RTML Design and Rational for ILC

Nikolay Solyak

Fermilab

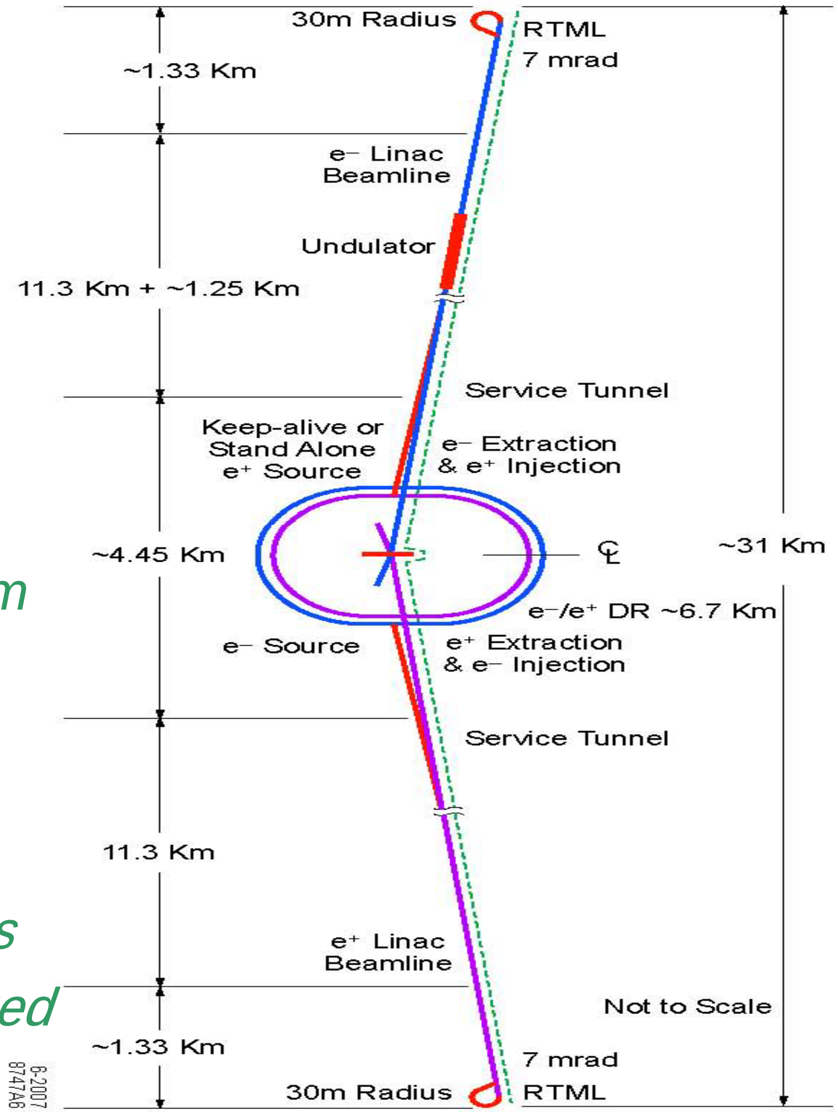
CLIC 08 workshop, CERN, Oct. 14-17, 2008

Outline

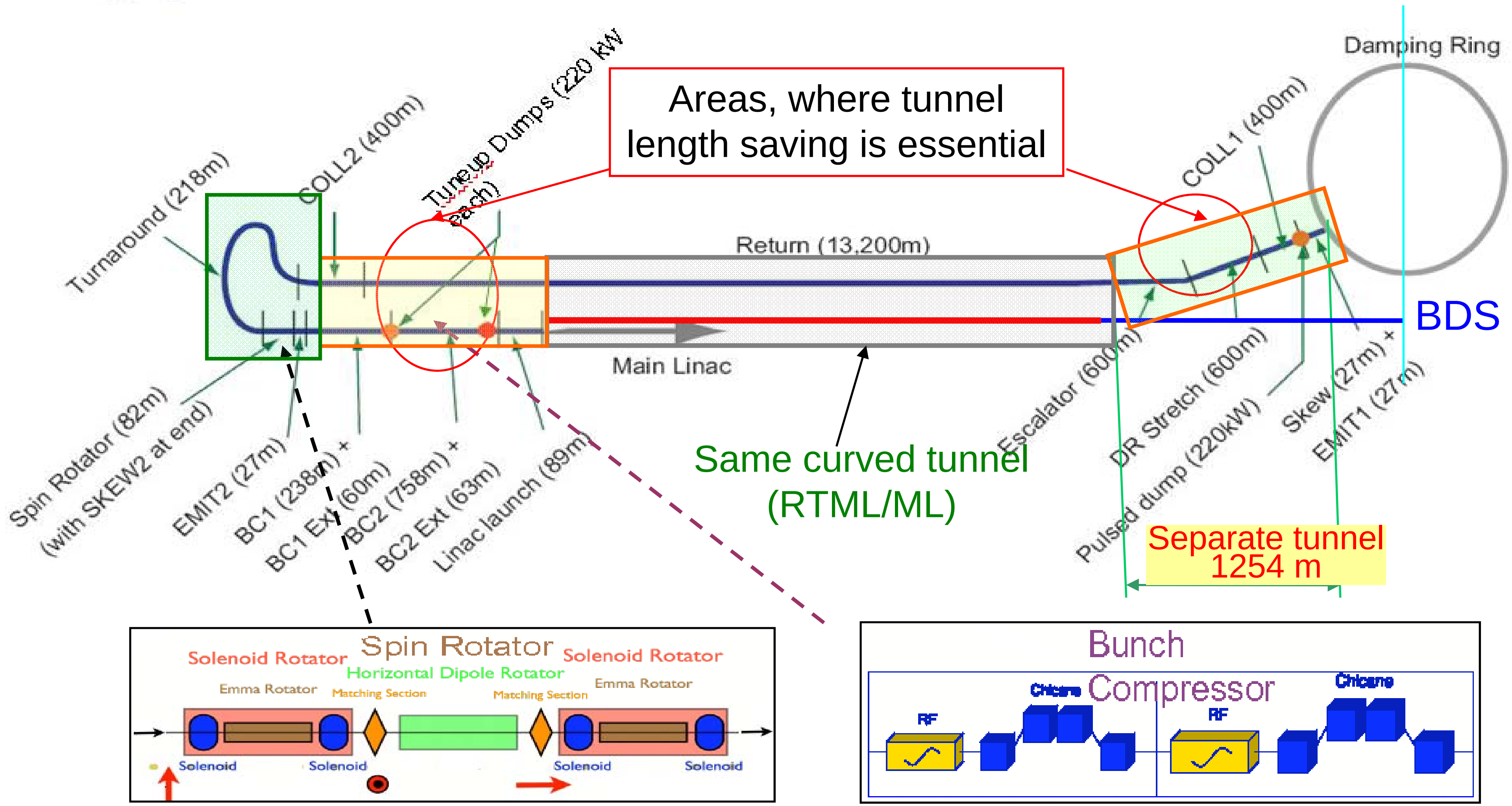
- RTML Optic Design (RDR)
- Technical Systems
- Emittance control
- Post-RDR changes

RTML Functions

- *Transport Beam* from DR to ML
  - *Match Geometry/Optics*
- *Collimate Halo*
- *Rotate Spin*
- *Compress Bunch (6mm→0.3mm)*
- *Preserve Emittance*
  - *- Budget for Vert.norm. emittance < 4nm*
- *Protect Machine*
  - *3 Tune-up / MPS abort dumps*
- *Additional constraints:*
  - *Share the tunnel with e-/e+ injectors*
  - *Need to keep geometries synchronized*



RTML Schematic (RDR)

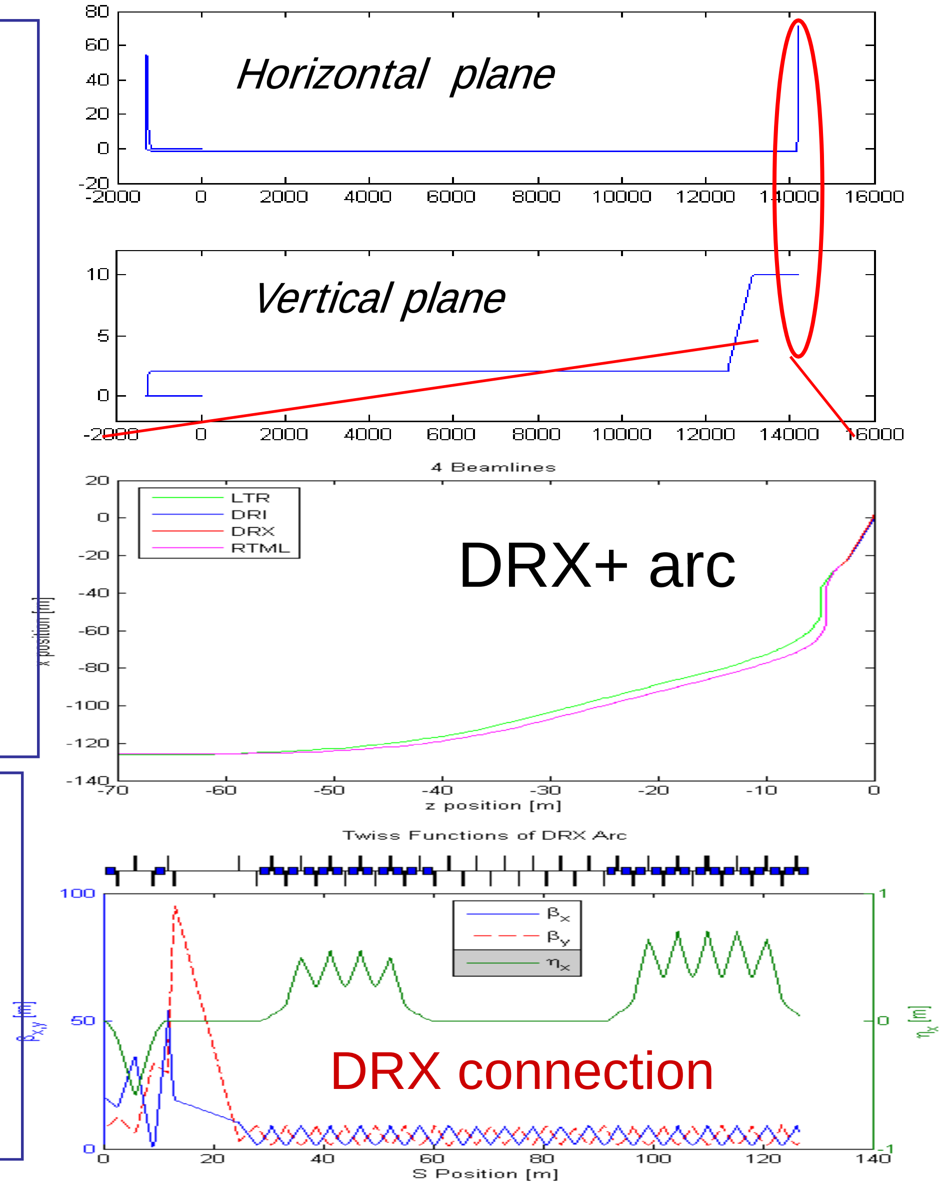


Note: e- and e+ RTMLs have minor differences in Return line (undulator in e- linac side) and Escalator (DR's at different elevations); they are otherwise identical.

