Emittance preservation in the RTML of ILC and CLIC

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- Ring to Main Linac section in CLIC
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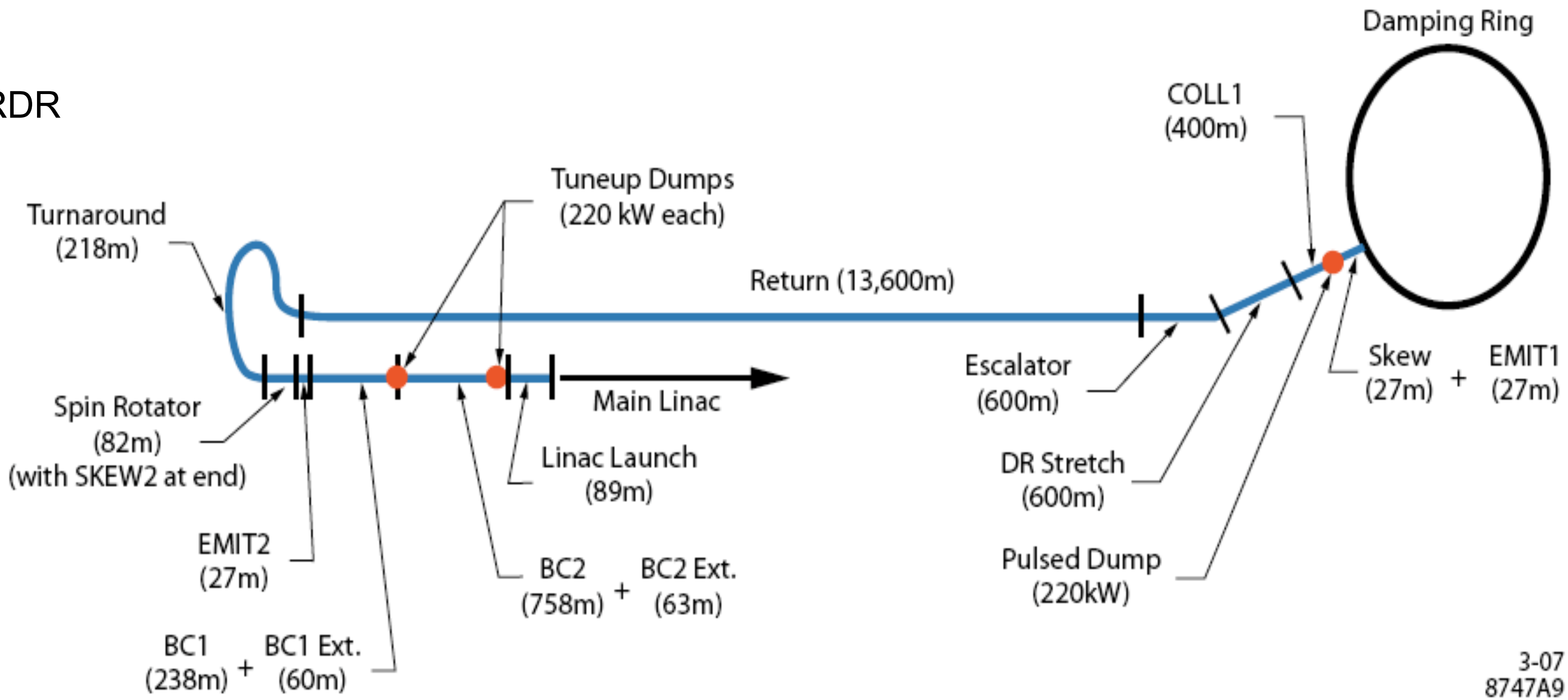
  - Expected performance

ILC-RDR RTML Layout

RDR



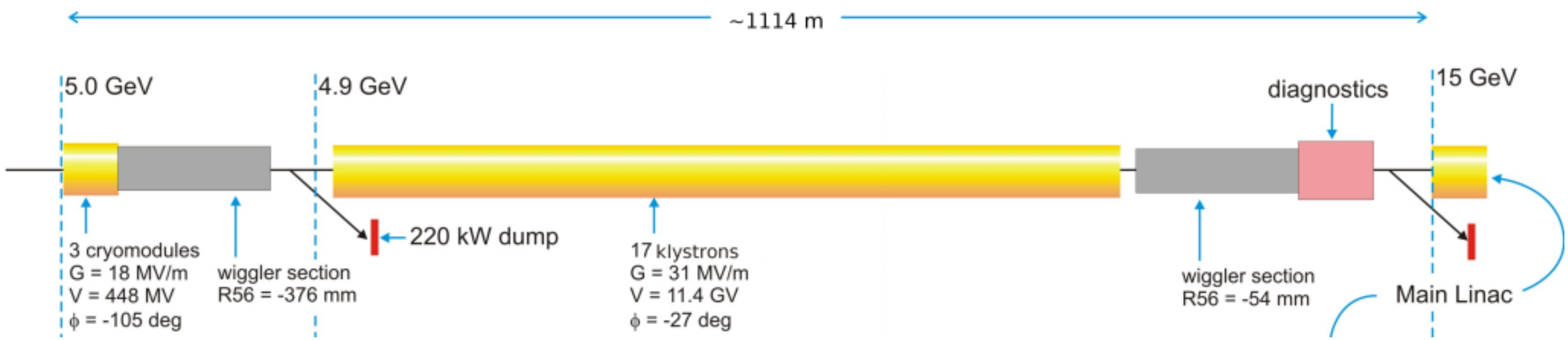
Entrance beam parameters

- Initial bunch length = 6/9 mm
- Final Bunch length = 1 mm
- Initial energy = 5 GeV
- Initial energy spread < 0.15%

Exit beam parameters

- Bunch length = 0.3/0.15 mm
- Energy = 15 GeV
- Energy spread = 1.07%

RDR Baseline: Two-Stage Bunch Compressor



- Compression from **6/9 mm** at DR exit to **0.2/0.3 mm** at ML entrance

  Stage 1: at 5 GeV, bunch length down to about 1 mm

  Stage 2: from 5 to 15 GeV, bunch length down to 200/300 um

- Compression ratio: up to ~45

- Two diagnostics stations

- Two extraction lines

RTML for SB2009

Major modifications to the RTML lattice are:

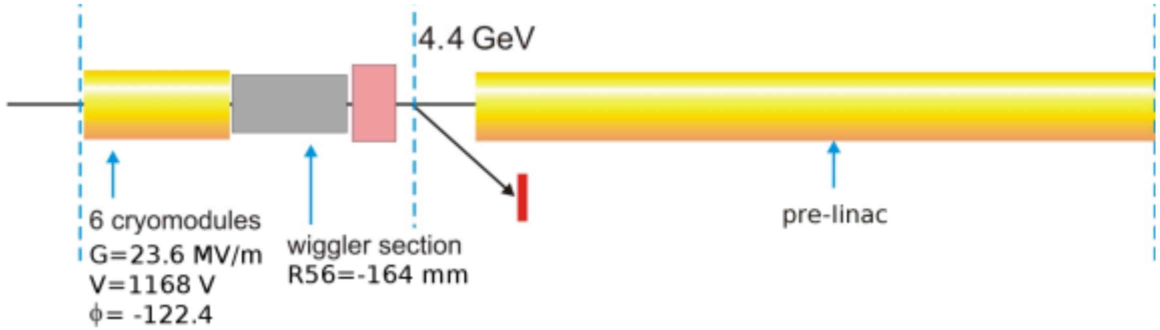
1) Single-stage bunch compressor

2) Re-design of the second extraction line, after bunch compressor, to accommodate larger energy spread (4% vs. 2.5%)

3) Re-design of the RTML lattice in central integration area, associated with new layouts of the DR, electron and positron sources and BDS

- *S-shape curved DR-to-Linac transition (in horizontal plane)*
- *Vertical dogleg*
- *Extraction line*
- *Correction, Diagnostics and Collimation sections*

SB2009: Single-Stage Bunch Compressor



- New design of the Damping Rings allows **6 mm** bunch length
- Final bunch length fixed to **0.3 mm**
- Compression factor can be reduced to **~20**

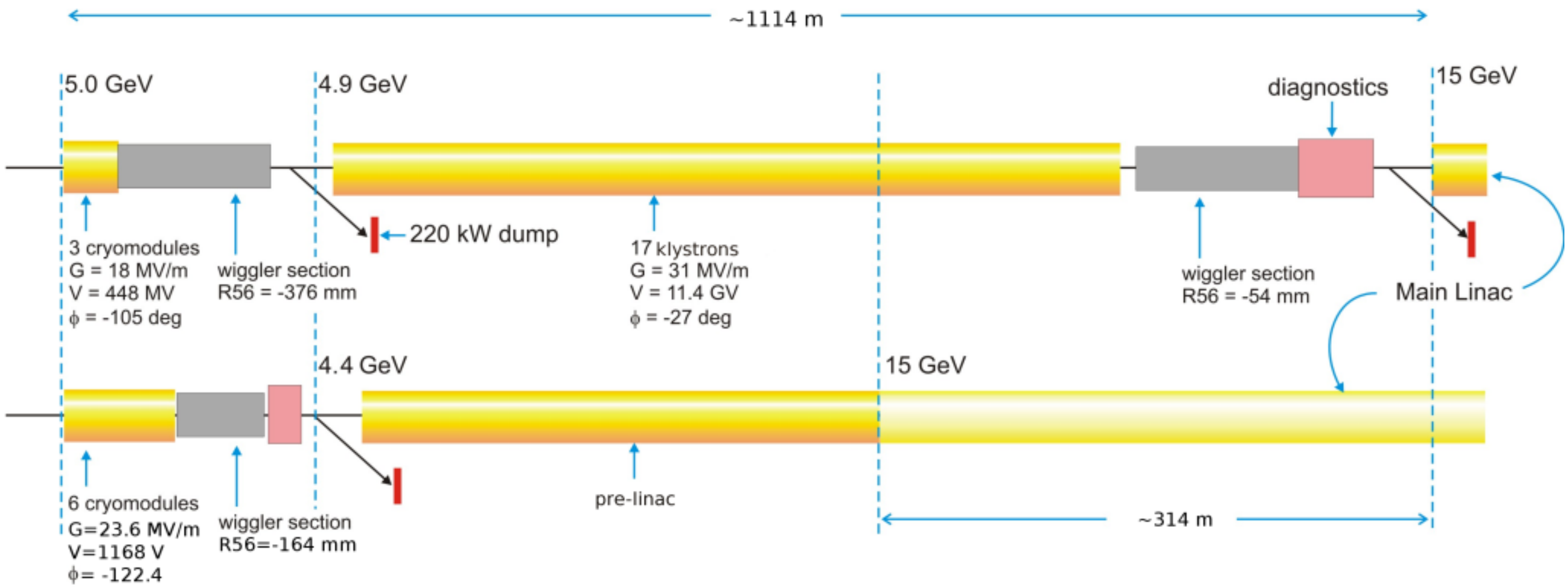
Design:

