Multi-Tier Accelerator Control System at KEK 8-GeV e^-/e^+ Linac

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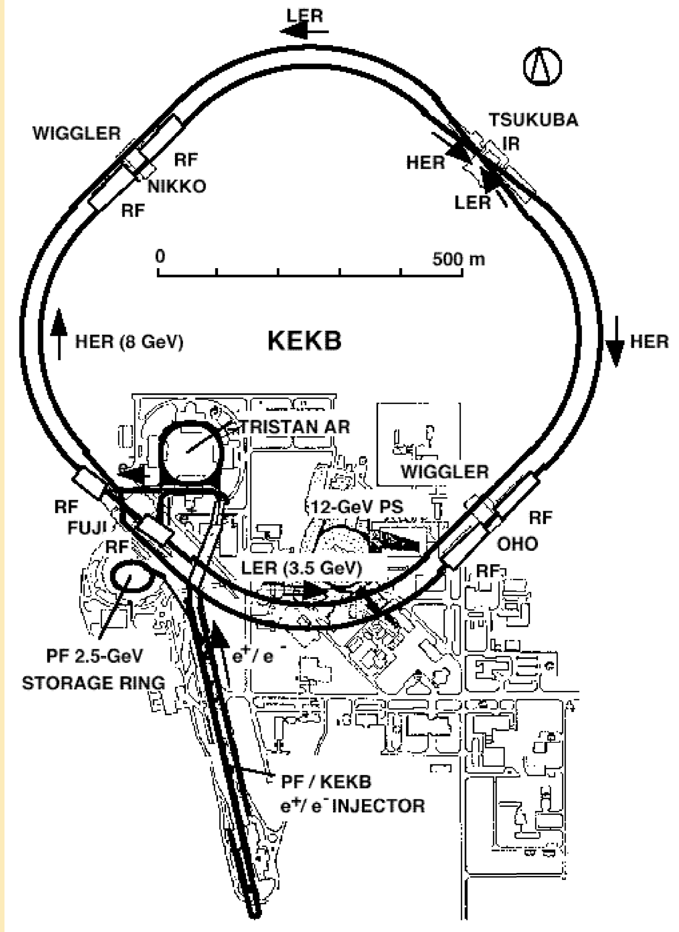
KEK 8-GeV linac injects electron and positron beams into the storage rings at B-factory (KEKB), Photon Factory (PF) and PF-AR. Because of frequent switching between these beam modes, a reliable beam operation of the linac is crucial. For this end a multi-tier control system has been developed and used. The lower-layer servers abstract hardware characteristics and the upper-layer server represents the property of accelerator equipment and the beam to the operation software. It also provides the interface to the downstream storage rings, which are operated by different control systems. The network and computer systems employ high-availability technologies in order to increase the reliability. Using these control services many pieces of operation software have been developed. They all provide essential functions to maintain the stable operation of the linac.

I. Introduction, KEKB Linac

- KEKB Asymmetric Collider Complex and Belle Detector for CP-Violation Study
- Stable and Robust Operation of Linac for Higher Experiment Efficiency
- Many Active Operation Parameters at Microwave Systems, etc.
- Frequent Switching between

KEKB e^-	**8 GeV** 1.28 nC Single Bunch
KEKB e^+	3.5 GeV 0.64 nC Single Bunch
	(Primary e^- **10 nC**)
PF e^-	2.5 GeV 0.2 nC Multibunch
PFAR e^-	2.5 GeV 0.2 nC Multibunch

