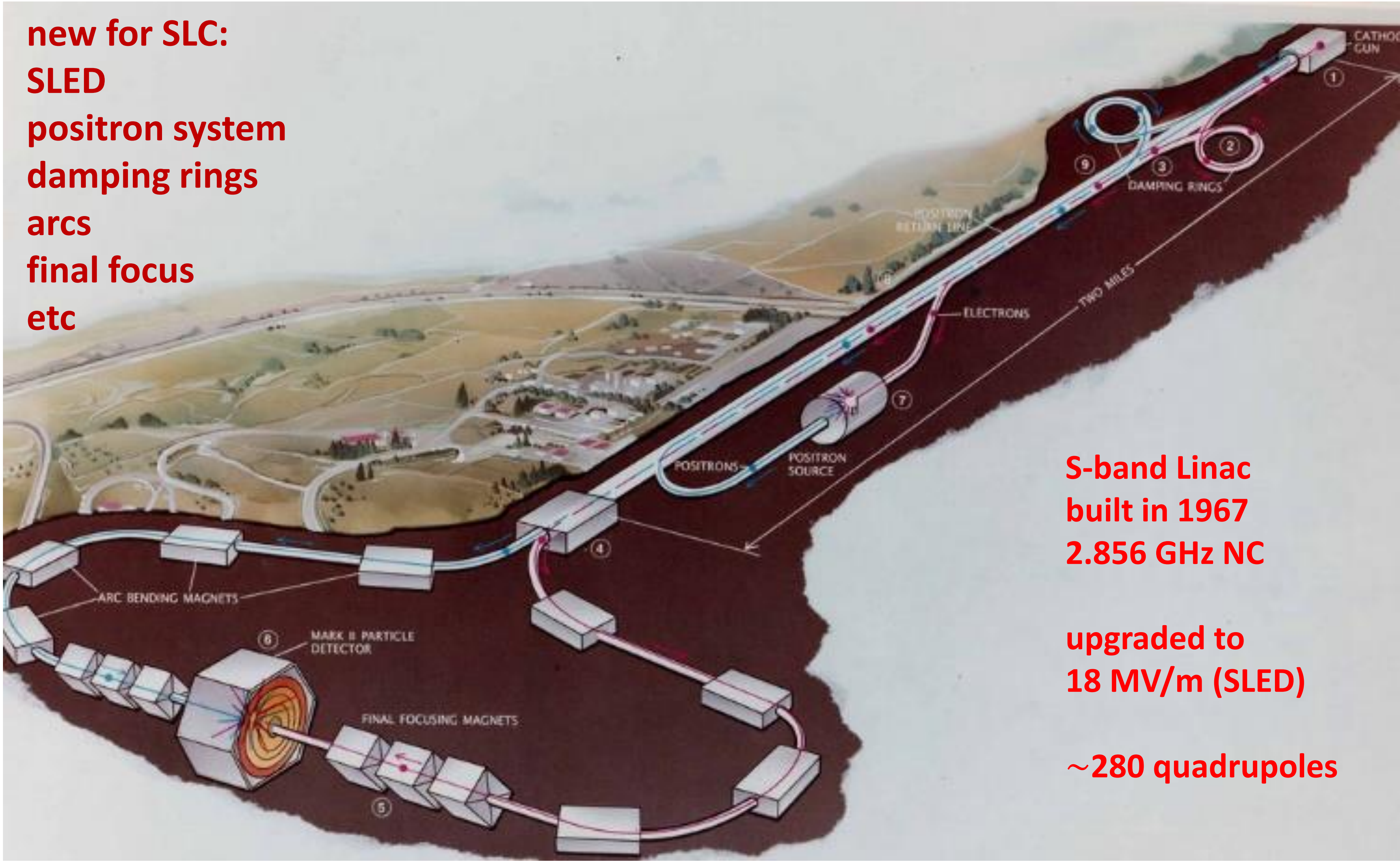
lessons from the SLC

Frank Zimmermann

CERN Accelerator School on Future Colliders

Friday 2 March 2018

new for SLC:
SLED
positron system
damping rings
arcs
final focus
etc



S-band Linac
built in 1967
2.856 GHz NC

upgraded to
18 MV/m (SLED)

~280 quadrupoles

SLAC Linear Collider - The first and only linear collider (1987/89-1998); ~two years to produce 1st Z's; competitor circular LEP started in 1989

SLC was proposed in 1979
by Burt Richter

(who a few years earlier
had proposed LEP….)

What SLC is trying to do is ***"like shooting two guns at one another from 100 miles apart and getting the bullets to hit".***

New Scientist, 19 May 1988

Physics Dream Machine Is Imperiled

Technical problems plague Stanford's Linear Collider, threatening its ability to produce breakthroughs in particle physics Expectations were running high. For months, the Stanford Linear Collider (SLC), an innovative particle accelerator nearing completion at the Stanford Linear Accelerator Facility (SLAC) in Palo Alto, Calif. had been preparing for its debut. This was the machine that would mint a million Z0 particles a year. Close study of the Z0—it's mass, for example-

By Robert Crease | September 5, 1988 The Scientist Magazine

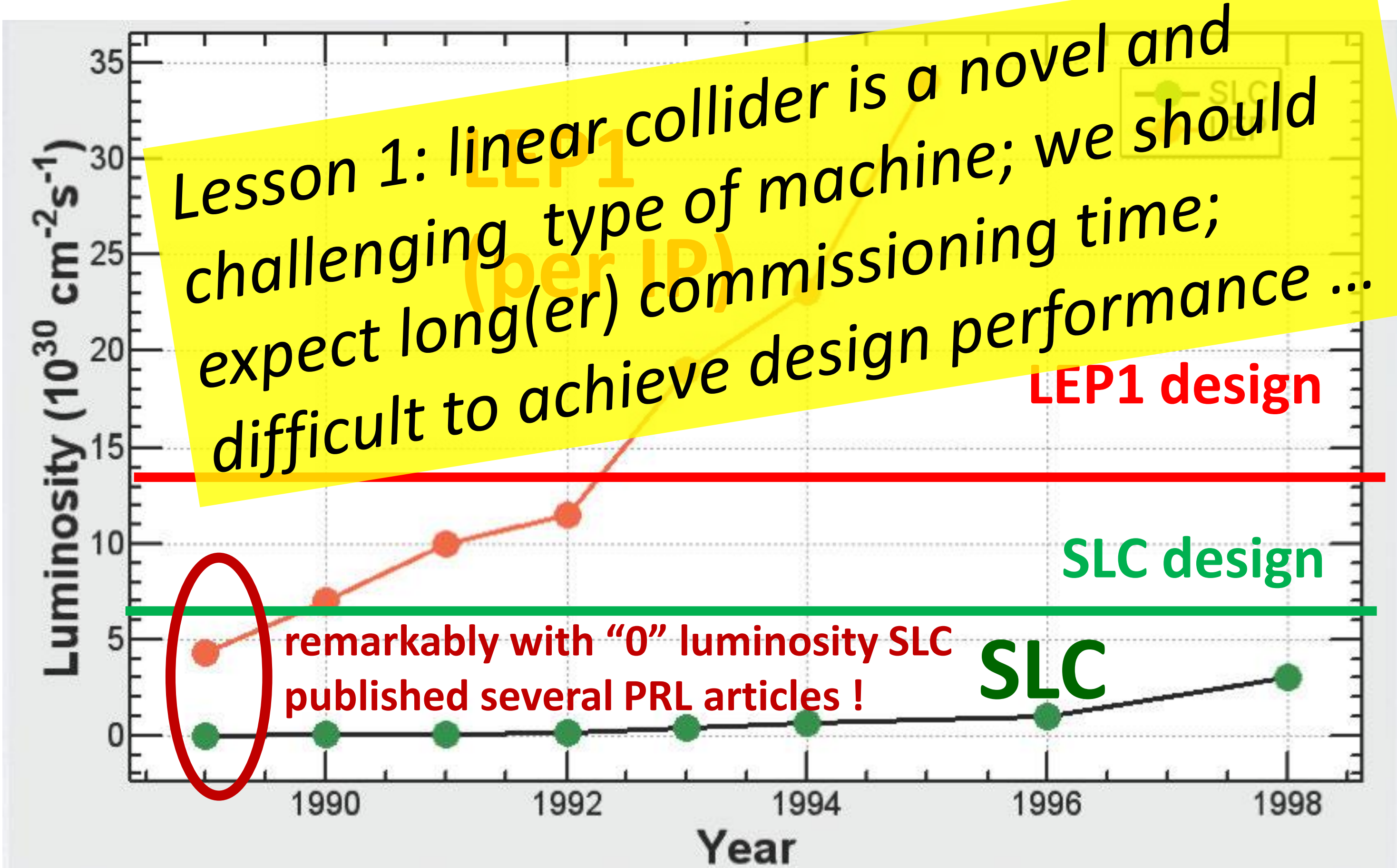
Laboratory management supercharged the already exuberant atmosphere by issuing news releases advertising the imminent birth of Z0 particles. The media was duly impressed. **"For the first time in five years," gushed the New York Times on July 19, "high-energy physicists in the United States are poised to seize a commanding lead from colleagues in Europe."**

No such luck. On June 24, the machine was switched on for what was called "a physics research run," but the experiment never got rolling.

"Nobody believed that, with a new kind of accelerator, we'd flip a switch and be up to specs," says lab director Burton Richter. "But nobody believed we'd have this much trouble getting started either."
'Well make it go," says Richter, "but don't ask me when. We have a lot of work to do."
Meanwhile, the delay is eating away at the SLC's lead over its European rival, the Large Electron Positron (LEP) accelerator at CERN in Geneva, Switzerland. And even though the SLC had already proved the value of its innovative design, its troubles are threatening not only to harm the reputations of the Stanford scientists, but to wipe out their daring approach to accelerator…

commissioning time & performance of the first linear collider

Lesson 1: linear collider is a novel and challenging type of machine; we should expect long(er) commissioning time; difficult to achieve design performance …



CERN-SL-2002- 009 (OP), SLAC–PUB–8042

SLC

- **peak $\sim {}^{1}/_{2}$ design after 11 years, average $\sim {}^{1}/_{4}$ design**

PRL articles from the early years

VOLUME 62, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1989

First Observation of Beamstrahlung

G. Bonvicini, E. Gero, R. Frey, and W. Koska

University of Michigan, Ann Arbor, Michigan 48109

Stanford Linear Acceler

CE

Collisions of electron and positr

led to the first detected emission

VOLUME 62, NUMBER 25 PHYSICAL REVIEW LETTERS 19 JUNE 1989

Observation of Beam-Beam Deflections at the Interaction Point of the SLAC Linear Collider

P. Bambade,[1],[a] R. Erickson,[1] W. A. Koska,[2] W. Kozanecki,[1] N. Phinney,[1] and S. R. Wagner[3]

[1]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*

[2]*University of Michigan, Ann Arbor, Michigan 48109*

[3]*University of Colorado, Boulder, Colorado 80309*

(Received 21 February 1989)

ection of high-energy electron and
's. Measurements of the deflection
ıomenon, which is sensitive both to
s been used successfully to optimize
ollider.

VOLUME 63, NUMBER 7 PHYSICAL REVIEW LETTERS 14 AUGUST 1989

Initial Measurements of Z-Boson Resonance Parameters in e^+e^- Annihilation

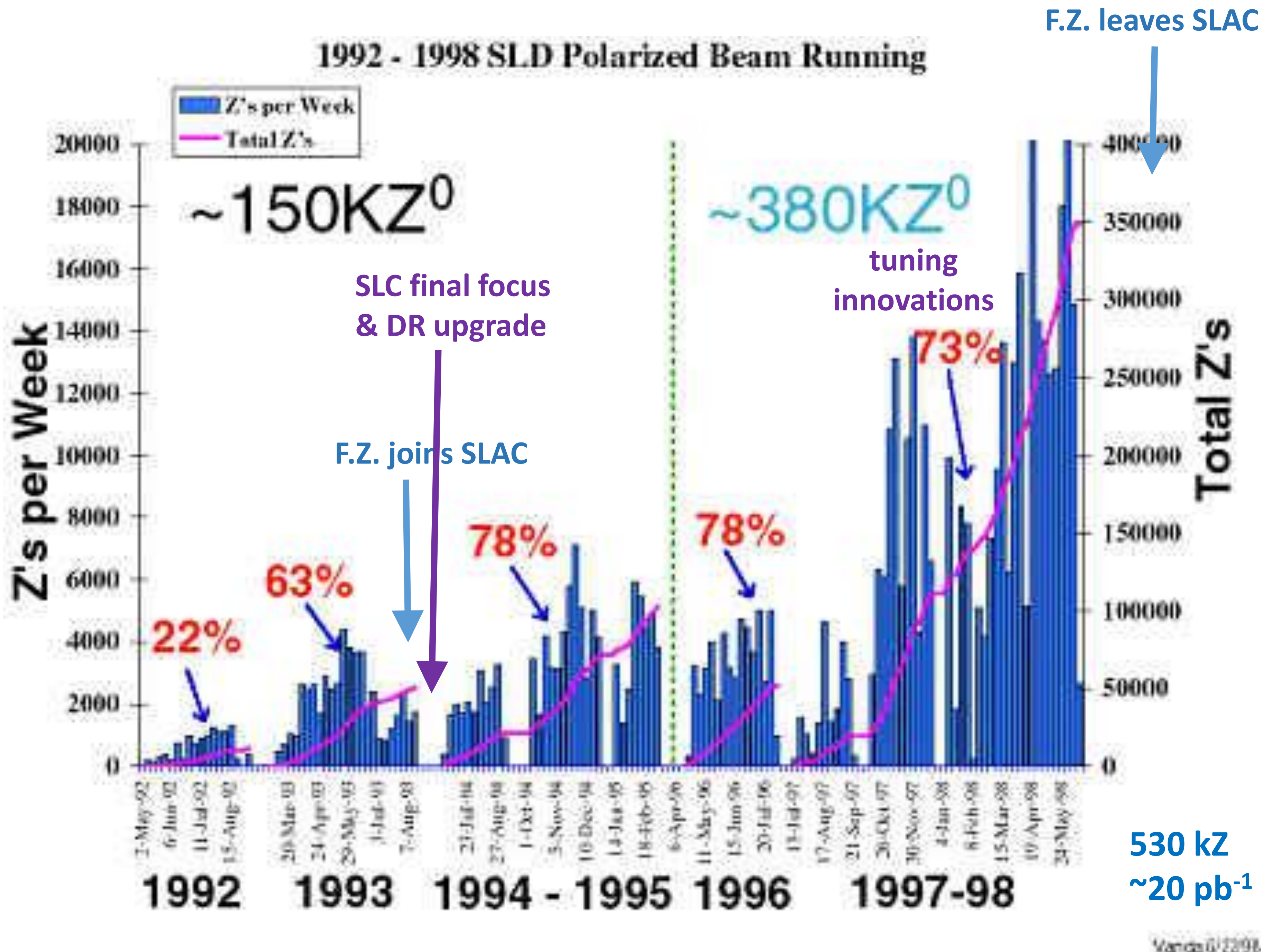
G. S. Abrams,[1] C. E. Adolphsen,[2] R. Aleksan,[3] J. P. Alexander,[3] M. A. Allen,[3] W. B. Atwood,[3] D. Averill,[4] J. Ballam,[3] P. Bambade,[3] B. C. Barish,[5] T. Barklow,[3] B. A. Barnett,[6] J. Bartelt,[3] S. Bethke,[1] D. Blockus,[4] W. de Boer,[3] G. Bonvicini,[7] A. Boyarski,[3] B. Brabson,[4] A. Breakstone,[8] M. Bre... K. L. Brown,[3] F. Bulos,[3] P. R. Burchat,[2] D. L. Burke,[3] R. J. Cence,[8] J. Chapman,[7] M. Chmeissani,[7] J. Clendenin,[3] D. Cords,[3] D. P. Coupal,[3] P. Dauncey,[6] N. R. Dean,[3] H. C. DeStaebler,[3] D. E. Dorfan,[2] J. M. Dorfan,[3] P. S. Drell,[1] D. C. Drewer,[6] F. Dydak,[3] S. Ecklund,[3] R. Elia,[3] R. A. Erickson,[3] J. Fay,[1] G. J. Feldman,[3] D. Fernandes,[3] R. C. Field,[3] T. H. Fieguth,[3] G. E. Fischer,[3] W. T. Ford,[9] C. Fordham,[3] R. Frey,[7] D. Fujino, ... T. Glanzman,[3] G. Goldhaber,[1] J. J. Gom... Wiesmann,[3] G. Hanson,[3] R. Harr,[1] B. ... C. Hearty,[1] D. Herrup,[1] C. A. Heusch, ...

3.8±1.4 ν families

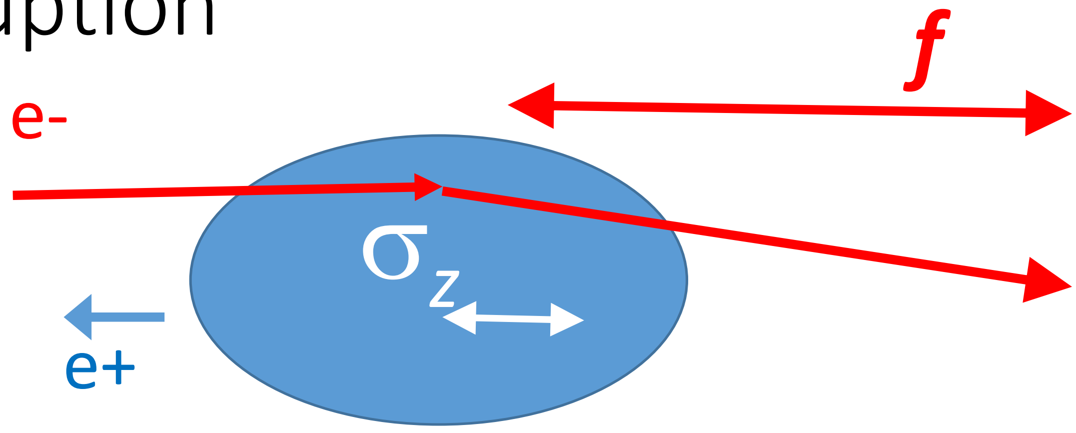
VOLUME 70, NUMBER 17 PHYSICAL REVIEW LETTERS 26 APRIL 1993

First Measurement of the Left-Right Cross Section Asymmetry in Z Boson Production by e^+e^- Collisions

K. Abe,[29] I. Abt,[15] P. D. Acton,[5] C. E. Adolphsen,[27] G. Agnew,[5] C. Alber,[10] D. F. Alzofon,[27] P. Antilogus,[27] C. Arroyo,[11] W. W. Ash,[27] V. Ashford,[27] A. Astbury,[32] D. Aston,[27] Y. Au,[11] D. A. Axen,[4] N. Bacchetta,[22] K. G. Baird,[25] W. Baker,[27] C. Baltay,[35] H. R. Band,[34] G. Baranko,[10] O. Bardon,[18] F. Barrera,[27] R. Battiston,[23] A. O. Bazarko,[11] A. Bean,[7] G. Beer,[32] R. J. Belcinski,[19] R. A. Bell,[27] R. Ben-David,[35] A. C. Benvenuti,[2] R. Berger,[27] S. C. Berridge,[28] S. Bethke,[17] M. Biasini,[23] T. Bienz,[27] G. M. Bilei,[23] F. Bird,[27] D. Bisello,[22] G. Blaylock,[8] R. Blumberg,[27] J. R. Bogart,[27] T. Bolton,[11] S. Bougerolle,[4] G. R. Bower,[27] R. F. Boyce,[27] J. E. Brau,[21] M. Breidenbach,[27] T. E. Browder,[27] W. M. Bugg,[28] B. Burgess,[27] D. Burke,[27] T. H. Burnett,[33] P. N. Burrows,[18] W. Busza,[18] B. L. Byers,[27] A. Calcaterra,[13] D. O. Caldwell,[7] D. Calloway,[27] B.


F.Z. leaves SLAC
1992 - 1998 SLD Polarized Beam Running
Z's per Week
Total Z's
~150KZ^0
~380KZ^0
SLC final focus
& DR upgrade
tuning
innovations
F.Z. joins SLAC
22%
63%
78%
78%
73%
Z's per Week
Total Z's
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
400000
350000
300000
250000
200000
150000
100000
50000
0
1992
1993
1994 - 1995
1996
1997-98
530 kZ
~20 pb^{-1}

luminosity enhancement from beam-beam "disruption"



"disruption parameter" = bunch length / focal length

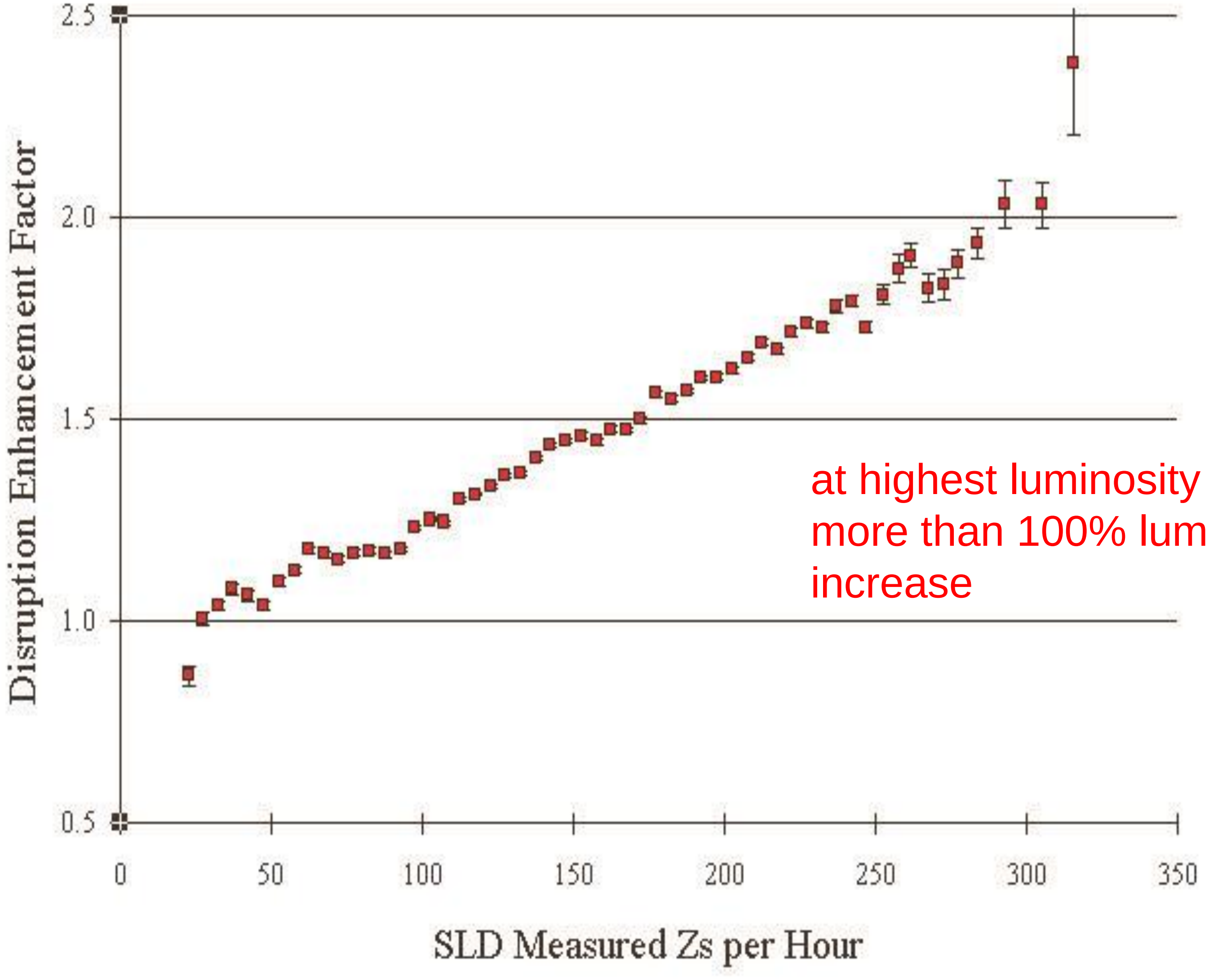
$$D_{x,y} = \frac{\sigma_z}{f_{x,y}} = \frac{2 r_p N_b \sigma_z}{\gamma \sigma_{x,y} \left(\sigma_x + \sigma_y\right)}$$

$$L = L_0 \, H_D\left(D_x, D_y, \sigma_z/\sigma_y \, , \sigma_z/\beta_y^*\right)$$

L_0: luminosity for constant beam size

H_D: disruption enhancement factor

beam-beam disruption at the SLC



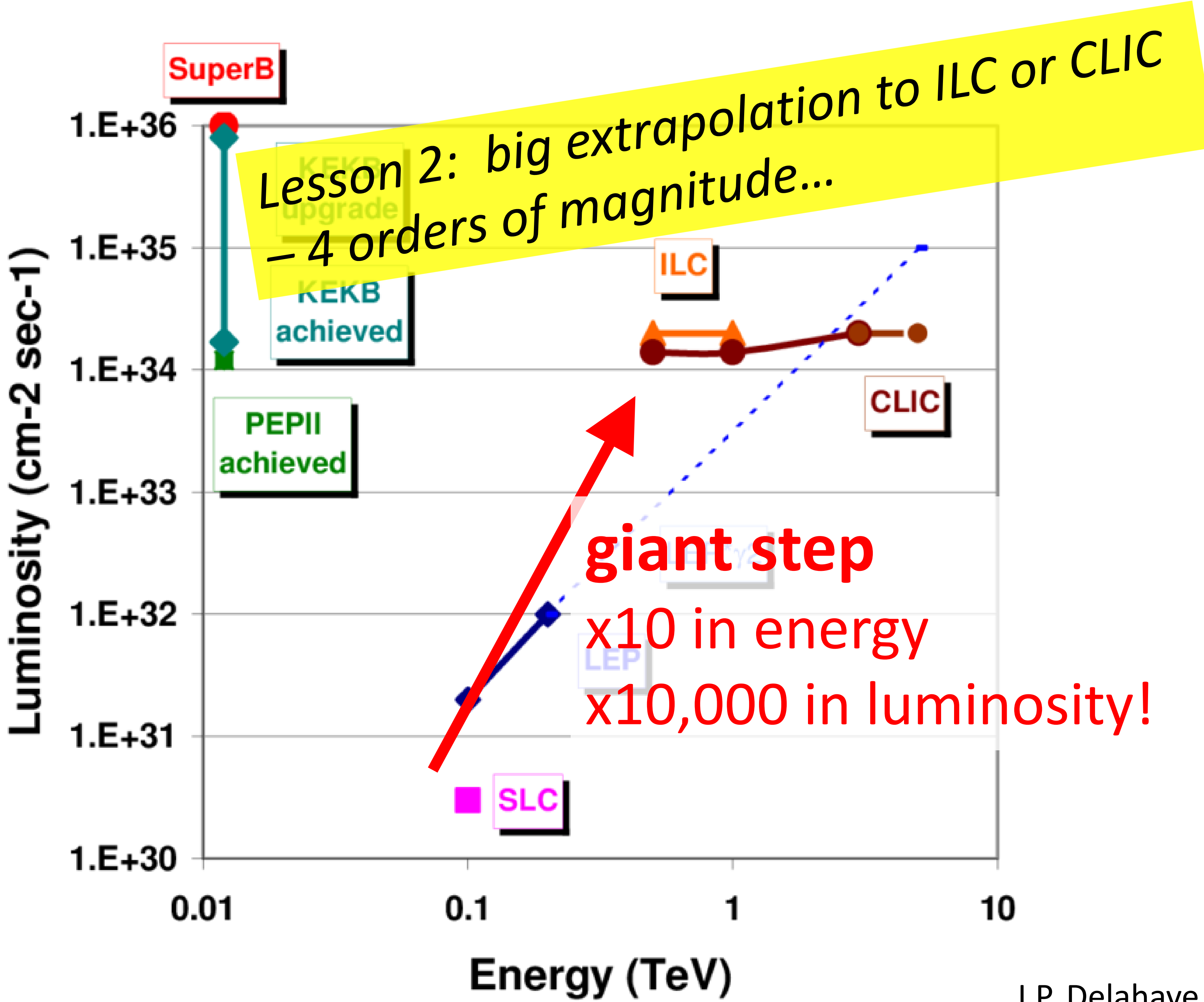
at highest luminosity
more than 100% luminosity
increase

design versus reality

parameter	design*	achieved 1998
repetition rate [Hz]	180	**120**
bunch population [10^{10}]	7.2	**3.7 (e^-), 3.4 (e^+)**
norm.emittance in final focus $\gamma\varepsilon_{x,y}$ [μm]	42, 42	**54, 10**
IP bunch length [mm]	1.0	1.0
IP beta function $\beta_{x,y}$* [mm]	5, 5	**2.8, 1.5**
IP beam size $\sigma_{x,y}$* [μm]	1.65, 1.65 (round)	1.84, 0.98 measured** [1.34, 0.39 expected**]
e^- polarization at IP	0	**73% (1998)**
disruption enhancement	2.2	**2.0**
luminosity [10^{30} $cm^{-2}s^{-1}$]	6.0	**1.4** (average Jan-May'98)

