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Future Linear Colliders: CLIC, ILC, NC

(e+e-, $\gamma\gamma$ options for Z, W, Higgs,Top and TeV)

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GARD APB Workshop, WG3
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Introduction

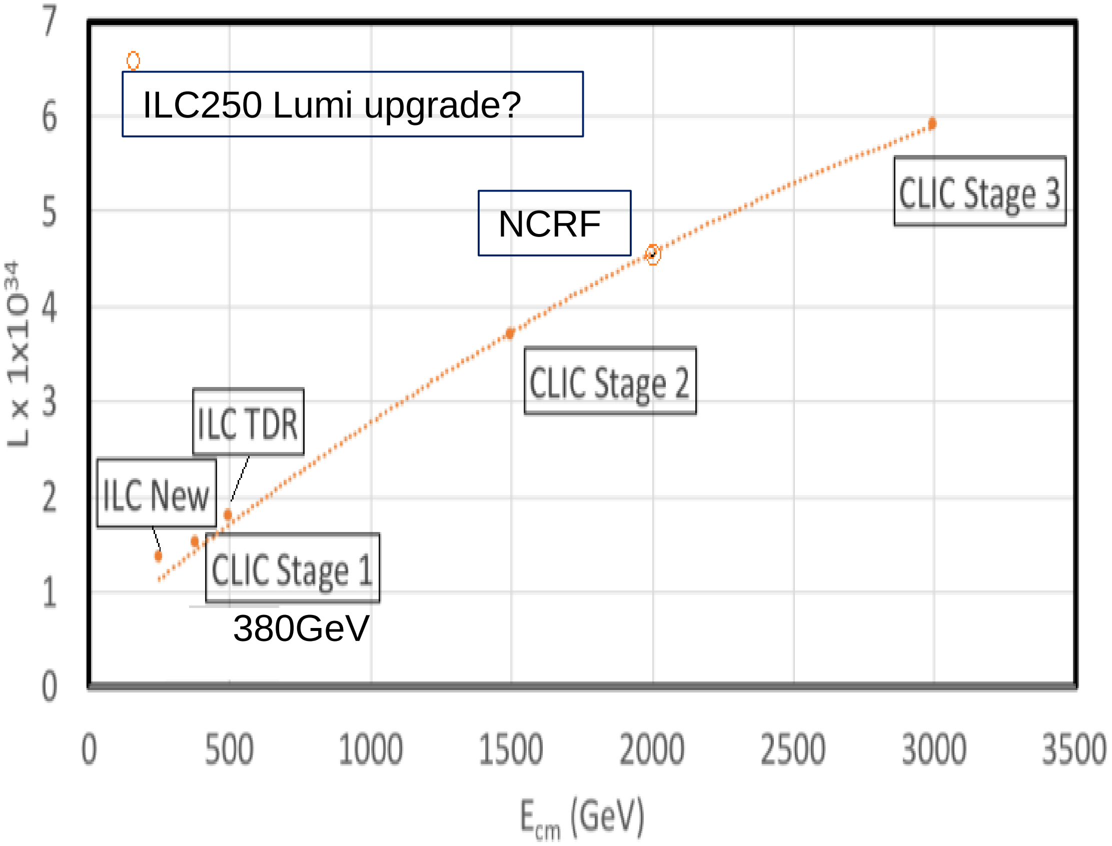
Few lepton LC projects under studies:

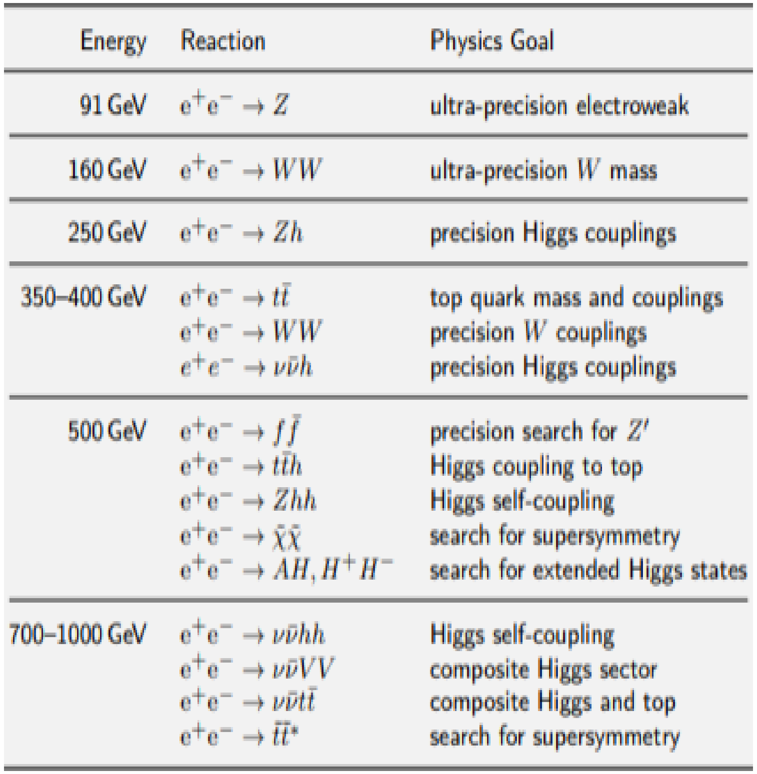
- ILC – L-band superconducting linac, E_{cm} = 1TeV
- CLIC/CERN – X-band NC linac, two beam accelerator scheme, E_{cm} = 3TeV
- NCRF - C-band NC technology at cryogenic temperature-77K, E_{cm} = 2TeV (recent proposal, SLAC)

All projects are considering staging approach:

- 1st stage E_{cm}-250 GeV- ILC (Higgs physics) or 380GeV CLIC (Top factory) with possibility to run at lower energy for Z physics. Advantage: study known physics in depth, minimize risks and costs.
- 2nd/3rd stages for intermediate or highest energy. Possible to use better technology available at that time.
- For each stage the project considers further Luminosity/Energy upgrade scenarios which requires R&D efforts.

