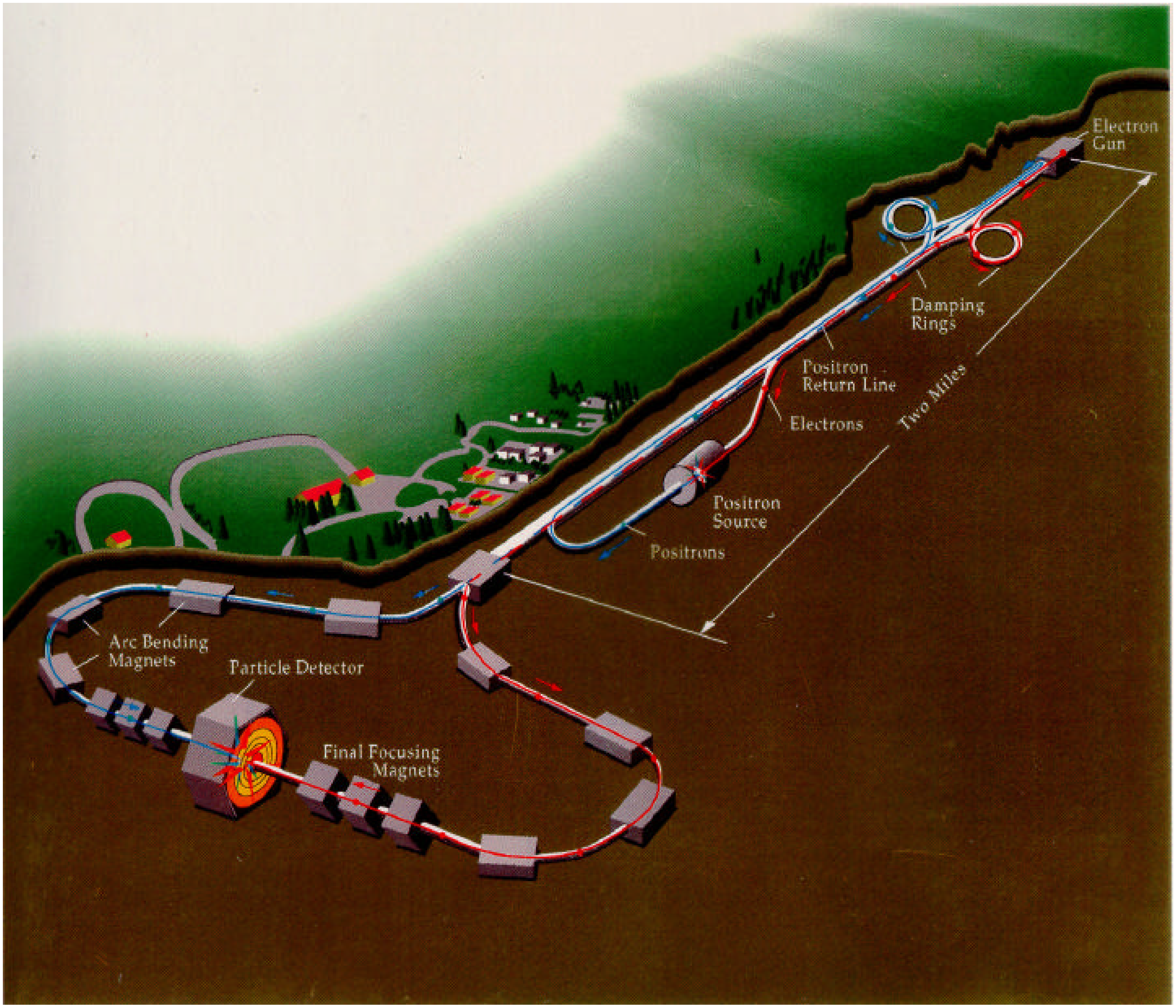
The SLC

N. PHINNEY
SLAC

SLD Collaboration Meeting
San Francisco, California

October 5, 2001


Electron Gun
Damping Rings
Positron Return Line
Electrons
Two Miles
Positron Source
Positrons
Arc Bending Magnets
Particle Detector
Final Focusing Magnets

SLC Overview

SLC is unquestionably the most difficult accelerator ever operated

The challenges were grossly underestimated
the delusion of a quick, cheap triumph like SPEAR persisted for years in spite of overwhelming evidence to the contrary

SLC also had more near-death experiences than any other accelerator
successive HEPAP subpanels called for termination only to see it rise from the ashes

The world-class physics that eventually came out of the SLD program is a triumph
due to years of hard work and innovations by countless people

All TeV linear collider proposals build on the knowledge and experience from SLC

Luminosity

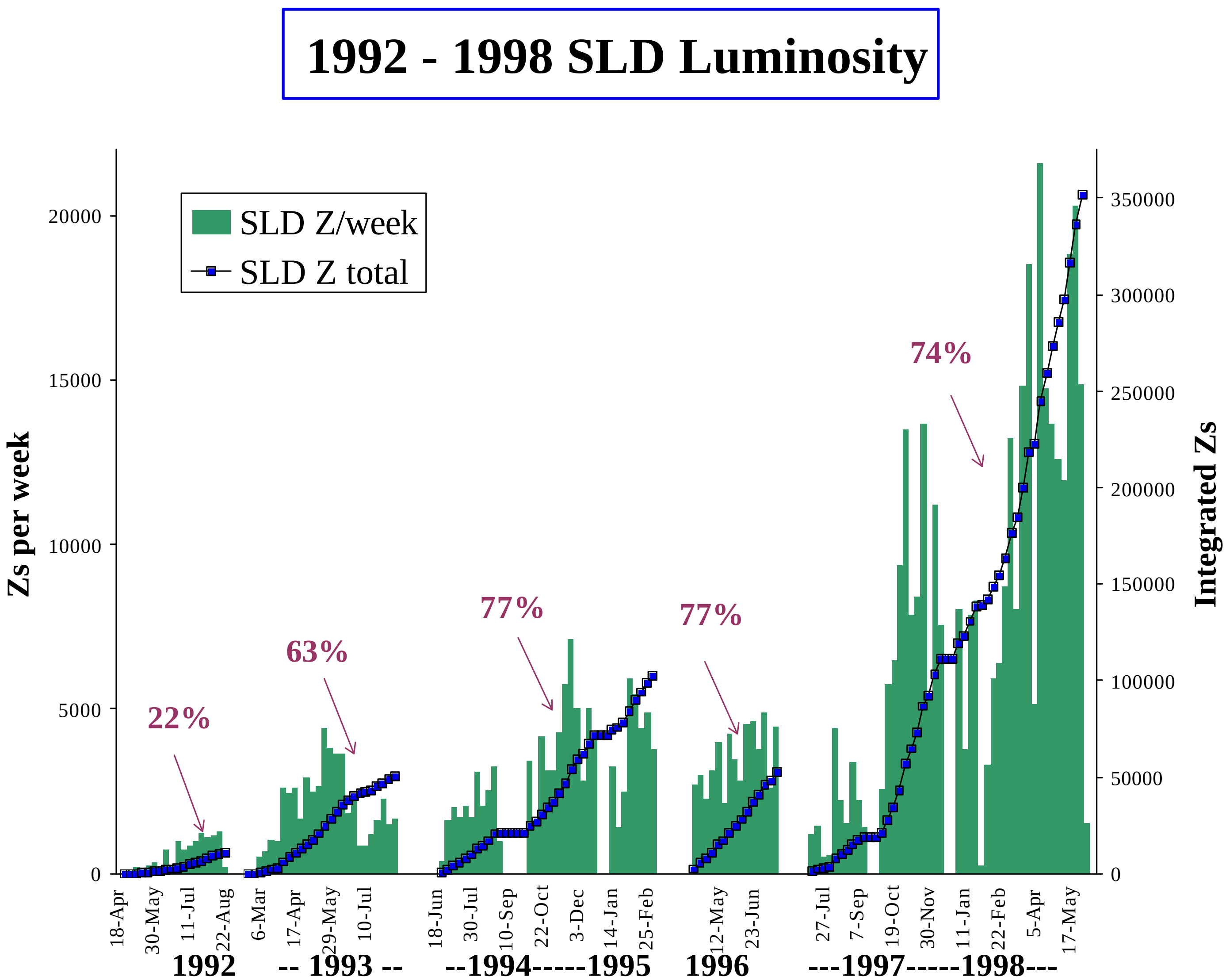
$$L = \frac{N^{+} N^{-} f}{4\pi\,\sigma_x \sigma_y} H_d$$

		Design	1998
Repetition rate, f	(hz)	180	120
Intensity, N	(10^{10})	7.2	4.0
σ_x	(μm)	1.65	1.5
σ_y	(μm)	1.65	0.65
$\sigma_x * \sigma_y$	(μm^2)	2.7	1.0
Disruption factor, H_d		2.2	2.0
Luminosity(10^{30}/cm^2/sec)		6.0	3.0

