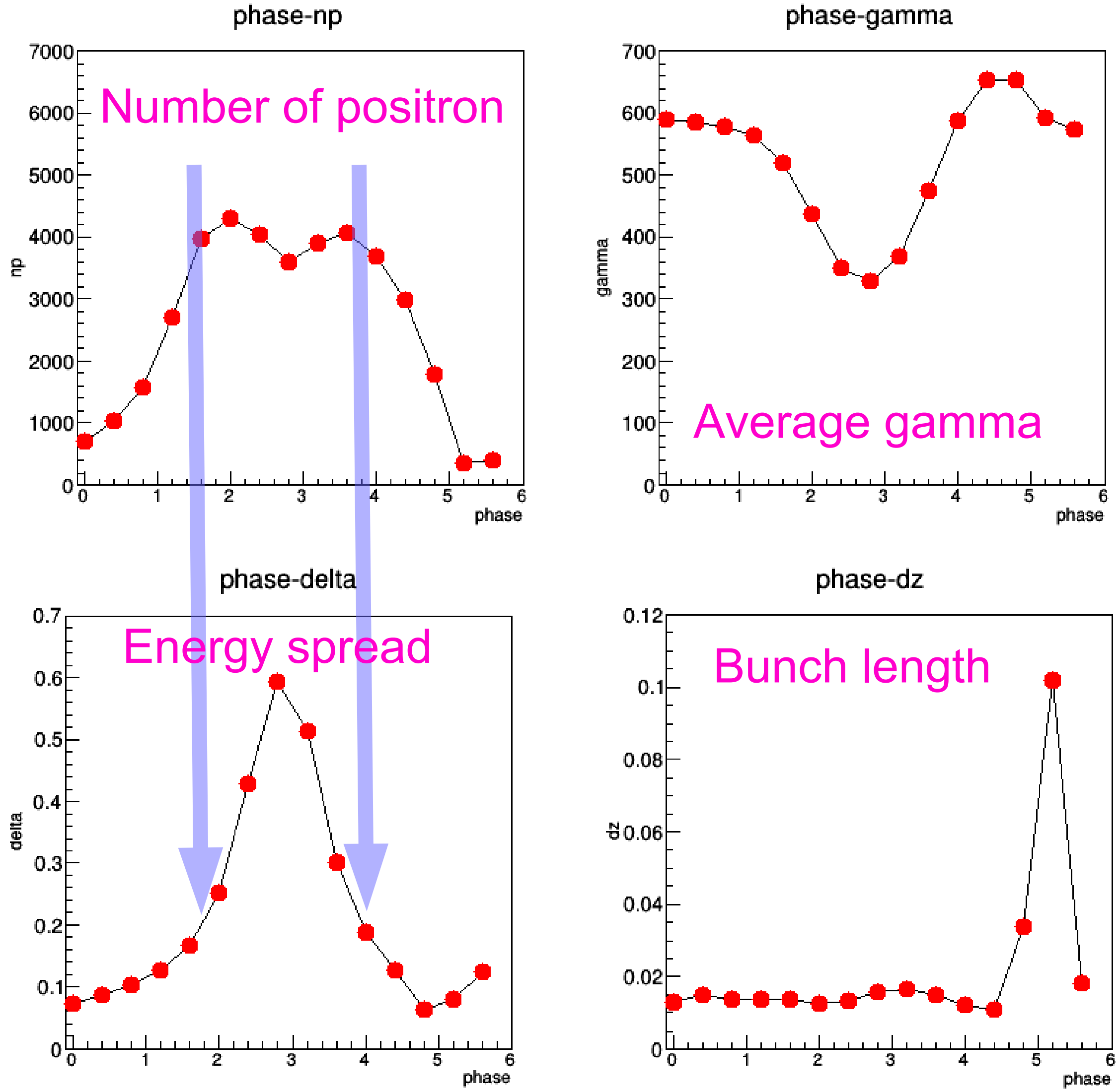
4.8GeV, 3.5mm, Multi-Cell





Captured Positrons (up to 250 MeV)

- Number of captured positron is large over a wide range of phase.
- The energy spread is reasonable only in a couple of narrow rages.
- These two ranges correspond to the acc- and dec-capture.

