Accelerator Types and Needs for DSP

Tom Shea
ORNL

Outline

- Overview of Accelerators
- DSP Technology Intro
- Performance Challenges With Examples
- Considerations of the Accelerator Environment
- Final Comments

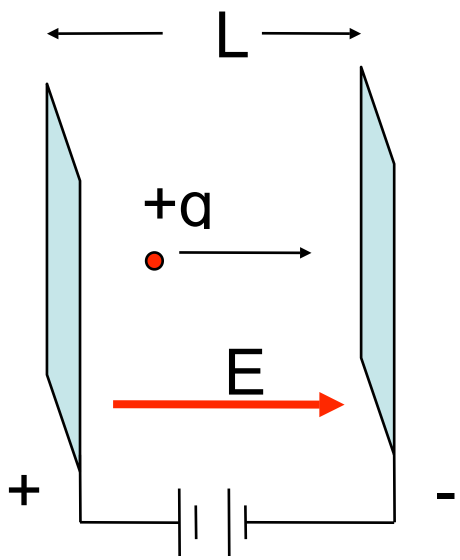
Overview of Accelerators

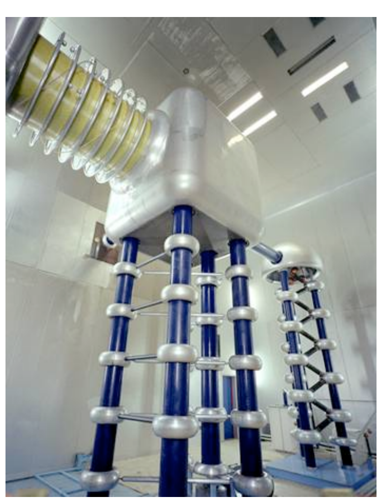
Accelerator Inventory

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

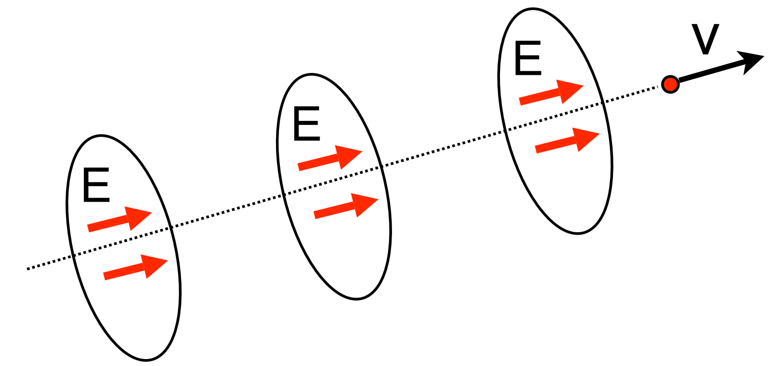
Acceleration Techniques

$$\Delta W = qV_0$$



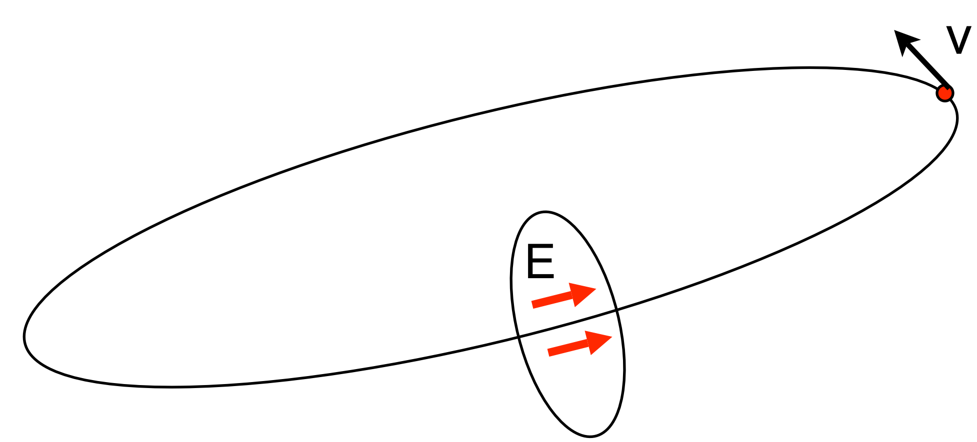


Two approaches for accelerating with time-varying fields (to get above 20 MeV/n or so)



Linear Accelerators

Use many accelerating cavities through which the particle beam passes once: Linacs

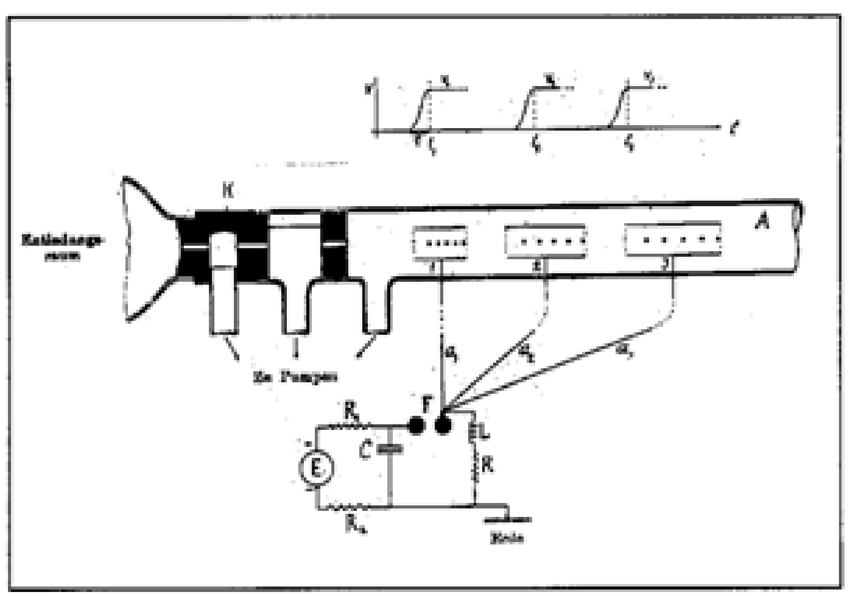


Circular Accelerators

Use one or a small number of Radio-frequency accelerating cavities and make use of repeated passage through them. This approach is realized in circular accelerators: Cyclotrons, synchrotrons and their variants

Linac Concept

- Ising and Wideroe suggested to repeatedly apply a much smaller voltage in a linear accelerator by using time-varying fields
- In this way, a high particle beam energy could be attained by repeatedly applying voltage “kicks”



Ising’s idea

R. Wideroe

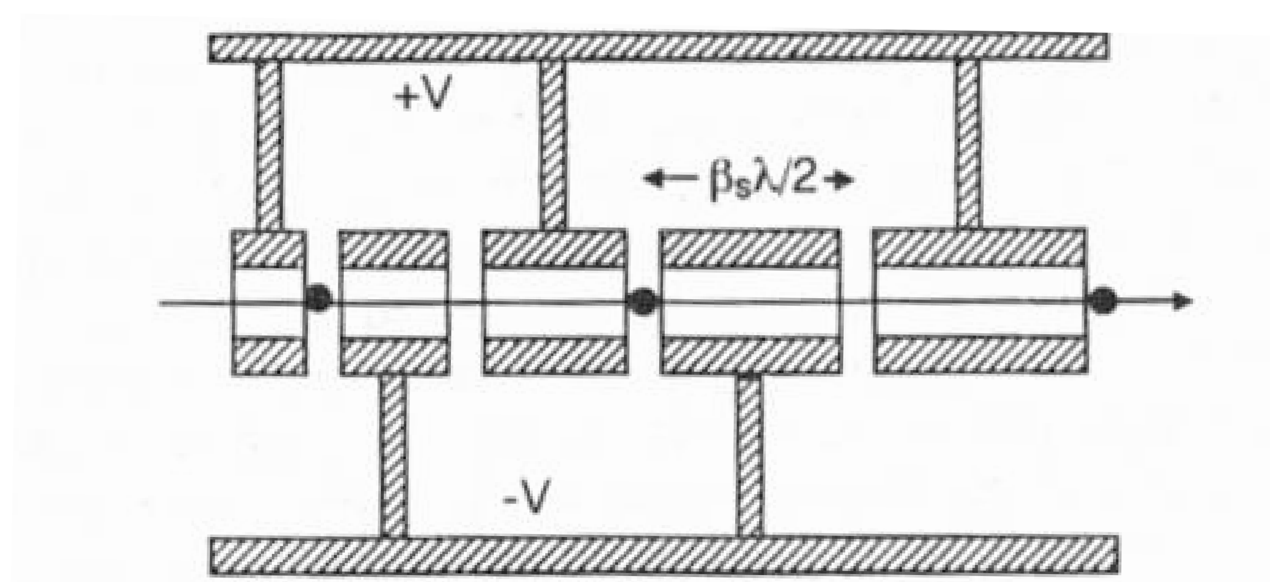
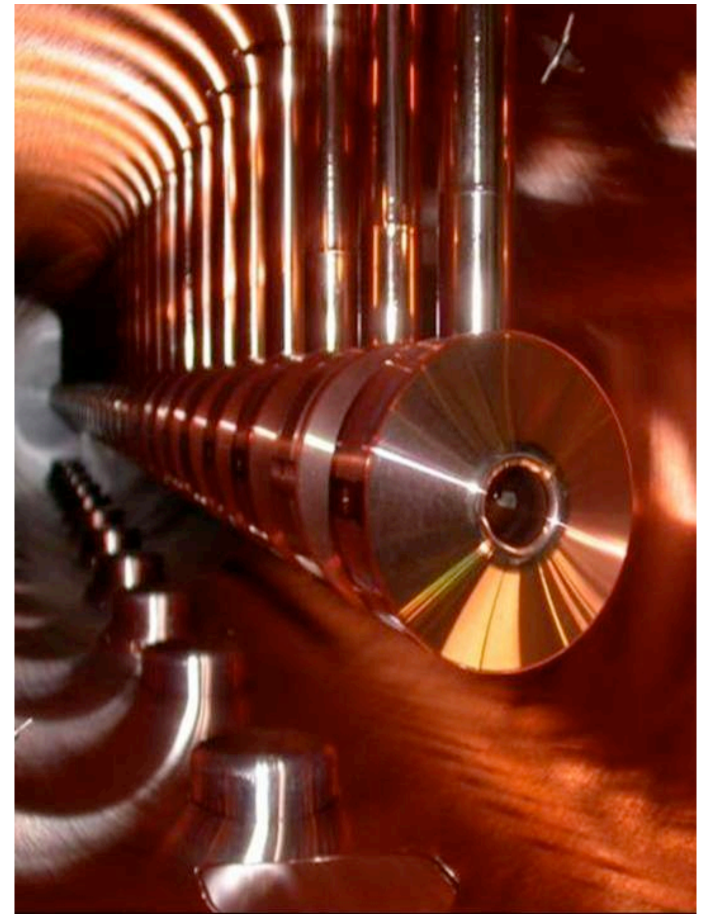


Figure 4.4 Wideröe or Sloan–Lawrence or interdigital structure.

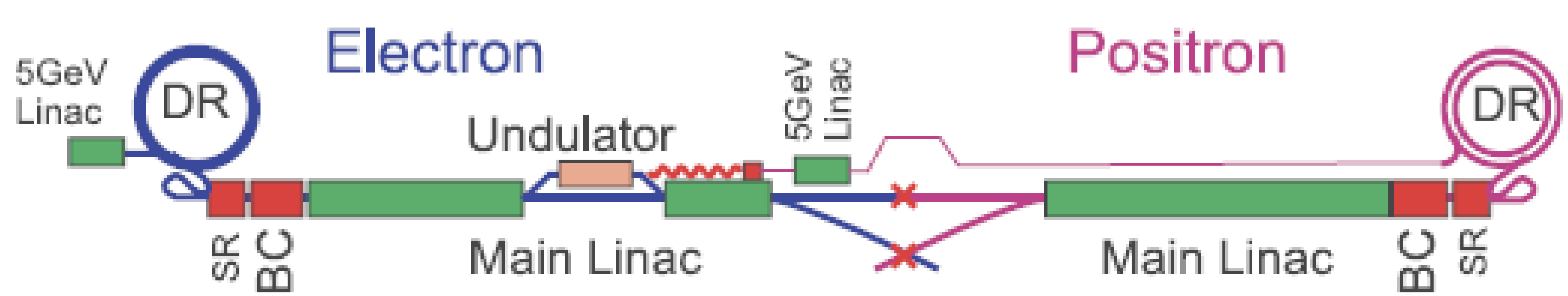
Modern Linacs

- The two largest proton linear accelerators are the LANSCE linac at Los Alamos (800 MeV) and the Spallation Neutron Source Linac at ORNL (1000 MeV)
- Largest linac is at SLAC; largest under consideration is ILC (31 km total length)
- Electron and hadron linacs now will look similar: most recent and future projects have settled on superconducting cavities.



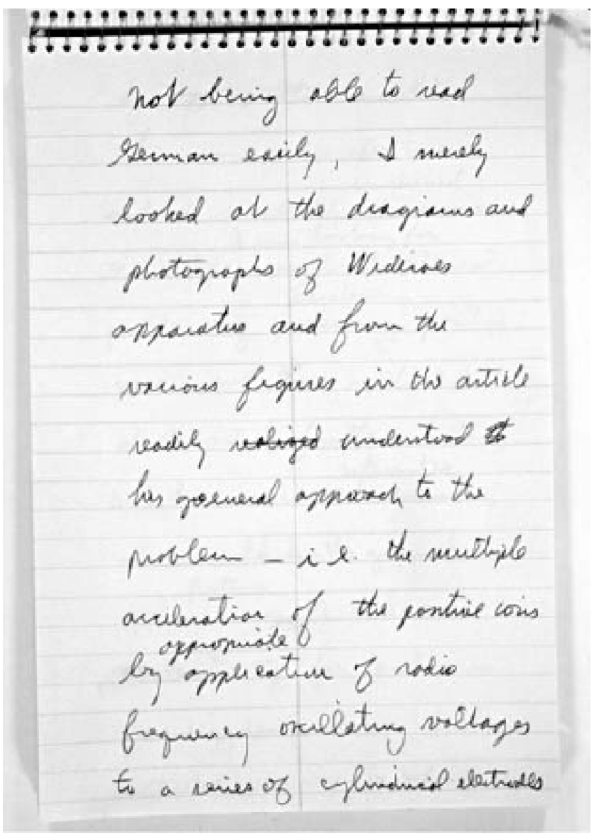
ILC

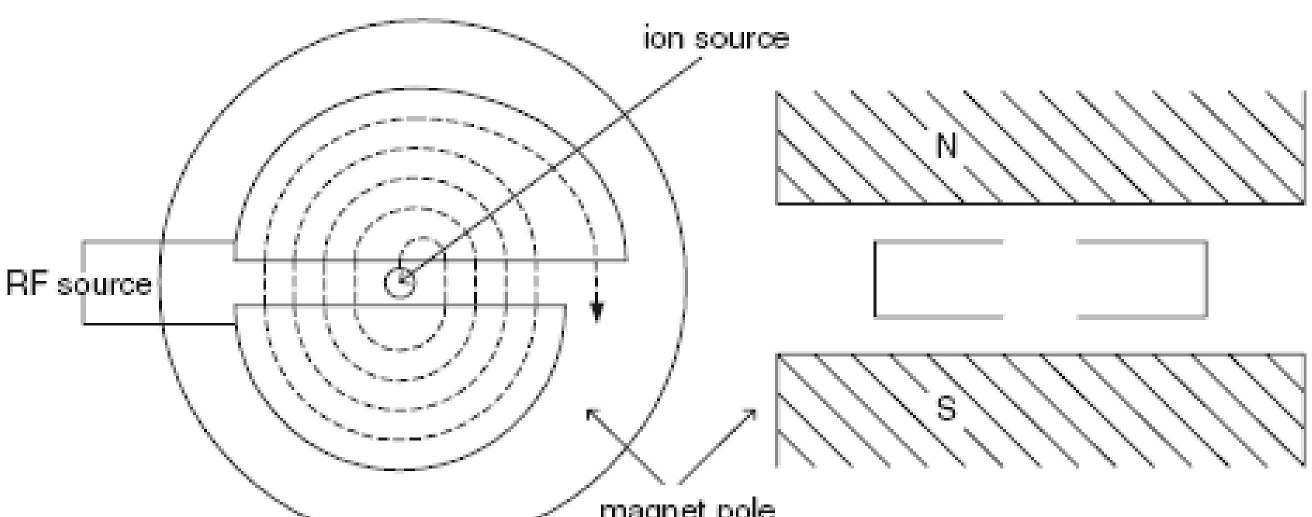
- 500 GeV lepton machine
- peak luminosity of 2e34



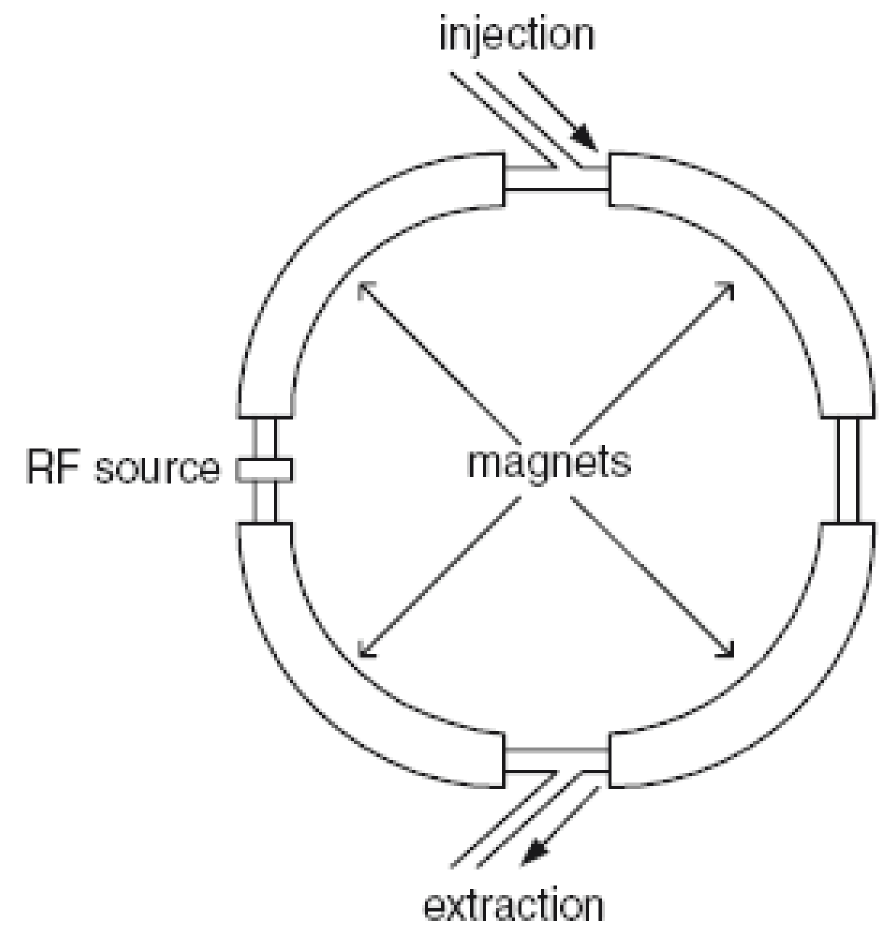
Circular Machines

Lawrence's Application of Wideroe's Idea: The Cyclotron



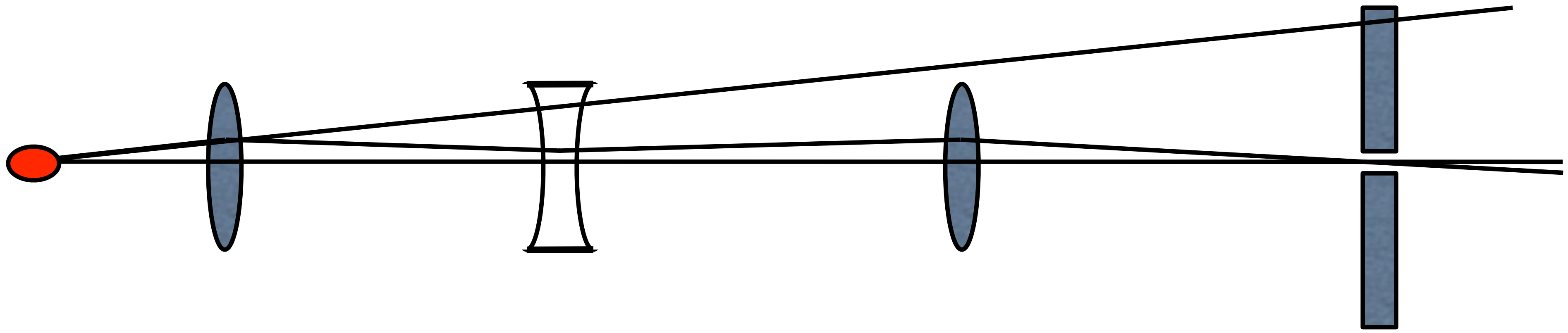


The synchrotron concept - ramped magnets for constant radius - was first proposed in 1943 by the Australian physicist Mark Oliphant.

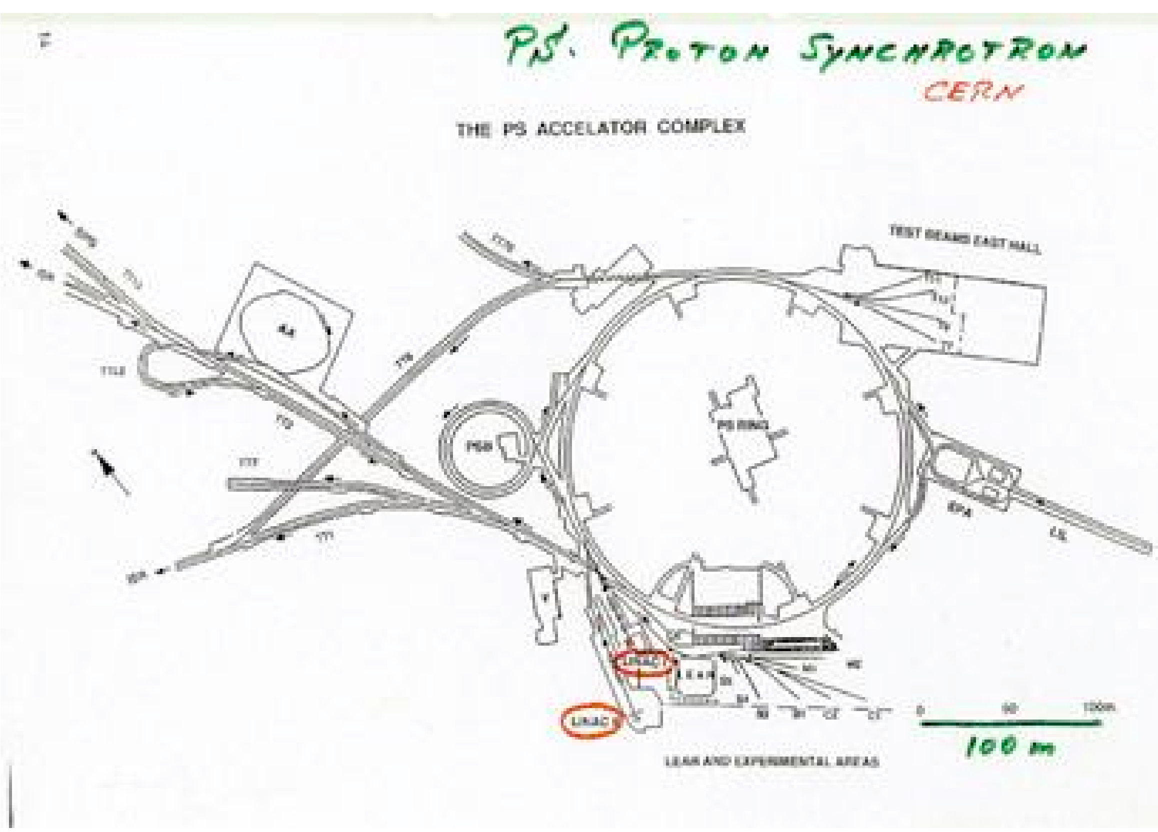


$$\frac{1}{\rho[m]} = 0.3\frac{B[T]}{\beta E[GeV]} = 0.3\frac{B[T]}{cp[GeV]}$$

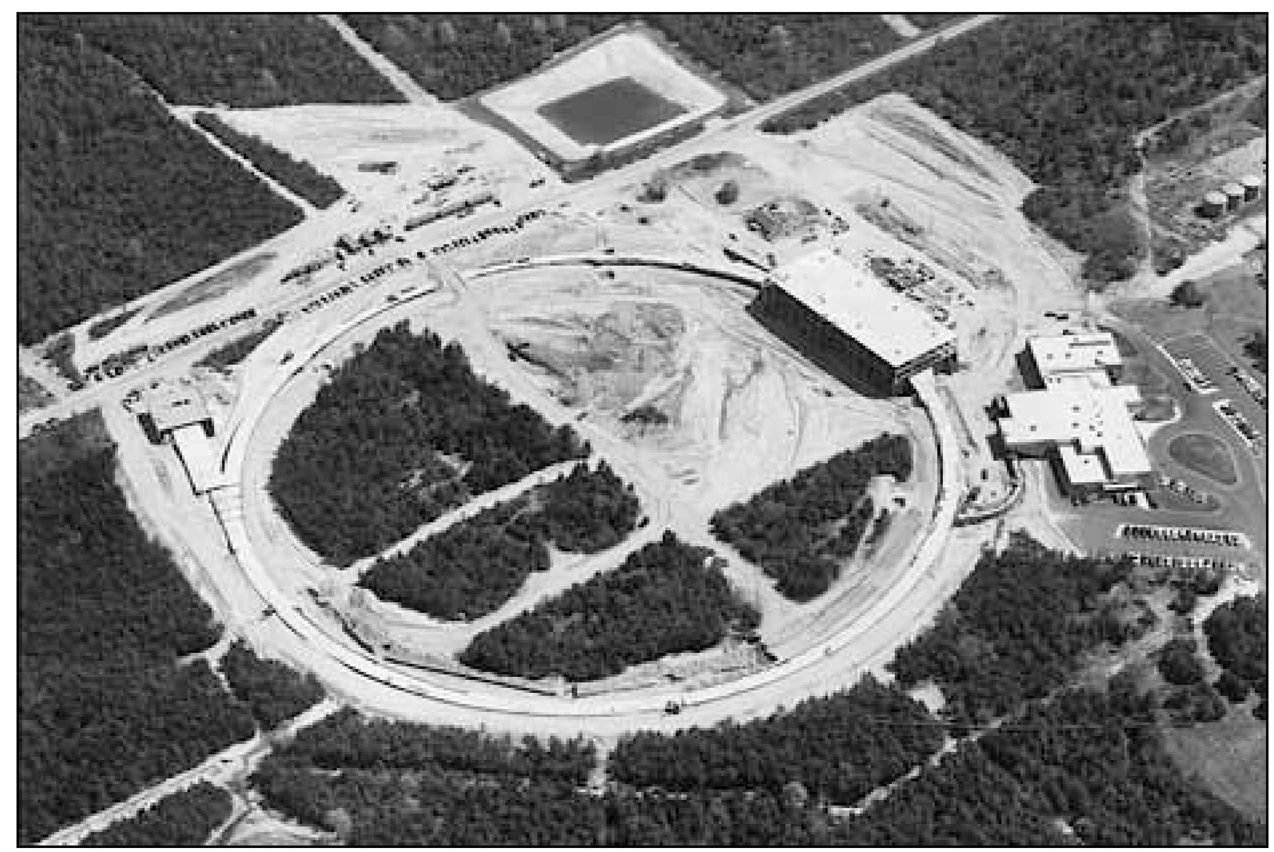
Strong-focusing Synchrotrons



The synchrotron concept was first proposed in 1943 by the Australian physicist Mark Oliphant. "Strong" or "Alternating Gradient" focusing concept first applied to particle accelerators by Courant, Livingston and Snyder. First AG synchrotron: Cornell in 1954.

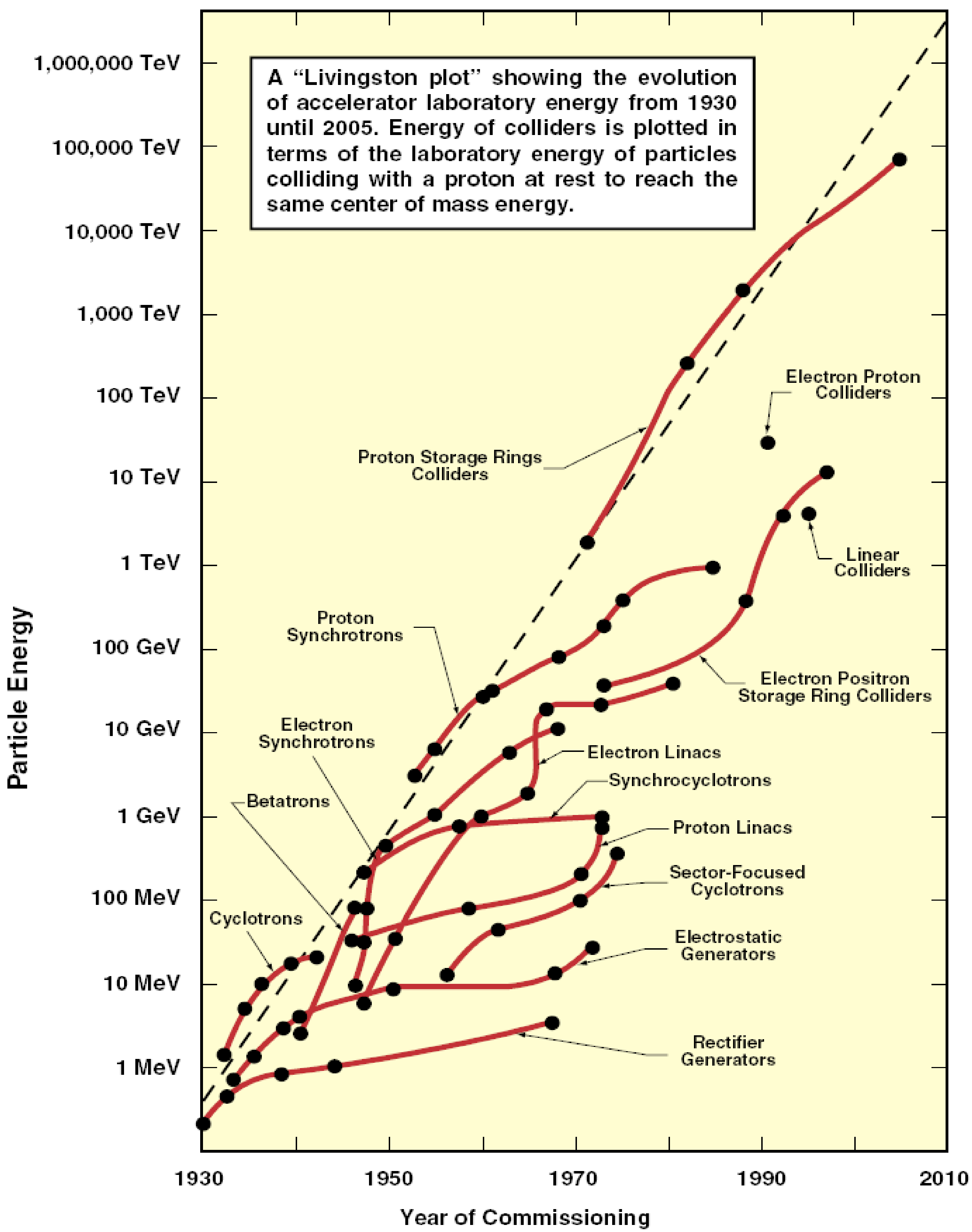


CERN PS (~28 GeV) started operations in 1959.



