SINGLE-STAGE BUNCH COMPRESSOR FOR ILC-SB2009

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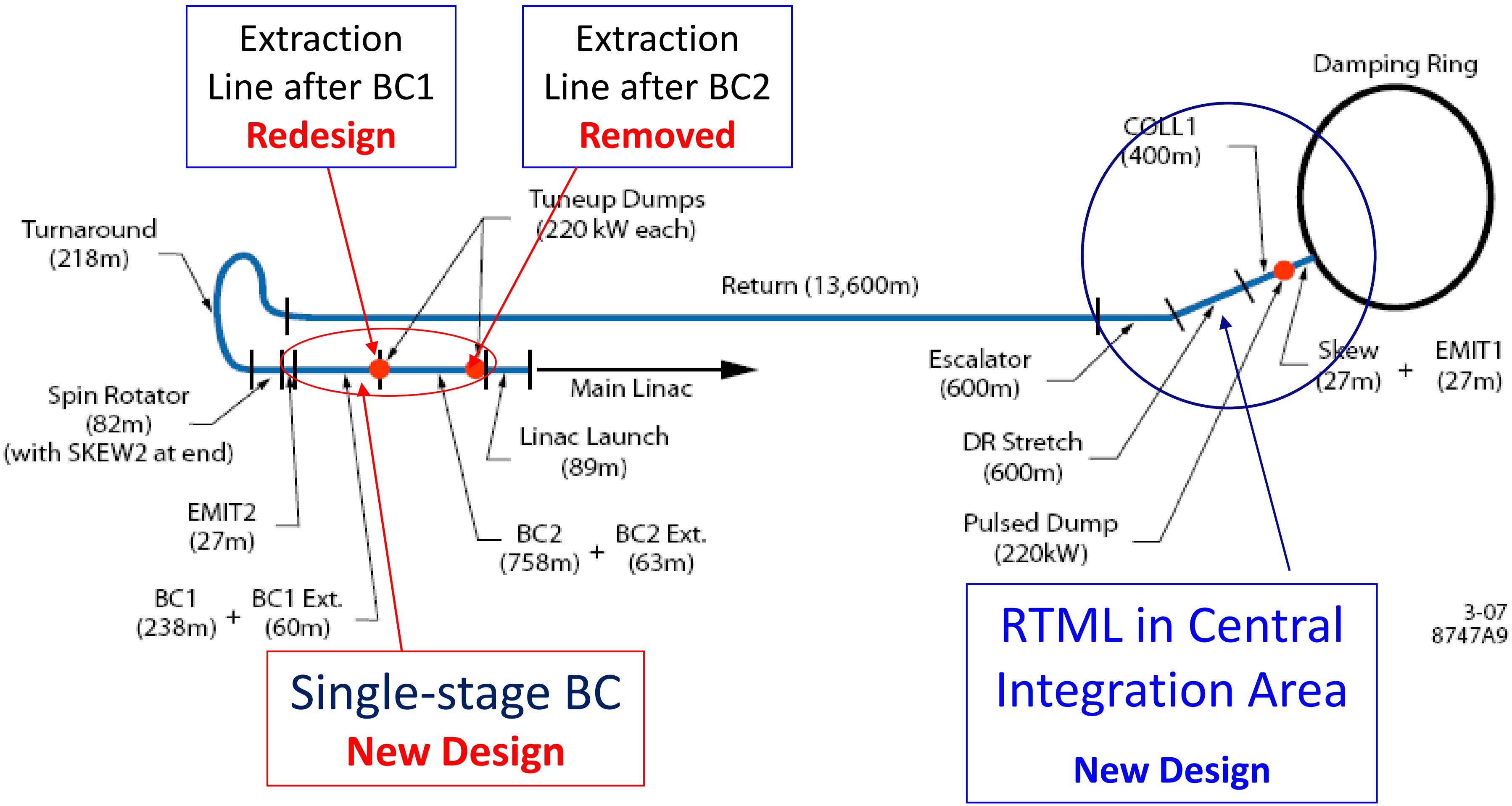
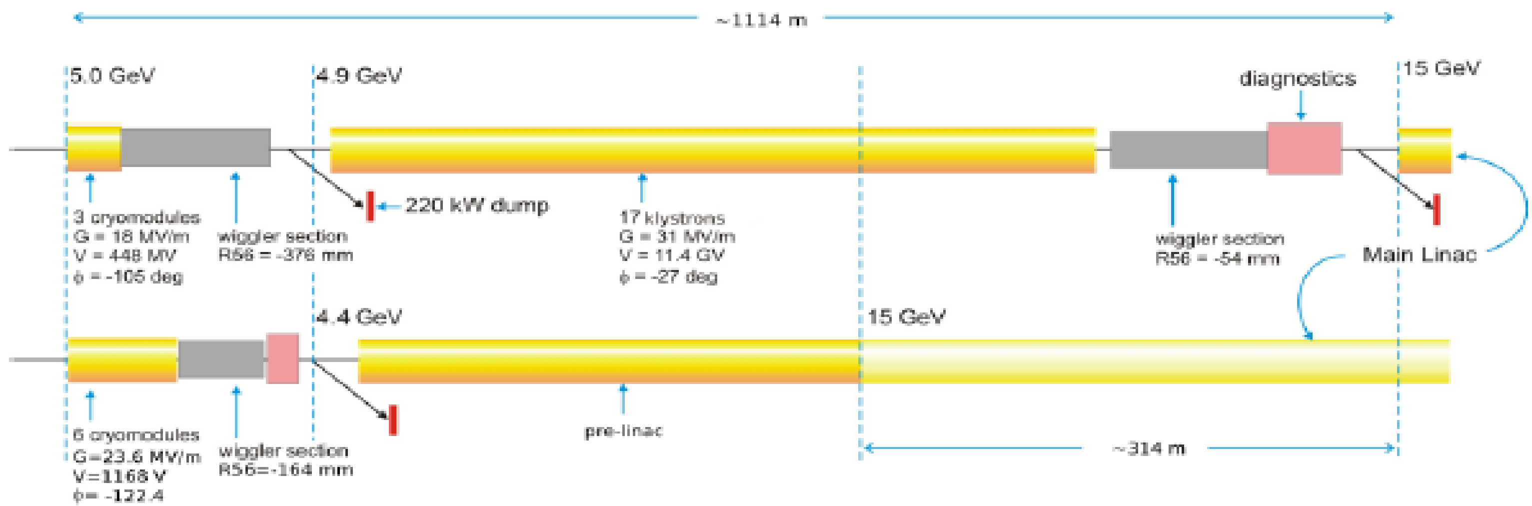
Outline