*SLC Design Handbook, December 1984

**SLAC-CN-418 (1998)


Lesson 2: big extrapolation to ILC or CLIC
– 4 orders of magnitude…
SuperB
KEKB
achieved
PEPII
achieved
ILC
CLIC
SLC
giant step
x10 in energy
x10,000 in luminosity!
1.E+36
1.E+35
1.E+34
1.E+33
1.E+32
1.E+31
1.E+30
Luminosity (cm-2 sec-1)
0.01
0.1
1
10
Energy (TeV)

J.P. Delahaye

a few selected SLC challenges & highlights

- fighting resonances

  e+ return, two-beam linac wake, arc spin rotator

- keeping the beam stable

  jitter, e+, vibration, damping ring instability

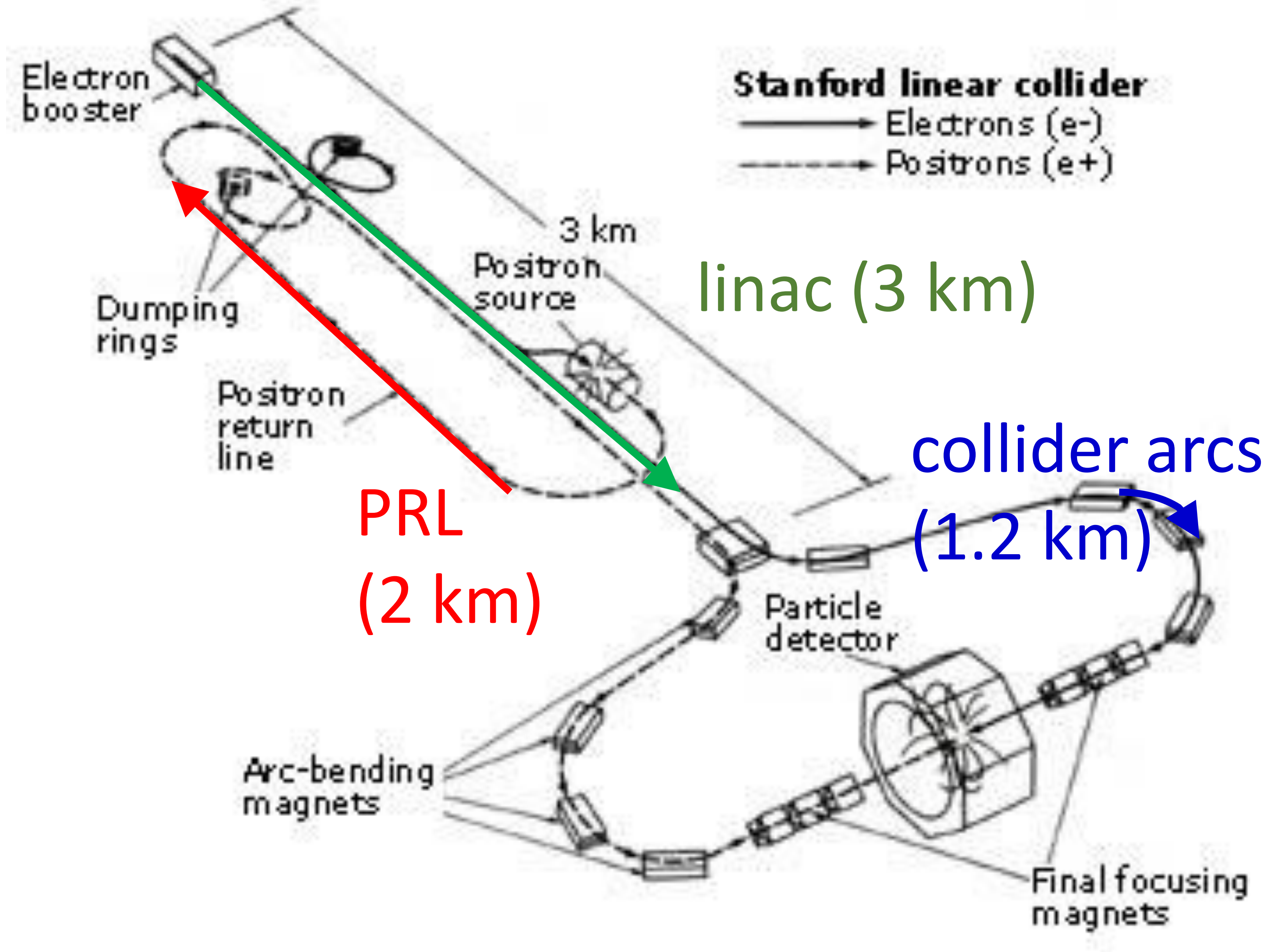
- making a small beam spot

  design, errors/tuning, the unknowns

- beam halo & detector background

  modelling halo, suppressing muon background

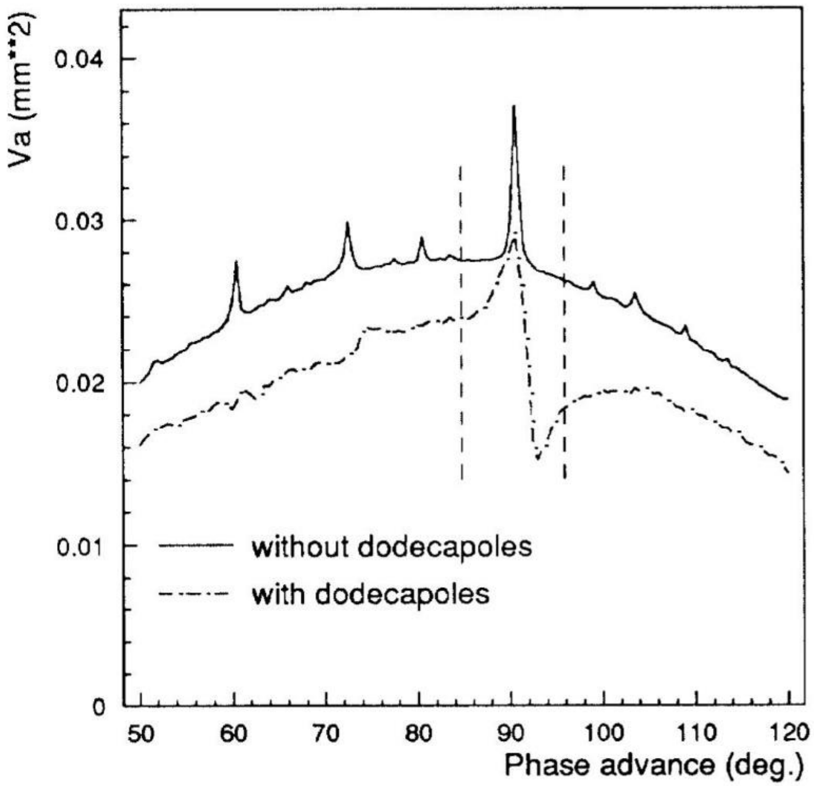
resonances in a linear collider … ?


Stanford linear collider
Electrons (e-)
Positrons (e+)
Electron booster
Dumping rings
3 km
Positron source
linac (3 km)
Positron return line
PRL
(2 km)
collider arcs
(1.2 km)
Particle detector
Arc-bending magnets
Final focusing magnets

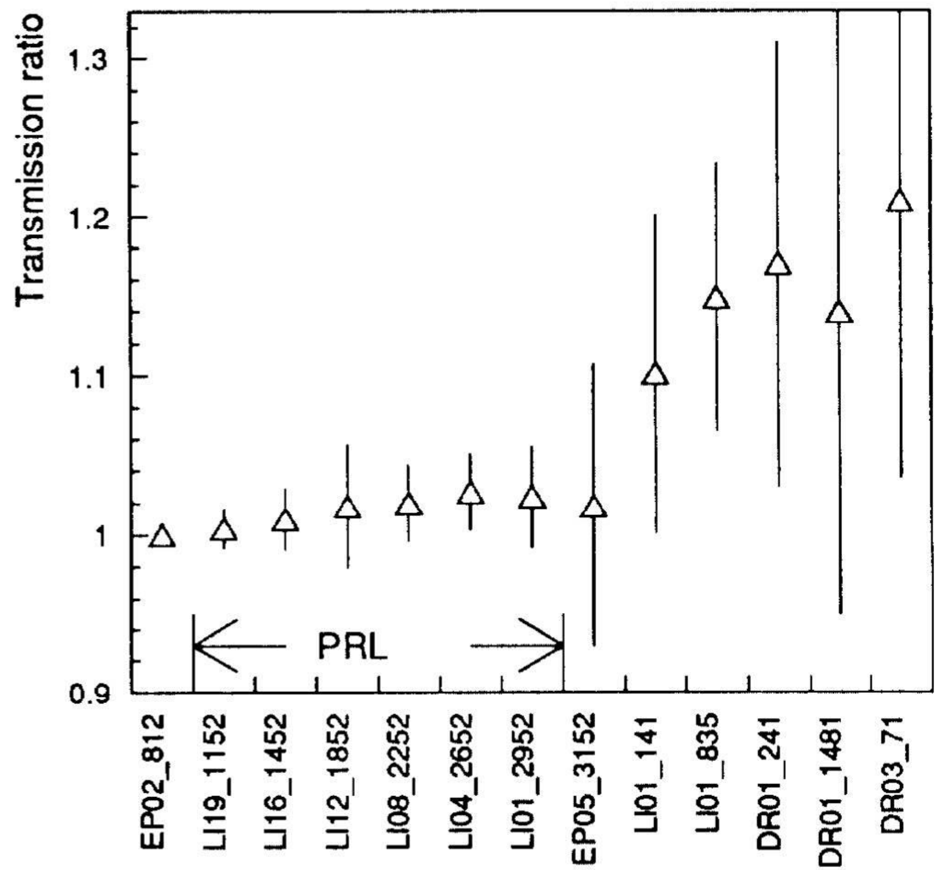
H. Braun et al., PAC91

positron return line (PRL)

2 km long transport line), consisting of **75 FODO cells**, nonlinear field errors (12-pole in quadrupoles), chromatic errors, etc.



PRL acceptance as a function of phase advance per FODO cell

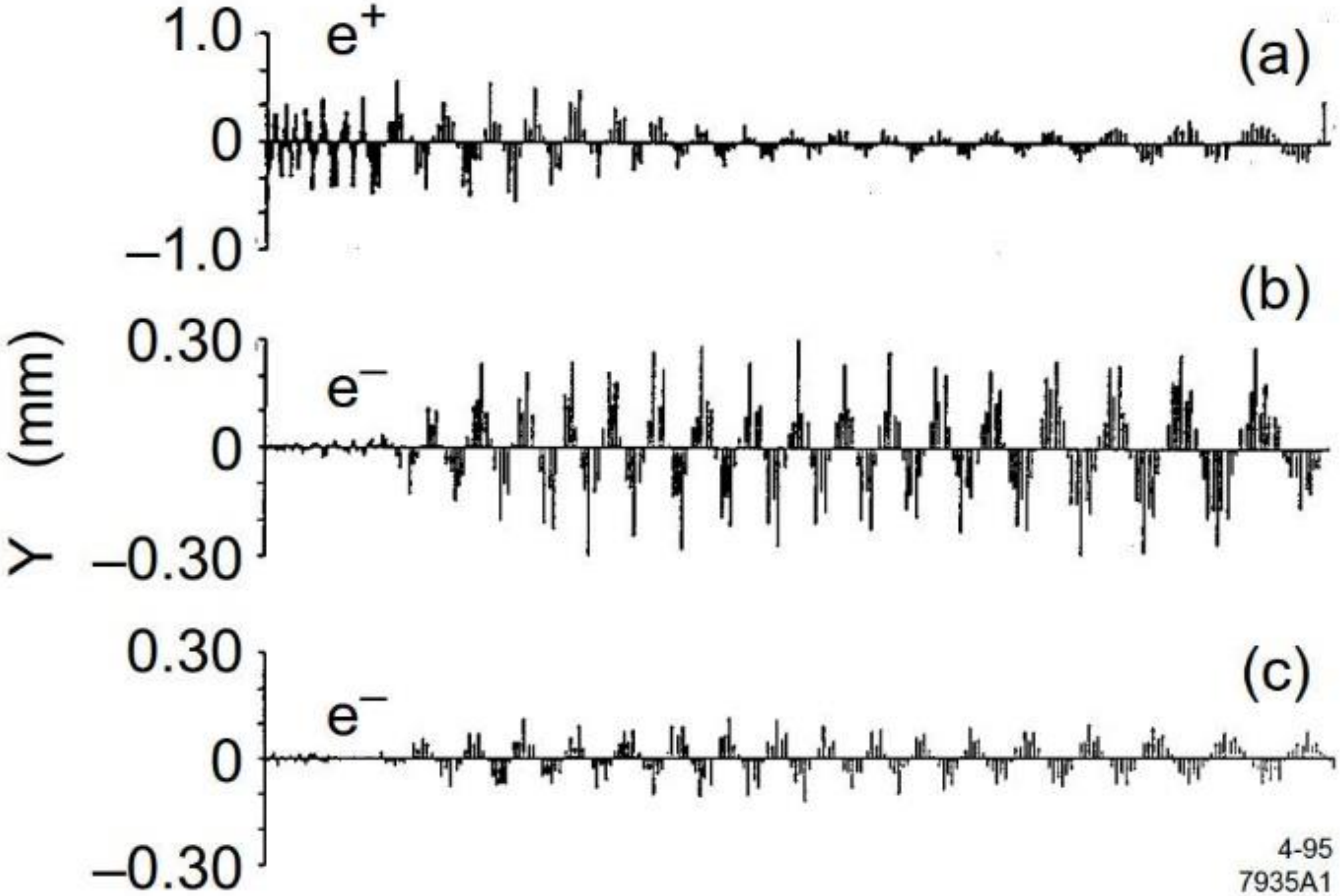


Transmission of the 75' lattice normalized to the transmission of the 90" lattice

phase advance of 90 degree / cell drives resonance

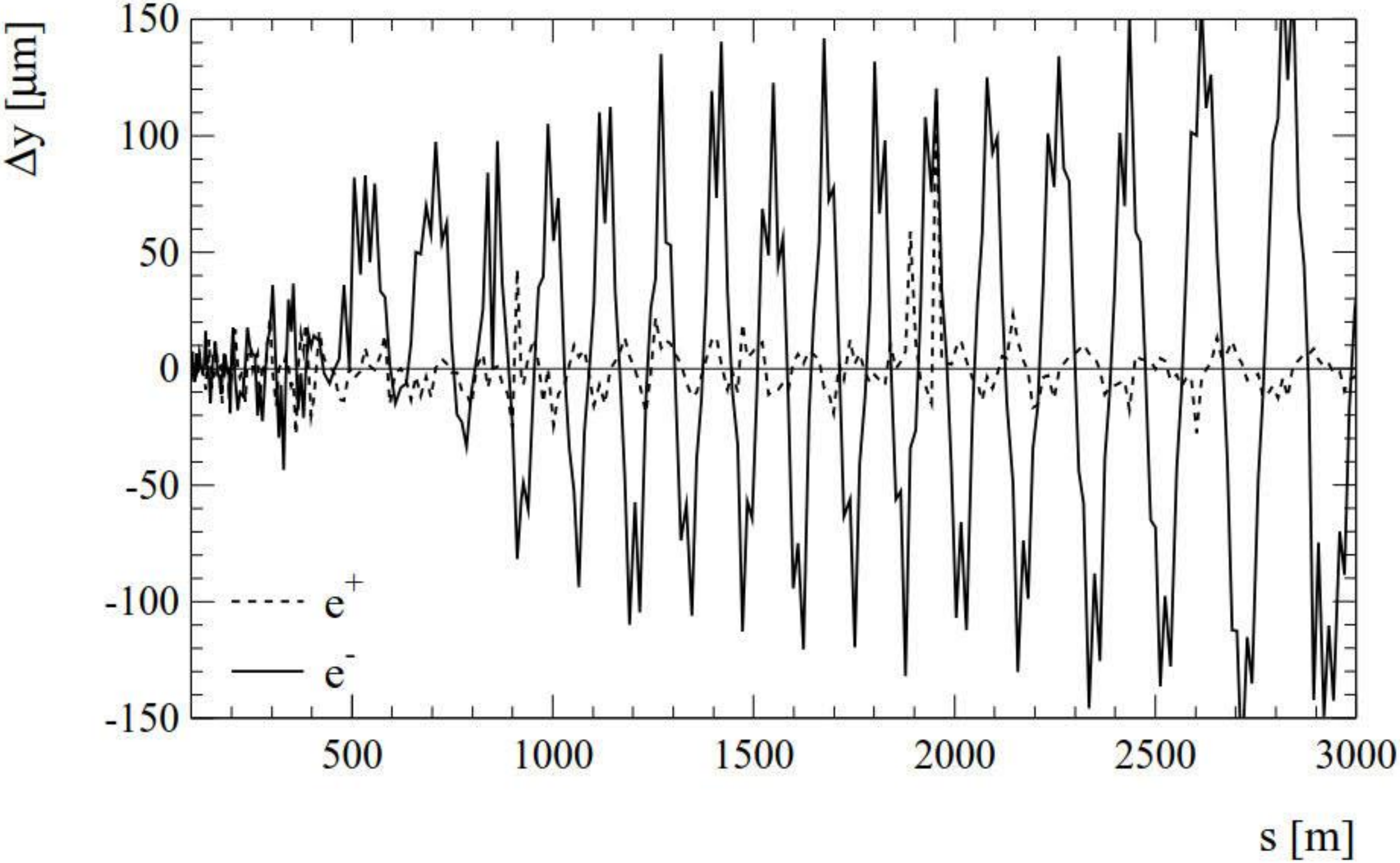
e+ and e- bunches in main linac

C. Adolphsen et al., PAC95



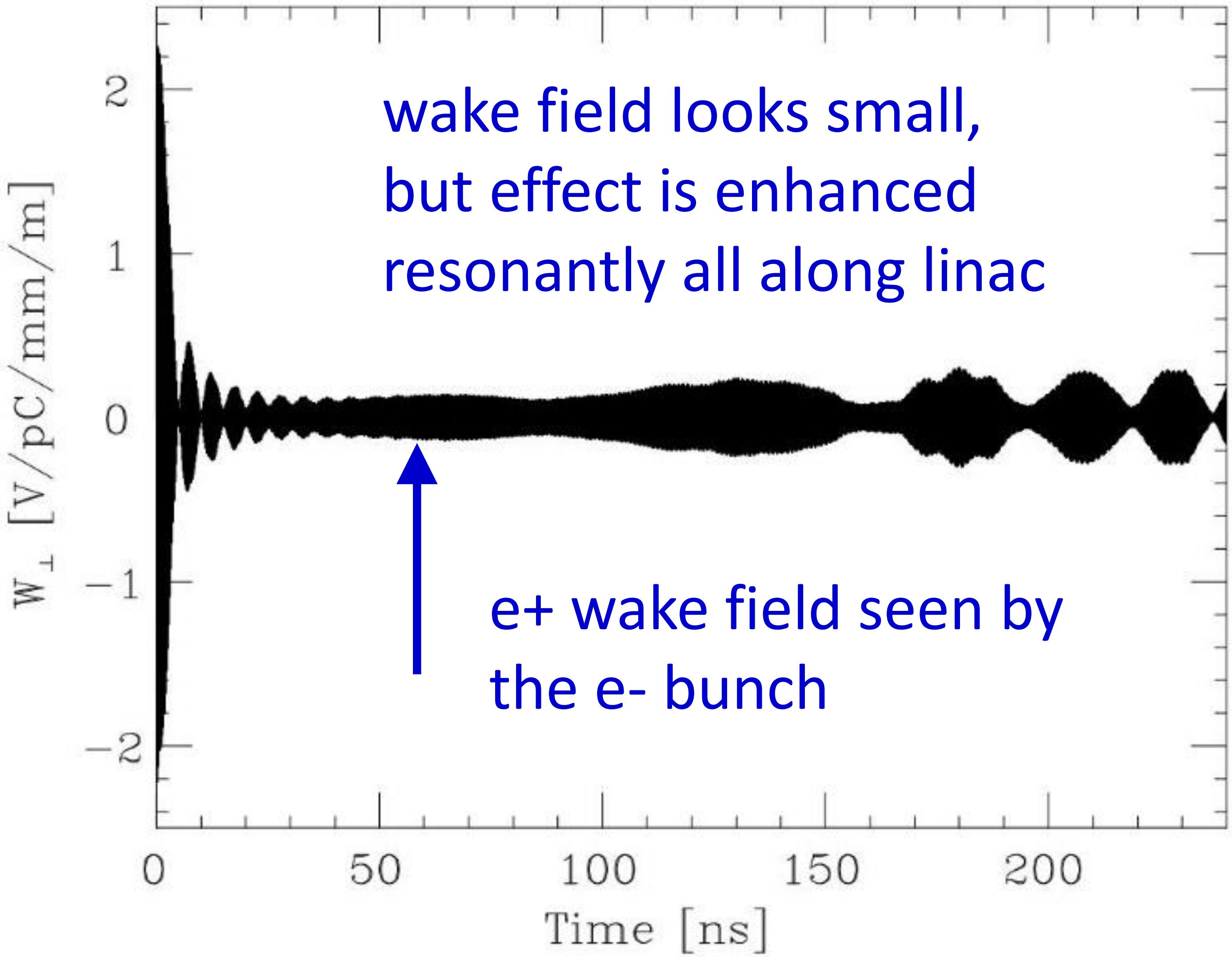
vertical e+ oscillation introduced before the linac (a) and the long range wakefield induced e- oscillation (b) before and (c) after implementation of the split tune lattice

F.-J. Decker et al., LINAC'96



difference orbit in the electron beam by moving the leading positron bunch by one bucket (~0.3 ns) from 59 ns

F.-J. Decker et al., LINAC'96

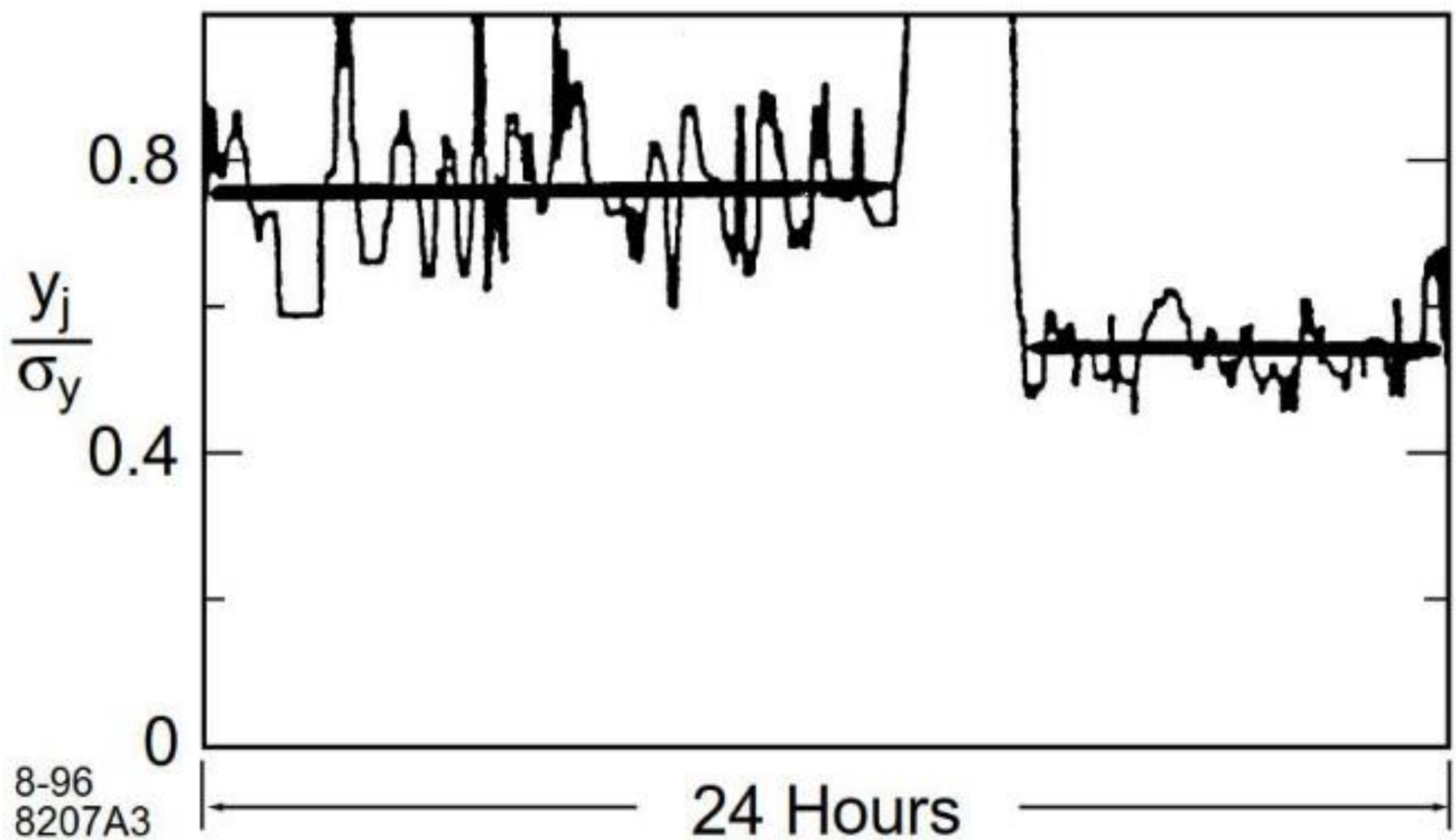


theoretical calculation of the transverse wakefield vs time for the lowest dipole modes of the SLAC structure

