

ILC RTML Introduction

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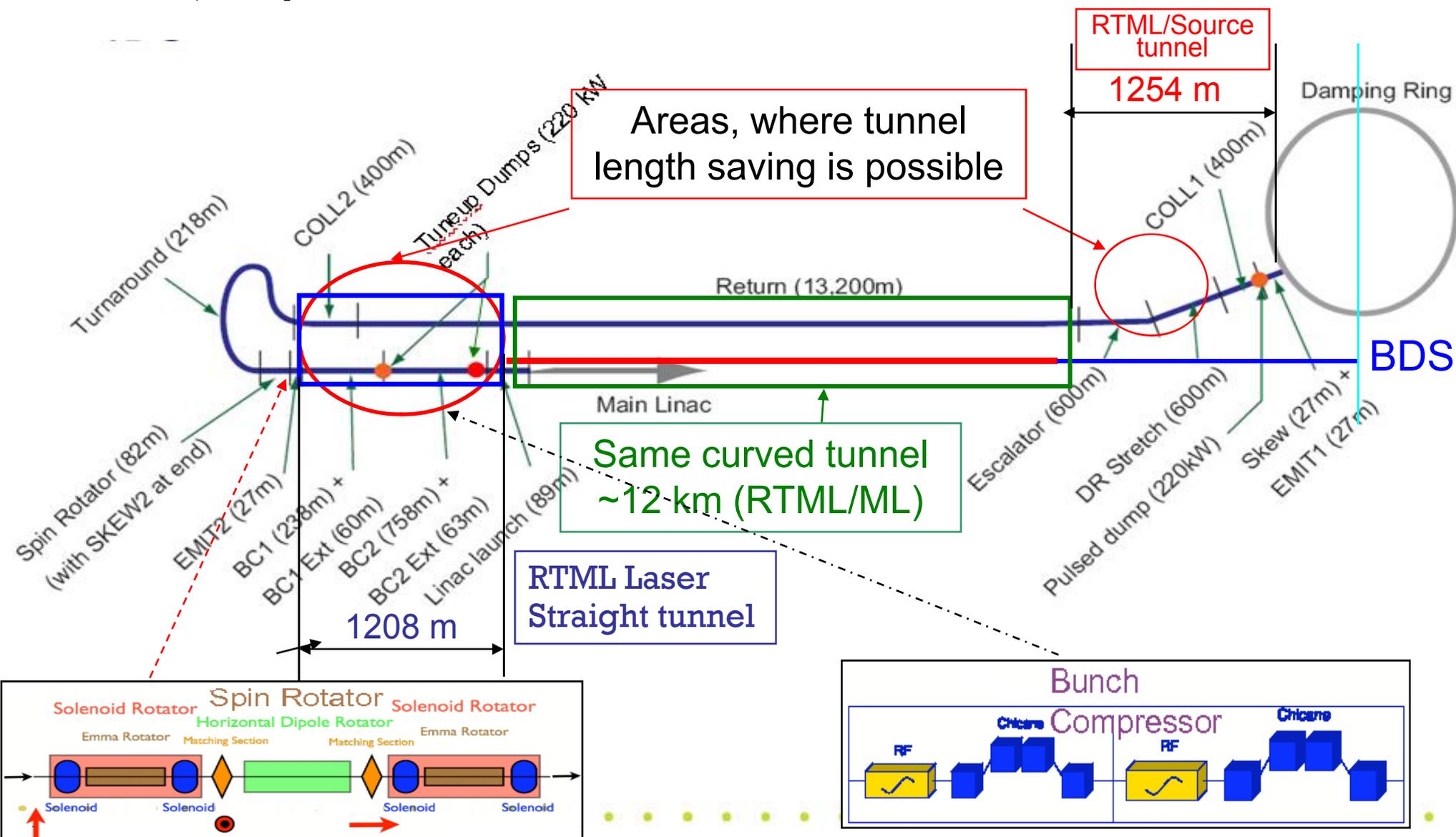
Fermilab

- ➡ RTML function and RDR design
- ➡ Minimum machine and Single-stage BC
- ➡ Emittance preservation in RTML
- ➡ Stray magnetic fields studies
- ➡ Slow ground motion Studies at FNAL
- ➡ Summary

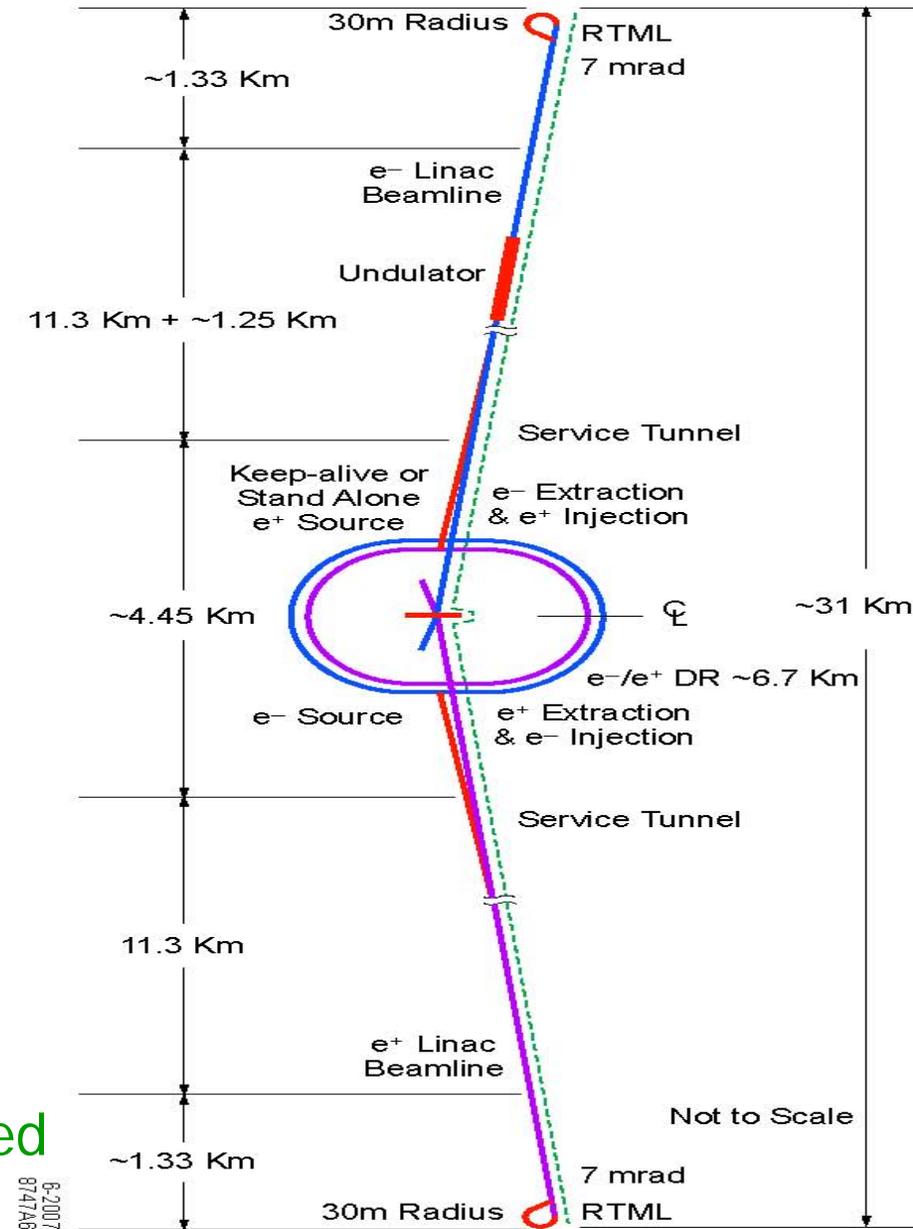


RTML Schematic (RDR)

Note: e- and e+ RTMLs have minor differences in Return line (undulator in e-linac side), they are otherwise identical.



- *Transport Beam from DR to ML*
 - *Match Geometry/Optics*
- *Collimate Halo*
- *Rotate Spin*
- *Compress Bunch*
- *Preserve Emittance*
 - *vertical norm. emittance < 4nm*
- *Protect Machine*
 - *3 Tune-up / MPS abort dumps*
- *Additional constraint:*
 - *Share the tunnel with e-,e+injectors*
 - *Need to keep geometries synchronized*

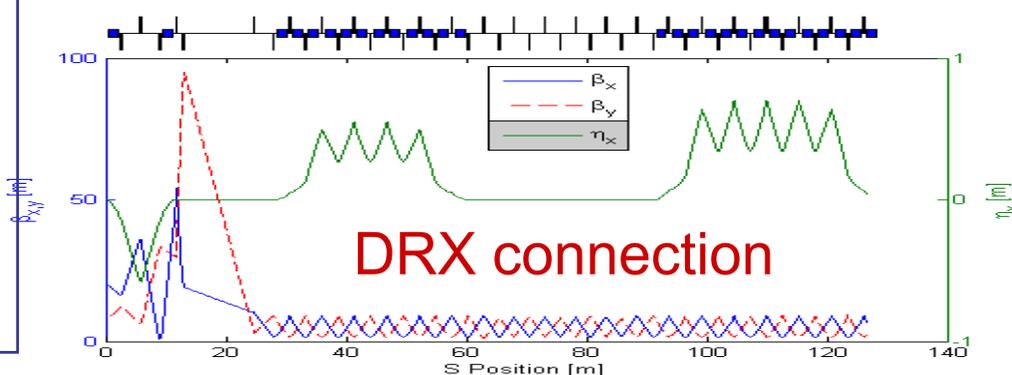
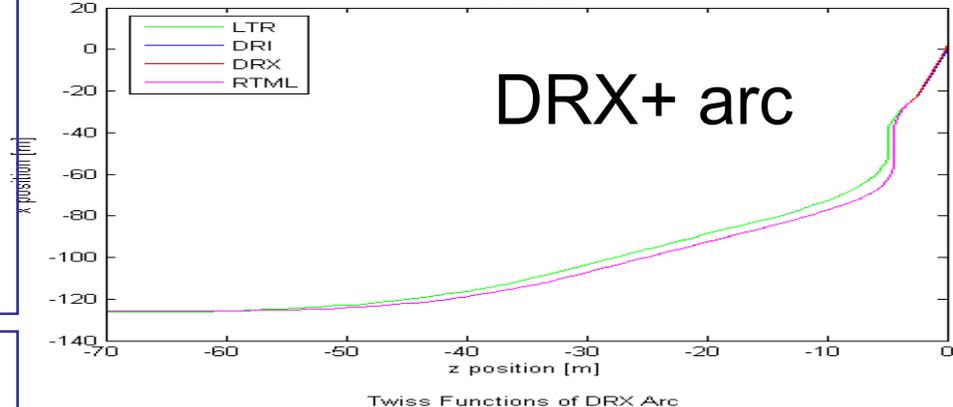
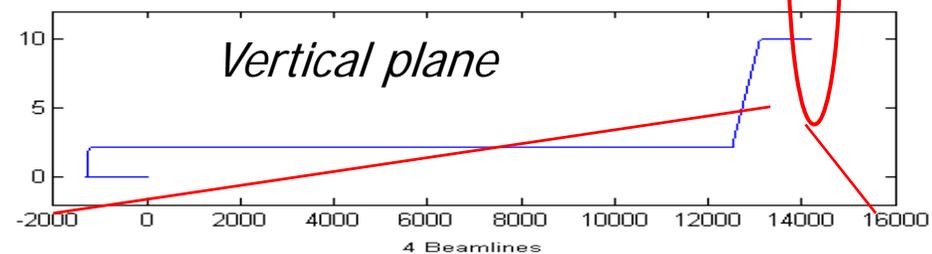
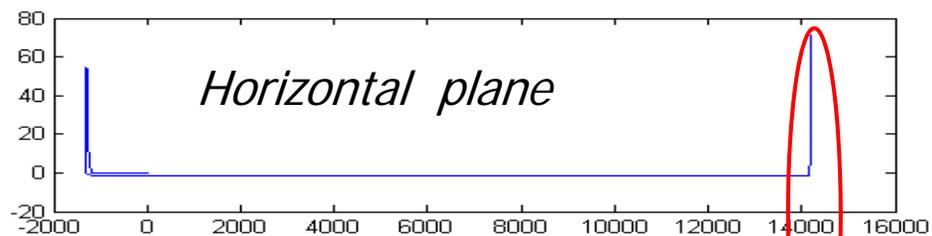




RTML Optics Design (RDR)