- BC1S: 6 crymodules RF section from 5 to 4.37 GeV; Wiggler; Diagnostics; Extraction

- Pre-linac: from 4.37 to 15 GeV, configuration and parameters are identical to those of main linac

- now it is considered as an extension of the ML

BC1+BC2 and BC1S: Differences



What we gain:

- Reduction in beamline and associated tunnel length (~314 meters)
- Removal of the second 220 kW/15 GeV beam dump and extraction line components
- Removal of one section of the beam diagnostics

What we loose:

- Less flexibility (not support for 200 um bunch length)
- Larger energy spread at BC exit: 3.5% @ 4.4 GeV
- Emittance preservation and additional tuning issues (e.g. DFS in the main linac)

Beam Parameters

• **BC1**
- Initial bunch length = 6/9 mm
- Final Bunch length = 1 mm
- Initial energy = 5 GeV
- Final energy = less than 5 GeV
- Initial energy spread = 0.15%
- Final energy spread = 2.5%

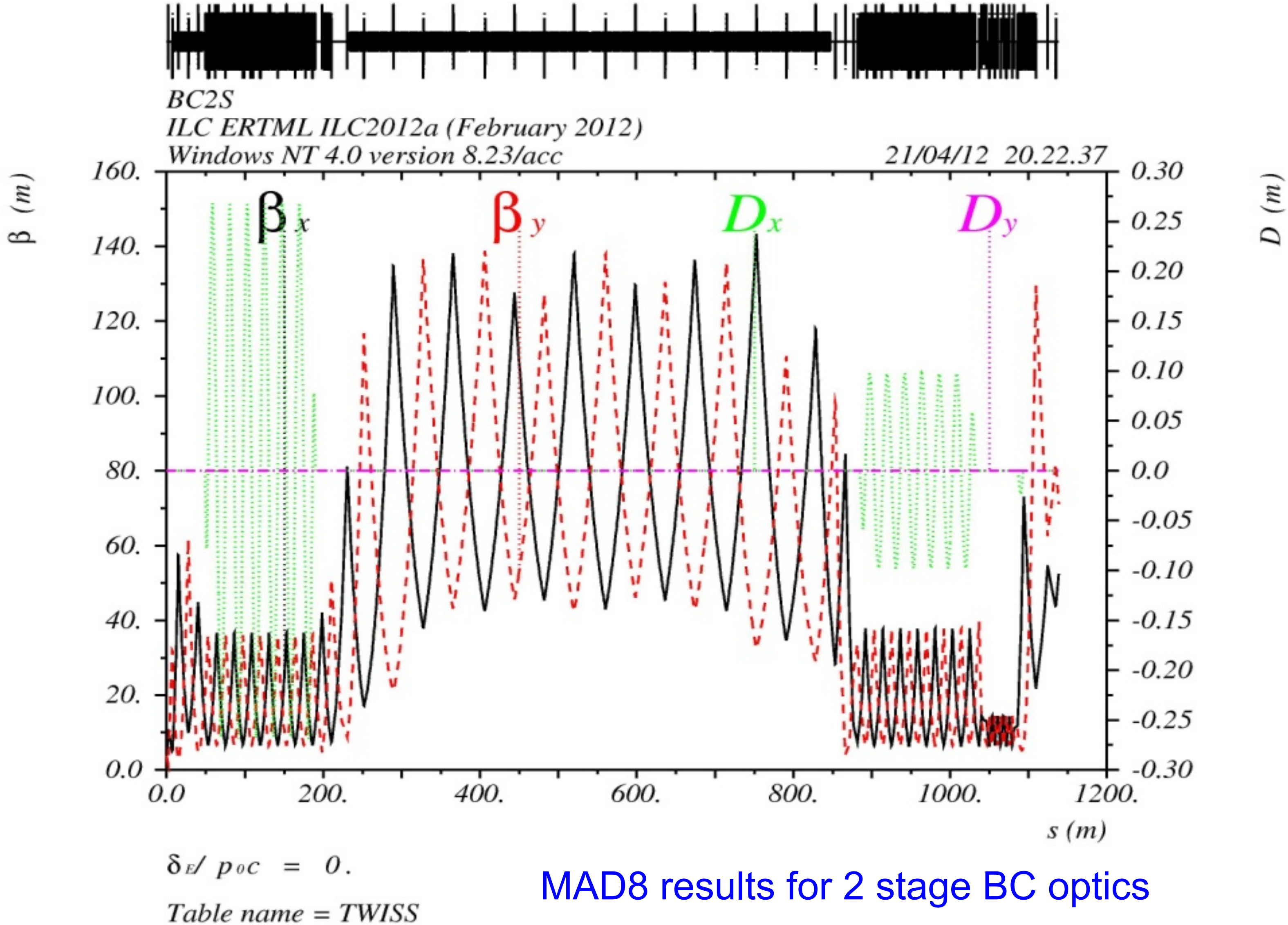
• **BC2**
- Initial bunch length = 1 mm
- Final Bunch length = 0.3/0.15 mm
- Initial energy = less than GeV
- Final energy = 15 GeV
- Initial energy spread = 2.5%
- Final energy spread = 1.07%

• **BC1S**
- Initial bunch length = 6 mm
- Final Bunch length = 0.3 mm (0.265 mm)
- Initial energy = 5 GeV
- Final energy = 4.37 GeV
- Initial energy spread = 0.15%
- Final energy spread = 3.5% (4.13%)

• **Pre-Linac**
- Bunch length = 0.3 mm
- Initial energy = 4.37 GeV
- Final energy = 15 GeV
- Initial energy spread = 3.5%
- Final energy spread = 1.08% (1.18%)

Two-Stage Bunch Compressor Optics

Use ILC type CM in BC1 and BC2 (was different styles in RDR)
Minor modifications in Wiggler parameters
Optimized for 6 mm bunch length

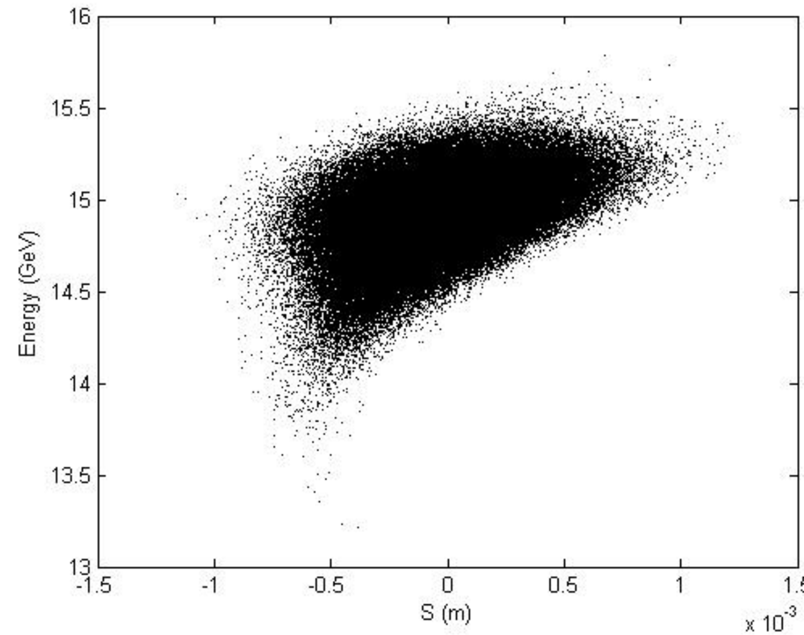


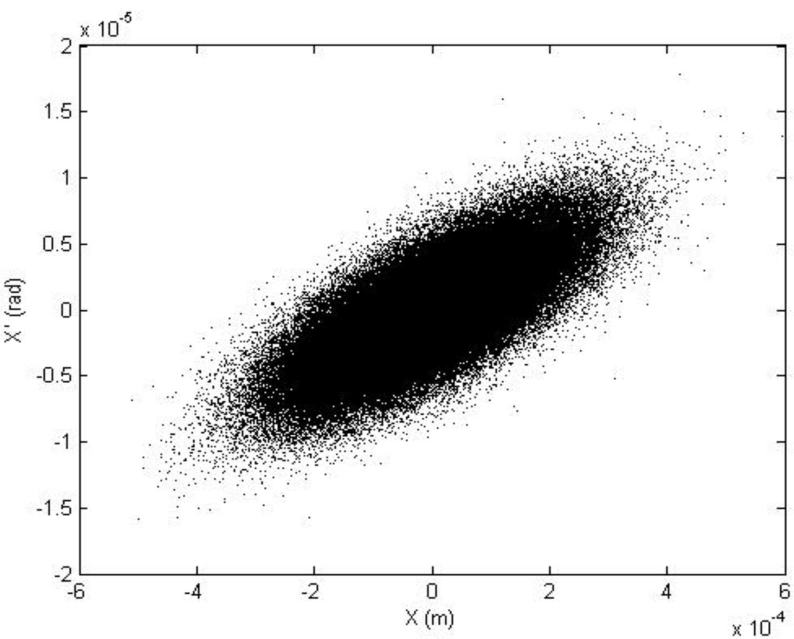
MAD8 results for 2 stage BC optics

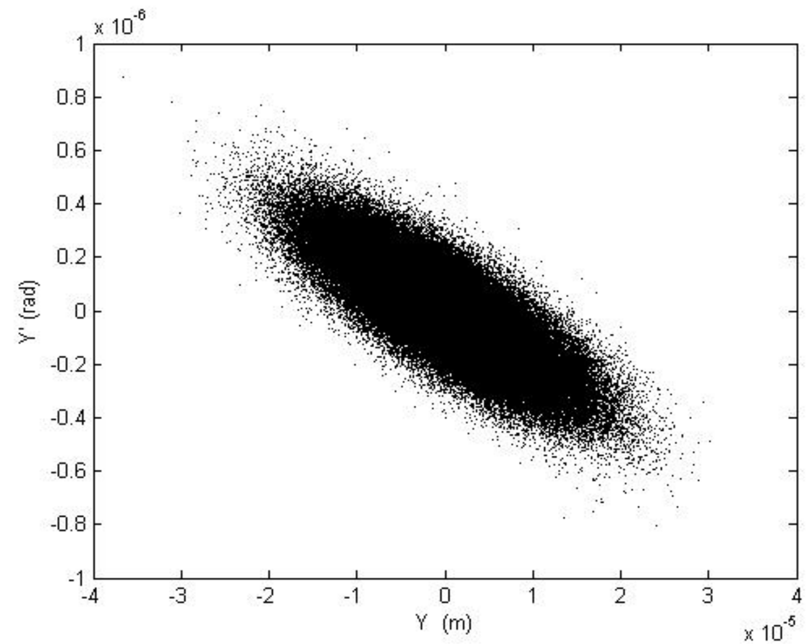
Simulations of ILC 2-stage BC

Parameters:

