Possible Beam Conditions in ILC

- Overview of ILC Accelerator
  (May be omitted if the audience is familiar with ILC → then, jump to page 16)
- Diversified application of ILC beam to other purpose

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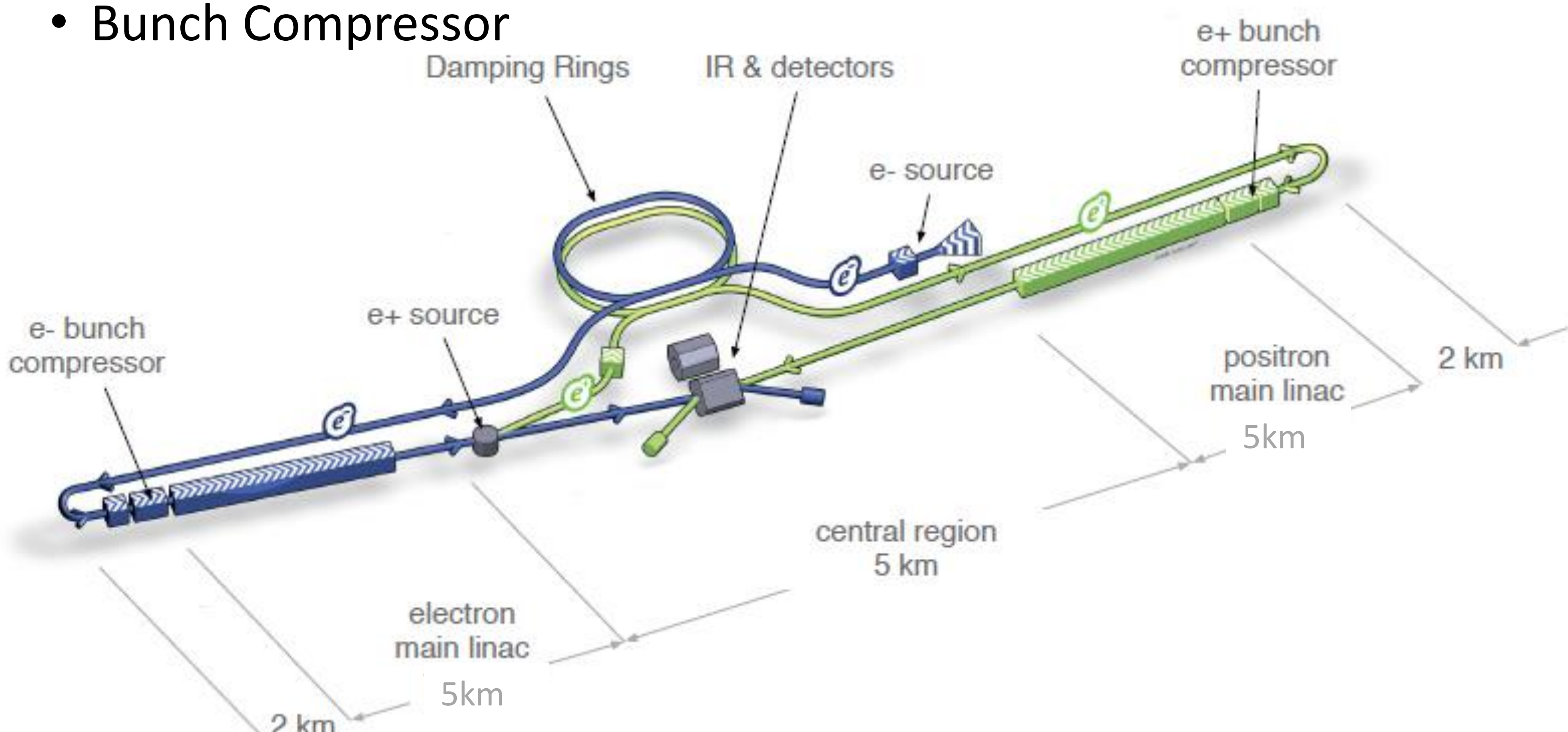
ILC Layout

- Electron Source
- Positron Source
- Damping Ring
- Bunch Compressor
- Main Linac
- Beam Delivery System
- Beam Dump



Basic Beam Parameters

- Repetion frequency 5 Hz
- Damping Rings
  - Beam energy 5 GeV
  - Circumference 3238.7 m
  - Stored bunches 1312
  - Bunch interval 6.15 ns (several ns gaps exist)
  - Number of particles per bunch 2×10^{10}
  - Equilibrium rms bunch length 6 mm
  - Equilibrium rms energy spread 0.11%
  - Equilibrium emittance (normalized)
    - horizontal 4.0 μm.rad (smaller than in TDR)
    - Vertical 20 nm.rad
- Interaction Point
  - Beam energy 125 GeV
  - Number of bunches per pulse 1312
  - Bunch interval 554 ns
  - Pulse length 0.73 ms
  - RMS bunch length 0.3 mm
  - RMS energy spread (e-/e+) 0.19/0.15 %
  - Equilibrium emittance before collision (normalized)
    - horizontal 5.0 μm.rad (smaller than in TDR)
    - vertical 35 nm.rad

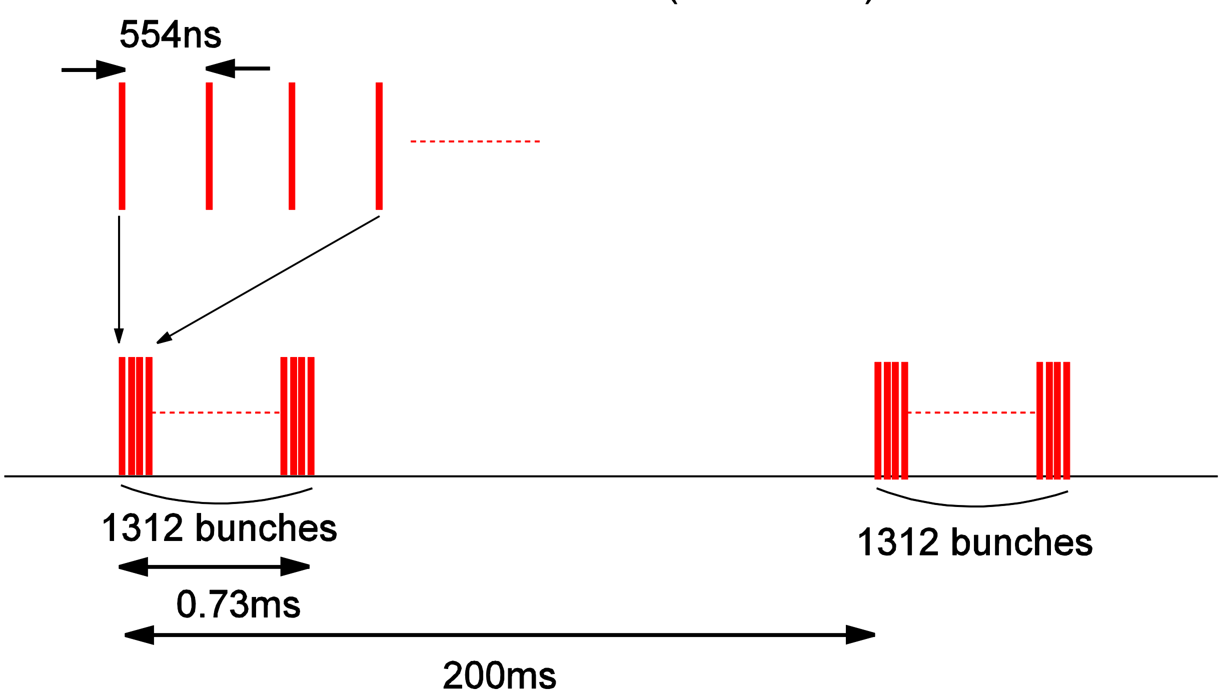
Basic Beam Parameters (baseline, 5Hz)

• Repetition frequency	5Hz
• Number of bunches per pulse	1312
• Number of particles per bunch	2x10^10
• Bunch interval	554 ns
• Bunch length	0.3 mm