F.-J. Decker et al., LINAC'96

solution: split phase advances in x and y

$\Delta\varphi_x^{e-} = \Delta\varphi_y^{e+}$, $\Delta\varphi_y^{e-} = \Delta\varphi_x^{e+}$ but $\Delta\varphi_{x(y)}^{e-} \neq \Delta\varphi_{x(y)}^{e+}$



jitter reduction after the introduction of the split-tune lattice

T. Limberg, P. Emma, R. Rossmanith, 1993

spin-betatron resonance in the SLC North arc

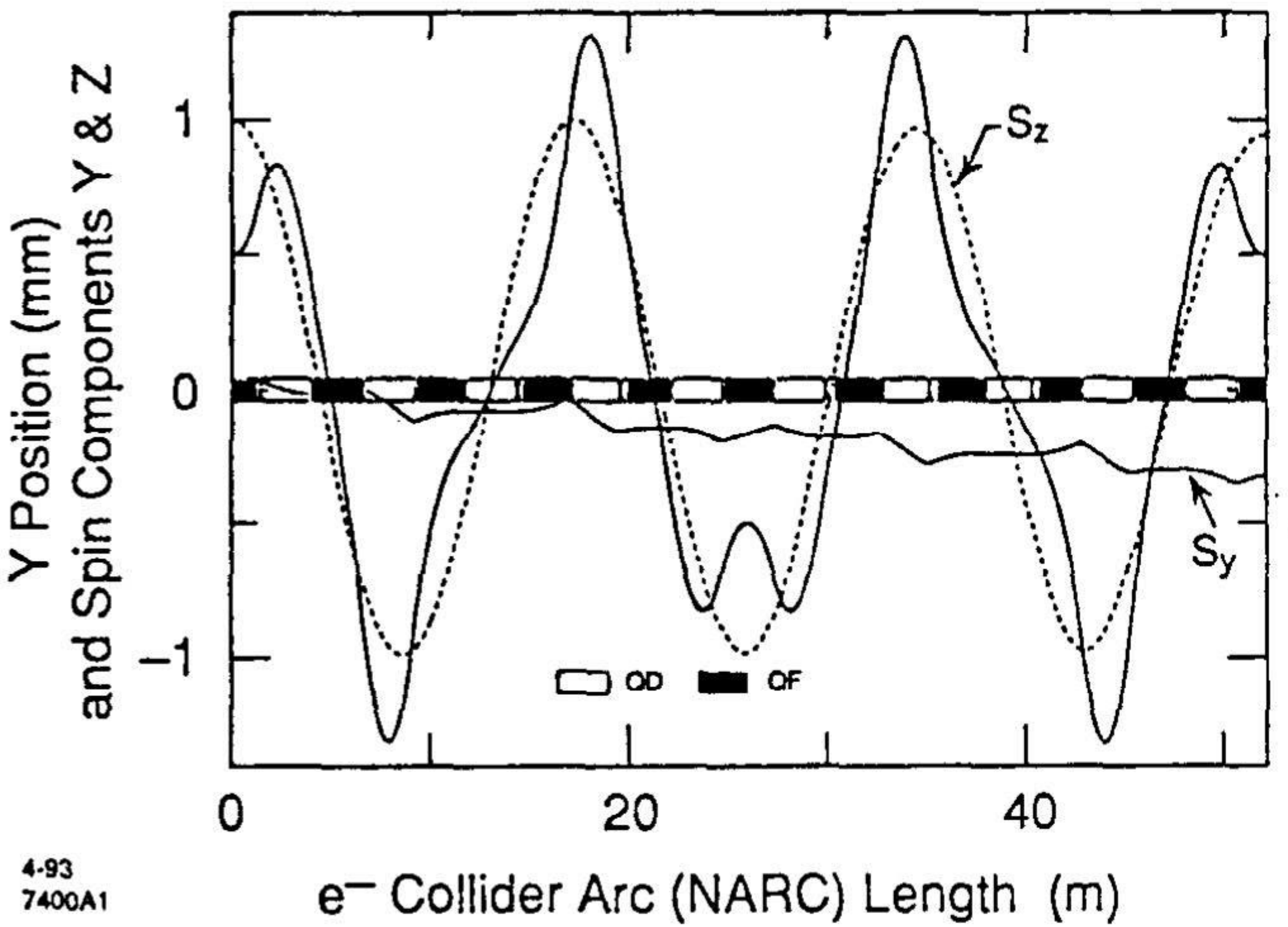
if an electron is deflected in a transverse magnetic field by an angle φ, the spin is rotated around the field axis by

$$\phi = a\gamma\varphi$$

where $a = \frac{\alpha}{2\pi} \approx 0.0011614$ is the anomalous magnetic moment of the electron and γ the Lorentz factor

at beam energy corresponding to peak *Z* boson production (45.60 GeV) spin phase advance $\Delta\phi$ = vertical betatron phase advance (108 deg/cell)

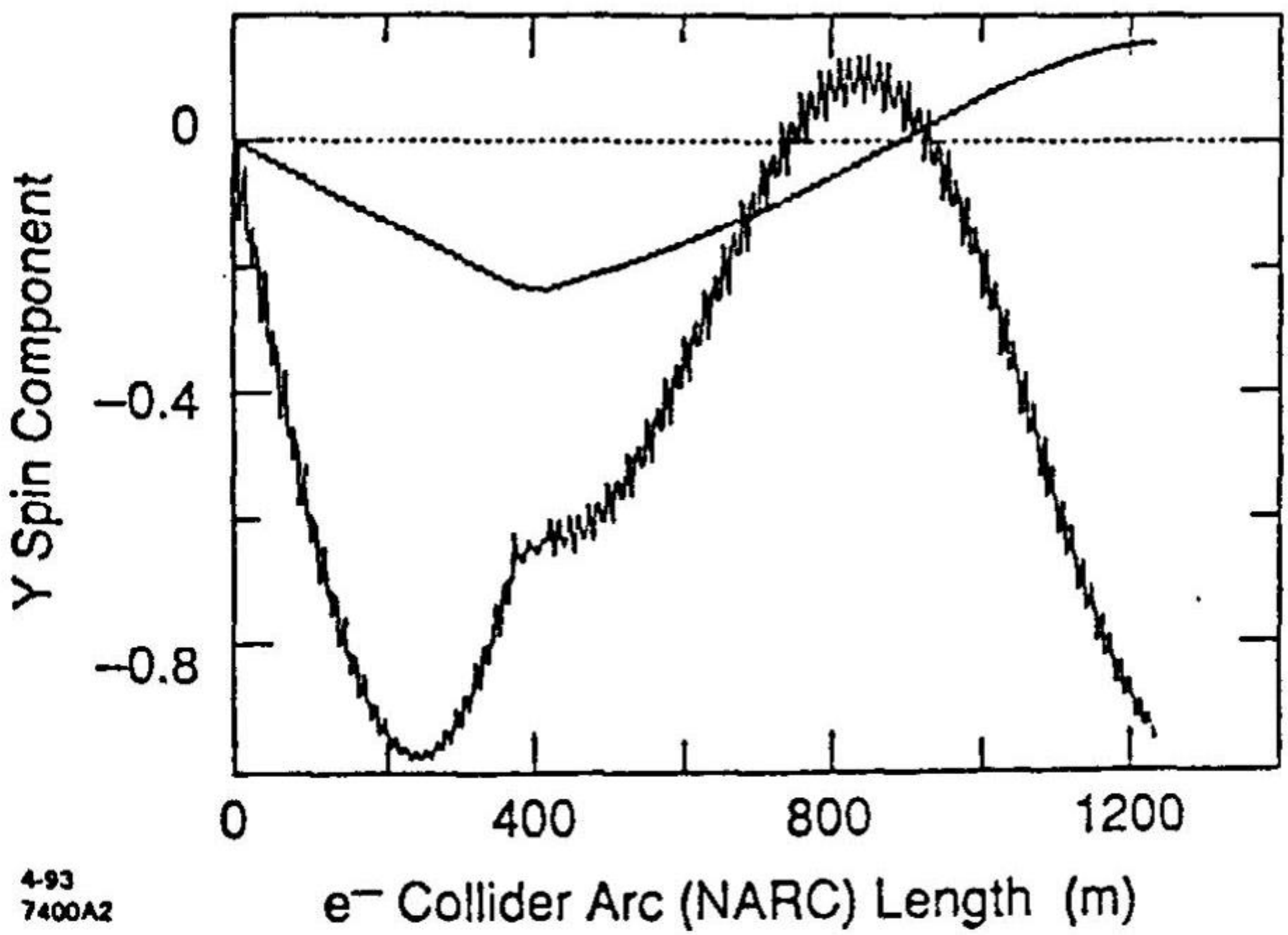
T. Limberg, P. Emma, R. Rossmanith, 1993



vertical orbit and vertical & longitudinal spin components over the first of twenty-three achromatic sections of the arc; the particle is launched with a vertical offset of 0.5 mm, the spin with longitudinal orientation

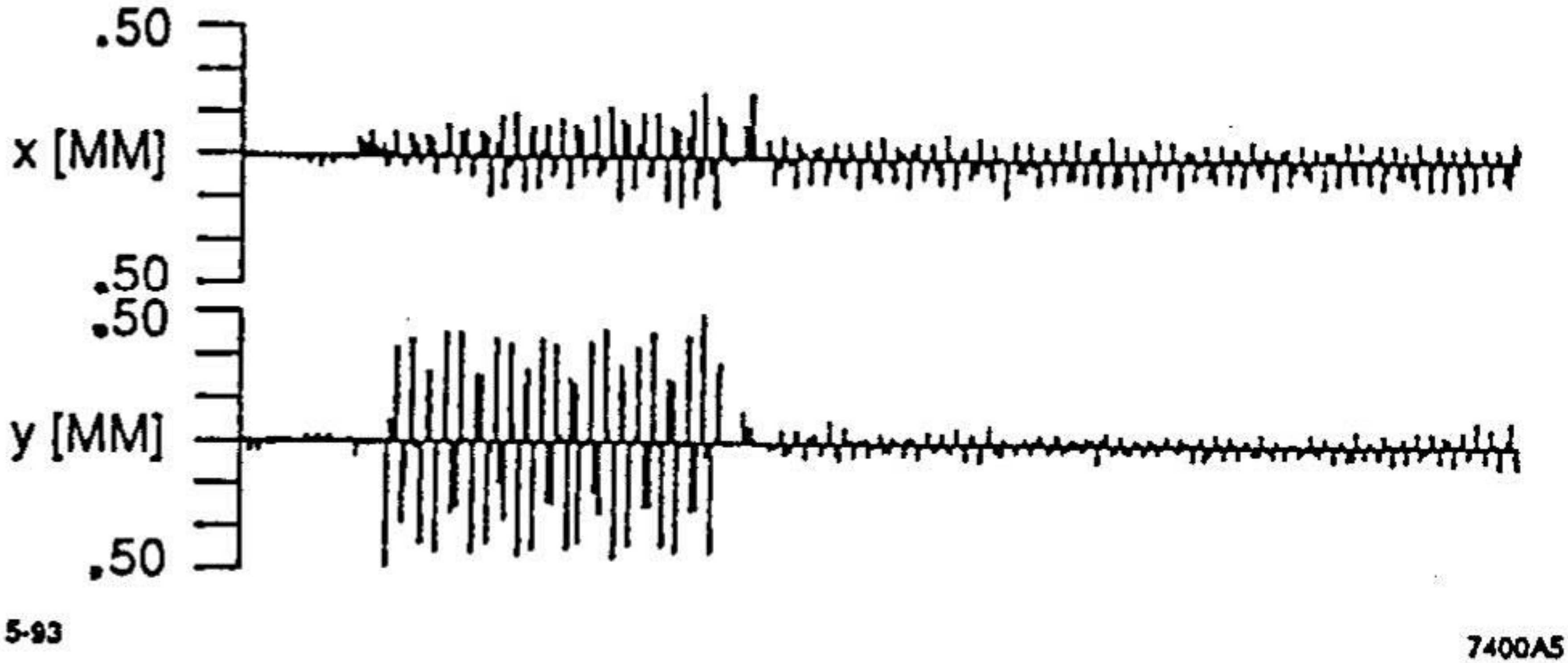
T. Limberg, P. Emma, R. Rossmanith, 1993

vertical spin component over entire arc for particles of 0.5 & 0.05 mm vertical launch offset



T. Limberg, P. Emma, R. Rossmanith, 1993

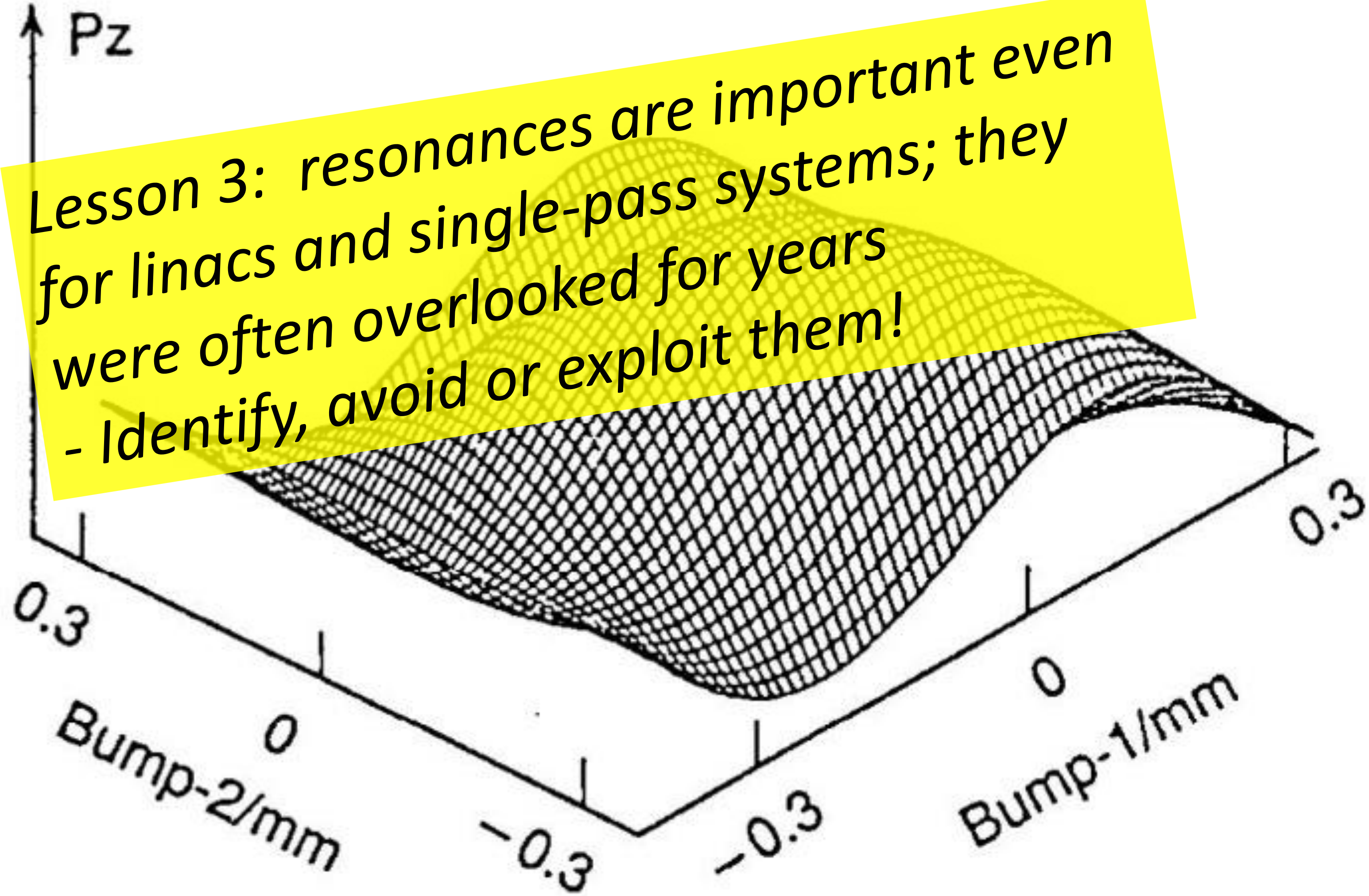
IP polarization controlled with arc spin bumps



difference orbit in the North Arc showing typical spin bump; this bump rotates the spin by 60 degrees. Also note the x-y coupling due to arc rolls

T. Limberg, P. Emma, R. Rossmanith, 1993

Lesson 3: resonances are important even for linacs and single-pass systems; they were often overlooked for years - Identify, avoid or exploit them!

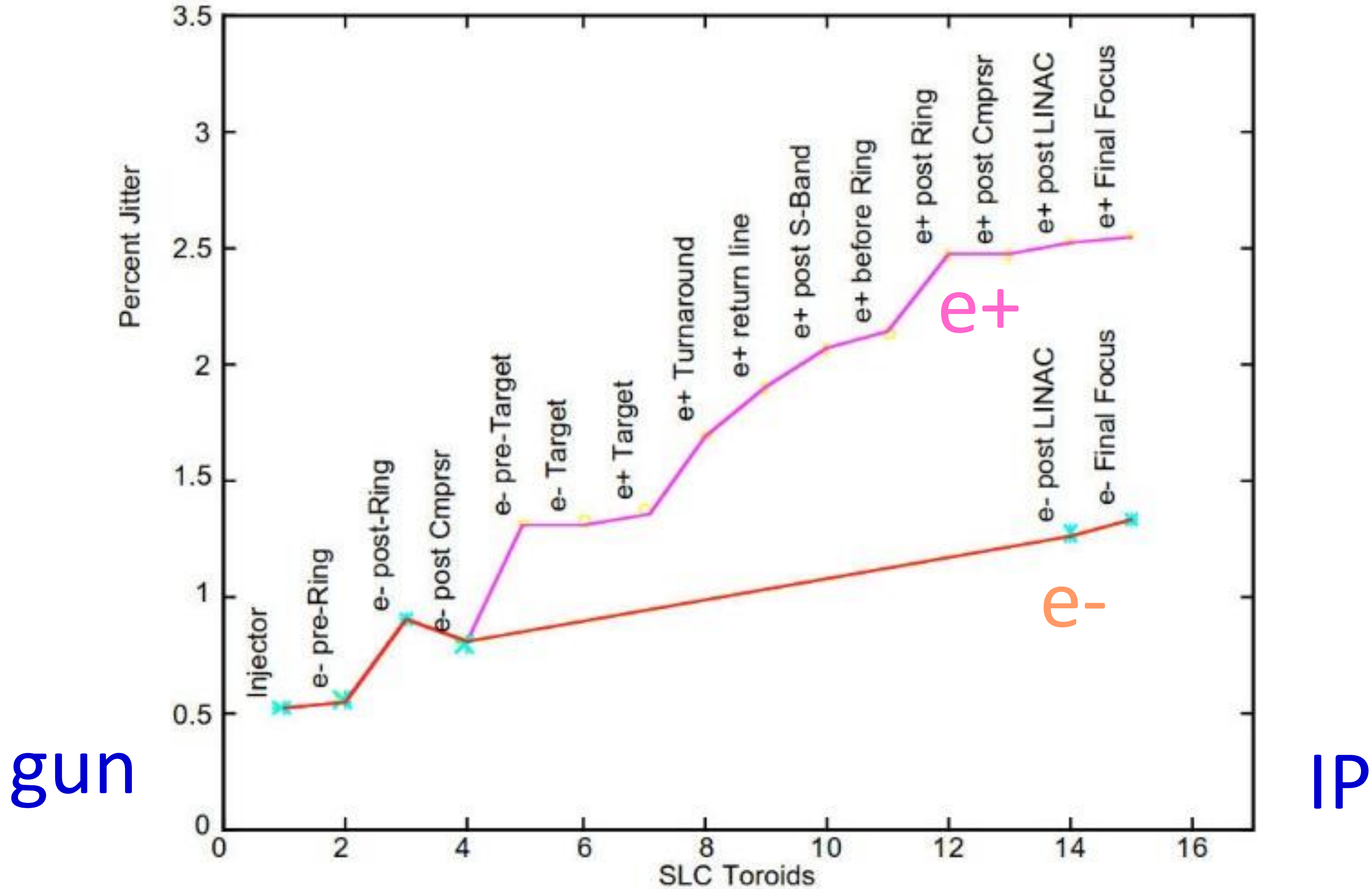


fit to 9-point grid scan with arc polarization bumps

… the SLC jitter wars …

rms intensity jitter (1994)

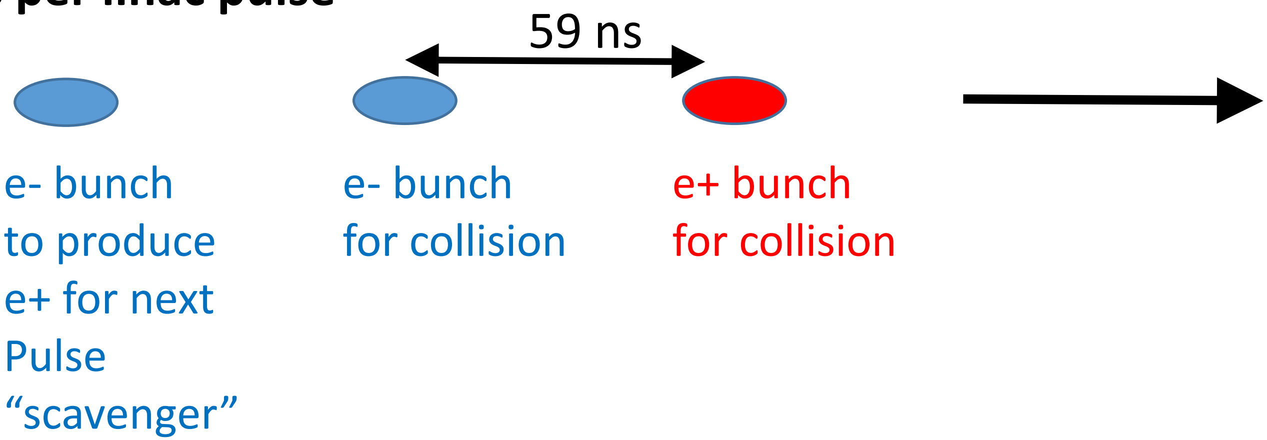
C. Adolphsen et al., PAC95



the value plotted at each toroid is the mean of the rms jitter recorded over the entire 1994 run; **in addition, beam orbit jitter $\Delta y \geq \sigma_y/2$, and also beam size variation of similar size**

e+ production instability

3 bunches per linac pulse



beam loading in the linac: each bunch extracts energy from the RF structures

if N_{e+} too high or too low, the e- bunch(es) will see too low or too high a field and will have the wrong energy at extraction, which will make them lose more particles in the energy-aperture limited line upstream of the e+ production target
→ next e+ bunch will have low(er) intensity

$\Delta N_{e+} = \pm 1\% \rightarrow \Delta E_{e-}/E_{e-} = 3.3 \times 10^{-5} \rightarrow \Delta N_{e+} = -0.2\%$ on next pulse,
quadratic dependence

logistic equation: $x_n = 1 - C x_{n-1}^2$

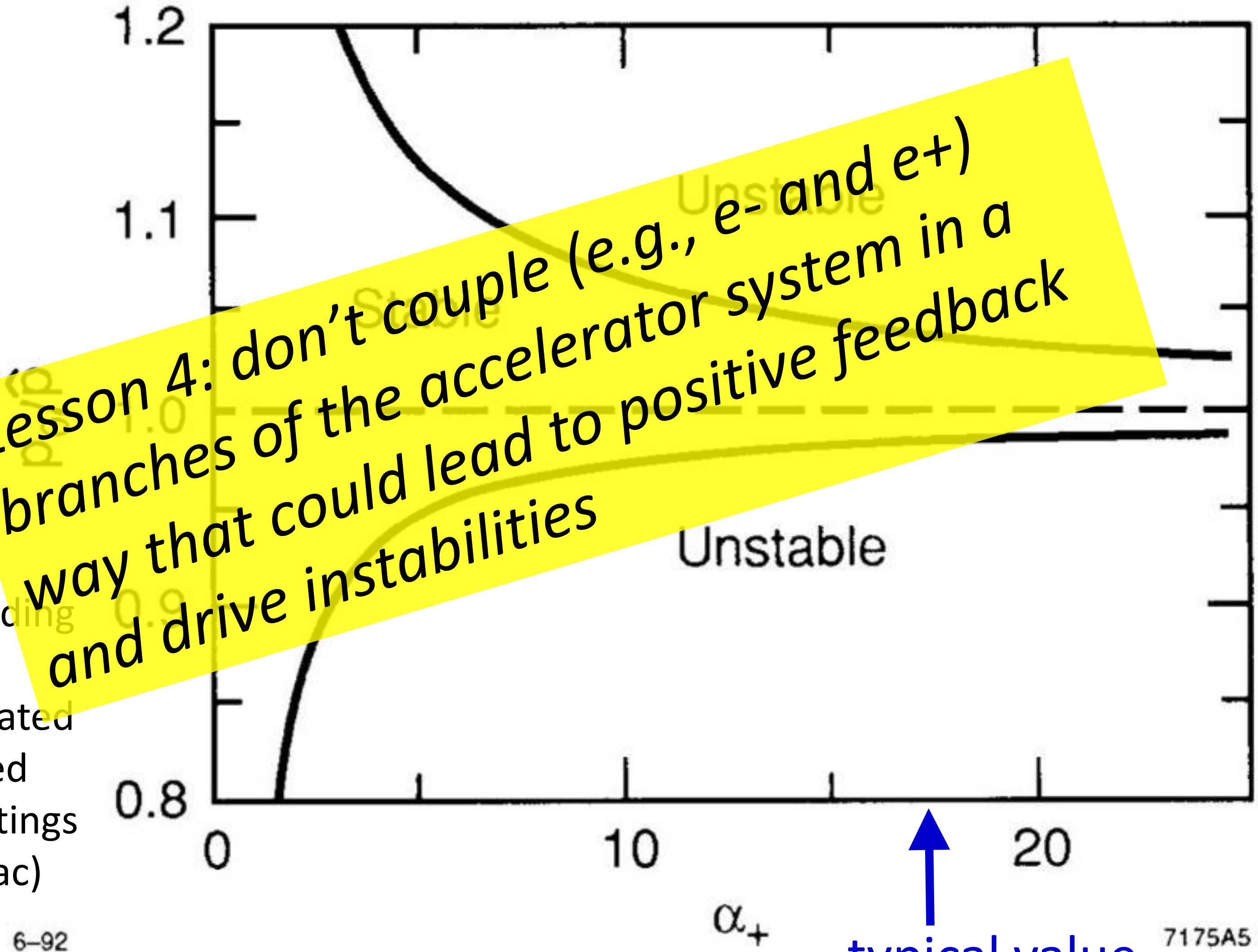
P. Krejcik, V. Ziemann, SLAC-PUB-5725

e+ production – local stability analysis

actual
e+ bunch
charge

over

bunch
charge
for which
beam loading
is
compensated
(controlled
by RF settings
in the linac)