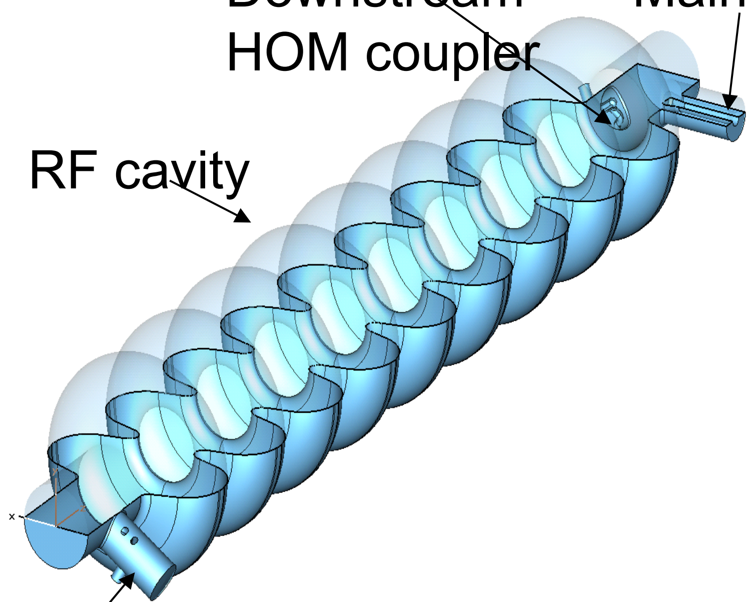
Initial Energy: 5 GeV
Initial Norm. Emittance (H/V):   8e-6/20e-9 m rad
Acc. Gradient (BC1/BC2): 18.7/27.1 MV/m
Total Voltage (BC1/BC2): 465/11700 MV
RF phase (BC1/BC2): -115/-30 deg
R_{56} (BC1/BC2): -375.8/-55.2 mm
Norm. Emittance Growth (H/V): <0.75/<2.0 %
Final Energy: 14.91 GeV





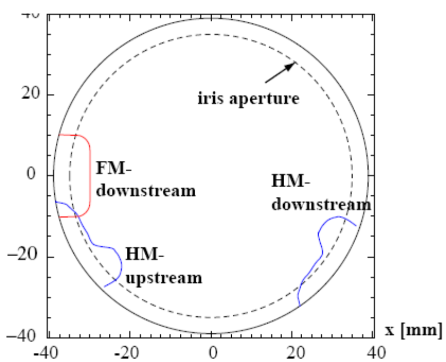


Simulations of Coupler Kick and Wakes



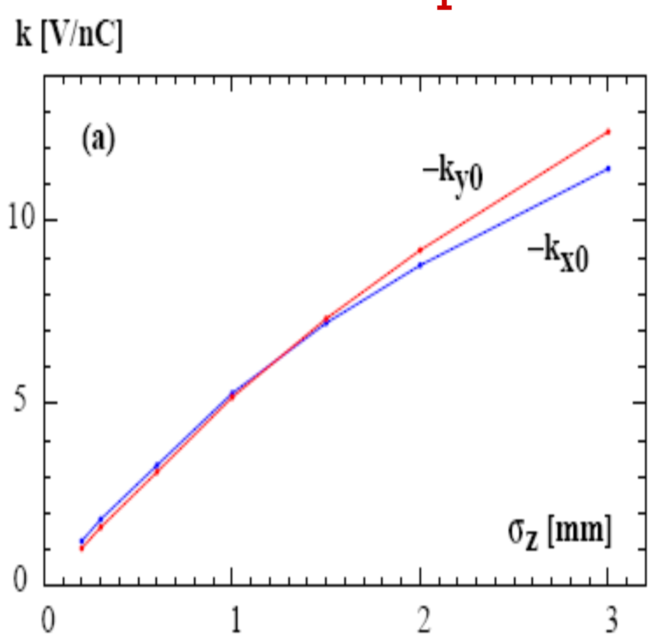
The couplers break the RF field symmetry and cause transverse RF kick and Wakes DESY,2007. Simulations DESY/FNAL/SLAC

Total RF KICK	FNAL $Q=3.5\times10^6$ HFSS	DESY $Q=2.5\times10^6$ MAFIA	SLAC $Q=3.5\times10^6$ OMEGA3P
$10^6 \cdot (V_x/V_z)$	-105.3+69.8i	-82.1+58.1i	-88.3-60.2i*
$10^6 \cdot (V_y/V_z)$	-7.3+11.1i	-9.2+1.8i	-4.6+5.6i

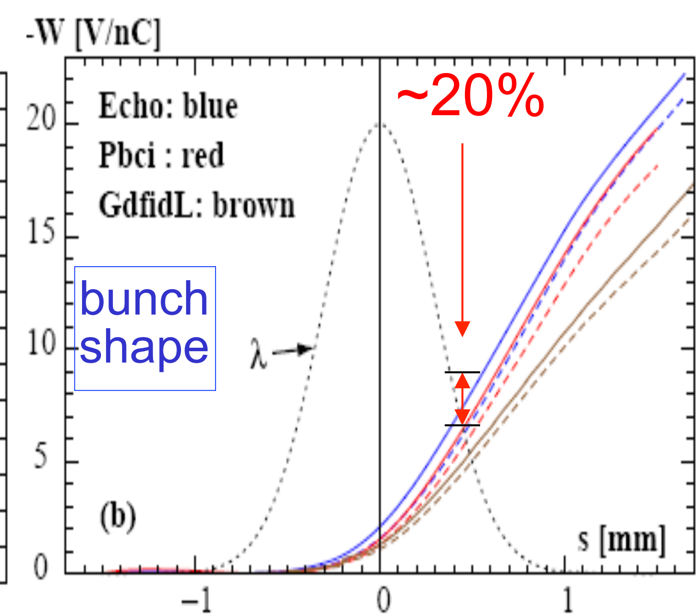


The profiles of the 3 couplers, as seen from the downstream end.

Coupler Transverse Wakefield



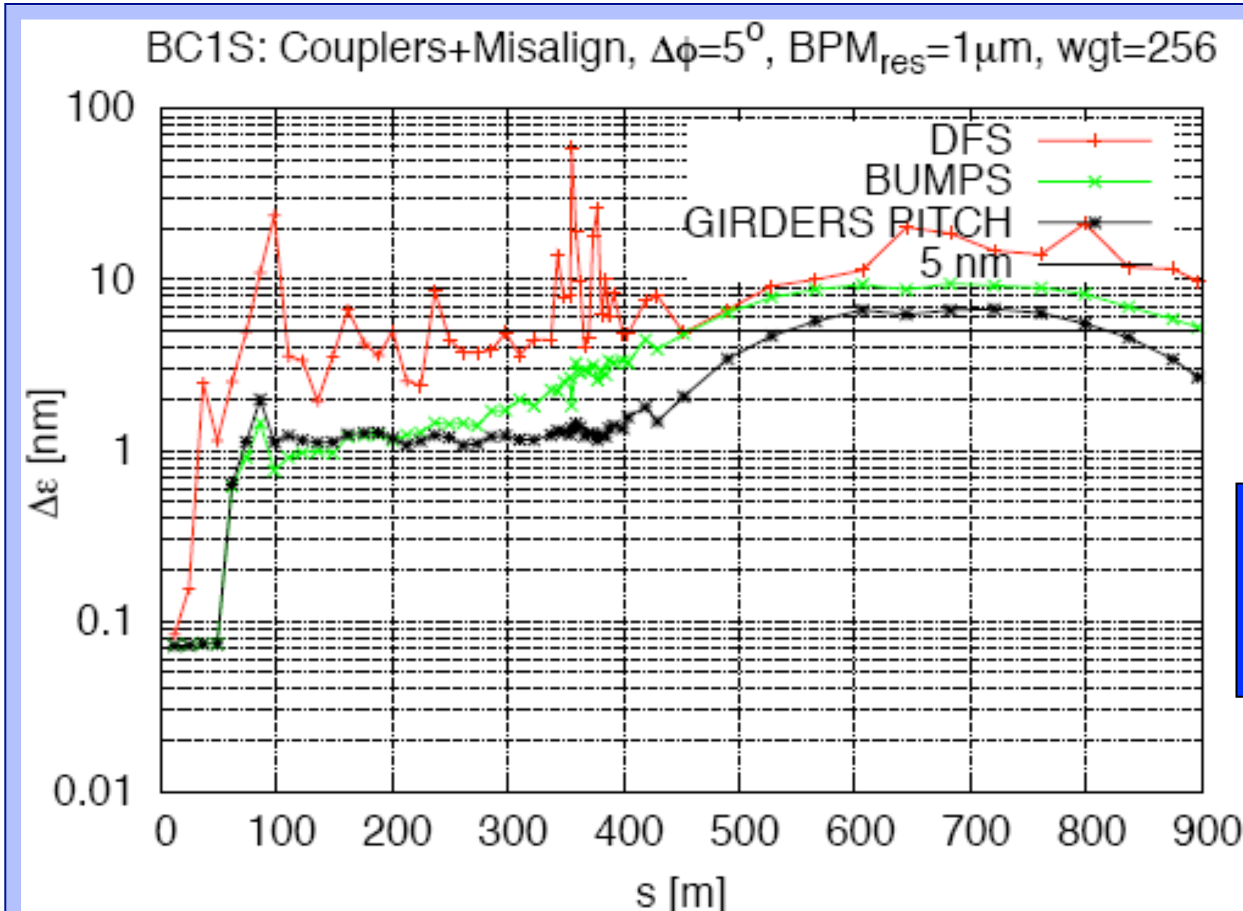
On-axis kick factor vs. σ_z



$W_x(s)$-solid,, $W_y(s)$-dashed for σ_z = 300 μm.

Effect of couplers on emittance growth see in V.Yakovlev talk

Coupler and Misalignments in BC1S



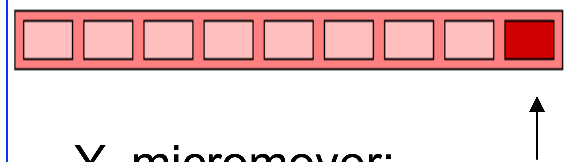
10 nm
5 nm
2.6 nm

2.2 nm from coupler only

- Emittance Growth along the beamline, 1 machine

New proposal !!!