• Horizontal normalized emittance	5 μm
• Vertical normalized emittance	35 nm
• Horizontal beam size at IP	515nm
• Vertical beam size at IP	7.7nm

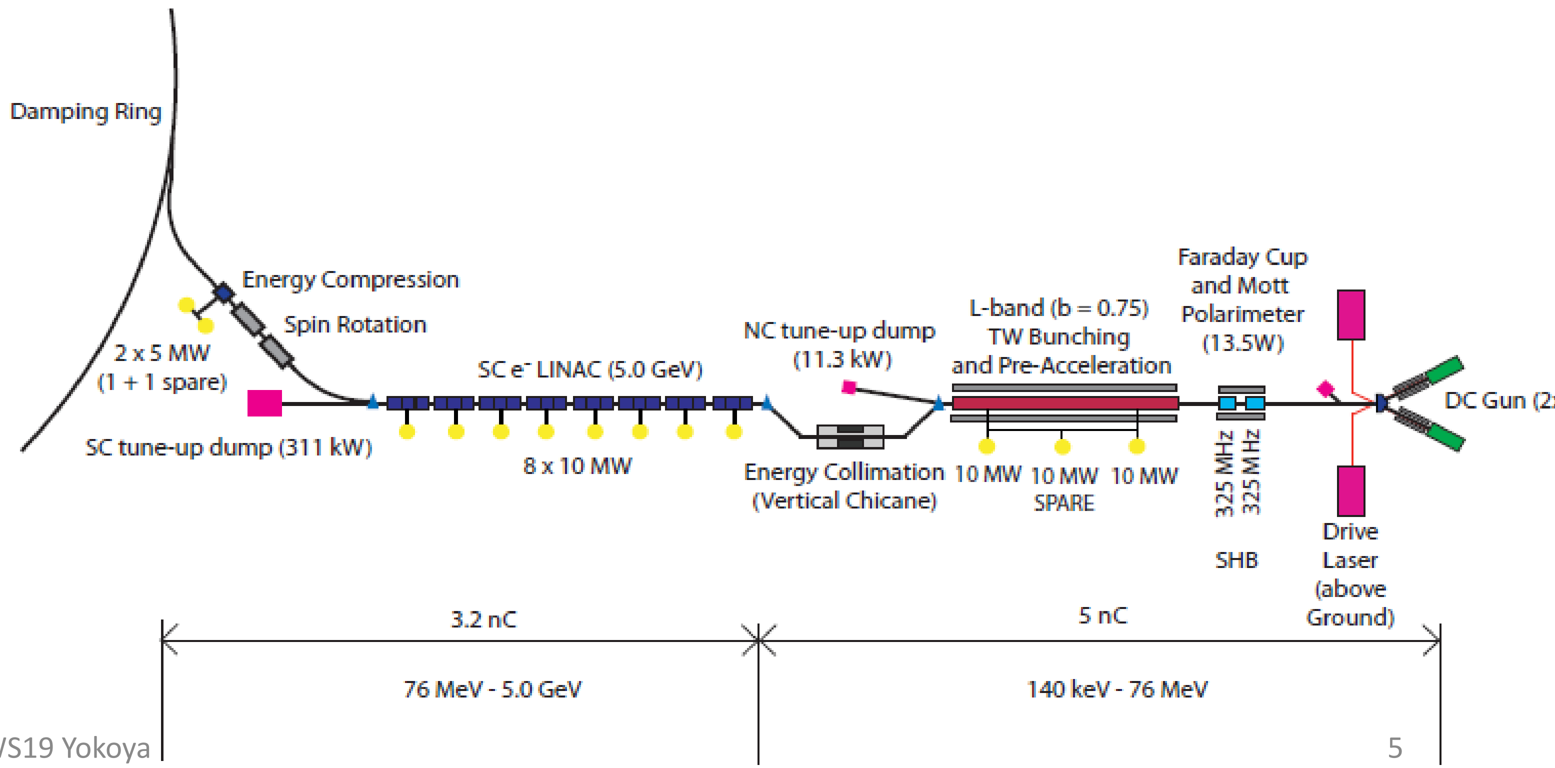
(E_{CM} = 250GeV)

Beam Pulse Structure (Low Power)



Electron Source

- Polarized Electron Source
  - Strained GaAs superlattice
  - Polarization >80% (90% possible recently)
  - Use photo-cathode DC gun. The bunch length is longer than in, e.g., Eu-XFEL gun (sufficient for ILC because of the damping ring)
- Accelerated to 5GeV and injected to the Damping Ring



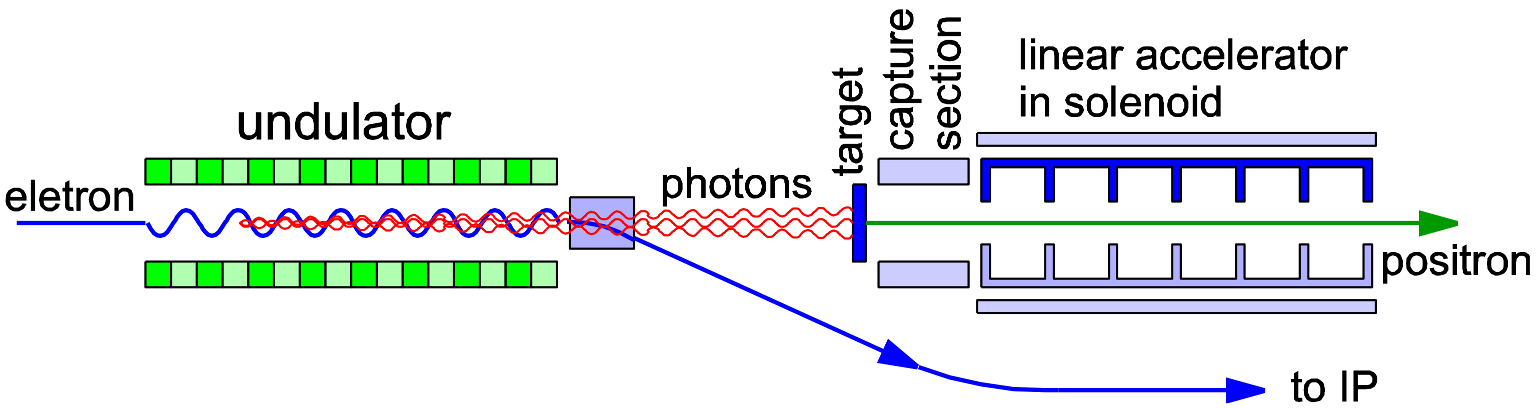
Positron Source (1)

- One of the challenging area in Linear Collider
  - ~10^{14} positrons/sec
- Baseline
  - Undulator scheme
- Backup scheme
  - e-driven scheme
- Status last year
  - Report on the ILC Positron Source, May 23, 2018.