Linear colliders: Luminosity and Energy Upgrades

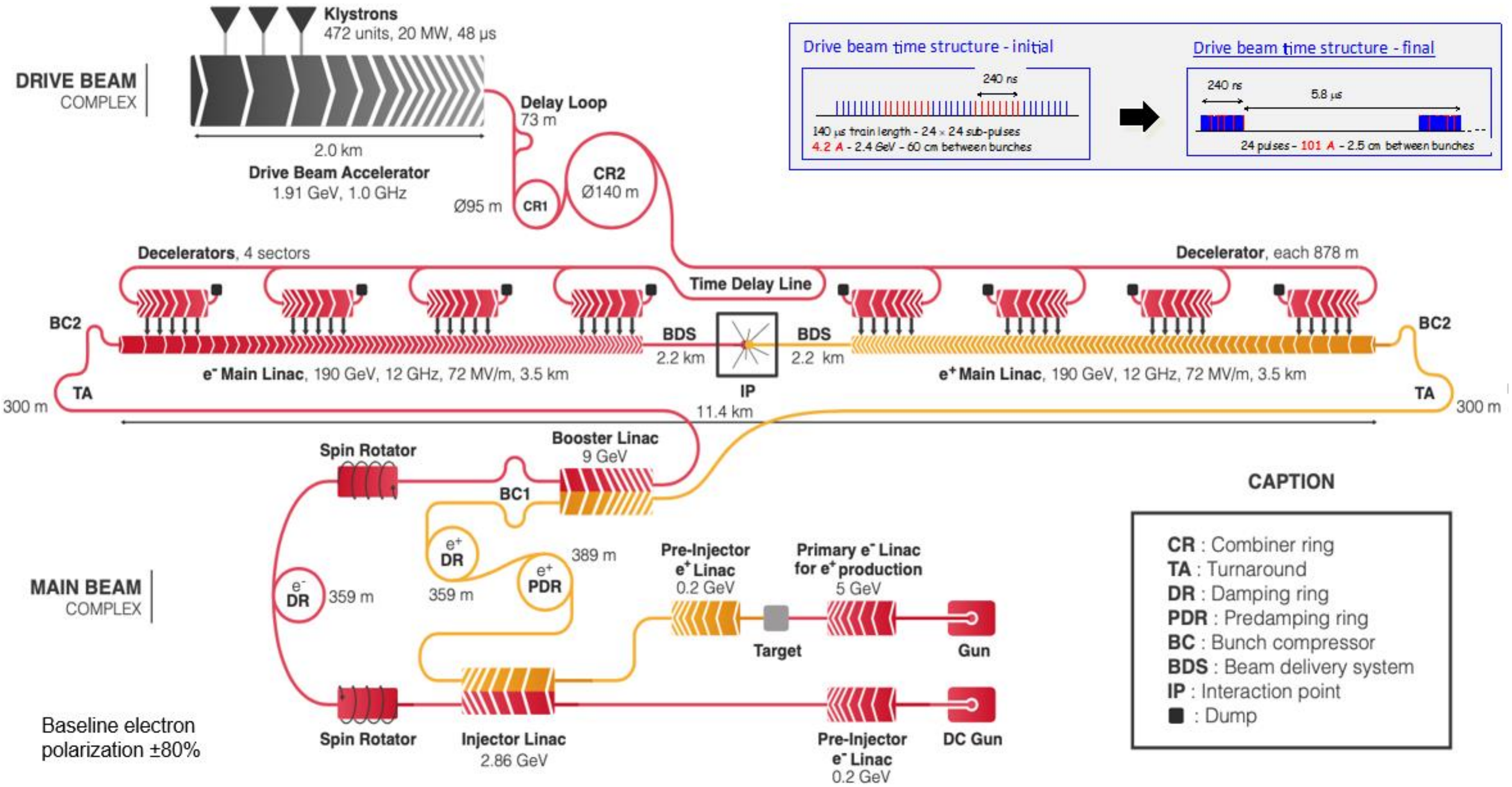




Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$ $e^+e^- \to WW$ $e^+e^- \to \nu\bar{\nu}h$	top quark mass and couplings precision W couplings precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$ $e^+e^- \to t\bar{t}h$ $e^+e^- \to Zhh$ $e^+e^- \to \tilde{\chi}\tilde{\chi}$ $e^+e^- \to AH, H^+H^-$	precision search for Z' Higgs coupling to top Higgs self-coupling search for supersymmetry search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$ $e^+e^- \to \nu\bar{\nu}VV$ $e^+e^- \to \nu\bar{\nu}t\bar{t}$ $e^+e^- \to \tilde{t}\tilde{t}^*$	Higgs self-coupling composite Higgs sector composite Higgs and top search for supersymmetry

Need more beam dynamic studies and optimization for low energy options (Z-pole, WW, Higgs, Top)

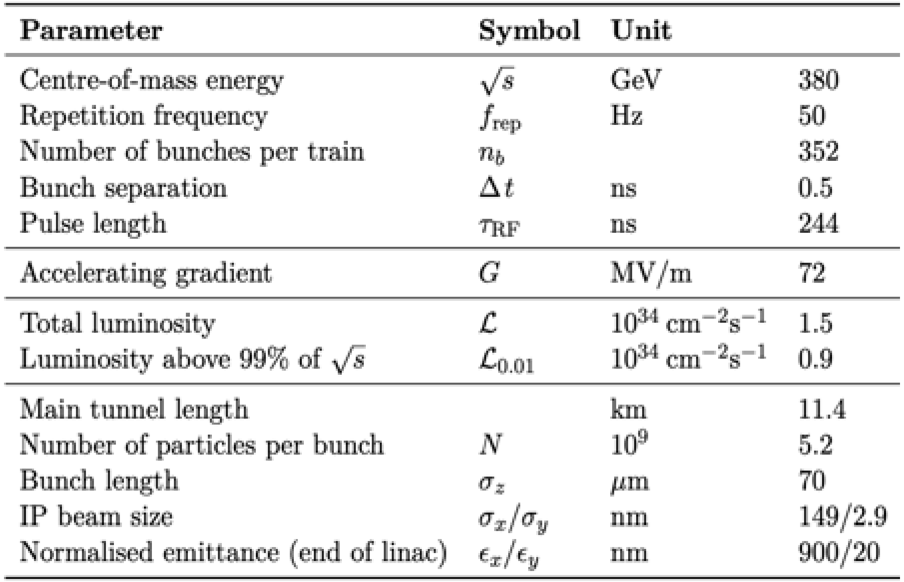
Layout of CLIC 380 GeV → 3TeV



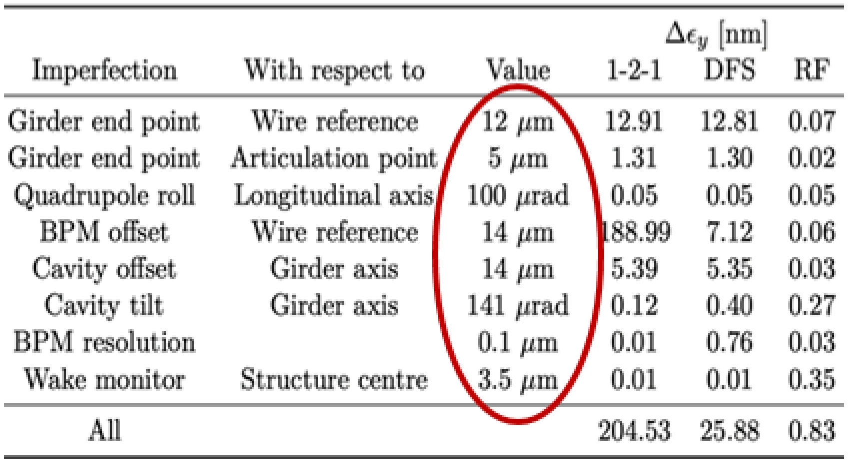
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Baseline electron polarization ±80%

CLIC 380 GeV main parameters



Parameter	Symbol	Unit	
Centre-of-mass energy	$\sqrt{s}$	GeV	380
Repetition frequency	f_{rep}	Hz	50
Number of bunches per train	n_b		352
Bunch separation	Δt	ns	0.5
Pulse length	τ_{RF}	ns	244
Accelerating gradient	G	MV/m	72
Total luminosity	$\mathcal{L}$	10^{34} cm^{-2}s^{-1}	1.5
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9
Main tunnel length		km	11.4
Number of particles per bunch	N	10^9	5.2
Bunch length	σ_z	μm	70
IP beam size	σ_x/σ_y	nm	149/2.9
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20



			$\Delta\epsilon_y$ [nm]		
Imperfection	With respect to	Value	1-2-1	DFS	RF
Girder end point	Wire reference	12 μm	12.91	12.81	0.07
Girder end point	Articulation point	5 μm	1.31	1.30	0.02
Quadrupole roll	Longitudinal axis	100 μrad	0.05	0.05	0.05
BPM offset	Wire reference	14 μm	188.99	7.12	0.06
Cavity offset	Girder axis	14 μm	5.39	5.35	0.03
Cavity tilt	Girder axis	141 μrad	0.12	0.40	0.27
BPM resolution		0.1 μm	0.01	0.76	0.03
Wake monitor	Structure centre	3.5 μm	0.01	0.01	0.35
All			204.53	25.88	0.83

