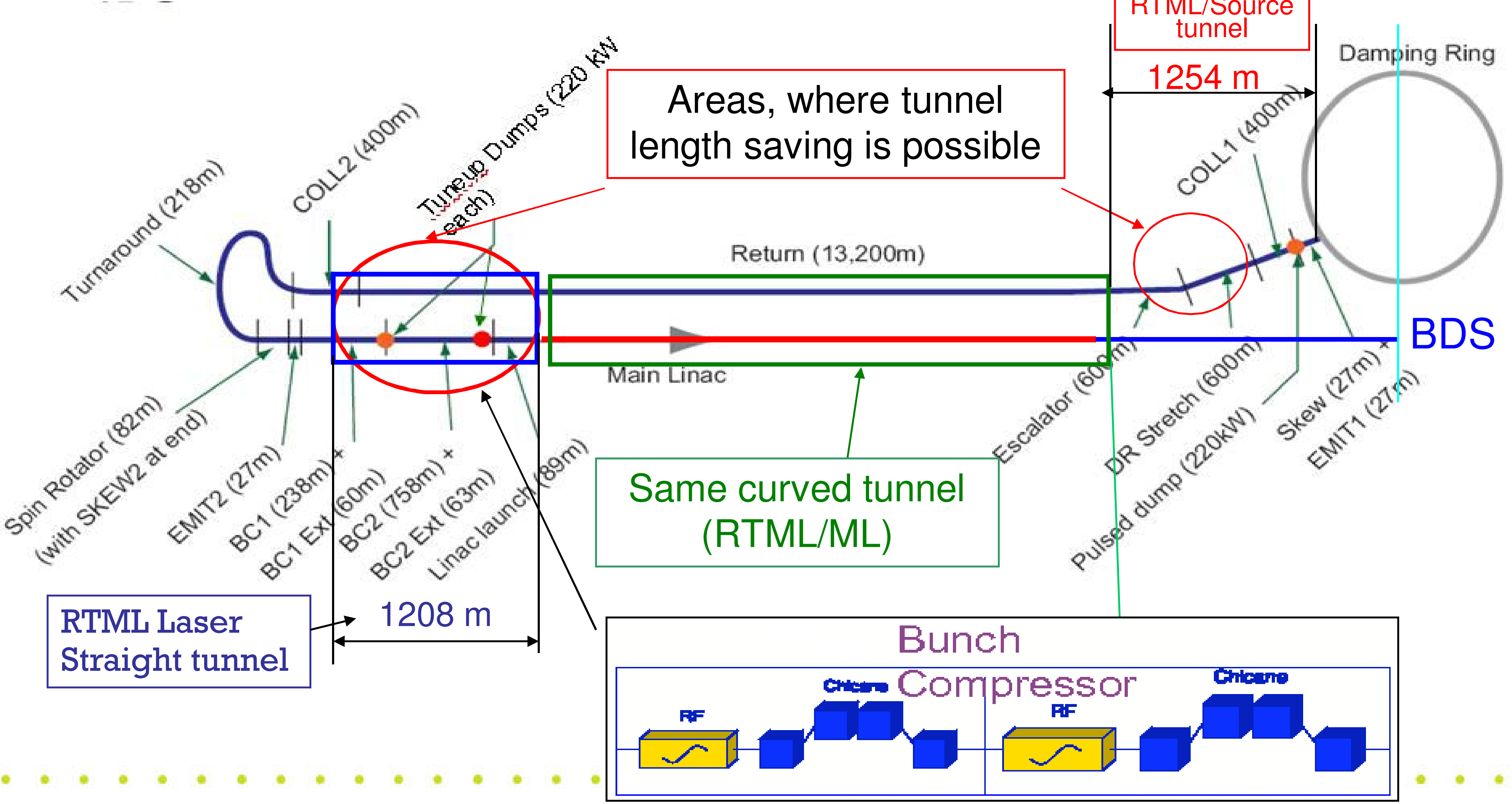
Single-stage Bunch Compressor

Nikolay Solyak

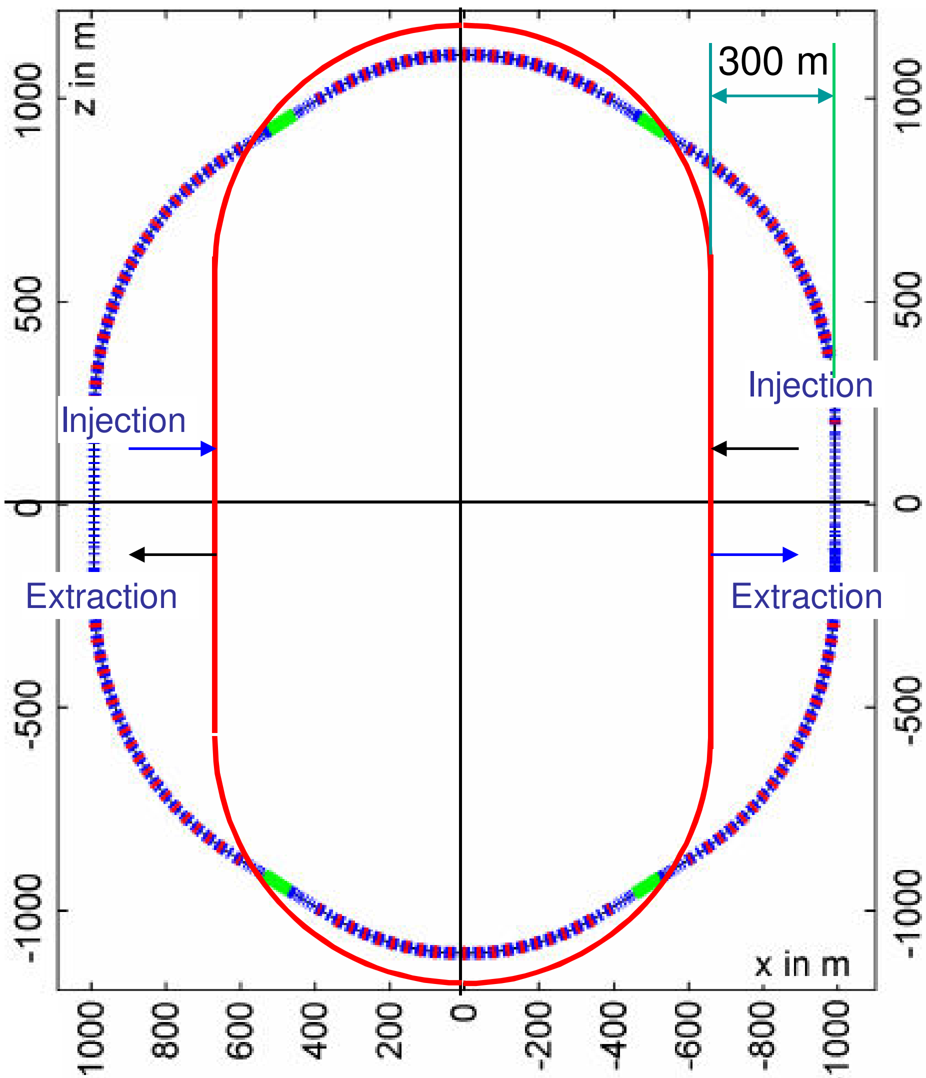
Fermilab

RTML Schematic (RDR)

Note: e- and e+ RTMLs have minor differences in Return line (undulator in e- linac side) and Escalator (DR's at different elevations); they are otherwise identical.



ILC Damping Ring



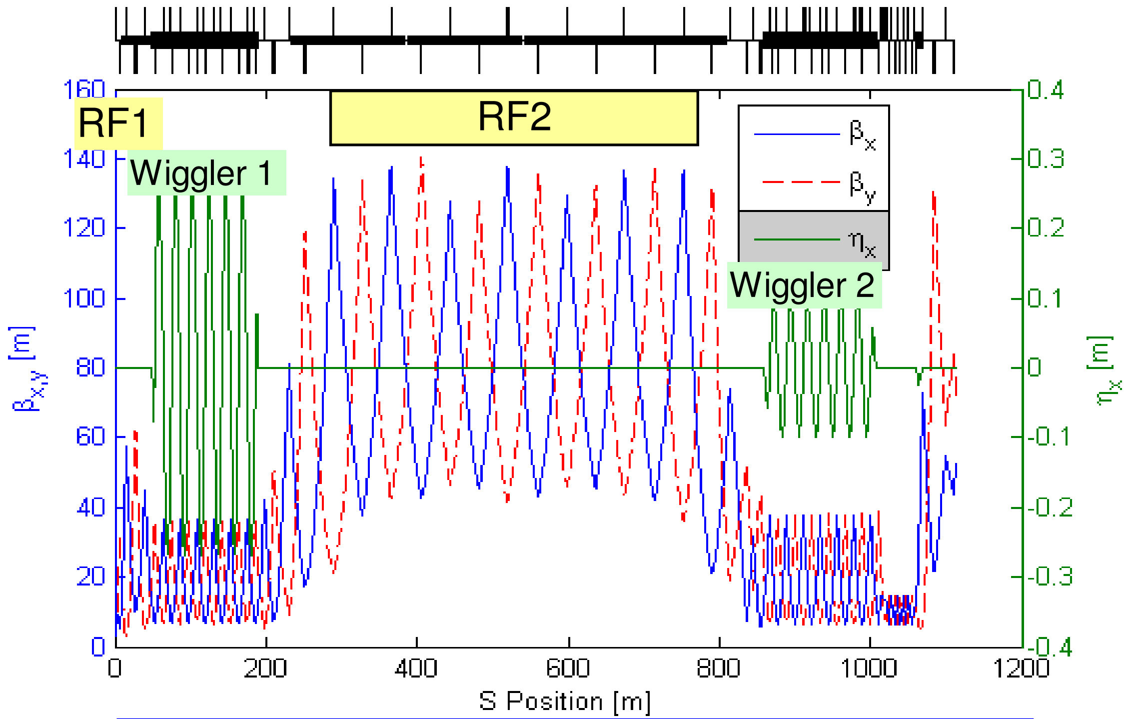
Layout of the ILC Damping Ring

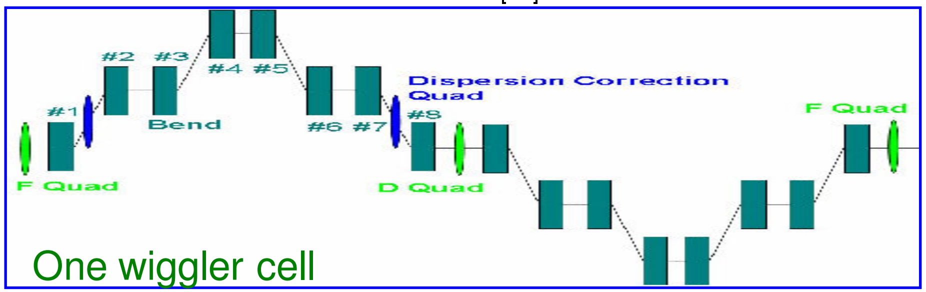
blue - old RDR (2007); red - new DCO (Feb.2008)

