Reference Design of the ILC RTML

PT

SLAC

Outline

- RTML Functions and Design
- Cost breakdown
- Technical Systems
- Wrap-up

RTML Functions

"The function is a task, action, or activity which must be performed or achieved. It is the specific purpose or intended use for something. The VM Process requires that the description of a function be reduced to the simplest and most accurate expression possible. This is accomplished by employing only two words, an active verb and a measurable noun, to define the function."

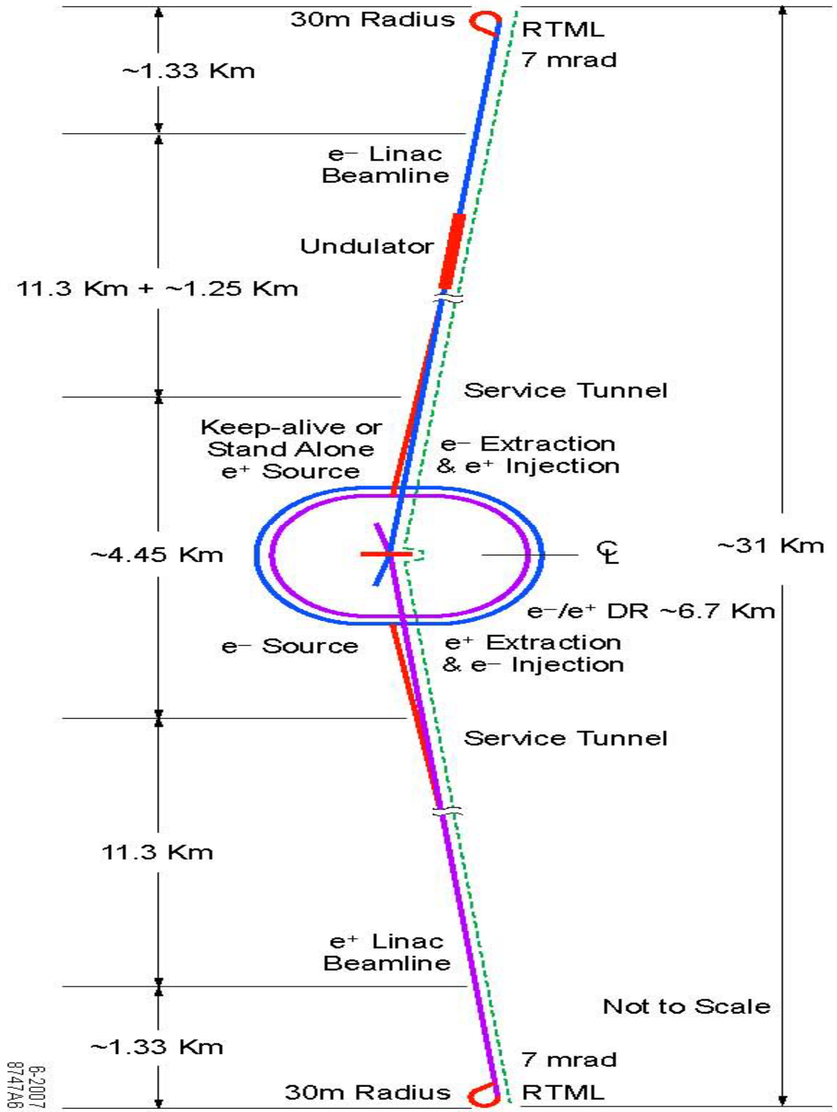
US DOE Policy 413.2, *Value Management*

- *Transport Beam*
  - **(or, *Match Geometry*)**
- *Collimate Halo*
- *Rotate Spin*
- *Compress Bunch*

- *Preserve Emittance*
- Protect Machine

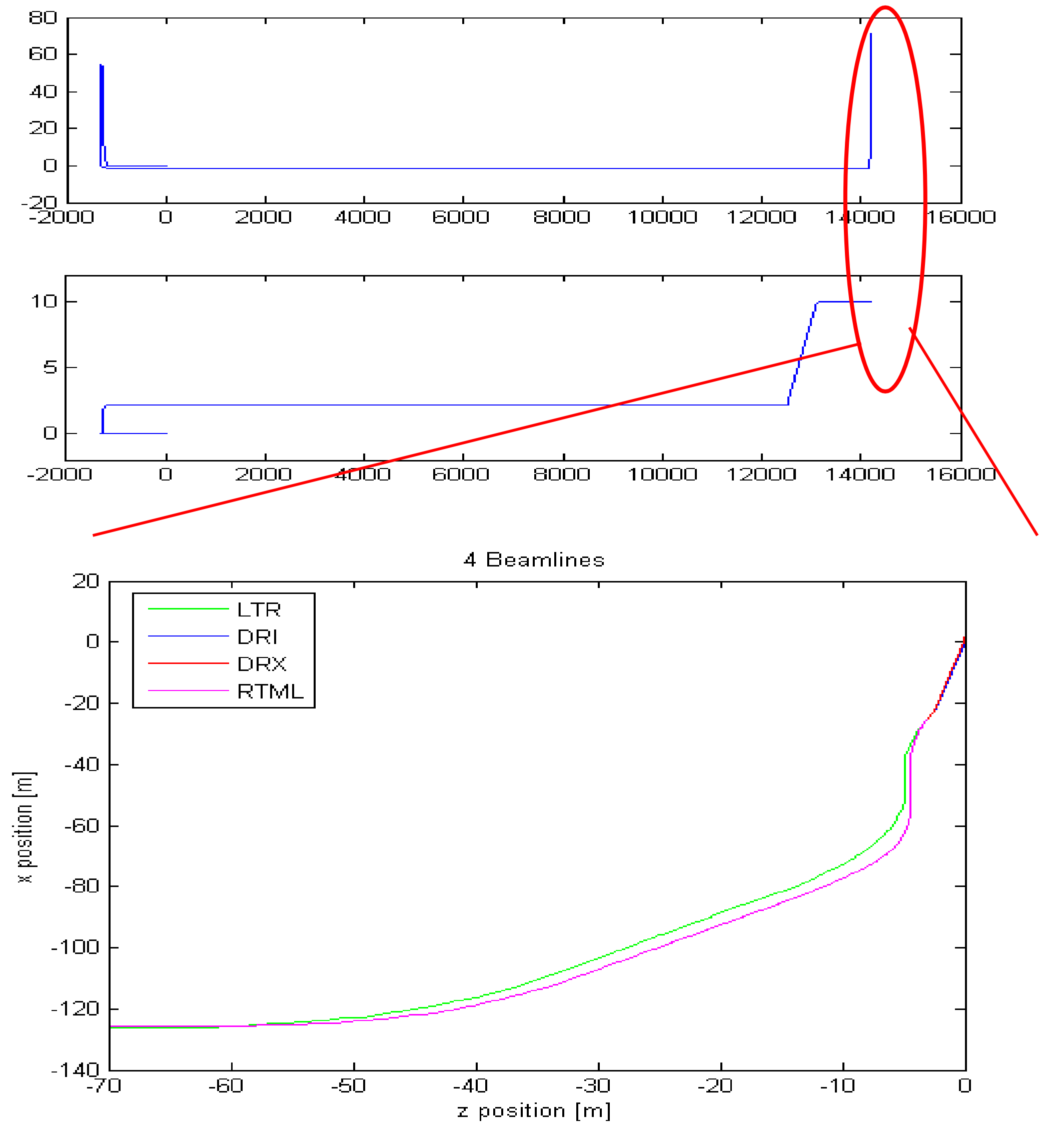
Geometry Matching

- DR location:
  - **Center of ILC Site**
  - **~10 m above plane of BDS**
- ML upstream location
  - **Near extreme ends of ILC site**
  - **In the "plane" of BDS**
- RTML needs to connect these two systems
  - **Down to linac level**
  - **Out past end of linac**
    - Leave room for BC
  - **Turn beam around**
- Additional constraint: injectors
  - **Share the tunnel with RTML**
  - **Need to keep geometries synchronized**



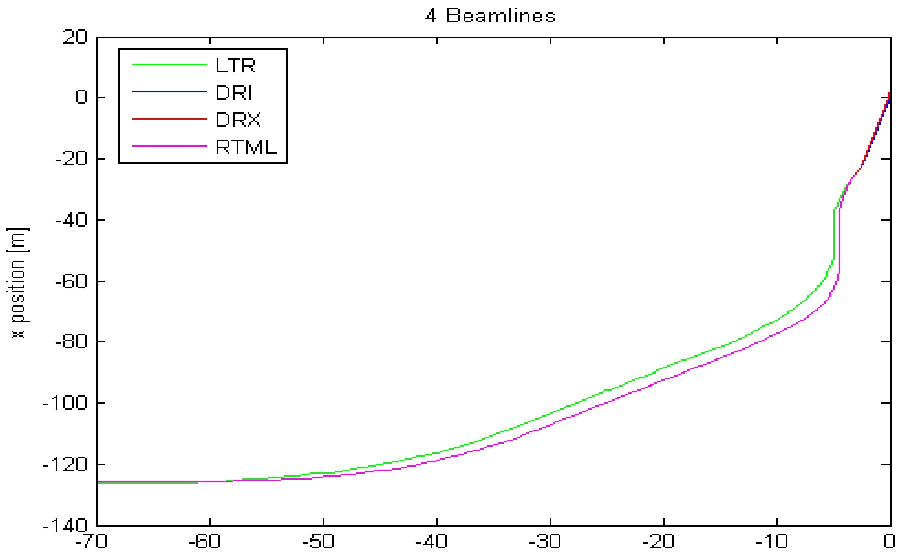
Geometry Matching (2)

