Technical considerations of ILC e-driven positron source

Toshiyuki OKUGI, KEK

2015/11/05

Source WS

LCWS2015, Whistler (CANADA)

Technical considerations of ILC e-driven positron source

1. *Rotating Target & Flux concentrator*
2. *RF structure in capture section*
   - *Beam current is 2A (Beam loading compensation)*
   - *Beam loss power in structure is more than 50kW.*
3. *Timing system*
4. *Laser for e-gun of drive beam*
5. *Injection kicker*
6. *Klystron bandwidth for beam loading compensation with triplet bunches*
   (The beam loading evaluation is only without gaps)
7. *Transient beam loading in DR*
8. *Transmission efficiency evaluation with realistic alignment errors*
9. *Evaluation of achievable positron yield*

Evaluation of positron yield

Present design of positron yield evaluation

Positron yield for single bunch beam

	SLC (experiment)	SuperKEKB (design)	ILC e-driven PS (design)
Electron beam energy	33 GeV	3.3 GeV	6 GeV
Beam size at target	0.6 mm	0.7 mm	4.0 mm
Aperture for 1st cavity	18 mm	30 mm	60 mm
Gradient for 1st cavity	40 MV/m	14 MV/m	8 MV/m
Positron yield	1.1 e+/e- at DR (1.4 e+/e- at LTR)	0.89 (0.30 at now) e+/e- at Capture Out	1.5 e+/e- at DR
Energy acceptance	+/-2.5%	I could not find the number at DR	+/-0.75 %
Transverse acceptance	0.01 m		0.07 m

The present design of the ILC e-driven positron source is
- *the beam energy is much smaller than SLC.*
- *beam spot size at target is much larger than SLC .*
- *accelerating gradient is much smaller than SLC (optimum is > 15MV/m)*

But, the positron yield for ILC e-driven positron source is designed to be higher than SLC (and superKEKB).

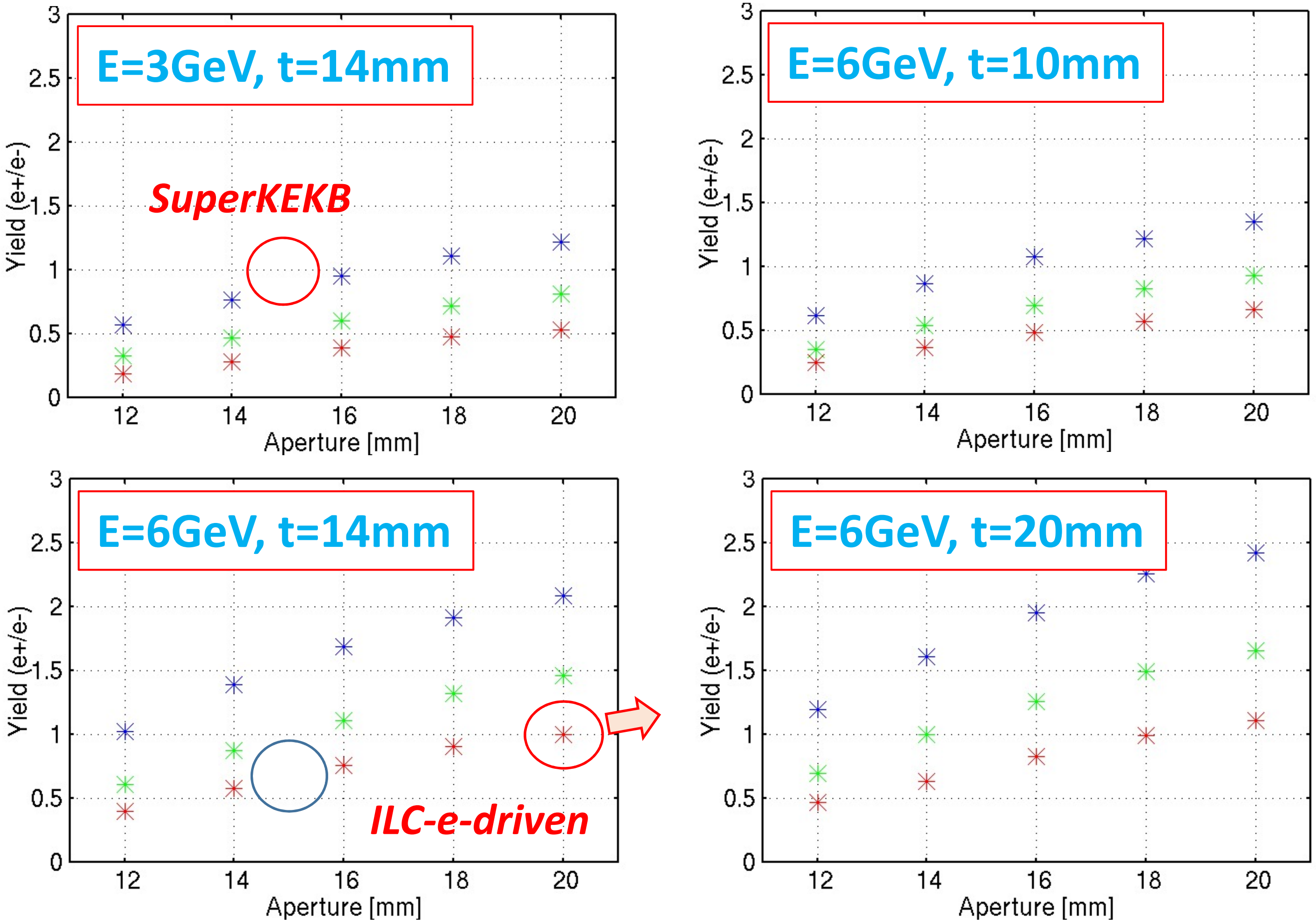
Comparison with SperKEKB

Electron Spot Size Dependence
after Energy Compressor
with Longitudinal & Transverse Cut

(1) Electron Beam Size = 4mm ;
used for the GEANT4 data set

(2) Electron Beam Size = 3mm ;
X=3*X/4, Y=3*Y/4 for (1)

(3) Electron Beam Size = 2mm ;
X=2*X/4, Y=2*Y/2 for (1)



Capture Section
E=250MeV
V = 16.6MV/m
B= 0.5T

Flux Concentrator
r=12mm

When we assumed the same aperture,
superKEKB has larger positron yield than ILC e-driven source

T.Okugi, ILC positron phone meeting (2013/01/30)

Key issue is large aperture

	SLC (experiment)	SuperKEKB (design)	ILC e-driven PS (design)
Electron beam energy	33 GeV	3.3 GeV	6 GeV
Beam size at target	0.6 mm	0.7 mm	4.0 mm
Aperture of flux concentrator	7mm	7mm	16mm
Aperture for 1st cavity	18 mm	30 mm	60 mm
Gradient for 1st cavity	40 MV/m	14 MV/m	8 MV/m
Positron yield	1.1 e+/e- at DR (1.4 e+/e- at LTR)	0.89 (0.30 at now) e+/e- at Capture Out	1.5 e+/e- at DR
Energy acceptance	+/-2.5%		+/-0.75 %
Transverse acceptance	0.01 m		0.07 m

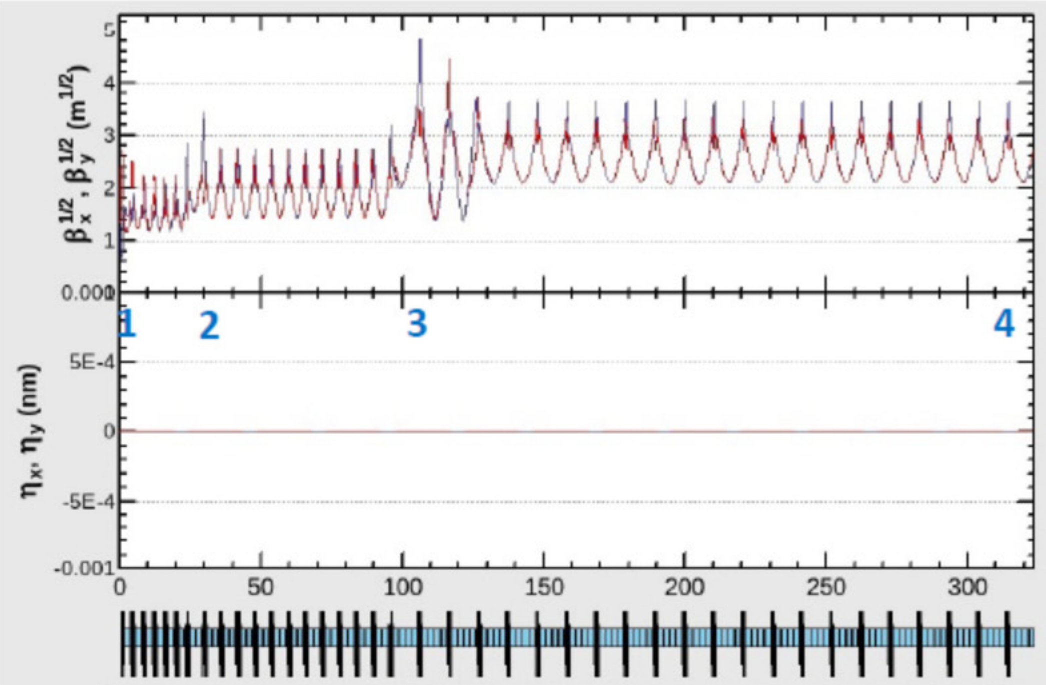
Key point to get such a large number of positron is the wide aperture of the beamline to be transport the large transverse emittance beam to large acceptance DR.

But, we have difficulties to widen the apertures.

- *Power supply for flux concentrator (roughly 1 order higher power to superKEKB)*
- *RF structure with large aperture etc.*

No margin for transverse acceptance

T.Okugi LCWS13



From 250MeV to 5GeV

If we assumed to

Wx+Wy= 0.07/γ and βx = βy = 2.0 m,

sqrt (βx Wx + βx Wx) = 0.0189 m at 200MeV

sqrt (βx Wx + βx Wx) = 0.0169 m at 250MeV

sqrt (βx Wx + βx Wx) = 0.0154 m at 300MeV

Same acceptance to DR (twice for undulator PS)

RF System

L = 2m each

a = 0.017 m (minimum)

V = 35-45MV / structure

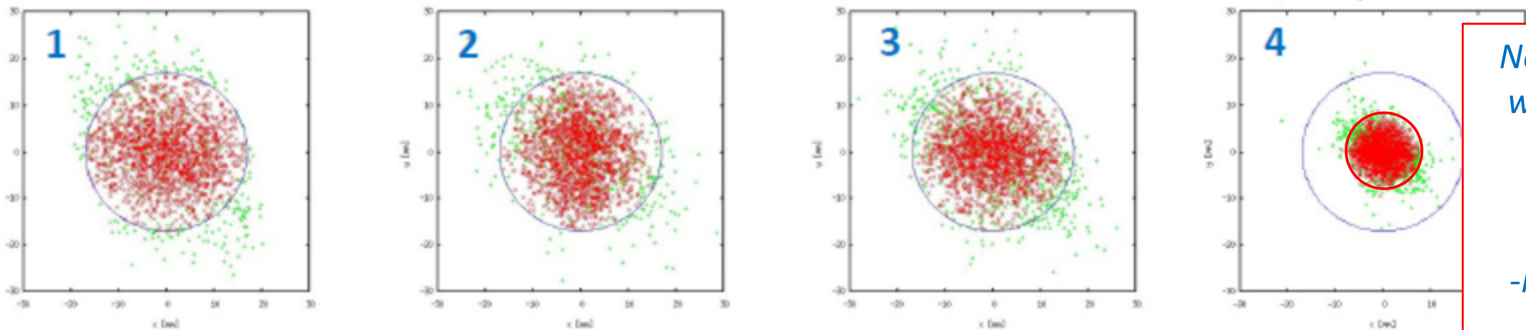
with Beam Loading Compensation

(Beam Current) = 3.5e10/bunch

When we transport the beam to 2m long L-band structure without Solenoid field, the beam energy should be E>250MeV.

Red ; trasmitted particle

Green ; lose particle



Now the aperture was smaller than LCWS2013 to use S-band

-Make tolerance small

- Make transverse wake large !

Beam loss was generated by optics mismatch, misalignment, transverse wake etc.

Timing System

Electron driven bunch pattern to fit the filling pattern in DR

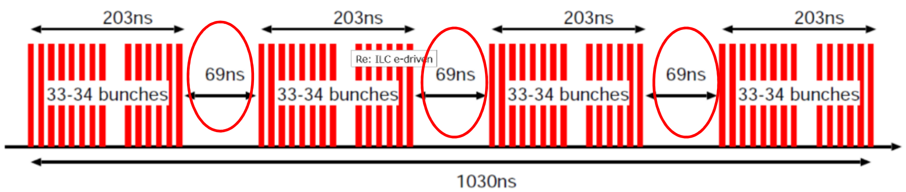
B. List

type	h	k_b	N_{bunch}	n_b	g	n_t	N_t	Q_b [$10^{10}e$]	t_b [ns]	I_{ML} [mA]	t_{pulse} [μs]
SB2009 nominal values								$c = 3248$ m			
DRFS	7042	463	1312	–	–	–	–	2.00	712	4.5	935
KCS	7042	347	1312	–	–	–	–	2.00	534	6.0	700
FP(e^-)	7042	231.5	2625	–	–	–	–	2.00	356	9.0	935
FP(e^+)	7042	231.5	1312	–	–	–	–	2.00	356	9.0	935
Solution 1								$c = 3238.68/3239.14$ m			
DRFS	7022	476	1312	4	33	23	59	2.00	732	4.4	961
KCS	7022	360	1312	4	45	34	39	2.00	554	5.8	727
FP(1Ring)	7022	238	2625	2	31	45	59	2.00	366	8.8	961
FP(2Ring)	7022	238	1312	4	75	23	59	2.00	366	8.8	961

In order to inject the electron beam to DR by same filling pattern, train spacing and number of bunch should be changed train-by-train.