Girder Pitch optimization



Y- micromover:
- Range 300 um
- Step size 10 um

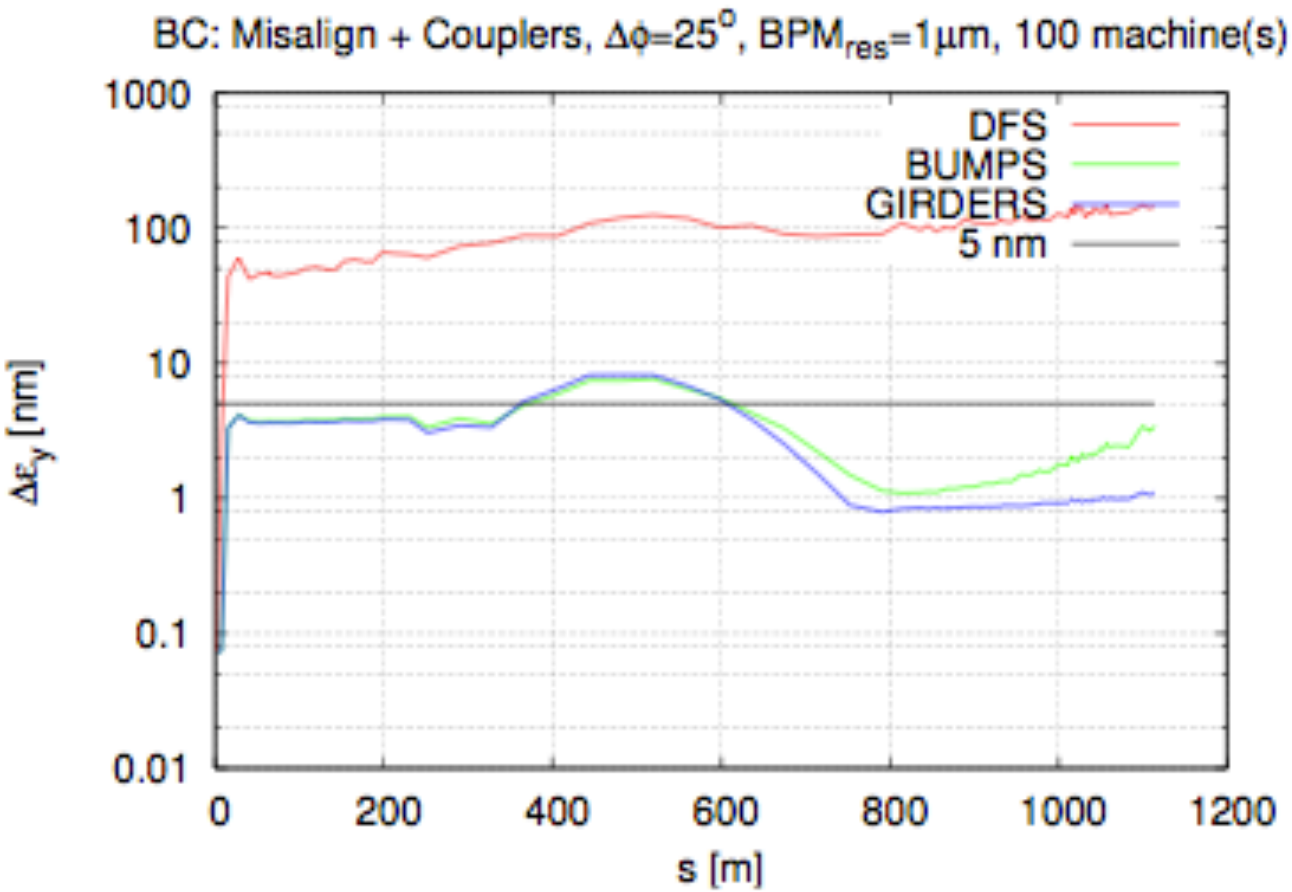
#N of adjustable CM's

- RF section of BC1S - 1 every 2 (total 3)
- Pre-linac: 1 every 12 CM's (total 3)

- BC1S (incl. diagnistics+matching+Pre-linac (5➔15 GeV))
- Standard misalignments (300 um/300urad); ISR +coupler RF kick/wake
- 1-to-1, DFS and bumps, girder optimization

Coupler and Misalignments in BC1+BC2

- Correction: 1:1 + DFS + Dispersion Bumps + Girder Optimization
- Emittance growth along the line for 100 seeds:



⇒ Minimum of the emittance is at $\omega = 2048$

⇒ Average of final vertical emittance growth is 1.09 nm (1.48 nm 90% c.l.)

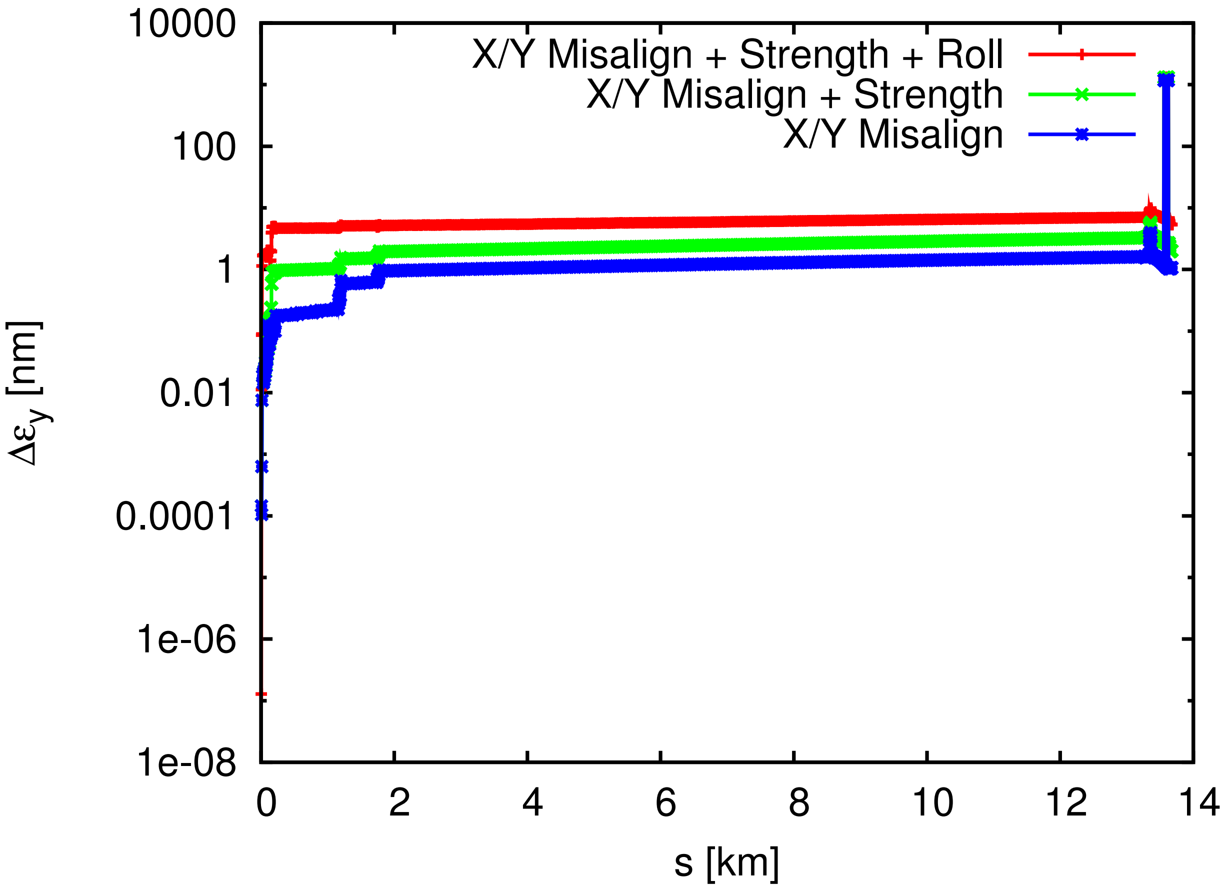
Emittance growth summary in BCs

Region	Errors	Emittance Increase (nm)		Correction
		average	90% CL	
BC1+BC2	X/Y/X'/Y' Offsets	0.98	1.6	DFS + knobs + Girders
	+ Quad Strength	-	-	DFS + knobs + Girders
BC1+BC2 w/Couplers	X/Y/X'/Y' Offsets	1.09	1.48	DFS + knobs + Girders
	+ Quad Strength	-	-	DFS + knobs + Girders
BC1S w/Couplers	X/Y/X'/Y' Offsets	2.3	-	DFS + knobs + Girders
	+ Quad Strength	-	-	DFS + knobs + Girders

- **Emittance growth due to misalignments and couplers seems to compensated both for BS1S and BC1+BC2**
- **Girder pitch optimization is very effective to counteract coupler kicks, both for BS1S and BC1+BC2**
- **In BC1S, Crab Cavity seems to be similar effective, but it would require a new hardware and slight redesign of the cryomoodule**

Emittance Growth in “Front-End”

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps + Coupling Correction
- Emittance growth along the line for 1000 seeds:



⇒ X/Y Offsets: Final average emittance growth is 1.06 nm (1.58 nm 90% c.l.)

⇒ Add Quad/Sbend Strength: Final average emittance growth is 2.01 nm (3.51 nm 90% c.l.)

⇒ Add Quad/Sbend Roll: Final average emittance growth is 5.36 nm (9.94 nm 90% c.l.)

Emittance Growth in RTML

Region	Errors	Emittance Increase (nm)		Correction
		average	90% CL	
Escalator + Getaway + RL	X/Y Offsets	0.48	0.52	KM + knobs + CC
	+ Quad Strength	0.68	1.25	KM + knobs + CC
	+ Quad/Sbend Roll	1.87	3.23	KM + knobs + CC
Turnaround + Spin Rotator (OFF)	X/Y Offsets	2.26	5.33	KM + knobs
	+ Quad/Sbend Strength	3.69	8.12	KM + knobs
	+ Quad/Sbend Roll	6.11	12.73	KM + knobs
Turnaround + Spin Rotator (ON)	X/Y Offsets	2.14	4.83	KM + knobs
	+ Quad/Sbend Strength	4.63	9.42	KM + knobs
	+ Quad/Sbend Roll	6.86	13.66	KM + knobs
Entire "Front End"	X/Y Offsets	1.06	1.58	KM + knobs + CC
	+ Quad/Sbend Strength	2.01	3.51	KM + knobs + CC
	+ Quad/Sbend Roll	5.36	9.94	KM + knobs + CC

- Dynamic effects are not included
- Emittance growth is large (pre-RDR budget 4nm, might be ≤10nm)
- Need further studies to reach goal for emittance growth
- Cross-checking with different codes (important)

ILC RTML Extraction Line Summary

S. Seletskiy

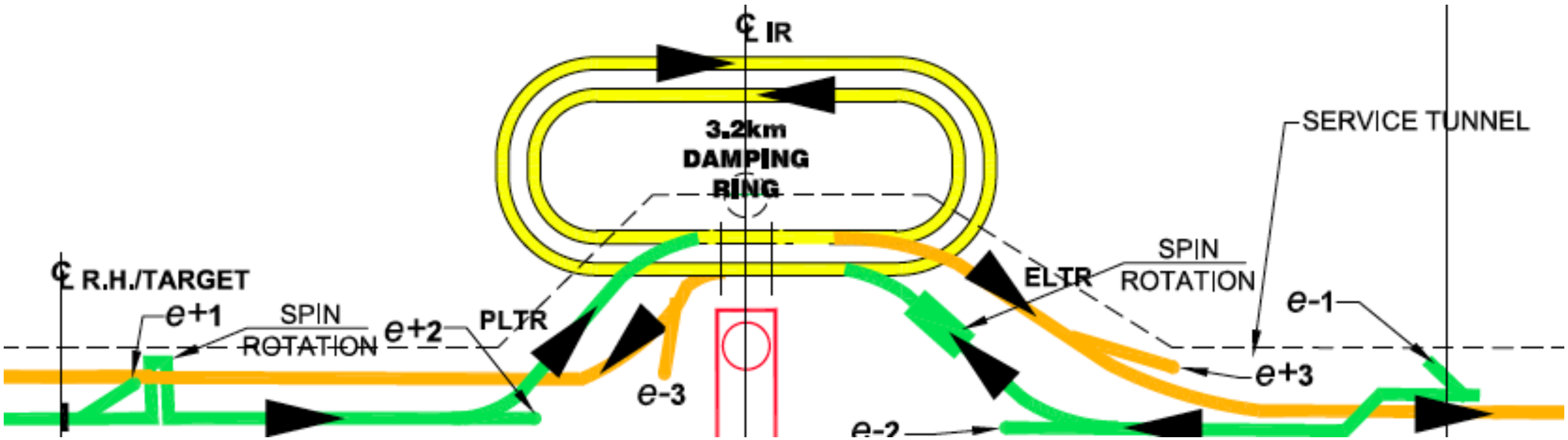
ILC RTML extraction line located downstream a single-stage bunch compressor was finalized.