Optics Design (RDR)

- Horizontal Arc out of DR ~km straight
  - **In injector tunnel**
- "Escalator" ~0.6 km vertical dogleg down to linac tunnel
- Return line, weak FODO lattice
  - **In linac tunnel**
  - **Vertically curved**
- Vertical and horizontal doglegs
- Turnaround
- 8° arc in spin rotators
- BCs are net straight

DR-RTML hand-off point defined
extraction point where η,η' → 0
RTML mostly defined by need to follow LTR geometry
Stay in same tunnel
Design is OK at *conceptual* level

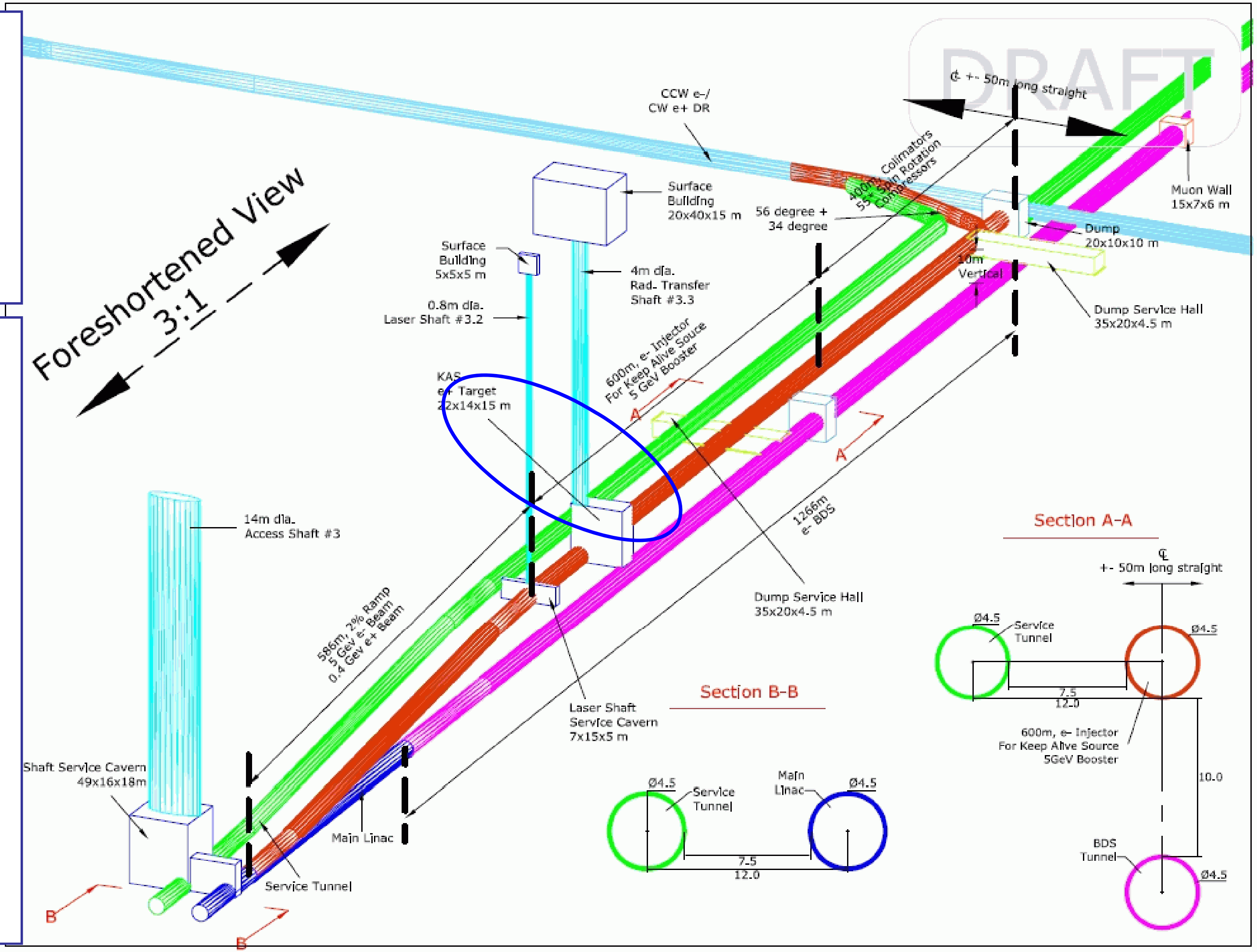


DR connection (RDR)

- Both sides need 5GeV SC linacs (e^+/e^- sources);
- e^+ side also needs KAS and e^+ transfer line from undulator

Post RDR modifications

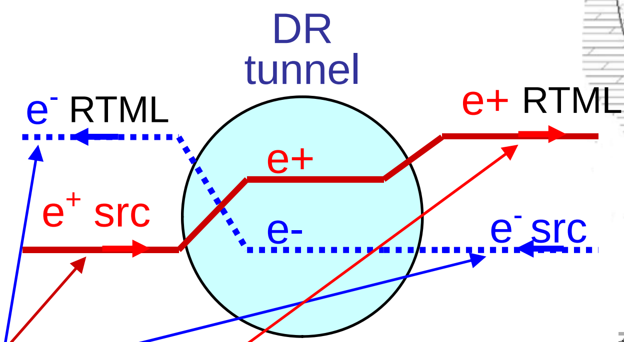
- No elevation for the service tunnel
- ML and RTML tunnels merge in horizontal plane
- New DR design
- Shorter tunnel shared with KAS ?

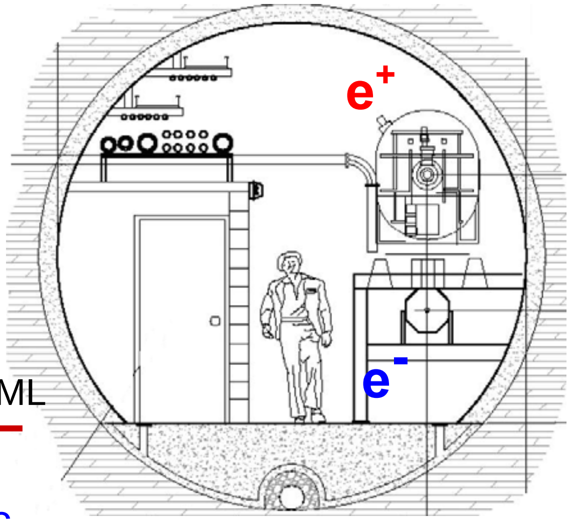


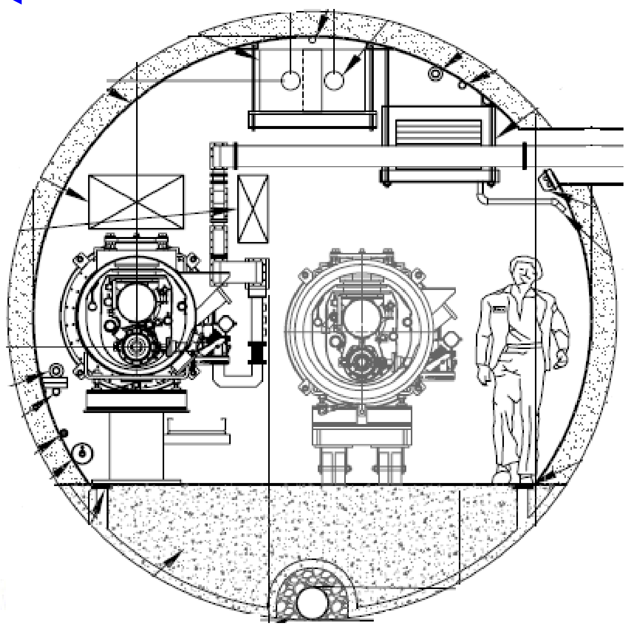
DRX Connection (2)

- Current design is entirely planar (horizontal plane)
- DRs are in different planes
- Sources need cryomodules and SC solenoids
  - **Big heavy objects which want to sit on the floor**
- Working agreement between sources, DR, RTML, CFS:
  - CMs and SC solenoids always sit on floor
  - RTML hangs from source tunnel ceiling at same location as in linac tunnel

DR Tunnel – 1.44 m
Vertical separation



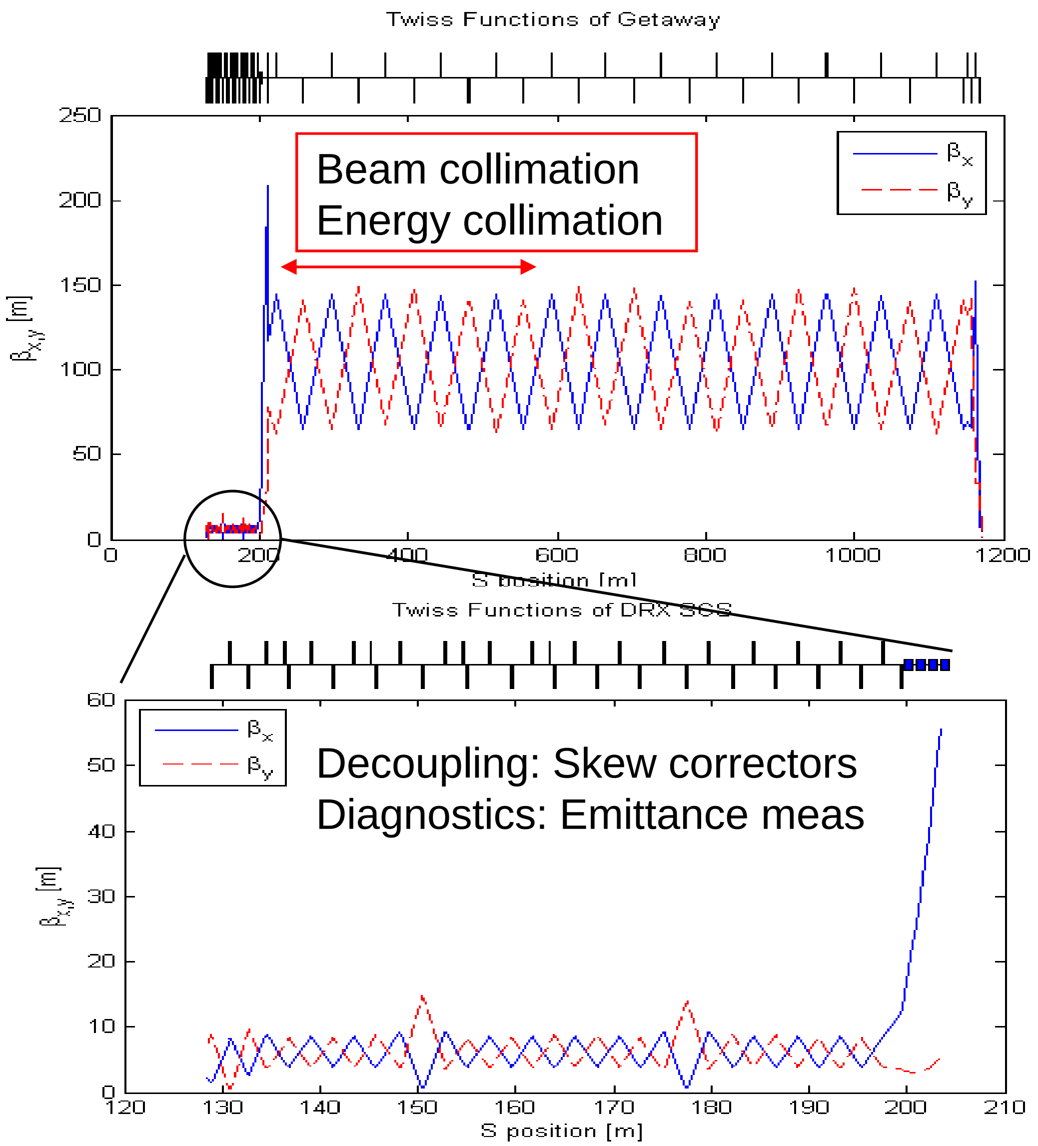




ML Tunnel - 2.14 m
Vert. beam separation

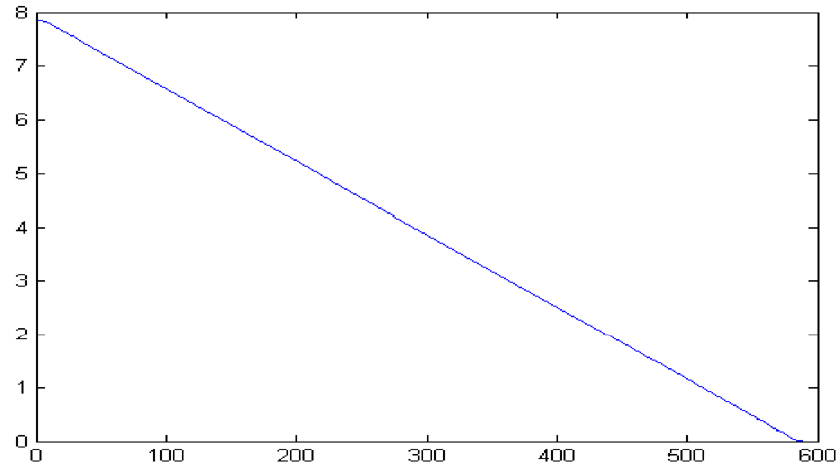
"Getaway" Straight (or "DR Stretch")