SLC History

1979	First proposed, began design studies	
1985-87	Construction	
1989	1st Z in Mark II detector on April 11	
	Mark II run to Nov, 1990	~1200 Zs
1991	SLD engineering run	~300 Zs
1992	1st SLD Physics Run	10000 Zs
	Electron polarization	22%
1993	SLD Physics Run	50000 Zs
	switched to Flat Beam optics	
	Strained lattice cathode	62%
1994-5	SLD Physics Run	100000 Zs
	Major upgrades to Damping Rings and Final Focus	
	Thinner layer cathode	77%
1996	Short SLD Physics Run with new Vertex Detector VXD3	50000 Zs
1997-8	Major SLD Physics Run with VXD3	> 350000 Zs

SLC <-> NLC



SLD Collaboration - October 5, 2001

SLC 1980

Richter returned from sabbatical at CERN

where he had convinced them to build LEP
and started the SLC as competition

First step - 10 sector 'feasibility test'

damped e- bunches –> BL90 analyzer

Construction started on SLC injector

CID - Collider Injector Development
South Damping ring - (was to be 2 in 1 vault)
Linac upgrade - klystrons, quads, correctors

Breidenbach began building control system

with Grp C staff - Siegrist, Jobe, others
+ new hires - Sheppard, NP, Bogart, Thompson
modernizing SLAC controls was a challenge
pre-Ethernet, VAX 11-780 1 Mbyte
"Computer" was hated as interference
Operations green-thumb, not model-based

SLC 1984

Richter became SLAC director

Rae Steining took over SLC project

Damping Ring commissioned

large diverse team - many now elsewhere

Delahaye (SL Division head, CERN), Jowett

Wiedemann (SSRL)

Ruth, Chao, Raubenheimer, Ross, etc. SLAC

(later) Hutton (Accel. Dept head, TJNAF)

SLC Design Handbook published

ed. R. Erickson

design current 5.0 –> 7.2 10^{10} @ last minute

due to SR emittance growth in Arcs

SLC Construction authorized

ARCs & Final Focus

Positron Production, 2nd Damping ring

SLC 1987 - 1988

1987 - Construction complete

magnitude of problems began to be apparent

ARCs - 1st beam revealed major problems

optics errors + terrain-following rolls

“PhaseFix, RollFix, RitFix, SkewFix, …”

ArcBusters - Barklow, Emma, Walker, Krejcik (1990)

January, 1988 - Mark II moved on beamline

Steining headed new Accelerator Department

Memo by R. Steining

On April 6, 1988, both beams were brought simultaneously through the IP into dumps. The number of e+ and e- per pulse were 0.3 and 0.5 10^{10}, at a repetition rate of 10 pps.

The background in the Mark II detector has been analyzed. The main problem …(is) muons. … additional collimators … should cut the background to a level which will allow operation … with currents 1.0 10^{10} in each beam.

August 1, 1988 - Emergency Task Force

Richter led SLC, Breidenbach led controls, Schalk led software, Steining left SLAC

SLC 1989 - 1991

April 11, 1989 - 1st Z detected by Mark II

October, 1989 - Task force disbanded

- Mark II had ~ 500 Zs
- LEP had begun physics in September, 1989
- Loma Prieta earthquake

December, 1989 - SLC 'White Paper'

Breidenbach, Burke, Himel, Paterson,
Ruth, Seeman, Sheppard

1991 … will be the first full year of physics running with the new detector, the SLD. The integrated luminosity goal for 1991 is 10^5 Z particles with polarized electrons.

August, 1990 - Program Coordinator (NP)

- balance conflicting Mark II/ PEP/ SLD needs

November, 1990 - Mark II Run ended

- Record day was 15 Zs on tape
- PEP physics program terminated

January, 1991

- 100-year freeze - December 23, 1990
- SLC Steering committee formed

SLC PERFORMANCE IN 1991

M. Breidenbach, D. Burke, T. Himel,
J. Paterson, J. Seeman, J. Sheppard, R. Ruth

December 1989
Revised January 1990

TABLE I.E.1. SLC PERFORMANCE & GOALS

	Independent Parameter Targets[a] for 1991 Program	Achieved in 1989	1990	Possible Scenarios for 1991 Parameters		
Intensity at IP				(A)	(B)	(C)
$N^-(10^{10})$	6	2	3.5	4	5	5
N^+	6	1.3	2.5	3.5	4	5
Rep. rate	120	60	120	120	120	120
Effective emittance at IP[b]						
ϵ_x^- (10^{-10}rad-m)	4	6	6	4	6	5
ϵ_y^-	3	5	5	3	4	3.5
ϵ_x^+	4	6	6	4	6	5
ϵ_y^+	3	5	5	3	4	3.5
Beam divergence at IP (μrad)	350	220	220	300	300	300
Beam size effective[c]						
σ_x (μm)	1.7	3.3	3.3	1.7	2.55	2.1
σ_y	1.34	2.7	2.7	1.34	1.56	1.4
Pinch enhancement		1.0	1.0	1.15	1.1	1.2
Luminosity (10^{30} cm^{-2} s^{-1})		0.014	0.094	0.67	0.52	0.97
Events/hour		1.6	11	79	62	113
Efficiency (short term)[d]		0.25	0.3	0.5	0.5	0.4
Effective rate						
Events/day		9.6	79	947	750	1090
No. of scheduled days of operation		160	120[e]	250	250	250
No. of days for accel. dev. & maint.		30	40	100	50	100
No. of days data taking		130	80	150	200	150
Number of Z's[f]		624	3.2K	71K	75K	81K

SLC Steering Committee

Nan Phinney - Chair

Bill Ash, Stan Ecklund, Tom Himel
Marc Ross, Ron Ruth, John Seeman
John Sheppard, Bob Siemann, Nick Walker

CHARGE TO THE COMMITTEE :

PLANNING AND COORDINATION OF 1991 RUN

1) Develop a Run Plan in coordination with the SLC system physicists which sets realistic and measurable goals and milestones

2) Review Projects critical to meeting those goals and ensure that sufficient resources and priorities are assigned

3) Review and Approve Machine Development Experiments

4) Develop a Weekly Run Schedule that includes goals, priority experiments, alternative backup experiments, and SLD time

5) Review the Progress of the Run and make necessary midcourse corrections

Steering Committee Impact

Detailed analysis of each run

what went wrong? right?

Careful planning of turn-on & machine dev.

step by step commissioning schedules
MD in 2-4 day blocks - limit edge effects
Focus on highest priority issues for luminosity
Backup MD list - use serendipitous downtime

Added resources to critical areas from Accelerator Theory & SLD

Positron Task Force - Siemann/Krejcik
Fast Feedback - Himel/Rouse
Damping Ring Upgrade - Siemann/Limberg
Final Focus Upgrade - Walker/Irwin

Broad-based attack on reliability issues

Breidenbach/Ross/Ops maintenance, etc.

Rigid control of maintenance activities

Repair Opportunity Day approval/signoff

SLC/SLD 1991 - 1993

Steady progress

Numerous improvements each year to hardware, tuning, diagnostics

Much time/effort for machine development

Set achievable goals and met them

1991 - SLD Engineering Run

Goal 3-500 Zs   Delivered 350 Zs

Achieved 3 * 1990 Luminosity/pulse

1992 - 1st SLD Polarized Run

Goal 10K Zs   Delivered 11K Zs

Achieved 4 * 1991 average Luminosity

10K Zs won dinner bet with O'Fallon, Hess

1993 - SLD Run

Goal 50K Zs   Delivered 50K Zs

Achieved 2-3 * 1992 Luminosity

1991 Run - May-August

Turn-on started before SLD installation complete

allow time for machine studies

SLD run started late July through August

Repetition rate limited to 60 hz by budget

Major improvements:

Positron yield stable at > 1.0 (task force)

factor of 2 at IP

Matching –> linac to 2nd order (Emma)

Linac alignment, feedback, orbit bumps

(Seeman, Adolphsen, Himel)

ARC optics controlled (Barklow)

Superconducting FF triplets (Ash)

smaller ß*

+ dozens of minor upgrades

Machine uptime - 60%

(was ~15% in 1990)

SLC STATUS - 1992 RUN

January-February — Machine Startup
March - SLD Run — unpolarized
April — Polarized Gun Installation and Commissioning
May-August 15 — SLD Physics Run
August 15 - September — Increase Luminosity

Average Luminosity is 4 * 1991

Z^os on tape / day is 5 - 10 * 1991

Biggest gains have come from

- 120 Hz operation factor of 2
- Machine uptime 60-70 %
- Improved SLD/SLC Efficiency 70%
  Better integration of machine and detector
- Improvements in intensity, emittance control and tuning factor of 2