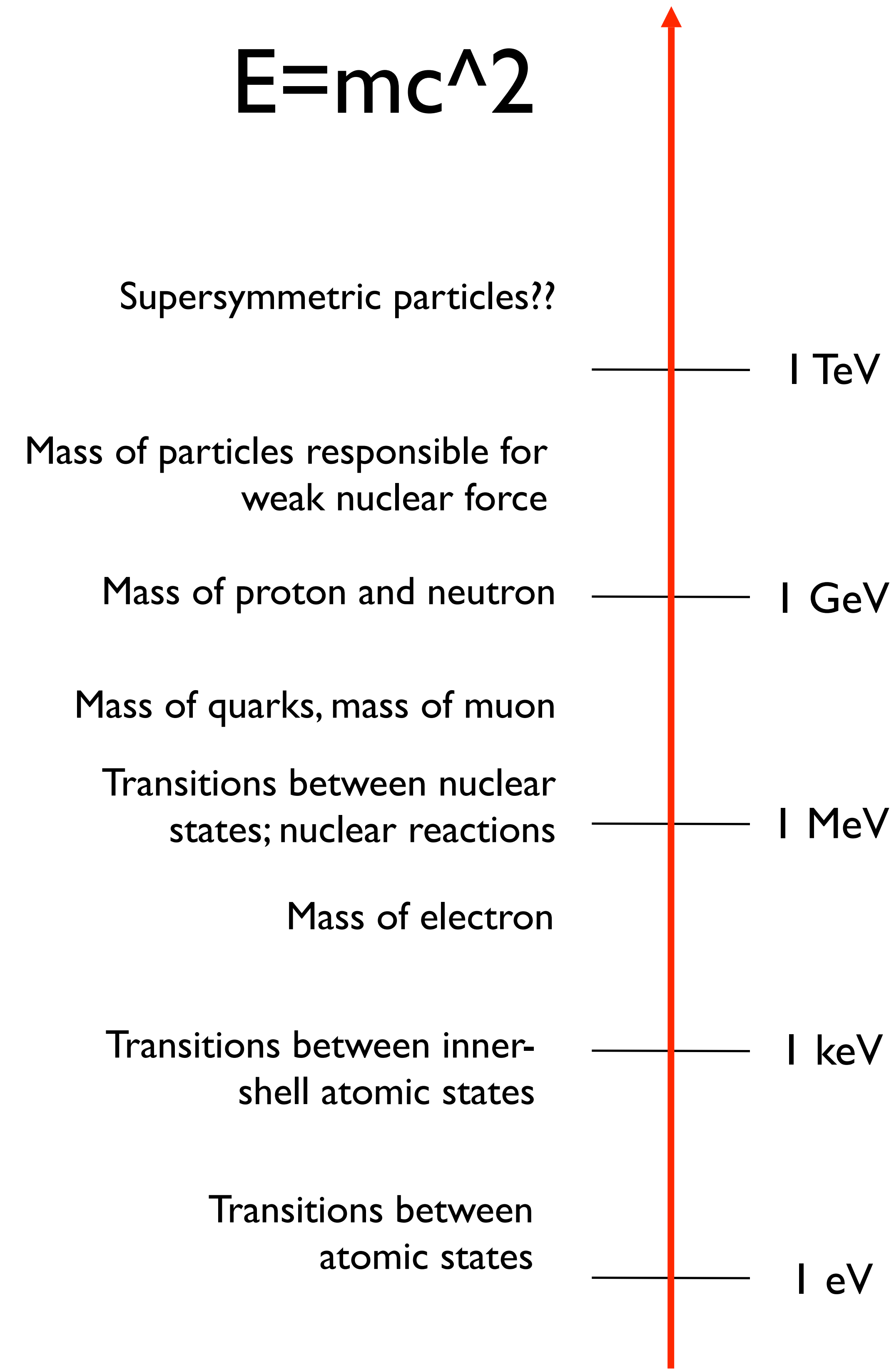
Brookhaven AGS (~33 GeV) under construction in 1957. Started operations in 1960.

Energy



A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.
1,000,000 TeV
100,000 TeV
10,000 TeV
1,000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
Particle Energy
1930
1950
1970
1990
2010
Year of Commissioning
Electron Proton Colliders
Proton Storage Rings Colliders
Linear Colliders
Proton Synchrotrons
Electron Positron Storage Ring Colliders
Electron Synchrotrons
Electron Linacs
Synchrocyclotrons
Betatrons
Proton Linacs
Sector-Focused Cyclotrons
Cyclotrons
Electrostatic Generators
Rectifier Generators

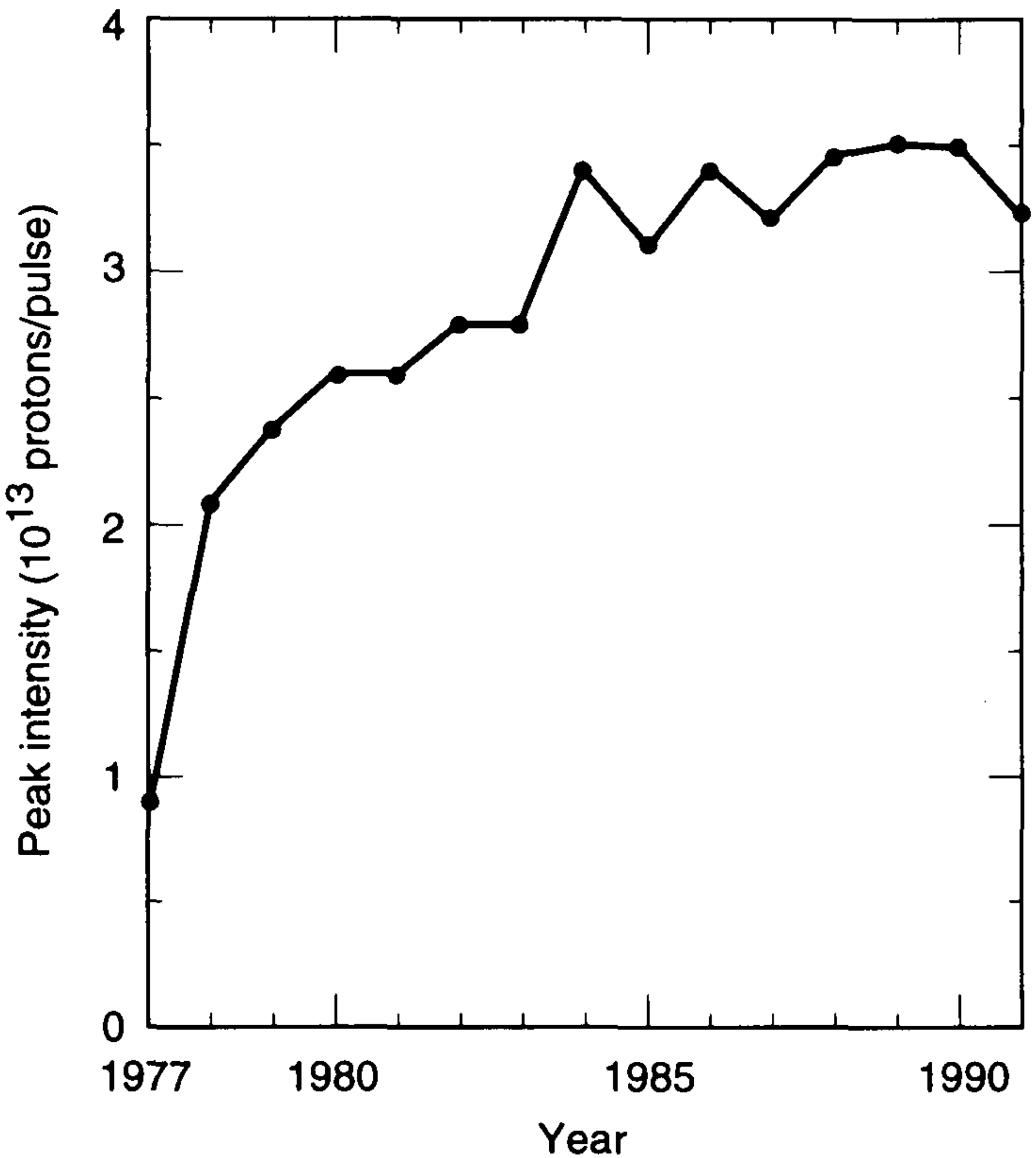
E=mc^2



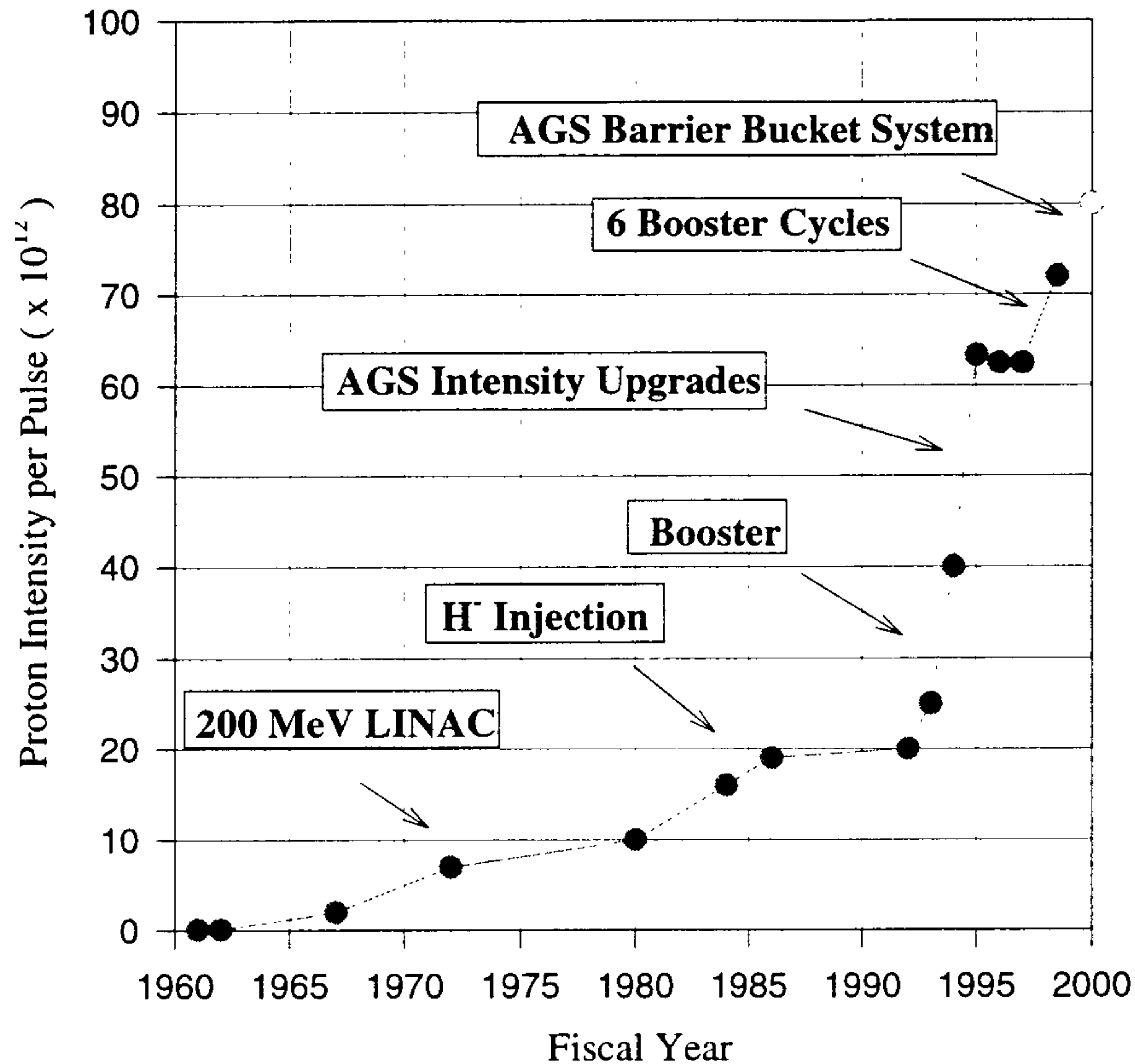
Supersymmetric particles??
1 TeV
Mass of particles responsible for weak nuclear force
Mass of proton and neutron
1 GeV
Mass of quarks, mass of muon
Transitions between nuclear states; nuclear reactions
1 MeV
Mass of electron
Transitions between inner-shell atomic states
1 keV
Transitions between atomic states
1 eV

Increasing intensity

PS

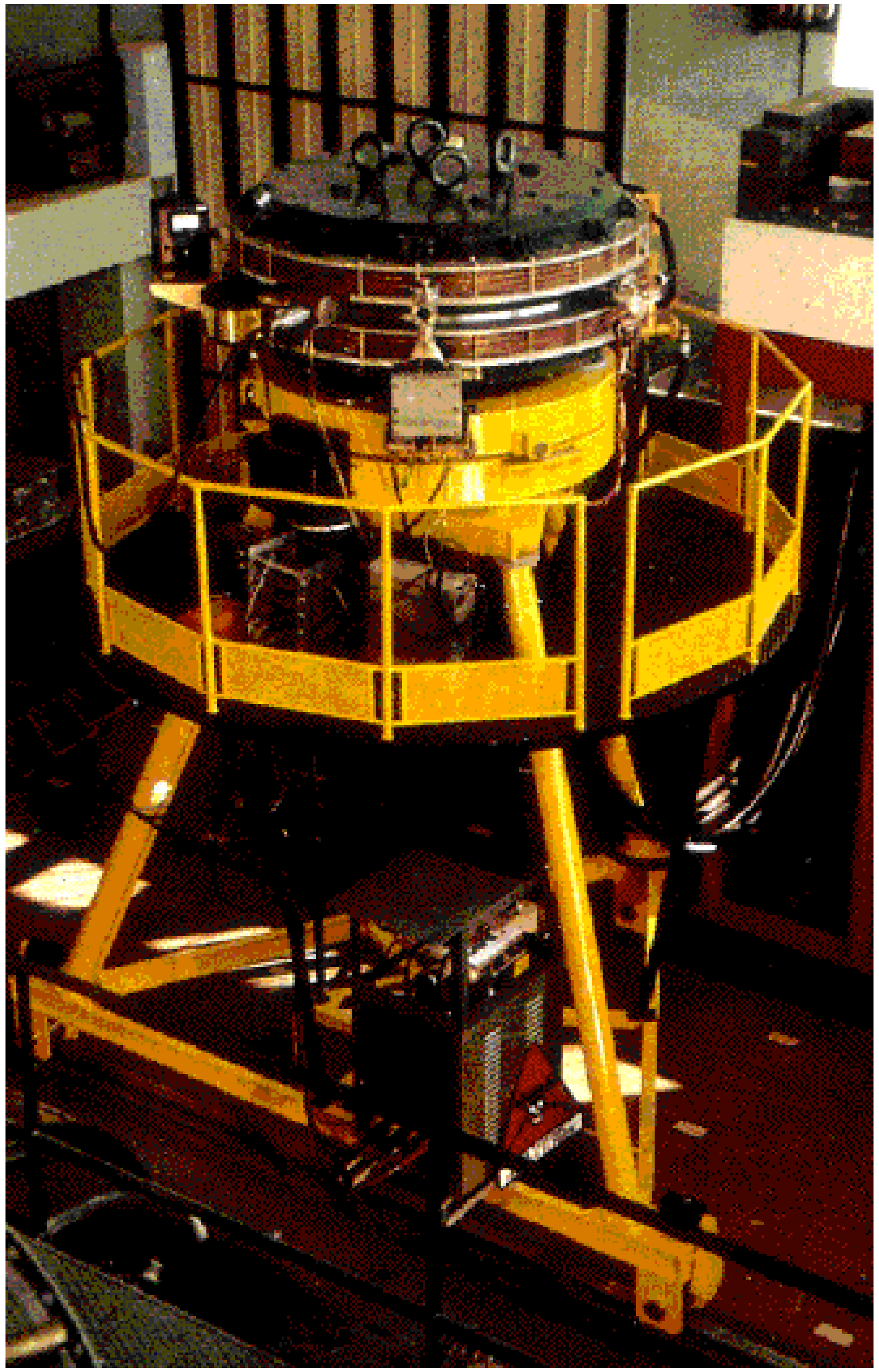


AGS



Colliders

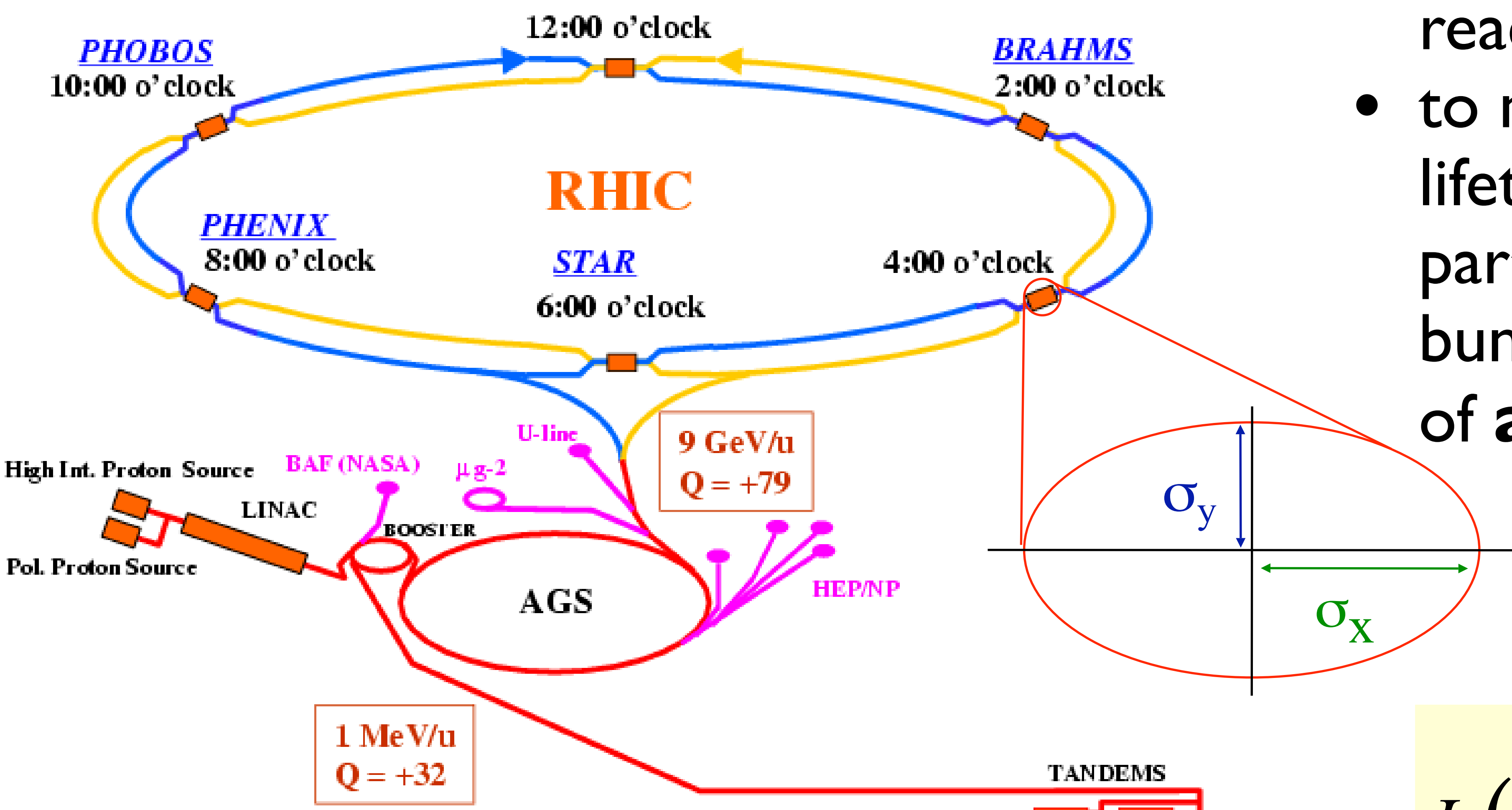
- Circular or linear, common goal is to maximize center-of-mass energy available for particle production



Bruno Touschek built the first successful electron-positron collider, ADA, at Frascati, Italy (1960)

Eventually, went up to 3 GeV

Collider Figure of Merit: Luminosity



- probability of an interesting reaction can be small
- to make a discovery in your lifetime: small bunches, lots of particles per bunch, high bunch rate, reliable operation of **accelerator complex**

for Gaussian beam

$$I_1(x,y) = \frac{n_1}{2\pi\sigma_x\sigma_y} e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{y^2}{2\sigma_y^2}}$$

Luminosity = number of interactions per unit area per unit time:

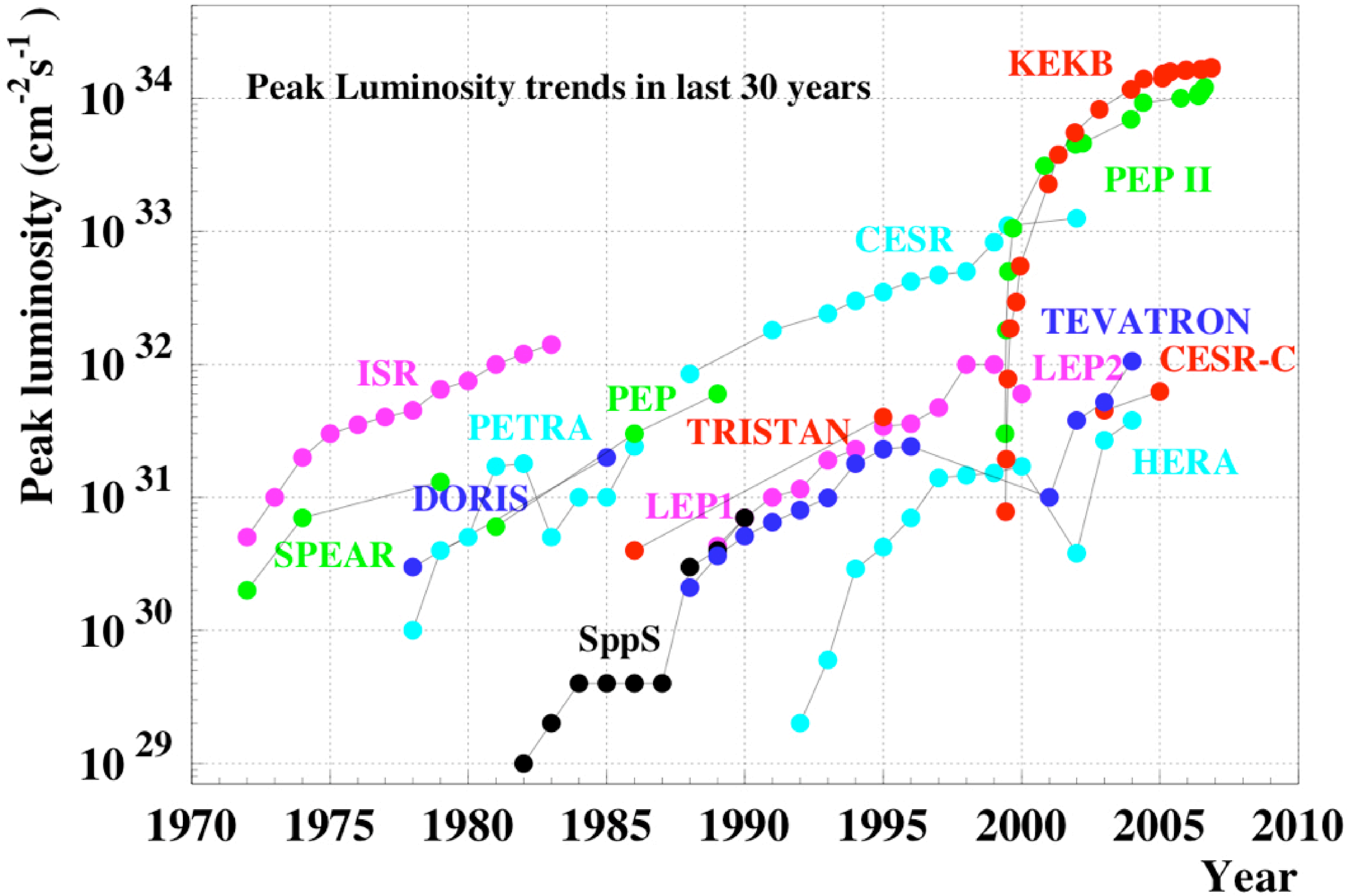
$$L = f\int_{-\infty}^{\infty} dx_1 dy_1 dx_2 dy_2 I_1(x_1,y_1) I_2(x_2,y_2)\delta(x_1-x_2)\delta(y_1-y_2)$$

$$= f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

n_1, n_2 = particles per bunch

f = frequency of bunch collisions

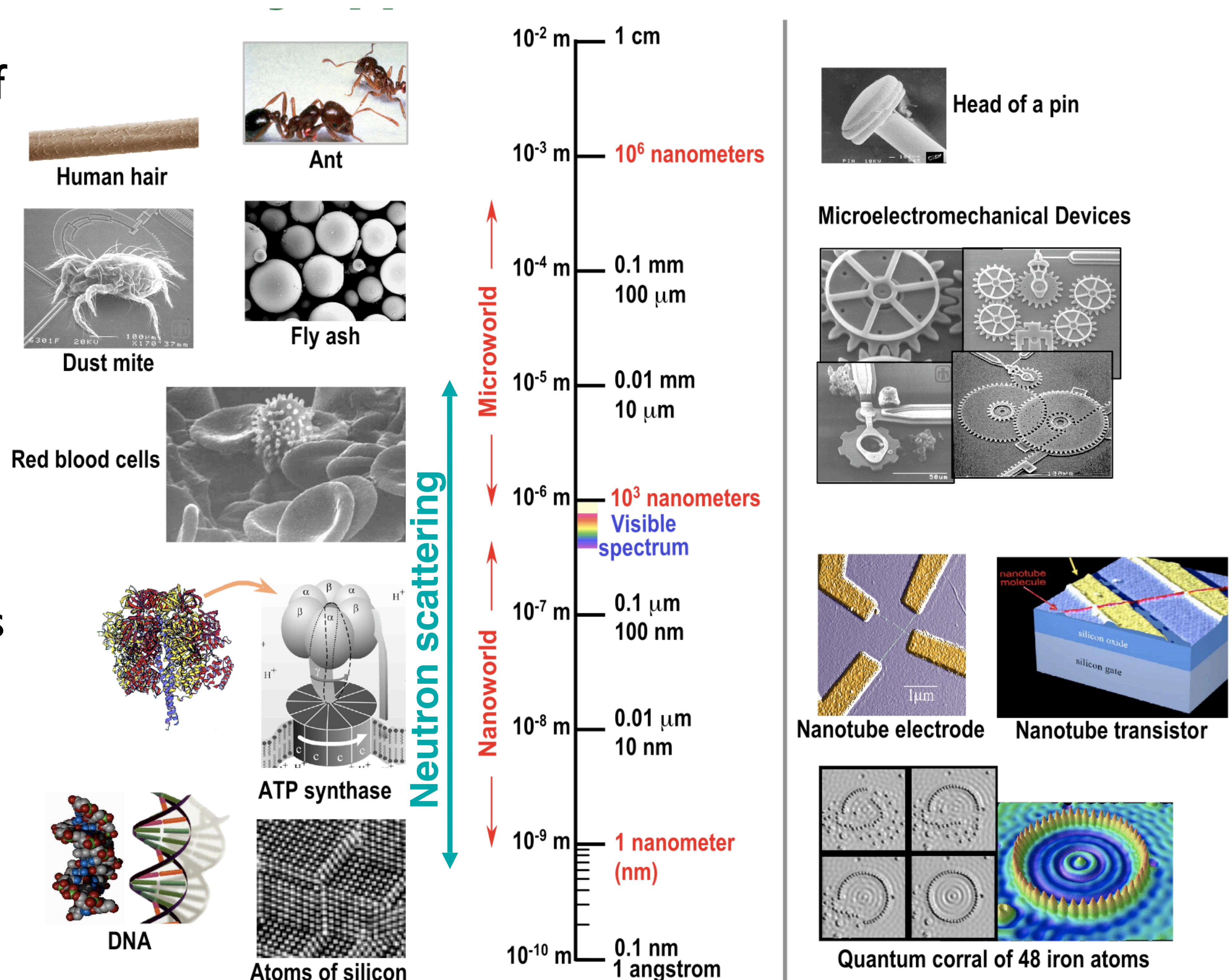
Luminosity Trends



	ILC e- + e+	RHIC		LHC	
		p+p	Au+Au	p+p	Pb+Pb
Maximum beam energy (TeV/u)	0.25	0.25	0.10	7.0	2.76
Luminosity (10^{30} cm^{-2}s^{-1})	2×10^{4}	6	5×10^{-4}	10^{4}	10^{-3}