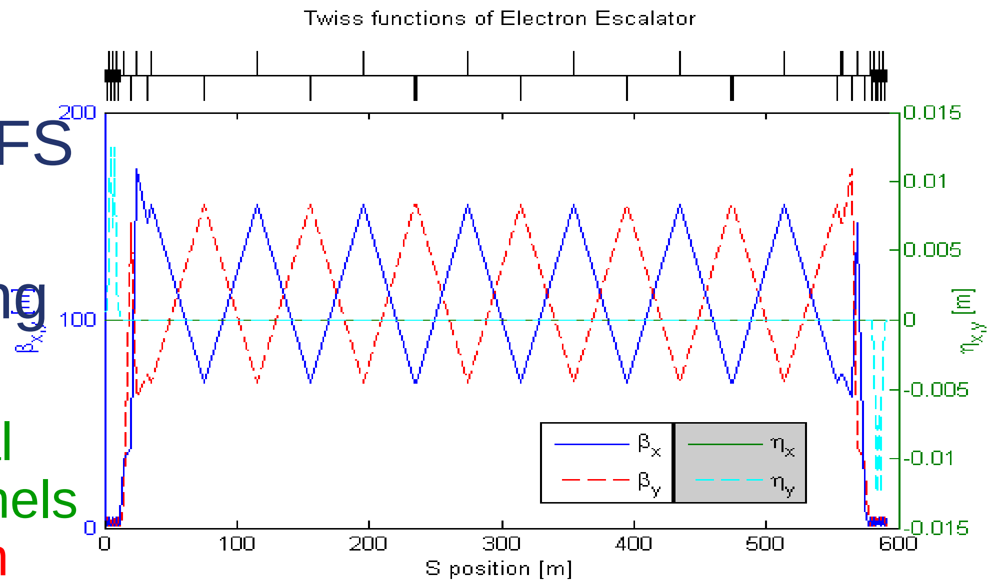
- About 1.1 km long
- Has two parts
  - **"Low-beta" region with decoupling and emittance measurement**
  - **"High-beta" region with collimation system**
- Includes PPS stoppers
  - **For segmentation**
- Good conceptual design
  - **Need to match exact required system lengths**
  - **Beta match between low- and high-beta optics not great**
- Length of "Getaway'' can be minimized to ~ 500m



Escalator

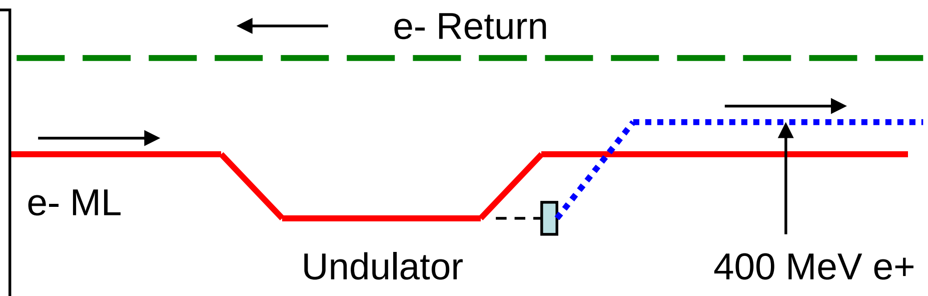
- Vertical dogleg
  - –Descends 7.85 meters over ~590 m
  - – Uses 2 vertical arcs separated by weak FODO lattice
- Good conceptual design
  - – Uses Keil-style eta matching
  - – Beta match between "strong" and "weak" lattices not great
- Escalator-linac tunnel connection does not match CFS design
- Need to make match according CFS design
  - – Shorter length for smaller vertical separation of the DR and ML tunnels and larger slope, min ~200-300 m

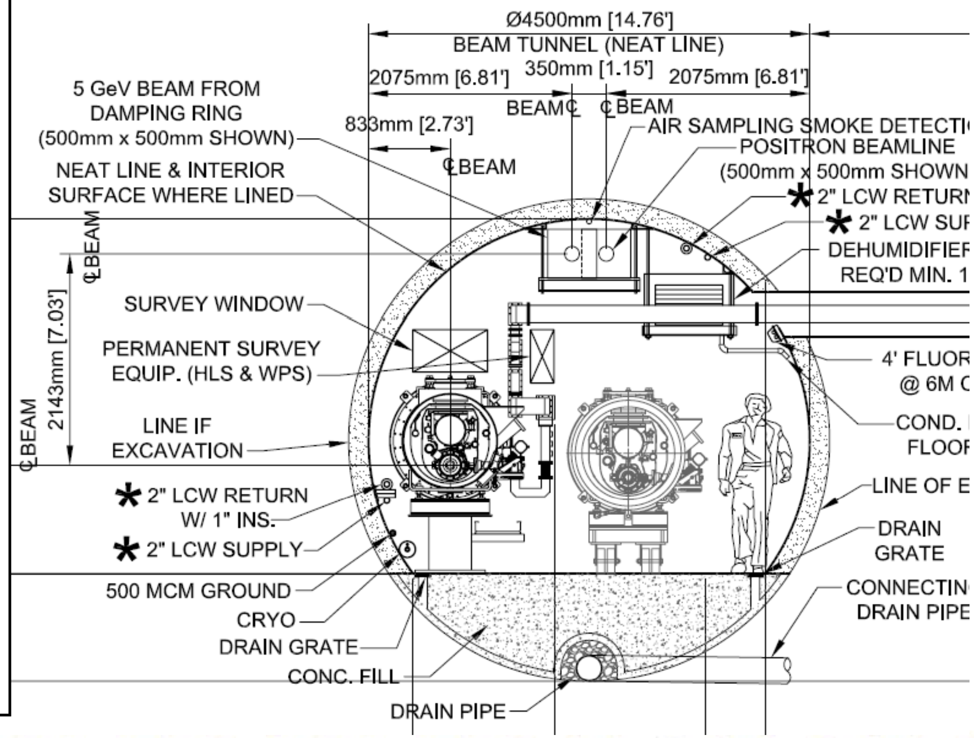




Return Line

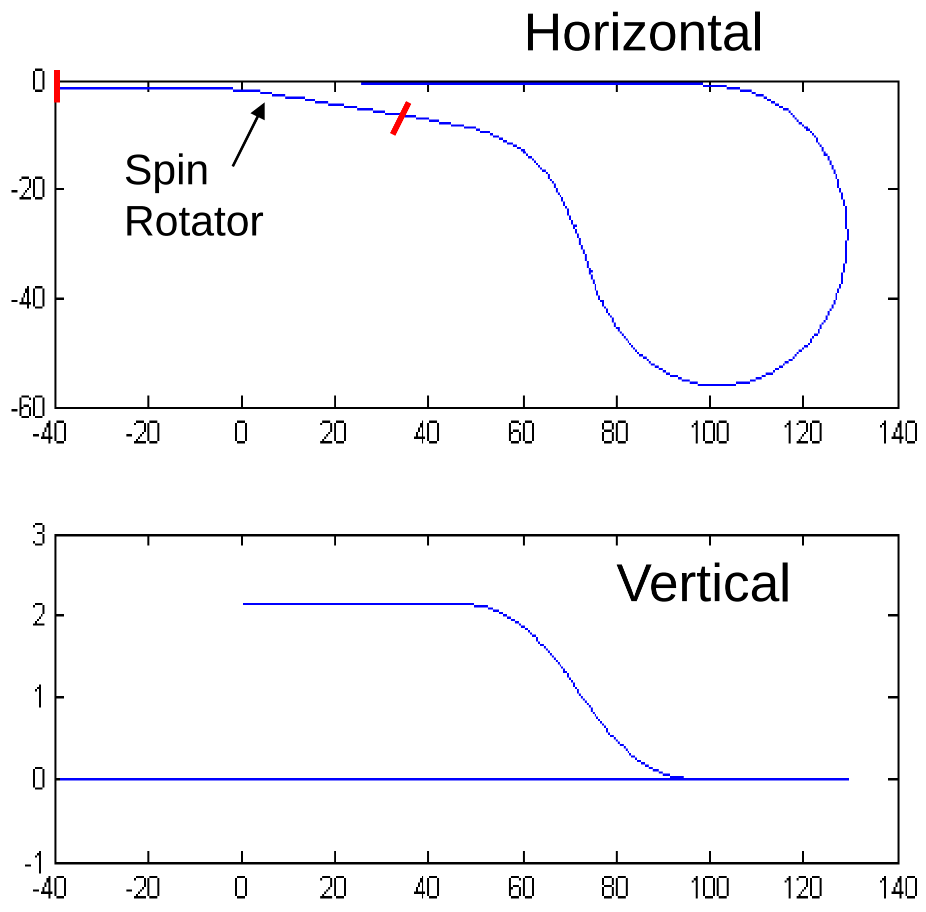
- Weak FODO lattice at ML ceiling elevation (1Q/~36m), XY_{corr}+BPM
- Vertically curved tunnel thru ML area
  - **Dispersion matching via dipole correctors**
- Laser-straight tunnel thru BC area
- Electron line ~1.2 km longer than positron
  - **Goes thru undulator area**
- Electron Return line and positron transfer line need to be exchanged





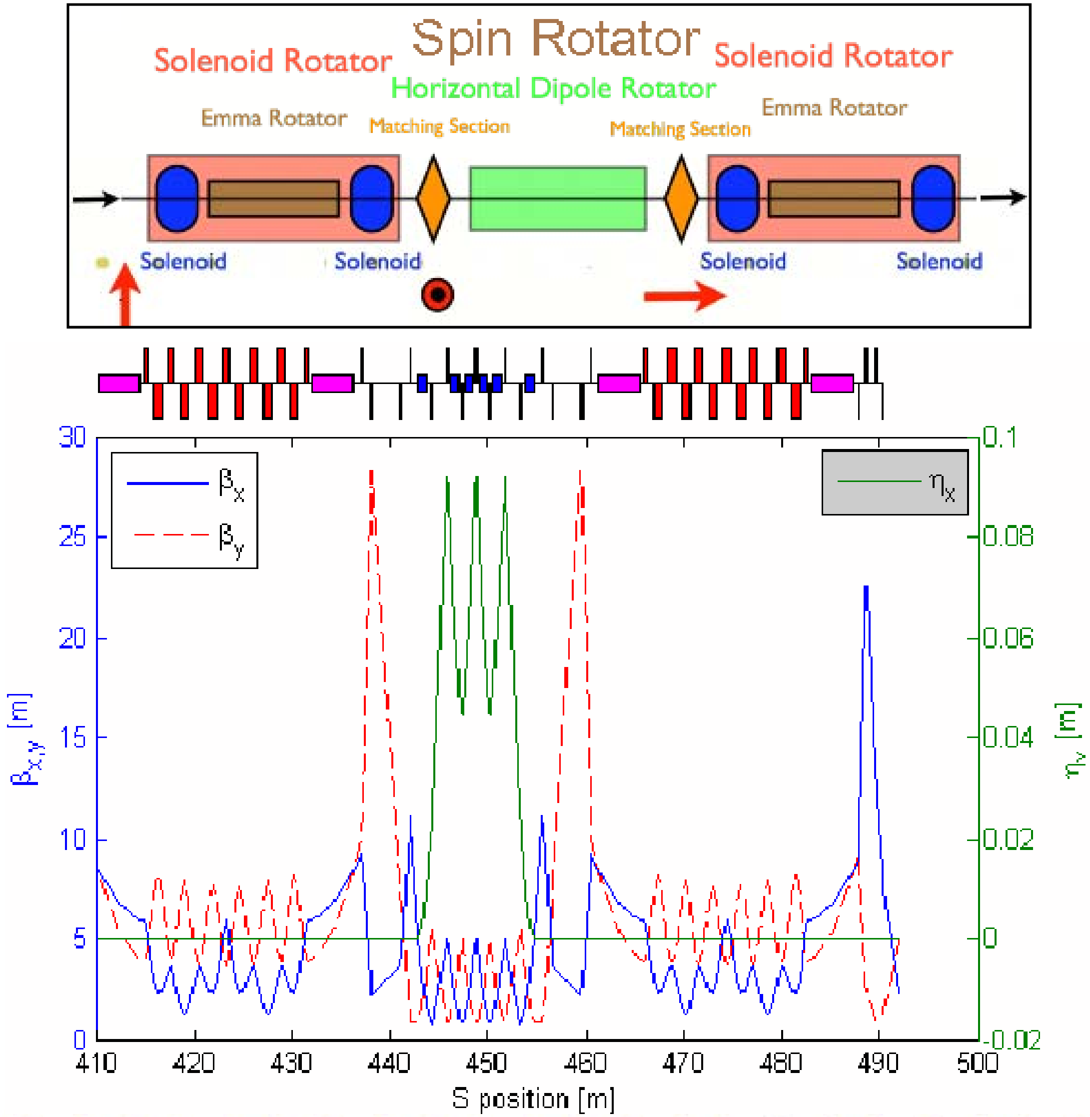
Turnaround (D & B)

- Actually does 3 jobs
  - **Turns the beam around**
    - Note: need to bend *away* from service tunnel
  - **Brings beam down from ceiling to linac elevation (near floor)**
    - Vertical dogleg
  - **Adjusts x position to meet linac line**
    - Horizontal dogleg
- Order: H dogleg, V dogleg, turnaround
- Risk - high packing area ~90% magnets. Tunnel length is already min.