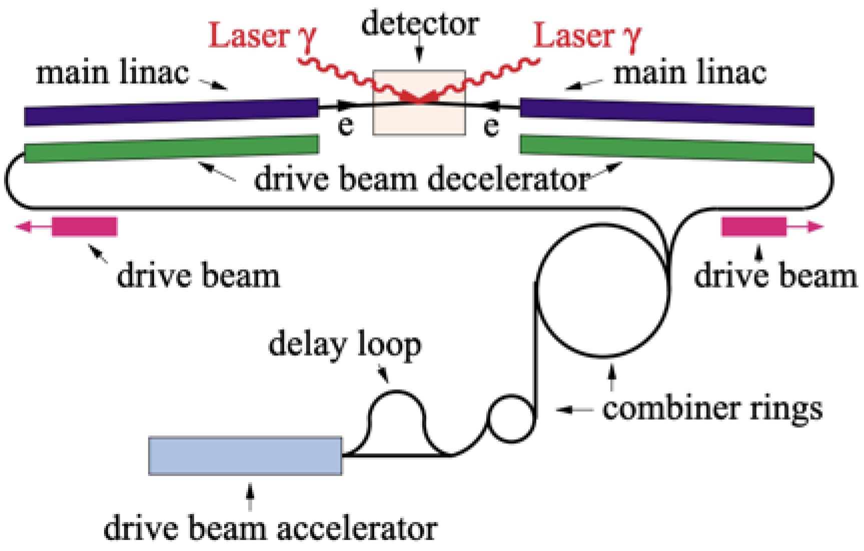
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} \frac{1}{\sqrt{\beta_y \epsilon_y}} N n_b f_r .$$

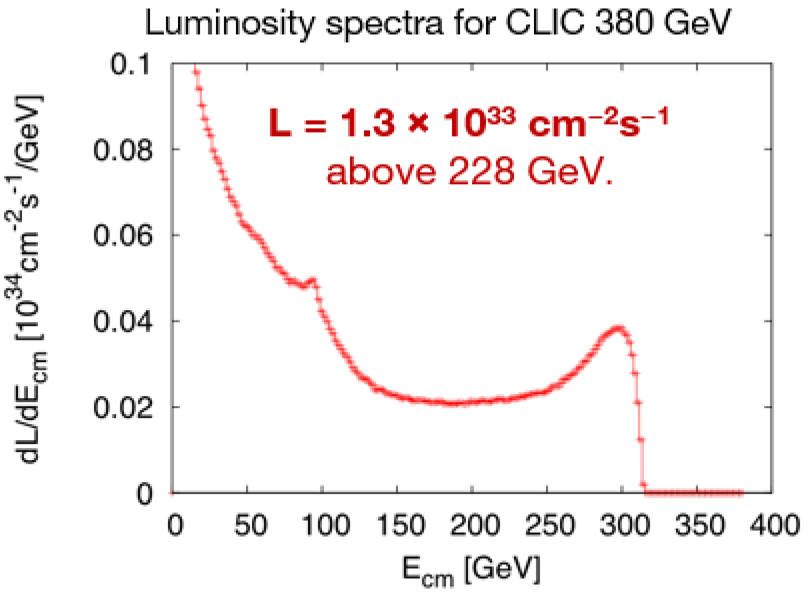
Vertical emittance estimations and budgets:

at DR extraction: 5 nm
at RTML exit: < 10 nm
at ML exit: < 20 nm
at IP: < 30 nm
(>90% probability)

- *Alignment tolerance ~10 μm, BPM res~0.1 μm*
- *main sources of imperfections are misalignments (static/dynamic) and ground motion.*
- *Wakefields – dominant contribution to emittance*

CLIC as a γ-γ collider





Two advantages of γ-γ collider:

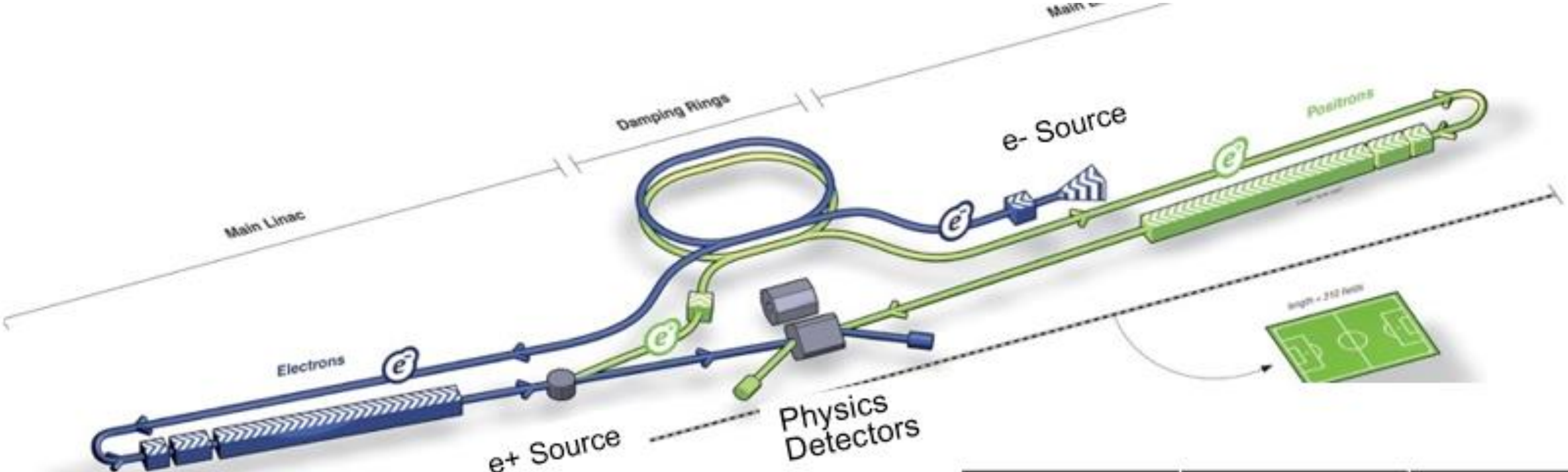
- Larger cross sections
- Polarized collisions (80% of e-)

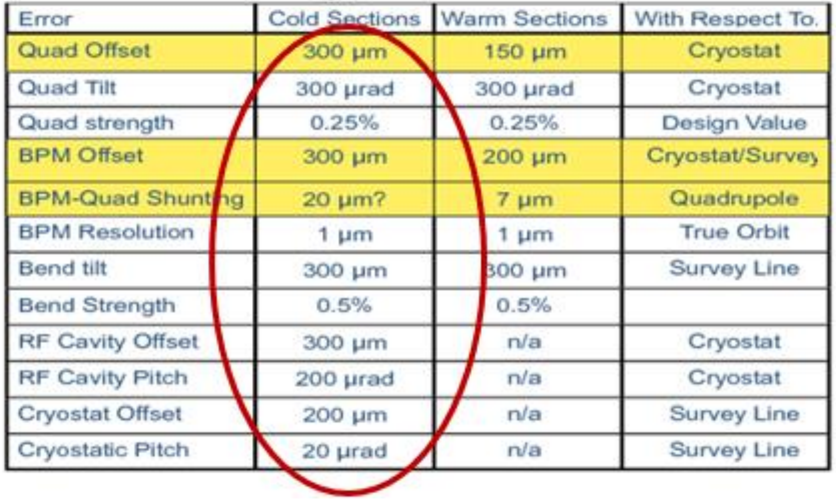
	e^-e^-	$e^-\gamma$	$\gamma\gamma$	units
Total Lumi	0.7	1.1	1.73	10^{33} cm^{-2}s^{-1}
Peak Lumi	0.3	-	0.9	10^{33} cm^{-2}s^{-1}

Luminosity from e-e- collisions is lower than e+e- collisions, due to defocusing repulsive beam-beam forces.

