The Road to Bangalore

A Brief Historical Chronology of Linear Colliders up to 2006

Presentation by

Gregory Loew, SLAC

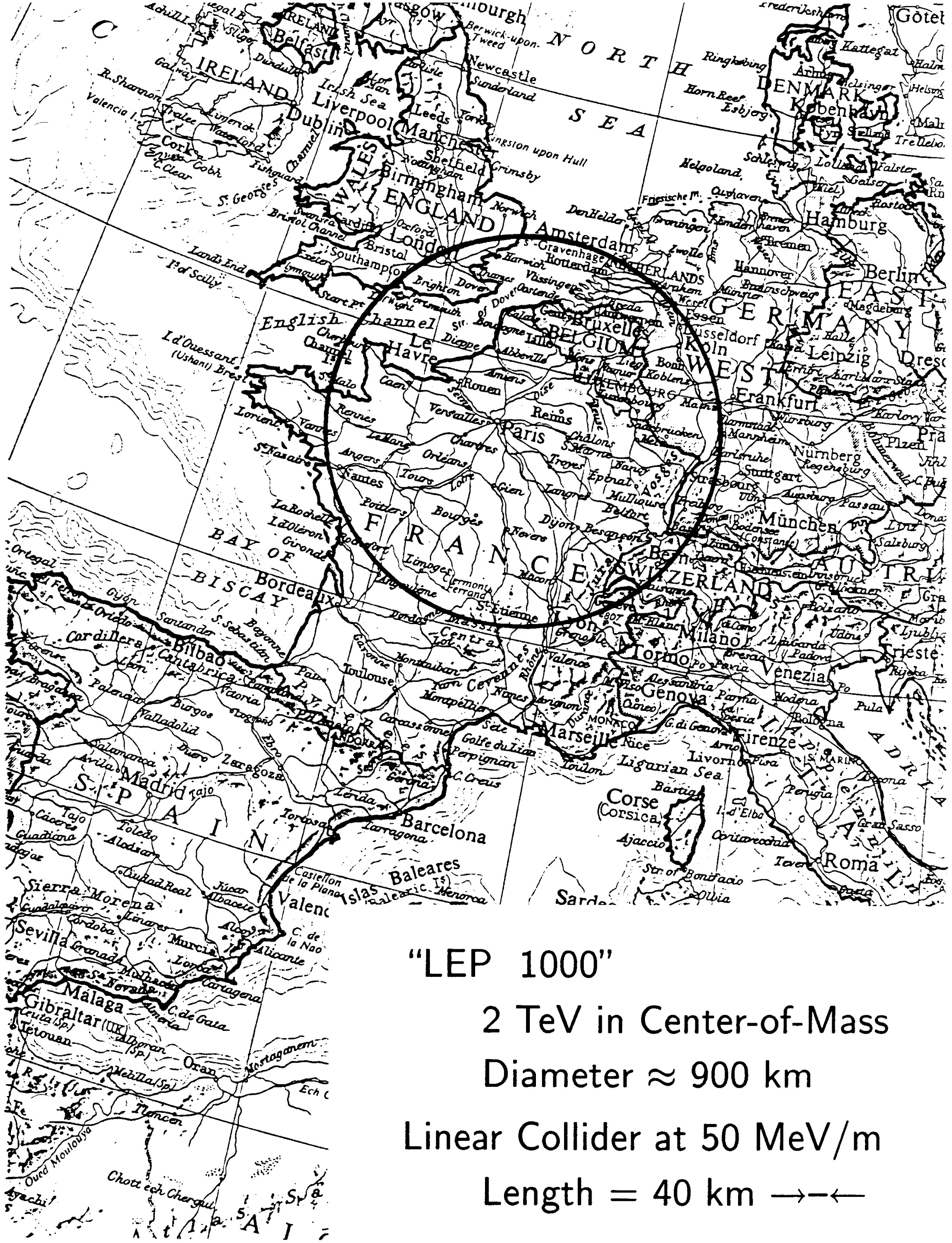
March 9-12, 2006

Awakening of the Linear Colliders
1960's – 1970's

- **The 1960's and 1970's witnessed the proliferation and success of the lepton-lepton colliding beam storage rings. Starting with the Stanford-Princeton and the INP $e^- e^-$ machines, numerous $e^+ e^-$ colliders followed: ADA, ACO and VEPP1, ADONE, CEA, SPEAR, DORIS, VEPP2, 3 and 4, PEP-1, PETRA and eventually TRISTAN, BEPC-1 and LEP.**

