Operation at Z-pole for ILC@250

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Z-pole Operation of ILC@250

- This report presents preliminary study results about the Z-pole (E_{CM} =91.2GeV) operation of ILC@250, assuming the undulator scheme for positron production.
- The possibility of Z-pole operation was discussed at the LCWS2016 at Morioka in Dec.2016 .
  - LCWS2016-ZpoleOperation-Yokoya.pptx in https://agenda.linearcollider.org/event/7371/contributions/38173/
  - It only gave a speculation by a scaling law and some comments on the issues to be studied
- The situation has changed since then
  - ILC energy is now 250GeV rather than 500GeV with a shorter linac
  - The baseline luminosity at 250GeV has been improved from 0.82E34 to 1.35E34 since AWLC at SLAC in Jun.2017, by adopting a reduced (halved) horizontal emittance with a new lattice of the damping ring.

Issues to Be Considered

- Repetition rate
- Damping Ring
  - Dynamic aperture
- Main Linac
  - Alternating operation 125GeV ←→ 45.6GeV
  - Emittance growth due to the low gradient
- BDS
  - Momentum bandwidth
  - Collimation depth
  - Final quads
- Beam-Beam

Repetition Rate

- Obviously, the electron beam with energy E=91.2/2=45.6 GeV is not sufficient to produce the positron beam
- TDR adopted 5+5Hz operation at E_{CM} =250GeV, assuming the power system for 500GeV
  - 5Hz to produce positron, 5Hz for colliding beam
  - Assumed positron production at E_e=150GeV
  - No power problem
    - The required power for 150GeV (5Hz) + 45.6GeV (5Hz) is lower than that for 250GeV (5Hz)
- However, the power system of ILC@250 is not sufficient for 5+5Hz operation
- Here, we assume 3.7+3.7 Hz operation is possible
  - This value was estimated by T. Matsumoto
  - Klystron output power can be changed at 5Hz but the loaded Q ($5.46x10^6$) cannot be changed
  - Assume same bunch interval (554ns) for 125 and 45.6GeV
  - Parameters:
    - Gradient 31.5 ←→ 8.76 = 31.5x (45.6-15)/(125-15) MV/m
    - Peak power per cavity 189 ←→ 77.2 kW
    - Klystron peak power 9.82 ←→ 4.15 MW
    - Klystron efficiency 67% ←→ 53%
    - Modulator output 14.66 ←→ 7.83 MW
    - Fill time 0.927 ←→ 0.328 ms
    - RF pulse length 1.65 ←→ 1.06 ms
    - Rep rate 5 ←→ 3.73 Hz

Damping Ring

- Horizontal emittance improved 6μm → 4μm (AWLC2017@SLAC)
- Reinforce the wigglers for the shorter time for damping
  - 5Hz: 200ms → 3.7+3.7Hz : 270ms/2=135ms
  - Wigglers are ready (TDR)
- Dynamic aperture of the new lattice with stronger wigglers must be confirmed
  - It may be possible to split 270ms into, e.g., 150ms+120ms such that more time is assigned for the beam for collision
  - Here, we assume OK.

Main Linac (1)