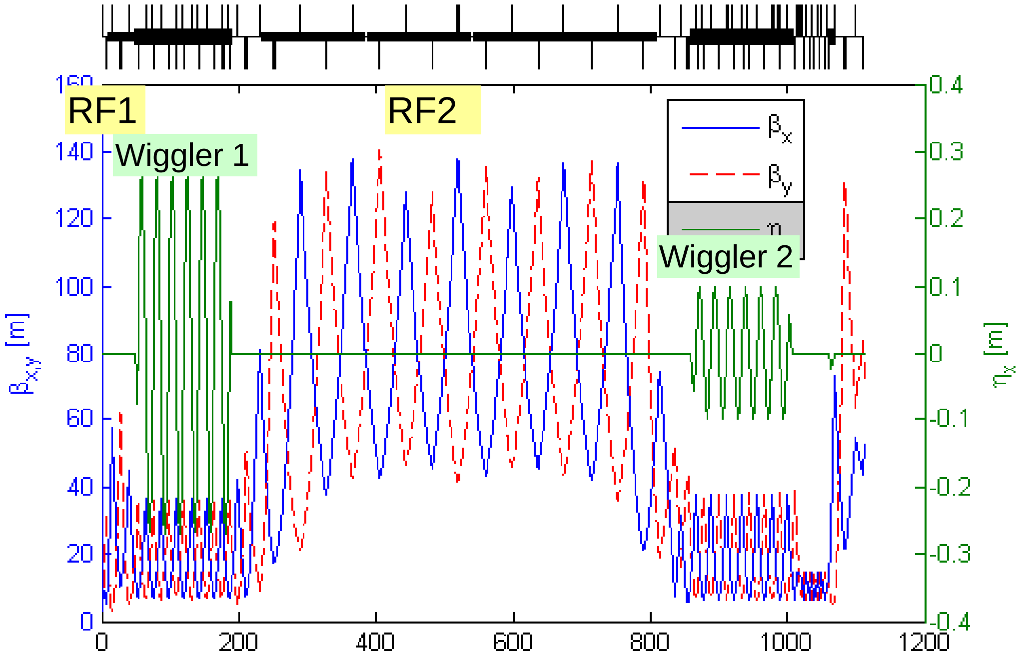
Spin Rotation

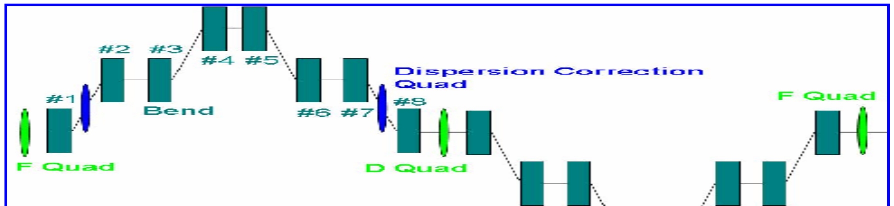
- **Design based on Emma's from *NLC ZDR. Arbitrary spin orientation in IP***
  - **2 solenoids with Emma rotator between them**
    - Rotate spin 90° in xy plane while cancelling coupling
  - **8° arc**
    - Rotate spin 90° in xz plane
  - **Another 2 solenoids + Emma rotator**
- Basic design seems sound
  - **Very small loss in polarization from vertical bending in linac tunnel**



ILC Baseline 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 qua 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





One wiggler cell

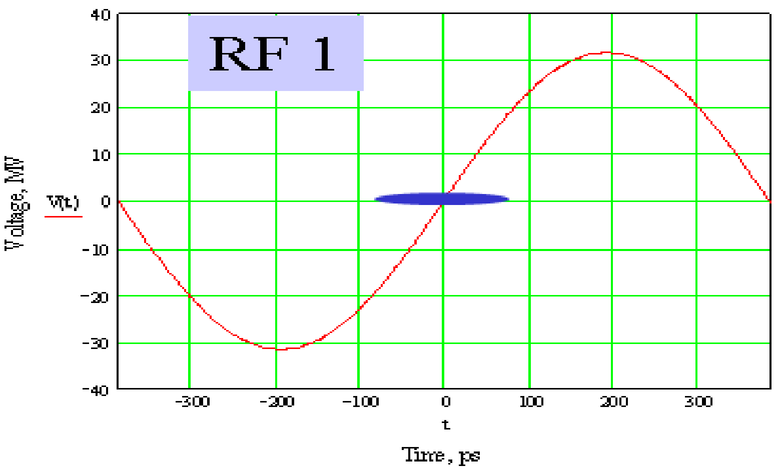
RF system
- BC1: 3 CMs with quads (+spare kly)
- BC2: 14 RFunits (3CM's each)+1spare
- Total 48 CM's per side

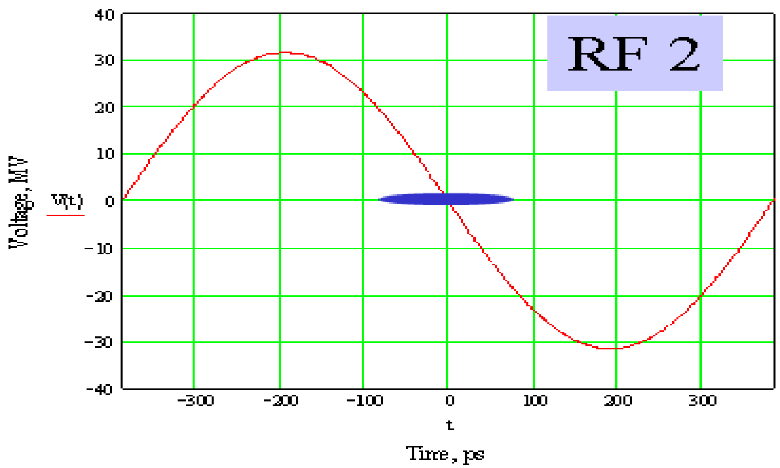
BC: Phase and amplitude stability

The required tolerances for amplitude and phase stability in BC are very tough:

- Phase stability tolerance: 0.25°/0.16° – long/short bunch
- Amplitude stability tolerance: 0.5%/0.35% rms – long/short bunch

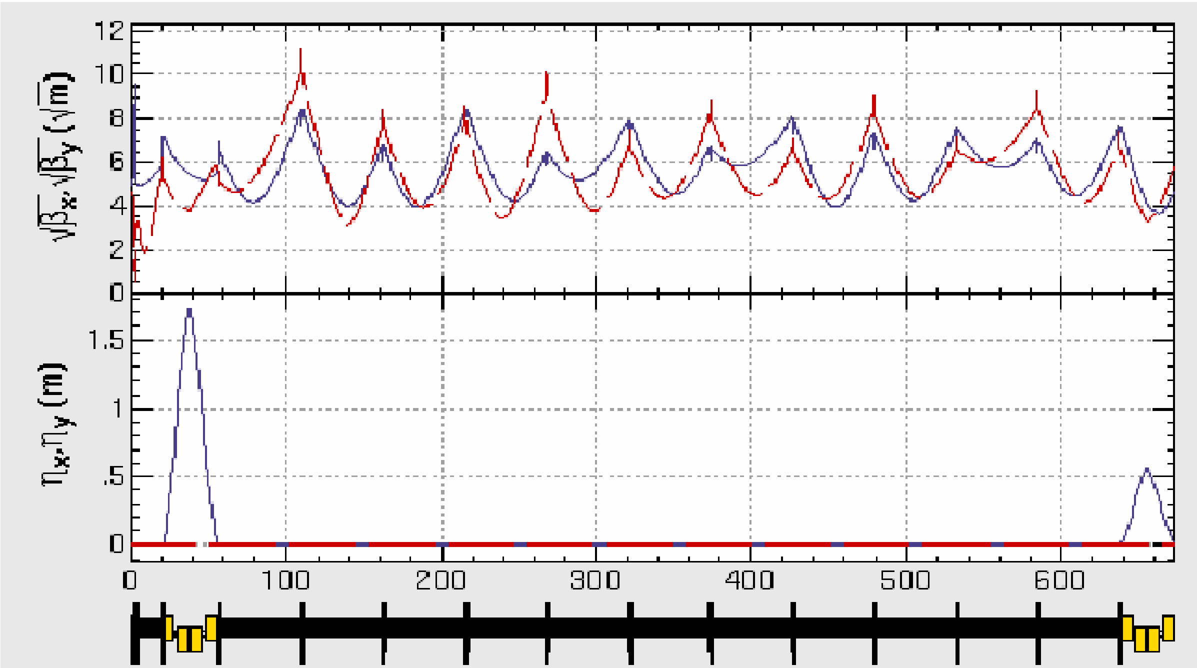
- Bunch compressor RF cavities operate close to zero-crossing:
  - Phase 105° off-crest (BC1)
  - Phase 27.6° off-crest (BC2)
- The gradient in the RF system ~30 MeV/m. Zero crossing regime – complication for LLRF system.
- Study of the phase and amplitude stability of the RF system @ FLASH (2009).





Alternative Bunch Compressor

- An alternate bunch compressor design exists (~700m)
  - ***6-cell wigglers (~150 m each, 102 bend magnets) replaced by chicanes (~40 m each, 4 bend magnets)***
  - ***Advantages:*** *Shorter, Simpler, Cheaper (less magnets)*
  - **Disadvantages:** *Big x offset from straight line (~1.8 m)*
    - » *Doesn't have natural locations for dispersion tuning quads*
  - ***Length Saving: ~ (200 ÷ 300 m)***

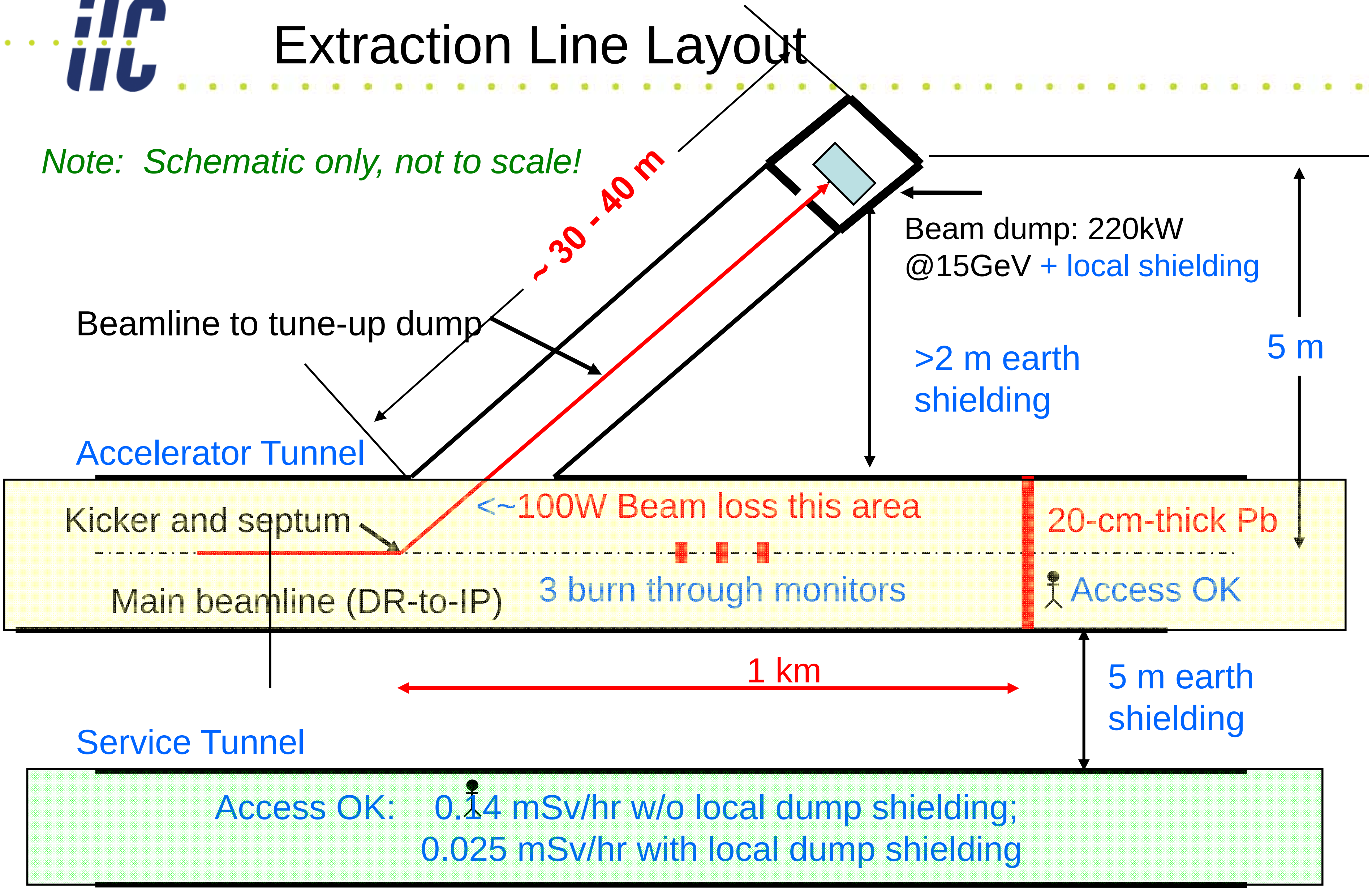


Initial Energy Spread [%]	0.15
Initial Bunch Length [mm]	6.0
Initial Emittance [µm]	8 / 0.02
BC1 Voltage [MV]	348
BC1 Phase [°]	-114
BC1 R_{56} [mm]	-474.2
End BC1 Bunch Length [mm]	1.1
End BC1 Energy [GeV]	4.86
End BC1 Energy Spread [%]	1.1
BC2 Voltage [MV]	11,800
BC2 Phase [°]	-45
BC2 R_{56} [mm]	-50.8
End BC2 Bunch Length [mm]	0.15
End BC2 Emittance [µm]	8.3 / 0.02
End BC2 Energy [GeV]	13.26
End BC2 Energy Spread [%]	2.2