- New ILC DR lattice is shorter.
- Bunch length = 6 mm
  In old RDR design:
  - 9 mm (easy)
  - 6 mm (more challenge)
- Energy spread = 0.13 %
- New DR increases the length of the RTML linac in each side (e^+ and e^-) of ~300 m, but not CFS
- Need redesign/adjust DRX lattice to accommodate changes in DR

ILC Baseline 2-stage Bunch Compressor

- Longitudinal emittance out of DR:
  - ***6mm (or 9 mm) RMS length***
  - ***0.15% RMS energy spread***
- Want to go down to 0.2-0.3 mm
- *Need some adjustability*
- Use 2-stage BC to limit max energy spread
  - ***1st: Compress to 1 mm at 5 GeV***
  - ***2nd: Accelerate to 15 GeV and Compress to final bunch length***
- Both stages use 6-cell lattice with quads and bends to achieve momentum compaction (wiggler)
  - ***Magnet aperture ~ 40cm***
- Total Length ~1100 m (incl. matching and beam extraction lines)
- Minimum design is possible if assume compression 6→0.3 mm only
  - *Shorter 2-stage BC*
  - *Or short single-stage BC*
  - *Cheaper magnets*



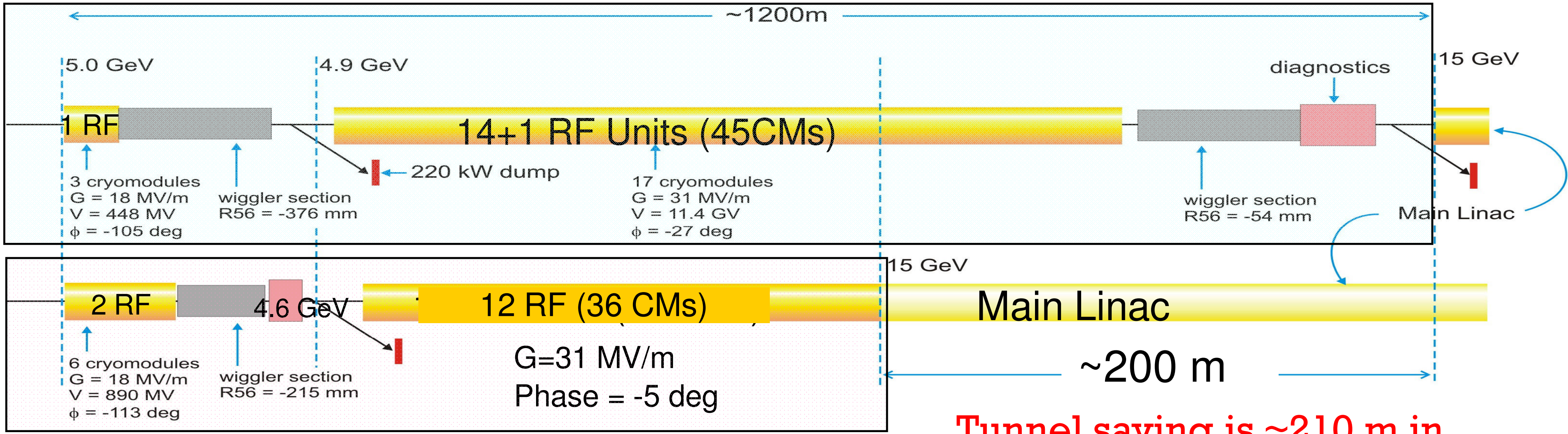


RF system

- BC1: 3 CMs with quads/each (+spare kly)
- BC2: 14 RFunits (3CM's each)+1spare
- Total 48 CM's per side

RTML in Minimum Machine Configuration

The RTML two-stage Bunch Compressor (top) and a possible short single-stage compressor (bottom). Lengths compared for 15 GeV.



Tunnel saving is ~210 m in BC1S current design.

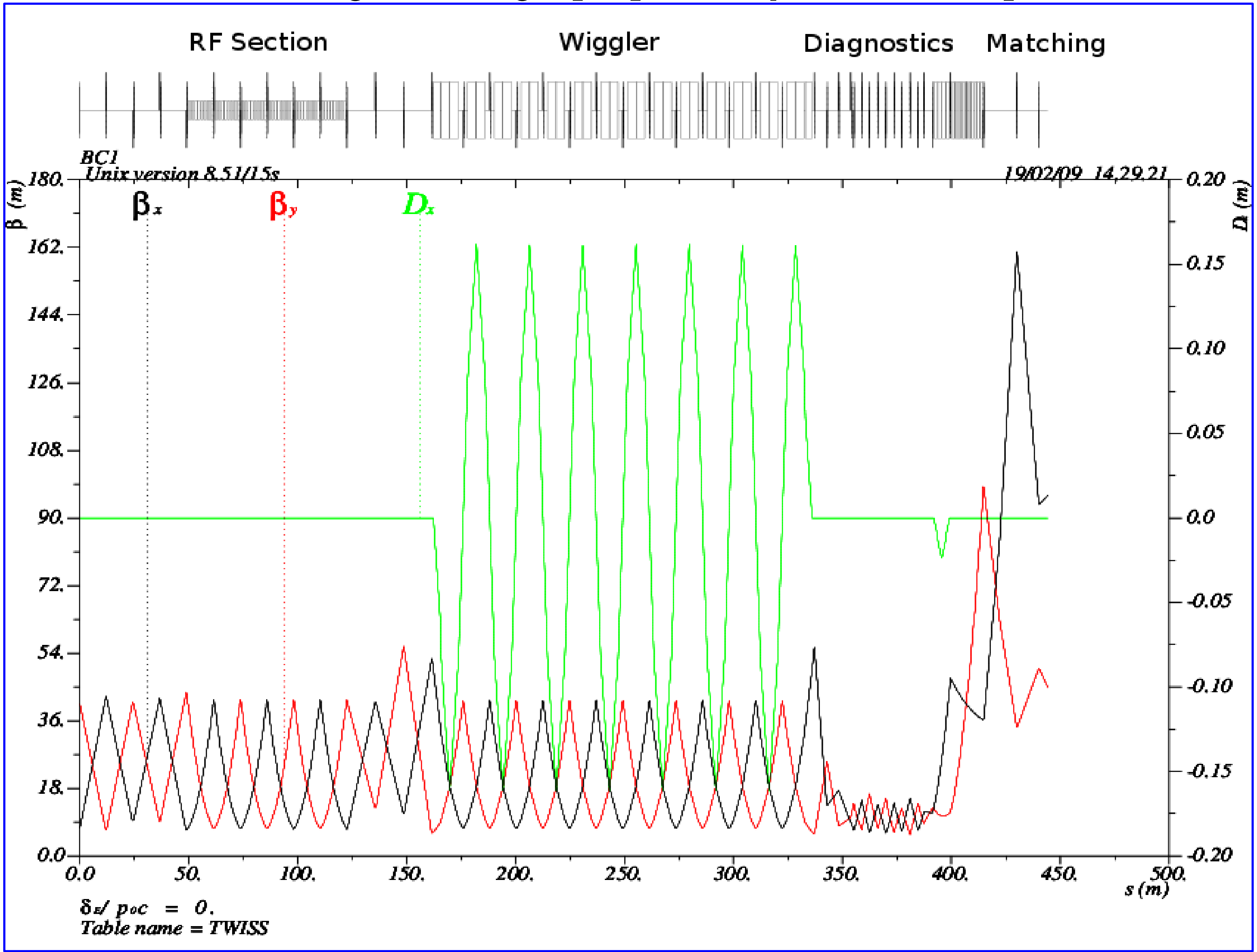
Single-stage BC is possible, if not support flexibility of parameter set

Changes from RDR: 9(6)mm→0.3(0.2)mm to 6mm →0.3mm (x20 compression)

- ❖ Reduction in beamline and associated tunnel length by an equivalent of ~200-250 m (including some in SCRF linac)
- ❖ Removal of the second 220 kW dump and dump line components
- ❖ Shortening of the diagnostics sections (lower energy)

Single-Stage BC Lattice

Based on the original design, proposed by PT et al. in April 2005:



Bunch Length:
- 6 mm → 0.3 mm

Total length = 423 m
- RF Section
- Wiggler
- Diagnostics & EL
- Matching section

Final energy 4.3 GeV

Pre-Linac:
- 4.3 GeV → 15 GeV

Design Characteristics

- The beam properties at injection are:

Charge	2e10 (3.2 nC)
Energy	5 GeV
Energy spread	0.15% (actually 0.13% from Damping Ring)
Bunch Length	6 mm

- Properties of the bunch compressor are:

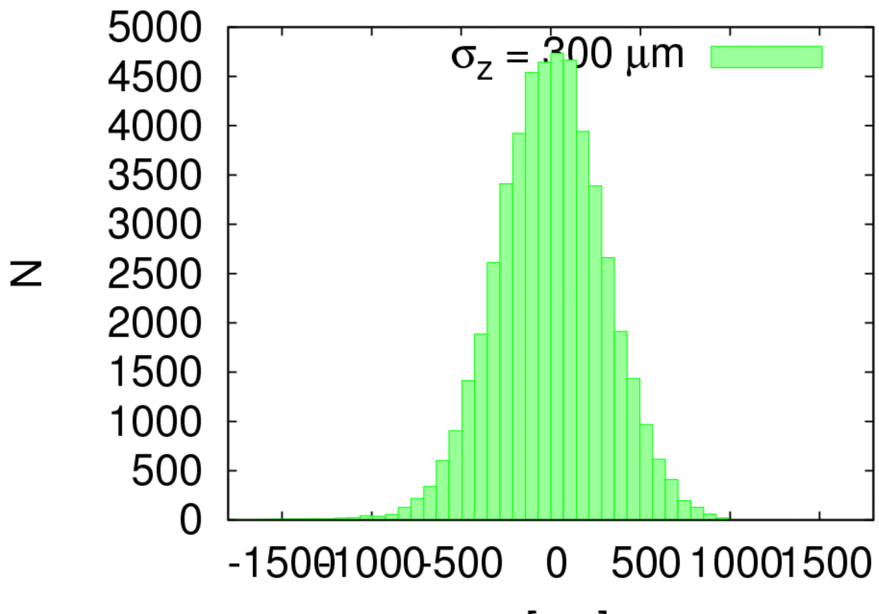
Integrated voltage	1275.2 MV @ 1.3 GHz
Cavity gradient	≈25.6 MV/m
Accelerating Structures	48 (6 cryomodules; old-type : quadrupole is at the END)
Phase	-119.5 degrees
Energy Loss	627.9 MeV
R_{56}	-147.5 mm
Total length	~ 423 m

- Pre-Linac Acceleration: 36 CM, same structures used in the ML

⇒ Desired final bunch length : 0.3 mm

⇒ Desired energy spread at ML entrance (baseline): 1.07%

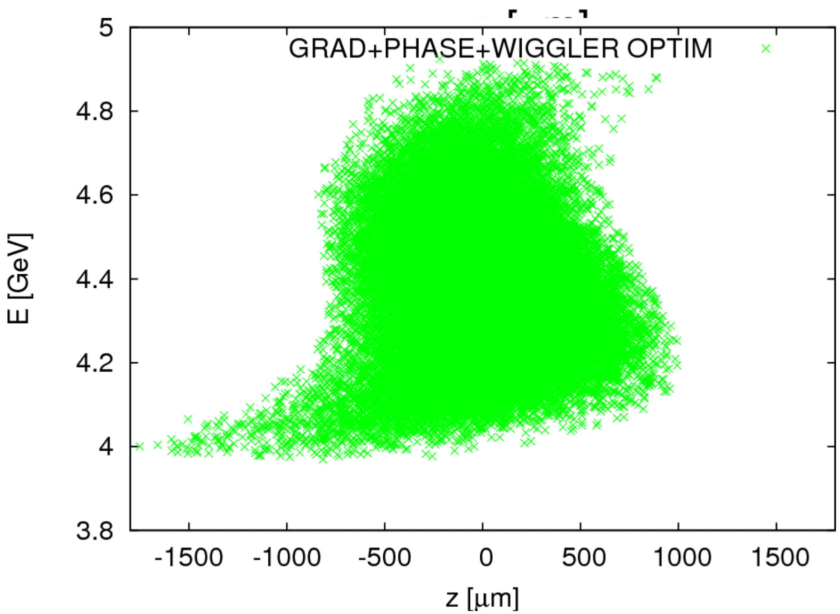
Beam Profiles @ BC1S exit

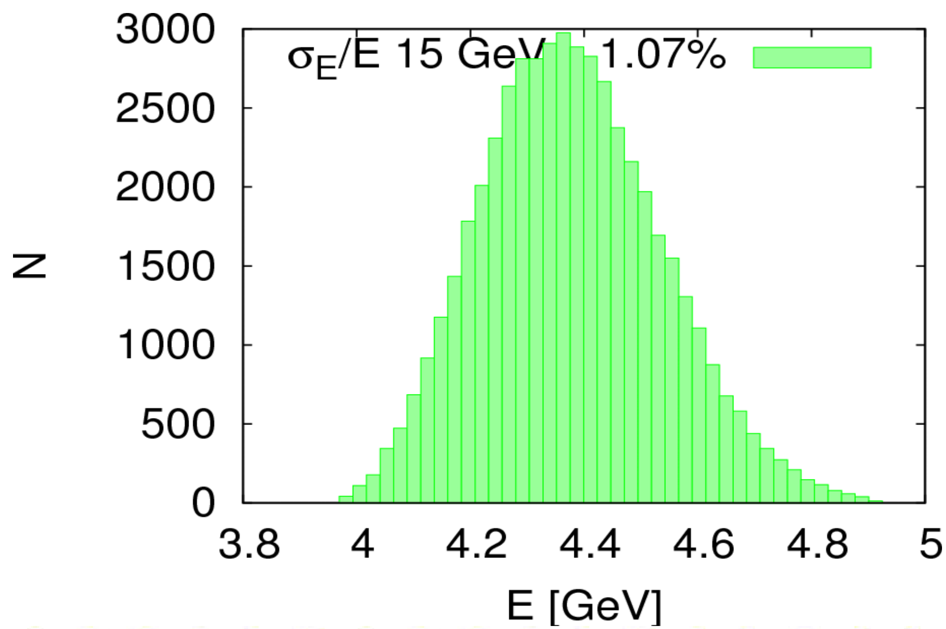


After parameters optimization, including:

- RF phase and amplitude and
- wiggler magnets

- Final bunch length = 300 um
- Energy spread @ 4.3 GeV = 3.54 %
- Energy spread @ 15 GeV = 1,07 %





Components of Single-Stage BC

- **RF Section:**
  - **Total length ~ 75 m**
  - **6 cryomodules (old type now)**
    - 48 accelerating structures
      - Acc gradient = 23.58 MV/m
      - RF phase = - 122.38 deg
      - Energy loss = 627.9 MeV
  - **6 quadrupoles/(X,Y) correct**
  - **2 klystrons (or ML RF distr)**
- **Wiggler:**
  - **6 cells; Total length ~ 160 m**
  - **R_{56} = -147.5 mm**
- **Diagnostics:**
  - **Taken from BC2 (EL is 10 m shorter)**
    - Possibly, the length can be reduced more.
  - **4 LW, LOLA Cavities, Bunch Length Monitor, Phase Monitor**
- **Pre-Linac (same configuration as ML, curved ?):**
  - **Post-acceleration linac from 4.3 to 15 GeV**
  - **E_{acc}=31.5 MV/m, no spares in CM and klystrons**

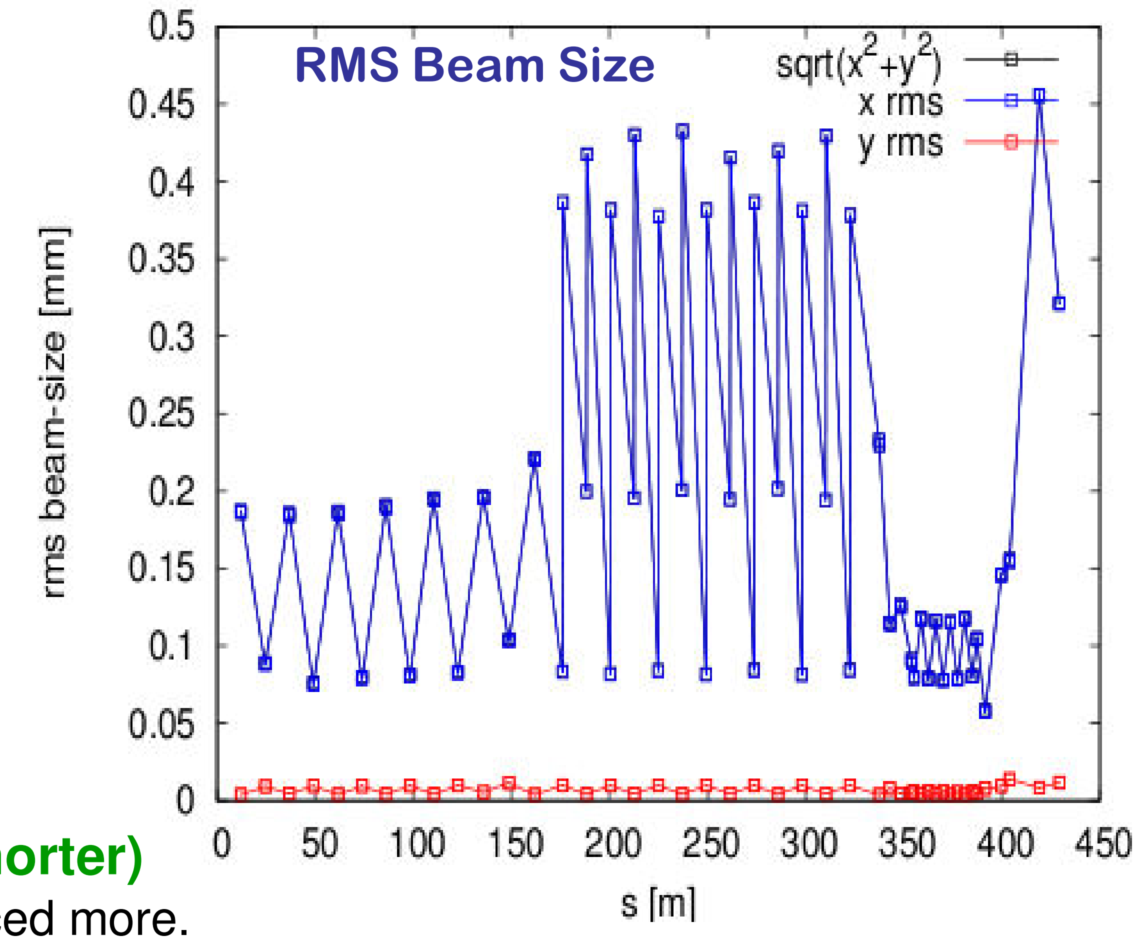


Table of Components

➔ **BC1S + PRELINAC**: total length = 886.4 m

BC1STAGE	number	unit	total	BC1S_PRELINAC	number	unit	total	TOTAL
rf units	2	-	2	rf units	12	-	12	14
cryomodules	2 × (CMQ -CMQ-CMQ)	-	6	cryomodules	12 × (CM -CMQ-CM)	-	36	42
quadrupoles	45	-	45	quadrupoles	12	-	12	57
bpms	45	-	45	bpms	12	-	12	57
acc structures	2 × (8+8+8)	-	48	acc structures	12 × (9+8+9)	-	312	360
length	423.37	m	423.37	length	462.97	m	462.97	886.4 m