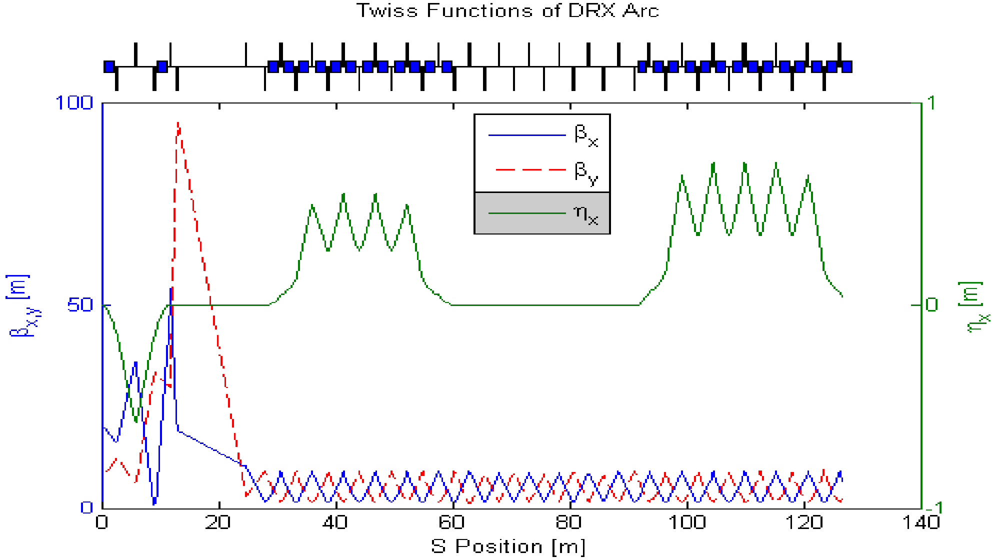
- Horizontal Arc out of DR
- ~km straight
  - **In injector tunnel**
- "Escalator" vertical dogleg down to linac tunnel
- ~11 km FODO lattice
  - **In linac tunnel**
  - **Vertically curved to ~match gravitational equipotential**
- Vertical and horizontal doglegs
- Turnaround
- 8° arc in spin rotators
- BCs are net straight



DRX Connection

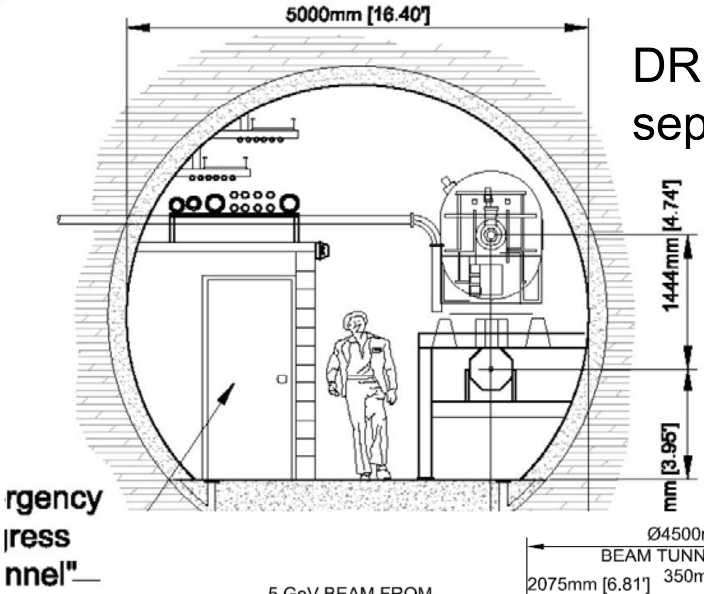
- DR-RTML hand-off point defined
  - **Point in extraction system where η,η' → 0**
- RTML system mostly defined by need to follow LTR geometry
  - **Stay in same tunnel**
- Design is OK at *conceptual* level
  - **LTR-RTML x offset as large as 2.1 m – needs to be fixed**
  - **Uses Keil-style dispersion matching**
    - Requires separate PS for matching bends



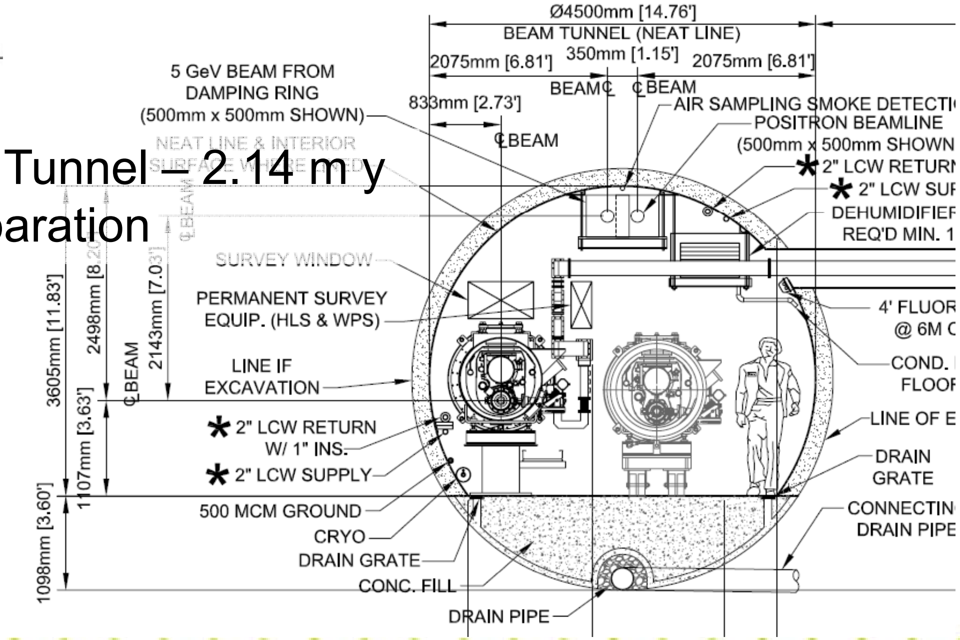


DRX Connection (2)

- Current design is entirely planar
  - **All bending in *xz* 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:
  - **Lower ring is e-**
  - **CMs and SC solenoids always sit on floor**
  - **RTML hangs from source tunnel ceiling at same location as in linac tunnel**



