ILC BDS and Crab Cavity Expectations

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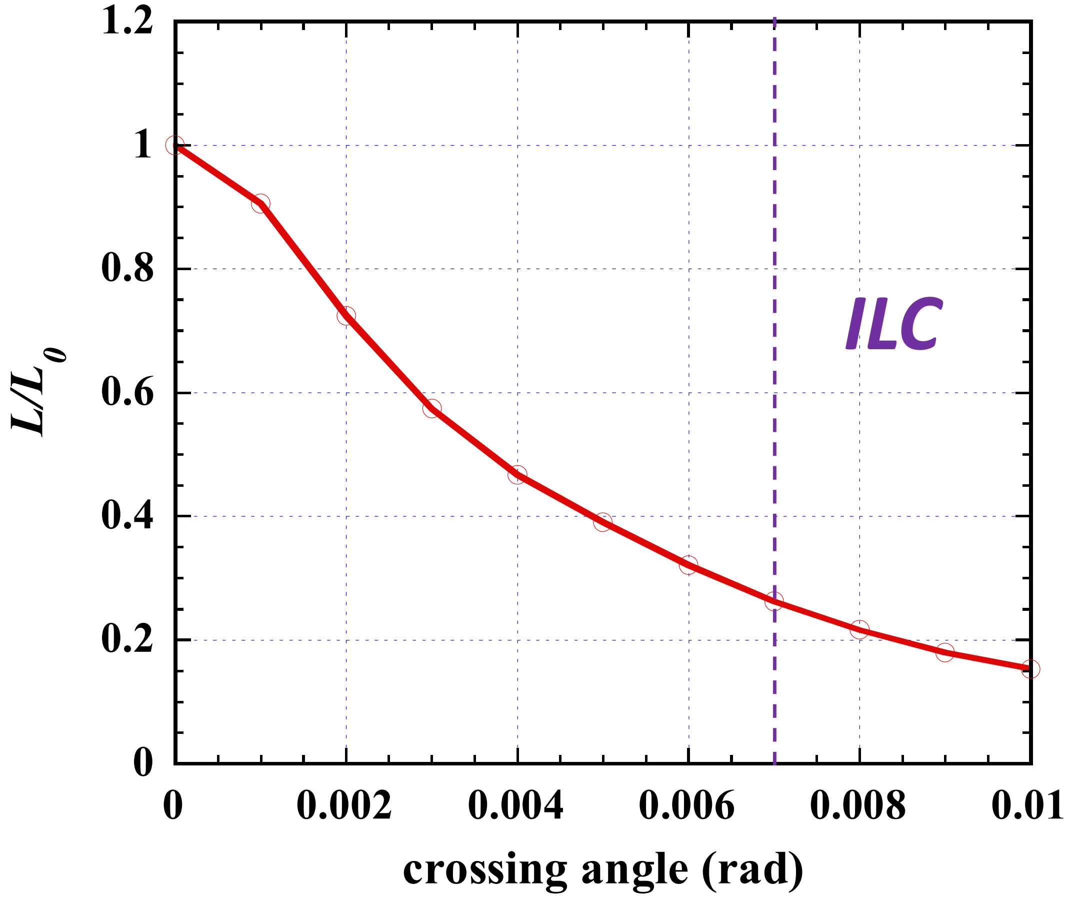
2023/04/04
Down Selection Review on Crab Cavity Design

Introduction

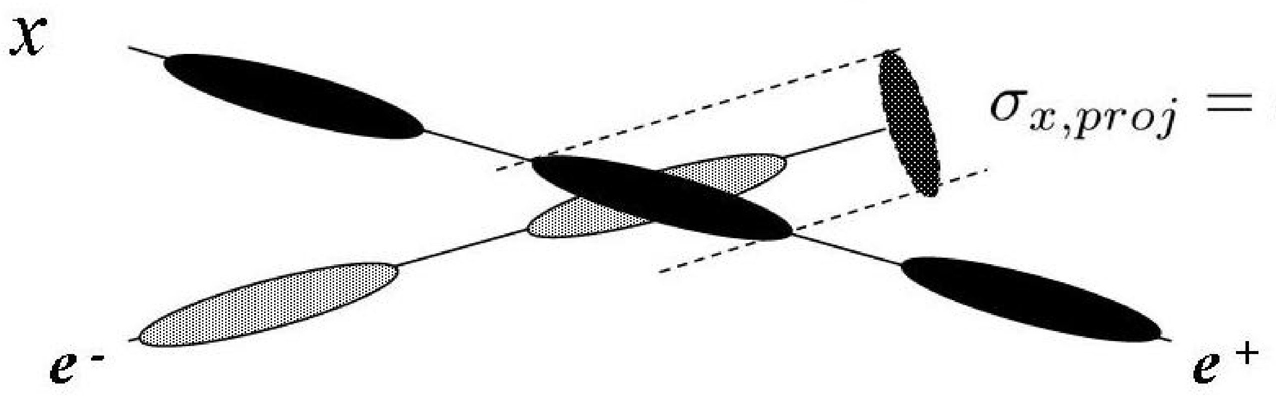
Effect of crossing angle

ILC RDR parameter, by CAIN simulation



- ***The large crossing angle is good to separate the injection/extraction beams.***
- ***But, when we set the large crossing, the luminosity is reduced.***
- ***ILC design has 14 mrad crossing angle.***

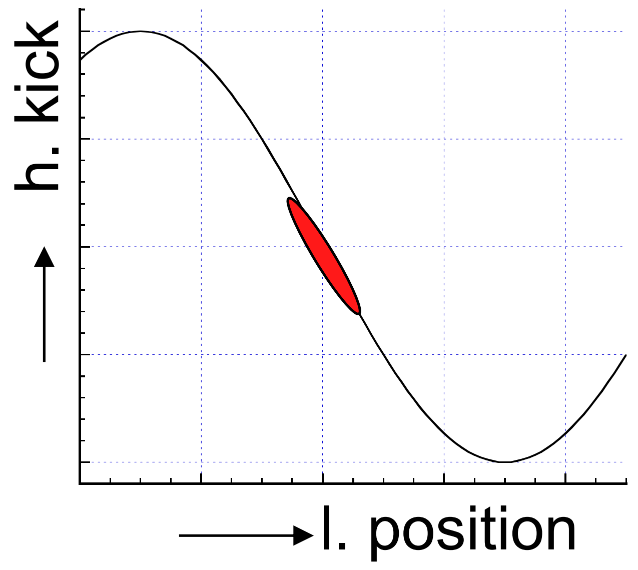
Projected Beam Size

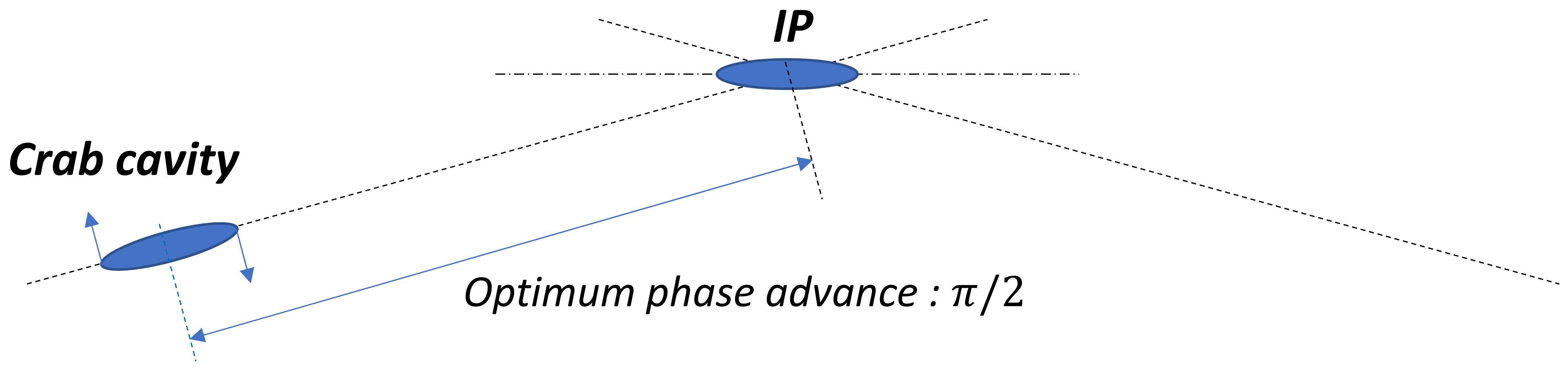


$$\sigma_{x,proj} = \sigma_{x0}\sqrt{1+\left(\frac{\sigma_z \sin\phi}{2\ \sigma_{x0}}\right)^2}$$

Crab crossing

By shifting the forward and backward positions of the beam at the interaction point in accordance with the crossing angle, it is possible to create a pseudo head-on collision.

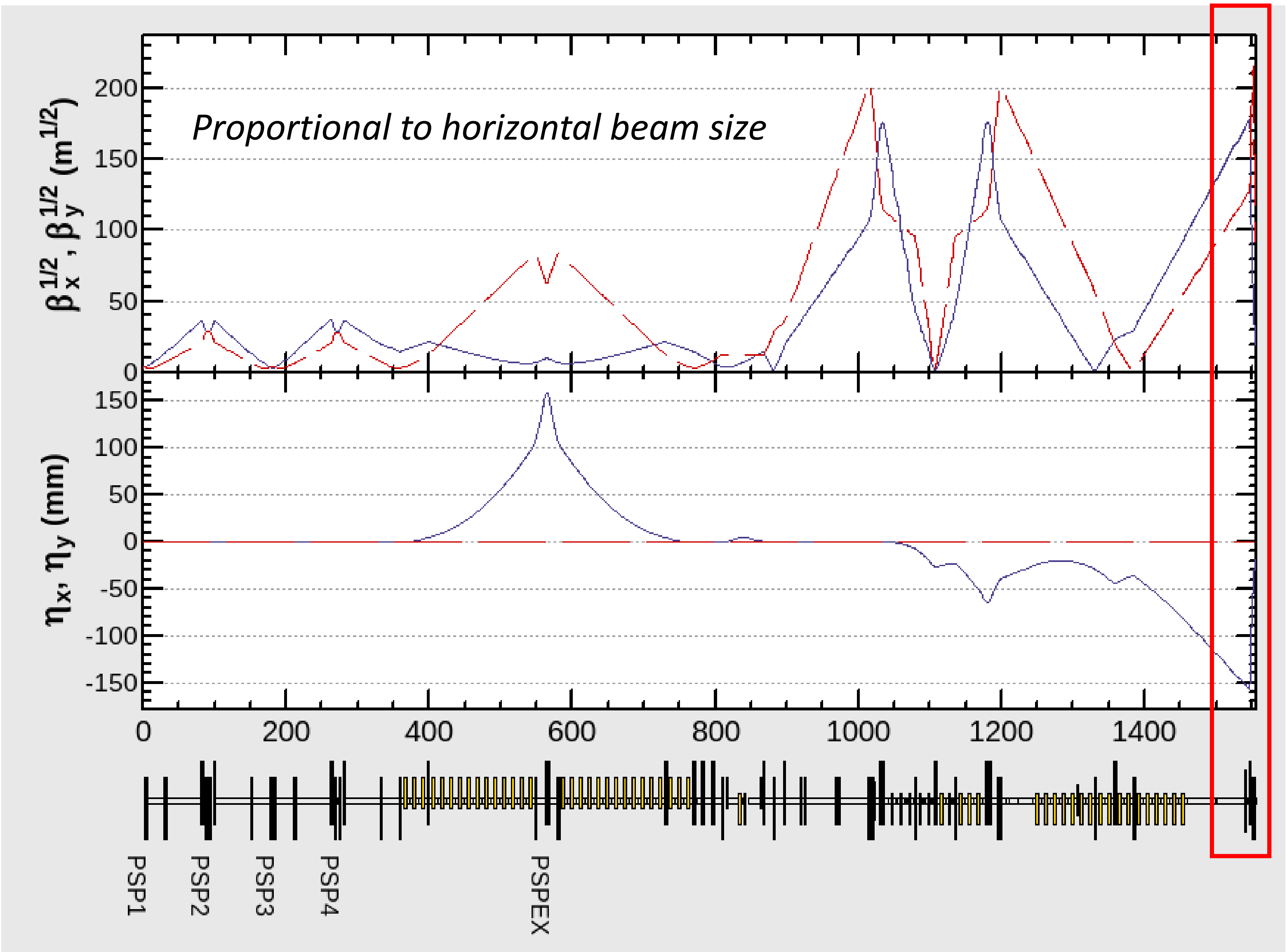




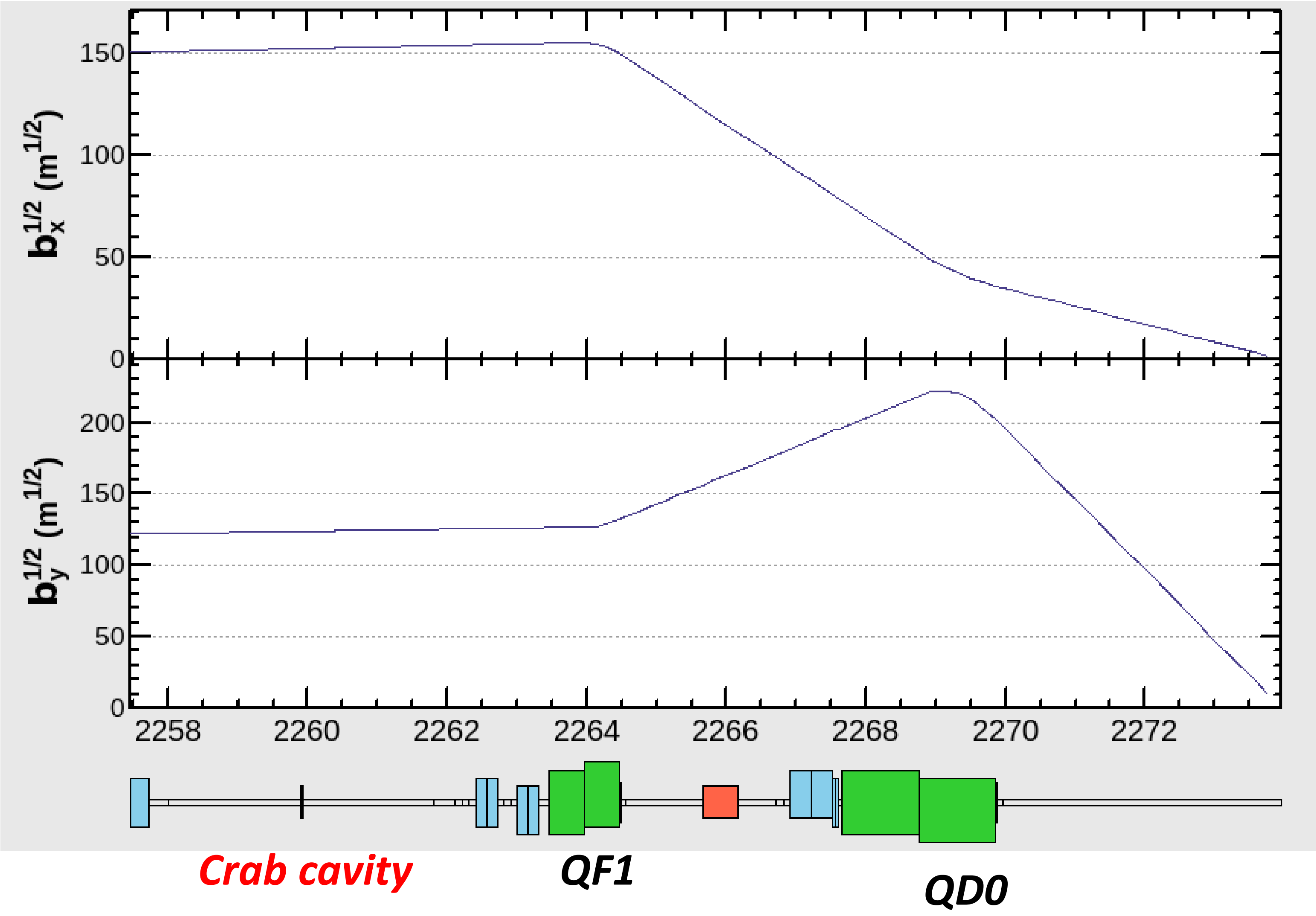
- *The horizontal position difference at IP is maximum, when the phase advance between the crab cavity and IP is* $\pi/2$.
- ***Amplitude of the position difference can be controlled by changing the amplitude of the crab cavity.***

ILC crab cavity arrangement

ILC BDS beamline



around IP

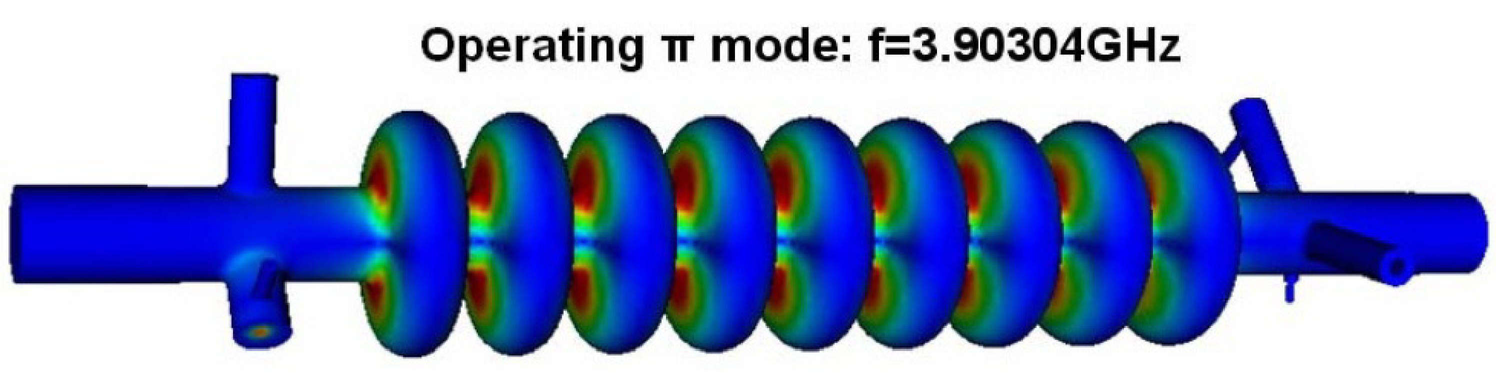


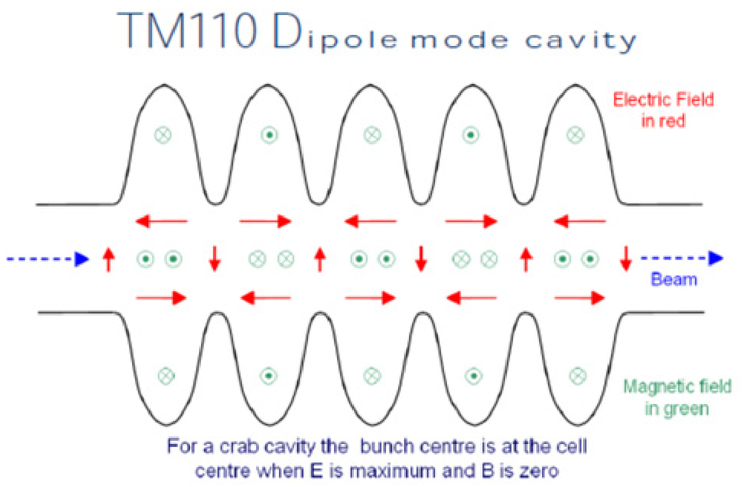
In ILC, it is assumed that a crab cavity is placed in front of the interaction point in order to suppress the luminosity reduction due to the crossing angle.

