ILC Accelerator at Z, H and tt

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TDR

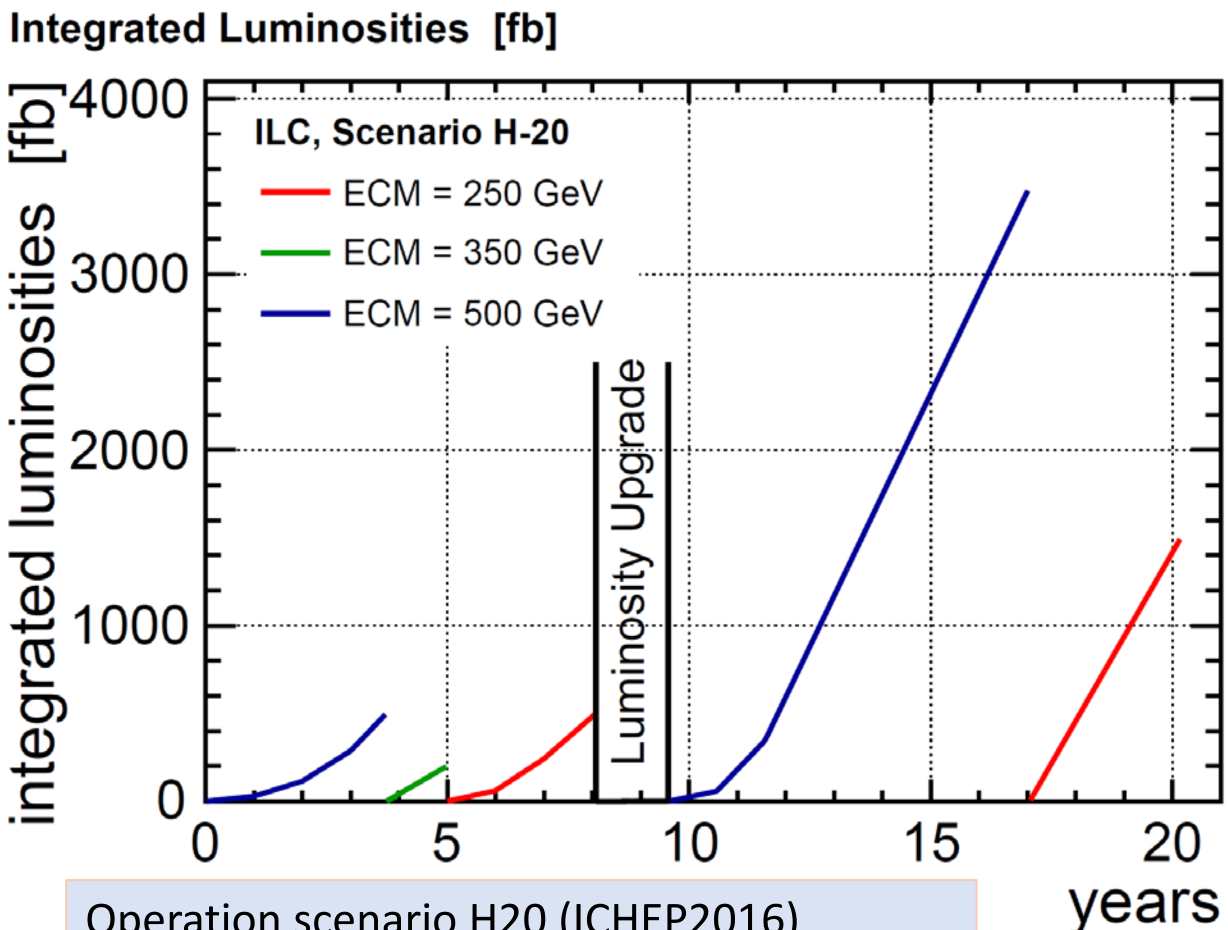
- ILC-TDR (Technical Design Report) describes the design optimized for E_{CM} = 500GeV
- Parameter sets for 200, 230, 250, 350 and 1000GeV are also given but not in detail
  - Next slide. The values of luminosity corrected after TDR
- There is no official parameter set for 92 GeV
- Basically, linear colliders are not good at low energies

IP and General Parameters (correction Apr.2015 included)