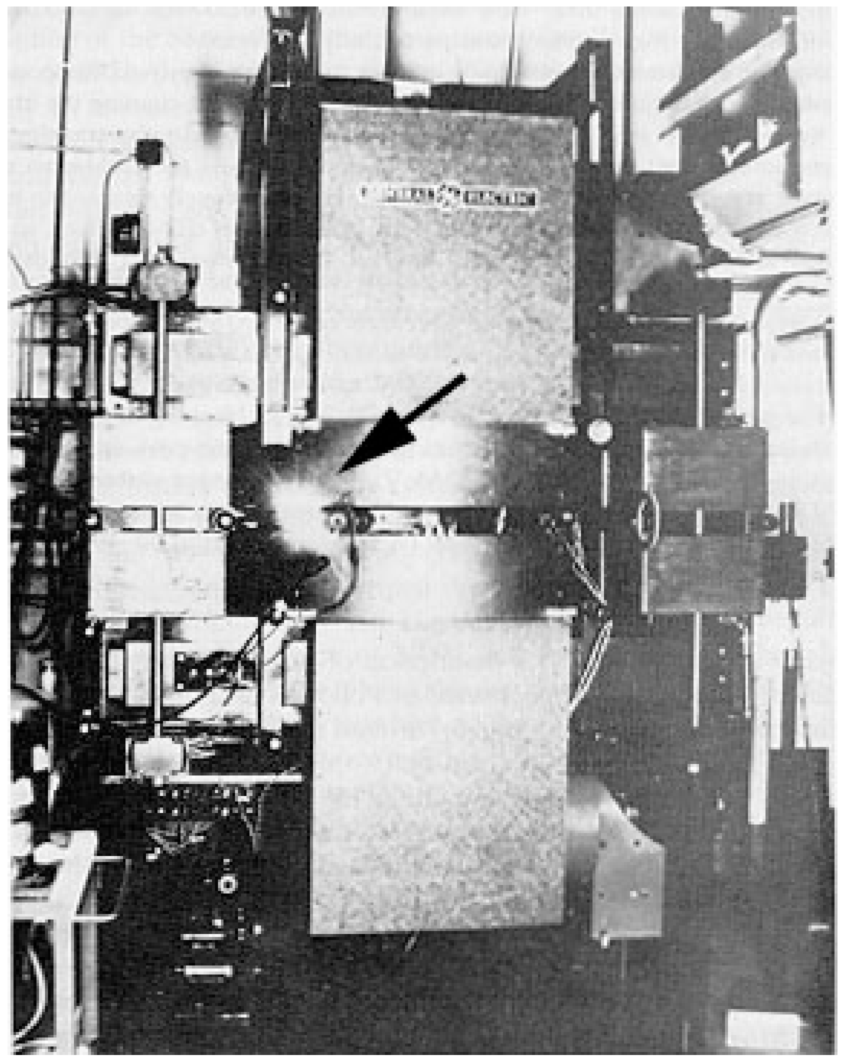
Secondary Beams

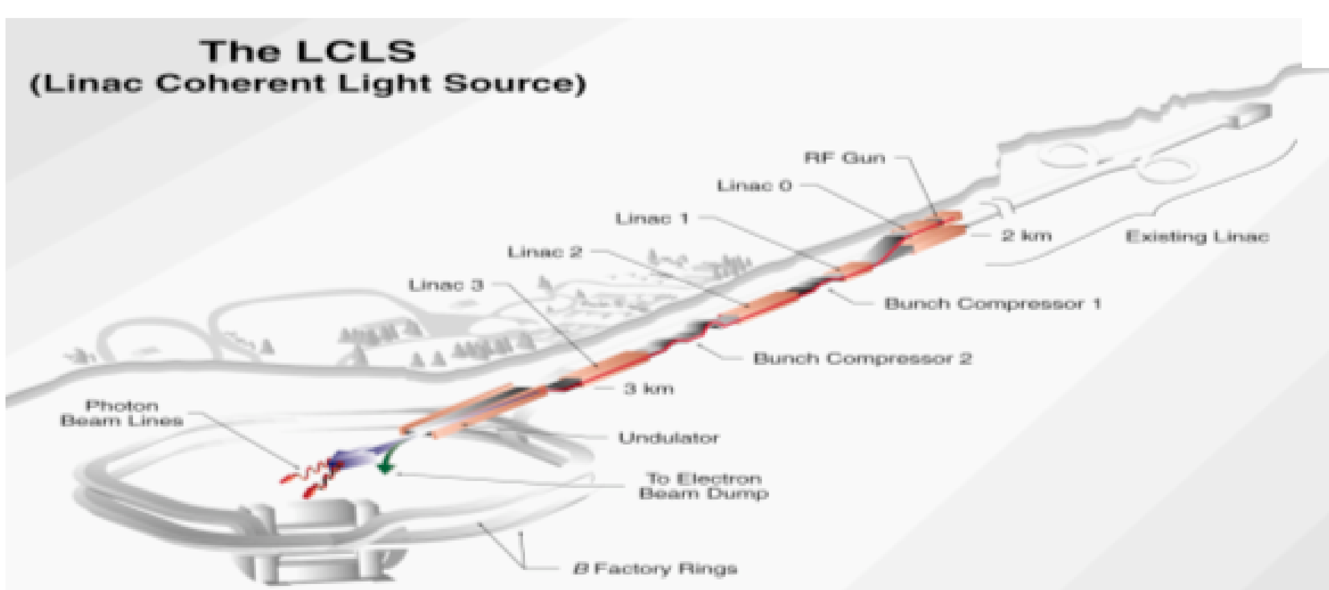
- Secondary beams of neutrons and photons
- Produced at or moderated to wavelengths appropriate for the study of materials and their properties
- Also, neutrinos, radioactive ion beams etc. for physics

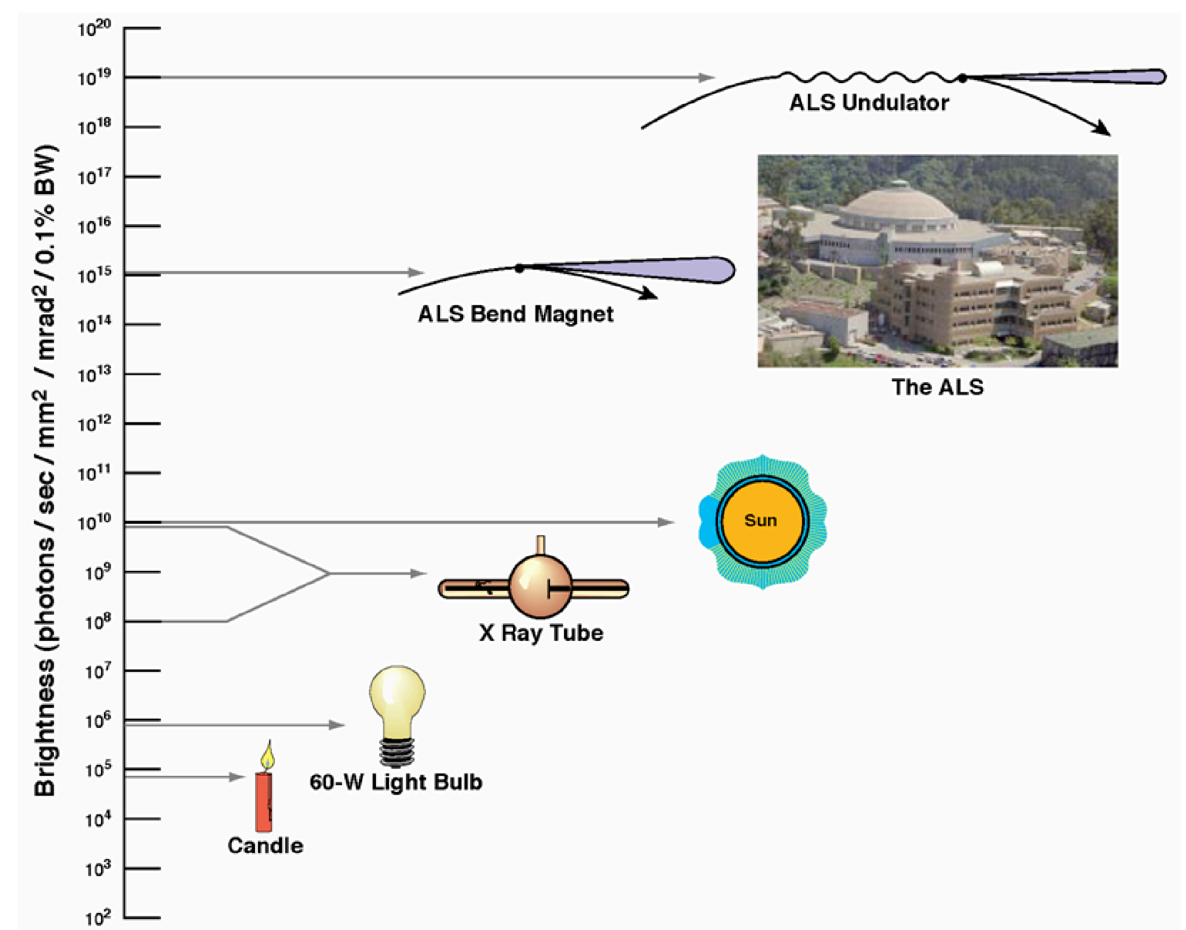


Accelerator–Based Light Sources

70 MeV electron synchrotron at General Electric, Schnectady, NY, 1947

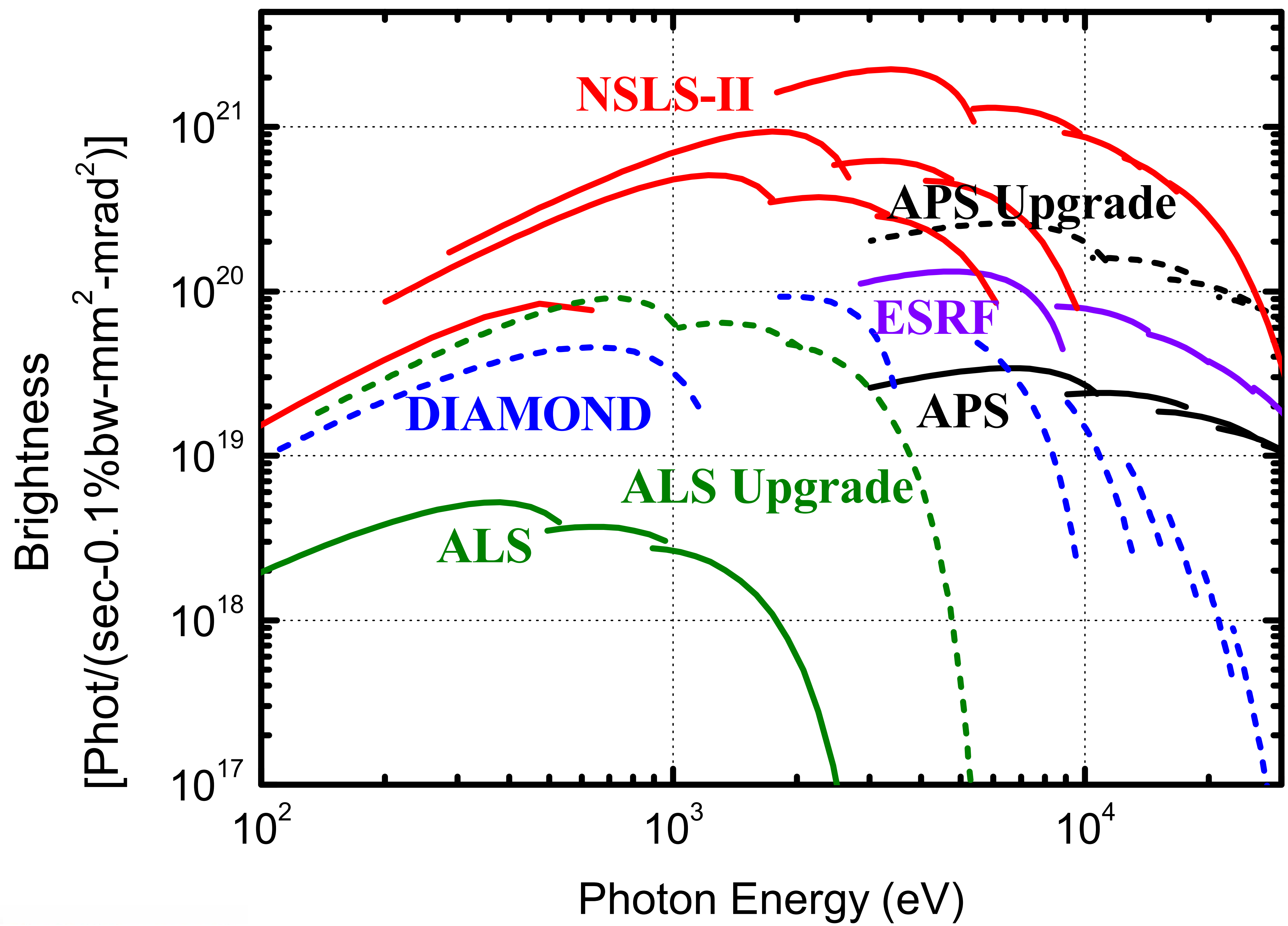






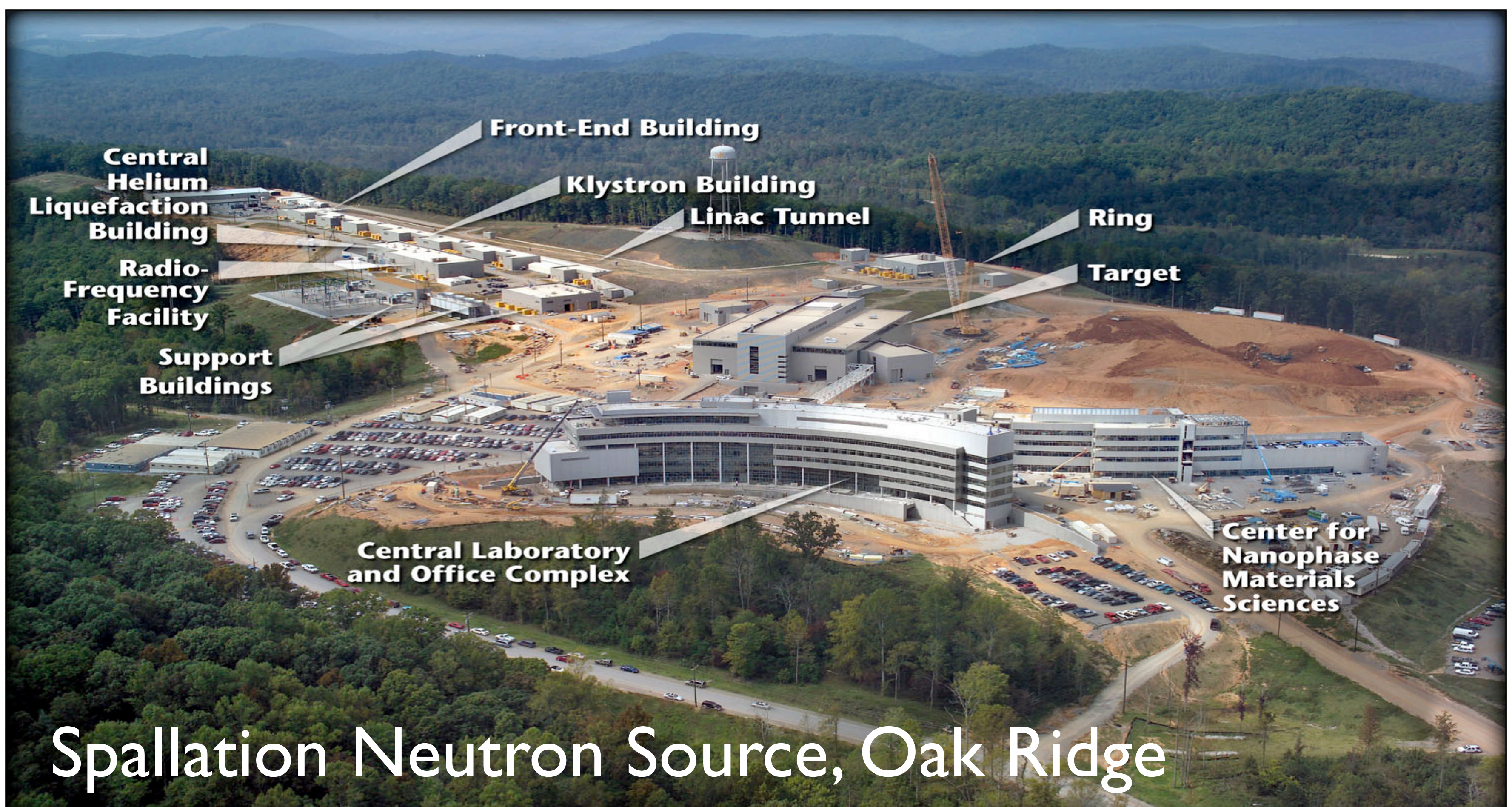
Light Source Brightness

4th generation up here ↑

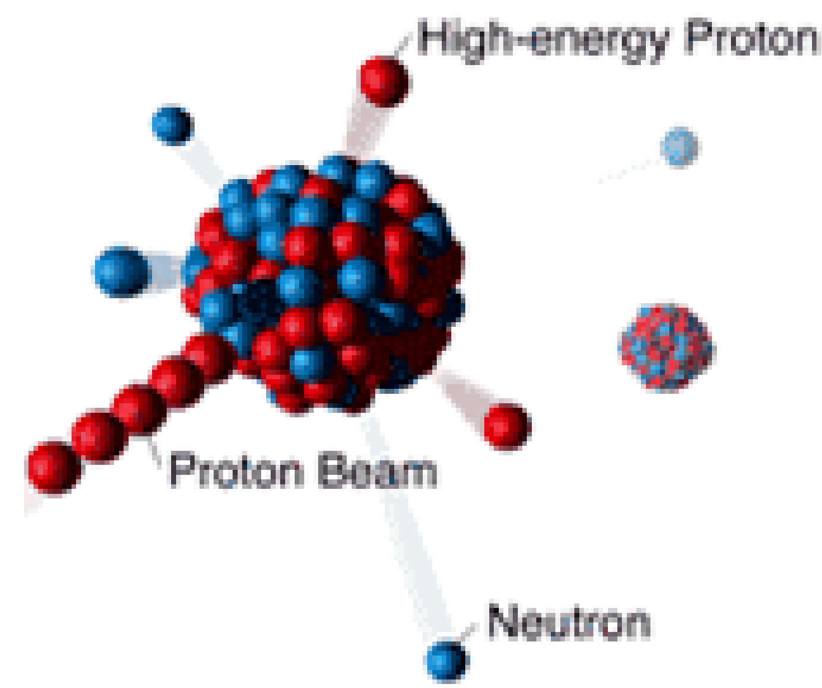


Accelerator-Based Neutron Sources

- High-energy protons are used to generate neutrons from a heavy metal target via the spallation process
- Several labs, ISIS(RAL, UK), LANSCE (Los Alamos), SNS (ORNL), IPNS (Argonne), J-PARC (Japan) operate or are building these types of machines
- They use ~1 GeV protons accelerated by linacs or synchrotrons



Spallation Neutron Source, Oak Ridge



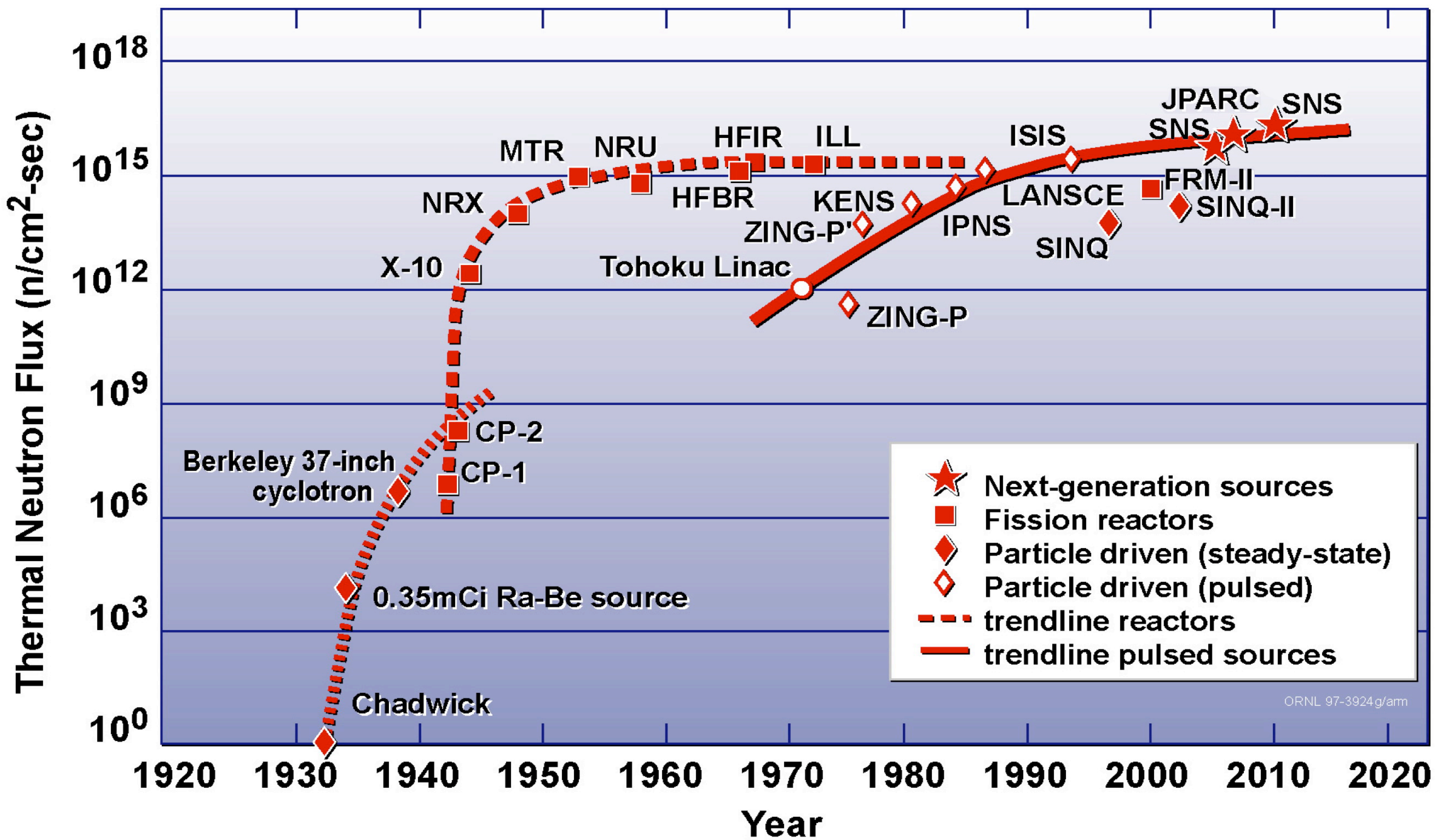
Neutron Source Performance

Reactor-based source:

- neutrons produced by fission reactions
- Continuous neutron beam
- 1 neutron/fission

Accelerator based source:

- 25 neutrons/proton for Hg
- A pulsed beam with precise t_0 allows neutron energy measurement via TOF



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Reactors have reached the limit at which heat can be removed from the core

Pulsed sources have not yet reached their limit and hold out the promise of higher intensities: **Proportional to proton beam intensity on target.**

Meanwhile, back in the electronics lab...

Once Upon a Time, there was a job called: "Audio Frequency Analog Engineer"

Their products:

- Mixers
- Equalizers
- Crossover networks
- Reverbs
- Fuzz Boxes….

Bob Widlar, "inventor of the IC Op-Amp" and other analog gems
http://www.elecdesign.com/Globals/PlanetEE/Content/3080.html

Nowadays, an "Audio Frequency Analog Engineer" is any high-school kid with a PC and SoundBlaster Card

Their products:

- Mixers
- Equalizers
- Crossover networks
- Reverbs
- Fuzz Boxes

Emulated on a PC or programmable DSP

PLUS:

- Synthesizers and guitar amp modeling
- Time warp function that squeeze 20% off of a song's play time *without altering the pitch.*
- Real-time pitch correction makes even Leonard Cohen sing on key

…try doing that with an op-amp!

The Other Super Collider

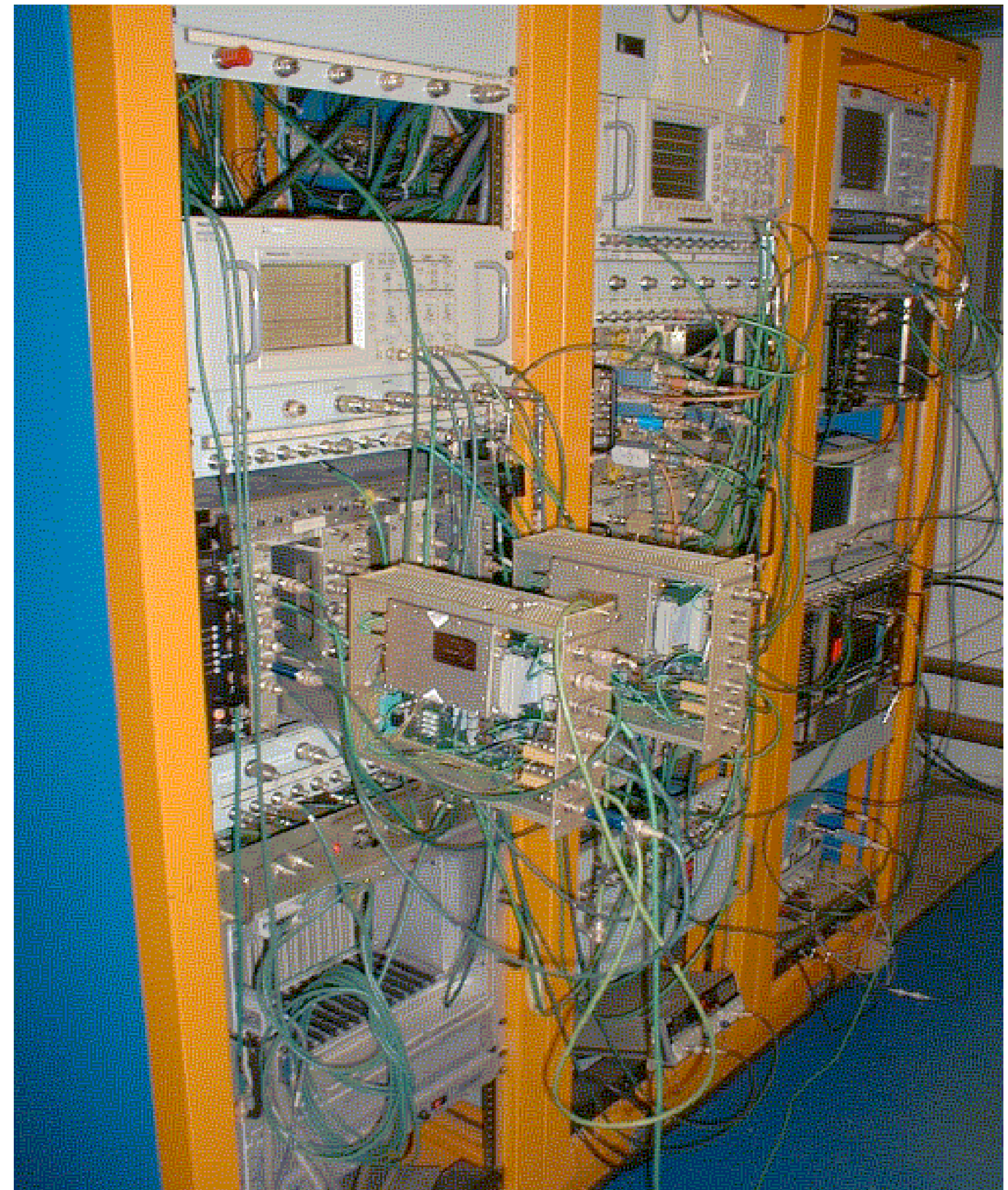
What Unemployed the Audio Analog Engineers?

- ADC/DAC Sampling Rates and Accuracies (192 kSa/s, >100dB SINAD) exceeded requirements
  - *Audio requirements set by human ear*
- Digital Processing capability exceeded requirements at reasonable cost
  - *PC's CPU executes 50,000 instructions per audio waveform sample*

Once Upon a Time, there was a job called: "Low-Level ***Radio Frequency*** Analog Engineer"

Their products:

- Mixers
- Equalizers
- Phase Shifters
- Down converters
- Phase-locked Loops



Fermilab's Booster Low-Level RF system - 2004

Nowadays, a "LLRF Analog Engineer" is *(or should be)* any old programmer with a fast digitizer and an FPGA

Their products:

- Mixers
- Equalizers
- Phase Shifters
- Down converters
- PLLs

Implemented in FPGA's

PLUS:

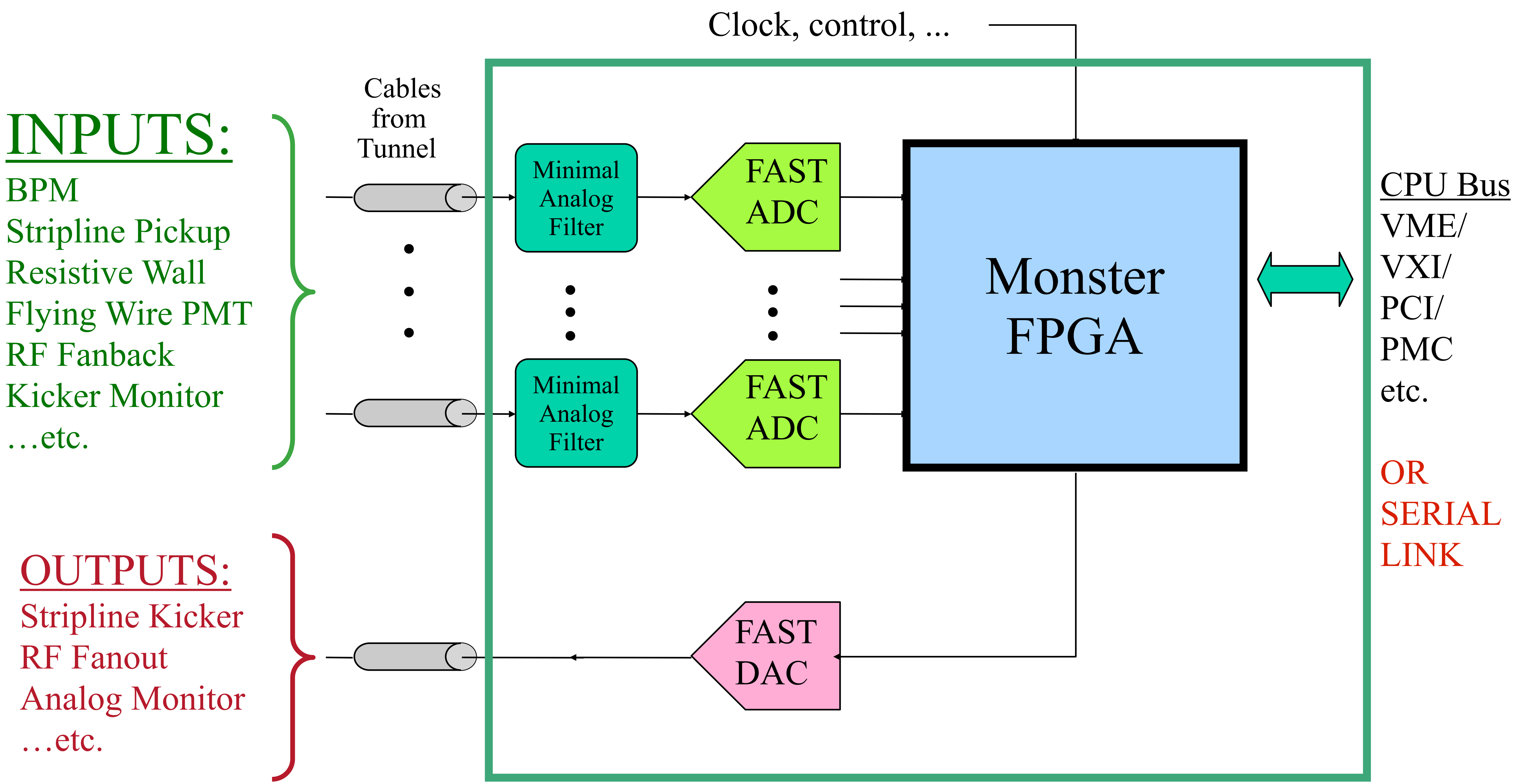
- Direct Digital Synthesis of complex RF waveforms
- Built-in system diagnostics
- Digital Reproducibility (&spares!)
- High Speed Serial Links
- Multi-user support

What Unemploys the Analog RF Engineers?