Crab Cavity Design & Prototyping in TDR phase

Design & prototypes been done by UK-FNAL-SLAC collaboration.

Prototype of crab cavity was built at FNAL.





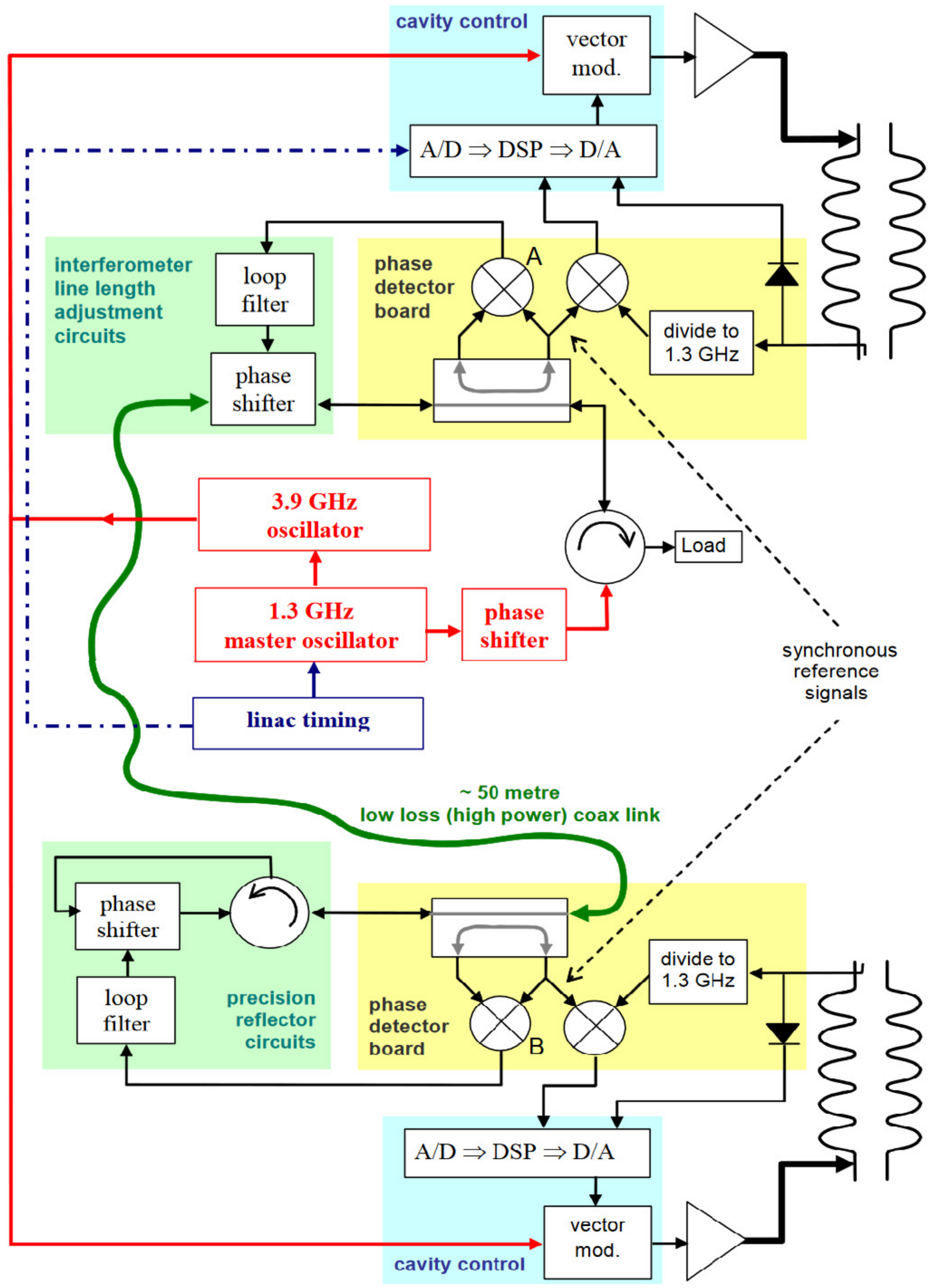
For a crab cavity the bunch centre is at the cell centre when E is maximum and B is zero

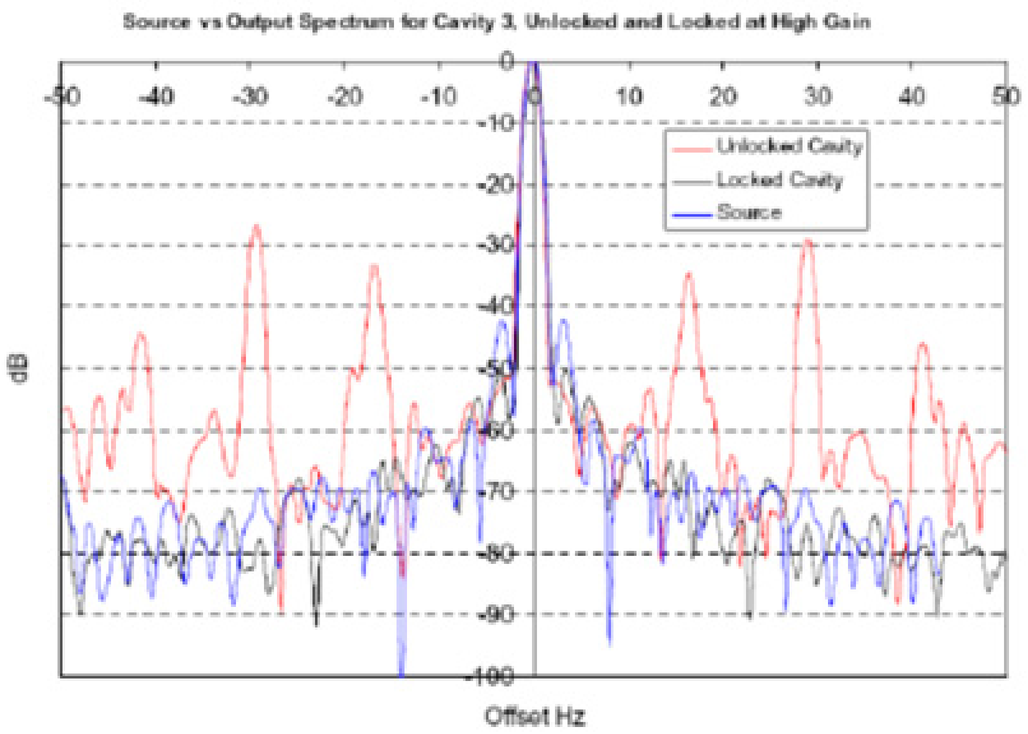
Prototype of 3-cell Crab Cavity

3.9GHz cavity achieved 7.5 MV/m (FNAL)

Phase lock for 2 crab cavities in TDR phase

It is very important to synchronize the RF for 2 crab cavities.





The Cockcroft Institute

ASTeC

SLAC

Phase lock achieved for both cavities

10° r.m.s. *for unlocked*

0.135° r.m.s. *for phase-locked*

Requirement from ILC BDS group about the crab cavity

Discussion of ILC BDS and crab cavity group

We discussed with the crab cavity group about the requirement from ILC BDS side several times.

2020 November : Crab cavity location and the basic requirement

2021 May : Tolerances of the crab cavity

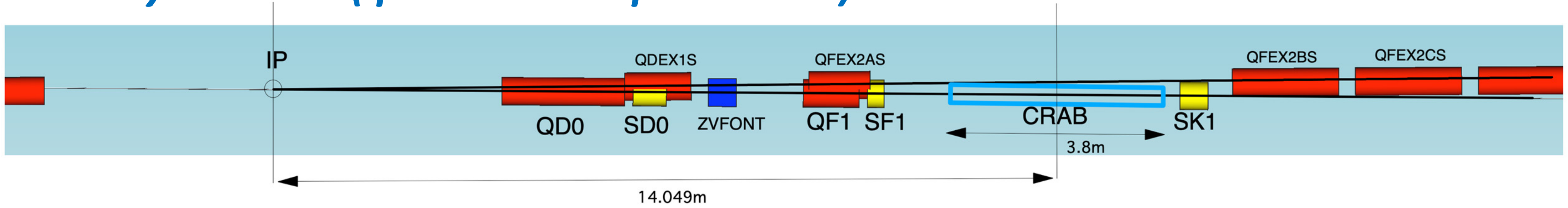
2022 February : Joint meeting of IDT WG2 crab cavity (WP-3) and BDS group

2022 August : Crab cavity geometrical requirement

Crab cavity location

Crab cavity location (present ILC optics deck)

two beamline distance
14.05m x 0.014rad = 197mm



Crab cavity location (alternative)

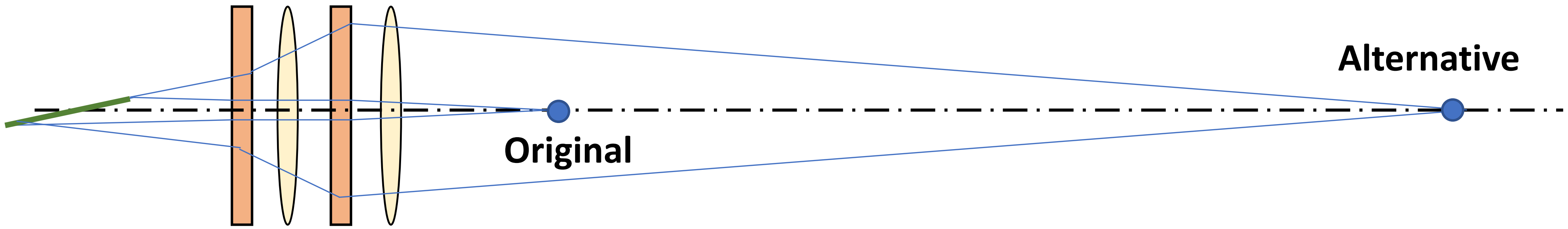
two beamline distance
77m x 0.014rad = 1078mm

drawn by H. Hayano

- ➢ *Since lots of magnets will be put in the dump line, the next neighbor candidate to put the crab cavity* ***is 77 m from the IP*** *in order to avoid the positional influence of the magnets in the dump line.*
- ➢ *The requirement of the relative RF jitter is independent to the crab cavity location. But the jitter requirement for the next neighbor location is tighter for the distance between the crab cavities (28m and 154m).*

	Present	***Alternative***
Longitudinal distance from IP	14.05 m	77 m
Horizontal distance from dump line	0.197 m	1.078 m
R12 (crab cavity to IP)	17.4 m	12.2 m
relative timing jitter requirement	49 fs rms. (2 % luminosity drop)	

Effect to the luminosity



Horizontal beam orbit at FD was changed from the bunch head to the bunch tail

- ➢ *The vertical focal position was shifted from the bunch head to the bunch tail*

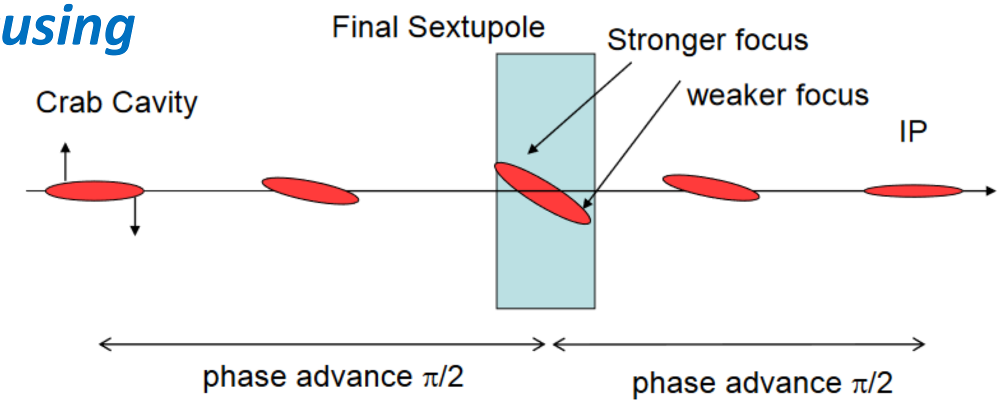
Beam waist shift

z	Present			Alternative		
	σ_x/σ_{x0}	σ_y/σ_{y0}	Δ_y/σ_z	σ_x/σ_{x0}	σ_y/σ_{y0}	Δ_y/σ_z
+600 um	1.0010	1.0138	+0.14	1.16	1.45	+1.03
+300 um	1.0005	1.0044	+0.07	1.05	1.13	+0.51
0	1	1	0	1	1	0
- 300 um	1.0005	1.0044	-0.07	1.05	1.13	- 0.51
- 600 um	1.0010	1.0138	-0.14	1.16	1.45	- 1.03
Luminosity reduction	0.5 % (geometrical)			16 % (geometrical)		↑

Bunch head ⇕ **Bunch tail**

Weak focusing ⇕ **Strong focusing**

Traveling focusing



The luminosity for the alternative location will be increased than that evaluated as the geometrical luminosity by the traveling focusing of the beam-beam effect.

Discussion in November 2020

- Although traveling focusing cannot be used with the present position of the crab cavity, the same level of luminosity increase can be expected by slightly shifting the beam waist from the focal point (**the difference in luminosity is slight**).

- The alternative location is good for traveling focusing, but there is a risk that the condition will be broken due to design changes, etc. **Crab crossing and focusing problems should be independent.**

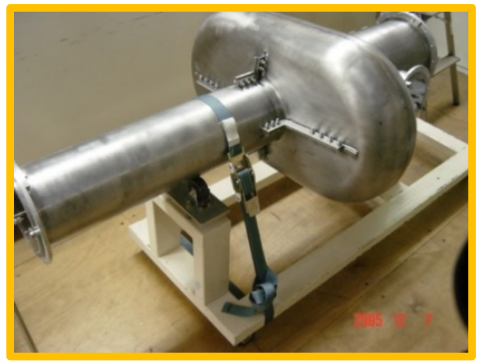
- By not including an extra device between the crab cavity and the focal point**, it is less susceptible to unexpected errors**.

- **Even with the present position of the crab cavity, the distance from the extraction line is within the acceptable range.**

Considering these factors, **it was decided to consider the present crab cavity position**.

Basic parameter for ILC crab cavity

KEKB crab cavity



Total kick voltage

- ✓ *The kick voltage was evaluated* ***for E_{CM}=250GeV ILC (beam energy is 125 GeV).***
- ✓ *Total voltage for the crab kick is smaller for the higher RF frequency.*

Cavity gradient

- ✓ *Cavity gradient was evaluated* ***by scaling to the KEKB dipole crab cavity as a reference****.*
- ✓ *The actual cavity gradient should be evaluated to be design-by-design.*

Relative RF phase jitter

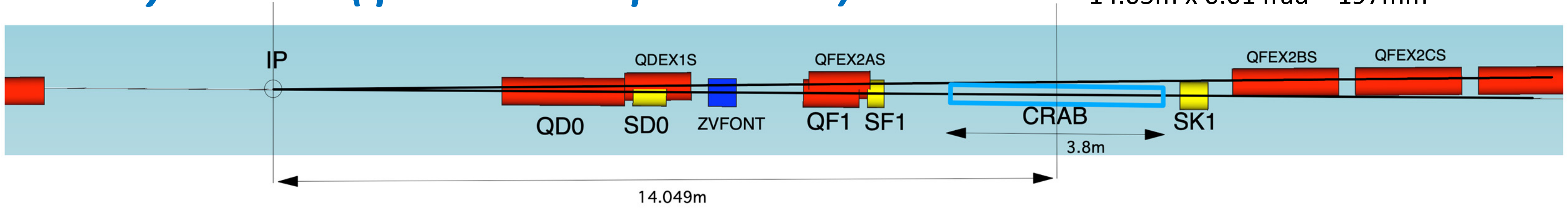
- ✓ *Since the requirement of the timing jitter is independent to the RF frequency,* ***the requirement of the phase jitter is severe for the lower frequency.***

Frequency		3.9 GHz	1.3 GHz	
# of cell		9 cell	3 cell	9 cell
Total length (pi/2 mode)		0.346 m	0.346 m	1.038 m
Total kick voltage	***Present location***	0.615 MV	1.845 MV	
	Alternative (s=77m)	0.878 MV	2.633 MV	
Cavity gradient	***Present location***	8.14 MV/m	24.4 MV/m	8.14 MV/m
	Alternative (s=77m)	11.6 MV/m	34.9 MV/m	11.6 MV/m
Relative RF phase jitter		0.069 deg rms. (49 fs rms.)	0.023 deg rms. (49 fs rms.)	