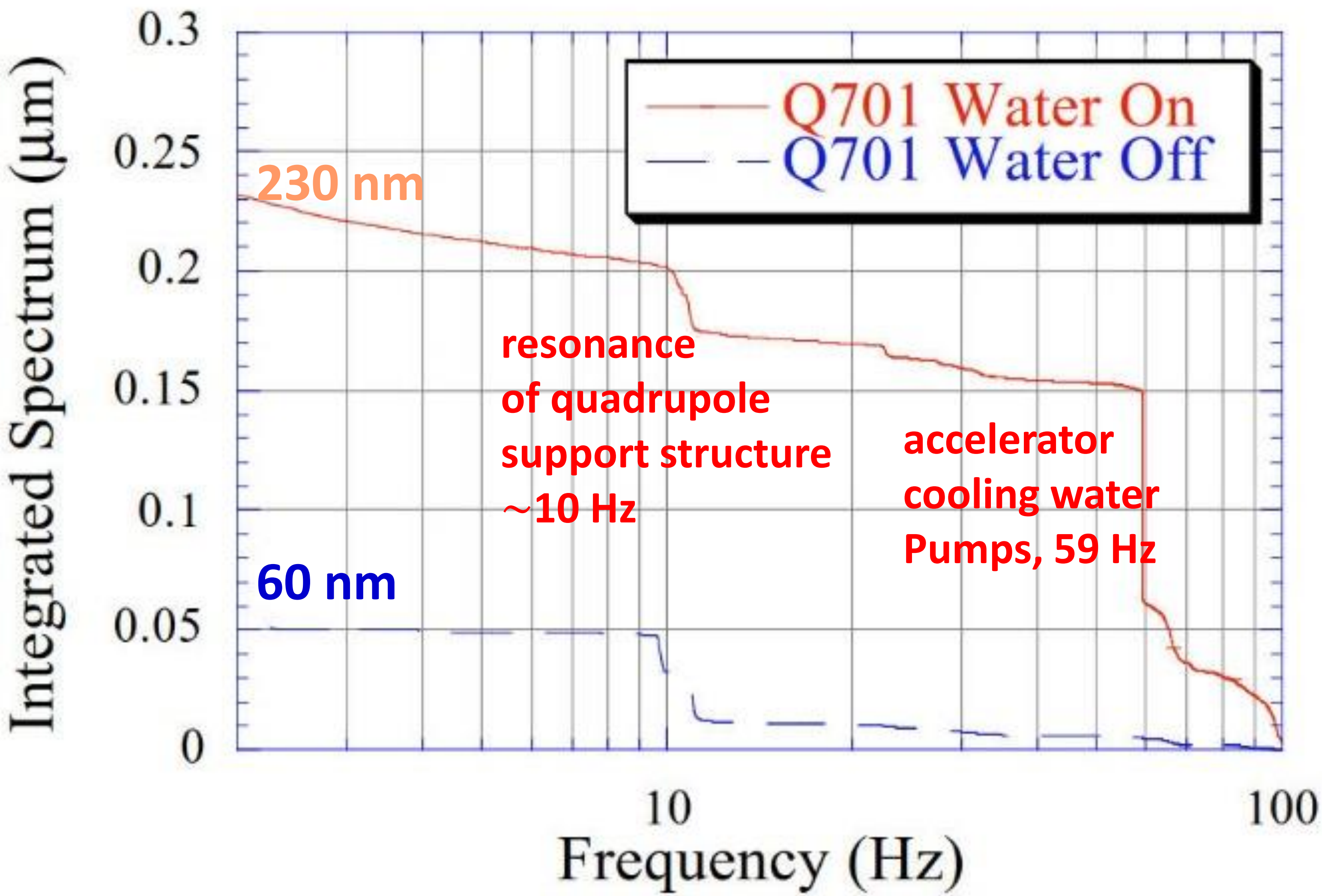


Lesson 4: don't couple (e.g., e- and e+) branches of the accelerator system in a way that could lead to positive feedback and drive instabilities

typical value for SLC

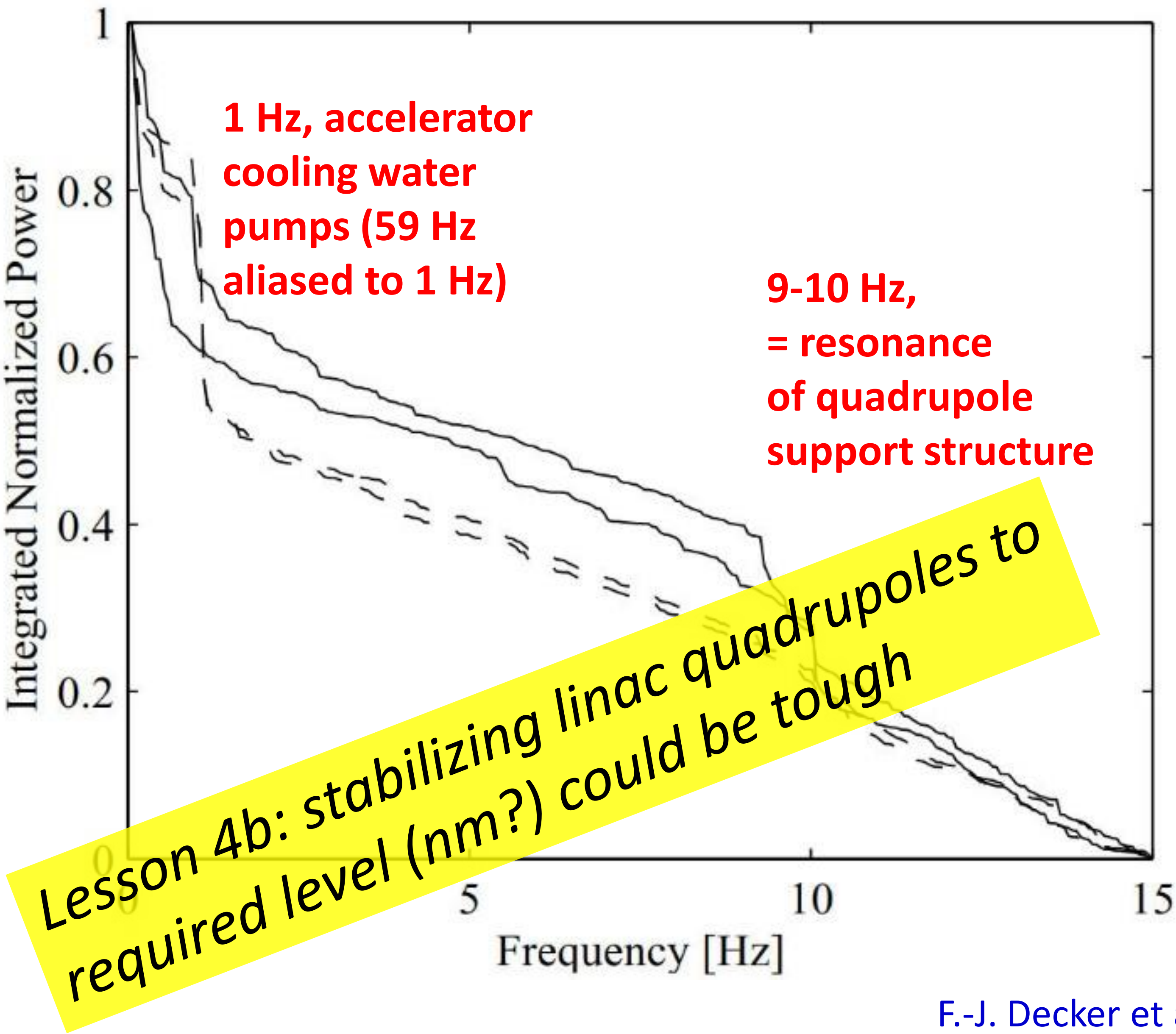
P. Krejcik, V. Ziemann, SLAC-PUB-5725

linac quadrupole vibration



J.L. Turner et al, PAC'95

power spectrum of linac beam orbit jitter

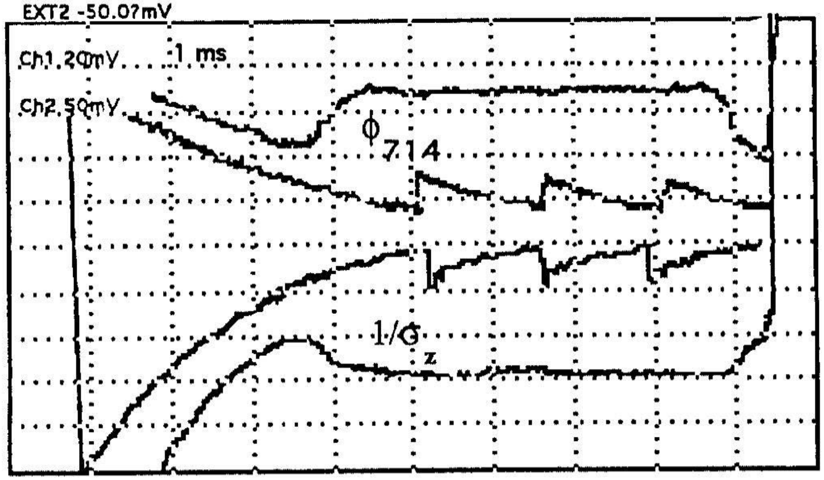


F.-J. Decker et al, LINAC'98

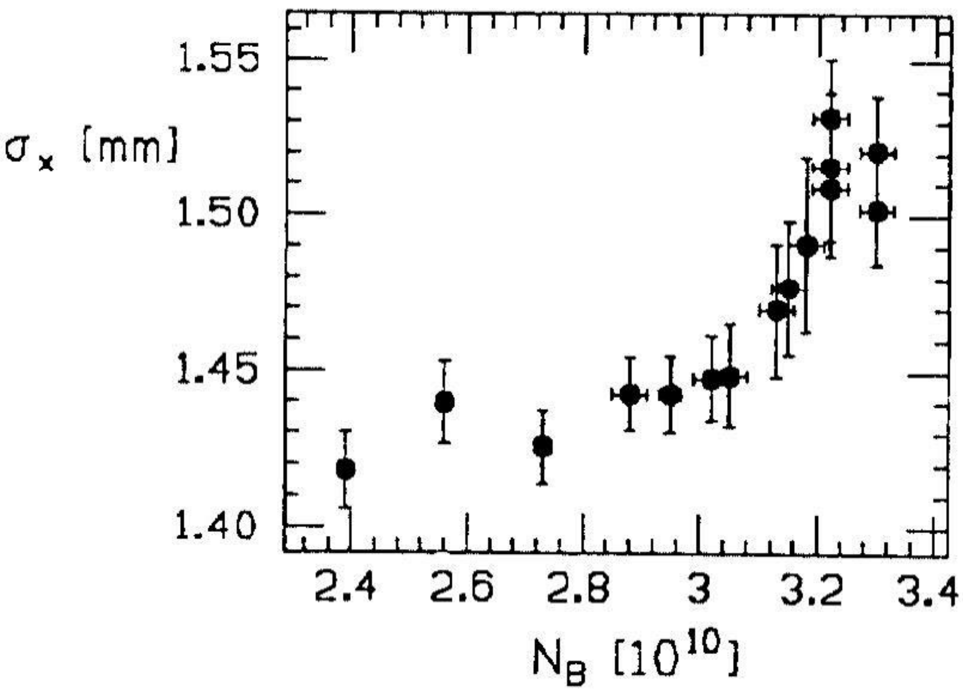
one *amplifier of jitter* was the linac wake field (already seen); one *random source* was the longitudinal microwave instability “sawtooth instability”) in the damping ring

P. Krejcik et al., PAC95

1993 data



inverse bunch length and beam phase signals exhibit sawtooth behavior during the instability



energy spread (σ_x at $D \neq 0$) shows instability onset at N_{th} ~3×10^{10}

K. Bane et al., PAC95

SLC DR vacuum chamber upgrade 1994

Table 1. Vacuum Chamber Inductance (nH)

Element	**Old Chamber** †	**New Chamber***
Synch. Radiation Masks	9.5	----
Bellows	----	1.1
Quadrupole to Dipole Chamber Transitions	9.3	2.4
Ion Pump Slots	0.2	0.05
Kicker Magnet Bellows	4.1	----
Flex Joints	3.6	----
Beam Position Monitors	3.5	0.2
Other	2.4	2.4
TOTAL	33 →	6

traditional wisdom

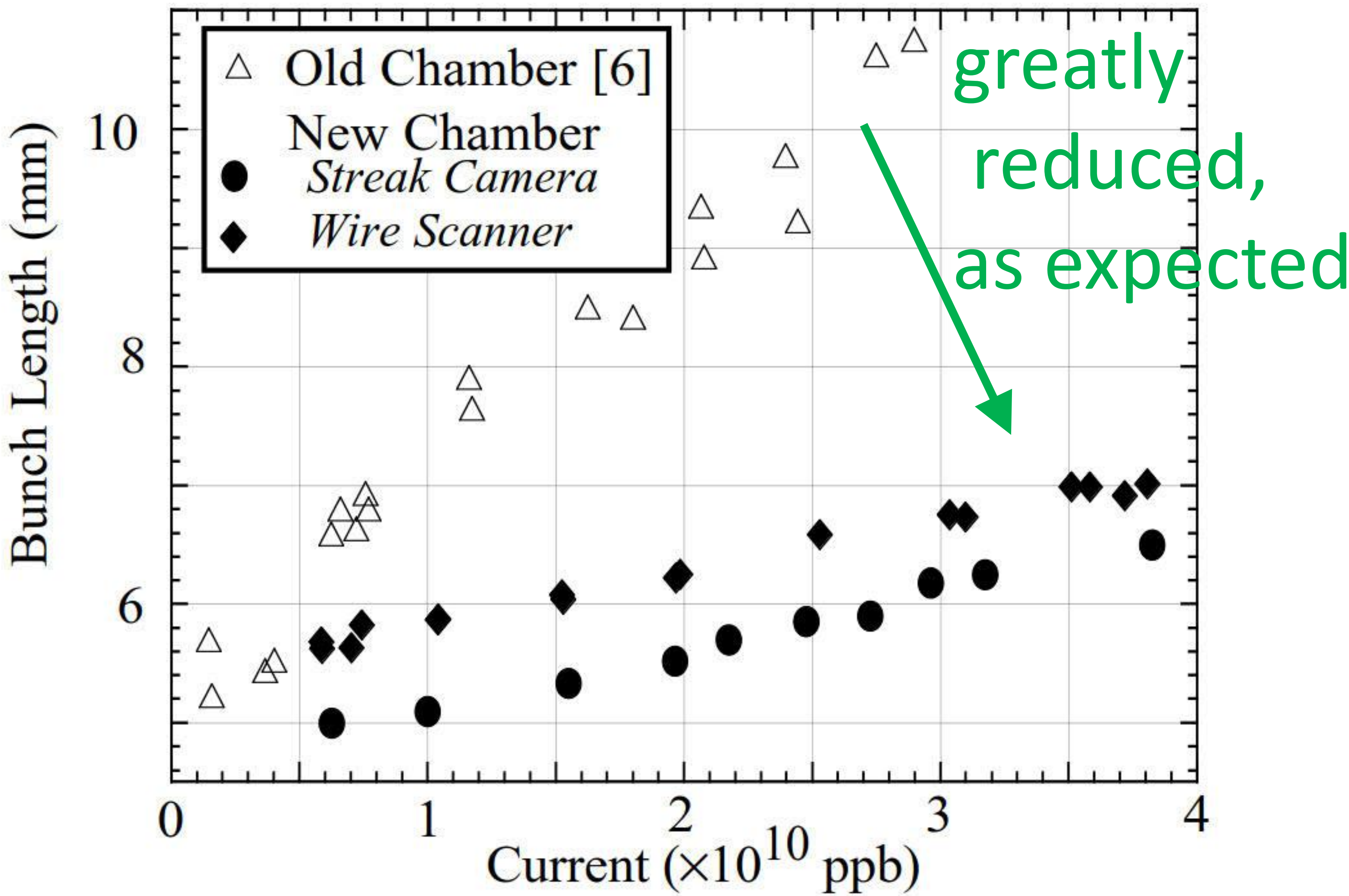
$N_{th} \propto 1/Z$

† From ref 1. Bellows included in Table 1 of [1] were shielded in a previous upgrade. Changes to that table from recent calculations are included here.

* Many of the impedance calculations are in ref 2.

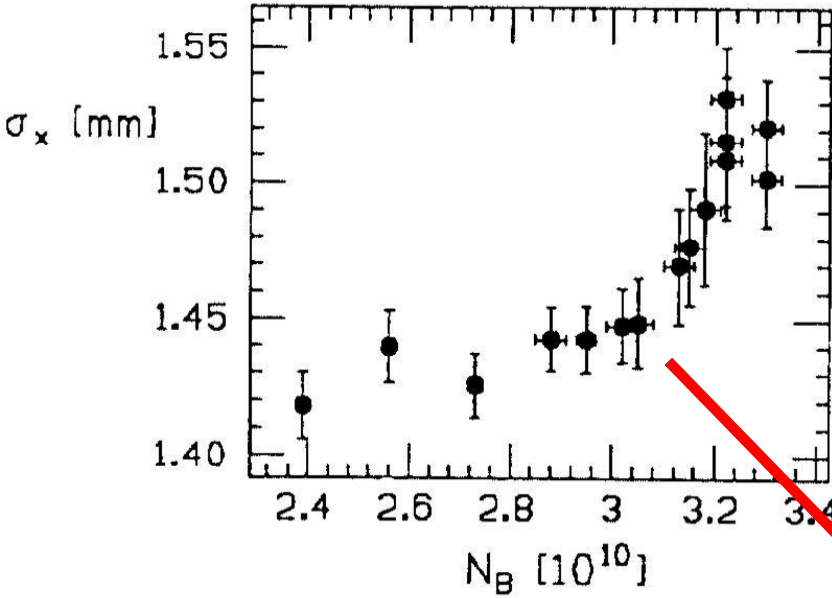
K. Bane et al., PAC95

bunch length dependence on current



K. Bane et al., PAC95

threshold of sawtooth instability



1993 old chamber

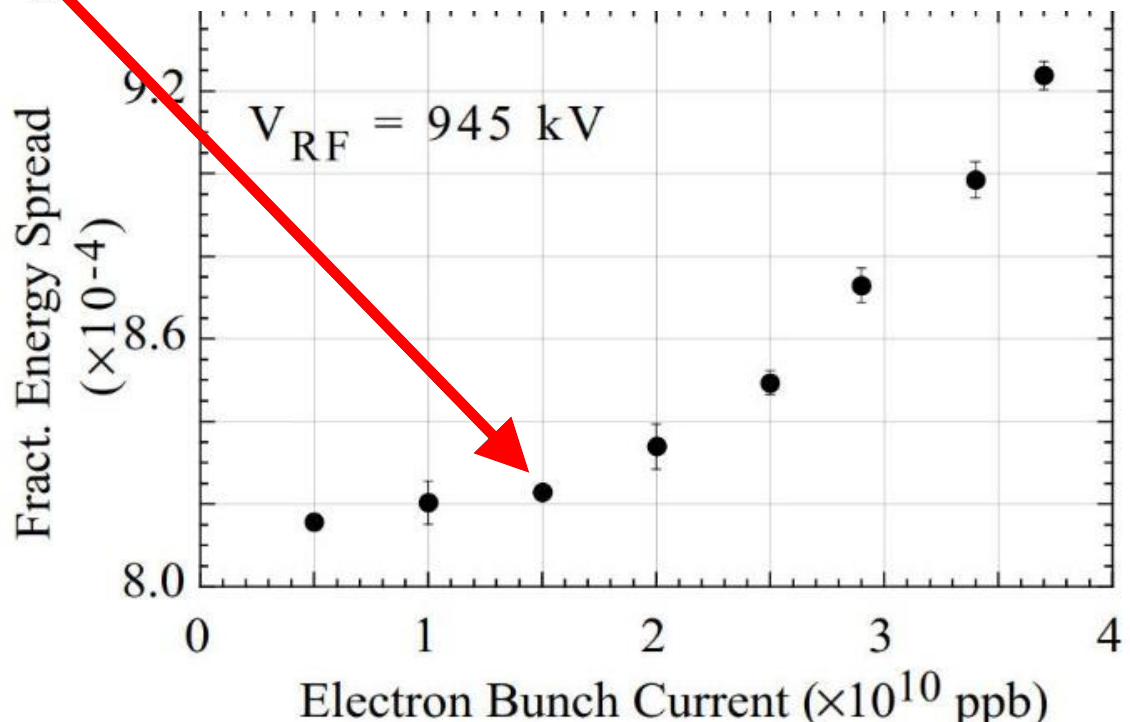
N_{th} ~3x10^{10}

threshold reduced!

by ~1/2, not expected!?

1994 new chamber

N_{th} ~1.5x10^{10}



K. Oide's theory had actually predicted that instability threshold decreases if ratio ReZ/ImZ increases!

formalism

KEK Preprint 90- 10
April 1990
A

Longitudinal Single-Bunch Instability in Electron Storage Rings

Katsunobu Oide

and

Kaoru Yokoya

KEK, National Laboratory for High Energy Physics
Oho, Tsukuba, Ibaraki 305, Japan

ABSTRACT

A new method was investigated to obtain the threshold intensity of the longitudinal single-bunch instability of an electron beam in a storage ring. The deformation of the equilibrium distribution in a bunch due to the wakefield induced by itself is included in this method. The results becomes significantly different from those without the deformation, and are confirmed by a multi-particle tracking simulation.

PACS numbers: 29.20.Dh, [illegible].10.+t, 41.80.Ee

* *Submitted to Phys. Rev. Lett.*

prediction

KEK Preprint 94-138
November 1994
A

A Mechanism of Longitudinal Single-Bunch Instability in Storage Rings

Katsunobu Oide

KEK, National Laboratory for High Energy Physics
Oho, Tsukuba, Ibaraki 305, Japan

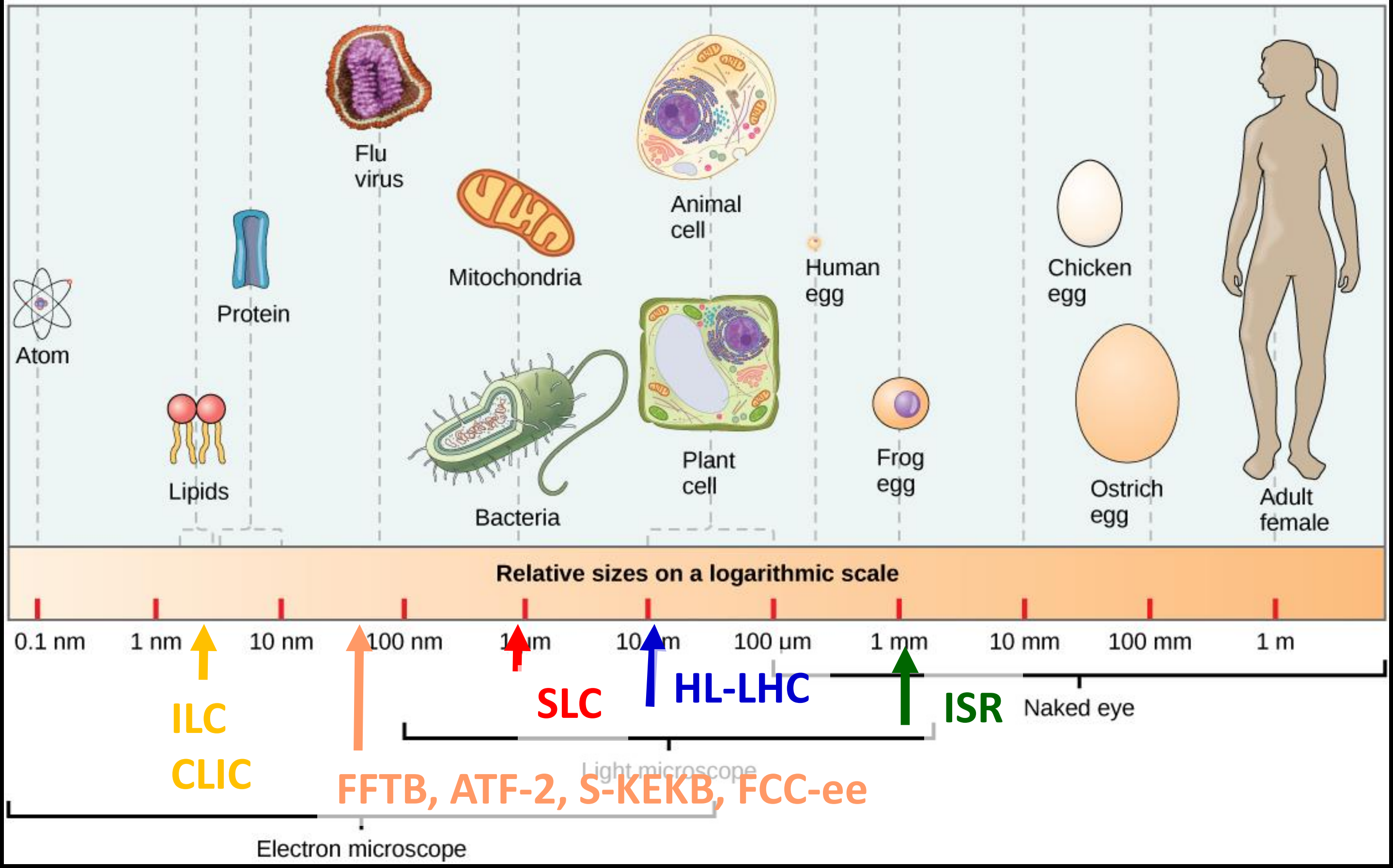
ABSTRACT

A new type of longitudinal single-bunch instability in storage rings is found. This instability is resulted from an interaction of two coherent synchrotron motions with different amplitudes. The frequency spread of incoherent synchrotron motion in a bunch generated by the potential-well distortion plays an essential role in this instability. The system becomes unstable when synchrotron frequencies of two different amplitudes degenerate. In an extreme case with the pure-resistive (δ-function) wake potential, it is shown that the system is always unstable, *i.e.*, the threshold intensity is zero.