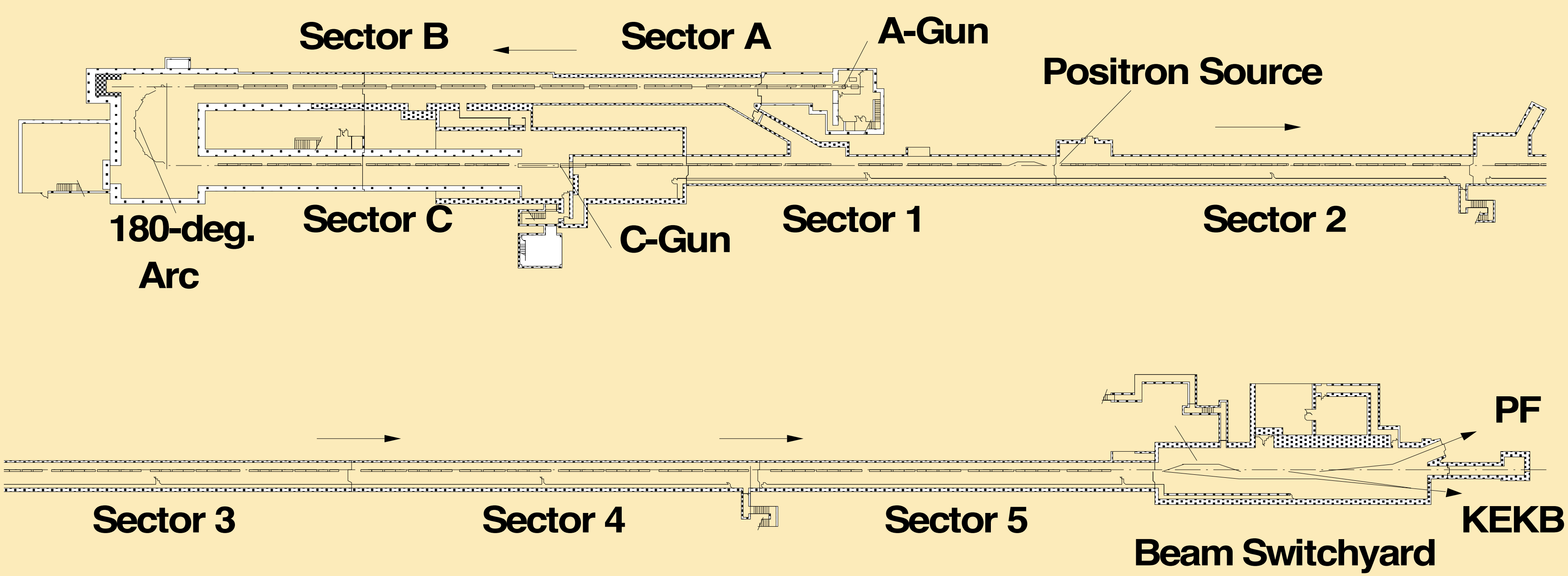


Linac / Ring Upgrade and Commissioning

- 1995 - 1998, Upgrade from 2.5GeV 0.1nC to 8GeV or 10nC
  x2.5 Acceleration Gradient with Energy Doubler (SLED)
  40% Extension with J-shape because of the Site Limit
  Continuing Injection to PF during Construction
- 1998 - Linac Commissioning
  Overcome many Issues on Beam Physics, Stability, etc.
  Indispensable for the Design and Construction
  of the Next Generation Accelerators
- 1999 - Ring Commissioning and Operation
  40 Persons in Commissioning Group (KCG),
  Linac Commissioning Group (LCG, 20) is a part of KCG
  All Linac/Ring Operation from KEKB Control Room
  Struggling with Beam Size, High-Current (Heating)
  Peak Luminosity 30 x 10^{32} /cm^2/sec, Int. Lum. 17/fb
  Improving Daily !!

Layout of KEKB Linac

- 600m Linac with 59 S-band rf Stations,
  Most of them has SLED with Gain of 160MeV
- Double (114MHz, 571MHz) Sub-Harmonic Bunchers
  to Achieve 10ps and 10nC Bunch
- ~700 Magnets for Beam Transport and ~100 BPM's, etc.



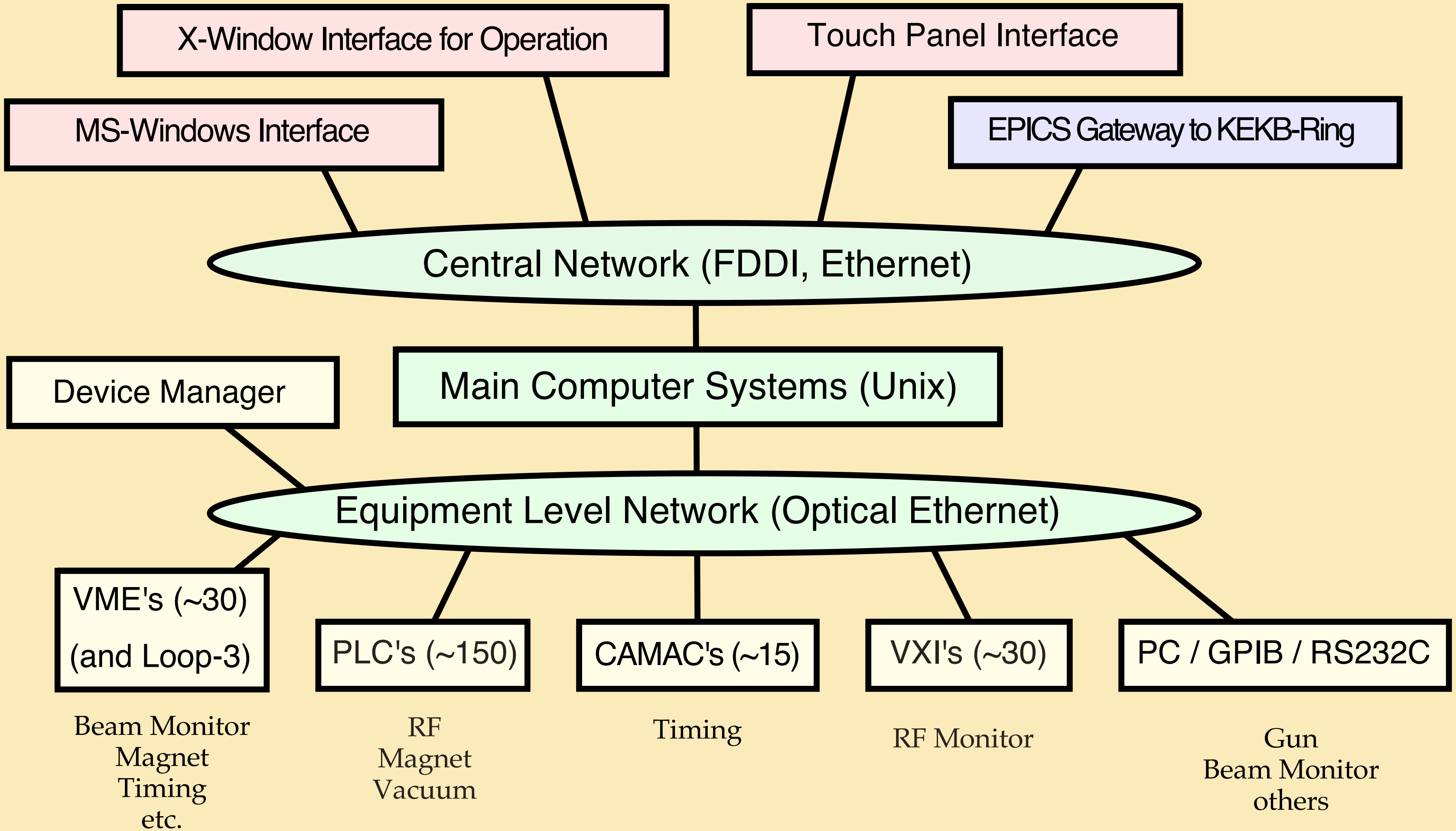
II. Linac Control System Overview

- Rejuvenation in 1993
  with a New Equipment-Oriented Design
- Unix, VME, TCP/IP,
  International and de-facto Standards
- Old Field Controllers Kept Running
- No Strict Standard for Field Controllers
  but Diskless and Ethernet/UDP at Least
- Redundant Unix Servers and Networks
- Multi-tier Server Software for Beam/Equipment Services
- Homemade RPC Protocol at both Internal / External
- Upper Layer Software Hides Lower Layer Differences
- Memory-Resident Hashed Database
  and Cached Field Information
- Not an EPICS System but Has Gateway to It