- The extraction line is capable of accepting and transmitting up to 220kW of beam power.

- The EL can be used for both fast intra-train and continual extraction, and is capable of accepting both 0.15% and 3.54% energy spread beams at 5MeV and 4.37MeV respectively.

This design can be tweaked. For instance one can reduce strength of the sextupoles sacrificing size of the beam dump window.

Central Area



In SB2009, damping rings circumference has been reduced to 3.2 km

RDR DR extraction was at about 1 km from the central plane, in the direction of the turnaround, now the DR ext is located at about 100 meters from the central plane

This change required a redesign of the beamlines. This resulted in a simplification of their geometries in terms of number of horizontal and vertical doglegs

Main advantage of this change is the simplification in the overall layout

Possible risks might arise from the performances of the new system from the point of view of the low emittance transport

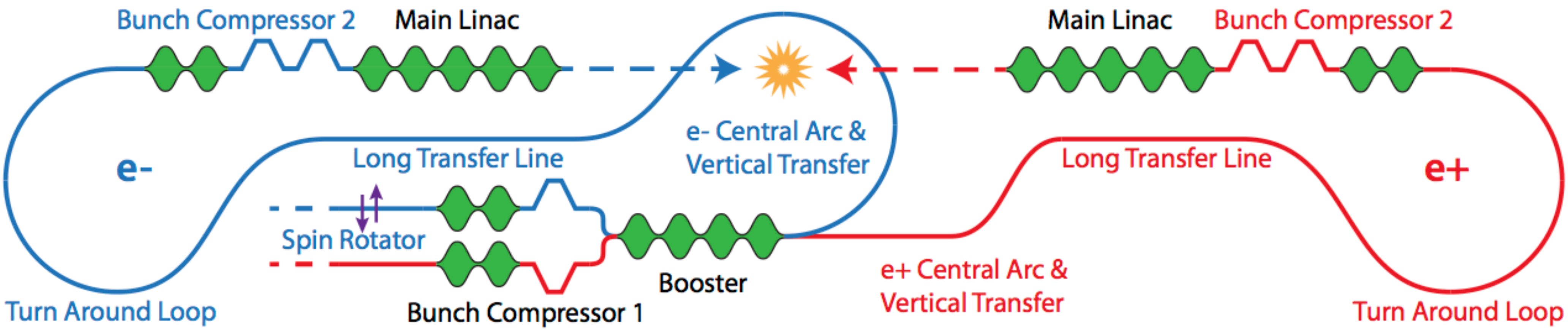
Proposed Relevant Studies

Beam physics simulation to study effect of coupler RF kick, alignment and phase/amplitude stability of the RF system and provide requirements. The goal to demonstrate that RTML emittance budget can be achieved and beam parameters at the exit of RTML system provide acceptable emittance budget in Main Linac

Experimental studies of amplitude and phase stability, required for single-stage bunch compressor at FLASH/DESY facility (9 mA studies). This study is required to both RDR and SB2009 configurations

Re-design RTML section from DR tunnel to ML tunnel. It requires close coordination with other AS involved: DR and electron/positron sources.

CLIC RTML



Particle energy	E_0	2.86	GeV
Bunch charge	Q_0	0.65	nC
RMS bunch length	σ_s	1600	µm
RMS energy spread	σ_E / E_0	0.13	%
uncorr. energy spread	σ_E / E_0	0.13	%
Energy chirp	u	0	1/m
Normalized emittance	$\varepsilon_{n,x}$	500	nm rad
	$\varepsilon_{n,y}$	5	nm rad
Polarization	P	?	%
Phase offset 2GHz	$\Delta\phi$	0	deg

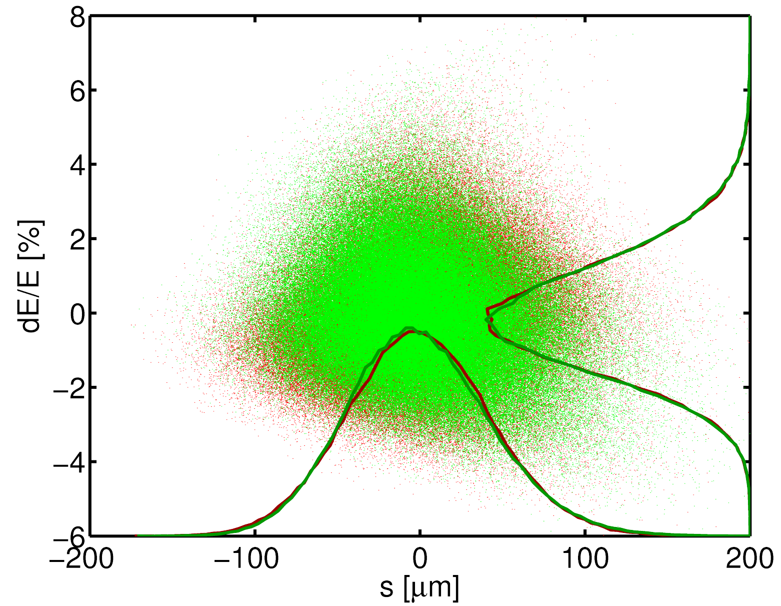
@ exit of damping rings

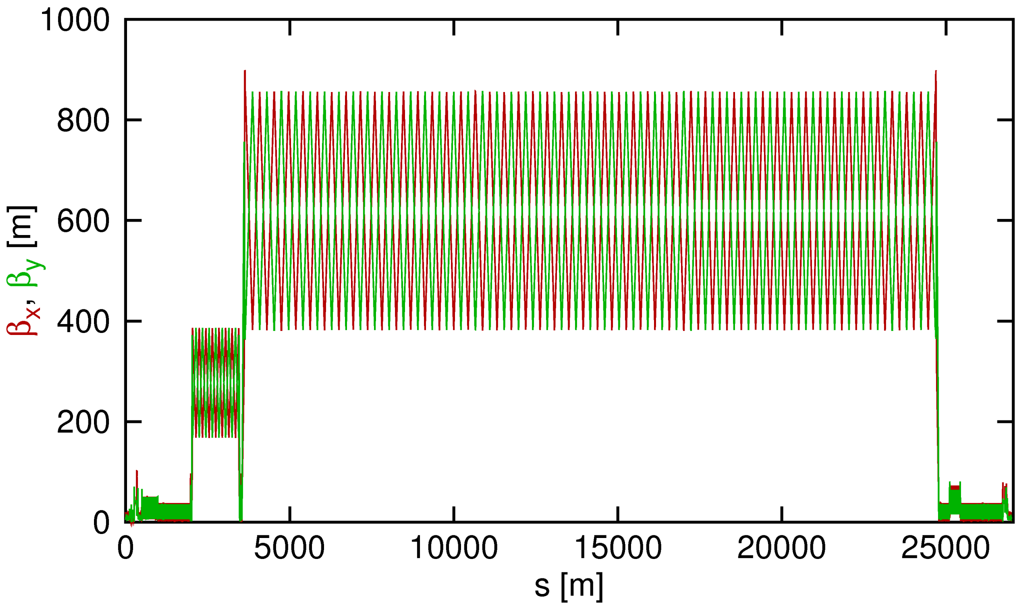
Particle energy	E_0	9	GeV
Bunch charge	Q_0	> 0.6	nC
RMS bunch length	σ_s	44	µm
RMS energy spread	σ_E / E_0	< 1.7	%
uncorr. energy spread	σ_E / E_0	< 1.7	%
Energy chirp	u	0	1/m
Normalized emittance	$\varepsilon_{n,x}$	< 600	nm rad
	$\varepsilon_{n,y}$	< 10	nm rad
Polarization	P	?	%
Phase offset 12 GHz	$\Delta\phi$	0	deg

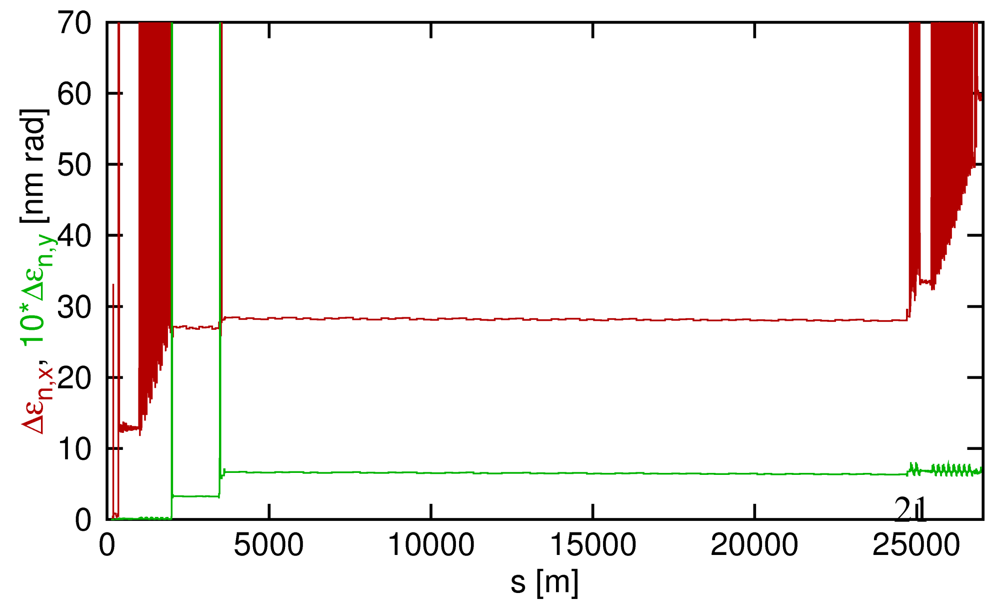
@ entrance of main linac

CLIC RTML Status (post CDR)