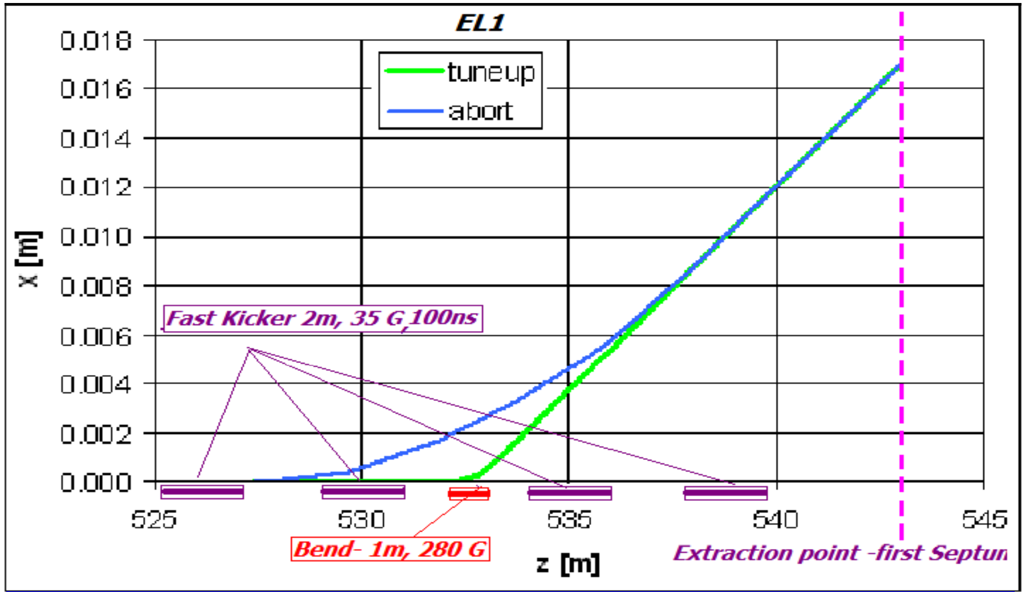
Pulsed Extraction Lines

- 3 Extraction Lines in each RTML side for emergency beam abort (MPS) and tune-up
  - **EL1 - after DR exit, diagnostics, global correction**
  - **5 GeV, $\sigma_E = 0.15\%$**
    - Keep DRs running @ full power during access
    - Keep DRs and extraction tuned during access
    - MPS abort (~100ns)
  - **ELBC1 - after BC1**
  - **5 or 4.88 GeV, $\sigma_E = 0.15\%$ and 2.5%**
    - Tune up BC1 without beam in BC2
    - MPS abort
  - **ELBC2 - after BC2**
  - **15 GeV, $\sigma_E = 0.15\%$ and 1.8%**
    - Tune up BC2 without beam in linac
    - MPS abort
- All have 220 kW beam handling power
  - **Full power for DRX, BC1**
  - **1/3 power for BC2**

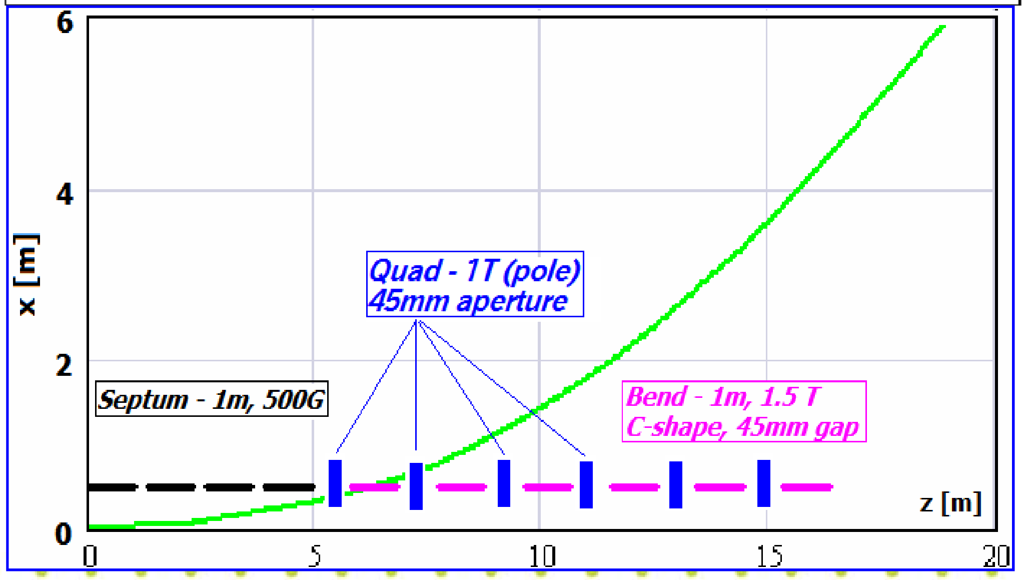
Extraction Line Layout



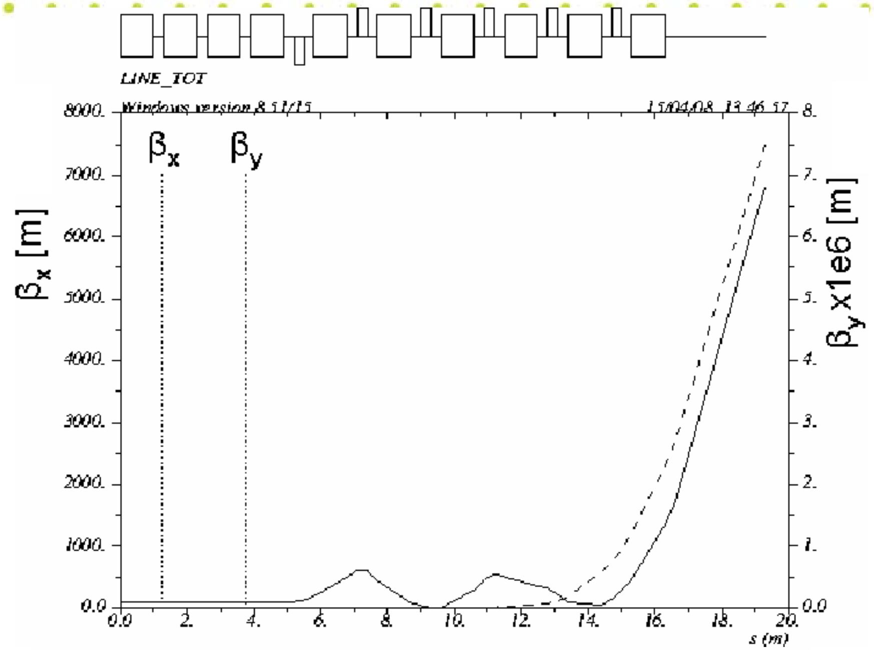
EL1 design



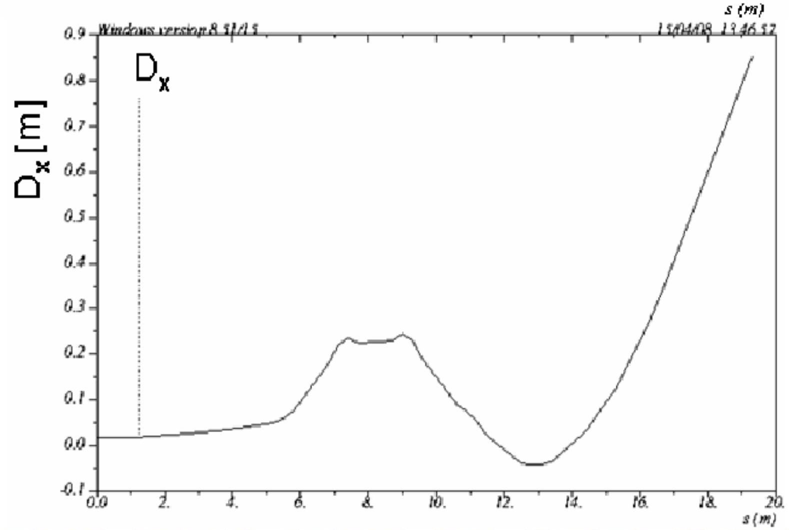
EL1
tuneup
abort
x [m]
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
525
530
535
540
545
z [m]
Fast Kicker 2m, 35 G,100ns
Bend- 1m, 280 G
Extraction point -first Septum



x [m]
6
4
2
0
0
5
10
15
20
z [m]
Quad - 1T (pole)
45mm aperture
Septum - 1m, 500G
Bend - 1m, 1.5 T
C-shape, 45mm gap



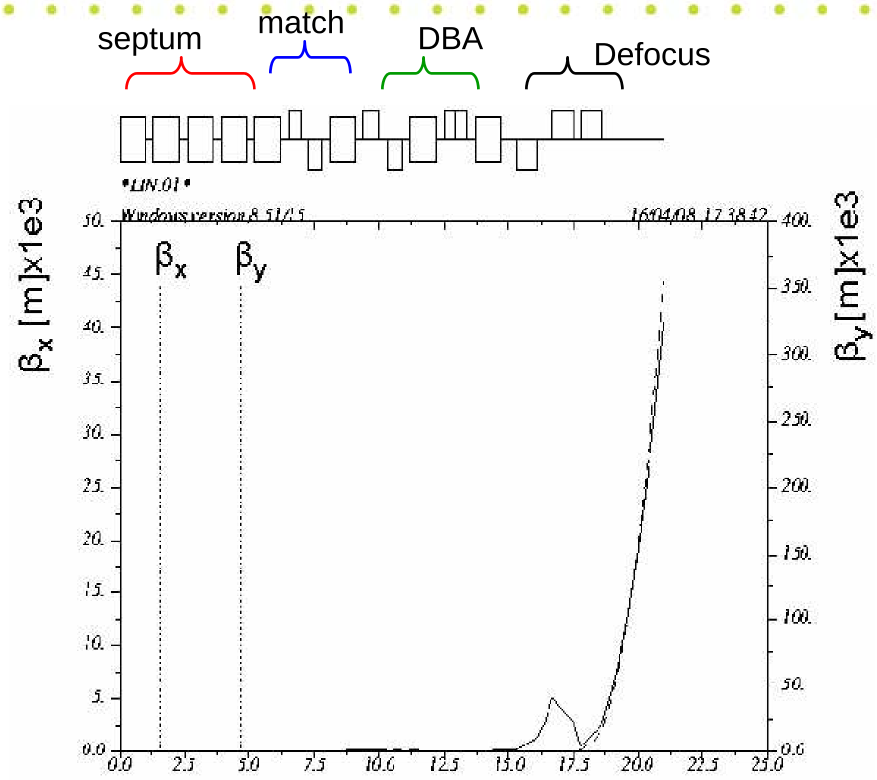
LINE_TOT
Windows version 8.51/15
15/04/08 13.46.57
β_x
β_y
β_x [m]
β_y x1e6 [m]
s (m)