Ref: E. Marin, “Gamma-gamma considerations for CLIC”, Photon beam workshop, Padova, Nov.27-28, 2017

ILC250 Layout and parameters





Error	Cold Sections	Warm Sections	With Respect To.
Quad Offset	300 µm	150 µm	Cryostat
Quad Tilt	300 µrad	300 µrad	Cryostat
Quad strength	0.25%	0.25%	Design Value
BPM Offset	300 µm	200 µm	Cryostat/Survey
BPM-Quad Shunting	20 µm?	7 µm	Quadrupole
BPM Resolution	1 µm	1 µm	True Orbit
Bend tilt	300 µm	300 µm	Survey Line
Bend Strength	0.5%	0.5%	
RF Cavity Offset	300 µm	n/a	Cryostat
RF Cavity Pitch	200 µrad	n/a	Cryostat
Cryostat Offset	200 µm	n/a	Survey Line
Cryostatic Pitch	20 µrad	n/a	Survey Line

Item	ILC250	ILC500
C.M. Energy	250 GeV	500 GeV
Length	20.5 km	31km
Luminosity, $\times10^{34}cm^{-2}s^{-1}$	**1.35**	3.6
Repetition	5 Hz	5 Hz
N_bunches	1312	2625
Beam Current	5.8 mA	8.8 mA
Beam size, y	7.7 nm	5.9 nm
Cav.Grad Q_0	31.5~35 MV/m $1\text{-}1.6\times10^{10}$	31.5 MV/m 0.8×10^{10}

Misalignments ~100µm, BPM res = 1µm

High luminosity upgrade in ILC250 (workshop 2019, FNAL)

H.Padamsee et.al., “Impact of high Q on ILC250 upgrade for record luminosities and path toward ILC380”, (2019)

Higgs factory (FCC vs. ILC250):

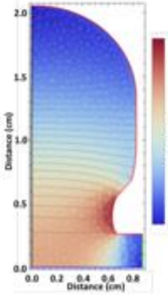
FCC-ee: L=1.7x10^{35}; 100km; cost=10.5B CHF (tunnel, no detector)
ILC250: L=1.35x10^{34}; 20km; cost ~5.5 B ILC Units ($), polarization (x2.5) + Lumi upgrade x2 ➔ L (1.35x2x2.5) = 6.8x10^{34} (effective with polarization)

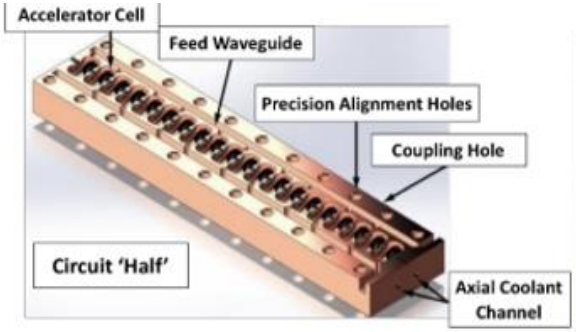
New proposal: Upgrading ILC250 Lumi to 8.1x10^{34} , effective L=2x10^{35} with additional cost +2.2 B ILCU, total cost 7.7 B ILCU.

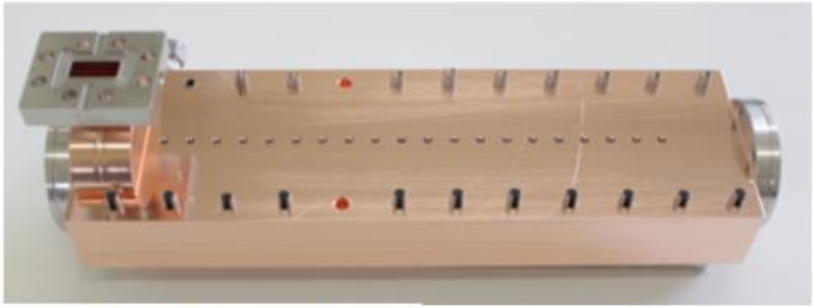
- AC power: ILC250: 267MW vs. FCC: 300MW
- Steps:
  - ✓ SRF: Q0=2x10^{10} at 31.5MV/m
  - ✓ twice the number of bunches (1,312→2,624) – 45% longer pulses
  - ✓ increase the repetition rate from 5 Hz to 15 Hz
  - ✓ Average beam power x6 (5.3MW → 31.5MW)
- System to study: DR (damping time, SC, electron cloud), Positron production(x3), Beam Dumps (x3)

New concept of the C-band NC Acc. Structure for LC

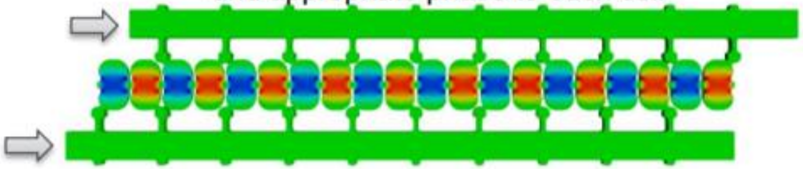
An Advanced NCRF Linac Concept for a High Energy e+e- Linear Collider, *K. L. Bane et al., SLAC, ArXiv 1807.10195 (2018)*

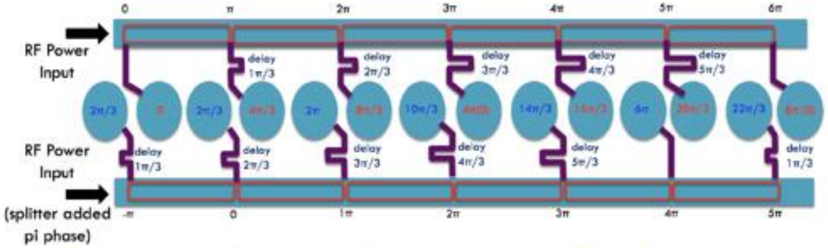




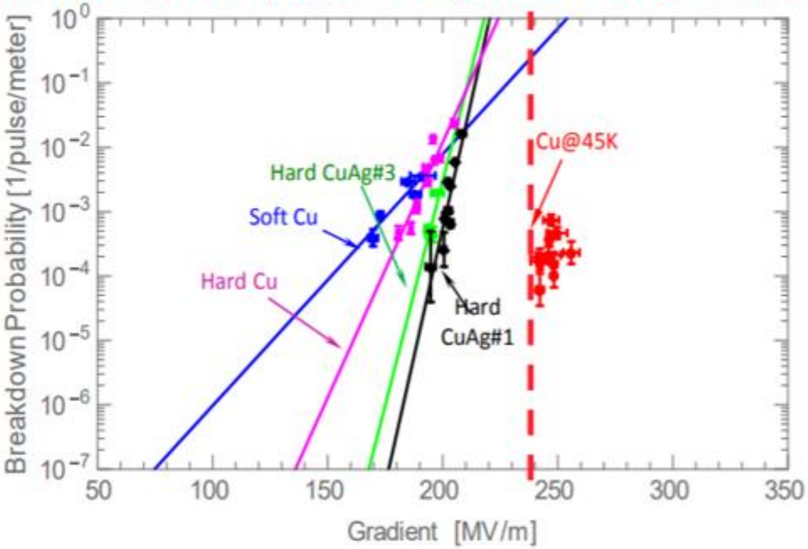


Carefully designed to provide equal power distribution and appropriate phase to each cell





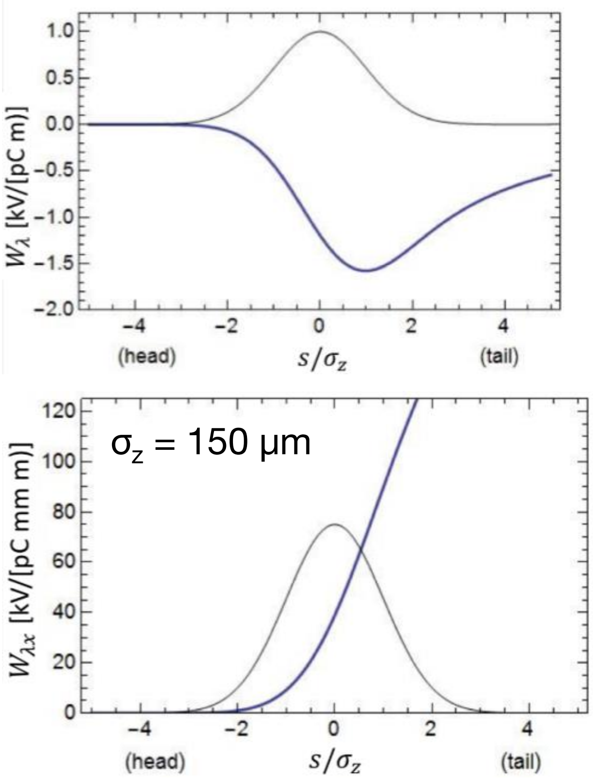
Advantage of cryogenic temperature for gradient



Advantage: high gradient in cells (SW)
Disadvantage: complicated distribution system