➔ **BC1+BC2**: total length = 1093.5 m

BC1	number	unit	total	BC2	number	unit	total	TOTAL
rf units	1+spare kly		1	rf units	15	-	15	16
cryomodules	(CMQ -CMQ-CMQ)	-	3	cryomodules	15 × (CM -CMQ-CM)	-	45	48
quadrupoles	29	-	29	quadrupoles	59	-	59	88
bpms	27	-	27	bpms	57	-	57	84
acc structures	(8 + 8 + 8)	-	24	acc structures	15 × (9 + 8 + 9)	-	390	414
length	221.8	m	221.8	length	871.66	m	871.66	1093.5 m

Diagnostics and extraction

BC1 Diagnostics

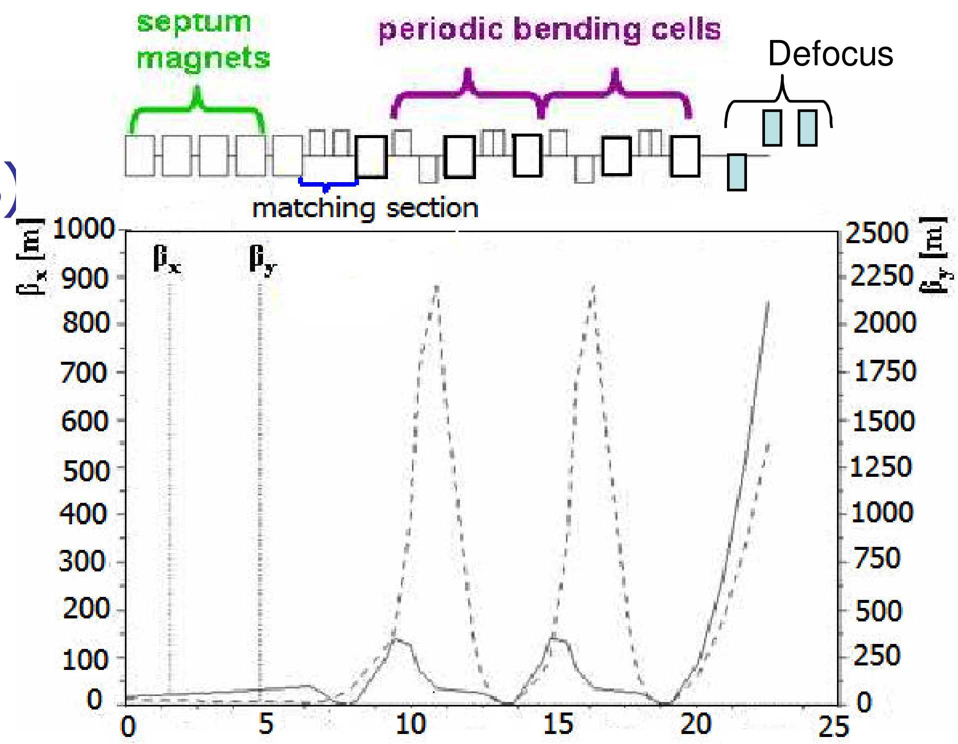
Elements	Description
DR30CM, PHASMON, LOLABC, BLMO_HORN, DBC1_X1,	Drift, Phase monitor, LOLA deflecting cavity, Bunch length monitor, Drift
BPMQ079, 2*QFBC1X1, XCOR, YCOR, DR30CM,	BPM, F-Quad, *XY*-Correctors, Drift
4*(HKEXT_BC1,DR30CM), 2*BEXT_BC1,	Extraction Kickers, Extraction Bends,
4*(DR30CM,HKEXT_BC1), DR30CM,	Extraction Kickers, Drift,
BPMQ079, 2*QDBC1X1, XCOR, YCOR, &	BPM, D-Quad, *XY*-Correctors,
DR30CM, LOLAPROF, DBC1_X2, BC1YGIRDER	Drift, LOLA profile monitor, Drift

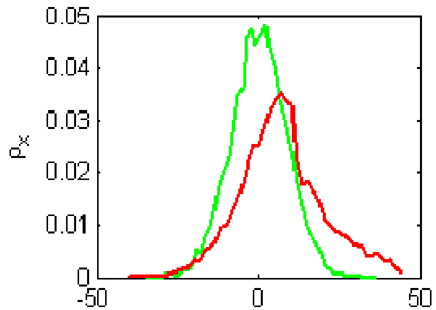
BC2 Diagnostics → BC1S

Elements	Description
BPMQ079, 2*QDBC2D, XCOR, YCOR, DR30CM, WS,	BPM, D-Quad, *XY*-Correctors, Drift, Laser wire,
DR30CM, PHASMON, LOLABC, DR30CM, LOLABC, DBC2Dss3,	Drift, Phase monitor, LOLA deflecting cavity, Drift,
BPMQ079, 2*QFBC2D, XCOR, YCOR, DBC2D,	BPM, F-Quad, *XY*-Correctors, Drift,
BPMQ079, 2*QDBC2D, XCOR, YCOR, DR30CM, WS, DBC2Ds,	BPM, D-Quad, *XY*-Correctors, Drift, Laser wire, Drift,
BPMQ079, 2*QFBC2D, XCOR, YCOR, DBC2D,	BPM, F-Quad, *XY*-Correctors, Drift,
BPMQ079, 2*QDBC2D, XCOR, YCOR, DR30CM, WS,	BPM, D-Quad, *XY*-Correctors, Drift, Laser wire,
DR30CM, BLMO_HORN, LOLAPROF, DR30CM, LOLABC, DBC2Dss4,	Drift, Bunch length monitor, LOLAPROF, Drift, LOLABC, Drift,
BPMQ079, 2*QFBC2D, XCOR, YCOR, DBC2D,	BPM, F-Quad, *XY*-Correctors, Drift,
BPMQ079, 2*QDBC2D, XCOR, YCOR, DR30CM, WS, DBC2Ds,	BPM, D-Quad, *XY*-Correctors, Drift, Laser wire, Drift,
BPMQ079, 2*QFBC2D, XCOR, YCOR, DBC2D,	BPM, F-Quad, *XY*-Correctors, Drift,
BPMQ079, 2*QDBC2D, XCOR, YCOR, DR30CM,	BPM, D-Quad, *XY*-Correctors, Drift,
LOLAPROF, DR30CM, LOLABC	LOLAPROF, Drift, LOLABC

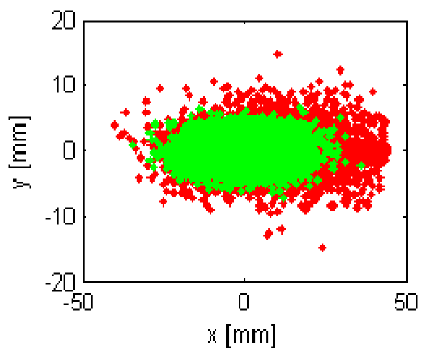
Removing of ELBC2 and dump

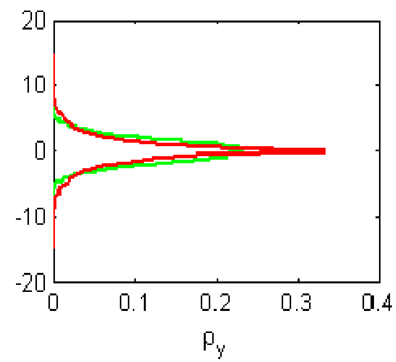
- ELBC2 length ~25 m (longest one)
- 6 septum+6 bends+12 quads,
- two collimators: 5.2 kW (protect quads) and 14.1 kW (dump window)
- 10 fast kickers and pulsed bend in the main beamline to extract beam
- Beam dump 220 kW @ 15 GeV





0.15% (green)
and 1.8% (red)
energy spread





	2 coll	1 coll	No coll
Final quads	1T 45mm	1T 45mm	2T 80mm
Collimat	5.2 kW 14.1kW	5.2kW	No coll
Dump window	12.5 cm	30 cm	100 cm

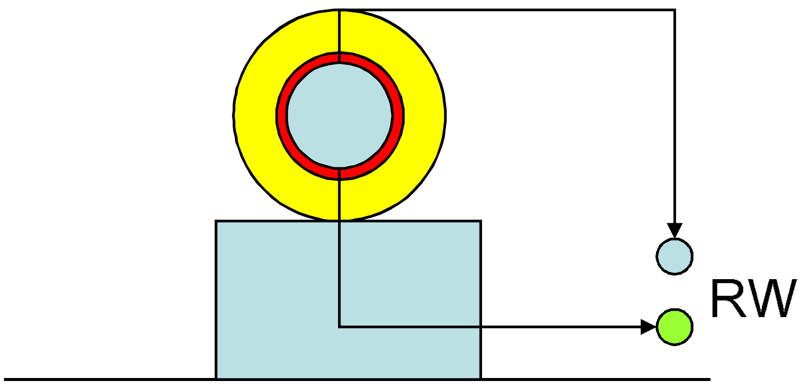
Specifications (electron side)

magnets					
type	N	L [m]	aperture [cm]	max B [G]	comments
emergency abort kickers1	8	2		70	ramped up to designed B in 100ns; peak power 0.5 MW
emergency abort kickers2	(10) 10	1		90	ramped up to designed B in 100ns; peak power 1 MW
pulsed bend	(1) 3	1		890	in 1st and 2nd lines Bmax=280G
septum bends	(6) 14	1		1000	in1st and 2nd lines Bmax=500G
bends	(6) 14	1	4	20000	
quads1	(4) 8	0.8	4	10000	
quads2	(2) 4	0.5	4	10000	
quads3	(2) 4	0.6	4	10000	
quads4	(3) 9	1	4	10000	
quads5	(2) 2	1.6	4	10000	

other	
BPM	button style BPMs they are part of the vacuum chamber
collimators	12mm and 30 mm fixed apertures; take 3kW/train and 9.5kW/train respectively
aluminum ball dump	2 dumps with window radius R=5 cm; one dump with window radius R=2cm