- Motivation and Lattice description
  - Parameter choice and optimization
  - Tuning flexibility for shorter bunches
- Performance overview
  - Comparison single-stage BC vs. two-stage BC
  - Performance of entire RTML (SB2009 design)
  - Issues for 10 Hz operation
- Other changes in RTML (SB2009)
  - New Extraction Line and Beam Dump
  - RTML lattice in Central Area
  - RTML LET start-to-end Simulation (emittance budget)
- Summary / Conclusion

RTML changes in SB2009 vs. RDR



What do we gain or loose with BC1S ?



- What do 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 do we loose
  - Less flexibility
  - Larger energy spread at BC exit
  - Emittance preservation and additional tuning issues (see DFS in the main linac)

SB2009 Beam Parameters

⇒ Damping Ring exit bunch length is fixed to 6 mm

⇒ Single-Stage Bunch Compressor ⇒ final bunch length fixed to 300 μm

⇒ Main Linac starts at 4.4 GeV

- Dampig Ring exit

Property	Symbol	Value	Unit
Energy	E_0	5	GeV
Bunch charge	Q_0	3.2	nC
RMS bunch length	σ_0	6	mm
RMS energy spread	σ_E/E_0	0.15	%
Normalized emittance	$\epsilon_{\eta,x}$	10'000	nm
	$\epsilon_{\eta,y}$	20	nm

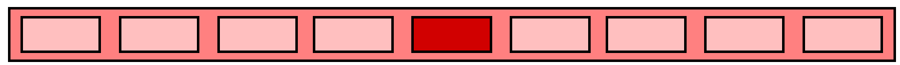
- Main Linac entrance

Property	Symbol	Value	Unit
Energy	E_0	4.4	GeV
Bunch charge	Q_0	3.2	nC
RMS bunch length	σ_0	300	μm
RMS energy spread	σ_E/E_0	3.4 (1.07*)	%
Normalized emittance	$\epsilon_{\eta,x}$	$<$ 12'000	nm
	$\epsilon_{\eta,y}$	$<$ 25	nm