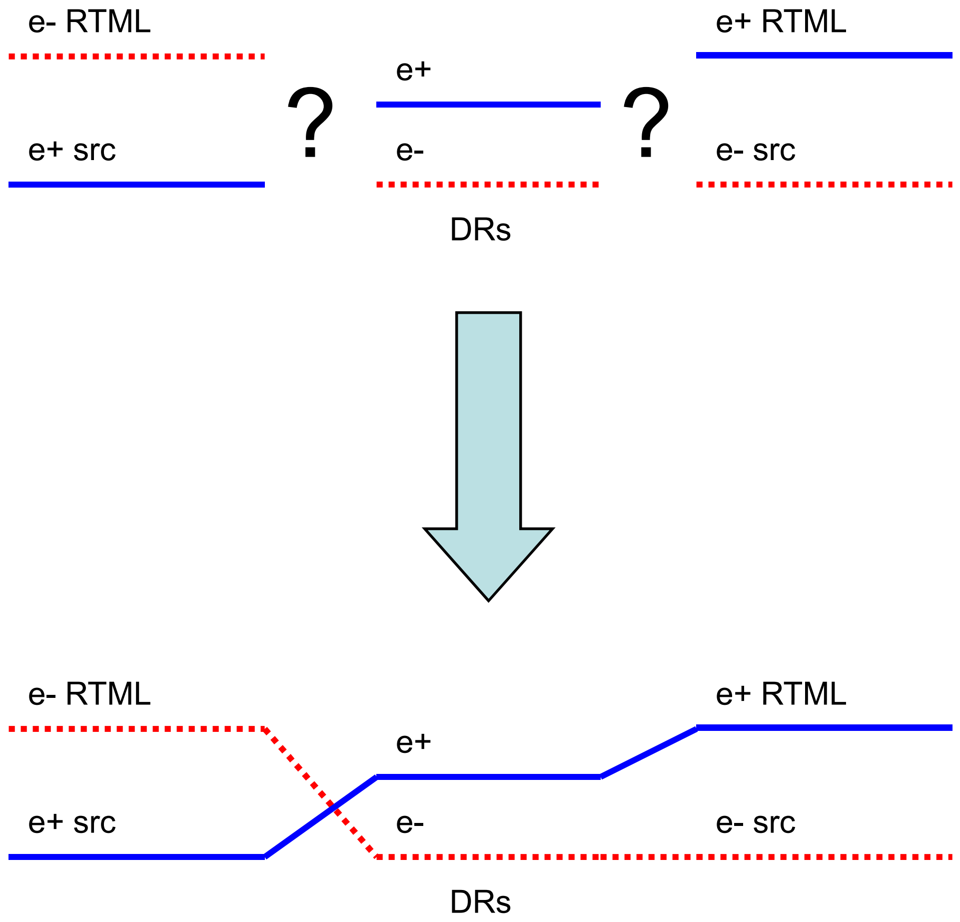
DR Tunnel – 1.44 m y separation



ML Tunnel – 2.14 m y separation

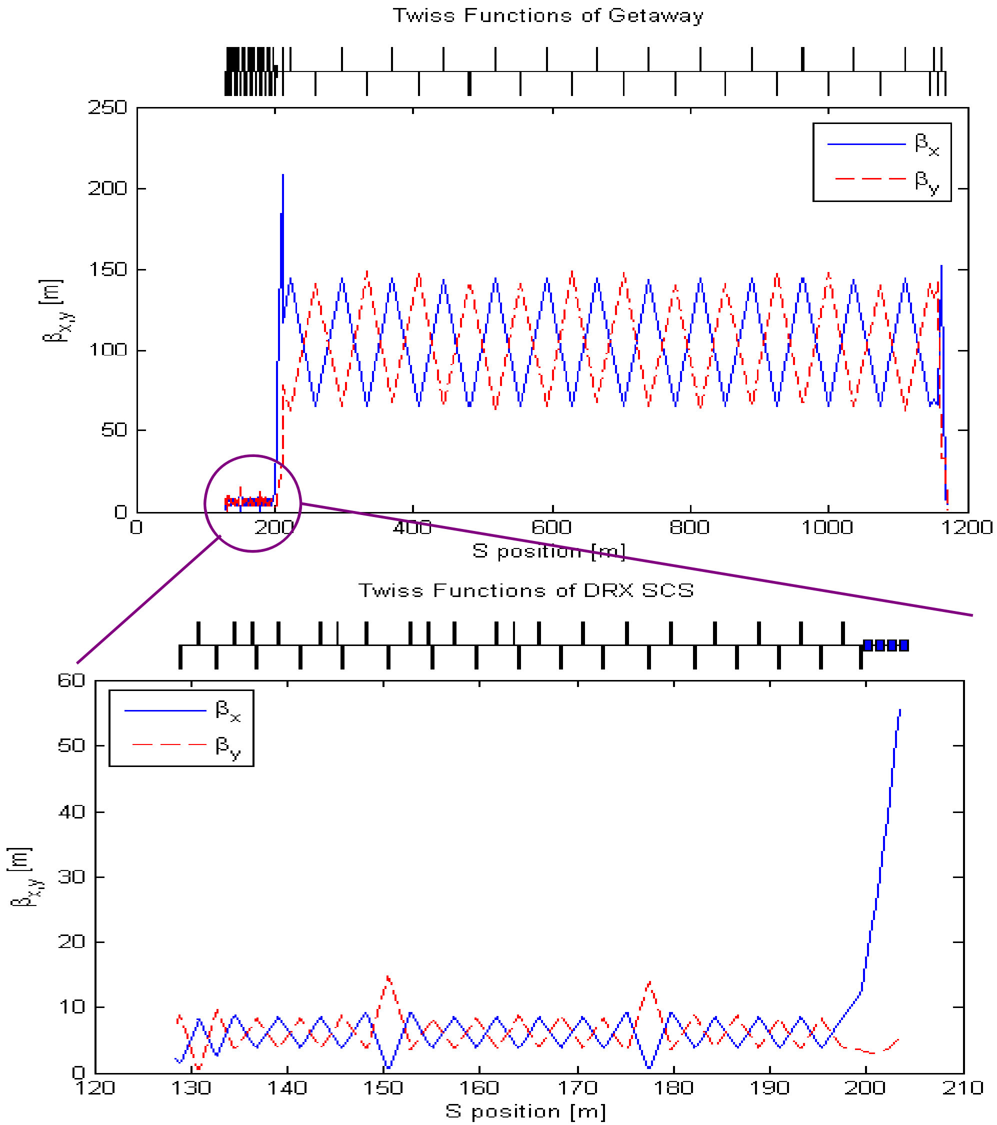
DRX Connnection (3)

- Current design does not incorporate optics to manage vertical offsets
- Probably implies changes to LTR design as well, maybe DR inj / ext lines?
- Not yet examined / resolved other possible conflicts with source beamlines



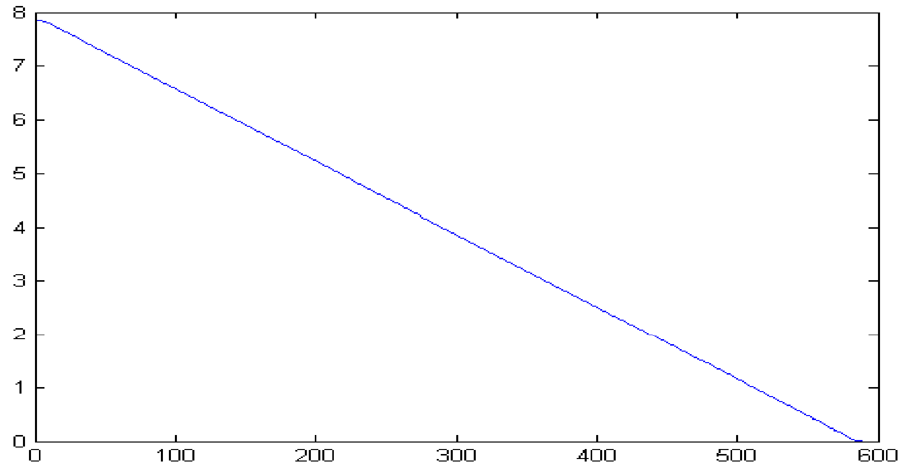
"Getaway" Straight (or "DR Stretch")

- 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
  - Need to consider conflicts with source beamlines in this area
  - Beta match between low- and high-beta optics not great

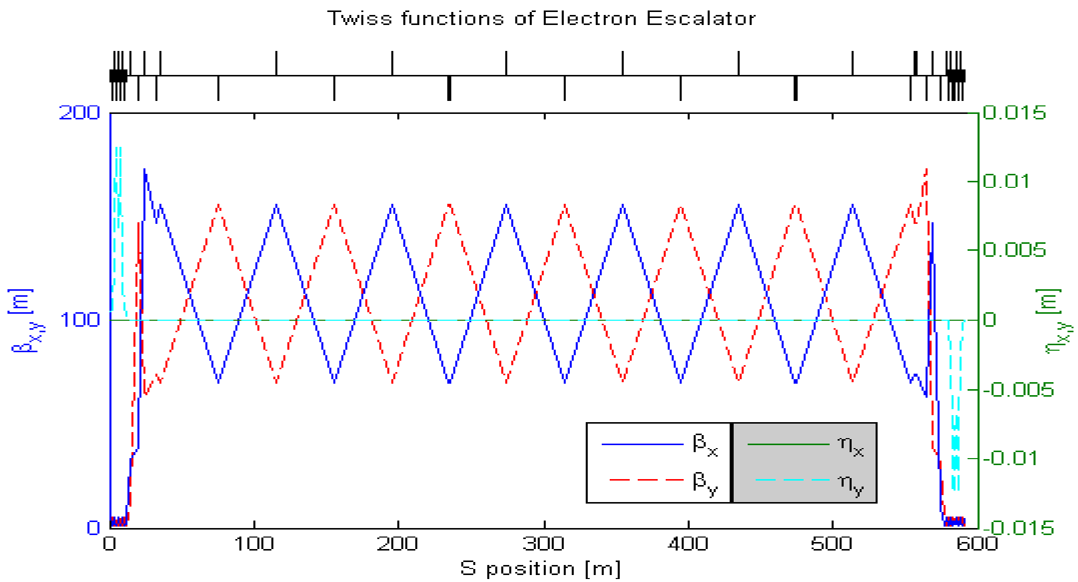


Escalator

- Vertical dogleg
  - Descends 7.85 meters over ~590 m
    - < 1° slope
  - Uses 2 vertical arcs separated by weak FODO lattice