			Baseline					L Upgrade	Ecm Upgrade	
Centre-of-mass energy	E_{cm}	GeV	200	230	250	350	500	500	1000	1000
Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2	2	2	2	2	2	1.737	1.737
Bunch separation	Δ_{tb}	ns	553.8	553.8	553.8	553.8	553.8	366.2	366.2	366.2
Bunch separation $\times f_{RF}$	$\Delta_{tb}\ f_{RF}$		720	720	720	720	720	476	476	476
Pulse current	I_{beam}	mA	5.79	5.79	5.79	5.79	5.79	8.75	7.60	7.60
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.206	0.194	0.190	0.158	0.125	0.125	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.187	0.163	0.150	0.100	0.070	0.070	0.043	0.047
Electron polarisation	P-	%	80	80	80	80	80	80	80	80
Positron polarisation	P+	%	31	31	30	30	30	30	20	20
Horizontal emittance at IP	$\gamma\varepsilon_x$	μm	10	10	10	10	10	10	10	10
Vertical emittance at IP	$\gamma\varepsilon_y$	nm	35	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	16	14	13	16	11	11	22.6	11
IP vertical beta function	β_y^*	mm	0.34	0.38	0.41	0.34	0.48	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	904	789	729	684	474	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.80	7.69	7.66	5.89	5.86	5.86	2.77	2.66
Horizontal distruption parameter	Dx		0.210	0.239	0.257	0.210	0.304	0.304	0.108	0.199
Vertical disruption parameter	Dy		24.3	24.5	24.5	24.3	24.6	24.6	18.7	25.1
Geometric luminosity	L_{geom}	10^{34} /cm^{2}s	0.296	0.344	0.374	0.518	0.751	1.504	1.768	2.643
Average beamstrahlung parameter	Υ_{av}		0.013	0.017	0.020	0.030	0.062	0.062	0.127	0.203
Maximum beamstrahlung parameter	Υ_{max}		0.031	0.041	0.048	0.072	0.146	0.146	0.305	0.483
Average number of photons / particle	n_γ		0.95	1.08	1.16	1.23	1.72	1.72	1.43	1.97
Luminosity	L	10^{34} /cm^{2}s	0.59	0.73	0.82	1.03	1.79	3.60	3.02	5.11
Luminosity enhancement factor	H_D		1.99	2.12	2.19	1.99	2.38	2.39	1.71	1.93
Fraction of luminosity in top 1%	$L_{0.01}/L$		0.913	0.886	0.871	0.7743	0.583	0.583	0.592	0.445
Average energy loss	δ_{BS}	%	0.65	0.83	0.97	1.85	4.49	4.49	5.59	10.53
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	45	56	62	94	139	139	200	383
Total pair energy per bunch crossing	E_{pairs}	TeV	25	38	47	115	344	344	1338	3441

Proposed Operation Scenario (ICHEP2016)

- 500GeV machine assumed
- Start with 500GeV, then, →350, → 250GeV
- Luminosity upgrade: 1312 bunches → 2625 bunches



Operation scenario H20 (ICHEP2016)

10Hz Operation at 250GeV

- Beaseline design in TDR: 5Hz
- 10Hz operation is possible at 250GeV
  - Assume 500GeV machine
  - 10Hz possible only at 250GeV
    - < 250GeV: poor positron yield
    - > 250GeV: power excess
  - Proposed after TDR (~summer 2013)
  - Damping rings support 10Hz operation (already in TDR)
    - Strong wigglers, doubled RF system
  - Linac RF system accepts 10Hz
    - Klystron ready (XFEL)
  - Total power nearly the same as 5Hz at 500GeV
    - Gradient is only half of 500GeV
  - The only uncertainty is positron target
- Proposed scenario (ICHEP2016) assumes 10Hz collision

Luminosity Limit at 250GeV

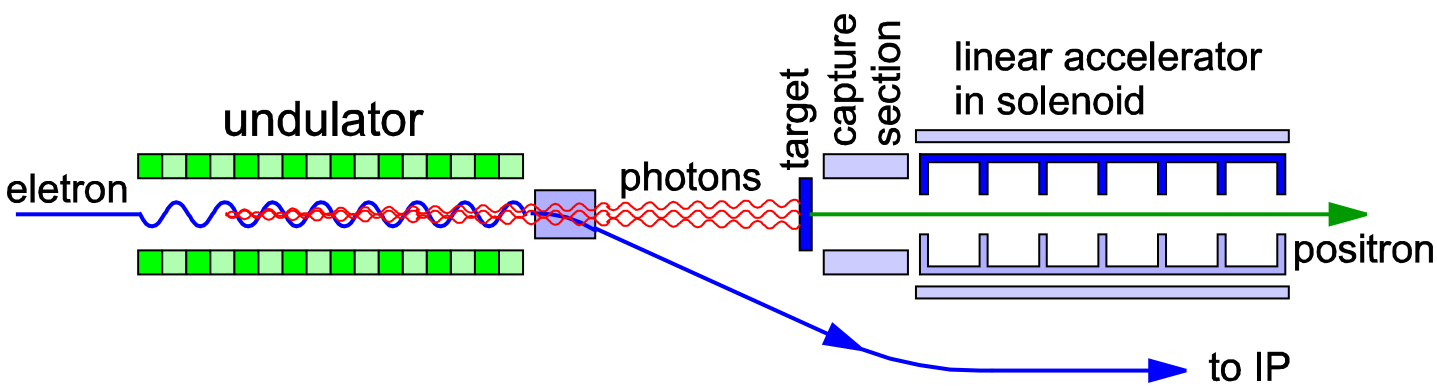
- Simple scaling: L proportional to E_{CM}

$$\mathcal{L} = f_{rep} \frac{n_b N^2}{4\pi \sigma_x^* \sigma_y^*} \times H_D$$

- Geometric emittance proportional to $1/\gamma$
- However, beam angle spread gives a strong constraint at < 250GeV
  - Causes background from synchrotron radiation of large amplitude particles in the final quads
  - Deep collimation necessary
- This effect is already visible at 250GeV
- TDR gives 0.82 x 10^{34} @250GeV
  - 1.79 x 10^{34} @500GeV