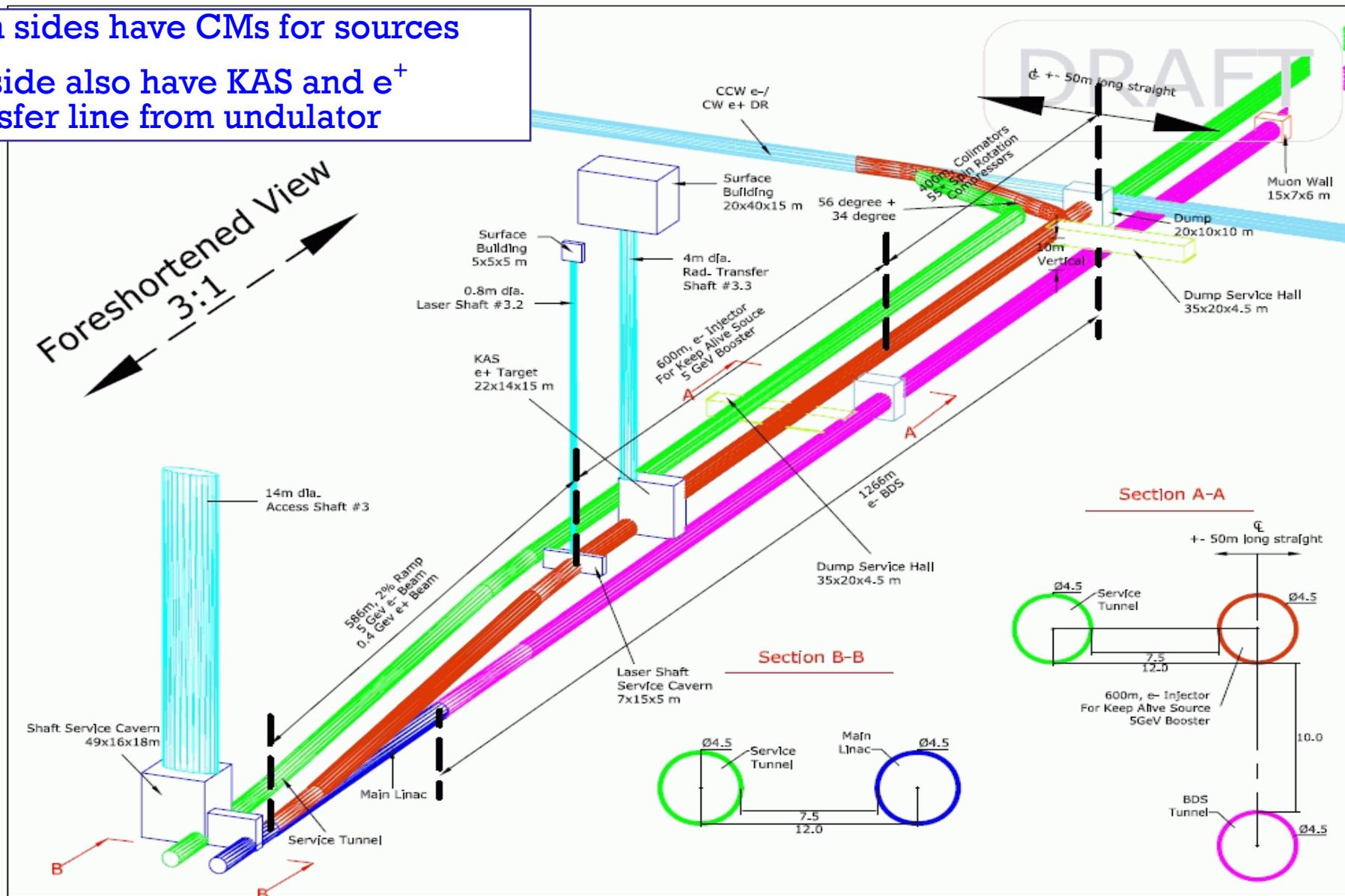
- Horizontal Arc out of DR ~ 1.1 km straight
 - In injector tunnel
- “Escalator” ~ 0.6 km vertical dogleg down to linac tunnel
- Return line (weak FODO lattice) ~ 13 km
 - In linac tunnel
 - Vertically curved
- Vertical and horizontal doglegs
- Turnaround
- 8° arc in spin rotators
- BCs are net straight
- ML launch

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



DR connection (RDR)

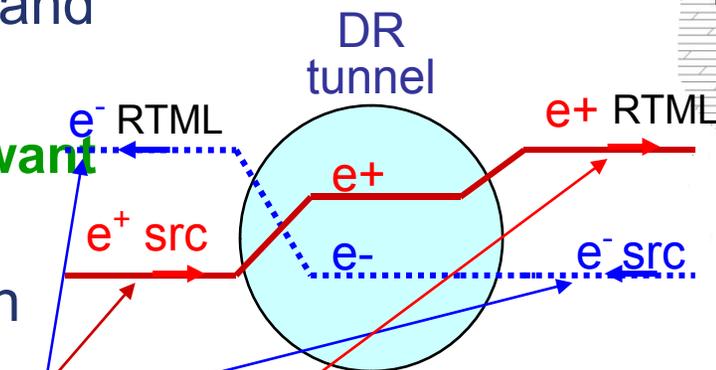
- Both sides have CMs for sources
- e^+ side also have KAS and e^+ transfer line from undulator



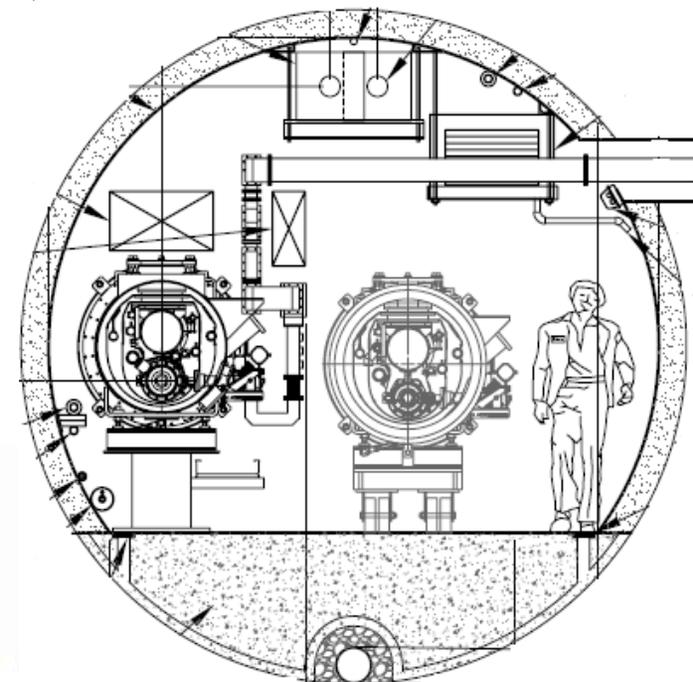
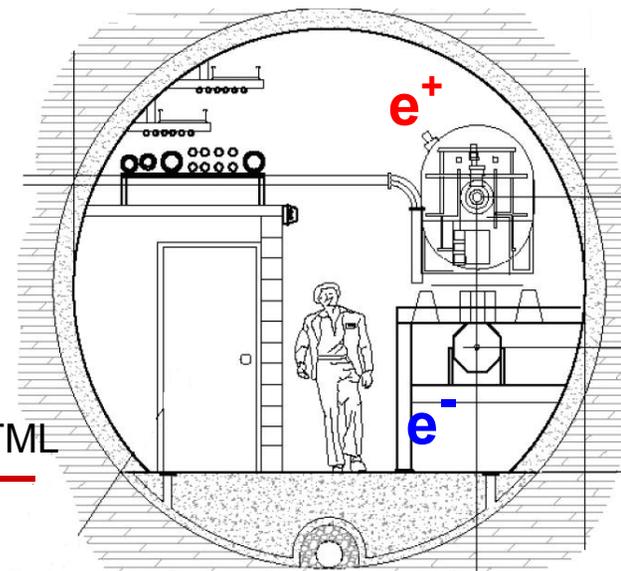
DRX Connection

- 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



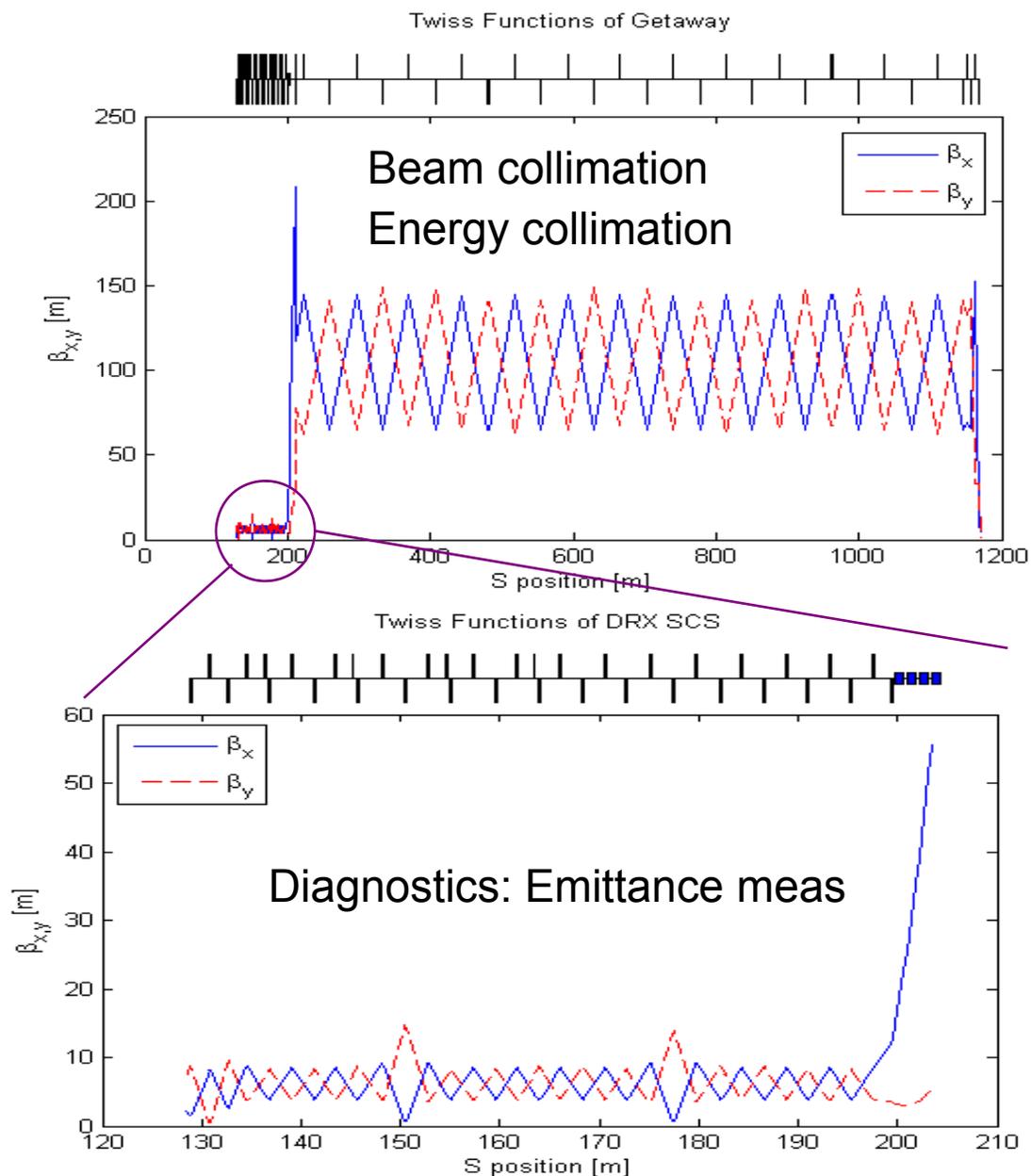
ML Tunnel - 2.14 m Vertical beam separation