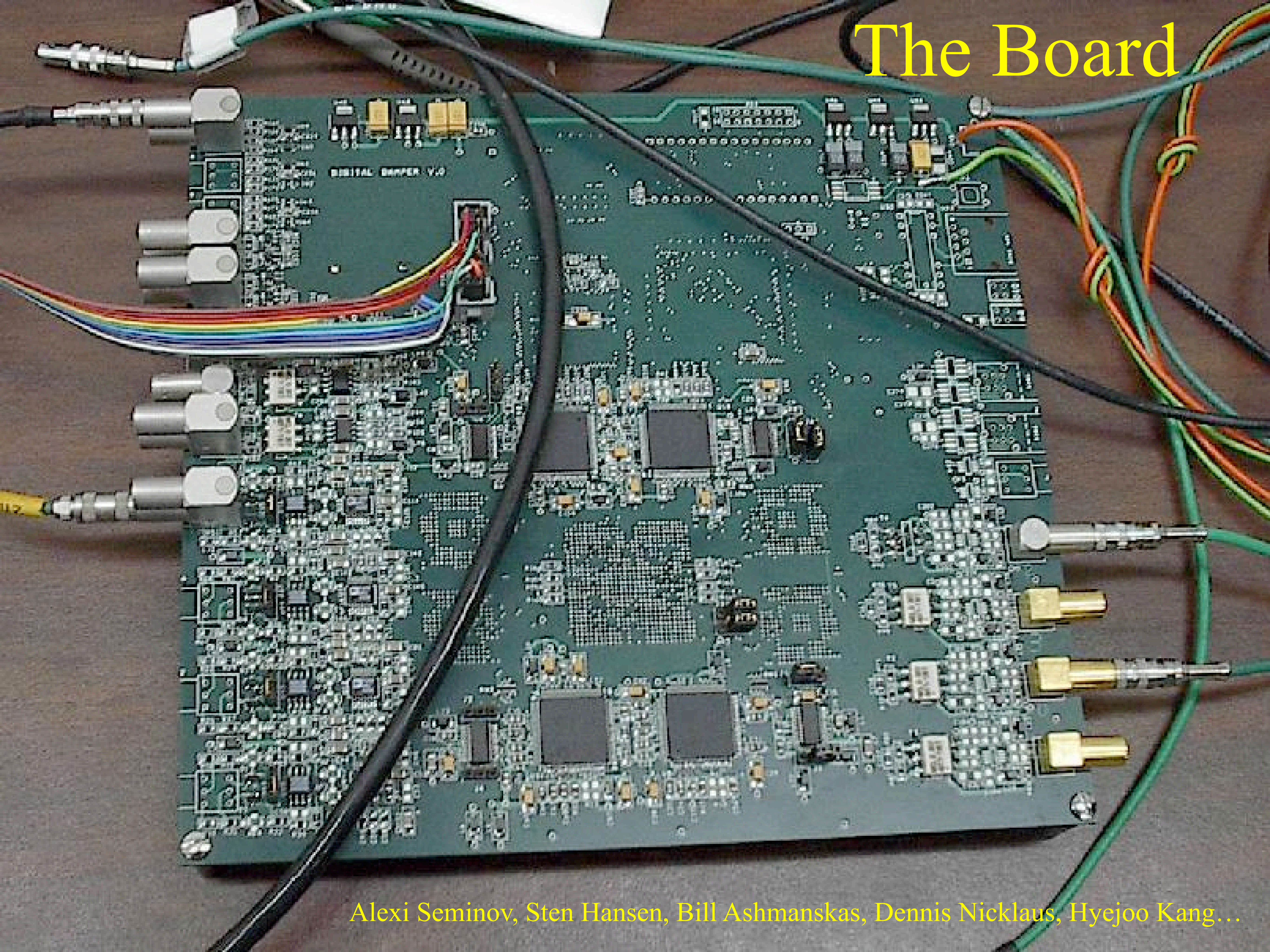
- ADC Sampling Rates and Accuracies exceed requirements
  - ~ *4 samples per RF period gives bunch-by-bunch phase and amplitude*
- Digital Processing capability exceeded requirements at reasonable cost
  - *FPGAs and DSP's*

For ~100 MHz or less: **GAME OVER**

Algorithm Independent Hardware for Accelerator Instrumentation & Control

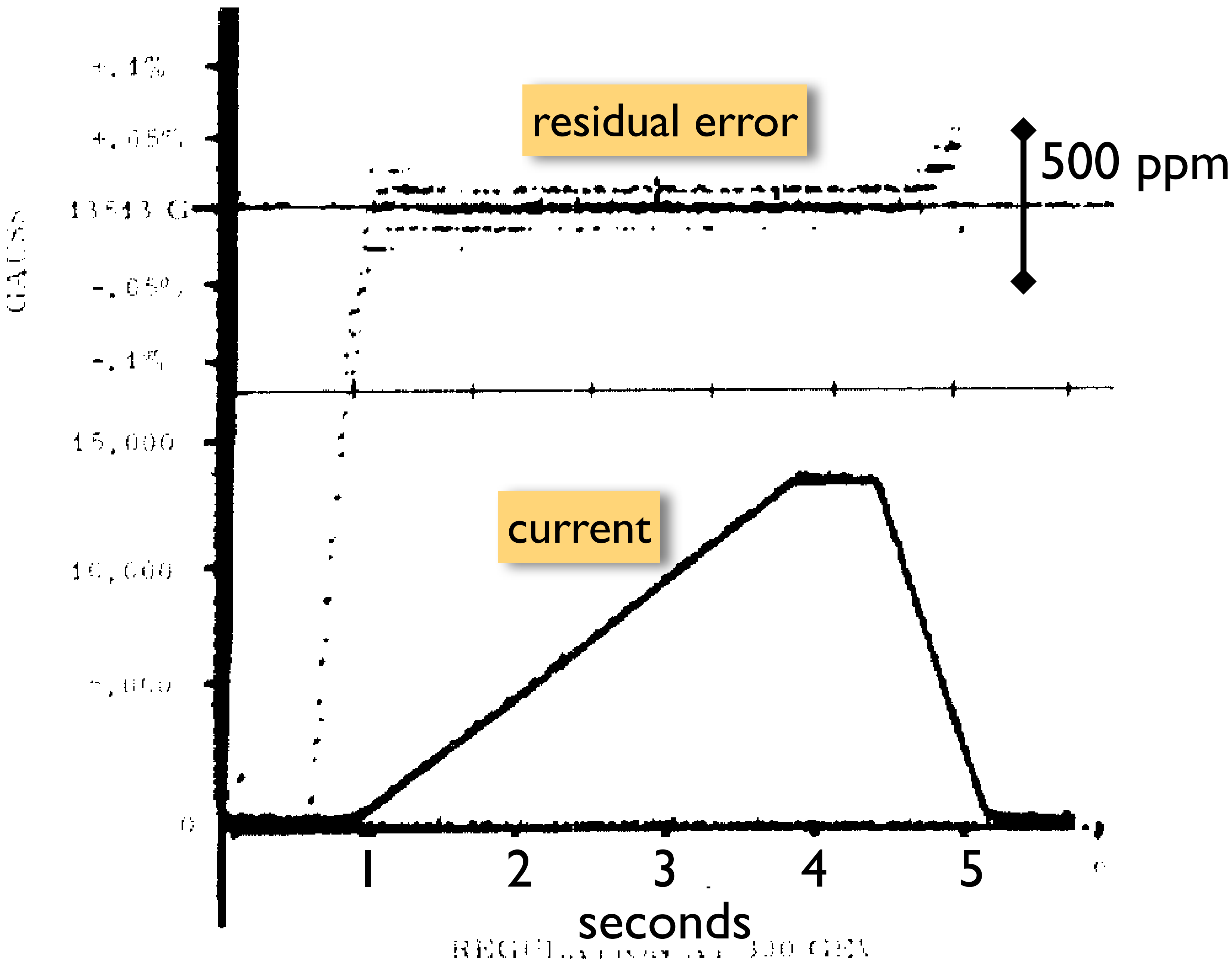


The Board



Alexi Seminov, Sten Hansen, Bill Ashmanskas, Dennis Nicklaus, Hyejoo Kang…

NAL Main Ring Dipole and Quad Supplies

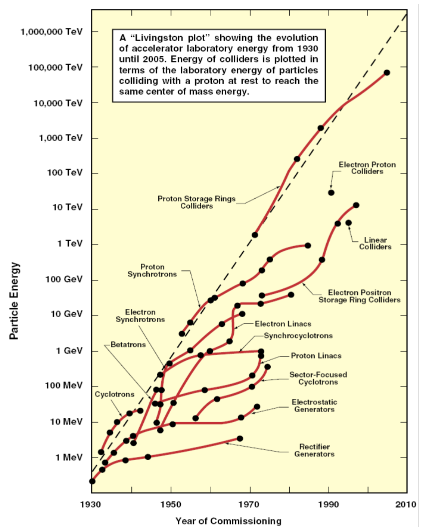


- Deployed in the early 70's
- MAC16 computer in regulation loop, 720 Hz sample rate
- Employed simple feedforward to achieve 1 LSB regulation during slow extraction (100 ppm)
- See Hermann's lecture for modern implementation and performance in LHC

Performance Challenges with Examples

- Energy
  - Large facilities: high channel counts
- Intensity
  - Beam loading
  - Loss minimization
  - Coherent instabilites
- Luminosity
  - Emittance/beam preservation
  - Interaction point control
- Brightness
  - Related to stability
- Operational Improvements
  - Machine protection
  - Subsystem enhancements

Energy

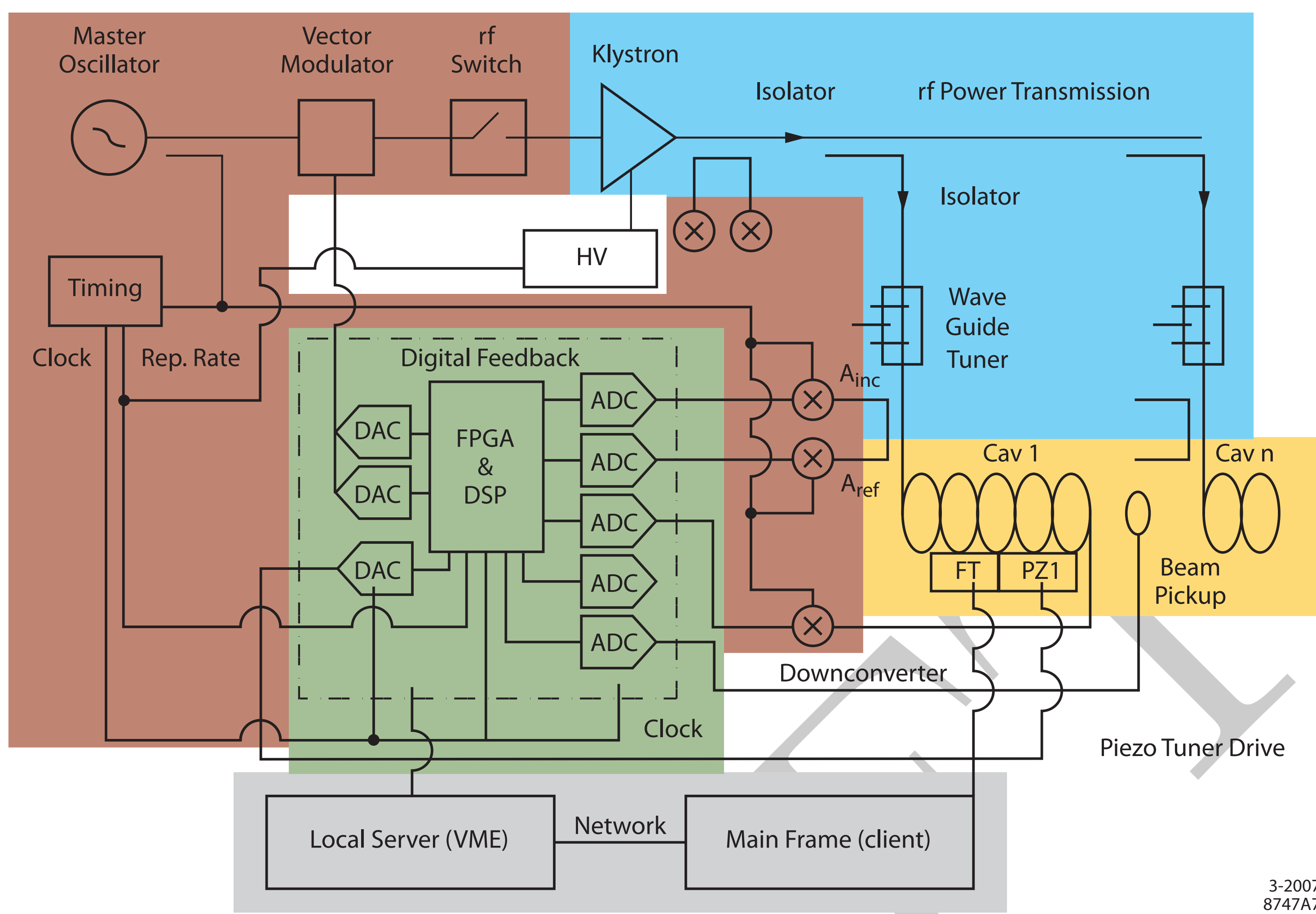


A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.
Particle Energy
1,000,000 TeV
100,000 TeV
10,000 TeV
1,000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
Year of Commissioning
1930
1950
1970
1990
2010
Electron Proton Colliders
Proton Storage Rings Colliders
Linear Colliders
Proton Synchrotrons
Electron Positron Storage Ring Colliders
Electron Synchrotrons
Electron Linacs
Synchrocyclotrons
Betatrons
Proton Linacs
Sector-Focused Cyclotrons
Cyclotrons
Electrostatic Generators
Rectifier Generators

ILC RF Scale

To reach 500 GeV c.m. energy with linacs:

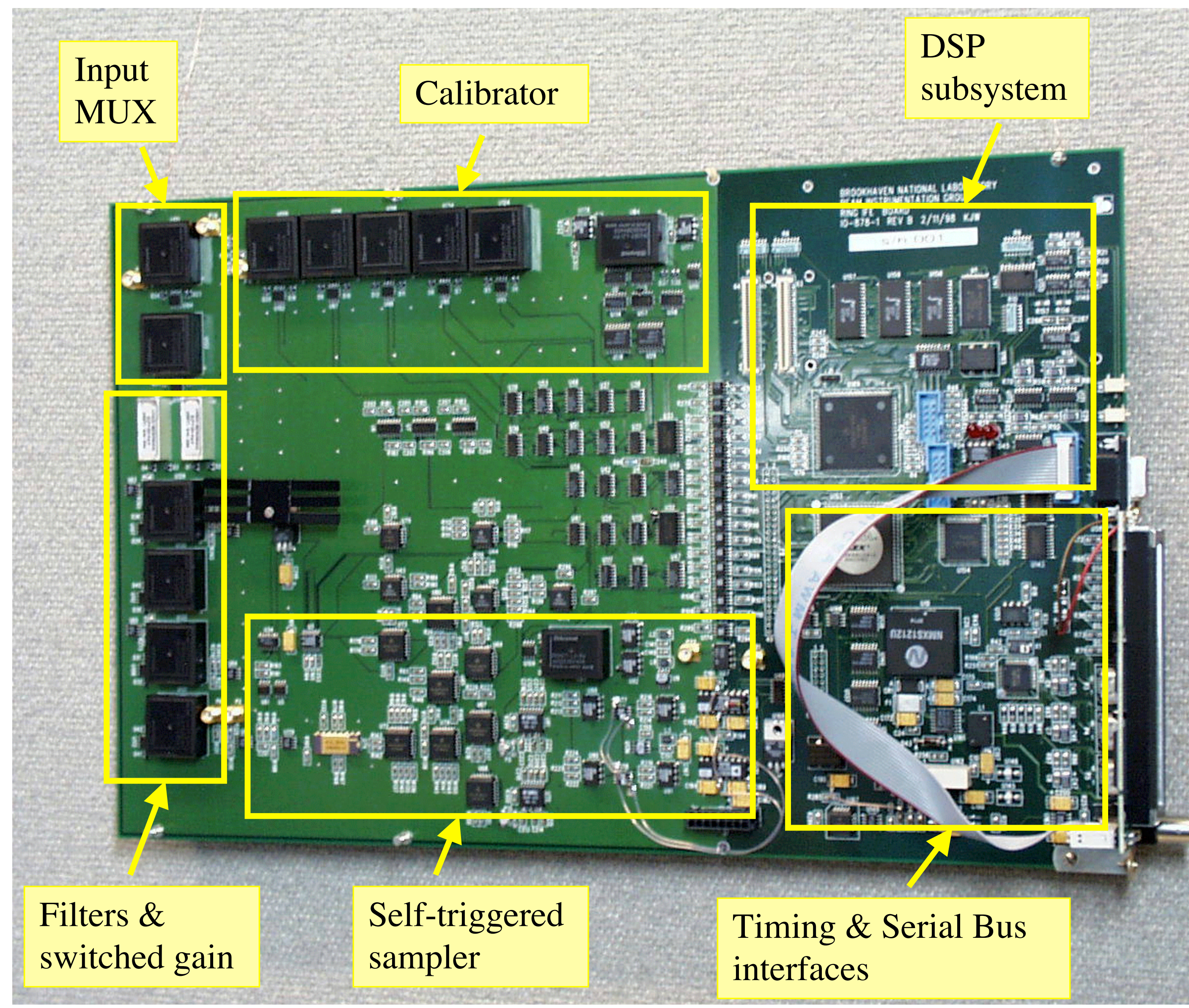
- 16,088 SC Cavities: 9 cell, 1.3 GHz
- 1848 CryoModules(LHC 1232 dipole cryounits)
- > 600 RF Units (#CM/3) supported by LLRF units:
  - each with about 95 ADCs, 6 DACs
  - 0.07% amplitude, 0.35% phase regulation in main linac to achieve energy stability of 0.1%



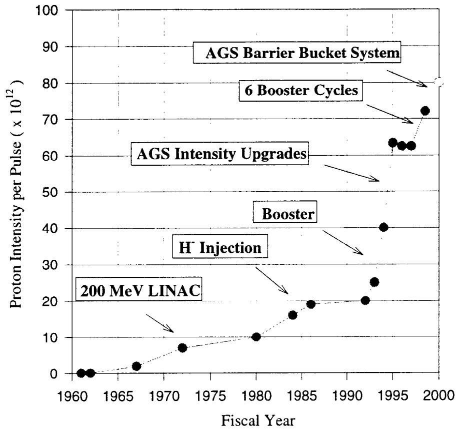
Large Scale BPM Production

- about 800 units manufactured
- Required: affordability, built in test, remotely configurable
- Integrated, single board design
- 1990's low cost design:
  - 78 kHz turn by turn sampling (audio)
  - fixed point DSP
  - Firewire serial

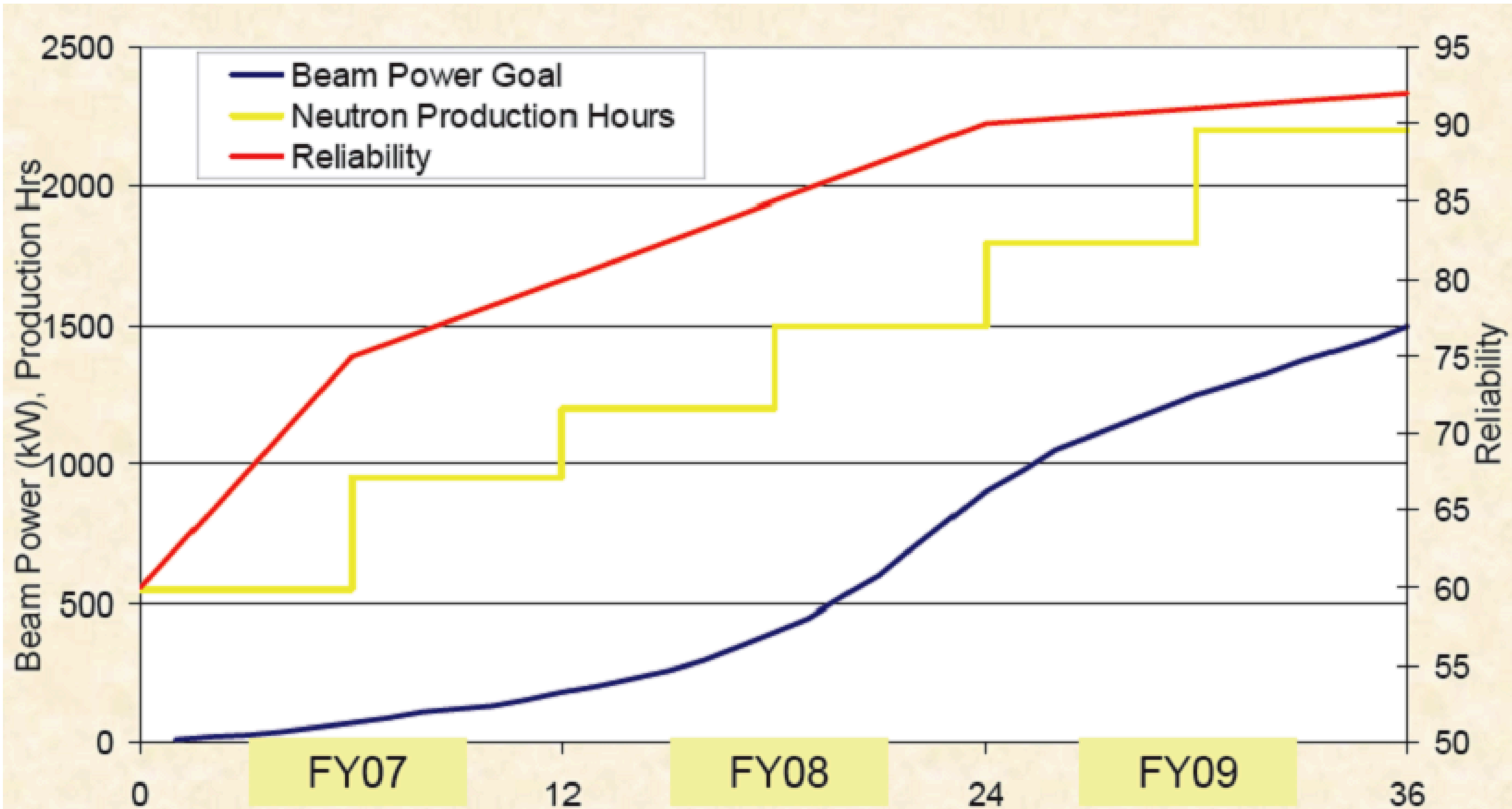
RHIC electronics



Intensity

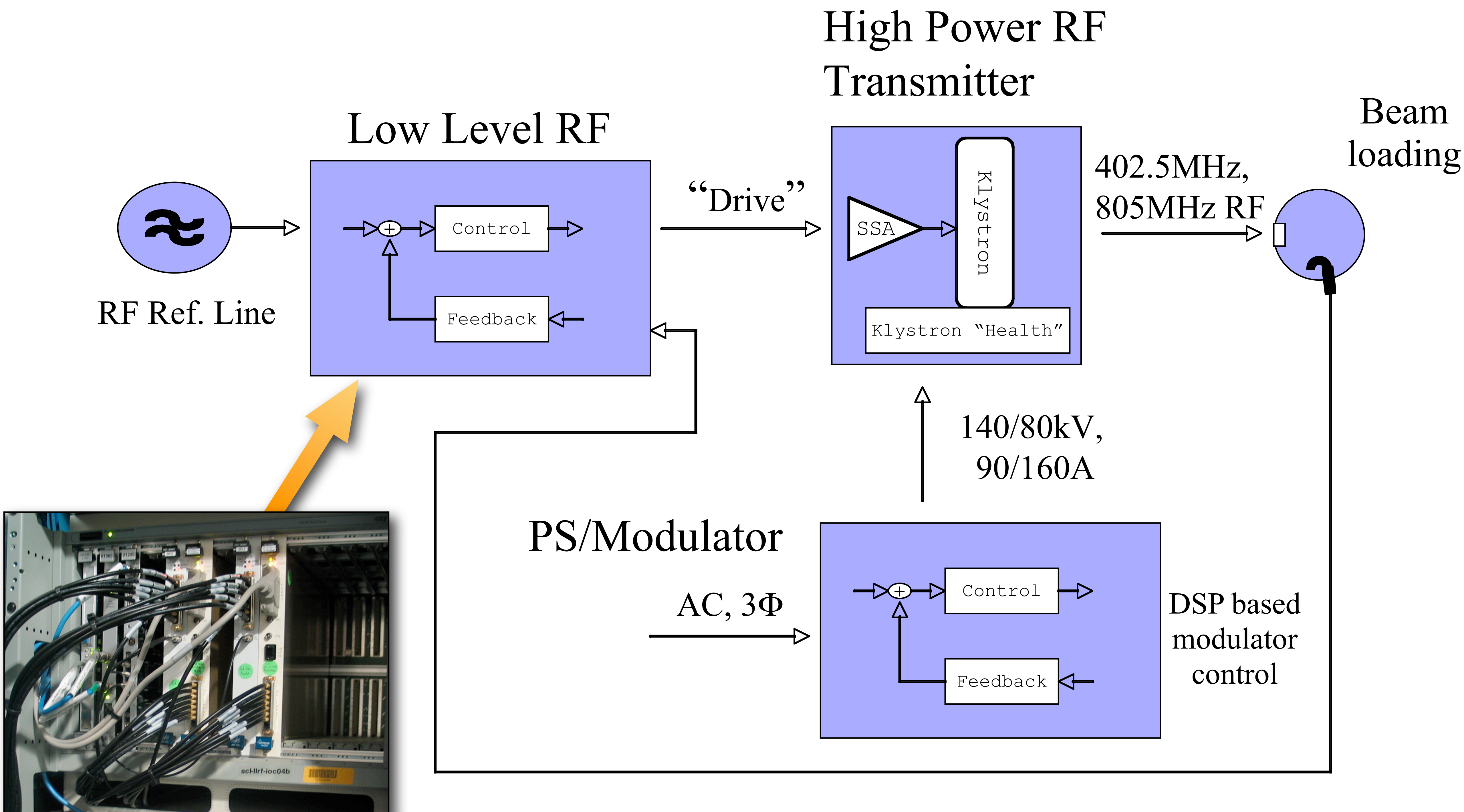

AGS Barrier Bucket System
6 Booster Cycles
AGS Intensity Upgrades
Booster
H⁻ Injection
200 MeV LINAC
Proton Intensity per Pulse (x 10^{12})
Fiscal Year
100
90
80
70
60
50
40
30
20
10
0
1960
1965
1970
1975
1980
1985
1990
1995
2000

SNS Goals



- MW operation requires 1 ms pulse length in linac, at 60 Hz, 10^14 protons per pulse, 1 GeV output, with only 1 Watt per meter loss.
- Consistent linac LLRF regulation goal: 0.5% amplitude, 0.5 degrees phase (402.5 and 805 MHz)

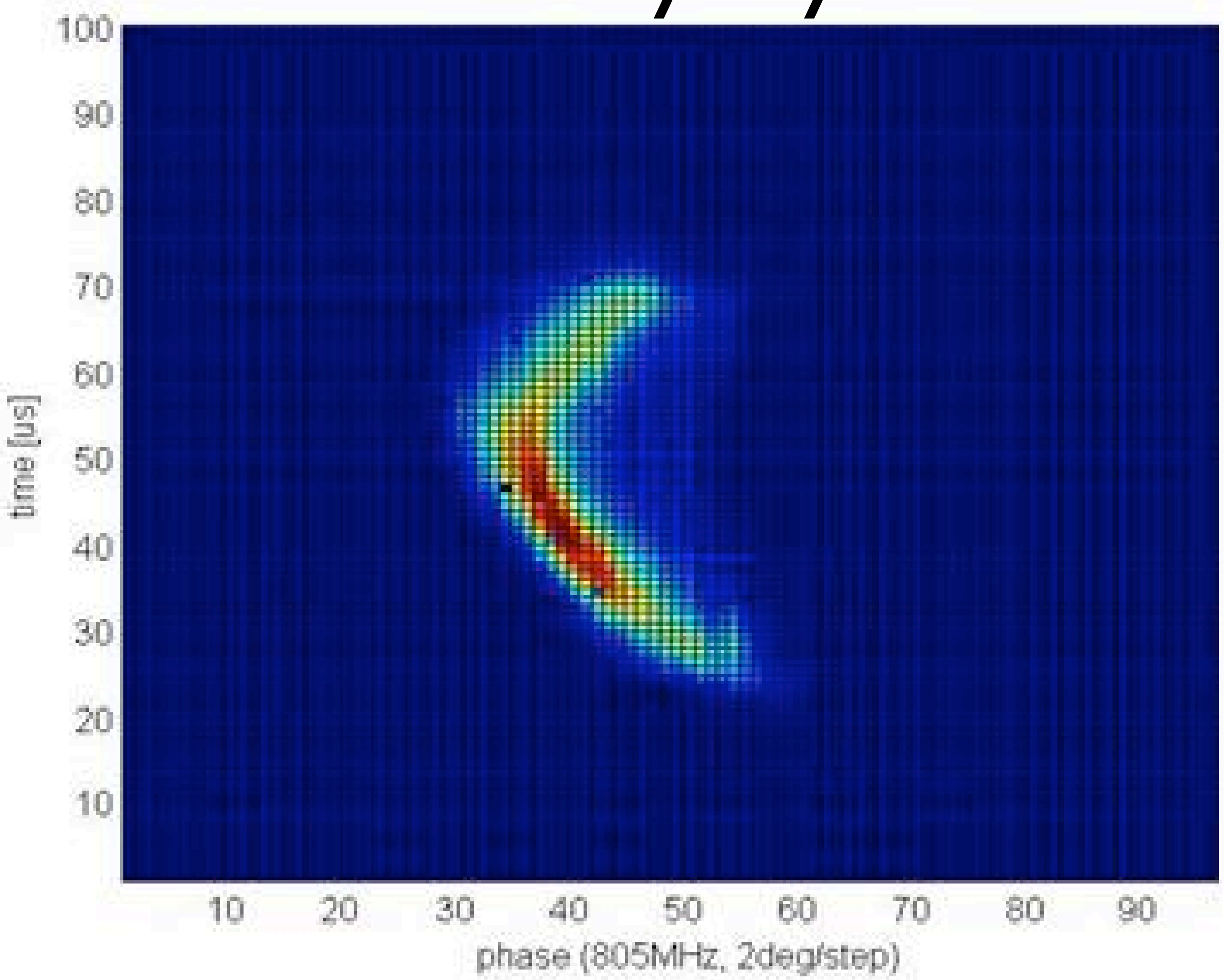
Linac RF Components



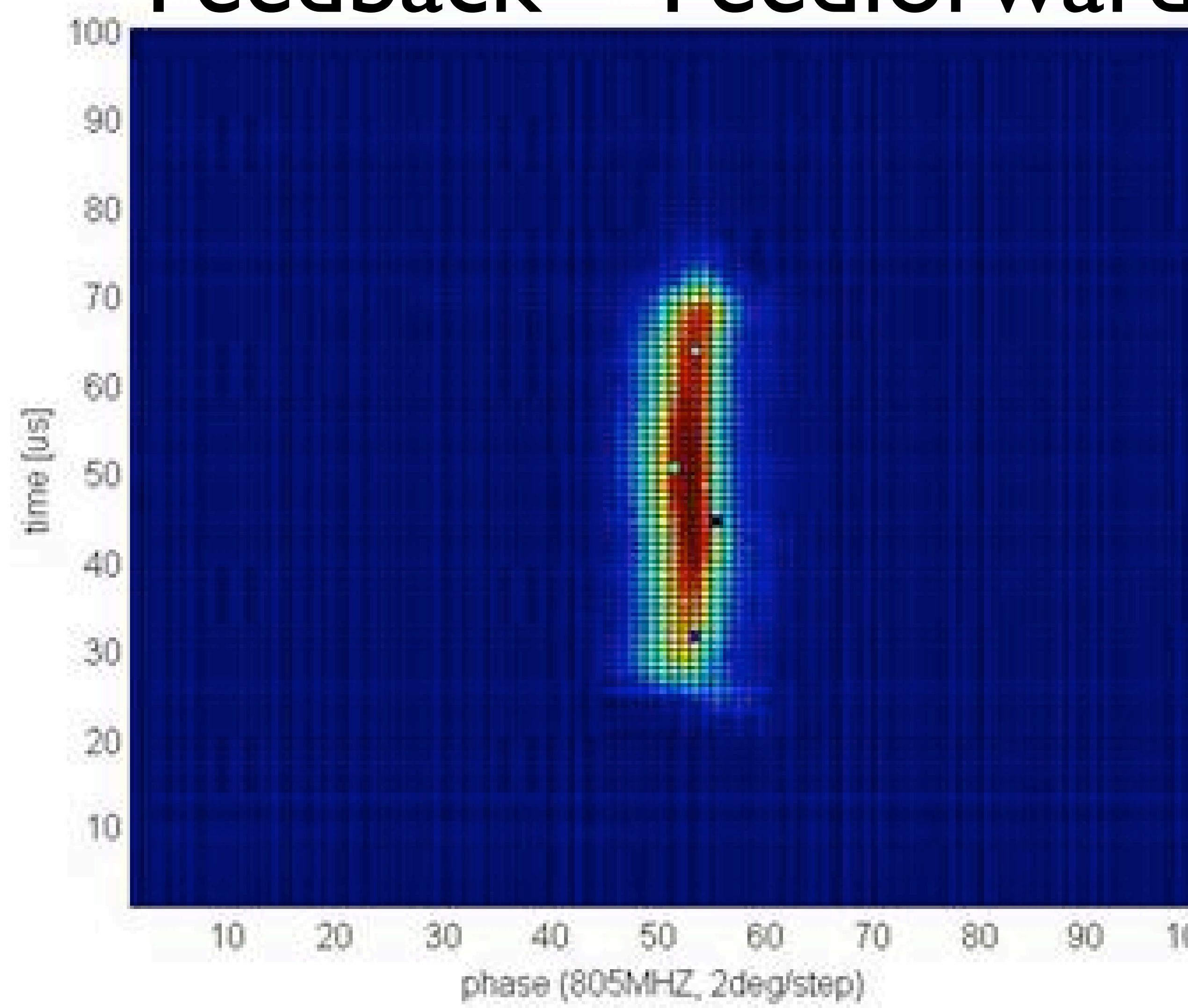
See LLRF lecture for general beam loading analysis and implementation details