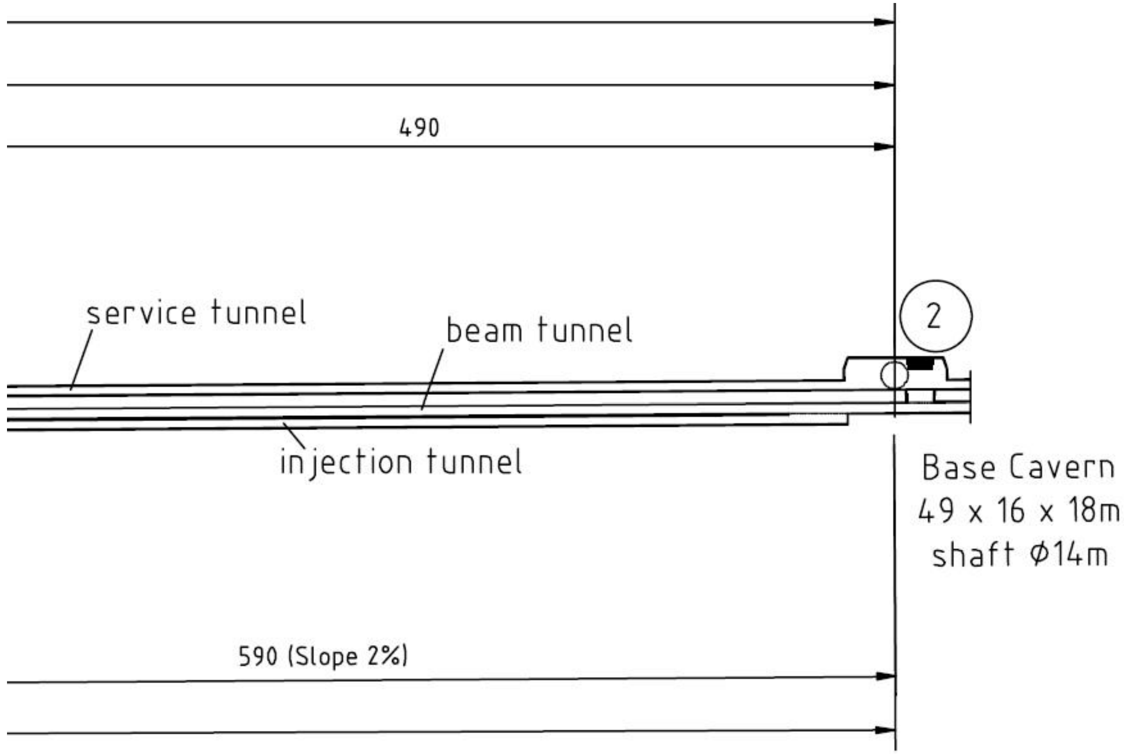


- Good conceptual design
  - Geometry match not exact
  - Uses Keil-style eta matching
  - Beta match between "strong" and "weak" lattices not great
  - Positron return line confilicts?



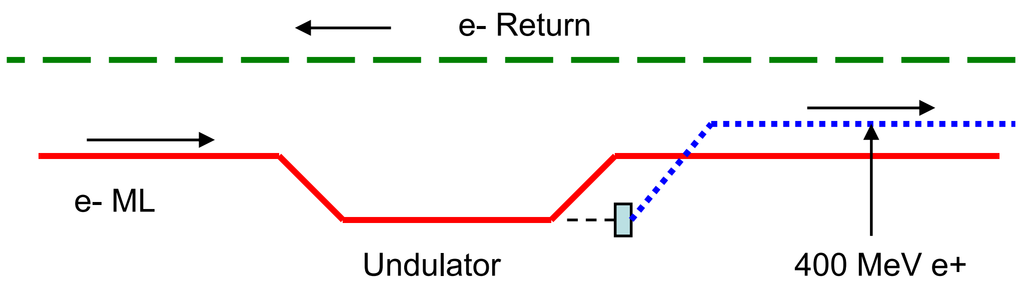
Escalator (2)

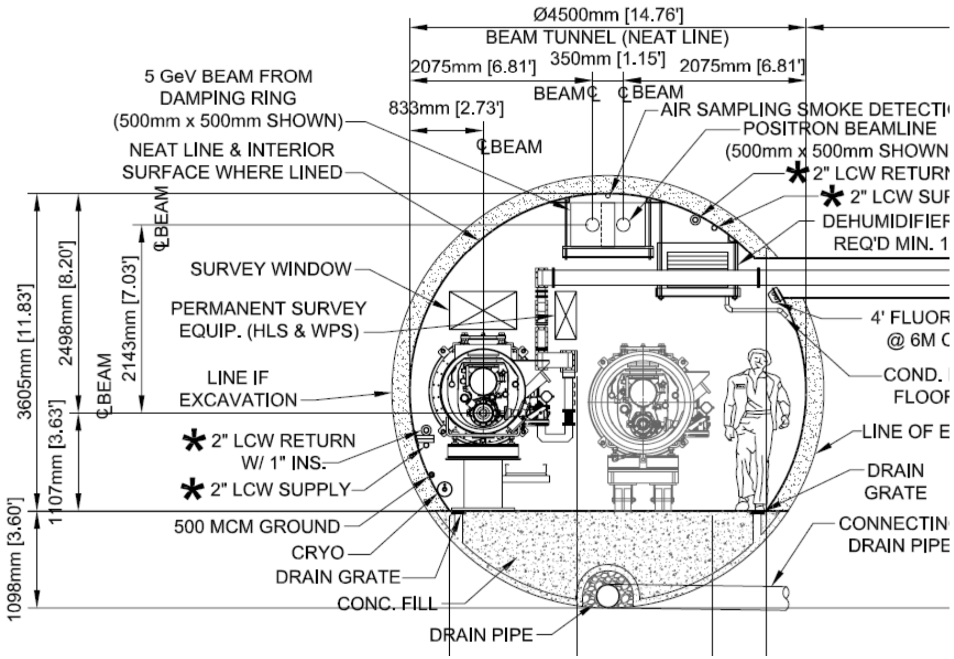
- Escalator-linac tunnel connection does not match CFS design
  - **Optics design: beamline comes down from above and joins line in ML tunnel**
  - **CFS: Escalator comes down next to ML tunnel, connects in horizontal plane**
- Need to make these match



Return Line

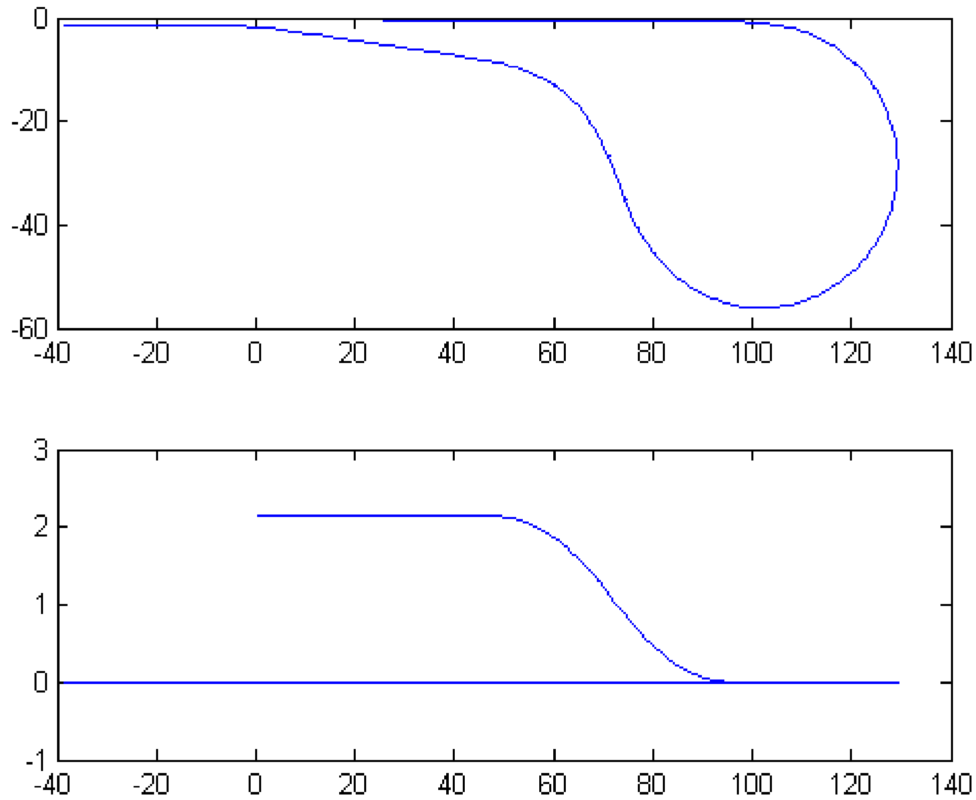
- Weak FODO lattice at ML ceiling elevation
- Vertically curved tunnel thru ML area
  - **Dispersion matching via dipole correctors**
- Laser-straight tunnel thru BC area
- Electron line 1.2 km longer than positron
  - **Goes thru undulator area**
- System lengths probably not exactly right
- Electron Return line and positron transfer line need to be exchanged