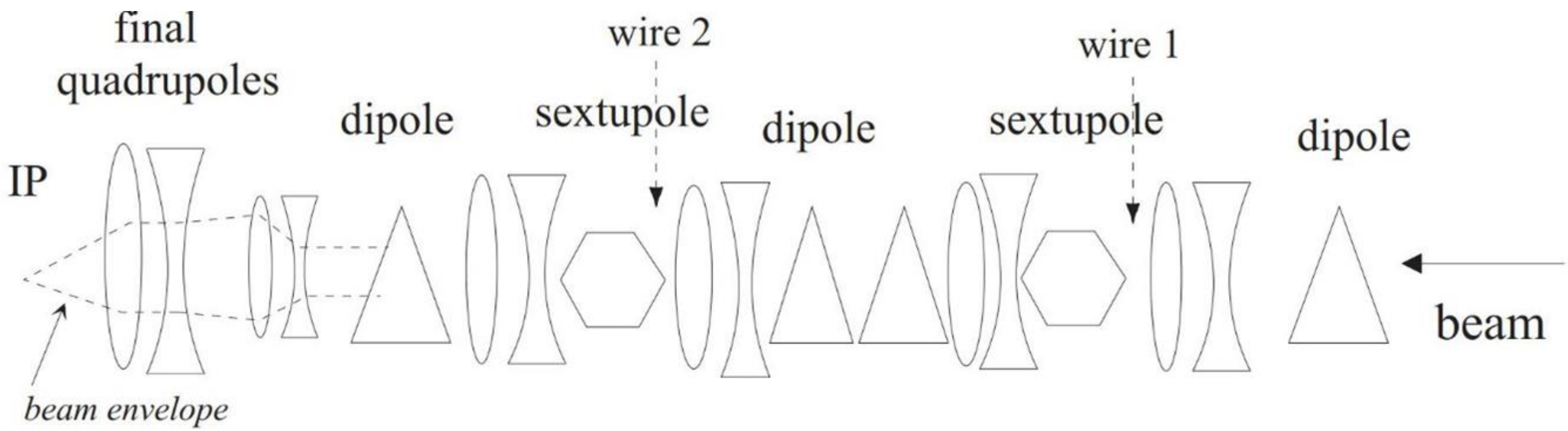
Submitted to Particle Accelerators.

Lesson 5: cross-check, simulate, and prepare for the unexpected

… and the nanobeam challenge



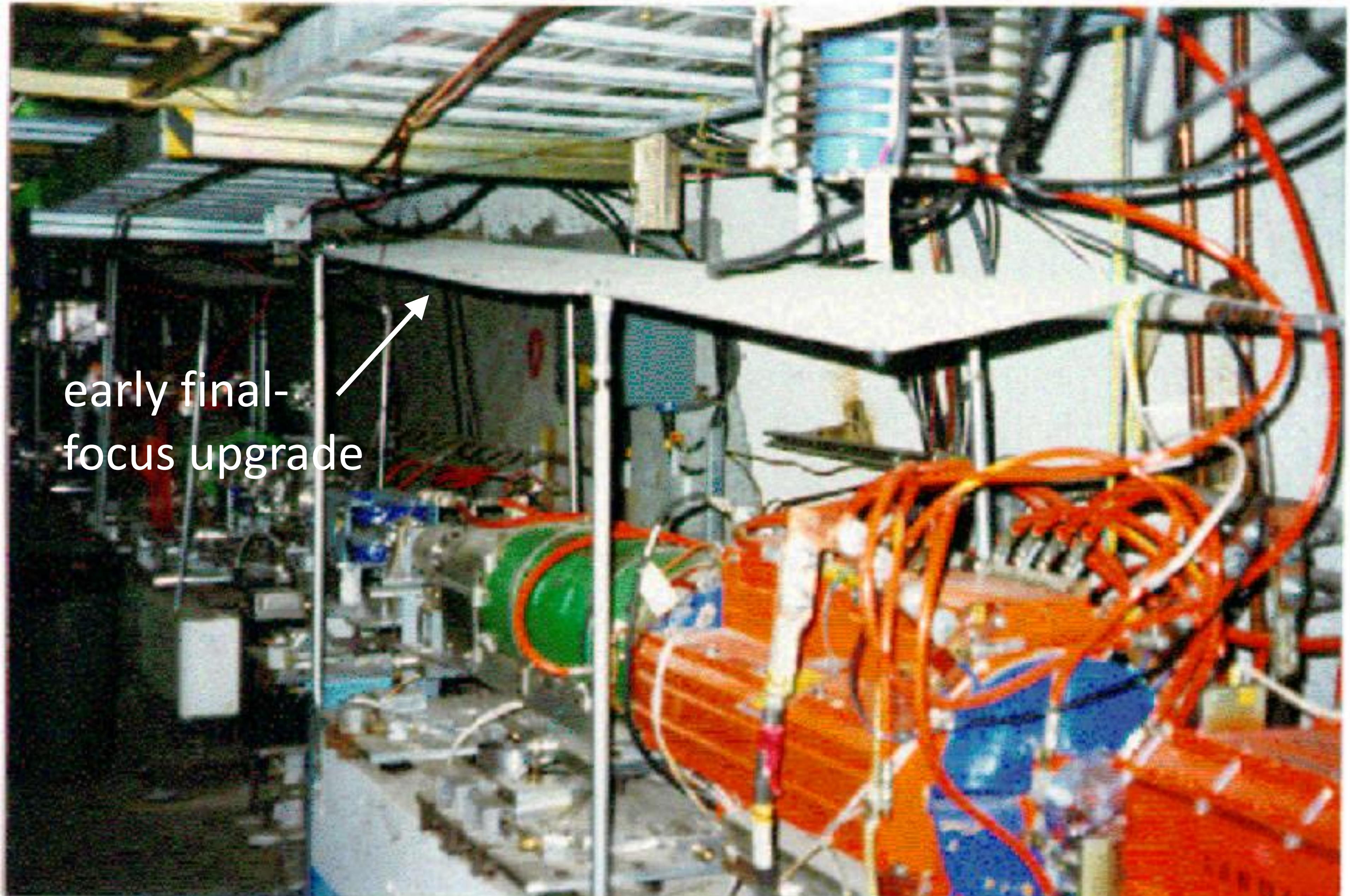
schematic of final focus system



IP

final triplet

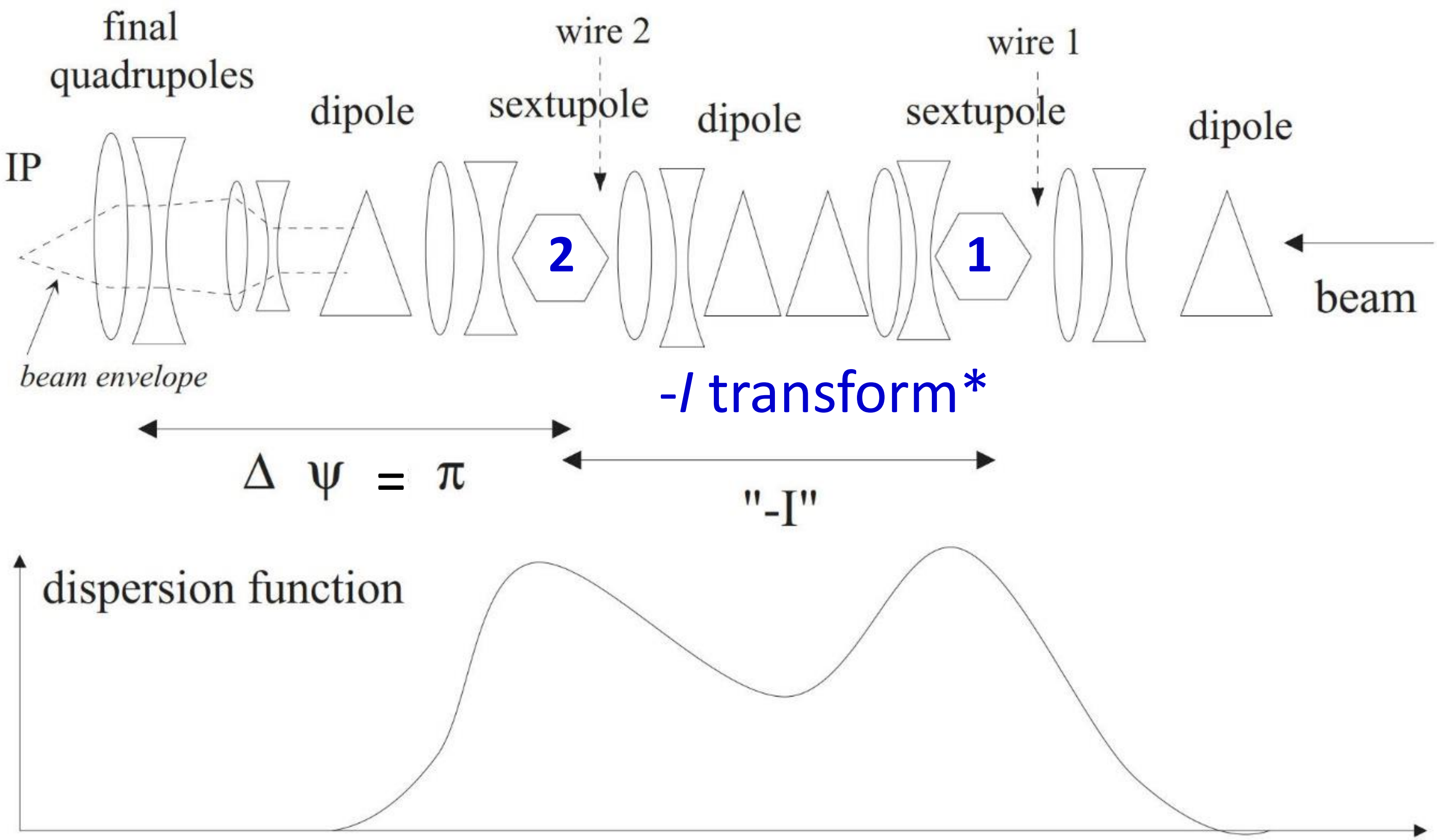
dipoles,
quadrupoles,
sextupoles, …



photograph of the SLC final focus, ~1996

Paul Emma and Olivier Napoly inspecting the spare superconducting final triplet of the SLC, in the SLD collider hall, 1996

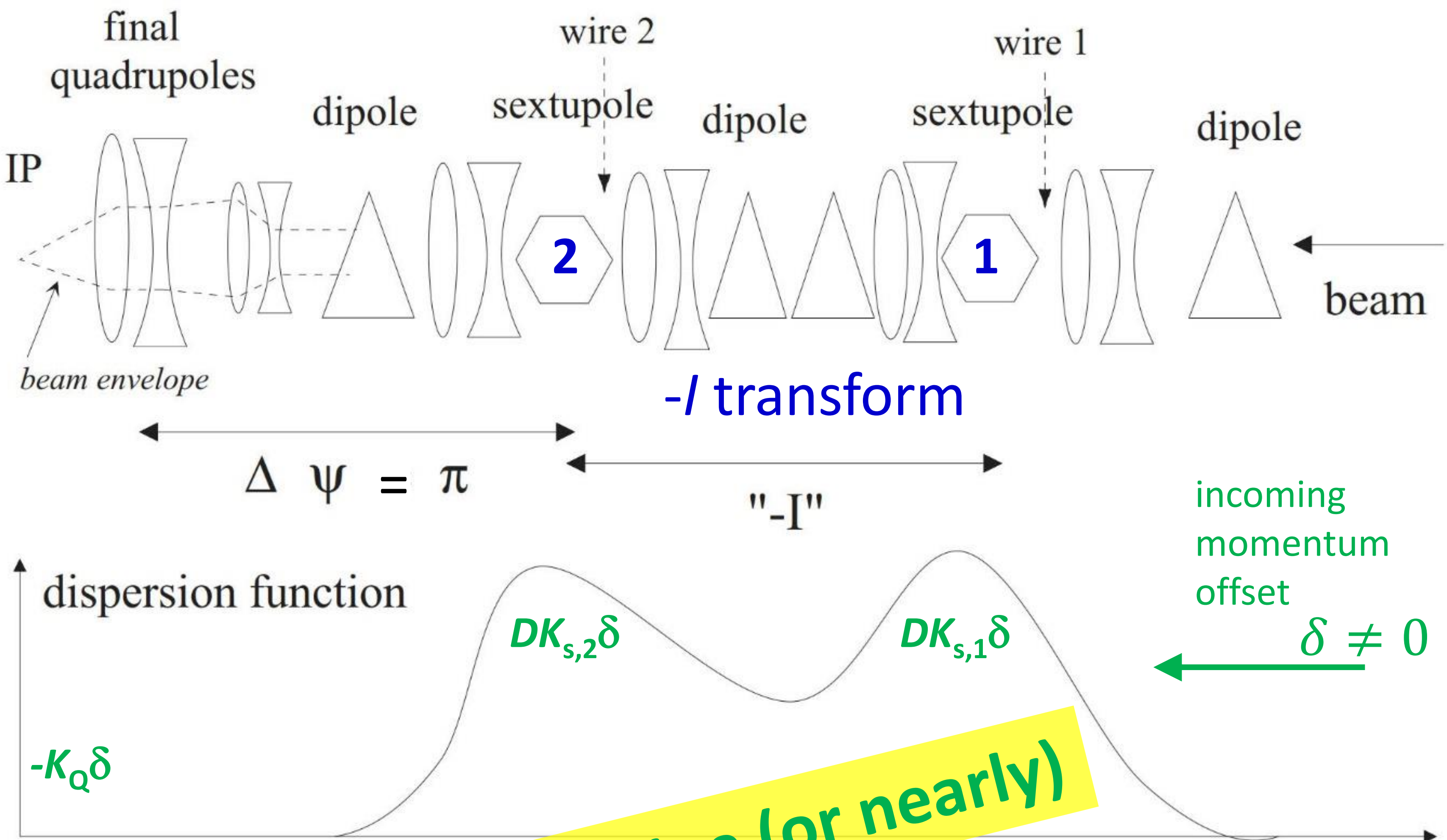
schematic final focus system



$$x_2' = -x_\beta' - \frac{1}{2}K_{s,1}(x_\beta^2 + 2x_\beta D_i\delta + D_i^2\delta^2) + \frac{1}{2}K_{s,2}(x_\beta^2 - 2x_\beta D_i\delta + D_i^2\delta^2)$$

*patented by K. Brown

chromatic correction

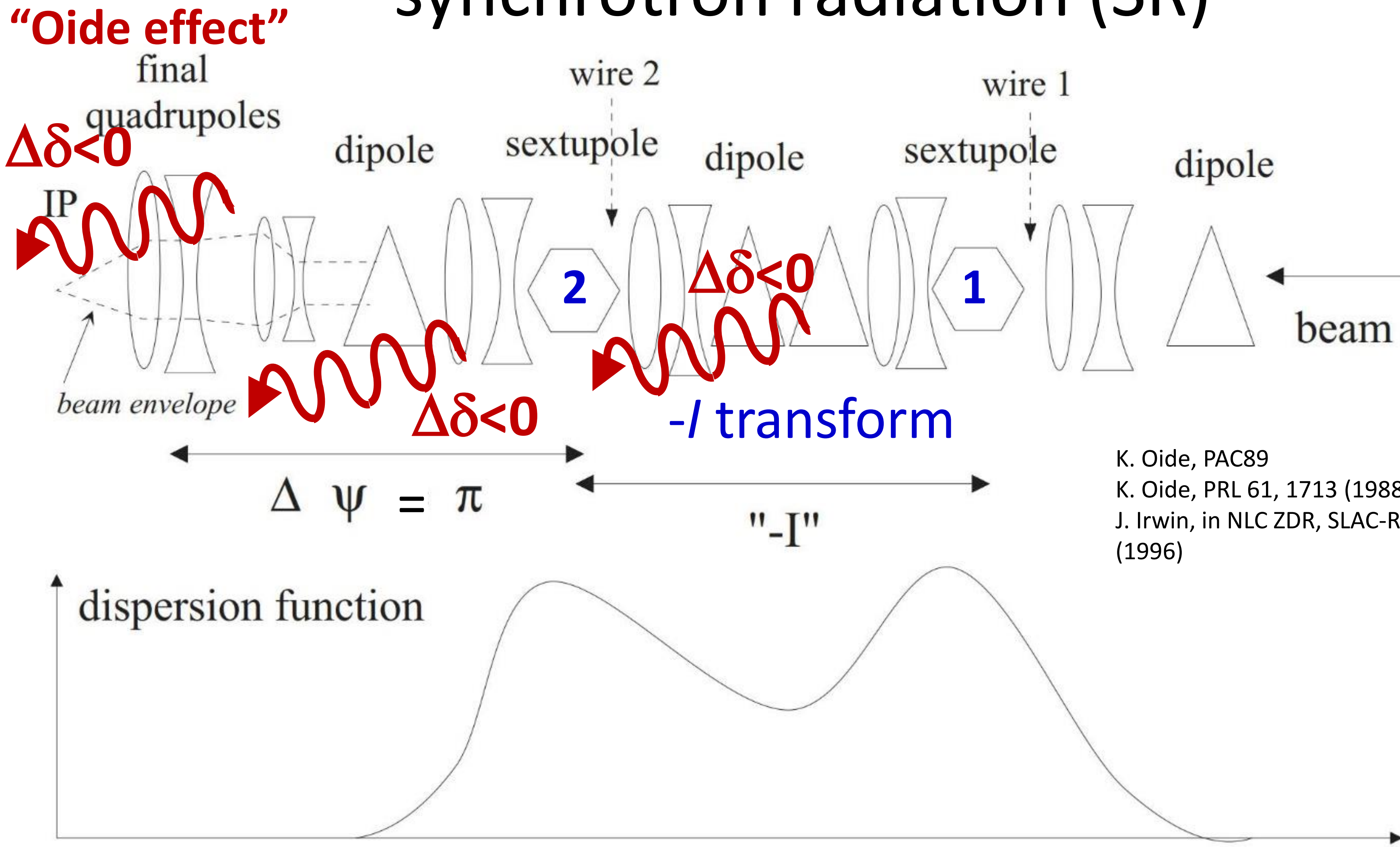


everything fine (or nearly)

$$x_2' = -x_\beta' - \frac{1}{2}K_{s,1}(x_\beta^2 + 2x_\beta D_i\delta + D_i^2\delta^2) + \frac{1}{2}K_{s,2}(x_\beta^2 - 2x_\beta D_i\delta + D_i^2\delta^2)$$

$K_{s,1}=K_{s,2}$: $$x_2' = -x_\beta' - 2K_s x_\beta D_i\delta.$$

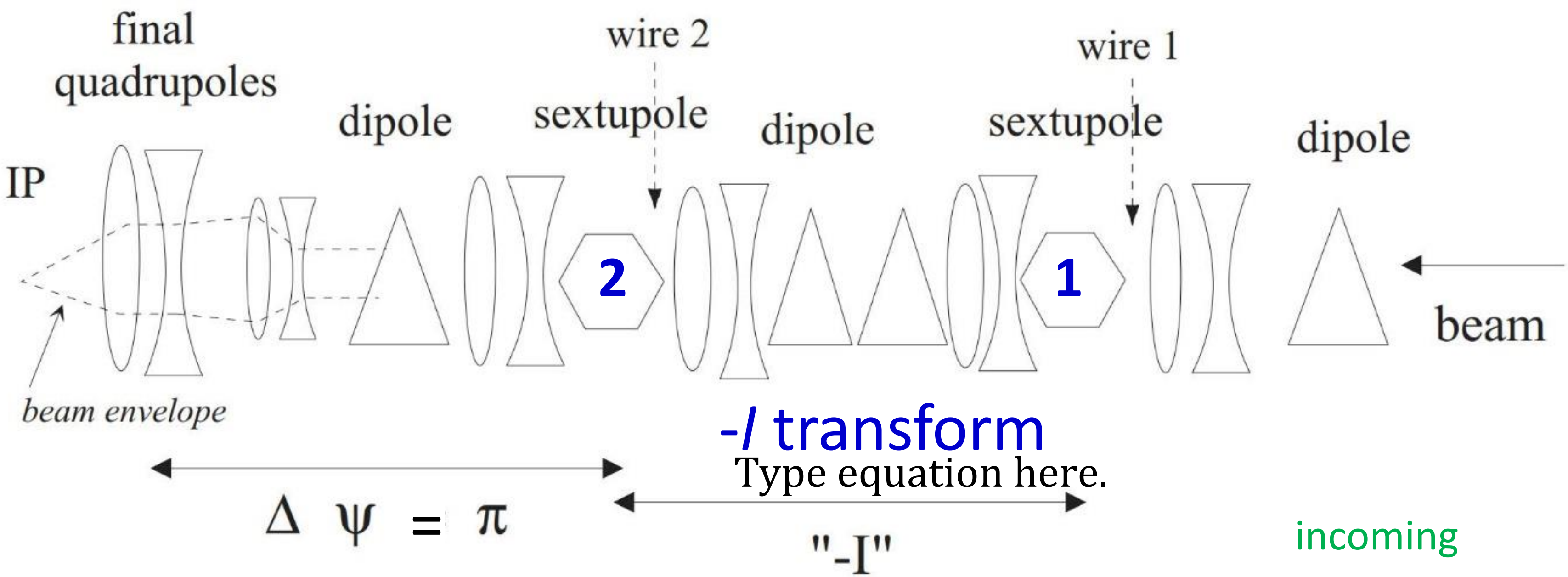
synchrotron radiation (SR)

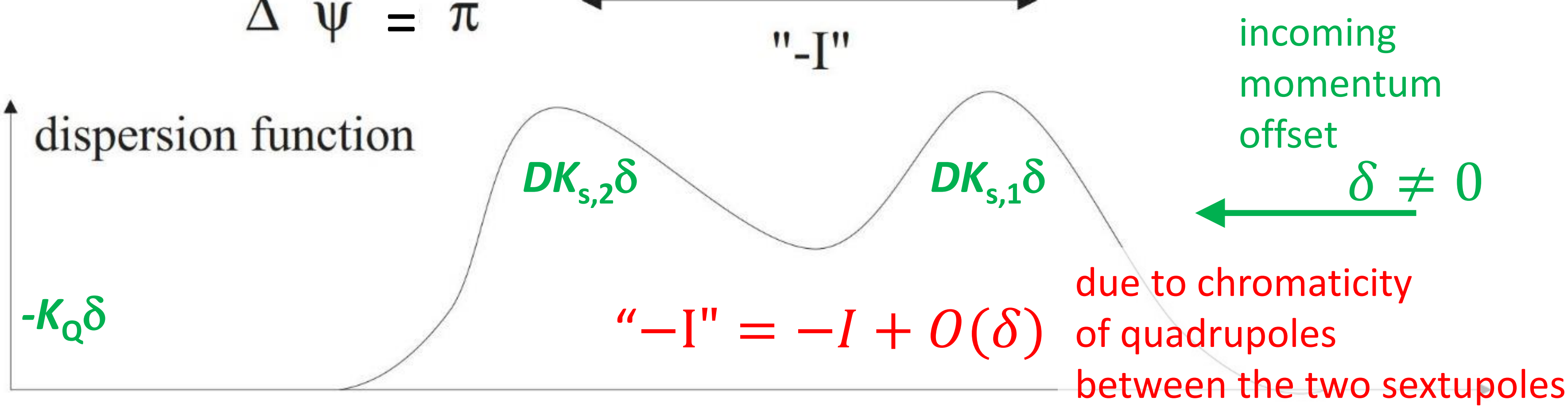


K. Oide, PAC89
K. Oide, PRL 61, 1713 (1988)
J. Irwin, in NLC ZDR, SLAC-R-485 (1996)

energy loss due to SR in final quadrupole and final dipole(s) not chromatically corrected

another problem: chromatic breakdown of -*I*





$$x_2' = -x_\beta' - \frac{1}{2}K_{s,1}(x_\beta^2 + 2x_\beta D_i\delta + D_i^2\delta^2) + \frac{1}{2}K_{s,2}(x_\beta^2 - 2x_\beta D_i\delta + D_i^2\delta^2)$$

$K_{s,1}=K_{s,2}$: $x_2' = -x_\beta' - 2K_s x_\beta D_i \delta + c_1\, x\, x'\, \delta + c_2\, x^3\, \delta + \ldots$

from “TRANSPORT” Description (SLC design)

SLAC-75

A First- and Second-Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers

Karl L. Brown

SLAC Report-75

June 1982

Under contract with the Department of Energy

Contract DE-AC03-76SF00515

```
*BEAM*     1.        299.79248 MEV
  0.000 CM                              0.000  2.000 N
                                   0.000  3.000 R    0.000
                                   0.000  4.000 N    0.000  0.000
                                   0.000  5.000 R    0.000  0.000  0.000
                                   0.000  6.000 N    0.000  0.000  0.000  0.000
                                   0.000  7.000 N    0.000  0.000  0.000  0.000  0.000
*2ND ORDER*   17.          GAUSSIAN DISTRIBUTION   2.   2.
*EPS*      16.    "BETA"     1.   0.25000E+00
*BEND*     4.        74.05000 CM     10.00000 KG     0.50000    ( 100.000 CM , 42.428 DEG )
  74.050 CM
*TRANSFORM 1*
      0.86602  0.70712  0.00000  0.00000  0.00000  0.26796
     -0.35356  0.86602  0.00000  0.00000  0.00000  0.70712
      0.00000  0.00000  0.86602  0.70712  0.00000  0.00000
      0.00000  0.00000 -0.35356  0.86602  0.00000  0.00000
     -0.70712 -0.26796  0.00000  0.00000  1.00000 -0.06675
      0.00000  0.00000  0.00000  0.00000  0.00000  1.00000
0*2ND ORDER TRANSFORM*
 1 11 -6.101E-02
 1 12  6.440E-01   1 22  1.220E-01
 1 13  0.000E+00   1 23  0.000E+00   1 33 -2.992
 1 14  0.000E+00   1 24  0.000E+00   1 34  3.158
 1 15  0.000E+00   1 25  0.000E+00   1 35  0.000
 1 16  3.749E-01   1 26  1.592E-01   1 36  0.000E

 2 11  1.610E-01
 2 12  1.220E-01   2 22 -3.220E-01
 2 13  0.000E+00   2 23  0.000E+00   2 33 -1.579
 2 14  0.000E+00   2 24  0.000E+00   2 34  1.220
 2 15  0.000E+00   2 25  0.000E+00   2 35  0.000
 2 16  4.003E-01   2 26 -1.131E-01   2 36  0.000E

 3 11  0.000E+00
 3 12  0.000E+00   3 22  0.000E+00
 3 13 -1.220E-01   3 23 -6.316E-02   3 33  0.000E+00
 3 14  6.440E-01   3 24  2.440E-01   3 34  0.000E+00   3 44  0.000E+00
 3 15  0.000E+00   3 25  0.000E+00   3 35  0.000E+00   3 45  0.000E+00   3 55  0.000E+00
 3 16  0.000E+00   3 26  0.000E+00   3 36  1.131E-01   3 46  9.340E-02   3 56  0.000E+00   3 66  0.000E+00

 4 11  0.000E+00
 4 12  0.000E+00   4 22  0.000E+00
 4 13  1.579E-02   4 23  5.984E-03   4 33  0.000E+00
 4 14 -1.280E-01   4 24 -3.158E-02   4 34  0.000E+00   4 44  0.000E+00
 4 15  0.000E+00   4 25  0.000E+00   4 35  0.000E+00   4 45  0.000E+00   4 55  0.000E+00
 4 16  0.000E+00   4 26  0.000E+00   4 36  3.384E-01   4 46  1.251E-01   4 56  0.000E+00   4 66  0.000E+00

 5 11 -2.245E-04
 5 12 -1.310E-01   5 22 -3.698E-01
 5 13  0.000E+00   5 23  0.000E+00   5 33 -1.557E-02
 5 14  0.000E+00   5 24  0.000E+00   5 34  1.190E-01   5 44 -3.057E-01
 5 15  0.000E+00   5 25  0.000E+00   5 35  0.000E+00   5 45  0.000E+00   5 55  0.000E+00
 5 16 -3.202E-02   5 26 -2.801E-01   5 36  0.000E+00   5 46  0.000E+00   5 56  0.000E+00   5 66 -1.814E-03

  -14.050  18.969 N
  -46.687  53.231 R    0.918
    0.000  10.080 N    0.000  0.000
    0.000  11.472 R    0.000  0.000  0.386
  [illegible]  14.802 N  [illegible]
    0.000   7.000 N    0.099  0.093  0.000  0.000 -0.032
```

“R-matrix” (linear)

“T-matrix” (second order)

+ “U-matrix” (3^{rd} order, not shown)

to "Lie algebra" description and Optimization (SLC final focus upgrade, N. Walker, J. Irwin, 1993)

John Irwin, The Application of Lie algebra techniques to beam transport design, Nucl. Instrum. Meth. A298 (1990) 460-472

Nuclear Instruments and Methods in Physics Research A298 (1990) 460–472
North-Holland

The application of Lie algebra techniques to beam transport design *

John Irwin

Stanford Linear Accelerator Center, P O. Box 4349, Stanford University, Stanford, California 94309, USA

Using a final focus system for high-energy linear colliders as an example of a beam transport system, we illustrate for each element, and for the interplay of elements, the connection of Lie algebra techniques with usual optical analysis methods. Our analysis describes, through fourth order, the calculation and compensation of all important aberrations.