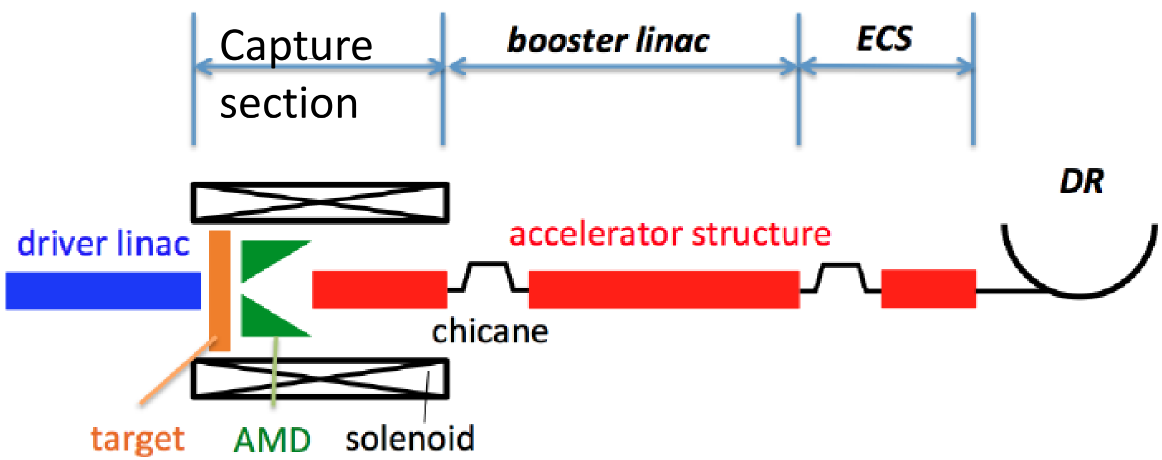
Baseline Positron Production Scheme

- Undulator method
- Undulator
  - Placed at the end of the electron linac
  - Helical, superconducting
  - Length ~150m (~230m when highly polarized positron is needed)
  - K=0.92, λ=1.15cm, (B=0.86T on the axis)
  - beam aperture 5.85mm (diameter)
- Target: rotating titanium alloy
- Flux Concentrator for positron capture
- Normal-conducting acceleration up to 400MeV
- Polarization ~30% (~60% with photon collimator and longer undulator)



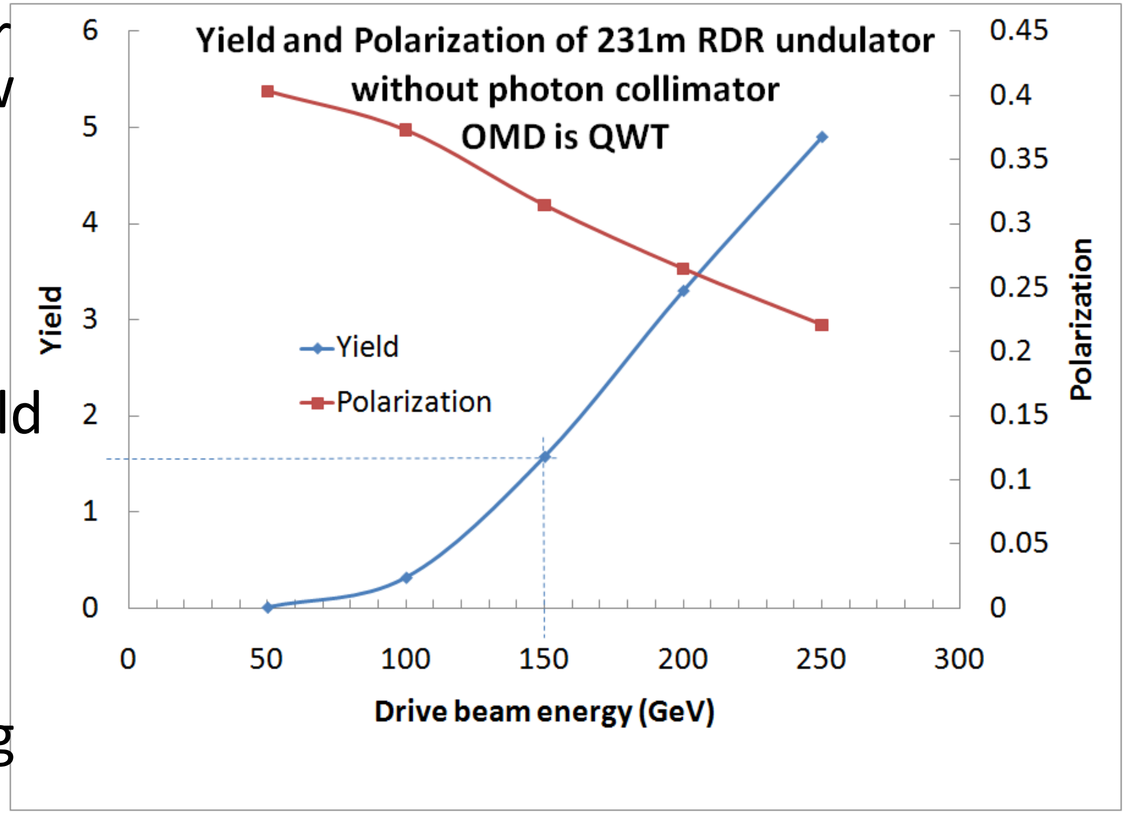
e-Driven Positron Source

- Conventional method (electron-driven source) is also being considered
- Hit ~5 GeV electrons on a target, and collect the generated positrons
- All normal-conducting
- No polarized positron
- 10Hz collision impossible (up to ~6.1Hz)