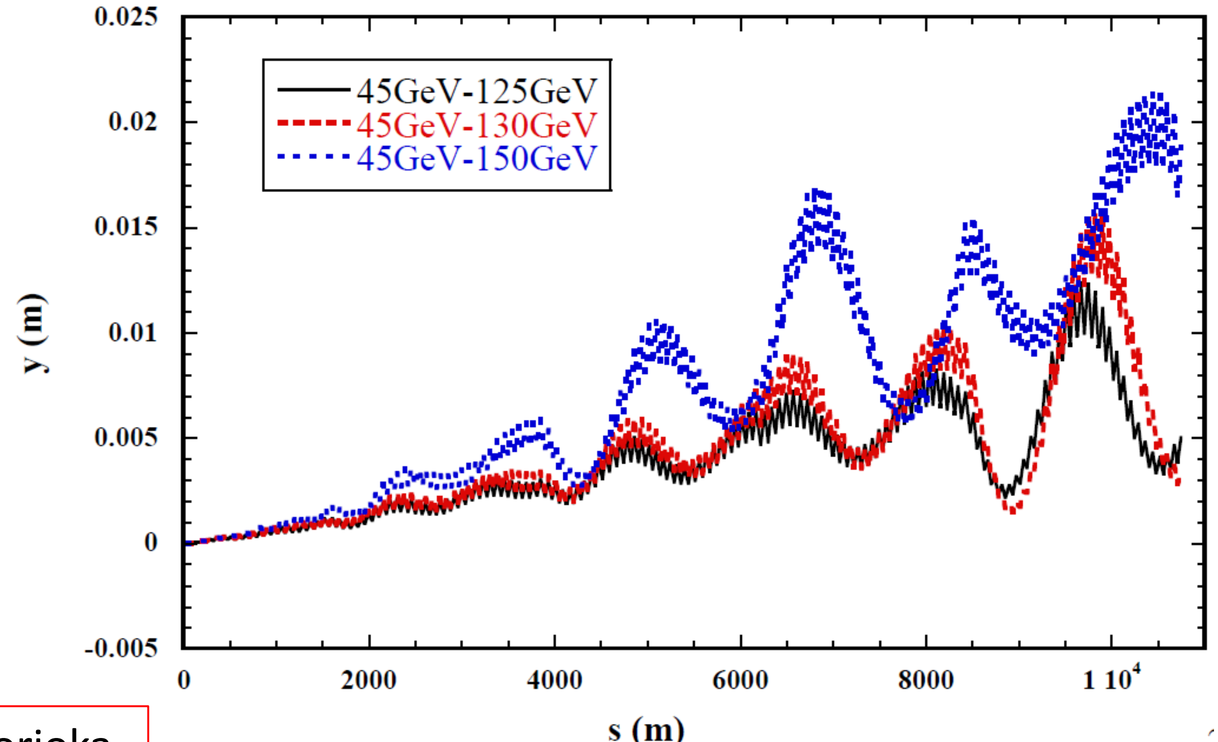
- Orbit difference between 125 and 45.6GeV beams (due to the vertical curvature of the earth)
  - Kubo's estimation in LCWS2016 was ~10mm for ILC@500 (45GeV ←→ 150GeV in 10km linac) (see next page)
  - Must be smaller for 45←→125GeV in 5km linac
  - Can be corrected by pulsed magnets at the end of electron main linac
- Emittance degradation in the undulator (not a linac issue)
  - Resistive wall wake
  - Presumably OK
  - But, if not, we need a beamline to bypass the undulator section (~700m, not expensive at all) and pulsed magnets

Beam Dynamics : Positron production beam

- 2 different energy beams in electron main linac
- Orbit is tuned for the colliding beam ($E_{CM}/2$)
- The positron production beam (125GeV or 150GeV) will shift vertically due to earth-following curvature)

250GeV
Linac !!

- The orbit difference is O(1mm) for $E_{CM}/2$=100GeV,
- but >10mm for $E_{CM}/2$=45
- Orbit difference itself can be corrected by pulsed magnets at ML exit



K.Kubo LCWS2016 @Morioka

K.Kubo EDMS D*01133735

Main Linac (2)