~220kW Aluminum Ball Dumps

50cm Diameter x 2m long Aluminum Ball Dump with Local Shielding

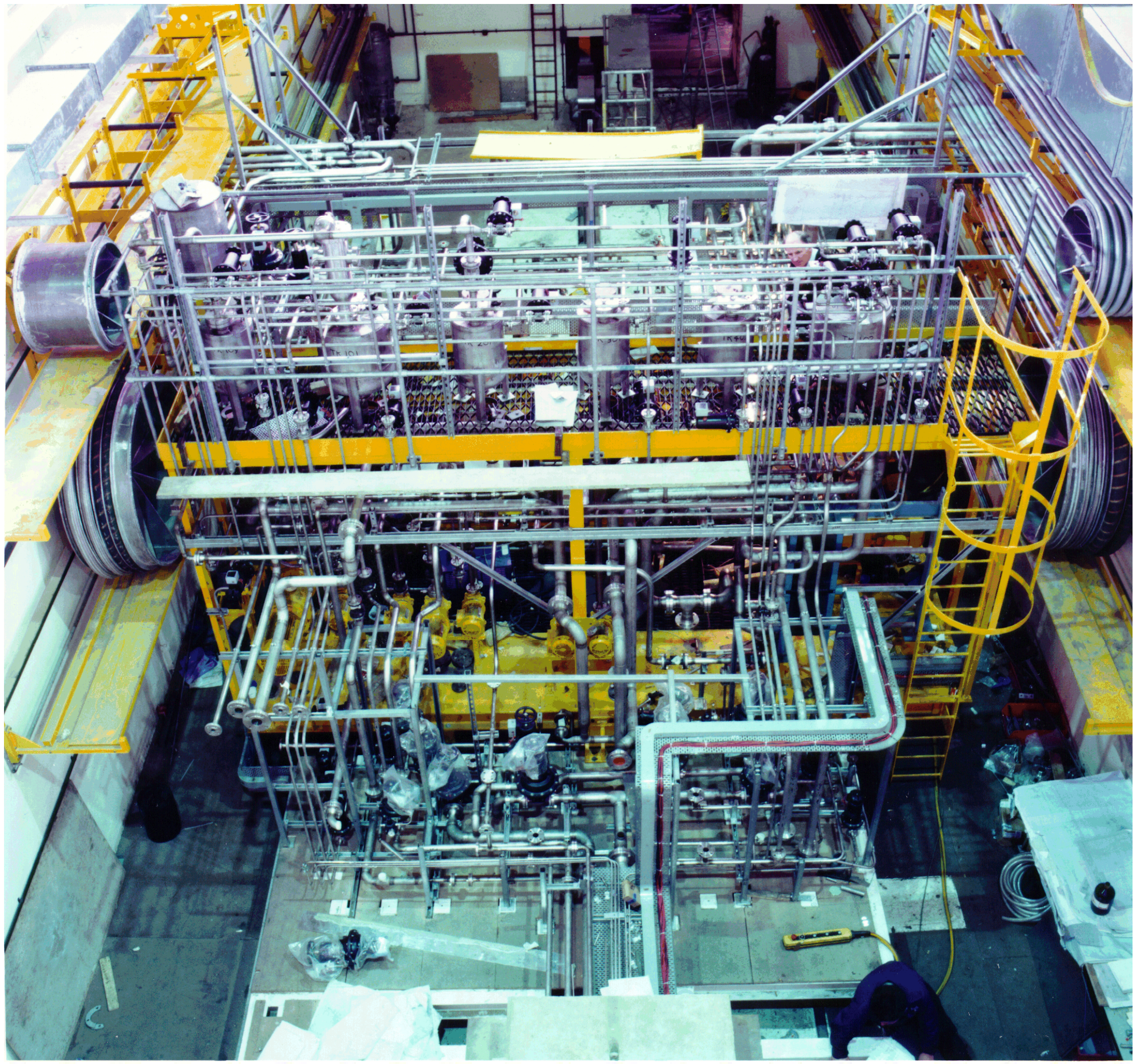


Cost (~$1M each) is dominated by:
- **3-loop radioactive water processing system**
- **The CFS infrastructure, shielding, etc.**

Similar dumps in use at SLAC

Remove 2 Dumps after BC2

50kW 3-loop 2006 Rad Water Cooling for ISIS Neutron Spallation Targets



Emittance Growth in RTML

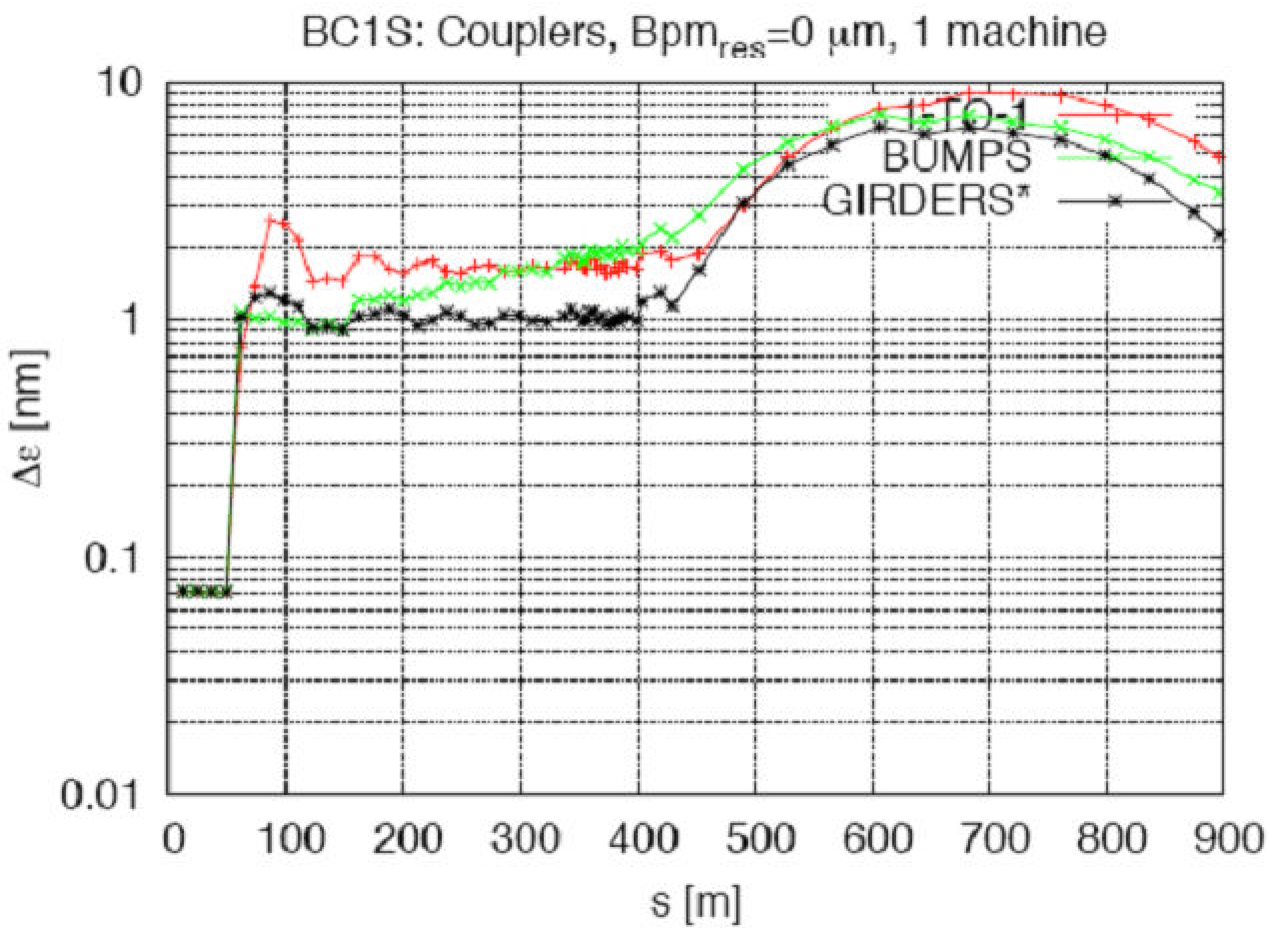
Summary of Studies before MM (LET meeting, Dec.2007 SLAC)

Region	BBA method	Dispersive or chromatic mean emittance growth	Coupling mean emittance growth
Return Line	KM and FF to remove beam jitter	0.15 nm	2 nm (with correction)
Turn around Spin rotator	KM and Skew coupling correction	1.52 nm (mostly chromatic)	0.4 nm (after correction)
Bunch Compressor	KM or DFS and Dispersion bumps	>5 nm (KM+bumps) 2.7 nm (DFS+bumps)	0.6 nm (w/o correction)
Total		~5 nm almost all from BC	3nm (w/o complete correction)

- Effect of coupler RF kick & wakes is not included
- 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)

Emittance Growth due to Couplers in BC1S

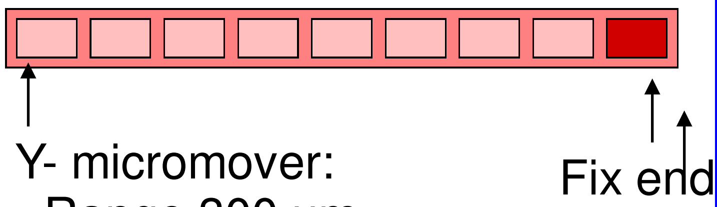
Vertical emittance growth after corrections (no misalignments, BPM resolution 0)



=> Final emittance growth Δε=2.2 nm

New proposal !!!