Control Network System

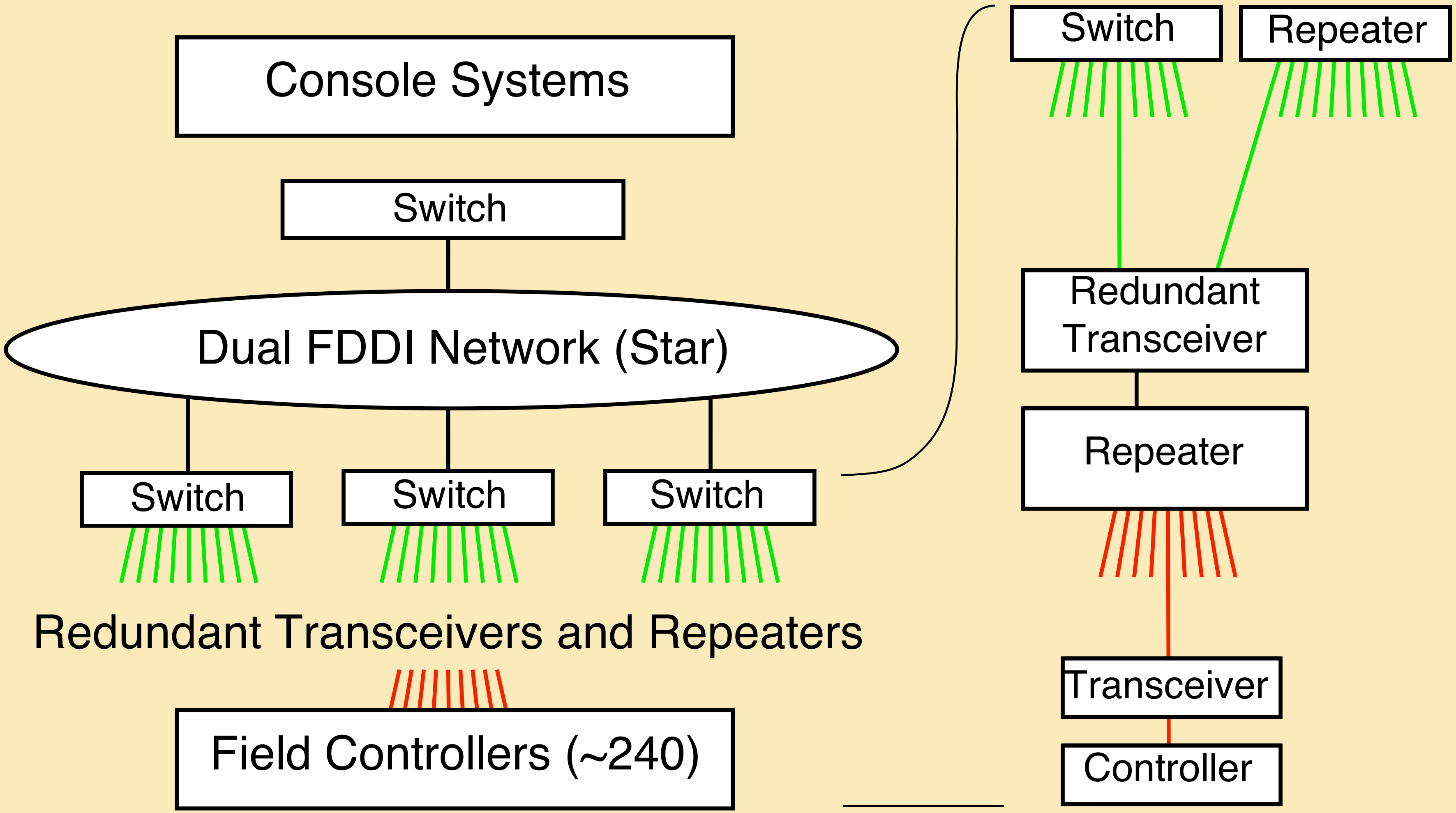
- FDDI and 100Base-Tx Ethernet at Center (about 100 computers/controllers)
- 10Base-FL/100Base-Fx (Optical) Ethernet at Fields to Avoid Klystron Noises
- About 240 10Base-FL Field Controllers
- Layered Switches and Repeaters in Star Topology
- Redundant Configuration at Central Network and Upper Field Networks

Physical Configuration of KEK Linac Control System



There are many kinds of local controllers, but they all communicate through UDP/RPC over switched redundant optical Ethernet segments.

Network Configuration of Linac Controls



33 field network stations are connected with central switches on FDDI through redundant 10Base-FL Ethernet. Each station is connected to 4 to 10 field controllers. All connections at fields use 10Base-FL because of the klystron noises. Network traffic at important points are monitored via SNMP.

III. Multi-Tier Architecture in Linac Controls

- Providing Accelerator Oriented Services at the Top
- Accommodating Many Different Kind
  of Physical and Virtual Components
- Should Survive Long Term
  in spite of Technology Advance
  Replacing/Adding Part by Part
- Robust but Flexible by Nature
- Opposite Direction to EPICS in Some Sense,
  but Works with EPICS at KEKB Ring

Accelerator Equipment Oriented and Beam Parameter Oriented Services

- Instead of Channels, A Server Represents a Group of Meaningful Information at Each Level
- Each Level Consists of Several Different Servers and May Communicate with Upper and Lower Levels
- Some Services are Useful for Engineering Works Such as Calibrations and Troubleshooting and are Used by Upper Level Servers as well
- Other Services are Useful for Advanced Operations and are Used by Beam Feedback Loops or Physicists
- Layered Architecture with well-defined Interface is Important