* at 15 GeV

RF-System Description

- 6 Type-4 cryomodules (quadrupole in the middle) in a fodo lattice with 90 degrees phase advance per cell



- Characteristics of the rf-system compressor are:

Integrated voltage	1,332 MV @ 1.3 GHz
Cavity gradient	≈26.8 MV/m
Accelerating Structures	48 (6 Type-4 cryomodules)
Phase	-127.7 degrees
Energy Loss	815.2 MeV

- Design is optimized (RF phase, acc gradient, R_{56}) to achieve:

  $\Rightarrow$ final bunch length : 0.3 mm

  $\Rightarrow$ energy spread at ML entrance (baseline): 1.07%

Cost reduction

(BC1+BC2) vs. (BC1S+preLinac)

	BC1+BC2	BC1S+preLinac
Length [m]	1114	800
RF units/klystrons	16/17	14(*)
Cryomodules	48	42
Cavities	414	360
Quadrupoles	88	61
BPMs	84	59

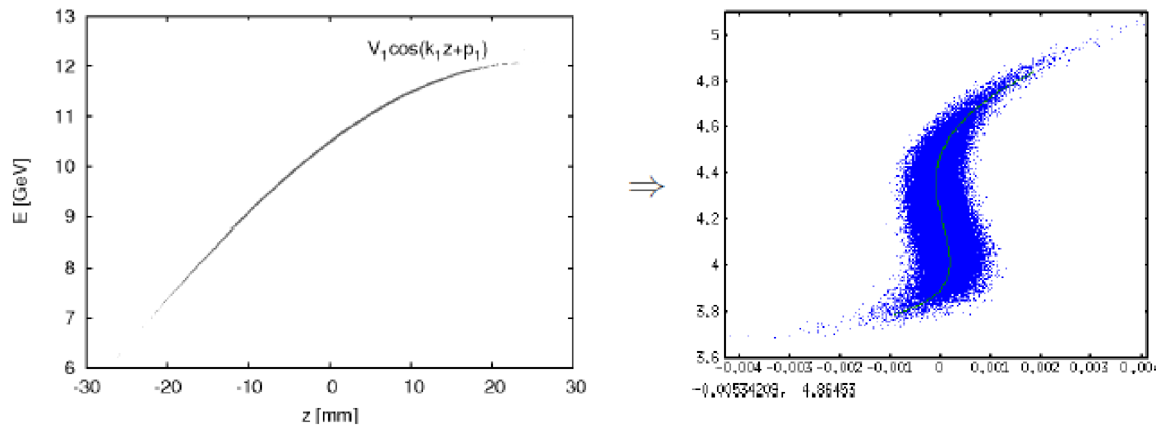
(*) No spares in BC1S (Klystrons and CM) so far

BC1 Instrumentation	BC2 Instrumentation (BC1S)
phase monitor, bunch length minitor, LOLA profile monitor	phase monitor, bunch length minitor, LOLA profile monitor
	4 laser wires

Compression from 6mm to 200 μm

Many efforts have been done to compress bunches down to 200 μm with a single-stage BC

- Major problems are the intrinsic non-linearities of the system:
  - off-crest RF-phase



- $T_{566} \neq 0$, for a wiggler $\Rightarrow$ $\boxed{T_{566} \approx -\frac{3}{2} R_{56}}$

Minimum bunch length achieved ~250 μm

In order to obtain bunches shorter than 250 μm we have to reduce T_{566} by introducing:

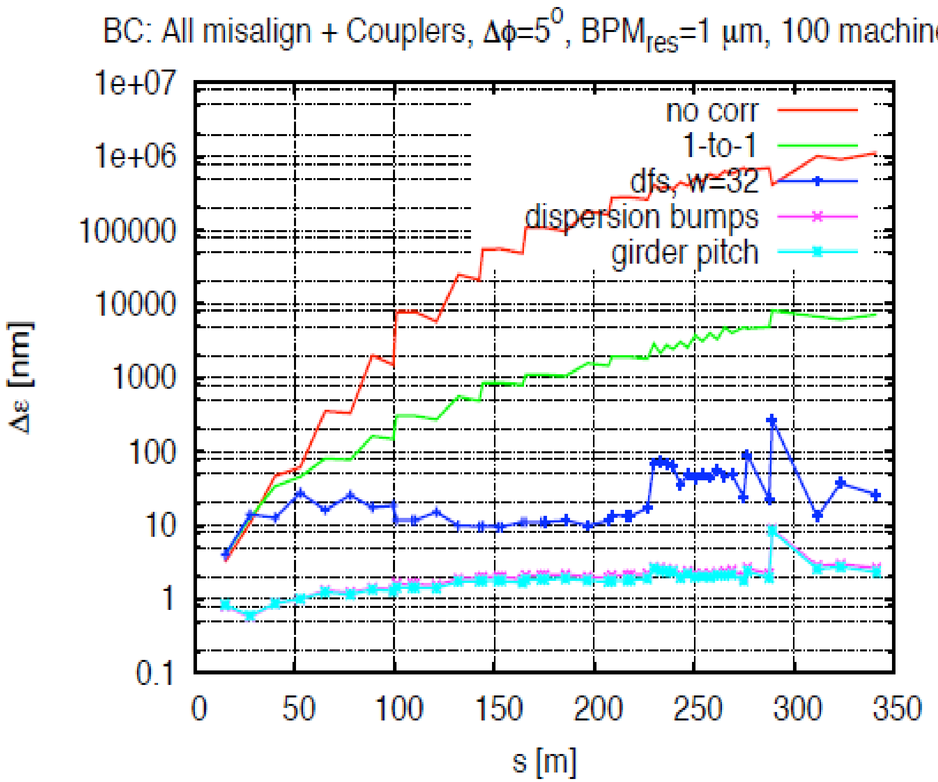
- *sextupoles*
- *3^{rd} harmonic cavity*

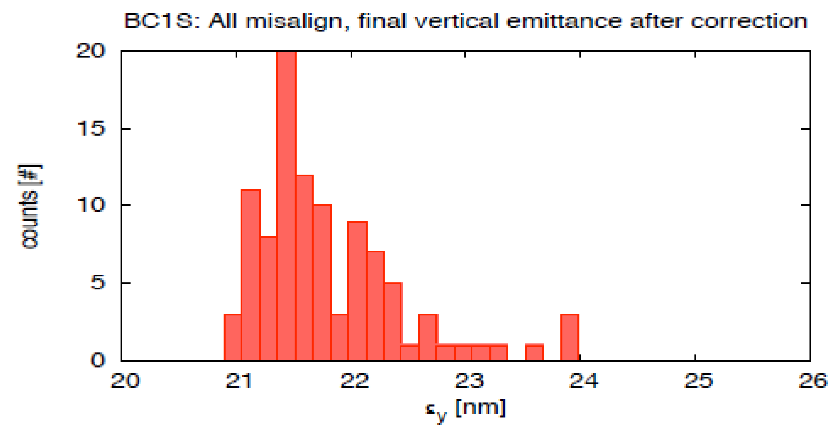
R56	STD	STD+3rd	STD+Sextupoles	STD+3rd + Sextupoles
-0.120	249	226	234	220
-0.100	241	223	237	236

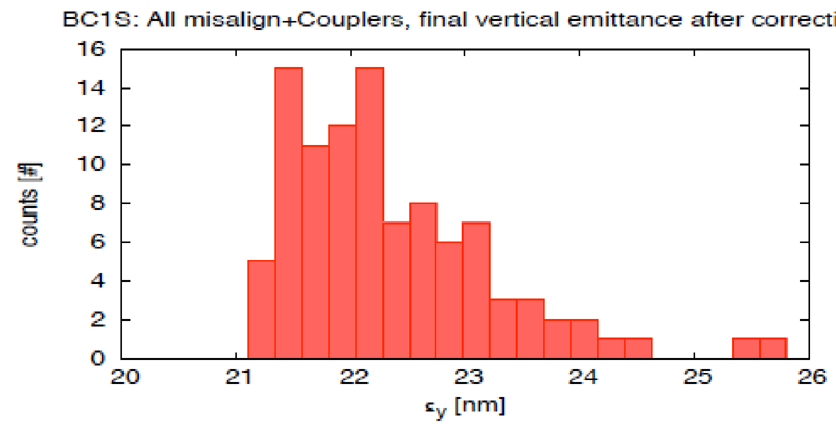
*STD – current single-stage compressor design (standard)