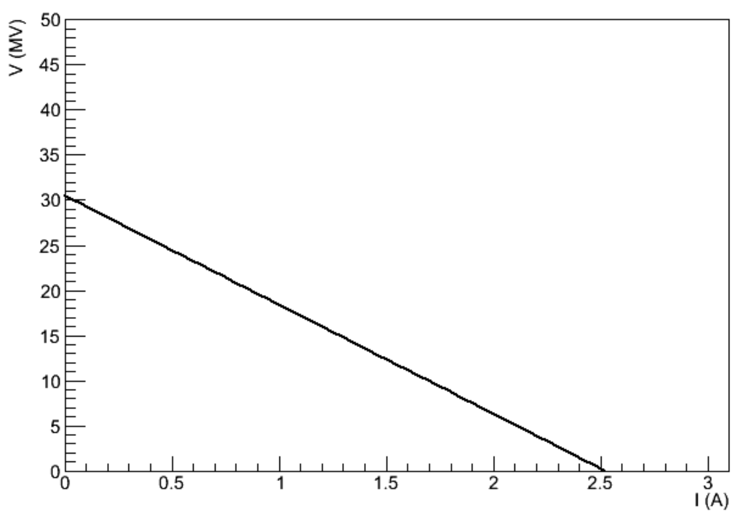


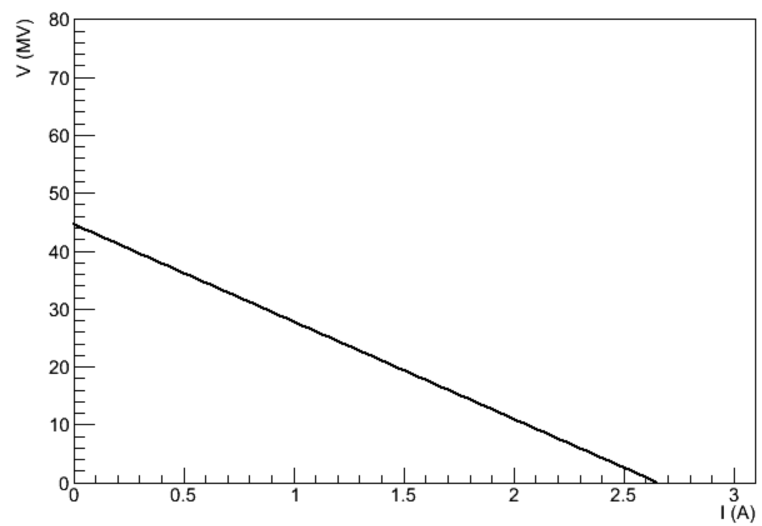
Booster Simulation

- Booster + ECS is simulated with SAD code.
- Output of GPT is transferred to SAD input.
- The beam loading current is assumed to be a constant (0.78A).
- The booster consists from L-band + S-band unit.
- ECS is composed from four chicanes + L-band RF.
- The yield and transmission is evaluated.

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.
- 80MW S-band Klystron drives two S-band acc.