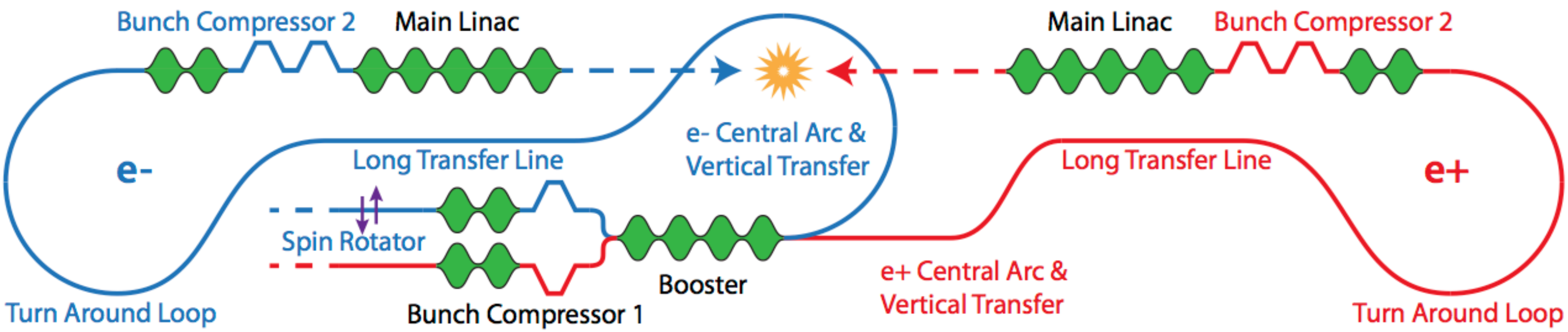
- A complete set of lattices exists
- ISR, CSR and short-range wakefields have been considered
- Design shows good performance (within the specifications)
- First evaluations of misalignment tolerances have been performed in the return line and turn around loops:
  - micron range, tightest in turn around loops
  - DFS works for pre-alignment of ~100µm (sextupoles ~50µm)



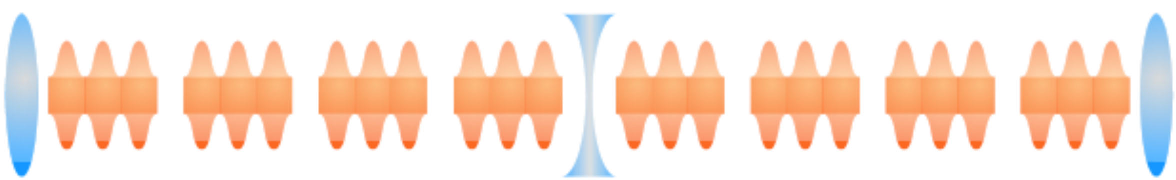




Layout: Booster Linac

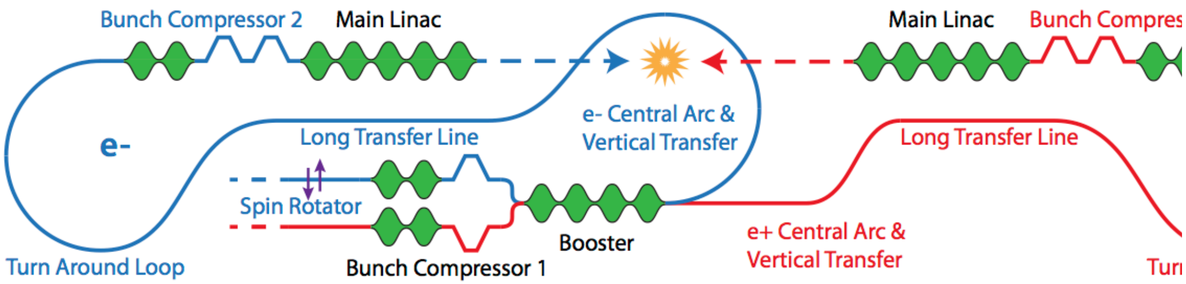


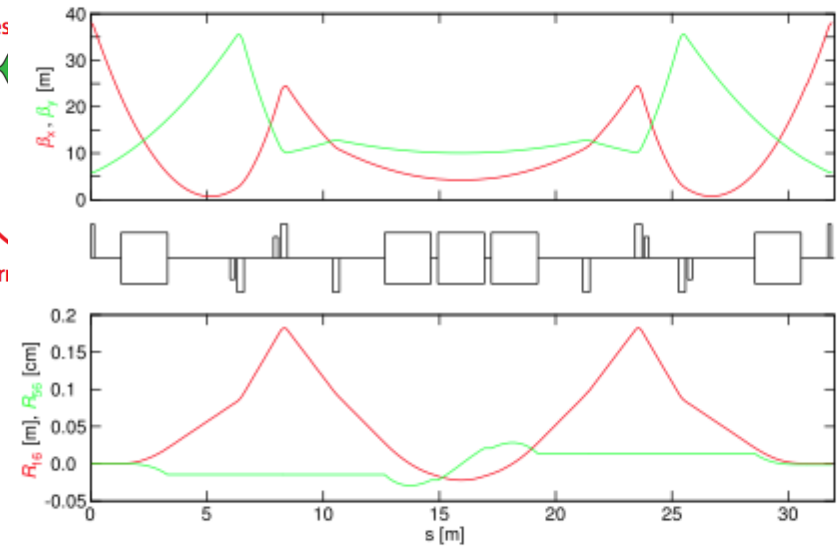
- Electrons and positrons share the same booster linac, from 2.86 to 9 GeV energy



6140 MV integrated voltage, 2 GHz frequency, 15 MV/m gradient, 410 m of cavities, 1.5 m cavity length, 274cavities embedded in a FODO lattice with 8 cavities per cell, total length 472 m.

Layout: Transfer Lines

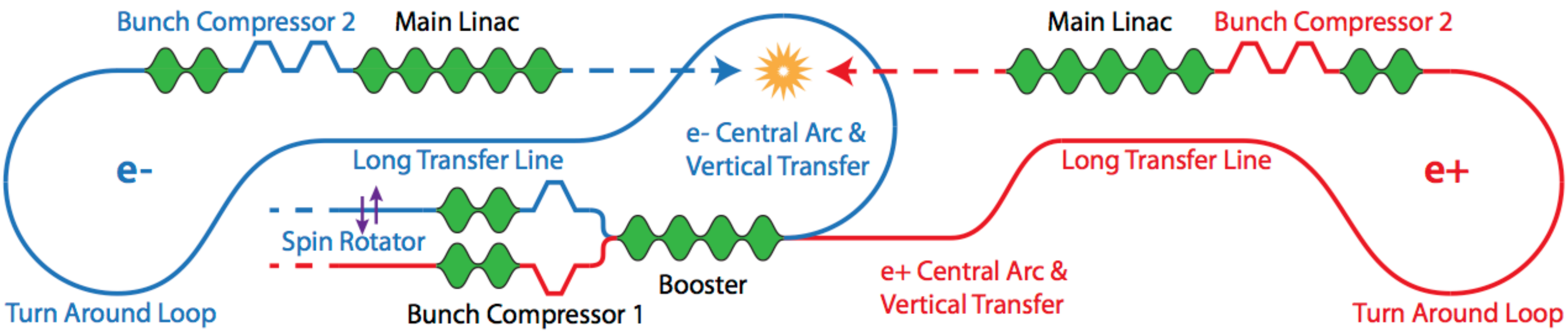




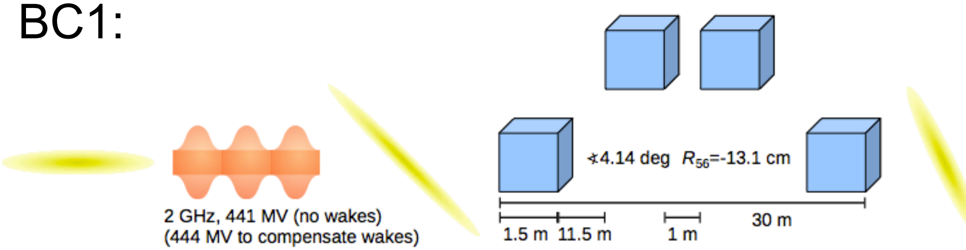
- Each RTML consists of about 26.3 km of beamlines: 21km for each transfer lines; 2km for each turn around loop
- The long transfer lines use a FODO lattice with 438m long cells for 9 GeV beam energy
- Fast ion beam instability, resistive wall wakes, stray fields

- TA uses a complex achromatic and isochronous lattice with strong quadrupoles and sextupoles: 2km long, 822 magnets
- TA is tuned to minimize emittance growth induced by ISR (CSR is sufficiently weak)
- The central electron arc uses the same lattice as the turn around loop. All other arcs are at least similar to the turn around loop.

Layout: Bunch Compressors



BC1:

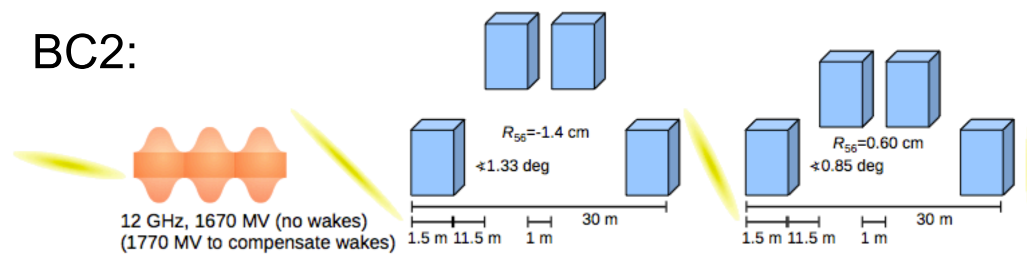


E_0	2.86	GeV
σ_s	1600	μm
$\sigma_{E,unc}/E_0$	0.13	%
$1/E_0\ dE/ds$	0	1/m
$\sigma_{E,tot}/E_0$	0.13	%

E_0	2.86	GeV
σ_s	1600	μm
$\sigma_{E,unc}/E_0$	0.13	%
$1/E_0\ dE/ds$	-6.45	1/m
$\sigma_{E,tot}/E_0$	1.04	%

E_0	2.86	GeV
σ_s	300	μm
$\sigma_{E,unc}/E_0$	0.69	%
$1/E_0\ dE/ds$	-25.8	1/m
$\sigma_{E,tot}/E_0$	1.04	%

BC2:



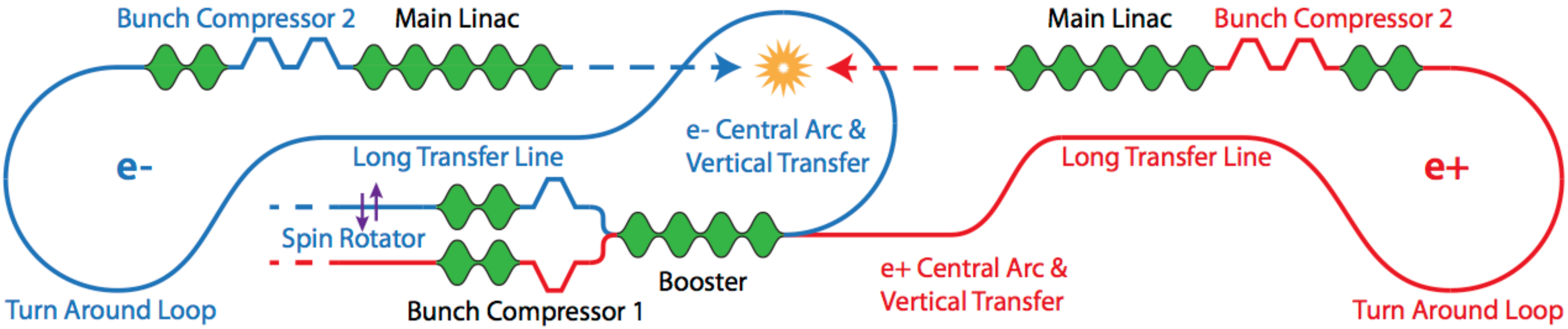
E_0	9	GeV
σ_s	300	μm
$\sigma_{E,unc}/E_0$	0.22	%
$1/E_0\ dE/ds$	-8.21	1/m
$\sigma_{E,tot}/E_0$	0.25	%

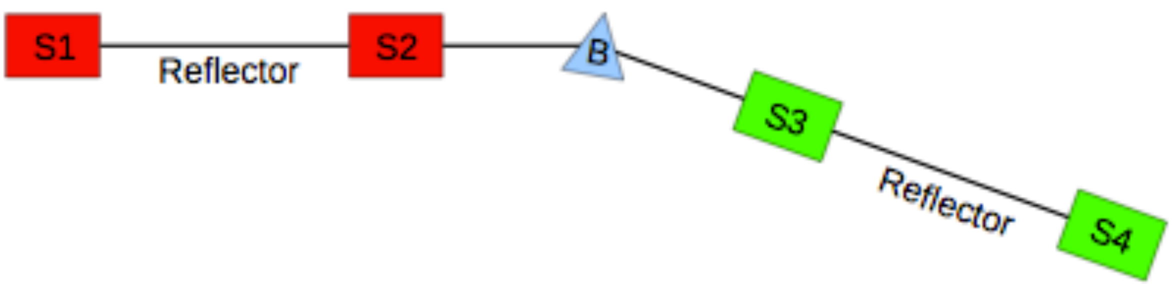
E_0	9	GeV
σ_s	300	μm
$\sigma_{E,unc}/E_0$	0.22	%
$1/E_0\ dE/ds$	-49.5	1/m
$\sigma_{E,tot}/E_0$	1.14	%

E_0	9	GeV
σ_s	100	μm
$\sigma_{E,unc}/E_0$	0.66	%
$1/E_0\ dE/ds$	-135	1/m
$\sigma_{E,tot}/E_0$	1.14	%

E_0	9	GeV
σ_s	44	μm
$\sigma_{E,unc}/E_0$	1.6	%
$1/E_0\ dE/ds$	0	1/m
$\sigma_{E,tot}/E_0$	1.6	%

Layout: Spin Rotator





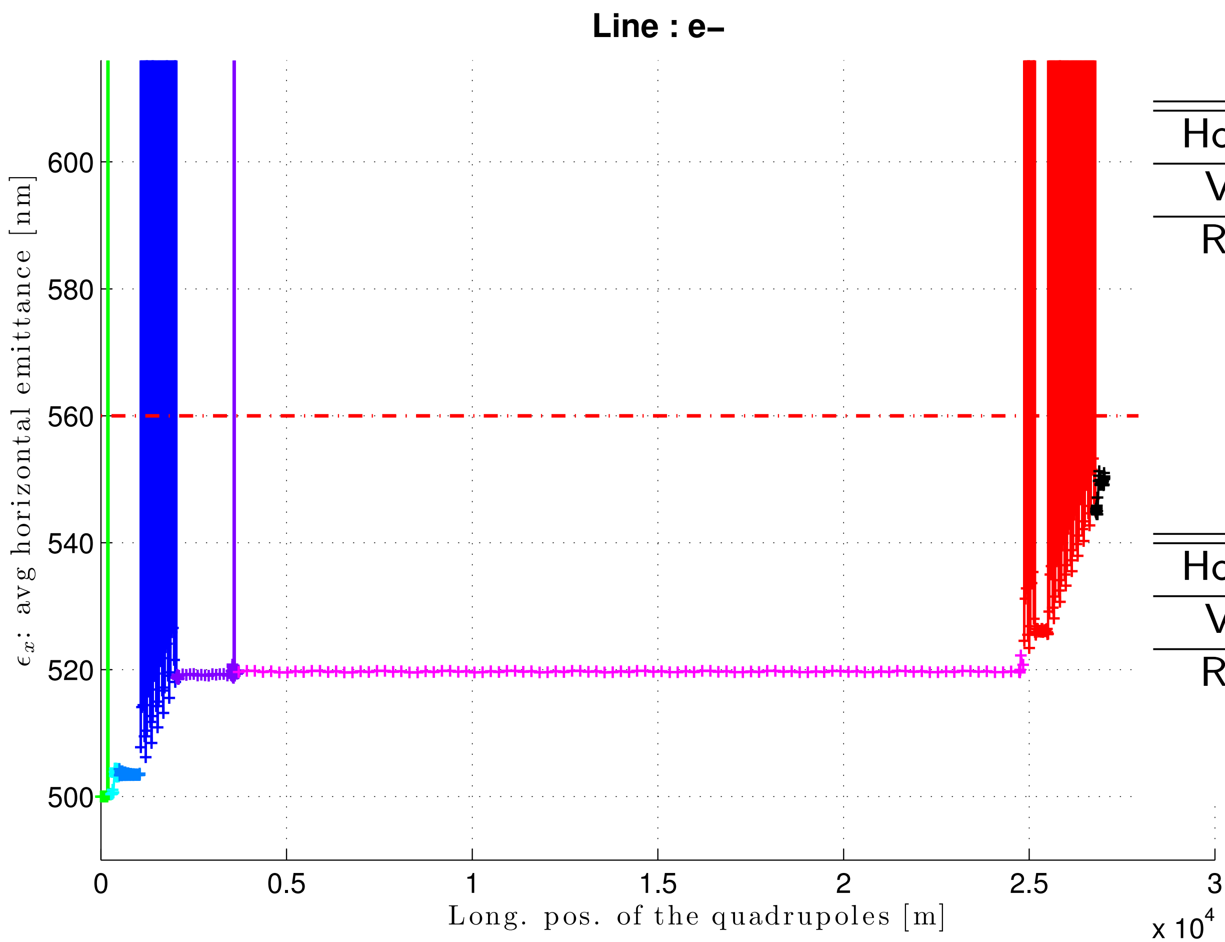
total length ≈ 135 m

- To avoid spin dilution the spin vector is oriented in vertical direction in the damping rings
- Any orientation of the SR at IP should be possible
- Since injectors and main tunnel are parallel the electron spin rotator can be located in front of BC1. All bends after rotation are compensated (figure-eight movement) and energy spread will not induce any spin dilution (for the positrons, as the bends are not fully compensated (180 deg total bending), a 2% polarization loss would be induced)

CLIC RTML emittance budgets

	design	static	dynamic
$\Delta\epsilon_x$[nm]	60	20	20
$\Delta\epsilon_y$[nm]	1	2	2

e− line: horizontal emittance



Property	Symbol	Value	Unit
Horizontal emittance	ϵ_x	500	nm
Vertical emittance	ϵ_y	5	nm
RMS bunch length	σ_z	1600	μm

Table: @ exit of damping rings

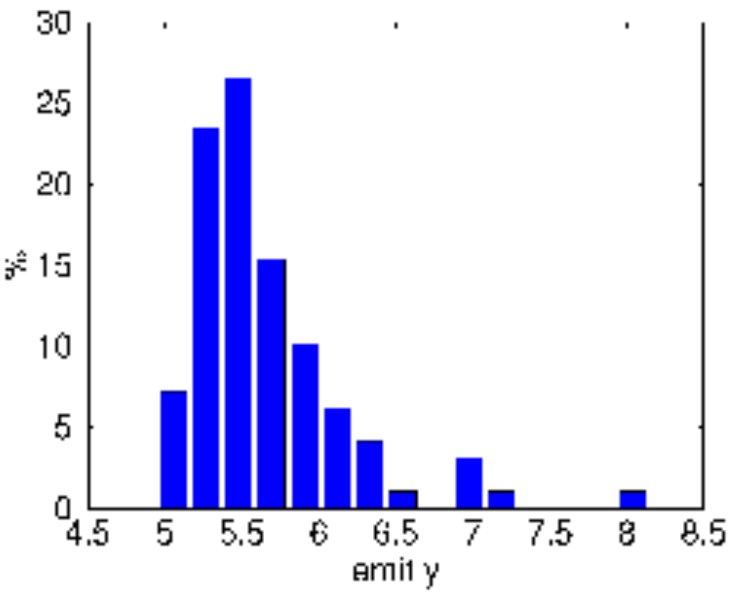
↓ RTML

Property	Symbol	Value	Unit
Horizontal emittance	ϵ_x	$<$600	nm
Vertical emittance	ϵ_y	$<$10	nm
RMS bunch length	σ_z	44	μm

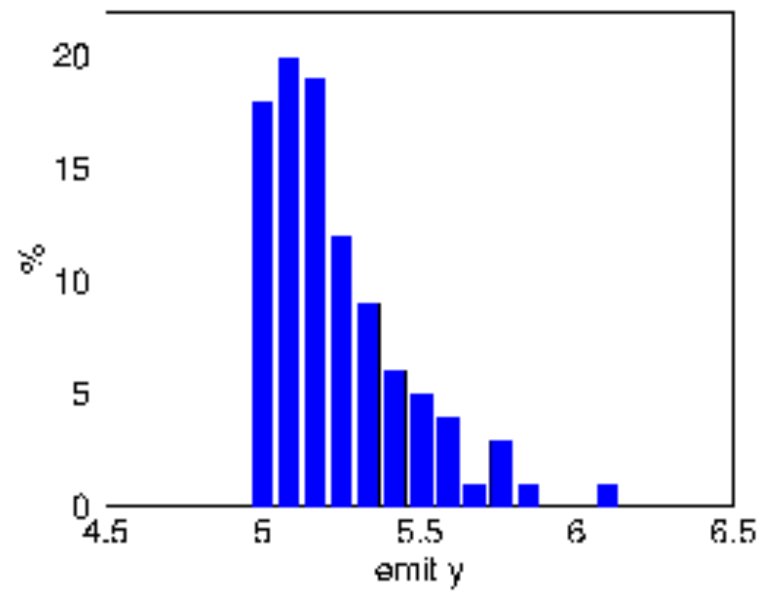
Table: @ entrance of main linac

Misalignment in the Turnaround

- each turn around loop consists of 822 magnets and is ~2 km long
- outgoing beam position has to stay within 10% of beam size,
  in vertical plane ~1 µm beam size => 100 nm tolerance => 100 nm BPM resolution



100 µm rms quads and bends,
50 µm rms sextupoles,
1 µm rms BPMs, 100 nm BPM resolution
=> p90 = 6.2 nm rad after DFS



1 µm rms all magnets,
1 µm rms BPMs, 100 nm BPM resolution
=> p90 = 5.6 nm rad after SVD

A trivial but important remark: Outgoing beam position jitter depends only on our knowledge of BPM position and BPM resolution at the end of the loop!