Phase Distribution Along Pulse

Early try



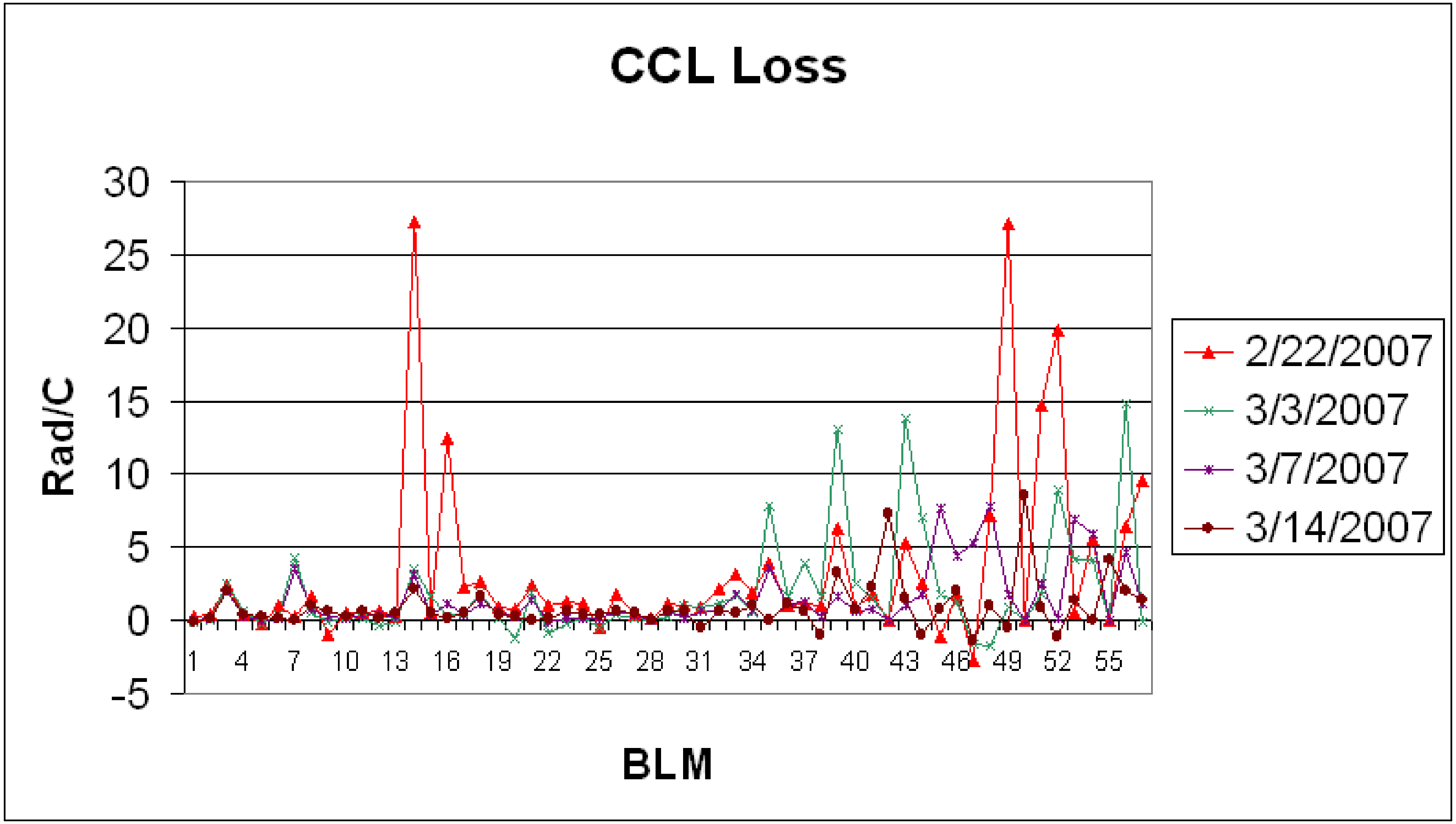
Optimized
Feedback + Feedforward



Off momentum particles could be lost and activate machine downstream

Tuning for Low Loss

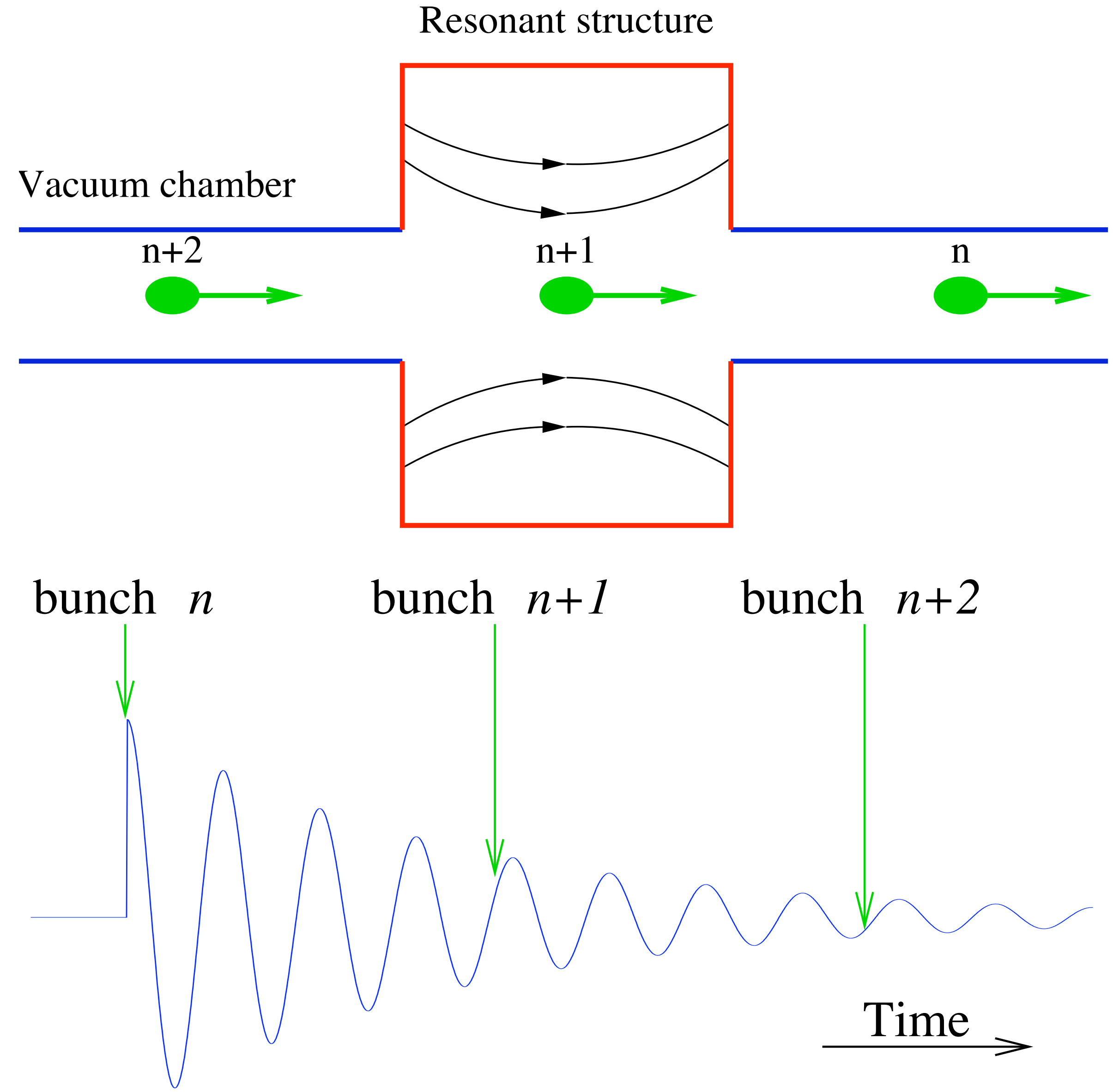
To allow hands-on maintenance:
< 1 Watt/meter beam loss



Digital control (particularly LLRF) is critical for rapid startup and achieving a low loss beam run

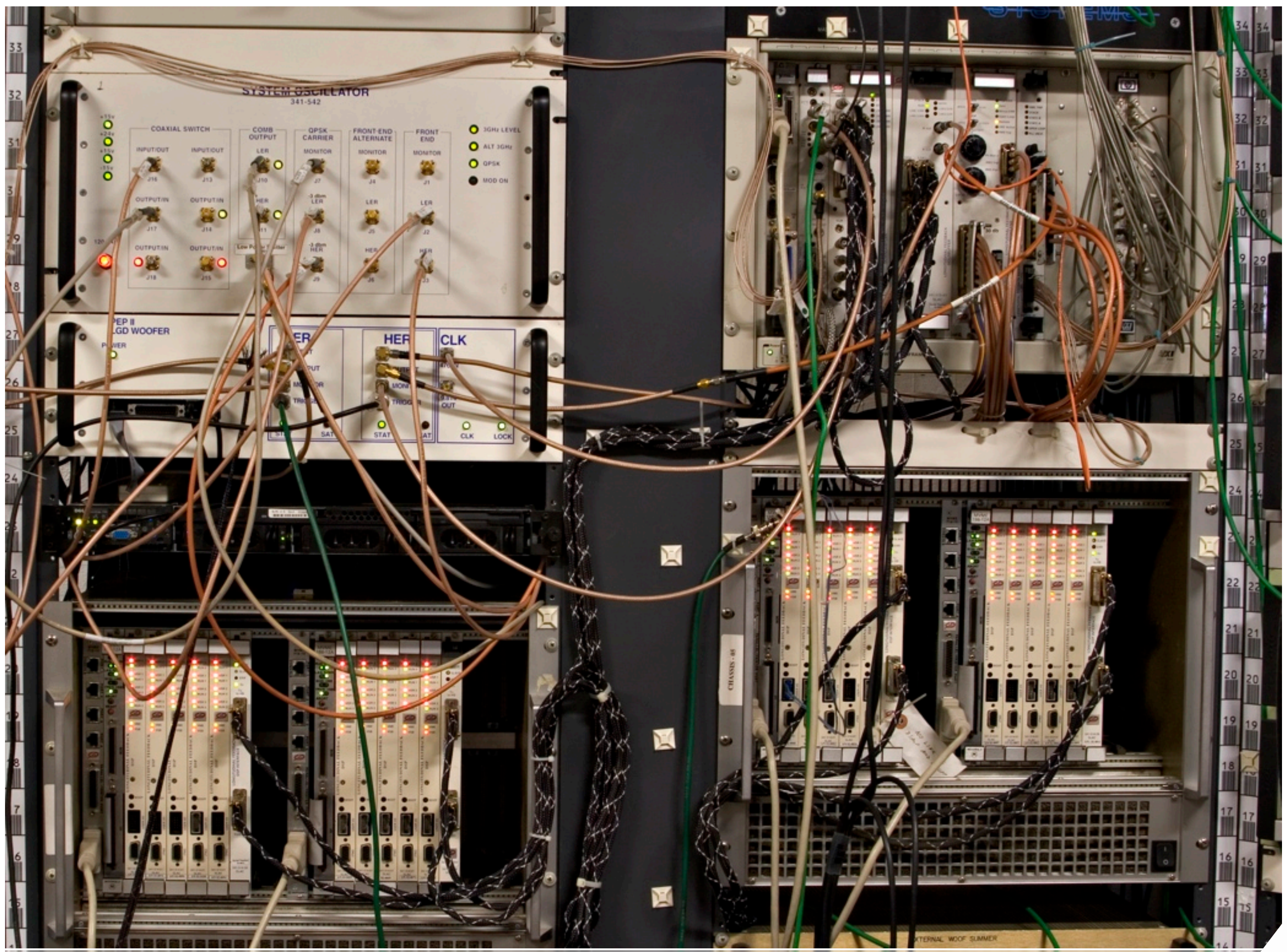
Instabilities

- Residual Gas
  - (-) e-p instability in hadron rings
  - (+) fast ion instability in electron rings
  - Countermeasures: good vacuum, clearing gap, solenoids, **active feedback**, ...
- Wall impedance
  - Resistive wall
  - Broadband inductive
  - Cavity modes
  - Countermeasures: shielded components (bellows, ports,...), HOM couplers, **active feedback**, ...

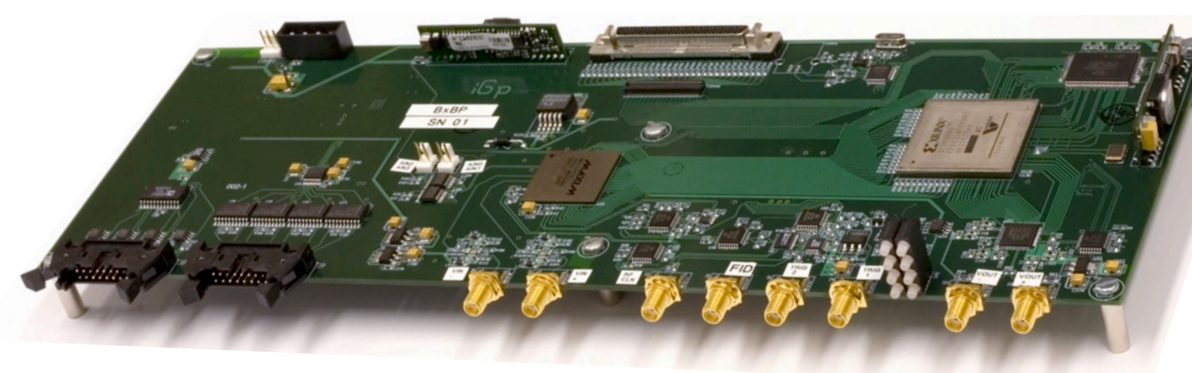


More on this during feedback lecture

Digital Feedback Systems

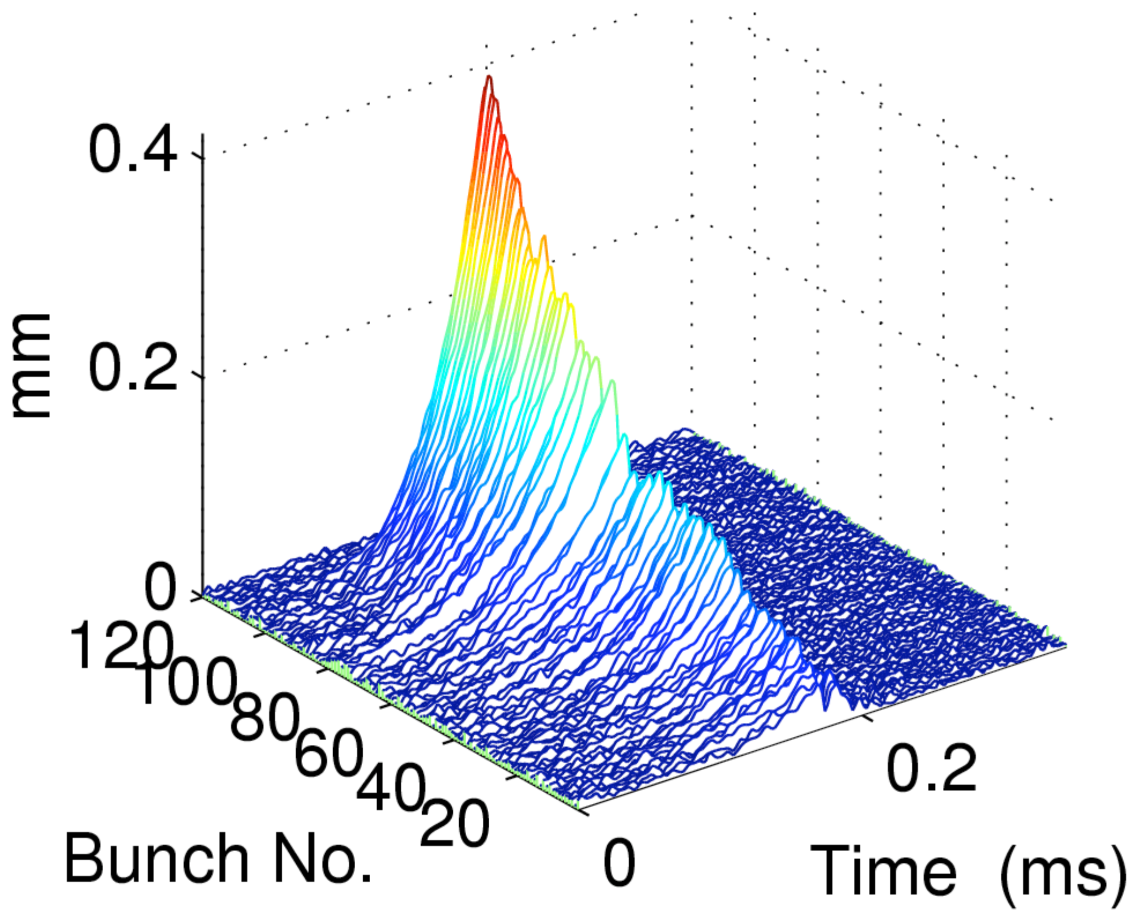


1990s

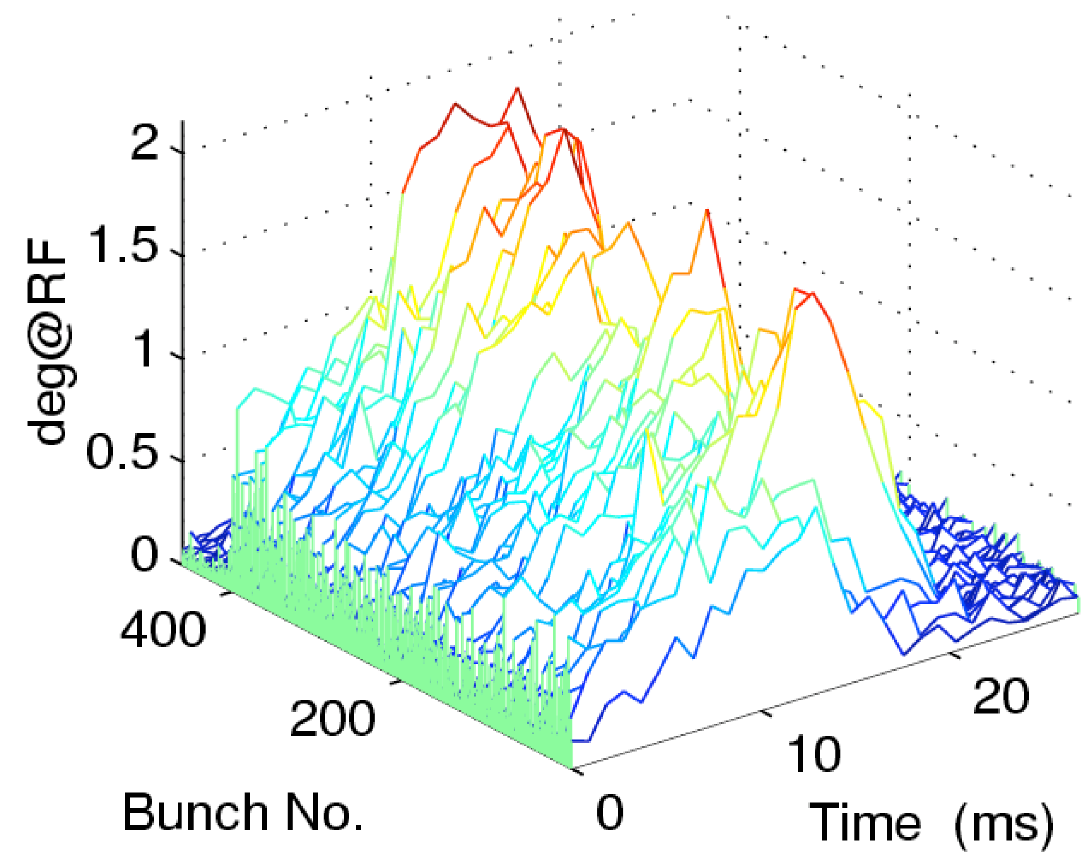


2000s

Grow then Damp



Horizontal grow/damp in DAΦNE - resistive wall



Longitudinal grow/damp in PLS - cavity HOMs

AGS Resistive Wall Instability

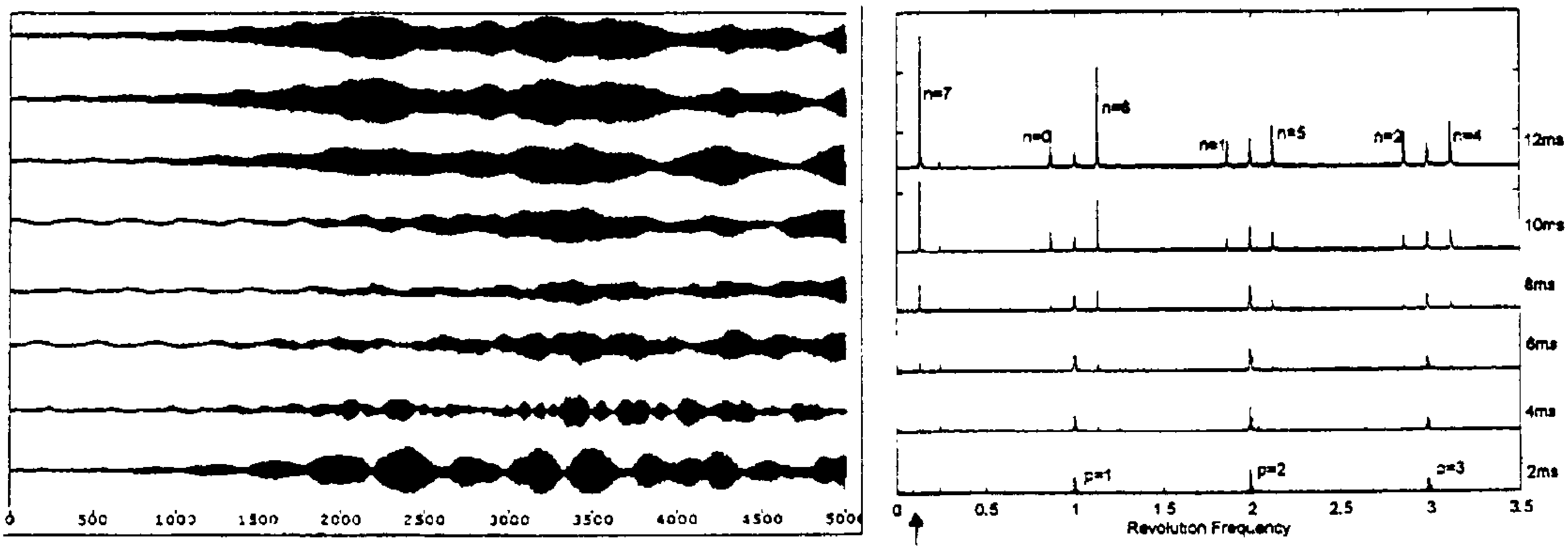
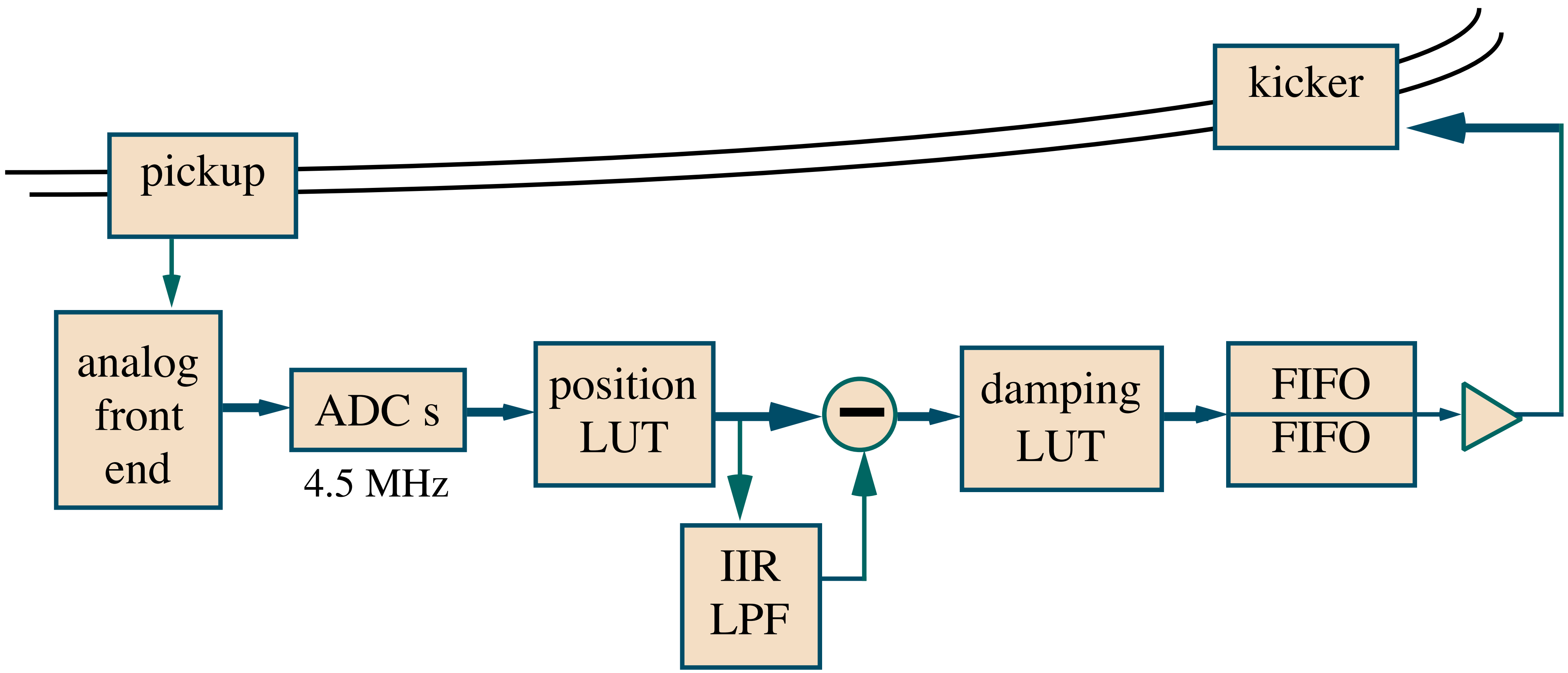


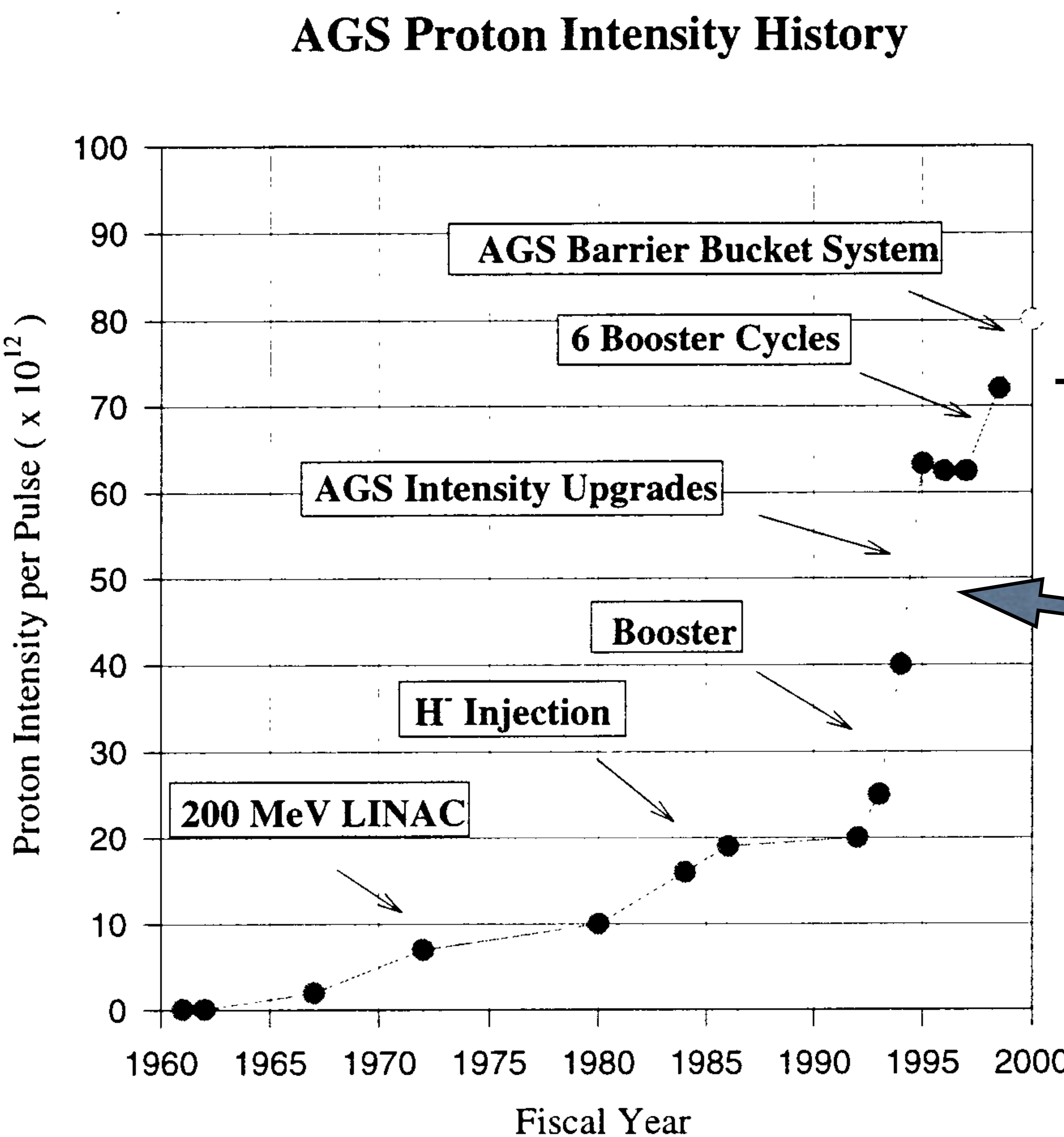
FIGURE 3. The left figure shows the growth of a vertical coupled bunch instability at AGS injection energy of 1.5 GeV for the eight bunches. The horizontal scale is in turns. The right graph shows the evolution of the frequency components during the growth of the instability.