  http://edmsdirect.desy.de/item/D00000001165115

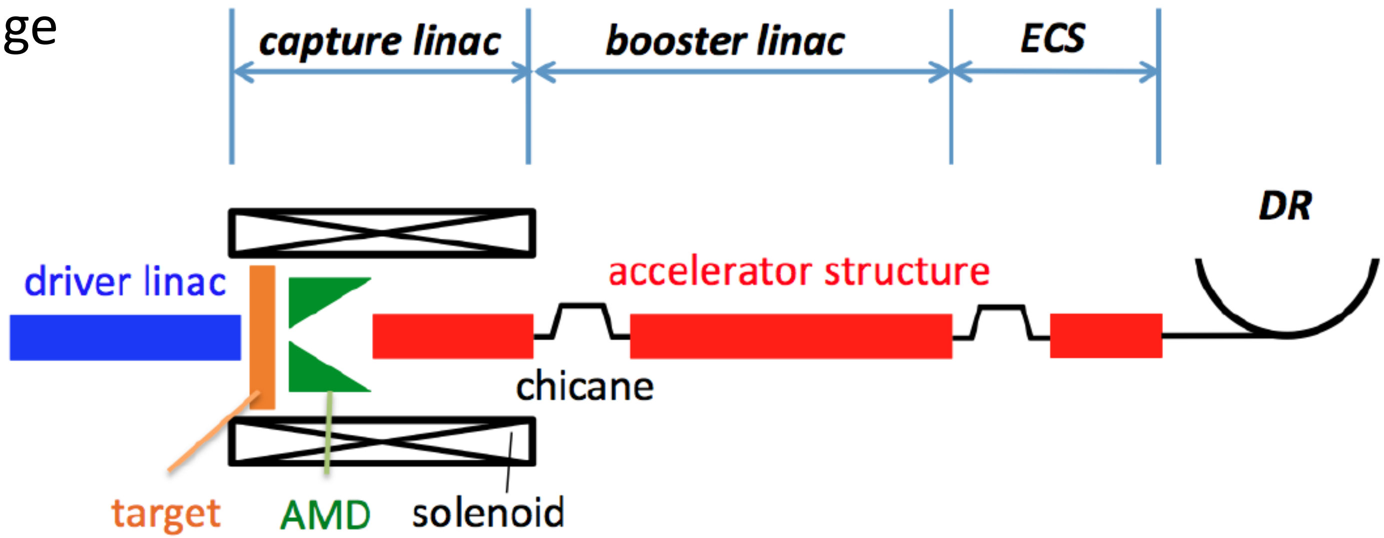
Positron Source (2)

- Undulator scheme
  - Create photons over several MeV by leading the electron beam >125GeV through undulator
  - Irradiate these photons to a target to produce positrons
    - The photon beam will be mentioned later
  - Use helical undulator. Hence the positron beam is polarized (~30% in baseline design. Later upgrade to ~60%)
  - Still some R&D issues remaining (in particular the target)

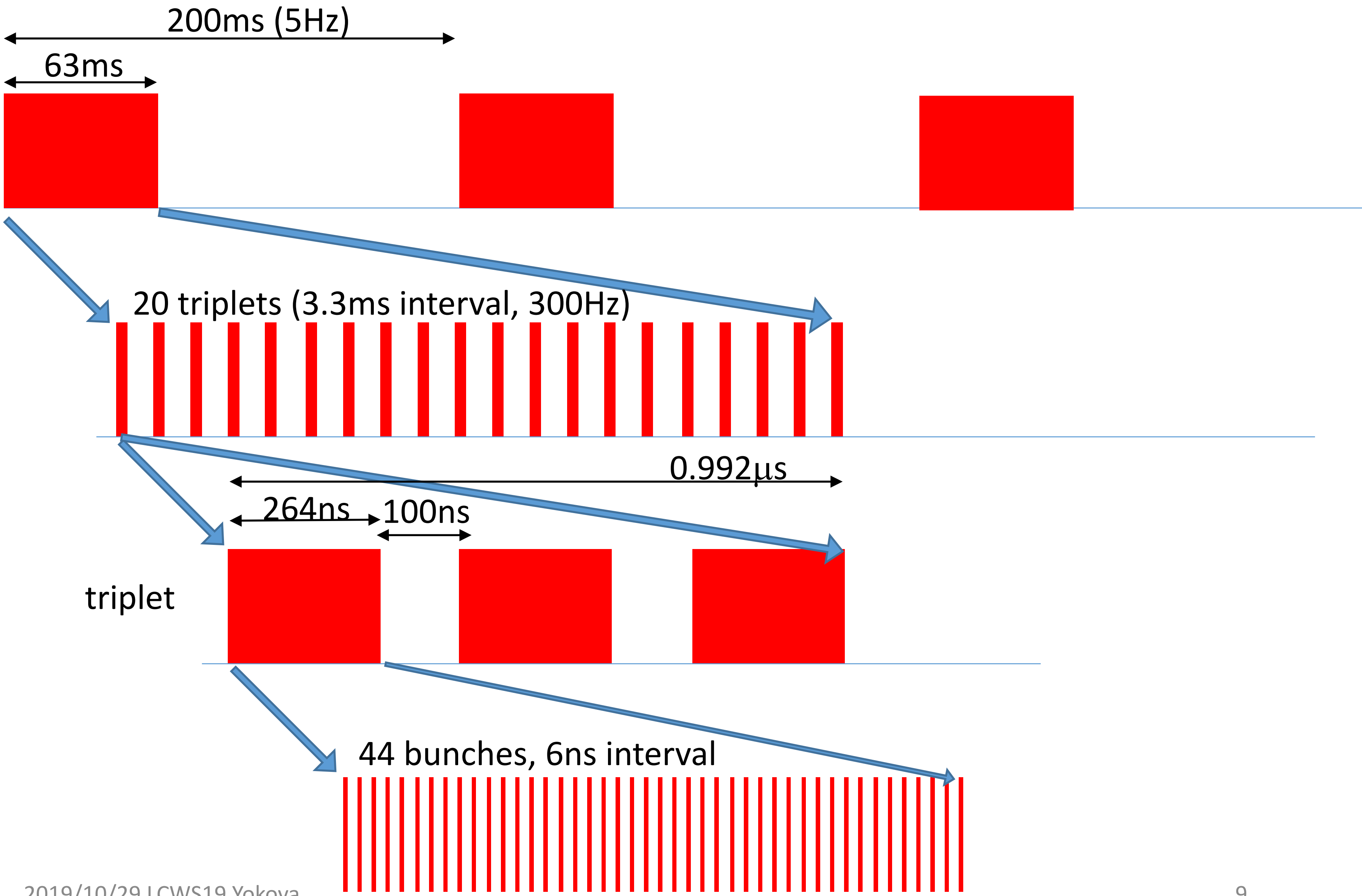


Positron Source (3)

- Electron-driven scheme
  - Backup
  - Usual method of positron production but more positrons/sec
  - Unpolarized
- The pulse structure at production (before damping ring) is different from that in the undulator scheme)
  - Same after Damping Ring
  - 5Hz (200ms interval)
  - Next page