- *33 or 34 bunches/train*
- *70.77 ns or 76.92 ns of train gap*

Should be change pulse-by-pulse



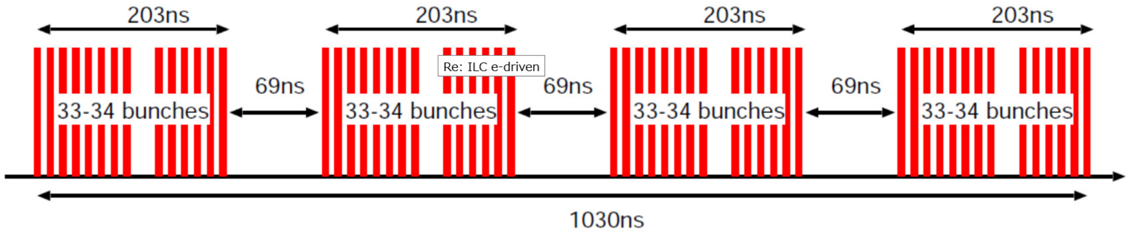
180 degree phase change within 70ns for gun seed laser

Filling Pattern in DR (TDR baseline)

Train in DR	Number of bunch	Train gap in DR (unit; bunch separation)
1	34	12.5
2	34	**11.5**
3	34	12.5
4	34	**11.5**
5	34	12.5
6	34	**11.5**
7	34	12.5
8	34	**11.5**
9	34	12.5
10	34	**11.5**
11	34	12.5
12	**33**	12.5
13	34	12.5
14	**33**	12.5
15	34	12.5
:	:	:
38	**33**	12.5
39	34	12.5

A half and integer

Timing chart in the CR backup report



39 train in DR

(Train Interval)= 74ns (12.00 bunch separation ; one of the proposal at 06/05)
-> 69ns (11.25 bunch separation ; design in report)
-> 90 degree of gun laser phase should be shifted within 69ns.

(Last train gap) = 77ns (one of the proposal at 06/05)
-> 252ns (design in report)

Timing of ML (proposed at 06/05)

N in ML	RF buckets	Interval (ns)
1	1	
2	361	554 ns
3	721	554 ns
:	:	:
20	6841	554 ns
21	181	557 ns
22	541	554 ns
:	:	:
39	6661	554 ns
40	5	563 ns
41	365	554 ns

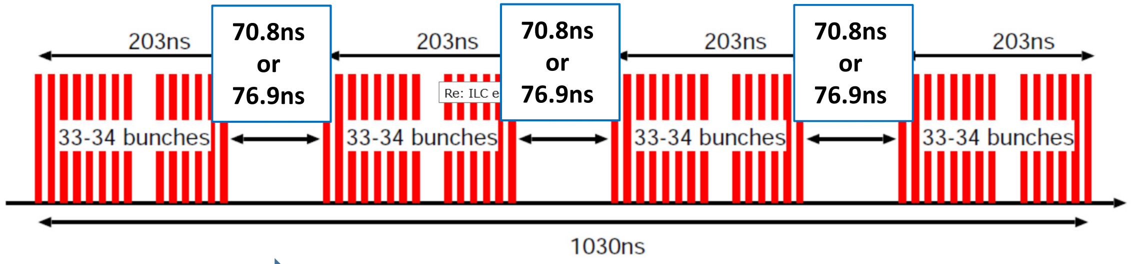
Timing of ML (design in report)

N in ML	RF buckets	Interval (ns)
1	1	
2	355	545 ns
3	709	545 ns
:	:	:
20	6727	545 ns
21	178	728 ns
22	532	545 ns
:	:	:
39	6550	545 ns
40	5	734 ns
41	359	545 ns

The large bunch separation gap is generated every 19 or 20 bunches in ML.

The timing system requires
- to modify to be complex timing system for e-gun of electron source and kickers.

One of laser specification for E-gun of drive beam to match the DR filling pattern



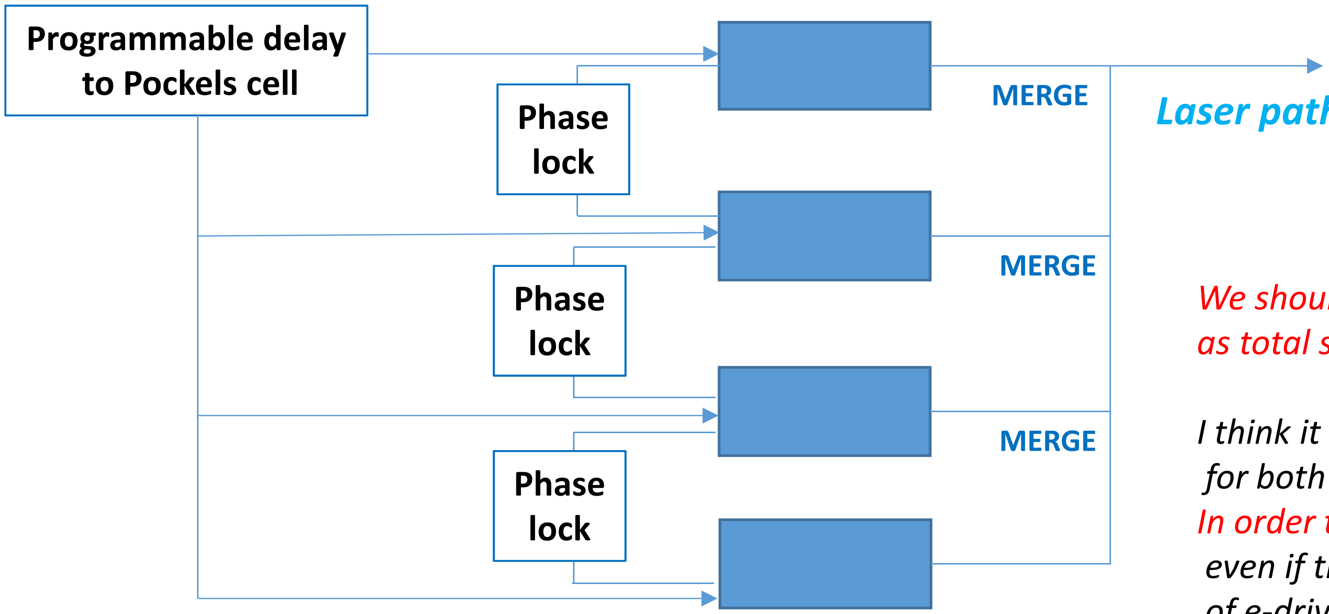
180degree phase change

180degree phase change

180degree phase change

It is difficult to make single laser system.

Example of multiple laser system to match the original DR filling pattern



Laser path should be merged

We should take care of DR filling pattern as total system.

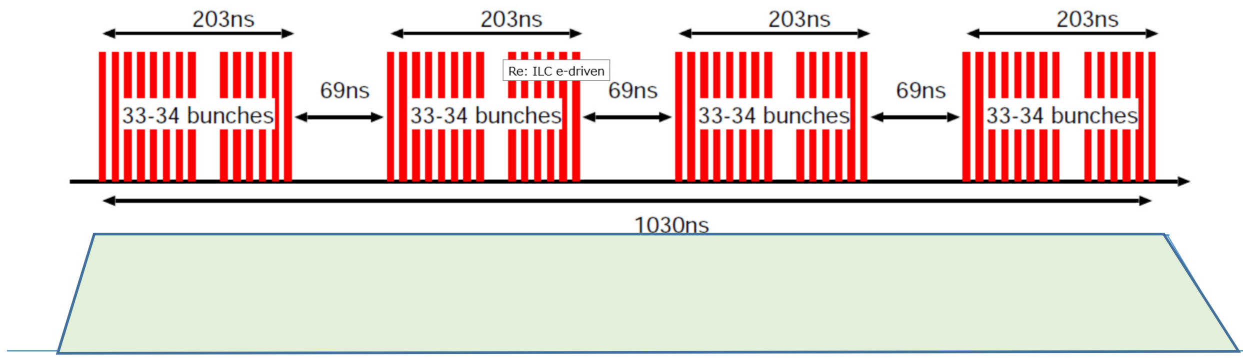
I think it is better to keep DR filling pattern for both positron sources (compatible)
In order to make total timing system easy,
even if the laser system for drive beam of e-driven positron source is difficult.

Present design is not also operated with single laser system, because train gap is not integer.

Requirement of injection kicker for e-diven source in the CR backup report

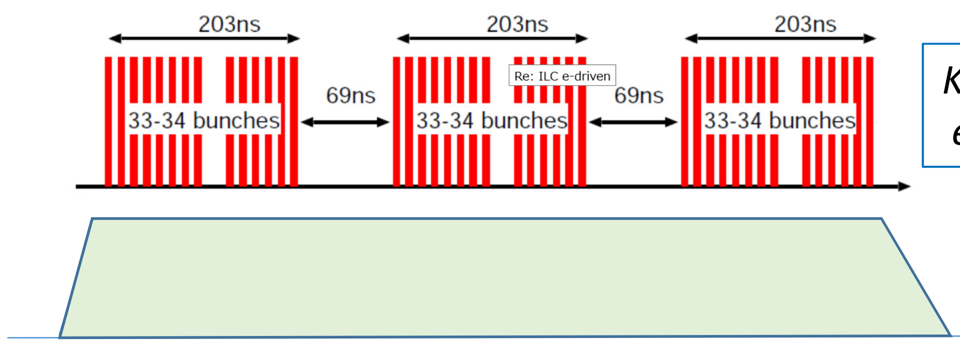
~~*20 pulses in report*~~

Beam will be injected to DR by 10 pulses (9 for 4 train, 1 for 3 train injection)



39 train in DR

1030ns flat-top for 9/60



Kick-out for 1st train even for present large gap solution.

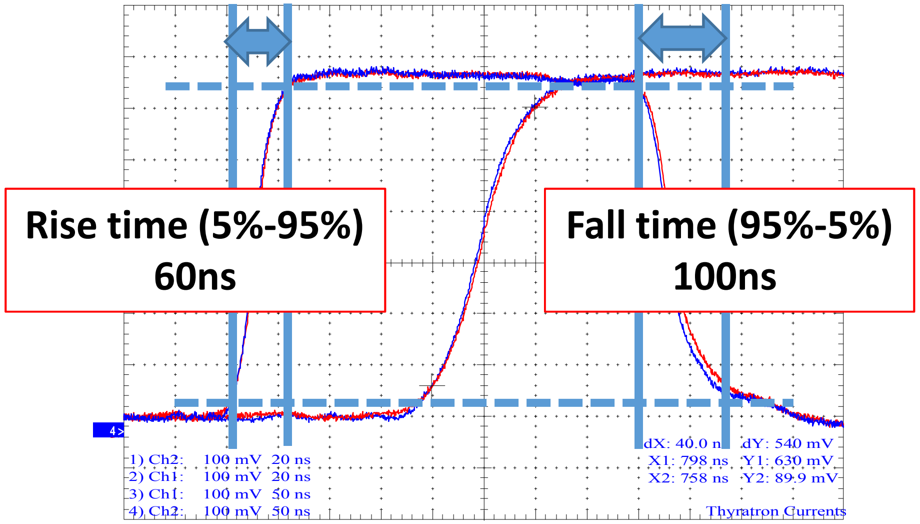
740ns flat-top for 1/60

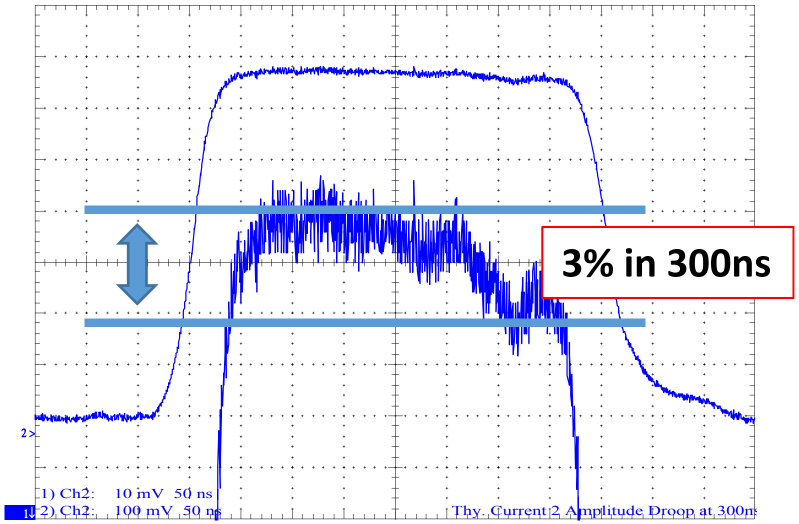
Stop triggers for 50/60

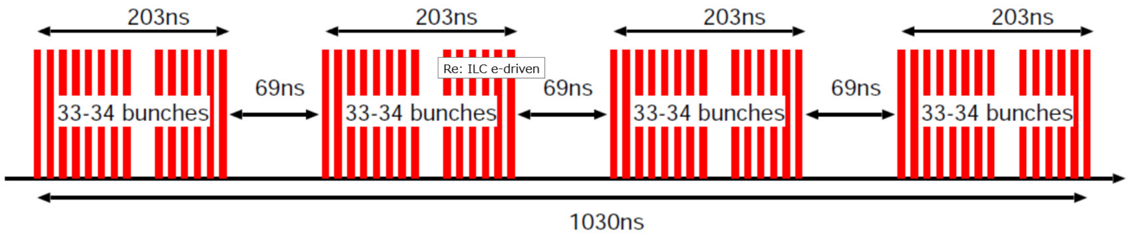
We need the kicker system with two different pulse widths, and very special configuration of kicker operation is required.