AGS Transverse Feedback



- Digital filter implemented in PLD
- Simple implementation, dramatic results
  - Record intensities well beyond transverse instability threshold

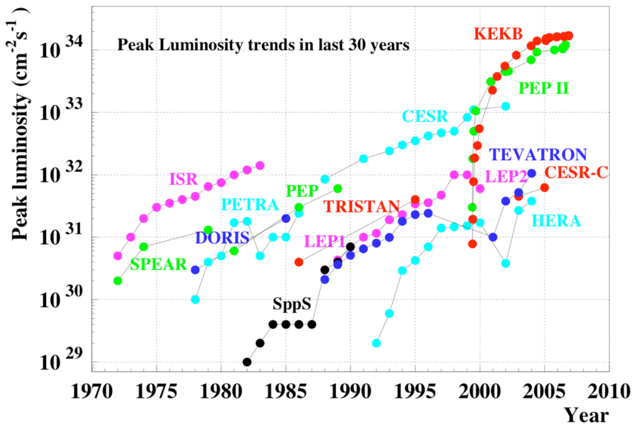
Increasing intensity



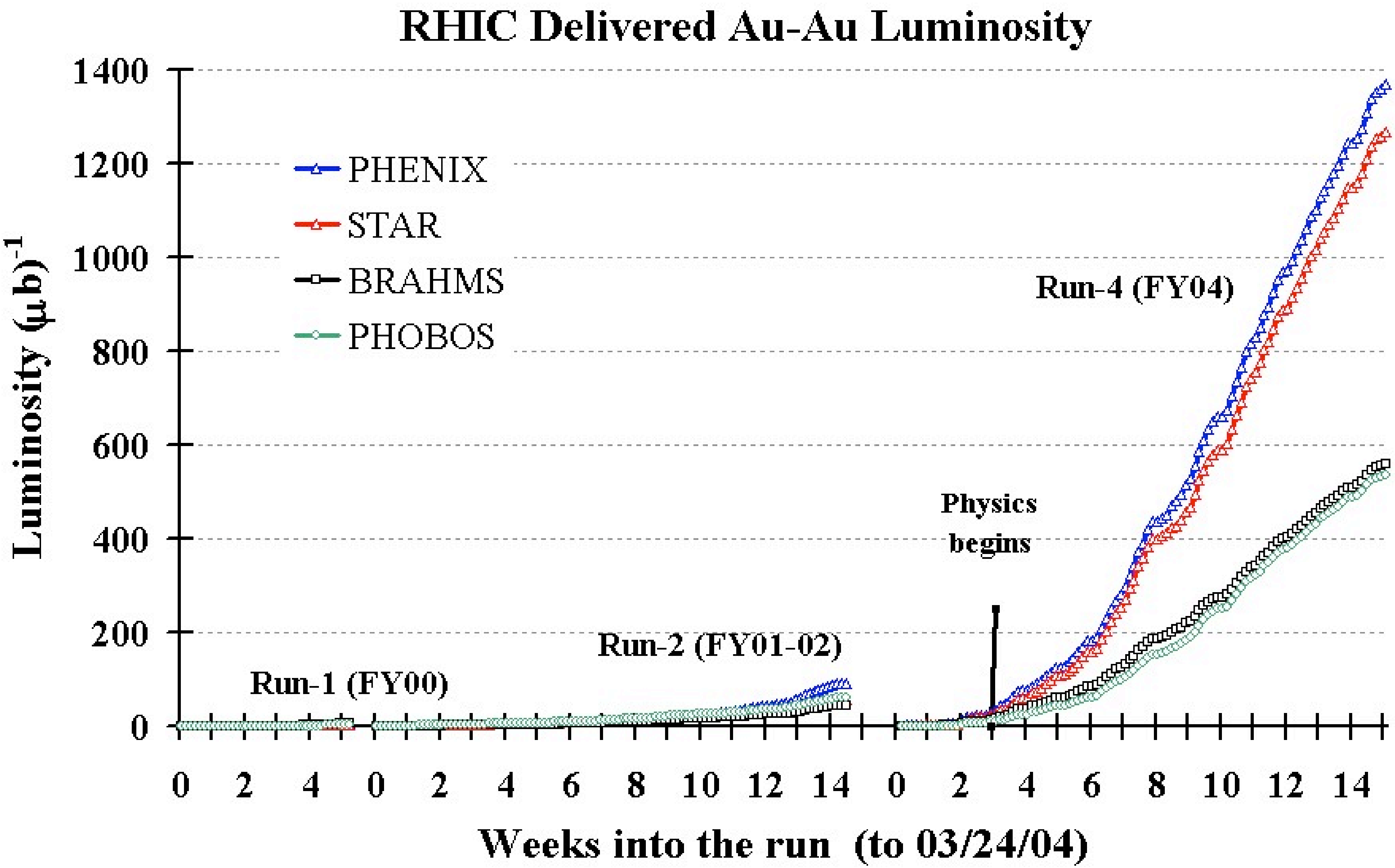
7000X
design spec

transverse
feedback

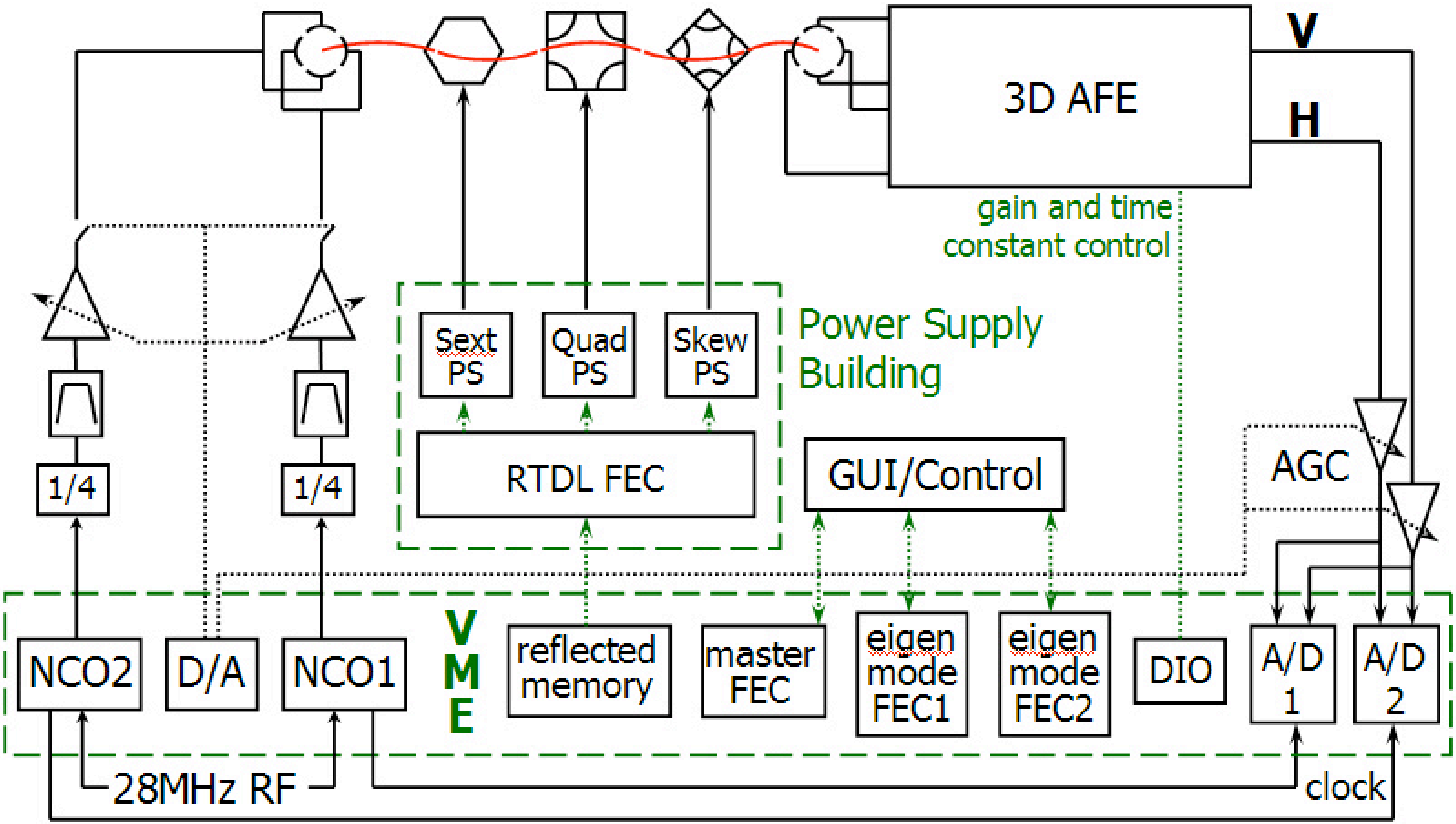
Luminosity


Peak Luminosity trends in last 30 years
Peak luminosity (cm^-2 s^-1)
Year
KEKB
PEP II
CESR
TEVATRON
CESR-C
LEP2
HERA
ISR
PETRA
PEP
TRISTAN
DORIS
LEP1
SPEAR
SppS
10 34
10 33
10 32
10 31
10 30
10 29
1970
1975
1980
1985
1990
1995
2000
2005
2010

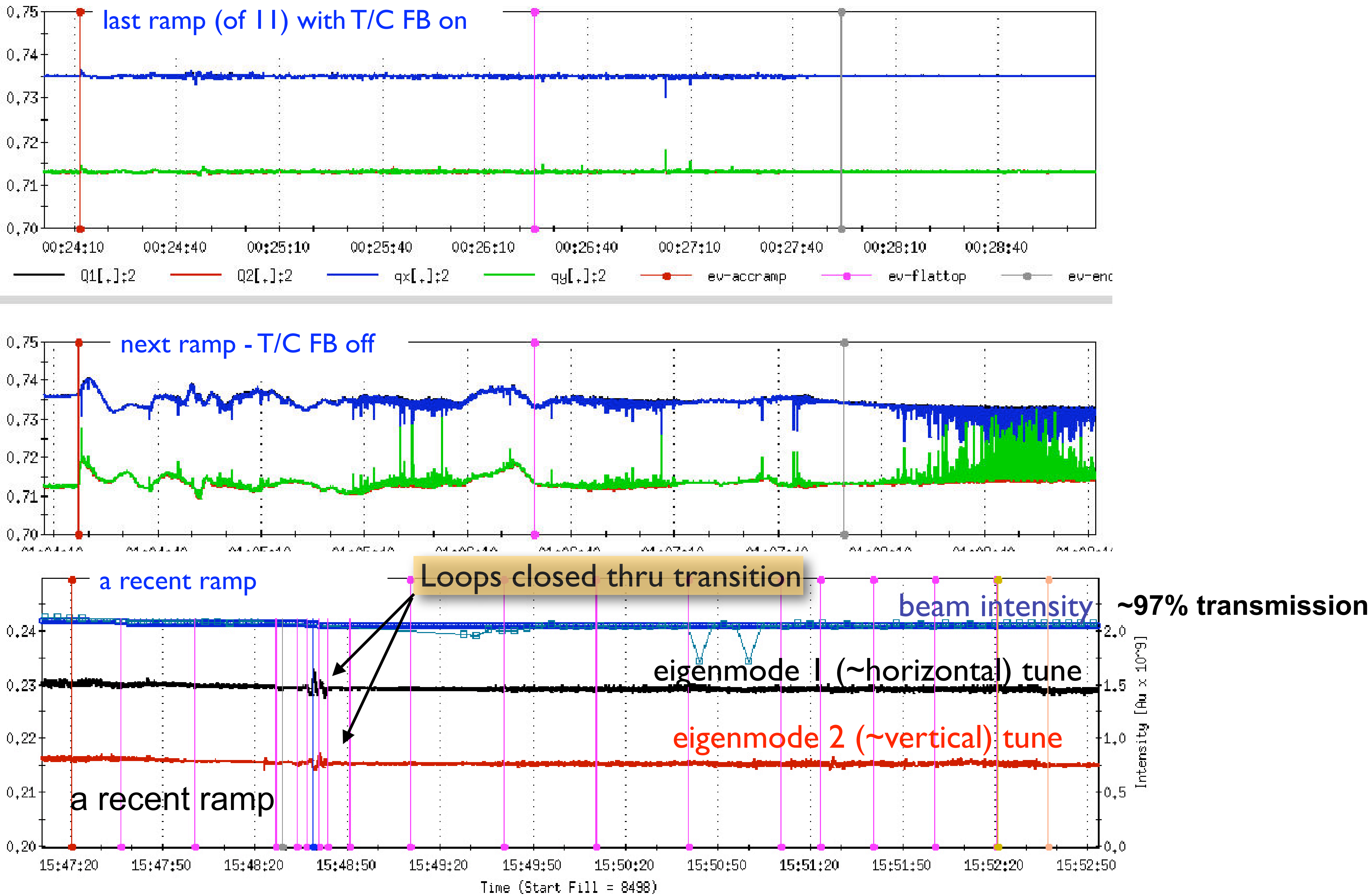
Experimenter's View of Performance: Integrated Luminosity



RHIC Run 6 Tune Chromaticity and Coupling Feedback

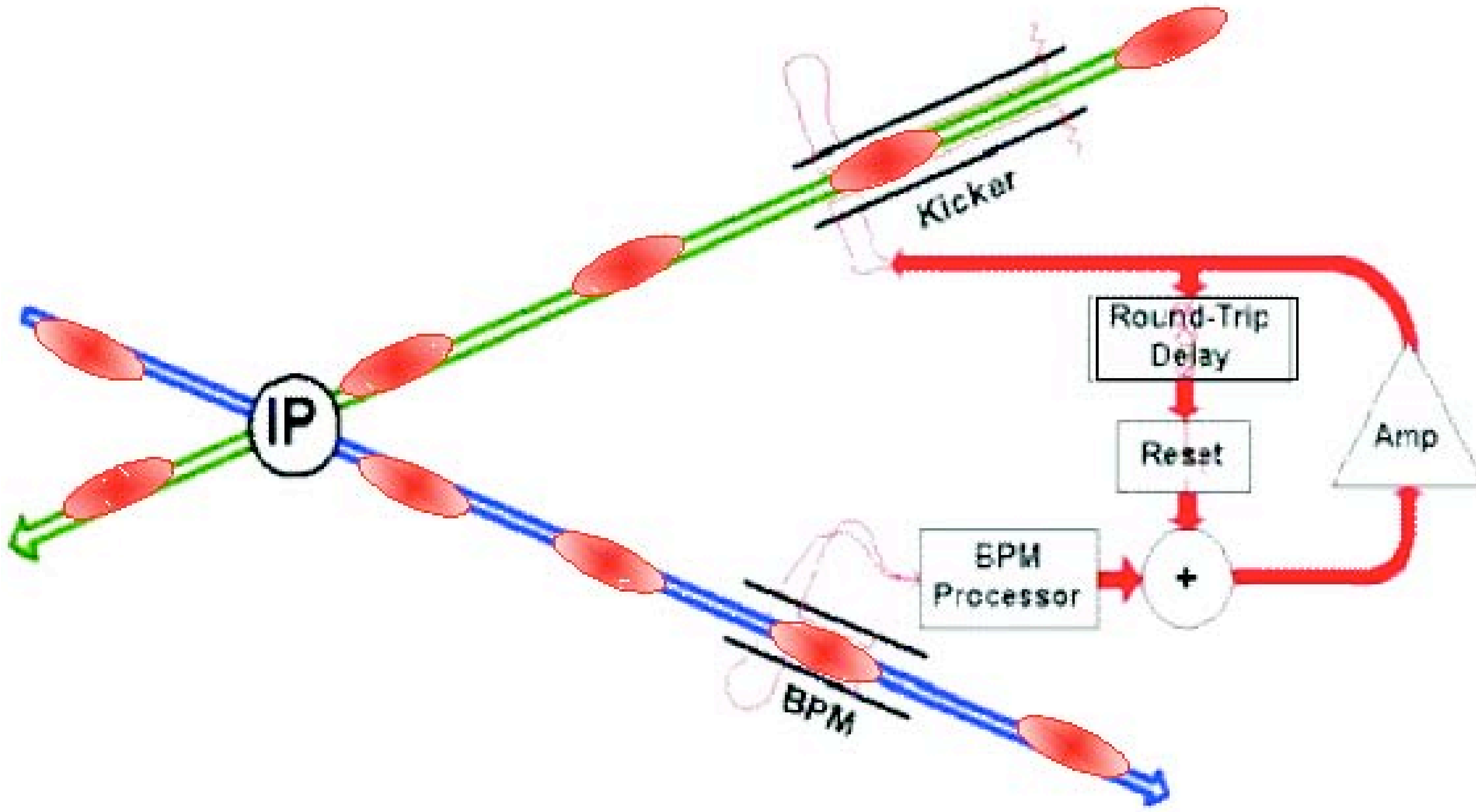


Results of Ramps with Feedback



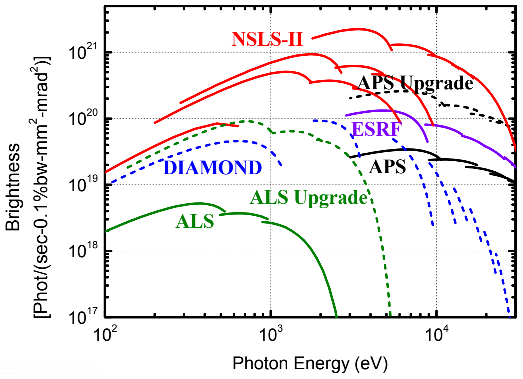
ILC Intra-train Feedback

- RMS vertical beam size at IP is 5.7 nm, so nm offsets will noticeably reduce luminosity
- Control offsets to nm level by measuring result of stong beam-beam kick and feeding back to incoming beam
- Performance issue: latency



Source of delay	Contribution to latency (ns)
Beam time-of-flight	7
Signal return time	15
BPM processor	7
ADC/DAC	40
FPGA processing	25
I/O	3
Amplifier risetime	40
Kicker fill time	3
Total	**140**

Brightness



NSLS-II
APS Upgrade
ESRF
APS
DIAMOND
ALS Upgrade
ALS
Brightness [Phot/(sec-0.1%bw-mm^2-mrad^2)]
Photon Energy (eV)
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^2
10^3
10^4

To Utilize Brightness, Users Need Stability

SPEAR

experiment parameters	beam orbit	beam size	beam energy/ energy spread
< 0.1% intensity steering to small samples	$\Delta x,y < 5\%\ \sigma_{x,y}$ $\Delta x',y' < 5\%\ \sigma'_{x,y}$	$\Delta\sigma_{x,y} < 0.1\%\ \sigma_{x,y}$ $\Delta\sigma'_{x,y} < 0.1\%\ \sigma'_{x,y}$	$\Delta E/E(\text{coher}) < 10^{-4}$ $\Delta E/E(\text{rms}) < 10^{-4}$
< 10^{-4} photon energy resolution	$\Delta x' <\sim 5\ \mu\text{rad}$ $\Delta y' <\sim 1\ \mu\text{rad}$ (undulator)		$\Delta E/E(\text{coher}) < 5 \times 10^{-5}$ $\Delta E/E(\text{rms}) < 10^{-4}$ (und n = 7)
timing, bunch length		$\Delta\sigma_t < 0.1\%\ \sigma_t$	$\Delta E/E(\text{coher}) < 10^{-4}$

- Stability requirements for small beams may be relaxed if beam size at experiment is limited by beam line optics (e.g. mirror slope error, point-spread function, etc.)
- Stability requirements depend on time interval

Time Scales

- **Disturbance time scale << experiment integration time:**

  Orbit disturbances blow up effective beam σ and σ', reduce intensity at experiment, but do not add noise

  For $\Delta\varepsilon/\varepsilon = \varepsilon_{cm}/\varepsilon_o < \sim 10\%$: **$\Delta y_{cm}$(rms) < ~0.3 σ_y** **$\Delta y'_{cm}$(rms) < ~0.3 $\sigma_{y'}$**

  Note: can have frequency aliasing if don't obey Nyquist….

- **Disturbance periods ≥ experiment integration time:**

  Orbit disturbances add noise to experiment

  For $\Delta\varepsilon/\varepsilon = \sim 2\sqrt{\varepsilon_{cm}/\varepsilon_o} < \sim 10\%$: **$\Delta y_{cm}$(rms) < 0.05 σ_y** **$\Delta y'_{cm}$(rms) < 0.05 $\sigma_{y'}$**

- **Disturbance periods >> experiment time (day(s) or more):**

  Realigning experiment apparatus is a possibility

- **Sudden beam jumps or spikes can be bad even if rms remains low**

  Peak amplitudes can be **> x5** rms level

- **Most demanding stability requirements:**

  Orbit disturbance frequencies approximately bounded at high end by data sampling rate and a low end by data integration and scan times

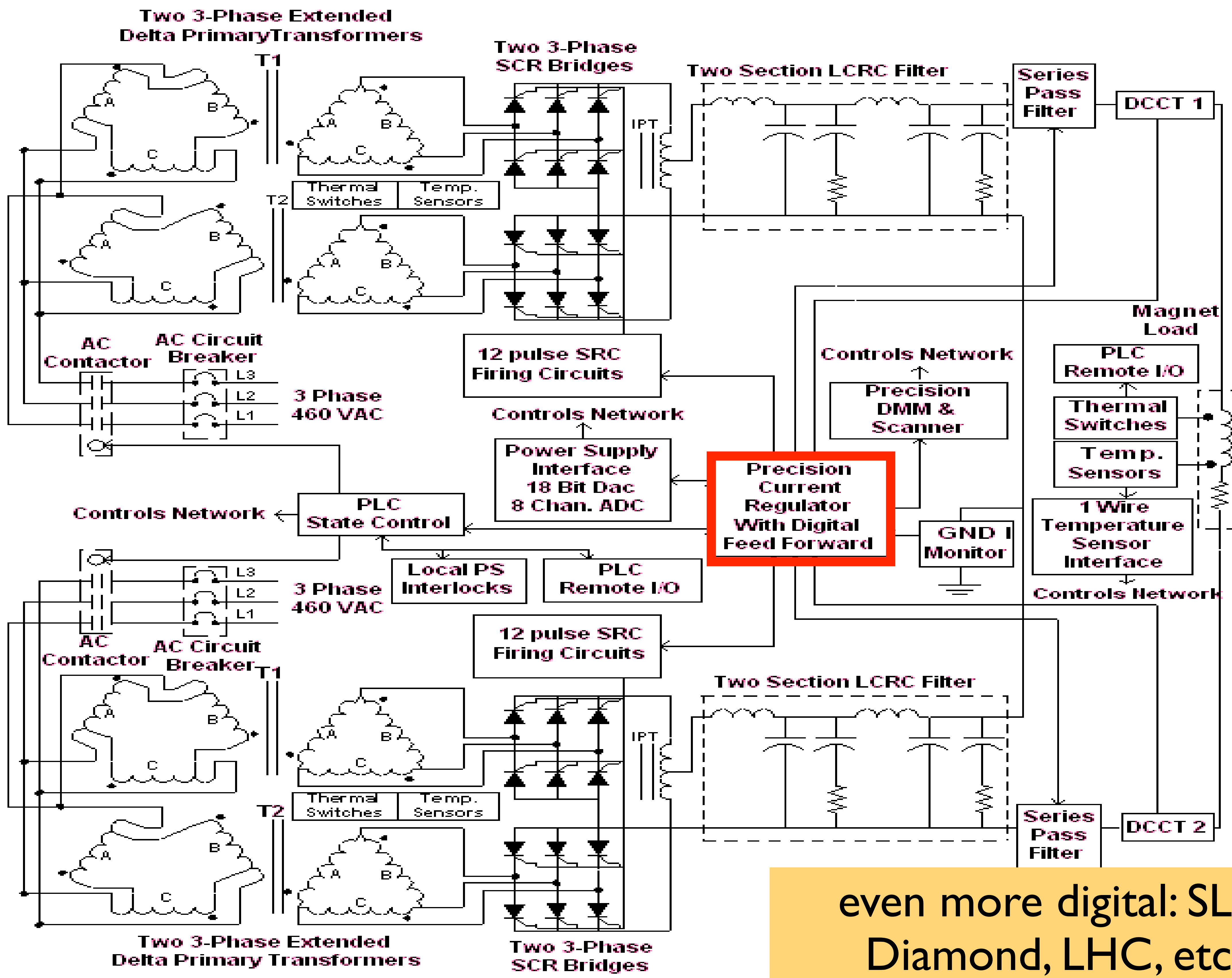
  ⇒ noise not filtered out

NSLS II Proposed Dipole Supply Parameters

- Each main dipole magnet bending angle of 0.1047 rad. Current ripple spec. (referred to Imax) of 5 ppm for freq. 60 Hz and greater. This gives a ~ 524 nrad noise in the horizontal direction.
- power supply parameters:
  - resolution of reference current 18 bit $\pm$ 1LSB
  - stability (8 h-10 s) – referred to Imax 40 ppm
  - stability (10s-300 ms) – referred to Imax 20 ppm
  - stability (300 ms- 0 ms) – referred to Imax 10 ppm
  - absolute accuracy – referred to Imax 100 ppm
  - reproducibility long term – referred to Imax 50 ppm

(a 1960s example: 10ppm design goal for MURA ring, eventually first dedicated light source)

Power Supply Diagram

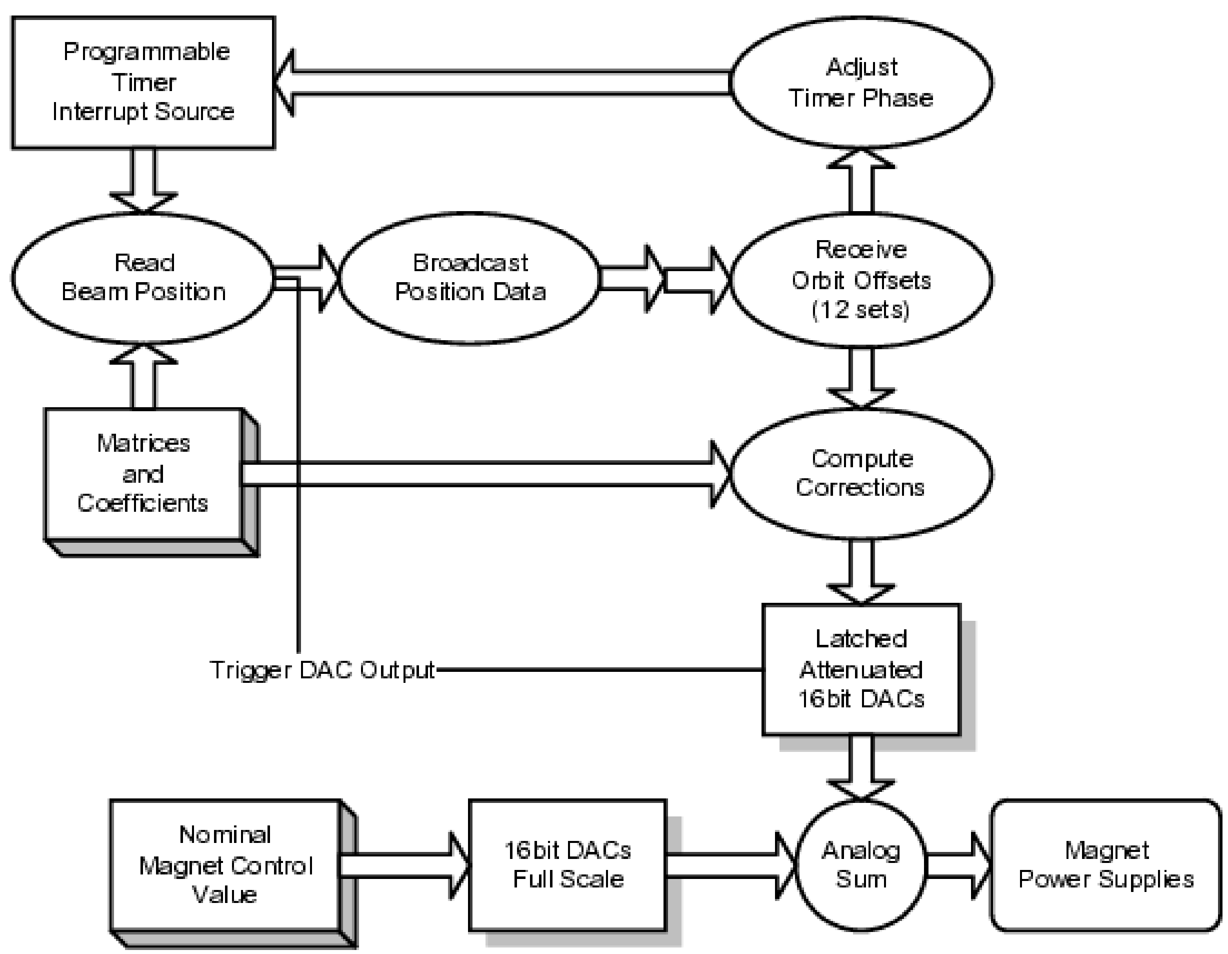


even more digital: SLS, Diamond, LHC, etc

ALS Orbit Feedback

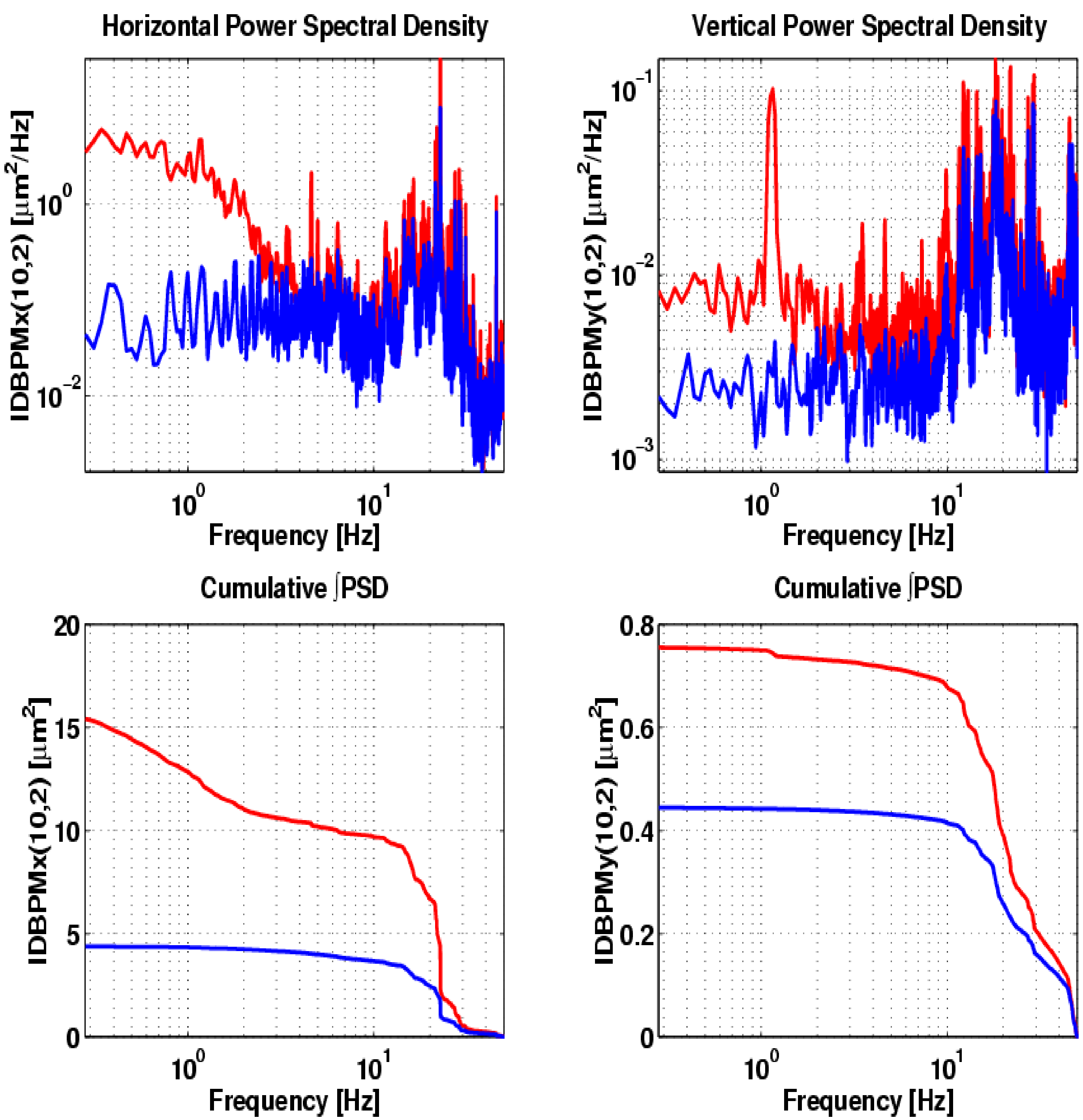
- Motivation: Fast Orbit stability with passive measures already very good (2-4 microns rms). Improvement into <μm range required active/fast feedback

Distributed Fast Beam Position Feedback 1.0 12/00



- Combination of fast and slow feedback – no frequency deadband
- Fast Feedback currently 24 BPMs in each plane and 22 correctors in each plane. 1.11 kHz update rate, bandwidth DC-60 Hz. Only ½ of singular values used.
- Slow Feedback 52 BPMs/plane, 26 horizontal correctors, 50 vertical correctors, RF frequency correction. 1 Hz update rate, about 60% single step gain, bandwidth DC-0.1 Hz. Typically all SVs used.
- Slow feedback communicates with fast feedback to avoid interference in frequency overlap range. Setpoints/golden orbit used by fast feedback is updated at rate of slow feedback.