Girder Pitch optimization



Number of adjustable CM's

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

Summary of BBA Setup in BC1S

- Misaligmments are 300 μx, BPM resolution is 1 μm
- RF-Kick and wakes

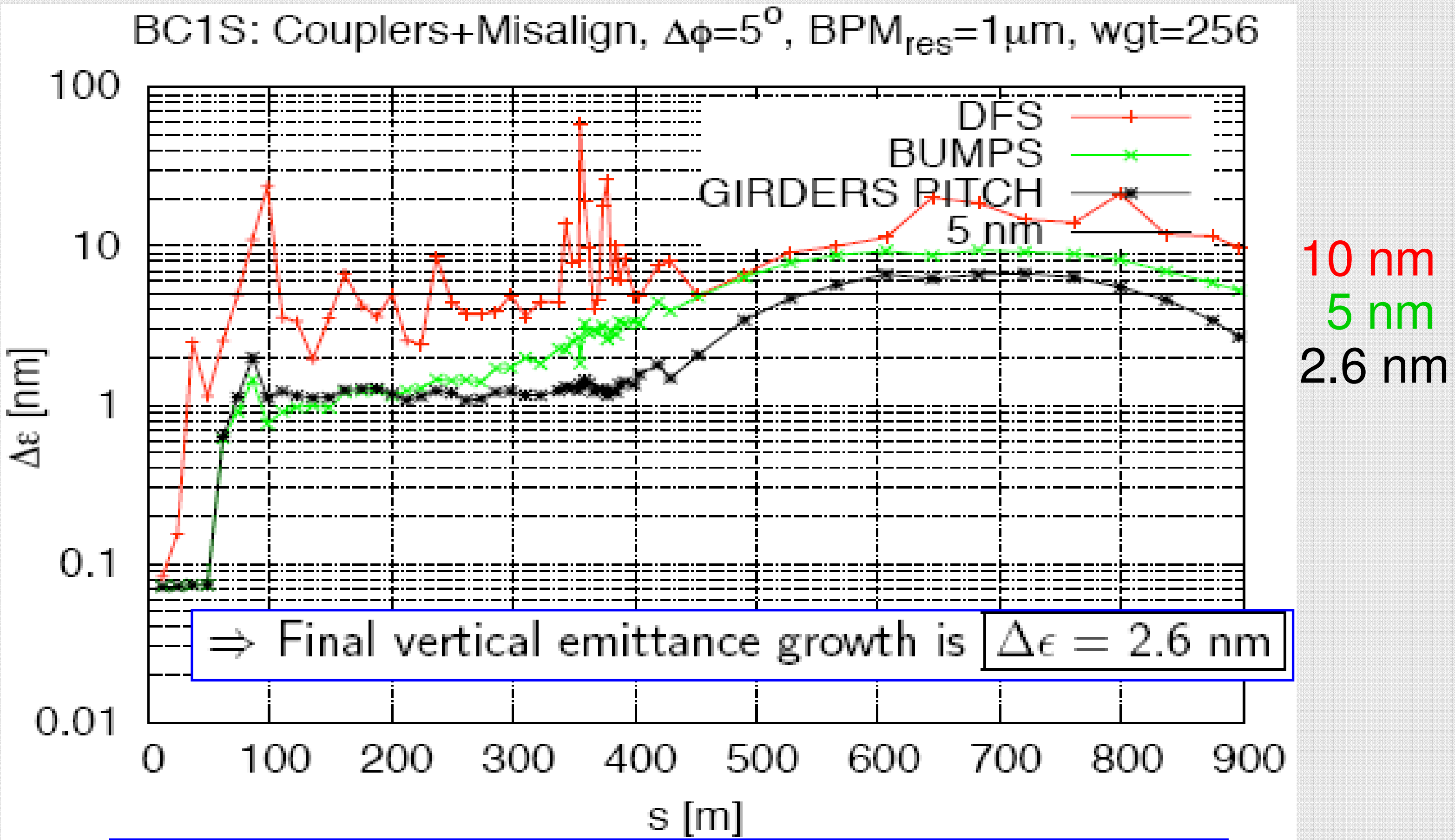
- Dispersion Free Steering
  - two test beams
  - $\Delta\phi = \pm 5^o$ phase offset in the RF section of BC1
  - phase syncronization at entrance of Pre-Linac is necessary

    $\Rightarrow$ otherwise RF-Kicks spoils the test beams, due to their large phase difference (6 σ_z $\approx$ 6 mm)

- Dispersion bumps optimization
  - minimize the final dispersion-corrected emittance by changing the dispersion at entrance

- Girder Pitch optimization
  - using 3 CM in BC1S, 1 every 2
  - using 3 CM in BC1S pre-linac, 1 every 12

Coupler and Misalignments in BC1S



- Emittance Growth along the beamline, 1 machine

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

Emittance Growth in Bunch Compressor

Summary Table of Vertical Emittance Growths

	Technique	Misalignments	Couplers(1)	Misalign+Couplers
BC1S	DFS	14.8 nm	4.8 nm	27.0 nm
	BUMPS	1.47 nm	3.4 nm	4.6 nm
	GIRDER	0.8 (*) nm	2.2 nm	2.6(*) nm

	Technique	Misalignments	Couplers(1)	Misalign+Couplers
BC1+BC2	DFS	91.2 nm	7.7 nm	371.0 nm
	BUMPS	2.1 nm	4.3 nm	6.9 nm
	GIRDER	-	0.8 nm	2.0 nm

(1) 1 machine (*) 40 machines

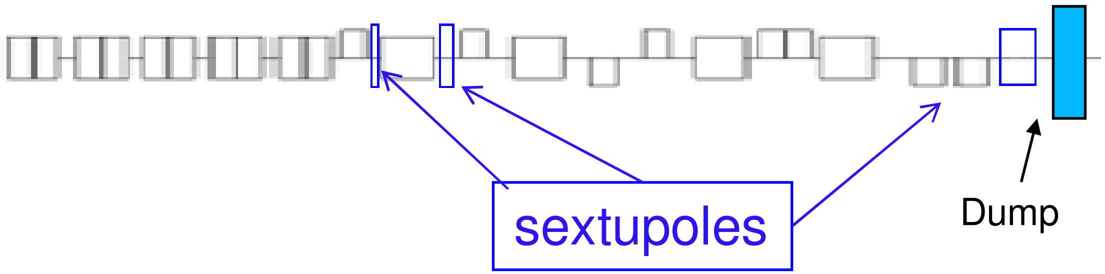
A.Latina, TILC09

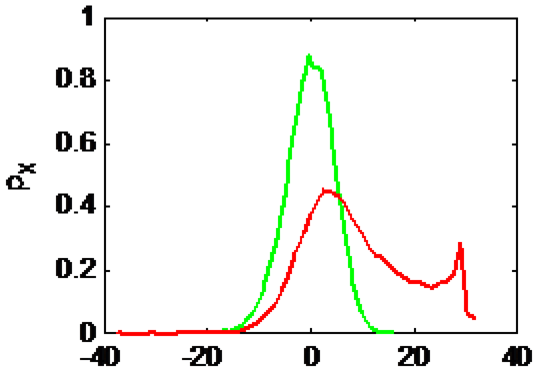
- **Emittance growth due to <u>misalignments and couplers </u>seems to compensated both for BS1S and BC1+BC2**
- **Girder pitch optimization is very effective to counteract coupler kicks, both for BS1S and BC1+BC2**
- **In BC1S, Crab Cavity seems to be similar effective, but it would require a new hardware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

Re-design of the ELBC1

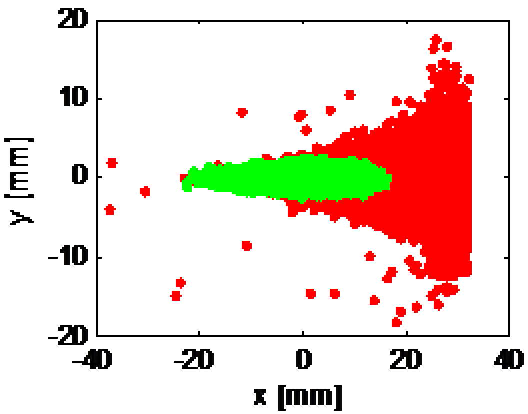
- Motivation: Accommodation of larger energy spread (3.6 % vs. 2.5% in previous design)
  - For the beam with high energy spread, there is a substantial blowup in the beam size from chromaticity and nonlinear dispersion at the end of the beamline.
- Few options were studied (TILC09, S.Seletskiy)
  - No collimation, sextupoles at the beginning/end
  - No collimation, sextupoles at the end
  - Weak collimation and Sextupole
  - Strong collimation with 2 collimators
- Needs more studies with experts to choose final design. Decision for the final design must be taken through cost optimization process.