A complete wakefield analysis requires advanced beam dynamics

20-cell detuned and damped C-band structure, L=351mm



Longitudinal (top) and Transverse (bottom) bunch wake

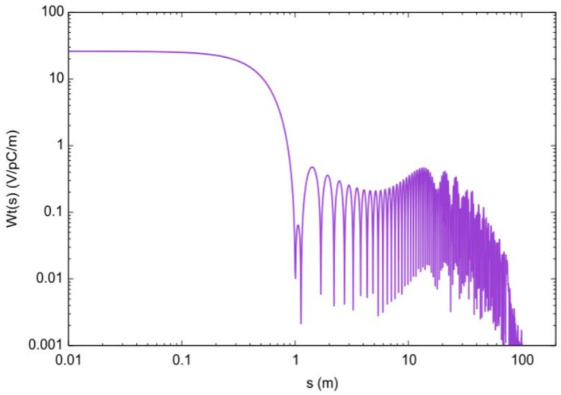
Cost/power estimation:

(If DOE-HEP GARD goal for RF power of \$2/*peak* kW could be achieved)

Main Linac 2x1TeV: 3.2 B\$/TeV

AC power for RF : 172 MW

Power for Cryocooling:170MW



Long-range wakefield for the first dipole band with cell detuning (f=9.5 GHz with $\Delta f/f$ = 5.6%) and an artificial damping factor Q_{damp}=1000

Possible Challenges

- Strong wakes – need careful study.
- Potentially large facilities jitter from boiling nitrogen. Require hard on the feedbacks and make short pulse lengths problematic.
- In general, all the normal sort of beam dynamics studies need to be done that were performed for NLC/ILC/CLIC in this regard

Emittance preservation and Beam-based alignment of the Accelerator

- Luminosity of LC is defined by beam emittance and beam stability at IP.
  - Ultra-low vertical emittance out of DR: 5nm-CLIC, 20nm-ILC
  - IP requirements: 30nm-CLIC; 40nm-ILC → tight budget for RTML, ML, BDS
  - IP feedback system to keep beams in collision
- Challenges (tasks):
  - Preserve low emittance in multi-km accelerator up to IP:
    - Simulation codes/framework are developed, codes were benchmarked
    - Low Emittance Transport studies in progress for each subsystem
    - Beam-Based Alignment (BBA) algorithms are proposed and tested
    - Many static/dynamic errors are included, not all in a time
  - Start-to-end (S2E) simulations not done yet
  - Testing and study BBA/tuning algorithms on real accelerators
    - FLASH (9mA), FACET, FERMI@Elettra(Trieste), ATF2-FFstudies, …
  - Develop advanced simulations of the physical processes, which can limit performance of the accelerator.
    - E-cloud in DR, Dark current and radiation in ML, PS target, …
  –

Sources of emittance degradation and BBA

- Synchrotron radiation
  - DRX arc, turnaround, BC wigglers
- Beam-ion instabilities
- Beam energy and position jitter
  - From DR, RF stability
  - From magnetic stray fields (nT scale)
- Dispersion
  - DR extraction
  - Misaligned quads
  - Rolled bends
- Coupling
  - DR extraction septum
  - Rolled quads, sextupoles
  - Misaligned bends
  - Quad strength errors in spin rotator
- Pitched RF cavities
  - Produce time-varying vertical kick
- Coupler kick
- RF phase jitter (BC and ML)
  - Varies IP arrival time of beams
- Beam halo formation
- Collimator and cavity Wakefields
- Resistive wall wakes in vac. chamber
- Space charge
- Ground motion

BBA at ILC ML / RTML/ BDS

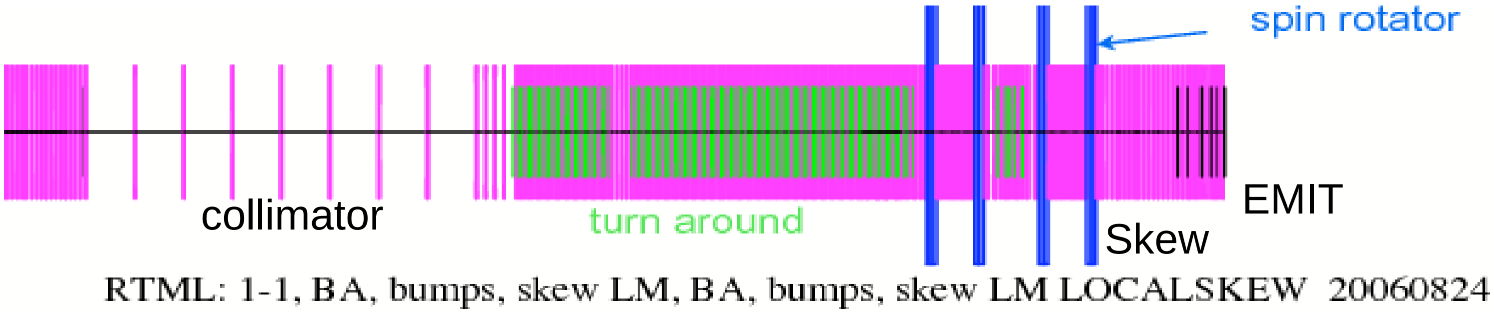
Several BBA used:

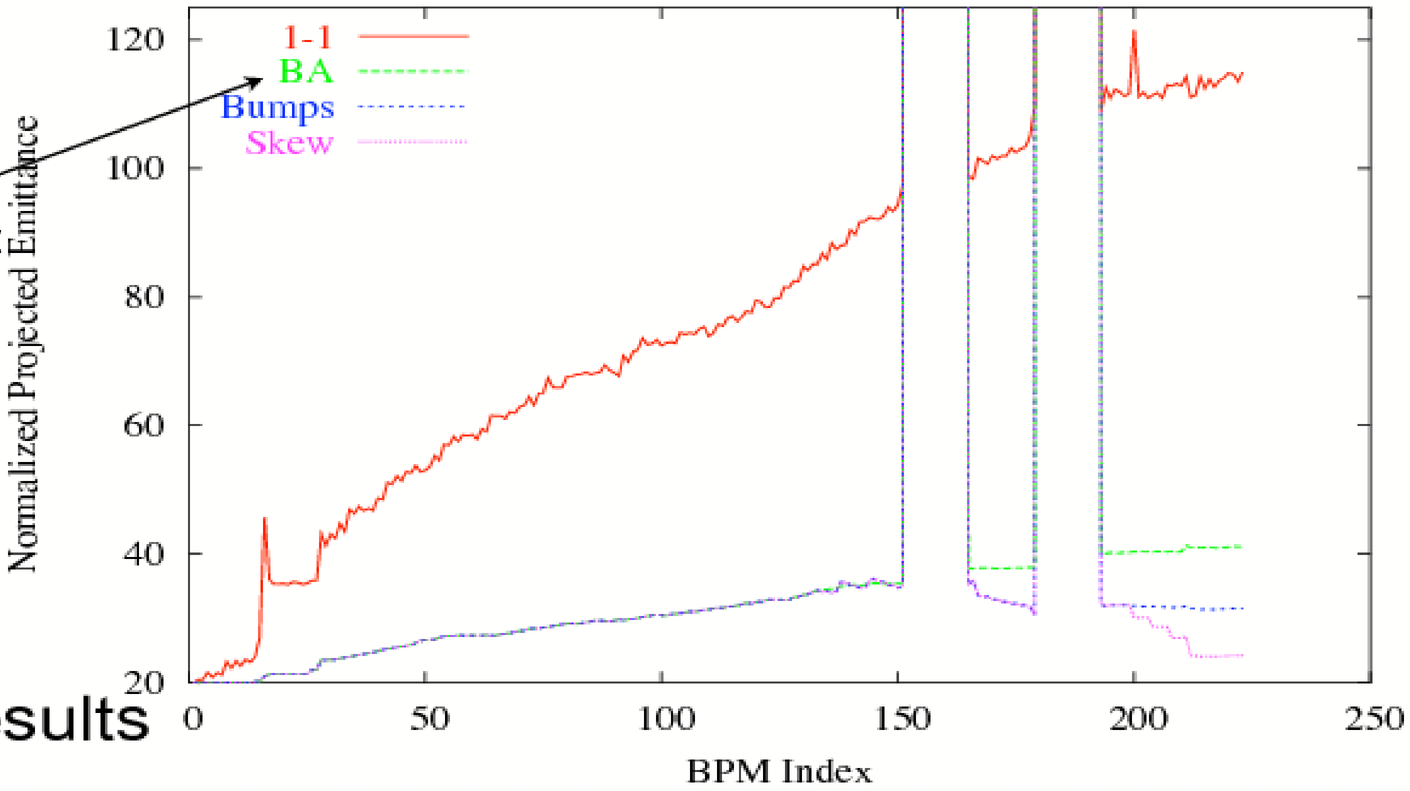
- Ballistic Alignment (BA)
- 1-2-1 correction
- Kick minimization (KMS)
- Dispersion Free Steering (DFS)
- Wakefield Steering (WFS)
- Global corrections
  - Orbit bumps, SVD knobs
  - Dispersion Bumps
  - Wakefield bumps
- 4D Coupling Correction (skew quads)
- Adaptive alignment