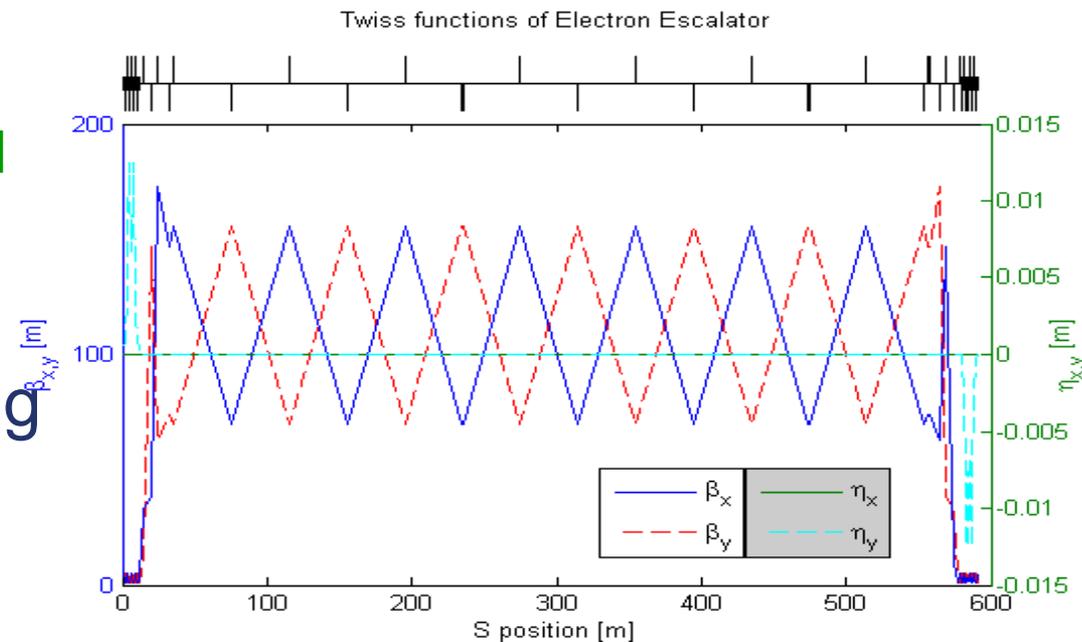
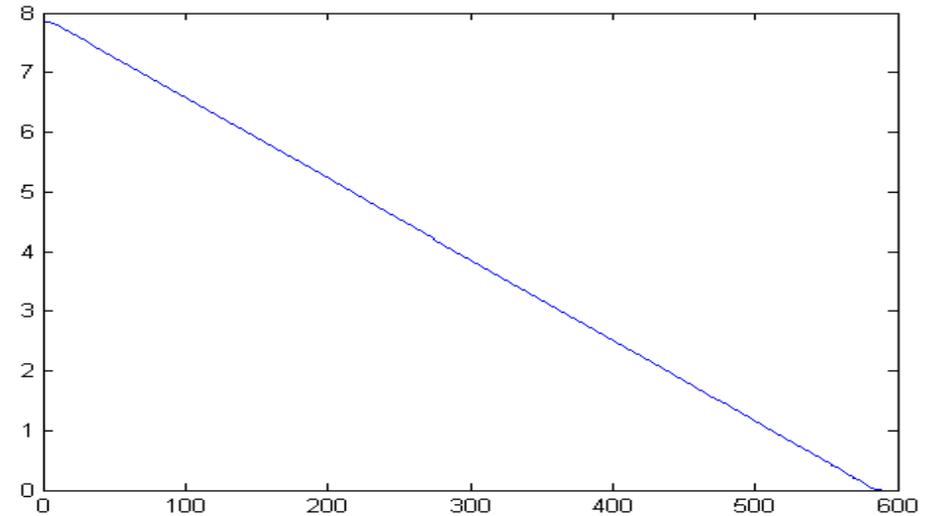


“Getaway” Straight (or “DR Stretch”)

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

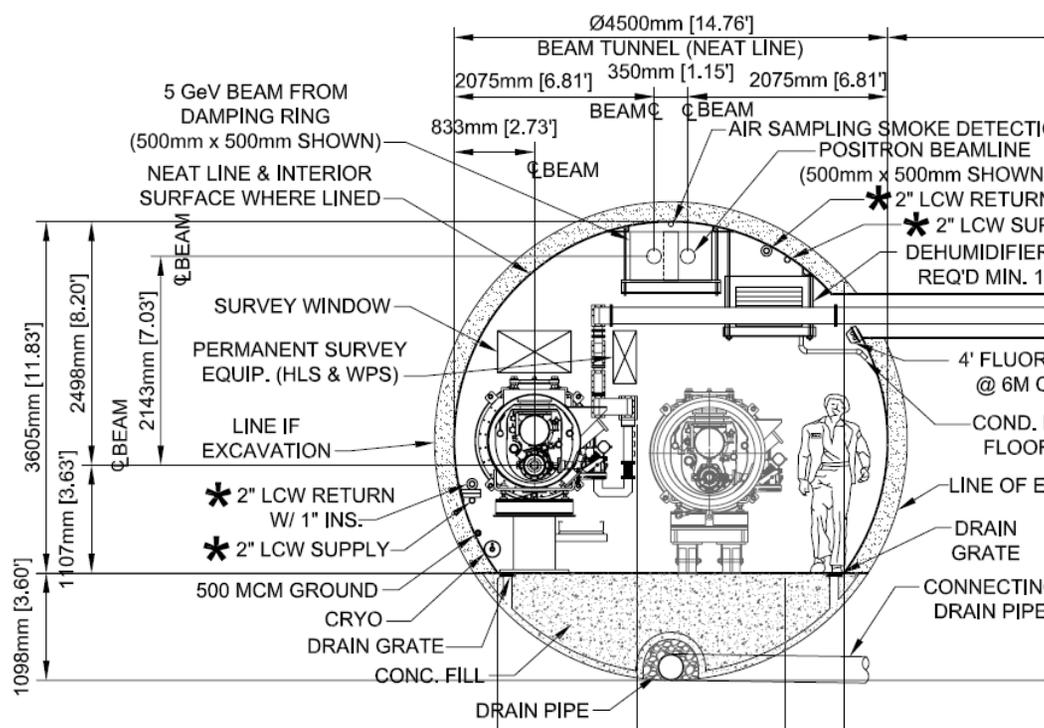
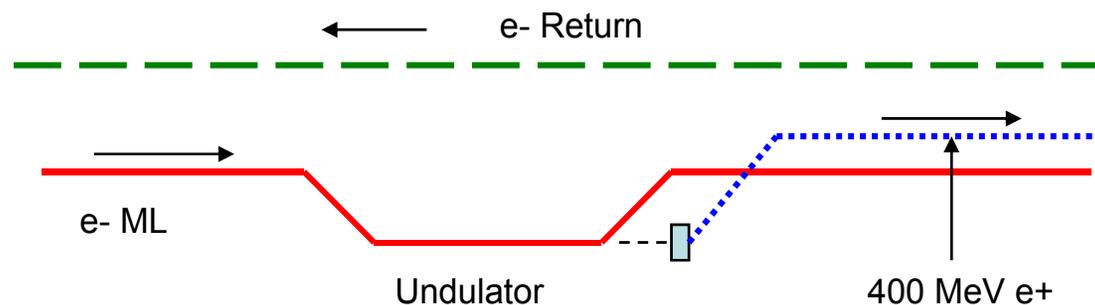


- Vertical dogleg
 - Descends 7.85 meters over ~590 m
 - Uses 2 vertical arcs separated by weak FODO lattice
- Good conceptual design
 - Escalator-linac tunnel connection does not match CFS design
 - Uses Keil-style eta matching
 - Beta match between “strong” and “weak” lattices not great
 - Positron return line conflicts?
- Need to make match according CFS (new?) design



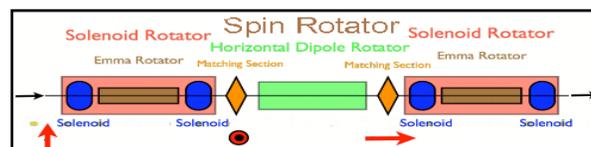
Return Line

- Weak FODO lattice at ML ceiling elevation (1Q/~36m)
- 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

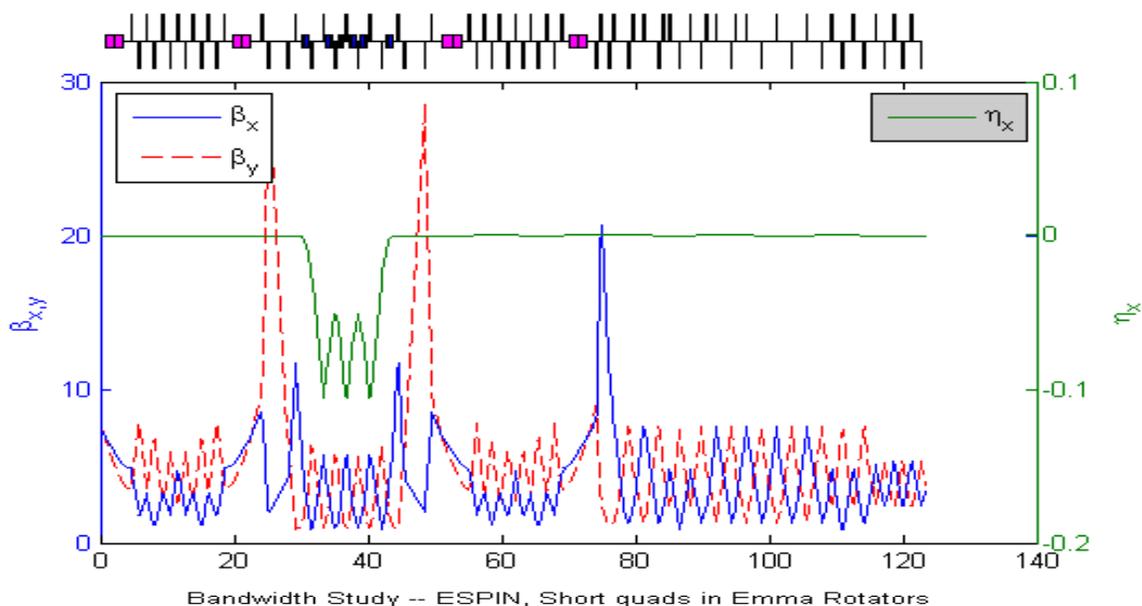


Spin Rotation

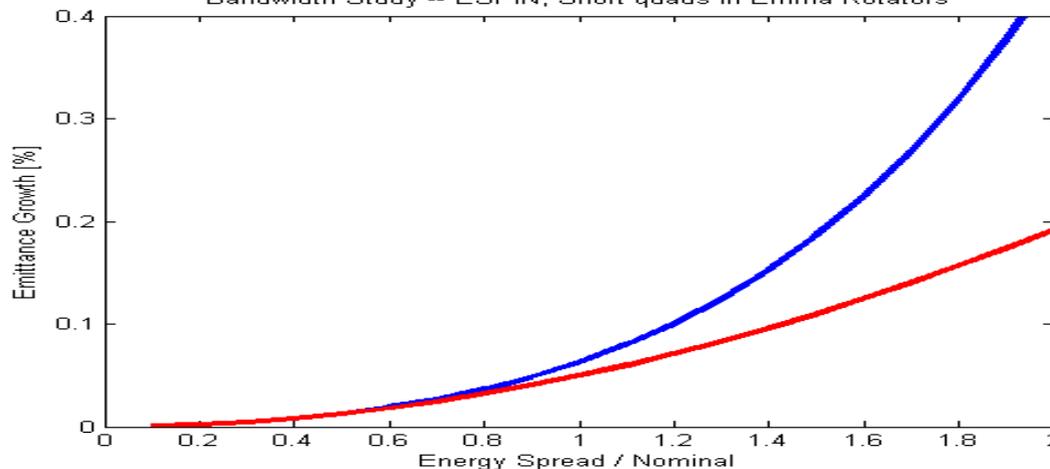
- Design based on Emma's from *NLC ZDR*
 - **2 solenoids with Emma rotator between them**
 - Rotate spin 90° in xy plane while cancelling coupling
 - **8° arc**
 - Rotate spin 90° in xz plane
 - **Another 2 solenoids + Emma rotator**
- Basic design seems sound
 - **Very small loss in polarization from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