Turnaround

- 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**



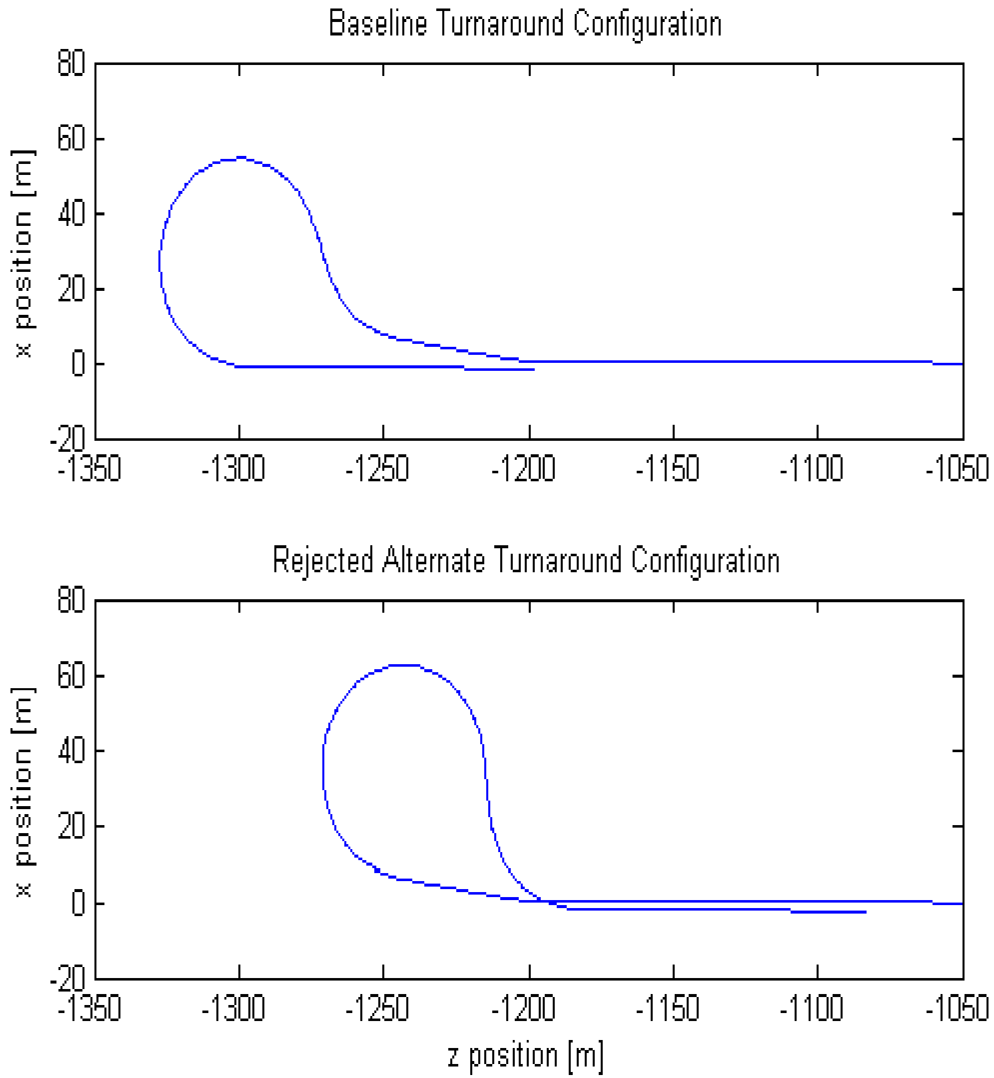
Turnaround (2)

Why is there a horizontal dogleg in front of the turnaround?

- Without the dogleg, “bare” turnaround produces a shift Δx = 1.44 meters
- From CFS drawings, need a shift of Δx = 1.59 meters
- Could in principle achieve the same offset by reducing the mean curvature of the turnaround by 10%
- Would increase length of turnaround ~10%
- Turnaround tunnel is drill and blast, *very* expensive per linear foot compared to TBM
- Putting in a dedicated dogleg seemed a better solution
- Easier to adapt dogleg solution as design evolves and horizontal offset changes

Turnaround (3)

- Selected geometry uses a big arc followed by a small reverse arc
- Could also select the opposite geometry – small arc, big reverse arc
  - **Advantage: smaller site footprint**
  - **Disadvantage: need to add 3 cells to turnaround**
    - Cost of contents
    - Cost of drilled tunnel vs TBM tunnel
  - **Disadvantage: beamline crosses itself**
    - Correction = move VDOG into turnaround, thus increasing length of drilled tunnel even more



Bunch Compressor Geometry

- Bunch compressor is net straight
  - **No net bend, no net offset**
- Simplifies site geometry
- Allows use of chicane or wiggler BCs
  - **Easy to adjust momentum compaction**
    - Increases flexibility of BC
- Rules out use of arc or dogleg BCs
  - **Potentially useful optical properties**
  - **Was fine pre-Valencia**
    - Smaller longitudinal emittance from DR
  - **So far still seems acceptable**
    - Still understanding all the issues in longer bunch from DR, momentum compaction from DRX arc + turnaround

Pulsed Extraction Lines

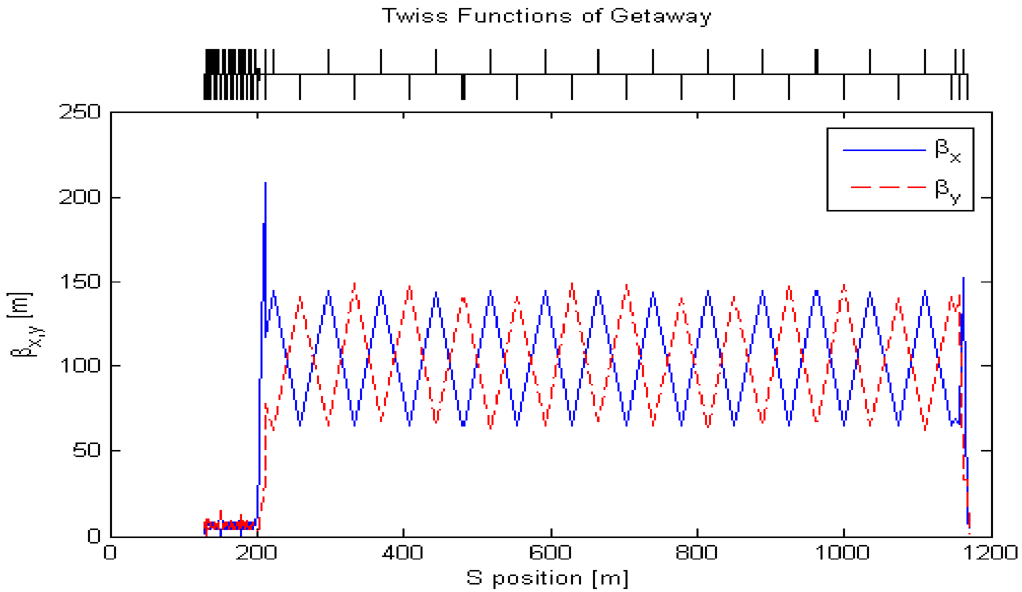
- Current design calls for 3
  - **After DR Ext, diagnostics, global correction**
    - Keep DRs running @ full power during access
    - Keep DRs and extraction tuned during access
    - MPS abort
  - **After BC1**
    - Tune up BC1 without beam in BC2
    - MPS abort
  - **After BC2**
    - Tune up BC2 without beam in linac
    - MPS abort
- All have 220 kW beam handling power
  - **Full power for DRX, BC1**
  - **1/3 power for BC2**
- No real designs for these in RDR
  - **Side effect of post-Vancouver redesign**
- Designs being developed now
  - **Do we need all 3?**
  - **Do they all need 220 kW power handling?**
  - **Do they all need MPS abort capability?**

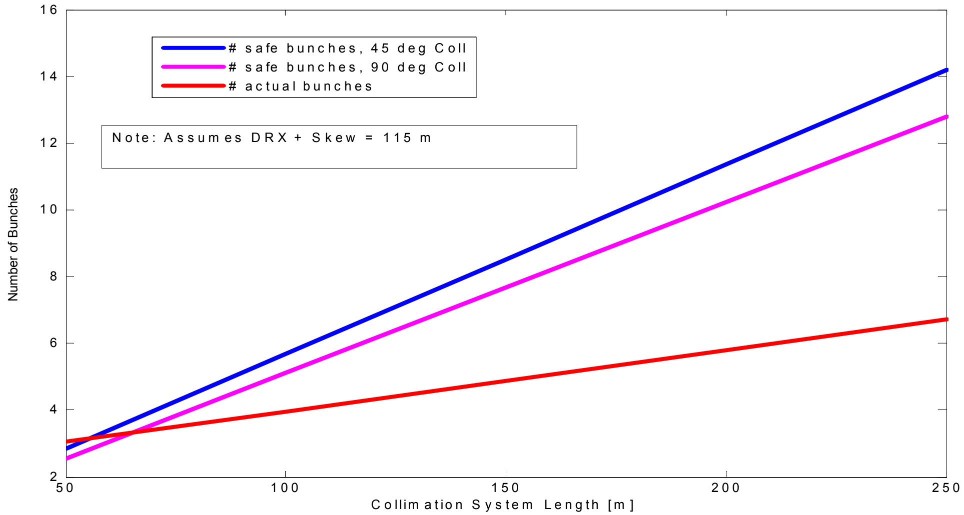
Halo Collimation

- SLC experience:
  - **Halo collimated at end linac + FF was ~10^{-3} of total beam power**
  - **All halo *seemed* to be from DR**
- ILC specification:
  - **BDS wants to limit halo at end linac to ~10^{-5} of total beam power**
- Want to collimate after DR
  - **Assume SLC experience relevant to ILC, and set BDS specification as requirement**
    - Halo power ~ 220 W
    - Must reduce halo by 2 orders of magnitude
    - Provide machine protection
      - Collimators stop out-of-control beam from DR
      - Need to keep out-of-control beam from frying collimators, too!