Tolerances of the crab cavity (May 2021)

Crab cavity location (present ILC optics deck)

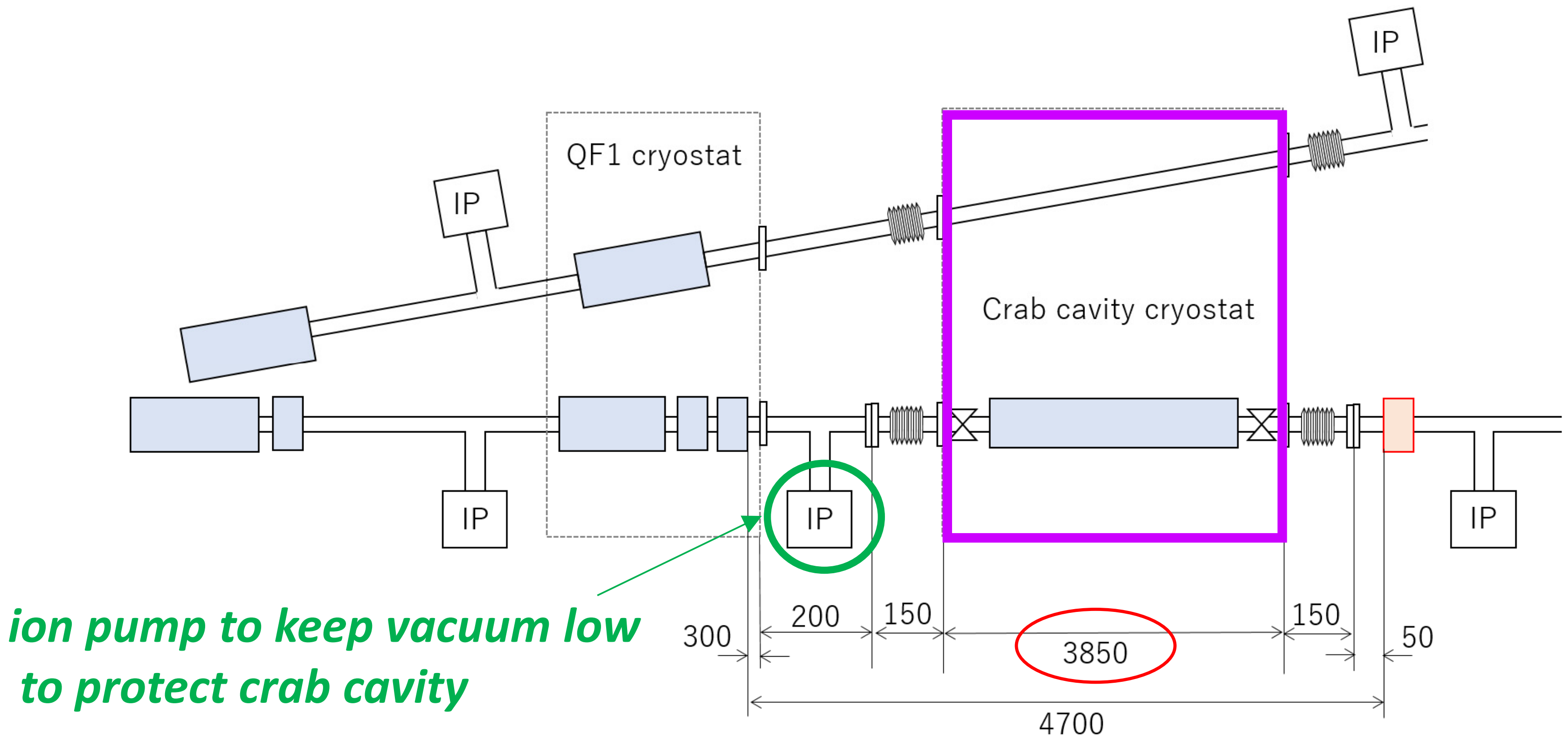
two beamline distance
14.05m x 0.014rad = 197mm



The tolerances were calculated only by geometrical effect, not included the beam-beam effect

	Parameters
Longitudinal distance from IP	14.05 m
Horizontal distance from dump line	0.197 m
Minimum aperture	**20 mm diameter (same as FD magnets)**
Beam sizes at crab cavity (x / y / z)	**0.97 mm / 66 um / 300 um**
R12 (crab cavity to IP)	17.4 m
R34 (crab cavity to IP)	**2.5 m**
Tolerance of horizontal beam tilt angle	0.35 mrad rms. (2% luminosity drop)
Tolerance of vertical beam tilt angle	7.4 urad rms. (2% luminosity drop)
Tolerance of cavity amplitude	**3.5 % rms. / cavity (2% luminosity drop)**
Tolerance of rotation of cavity field	**5.2 mrad rms. / cavity (2% luminosity drop)**
relative timing jitter requirement	49 fs rms. (2 % luminosity drop)

Crab cavity geometrical requirement (August 2022)



ion pump to keep vacuum low to protect crab cavity

- *Outer pipe diameter for extraction line is 90mm.*
- Inner pipe diameter for incoming beamline (crab cavity side) is 20mm.

- *To avoid contamination of the crab cavity, the vacuum in the warm section must be kept lower than that of the crab cavity when opening the gate valve of the crab cavity.*
- ***Only the warm section on the side of the crab cavity should have an ion pump.***
- ***The space available for the crab cavity is 3850mm*.**
- ***The crab cavity cryostat must be designed to include gate valves and thermal shields on both sides.***

Request from BDS Group

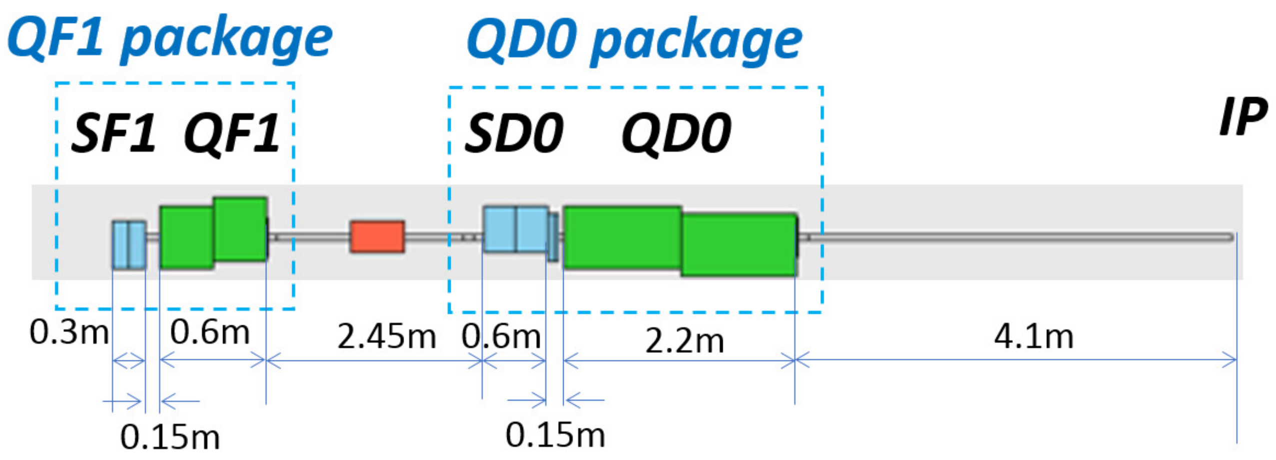
We would like you to select a technology *from among those that meet the following criteria**, with the primary focus on stability, such as difficulty of breakdown and stability of mode.***
We are not familiar with these aspects, so we would like the selection to be done in a professional and neutral manner.

Absolute requirements

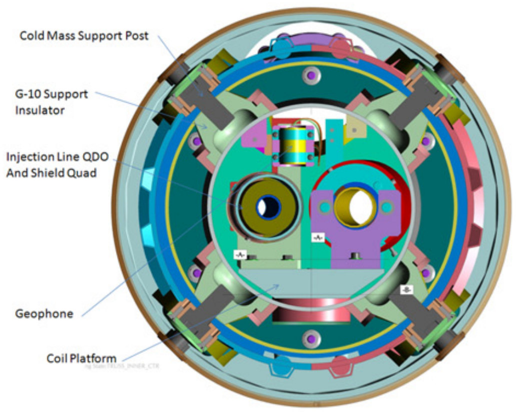
(1) Must fit within the beamline. **The crab cavities should accommodate to ECM=250 GeV, but preferably it should be able to accommodate to ECM=500 GeV using the same technology with additional cavities, etc.** For ECM=1TeV, the Final Doublet is also expected to be a completely different technology, and the geometry is also expected to be changed, so it is not necessary to use the same technology.

(2) Pipe diameter of 20 mm or more is required. Pipes in the extraction line should also be able to pass through.

Final doublt design



QD0 Cryostat



QD0 cryostat is the package of QD0, SD0 and extraction quadupole QDEX0.

Outer radius of the cryostat is 110mm.

Inner radius of beam pipe for QD0, SD0 is 10mm.
Inner radius of beam pipe for QDEX0 is 13mm.

Field strength of FD magnets

List of FD magnets for (QF1 L*)=9.1m, (QD0 L*)=4.1m

E_{CM} [GeV]	MAGNET	L* [m]	Length [m]	B $^{(1)}$ or 2B$^{(2)}$	B at coil [T] (*)
250	QD0	4.10	1.10	124.23	1.739
	SD0	6.45	0.60	2597.3	0.2545
	QF1	9.10	0.50	134.81	1.887
	SF1	10.25	0.30	2774.1	0.2719
500	QD0	4.10	2.20	124.66	1.745
	SD0	6.45	0.60	4310.5	0.4224
	QF1	9.10	1.00	144.40	2.022
	SF1	10.25	0.30	4395.5	0.4308
1000	QD0	4.10	2.20	249.32	3.491
	SD0	6.45	0.60	8563.0	0.8392
	QF1	9.10	1.00	288.79	4.043
	SF1	10.25	0.30	8892.1	0.8714

(*) Evaluated with simple scaling with R=0.014m, actual field will be larger than this simple scaling

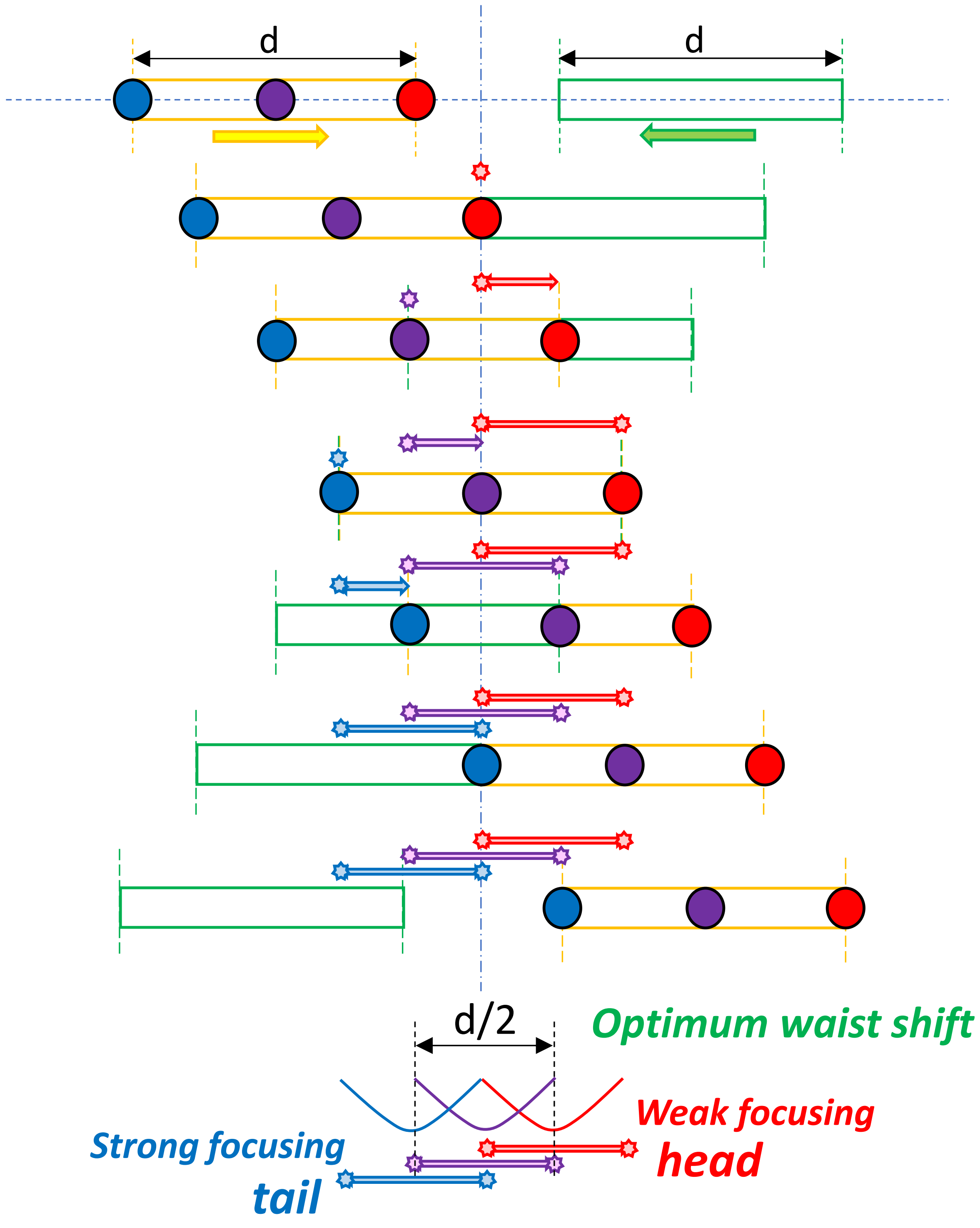
- *The design of the Final doublet assumes that it can handle up to 500 GeV using the same magnets.*
- *However, I believe a significant modification is needed for 1TeV operation.*
- *So that we can handle the final doublet for any energy upgrade scenario up to about 500GeV.*
- ***As for the crab cavity, I think it is desirable to have a technology that assumes an energy upgrade to about 500 GeV.***

Backup

Traveling focusing

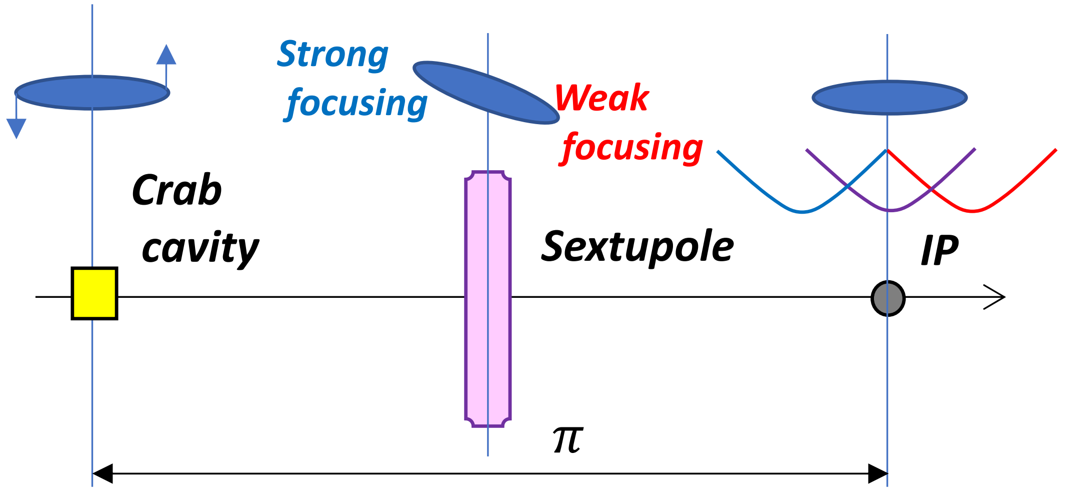
Traveling Focusing

Focus position is shifted from the bunch head to the bunch tail.



How to make the focus shift

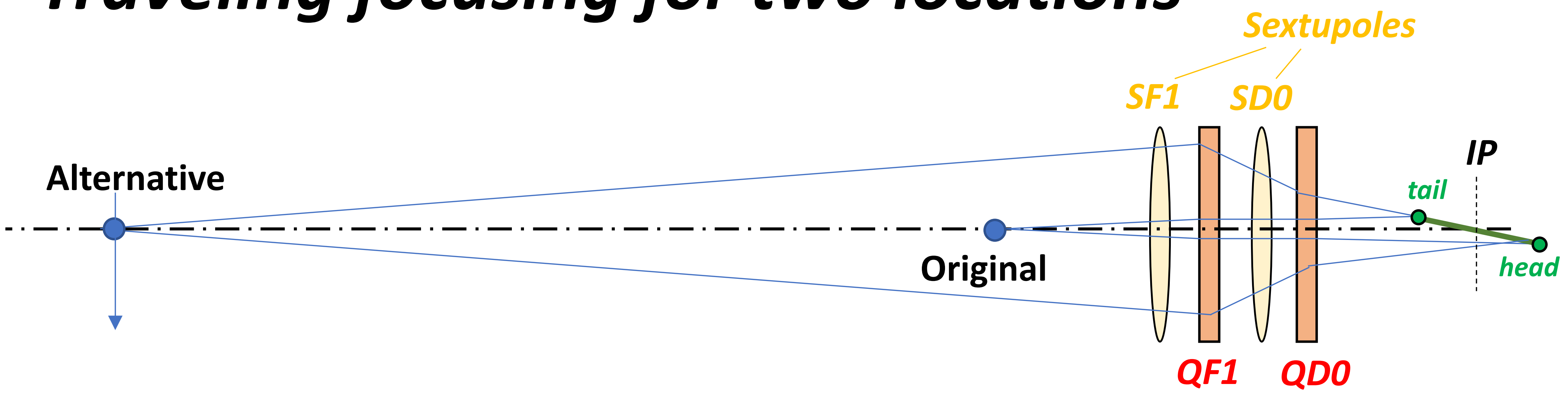
Position difference at bunch head and tail ⇨ *Different focusing at bunch head and tail*



- *When the phase advance between the crab cavity and IP is π, the horizontal position difference at IP is 0.*
- ***Amplitude of the focus shift can be controlled by changing the amplitude of the crab cavity.***

- *The traveling focusing is effective to reduce the hour-glass effect, especially for $\sigma_z > \beta_y^*$.*
  The hour-glass effect is not so strong for ILC250, but we have a few % of the luminosity improvement by the hour-glass effect ($\sigma_z = 300\mu m$, $\beta_y^* = 410\mu m$).
- *Since a beam is crossing to another beam with smaller beam size, the beam-beam effect is stronger.*

Traveling focusing for two locations



Horizontal beam orbit at FD is changed from the bunch head to the bunch tail

- ➢ *The vertical focal position was shifted from the bunch head to the tail.*

Waist shift

z	***Original***		***Alternative***	
	$\Delta\sigma_x$ at QF1	*$\Delta w_y/\sigma_z$ at IP*	*$\Delta\sigma_x$ at QF1*	*$\Delta w_y/\sigma_z$ at IP*
$+600\ \mu m\ (+2\sigma_z)$	$+1.30\ \mu m$	+0.14	$+13.1\ \mu m$	+1.03
$+300\ \mu m\ (+1\sigma_z)$	$+0.65\ \mu m$	+0.07	$+6.6\ \mu m$	+0.51
0	0	0	1	0
$-300\ \mu m\ (-1\sigma_z)$	$-0.65\ \mu m$	-0.07	$-6.6\ \mu m$	- 0.51
$-600\ \mu m\ (-2\sigma_z)$	$-1.30\ \mu m$	-0.14	$-13.1\ \mu m$	- 1.03

Bunch head

⇕

Bunch tail

Weak focusing

⇕

Strong focusing

Crab crossing

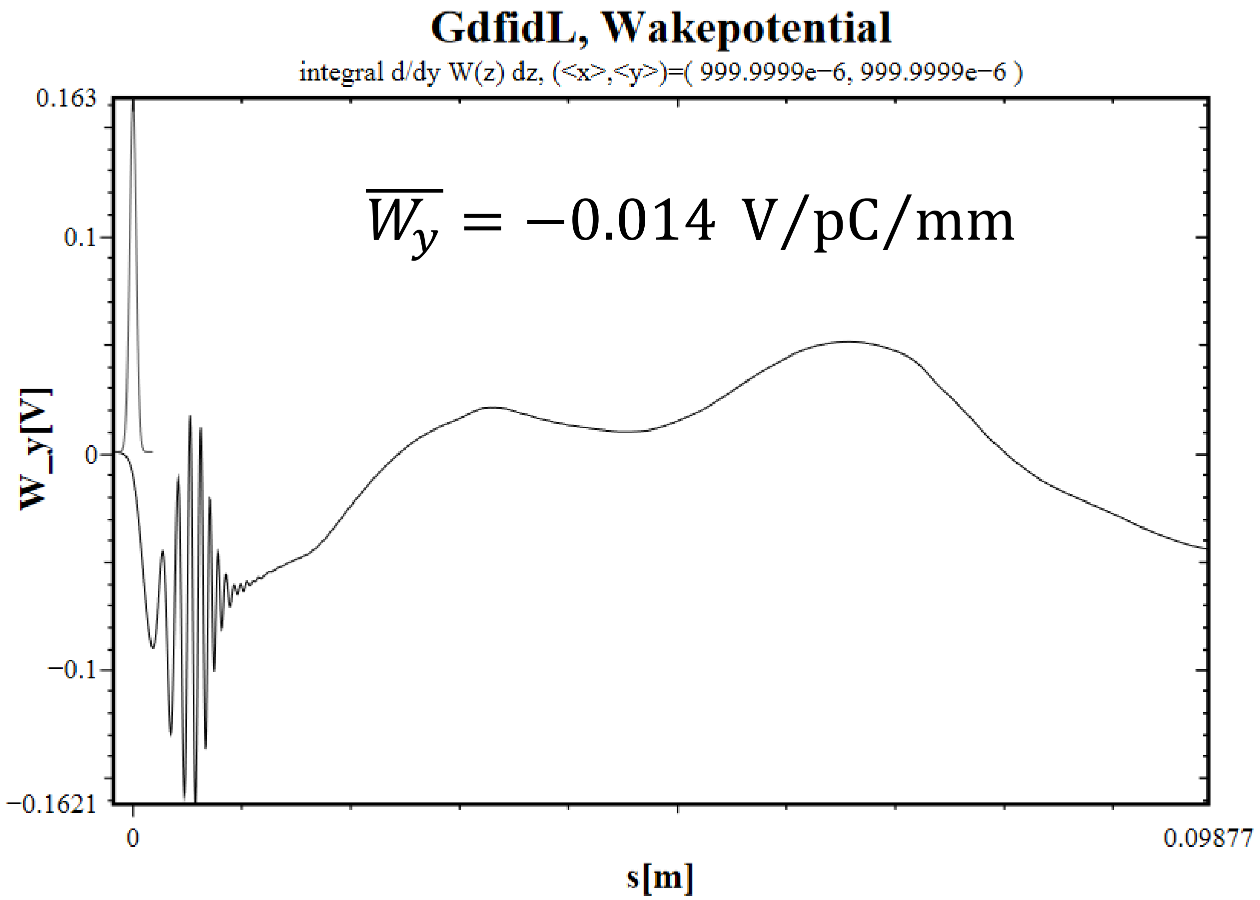
Crab crossing
+
Traveling focusing
(almost optimum amount)

But, we cannot change the strength of crab crossing and traveling focusing independently.