Plug-in Servers Ease Future Upgrade

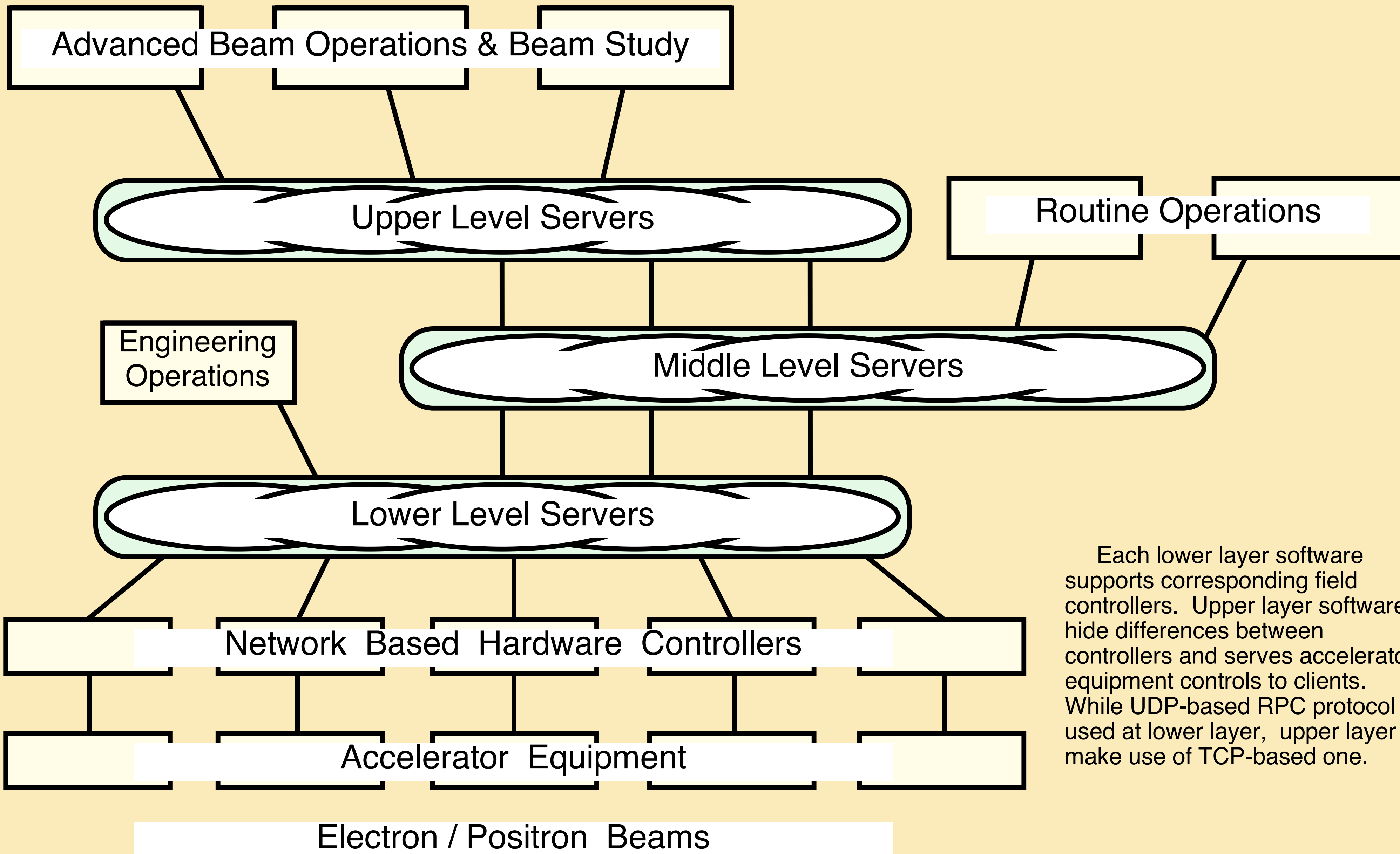
- Easy to Add New Servers at the Top
  or to Add New Hardware at the Bottom
  or Even to Replace a Middle Level Server

- Already Have been Working for 8 Years,
  Have Supported KEKB Commissioning
  and Still Are Improving

- Accommodating 20-Year-Old Controllers
  and Recent Network Based Controllers
  at the Same Time

- Most Services Are Synchronous,
  While New Services Supports Asynchronous Access

Multi-Tier Server Architecture



Each lower layer software supports corresponding field controllers. Upper layer software hide differences between controllers and serves accelerator equipment controls to clients. While UDP-based RPC protocol is used at lower layer, upper layer make use of TCP-based one.

IV. Performance of KEKB Linac Control Operation Examples

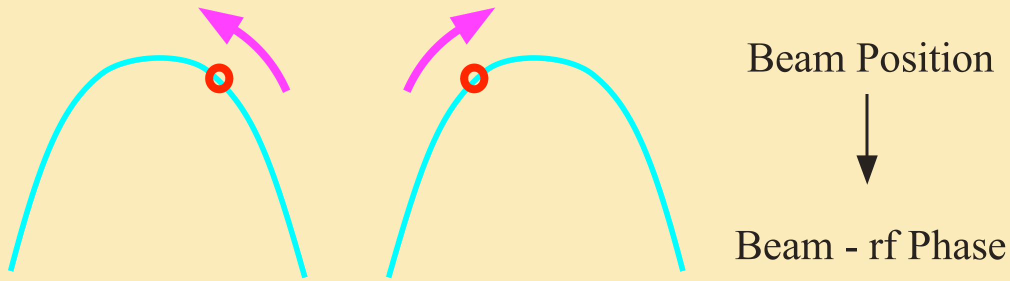
- 4 Downstream Rings Require Quite Different Beams
- Switching Reproducibility and Reliability are Crucial
- 7300 hours of Operation in FY1999