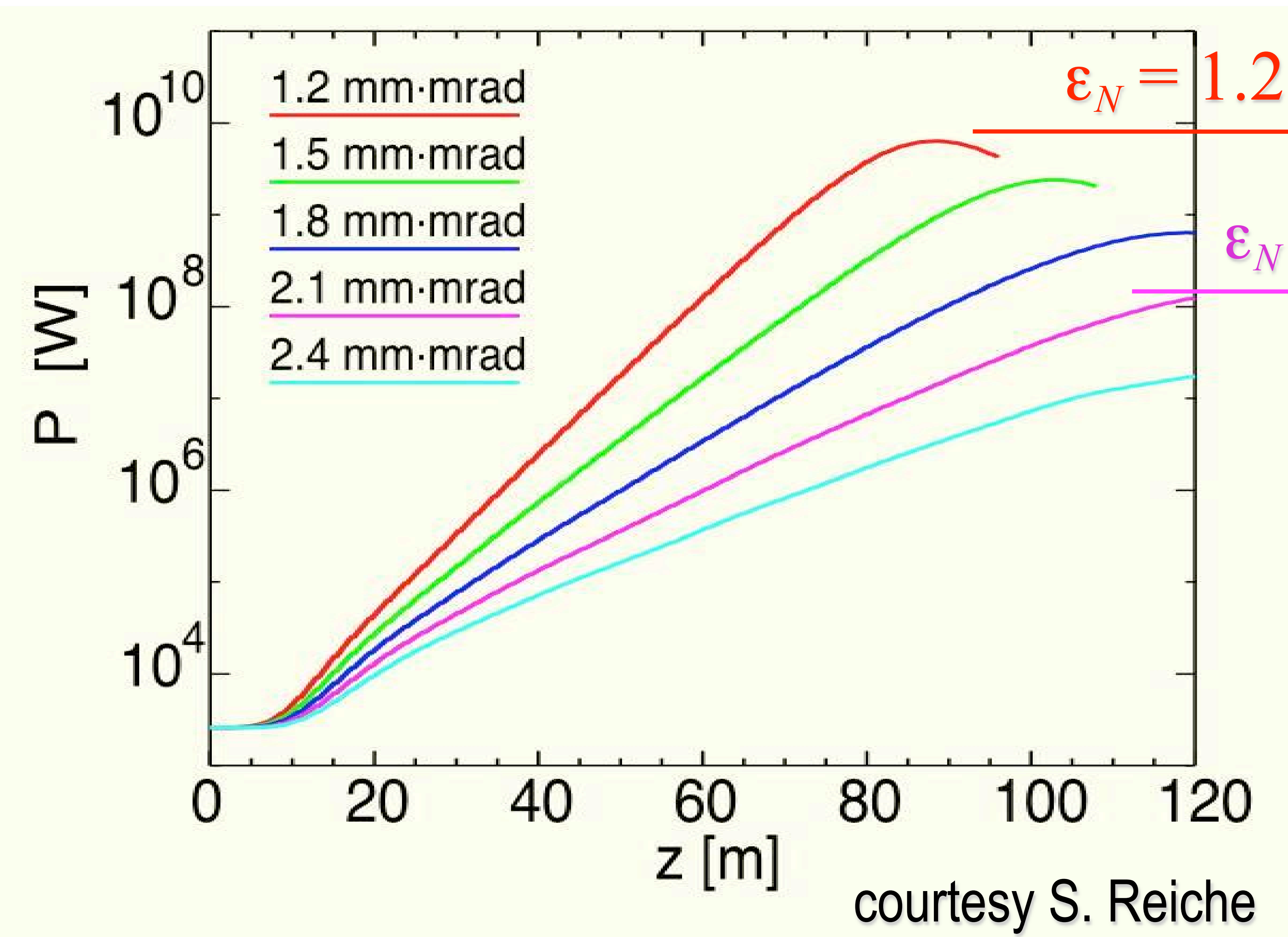
Beam spectra with feedback



- Beam motion with feedback in open (red) and closed loop (blue) at out of loop BPM.
- Feedback is very effective for moderate frequencies. Right now closed loop bandwidth (3 dB) is about 80 Hz.
- Correction at low frequencies below the individual BPM noise floor (only ½ of SVs used).

LCLS Output

- Slice emittance >1.8 μm will not saturate
- leads to unstable output power



$\varepsilon_N = 1.2\ \mu\text{m}$ → $P = P_0$

$\varepsilon_N = 2.0\ \mu\text{m}$ → $P \approx P_0/100$

electron beam must meet brightness requirements

LCLS Machine Stability Tolerance Budget

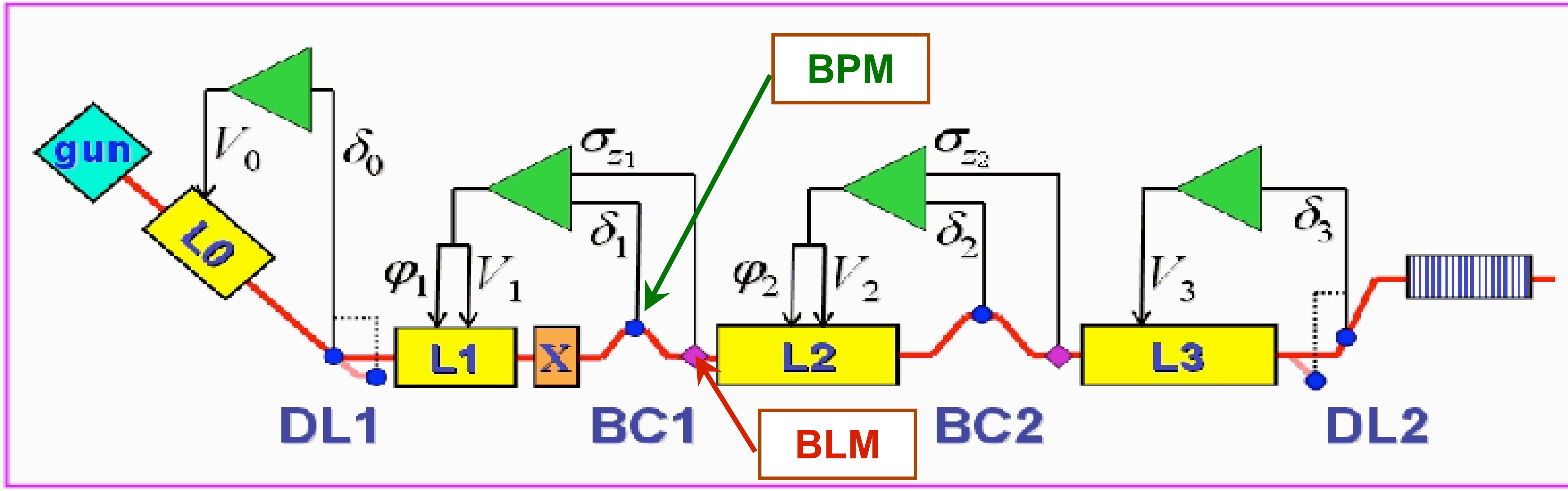
$|\langle \Delta E/E_0 \rangle| < 0.1\%$ <u>and</u> $|\Delta I/I_0| < 12\%$

Parameter	Symbol	LCLS	Unit
Gun timing jitter	Δt_0	0.80	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean L0 rf phase	φ_0	0.10	deg
mean L1 rf phase	φ_1	0.10	deg
mean L*h* rf phase X-band	φ_h	0.50	X- deg
mean L2 rf phase	φ_2	0.07	deg
mean L3 rf phase	φ_3	0.15	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	%
mean L*h* rf voltage	$\Delta V_h/V_h$	0.25	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	%

RMS tolerance budget for <12% rms peak-current jitter or <0.1% rms final *e*− energy jitter. All tolerances are rms levels and the voltage and phase tolerances per klystron for L2 and L3 are $\sqrt{N_k}$ larger, assuming uncorrelated errors, where *Nk* is the number of klystrons per linac.

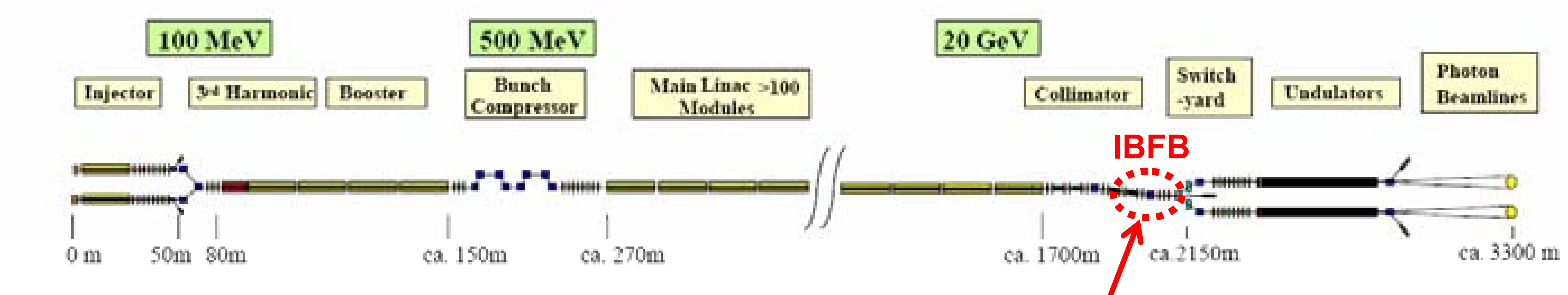
Tightest tolerance is 0.5° X-Band,
Or 120 femtoseconds

LCLS beam-based RF feedback loops



- Observables (6):
  - Energy: E_0 (at DL1), E_1 (at BC1), E_2 (at BC2), E_3 (at DL2)
  - Coherent Radiation power bunch length: $\sigma_{z,1}$ (at BC1), $\sigma_{z,2}$ (at BC2)
- Controllables (6):
  - Voltage: V_0 (in L0), V_1 (in L1), V_2 (effectively, in L2)
  - Phase: φ_1 (in L1), φ_2 (in L2), φ_3 (in L3)

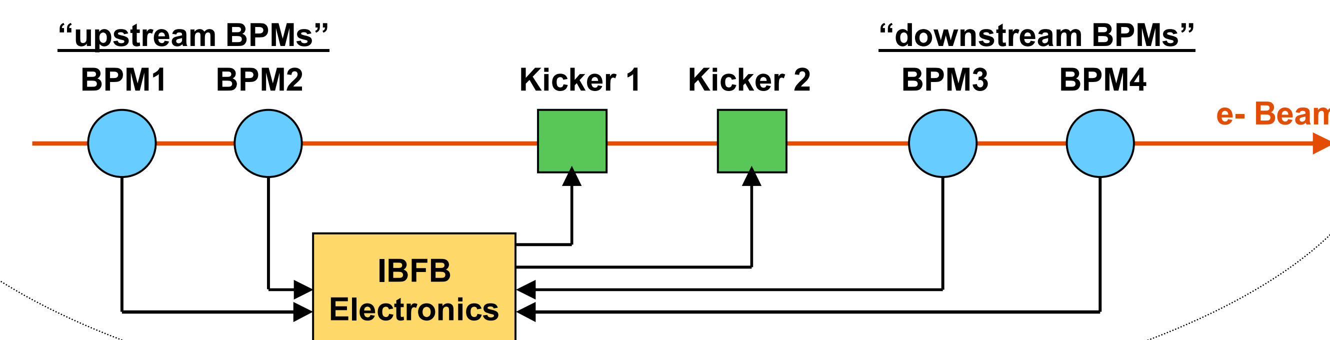
XFEL transverse feedback



XFEL Main Linac Parameters

- Q = 1 nC, L ~ 80 fs, E = 20 GeV max.
- Beam size ~ 30 μm (undulators)
- **Trains of ~ 3000 bunches, spacing 200 ns, 10 Hz**

IBFB Topology for Horizontal Plane (Same for Vertical Plane)



Motivation

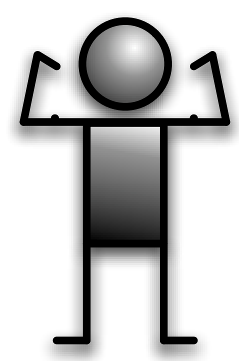
- Need ~σ/10 transverse position stability in undulators
- Possible x/y beam position perturbation: water/helium flow, ground motions, power supply jitter, switching magnets, RF transients and jitter, photo-cathode laser jitter & related beam current variations, long range wakefields
- Use IBFB to damp perturbations (up to some 100 kHz)

Transv. IBFB Specifications	FLASH	XFEL
bunch-by-bunch stability - at location of IBFB - along undulators	< σ/10 5 - 15 μm < 5 μm	< σ/10 3 - 10 μm < 3 μm
max. beam position correction max. position offset at pickups	< 10 · σ < 1.5 mm	< 10 · σ < 1 mm
bunch-by-bunch resolution	≤ 2 μm	≤ 1 μm
system latency	< 1000 ns	< 200 ns

IBFB Concept & Topology

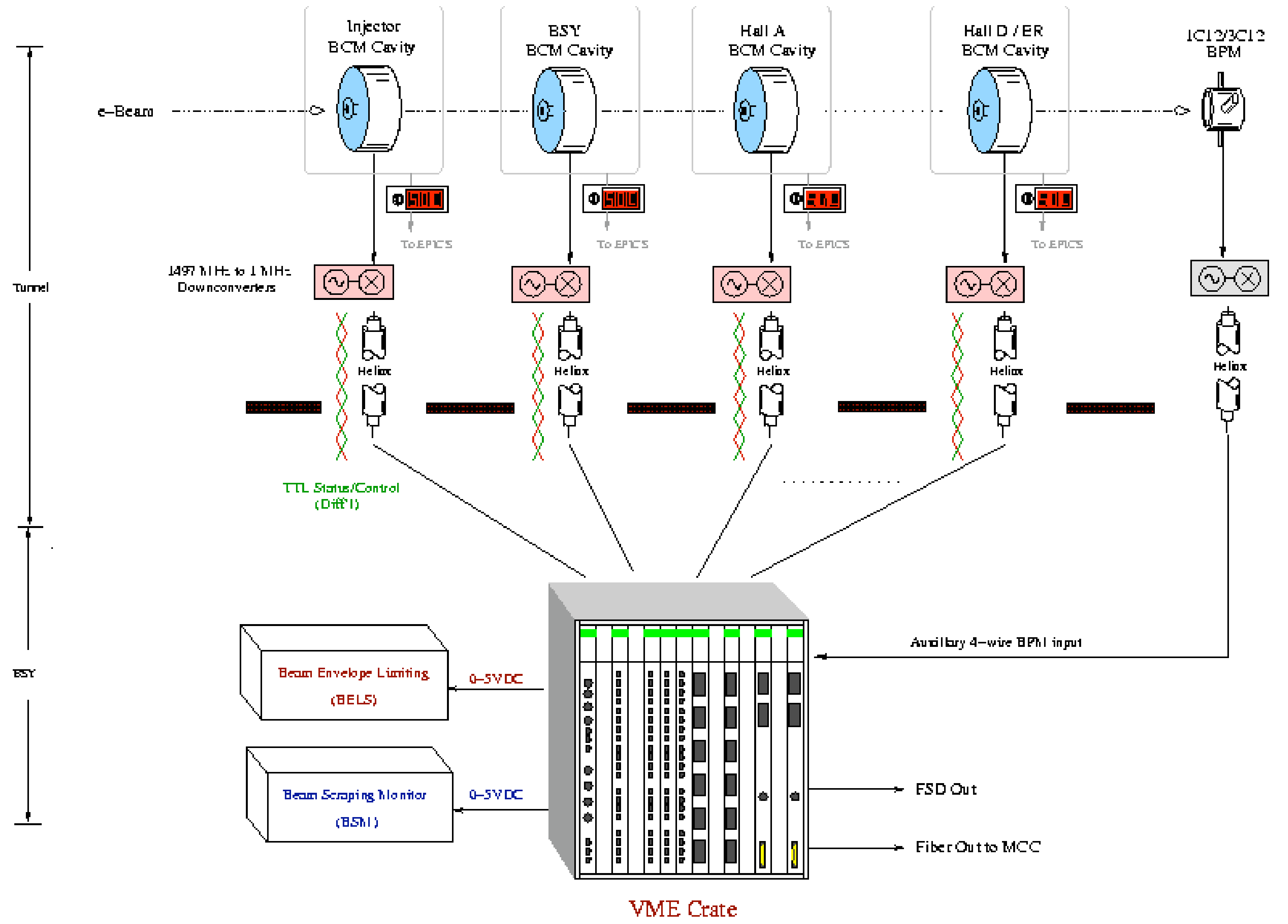
- Calculate kicks for bunch N from upstream BPM positions of bunches N-1, N-2, N-3, ... (using an optics model) to reduce latency (upstream BPM signals travel in same direction as beam)
- Use downstream BPMs to check & adapt model (slowly)

Operational Improvements

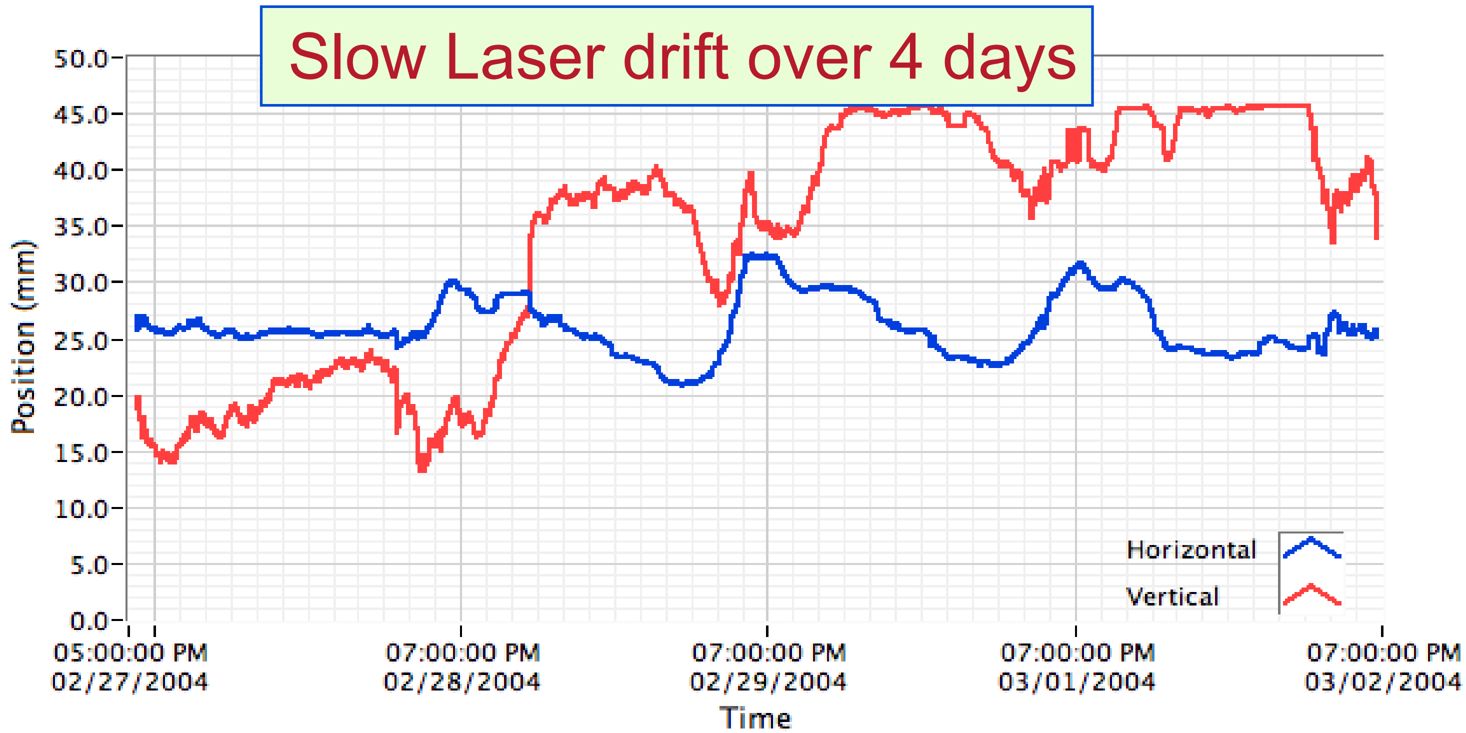


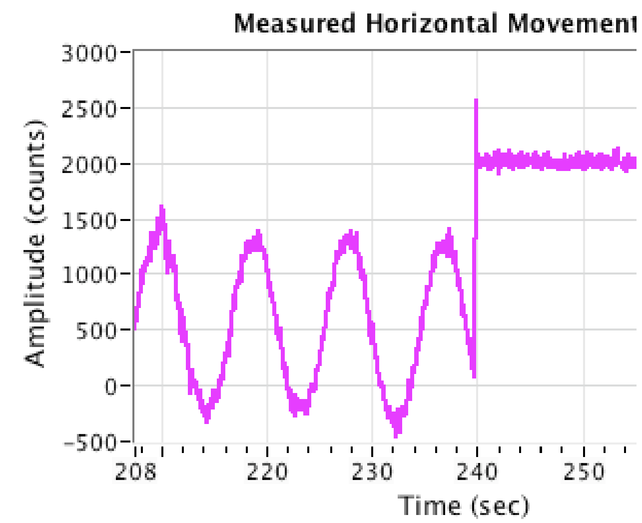
Protecting CEBAF

- 1500 MHz cavity pickups
- stability: 100 nA
- Minimum detectable loss: 200nA
- DSP-based system provided stability, and an order of magnitude better sensitivity over analog system

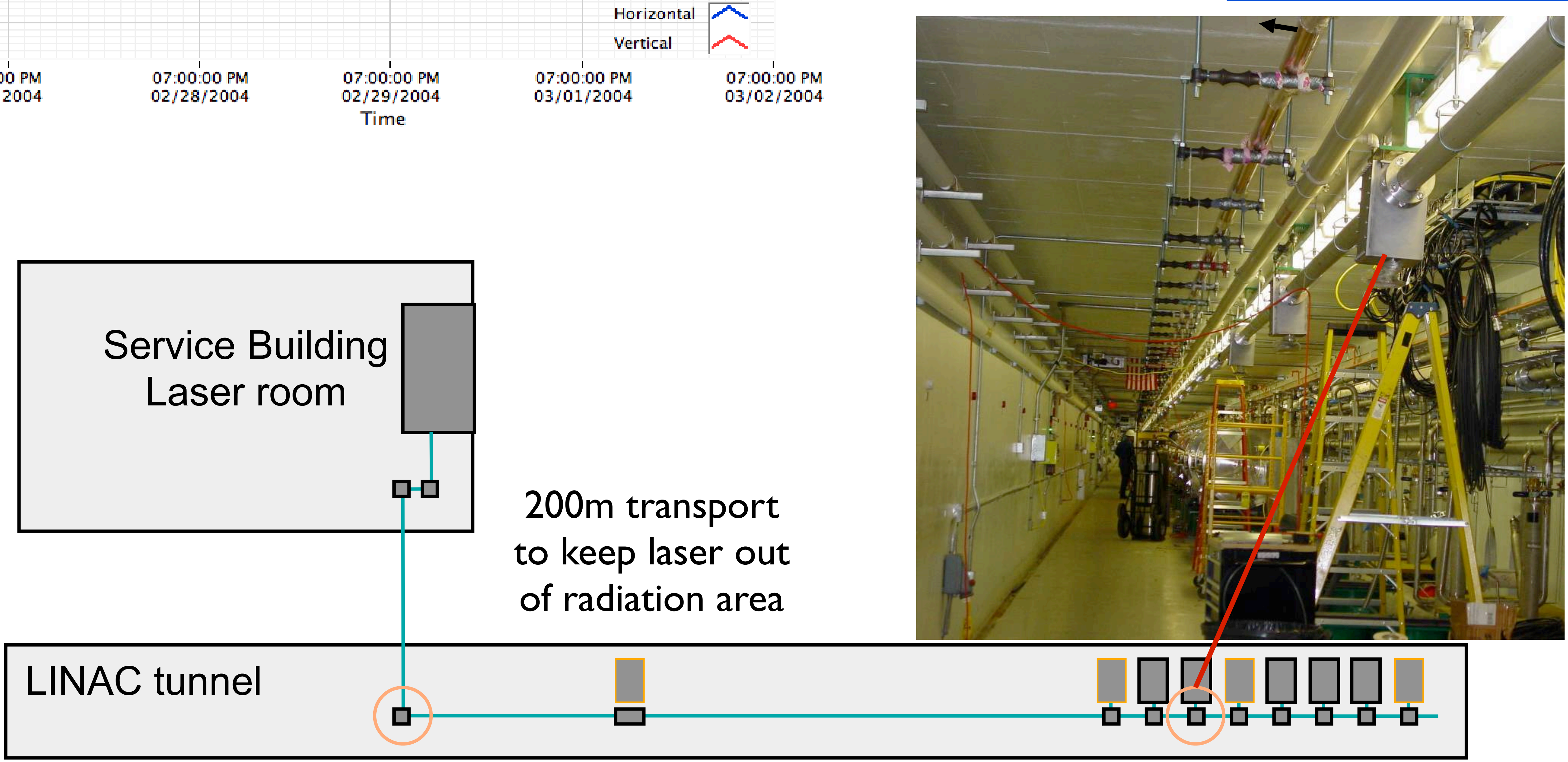


Laser Stabilization

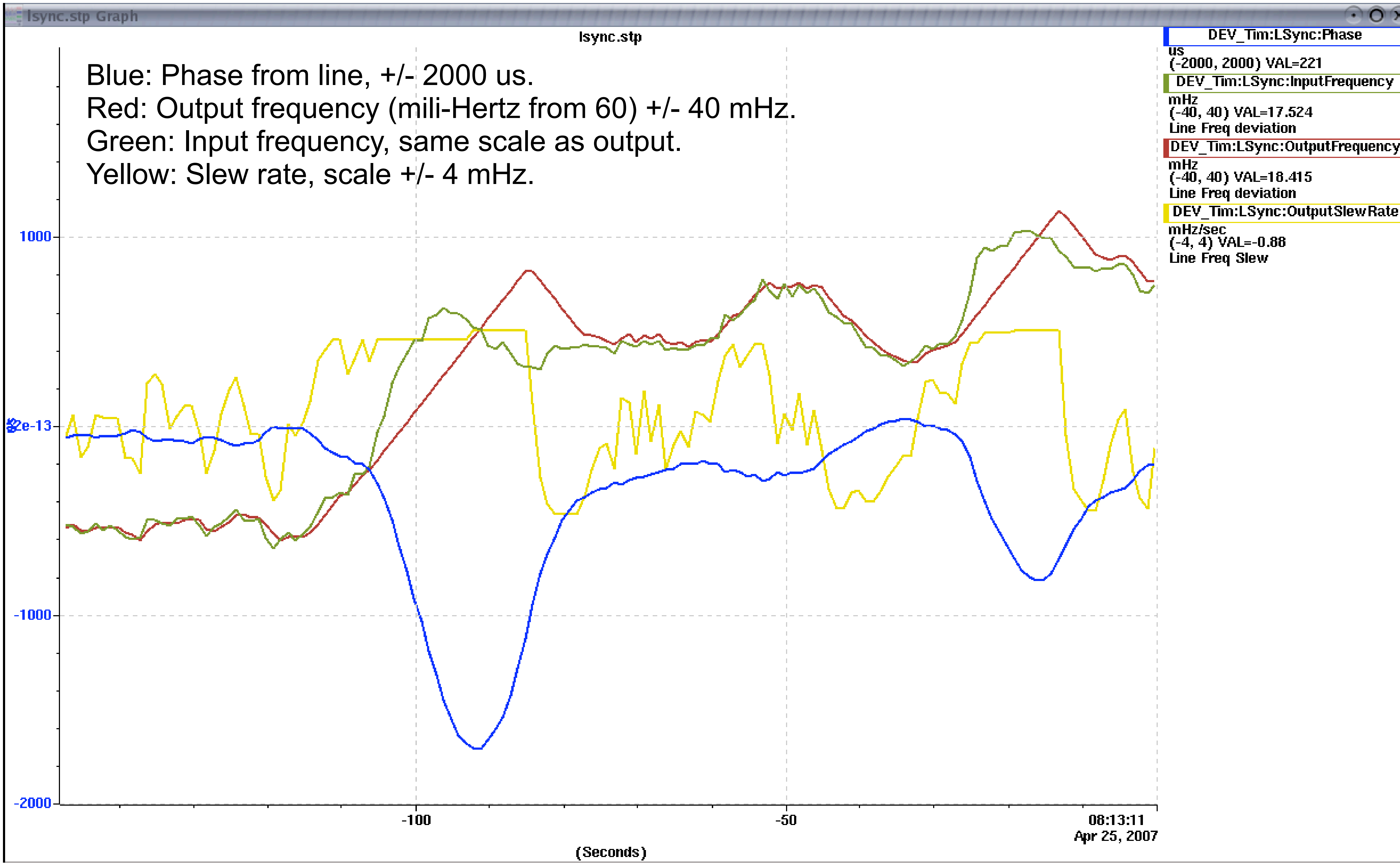




Sinusoidal steering error, then stabilization enabled (Quad sensor, piezo actuator, FPGA feedback)