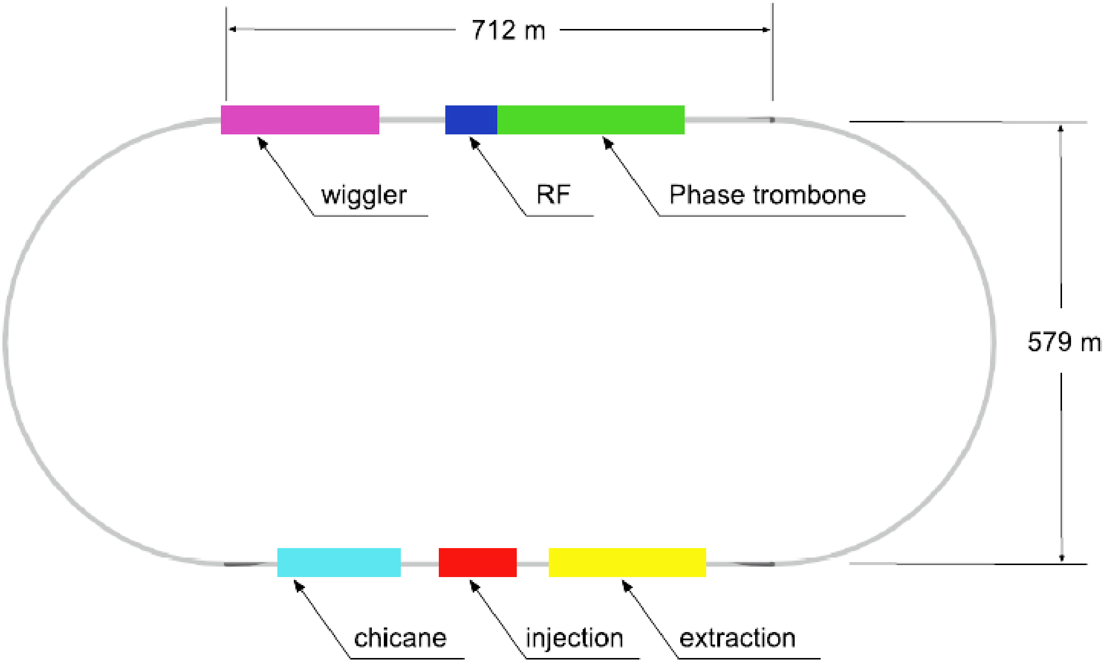


e-Driven Scheme Pulse Structure



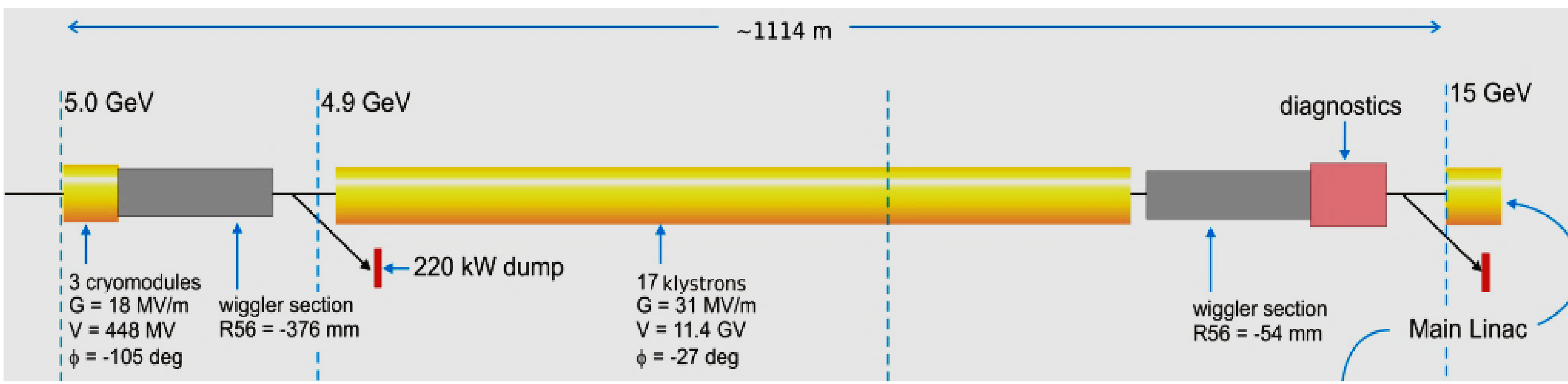
Damping Ring

- 5GeV, circumference ~3km
- 1312 bunches (~6ns interval)
- The bunches stay 200ms (5Hz)
- Extracted beam
  - Normalized emittance 4μm.rad x 20 nm.rad
  - Relative RMS energy spread 0.11%, RMS bunch length 6mm



Bunch Compressor

- Compress 6mm (rms) bunch into 0.3mm
  - Capability down to 0.15mm
- Double stage, total length ~1.1km
- Energy spread x20 (5.5MeV → 110MeV)
- Beam energy 5GeV → 15GeV

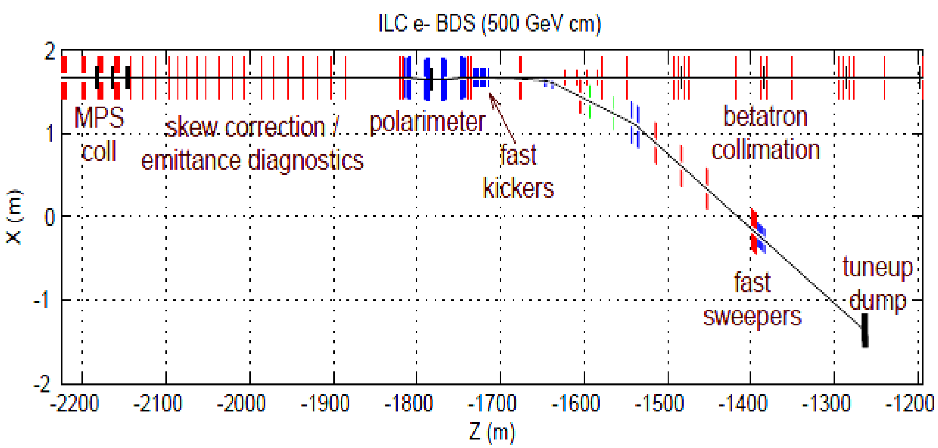


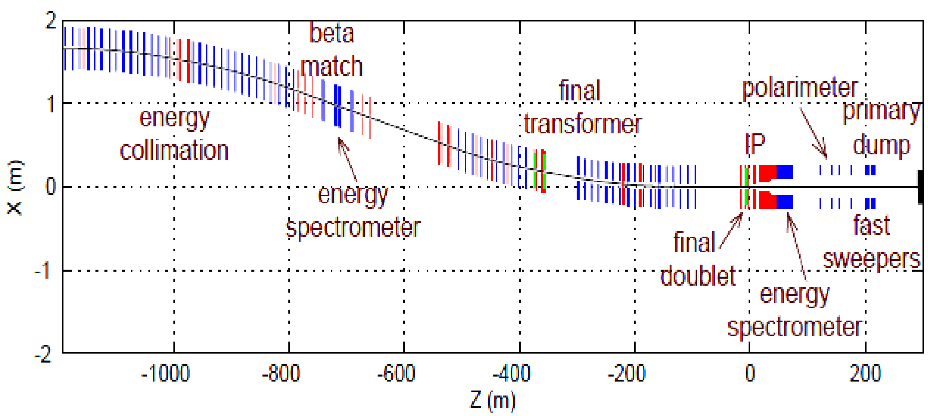
Main Linac

- 15GeV → 125GeV
- Total length ~5km x 2
- Average accelerating gradient 31.5MV/m
- Repetition rate 5Hz
- 554nsec interval, 1312 bunches, pulse length 0.727ms
- Bunch population 2×10^{10}
- Bunch length (rms) 300μm
- No beam dump prepared in the middle

BDS (Beam Delivery Section)

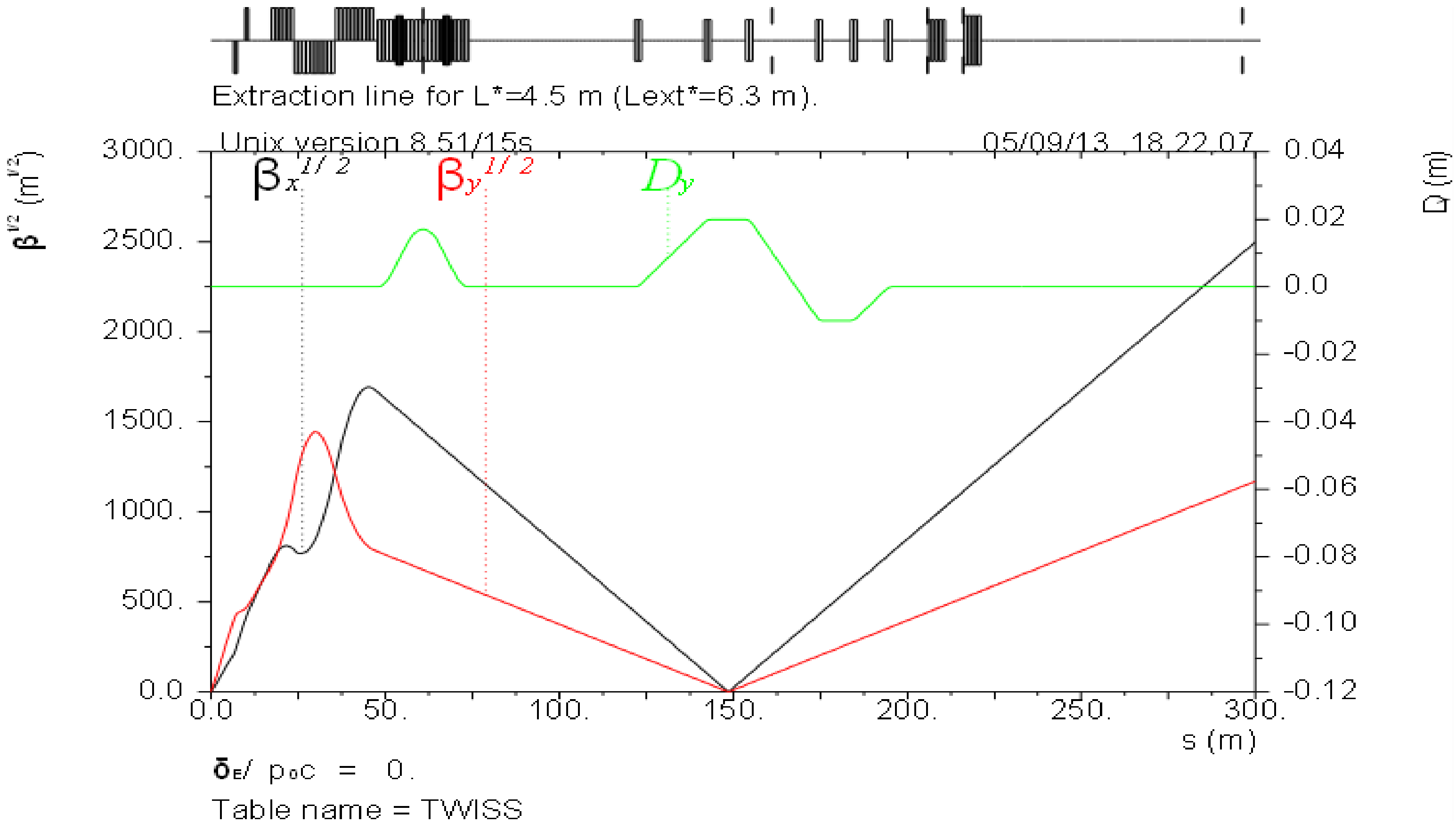
- Total length 2254m x 2
- Can be used at E_{CM}=1TeV by adding some magnets
- There is a beam dump for the main linac tune-up
- IP (Interaction Point)
  - Beam energy 125GeV
  - Bunch length 300μm
  - RMS beam size 515nm x 7.7nm
  - Normalized emittance 5μm x 35nm