RF Feed-Back (FONT) and Feed Forward system

Static tuning in part of ILC RTML (upstream BC1)

COLL2
Turnaround
Spin rotator
SKEW
EMIT2





KM works ~about the same as BA, A little better

Jeff Smith results

CLIC RTML BBA studies (example of S2E simulations)

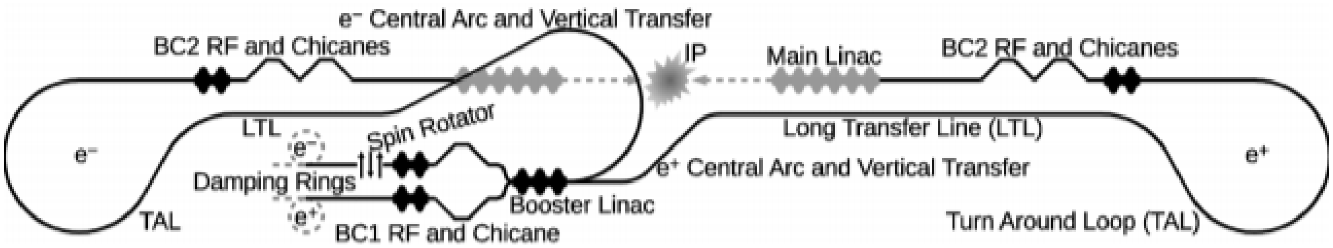
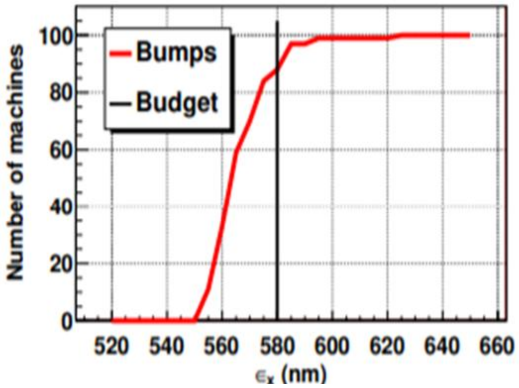
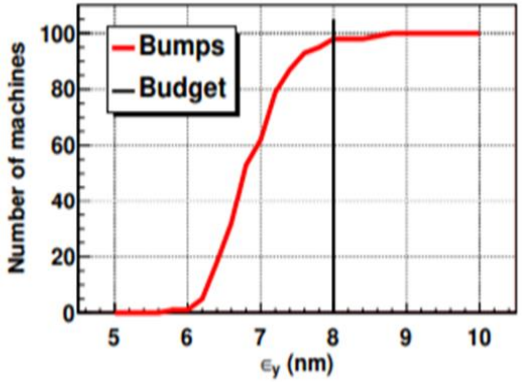


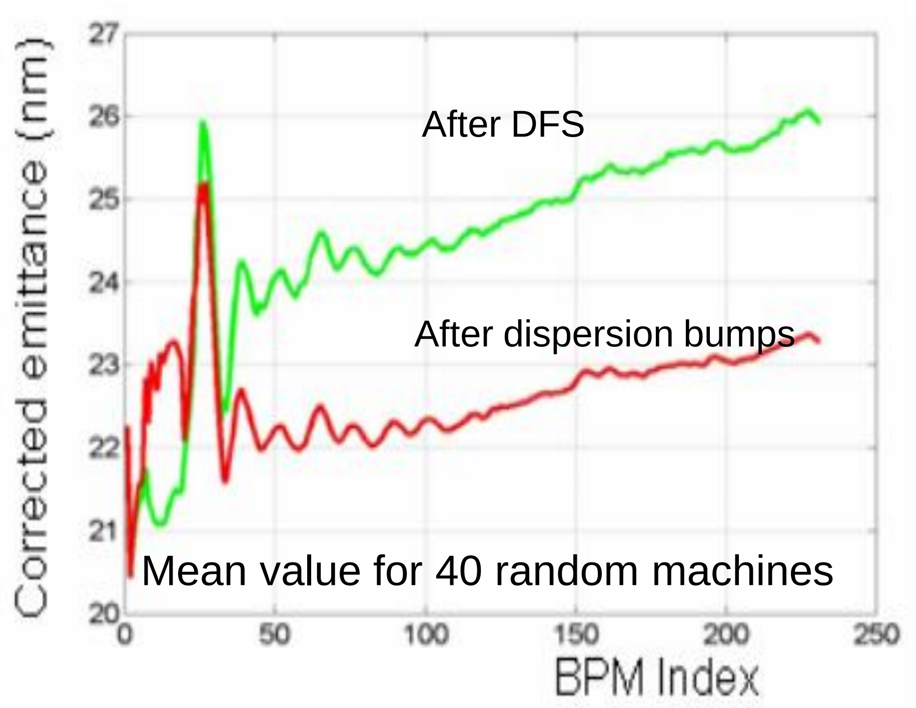
Figure 1. A sketch of the RTML for the CLIC.

- RTML was studied independently for each subsystem. However, it can be foreseen that performing the BBA for the entire RTML is much more difficult than for a individual section.
- Static misalignment/errors only: Magnet strength 1%, position/roll = 30μm/100 μrad, BPM res=1 μm
- BBA: 1-2-1 correction, DFS, emittance tuning bumps,
- Most dynamic errors are not included (beam jitter, stray fields, ground motion, RF, SR, etc.)





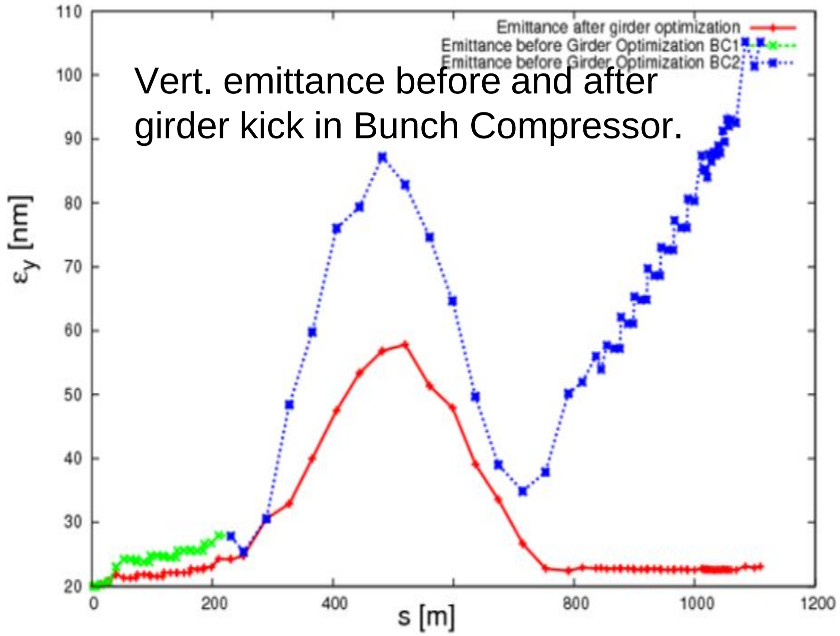
Example: ILC500 ML emittance preservation studies