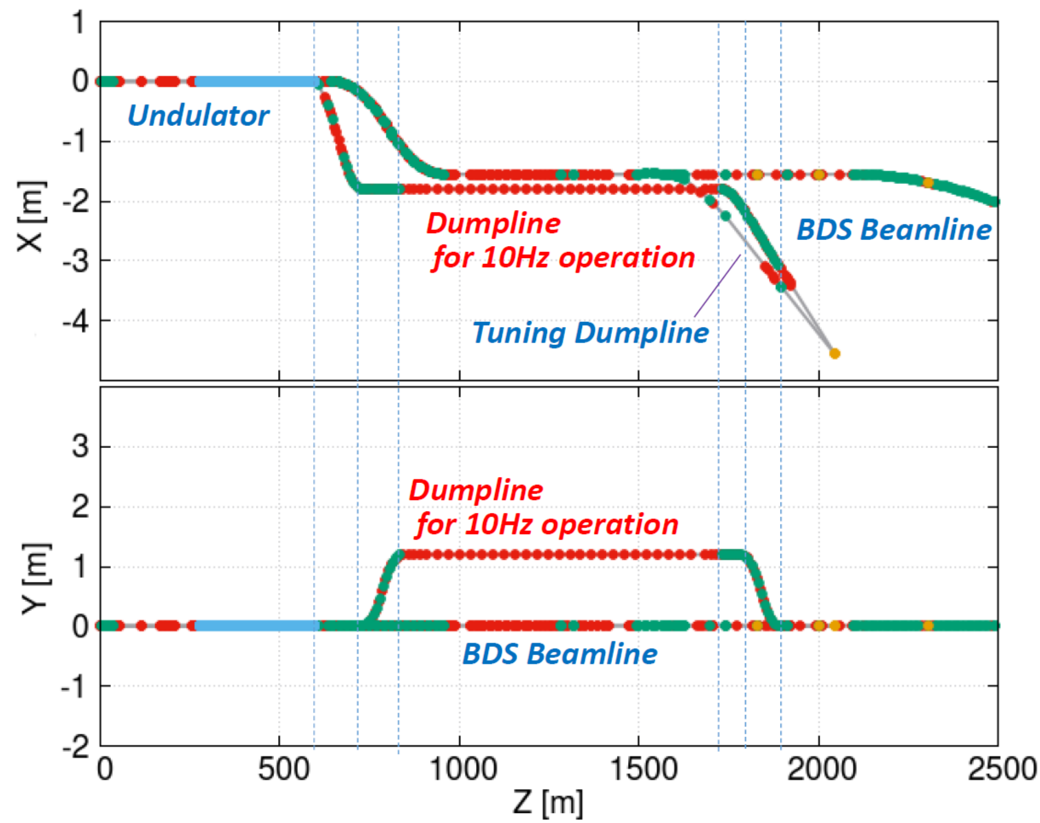
Operation Below 250GeV

- The positron production scheme using undulator causes a problem at low energies
- For E_{CM}>250GeV, use electron for collision:
  - i.e., $E_e = E_{CM}/2$
- Positron production yield depends on E_e →
- Poor production rate below E_e=125GeV
- Study being done for shorter pitch, e.g., using Nb_3Sn, but not ready.
  - Z-pole is anyway impossible



5+5Hz Operation

- For E_{CM} < 250GeV,
  - Operate electron linac at 10Hz
    - 5Hz for colliding beam ($E_e = E_{CM}/2$)
    - 5Hz for positron production (E_e = 150 or 125GeV)
  - Already in TDR
  - This is the reason that DRs are ready for 10Hz operation
- Spent electron after positron production must be dumped
- Operation at Z-pole is possible in simple principle but................