1. Introduction

The techniques described here can be used for beamline design in quite general circumstances. We are introducing them for a final focus system design in linear colliders because this is where we have applied them and to provide a specific context for our discussion. Other optical systems may require modifications or extensions to the methods we introduce here. We have kept the formalism and mathematics to a bare minimum, hoping to simplify the presentation and clarify its connection with other methods. The territory we sketch is the tip of the iceberg of Lie algebraic methods. In the last section we describe briefly a broader context, though the interested reader will need to consult the extensive literature on this subject [1]. As far as we know the particulars we present here are original, however the essence of the method comes from Alex Dragt and collaborators.

2. Hamiltonians, kicks, and Poisson brackets

2.1. Hamiltonian reminders

The elegant and powerful formulation of classical mechanics given by Hamilton is summed up in pairs of first order differential equations:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\partial H}{\partial p_x}, \qquad \frac{\mathrm{d}p_x}{\mathrm{d}t} = -\frac{\partial H}{\partial x}. \tag{1}$$

The state of motion of a particle is described by giving a position and a momentum, which can be identified with a point in a $2n$-dimensional space of these variables, for n degrees of freedom. The velocity of this point in this space is prescribed by one function defined in this space, the Hamiltonian, as indicated above. Thus one function determines completely the ensuing motion once initial conditions are specified.

The Hamiltonian function for the motion of particles in magnetic optical elements can be derived, after introduction of the appropriate coordinates and approximations, from the Hamiltonian for motion in a general electromagnetic field. This procedure has been described in many places [2]. The principal elements in our beamline consist of static transverse magnetic fields. If one chooses the distance s measured along the design orbit as the time-like variable, then within uniform elements with no dipole field the Hamiltonian can be transformed to

$$H = \left[p^2 - p_x^2 - p_y^2\right]^{1/2} - \frac{e}{c}A_s(x, y), \tag{2}$$

where p_x and p_y are the transverse components of the momentum, p is the total momentum of the particle, e is the electronic charge, c is the speed of light and A_s is the magnetic vector potential in the s direction.

For p much greater than p_x or p_y the square root can be expanded in powers of $(p_x^2 + p_y^2)/p^2$ as follows:

$$H = p\left\{1 + \frac{1}{2}\left(\frac{p_x^2 + p_y^2}{p^2}\right) - \frac{1}{8}\left(\frac{p_x^2 + p_y^2}{p^2}\right)^2 + \cdots\right\} - \frac{e}{c}A_s. \tag{3}$$

For particles of constant p the first term can be dropped and the transverse momentum variables changed from p_x and p_y to $p_x/p \equiv x'(\approx \mathrm{d}x/\mathrm{d}s)$ and $p_y/p \equiv y'$. The latter is a scale transformation for which Hamilton's equations remain intact if H is scaled by p. The new H is

$$H = \tfrac{1}{2}\left(x'^2 + y'^2\right) - \tfrac{1}{8}\left(x'^2 + y'^2\right)^2 + \cdots - \frac{e}{pc}A_s. \tag{4}$$

The scale transformation we performed here is not appropriate if the total energy is needed as a dynamical variable for the third degree of freedom. However, since

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

reminder of classical mechanics

Hamiltonian H

equations of motion $\frac{dx}{ds} = \frac{\partial H}{\partial p_x}$ $\frac{dp_x}{ds} = -\frac{\partial H}{\partial x}$

consider a function $U(x, p_x)$;

change of U as particle move around in phase space

$$\frac{dU}{ds} = \frac{dU}{dx}\frac{dx}{ds} + \frac{dU}{dp_x}\frac{dp_x}{ds} = \frac{dU}{dx}\frac{\partial H}{\partial p_x} - \frac{dU}{dp_x}\frac{\partial H}{\partial x} \equiv [U, H] = -[H, U]$$

in particular

$$\frac{dx}{ds} = -[H, x] \qquad \frac{dp_x}{ds} = -[H, p_x] \qquad \frac{dy}{ds} = -[H, y] \qquad \frac{dp_y}{ds} = -[H, p_y]$$

integration over a magnet / element from $s_1 to$ to $s_2 = s_1 + L$

$$x(s_1 + L) = \sum_{n=0}^{\infty} \frac{L^n}{n!}\frac{d^n x}{ds^n} = \exp\left(L\frac{d}{ds}\right) x \equiv \exp(L{:}-H{:})\, x\Big|_{x=x_1, p_x=p_{x1}, \ldots}$$

where $:-H:^n x = [-H, [-H, \ldots, [-H, x]] \ldots]$

in the following I will drop the colons

Lie algebra illustration ….

beam line with Hamiltonians in local coordinates

$$M = \ \dots \exp\left(-H_i(x_i, p_{xi}, y_i, p_{yi}, \delta)\right) R_{ji} \exp\left(-H_j(x_j, p_{xj}, y_j, p_{yj}, \delta)\right) R_{kj} \exp\left(-H_k(x_k, p_{xk}, y_k, p_{yk}, \delta)\right) \dots$$

linear transformations

nonlinear transformations

example: sextupole Hamiltonian

$$H_s(x_s, p_{xs}, y_s, p_{ys}, \delta) = \frac{1}{6} K_s(x_s^3 - 3x_s y_s^2)\left(1 - \underbrace{\frac{\delta}{1+\delta}}_{\equiv\ \bar{\delta}}\right)$$

"kicks" from sextupole

$$\Delta p_{xs} = [-H_s, p_{xs}] = -\frac{\partial H_s}{\partial x_s} = -\frac{1}{2} K_s(x_s^2 - y_s^2)(1 - \bar{\delta})$$

$$\Delta p_{ys} = [-H_s, p_{ys}] = -\frac{\partial H_s}{\partial y_s} = K_s x_s y_s (1 - \bar{\delta})$$

"Poisson bracket":

$$[a, b] \equiv \frac{\partial a}{\partial x}\frac{\partial b}{\partial p_x} - \frac{\partial a}{\partial p_x}\frac{\partial b}{\partial x}$$

beam line with Hamiltonians in IP coordinates

$$M \approx \ \exp\left(-H_{\mathrm{NL,tot,}*}(x^*, p_x^*, y^*, p_y^*, \delta)\right) R_{0,\mathrm{init}}$$

the regrouping is achieved with the help of two transformations:

similarity transformation

$$\exp A \exp B \exp(-A) = \exp C \quad \text{where } C = (\exp A)B$$

Campbell-Baker-Hausdorff formula*

$$\exp A \exp B = \exp C$$

$$\text{where } C = A + B + \frac{1}{2}[A, B] + \text{higher order terms}$$

"heart of the usefulness of Lie algebra approach"

*Henry Baker: Proc Lond Math Soc (1) 34 (1902) 347–360; ibid (1) 35 (1903) 333–374; ibid (Ser 2) 3 (1905) 24–47.
John. Campbell: Proc Lond Math Soc 28 (1897) 381–390; ibid 29 (1898) 14–32.
Felix Hausdorff: Berl Verh Saechs Akad Wiss Leipzig 58 (1906) 19–48.

chromatic breakdown of –*I* can be described by a similarity transformation

-*I* transform between sextupoles

$$\exp\left(-\frac{1}{2}K_s\beta_{x,s}^{1/2}\beta_{y,s}\bar{x}'^{*}\bar{y}'^{*2}\right)\exp\left(\frac{1}{2}\bar{\delta}K_q\beta_{y,q}\bar{y}^{*2}\right)\exp\left(\frac{1}{2}K_s\beta_{x,s}^{1/2}\beta_{y,s}\bar{x}'^{*}\bar{y}'^{*2}\right)$$

intermediate chromaticity in IP phase

where $\bar{x}^{*} \equiv x^{*}/\sqrt{\beta_x^{*}}$, $\bar{x}'^{*} \equiv \sqrt{\beta_x^{*}}x'^{*}$

→ leading new term in total Hamiltonian

$$\left[-\frac{1}{2}K_s\beta_{x,s}^{\frac{1}{2}}\beta_{y,s}\bar{x}'^{*}\bar{y}'^{*2},\frac{1}{2}K_q\beta_{y,q}\bar{y}^{*2}\bar{\delta}\right] = K_qK_s\beta_{x,s}^{\frac{1}{2}}\beta_{y,s}\beta_{y,q}\;\bar{x}'^{*}\bar{y}'^{*}\bar{y}^{*}\bar{\delta}$$

chromogeometric aberration affecting σ_y and depending on β_x^{*}!

Lesson 6: Lie algebra methods are a great approach for understanding final-focus aberrations and their interaction

effect of aberrations on IP beam size

$$\Delta y^* \approx \frac{\partial H_{\mathrm{NL,tot,*}}}{\partial p_y^*}$$

and

$$\Delta \sigma_y^{*2} \approx \langle (\Delta y)^2 \rangle - \langle \Delta y \rangle^2$$

$\langle \ldots \rangle$: average over (initial/linearly transformed) bunch distribution, often assumed as Gaussian

$\langle y^2 \rangle = \sigma_y^2 \qquad \langle y^4 \rangle = 3\sigma_y^4 \qquad \langle y^6 \rangle = 15\sigma_y^6$

design contributions to IP spot size

for all types of final focus system there are aberrations due to the chromatic breakdown of the "-I" transforms between sextupoles

famous LC expert told me
"σ_y^* does not depend on β_x^*"
??!?

$$\sigma_y^{*2} =$$

$$\beta_y^* \varepsilon_y$$ linear spot size

$$+\Delta\sigma_{y,SR}^{*2}$$ contribution from SR in bends and quadrupoles

"long sextupole effect" (K. Oide)

"chromatic breakdown of linear optics"

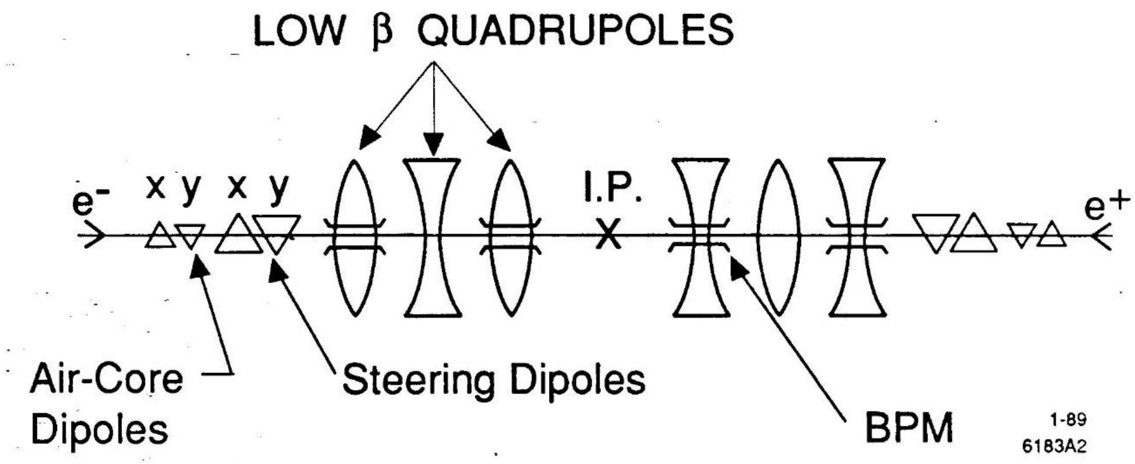
$$+a\frac{\varepsilon_x}{\beta_x^*}\sqrt{\frac{\varepsilon_y}{\beta_y^*}} + \cdots + b\sigma_\delta\sqrt{\frac{\varepsilon_x}{\beta_x^*}}\sqrt{\frac{\varepsilon_y}{\beta_y^*}} + \sum_{ikl} c_{ikl}\left(\frac{\varepsilon_x}{\beta_x^*}\right)^{i/2}\left(\frac{\varepsilon_y}{\beta_y^*}\right)^{k/2}\sigma_\delta^l$$

higher-order aberrations scale with higher powers *x* and *y* divergence and momentum spread aside from design imperfections additional dilutions arises from errors, spurious dispersion, waist shift, etc. ;

we need to constantly cancel additional aberrations by scanning, correcting or "tuning" ; this requires:

1. (quasi-orthogonal) tuning knobs; at the SLC we used nonlinear "Irwin knobs"
2. a tuning signal; at the SLC we used: beam-beam deflection (two beams), laser wires (single beam), beamstrahlung, luminosity

beam-beam deflection scan at SLC

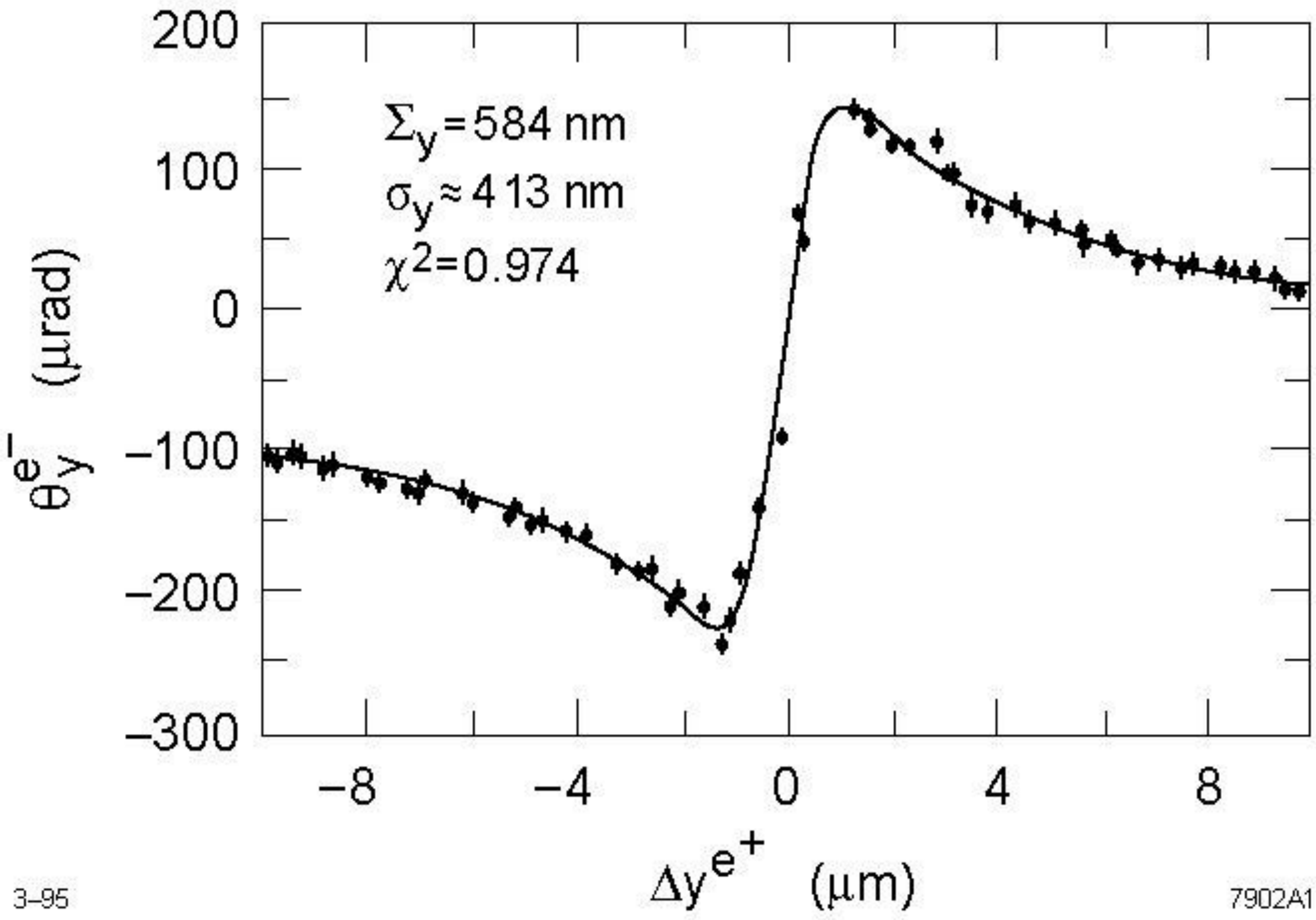


$$\Delta y' + i\Delta x' = -\frac{\sqrt{2\pi} N_b r_p}{\gamma} \frac{1}{\sqrt{\sigma_x^2 - \sigma_y^2}} \left\{ w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right) \right\}$$

Note: centroid deflection is obtained by replacing $\sigma \rightarrow \Sigma \equiv \sqrt{\sigma_{e-}^2 + \sigma_{e+}^2}$

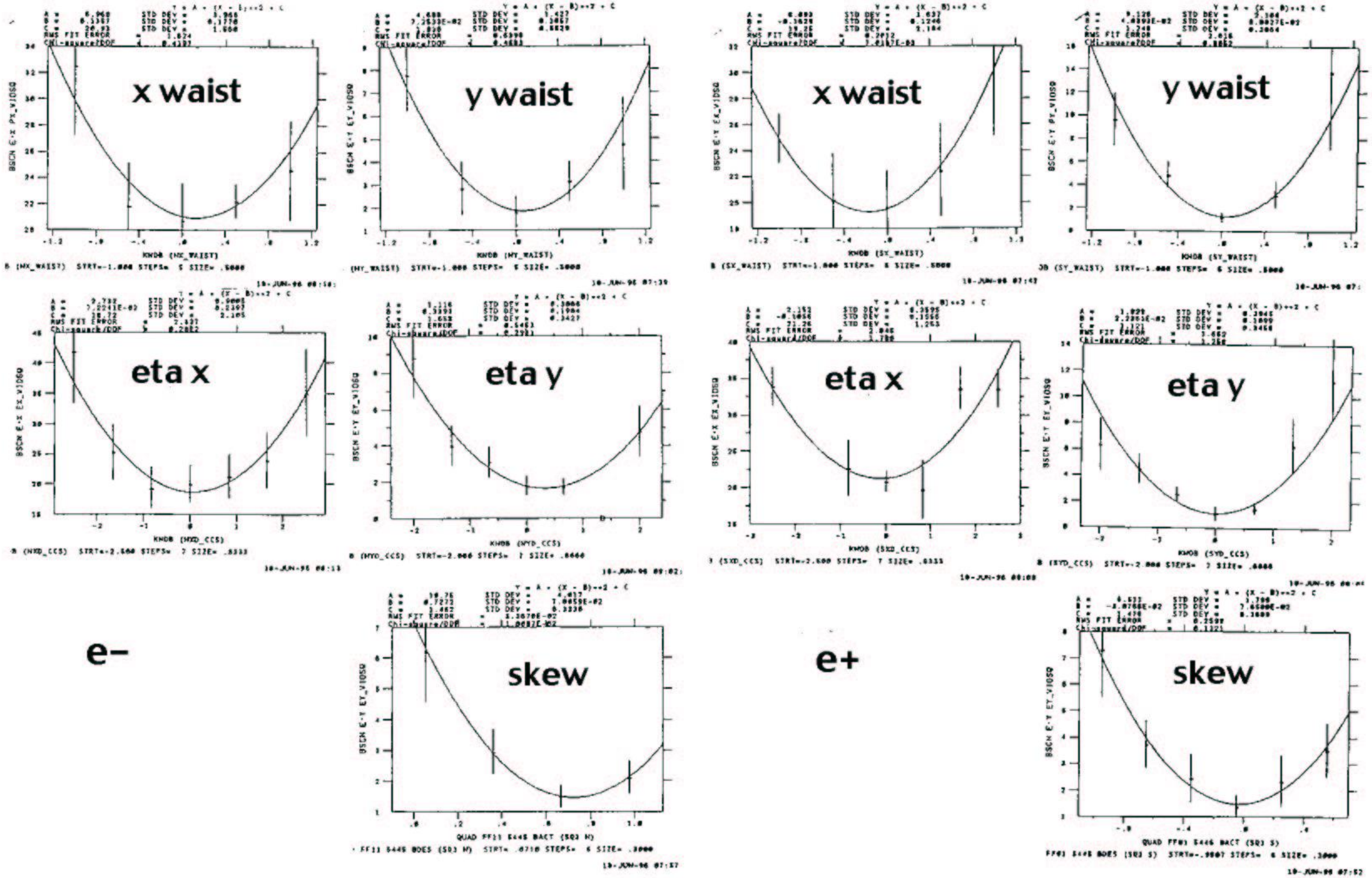
V. Ziemann, "Beyond Bassetti and Erskine: Beam-beam deflections for non-Gaussian beams", 1991

beam-beam deflection with flat beams



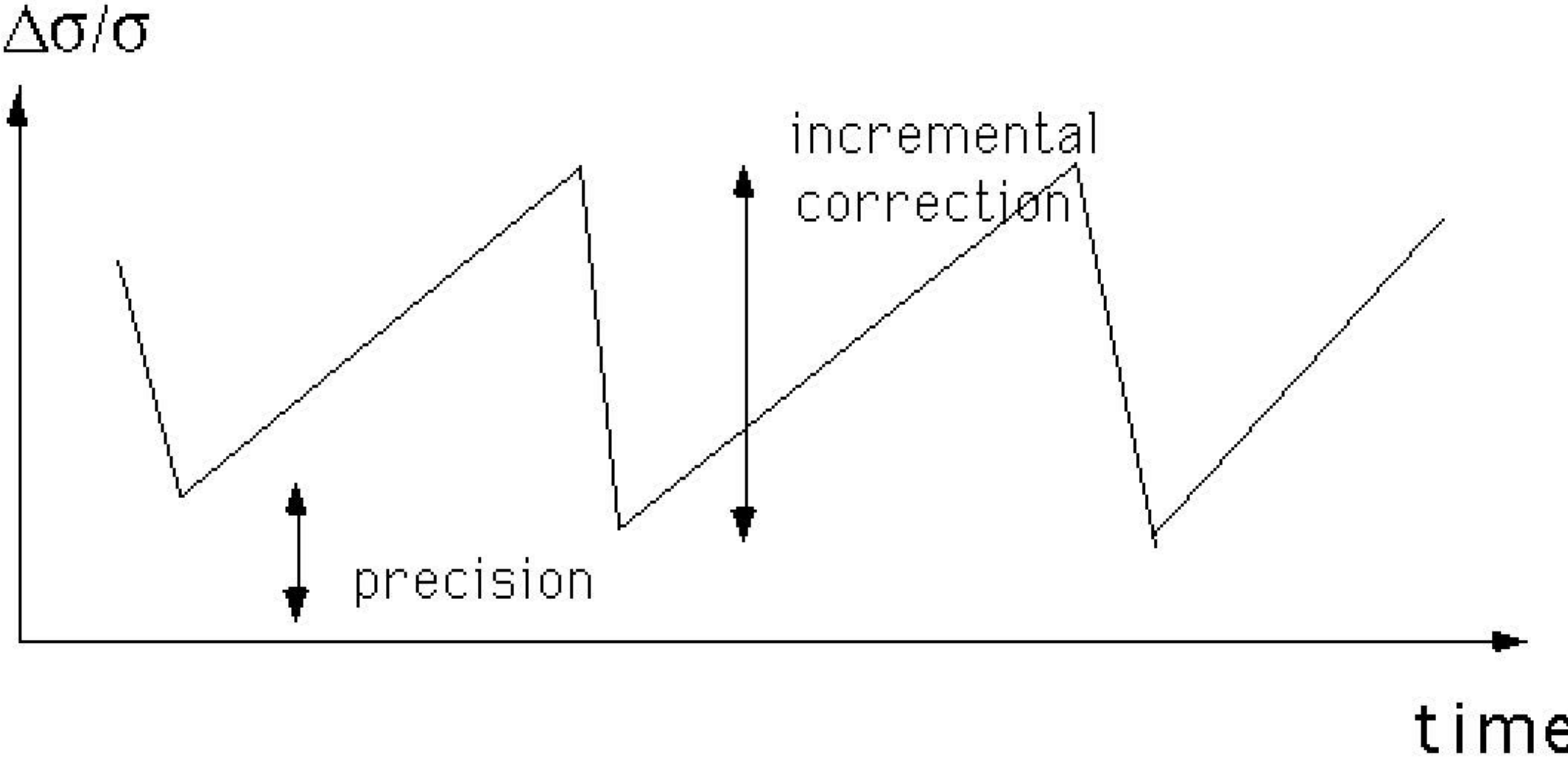
SLC vertical beam-beam deflection scan at low bunch charge, demonstrating a single-beam size of about 410 nm (1994/95) as expected