Emittance growth due to misalignments

- Nominal errors and BPM resolution
- Couplers are considered
- Vertical emittance along BC1S







➔ *Final vertical emittance growth is ~2.3 nm (average over 100 machines)*

Performance single-stage vs. two-stage BC

Summary Tables for the Bunch Compressors

- These simulations:

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 in "Front-end"

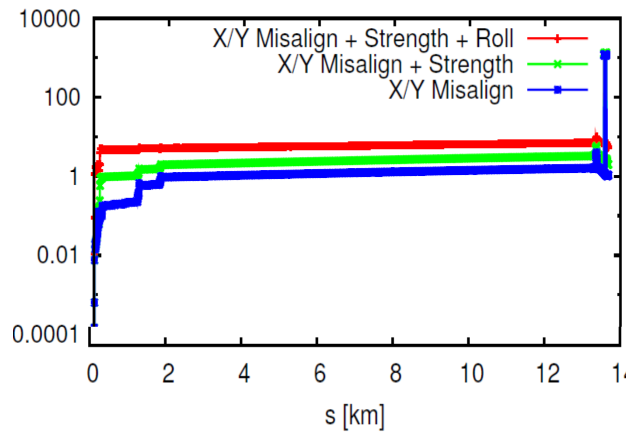
Region	Errors	Emittance Increase (nm)		Correction
		average	90% CL	
Escalator + Getaway + RL	X/Y Offsets	0.48	0.52	KM + knobs + CC
	+ Quad Strength	0.68	1.25	KM + knobs + CC
	+ Quad/Sbend Roll	1.87	3.23	KM + knobs + CC
Turnaround + Spin Rotator (OFF)	X/Y Offsets	2.26	5.33	KM + knobs
	+ Quad/Sbend Strength	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

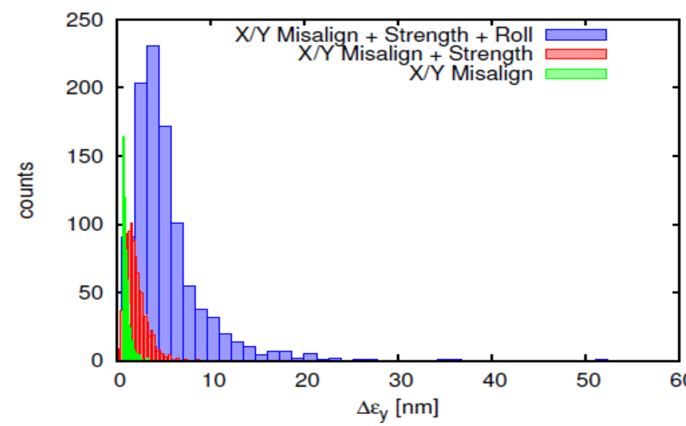
Entire RTML (w/o BC1S)

Vertical Emittance growth (average)

and

Histogram for 1000 seeds





RF parameters for considered scenario (PHG)

For Main Linac ⇨

Single-stage Compressor

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Eacc = 26.8 MV/m

Scenario		Full Power	Low Power		10Hz - Low P	
RF configuration		KCS & DRFS	KCS	DRFS	KCS	DRFS
I_beam	mA	9	6.2	4.5	6.2	4.5
# bunches/train		2625	1312		1312	
# trains per second e+	Hz	5	5		5	
Max energy e+	GeV	250	250		125	
E_{acc} (during beam pulse)	MV/m	31.5	31.5		15.75	
Length of fill pulse	ms	0.595	0.86	1.19	0.86	1.19
Length of beam pulse	ms	0.97	0.70	0.97	0.70	0.97
Fall time (exponential)	ms	0.86	1.24	1.72	1.24	1.72
# train per second e-:	Hz	5	5		5	
Max energy e-	GeV	250	250		150	
E_{acc}(during beam pulse)	MV/m	31.5	31.5		18.9	
Length of fill pulse	ms	0.595	0.86	1.19	0.517	0.714
Length of beam pulse	ms	0.97	0.70	0.97	0.70	0.97
Fall time (exponential)	ms	0.86	1.24	1.72	0.75	1.03
# trains per second e-:	Hz				5	
max energy e-	GeV				125	
E_{acc} (during beam pulse)	MV/m				15.75	
Length of fill pulse	ms				0.43	0.595
Length of beam pulse	ms				0.70	0.97
Fall time (exponential)	ms				0.62	0.859