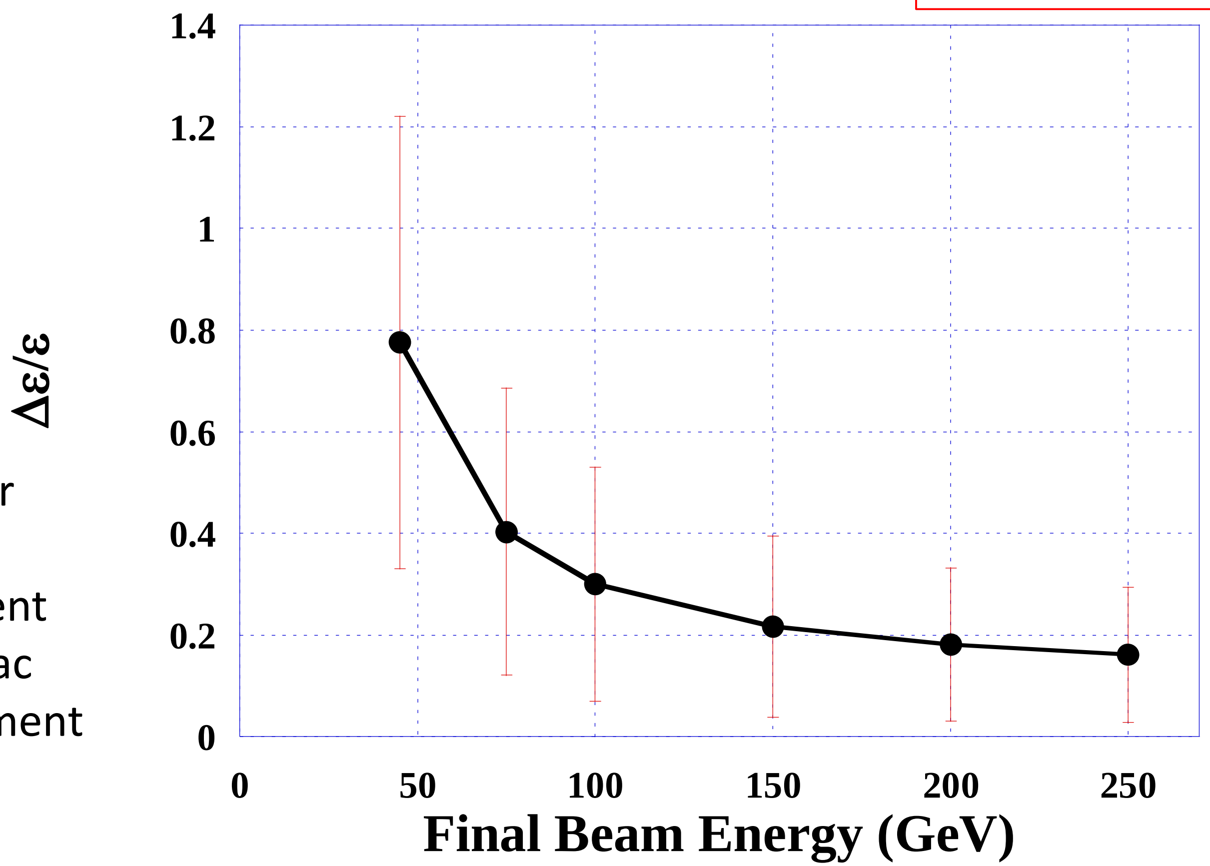
- Emittance growth of the beam for collision in the main linac (the beam for positron production is not an issue)
  - ε_{yDR} = 20nm, growth budget 10nm in ML
  - Full gradient operation followed by detuned cavities is ideal from beam dynamics and from klystron efficiency point of view
  - But 5Hz detuning by piezo is difficult (too large detuning). Must adopt uniform acceleration with reduced gradient.
  - Kubo's simulation showed $\Delta\varepsilon_y/\varepsilon_{yDR}$ = 0.8 when 250GeV 10km linac is operated for 45GeV (see next page)
  - The growth consists of mainly two terms:
    a. Proportional to (energy spread)^2
    b. Proportional to (wake)^2
  - Both are smaller than in the case of 45GeV in 250GeV linac
    a. is proportional to the linac length (for given energy spread)
    b. is proportional to 1/gradient^2
  - Should be OK for 45.6GeV operation of 125GeV 5km linac
    - Must be confirmed
  - Later, a longer bunch will be discussed in this report (BDS)
    - Energy spread is smaller : (a) becomes smaller
    - But wake is stronger : (b) becomes larger
    - Simulations needed

Emittance growth vs. final energy

Average of 40 random seeds. Error bar: standard deviation.

K.Kubo LCWS2016

- ε_0 = 20nm
- Linac length for 250GeV
- Uniform gradient over whole linac
- Random alignment errors
- DFS correction



20161201 K.Kubo, preliminary

Luminosity with a Simple Scaling

- $L = f_{rep} \times N_{bunch} \times N^2 / 4\pi \sigma_x \sigma_y$
- Naive scaling: $\sigma_x \sigma_y$ is proportional to sqrt($\varepsilon_x \varepsilon_y$) ~ $1/E_{CM}$ → $L \sim E_{CM}$
  - This would give 1.35E34 (250GeV, 5Hz) → 0.364E34 (91.2GeV, 3.7Hz)
- But the larger beam divergence near IP due to the larger emittance at low energies would cause background.
  - The synchrotron radiation from halo particles from upstream hit the final quadrupole magnets
  - IP beam angle is proportional to

$$\sqrt{\varepsilon_{x(y)}/\beta_{x(y)}}$$

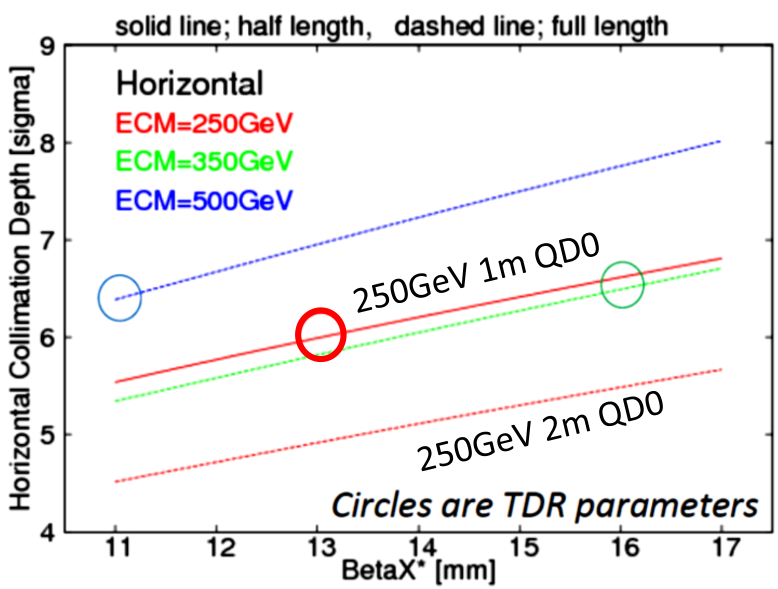
  - These particles must be collimated out in the collimator section
  - E_{beam}=125GeV with TDR parameters (ε_x=10μm/γ, ε_y=35nm/γ, β_x*=13mm, β_y*=0.41mm) are already at the limit of horizontal collimation depth ~6σ_x (vertical still has big room: >40σ_y). (see next page)