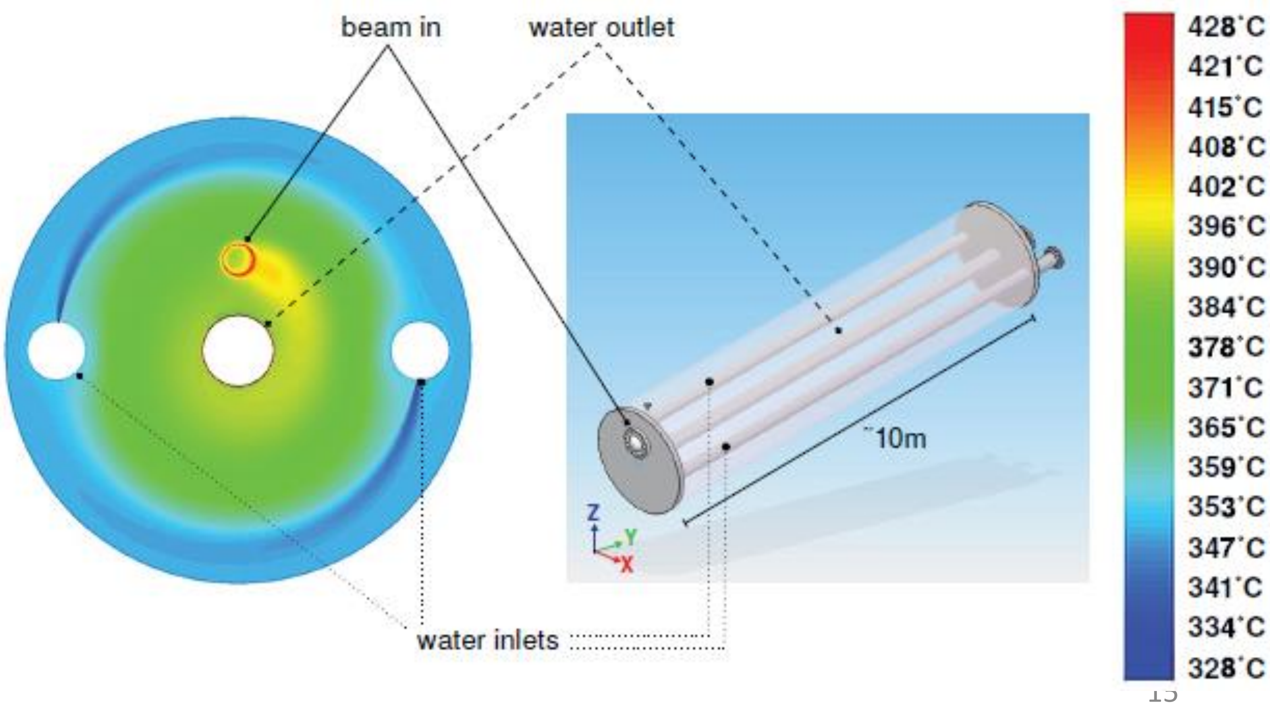
Beam Dump Line

- Crossing angle 14mrad
- Beam dump is located ~300m downstream from IP
  - The distance from the beam going to IP is ~300m x 14mrad = 4.2m
- Mirror focal point at the center for beam diagnostics



Main Beam Dump

- Designed for 17MW (can be used for E_{CM}=1TeV)
  - Up to 2.6MW with 250GeV, 1312 bunches
- Cooled by circulating, high-pressure water (10 atm)
- Diameter 1.8m, length 11m, Stainless vessel
- Receive the beamstrahlung from IP, too (up to 10% in power)



Diversified Use of the ILC Beam

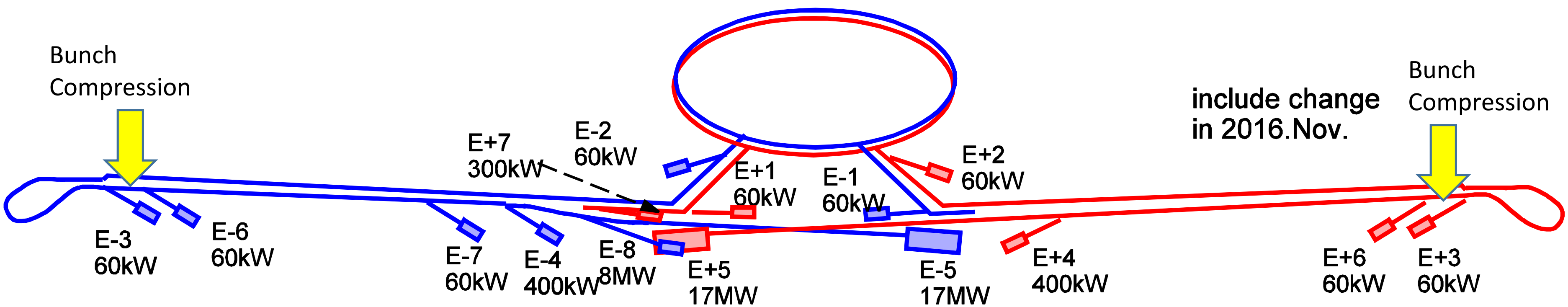
- ILC beam
  - Very high energy
  - Low emittance
  - High intensity (beam thrown away)
- Once ILC is built, people will certainly think of the possibility of using the beam for other purposes
- Expect a long life of ILC system
  - Luminosity-energy upgrade in the future desirable
- First consider parasitic usage under high-energy experiment of ILC250
  - Center-of-mass energy 250GeV
  - Beam energy maximum 125GeV

Parasitic Use of the Beam

- Destructive use of a part of the beam (extraction)
  - Take out the head (or tail) of the 1312 bunches
    - Fast kicker needed (rise/fall time < 0.5μs)
  - Take out a part of (rise/fall time < 200ms)
  - Might be possible to use the beam for a few hours/days (shutdown, summer time)
- Non-destructive use of the whole (or part) of the beam
  - For example, insert an undulator in the main beamline
  - In such a case a chicane is needed to separate the electrons and photons
  - Must not degrade the main beam emittance
- **Other possibilities not affecting the collision experiment**
  - Use of the beam after collision
  - Use of photons for producing the positron
  - Operate the electron injector (5GeV) at 10Hz, 5Hz for high energy experiment and 5Hz for parasitic use

Distribution of the Beam Dumps

- Extraction use will be most practical at the location of beam dumps
- Show below the schematic layout of the beam dumps
- Blue: electron, red : positron,. Yellow arrow : bunch compressor (bunch length 6mm at its upstream, 0.3mm downstream)
- The power number is the design upper limit of each dump (including 20% margin)
  - For commissioning or for emergency, except E-5, E+5, E+7, E-8
  - Therefore, the power of the full beam passing nearby exceeds the dump design (see next page)
  - Only E-5, E+5, E+7 can dump the full beam. (The design upper limit exceeds the full beam intensity because future upgrade is taken into account)
- It is not decided yet whether E-8 is to be constructed in ILC250GeV (Z-pole !!)