ATF fast epoxy kicker performance (made by SLAC)

measured by T.Naito







B. List

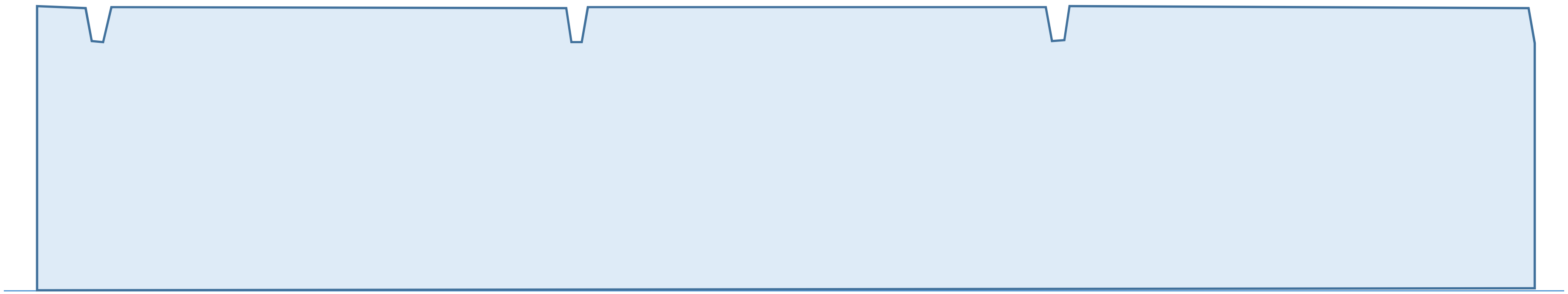
type	h	k_b	N_{bunch}	n_b	g	n_t	N_t	Q_b [$10^{10}e$]	t_b [ns]	I_{ML} [mA]	t_{pulse} [μs]
SB2009 nominal values								$c = 3248$ m			
DRFS	7042	463	1312	–	–	–	–	2.00	712	4.5	935
KCS	7042	347	1312	–	–	–	–	2.00	534	6.0	700
FP(e^-)	7042	231.5	2625	–	–	–	–	2.00	356	9.0	935
FP(e^+)	7042	231.5	1312	–	–	–	–	2.00	356	9.0	935
Solution 1								$c = 3238.68/3239.14$ m			
DRFS	7022	476	1312	4	33	23	59	2.00	732	4.4	961
KCS	7022	360	1312	4	45	34	39	2.00	554	5.8	727
FP(1Ring)	7022	238	2625	2	31	45	59	2.00	366	8.8	961
FP(2Ring)	7022	238	1312	4	75	23	59	2.00	366	8.8	961

- *Kicker rise/fall time and flat-top is tight.*
- *Difficult for DRFS option by small train gap.*
  (Very useful option to use high charge beam)

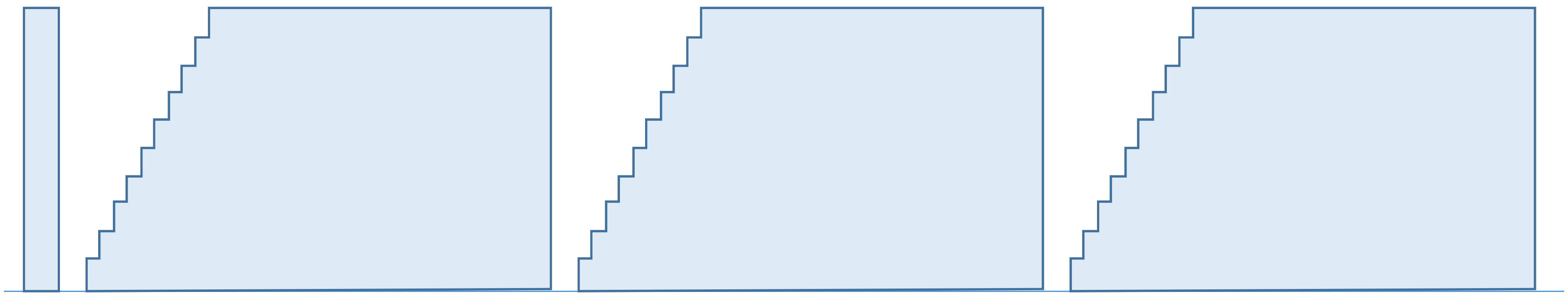
Injection kicker also must be developed.

Transient Beam Loading in DR

Beam Current in DR for undulator positron source



Beam Current in DR for e-driven positron source



Since the intensity variation is much larger than undulator positron source,
we must take care of transient beam loading in DR for e-driven positron source.

Summary of timing system

We should carefully design the timing system as total system.

I recommend to make a compatible timing system both for undulator and e-driven positron source (e-driven source should be fitted to the original DR filling pattern).

We must carefully design the injection kicker system.

Furthermore, we must take care of the transient beam loading in DR for e-driven positron source.

RF structures in capture section

The beam loading current in capture section (2A)
is 2 order larger than undulator PS and much larger than any machine in the world.

The radiation dose for capture structure
is much larger than undulator PS and any machine in the world.
- *Cell-to-cell frequency shift by temperature rise by beam loss*
- *Breakdown for high radiation condition*
- *Vacuum pumping*

Furthermore, we must use the RF structure with large aperture
to make large positron yield with large spot of drive-electron beam.

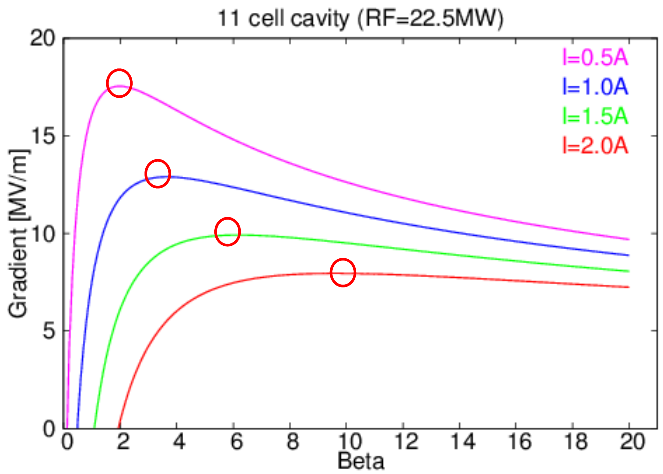
The largest technical difficulty is in capture section for present e-driven positron source.

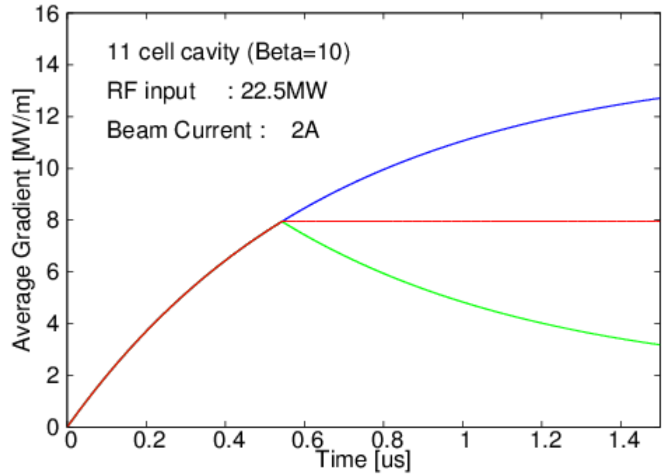
In present design, the multi-cell standing wave structure
is assumed in the capture section to make the aperture wide.

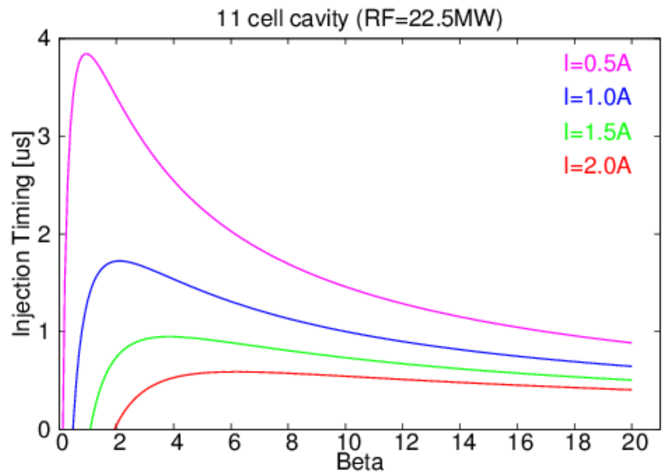
Present candidate RF structure of the capture section for e-driven positron source

Is the assumption OK ?

The transient beam loading for multi-cell standing wave structure was evaluated only by using formula of "single-cell standing wave structure"







We have no experience to operate such a large coupling normal conducting RF structure in the world.

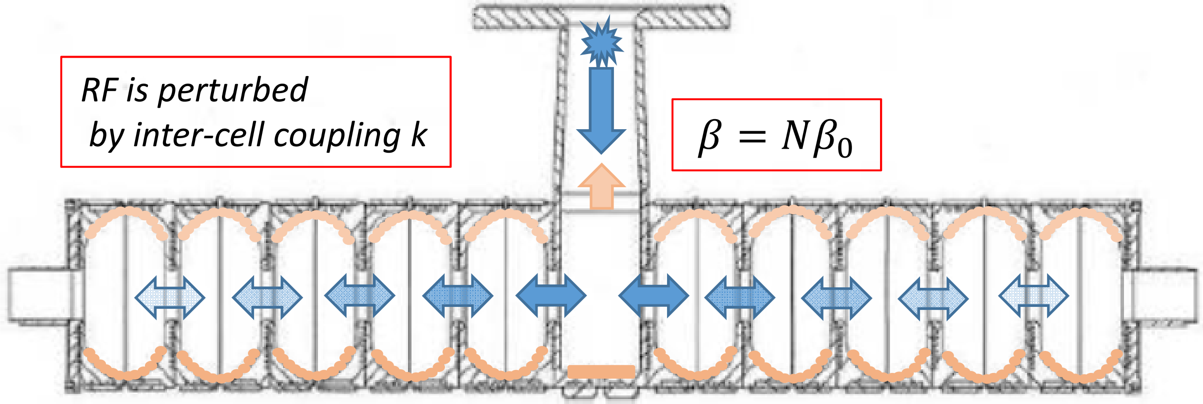
There are no circulator to accept the requirement.

In the report, the accelerating gradient was assumed to be optimized by changing the coupling constant (β) for each beam current.

But, it is difficult to change the coupling constant (iris of the coupling hole) so much for normal conducting structure.