Halo Collimation (2)

- Main collimation in "Getaway" Straight after laser wire detectors
  - **2 phases x 2 planes x 1 iteration**
    - Never checked collimation efficiency – assumed to be OK (only need 100x attenuation @ 5 GeV)
  - **Still need final energy collimation**
    - Clean up scattered particles with reduced energy
    - Dedicated chicanes? Or into dogleg which will go at bottom of escalator?
  - **Spoiler / Absorber scheme**
    - Absorbers protected by MCS in spoilers
    - Spoilers protected by proximity to DR extraction kickers
  - **Need to recheck collimator wakefields**
    - Quick look said it was OK
    - Needs more thorough recheck and documentation



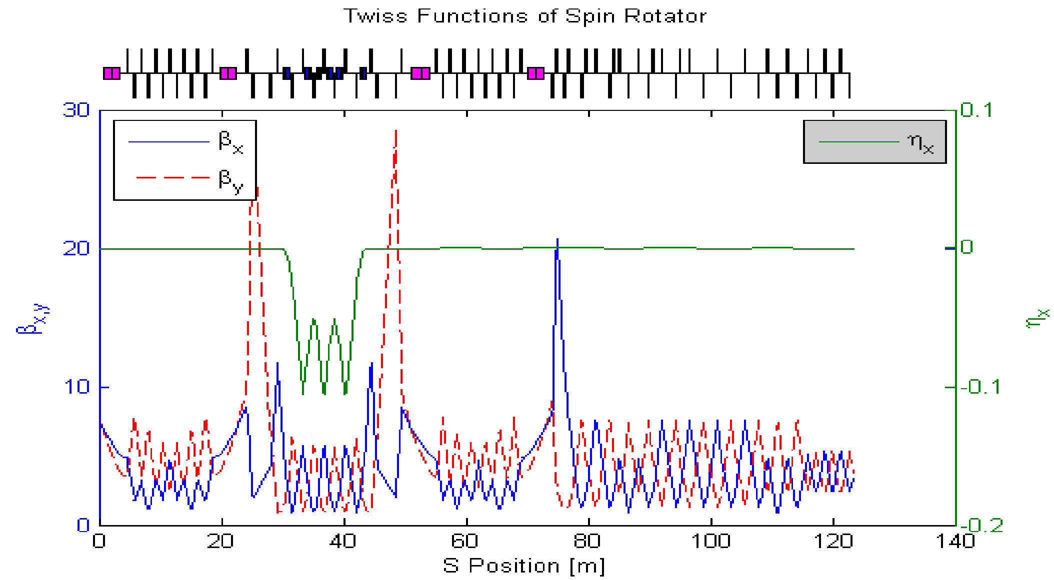


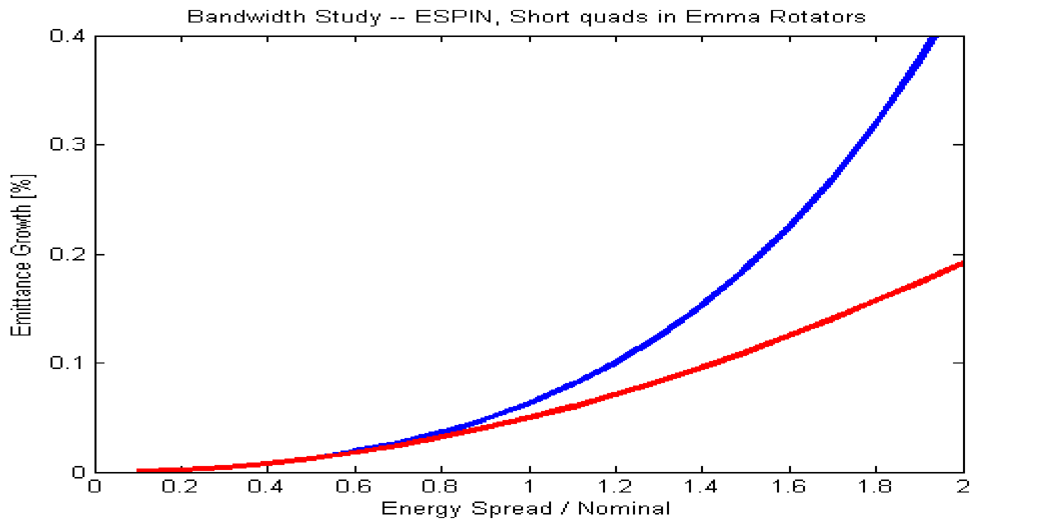
Halo Collimation (3)

- Need energy collimators after betatron collimation system
  - Scattered particles
  - Off-momentum particles / bunches from DR
- Additional energy collimators
  - In BC1 wiggler
  - In BC2 wiggler
- Need to understand machine protection issues for these collimators
  - They are a long way from DR ext kickers!

Spin Rotation

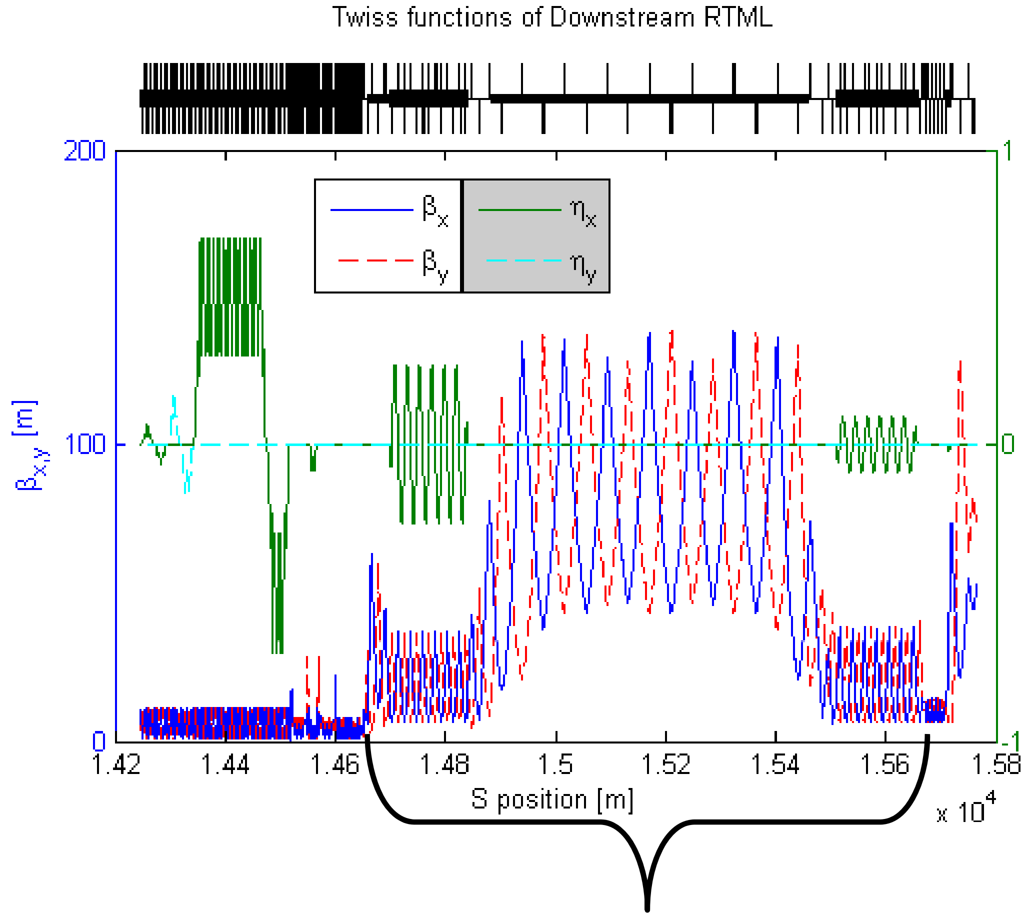
- Design based on Emma's from *NLC ZDR*
  - **2 solenoids with Emma rotator between them**
    - Rotate spin 90° in xy plane while cancelling coupling
  - **8° arc**
    - Rotate spin 90° in xz plane
  - **Another 2 solenoids + Emma rotator**
- Basic design seems sound
  - **Very small loss in polarization from vertical bending in linac tunnel**
- Important issue = bandwidth
  - **Off-energy particles don't get perfect cancellation of dispersion and coupling**





Bunch Compression

- Longitudinal emittance out of the DR:
  - **9 mm RMS length**
  - **0.15% RMS energy spread**
- Want to go down to 0.2-0.3 mm RMS at IP
  - **Need some adjustability**
- Use 2-stage BC to limit max energy spread
  - **Compress to ~1 mm at 5 GeV**
  - **Accelerate to ~15 GeV**
  - **Compress to final bunch length**
- DRX arc and turnaround have R_{56} = 2.9 m
  - **Need to include this in design**