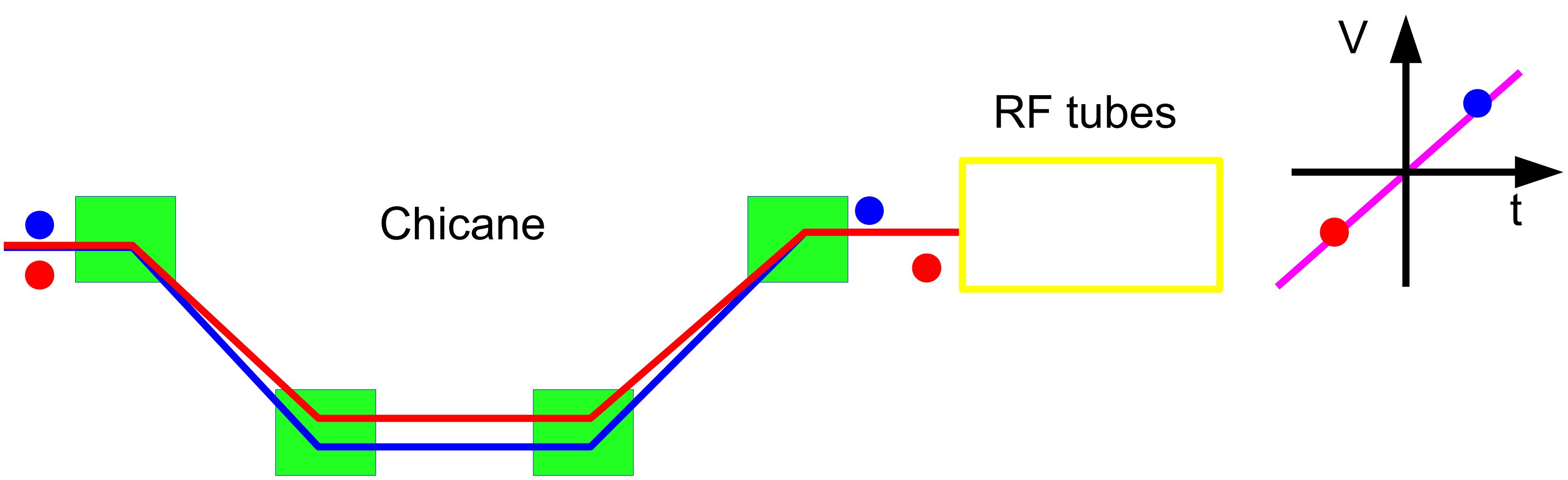




Lattice configuration	Number of lattice cells	Accelerating energy	energy at the exit	cell length	number of cells and section length (2 by 1)
4Q + 1L	12	252 MeV	502 MeV	3.8 m	12 : 45.6 m
4Q + 2L	22	924 MeV	1426 MeV	6.0 m	22 : 132.0 m
4Q + 4L	15	1260 MeV	2686 MeV	10.4 m	15 : 156.0 m
4Q + 4S	19	2394 MeV	5080 MeV	10.4 m	19 : 197.6 m

Energy Compressor

- DR longitudinal acceptance (±35mm in z, ±0.75% in δ ±/±) is too wide in z and too narrow in ʃ±/±.
- Energy compressor makes a good matching to the acceptance.
- Energy Compressor consists from a dispersive section with a momentum compaction and RF tubes.