Twiss Functions of Spin Rotator



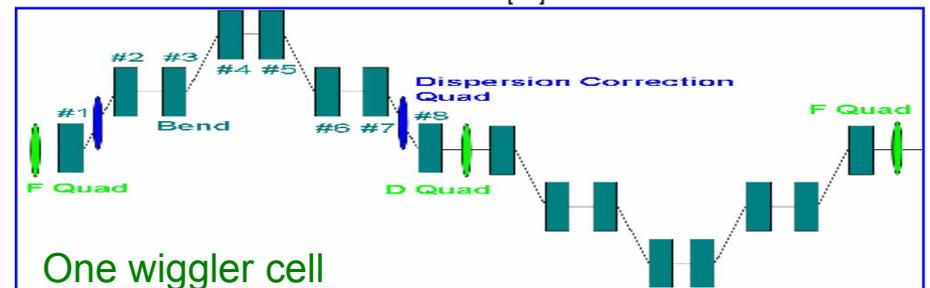
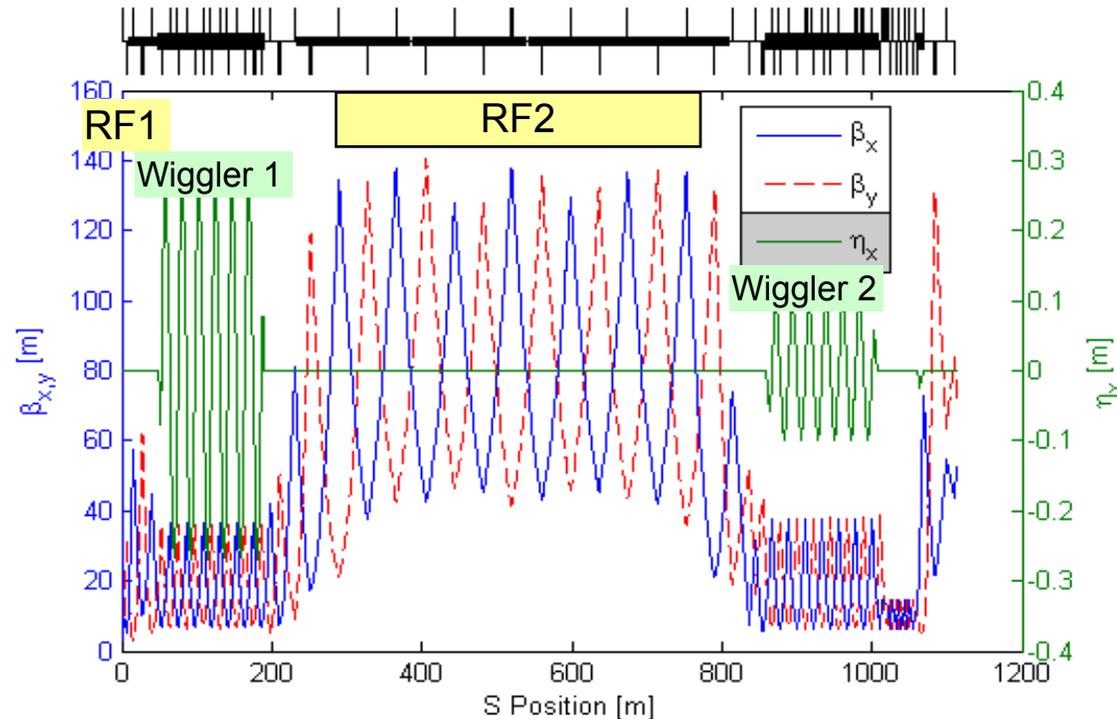
Bandwidth Study -- ESPIN, Short quads in Emma Rotators





ILC Baseline 2-stage Bunch Compressor

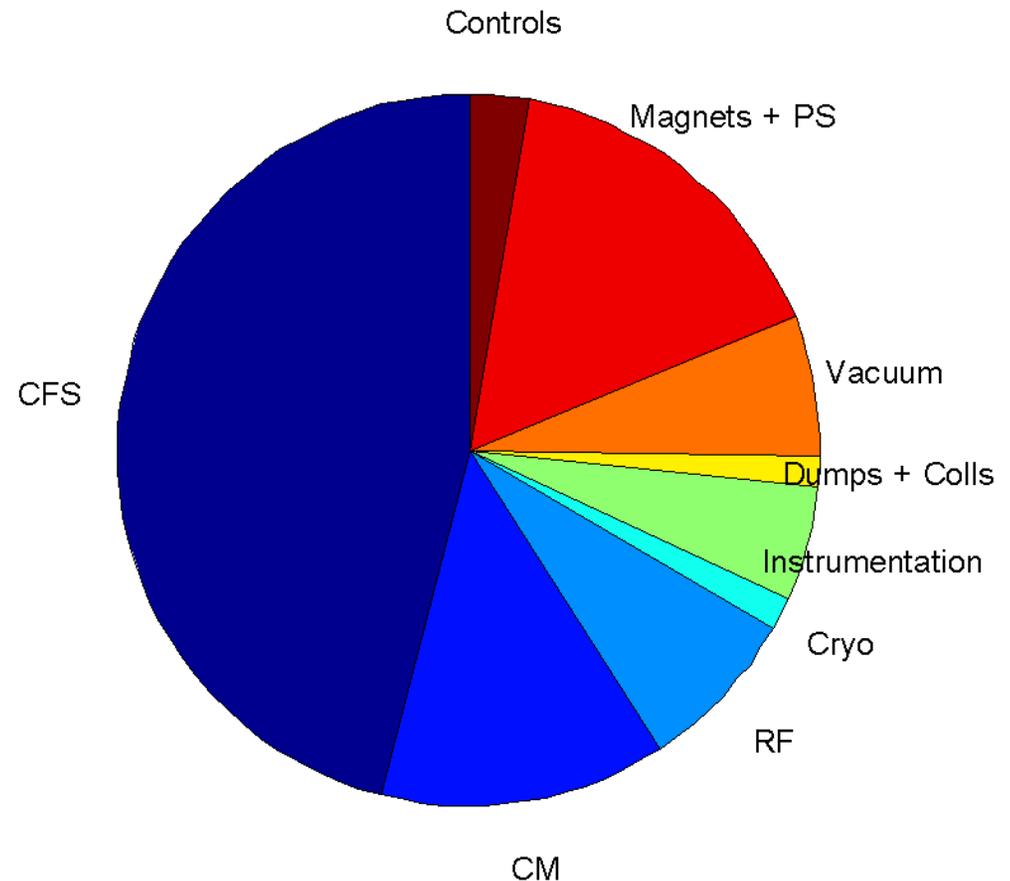
- Longitudinal emittance out of DR:
 - **6mm (or 9 mm) RMS length**
 - **0.15% RMS energy spread**
- Want to go down to 0.2-0.3 mm
- Need some adjustability
- Use 2-stage BC to limit max energy spread
 - **1st: Compress to 1 mm at 5 GeV**
 - **2nd: Accelerate to 15 GeV and Compress to final bunch length**
- 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

- 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**





RTML Risk Analysis (2007)

		Risk	Cost
(1) Packing fraction to tight (Turn-around)	Q*	Med	12
(2) Beam Motion at end of RTML Too Large		Low	2
(3) Optical Effects in RTML		Low	5
(4) Space charge tune shift in RTML		Med	5
(5) Ion Instability in e- line		Low	5
(6) Collimator Wakefields		Low	5
(7) Emittance Dilution : Magnetostatics		High	10
(8) Emittance Dilution Pitched RF Cavities		High	20
(9) Bunch Compressor Phase Stability		Med	60
(10) Performance of Feed-forward		Med	?

*Q - CONCERNS REQUIRING SIGNIFICANT CF&S MODIFICATIONS AND DECISIONS EITHER DURING EDR OR SHORTLY THEREAFTER



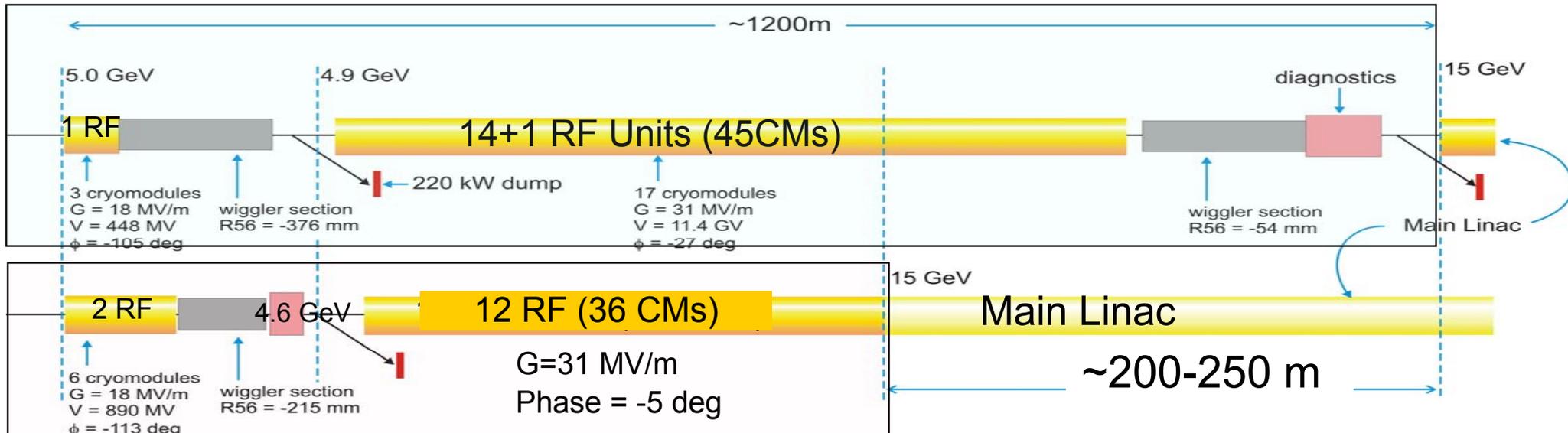
Minimum Machine configuration

- Cost-reduction strategy (2009)
- Major changes vs. Baseline configuration
 - **ML**
 - removal of the underground service tunnel (single underground tunnel housing the accelerator);
 - klystron cluster concept (RF power distribution alternative);
 - processed water cooling specifications (higher ΔT solutions).
 - **DR**
 - Shorter DR for Low power option (1320 bunches vs. 1625)
 - **RTML**
 - Single stage BC, Remove one Extraction Line with dump
 - **Source and BDS Integration (Central Region)**
 - Move undulator to 250 GeV
 - 10% KAS
 - Sources, undulator and 5 GeV e⁺/e⁻ Linacs in BDS tunnel
 - Shorter BDS



RTML changes in Minimum Machine Configuration

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



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

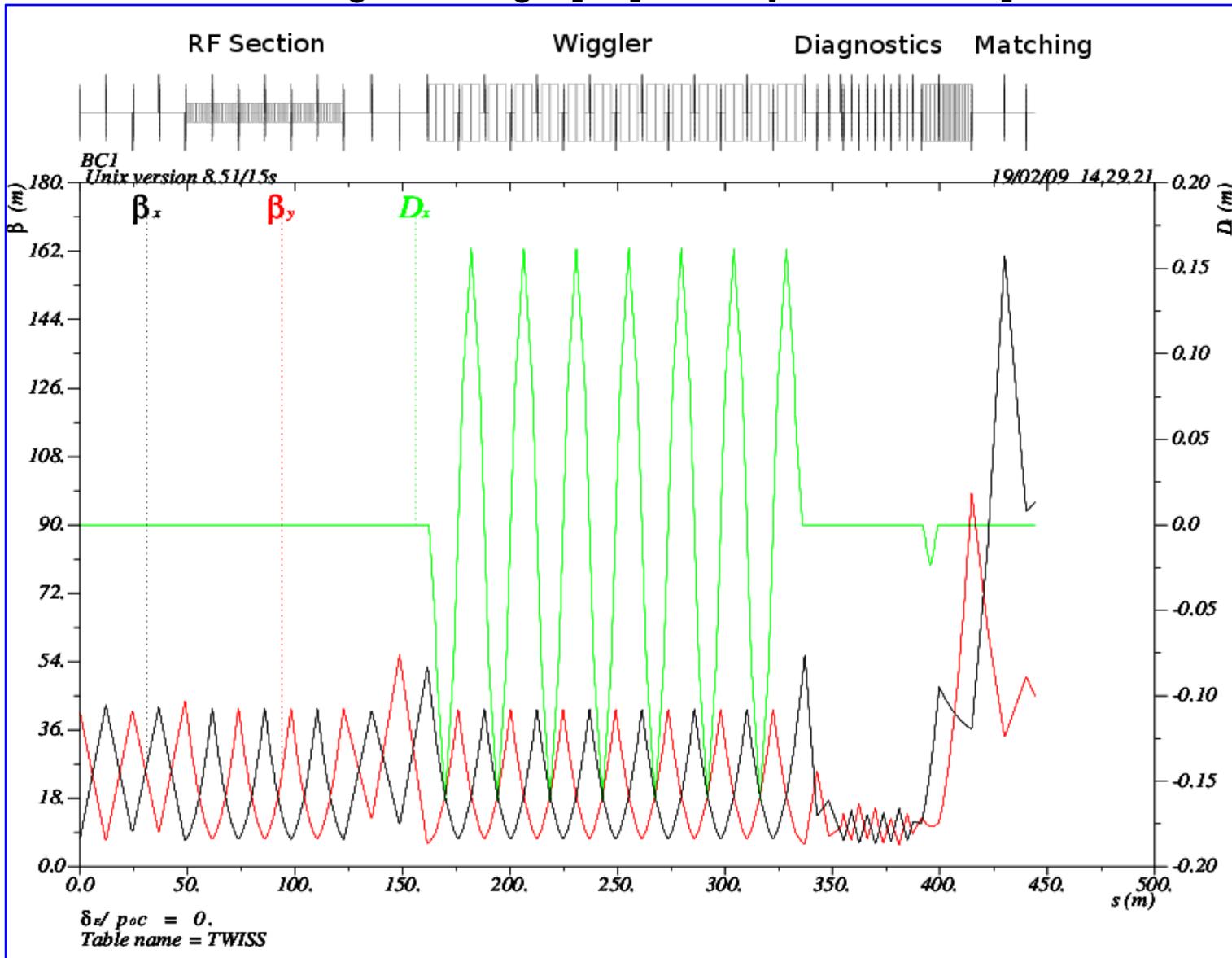
Changes from RDR: 9(6)mm \rightarrow 0.3(0.2)mm to 6mm \rightarrow 0.3mm (x20 compression)