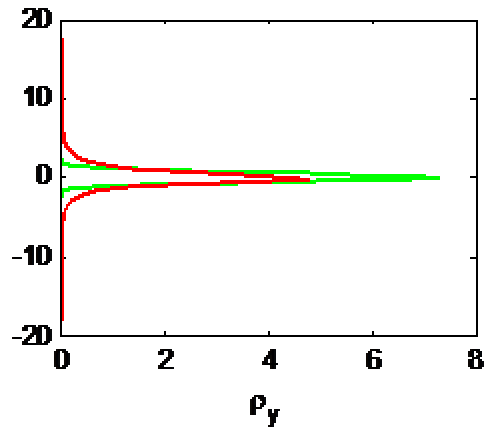
Not Collimated, case I





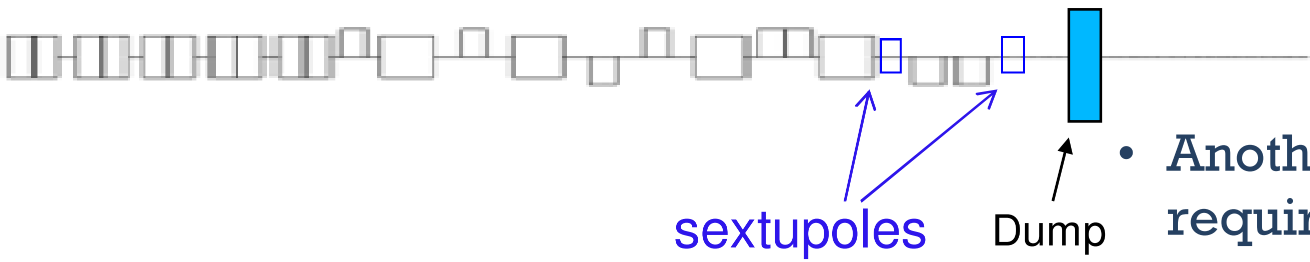
Dump window:
- **0.15% energy spread beam**
- **3.54% energy spread beam**



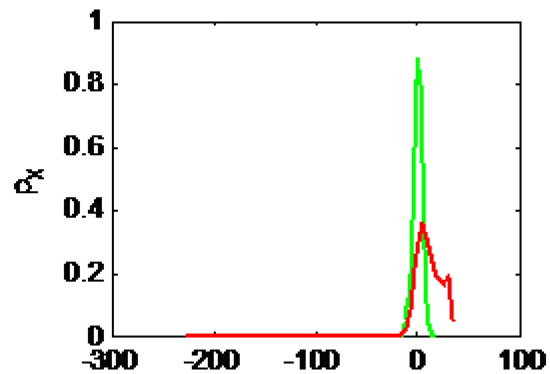


- Solution, which doesn't require any collimation for high δ beam
- Three strong (1T pole tip) sextupoles must be used to counteract the nonlinear dispersion and to fold beam tails.
- A "standard" dump window of 5inch diameter can accommodate the beam.
- The drawback of this solution is that the first sextupole is located in the region where separation between main and extraction beamlines is small, so we may need to build a sextupole of exotic shape.

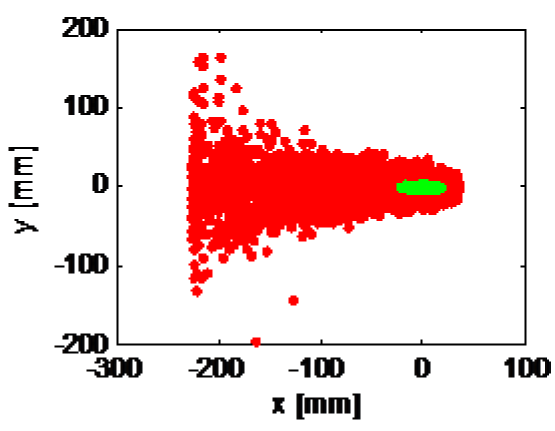
Not Collimated, case II

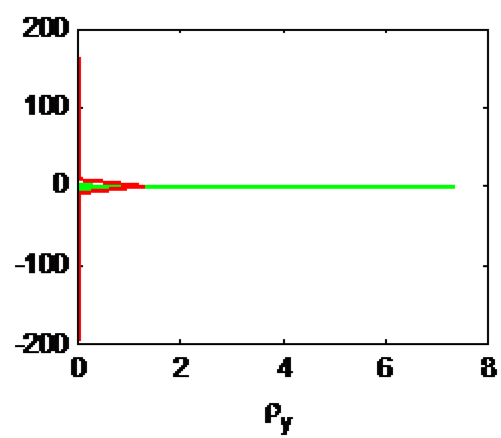


- Another non-collimated solution requires the final doublet quads and two tail-folding sextupoles of 12cm aperture and pole tip field up to 6T.
- The dump window radius must be 60cm in diameter.
- An obvious disadvantage of this scheme in addition to large dump window is SC magnets in the extraction line.

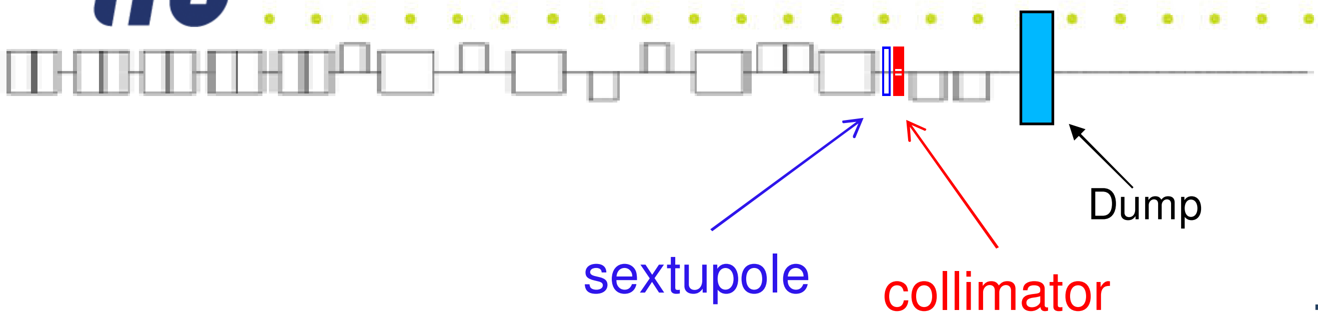


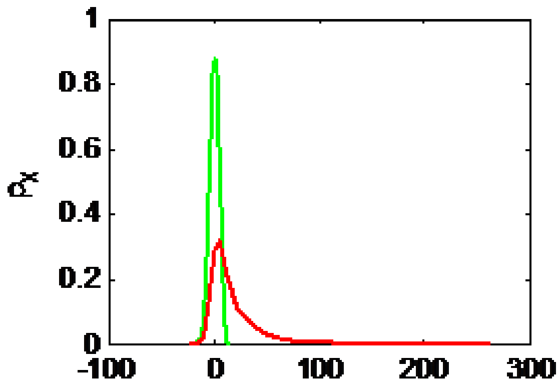
Dump window:
- **0.15% energy spread beam**
- **3.54% energy spread beam**



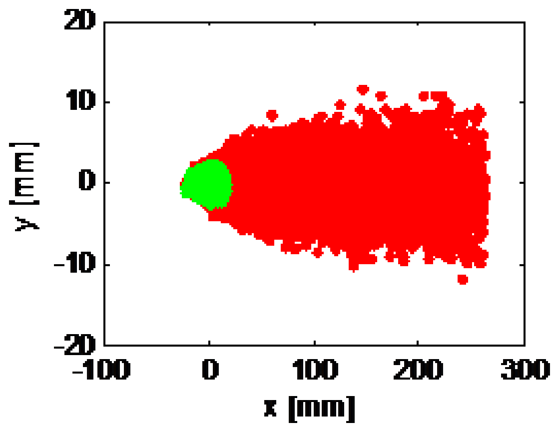


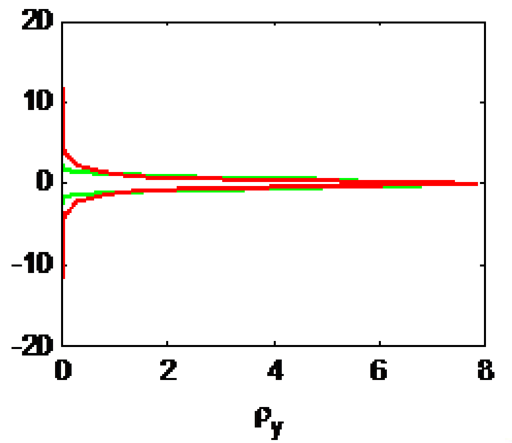
Weak Collimation





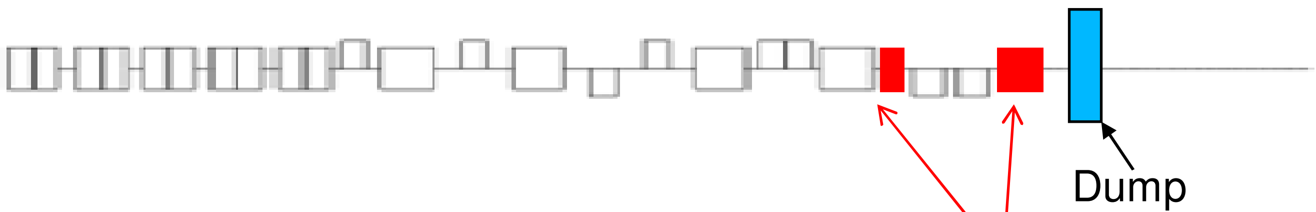
Dump window:
- **0.15% energy spread beam**
- **3.54% energy spread beam**



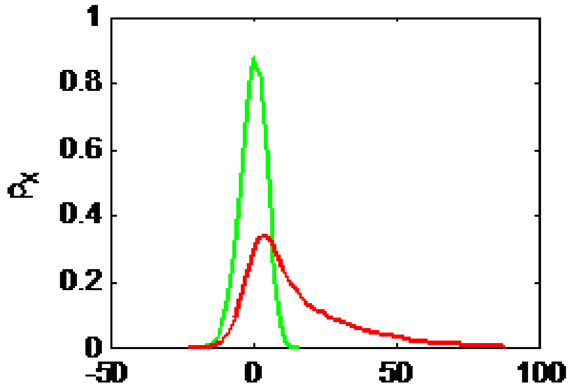


- Weak collimator (1.9kW/train) will be able to protect final doublet. Collimator's horizontal aperture is 7.4mm.
- The dump window radius must be 60cm in diameter.