SLC Improvements for 1992

Injector

- New "Y" Installation for Polarized Source
- Sector 0 Klystrons upgraded to 5045s
- Subharmonic Bunchers treated with TiN

Damping Rings

- Aperture increase for South LTR transfer line
- Passive Cavity to damp π-mode Oscillations - (both rings)
- New radiation hard epoxy kicker for North Damping Ring
- Octupoles for improved matching in NRTL line

Linac

- Collimator to protect Scavenger Line Lambertson
- Cascaded Fast Feedback
- Post kickers to control Scavenger beam orbit

Arcs and Final Focus

- Movers for AGF magnets to fine-tune dispersion
- New technique for finding FF Sextupole alignment

Diagnostics

- Wire scanners for NRTL, SRTL, Positron Return Line
- Fast gated Camera for Synchrotron Light measurements

1993 Run - February-August

Plan for Higher Luminosity

Beam intensity 4 10^{10}
and/or
Flat beam Optics

DR microwave instability limited intensity to

3.2 10^{10} electrons at IP
3.1 10^{10} positrons at IP

Switched to Flat beams in mid-March

Achieved emittance ratio of 10:1
Best **Zn ~ 6** (1992 best 2.8)

Goal: 2000-2500 Z^0/week on tape

Status: > 700 Z^0/day on tape — Best 1992 - 315
4400 Z^0/week on tape — Best 1992 - 1300

average 2500 Z^0/week

Mini-Workshop on SLC Improvements

November 16, 19 & 23 1992

CID

- Possibilities for larger cathodes or longer pulses

  –> full intensity with high polarization cathodes

Damping Rings

- New low emittance design

  –> Reduce emittances by a factor of 3

  –> Potential factor of 4 in luminosity

Final Focus

- Optics to correct 3rd order aberrations

  –> Potential factor of 2 in luminosity

Multibunch Operation

–> 2 or 3 bunches may be possible

Goal

-> 100-200 K Z^0s/year in FY94

1994 Run

- **Damping Ring Vacuum Chamber**

Improvements:

Raise threshold for microwave instability
Reduce bunch length –> better emittance
Reduce energy spread –> smaller IP size

Expected performance:

3.5-4 10^{10} per pulse at IP
energy spread < 0.2 %

- **Final Focus Optics Upgrade**

Improvements:

New quadrupoles and sextupoles to
reduce 3rd order aberrations
orthogonalize tuning
New wire scanners to improve diagnostics
Movers to align sextupoles

Expected performance:

Vertical beam size **0.4-0.5 micron**
Peak **Zn -> 10-15**

Intensity

Difficult route to higher luminosity

SLC experience:

Each increase in bunch current means new challenges

instabilities
wakefields = emittance growth
power handling

NLC learned this lesson early
design bunch intensity ≈ 1 10^{10}

1991 - limited by π-mode instability in rings
1992 - installed idling cavities
identified turbulent bunch lengthening
"sawtooth instability"
1994 - installed low impedance damping ring vacuum chambers

SLC slowly increased the bunch intensity to ≈ 4 10^{10}

Half of SLC design ≈ 7.2 10^{10}

pre-1994 Intensity Limit

"Flyer" pulses first seen by Mark-II in 1989

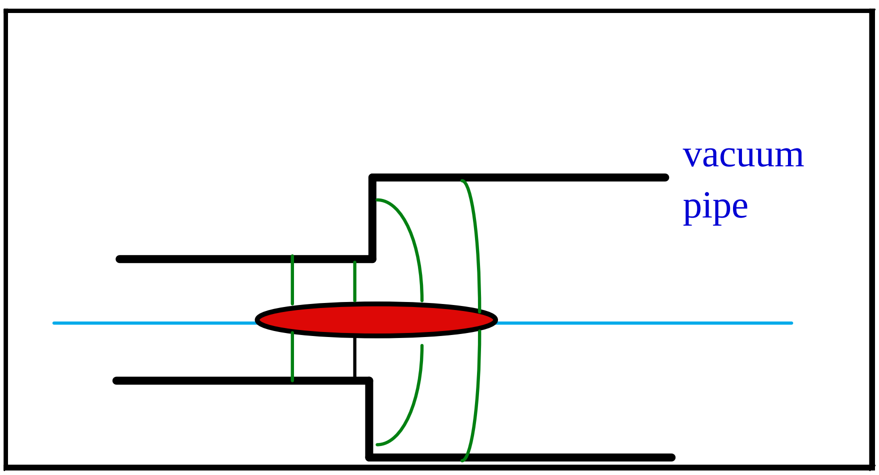
Energy-phase correlation diagnosed as "doughnut effect" in 1991

Diagnostic signal of bunch length during store revealed "sawtooth" instability in 1992

Threshold for instability $3 \cdot 10^{10}$ particles / bunch in the damping rings

Instability causes phase jitter at extraction which causes energy mismatch into the linac

Longitudinal Instability Mechanism



- **Step changes in vacuum chamber generate wakefields that interact with short bunches**

• **Turbulent bunch lengthening is not smooth, but works like a relaxation oscillator**

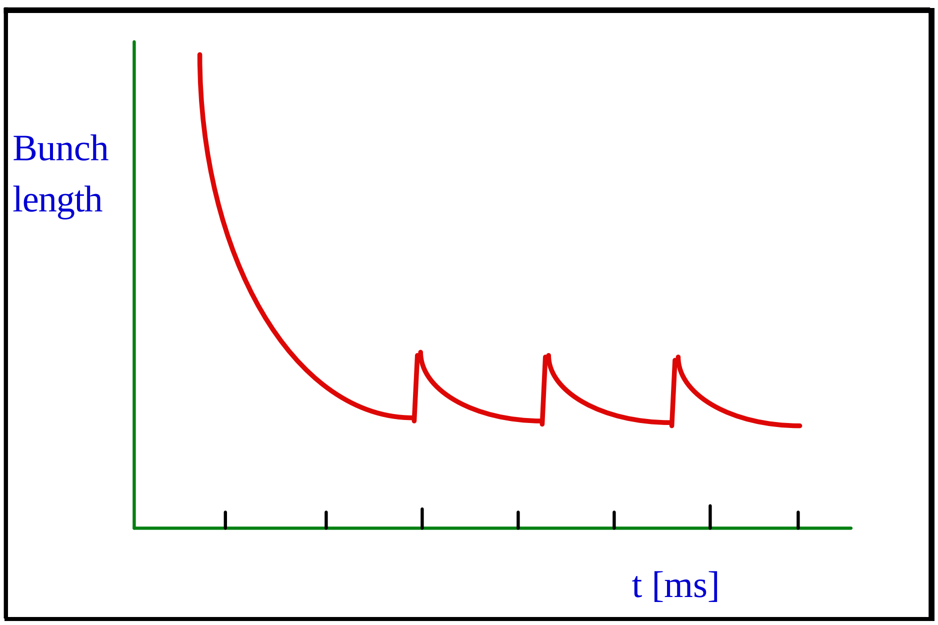
Sawtooth Instability

. bunch length damps down after injection until threshold is reached

. rapid (@ns) blowup in bunch length occurs

. blowup is self limiting (nonlinear)

. bunch damps until threshold reached again



Remedy for Raising the Intensity Limit

- **Replace chamber with smooth pipe to raise threshold for instability by a factor 2**

Pulse-to-Pulse Beam Jitter

RMS jitter at IP - 0.3-0.8 sigma

Some problems/solutions:

Quadrupole vibration

Feedback system performance

Long Range Wakefields (1995)