Short range wakefield of the crab cavity

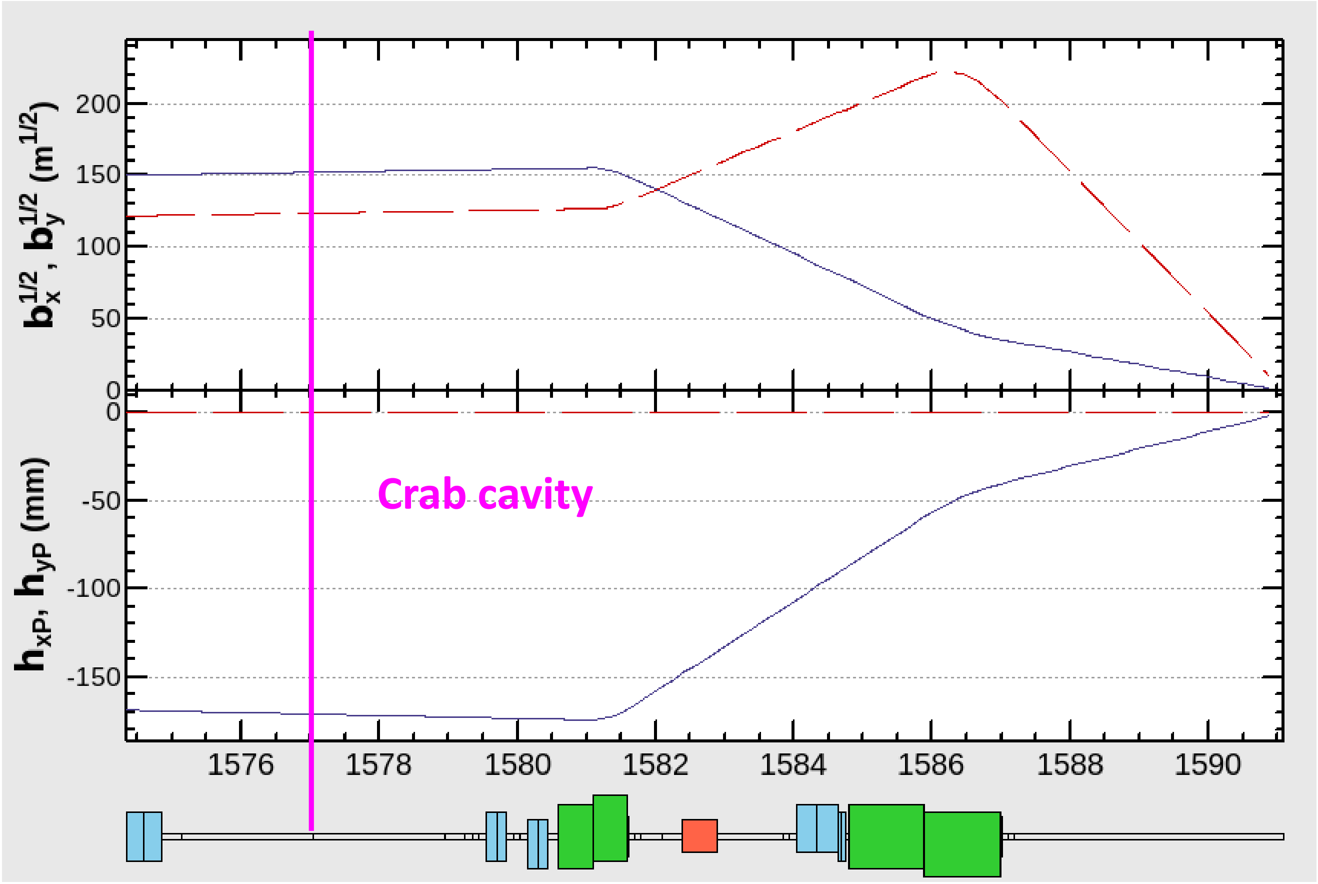
Shot range wakefield of the crav cavity

The short range wakefield was put to the ILC BDS optics deck (Ebeam=125GeV).



Wakefield calculation by Alexey Lyapin by GdfidL

- 1pC beam
- 1mm offset

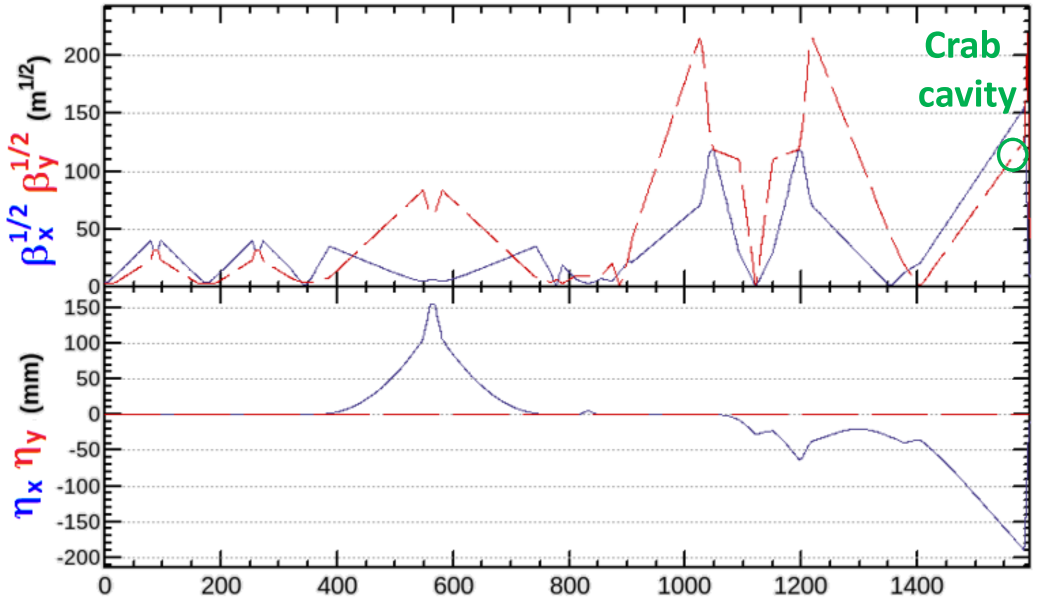


Put the wakefield here !

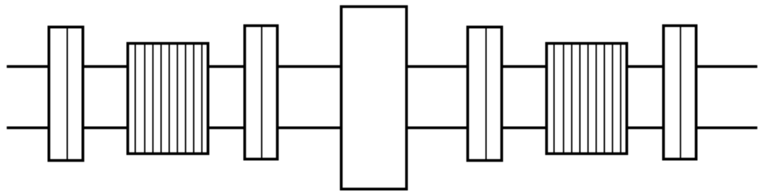
List of the wakefield sources in ILC BDS beamline

Total ***107*** *cavity BPM systems were put into the ILC collimator & final focus beamline as wakefield sources .*

Beam optics for ILC collimator / final focus



Component arrangement at BPM in simulation

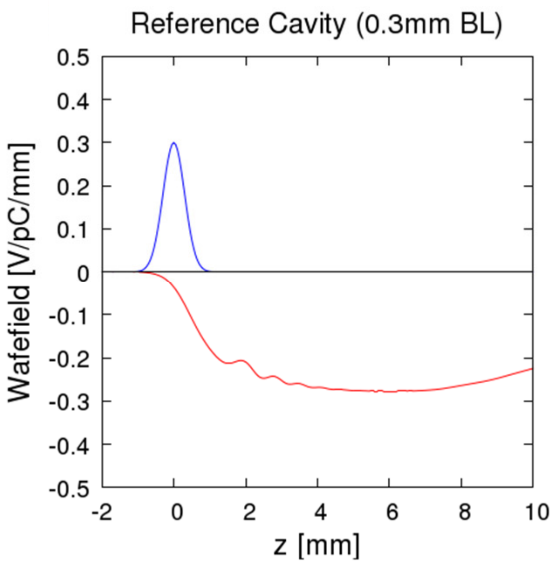


Case 1	**Case 2**
1 BPM	
2 bellows	⇒ masked
4 flanges	⇒ masked

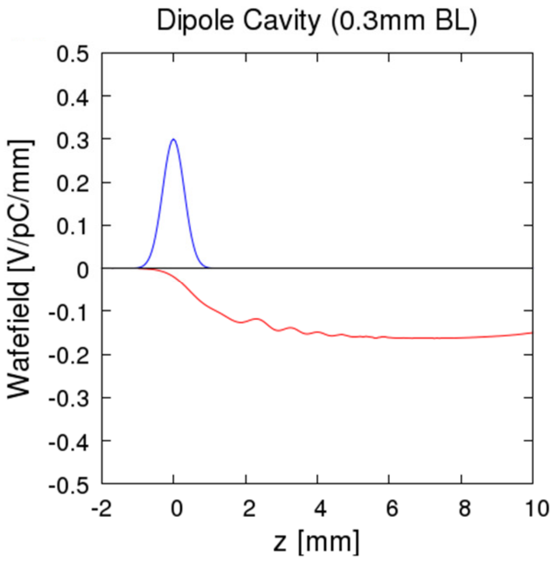
***Case 1 wakefield condition** :*
bellows and flange gaps are not masked.

***Case 2 wakefield condition** :*
cavity BPM wake is only put into beamline.
(bellows and flange gaps are masked.)

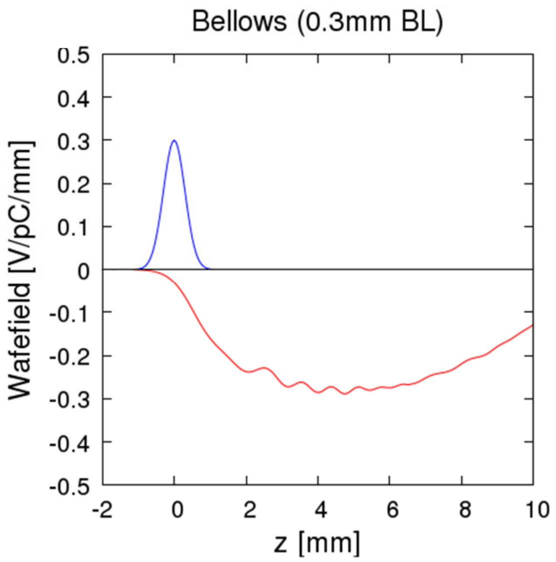
Locations of many wakefield sources are comparable or larger beta-function than crab cavity.



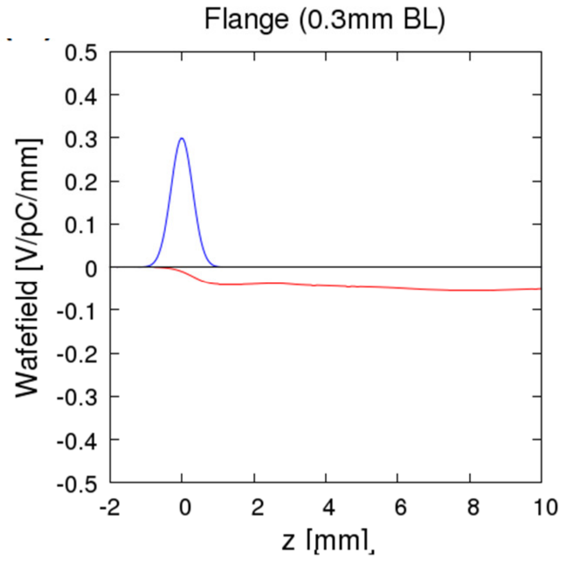
$\overline{W_y} = -0.048\ \mathrm{V/pC/mm}$



$\overline{W_y} = -0.025\ \mathrm{V/pC/mm}$



$\overline{W_y} = -0.040\,\mathrm{V/pC/mm}$



$\overline{W_y} = -0.014\,\mathrm{V/pC/mm}$

$\overline{W_y} = -0.014\ \mathrm{V/pC/mm}$ of crab cavity wake field is not dominant in the BDS beamline.

Simulation of dynamic wakefield effect for single bunch beam

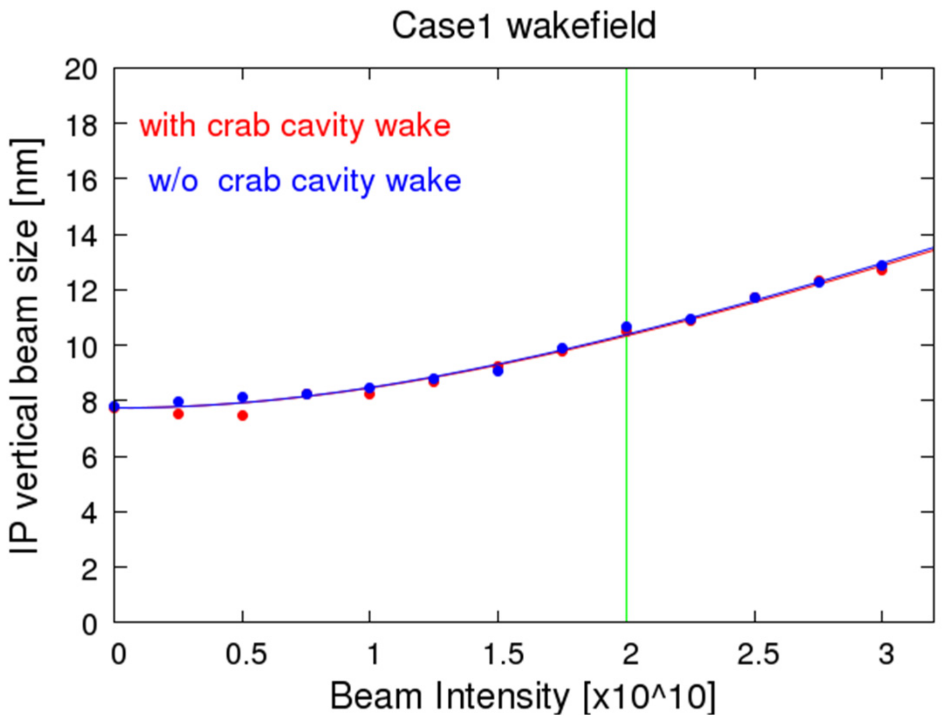
Effect of wakefield with orbit distortion (orbit jitter) was evaluated as

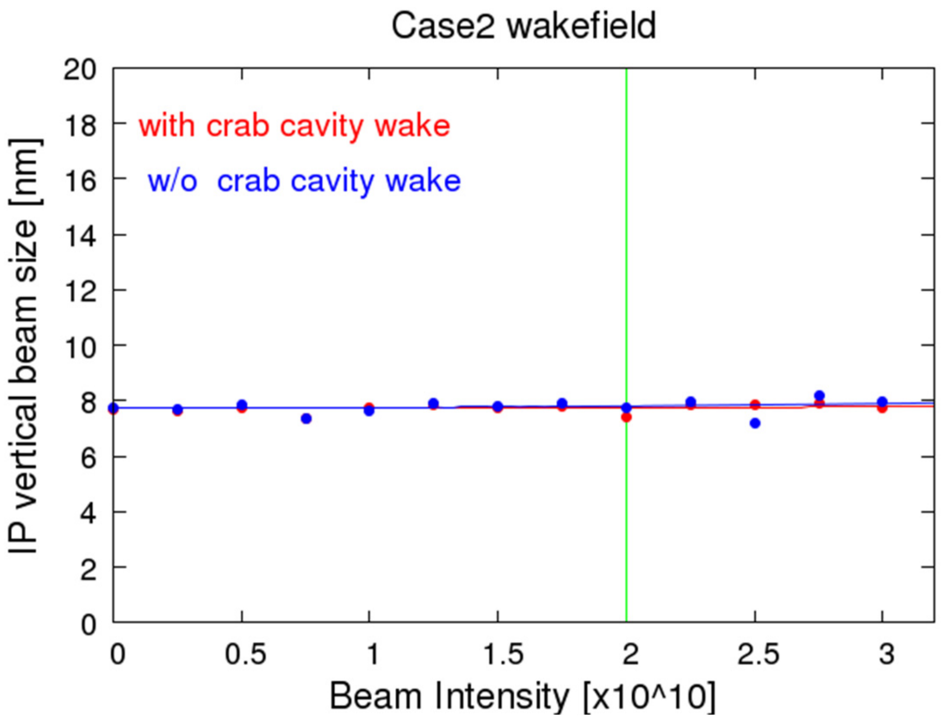
$$\frac{\sqrt{\sigma^2-\sigma_0^2}}{\sigma_0} \propto \frac{q}{E}\sum W\beta$$

q : bunch charge
W : strength of wakefield
E : beam energy
e : emittance
b : beta-function at wake source

	W[V/pC/mm]* beta [m]
Crab cavity	**-214**
ILC Case 1	-142352
ILC Case 2 (only cavity BPMs in BDS beamline)	-22104

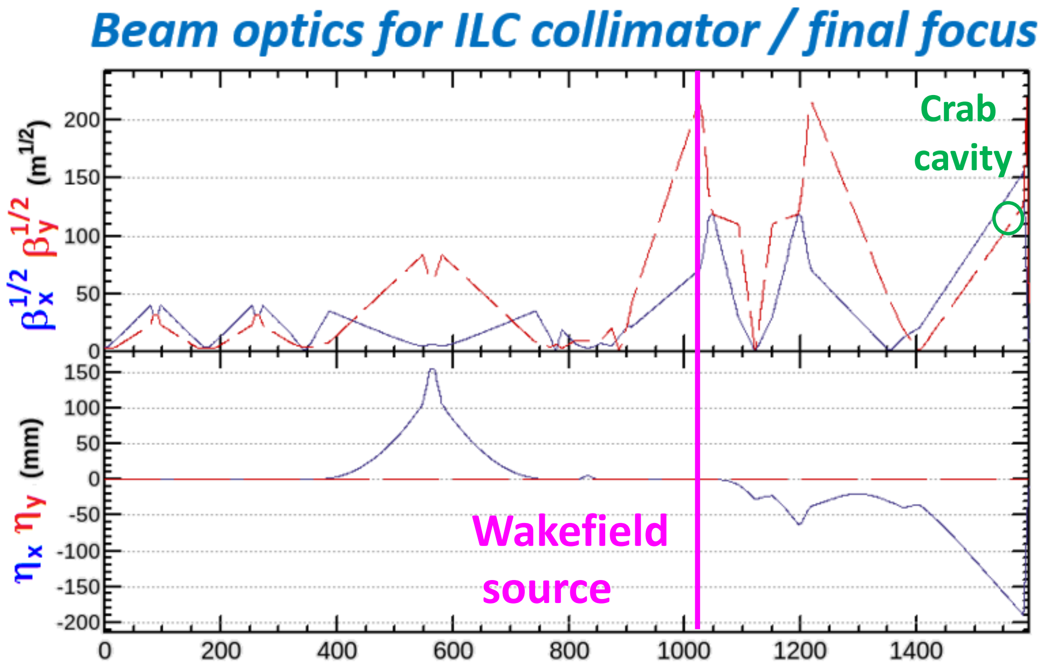
Roughly 1% of those for cavity BPMs in ILC BDS beamline





For the dynamic wakefield effect on the single bunch, the simulations did not show any discernible difference with and without the Crab cavity.