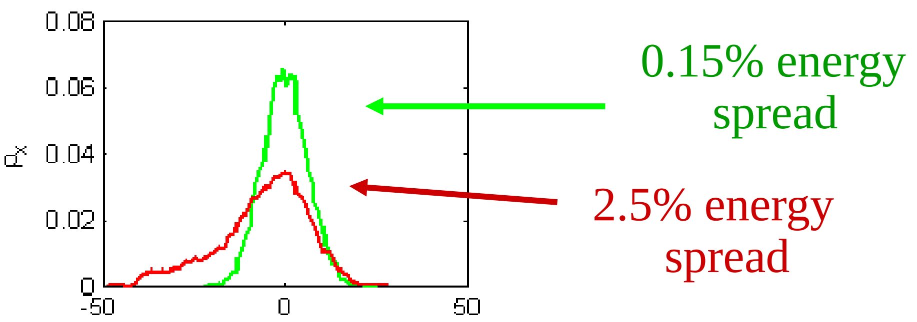


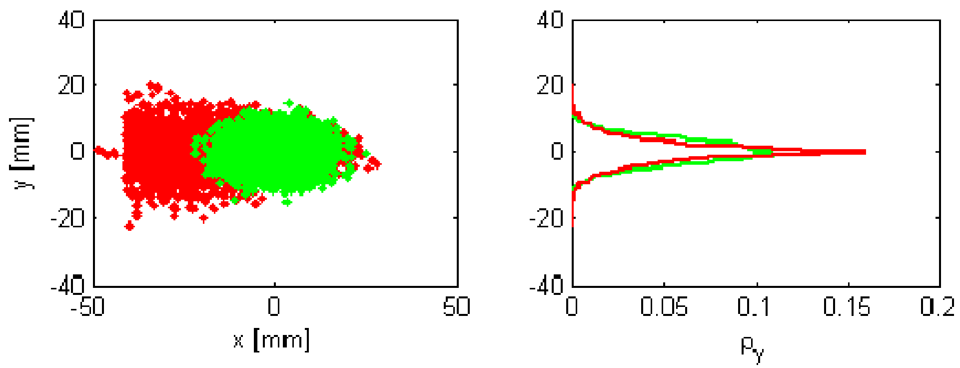
Windows version 8.51/15
15/04/08 13.46.57
D_x
D_x [m]
s (m)

ELBC1 Line Design

- Separation of the two lines at CM location (14m down) - 2m;
- Separation of the dump and the ML ~5 m;
- DBA to decouple dispersion and beam size issues
- Beam size on the dump window ~15 mm^2
- Length = 20.7 m



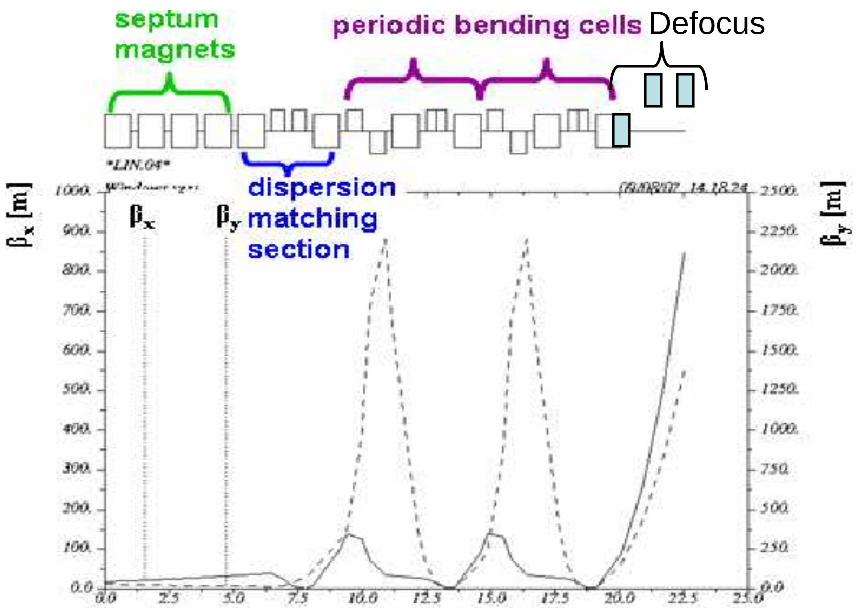


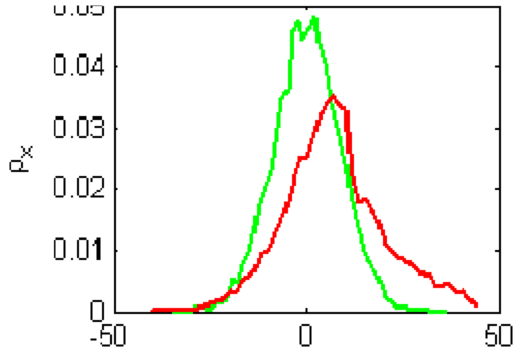


- Two collimators to protect downstream triplet
- intercepts 3.9 kW/train and 18.8 kW/train

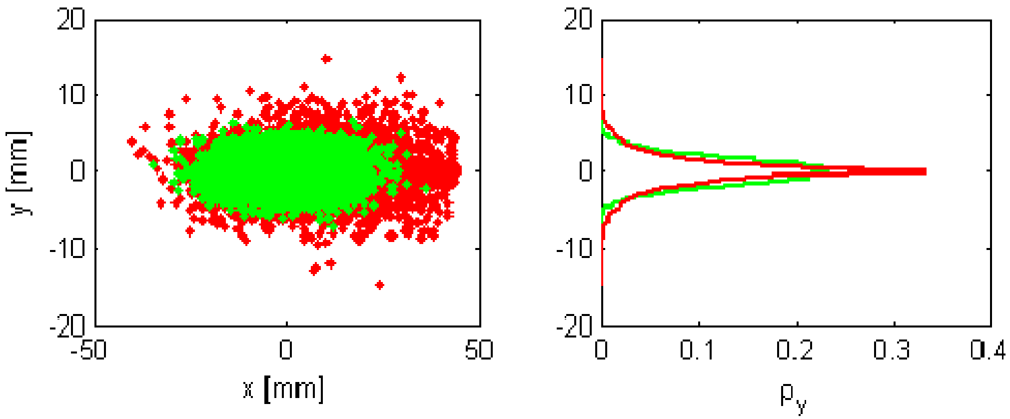
ELBC2 Design

- ELBC2 similar to ELBC1, but ~ 5m longer (extra bending cell)
  - 6 septum+6 bends+12 quads,
  - two collimators: 5.2 kW (protect quads) and 14.1 kW (dump window)





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

Halo and Energy Collimation

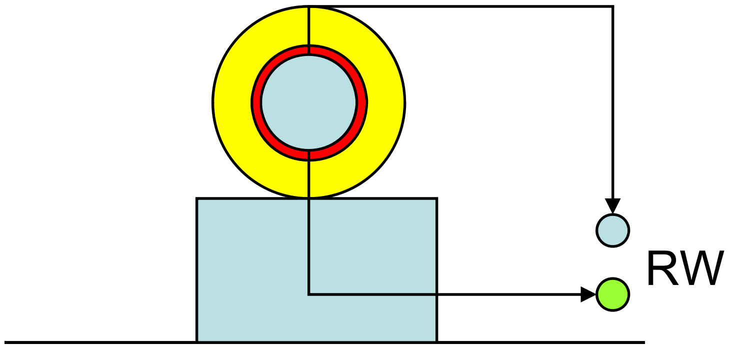
- ILC specification:
  - **Needs to limit halo at end linac to ~10^{-5} of total beam power**
- Halo Collimation after DR
  - **BDS specification as requirement**
    - Halo power ~ 220 W
    - Provide machine protection
      - Collimators stop out-of-control beam from DR
      - Need to keep out-of-control beam from frying collimators, too!
- Energy collimators after betatron collimation system
  - **Scattered particles**
  - **Off-momentum particles / bunches from DR**
- Additional energy collimators
  - **In BC1 wiggler**
  - **In BC2 wiggler**
- Collimators in Extraction Lines ELBC1 and ELBC2
- Need to understand machine protection issues for these collimators

Technical Systems

- Magnets and power supplies (~4600 Magnets)
  - **SC quads/correctors/solenoids (36/54/8),**
  - **RT quad, correctors, septa**
  - **Pulsed magnets, kickers, bends, FB/FF correctors**
- Vacuum system
  - **Current baseline**
    - 2 cm OD stainless chambers
      - Exceptions: BC bends, extraction lines, CMs
    - 20 nTorr in long line from DR to turnaround
      - Passivated to reduce outgassing rate
    - 100 nTorr in balance of system (turnaround to linac)
- Dumps and Collimators
  - **3 dumps per side with 220 kW capacity**
  - **Betatron and energy spoilers / absorbers with ~200 W capacity (20 adjustable aperture (5W) +28 fixed-aperture collimators)/side**
  - **Few collimators with ~10 kW capacity**

Six ~220kW Aluminum Ball Dumps

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

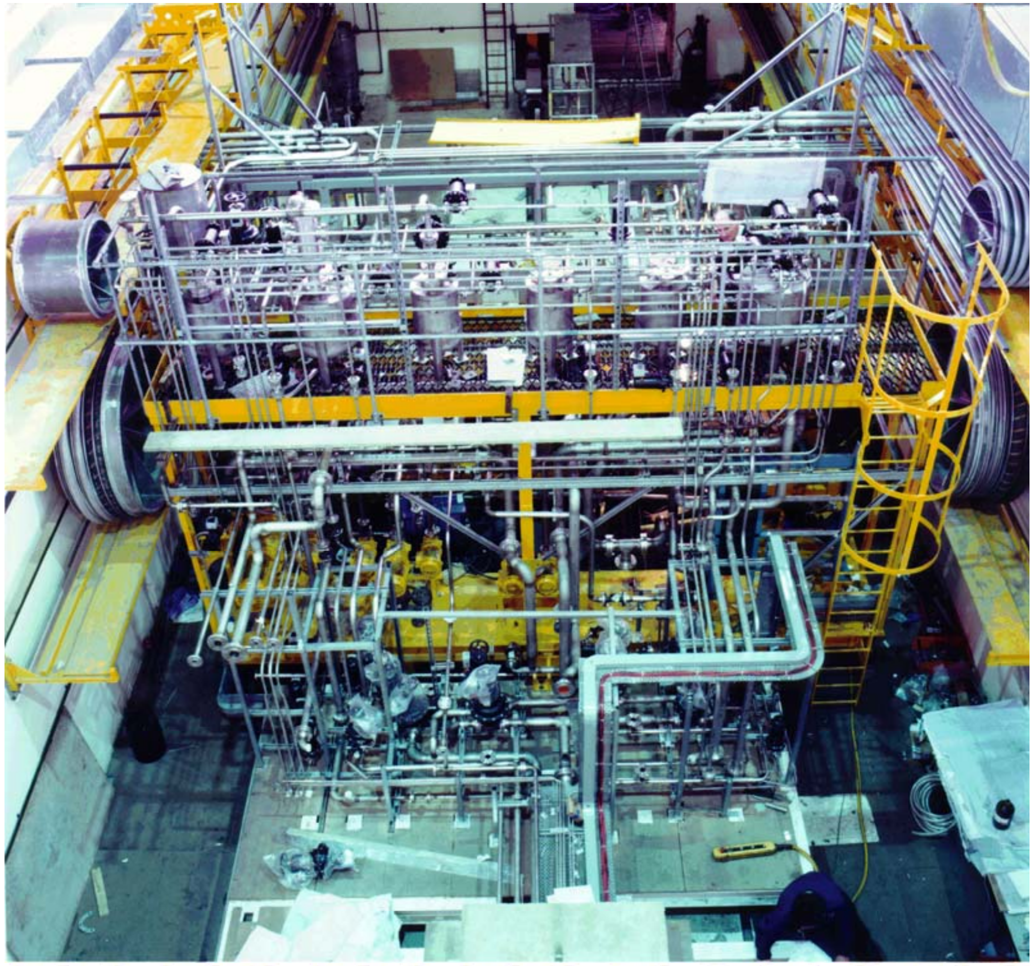


Cost ($1M each) is dominated by:

- **3-loop radioactive water processing system**
- **The CFS infrastructure, shielding, etc.**

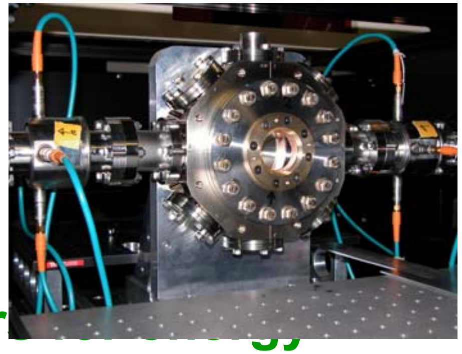
Similar dumps in use at SLAC

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



Technical Systems (2)