Multi-cell standing wave structure

RF is perturbed
by inter-cell coupling k



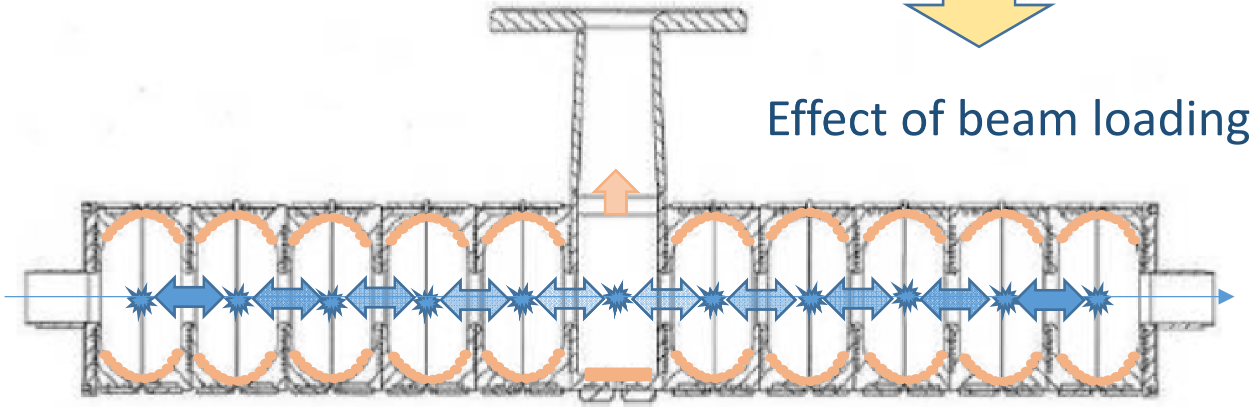
$\beta = N\beta_0$

Single Cell formula

Effect of RF power

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

Effect of beam loading



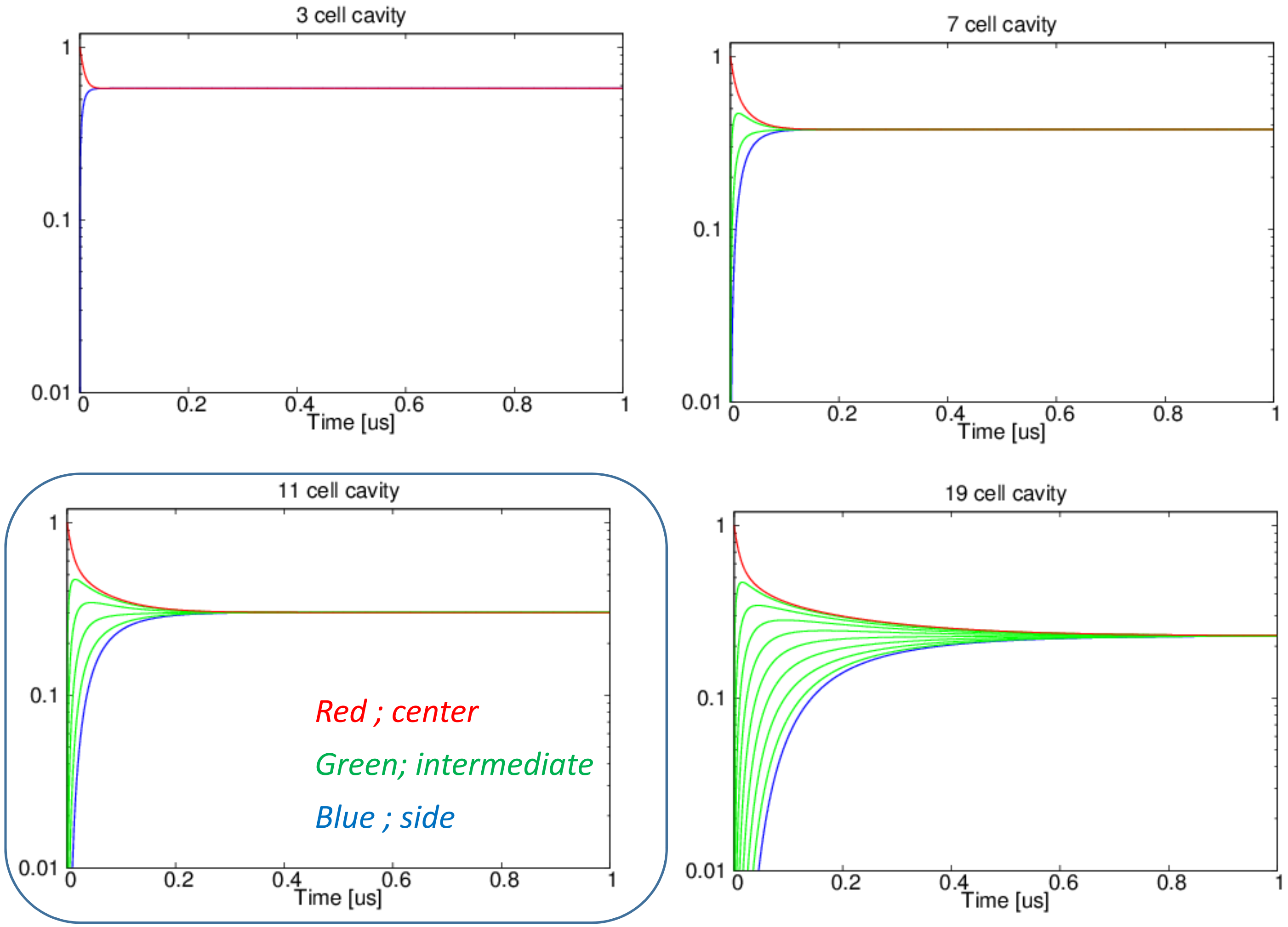
Cavity loss for center cell
(1+β) Qo

Cavity loss for other cell
Qo

RF perturbation in the multi-cell structure

inter-cell coupling constant ;   k = 0.0125

(capture structure for undulator source)



- *RF power was stored only center-cell for t < 0.*
- *RF power will perturb for t > 0.*
- *No wall loss*

The time to be steady state is proportional to N^2.

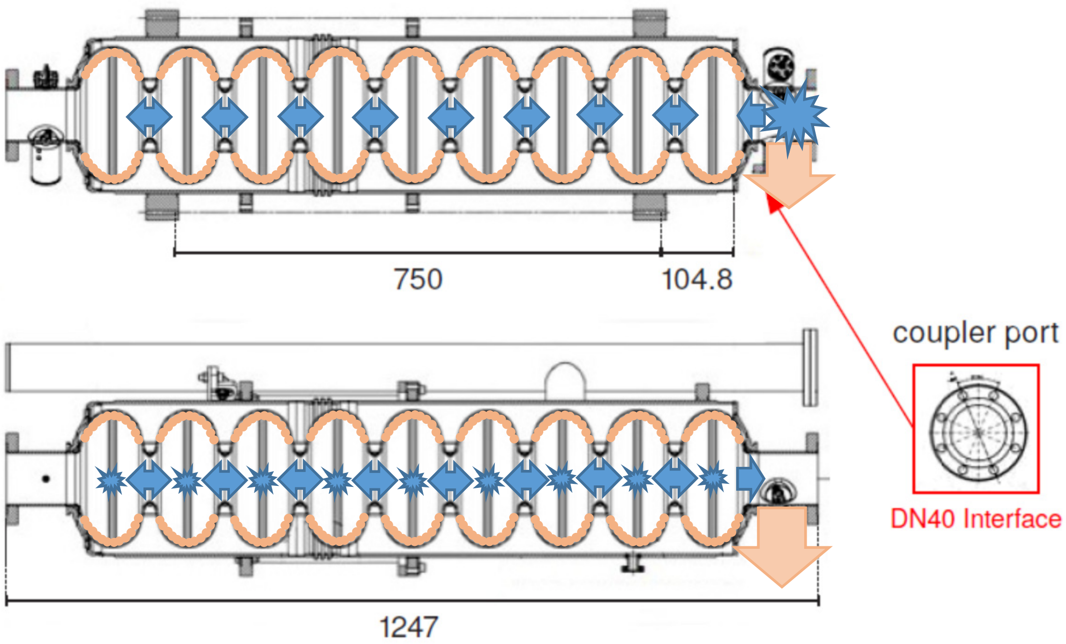
For 11 cell cavity, the perturbation time is roughly O(0.1us).

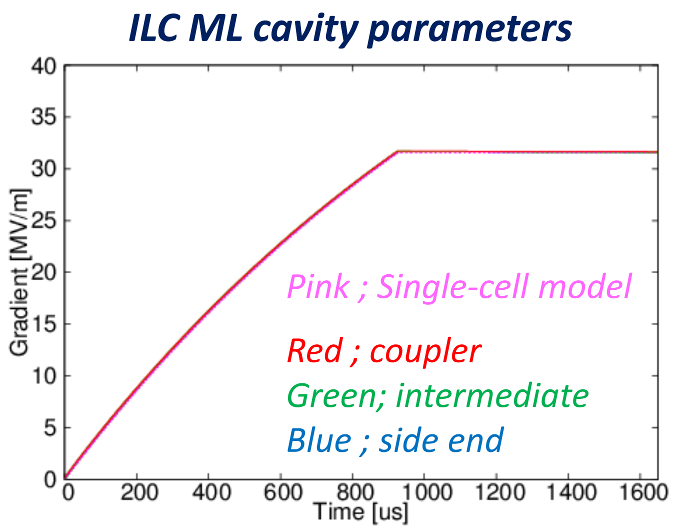
Evaluation of transient beam loading for super-conducting structure

- *Filling time of RF is O(ms) (Q-value for super-conducting structure is O(10^{10}))*
- *Perturbation time within multi-cell structure is O (0.1us)*

Inter-cell RF perturbation can be ignored.

Wall loss in the cavities can be ignored, because the coupling constant (β) is O(1000).





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

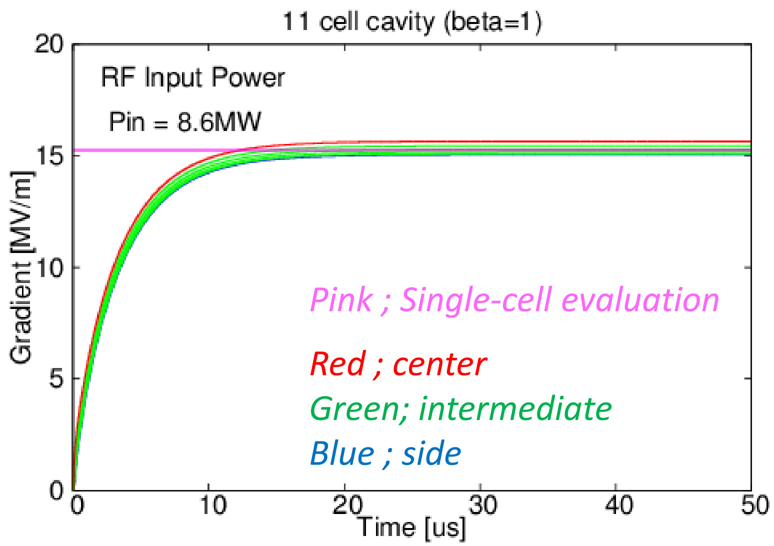
It is no problem to use the single cavity formula for super-conducting multi-cell structure.

OK

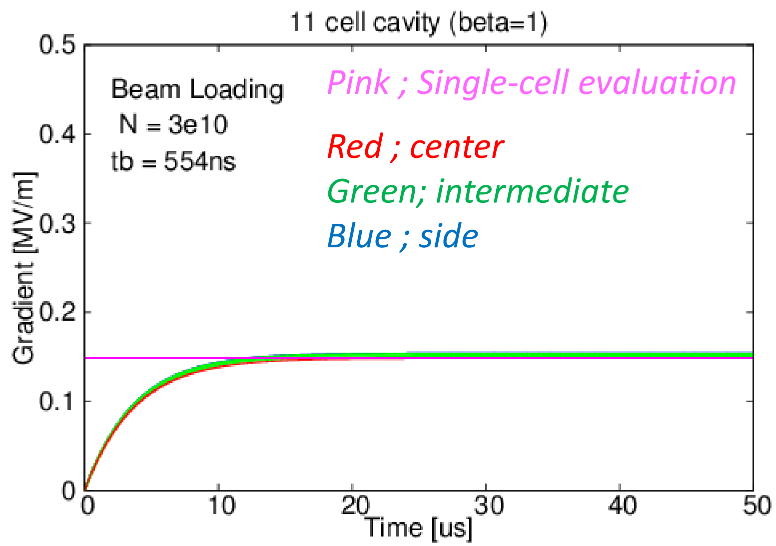
Evaluation of steady state for normal conducting cavity

Capture cavity for Undulator positron source

RF input



Beam Loading



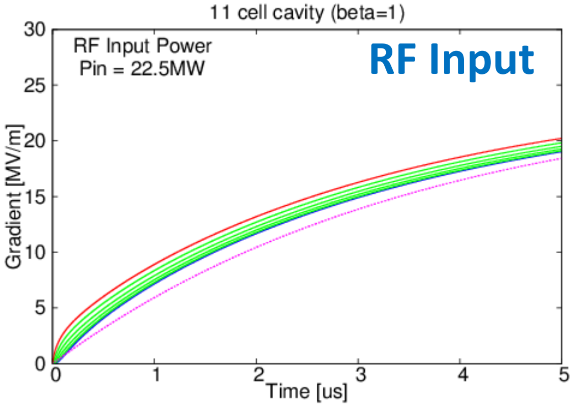
Since the beam current is very small for the capture cavity of undulation positron source, the effect of beam loading is only 1% of accelerating voltage.

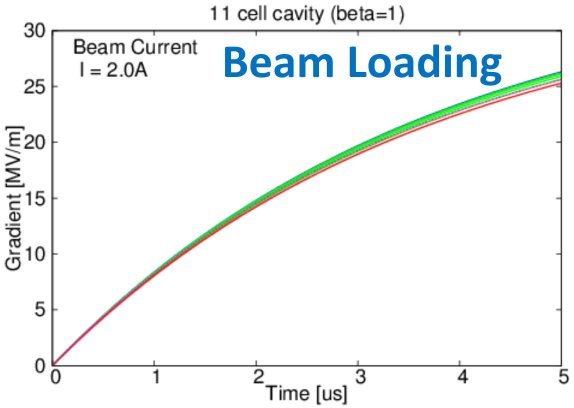
The accelerating voltage and beam loading for steady state are same to the evaluation with single cell formula for undulator PS parameter.