RF Power and cryogenic losses

$$P_g = \frac{V_c^2}{4Q_L(r/Q)}\left[\left(1+\frac{I(r/Q)Q_L}{V_c}\cos\phi\right)^2+\left(\frac{I(r/Q)Q_L}{V_c)}\sin\phi\right)^2\right] = \frac{I\cdot V_c}{4}\left(\frac{1}{\alpha}+2\cos\phi+\alpha\right)$$

- Min peak RF power $P_{\min} = \frac{I\cdot V_c}{2}(1+\cos\phi)$ when $\alpha = \frac{I(r/Q)Q_L}{V_c} = 1$
- Filling time: $T_f = \frac{2Q_L}{\omega}\ln\left(\frac{\sqrt{1+2\cos\phi+\alpha^2}}{\sqrt{1+2\cos\phi+\alpha^2}-1}\right)$
- Optimization to minimize RF over power: $P_{av} = \frac{I\cdot V_c\cdot F_{rep}}{4}\left(\frac{1}{\alpha}+2\cos\phi+\alpha\right)(T_f+T_b)f_{rep.rate}$
- Single-stage BC: *V_c=26.8 MV/m ; ϕ = -127.7°*

- *Full Power: 9mA; 5Hz; T_b=0.97 ms; => T_f=1.36 ms; P_{pk}=54.5 kW; P_{av}=636W*
- *Low P/KCS; 6.2mA; 5Hz; T_b=0.7 ms; => T_f=1.87 ms; P_{pk}=39 kW; P_{av}=501 W*
- *Low P/DRFS; 4.5mA; 5Hz; T_b=0.97 ms; => T_f=2.58 ms; P_{pk}=28 kW; P_{av}=502 W*

For 10 Hz operation:

- *LP/KCS: 6.2mA; 10 Hz => T_f=1.87 ms; P_{pk}=39 kW; P_{av}=1 kW (+50% vs. FP)*
- *LP/DRFS: 4.5mA; 10 Hz => T_f=2.58ms; P_{pk}=28 kW; P_{av}=1 kW (+50% vs. FP)*

Reference ML: *P_{pk}=280 kW; P_{av} (5Hz)=1.95 kW per cavity*

At 10Hz + 20% higher cryo-losses Need more accurate optimization to minimize cryo-losses

Optimum Cryo losses

Cryo-losses dominated by RF losses in cavity at 2K

- Full Power; 9mA; 0.97ms; 5Hz
  - α=2.5, *T_f=0.92 ms; P_{pk}=100 kW; P_{av}=0.95 kW (same as in ML at 31.5 MV/m, 5 Hz)*
- Low P/KCS; 6.2mA; 0.7ms; 5Hz
  - α=4; *T_f=1.19 ms; P_{pk}=126 kW; P_{av}=1.18 kW (-10%)*
- Low P/DRFS; 4.5mA; 0.97ms; 5Hz
  - α=4; *T_f=1.63 ms; P_{pk}=91 kW; P_{av}=1.2 kW (+10%)*

- 10 Hz operation:
  - Cryo-losses will be doubled

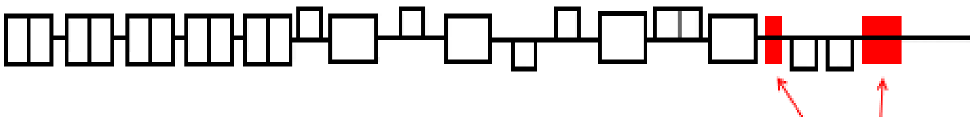
Single-stage BC in 10 Hz scenario

- Almost all RT components are working in CW regime
  - *Exception: Fast-kickers in two extraction lines (used for emergency beam abort)*