Calculations:
Predicted no problem

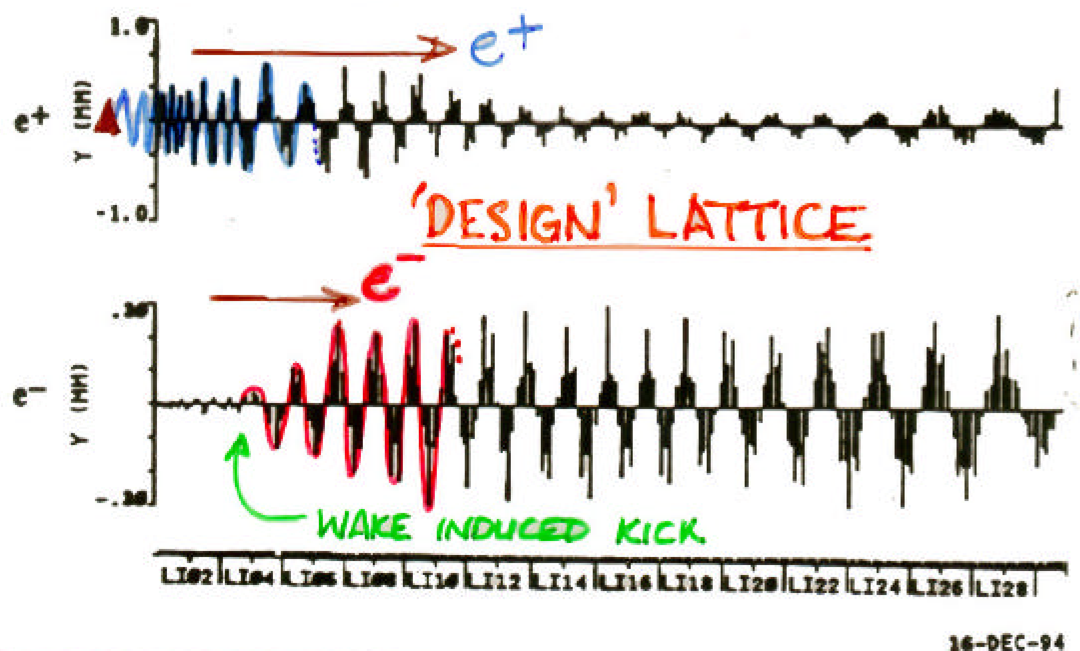
Observations:
Linac amplified jitter by factor of 6
e+/- jitter correlated
e^- jitter reduced factor of 2 if no e^+ beam

Experiment:
Measured e^- oscillation vs e^+ oscillation
Verified dependence on bunch spacing

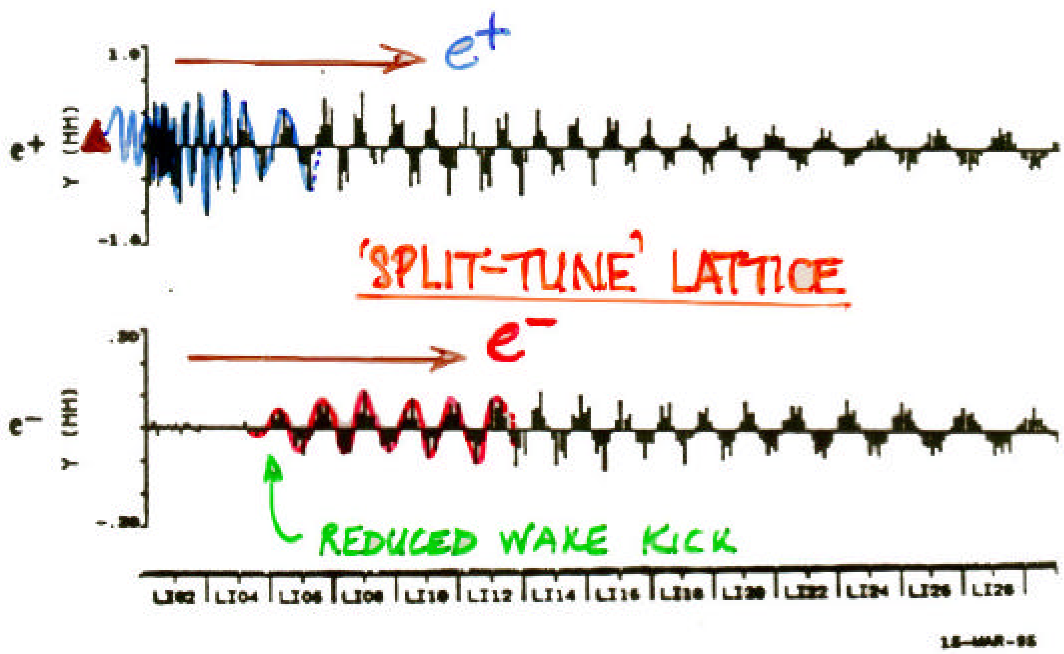
Solution:
Split-tune lattice reduced coupling
e^- vertical jitter reduced by 30-50%

Long Range Wakefield Kicks in the SLC Linac

SLC-Design Lattice:



Split-Tune Lattice:



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SLC Progress
was due to

People

100s of Physicists and Engineers

Many now leaders at other facilities

Tuning Techniques

Many innovative ideas

Diagnostics

High precision, non-invasive, distributed

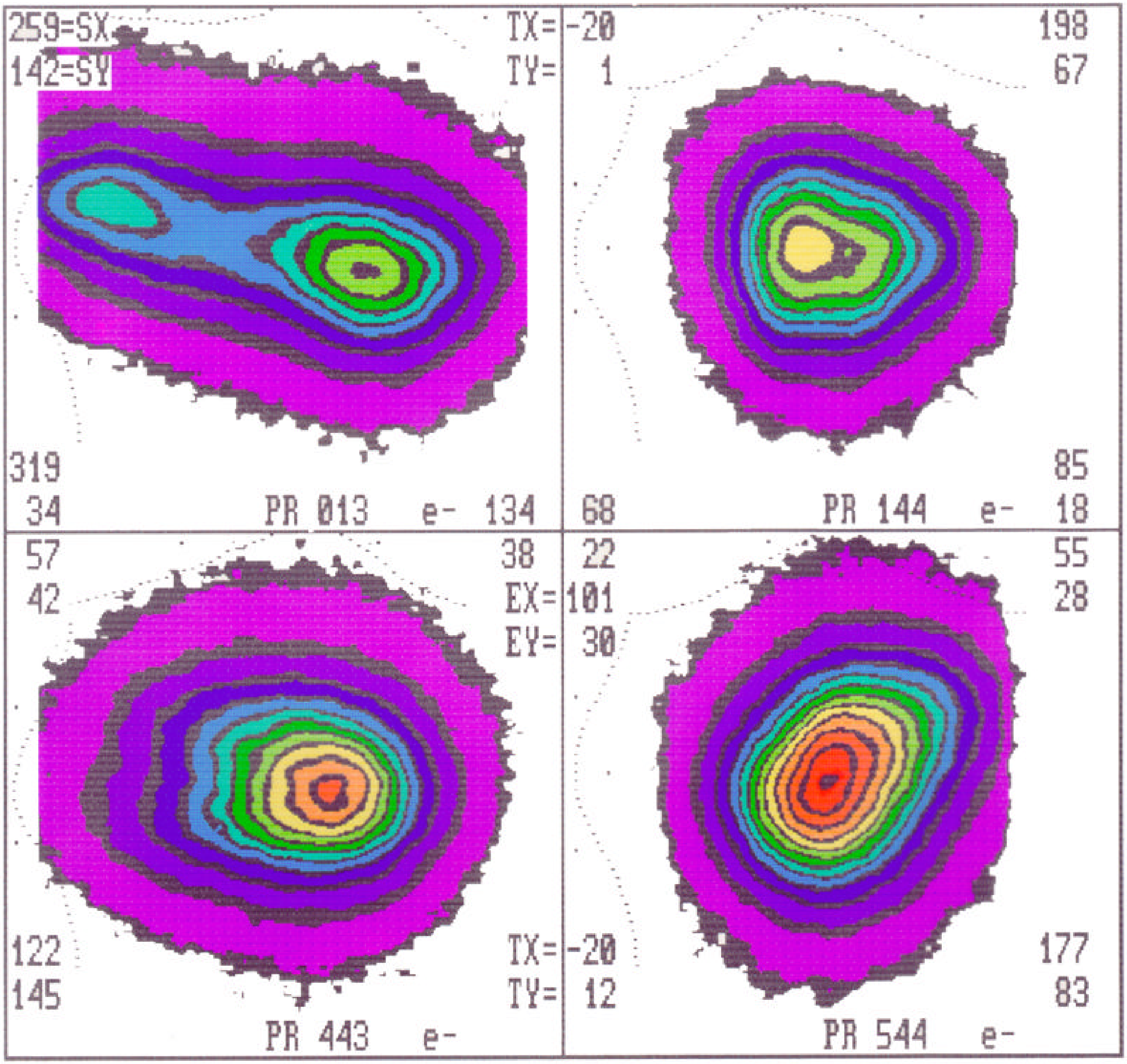
Monitoring and Trouble-shooting

Controls

Feedback, Automated procedures

Comprehensive Historical Data for analysis

End of Linac Beam Profiles



Colorized digital images of single pulses
analysed and displayed real-time

SLC Luminosity

Improvements

Progress due to development of techniques for

Emittance Control

Tuning Algorithms

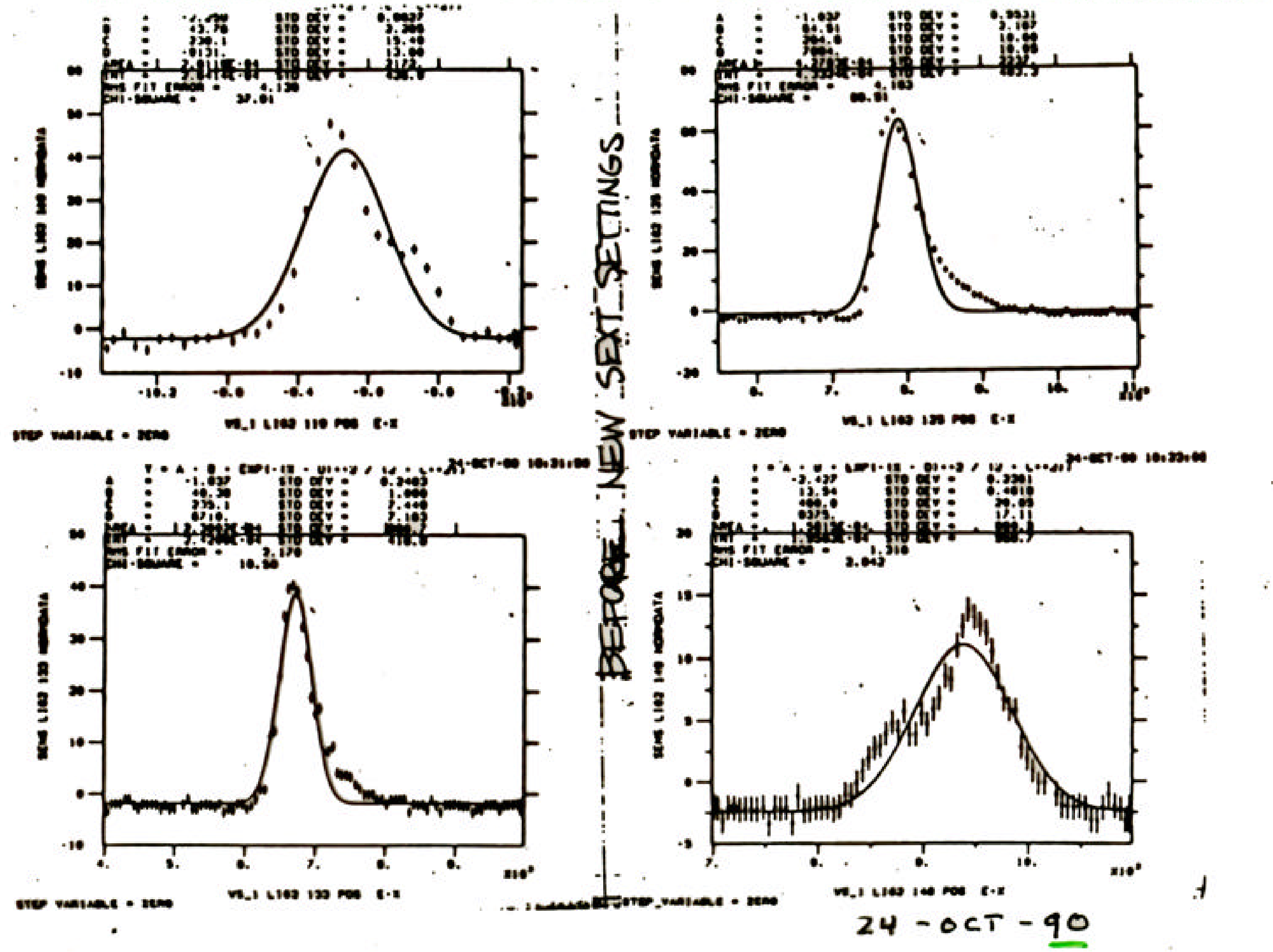
Stabilization

Key elements were

Diagnostics ~ 60 wire scanners

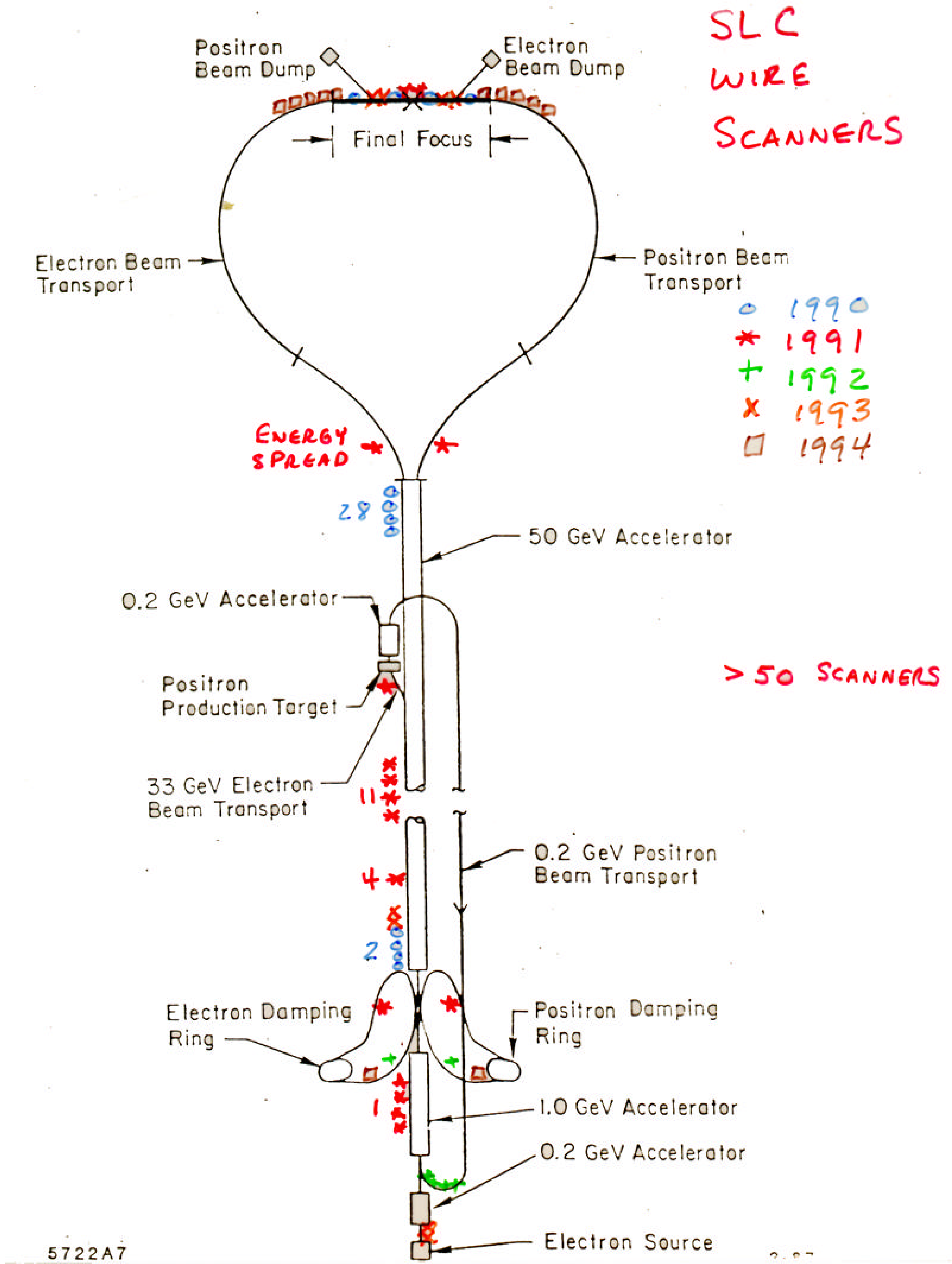
Beam-based Feedback
> 50 systems, controlling > 200 parameters

e^+. BEAM PROFILES MEASURED BY WIRE SCANNERS
AT INJECTION INTO LINAC BEFORE SEXTUPOLE OPTIMIZATION



Beam Size Monitor Evolution

- **1st wire scanners installed in 1990**
  could measure Linac e^+ for 1st time
- **Total of > 60 scanners installed**
- **Emittance analysis tools (including skew)**
- **Jitter compensation**
- **Hands off procedure ® history**
  scheduled scans, robust analysis
- **Multi-detector scan ® measure tails**
- **Hardware issues - wire size, breakage**
- **Laser wire ® measure single beam at IP**
  needed for NLC beam sizes
- **Breakthrough in last run**
  tune Linac ε on FF wires (SLD On)


SLC
WIRE
SCANNERS
Positron
Beam Dump
Electron
Beam Dump
Final Focus
Electron Beam
Transport
Positron Beam
Transport
1990
1991
1992
1993
1994
ENERGY
SPREAD
28
50 GeV Accelerator
0.2 GeV Accelerator
> 50 SCANNERS
Positron
Production Target
33 GeV Electron
Beam Transport
11
0.2 GeV Positron
Beam Transport
4
2
Electron Damping
Ring
Positron Damping
Ring
1.0 GeV Accelerator
1
0.2 GeV Accelerator
Electron Source
5722A7