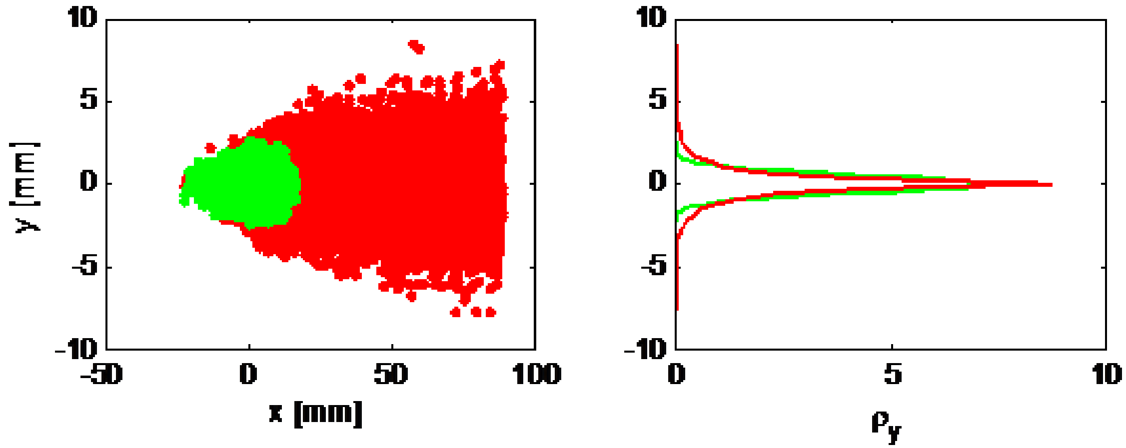
Strong Collimation



- Using two collimators to protect the doublet (2.2kW/train, 7.2mm horizontal aperture) and to collimate the beam on the dump window (11.7kW/train, 5cm horizontal aperture) one can accommodate beam with 20cm diameter dump window.



Dump window:
- **0.15% energy spread beam**
- **3.54% energy spread beam**



Collimation summary

	No collimation	No collimation SC magnets	1 collimator (weak collimation)	2 collimators (strong collimation)
Collimators			1.9kW/train; 7.4mm horizontal aperture;	2.2kW/train; 7.2mm horizontal aperture;
				11.7kW/train; 5cm horizontal aperture;
Sextupoles	1T pole tip field; exotic shape	Two sextupoles with 12cm aperture and pole tip filed <6T	1T pole tip field	
	Two <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

Plan FY09 (to do list)

Improvement of BC1S design:

- Replace the current Wiggler with the advanced design (similar to baseline)
  - equivalent cell length (24 meters) but more elements,
  - allows more flexibility: (skew quadrupoles, coupling correction, …)
- Replace the crymodules with new design

- Emittance preservation studies, incl. optimization of parameters and dynamic effects

- Estimations of incremental Cost of BC1S and BC1S

- Choice of the design for ELBC1 extraction line

Pros and Cons compared RDR

- Pros:
  - **Simpler and cheaper design:**
    - Less RF, less diagnostics, less magnets
    - Shorter tunnel
    - Reduction of number of extraction lines and beam dumps (>1/3)
  - **Emittance growth is comparable with RDR design**

Cons:

- **Low power beam option with shorter bunch is not supported in single stage BC**
- **Less flexibility**
- **Larger energy spread is more risky for tuning and emittance control**
- **Require designing of movers for cryomodule to compensate Coupler kick and cavity tilts**

Estimated Cost impact

- CFS: reduction of tunnels:
  - **210 m of regular tunnel**
  - **No service tunnel**
  - **No alcoves for 2 extraction lines and dumps (radiation area)**
  - **Possible more saving in tunnel in central area**
- Cost reduction due to reduction of hardware components (~30-40 M$)
  - **12 CMs**
  - **8 klystrons/modulator/PDS**
  - **2 extraction lines with 2 beam dumps**
  - **Magnets, fast kickers, septums, PS**
  - **Diagnostics: LOLA cavities, BPMs, etc..**
  - **Vacuum components**

Risks and Concerns

- Risk is comparable with risk for RDR baseline design, if not assume regime with higher bunch compression.

- Extraction line more complicated, moderate risk.

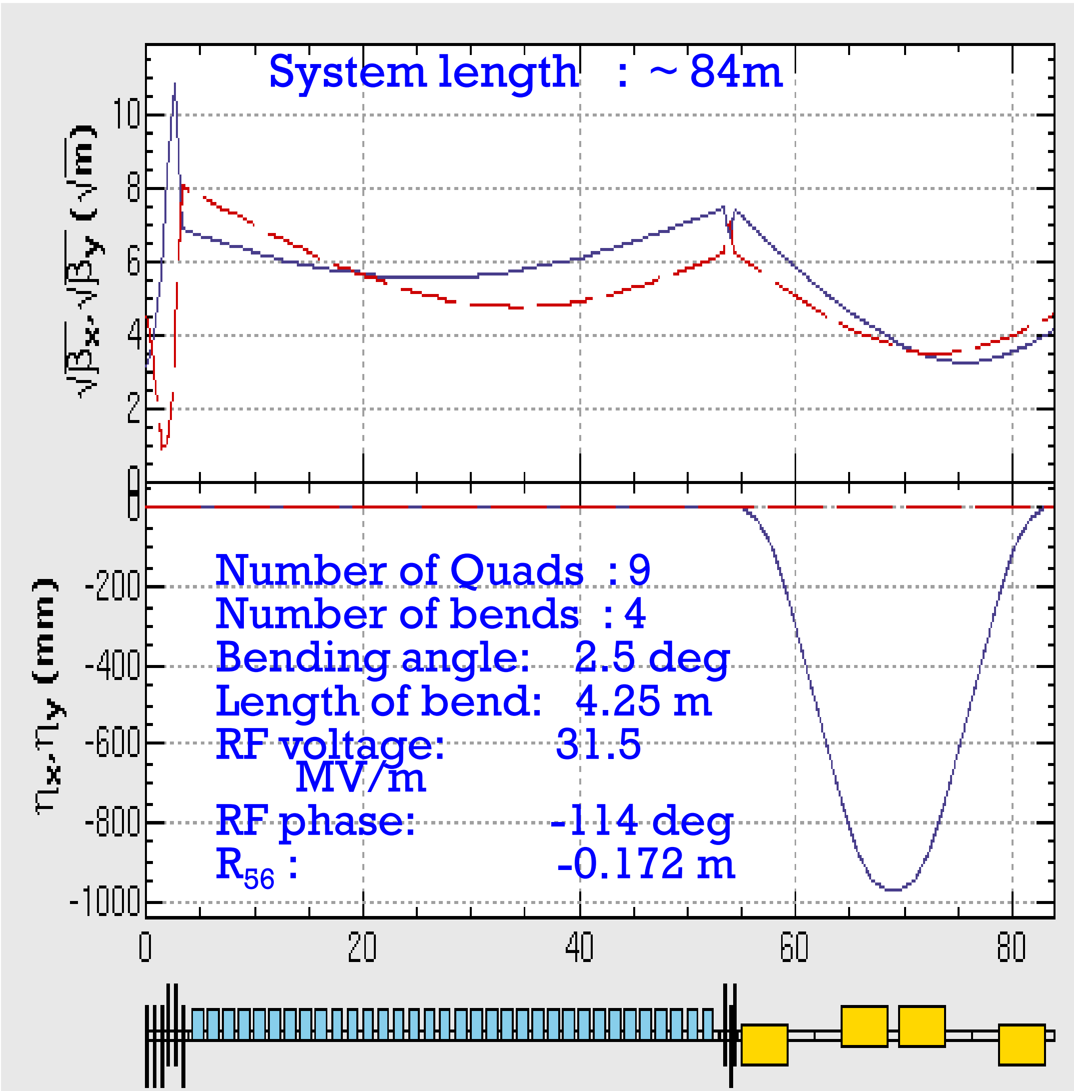
RTML in Central Area

- New configuration of the Central Area and DR design will require some changes in RTML design
  - **Need to complete configuration ASAP. It will be basis for RTML lattice design work and cost estimation**
    - Expected incremental cost due to this changes will be small
    - Biggest impact on CFS (tunnel)

Summary

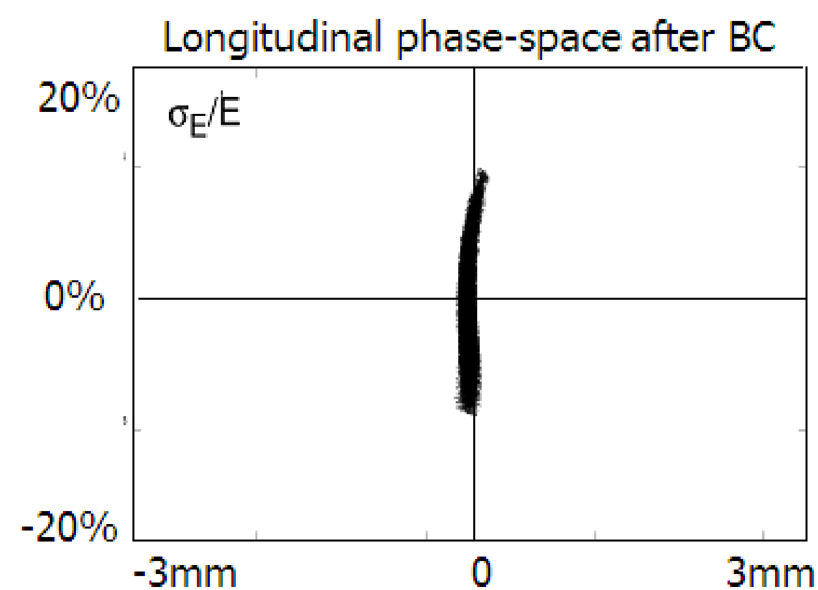
- Single stage Lattice is designed and studied. Design looks feasible.
- Emittance growth in bunch compressor can be effectively controlled, by using movers to adjust tilt of the cryomodules. (only few CM's with this features are needed). R&D is required.
- Extraction line is redesigned to accommodate bunch with a larger energy spread after BC. Few possibilities are studied. Need additional R&D to pick-up the best scheme.

Alternative Short Single-stage BC



	Initial	Final
Beam energy, GeV	5	4.57
Bunch length, mm	6	0.3
energy spread, %	0.15	3.46
X-Emittance, um	8.00	8.28
Y-Emittance, um	0.02	0.02*

* Kick from cavity tilts and coupler not included



(E-S Kim, LCWS09,Chicago)

Requires emittance preservation studies!!!