- Instrumentation
  - **BPM's at every quad, plus high dispersion points in wigglers**
    - Serve a number of functions: feedback, feed-forward, beam-based alignment and steering, energy diagnostic
    - room-temp C- or L-band (BC2 upstream) cavity BPM's
  - **3 suites of Laser Wires (LW) in each RTML**
    - 4 wires per suite, set up for 2D emittance measurement
  - **Bunch length measurement**
    - LOLA (3.9 GHz) + screens in each BC
    - Possibly EO monitors (not in RDR baseline)
  - **SLMO's (Synchrotron Light monitor) in BC wiggler spread measurement (4)**
  - **3 dedicated phase monitors per side**
  - **Toroids, 4 ion chambers and 150 photomultipliers (MPS)**



Technical Systems (3)

- 1.3 GHz SC RF system plus supporting utilities
  - **48 CMs per side (1 RF source per 3 CMs, as in ML)**
    - 3 CM x "8Q" in BC1
    - 15 RFunits x "9-8Q-9" in BC2
    - BC1: 2nd source with RF switch for redundancy
  - **LLRF issues**
    - Phase stability
    - Beam loading compensation
      - Beam loads RF at decelerating phase
      - Unlike ML, need to "jump" both amplitude and phase of RF source @ beam time
  - **Cryo system (~6.5% cost of ML Cryo system)**
    - Part of ML cryogenic system
      - Also supports SC solenoids in spin rotator
    - BC's are laser-straight
      - Probably OK – only ~1 km long

Sources of emittance degradation

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

LET BBA @ ILC RTML

Several BBA used:

- Ballistic Alignment (BA)
- Kick minimization (KM)
- Dispersion Free Steering
- Dispersion Bumps
- 4D Coupling Correction

- Adaptive alignment
- Wakefield Bumps

Feed-Back and
Feed Forward system

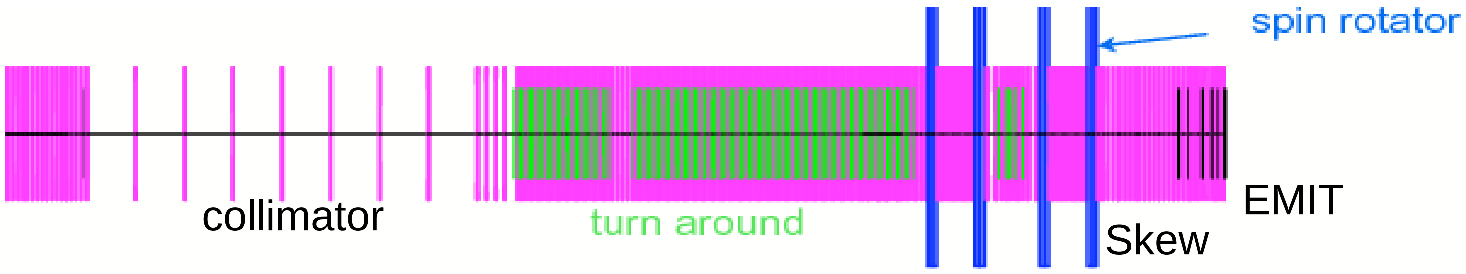
Survey Alignment

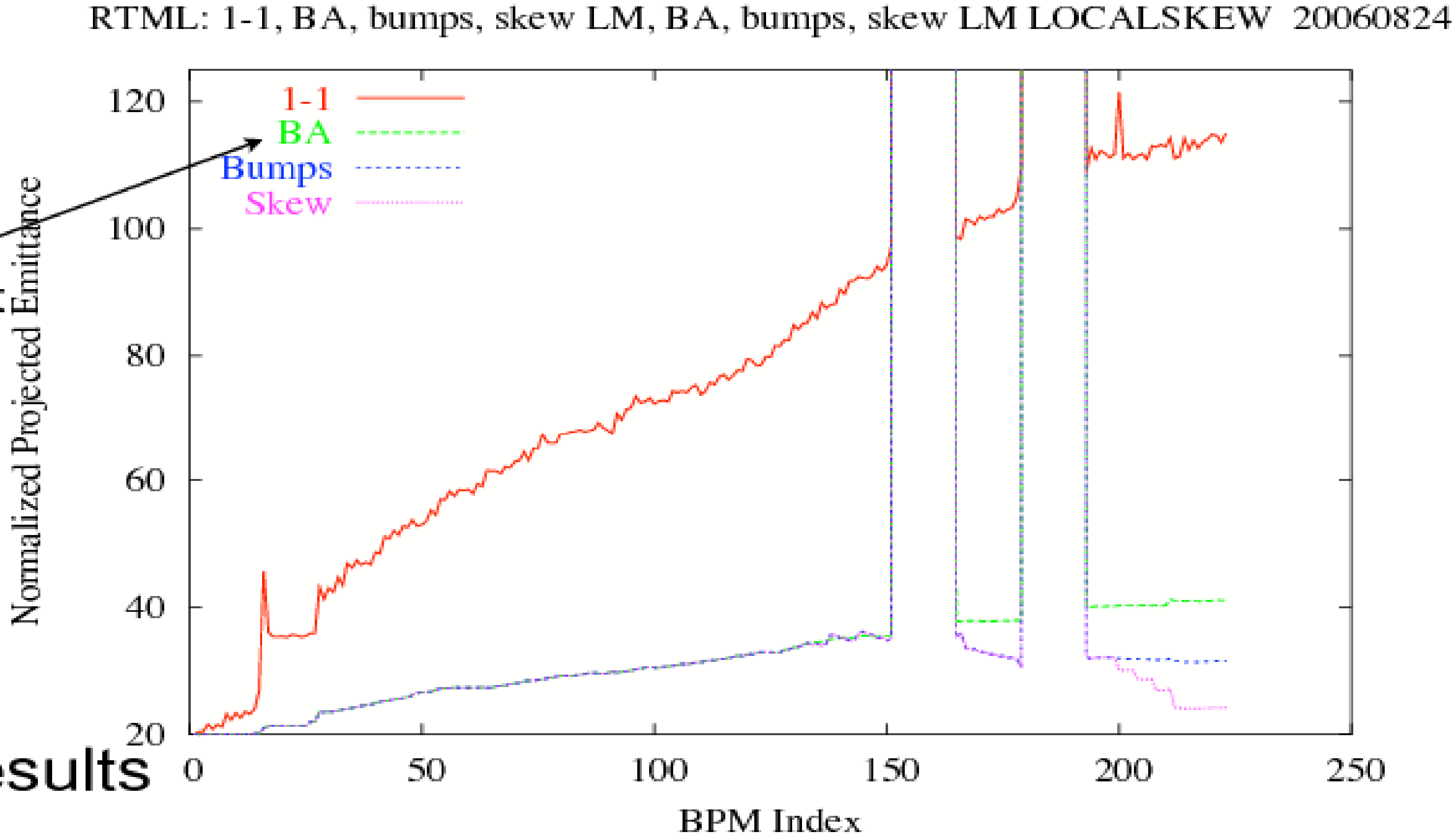
Our old canonical set, should consider more realistic misalignments...
Survey people would prefer we use cold specs for all components.

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

Static tuning in part of RTML (upstream BC1)

COLL2
Turnaround
Spin rotator
SKEW
EMIT2





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

Jeff Smith results

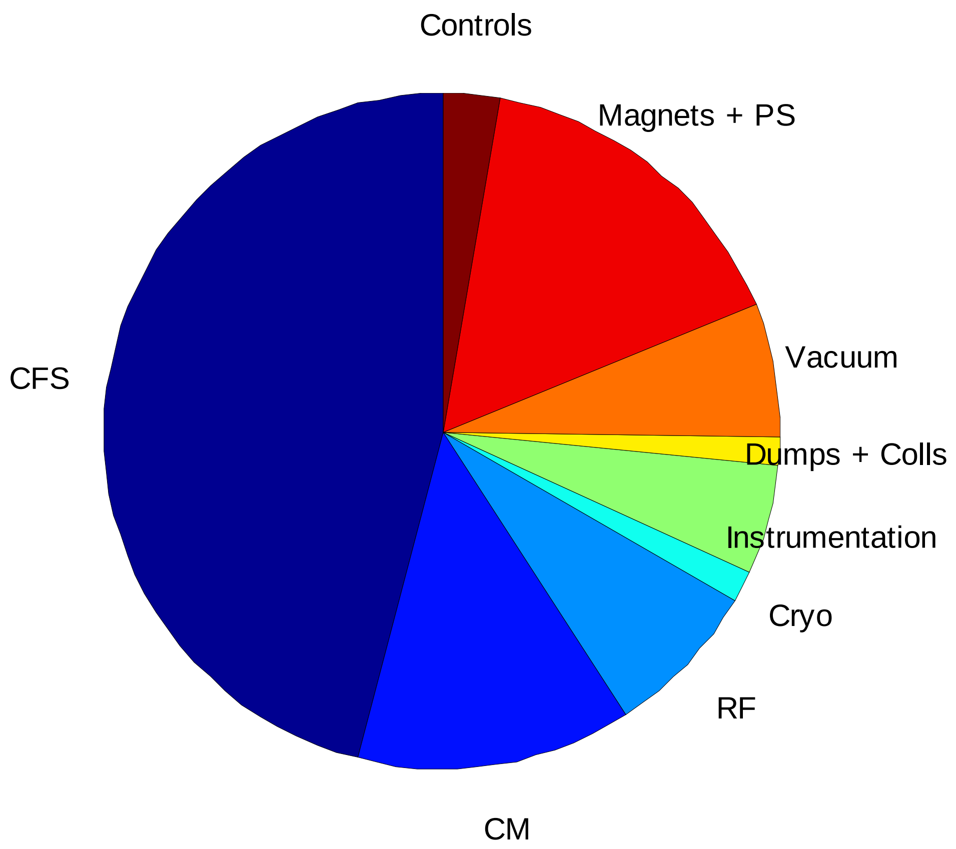
Emittance budget

- Not there yet... Budget just 4 nm (factor ~2 larger)

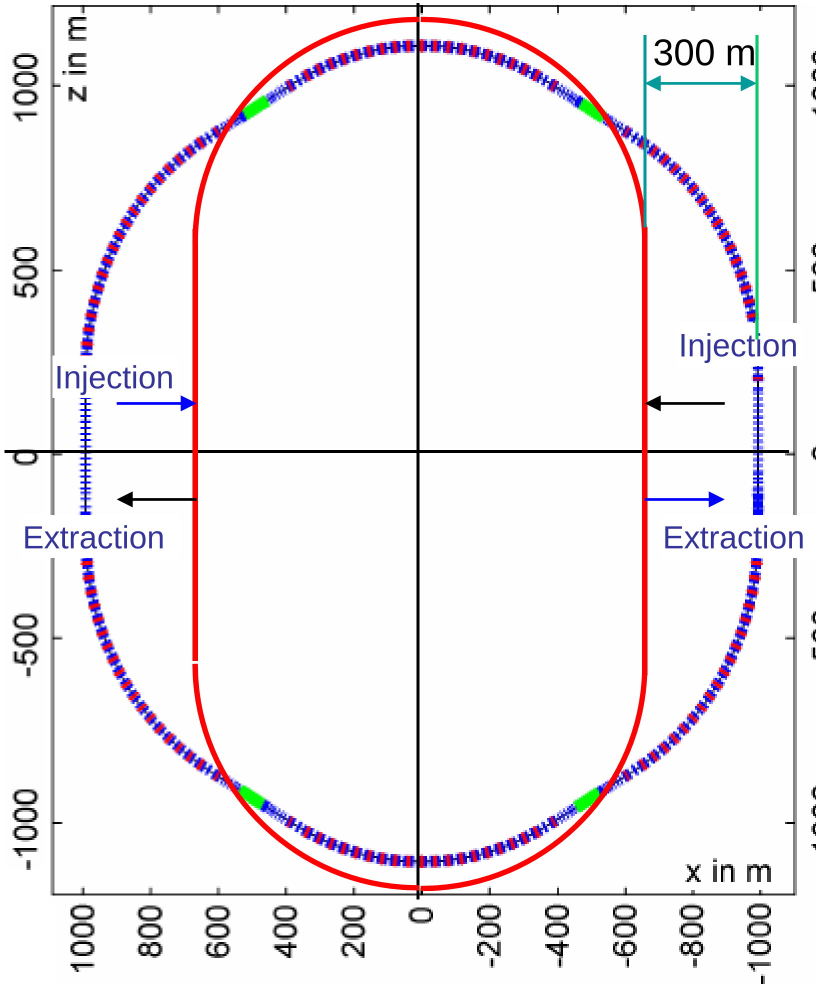
Region	BBA method	Dispersive or Chromatic mean Emittance Growth	Coupling mean emittance Growth
Return Line	Kick Minimization and feed-forward to remove beam jitter	0.15 nm	2 nm (without correction)
Turnaround and spin rotator	Kick Minimization and Skew Coupling Correction	1.52 nm (mostly chromatic)	0.4 nm (after correction)
Bunch Compressor	KM or DFS and Dispersion bumps	greater than 4.9 nm (KM + bumps) 2.68 nm (DFS and bumps)	0.6 nm (without correction)
Total		~5 nm almost all from BC	3 nm (without complete correction)