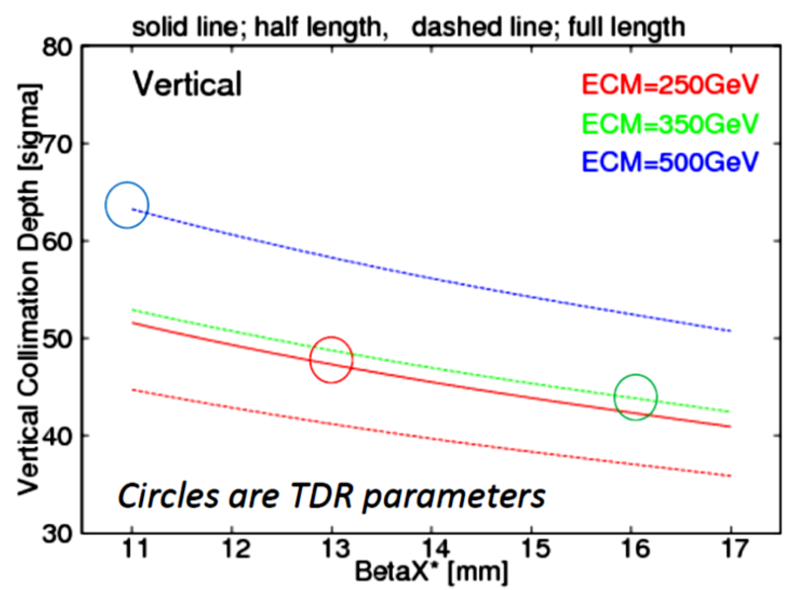
Collimation Depth with TDR Params

The collimation depth for various beam energy

ECM	BetaX*	BetaY*
250GeV	13mm	0.041mm
350GeV	16mm	0.034mm
500GeV	11mm	0.048mm

(QF1 L) = 9.5m*
(QD0 L) = 4.1m*





The circles shows the betas in TDR

T. Okugi, AWLC2017@SLAC

Luminosity with a Simple Scaling (2)

- Now, owing to the new DR design, the horizontal emittance has been improved : ε_x*=10→5μm/γ
- However, γ is 45.6/125 = 0.365 times smaller at Z-pole
- Hence, to keep the collimation depth ~6σ_x, the horizontal beta must be
  β_x*=13mm x 0.365/(5/10) = ~18 mm
  (same β_y*=0.41mm)
- Therefore, a simple scaling law predicts
  $L_{Z\text{-pole}} = 1.35 \times 10^{34} \times 0.365 \times \sqrt{13/18} \times (3.7\text{Hz}/5\text{Hz})$
  $= 0.31 \times 10^{34}$
- A beam-beam simulation by CAIN with these parameters (β_x*= 18 mm, β_y*=0.41mm, ε_x=5μm/γ, ε_x=35nm/γ, 3.7Hz, σ_z=0.3mm, σ_E/E= 0.41%) gives
  $L = 2.9 \times 10^{33}$, L(1%)=97.3%, n_γ = 0.92, δ_{BS} = 0.25%

BDS

- However, Momentum band width in FFS is a bottle neck
  - Beam energy spread σ_E/E=0.41% (proportional to 1/E, 0.15% for 125GeV)
    - Energy spread increase in ML and undulator is negligible
  - Horizontal emittance increases in FFS (β_x*=18mm, β_y*=0.41mm) from 5nm to more than 8nm
  - Better to use a smaller energy spread by adopting a longer bunch, e.g.,
    (σ_z, σ_E/E) = (0.3mm, 0.41%) → (0.41mm, 0.30%)
  - This combination makes the horizontal emittance at IP ~6.2nm (T. Okugi). The increase from 5nm is still sizable, but let us be satisfied with this.
- It may be possible to adopt new final quads with larger apertures dedicated to Z-pole operation (to relax the collimation depth)
  - Required fields are low for 45.6GeV
  - To be studied next time