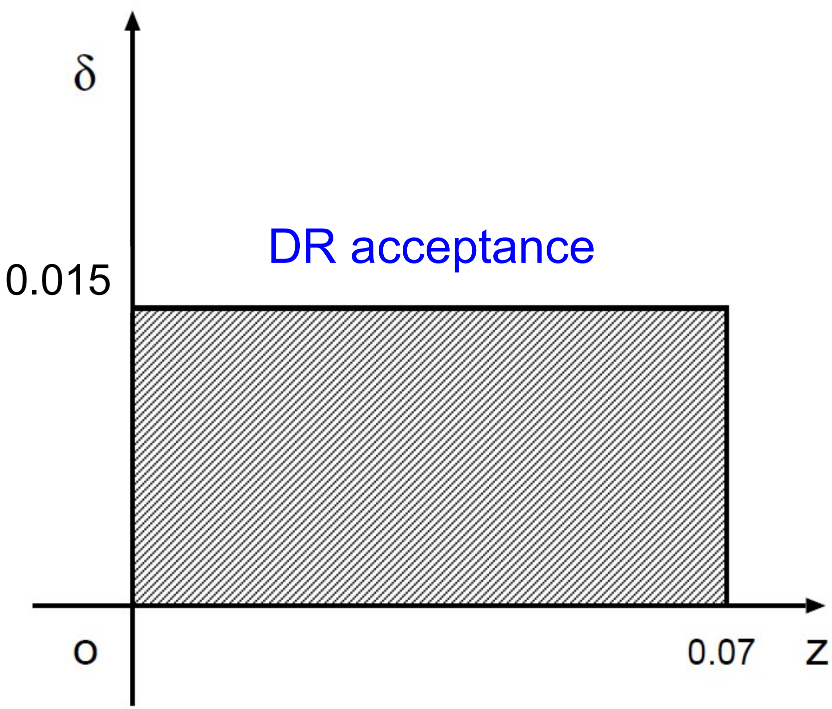
- **Matrix representation: momentum compation** $M_d = \begin{pmatrix} 1 & R_{56} \\ 0 & 1 \end{pmatrix},$
  RF cavity $M_{RF} = \begin{pmatrix} 1 & 0 \\ R_{65} & 1 \end{pmatrix}.$
- **Transfer matrix of EC section**

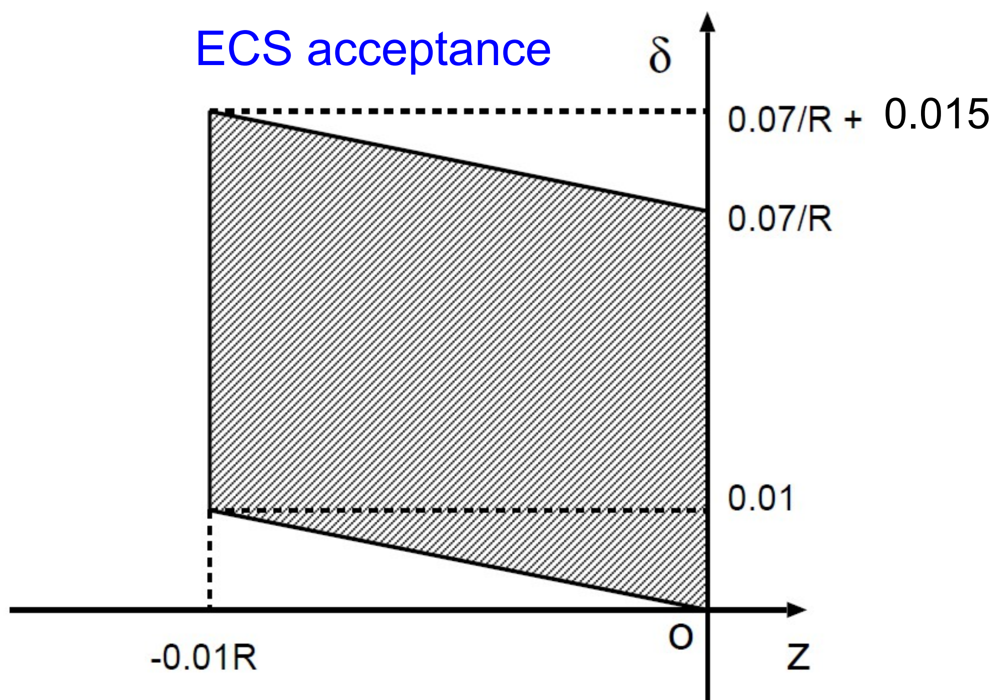
$$M_{EC} = \begin{pmatrix} 1 & R_{56} \\ R_{65} & R_{56}R_{65} + 1 \end{pmatrix},$$