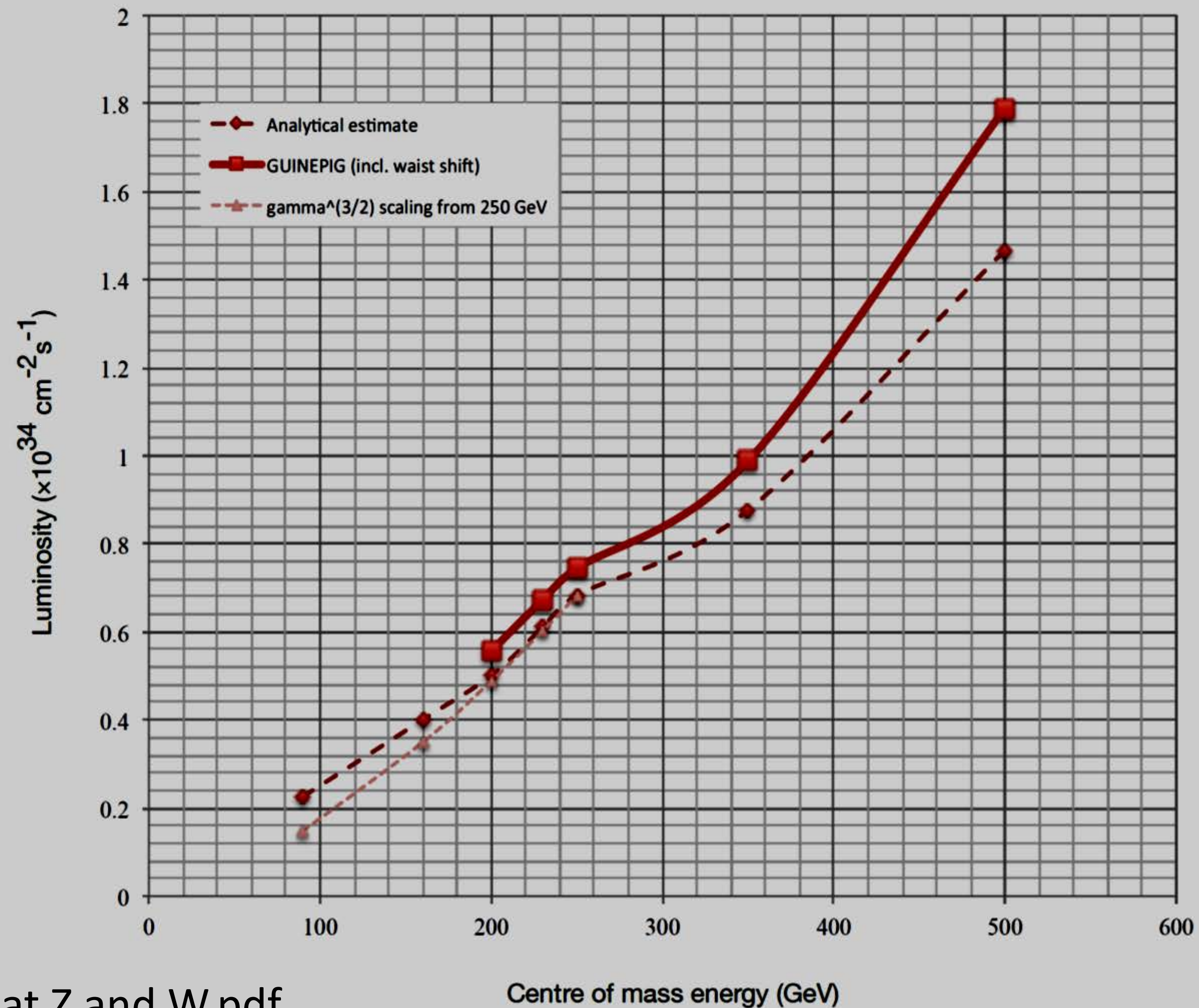


Electron dump line (Okugi, Santander 2016)

5+5Hz Operation Hardware

- Hardware requirements
  - 5Hz switching of accelerating gradient
    - Hardware not seriously studied, but should be OK
    - To turn-off some of the cryomodules is presumably impossible (5Hz detuning for empty cavities needed)
    - Lower gradient operation may cause some beam dynamics issues (discuss later)
  - Damping in 100ms in DRs
    - Strong wigglers already in TDR
  - 5Hz pulsed magnets needed before and after the undulator
  - Dump line and dump (up to 6.3MW) for the spent electron after producing positron

Luminosity vs. E_{CM}



N.Walker
ILC possibilities at Z and W.pdf

Figure 1: ILC luminosity parameters versus centre-of-mass energy. Data points are the published numbers [1], with the exception of the 90 GeV and 160 GeV analytical points. The $\gamma^{3/2}$ scaling (from the 250 GeV luminosity) is also shown.