OK for undulator PS capture cavities

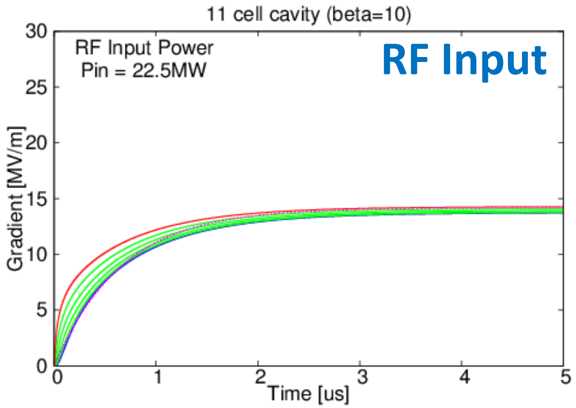
Behavior of RF perturbation for normal conducting cavity

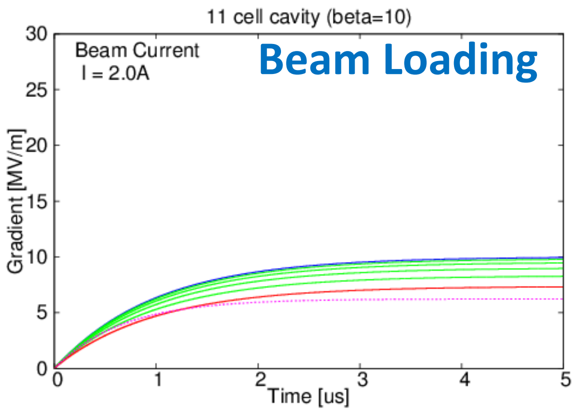
beta=1





beta=10





Parameter for the capture cavity of e-driven PS.

Pink ; Single-cell evaluation

Red ; center
Green; intermediate
Blue ; side

The time constant of input RF is different.

The time profile of input RF is not exponential.

Beam loading is larger than accelerating field.

By increasing the beta,
beam loading will be smaller than accelerating field.

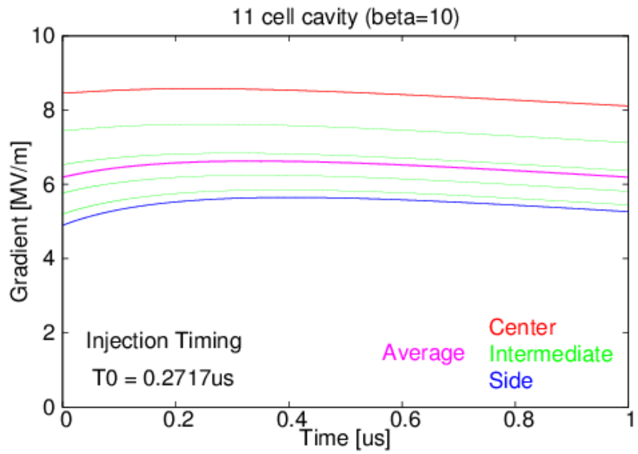
But,
- the reduction of beam loading was smaller than the evaluation of single cell formula.

- cell-to-cell field balance for beam loading will be large.

Transient beam loading compensation with multi-cell model

Performance for candidate structure

Cavity parameters were assumed to standing wave cavity for undulator source except for 11cell and $\beta = 10$.
(design at 9/30 report is 11cell and $\beta = 10.3$)



	Single cell model	Multi-cell model
Average Gradient	8.0 MV/m	6.2 MV/m
Injection Timing	0.543us	0.272us
Field def. in train	0 %	7 % peak-to-peak
Cell-to-cell field def.	0 %	50% peak-to-peak

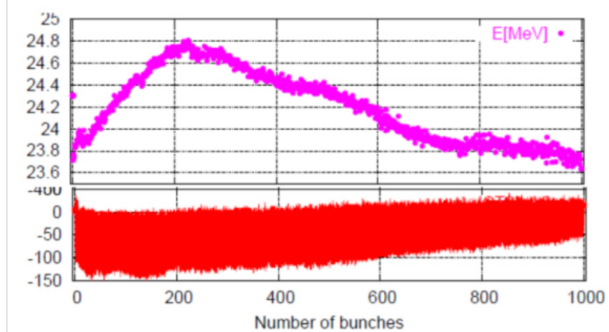
The transient beam loading for multi-cell standing wave structure is not evaluated by single cell formula.

NG

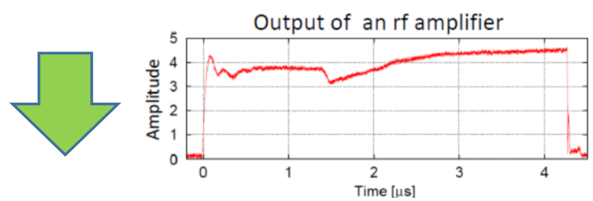
Example of Transient Beam Loading

S-band 12-cell standing wave structure
at LUCX, KEK (** 0.2A, 2.8us,* β*=1.1* ***)

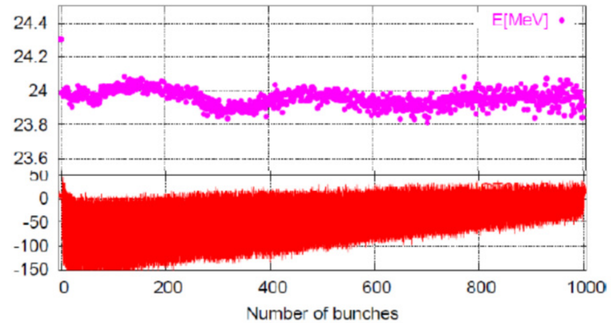
M.Fukuda, Proceedings of IPAC2015



Observation of field def.
(no Amplitude modulation)



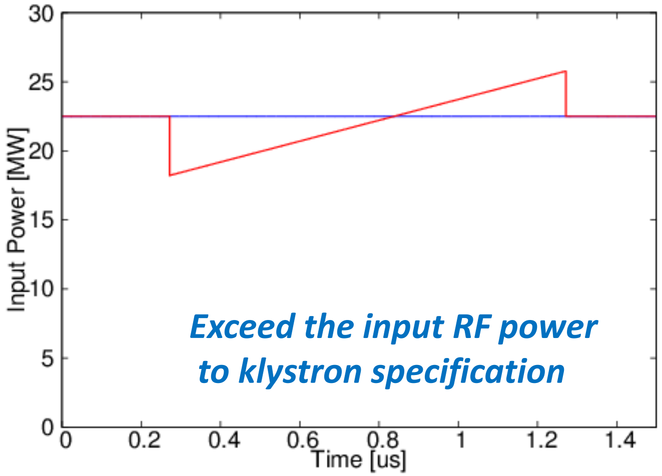
Amplitude modulation

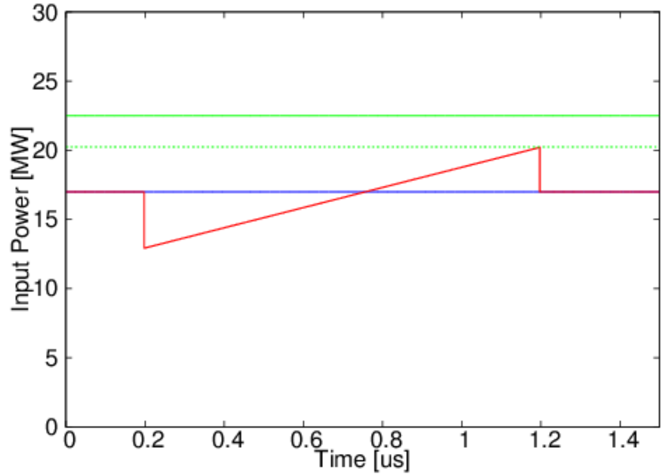


4% -> 1.3% peak to peak

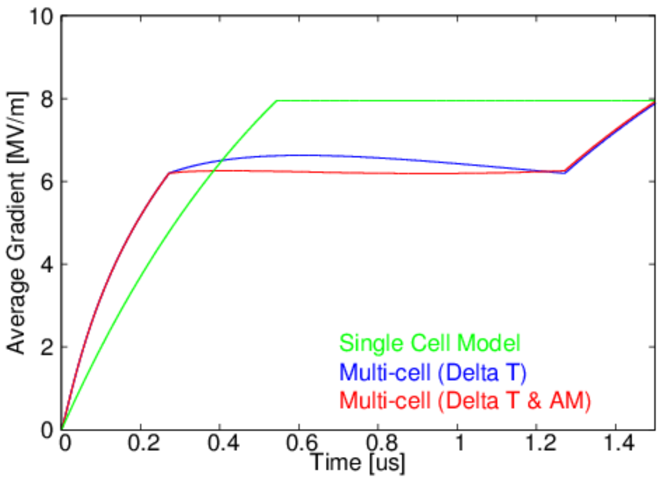
Amplitude Modulation

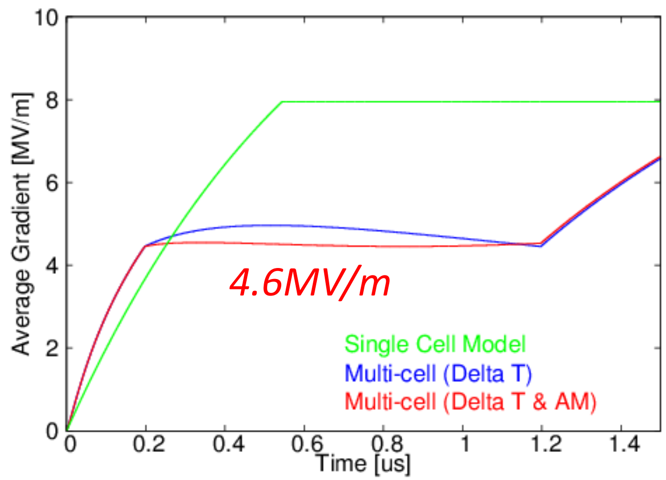
Since we will not operate the klystrons at saturation condition (to apply amplitude modulation), the input RF power should be reduced more (90% for ILC-ML RF).





90% of saturation level





50MW klystron to two 11cell cavities

8.0MV/m Single-cell model

4.6MV/m Multi-cell model

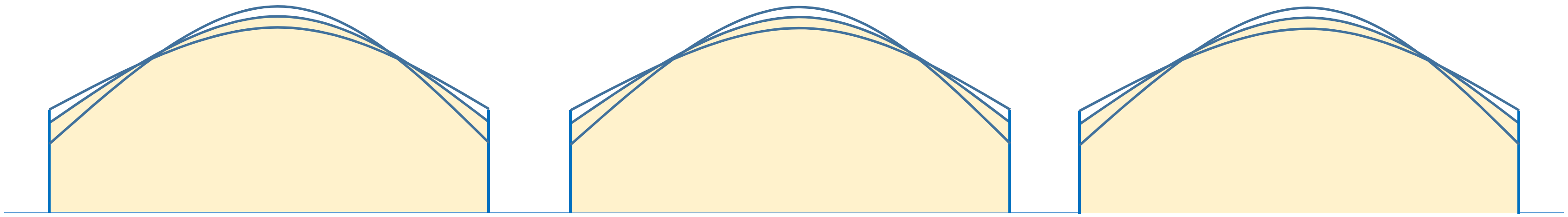
8MV/m can be calculated only when we assumed to the assumption of single cell formula. The optimum gradient should be > 15MV/m for deceleration capture.

Conditions, should be included the evaluation

Electric Field

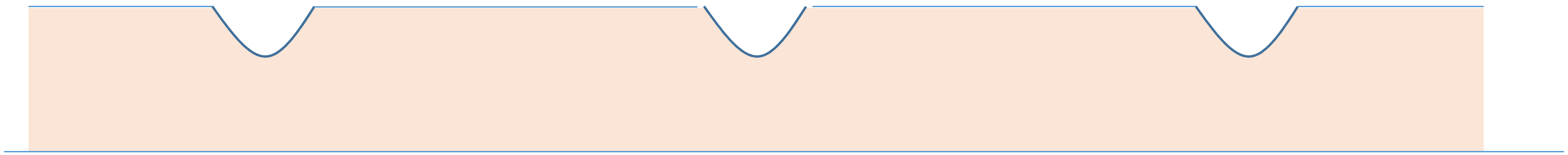
- *Lower gradient → reduction of the yield*
- *Cell-to-cell difference → reduction of the yield*
- *Time variation → the yield change in time*
- *Alignment errors → the effect of transverse wake*

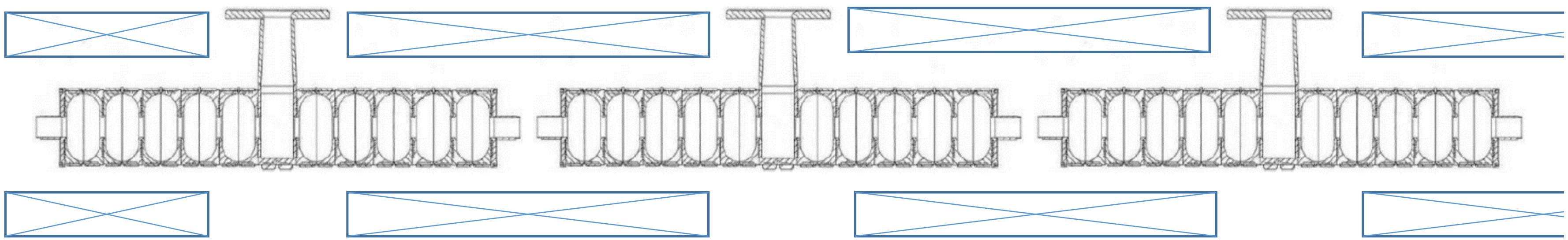
These are also strongly affect to positron yield evaluation



Magnetic Field

- *Effect of gap for waveguide → reduction of the yield*
- *Misalignment of solenoid → transverse wake at fringe*





Beam Tuning

Can we tune the beam ?