  But Only 73 hours of Beam Loss Time

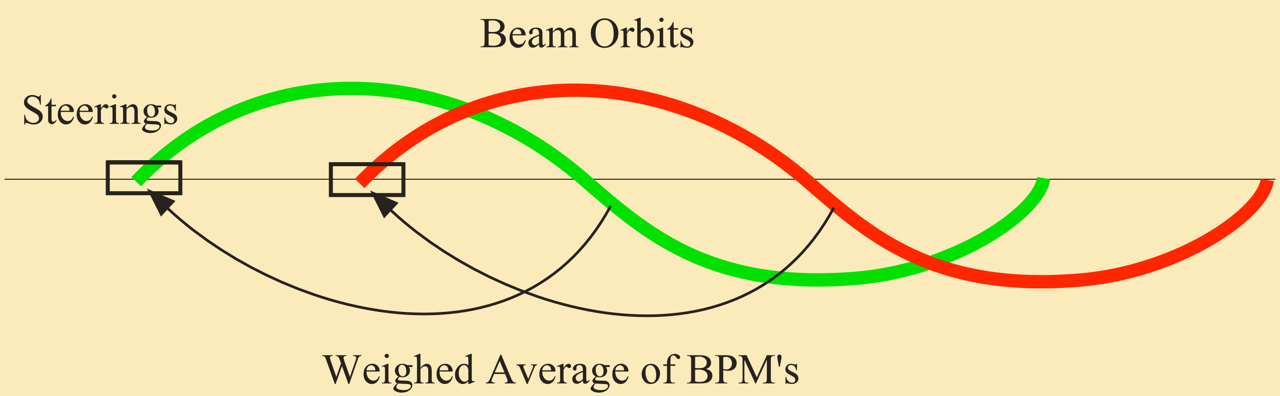
Ring	HER	LER	PF	PF-AR
Particle	electron	positron	electron	electron
Energy	8 GeV	3.5 GeV	2.5 GeV	2.5 GeV
Charge	1.28 nC	0.64 nC (primary 10 nC)	0.2 nC	0.2 nC
Bunch	single	single	1 ns	1 ns
Repetition	50 Hz	50 Hz	25 Hz	25 Hz
Store	580 mA	780 mA	400 mA	40 mA
Time	1-2 min	4-10min	3-5 min	2-5 min
Interval	1-2 hr	1-2 hr	24 hr	2-4 hr

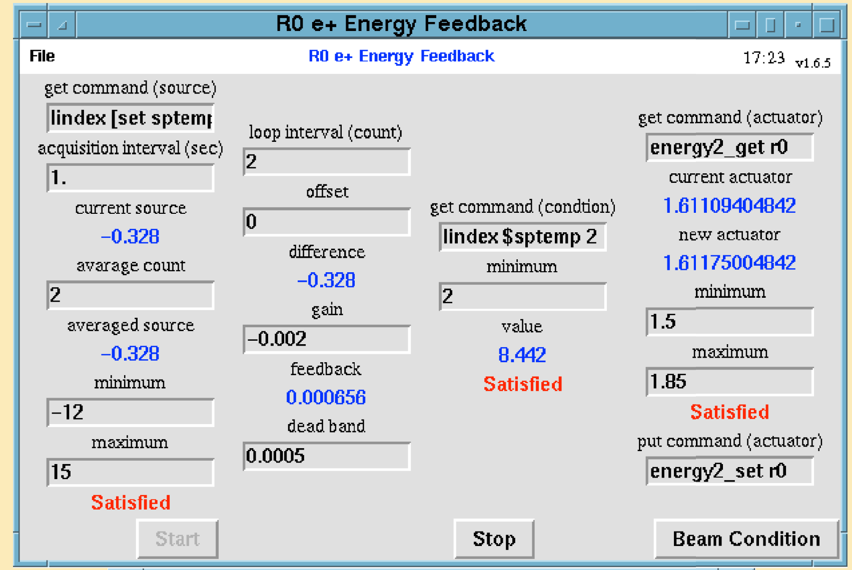
Beam Feedback Loops

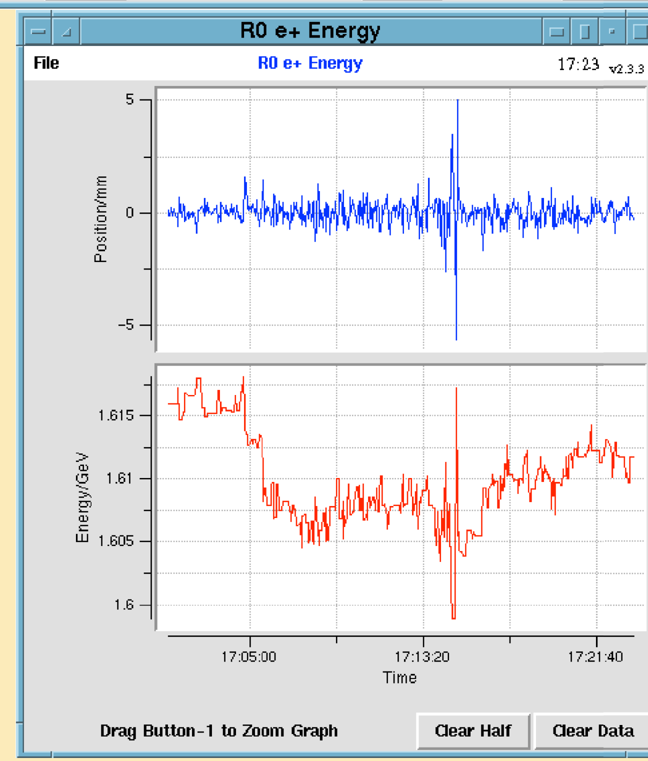
- More than 30
  Software Feedback Loops
- Energy Feedback