- **With a matching condition,**

$$R_{56}R_{65} + 1 = 0$$

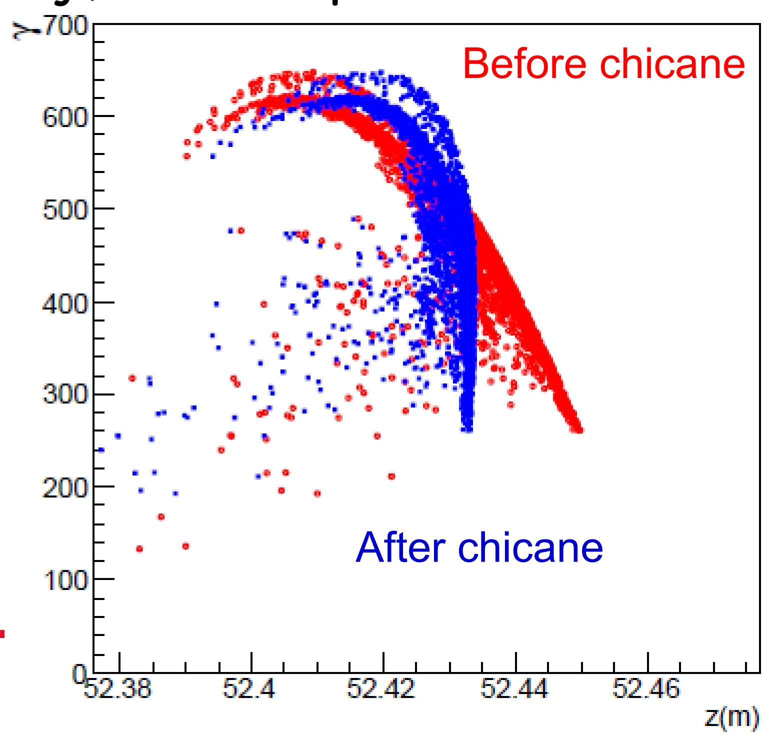
$$M_{EC} = \begin{pmatrix} 1 & R \\ -1/R & 0 \end{pmatrix},$$