Beam Dump Specification

- PB max = the beam power near the dump during ILC250GeV normal operation
- W = Beam dump design limit (including 20% margin)
  - PBmax > W : cannot dump the full beam
  - PBmax < W : to prepare for future upgrade

Name	Use of the dump	E	PB max	W
		GeV	kW	kW
E−1	Commissioning of electron injector	5	100	60
E−2	Extraction from electron DR	5	100	60
E−3	Just before electron bunch compression	5	100	60
E−4	tune−up of electron main linac	125	2500	400
E−5	Electron main dump	125	2500	17000
E−6	Just after electron bunch compression	15	300	60
E−7	Emergency dump just after electron main linac (protect undulator)	125	2500	60
E−8	Spent electron after producing positron (foe 5+5Hz)	150	3000	8000
E+1	Commissioning of positron production system]	5	100	60
E+2	Extraction from positron DR	5	100	60
E+3	Just before positron bunch compression	5	100	60
E+4	tune−up of positron main linac	125	2500	400
E+5	Positron main dump	125	2500	17000
E+6	Just after positron bunch compression	15	300	60
E+7	Dump of photons from undulator	~0.008	60	300

Use of Photons at Various Points

- Insertion device into the main beam line
  - Can be inserted anywhere in principle, if the beam is not degraded
  - But actually very difficult
    - Room for the insertion device, the line to restore the electron orbit, prepare a space for operators, etc.
- At the beam dump position (see page 18)
  - Look easy to insert at
    a. The end of electron injector [E-1], 5GeV
    b. Right after extraction from DR [E-2], 5GeV
    c. Before bunch compressor [E-3], 5GeV
    d. Right after bunch compressor [E-6], 15GeV
    e. Right after main linac [E-4], 125GeV
  - Seems best at (a) for 5GeV, and at (d) for 15GeV

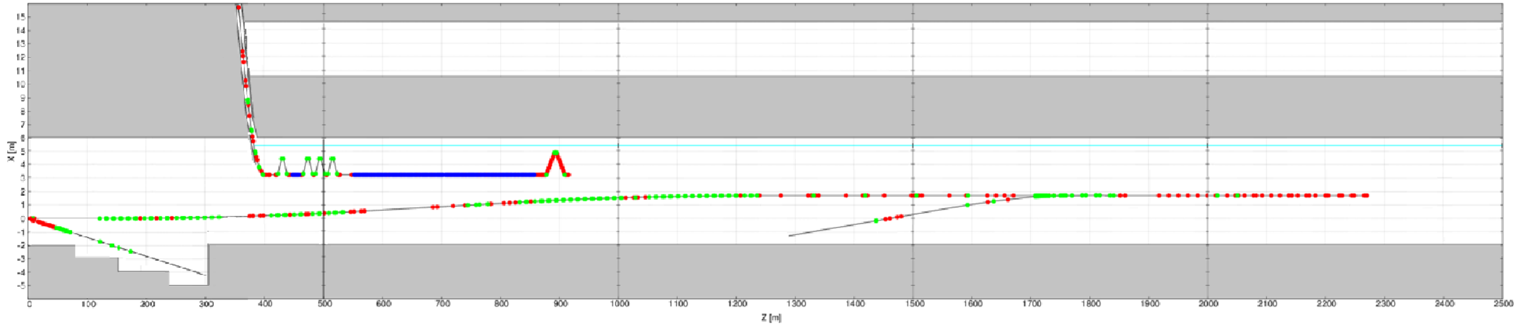
End of Electron Injector (1)

- 5GeV
- Can operate this injector at 10Hz (slight reinforcement of power consumption)
  - 10Hz collision experiment also in the scope
- 5Hz to DR (for collision), remaining 5Hz for light source
- Problem is the bunch length
  - ILC does not care about the bunch length and emittance because the beam is anyway injected to DR
  - Polarized electron gun requires DC gun. The bunch is long.
- Therefore, for using as FEL, it is necessary to prepare RF gun and bunch compressor. To prepare the tunnel width for this purpose will not be expensive.
  - Inject to Superconducting linac at 76MeV in TDR

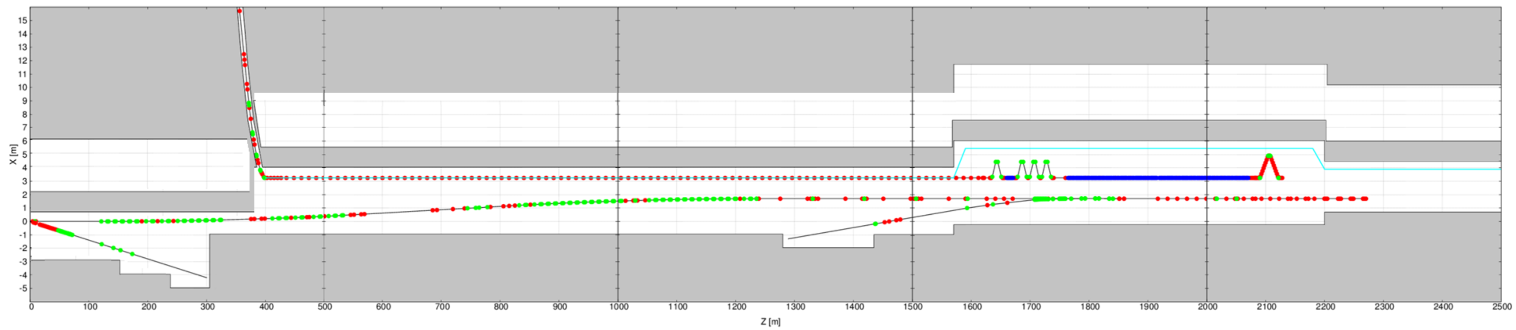
End of Electron Injector (2)

- The location of the electron linac was shifted as the figure below after TDR
  - Moved uostream (helium line from the right, avoid radiation from collimator to hit the superconducting cavities, etc.)
  - Therefore, there is ~1km space at downstream of 5GeV linac. Enough for placing undulator. But, where are the users?