- Orbit Feedback and Others

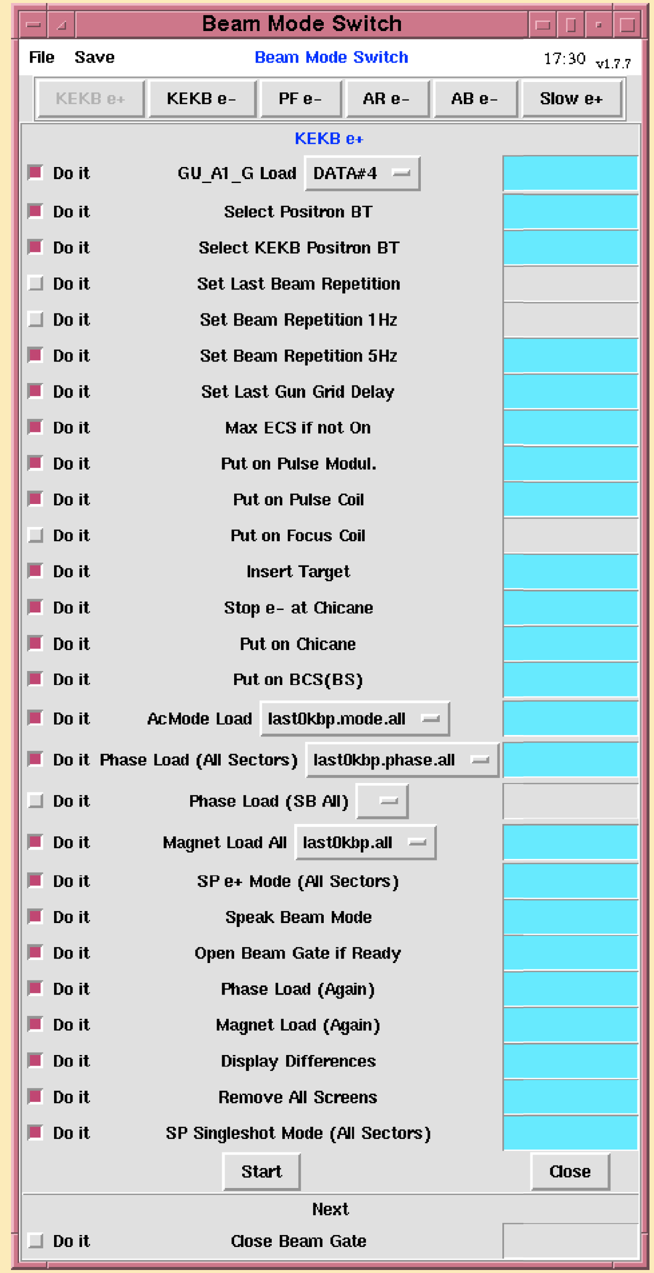




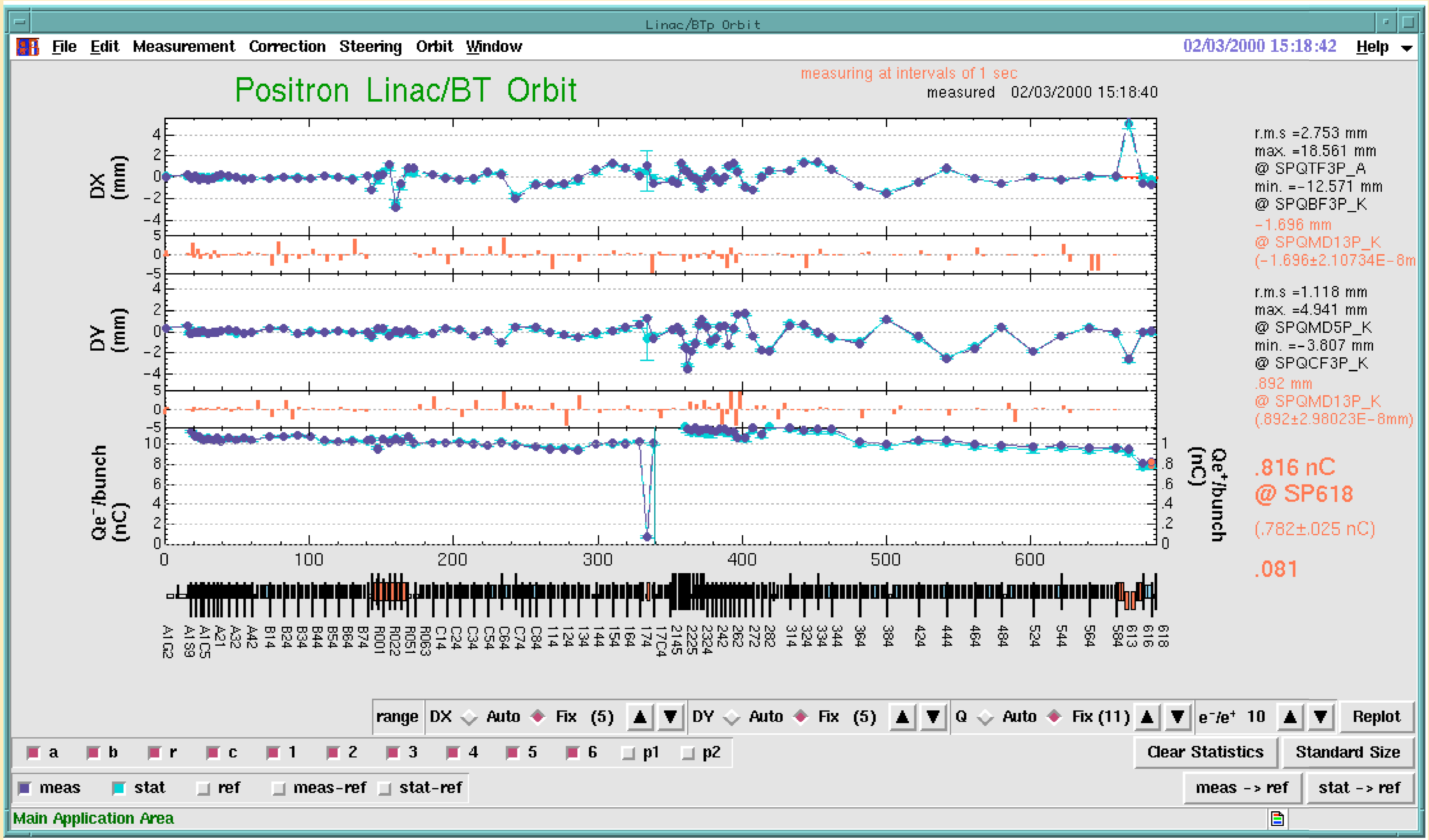


Beam Mode Switch

- Reproducibility of
  Linac Equipment Parameters
  and then Beam Parameters
- Easily Re-configurable Automatic
  Beam Mode Switch
- Fast and Robust
  with Failure Recovery
- Visual Feedback
- About 50 Times a Day



Example of Beam Intensity / Position Display (e^+)