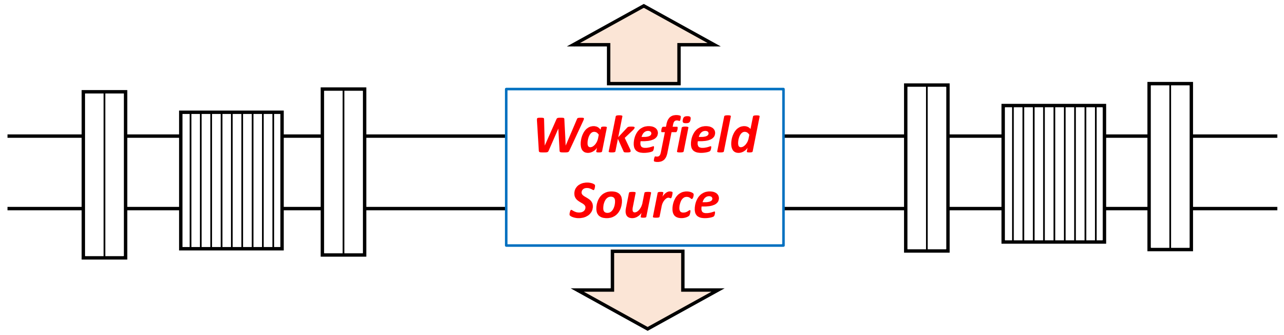
Simulation of static wakefield effect for single bunch beam



Beam optics for ILC collimator / final focus

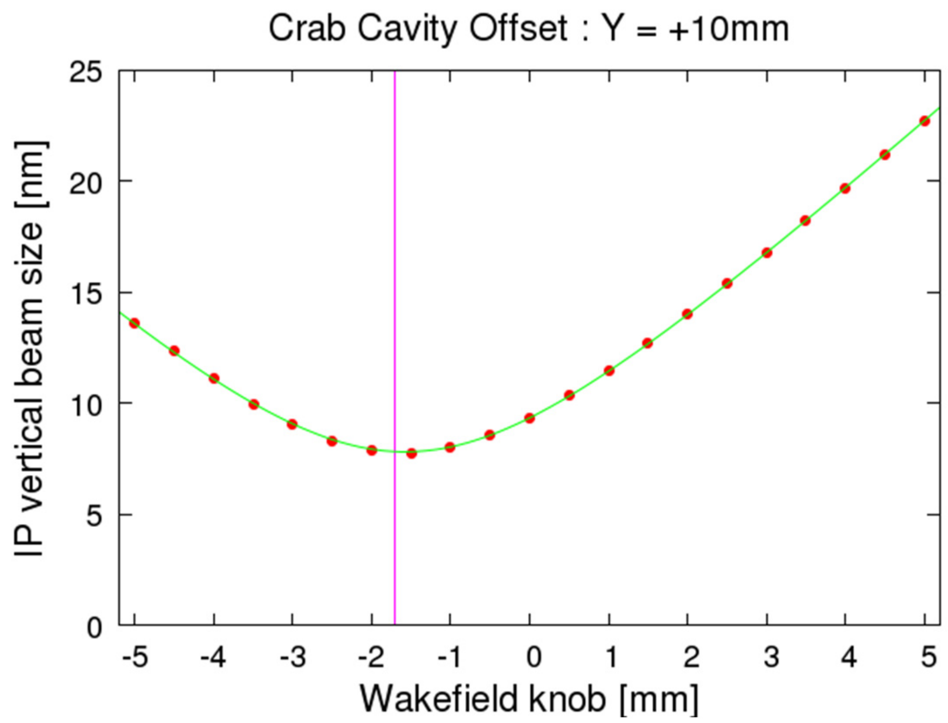
Wakefield knob

By changing the wakefield source position,
the wakefield of BDS beamline can be cancelled.

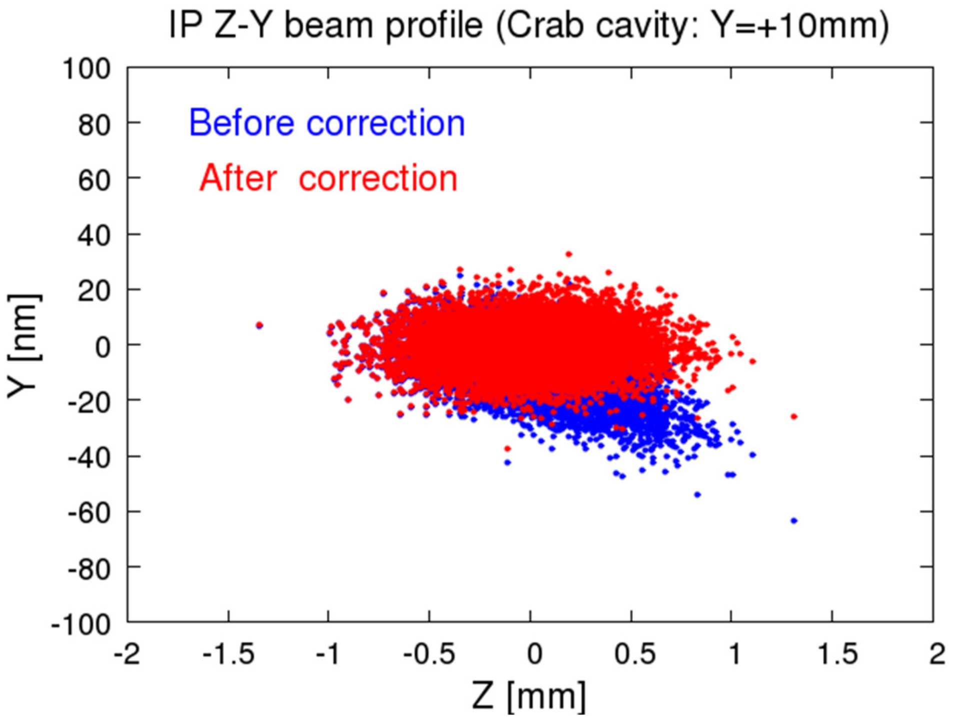


Wakefield knob was used C-ban reference cavity here.

- **Put +10mm offset to crab cavity**
  - IP vertical beam size was increased 7.7nm => 9.4nm
- **Apply the wakefield knob by -1.7mm**
  - IP vertical beam size was reduced 9.4nm => 7.7nm



Crab Cavity Offset : Y = +10mm



IP Z-Y beam profile (Crab cavity: Y=+10mm)

The effect of the sigle bunch static wakefield for crab cavity is not significant.
Even if we put 10mm offset, we can correct the effect by using wakefield knob.

Brief summary

- The impact of the Crab cavity on the single bunch wakedield is not significantly larger than those of other wakefield sources in the ILC BDS.

- Both static and dynamic effects were found to be acceptable in the simulations.

- When the short range wakefield is comparable to this sample, we don't have to consider the short range wakefiel effect.

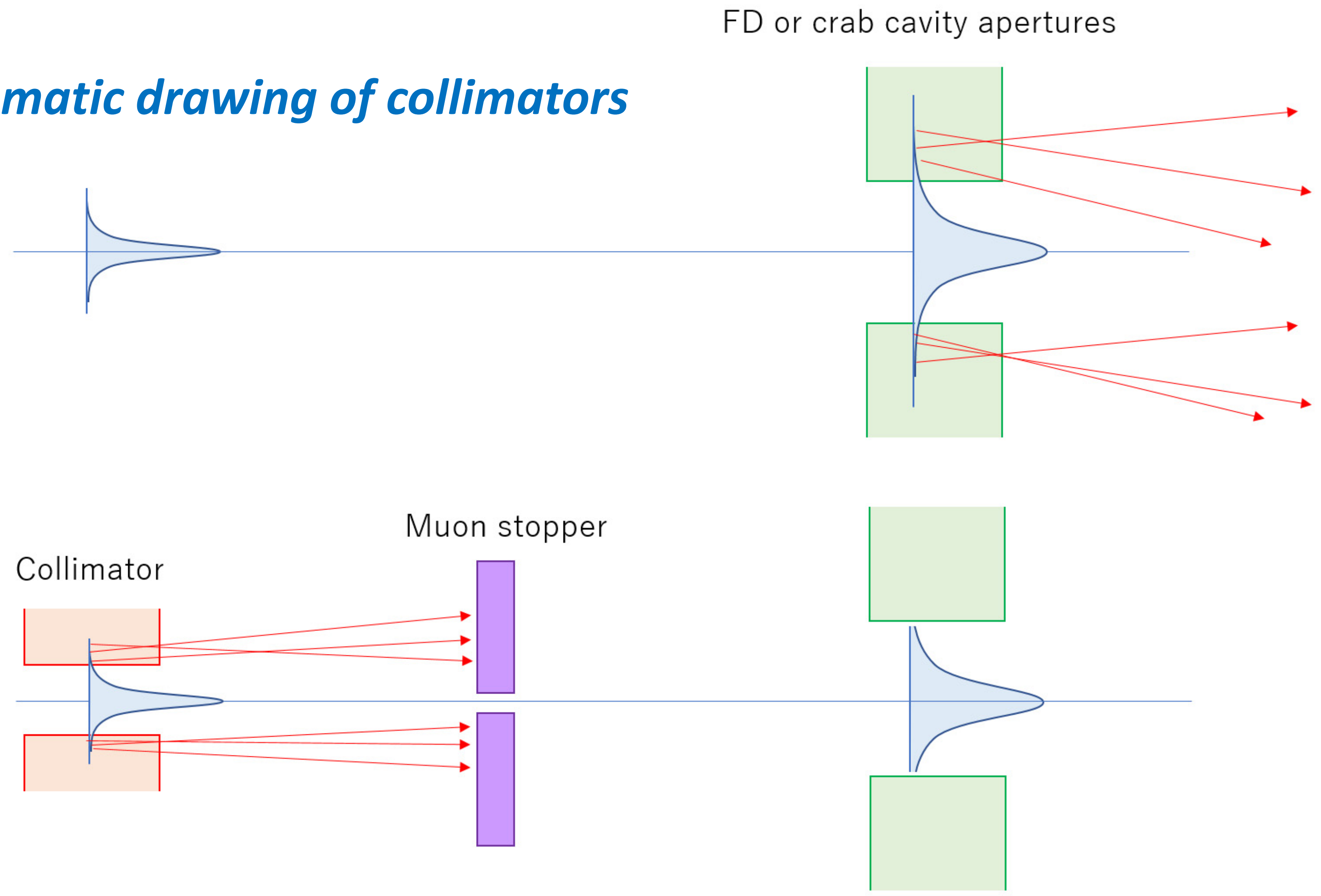
- Considering the large Q-value of superconductivity, I think we need to discuss carefully about the long range wakefield.The amplitude of the beam oscillation shown in the previous meeting, for example, may need to be carefully evaluated.

- As for the long range wakefield, it is an issue to investigate in detail the effect of resistive wall impedance in the pre-lab period in addition to the crab cavity.This may be an item to be considered at that time.

Aperture requirement of the ILC crab cavity

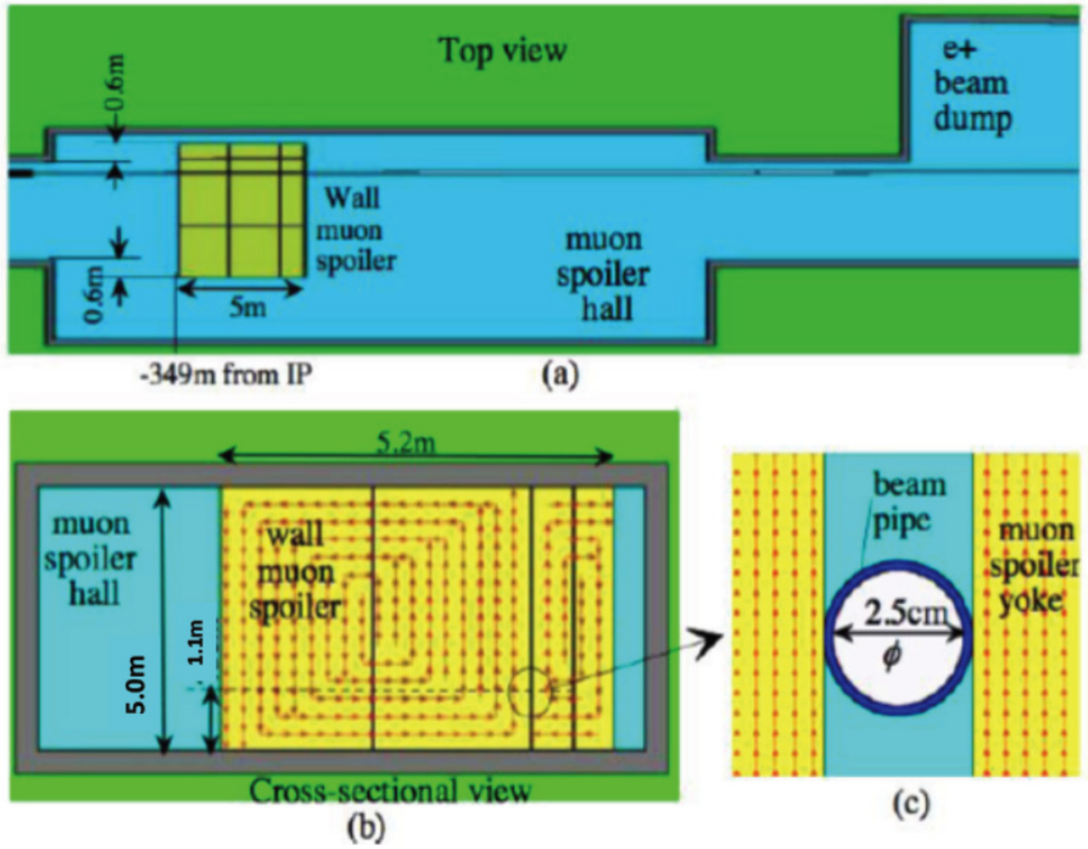
Concepts of the ILC collimator system

Schematic drawing of collimators

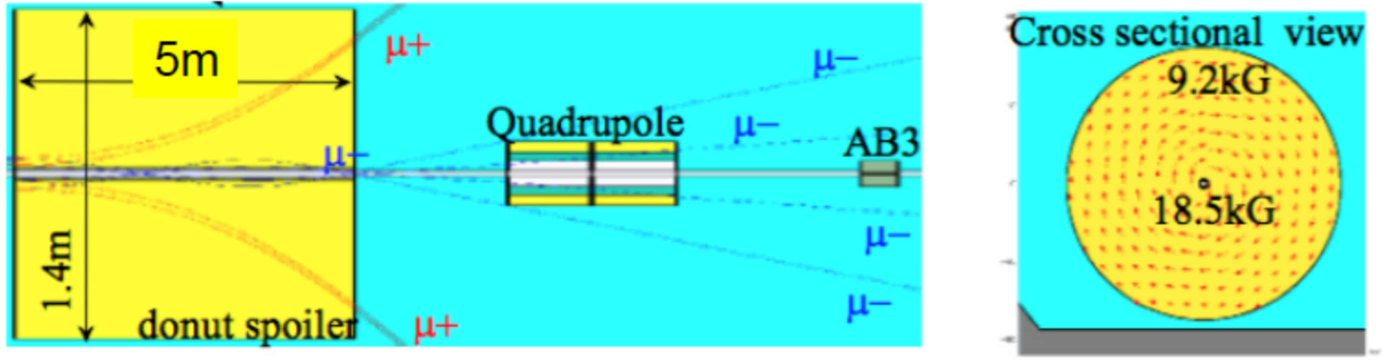


- *In ILC, a collimator is placed upstream to prevent the beam halo from hitting the final doublet or crab cavity.*
- *Since the beam halo hitting the collimator produces a large amounts of secondary particles (muons, etc.), it is necessary to install a large muon stopper to prevent the muons from reaching the detector.*

Muon wall



Muon spoiler (donuts spoiler)