Tuning Issues

(selected highlights)

- **New beam-based alignment techniques**
  including FF sextupoles & octupoles
- **Optics & dispersion matching algorithms**
- **4-D transfer matrix reconstruction - Arcs**
  including synchrotron radiation ε growth
  & effective spin tune to preserve P_e
  required HEP-style error analysis (Barklow)
- **2-beam dispersion free steering - Linac**
  later applied at LEP
- **Emittance control techniques**
  linac ‘bumps’ → cancel wakefield effects

All LC designs incorporate these methods

SLC provided 10 years of experience
® confidence in NLC

Stability Issues

Linear Colliders are inherently less stable than storage rings

Each pulse is an injected pulse

Real-time Monitoring

Tracking Changes

Studying Correlations

® **Improvements**

Feedback Systems

Control Energies and Trajectories

Maintain Collisions

Stabilize Polarized Source

Beam Optimization

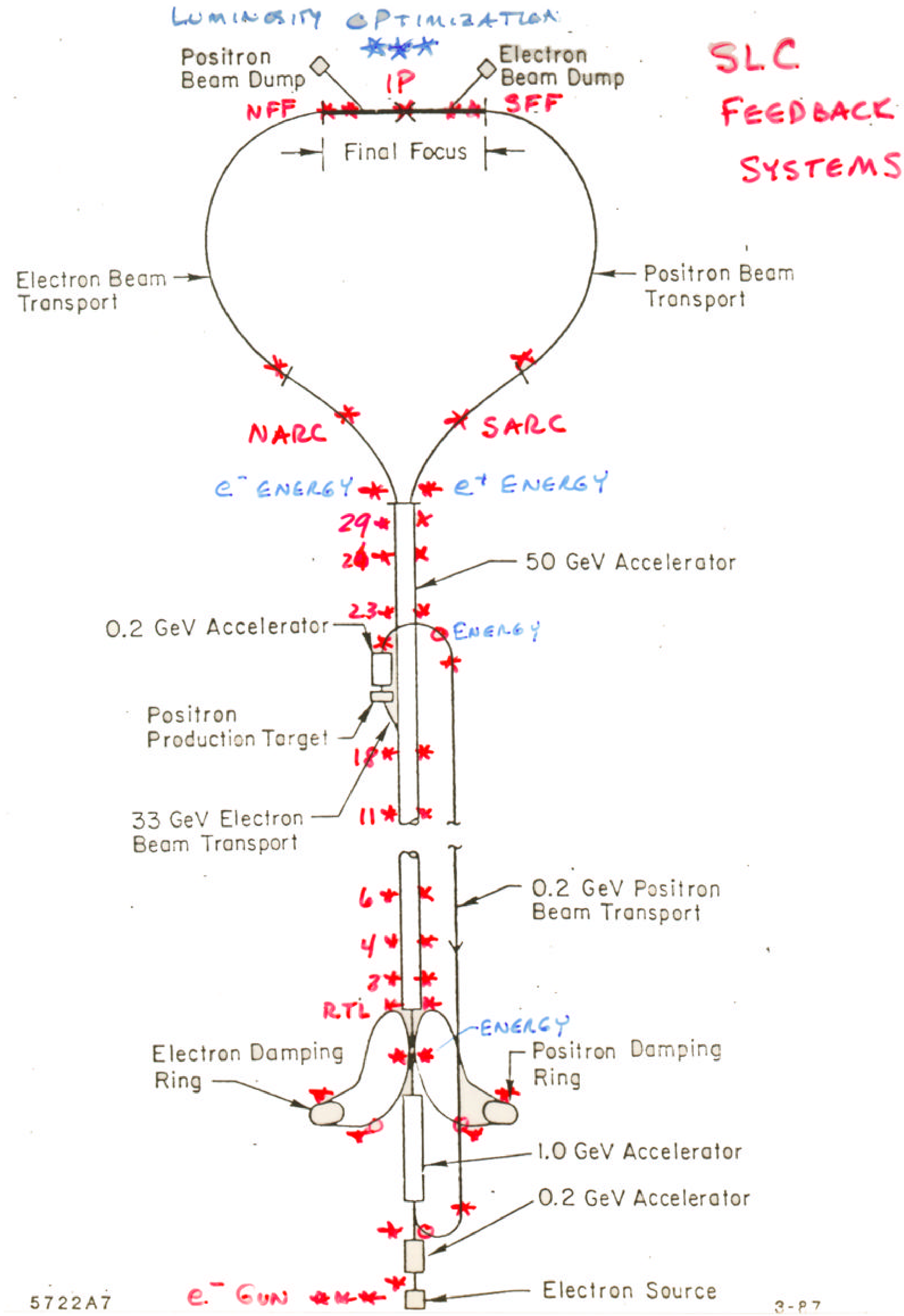
SLC had

> 50 Feedback Systems

Controlling > 200 Parameters

Feedback Evolution

- **1st ‘slow’ energy/orbit feedback in 1985**
- **Prototype pulse-to-pulse systems in 1987**
  used dedicated hardware at end of Linac
- **Pulse-to-pulse collision feedback in 1989**
- **Generic ‘fast’ feedback in 1991-93**
  database-driven, shared hardware
  ‘easy’ to add a new system anywhere
  Linac systems connected by adaptive cascade
- **Expanded online diagnostics**
  history, monitoring, FFTs
- **Luminosity optimization feedback in 1997**
  dithering, >1K pulse averaging
- **Emittance optimization attempted**



LUMINOSITY OPTIMIZATION
SLC
FEEDBACK
SYSTEMS
Positron
Beam Dump
IP
Electron
Beam Dump
NFF
SFF
Final Focus
Electron Beam
Transport
Positron Beam
Transport
NARC
SARC
e⁻ ENERGY
e⁺ ENERGY
29
26
50 GeV Accelerator
23
0.2 GeV Accelerator
ENERGY
Positron
Production Target
18
33 GeV Electron
Beam Transport
11
6
0.2 GeV Positron
Beam Transport
4
3
RTL
ENERGY
Electron Damping
Ring
Positron Damping
Ring
1.0 GeV Accelerator
0.2 GeV Accelerator
e⁻ GUN
Electron Source
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3-87

1994 Performance

Integrated Luminosity

Goal:

> 100 K Z_0s -> SLD

Total : > 100,000 Z_0 on tape
with ~80% polarization

DR and FF upgrades
100 nm Strained lattice cathode

Goal:

—> 4000-5000 Z_0/week on tape

Status:

> 1500 Z_0/day on tape

Best 1993 was 722

> 7000 Z_0/week on tape

Best 1993 was 4400

average ~ 4000 Z_0/week

-

SLC post-1995

SLD million Z run with VXD3 had been
approved in November, 1993
to start with 1996 run

SLC delivered 100K Z goal in 1994 run but
required extension through February, 1995
Longer than expected to see benefits from DR
and FF upgrades, minimal future upgrades

SLC schedule severely impacted by budget cuts,
also time for FFTB and ASSET runs

PEP-II construction had started
had priority, people and resources and
by 1996 required time for commissioning

1996 SLD run scheduled only Feb - June
NDR fire & vent in February, 1996

–> 50K Zs in 2.5 months

SLC 1997-98

Support from SLAC management was luke-warm at best - focus on PEP-II

SLC/SLD agreed to all out luminosity push
not much to lose !!!

Concentrated on low-cost, targeted upgrades
i.e., relocating existing hardware

ARDA created Task Force (Irwin/Zimmermann)
+ help from SLD (Bogart/Russell)

Many clever new ideas from NLC and SLC2000

GOAL: more than Double previous Luminosity

Made "Hail Mary" play at April, 97 DOE review
this successfully got SLD funding to run through mid-1998

Luminosity Projections

With 1996 parameters- intensity, emittance

N^-	= 3.8	N^+	= 3.6	10^{10}
ε_x	= 5.5	ε_y	= 0.9	in S28

Expected	=	150 Z/hr
Achieved	=	120 Z/hr (peak)
	60 Z/hr (typical)	