Static alignment tolerances

- Acceptable static misalignments after beam-based alignment (BBA) to produce 1 nm emittance growth
- 1 um BPM resolution
- In progress work: fine tuning of the parameters will lead to improvement (*)

Subsystem	Tol. after 1:1 - [μm]	Tol. after DFS - [μm]†
BC1	17 (11)	55 (24)
BOO	29 (19)	45 (23)
CA	7 (5)	14 (7)
LTL	153 (88)	280 (150)
TAL	6 (4)	9 (5)
BC2	1.4 (0.8)	3.5 (2)

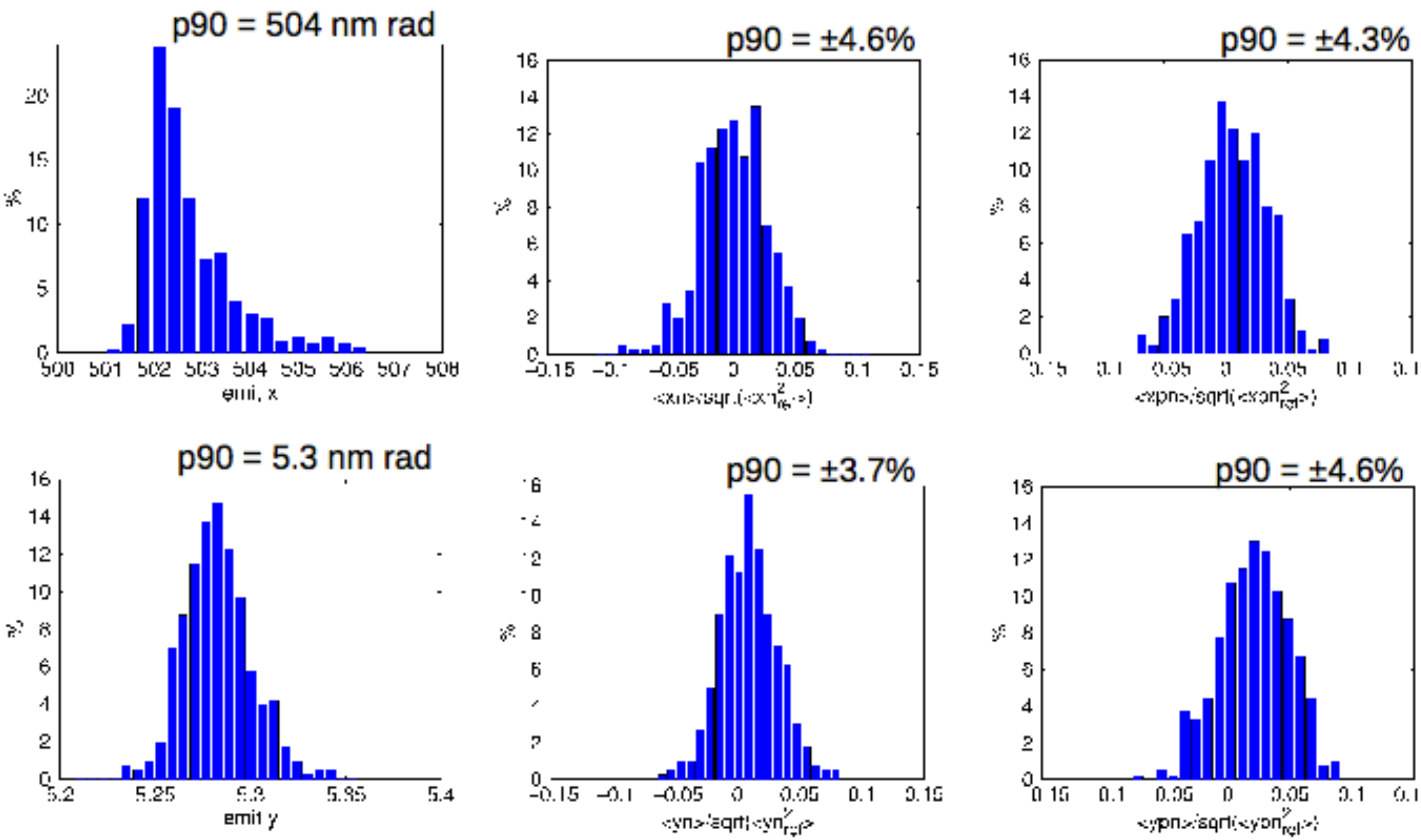
† *Average tolerance and percentile 90 in brackets.*

- In SR and LTL tols. seem slack $\lesssim 200\mu m$
- In BC1 and Booster, tols. seem moderate $\lesssim 50\mu m$
- In CA (VT), TAL and BC2, tols. seem tight $\lesssim 15\mu m$

(*) with 0.1 um resolution BPMs the tighter tolerances are relaxed by a factor ≈1.3.

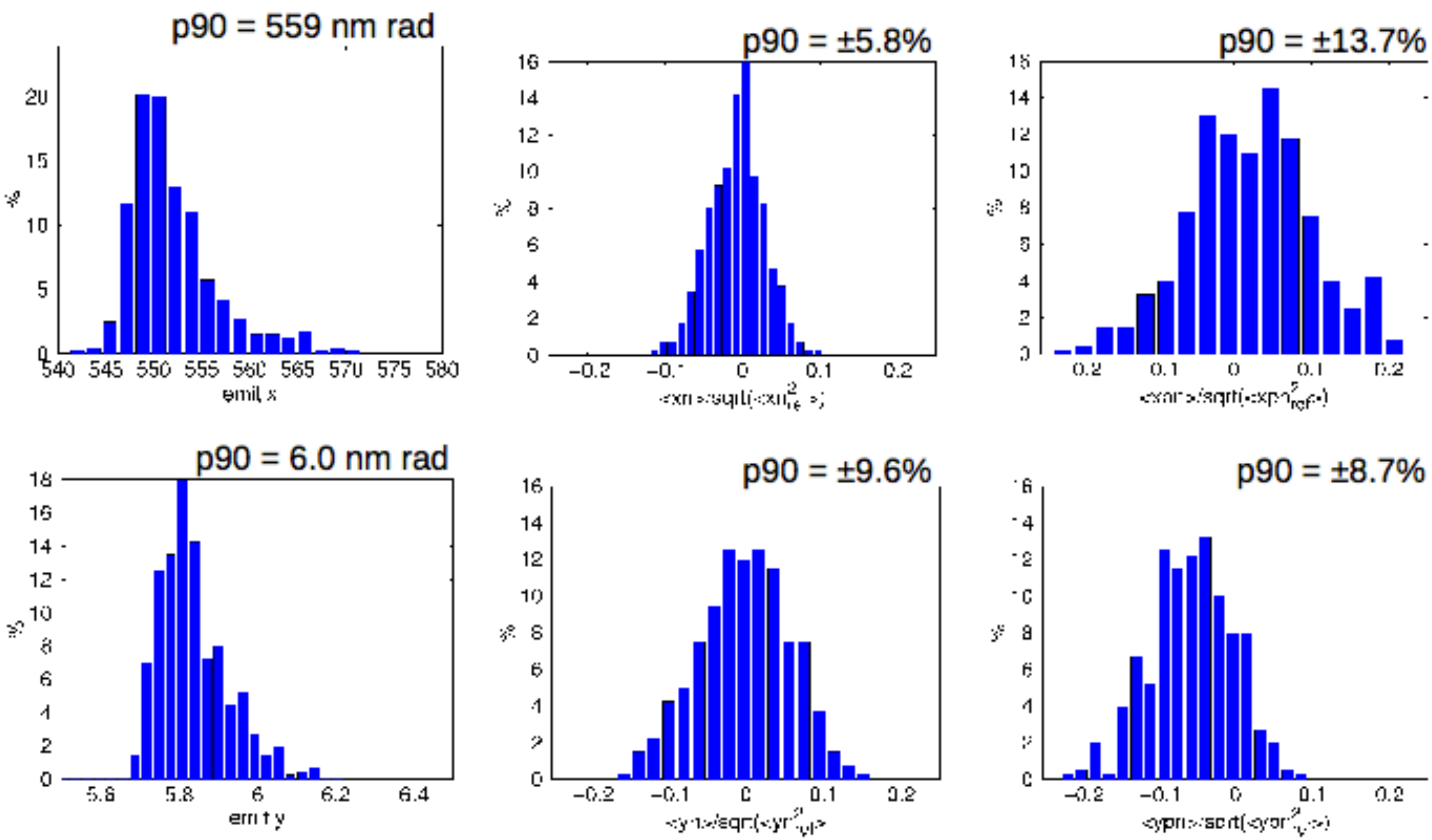
Incoming Beam Jitter

5% rms incoming electron beam jitter (Gaussian) ≈ 90% of cases within ±8% jitter, no correction, no misalignment, plots show final distribution in normalized phase space, no ISR, no wakes



Incoming Beam Jitter

5% rms incoming electron beam jitter (Gaussian) ≈ 90% of cases within ±8% jitter,
no correction, no misalignment, plots show final distribution in normalized phase space,
with ISR and short range wakes



CLIC Beam Physics R&D Program

Performances studies: magnet misalignments, magnet field errors, incoming bunch jitter, couplers' wakes, multi bunch wake fields, collimator wakefields

Design of missing sections:

- Diagnostics (in progress)
- Pre-linac Collimation (in progress)

Study transverse and longitudinal stability (in progress)

Design of feed-back and feed-forward loops for controlling dynamics imperfections

Conclusions

- Extensive studies exist both for CLIC and ILC
- CLIC shows tighter tolerances, optics review might be needed
- Dynamic studies need to be performed
- Longitudinal stability and feed- back / forward loops to cure dynamic imperfections
- None of these studies seems critical

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