Locking an Accelerator to a Spinning Wheel

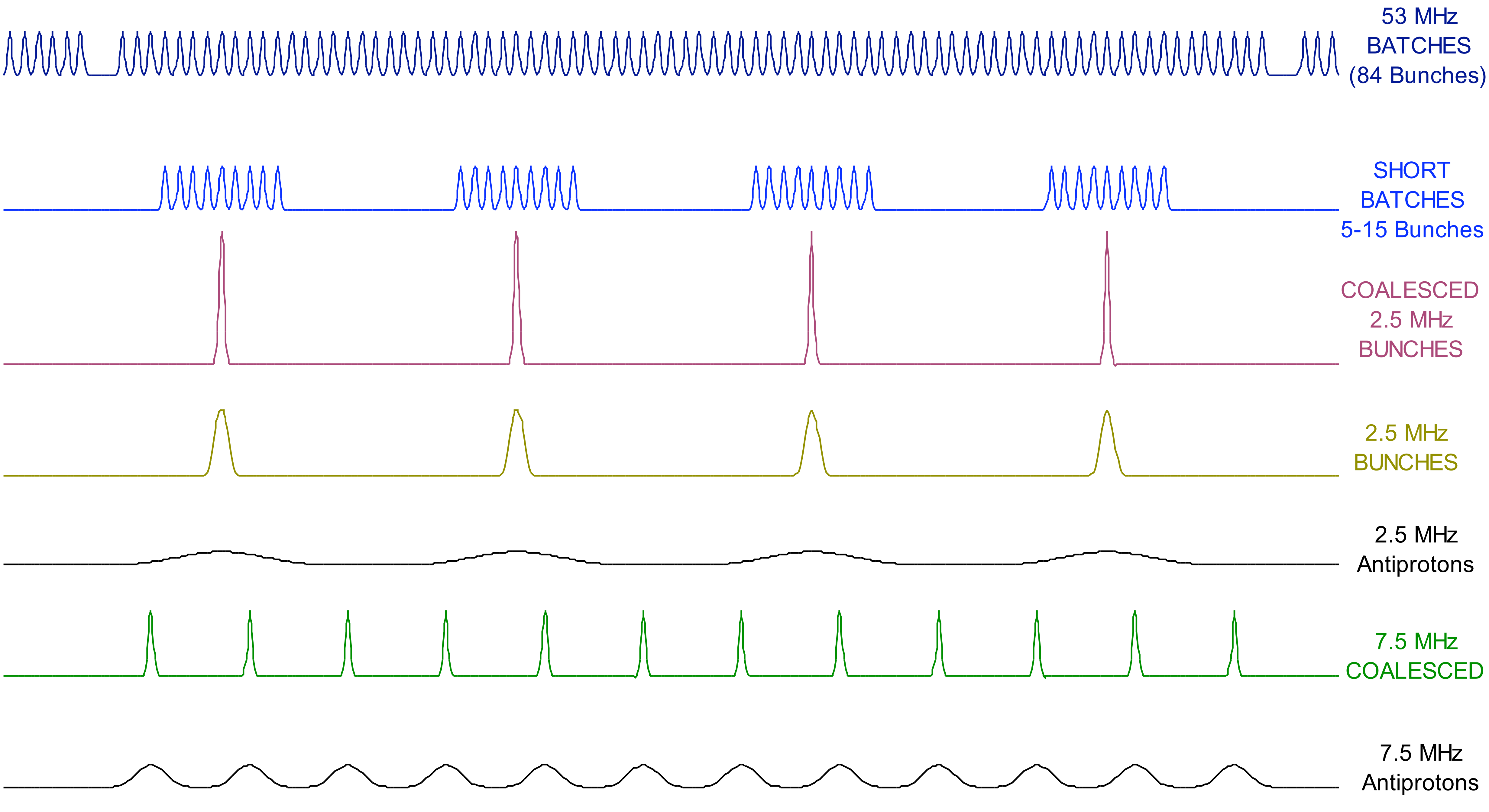


Considerations

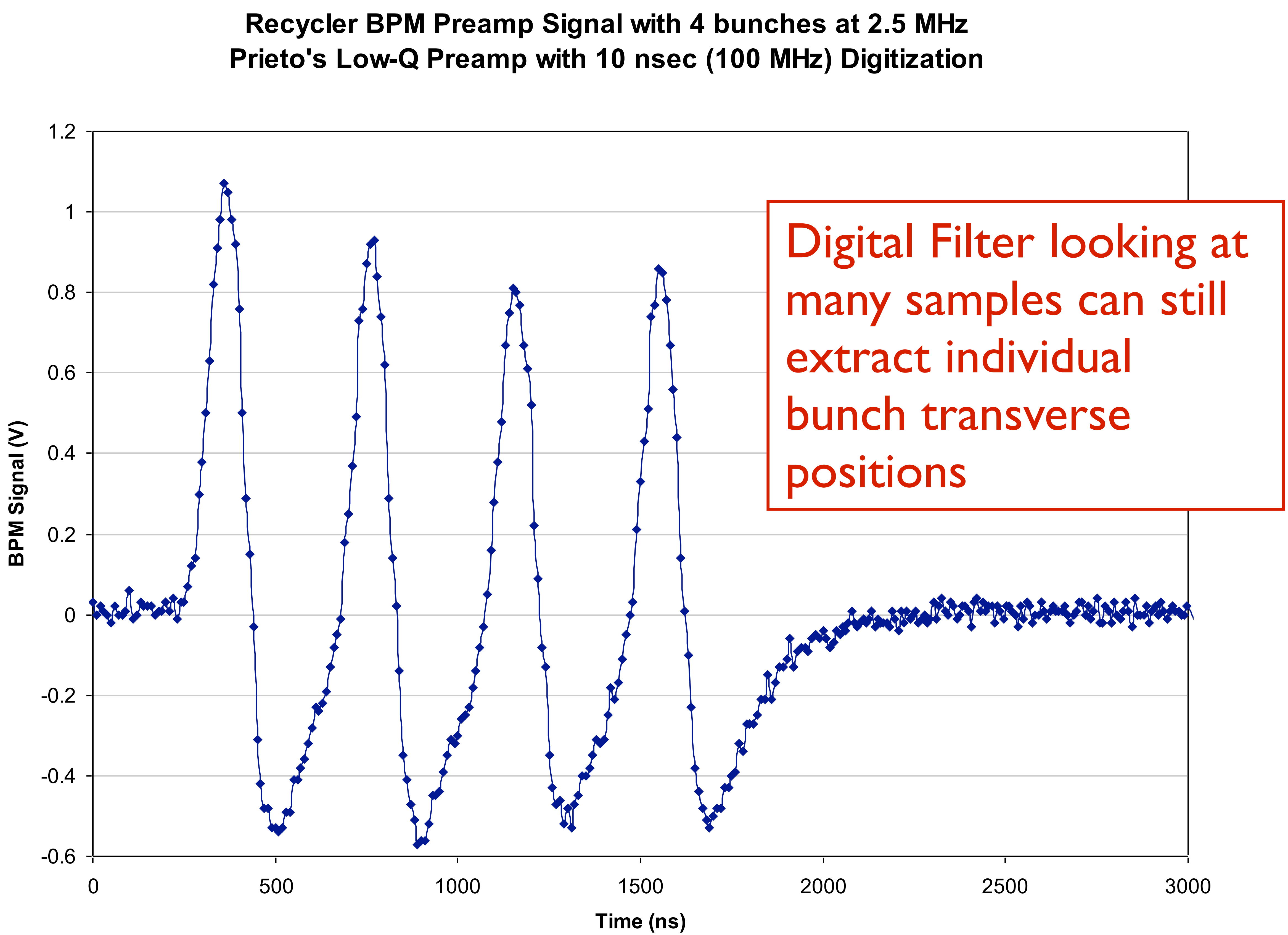
- Beam Signals
- Radiation Environment
- Obsolescence

Beam Signals

Beam Bunch Structures in Fermilab Main Injector

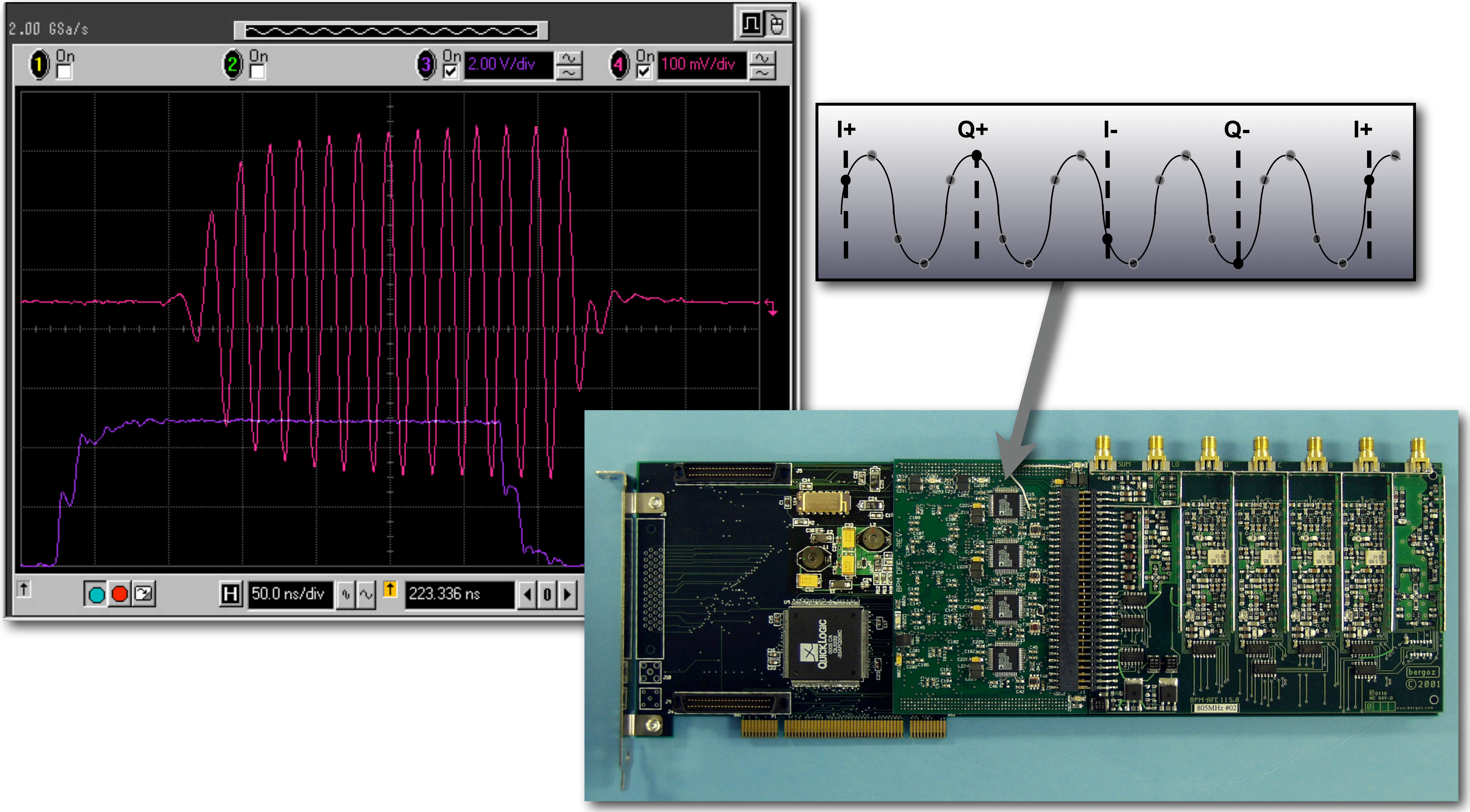


… dealing with this variety of beams would be painful in Analog…

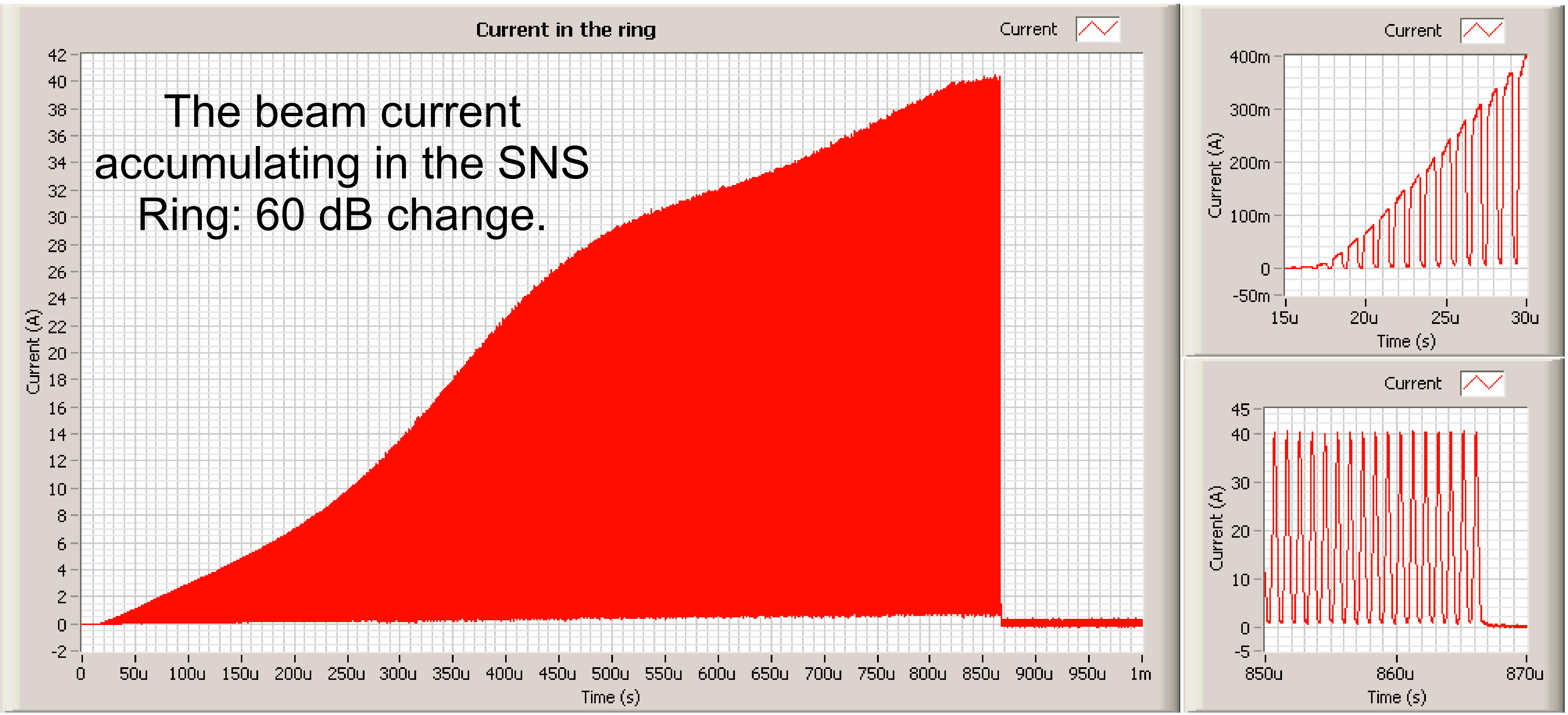


- Accelerator provides many possible sources of electromagnetic interference
- grounding, shielding, isolation techniques (Ott's book, and Analog to Digital Lecture)

Undersampling IF from a 300 ns Minipulse



Dynamic range during multi-turn injection

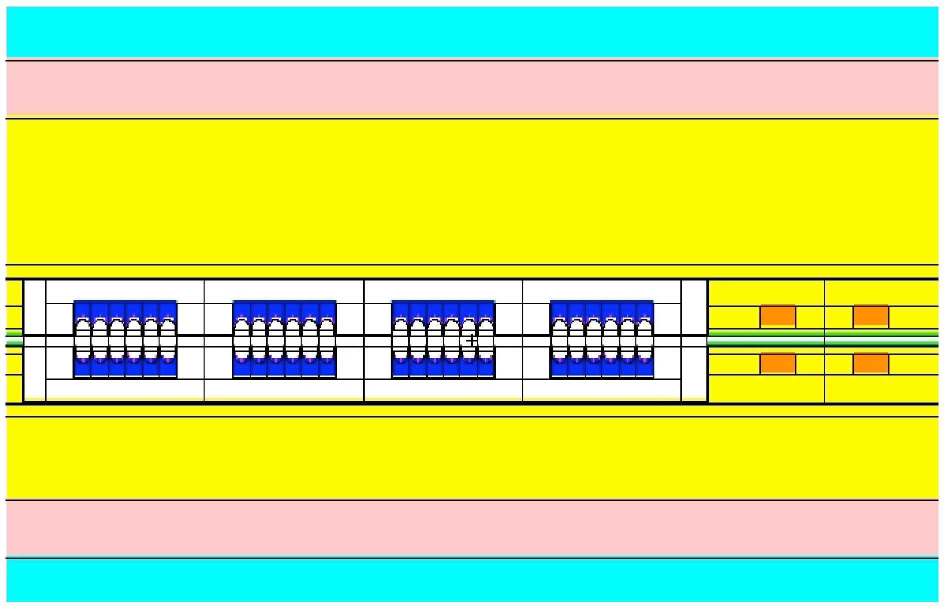


- Current Monitors: 4 ADCs in parallel to assure valid data in off-normal conditions
- Most others: switched gain

Radiation

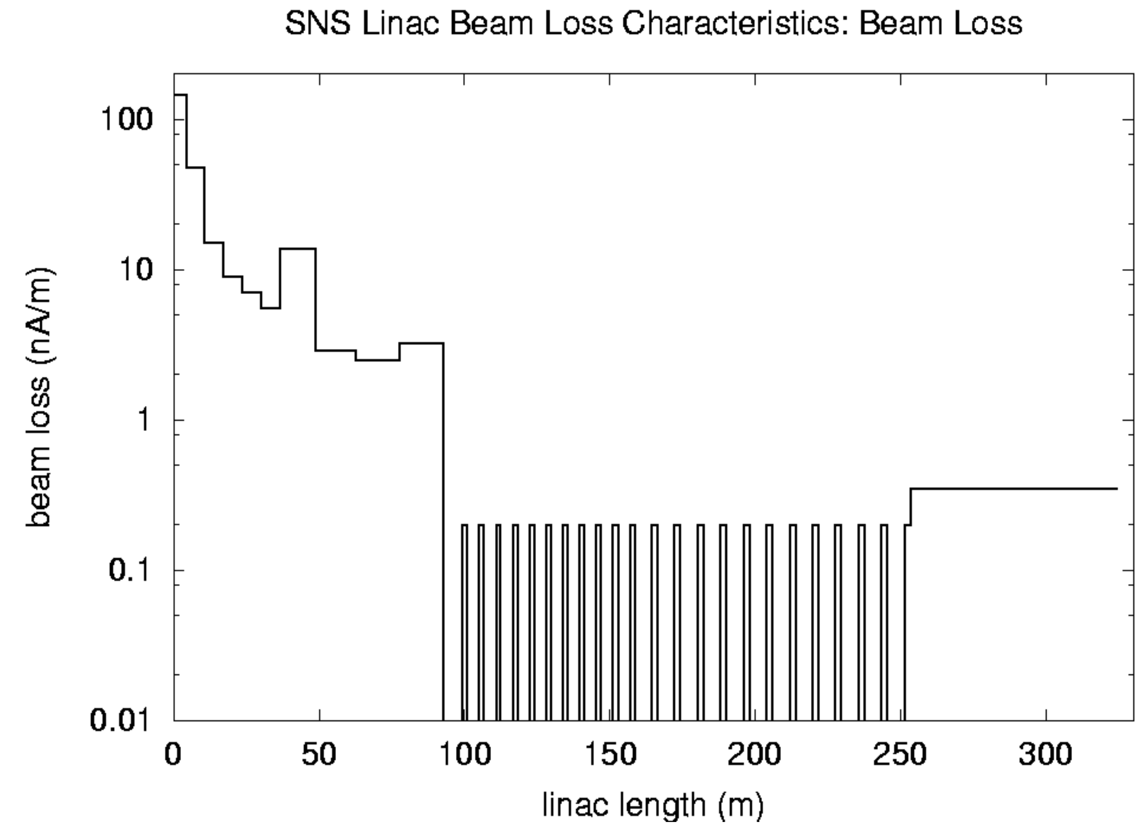
Radiation Dose Prediction

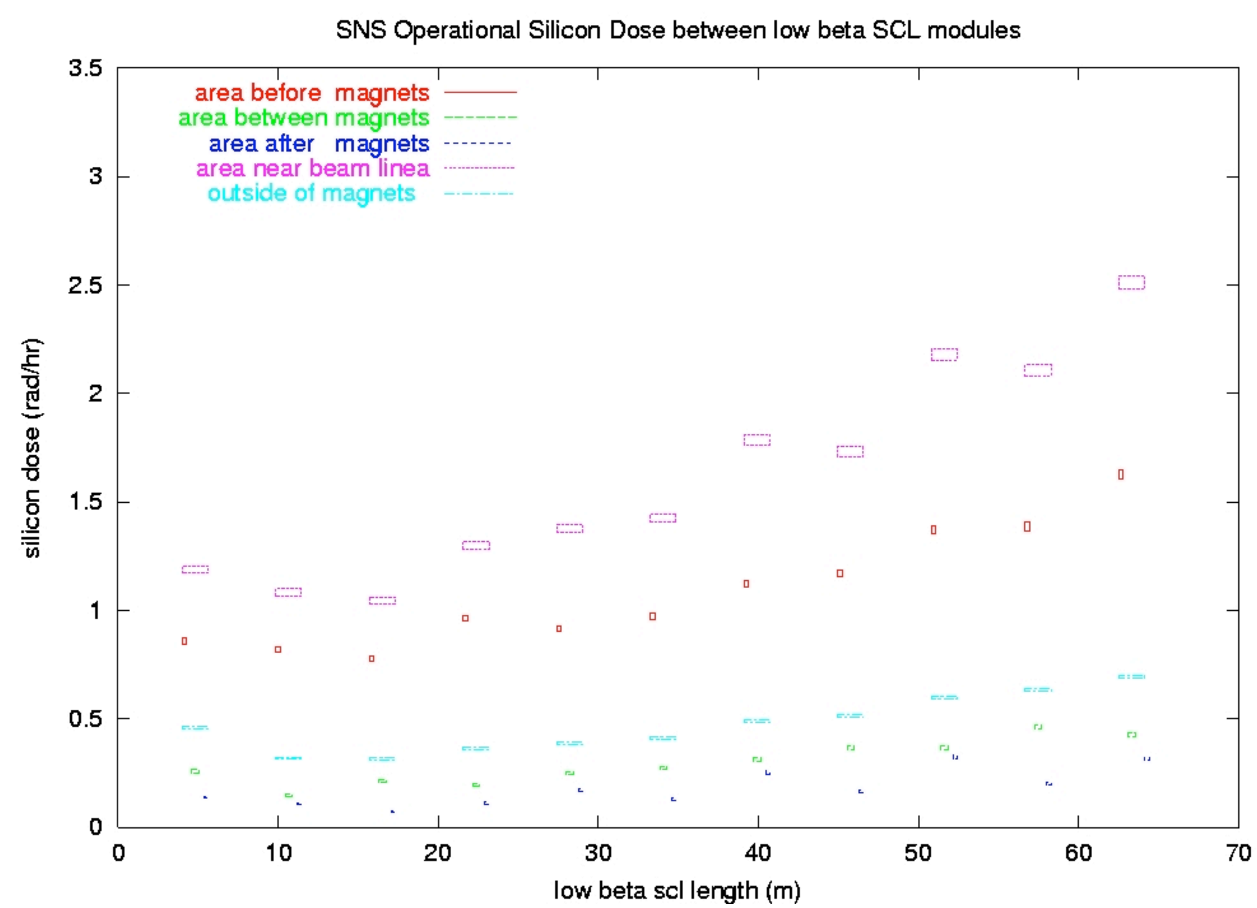
SNS SCL MCNPX Models:



Radiation Transport Calculations (MCNPX, FLUKA …) ⇒ calculate Absorbed Dose, Displacements-per-Atom in components directly or by folding particle fluxes with KERMA factors or displacement cross sections

⇒ life time prediction





Radiation Tolerance

Total Ionizing Dose	Technology
~1 MRad (Si)	Radiation Hardened ASIC
~100 kRad	Radiation hardened FPGAs with redundancy and SEU correction
~10 kRad	You and the afternoon lab materials

Obsolescence

SNS Commissioning runs and latest technology in use:

1 2 3 4 5 6 7 8 9

2002 2003 2004 2005 2006

Processors

Pentium III | Pentium 4 | Pentium EE | Pentium D | Core Duo

Gate arrays

APEX 20k | Stratix | Stratix II | Stratix III

Networking standards

10/100baseT | 10/100/1000baseT

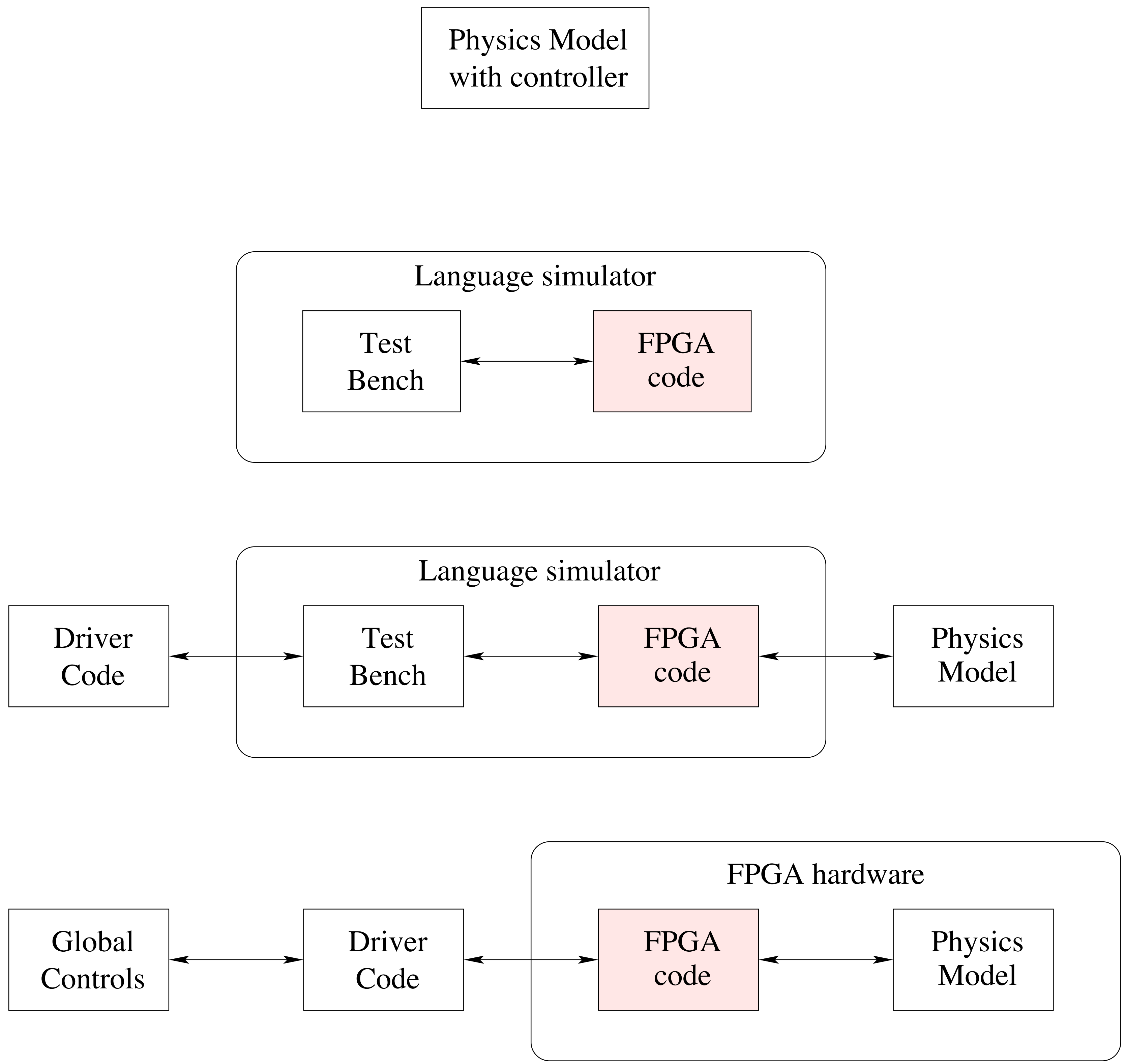
note: all ethernet interoperable and plug compatible (RJ45)

Final Comments

Assuring Success

- The goal: make it work, deploy it on time, build it within budget.
- Time and resources will be restricted
  - Phased deployment of features (or channels)
  - Watch for scope creep
    - scope of analog systems self limiting: “poetry”
    - for software based systems...“trashy novel”?
- Expectation Management. Clearly communicate:
    - interfaces
    - day one functionality
    - roadmap to full glory

Testing



Physics Model with controller
Language simulator
Test Bench
FPGA code
Language simulator
Driver Code
Test Bench
FPGA code
Physics Model
FPGA hardware
Global Controls
Driver Code
FPGA code
Physics Model

Commissioning

A few things that have made commissioning go smoothly in the past:

- Built in self test
- Access to raw waveforms, oversampled if possible
- Flexibility by using high level implementation
- NAD concept: keep integration independent of other systems, early vertical integration of first deployed channels
- Smile