Beam energy is measured after few 10 structures (beam current is different for every structure) .

Radiation dose for capture section

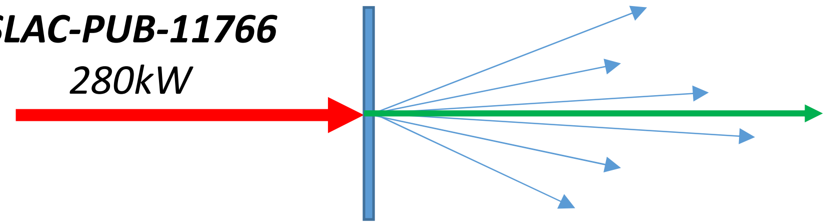
Radiation dose in capture section

The power loss was evaluated at PAC'05 by V. Bharadwaj et al. (SLAC-PUB-11766).

Electron driven Scheme

SLAC-PUB-11766

280kW

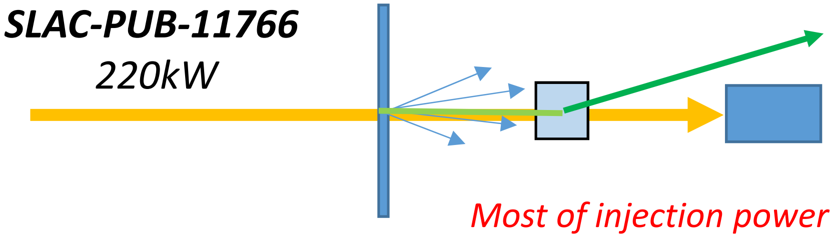


Most of injection power will be sprayed around target.

Undulator Scheme

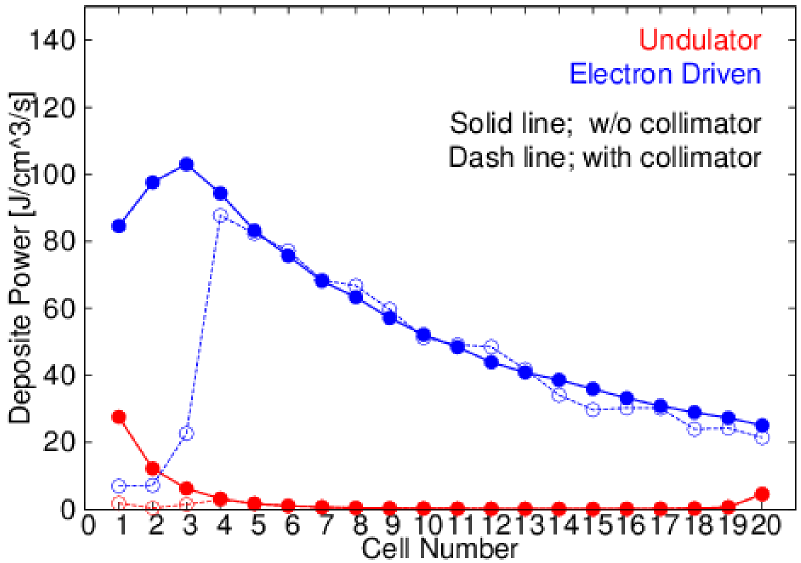
SLAC-PUB-11766

220kW



Most of injection power will be dumped to photon dump.

Power deposit of Innermost iris.



Injection beam power deposition

undulator scheme

6.1% in RF structure

1.5% in innermost iris for structures

Main radiation source is restricted around target.

Halo collimator between target and structure is effective.

electron driven scheme

53% in RF structure

22% in innermost iris for structures

Radiation source is distributed to wide area.

Heating of standing wave structure for ILC positron source

Effect of the capture cavity for undulator positron source was evaluated at PAC'05 by J. Wang et al. (SLAC-PUB-11767).

Table 3: Cavity Detunings for Different Loads

Case	Cavity detuning
Average RF losses only	-20.4 kHz
Average RF and particle losses	-58.6 kHz
Start of RF pulse, RF loss only	-19.5 kHz
End of RF pulse, RF loss only	-23.3 kHz
Transient detuning, RF only	-3.9 kHz
Start of RF pulse, RF and particle loss	-53.8 kHz
End of RF pulse, RF and particle loss	-68.9 kHz
Transient detuning, RF and particle loss	-15.1 kHz

RF only ***RF & beam loss***

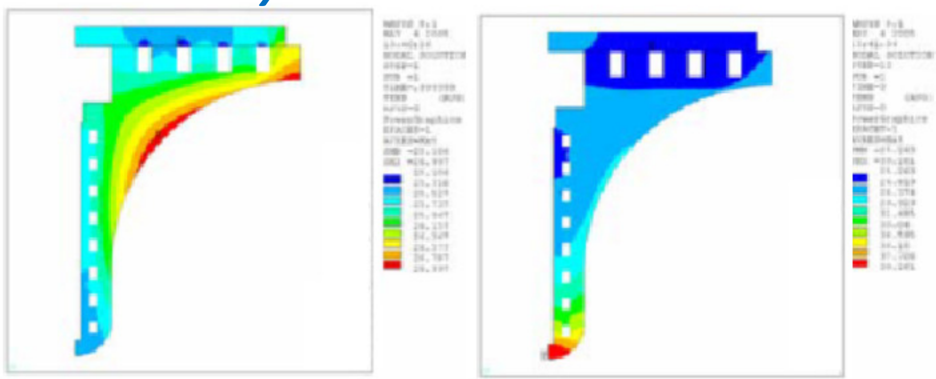
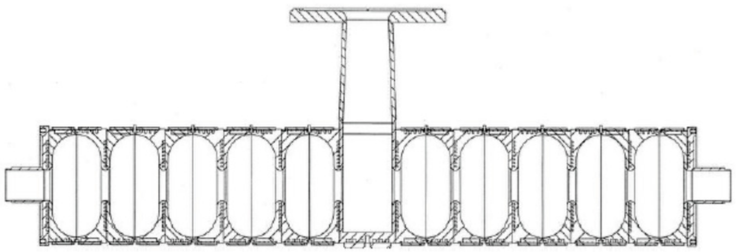


Figure 4: ANSYS thermal model with average RF losses (left) and thermal model with average RF and particle losses (right).



1st Cell frequency change (no collimator) for 220kW Photon Beam

Average frequency change ; 38.2 kHz

Transient frequency change ; 11.2 kHz
(within 1ms interval)

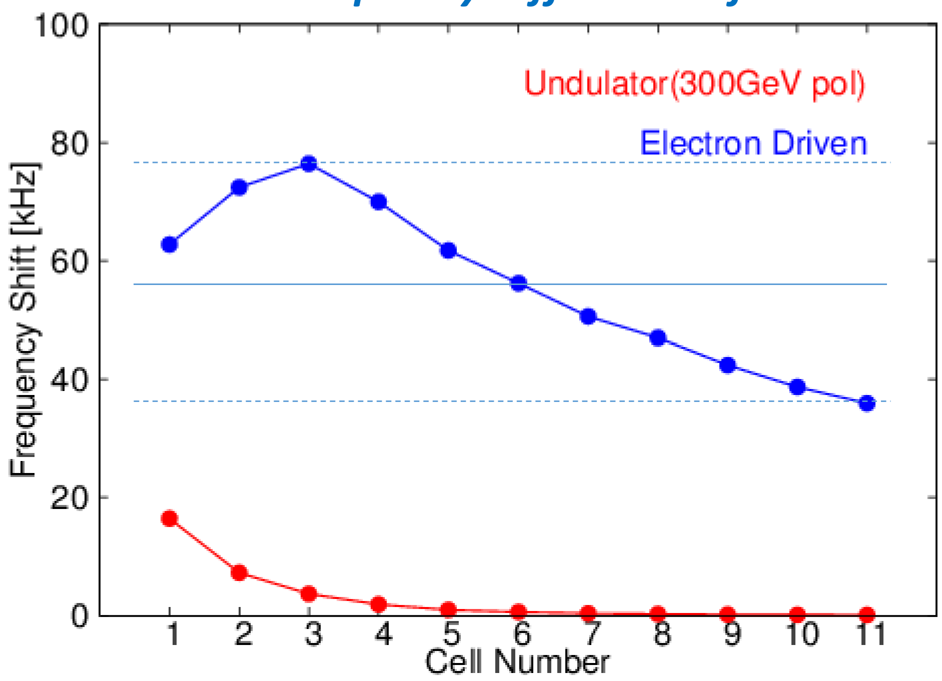
Scaled to present design

Since the parameters were changd from 2005, the power deposition was scaled to present parameter.

	e-driven	Undulator [300GeV]	
		unpolarized	polarized
Beam power to target	146kW *(6GeV & Nb=2.3e10)*	63.1kW	94.7kW
Acc. structure	77kW	3.8kW	5.8kW
Innermost iris only	32kW	0.9kW	1.4kW

Beam power for SLC positron source was < 40kW

Frequency difference of beam loss ON/OFF for e-driven scheme



Average frequency shift for beam loss ON/OFF

55kHz

We could store the RF in the cavity either the beam loss ON or OFF.

Frequency difference within 1 structure

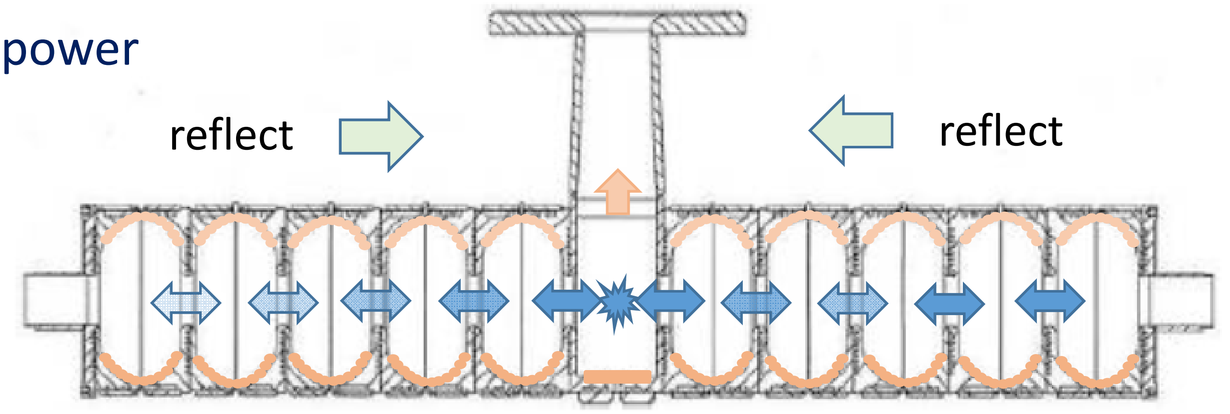
40kHz

The frequency tolerance for RF structure

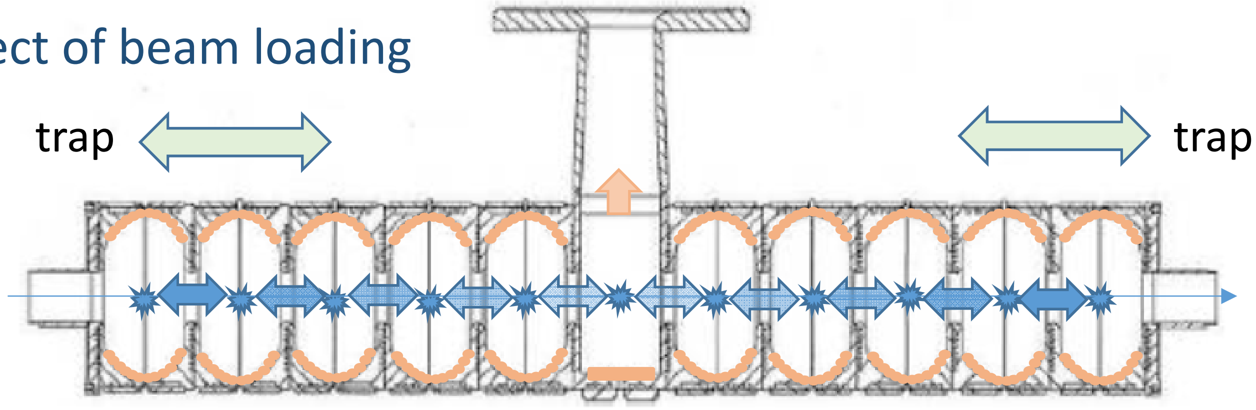
$$\Delta f = f/Q = 43.8kHz$$

Resonant frequency difference within multi-cell cavity

RF power



Effect of beam loading



RF distribution will be changed from the cavity with uniform resonant frequency.

We should evaluate the accelerating voltage both for RF input and beam loading by using the cavity model with different frequency within the structure.

Radiation protection

SLC Positron Target Arrangement in Beamline

The positron target was located to the separate area.
- to restrict the radio active area.
- to protect the devices from the radiation dose .