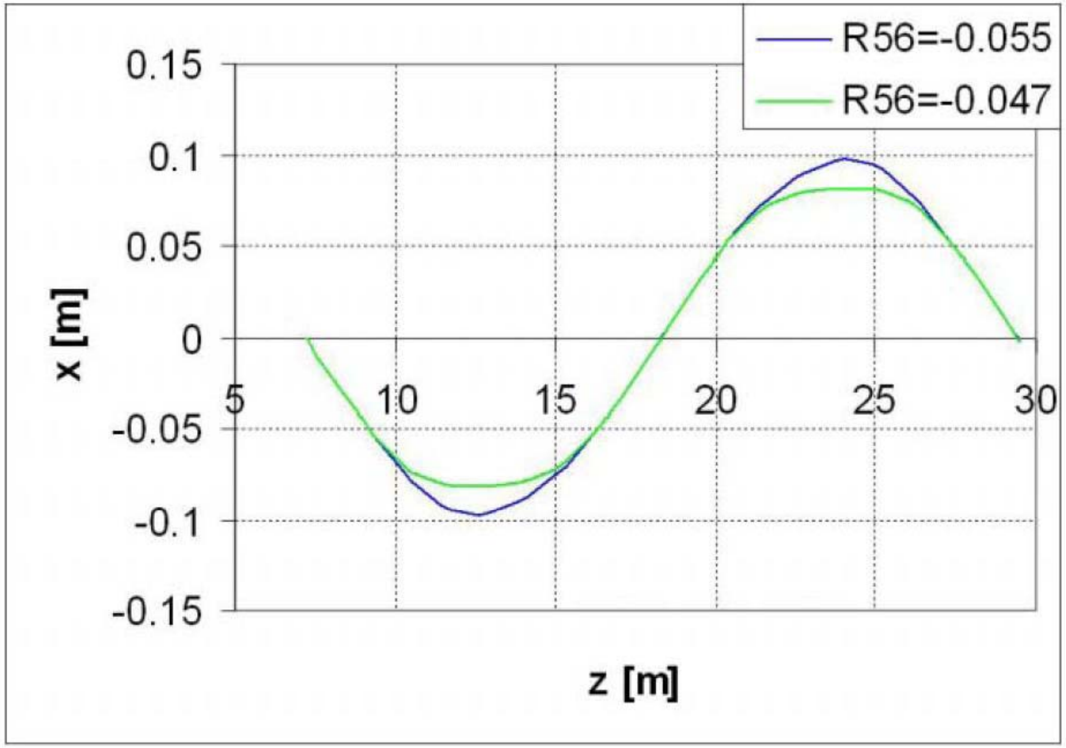
Bunch Compression (2)

- BC1 has 3 CMs with quad packages
  - Long bunch – need stronger focusing for WFs and cavity pitches
    - Not optimized
  - 1 RF source + 1 spare with waveguide switch
  - Low gradient, decelerating
    - T_{566} compensation
- BC2 has 14 linac-style RF units + 1 spare unit
  - Gradient ~same as ML
- Both stages use 6-cell lattice with quads and bends to achieve momentum compaction
  - "Wiggler"

Parameter	Nominal Value	LowN Value
Initial E	5.00 GeV	5.00 GeV
Initial σ_z	0.15%	0.15%
Initial σ_δ	9 mm	9 mm
BC1 Gradient	18.0 MV/m	18.1 MV/m
BC1 Phase	-104.9°	-105°
BC1 R_{56}	-376 mm	-353 mm
Post-BC1 E	4.88 GeV	4.88 GeV
Post-BC1 σ_z	~0.9 mm	~1.3 mm
Post-BC1 σ_δ	~2.5%	~2.5%
BC2 Gradient	30.2 MV/m	31.0 MV/m
BC2 Phase	-27.6°	-40.9°
BC2 R_{56}	-55 mm	-47 mm
Final E	15.0 GeV	13.7 GeV
Final σ_z	0.3 mm	0.2 mm
Final σ_δ	1.5%	2.7%

Bunch Compression (3) – Wiggler Design

- Need to be able to adjust R_{56} of wiggler
  - **Implies change of trajectory through bends**
- Need to have some locations where the trajectory does not vary
  - **BPMs, quads, collimators**
- Led to a complex design
  - **8 bends per half-cell**
  - **1st and 8th bend fixed in strength**
  - **Other bends adjustable**



Trajectories in one BC2 cell WRT tunnel axis for 2 BC Configurations.

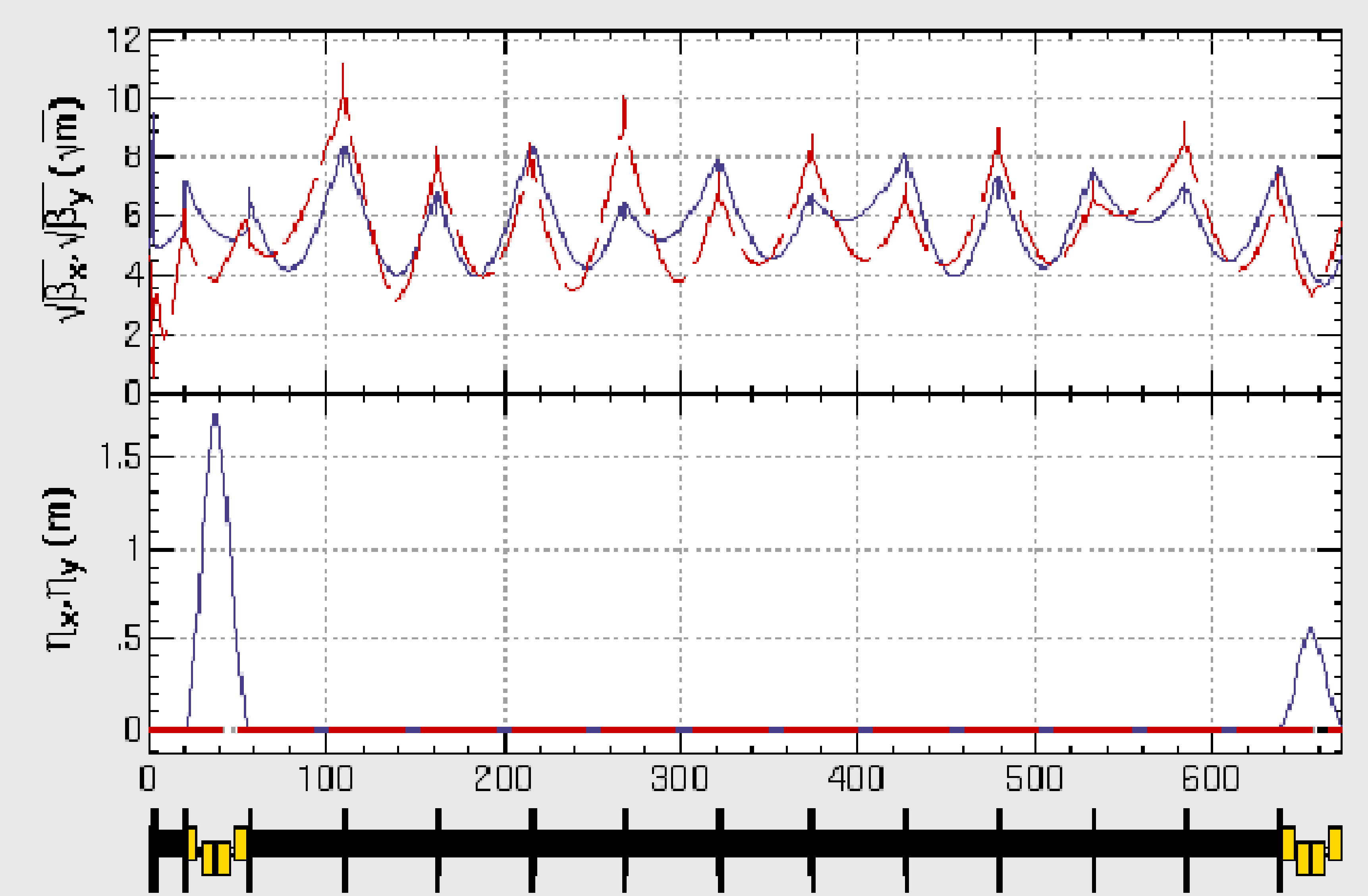
Bunch Compression (4) – Wiggler Design (2)

- Variation of trajectory in bends $\rightarrow$ wide poles and large good-field region required
  - **Makes BC bends more expensive**
- Current design calls for ~40 cm pole width for BC1 bends
  - **Larger than variation in trajectories**
  - **Legacy of 2006 design**
    - Had 2 configurations for each bunch length
      - "Alternate" configs had smaller emittance growth but larger R_{56} in BC1
  - **Right now, no "Alternate" BC configs**
    - Working to develop them
  - **Need to evaluate whether they are worth the extra cost and complexity in BC wiggler**

Bunch Compression (5)

- An alternate bunch compressor design exists
  - **6-cell wigglers (~150 m each, 102 bend magnets) replaced by chicanes (~40 m each, 4 bend magnets)**
  - **Advantages**
    - Shorter
    - Simpler
    - (Presumably) Cheaper
  - **Disadvantages**
    - Big x offset from straight line (~1.8 m)
    - Doesn't have natural locations for dispersion tuning quads
      - Needed to manage cavity pitches as well as "real" dispersion
- Need to carefully evaluate the two existing BC schemes
  - **Maybe neither one is optimal?**

Bunch Compression (6) – Alternate BC



Emittance Preservation

Or, more generically, “Luminosity Maximization”

- Sources of luminosity degradation we’ve thought about
  - **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 Wakefields**
- Sources we haven’t thought enough about
  - **Space charge**
  - **Resistive wall wakes in vacuum chamber**