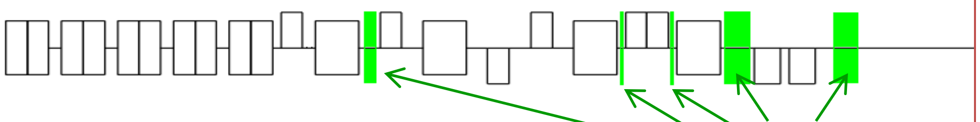
- RF system: 6 CM (2 RF units); E_{acc}=26.8 MV/m
  - *Cryogenic losses are similar (10%) for Full and Low power scenario with 5 Hz (~60kW plug power)*
  - *Cryogenic losses are 50%-100% higher for 10 Hz vs. 5Hz*
  - *Klystron should provide 10 Hz operation (XFEL specs)*

Redesign of the Extraction Line after BC1S

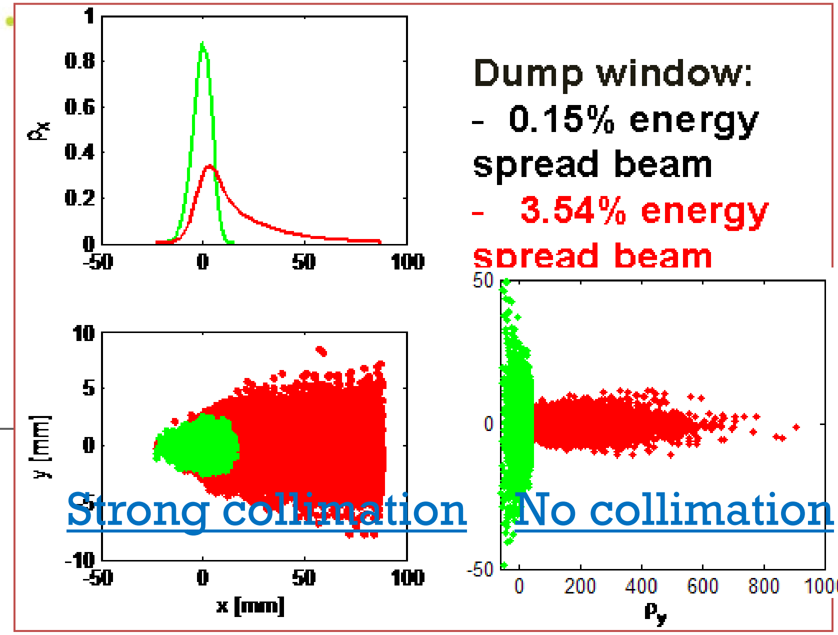
Designs for 3 Extraction Lines done



Option with Strong collimation

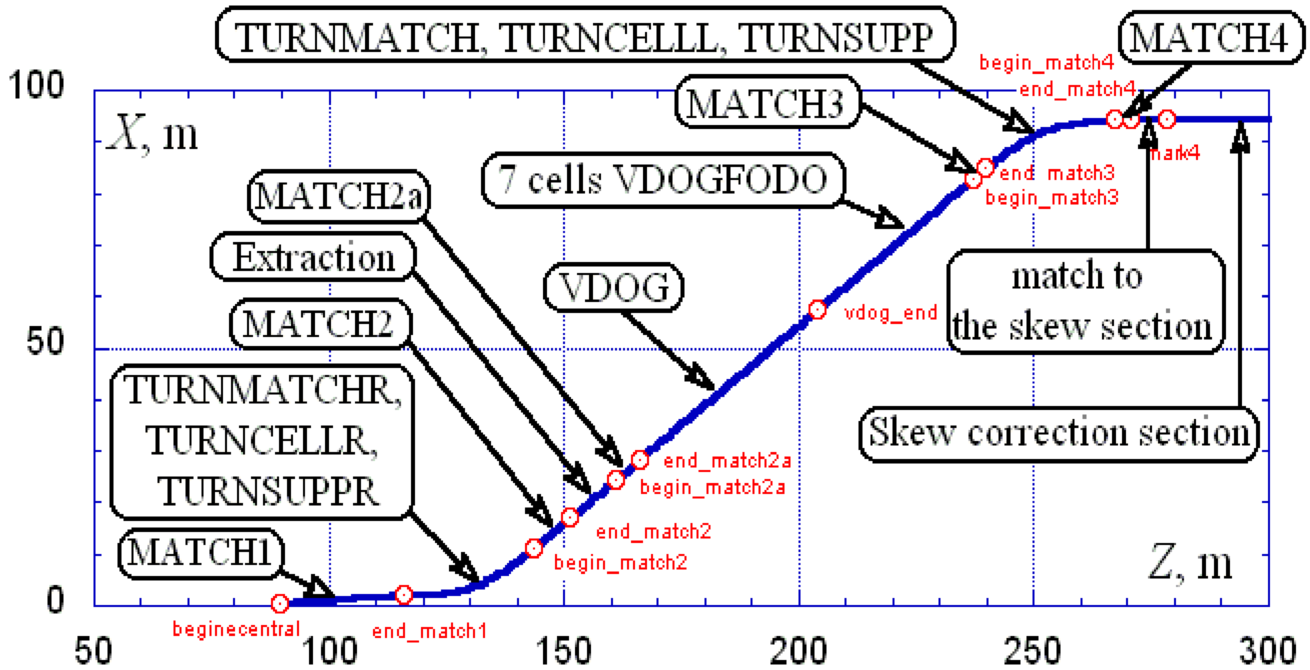


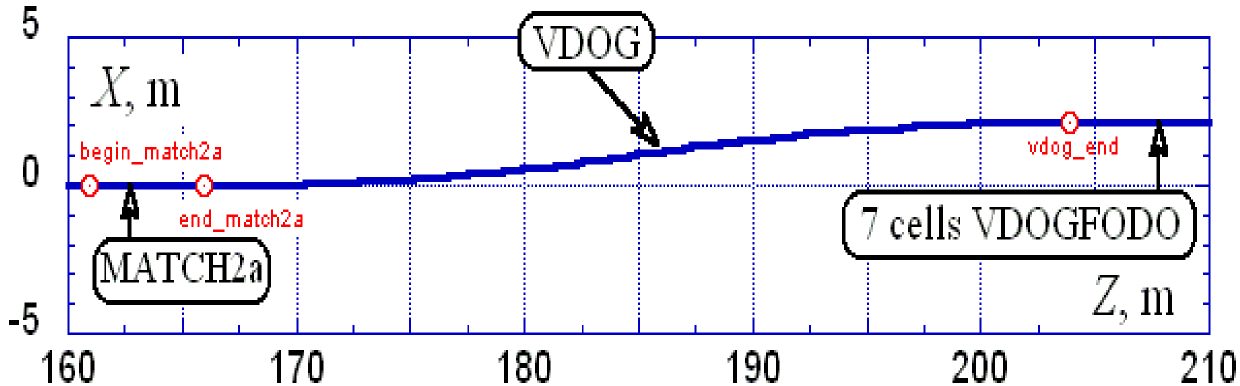
Option with No collimation



	No collimation	No collimation SC magnets	1 collimator (weak collimation)	2 collimators (strong collimation)
Collimators			1.9kW/train; 7.4mm H aperture	2.2kW &11.7 kW / train 7.2mm&50mm H aperture
Sextupoles	1T pole tip field; exotic shape	Two sextupoles 12cm aperture and pole tip filed <6T	1T pole tip field	
Dump window	12.5cm diameter	60cm diameter	60cm diameter	20cm diameter
Final doublet	5cm aperture; 1T pole tip field;	12cm aperture; Pole tip field<2.4T	5cm aperture; 1T pole tip field	5cm aperture; 1T pole tip field

New RTML lattice in Central Area





Conclusion

- Single-stage Bunch compressor is designed for SB2009.
- Performance of single-stage design is comparable with two-stage BC for compression from 6mm to 0.3 mm.
- Performances of the entire RTML have been evaluated, and resulted satisfactory. Budget for vertical emittance growth in RTML is ~8 nm.
- At 10 Hz operation scenario (low CM energy), the required average RF power and cryogenic losses should be doubled. It is not an issue for 6 cryomodules in BC, powered by 2 separate klystrons (less than for ML)
- Other RTML systems are CW => not sensitive to rep.rate.
- Design (modification) of other RTML beamlines for SB2009 is in good shape.
  - *Extraction Line after single-stage BC have been redesigned to accommodate larger energy spread (3.5% vs. 2.5% in RDR)*
  - *New RTML lattice was designed to accommodate proposed changes in accelerator layout in Central Area (DR, e+/e- sources, BDS)*