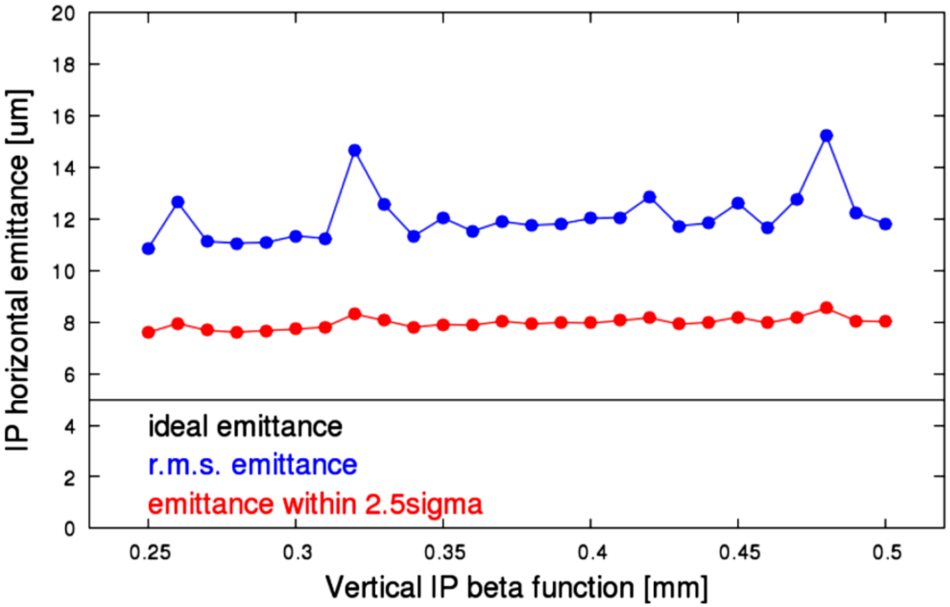
Increase of horizontal emittance in BDS due to the momentum band width

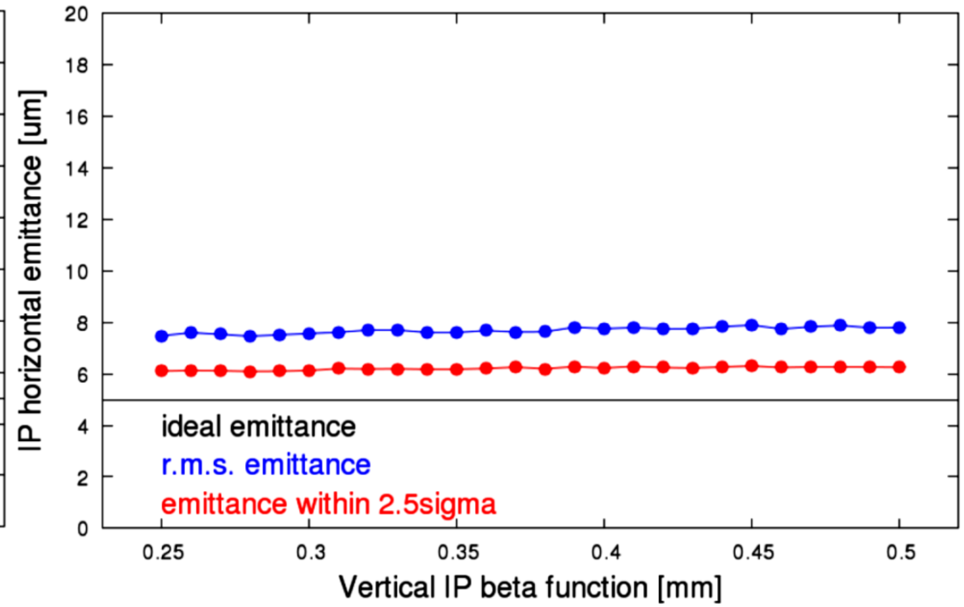
- Final emittance vs. β_y*
- 2 curves: r.m.s. emittave and 2.5σ emittance
- β_x*=18mm