- Positron Beam of 0.8nC was Achieved at the end of Linac

V. Conclusion

- Network-Based Multi-Tier Server Scheme
  Works Well in Linac Control System
- It Have been Supported KEKB Linac Upgrade, Commissioning
  and Advanced Operations in KEKB Accelerator Complex
- It Will Ease the Future Upgrade as Well
- Plan to Incorporate Other Control Protocols Such as CORBA
  to Make More Tight Communication between Accelerators

Linac Beam Parameters & Stability

- Precise Tuning of the Beam Parameters
  Energy, Orbit, Emittance, Energy Spread,
  Bunch Profile, Bunch Charge, Beam Timing
- Simultaneous Fluctuation of
  Electric Power or Temperature
- Interim Failure of Linac Equipment
- (may Lead to KEKB Luminosity Degradation)
- (Linac/Ring Equipment may be Damaged)

Beam Parameter Fluctuation & Stabilization

- If certain Instability was Observed;
- Multi-Parameter Tolerance Study was Carried
- We may have to Hunt the Source
  to Fix the Problem (if possible) or to Form a Closed Loop
- To Find the Source, Correlation Analysis
  and Singular Value Decomposition (SVD)
- Often the Source is Attributed to the Linac Injector Section
  where Many Devices/Parameters Reside
- Feedback Loop without Resolving the Real Source
  Choosing certain Pair of Monitor & Tuner, Still Effective
- (Instead of Simple Feedback, Sophisticated Method like
  Downhill Simplex or Global Orbit Correction
  But Important Defects may be Hidden)

Tolerance Study to Understand Fluctuations

- Single-Parameter Tolerance to Keep 90 % of Optimal Beam at Positron Target
- Good Reference to Consider the Beam Stability
- With Multi-Parameter Drifts, More Tight Limits
- Improved Surveillance Systems for rf and Timing Systems as well as Feedback Loops

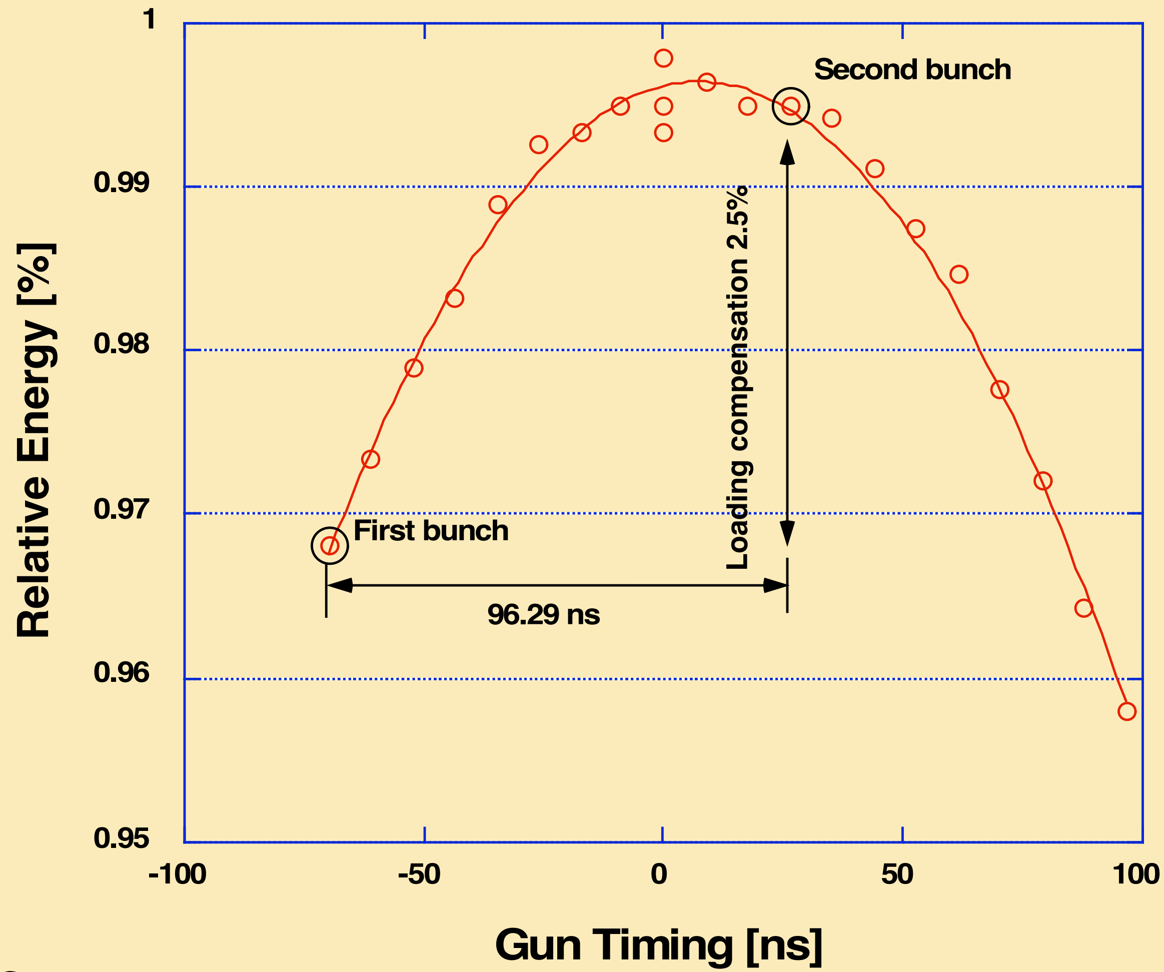
Gun Beam timing	**±45 ps**
Gun high voltage	**±0.38 %**
SHB1 (114MHz) phase	**±1.1 deg**
SHB2 (571MHz) phase	**±1.3 deg**
Buncher phase	**±1.7 deg**
Buncher power	**±0.47 %**
Sub-booster-A phase	**±3.5 deg**
Sub-booster-B phase	**±4.0 deg**