(a) TDR positron BDS tunnel



(b) proposed positron BDS tunnel

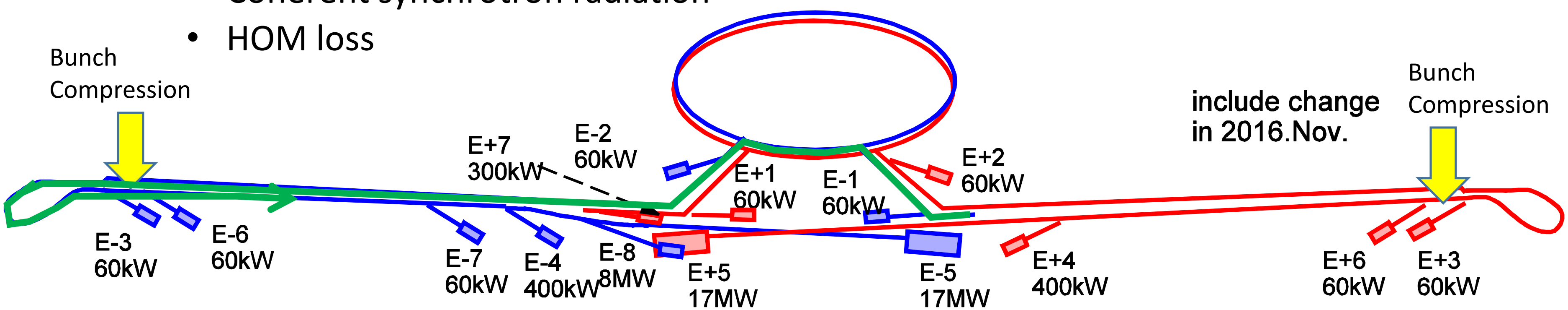


After Bunch Compression (15GeV) (1)

- [E-6, E+6]
- 15GeV, Low emittance (~4μm.rad x 20nm.rad)
- A bit large energy spread ~1.2%
- Short bunch (0.3mm)
  - Must be 0.3mm during collision experiment. But the compressor itself is capable of 0.15mm (but the energy spread is doubled)
  - **If 0.15mm is absolutely needed, it may be possible to get a machine time for a few hours/days (my personal view)**
- Full beam power ~300kW. Dump < 60kW
- For taking out ~10%, reinforcement of the beam dump E-6, E+6 is not necessary

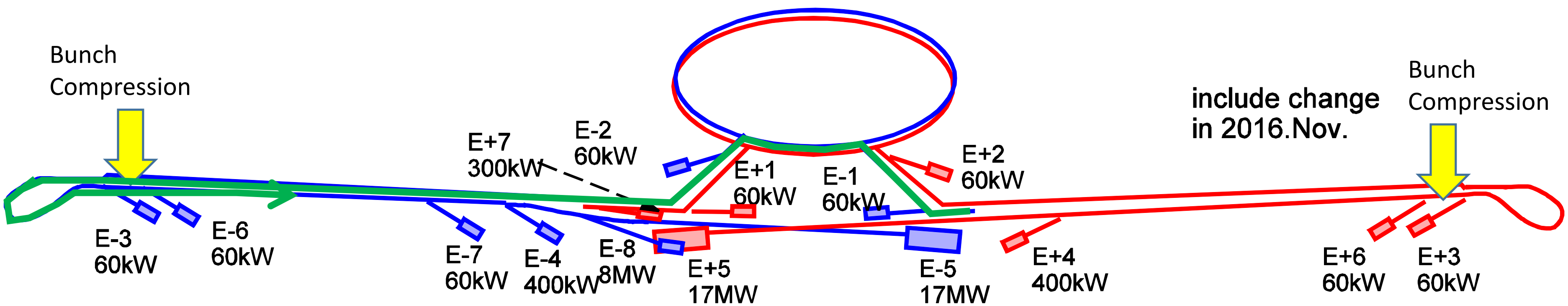
After Bunch Compression (15GeV) (2)

- Bunch length 0.15mm is too long for FEL
- May be shortened by the following way for electron (not positron)
- Prepare RF gun (unpolarized) as in the case of using 5GeV injector
- The bunch is lengthened if injected to DR in the usual way
- Instead, inject into DR and immediately extract as the green line below (or construct an additional parallel beamline
- And put to the bunch compressor
- <~10μm can be obtained, presumably
- Must study whether this is possible in 5+5Hz parasitic mode
  - The bunch compressor setup for 6mm→300μm can compress 200μm→10μm?
  - Coherent synchrotron radiation
  - HOM loss



Possibility of Extremely Short Bunch

- Some experiment requires
  - FACET @ SLAC ~20μm, further bellow in FACET-II
  - <10μm possible
  - But to what extent?
- “Ultra-Short-z Parameters for ILC” (V. Yakimenko, LCWS2018)
  - Collision with $\sigma_z < 0.1\mu m$ may suppress beamstrahlung
  - Interesting for QED
  - But for now very difficult for positron (DR of extremely small ongitudinal emittance necessary)



125GeV

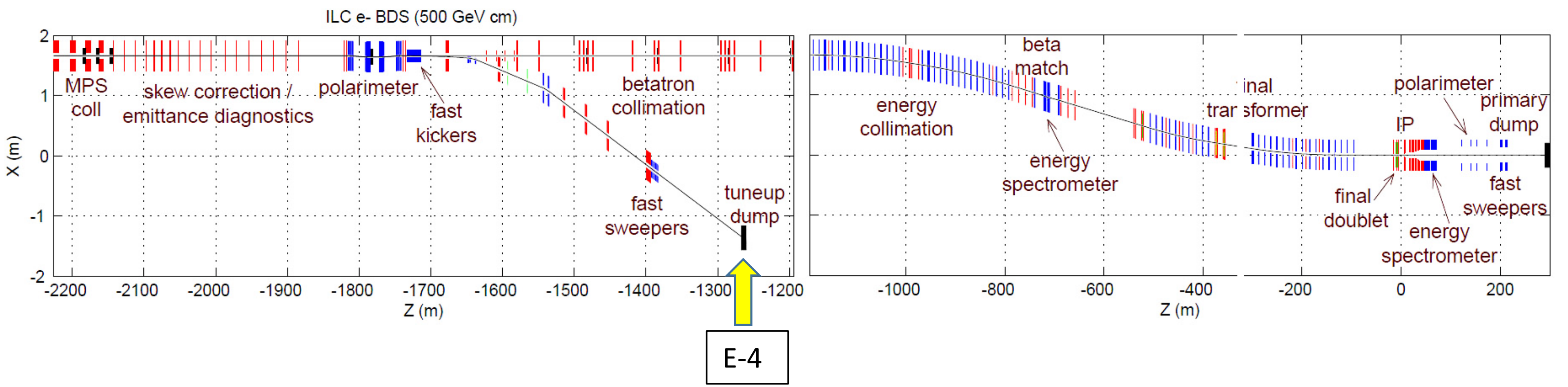
- [E-4, E+4] after Main Linac
- Energy 125 GeV ..... Light source use??
- emittance 5μm.rad x 35 nm.rad
- Energy spread 0.19% (e-), 0.15% (e+)
  - Electron energy spread is larger because of the undulator
- Bunch length 0.3mm
  - **As in the case of E+-6, must be 0.3mm during collision experiments**
  - **If 0.15mm is absolutely needed, it may be possible to get a machine time for a few hours/days (my personal view)**
- Full beam power 2.5MW, beam dump < 400kW
- No need of reinforcement of beam dump if 10% use
- Note: in the electron side the extraction at [E-7] gives almost the same beam parameter, but the maximum power is limited to 60kW because this is the emergency dump to protect the undulator. Hence, the merit is less compared with [E-4, E+4].

Use of Damping Ring Beam

- Space for inserting light sources is not considered for the moment
- Beam current ~0.5A
- Emittance 400pm x 2pm
- The equilibrium emittance is small. However, it takes time to reach the equilibrium and the beam is extracted immediately after reaching the equilibrium.
- Hence, it seems useless to use DR beam so long as the collision experiment is going on.
  - In some day, you may use electron DR when flat-beam electron gun become available.

Extraction of 45GeV Beam?