After DFS

After dispersion bumps

Mean value for 40 random machines



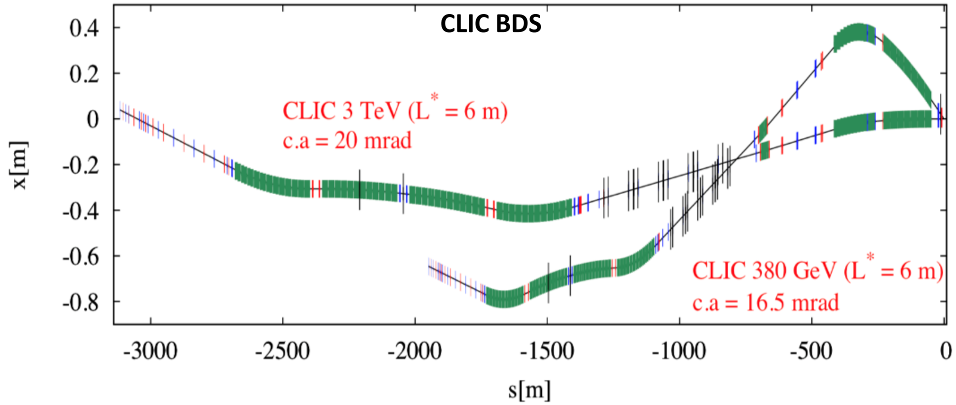
Vert. emittance before and after girder kick in Bunch Compressor.

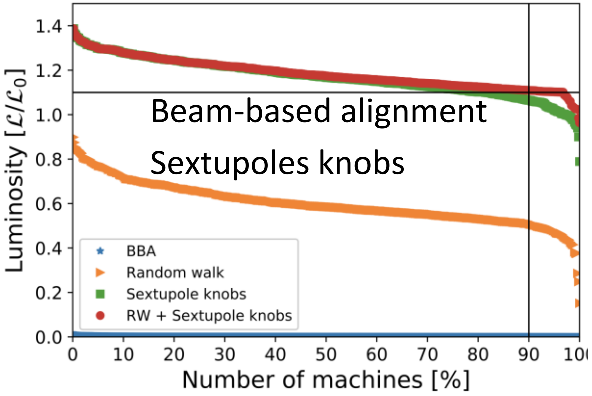
Most dynamic effects and ground motion are not included in these simulations

Table : Emittance Dilution due to Couplers Effects

	Lucretia	Placet	Analytical
	Main Linac		
Total rf kick	42.7	42.1	
After 1:1	0.1	0.2	0.1
Coupler Wake	0.4	0.3	
After 1:1	0.3	0.3	0.3
Rf kick +wake	45.3	46.4	
After 1:1	0.5	0.9	0.7
	Bunch Compressor		
RF Kick	74.5	68.7	
Wake Kick	3.3	2.9	
RF +Wake	85.3	79.3	
Girder kick	2.9	2.2	

Example: BDS tuning and low emittance preservation

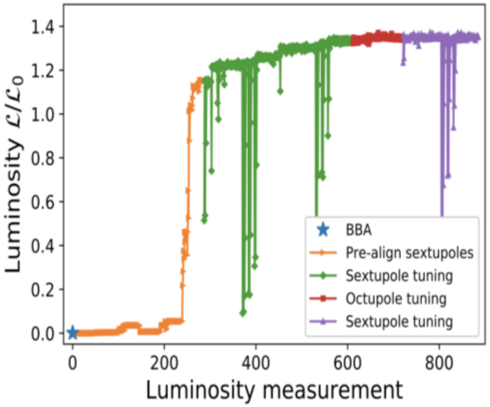




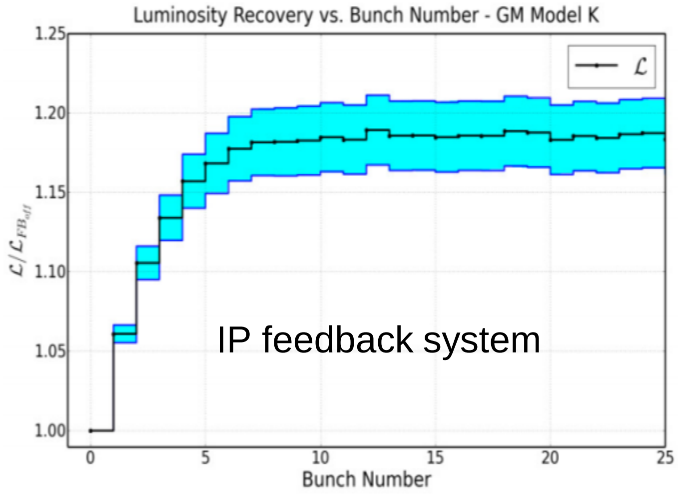
Beam-based alignment

Sextupoles knobs

484 (out of 500) machines successfully tuned (96.8%)



Placet+GUINEA-PIG



IP feedback system

Luminosity recovery through 25 bunches.
Shaded region is the standard error.

Conclusions

- Tuning Procedure (Effective Tuning)
- Realistic Scenario (static + dynamic imperfections)
- Performance achieved?

CLIC: 90% of machines reached ≥89%L_0

ILC: 90% of machines L ≥ 85%L_0

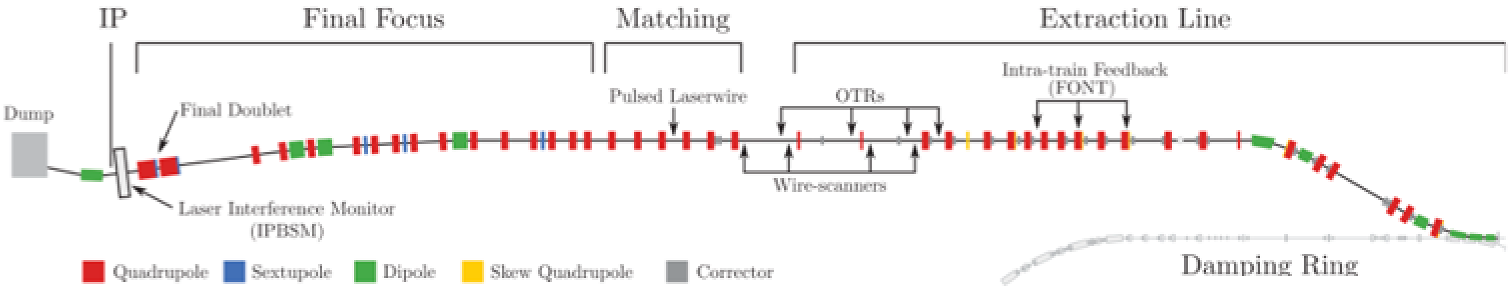
* Dynamic errors missing: Power supplies, magnet movers,...