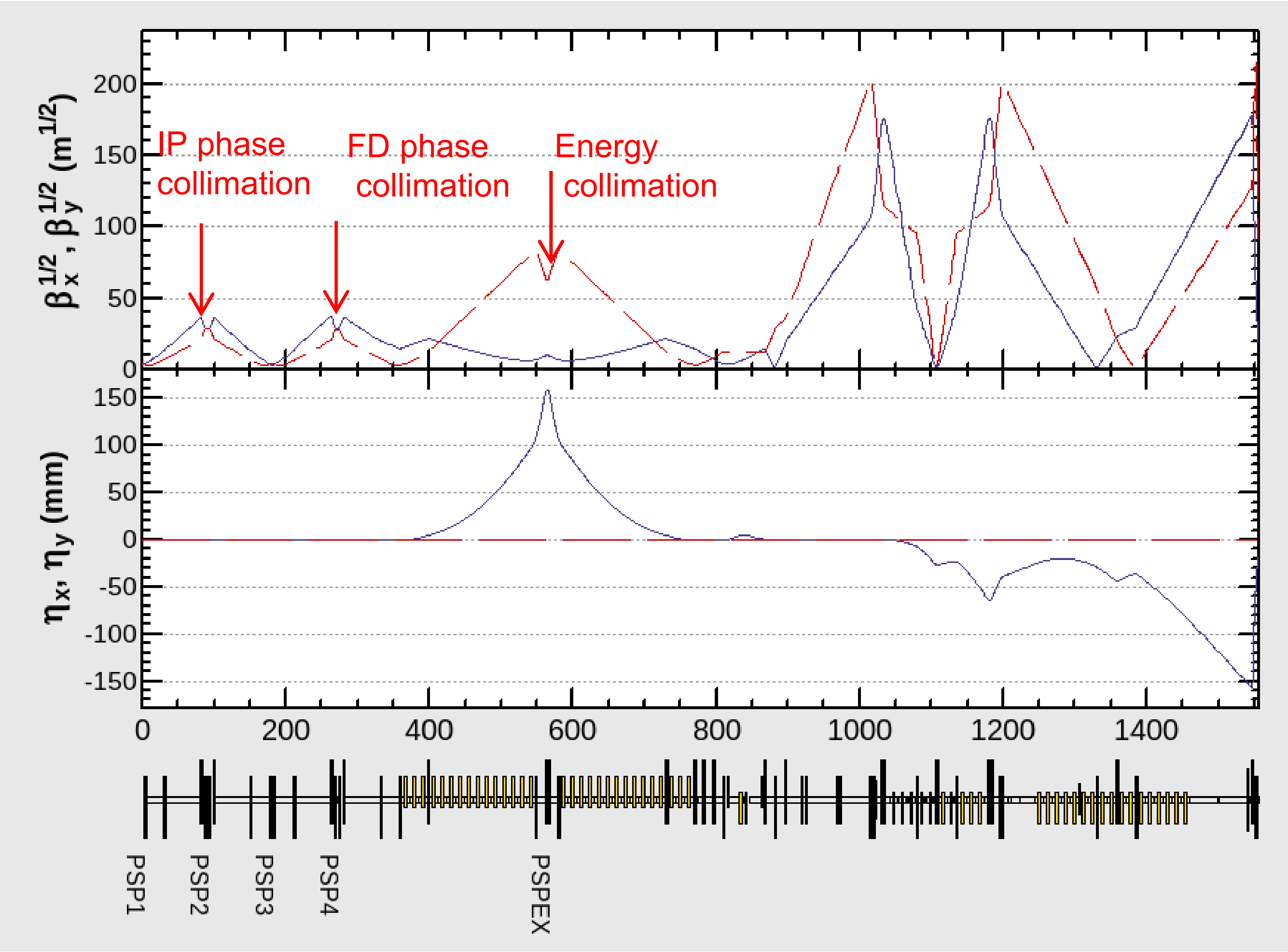


Consideration of collimation depth

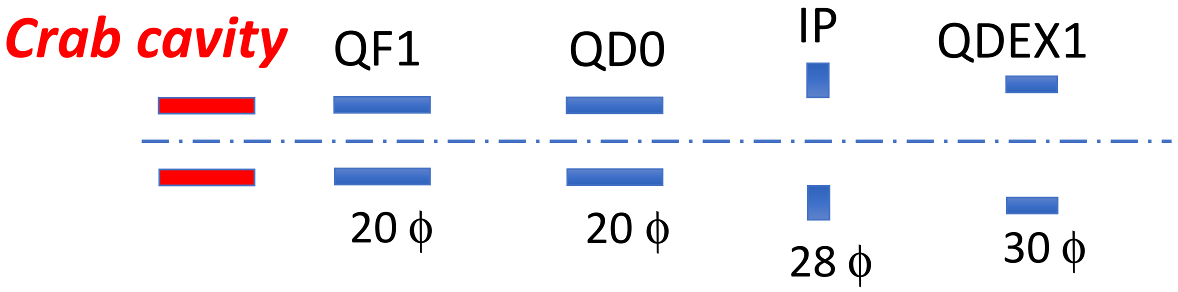
- *The aperture of ILC collimator is determined so that the halo particles and SR generated by the halo particles do not hit the SC device or inner detector.*
- *The collimation depth (aperture of the collimator relative to the beam size) should be larger because the more halo particles are cut at the collimators and much number of the muon background is generated for the smaller aperture of the collimator.*
- *The current design is limited by the aperture of the SC magnets before and after the detector, which is only 6σ of the beam size horizontally.*

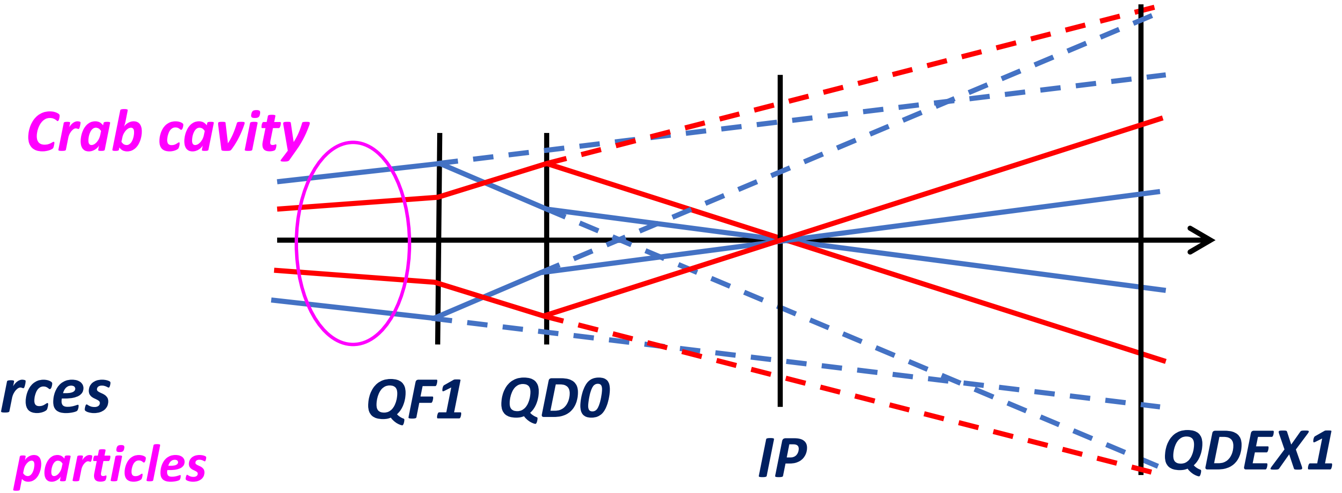
Arrangement of the Collimators

Beta Function at SP2/SP4 = (X; 1000m / Y; 1000m)
Phase Advance (SP2/SP4) = (X; 0.5 pi / Y; 1.5 pi)
Phase Advance (SP4/ IP) = (X; 5.5 pi / Y; 4.5 pi)
EtaX at SPEX = 0.150m



Collimation depth are determined by the following apertures





BG sources

1) *Halo particles*
2) *SR, generated by halo particles at QF1*
3) *SR, generated by halo particles at QD0*

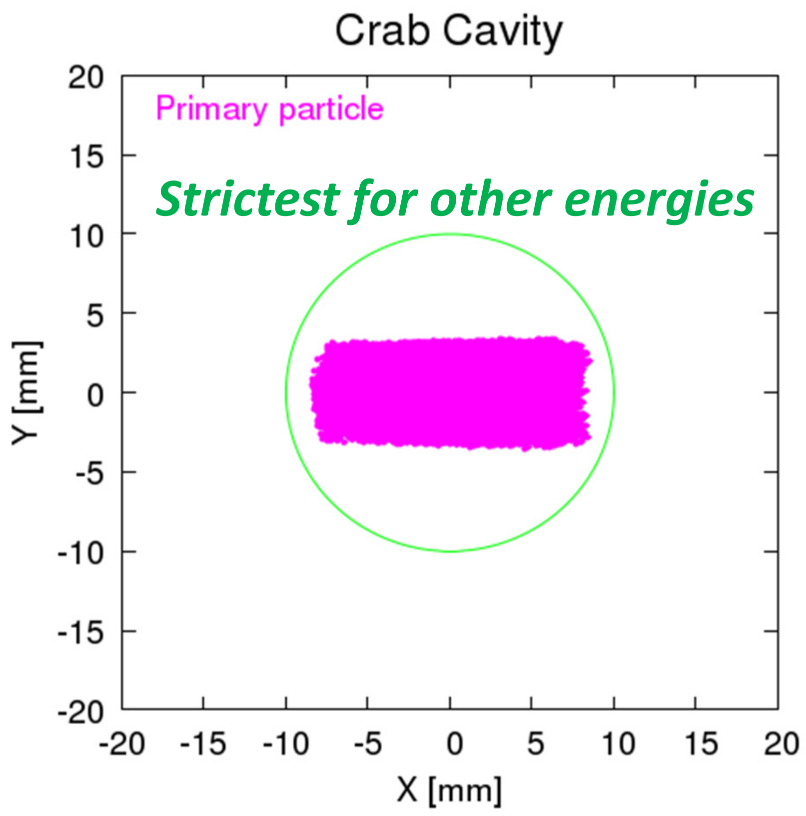
ILC IP parameters

- *The luminosity values were modified from the TDR description in CR-5.*
- *In CR-16, the horizontal emittance was reduced for ECM=250 GeV operation (no other energies were discussed).*

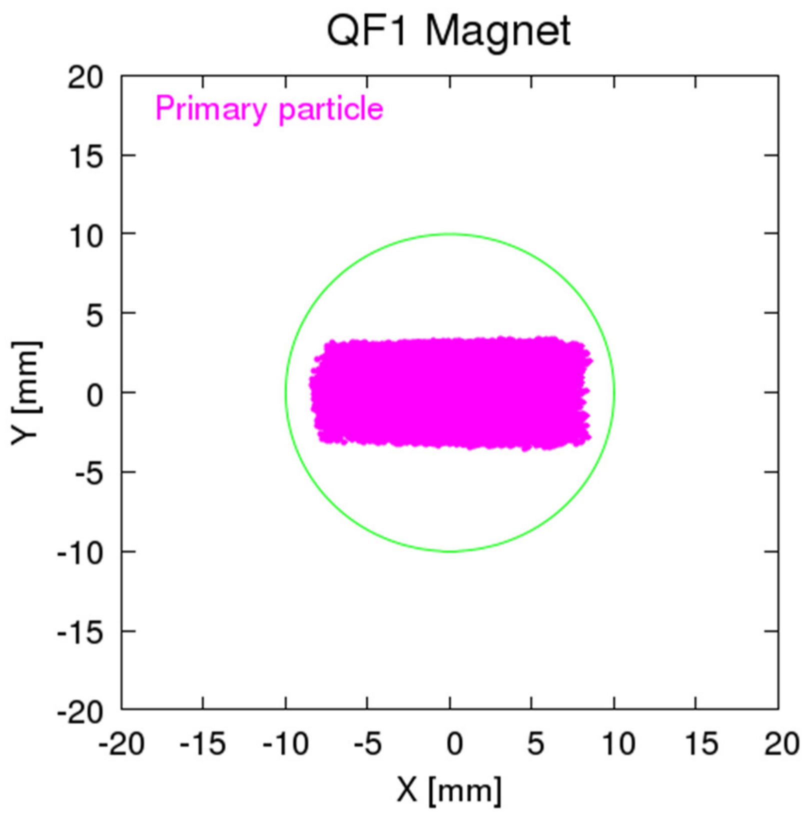
E_{CM} [GeV]	**250**		**350**	**500**
	TDR	**CR-16**	**TDR**	**TDR**
$\gamma\varepsilon_x$ [µm]	10	5	10	10
$\gamma\varepsilon_y$ [µm]	0.035	0.035	0.035	0.035
β_x^* [mm]	13	13	16	11
β_y^* [mm]	0.41	0.41	0.34	0.48
σ_x^* [µm]	0.729	0.515	0.684	0.474
σ_y^* [nm]	7.66	7.66	5.89	5.86
D_x	0.26	0.51	0.21	0.30
D_x	24.50	34.50	24.30	24.57
δ_{BS} [%]	0.96	1.90	1.53	4.50
L [$\times 10^{34}$]	0.82	1.35	1.00	1.79

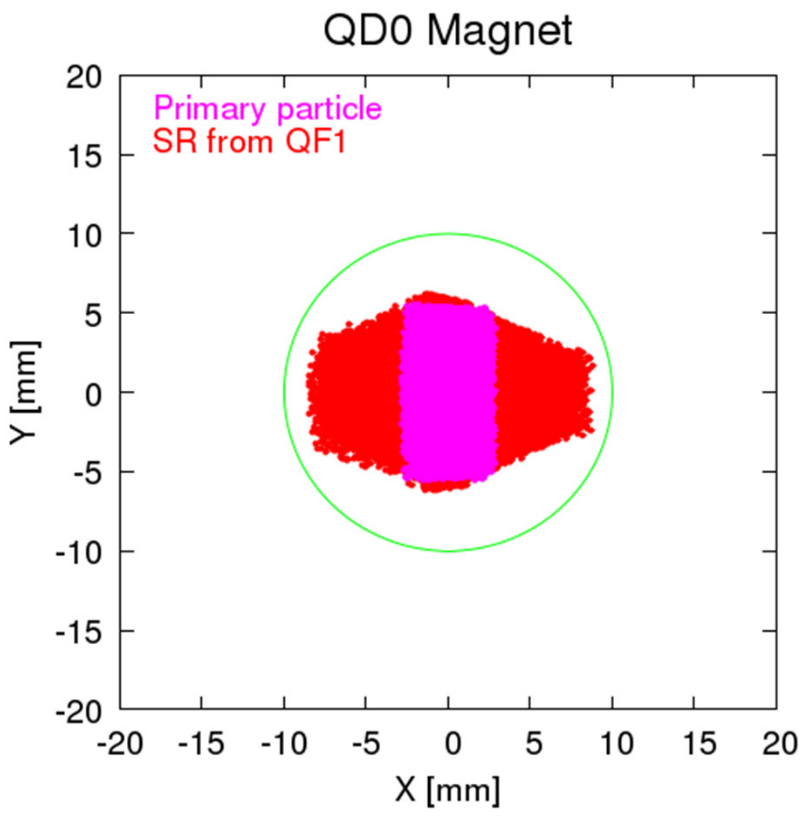
The collimation depths shown below are calculated based on the parameters of this latest ILC.

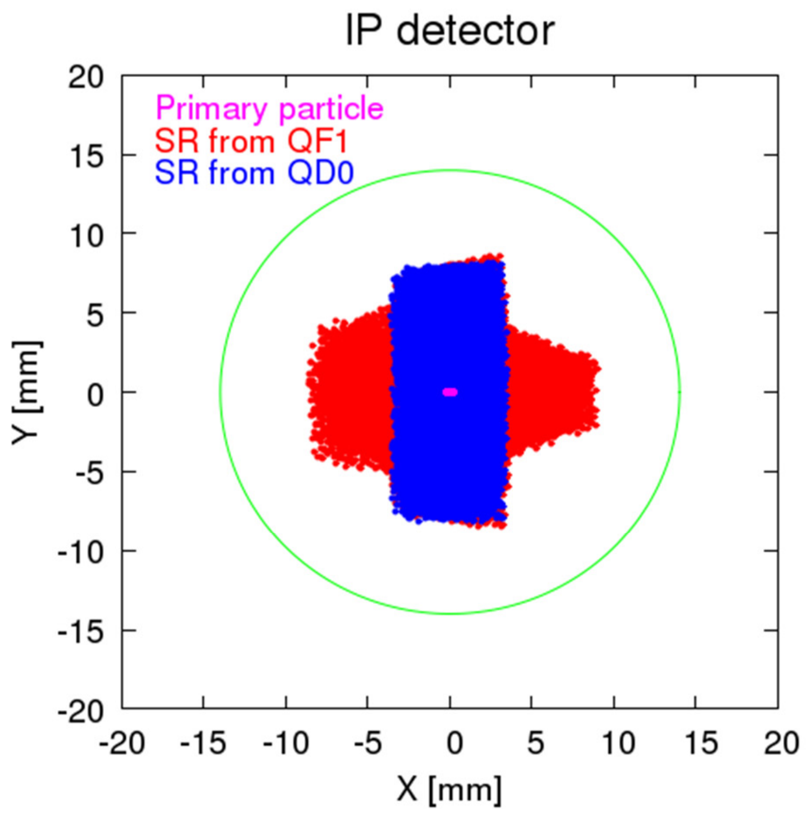
Result of simulation for collimation depth evaluation (ECM=250GeV)