With same parameters, larger Θ_x, larger H_D

Θ_x	= 475 µrad	H_D	= 1.9
Expected	=	250 Z/hr	

Improved IP tuning and wakefields

Typical (?)	=	150 Z/hr

With better Linac values- intensity, emittance

N^-	= 4.2	N^+	= 4.0	10^{10}
ε_x	= 4.0	ε_y	= 0.6	in S28
H_D	= 2.2			

Expected	=	500 Z/hr
Typical (?)	=	250-350 Z/hr

Goal: **250 Z/hour or Bust**

Raimondi & Usher

Led the effort to double luminosity

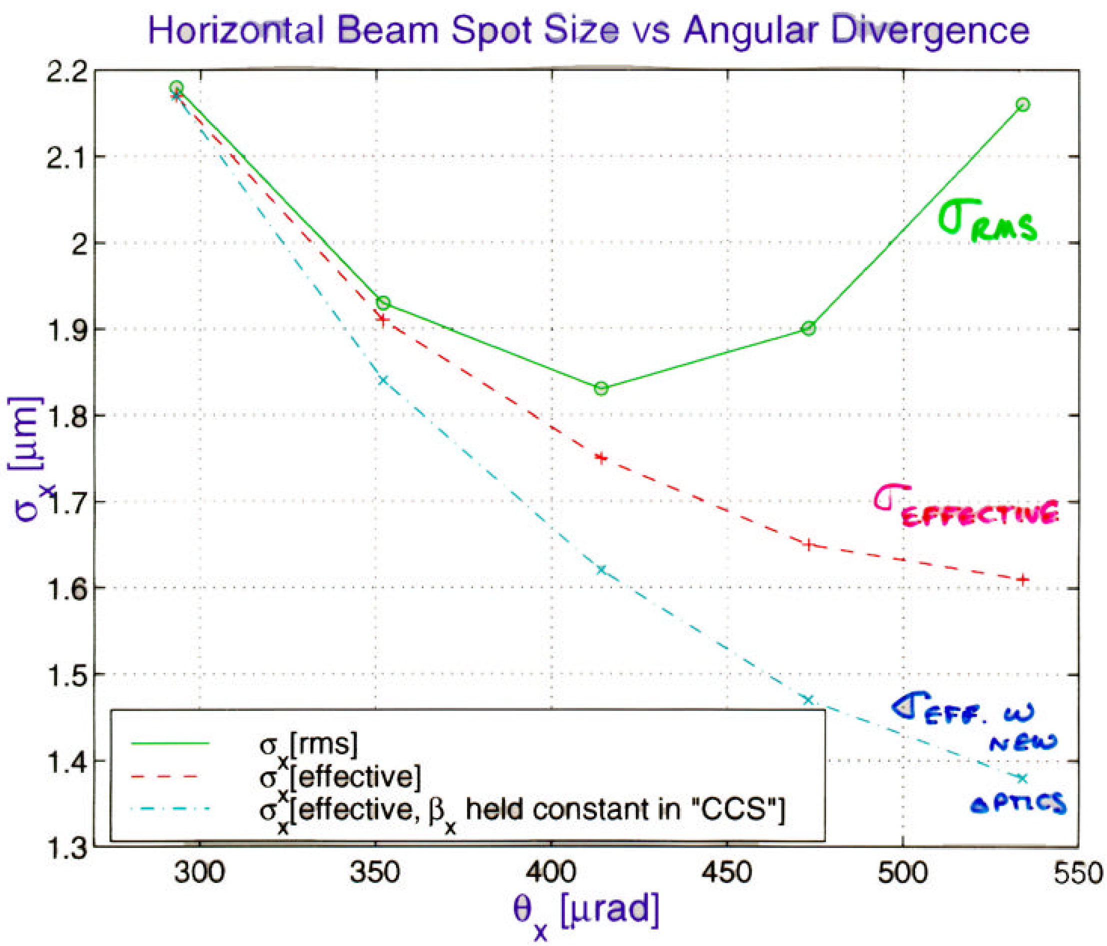
bold, brilliant ideas, endless hours @MCC

1. Produce smallest possible IP spots
   - New tuning techniques in RTL, Linac, Arc, FF
   - Demagnification moved closer to IP, stronger
   - Soften FF bend by misaligning quads (Xmas)
   - New PM octupoles (3/98 - $10K each)
2. Control backgrounds so not limitation
   - Spare DR sextupoles in BSY
   - FF colls moved to 45º in Arc Reverse Bend
3. Improve stability & reproducibility
   - facilitate quick recovery, average –> peak

10K/week in November, 1997 (Richter party)
15K/week in March - 20K/week in May, 1998

Run ended abruptly 1 wk early with e+ leak after all time record shift of > 2K Zs (250/hr * 8)

SIMULATION OF
σ_x VS θ_x^*



P. RAIMONDI

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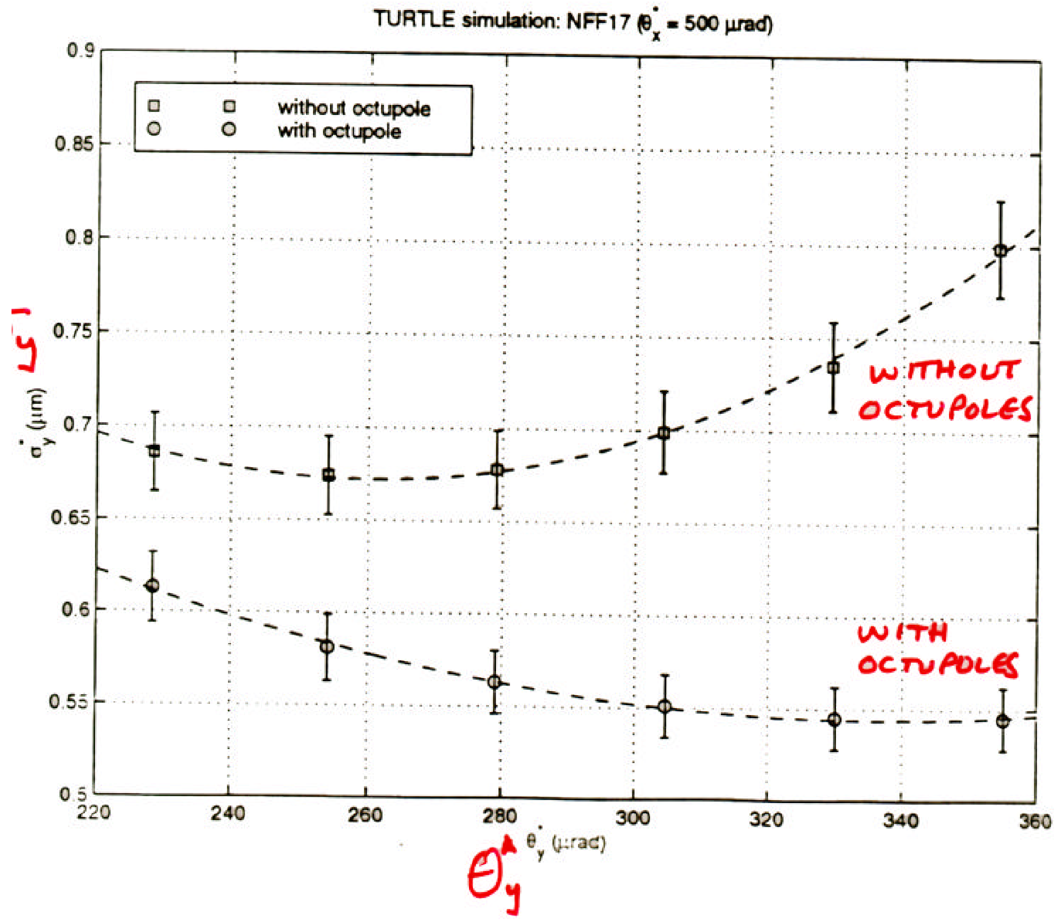
SIMULATION OF σ_y VS θ_y^*