Beam Monitors

- Computer Readable Beam Instrumentation
  - Strip-line type Beam Position Monitors (BPM)
  - Streak Cameras for Beam Bunch Profile
  - Wire Scanners for Transverse Beam Profile
- To Find the Beam Energy
  - BPM Readout where Dispersion is Large
- Noise: External Electric Noise mainly from Klystrons
  - Optimized with Integration/Frequency, Resolution, Dispersion
- Noise: Beam Orbit Fluctuation (Betatron Oscillation)
  - Can be Derived from Orbit at Straight Section

Two-Bunch Acceleration Study

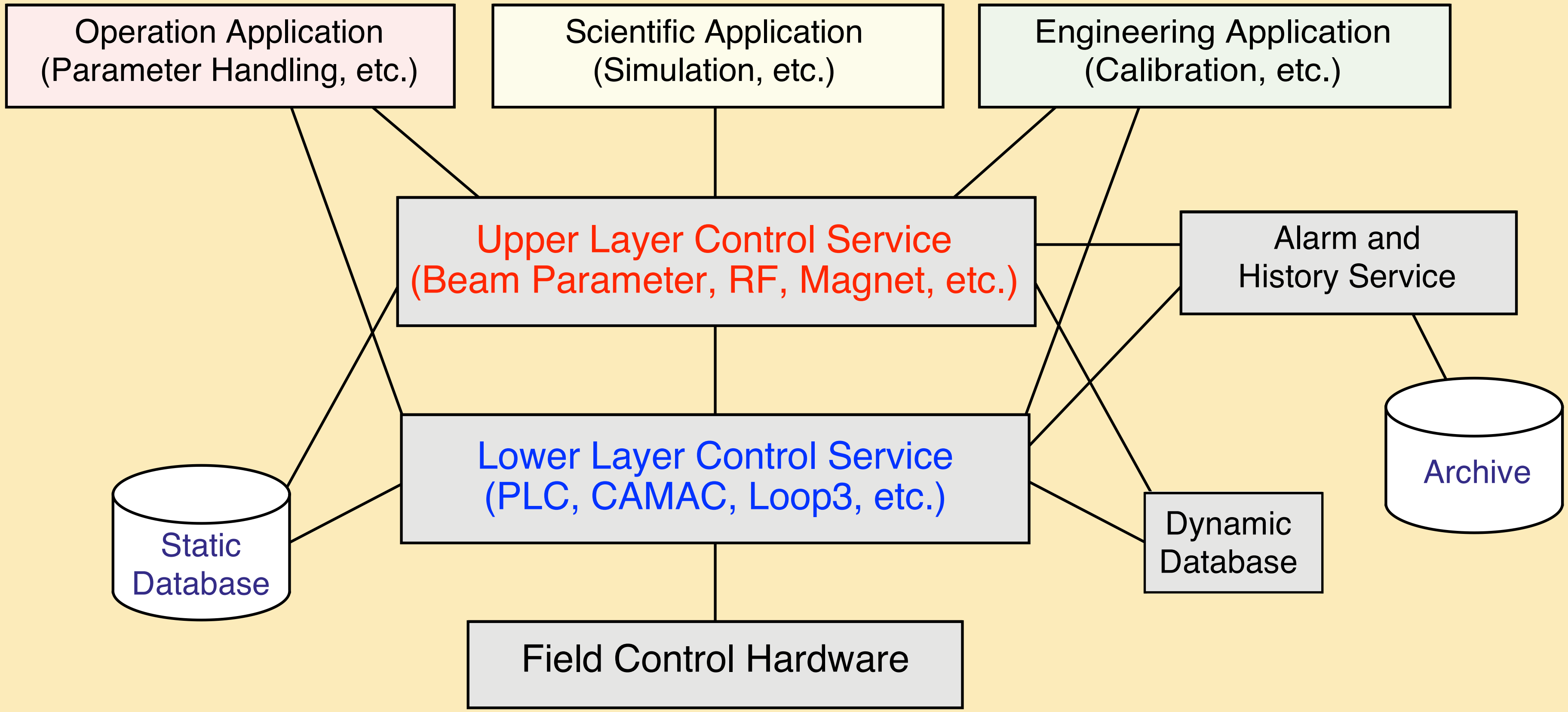
- Loading Evaluation
  - Comparing Beams
  - of 8nC & 0.8nC
- Relation between
  - Energy vs. Timing
- Results Seems to be
  - Promising
- Just Succeeded Test Injection
- Will soon Install
  - Feedbacks,
  - Beam Monitor Upgrades
  - Bunch Selection Upgrades



Design Beam and Achieved Performance

			8-GeV electron		3.5-GeV positron	
			Goal	Achieved	Goal	Achieved
(1) Gun	Energy	keV	200	200	200	200
	Intensity	nC/pulse	1.5	2	13	14
	Pulse width	ns	2	1.8	2	2.8
(2) Buncher	Energy	MeV	16	16	15	15
	Energy spread (σ)	MeV			2	2
	Intensity	nC/pulse	1.4	1.9	>10	11
	Efficiency			95%		90%
	Emittance γβε (σ)	mm	0.06	0.04	0.06	0.08
	Bunch width	ps	5	6	16	10
(3) Arc	Energy	GeV	1.5	1.7	1.5	1.7
	Energy spread (σ)	MeV	0.6%	0.29%	0.6%	0.38%
	Jitters (p-p)					0.1%
	Drift (with feedback)				<0.2%/h	
	Emittance γβε (σ)	mm		0.17		1.7
	Transmission			100%	>95%	100%
(4) e+ target	Energy	GeV			3.7	3.7
	Intensity	nC/pulse			>10	10
	Transmission					96%
(5) e+ Solenoid exit	Intensity	nC/pulse				2.4
	Specific yield	e+/e-GeV				6.8%
(6) Linac end	Energy	GeV	8	>8	3.5	>3.5
	Energy spread (σ)	MeV	0.15%	0.05%	0.125%	0.15%
	Intensity	nC/pulse	1.28	>1.28	>0.64	0.82
	Specific yield	e+/e-GeV				2.3%
	Transmission			>80%		
	Emittance γβε (σ)	mm	0.25	0.31	1.5	1.4
	Pulse repetition	pps	50	50	50	50

Logical Configuration of KEK Linac Control System



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