σ_E/E = 0.41%

T. Okugi

σ_E/E = 0.3%





Preliminary Parameters

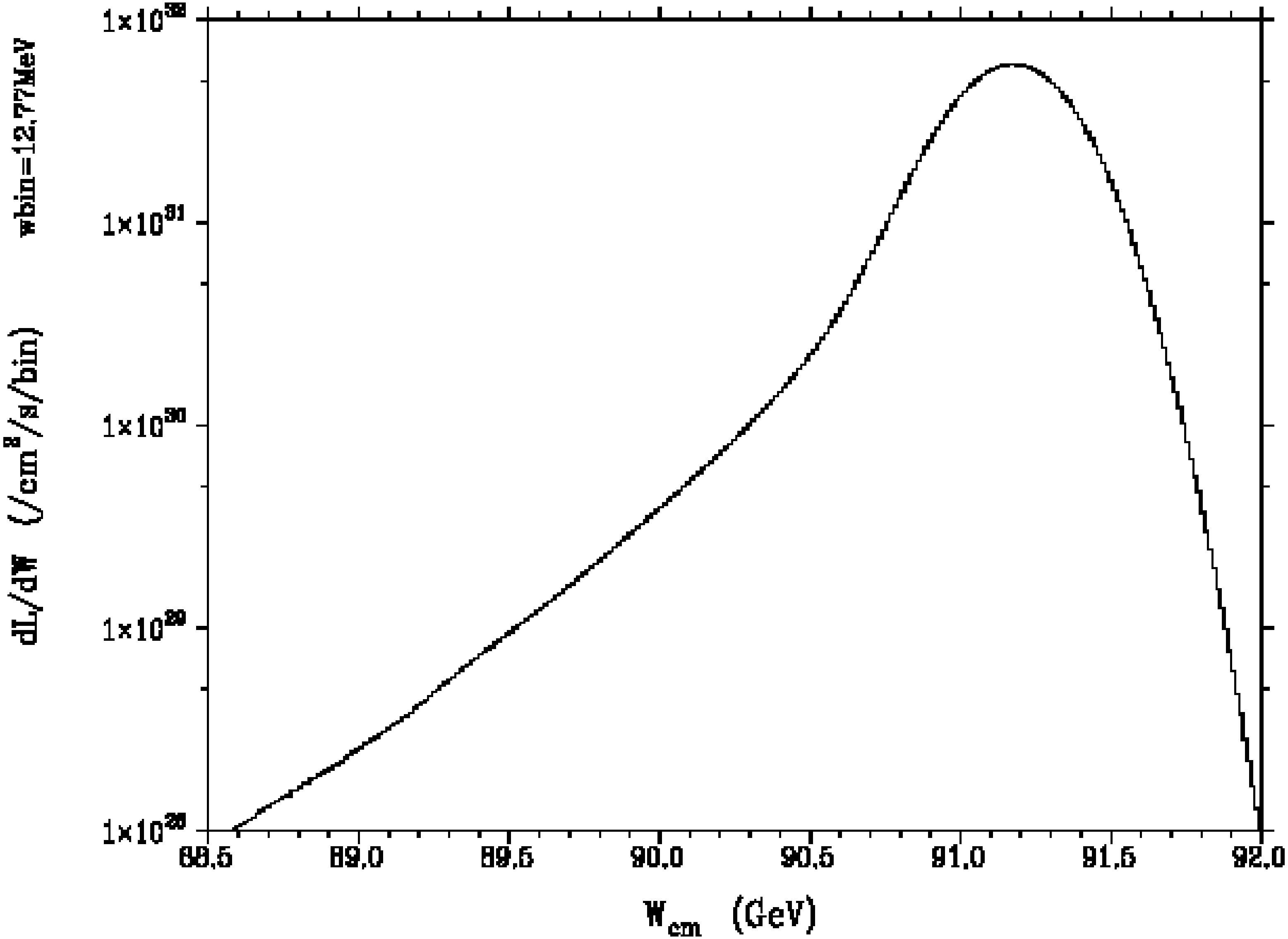
- We assume the parameters listed here →
- 45.6←→125GeV
- 3.7+3.7Hz operation
- (ε_{nx}*, ε_{ny}*) = (6.2nm, 35μm)
- (β_x*, β_y*) = (18mm, 0.39mm)
- L = 2.46 x 10^{33} /cm^2/s
- Center-of-mass energy spectrum : next pages (log and linear scale)
- Beamstrahlung is very small
  - But not easy to make use of this