Electron Driven Positron Source

The radiation dose for ILC electron driven positron source is 3-4 times larger than SLC.
(twice more for high luminosity option)

Can the positron target put the target to same tunnel ??

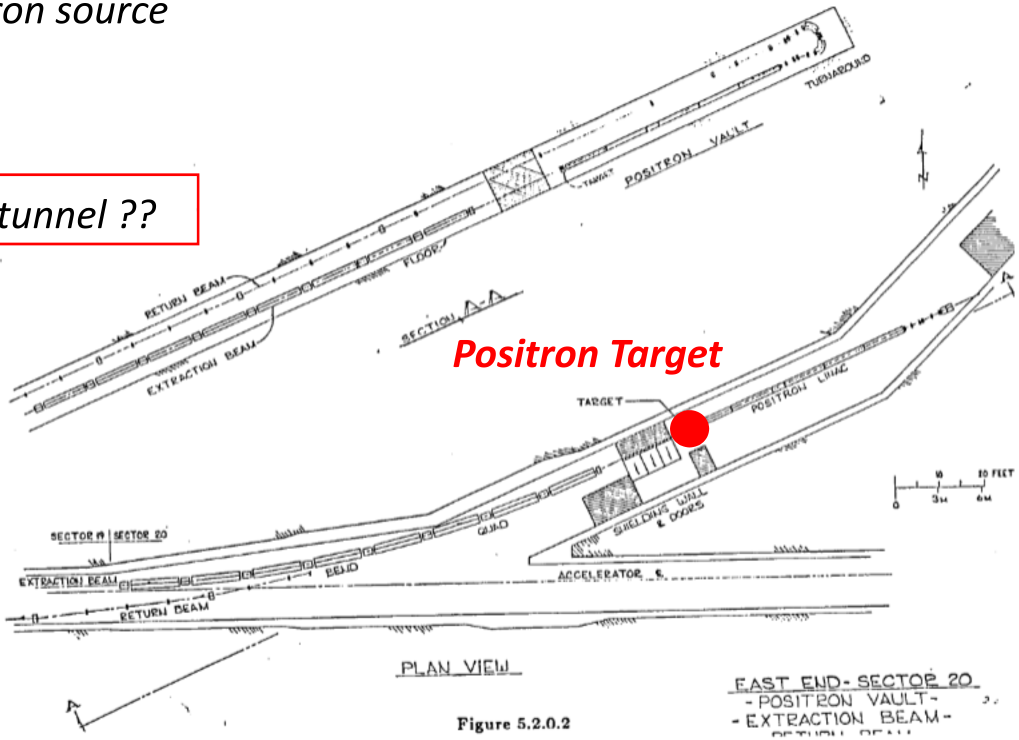


Figure 5.2.0.2

SLC Design Handbook

Beam loading compensation for multiple trains with standing wave structure

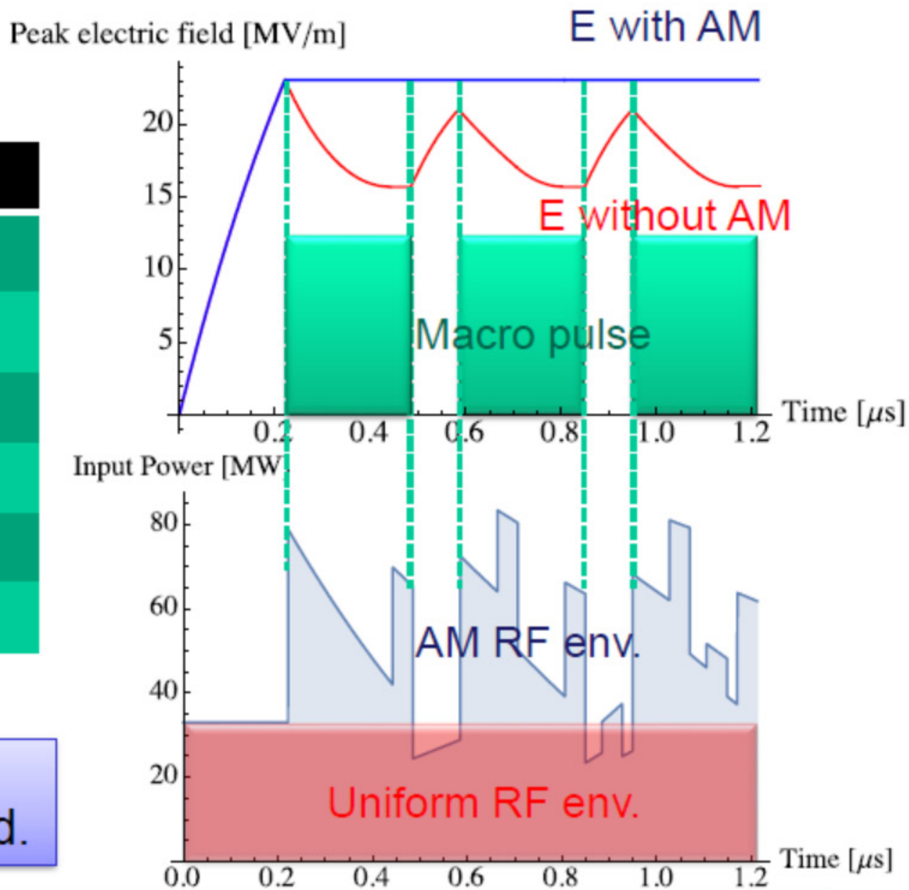
presented by M.Kuriki at AWLC2015

LINEAR COLLIDER COLLABORATION

S-band Traveling Wave (booster)

Accelerator parameters	
f	2.6 GHz
R	80 MΩ/m
Q	7100
Beam curr.	0.78 A
length	2 m
Filling time	0.22 μ sec

To maintain 20MV/m,
85MW peak RF power is required.

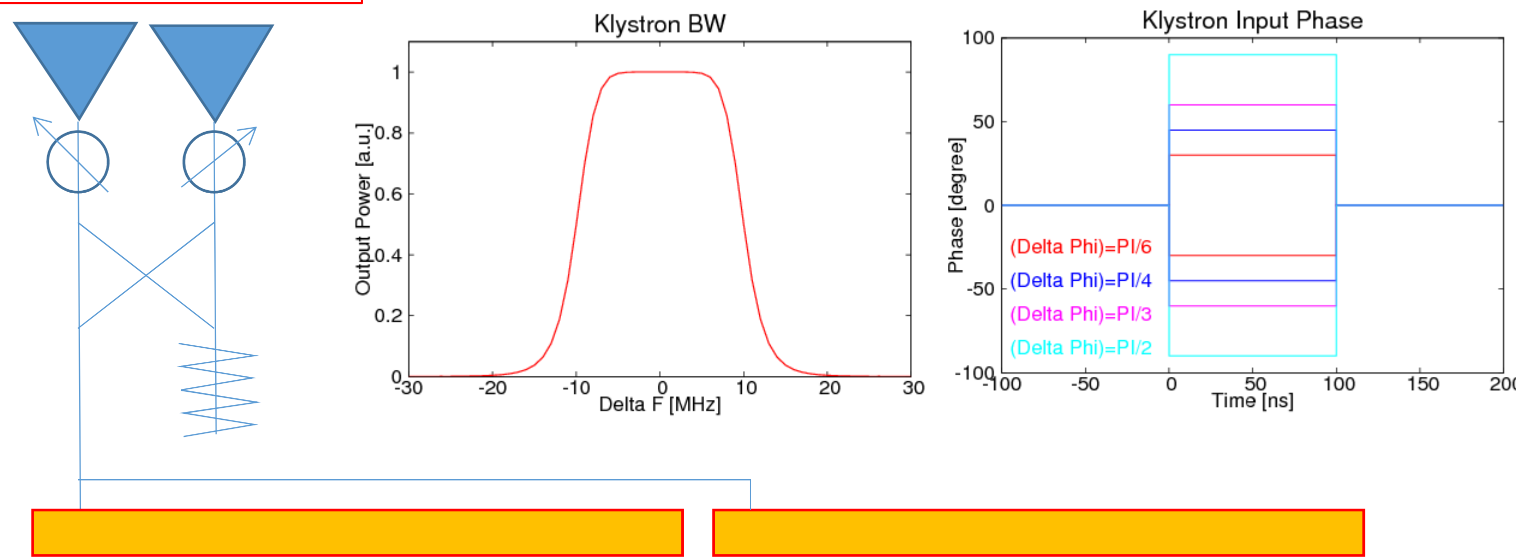


Beam loading compensation was evaluated by assuming extremely fast RF response time,
But the actual RF response time is limited by the klystron bandwidth.

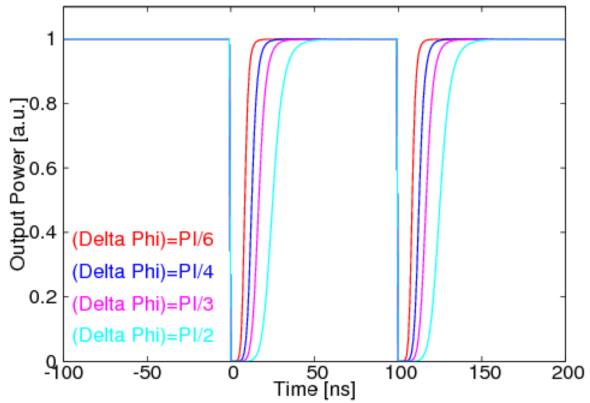
Effect of Klystron bandwidth

+/-10MHz of klystron bandwidth

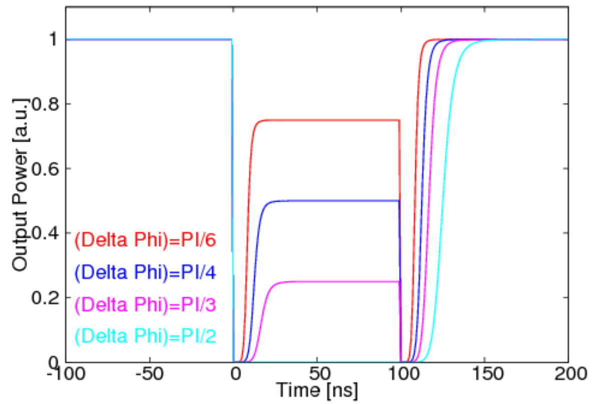
Klystron has finite BW



Klystron Output



RF power after combined 2 klystron output



When the RF phase was changed by 90degrees, the output power was not emitted about 30ns.

We must design the RF response time by assuming the actual hardware performances.

Summary

The physics process to produce the positrons by using electron beam itself is conventional method.

But, the present design of ILC electron driven positron source will not be constructed only by using the conventional technologies. It includes many challenging devices and techniques than undulator PS.

It means we need a lot of R&Ds to be realized. We should make R&D schedules for the technologies with limited resources, If we will make the design realistic.

Furthermore, it seems the present design is inconsistent for me (number of components, hardware design and evaluation of positron yield).

The consistent design of e-driven source is very important information in order to design the BDS tunnel with e-driven positron source.

I hope to have the consistent design of e-driven source as soon as possible in order to evaluate the tunnel length, CFS, number of component and the costs.

Backup

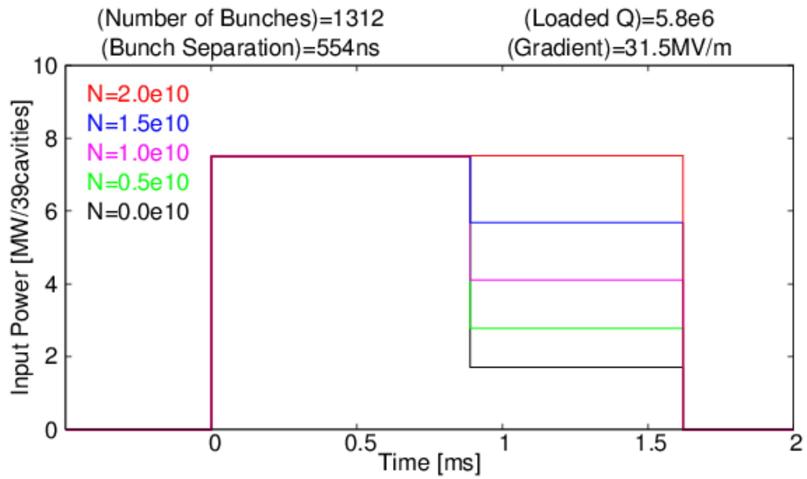
ILC TDR timing System (B.List)

It is better to design the positron source to be acceptable to every ILC beam parameters.

type	h	k_b	N_{bunch}	n_b	g	n_t	N_t	Q_b [$10^{10}e$]	t_b [ns]	I_{ML} [mA]	t_{pulse} [μs]
SB2009 nominal values								$c = 3248$ m			
DRFS	7042	463	1312	–	–	–	–	2.00	712	4.5	935
KCS	7042	347	1312	–	–	–	–	2.00	534	6.0	700
FP(e^-)	7042	231.5	2625	–	–	–	–	2.00	356	9.0	935
FP(e^+)	7042	231.5	1312	–	–	–	–	2.00	356	9.0	935
Solution 1								$c = 3238.68/3239.14$ m			
DRFS	7022	476	1312	4	33	23	59	2.00	732	4.4	961
KCS	7022	360	1312	4	45	34	39	2.00	554	5.8	727
FP(1Ring)	7022	238	2625	2	31	45	59	2.00	366	8.8	961
FP(2Ring)	7022	238	1312	4	75	23	59	2.00	366	8.8	961