F. Zimmermann et al., PAC95

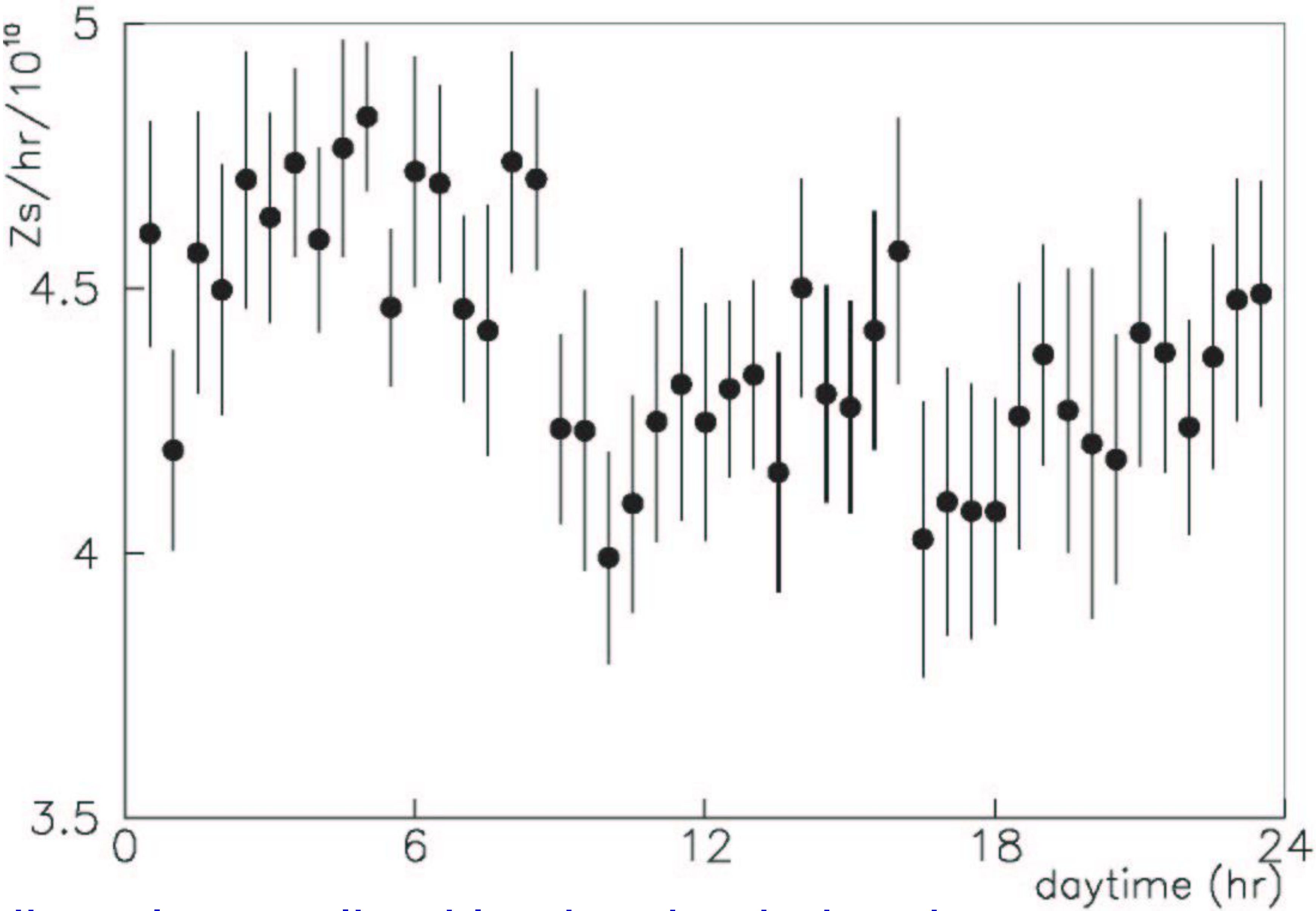


aberration scans at SLC collision point

tuning knobs control **waists, dispersion, coupling, sextupolar aberrations, ξ, higher-order terms,…** tuning optimization was repeated **in regular intervals** (hours)

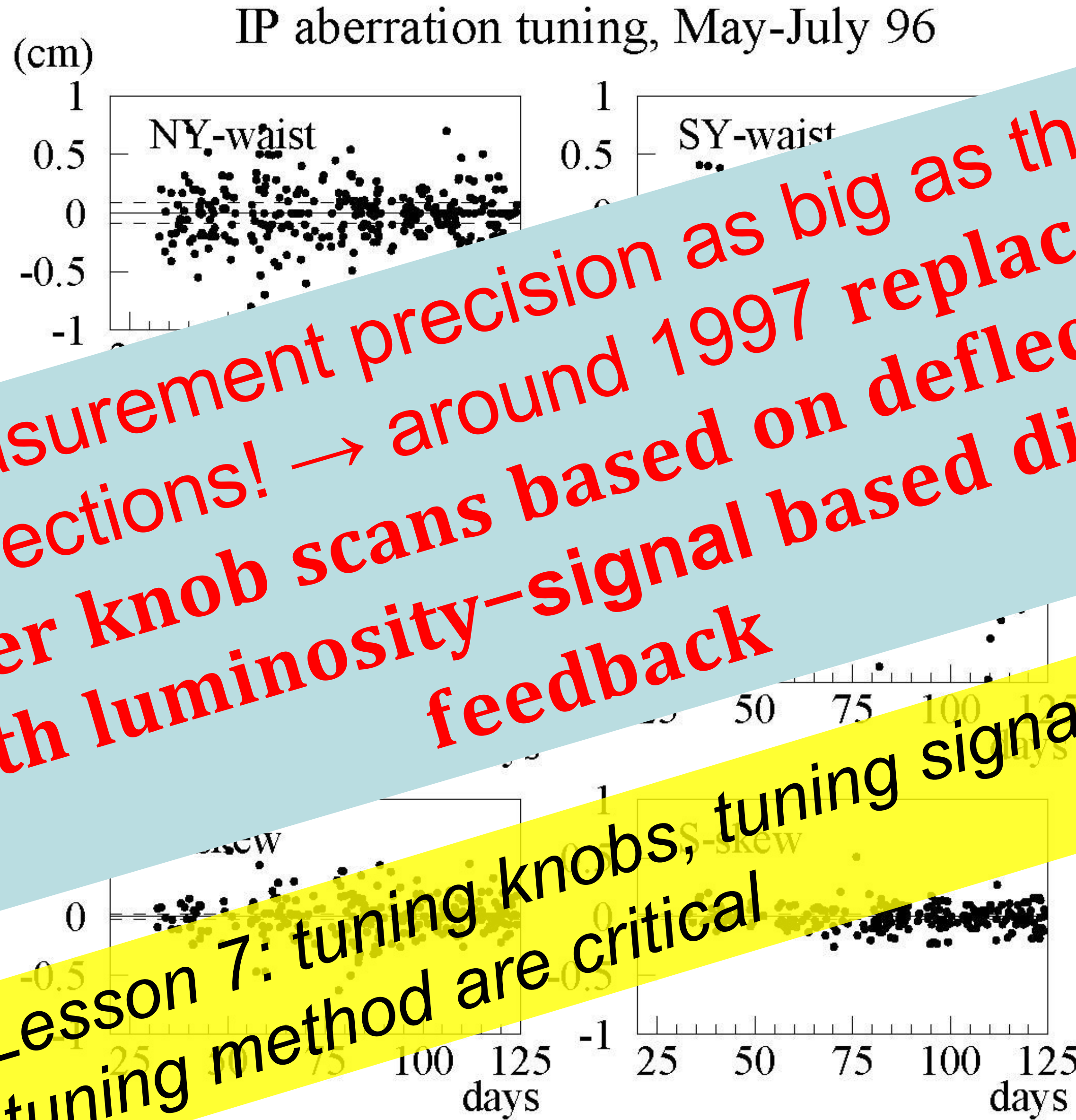


schematic of tuning effect and spot-size increase between tunings



diurnal normalized luminosity during the 1996 SLC run; steady increases in day & swing shifts, drops at 8&16 h

P. Emma et al., PAC97



measurement precision as big as the corrections! → around 1997 replaced **wider knob scans based on deflection with luminosity–signal based dither feedback**

Lesson 7: tuning knobs, tuning signal + tuning method are critical

incremental IP corrections of waist, dispersion and coupling during the 1996 SLC run

validating the final focus optics

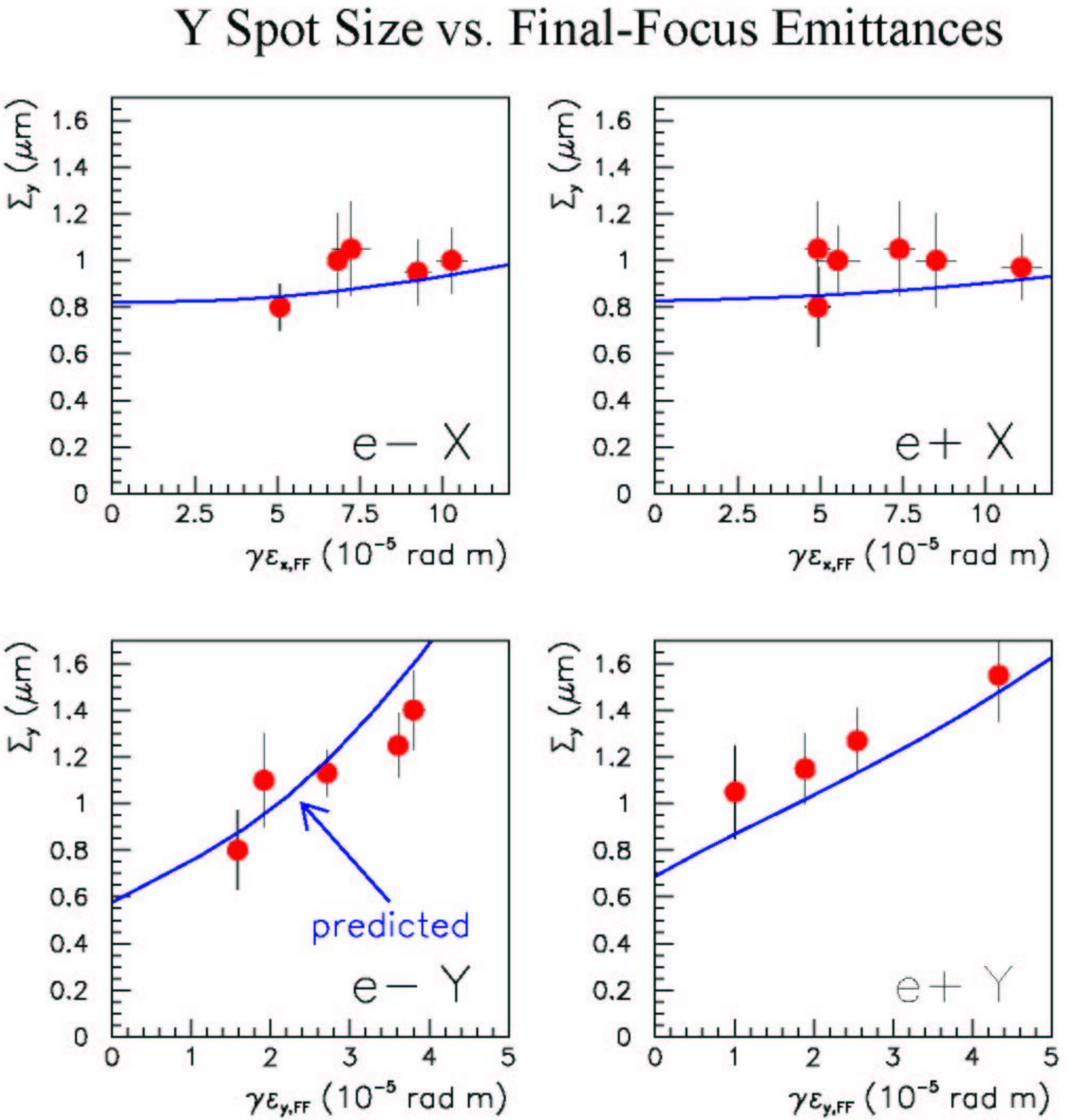
SLC examples:

spot size vs. beam emittance
(varied in the damping ring)

spot size vs. beam energy, launch orbit, etc.

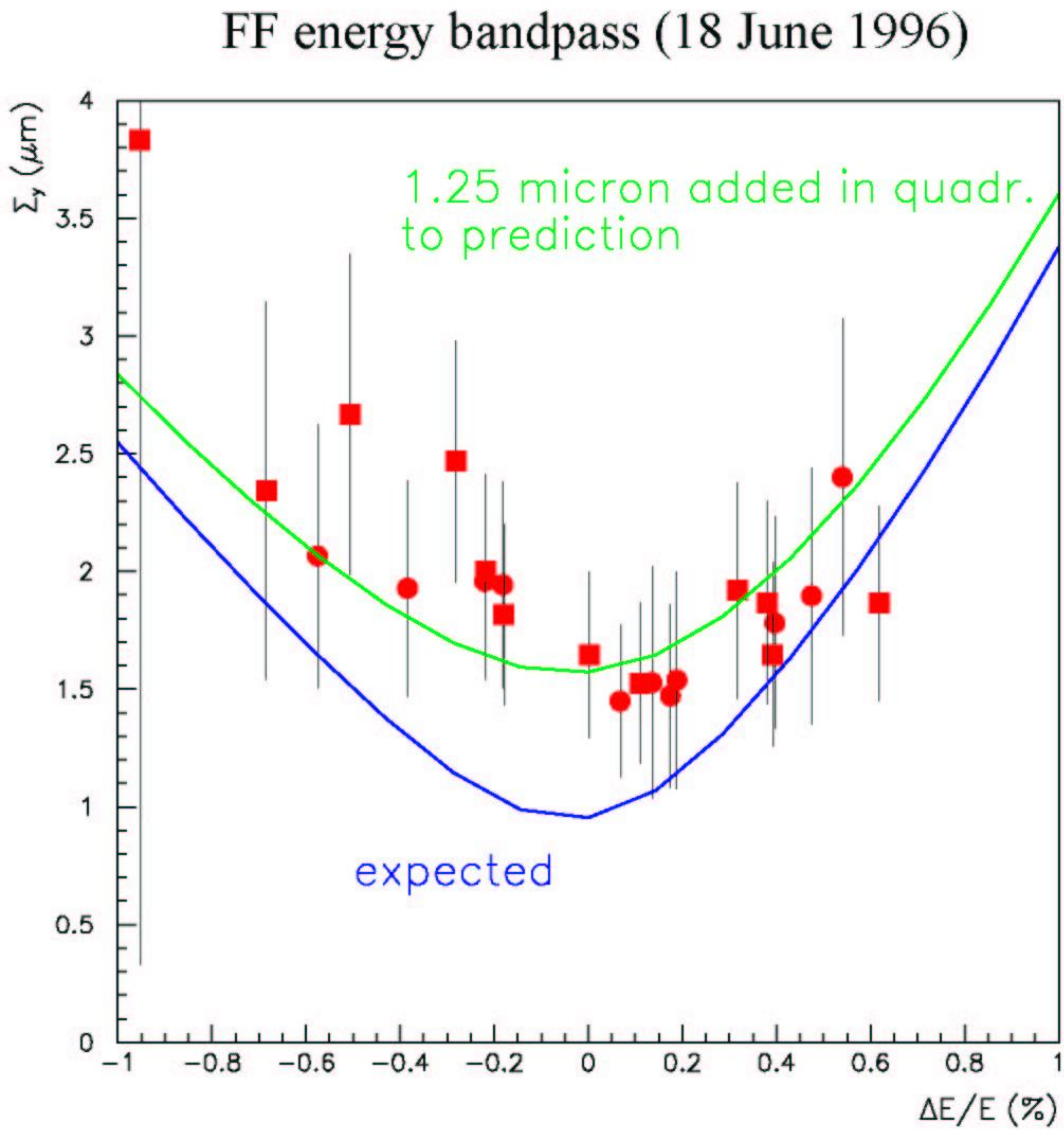
spot size vs β^* and intensity

SLAC-CN-405 (1996)



vertical convoluted IP spot size measured **at low charge** as function of the four beam emittances; solid line is SLC final-focus flight-simulator prediction

SLAC-CN-410 (1996)

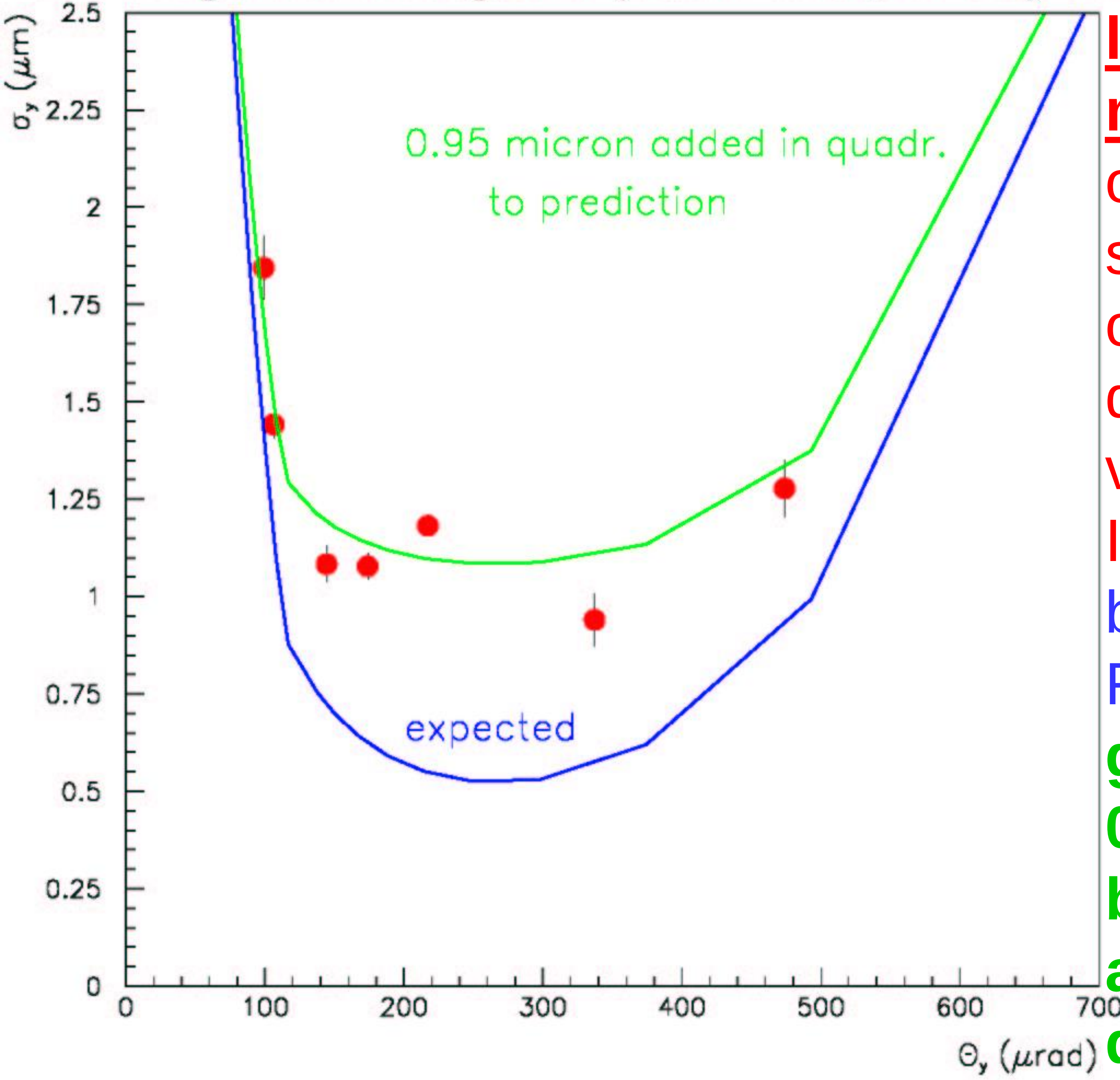


vertical convoluted IP spot size measured **at nominal SLC current** as function of centroid energy; rms energy spread ~ 0.1%;

blue line is FFFS prediction,

green line has 1.25 µm added

e+ Y-Spot vs Divergence (Laser Wire, 30 July 1996)



laser wire measurement of e+ IP beam size as function of vertical IP divergence, varied with Irwin knobs; blue line is FFFS prediction, **green line has 0.95 μm single-beam dilution added in quadrature**

1998 - last year of LHC operation

Lesson 8: average IP spot size always above expectation (impact on luminosity)

20 Jan – 20 May 1998, SLAC-CN-418

parameter	symbol	expected		measured	
		mean	rms	mean	rms
horizontal convoluted spot size	Σ_x^* [μm]	1.80	0.22	2.60	1.21
vertical convoluted spot size	Σ_y^* [μm]	0.55	0.13	1.38	0.91

$$\sigma_{y(x)} = \sqrt{\sigma_{y(x),0}^2 + \Delta\sigma_{y(x)}^2}$$

$\Delta\sigma_x$= 1.89 μm
$\Delta\sigma_y$= 1.27 μm
added in quadrature

remark: discrepancy similar for two-beam measurements (deflection scans) and single-beam tuning (laser wire)

how do we get a small spot size?

small emittances

- from damping ring
- emittance preservation in linac (wake fields, spurious dispersion)

final focus minimizing aberrations and synchrotron radiation effects

- **SLC type** (interleaved sextupoles)
- **FFTB type** (modular, non-interleaved sextuples)
- **compact ILC/CLIC/ATF-2** type w extremely local chromatic correction

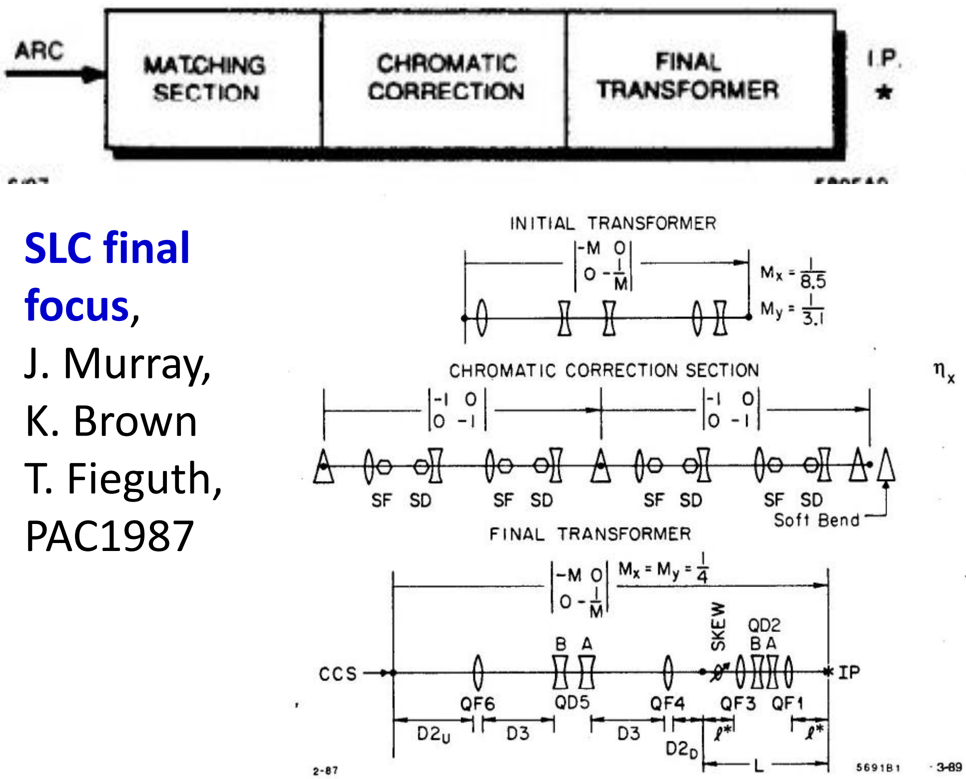
tuning recipe

- scanning orthogonal tuning knobs
- beam-beam deflection scans or luminosity dither feedback

stability

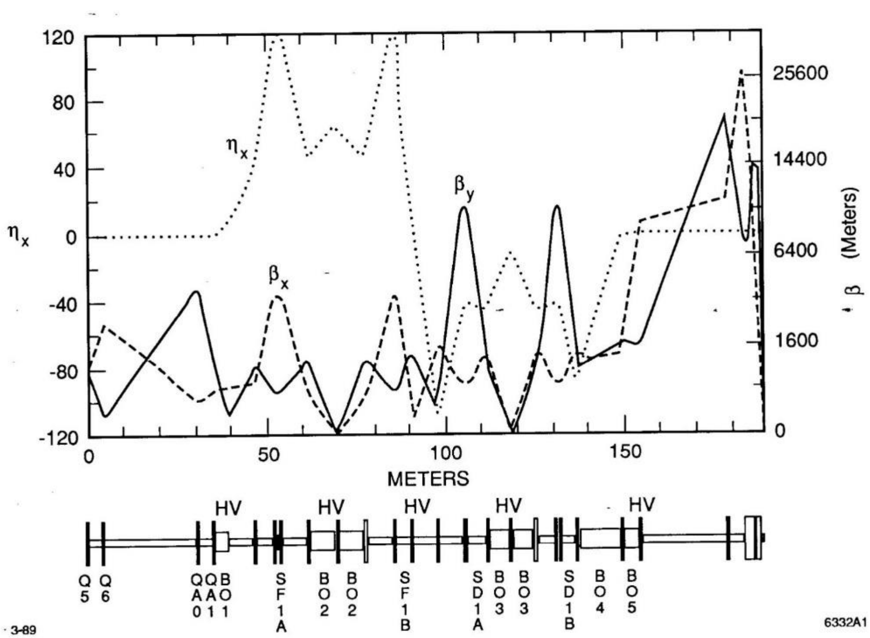
- pulse-to-pulse orbit stability (damping ring instability, wakes, kicker)
- pulse-to-pulse beam size / emittance stability