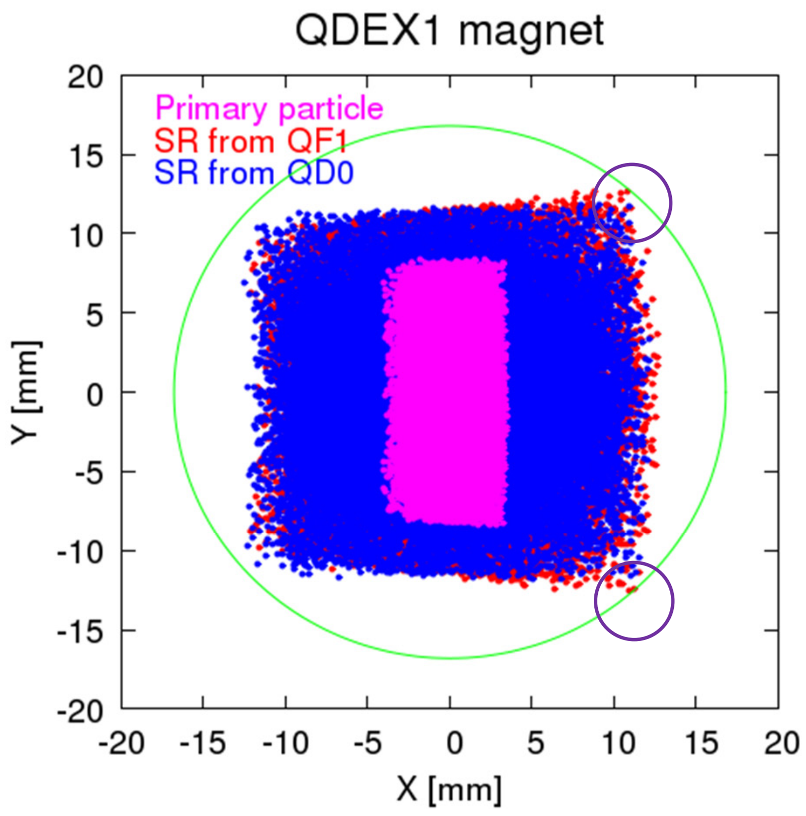

Crab Cavity

Strictest for other energies


QF1 Magnet


QD0 Magnet


IP detector

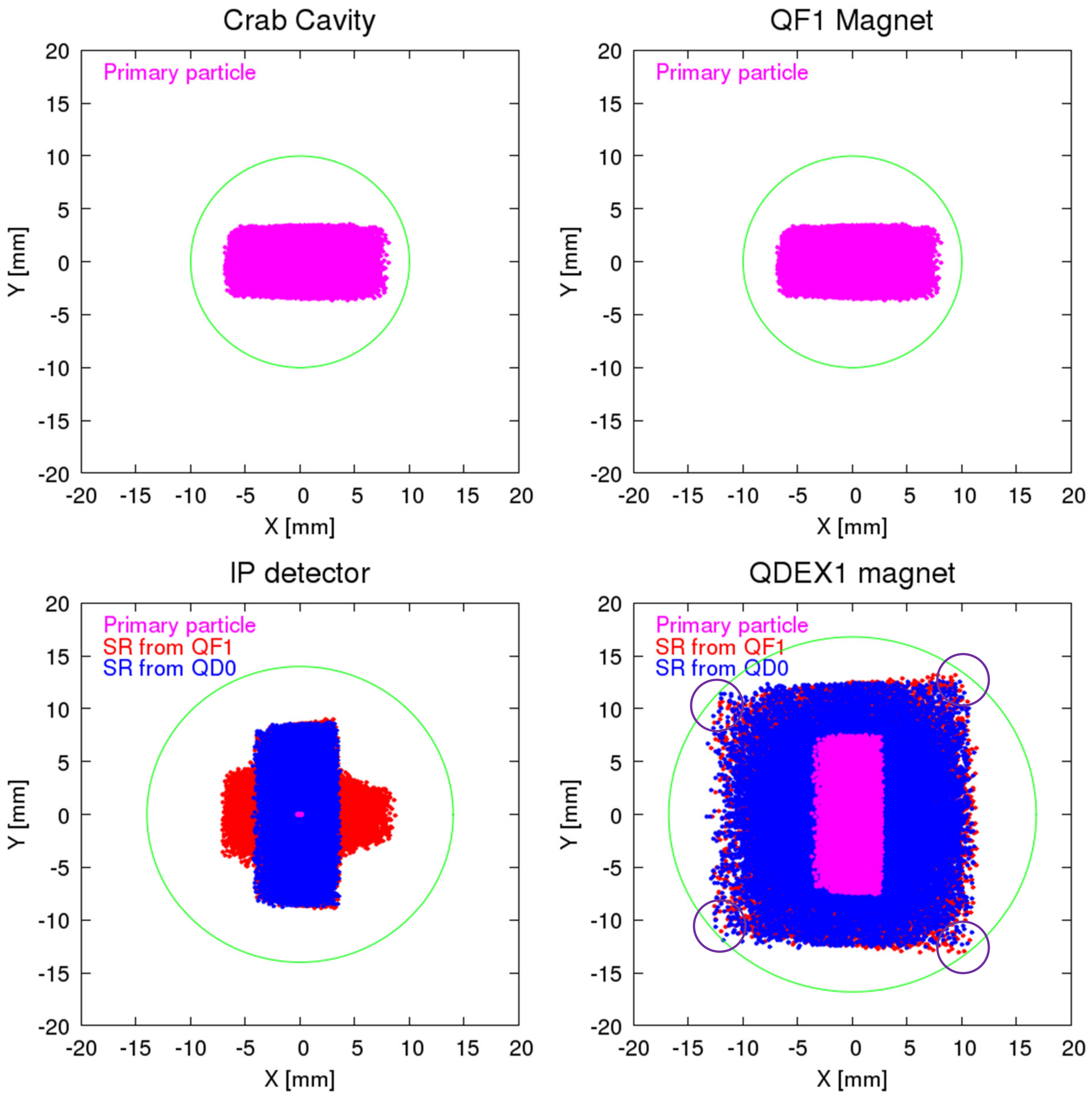

QDEX1 magnet

Maximum collimator full aperture

X : 3.06 mm
Y : 3.10 mm

- Collimator aperture is limited by SR from QF1 and QD0 to QDEX1
- The tightest apertures for the primary particle are the crab cavity and QF1.

Result of simulation for collimation depth evaluation (ECM=350GeV)



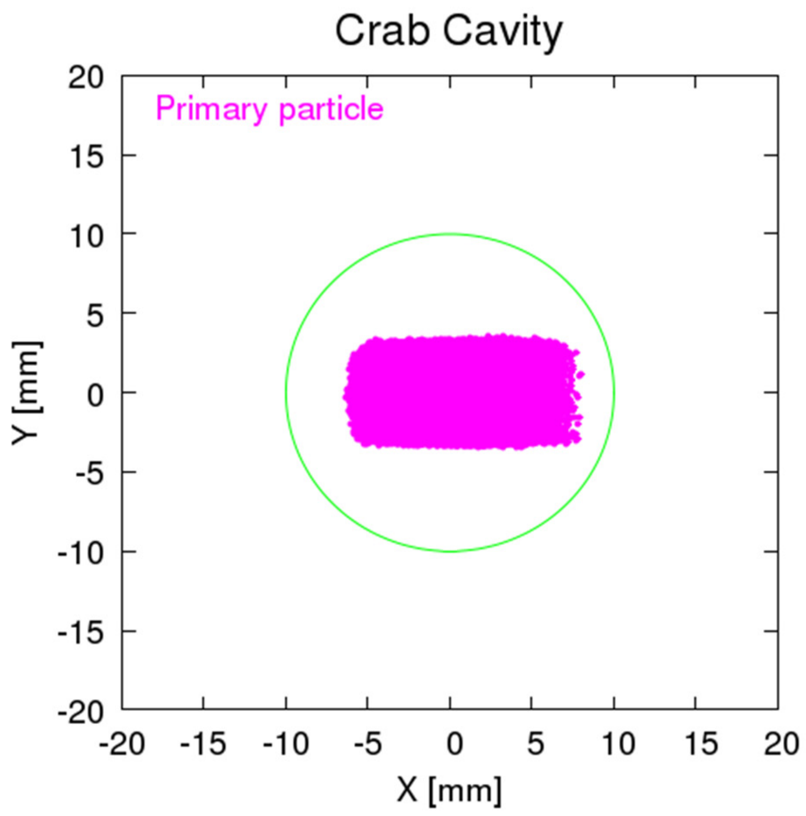
Maximum collimator full aperture

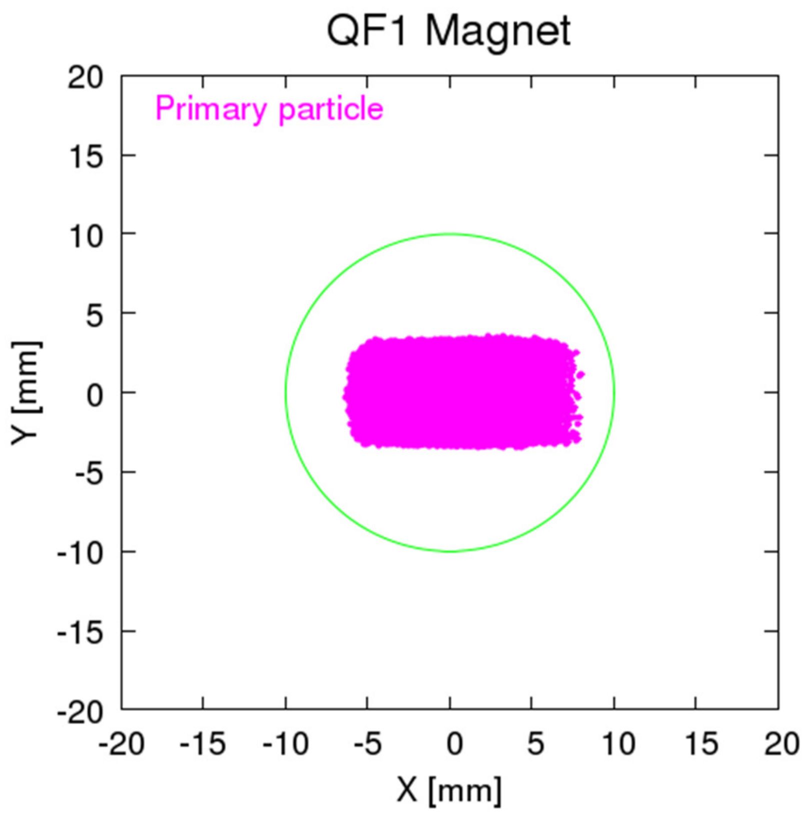
X : 2.74 mm

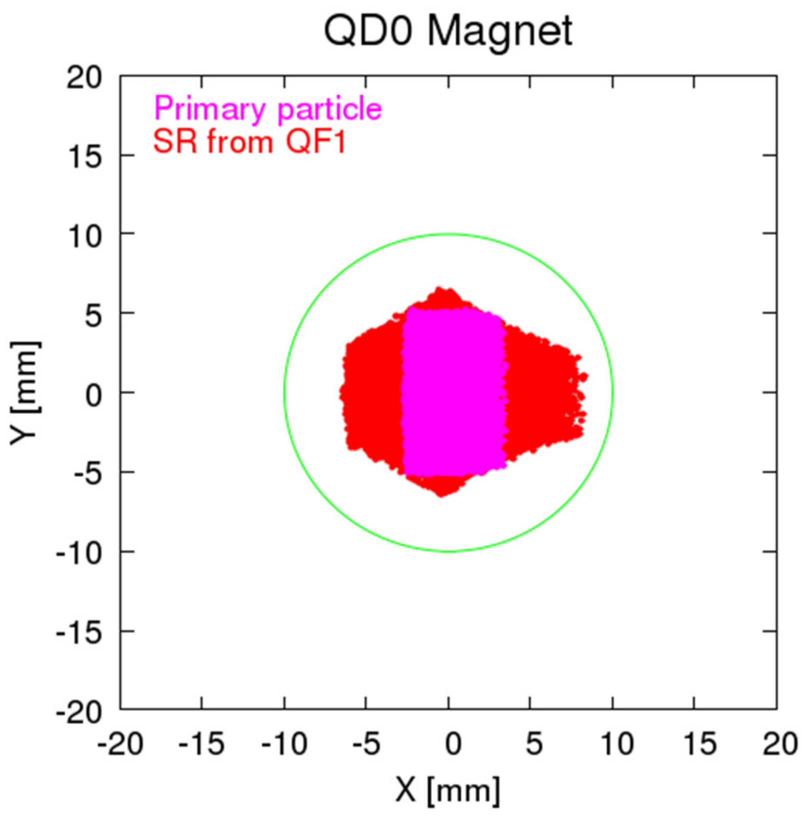
Y : 2.56 mm

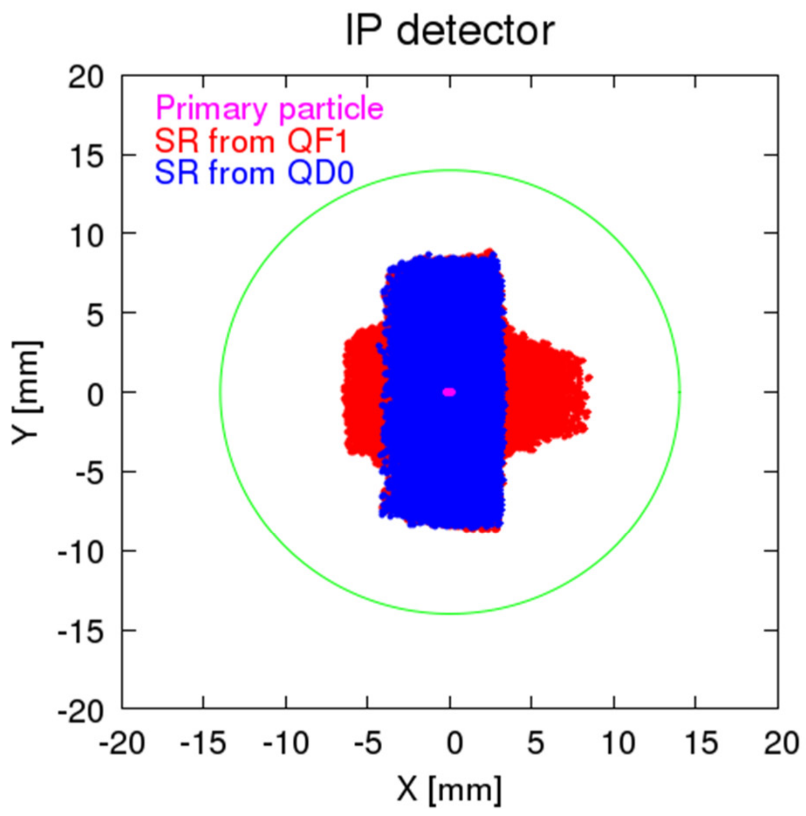
- Collimator aperture is limited by SR from QF1 and QD0 to QDEX1
- The tightest apertures for the primary particle are the crab cavity and QF1.

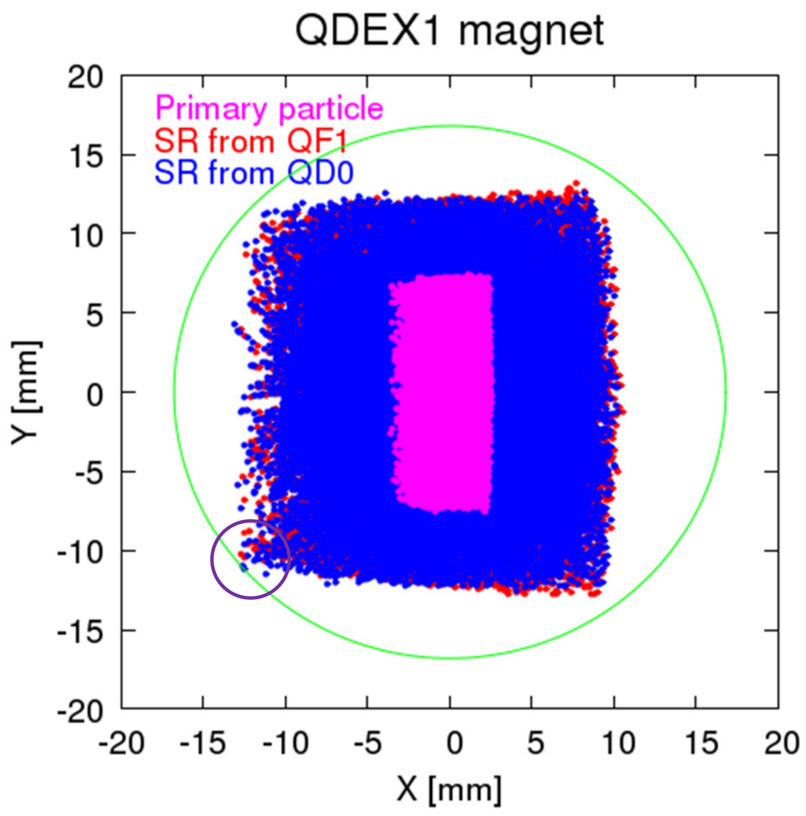
Result of simulation for collimation depth evaluation (ECM=500GeV)


Crab Cavity


QF1 Magnet


QD0 Magnet


IP detector


QDEX1 magnet

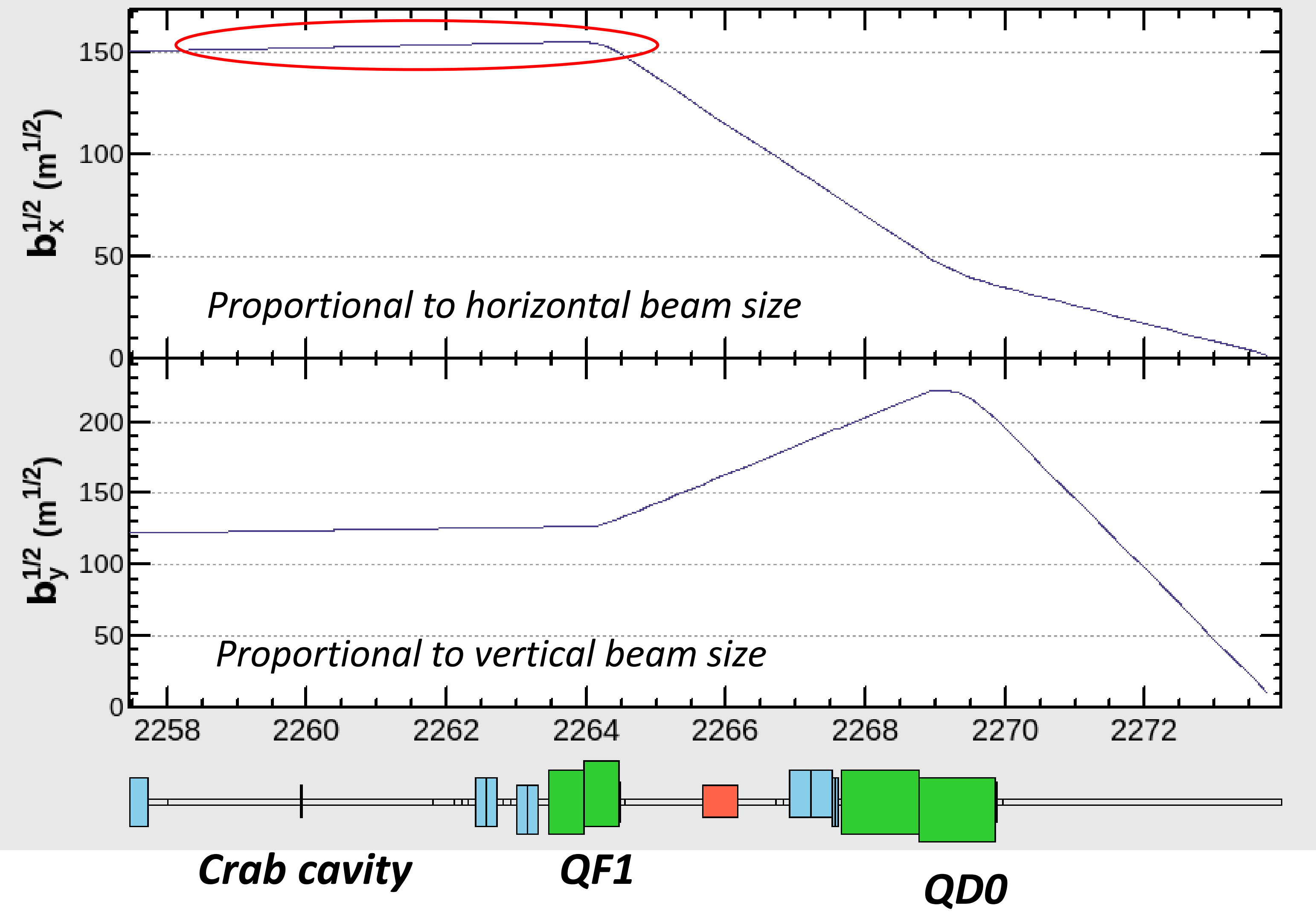
Maximum collimator full aperture

X : 2.06 mm
Y : 2.96 mm

- Collimator aperture is limited by SR from QF1 and QD0 to QDEX1
- The tightest apertures for the primary particle are the crab cavity and QF1.