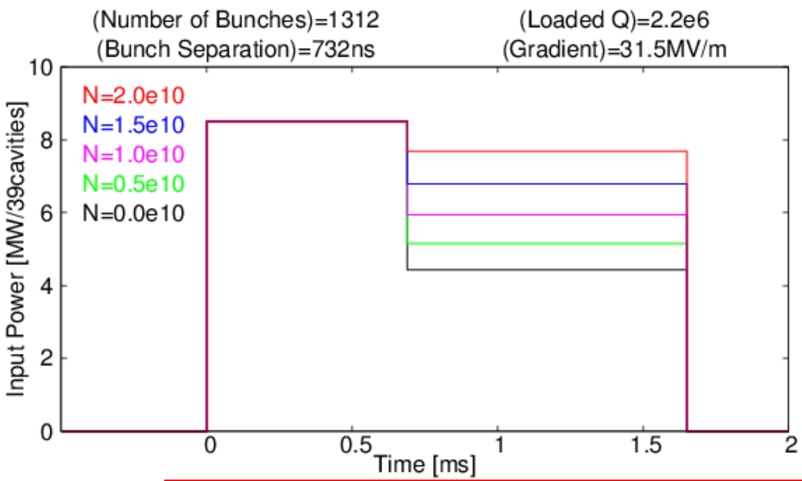
Main Linac RF for KCS (Baseline)

39 RF cavities for one 10MW klystron



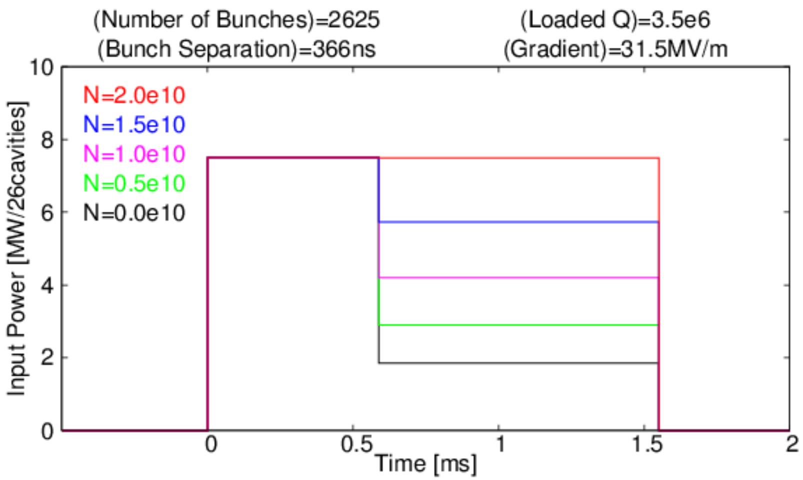
Main Linac RF for DRFS (Small DR Train Length)

39 RF cavities for one 10MW klystron
(same to baseline parameters)



Main Linac RF for FP (High Luminosity)

26 RF cavities for one 10MW klystron
(1.5 times larger than baseline parameters)



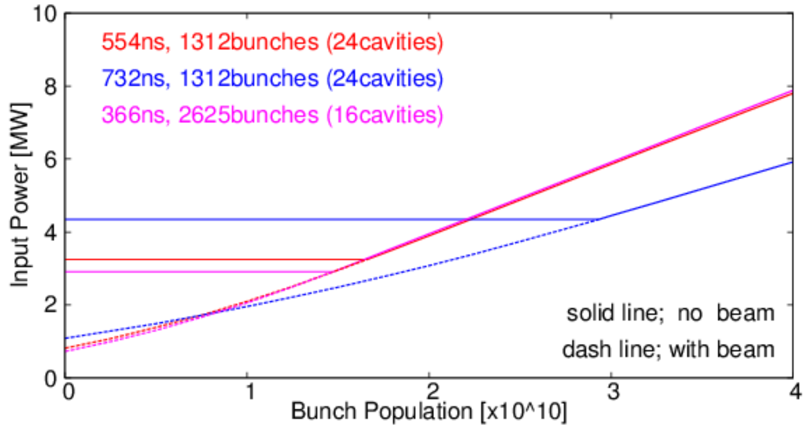
For lower intensity, the RF amplitude will be reduced after beam injection.

Superconducting RF system for Booster Linac

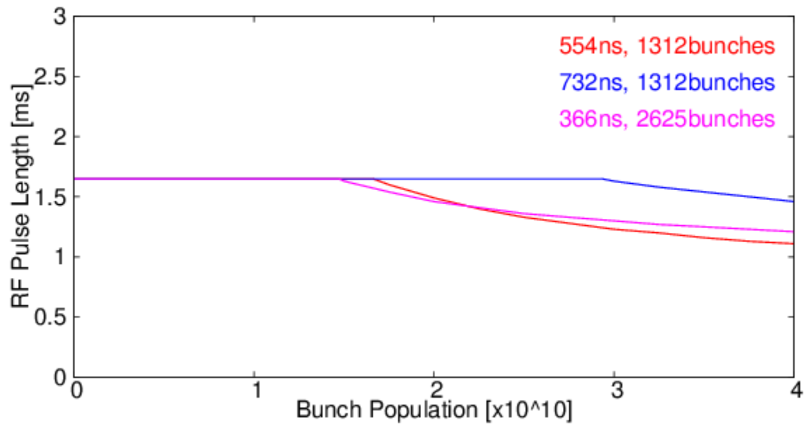
- *Accelerating Gradient ; V=27MV/m (easy to arrange the klystrons to cavity)*
- *Bunch population ; N=0-3e10 or more*
- *Same RF system to Main Linac*

type	h	k_b	N_{bunch}	n_b	g	n_t	N_t	Q_b $[10^{10}e]$	t_b [ns]	I_{ML} [mA]	t_{pulse} [μs]
SB2009 nominal values								$c = 3248$ m			
DRFS	7042	463	1312	–	–	–	–	2.00	712	4.5	935
KCS	7042	347	1312	–	–	–	–	2.00	534	6.0	700
FP(e^-)	7042	231.5	2625	–	–	–	–	2.00	356	9.0	935
FP(e^+)	7042	231.5	1312	–	–	–	–	2.00	356	9.0	935
Solution 1								$c = 3238.68/3239.14$ m			
DRFS	7022	476	1312	4	33	23	59	2.00	732	4.4	961
KCS	7022	360	1312	4	45	34	39	2.00	554	5.8	727
FP(1Ring)	7022	238	2625	2	31	45	59	2.00	366	8.8	961
FP(2Ring)	7022	238	1312	4	75	23	59	2.00	366	8.8	961

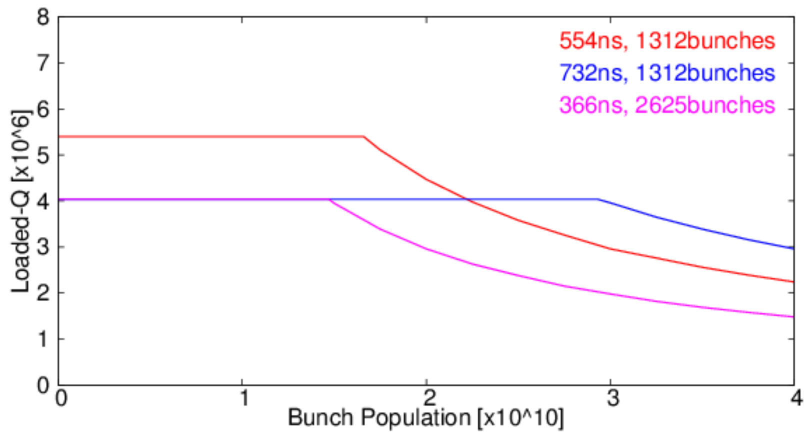
Requirement of RF power (< 10MW)



Requirement of RF pulse length (< 1.65ms)

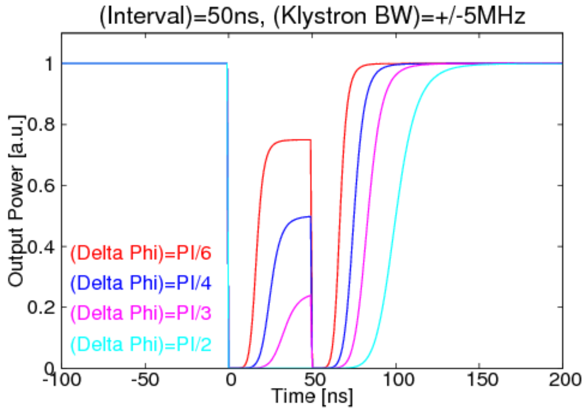


Requirement of loaded Q (1-10e6)

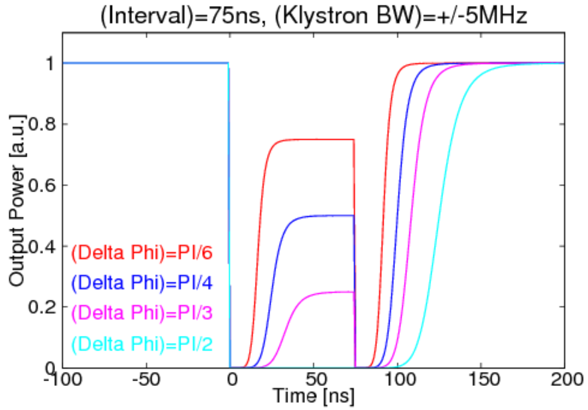


(Klystron Bandwidth) = +/- 5MHz

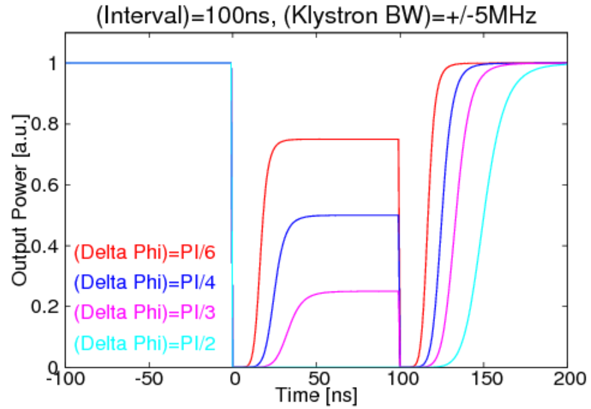
Δt = 50ns



Δt = 75ns

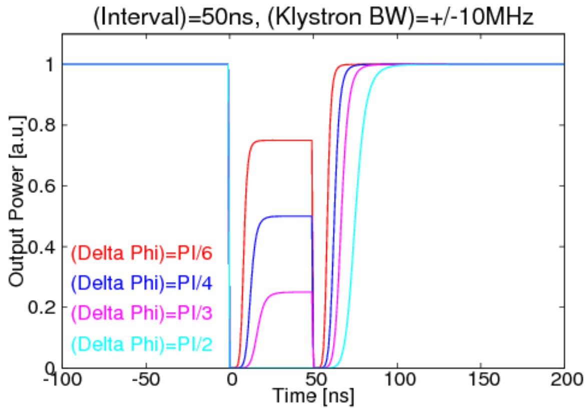


Δt = 100ns

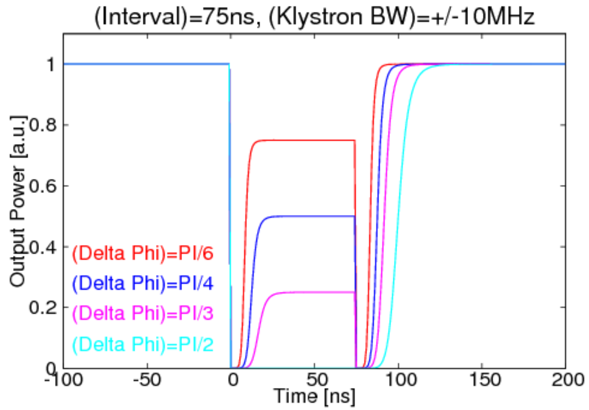


(Klystron Bandwidth) = +/- 10MHz

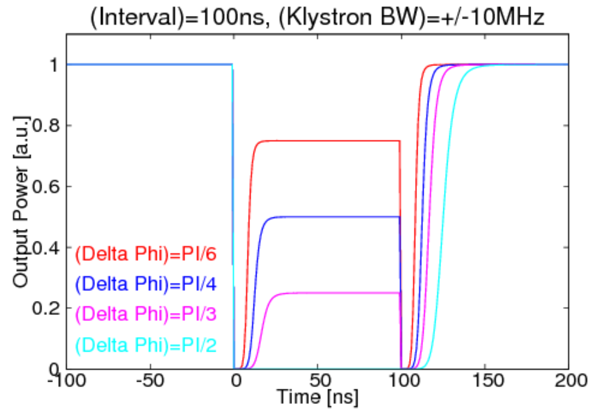
Δt = 50ns



Δt = 75ns



Δt = 100ns



バンド幅が狭くなると、応答時間も長くなる。

トレイン間の間隔が短くなれば、それに応じてクライストロンのバンド幅の条件が厳しくなる。