final-focus evolution

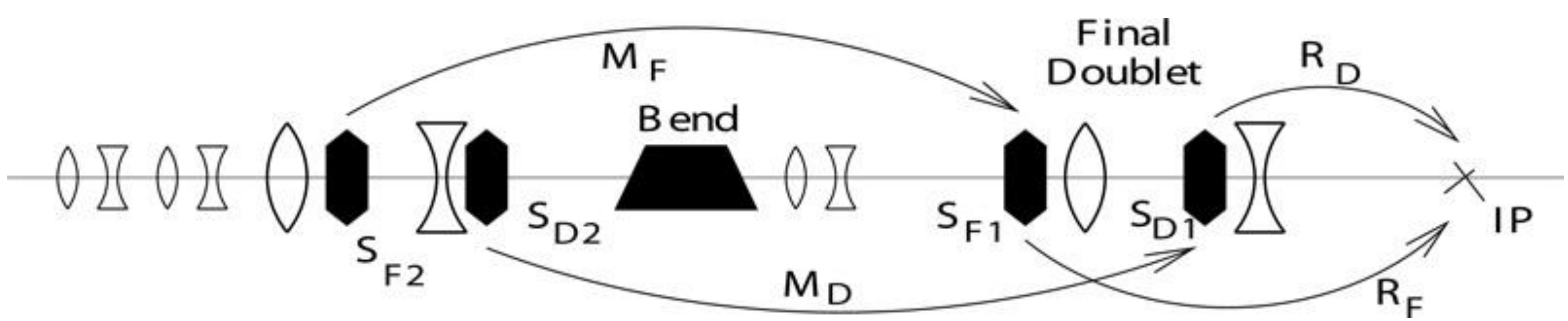


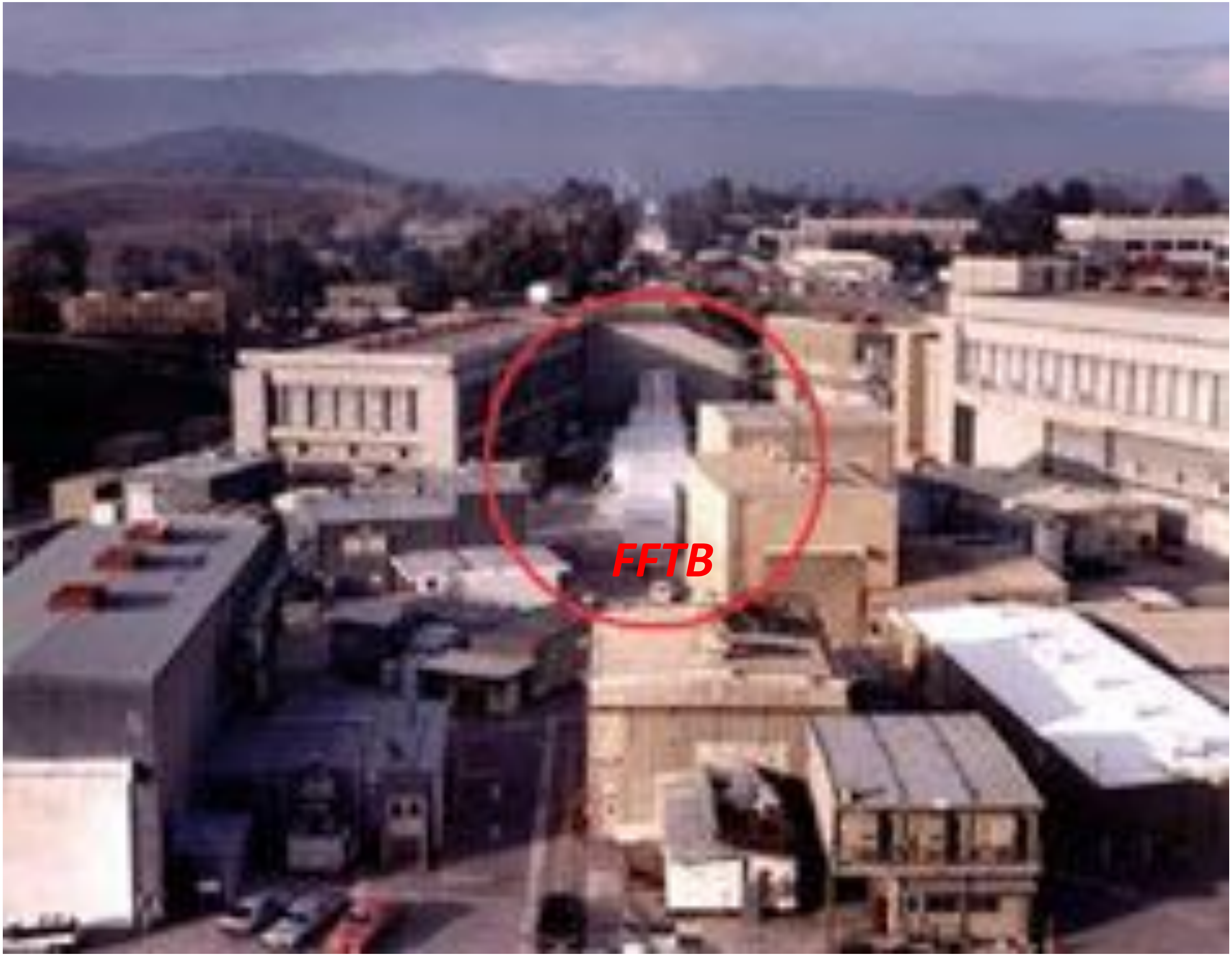
SLC final focus, J. Murray, K. Brown T. Fieguth, PAC1987

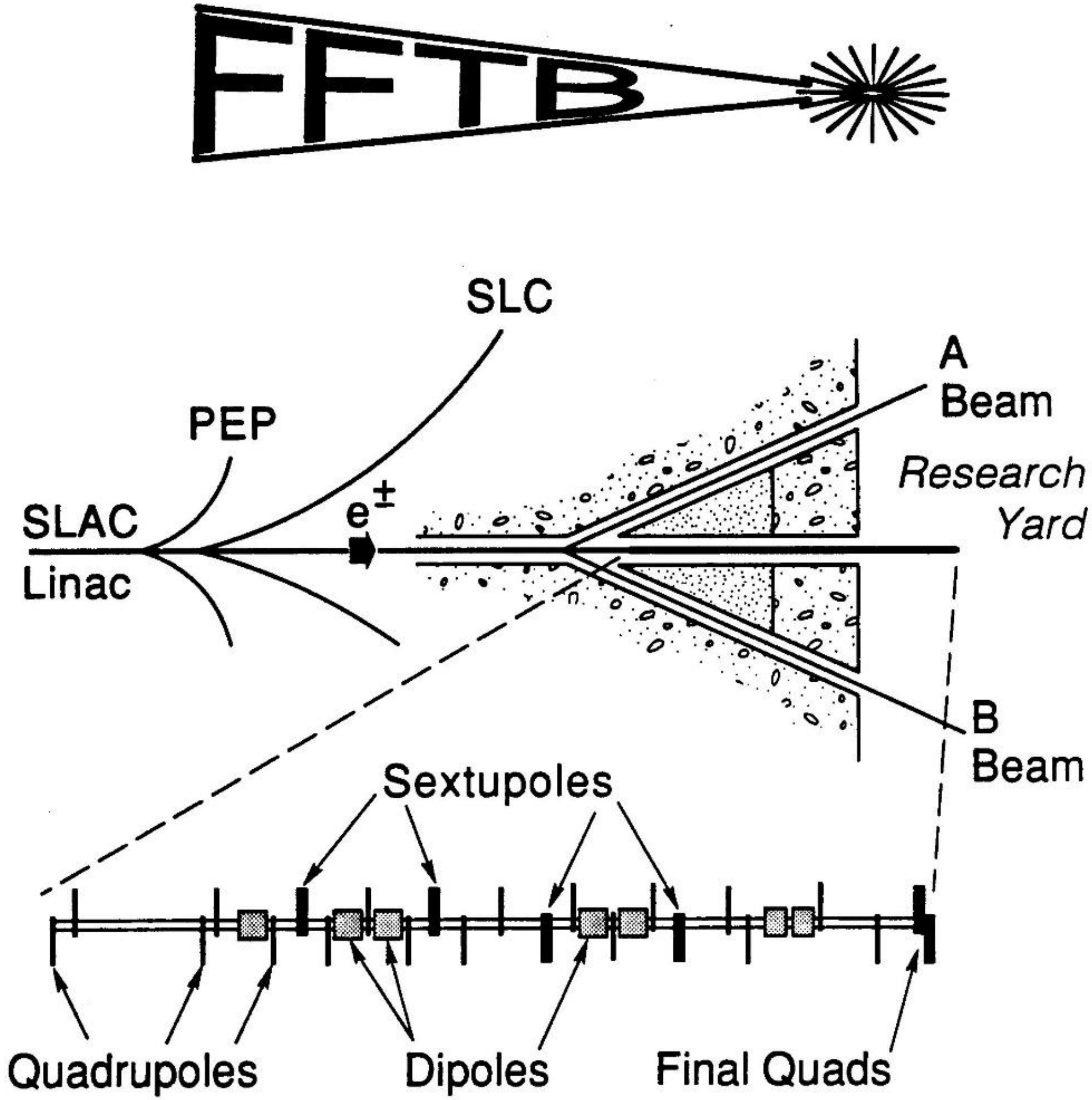
Non-interleaved modular final focus for the **FFTB**, K. Oide, IEEE PAC 1989



Compact final focus (**ATF-2**/ILC/CLIC), P. Raimondi, A. Seryi, Phys. Rev. Lett. 86, 3779 (2001)




FFTB



8-90 Final Focus Test Beam 6700A2

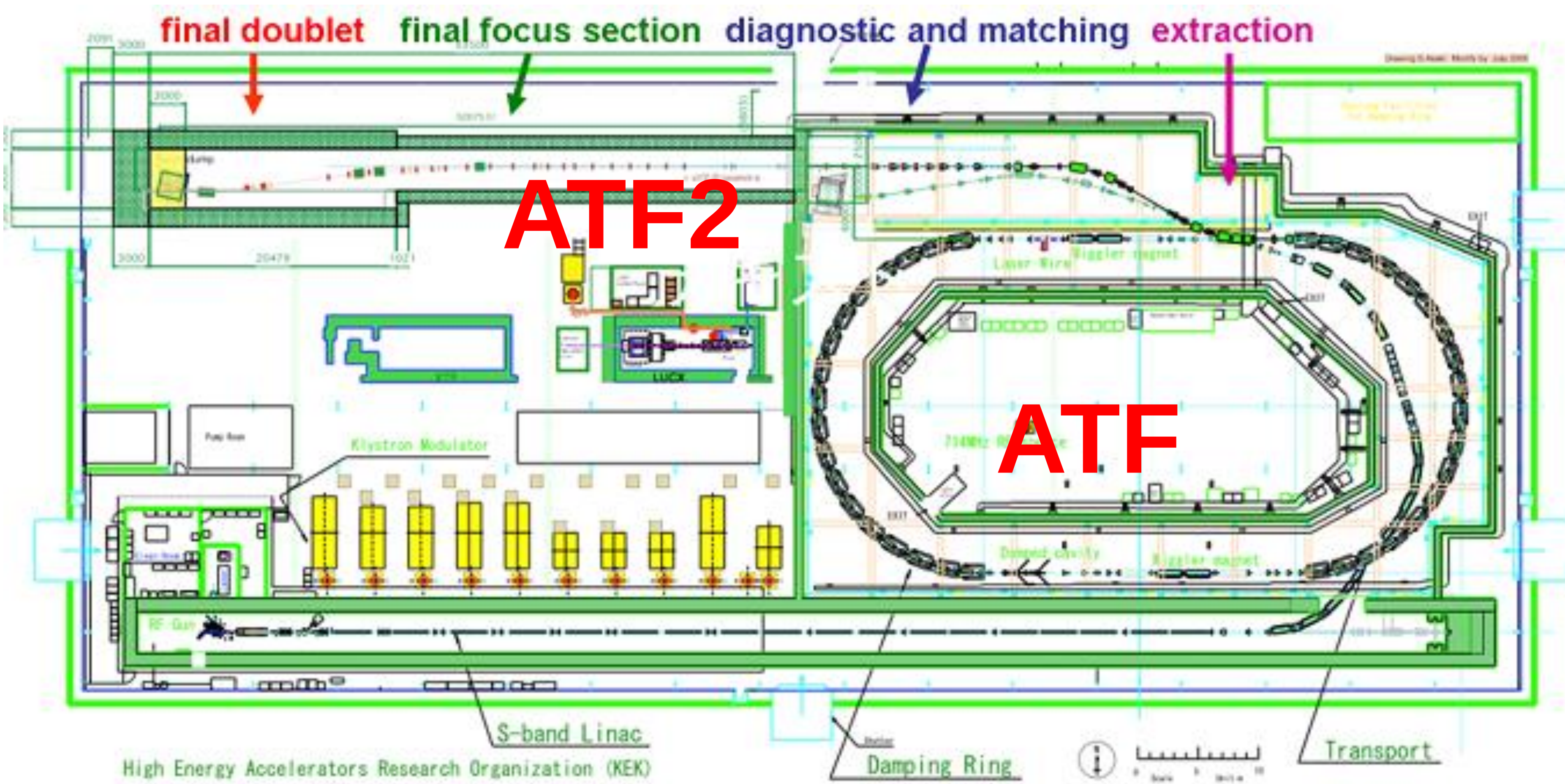
FFTB spot size results

date	spring 1994	fall 1994	fall 1995	spring 1997
time	3 weeks	2 weeks	1.5 weeks	1.5 weeks
expected	**50 nm**	**50 nm**	**50 nm**	**50 nm**
minimum spot size measured	**70 nm**	**70 nm**	**100-120 nm**	**120 nm**
residual & possible origin	**40 nm jitter/ vibration? (RFBPM/ laser-monitor housing)**	**40 nm jitter/ vibration?**	**100 nm collimator wakes?**	**100-110 nm jitter + sextupole aberration?**

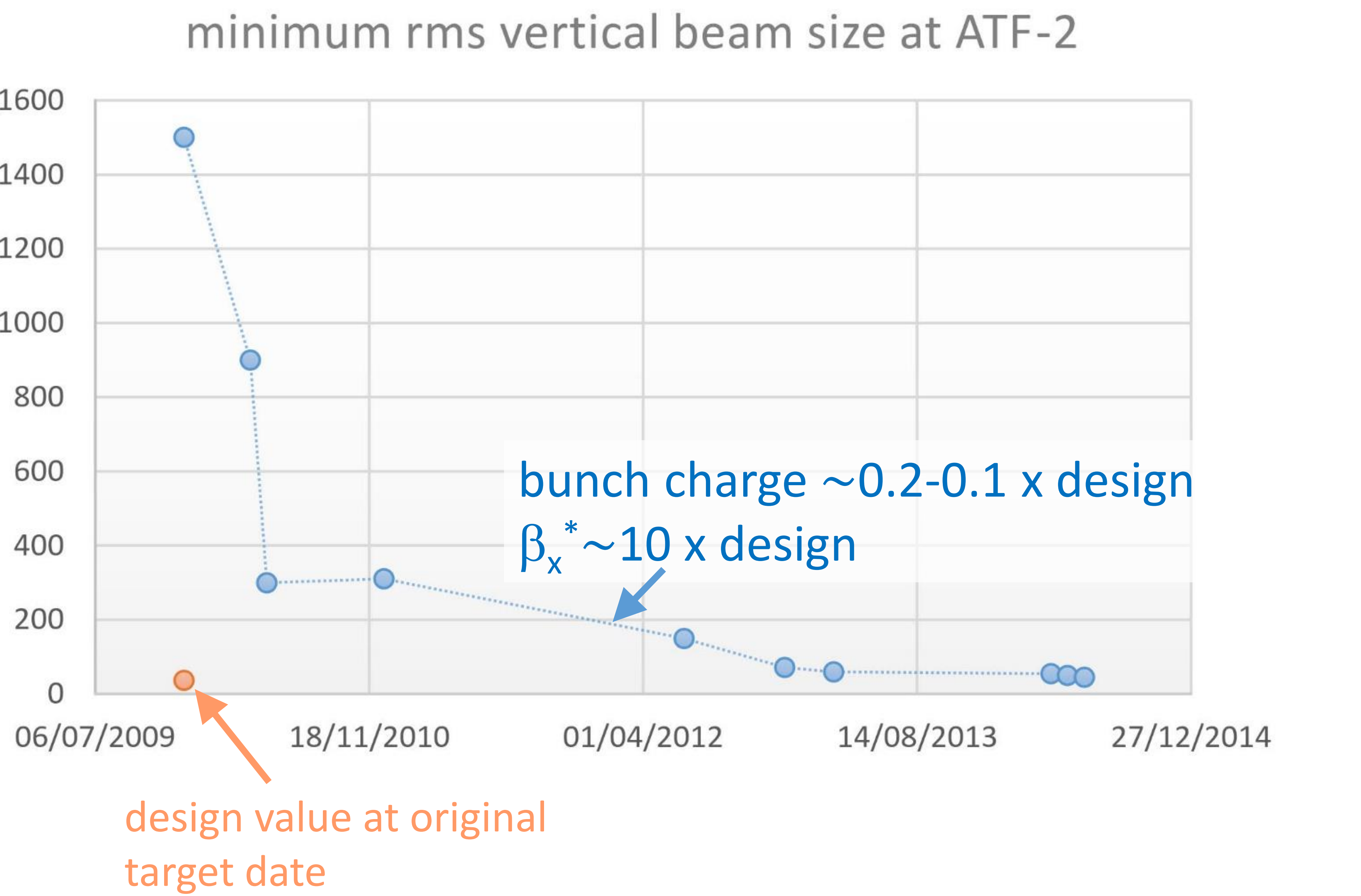
D. Burke, LC97

"The [FFTB] difference from 40 nm was attributed to significant jitter of the focused beam and was also partly due to limited accuracy in tuning the linear optics and the aberrations." [ATF2 proposal]

KEK / ATF (linac & damping ring) in operation since ~1995, ATF-2 (final focus) since ~2009 [proposed by A. Seryi et al.]



ATF-2: test facility for small spot size & viability of compact final focus


minimum rms vertical beam size at ATF-2
1600
1400
1200
1000
800
600
400
200
0
06/07/2009
18/11/2010
01/04/2012
14/08/2013
27/12/2014
bunch charge ~0.2-0.1 x design
β_x^*~10 x design
design value at original target date

ATF2 parameters & spot size

	design	May 2010	2015
bunch population [10^{10}]	0.5	0.5	**~0.05**
ε_x [nm]	2	1.7	1.7
ε_y [pm]	12	<10	<10
β_x^* [mm]	4.0	**40.0**	**40.0**
β_y^* [mm]	0.1	**1.0**	0.1
σ_y^* [nm]	37	**300**	45-65
σ_y^* [nm] expected	-	100	32-37
$\Delta\sigma_y^*$ [nm] residual	-	**280**	**~40**

Lesson 9: test facilities FFTB and ATF-2 had similar experience as SLC: getting expected spot size is much easier at low intensity and with relaxed parameters ; residual spot size increases not fully explained or understood

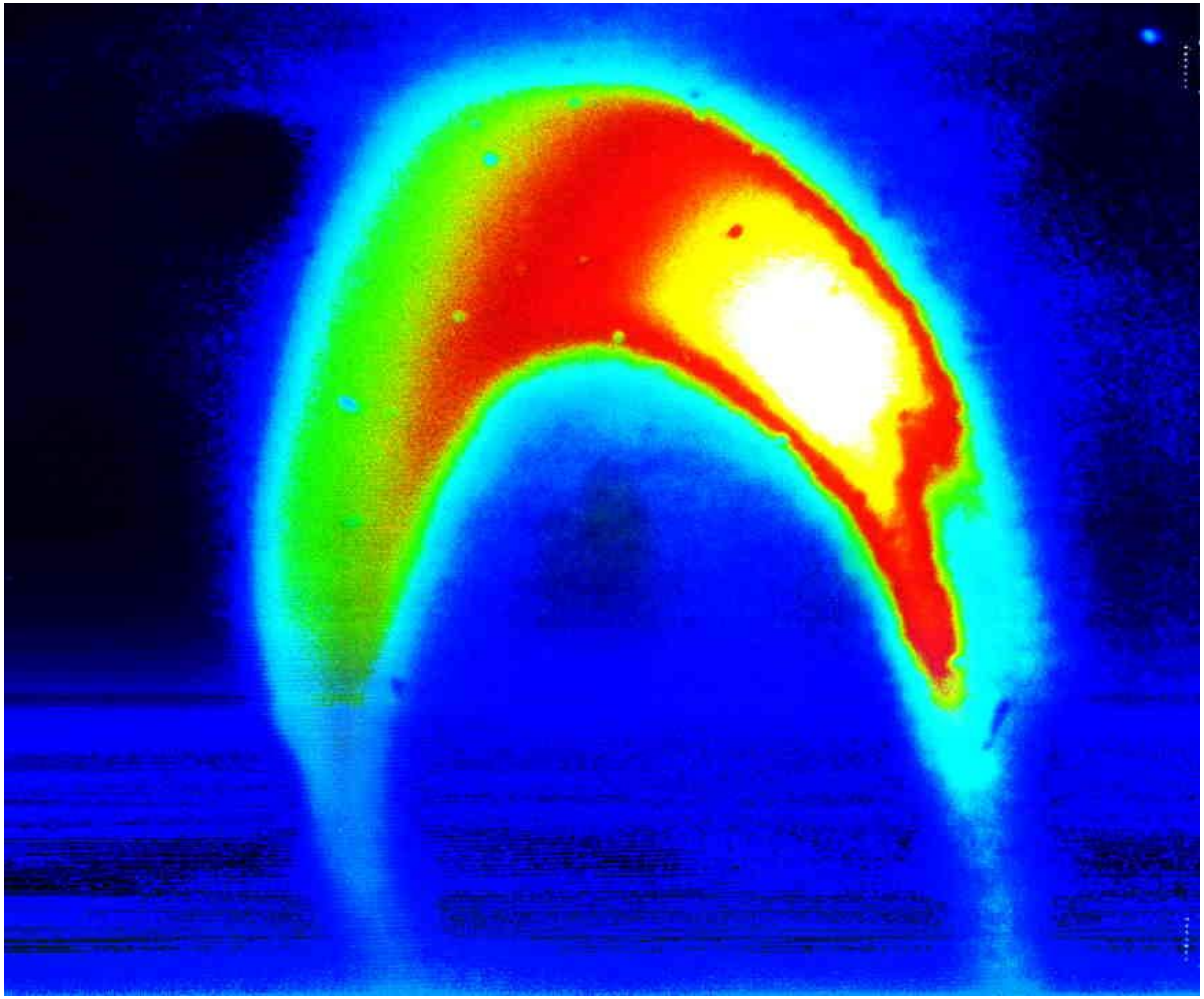
mission accomplished?

world record spot size achieved!

but ≤ 1% of design luminosity if this were a linear collider

halo and background …

Is there halo in linear colliders?



Yes, measured beam distribution at the end of the SLAC linac (projection on the x-y plane)!

let us look at the SLC prediction…

S L C
DESIGN HANDBOOK

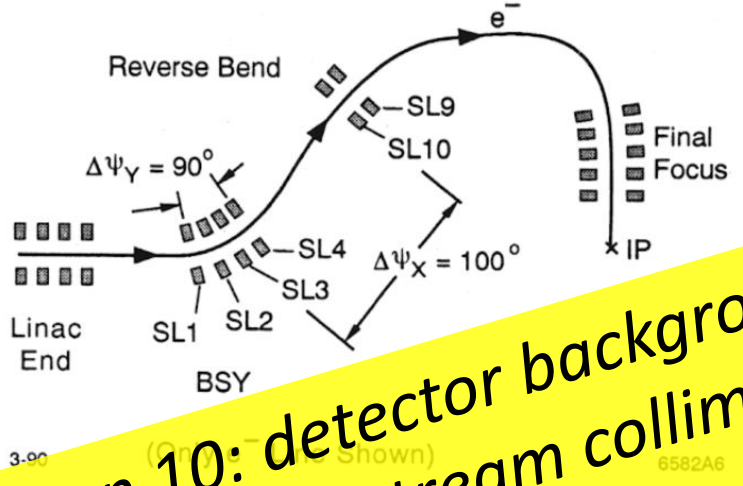
STANFORD LINEAR ACCELERATOR CENTER
STANFORD UNIVERSITY
Stanford, California 94305

December 1984

Prepared for DOE under Contract
No. DE AC03-76SF 00515

9.3 BACKGROUNDS This section is not yet ready for distribution.

collimation and beam-loss induced muon background



SLC solutions:
many collimators +
large toroidal magnets installed around the beam line to deflect particles traveling outside the beam pipe

Lesson 10: detector background from muons created by upstream collimation may seriously impact detector operation and constrain luminosity; large, expensive spoiler systems ("tunnel fillers") required fir next generation of linear colliders

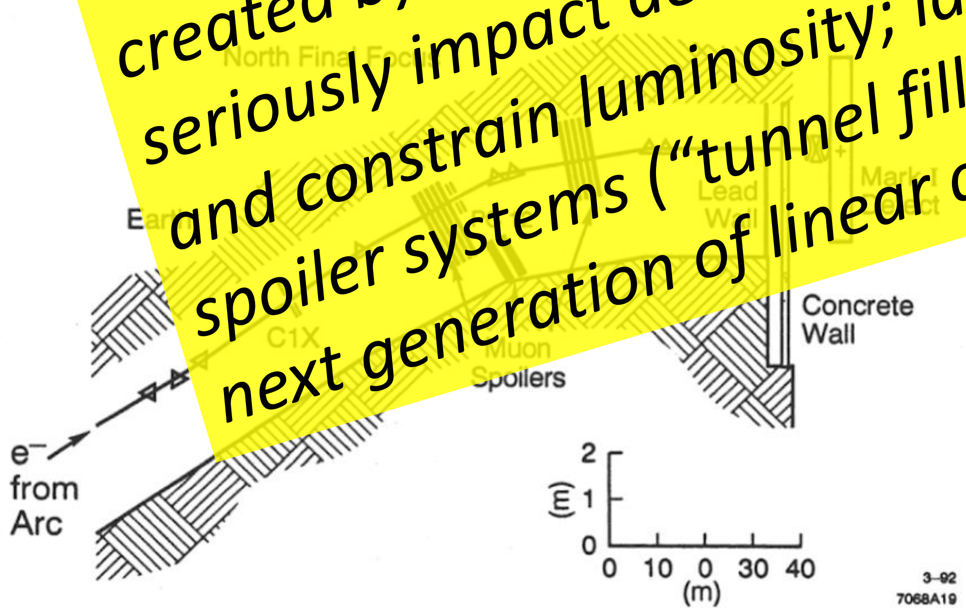


Figure 22. Layout of toroidal muon spoilers in the Final Focus tunnel at the SLC. The collimators C1X and PC12 are slits used to shadow the apertures of the final quadrupole lenses shown near the detector.

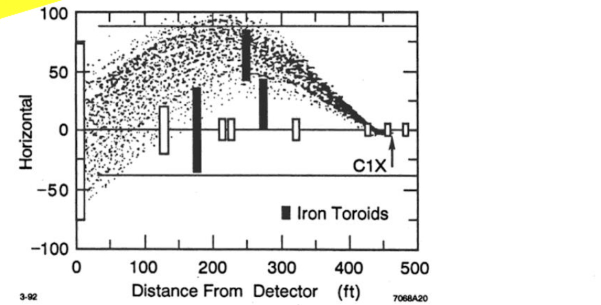


Figure 23. Trajectories of muons created in the collimator C1X that would reach the detector in the absence of toroidal fields.

D.L. Burke, Experimental Challenges at Linear Colliders, 1992 a few conclusions

SLC’s prime challenges and opportunities:

Halo ! Resonances ! Jitter ! Spot size ! Polarization !

SLC shows linear colliders = paradise for accelerator folks
→ new diagnostics, new mathematics, new tools, new methods, new phenomena, …

SLC spot-size puzzles continued at FFTB and ATF-2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