Cost and its Distribution

- CFS + BC RF system = 68% of costs
  - **Correlated – much of CFS cost is housing for BC cryomodules**
- Remainder dominated by RT beam transport
  - **Quads, correctors, BPMs, vacuum system**
- Small amount of "exotica"
  - **Non-BPM instrumentation, controls, dumps, collimators**



ILC Damping Ring – New Design



Layout of the ILC Damping Ring

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

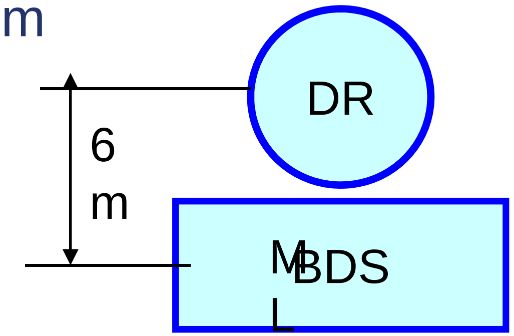
- New ILC DR lattice is shorter.
- Bunch length = 6 mm
  In old RDR design:
  - 9 mm (easy)
  - 6 mm (more challenge)
- Energy spread = 0.15%
- New DR increases the length of the RTML linac in each side (e^+ and e^-) of ~300 m, but not CFS
- Need redesign/adjust DRX lattice to accommodate changes in DR

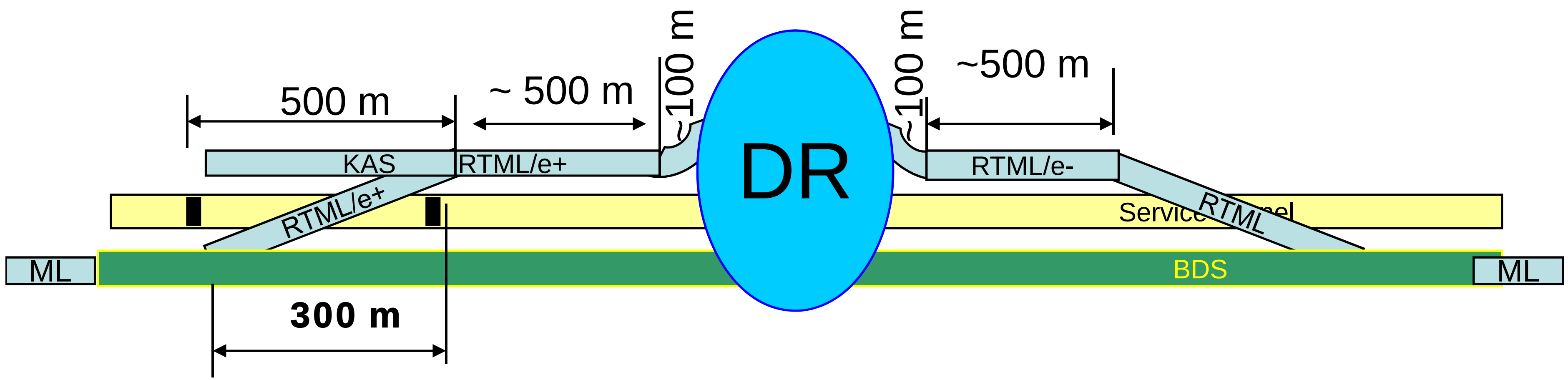
Possible configuration of the RTML/source tunnels

Discussion at Dubna ILC workshop, June, 2008

Minimum length of separate RTML/source tunnel

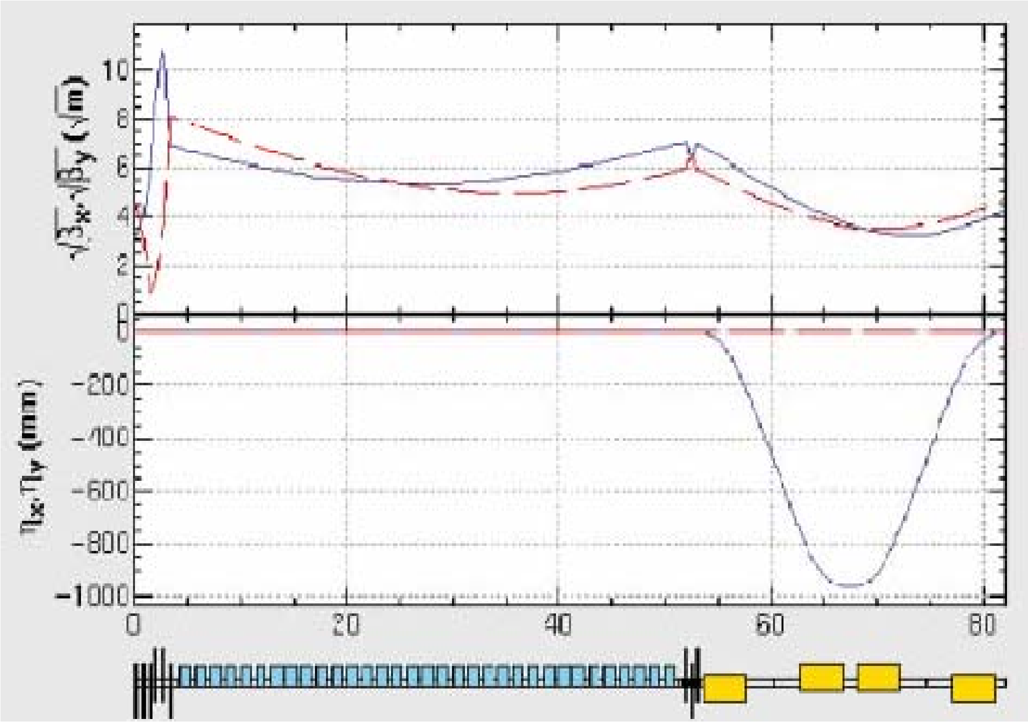
- Smaller vertical separation DR/BDS tunnel: 10m → 6 m
- Length constrains:
  - Electron source side (straight) ~ 500 m
  - Positron source: 950m=500(KAS)+450m(SCL/TRL)
  - RTML tunnel length ~ 900 m (now ~1250 m)





Possible tunnel saving ~ (600-700) m /side

Short Single stage BC (Eun-San Kim)-2006



Parameter	Units	Values
Legngth	m	80
Initial beam energy	GeV	5
Initial bunch charge	nC	3.2
Initial rms energy spread	%	0.15
Inital rms bunch length	mm	6
Initial emittance (H/V)	μm	8 / 0.02
RF phase	degree	-118
Chicane R_{56}	mm	-190
Bending angle	deg.	6
Length of a bend	m	4.16
End rms bunch length	mm	0.3
End energy	GeV	4.5
End bunch charge	nC	3.2
End emittance (H/V)	μm	8.3 / 0.02
End energy spread	%	3.5

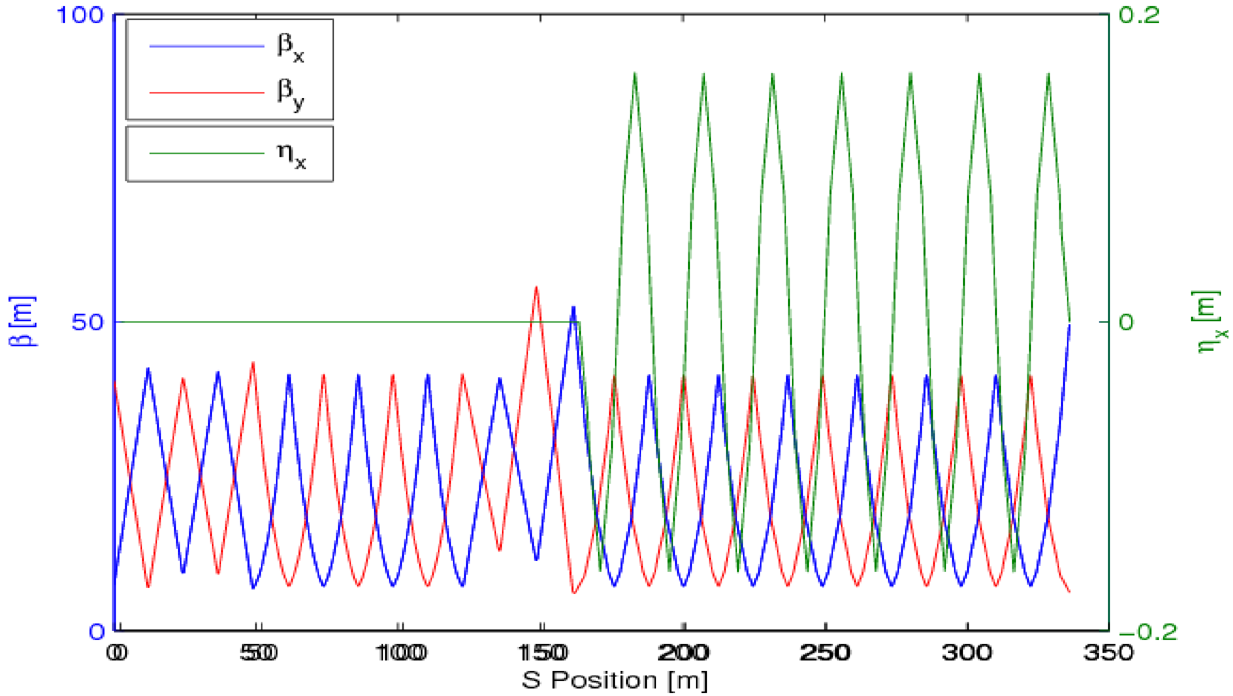
- Compress 6mm →0.3mm only
- Acceleration 4.5→15 GeV will require 15 RFunits (incl. 1 spare) ~ 600 m
- Energy spread @ 15 GeV 3.5%*(4.5/15) ~ 1%
- BC length ~700m. Saving ~ 1100-700 = ~ 400m
- No ELBC2 extraction line
- Disadvantages: No flexibility, tunability, larger emittance growth ???

Single-stage BC (PT, TOR, AW) - 2005

Input beam parameters

- *Energy = 5 GeV*
- *Energy spread = 0.15%*
- *Bunch length = 9 mm*

(In new DR design bunch length = 6mm)



Single –stage BC:

- In case 6→0.3mm energy spread ~ 4 %
- Acceleration from 4.6→15 GeV will reduce energy spread by factor of ~3
- BC length ~340m, post-acceleration ~600m, Saving 1100-940 = ~ 160m
- Disadvantages (compare to 2-stage BC):
  - Low flexibility and tunability, emittance growth ???

Further RTML work

- Study Possible Cost saving options:
  - Minimize length of RTML/source tunnel
  - Alternative 2-stage or 1-stage bunch compressor
  - Reduce pulsed extraction Lines from 3 per side to 2 per side
- Lattice design aand emittance studies
  - Re-evaluate/match geometry and optics to accommodate DR changes, CFS req's and cost saving options
  - Demonstrate require emittance budget for Static tuning
  - Dynamic tuning (ground motion, jitter, AC magnetic fields, etc)
  - Design FB/FF system
- Design/prototyping critical components

Acknowledgements

RTML team:

SLAC, FNAL, ANL, LBL, Cornell Univ., KEK, DESY, INFN, CERN, KNU/Korea, UBC, IHEP/China

Design and Performance:

P. Tenenbaum, J. Smith, S. Molloy, M. Woodley, S. Seletskyi, E.-S. Kim, D.Schulte, A. Latina, K. Kubo, M. Church, L. Wang, P. Spenzouris, M. Venturini, I. Reichel, J.Gao…

Engineering and Civil:

V. Kashikhin, P.Bellomo,T.Mattison ,Y.Suetsugu,J. Noonan, X.Qiong, P.Michelato, T.Markiewicz, R.Larsen, M.Wendt, John Carwardine, C.Saunders, T.Peterson, F.Asiri, J.-L Baldy, G.Aarons, T.Lackowski, …