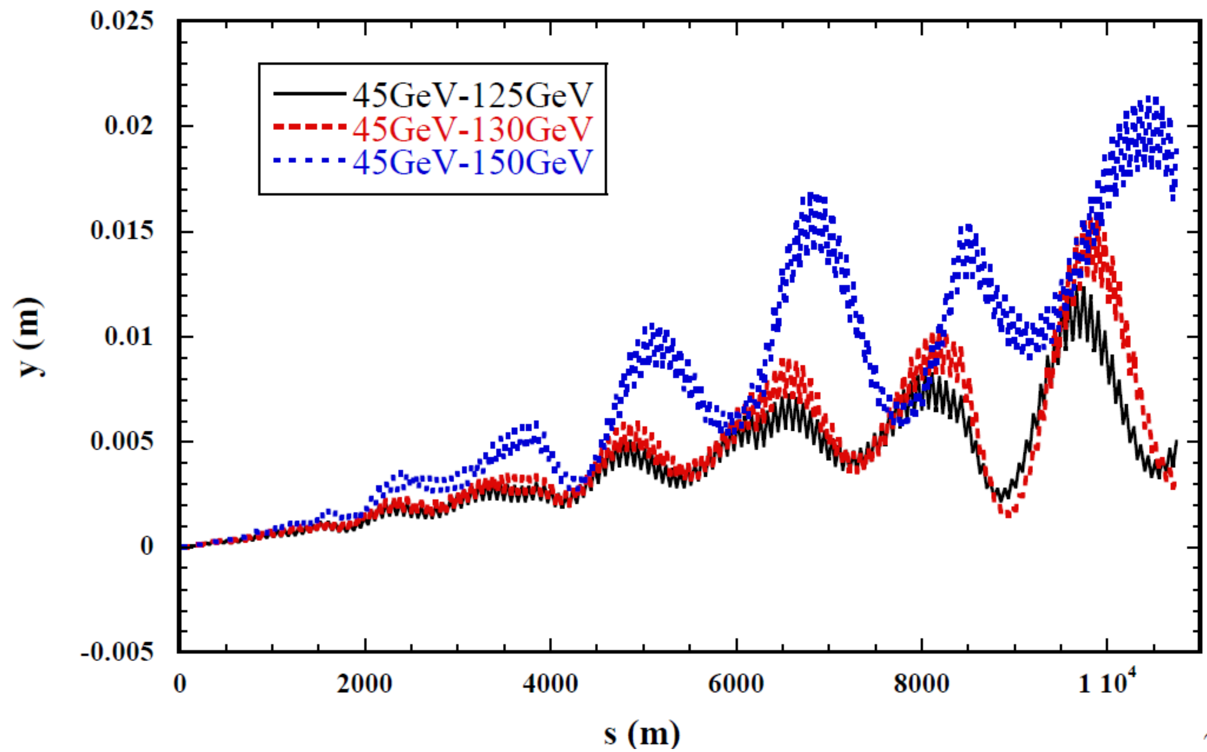
Luminosity at Z-pole

- $L = f_{rep} \times N_{bunch} \times N^2 / 4\pi\, \sigma_x \sigma_y$
- Naive scaling: $\sigma_x \sigma_y$ is proportional to $\mathrm{sqrt}(\varepsilon_x \varepsilon_y) \sim 1/E_{CM}$ → $L \sim E_{CM}$
- But the larger beam divergence near IP due to the larger emittance at low energies would cause background
- A more conservative scaling is $L \sim E_{CM}^{3/2}$ or E_{CM}^2
  - Horizontal angle is already at the limit at E_{CM} =250GeV
  - $L \sim E_{CM}^{3/2}$ if horizontal plane only
  - $L \sim E_{CM}^2$ if both planes
- This would results in $L=1.5\times10^{33}$ or 1×10^{33} at Z-pole
- Further reduction of luminosity may be expected because of the beam dynamics (emittance increase) of low gradient operation
  - → next pages
- Can still be used for detector calibration

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)

- 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 main linac exit



K.Kubo EDMS D*01133735

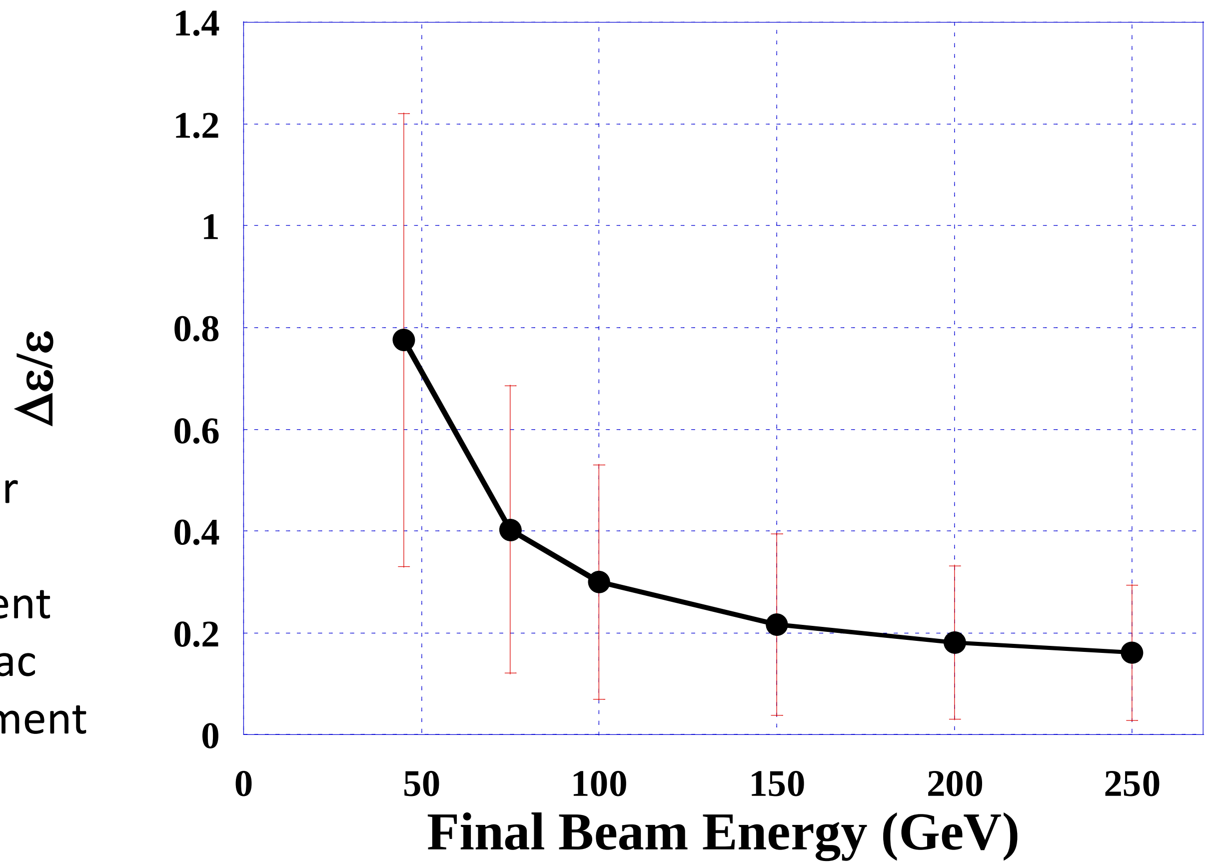
Beam Dynamics : Colliding Beam (1)