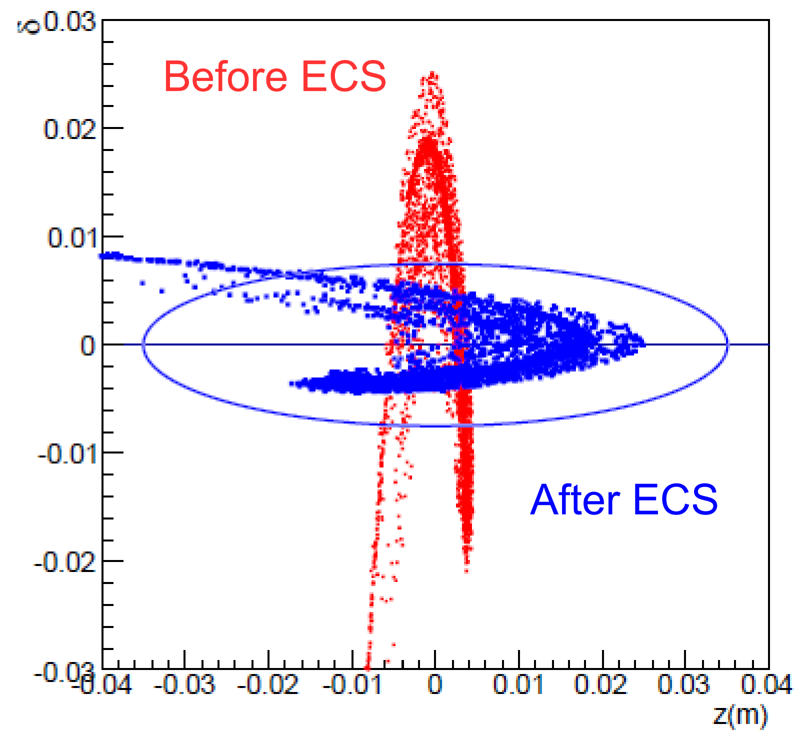




Particle Gymnastic

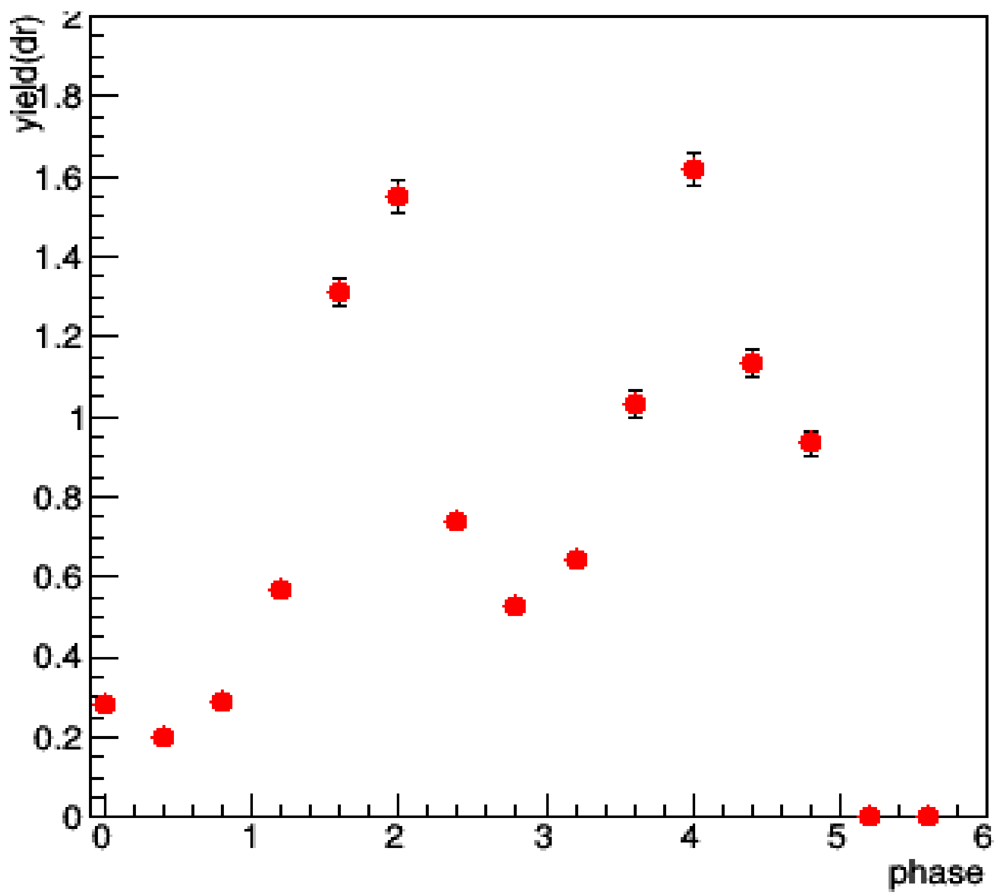
- Positron is captured, but with a large energy spread due to the low gradient.
- The energy spread can be compensated by the energy boos, but the energy spread by RF curvature is dominant. The chicane should be optimized to minimize the bunch length.
- Finally, ECS improves much the yield.





Positron Yield

- The yield is obtained as a function of the initial phase.
- The yield is up to 1.6.
- The beam loading current is 3.0A at this phase.
- If the beam loading current is suppressed down to the assumption in the capture simulation, the simulation becomes "consistent".
- Scraping "bad positrons" in the capture section?



4.8GeV Driver, Multi Cell model

Summary

- The positron yield for the conventional ILC positron source is evaluated by assuming a realistic RF unit and a realistic RF model.
- Comparing the previous study based on the single cell model, the yield is better with a higher loading current.
- The beam loading current in the capture section should be suppressed.
  - Improving the yield and decrease the drive beam current, or
  - Scraping "bad positron" in the early stage.