- Intense study necessary to design an extraction line in the middle of the main linac.
- Alternatively, it may be possible to lower the accelerating gradient once in several pulses such that the beam energy at the linac end becomes (for example) 45GeV
    - This has been considered for the operation of ILC250 for Z-pole experiment
    - Issues to be considered → next page
    - The plot below shows the electron side. The positron side is similar. ([E-4] → [E+4])



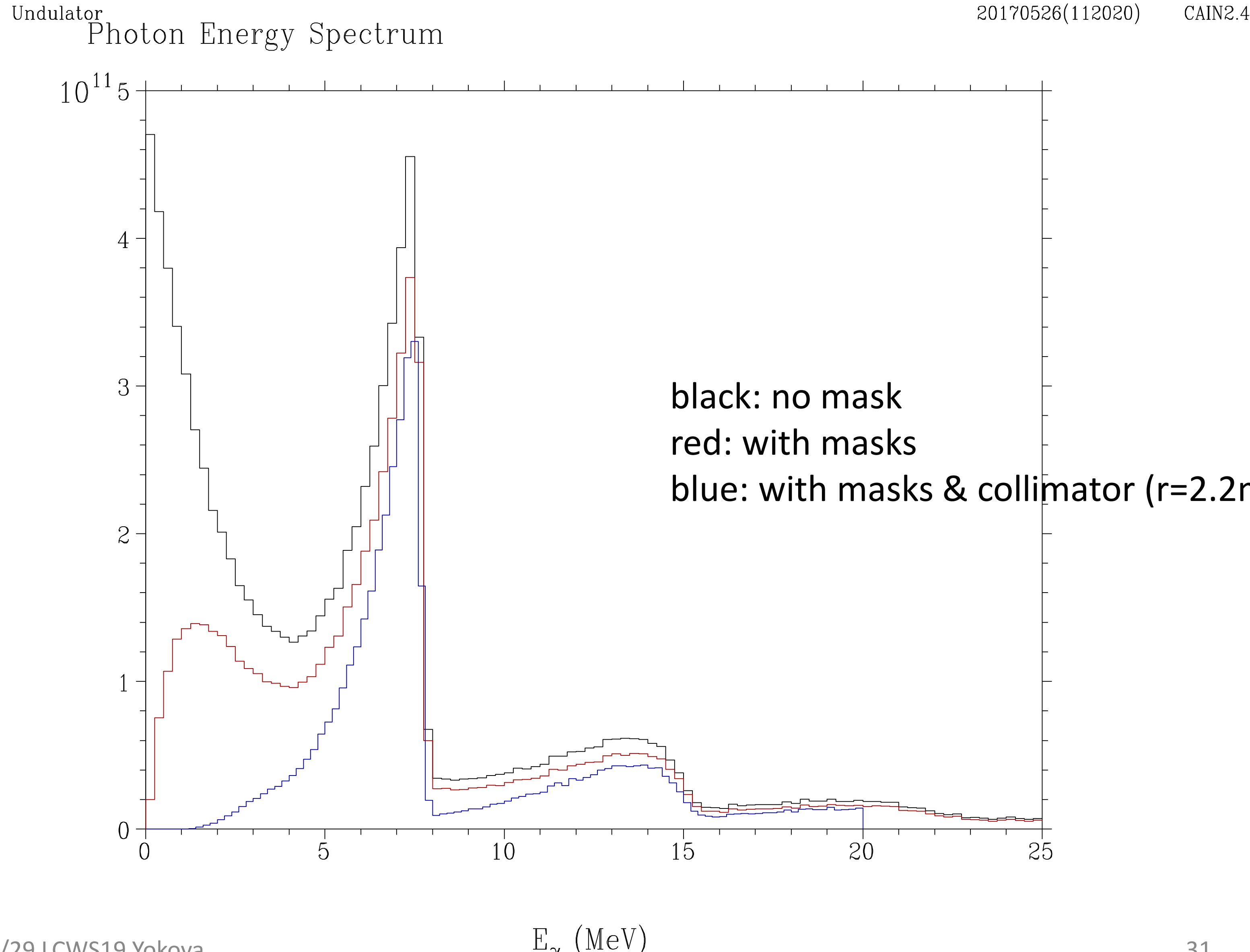
Extraction of 45GeV Beam (continued)

- Consider here only the parasitic use under 250GeV experiment
- Change, pulse-to-pulse, the quadrupole and steering magnets in the main linac is impossible. Retuning of orbit correction impossible.
  - We have studied the case, for Z-pole operation, of alternating 125 and 45GeV beam. But in that case the orbit is tuned for 45GeV beam. The degradation of 125GeV is significant, but is acceptable for positron production. Now, if the orbit is tuned for 125GeV, the degradation of 45GeV beam will be even more serious. No study has been done.
- But, to use 1 minute ~ 1 hour occasionally is perhaps possible
  - Then, we can tune the beam for 45GeV
- The final focus system contains dipole magnets. They cannot change. So, must construct another 45GeV beamline. → perhaps, reasonable to place the 45GeV experiment devices just before [E+4].
  - This dump line is set up to accept 125GeV beam during normal operation. Can we set for 45GeV? → Perhaps possible. Must study the required optics for the parasitic experiment.

Use of the Photons from Undulator

- Use of the Photons from Undulator for positron production [E+7]
  - Of course, no photon beam if positron is produced the electron-driven scheme
- There is almost no variety of the form of operation in ILC250
  - Electron energy 125GeV
    (more precisely, 128GeV at undulator entrance and 125GeV at exit)
  - Average photon energy 6.3 MeV
  - Number of photons generated (~400 per electron)
    8×10^{12} per bunch, 5.2×10^{16} per second
  - Average photon energy reaching the target 9.7 MeV
    (The low energy part is collimated out)
  - Average power to the parget ~ 50 kW
- Most photons hitting the target(thin, $0.2X_0$) go through the parget and reach the photon dump [E+7]
  - The energy deposit on the target ~2kW

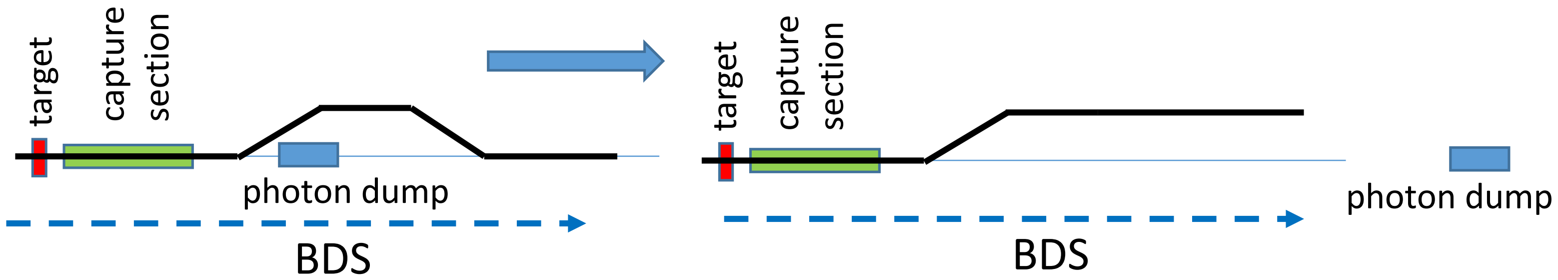
Photon Energy Distribution on Target



black: no mask
red: with masks
blue: with masks & collimator (r=2.2mm)

Location of the Photon Dump [E+7]

- The maximum power in the dump is considered to be ~300kW, taking into account future upgrade. Actual maximum power in ILC250GeV will be 60kW.
- In the TDR the dump (pressurized water, Ti-alloy window) is located at several 10s of meters from the target, but it has been shown the window cannt withstand.
- In the present design the dump is located ~2km downstream
- In this case the photons will fly through a pipe in the BDS tunnel. There are 2 parallel beamlines on the right and left (positron line to DR and colliding beam line) with ~1.5m interval.
- Must think of the size and location for the parasitic experiment
- The most important is the safety when this photon beam is intercepted by thye parasitic experiment.



Lots of Caveats

- We must discuss in advance what are the requirements for the parasitic experiments to the tunnel design
- Safety issues in intercepting the intense ILC beam
  - e.g., to stop full energy beam is almost impossible
- Personnel Protection System
  - Normal rule of ILC is that tunnel access is prohibited during beam operation (even to the service tunnel)
  - Where the experimentalists can sit must carefully be discussed
- Tunnel extension
  - Tunnel extension is not too expensive (in ILC standard) if it is built in the beginning
  - A problem of later addition is not that more cost is needed, but whether construction machines can be carried in where the accelerator components are sitting already

Summary

- There are a few places when the beam line may be used as light sources.
  - 5GeV electron injector
  - Right after 15GeV bunch compressor
  - Others
- The best parasitic mode parallel to Higgs experiment is the 5Hz+5Hz operation
- In any case possible changes of the machine design must carefully be examined
- Caution:
  - Safety in intercepting the beam
  - Tunnel access during beam operation
  - Construction at a later time