- Main linac
  - Low gradient operation necessary
    - Note: for the case e-driven source, emittance increase problem is not serious because “full gradient plus empty cavity” is possible
  - Emittance increase due to energy spread + misalignment: $\Delta\varepsilon$ proportional to $(\sigma_E/E)^2$ proportional to $(E_0/E)^2$
    - σ_E (fixed)
    - $(250/45)^2$ ~ 30 or, may be, (125/45)2 ~ 8
  - Emittance increase due to wakefield also proportional to $1/E^2$
  - Emittance budget in TDR to decide the alignment tolerance is $\Delta\varepsilon_y / \varepsilon_y$ = 10nm / 20nm = 0.5
- Undulator
  - Emittance increase due to resistive wakefield proportional to $1/E^2$
  - Radiated photon angle $1/\gamma = 10^{-5}$: intercepted by the downstream undulators
    Mask radius 2.3mm / length up to 200m ~ 10^{-5}
  - If the colliding beam cannot go through the undulator, a bypass line must be constructed

Emittance growth vs. final energy

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

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



20161201 K.Kubo, preliminary

Beam Dynamics : Colliding Beam (2)

- BDS
  - Final quads
    - QD0 is split into 2 parts (1m+1m) in TDR
    - Upstream half is turned off for E_{CM} = 250GeV operation (to make effective L* small)
    - However, further shorter magnet (0.5m) would not gain much
    - Anyways, replacement of QD0 is meaningless for calibration purpose
  - Emittance increase in BDS
  - Collimation depth
    - To avoid background, the collimators must cut the beam closer to the beam center
    - Must use the emittance increased in the main linac
- For all these beam dynamics issues, serious studies are needed

Giga-Z

- 5+5Hz scenario is not sufficient for Giga-Z
- N.Walker suggests a scheme below for Giga-Z
  - Split electron linac into 2 parts
  - Prepare an additional electron gun and a long transport line of colliding electron beam
- This would require a big change in the design

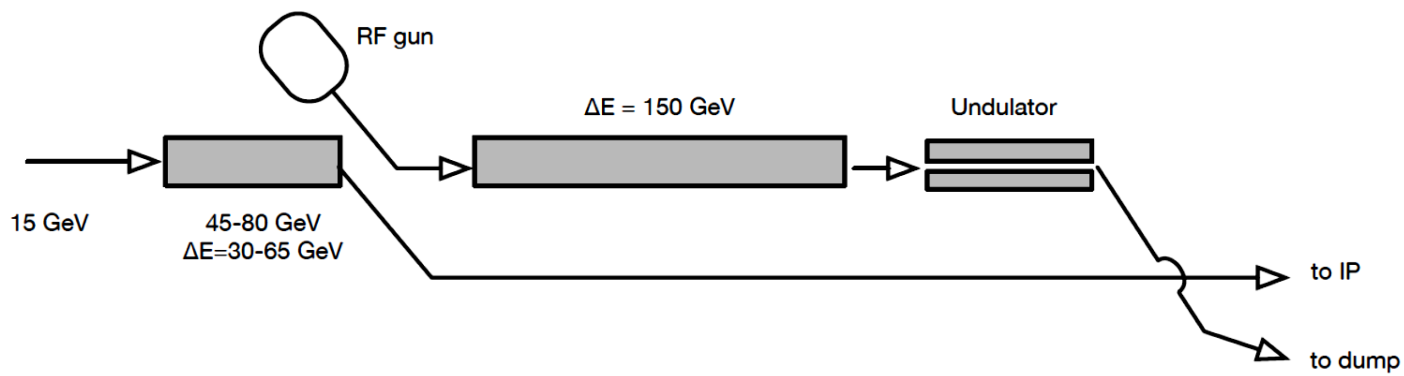


Figure 2: "Giga Z" configuration for polarised positron production.

Z-pole Operation: Summary

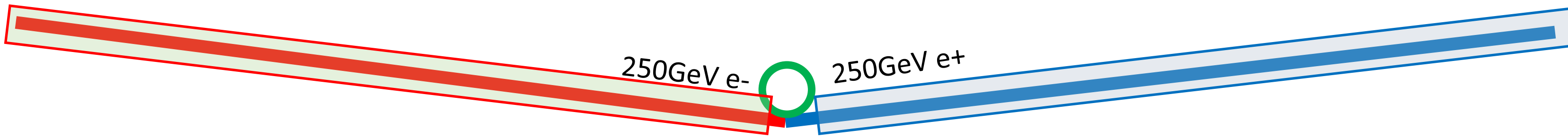
- One of the detector teams (ILD) requires the luminosity for detector calibration 2×10^{32} $1/cm^2/s$ at Z-pole
- This is presumably feasible by 5+5Hz operation, though serious studies are needed
- Once operation below 250GeV turns out to be necessary, the requirement of Z-pole calibration would not cause additional cost
  - If any operation below 250GeV (including calibration) is not needed, the cost saving is significant
- In any case the luminosity required for Giga-Z seems to be too far, unless strongly desired

Staging

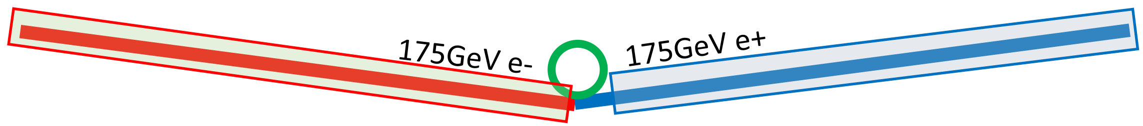
- Strong demand for cost reduction
- Improvement of linac technology is under study
  - Higher gradient: e.g., 31.5MV/m → 35MV/m
  - Higher Q values: e.g., 1×10^{10} → 2×10^{10}
  - Nitrogen infusion being developed at FNAL
  - But the cost reduction is at most 10-15%
- Recent trend is to consider staging to reduce the first stage cost
- Starting with E_{CM} = 250GeV is a reasonable choice
- The choice whether 500GeV tunnel or just 250GeV tunnel is still under debate