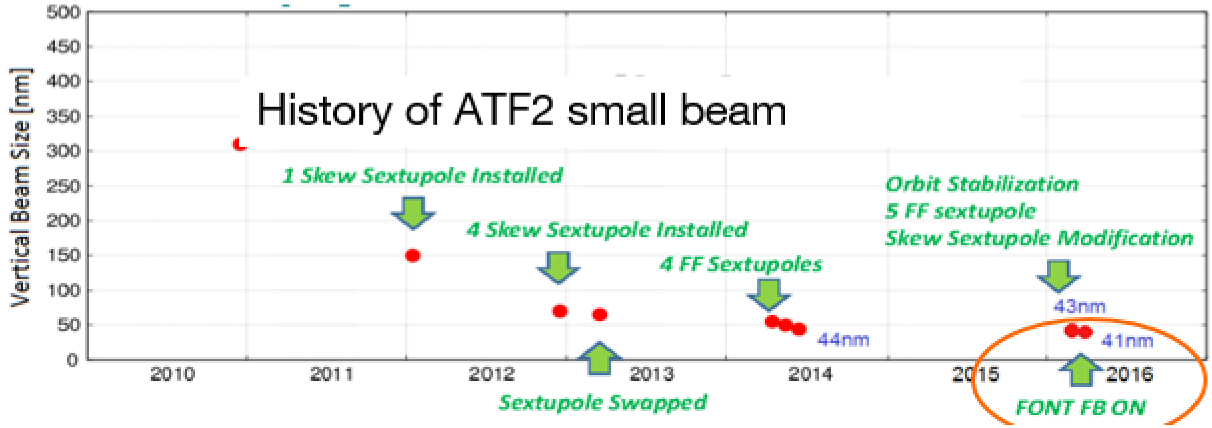
Test stand for ILC/CLIC Final Focus tuning/performance

Progress in FF Beam Size and Stability at ATF2

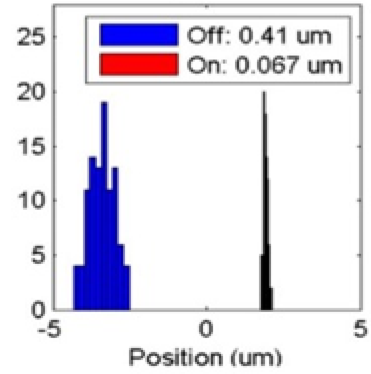
Goal 1: Establish the ILC final focus method with same optics and comparable beamline tolerances
ATF2 Goal : 37 nm → 6nm @ILC500GeV
Achieved **41 nm** (2016) →7.7nm@ILC250GeV

Goal 2: Develop a few nm position stabilization for the ILC collision
FB latency 133 ns achieved (goal: < 300 ns)
positon jitter at IP: 410 → 67 nm (2015)
(limited by the BPM resolution)





Nano-meter scale stabilization at IP

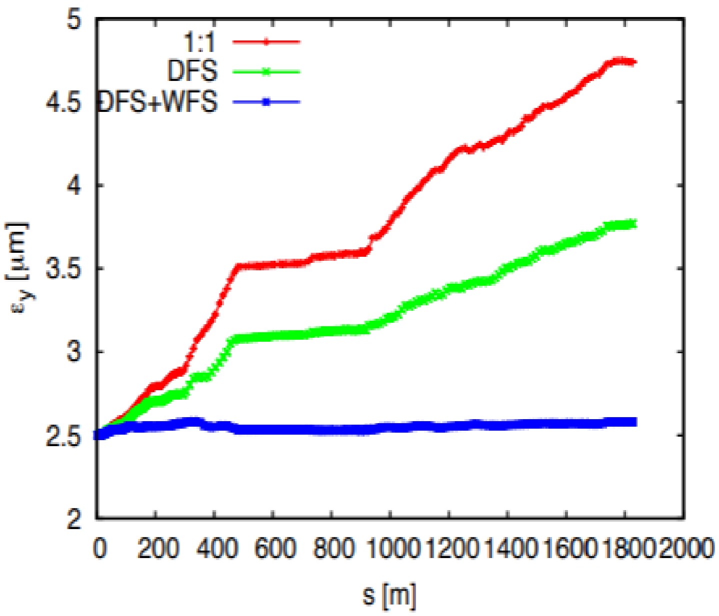


BBA algorithm testing

A. Latina et. Al., Tests of Beam-Based Alignment at FACET, CERN-ACC-2014-0148

Need for sophisticated automatic BBA techniques

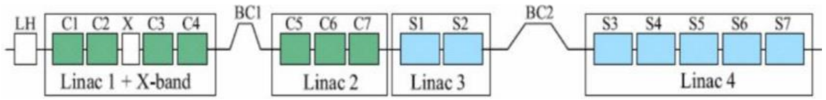
- orbit + dispersion correction (1:1 - DFS)
- Wake field free correction
- RF Alignment
- Emittance tuning bumps
- Benchmarked in codes

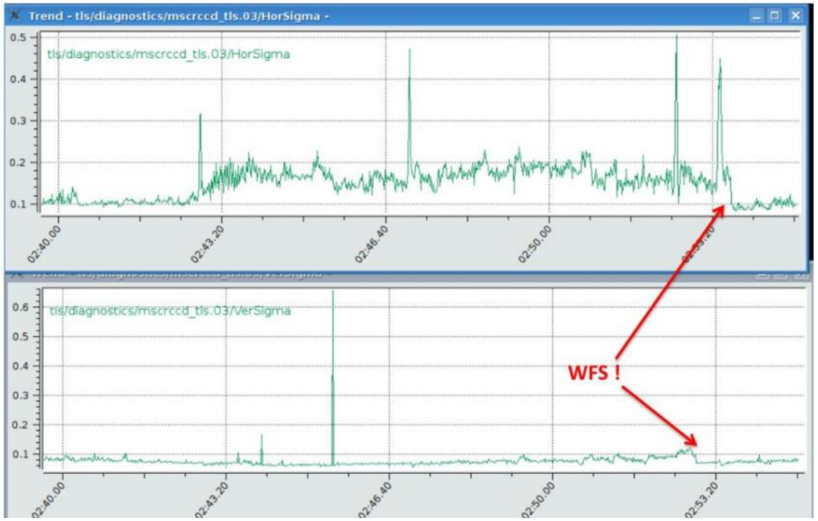


Vertical emittance growth improvements after DFS and WFS applied for 500m of SLC linac:

- SysID algorithms for model reconstruction
- DFS correction with GUI

FERMI@Elettra, Trieste (1.2GeV)





Emittance summary at Linac End:
(error: ~±0.05mm mrad)
Before correction: (H;V = 4.31; 3.21) mm mrad
After DFS: (H;V= 3.30; ---) mm mrad
After DFS+WFS: (H;V= 2.75; 2.57) mm mrad
(-35% in X, -20% in Y)

Timeline

- Low Emittance Transport and BBA studies

  Studies needed for all possible upgrade scenarios. Develop mitigation strategy for 'bad seed' where emittance is not achieved.

- Start-to-end static/dynamic simulations

  Develop framework to incorporate existing BBA techniques. Include static and most important dynamic errors.

  Timeline-over 3-5 years.

- Benchmarking BBA algorithms on the real accelerator facilities:

  Demonstrate robustness of BBA technique, mitigate limitations. Timeline - few years, if facilities will be available.

- Simulation of physical processes, which can limit performance: e-cloud in DR, dark current in ML, PS target, etc

  No reliable timeline. Need for Lumi/Energy upgrade scenarios over next decade.

Potential Challenges and Delays

- Full start-to-end simulations could be time consuming task. Parallel simulations are required.

- Availability of user facilities like EXFEL, LCLS-II for testing simulation BBA algorithms is limited, need special agreement and coordination for these studies

Ties-In with Grand Challenges

Grand challenge #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?

To produce beam size of nm scale and collide two multi-beam trains in IP is a challenging task. Beam size is orders of magnitude smaller than achieved in existing facilities. We need precisely control beam trajectory and emittances in tens of km linac.

Grand challenge #3 (beam control): How do we control beam distribution down to individual particles?

To control a distribution/emittance we need to develop robust beam-based alignment technique which able to adjust beam trajectory in the linac to control beam size and position in IP

Grand challenge #4 (beam prediction): How do we develop predictive "virtual accelerators"?

Develop accurate model of the accelerator with all imperfections to predict beam properties an

Relationship to HEP, NP, and BES Missions

- HEP: Relationship to HEP mission is in the Energy Frontier (lepton)

Resources for Project

Who?

- In past: CLIC and ILC collaboration, including US participants: SLAC, FNAL, BNL, Cornell and other Universities
- Right now: CLIC team and KEK, US labs have no funding
- Anyone can work on different aspects of BBA

Where (facilities)?

- Right now: Facet/SLAC-BBA, ATF2/KEK-Final focus R&D, FLASH/DESY – Multibunch RF stability, ASTA-wakes

Facilities can be used: Medium energy electron Accelerators

- EXFEL, LCLS-II, Facet, ATF2 for LET, BBA, Wakes etc.