Parameters of Operation at Z-pole

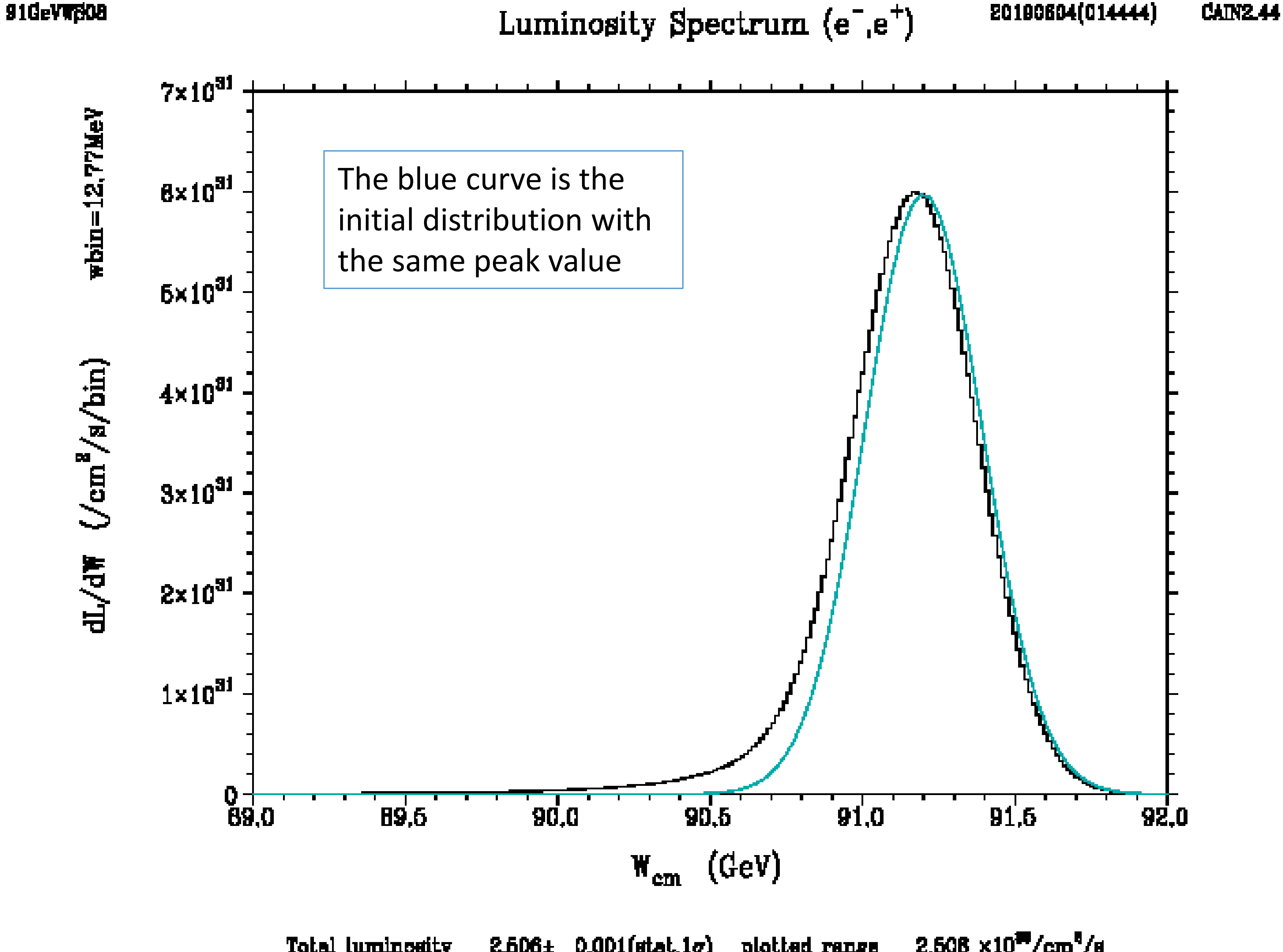
Center-of-Mass Energy	E_{CM}	GeV	91.2
Beam Energy	E_{beam}	GeV	45.6
Collision rate	f_{col}	Hz	3.7
Electron linac rep.rate		Hz	3.7+3.7
Electron energy for e+ prod.		GeV	125
Number of bunches	n_b		1312
Bunch population	N	10^{10}	2
Bunch separation	Δt_b	ns	554
RMS bunch length	σ_z	mm	0.3
RMS Beam energy spread	σ_p/p	%	0.41
Emittance from DR (x)	$\gamma\varepsilon^{DR}_x$	μm	20
Emittance from DR (y)	$\gamma\varepsilon^{DR}_y$	nm	4
Emittance at IP (x)	$\gamma\varepsilon^*_x$	μm	6.2
Emittance at IP (y)	$\gamma\varepsilon^*_y$	nm	35
Electron polarization	P_-	%	80
Positron polarization	P_+	%	30
Beta_x at IP	β^*_x	mm	18
Beta_y at IP	β^*_y	mm	0.39
Beam size at IP (x)	σ^*_x	μm	1.1183
Beam size at IP (y)	σ^*_y	nm	12.37
Disruption Param (x)	Dx		0.303
Disruption Param (y)	Dy		27.40
Geometric luminosity	Lgeo	10^{33}	1.117
Luminosity	L	10^{33}	2.46
Luminosity at top 1%		%	99.0
Number of beamstrahlung	n_γ		0.845
Beamstrahlung energy loss	δ_{BS}	%	0.158