Halo particle at crab cavity

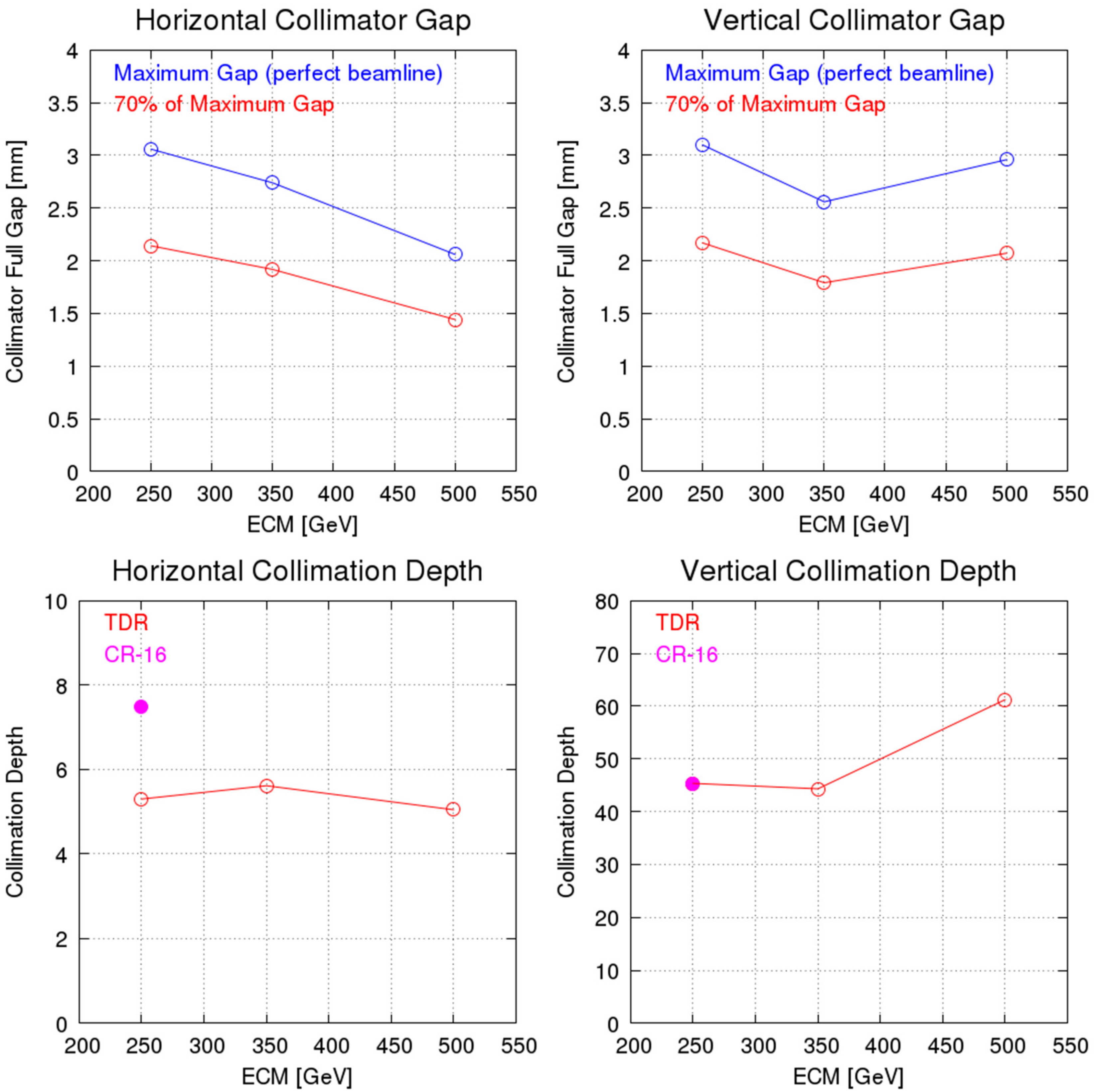
Beta functions around IP



- *Since horizontal beam size at crab cavity is comparable to that at QF1, the distribution of halo particles in the horizontal direction is almost the same.*
- *Although the aperture of the Crab cavity and QF1 do not directly define the collimation depth, **the aperture of the Crab cavity and QF1 is not so generous when the collimator aperture is set just not to hit the QDEX1**.*
- *Furthermore, **the tightest apertures for the primary particle are the crab cavity and QF1** for all beam energies.*
- *In the present design of the ILC, the diameter of the FD is 20mm up to ECM=500GeV.*
- ***From the point of view of the protection of the crab cavity**, it is not desirable to make the crab cavity narrower than the QF1.*

Summary of collimation depth for ILC BDS

- *The collimation depth is calculated assuming that the collimator is assumed to be* ***30% narrower than the ideal aperture****, because the actual accelerator is affected by alignment errors and other non-ideal conditions.*
- *At ECM=250 GeV, the* ***horizontal emittance was reduced by half in CR-16****, so the collimation depth is larger than the other energies due to this effect (****the collimator aperture does not change even if the emittance is reduced****).*



ILC IP parameters for higher beam energy

- *The actual specification of the parameters is not the subject of this meeting (**it should be discussed by other members such as ADI**).*
- *If we can achieve a horizontal emittance of 5um at ECM=250GeV, we should be able to find the best IP parameters for energies other than 250GeV, assuming the horizontal emittance at IP.*

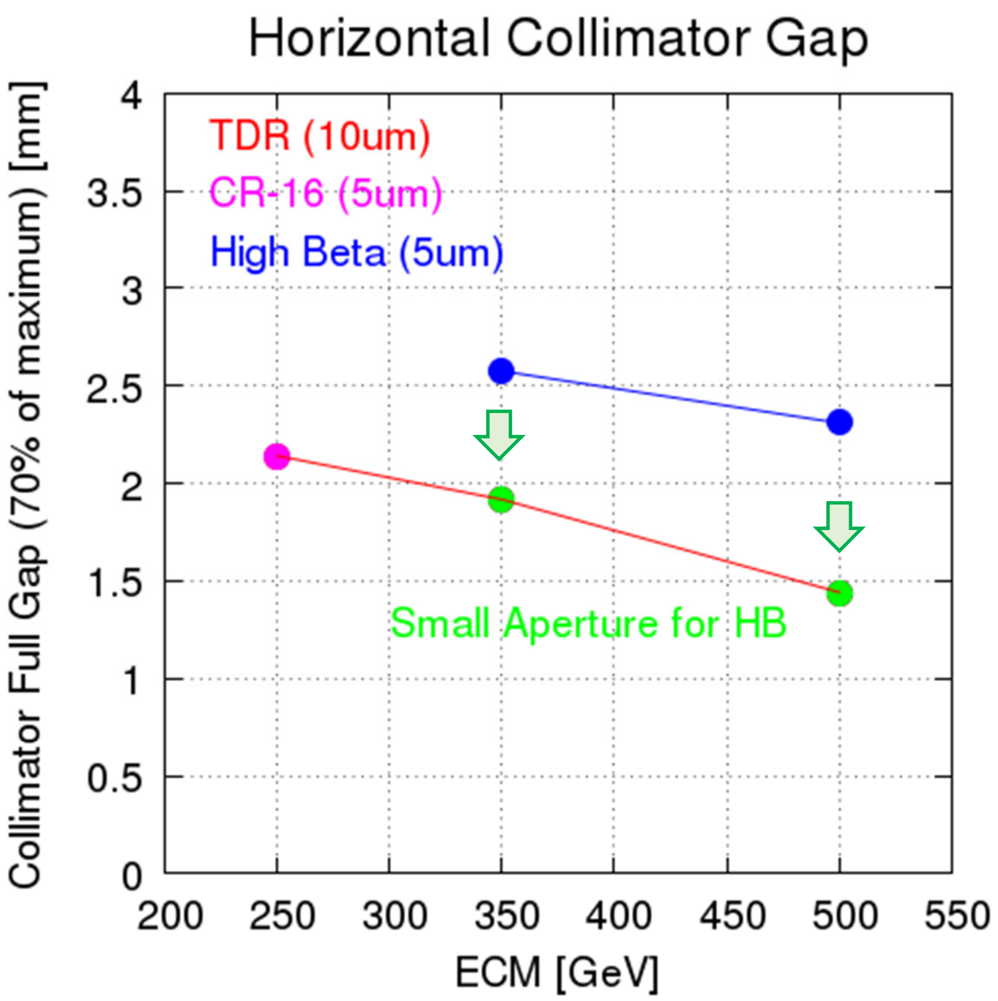
Lower horizontal emittance

- *Luminosity is increased. (factor 1.6 for ECM=250GeV)*
- *Disruption is increased. => it makes collision (FB) difficult.*
- *Energy loss by beamstrahlung is increased. => Large energy spread at collision*

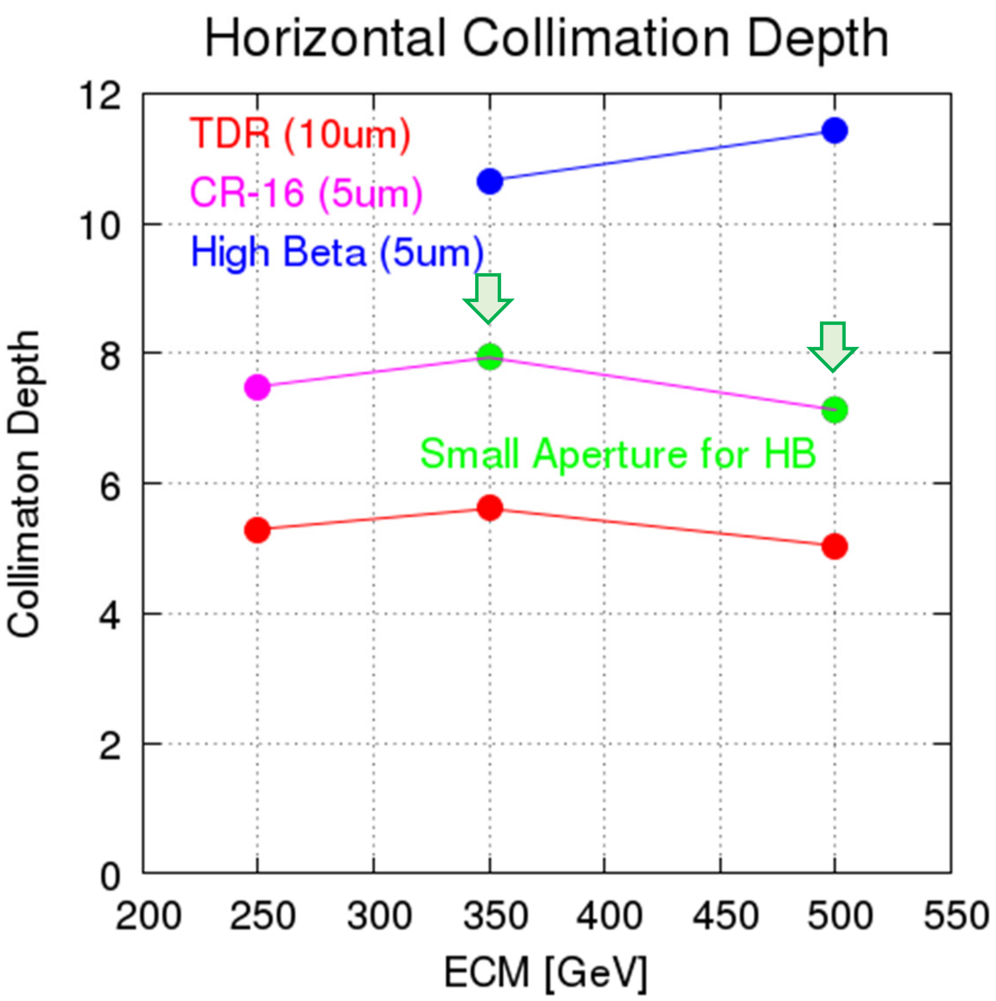
E_{CM} [GeV]	250		350			500		
	TDR	**CR-16**	**TDR**	**CR-16**	**High beta**	**TDR**	**CR-16**	**High beta**
$\gamma\varepsilon_x$ [μm]	10	5	10	5	5	10	5	5
$\gamma\varepsilon_y$ [μm]	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
β_x^* [mm]	13	13	16	16	32	11	11	22
β_y^* [mm]	0.41	0.41	0.34	0.34	0.34	0.48	0.48	0.48
σ_x^* [μm]	0.729	0.515	0.684	0.483	0.684	0.474	0.335	0.474
σ_y^* [nm]	7.66	7.66	5.89	5.89	5.89	5.86	5.86	5.86
D_x	0.26	0.51	0.21	0.42	0.21	0.30	0.60	0.30
D_x	24.50	34.50	24.30	34.24	24.30	24.57	34.57	24.57
δ_{BS} [%]	0.96	1.90	1.53	3.04	1.53	4.50	8.92	4.50
L [$\times 10^{34}$]	0.82	1.35	1.00			1.79		

Yokoya-san’s suggestion in the previous meeting

- *In high energy operation with a large horizontal beta function, the collimation depth becomes large, so it may be acceptable to reduce the collimator aperture up to a certain collimation depth.*
- *At that time, the spread of halo particles in the crab cavity will be smaller, so the aperture of the crab cavity can be reduced.*
- *Since 250 GeV and 500 GeV may have different requirements for the aperture of the crab cavity, we should design the technology for 250 GeV energy only at the first stage.*

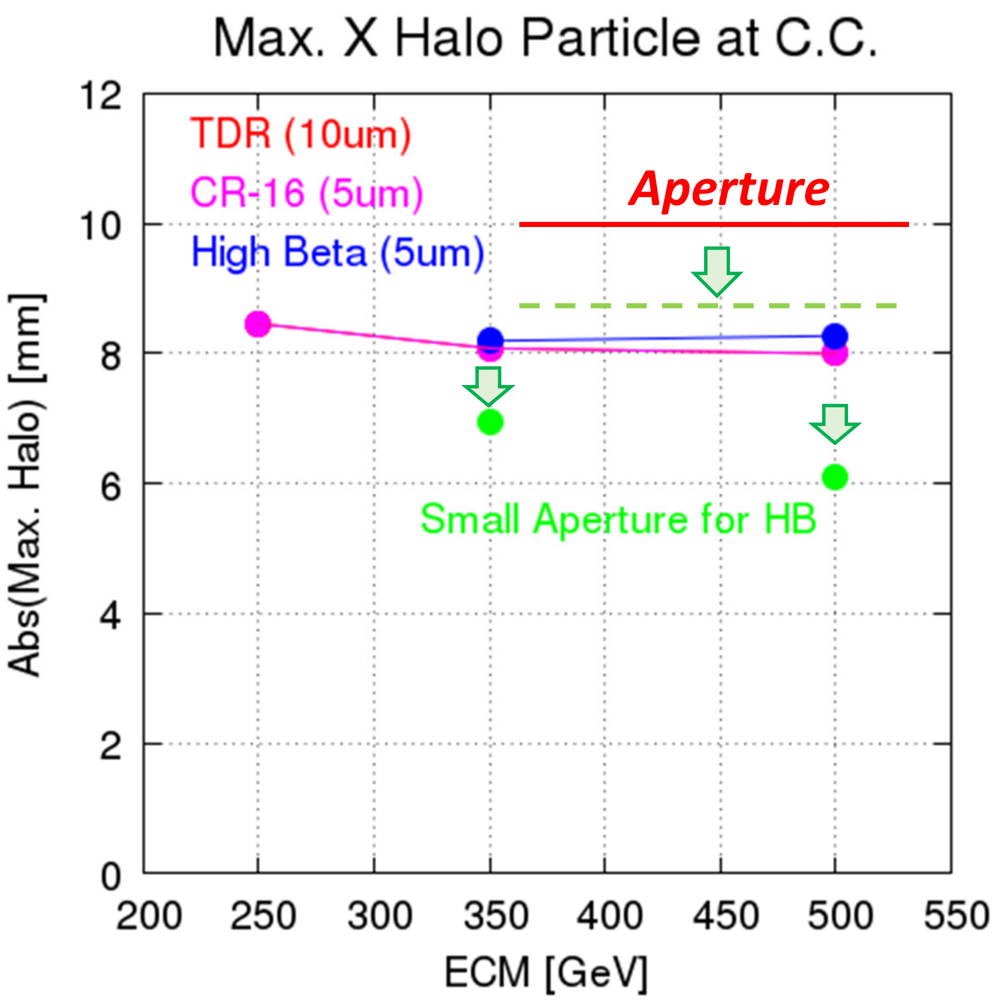


- *Tolerance of collimator setting*
- *Wakefield effect of collimator*
- *etc.*



- *Amount of muon background*

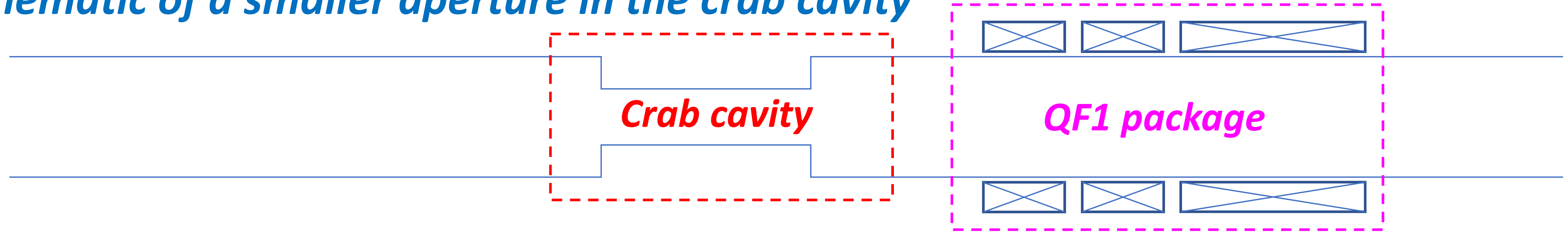
  (detector background)



- *Safety margin to hit particles*

  (protection of crab cavity)

Schematic of a smaller aperture in the crab cavity



Crab cavity

QF1 package

- In the present design of the ILC, the diameter of the FD is 20mm up to ECM=500GeV.
- When we adjust the beam, we make the collimator wider, so particles are more likely to hit where the aperture is narrower than others.
- **From the point of view of the protection of the crab cavity**, it is not desirable to make the crab cavity narrower than the FD.
- It is not decided (nor discussed) what IP parameter will be used except for ECM=250GeV (***It is not the focus point of today's discussion***).
- Even if any IP parameter is chosen,
  - ✓ ***The larger the collimation depth, the better***, because we do not know what kind of halo particle distribution the beam will have.
  - ✓ ***The larger the diameter of the collimator, the better.***

I believe that the aperture of the crab cavity should be more than 20mm of the FD aperture up to 500GeV.