Luminosity (2)

- Synchrotron Radiation
  - **Mainly managed by optics design**
  - **0.9 μm emittance growth in x**
    - ILC budget for x emittance growth from all sources, all areas = 2.0 μm
  - **Vertical bends in Escalator, Dogleg negligible**
  - **Analytic estimates indicate no CSR issues**
- Beam-ion instabilities
  - **Sets 20 nTorr pressure limit in Return line**
    - Limits jitter growth to 9% (ie, jitter out = 1.09 * jitter in)
    - For LowN, low bunch spacing
      - If LowN case eliminated, pressure spec can be relaxed

Luminosity (3)

- Beam Jitter
  - **Handled by feed-forward in turnaround and living clean**
  - **Sets limits on tolerable AC fields in Return line**
    - ~ 2 nTesla limit, comparable to measured value in ESB @ SLAC
  - **Can be improved by intra-train feedback as well**
    - Not in baseline
- Halo formation
  - **Not a problem in Return line**
    - Vacuum spec for ions much tighter than spec for halo
  - **Sets 100 nTorr vacuum spec downstream of Return line**
    - Results in 10^{-6} halo formation
- Collimator Wakefields
  - **Y wakes seem marginal for "razor blade" collimators**
  - **Probably OK for tapered collimators**
  - **Need to revisit this issue!**
    - Are standard expressions useful for 9 mm bunch length?
    - Are all wakes of full system included? (Resistive wakes of absorbers, etc)

Luminosity (4)

- Dispersion
  - **Local correction via steering / orbit control**
    - BBA – quads have individual power supplies
    - BPM at each quad
    - Y corrector at each quad, X corrector at each F quad
  - **Global correction via normal / skew quads in locations with dispersion**
    - DRX arc
    - Escalator (in principle)
    - Turnaround / vertical dogleg
    - BC1 / BC2 wigglers
      - Sets requirement for 6 cells with 90/90 phase advance
- Coupling
  - **Global correction via orthonormal skew quads**
    - Two decoupling systems
      - After DRX arc
      - After spin rotator
- Pitched RF cavity
  - **Global correction via BC dispersion knobs**
    - YZ coupling (pitch) + ZE coupling (off-crest running) = YE coupling (dispersion)

Luminosity (5)

- How well can we correct dispersion, coupling, cavity pitch?
  - **Studies with 2006 (pre-Vancouver) optics + Return line OK except for BC1 cavity pitch**
    - Can get in the realm of RTML emittance budget (4 nm vertical growth, 90% CL)
  - **BC1 cavity pitches blew budget by ~factor of 2**
    - Preliminary result – no attempt to improve upon this was made!
  - **Need to revisit in a more complete manner with up-to-date optics**
    - Likely to get worse

Luminosity (6) – RF Stability

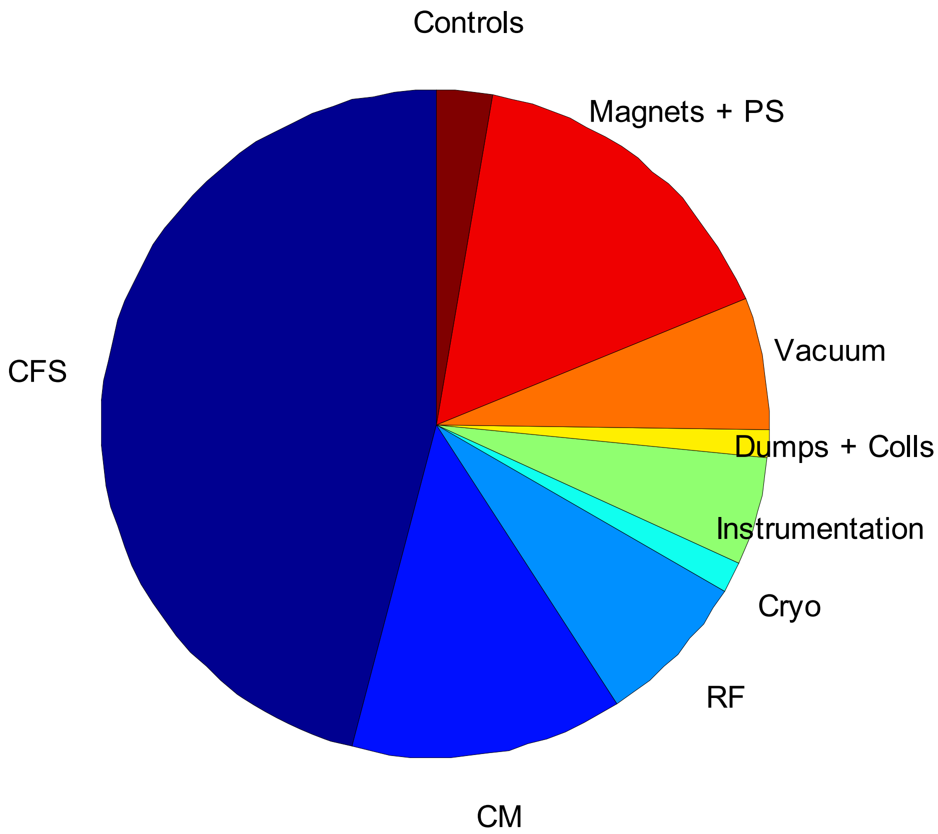
- Impacts luminosity through arrival time variation
- Nominal (0.3 mm RMS bunch length) case:
  - **0.24° RMS jitter of e- and e+ RF systems with respect to common master oscillator → 2% loss in integrated luminosity**
    - Assumed e- and e+ jitter not correlated with each other
    - Assumed all RF stations in e- system have same jitter
      - If jitter within e- / e+ systems uncorrelated, relaxes tolerances
  - **0.5% voltage jitter of e- and e+ RF systems wrt mean → 2% loss in integrated luminosity**
    - Similar assumptions and issues as for phase
  - **Lumi loss grows ~as square of RMS jitters**
- Short bunch case:
  - **No study done, but tolerance probably scales with bunch length**
      - IE, 0.16° RMS jitter or 0.35% voltage → 2% loss in integrated luminosity
- Assumed 3 levels of stabilization:
  - **Time scales up to ~1 second**
    - LLRF just has to achieve the necessary stability
  - **Time scales from ~1 second to ~minutes**
    - Measure and correct IP arrival times
      - Takes out slow drifts in LLRF
  - **Time scales > ~minutes**
    - Dither feedback – maximize lumi as function of controlled variation in arrival times
      - Takes out slow drifts in arrival time measurement system

Machine Protection

- RTML has machine protection issues ~similar to everywhere else in ILC
  - Possible exception: collimators
- RTML has 3 MPS intra-train extraction points
  - DRX, BC1, BC2
  - Do we need all of these?
    - Thought we did before central injector redesign
    - Need to rethink now in context of overall MPS design for ILC

Cost and its Distribution

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



More details in cost talk later today

Technical Systems

- Magnets and power supplies
  - **See talks later today!**
- 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)
    - Not *in situ* baked
    - No photon stops or water cooling in bend areas
- Dumps and Collimators
  - **3 dumps per side with 220 kW capacity**
  - **Betatron and energy spoilers / absorbers with ~200 W capacity**

Technical Systems (2)

- Instrumentation
  - **BPMs at every quad, plus high dispersion points in wigglers**
    - Serve a number of functions: feedback, feed-forward, beam-based alignment and steering, energy diagnostic
    - Original plan: dominated by room-temp C band cavity BPMs
    - Long DR bunches → L-band cavities may be more suitable upstream of BC2
      - Larger cost, larger tunnel footprint, lower natural resolution?
  - **3 suites of laser wires in each RTML**
    - 4 wires per suite, set up for 2D emittance measurement
  - **Bunch length measurement**
    - LOLA + screens in each BC
      - Originally used 2.9 GHz SLAC cavities as model
      - Want to go to either 2.6 or 3.9 GHz – need to choose!
    - Possibly EO monitors (not in RDR baseline, I think)
  - **SLMOs in BC wigglers for energy spread measurement**
  - **3 dedicated phase monitors per side**

Technical Systems (3)

- 1.3 GHz RF system plus supporting utilities
  - **48 CMs per side**
    - 3 “8Q” in BC1
    - 15 x “9-8Q-9” in BC2
  - **1 RF source per 3 CMs, as in linac**
    - BC1: 2nd source with RF switch for redundancy
  - **LLRF issues**
    - Phase stability, as discussed before
    - 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**
    - Part of ML cryogenic system
      - Also supports SC solenoids in spin rotator
    - BCs are laser-straight
      - Probably OK – only ~1 km long

Wrap-Up

(Calling these "conclusions" is probably an exaggeration)

- RTML is a large system by any standard
  - **Total length > ILC footprint**
  - **Total number of components enormous**
  - **Combined e+,e-RF systems > XFEL's**
- Impressive amount of design work done for RDR, nonetheless…
- …Technical maturity of RTML design is lagging
  - **Missing beamlines**
  - **Performance studies out of date and inadequate**
  - **Area, Technical, Global, Cost information are not consistent with each other**
  - **Many (most?) hardware performance specifications unknown**
  - **Required functions of various subsystems not reviewed**

Questions / Comments / Discussion