- ❖ 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 \rightarrow 0.3 mm

Total length = 423 m

- RF Section
- Wiggler
- Diagnostics & EL
- Matching section

Final energy 4.3 GeV

Pre-Linac:

4.3 GeV \rightarrow 15 GeV

PT lattice is modified to improve performances:

- **CM-3 \rightarrow CM-4**
- **Wiggler \rightarrow wiggler**
2007 PT/Seletskyi

(see: A.Latina talk)



Design Characteristics

- The beam properties at injection are:

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

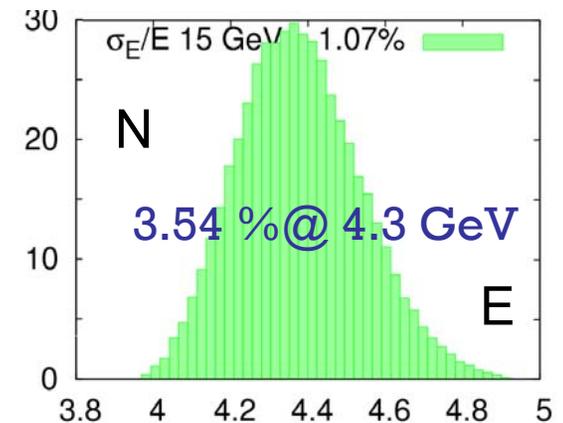
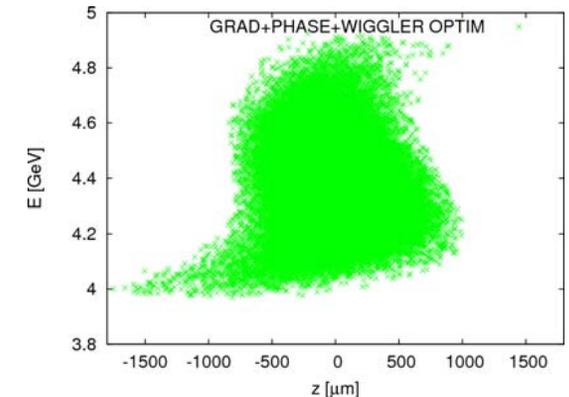
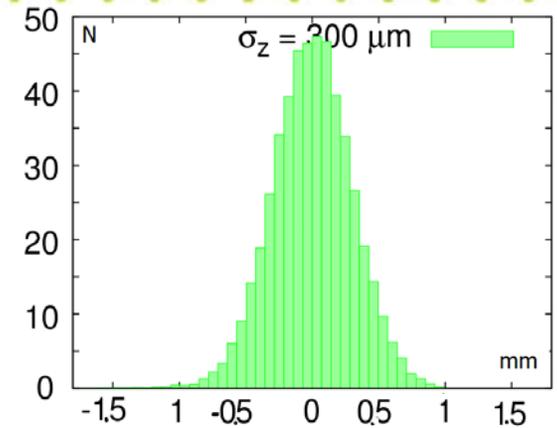
- Properties of the bunch compressor are:

Integrated voltage	1275.2 MV @ 1.3 GHz
Cavity gradient	≈ 25.6 MV/m
Accelerating Structures	48
Phase	-119.5 degrees
Energy Loss	627.9 MeV
R_{56}	-147.5 mm
Total length	~ 433 m

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

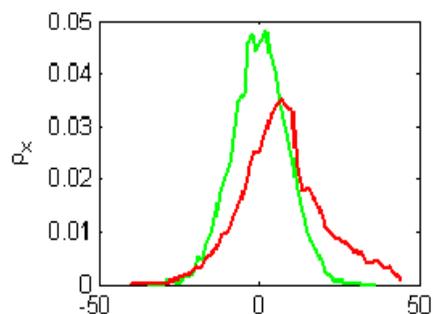
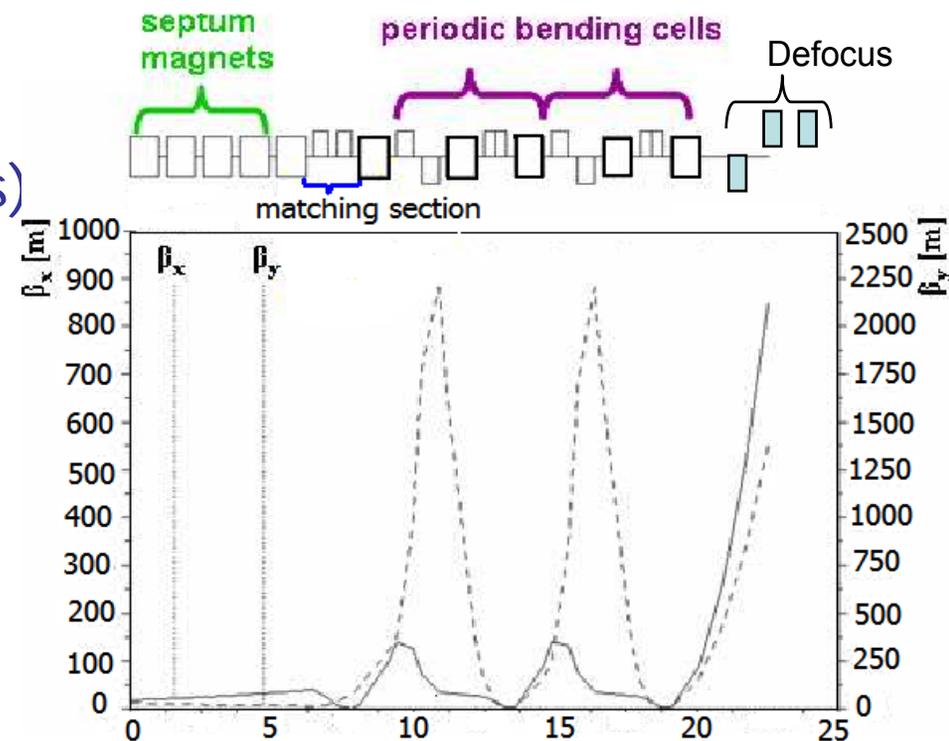
⇒ Desired final bunch length : 0.3 mm

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

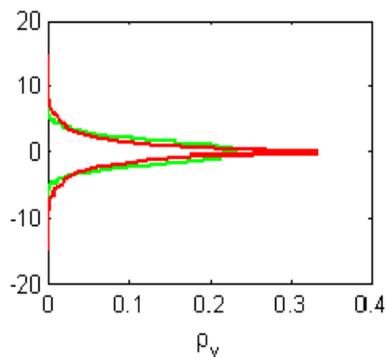
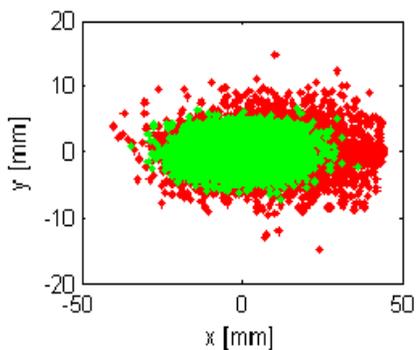


Removing of ELBC2 and dump

- 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

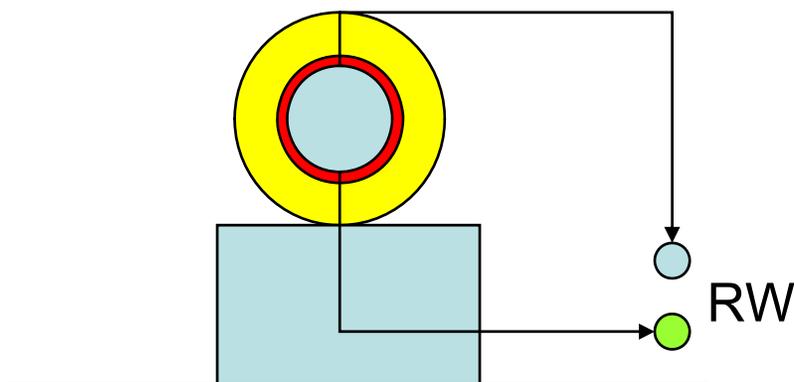


	2 coll	1 coll	No coll
Final quads	1T 45mm	1T 45mm	2T 80mm
Collimat	5.2 kW 14.1kW	5.2kW	No coll
Dump window	12.5 cm	30 cm	100 cm



~220kW Aluminum Ball Dumps

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



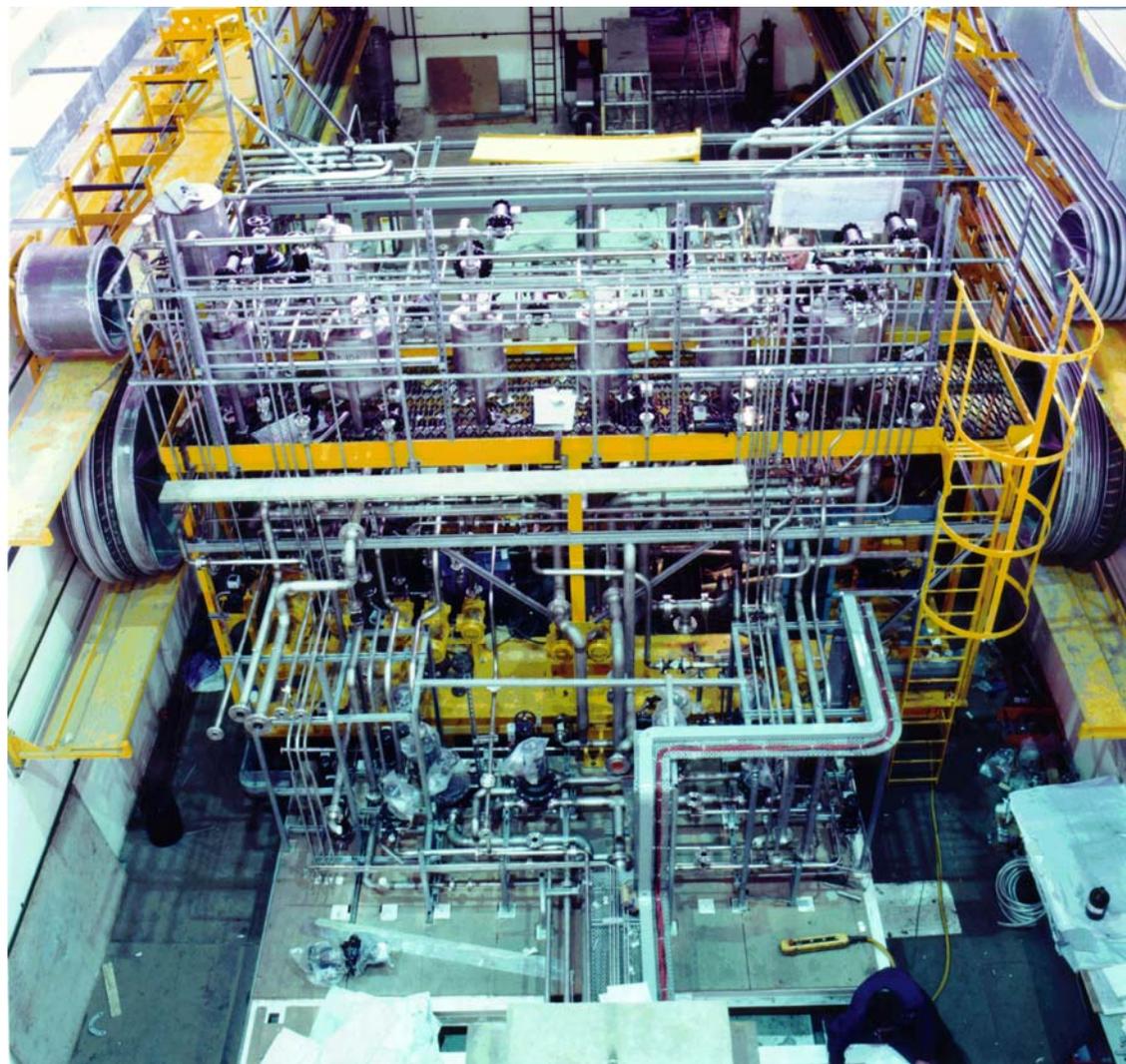
Cost (~\$1M each) is dominated by:

- 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**

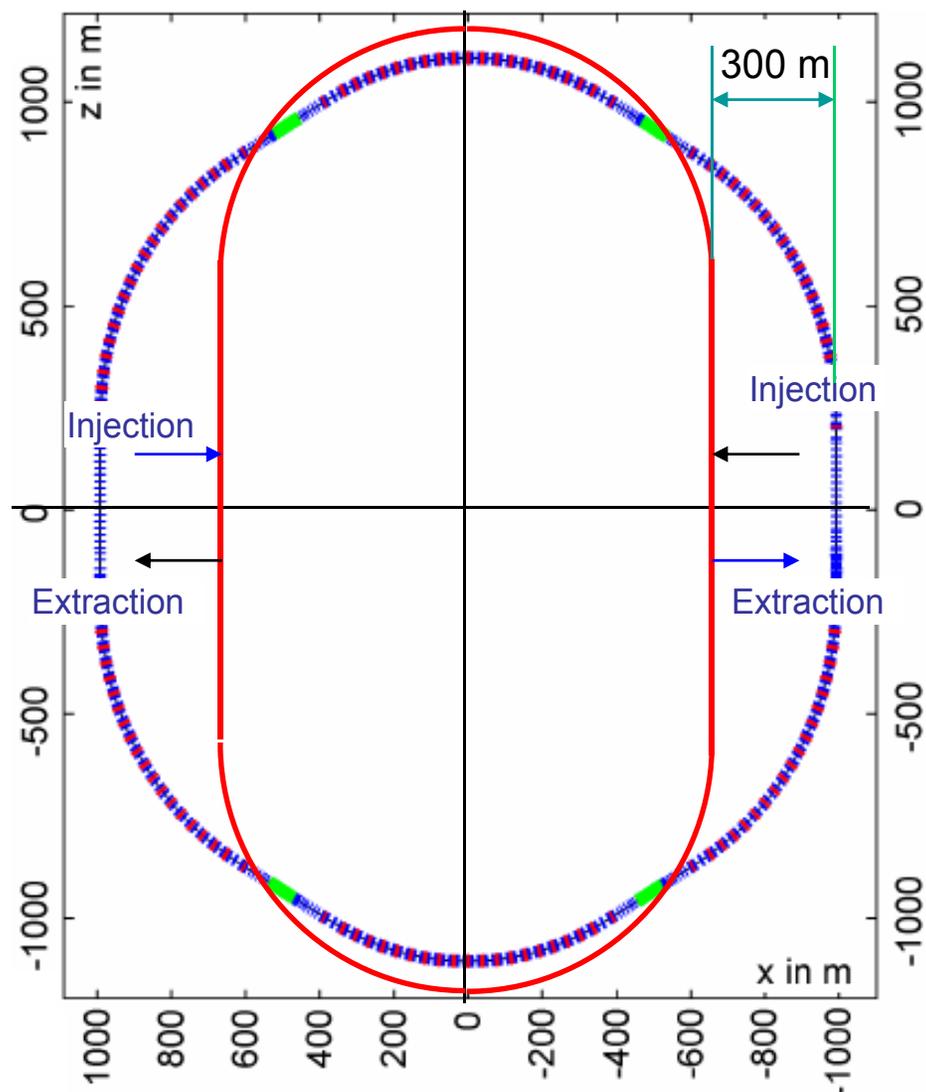


Re-design of the ELBC1

- **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.**

See more details in S.Seletskiy talk

ILC New Damping Ring



Layout of the ILC Damping Ring

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

- New ILC DR lattice is shorter.
- Bunch length = 6 mm; Energy spread = 0.13 %
In old RDR design:
 - 9 mm (easy)
 - 6 mm (more challenge)
- 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
- Compact DR (S.Guiducci, DESY AD&I)
 - SB 2009 (DSB) – 3.2 km (half-number of bunches)



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**

- New configuration of the Central Area and DR design will require 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)



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)

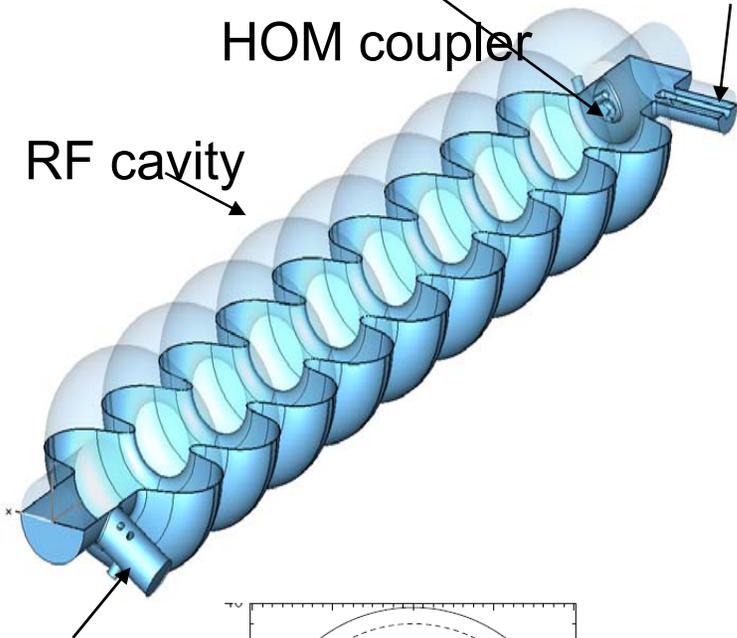
- Effect of coupler RF kick & wakes is not included
- Dynamic effects are not included
- Emittance growth is large (pre-RDR budget 4nm, might be $\leq 10\text{nm}$)
- Need further studies to reach goal for emittance growth
- Cross-checking with different codes (important)



Simulations of Coupler Kick and Wakes

Downstream HOM coupler Main coupler

RF cavity

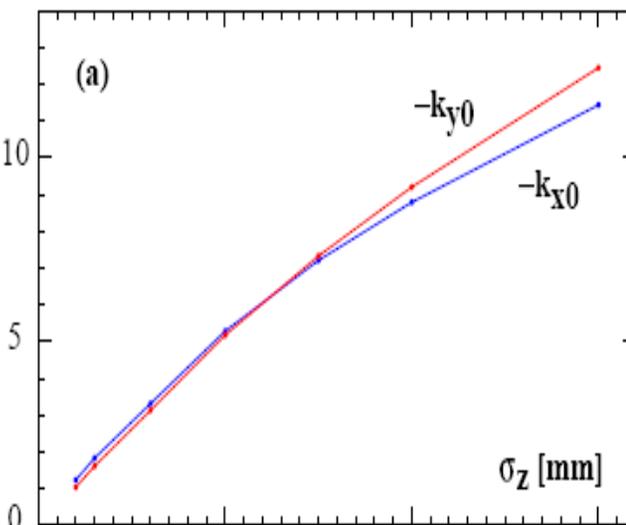


The couplers break the RF field symmetry and cause transverse RF kick and Wakes
 DESY,2007. Simulations DESY/FNAL/SLAC

Total RF KICK	FNAL $Q=3.5 \times 10^6$ HFSS	DESY $Q=2.5 \times 10^6$ MAFIA	SLAC $Q=3.5 \times 10^6$ 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

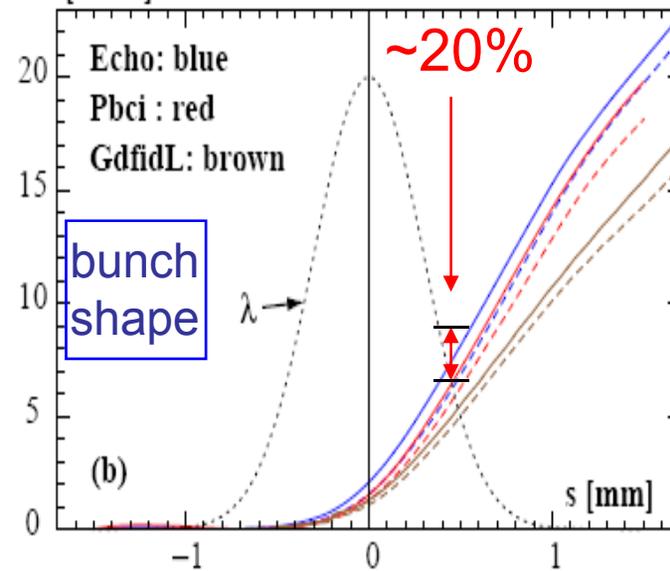
Coupler Transverse Wakefield

k [V/nC]

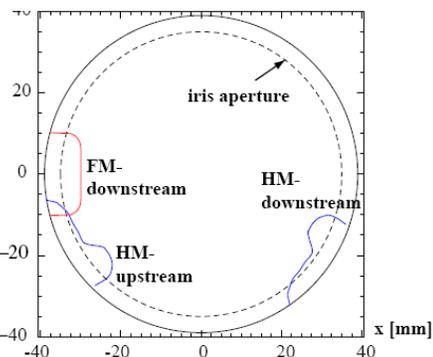


On-axis kick factor vs. σ_z

-W [V/nC]



$W_x(s)$ -solid,, $W_y(s)$ -dashed for $\sigma_z = 300 \mu\text{m}$.



Upstream HOM coupler

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

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

New proposal !!!

Girder Pitch optimization



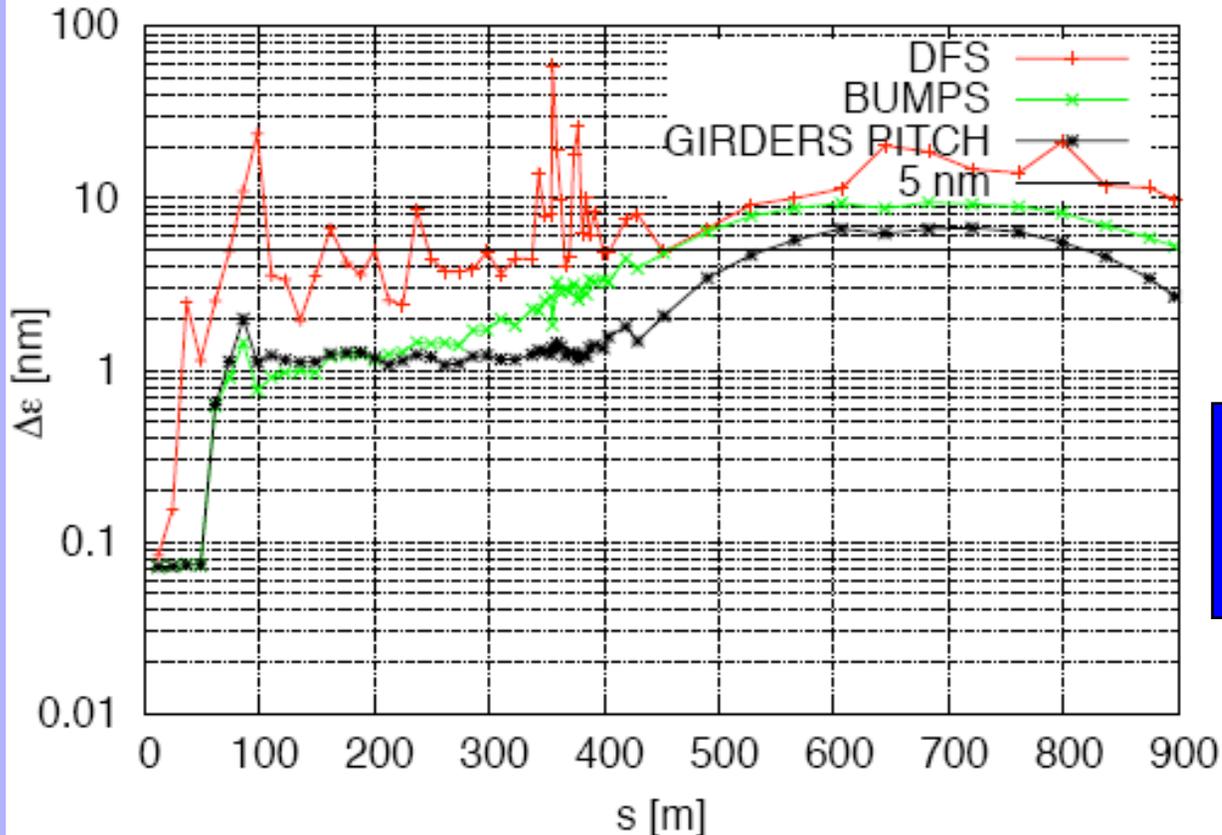
Y- micromover:

- Range 300 μm
- Step size 10 μm

#N of adjustable CM's

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

BC1S: Couplers+Misalign, $\Delta\phi=5^\circ$, $\text{BPM}_{\text{res}}=1\mu\text{m}$, wgt=256



10 nm
5 nm
2.6 nm

2.2 nm
from
coupler
only

● Emittance Growth along the beamline, 1 machine

- BC1S (incl. diagnostics+matching+Pre-linac (5 \rightarrow 15 GeV))
- Standard misalignments (300 μm /300 μrad); 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 misalignments and couplers seems to be compensated both for BC1S and BC1+BC2
- Girder pitch optimization is very effective to counteract coupler kicks, both for BC1S and BC1+BC2
- In BC1S, Crab Cavity seems to be similarly effective, but it would require a new hardware and slight redesign of the cryomodule



Stray magnetic fields (2)

RTML requirement for high frequency stray magnetic fields:
 $B < 2 \text{ nT}$ (K.Kubo, 2006)

Magnetic field examples

- Commercial SC solenoid - 10 Tesla (1 e+1)
- Earth magnetic field - 50 micro-Tesla (5 e-5)
- Cell phone - 100 nano-Tesla (1 e-7)
- Beating human heart - ~ 10 pico-Tesla (1 e-11)

Frequency dependence

- < 0.1 Hz (can be compensated by control system)
- > 100 kHz (attenuated in the structure)

Classification (following F.R.T.)

- 60 Hz and its harmonics (near-coherent with 5-Hz pulsing)
- Fields from RF systems (coherent with 5-Hz pulsing)
- Others (non-RF technical sources) (uncorrelated with pulses)

Previous work

- “Sensitivity to Nano-Tesla Scale Stray Magnetic Fields”, SLAC LCC Note-0140 (June 7, 2004) → Data from SLC End station B.

Conclusion (for NLC): *we are mostly OK*

- DESY (TESLA TDR study)



Stray Magnetic Field studies 2007 plans

RTML needs to transport low-emittance 5 GeV beam over ~15 km from DR to ML.
RDR requirement on stray magnetic fields in the RTML is less than 2 nT.

Proposal summary:

- Evaluate possible sources of the stray fields; consider effects of correlated and uncorrelated (with the beam cycle) sources.
- Survey the existing sites to verify assumptions in that analysis.
- If the result of this study would require, propose shielding approach for the beam pipe.
- Develop a stray field model suitable for incorporation into linac simulation frameworks.

Implementation plan (2007):

- Anticipated duration of this work is two years. The scope of the work can be subdivided in the following interleaving parts:
 1. Evaluate the expected magnetic field from multiple sources in the RTML environment:
 - 1.1 Correlated sources: RF systems.
 - 1.2 Power-line (60 Hz) and its harmonics.
 - 1.3 Miscellaneous random noise
 2. Survey multiple sites in existing installations (Fermilab, CERN, SLAC, etc..) to verify assumptions in stray field model. To accurately measure magnetic field in a wide range of frequencies and amplitudes from 10 microtesla (Earth magnetic field) to below nT is a challenge. We will need to develop a system that can perform this task.



Magnetic Stray Fields Studies

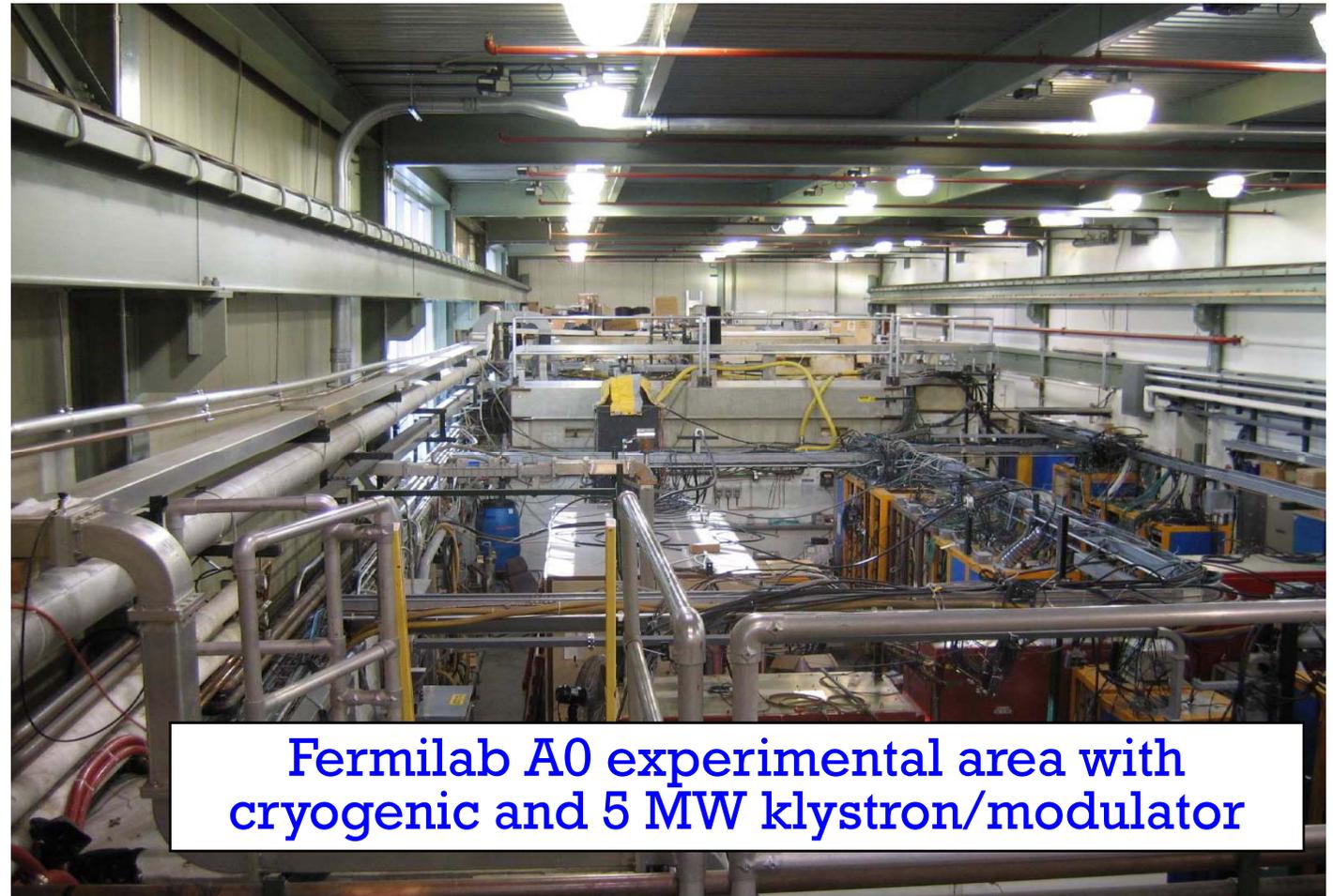
- RTML requirement for stray fields in Return Line $< 2\text{nT}$ ($\text{freq} > 1\text{Hz}$)
- SLAC measurements (at Station A) are promising ($\sim 2\text{nT}$)
- Need more studies for different sites. Stability of 60Hz is an issue

Hardware:

- 3-axis fluxgate magnetometer
- 0.1mT full scale
- DC to 3 kHz
- 20 pT/sqrt(Hz)

Measurement:

- Near klystron
- In shielded cave (20m from kly)
- Klystron On/Off

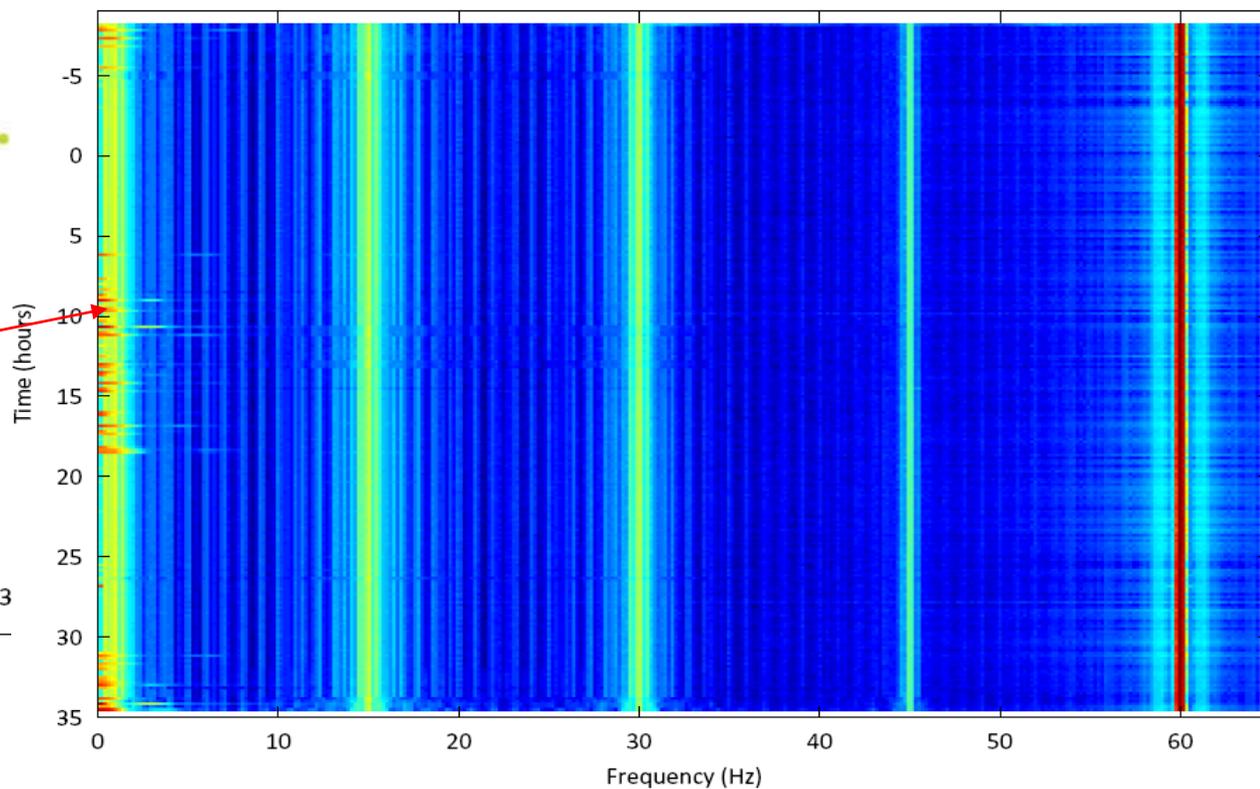


Fermilab A0 experimental area with cryogenic and 5 MW klystron/modulator



Stray magnetic fields measurements at A0:

Spectrogram and Integrated spectrum



(A0) Integrated spectrum w/o 60,180,3

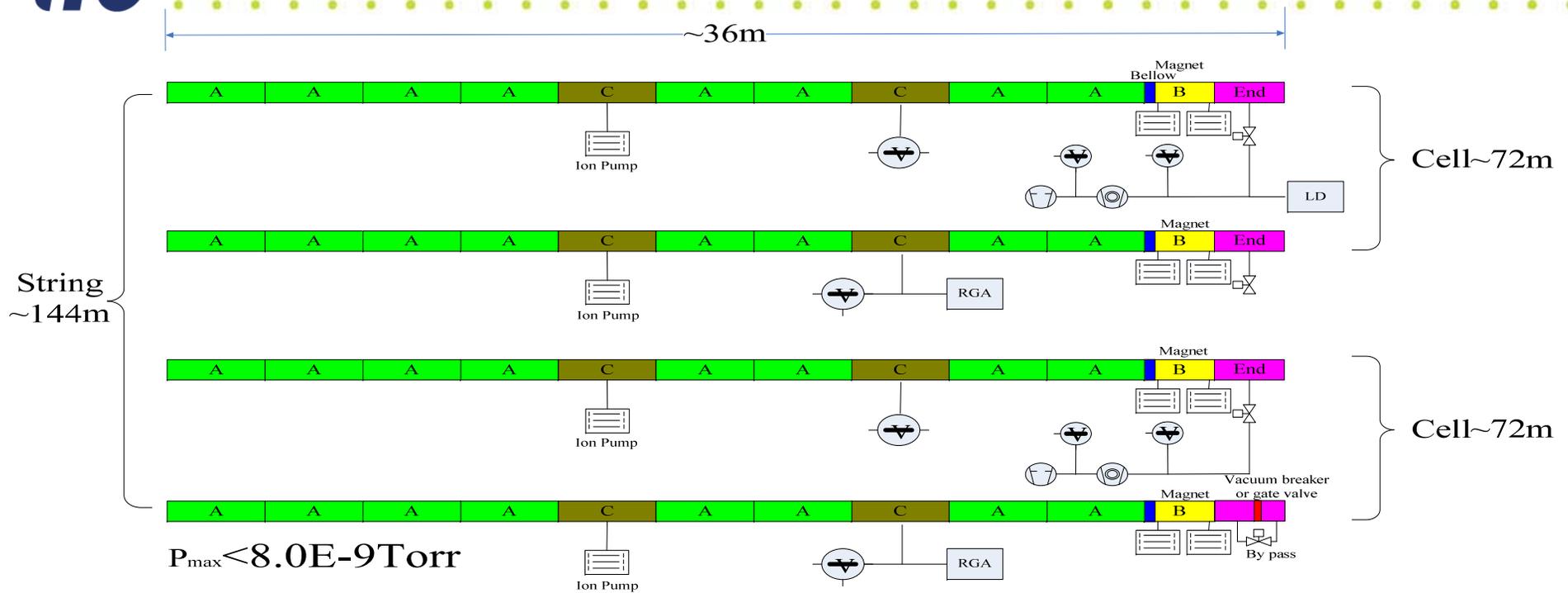


A0 - Noisy place

- 5MW Klystron
- Modulator
- Transformer
- Cryogenic
- Pumps
- Power Supplies
- Tevatron shaft
- Etc...

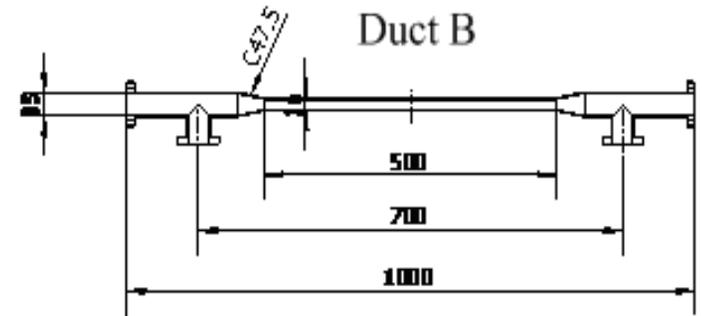


Vacuum system for RTML Return line



- Tight vacuum req. in Return Line (<10nTorr)
 - Passivated SS, ID=35mm, in magnet ID=16mm
 - 86 curved strings followed by 8 straight strings;
 - 1 bellow/1 quad magnet
 - If one string uses vacuum breaker, the next string uses gate valve.
- Final Report with Cost estimation

(Xiao Qiong, IHEP/China)



Slow Ground Motion and Vibration Studies at Fermilab

Goal:

Collect data and Study long term stability (different scales: day, month season, years) of the surface and deep tunnel. Analyze sources of ground motion including technical noise.

- **MINOS near detector**
 - 4 **BINP sensors**
 - 30 meters apart, 100 meters deep
 - 11 months of data
- **North Aurora Mine with 6 sensors**
 - 6 **BINP sensors**
 - 30 meters apart, 100 meter deep
 - 10 months of data with 2 sensor 2 months of data with 6 sensors
- **B0 and D0 interaction regions**
 - 8 **BINP sensors** each interaction region
 - On low beta quads and central detector
 - 5 months of data
- **A-F sectors**
 - 204 **Balluff sensors** one on each SC quad around the Tevatron
 - 30 meters apart
 - 5 months of data

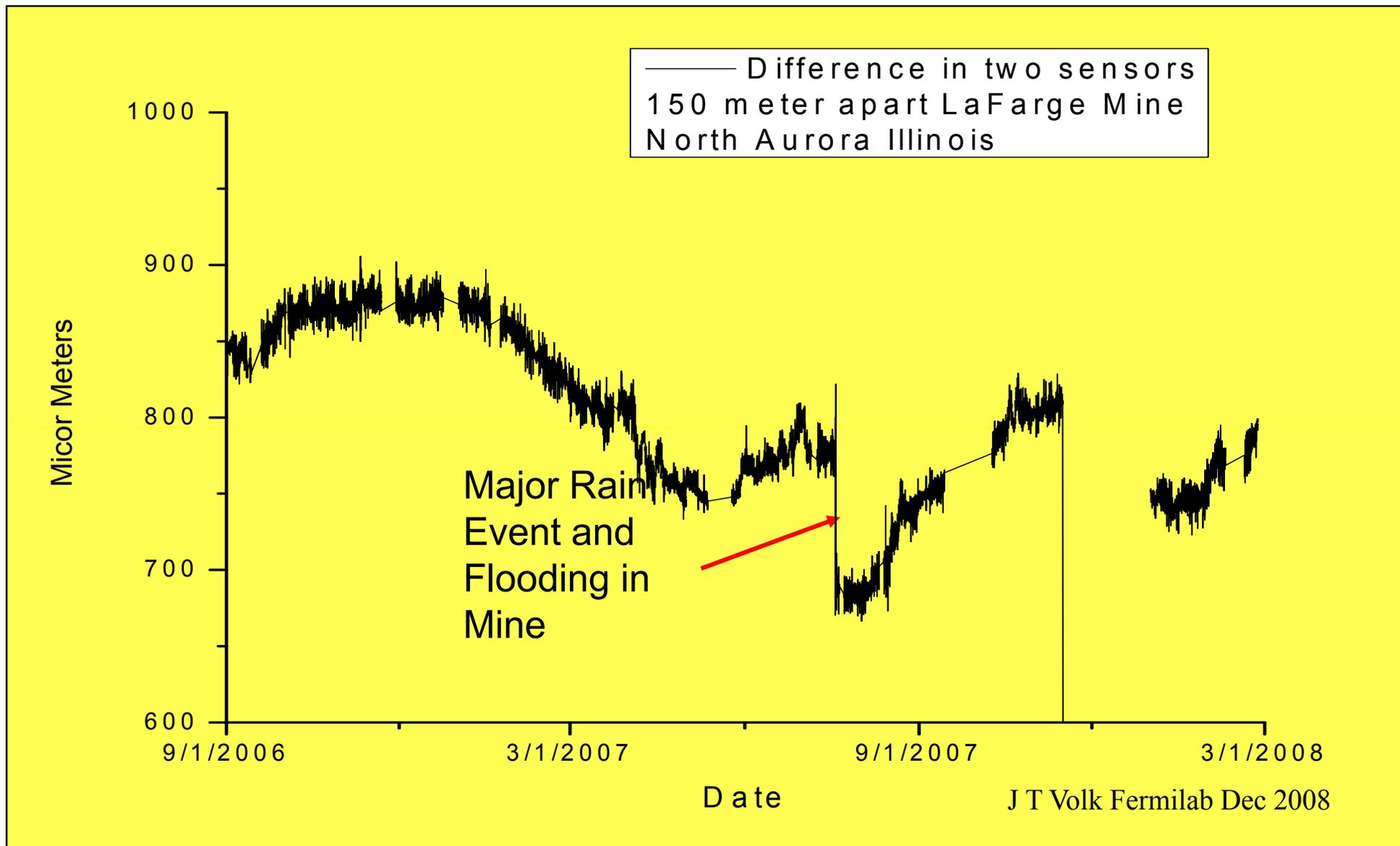


All are two pipe systems



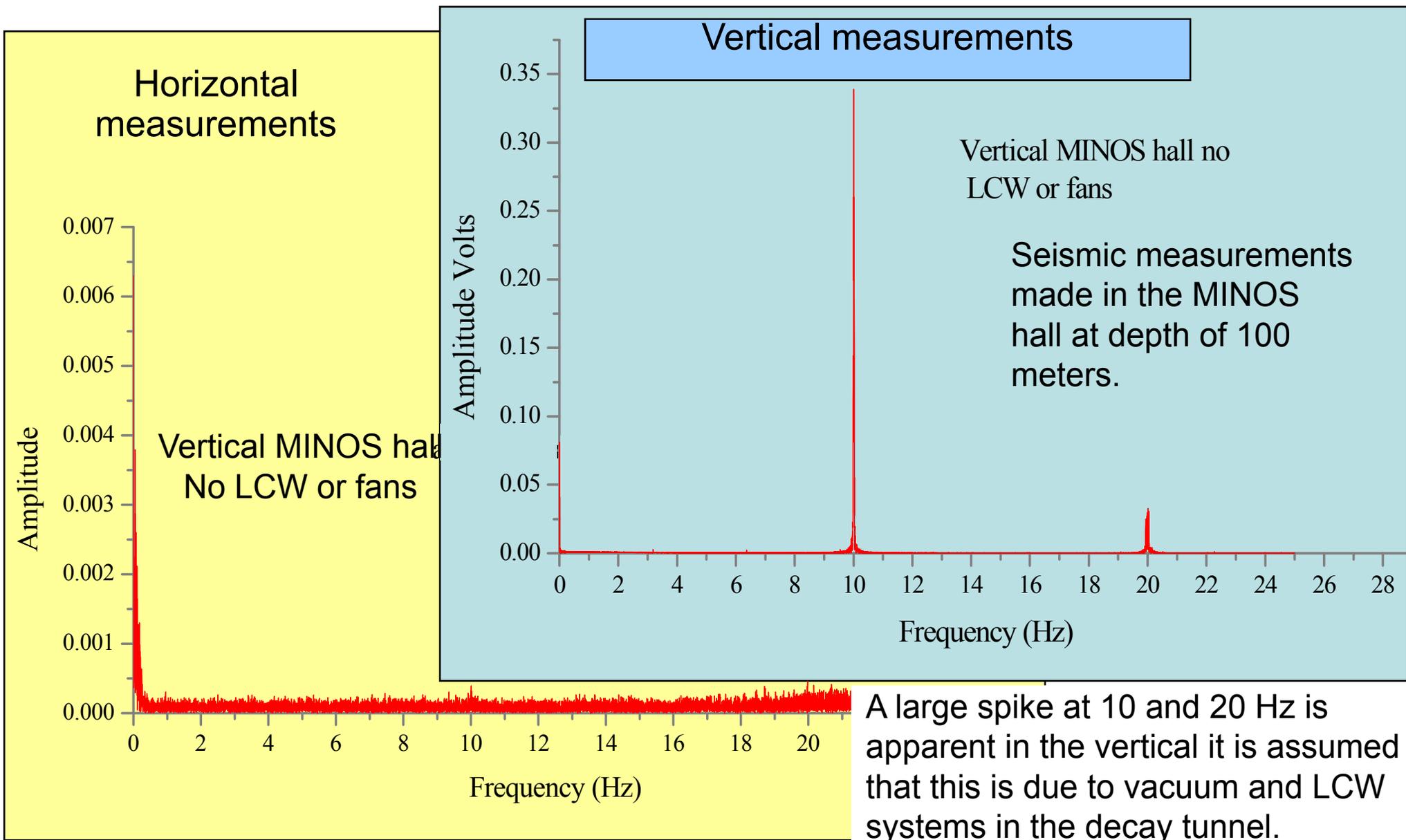
Difference in two sensors 150 meters apart

18 months of data





Seismometer measurements MINOS hall





Ground Motion Summary

- There are several HLS system taking data at Fermilab
 - **Aurora mine; MINOS hall; NML hall.**
- They are accurate and reliable can run for several years.
- They are useful for determining ground motion and tilt.
- The data are available at;
<http://dbweb1.fnal.gov:8100/ilc/ILCGroundApp.py/index>
- There are natural sources of motion: tides, rain fall, earth quakes both large and small.
- There are cultural sources such as sump pumps.
- Plans for new systems in the works.

J.T. Volk, Fermilab

- Single stage Bunch Compressor 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
- Magnetic Stray Fields measurements under way. Results are promising (mu-metal shielding is helpful)
- Slow ground motion data are available for analysis of their effect on emittance growth.