SHOWING EFFECT OF OCTUPOLES



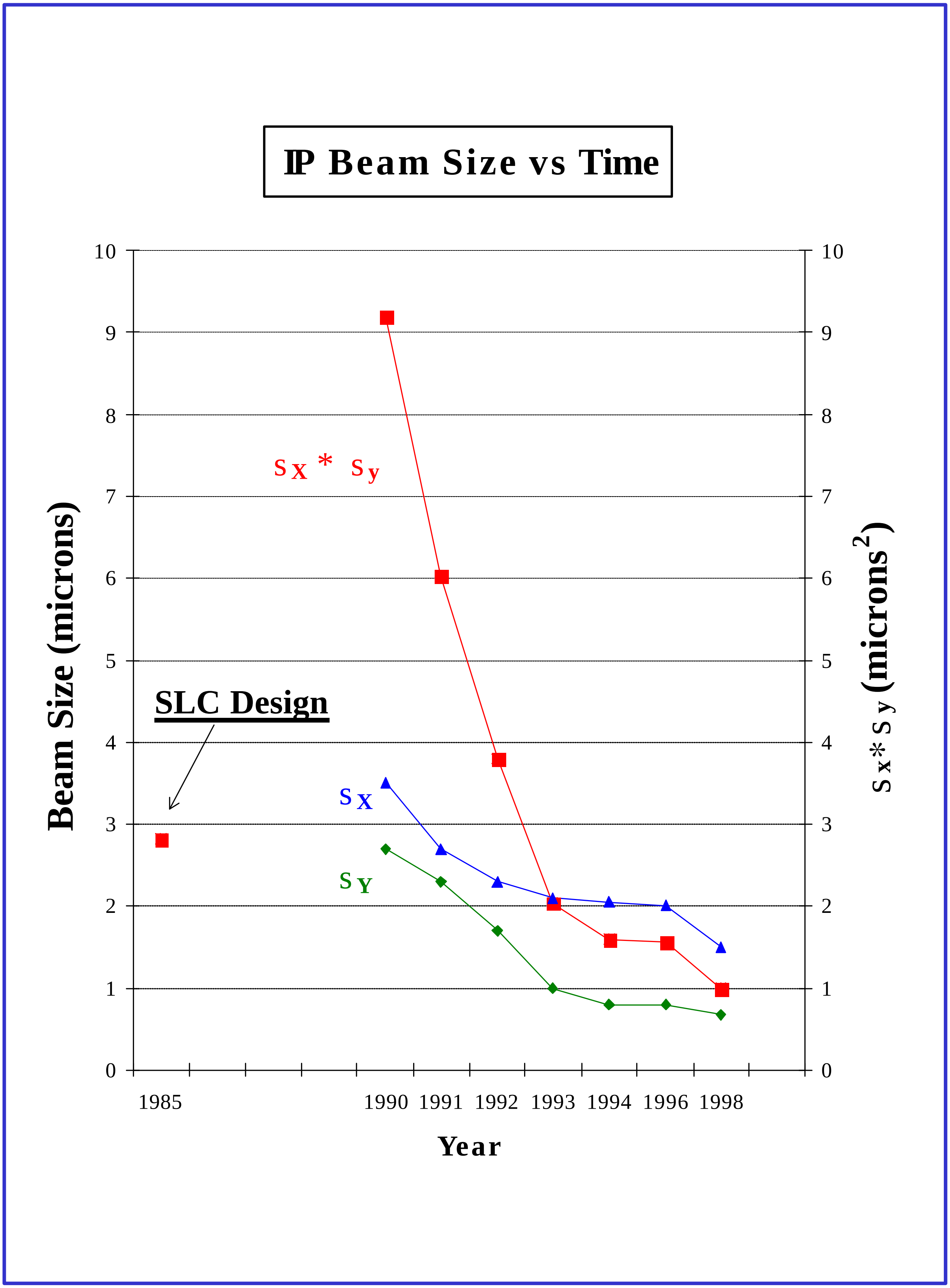
ABERRATIONS TO BE CANCELLED

$$U_{3246} \Rightarrow \Delta y \propto \Delta x' \Delta y' \left(\frac{\Delta E}{E} \right)$$

$$U_{3444} \Rightarrow \Delta y \propto \Delta y'^3$$

M. WOODLEY

Be


IP Beam Size vs Time
Beam Size (microns)
Sx*Sy (microns^2)
Sx * Sy
Sx
Sy
SLC Design
Year
10
9
8
7
6
5
4
3
2
1
0
1985
1990
1991
1992
1993
1994
1996
1998

Disruption Enhancement
(aka Pinch Effect)

1998 parameters:

$\Sigma_{x,y}$	=	2.1, 0.9 μm	$N^{+/-}$	=	$4.0 * 10^{10}$
$\theta^*_{x,y}$	=	450, 250 μrad	σ_z	=	1.1 mm
H_D	=	2.1 (predicted)			

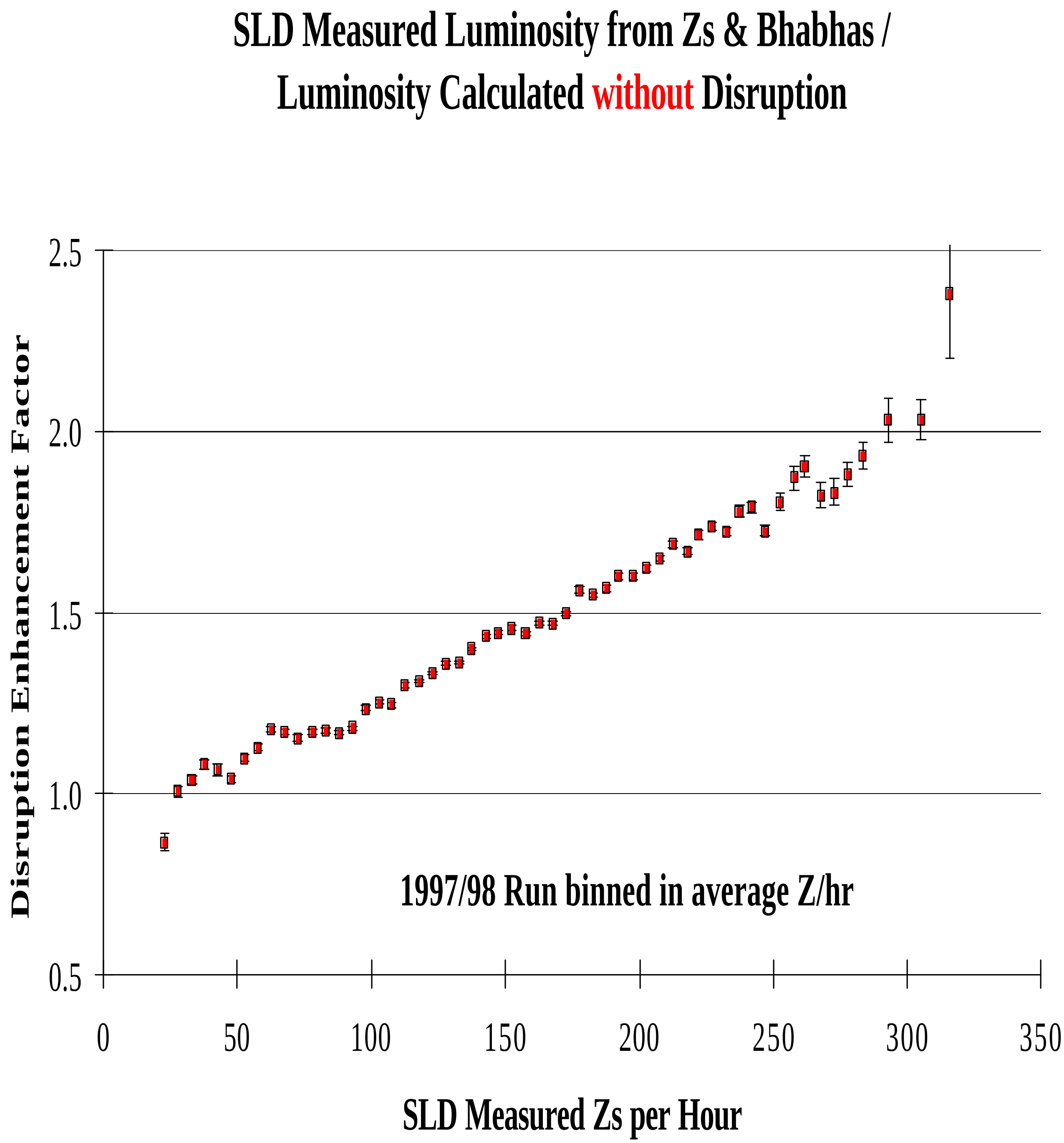
With these beams,
disruption enhancement is significant

Ratio of luminosity recorded by SLD detector
to luminosity predicted for rigid beams

$$H_D^{meas} = \frac{L_{SLD}}{L^0_{SLC}}$$

In excellent agreement with H_D^{theory}

$\boxed{\text{Measured enhancement} \quad > 100\%}$


SLD Measured Luminosity from Zs & Bhabhas /
Luminosity Calculated without Disruption
Disruption Enhancement Factor
2.5
2.0
1.5
1.0
0.5
1997/98 Run binned in average Z/hr
0
50
100
150
200
250
300
350
SLD Measured Zs per Hour

1997-98 SLC Run

Peak luminosity	300 Z^os / hr
	$3\ 10^{30}/cm^2/sec$

3 times previous record

Integrated luminosity	350,000 Z^os

≈ double total from all previous runs

Beam size	1.5 by 0.65 µm

3 times smaller than design

Disruption enhancement	100%

Luminosity steadily increased throughout run

Gains from improved tuning procedures
And reconfiguring existing hardware
with NO major hardware upgrades

SLC continued to provide valuable experience
–> future linear colliders

SLC LESSONS

With a New Accelerator technology expect a lot of hard work and surprises

(examples: SLAC Linac, storage rings, SLC)

The most difficult problems are usually those which were not expected

Diagnostics - best/most possible
Feedback
Powerful, flexible control system

Discipline of trying to produce physics forces you to discover and solve problems not required for a test project

SLC Luminosity History