Possible Staging Scenarios of ILC

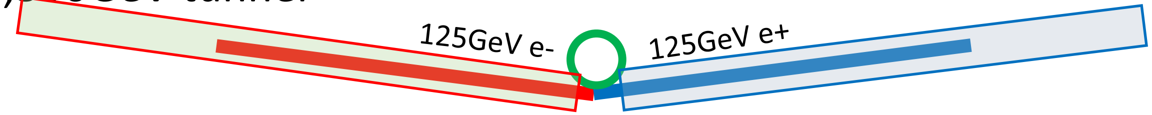
TDR 500GeV CM



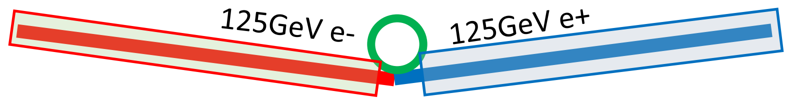
Option A:350GeV CM



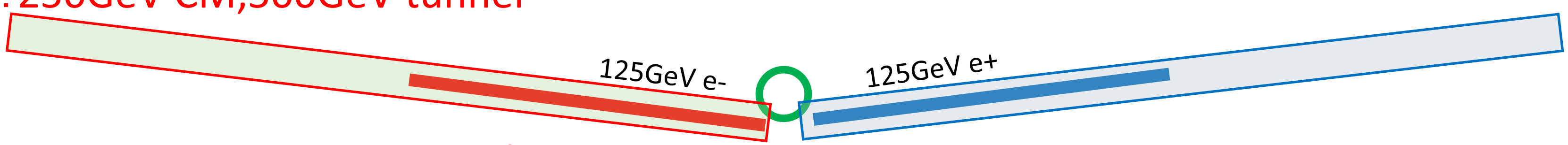
Option B:250GeV CM,350GeV tunnel



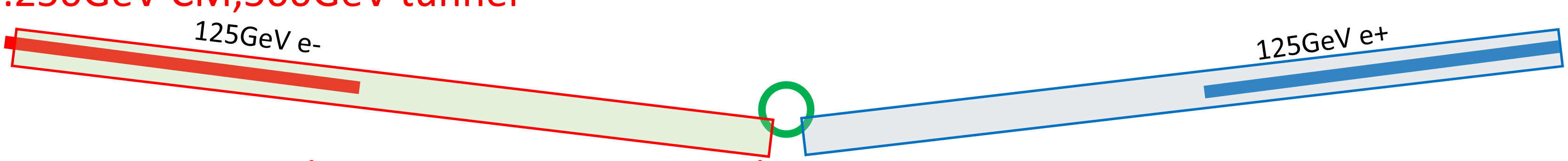
Option C：250GeV CM



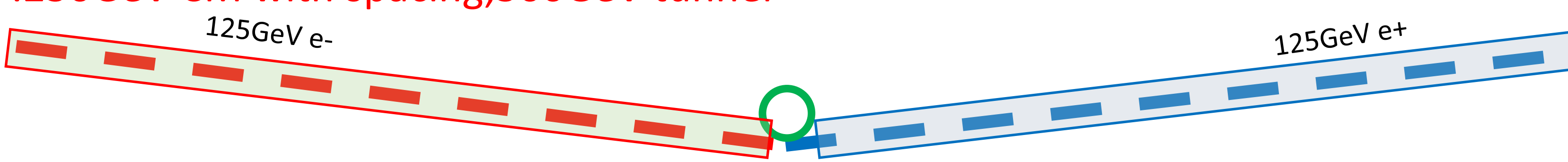
Option D：250GeV CM,500GeV tunnel



Option E:250GeV CM,500GeV tunnel



Option F:250GeV CM with spacing,500GeV tunnel



Physics Demand: Higher L @250GeV

- 10Hz collision @250GeV is possible only with option F
  - Requires full RF system of 500GeV
  - But this would be somewhat expensive
- With other options, the only way of raising the luminosity is to focus the beam more (in particular, in horizontal plane)
  - i.e., more beamstrahlung (1% → 4% is acceptable from physics)
  - L proportional to $1/\sigma_x$, δ_{bs} to $1/\sigma_x^2$

$$\mathcal{L} \approx C\frac{P_B}{E}\sqrt{\frac{\delta_{BS}}{\epsilon_{y,n}}}\min\left(1, \sqrt{\sigma_z/\beta_y^*}\right)$$

- However, the horizontal angle effect is the limiting factor
- What about re-designing the damping ring for lower horizontal emittance
  - Present design is very conservative in this respect

Summary

- Baseline luminosity at E_{CM} = 250GeV is ~ 0.82 x 10^{34}
- Luminosity can be doubled by doubling the number of bunches (1312→2625)
- Another factor of 2 is possible by 10Hz collision, If 500GeV machine is built
- Recently staging (starting at 250GeV) is demanded to reduce the first stage cost
  - 10Hz collision is presumably difficult
  - The only way to increase the luminosity at 250GeV is to lower the horizontal emittance
- Luminosity at Z-pole is somewhat low, though sufficient for detector calibration
- Giga-Z is not realistic unless strongly desired