91GeVW508 20190604(014444) CAIN2.44

Luminosity Spectrum (e^-, e^+)



Total luminosity 2.606± 0.001(stat.1σ) plotted range 2.606 ×10/cm²/s


Luminosity Spectrum (e⁻,e⁺)
CAIN2.44
The blue curve is the initial distribution with the same peak value
wbin=12.77MeV
dL/dW (/cm²/s/bin)
7x10³¹
6x10³¹
5x10³¹
4x10³¹
3x10³¹
2x10³¹
1x10³¹
0
89.0
89.5
90.0
90.5
91.0
91.5
92.0
W_cm (GeV)
Total luminosity 2.506± 0.001(stat.1σ) plotted range 2.506

Brief Explanation of Luminosity Increase since LCWS2016

- The range 1-1.5 x 10^{33} given in LCWS2016 came from L~ either E^2 or $E^{3/2}$
- Upper limit comes from the beam angle in x, the lower limit in both x & y. The former is the reality.
- If apply the luminosity improvement in AWLC2017 by factor 1.35/0.82=1.65, L=2.47 x 10^{33}
- The lower ε_{nx}* could give some more increase (~3 x $10^{33)}$ but it is cancelled by 5→3.7Hz
- Another complication is the momentum band width under large energy spread. This is (partly) cured by the longer bunch. The side effects (larger wake) must be checked.

Next Steps

- First step: confirm the present results
  - Damping ring dynamic aperture
  - Linac simulation for 45.6GeV beam in 125GeV linac with increased bunch length
  - BDS momentum band width and collimation depth
    - Note $\varepsilon_{nx}^* = 6.2$nm with $\beta_x^* = 18$mm will cause collimation depth < $6\sigma_x$
  - Also, 2625 bunches. Any problem (except positron production)?
- Second: possible drastic improvements, if needed
  - Better design of DR
    - smaller ε_{nx} , smaller longitudinal emittance (shorter bunch)
    - Tighter focusing (as is being considered in circular colliders)
  - Better design of BDS
    - Final quads with larger aperture (not vert much drastic)
    - Larger momentum band width with a drastic change of the lattice ????
- Third: ILC@500
  - Nick's idea

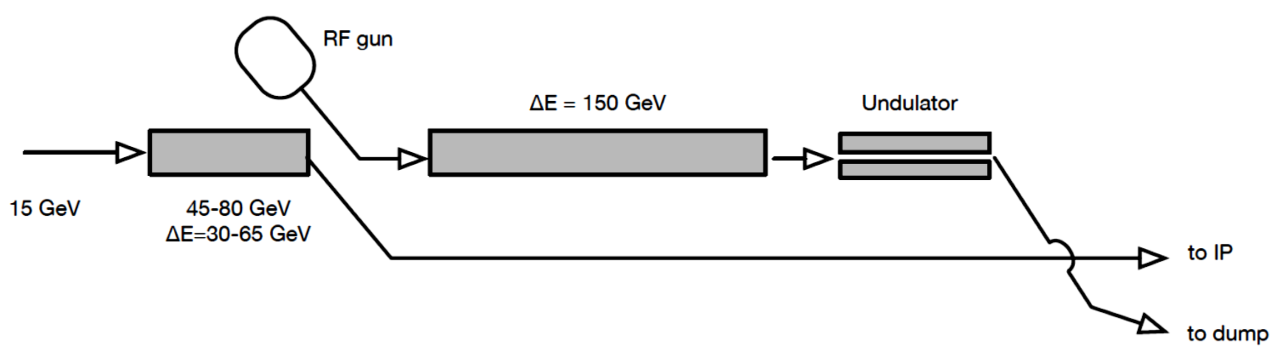


Figure 2: "Giga Z" configuration for polarised positron production.

Summary

- The previous report (LCWS2016@Morioka) suggested the expectation L=(1-1.5)x10^{33} /cm^2/s at Z-pole in 5+5Hz operation of ILC500
- ILC250 (shorter linac) is
  - worse in power : up to 3.7+3.7Hz operation
  - but better in the beam dynamics
- The previous luminosity improvement for ILC250 by smaller horizontal emittance (AWLC2017@SLAC) brings about significant effects for Z-pole operation
- Expected luminosity is now L ~ 2.46 x 10^{33} /cm^2/s, though preliminary
- This must be confirmed by more detailed simulations
- If you want higher luminosity, the bottle neck is the momentum band width of BDS under the large energy spread of the low energy beam