- **The success of these $e^+ e^-$ colliders also heralded their limits: at some energy exceeding LEP's design, their cost, scaling as E^2, would become prohibitive, even with superconducting RF.**

- **Between 1971 and 1978, $e^+ e^-$ linear colliders began to be discussed at INP, Novosibirsk by G. Budker, and associates A. Skrinsky, V.Balakin, A. Novokhatski, V. Smirnov (later of BNS Damping), and VLEPP Project was conceived. Budker died in 1977.**



"LEP 1000"

2 TeV in Center-of-Mass

Diameter $\approx$ 900 km

Linear Collider at 50 MeV/m

Length = 40 km $\rightarrow - \leftarrow$

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Awakening of the Linear Colliders 1960's – 1970's, cont.

- **U. Amaldi at CERN presented schemes for very high energy $e^- e^-$ and $e^+ e^-$ linear colliders (Phys Letters, 29 March 1976).**

- **The first international discussion of linear colliders took place at the ICFA Workshop at Fermilab in October 1978 where Richter, Skrinsky, Tigner, Rees and others wrote seminal paper on LC scaling laws and critical parameters.* The realization that LC costs would scale linearly with energy whereas storage rings costs scale as E^2 put the future of LC's on the map.**

- **In late 1978, B. Richter, realizing a storage ring competing with LEP could not be built on the SLAC campus, came up with the idea of the SLC.**

*** (J.E. Augustin, et al, Proceedings, Possibilities and Limitations of Accelerators and Detectors, Batavia 1979, 87-105.)**

Proceedings of the Workshop on Possibilities and Limitations of Accelerators and Detectors Held at Fermi National Laboratory

October 15-21, 1978

Limitations on Performance of e+ e- Storage Rings and Linear Colliding Beam Systems at High Energy

J.-E. Augustin, N. Dikanski, Ya. Derbenev, J. Rees, B. Richter, A. Skrinski, M. Tigner, and H. Wiedemann

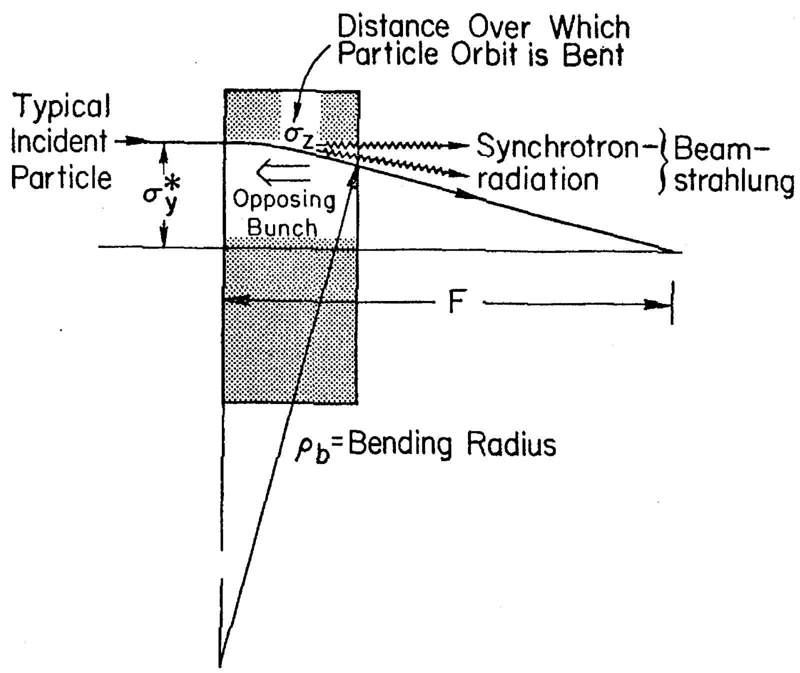
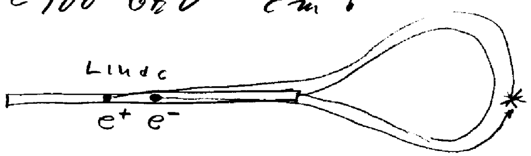


Fig. 1. Typical particle incident on an opposing bunch.

Burt Richter's Lab Notebook
18 Dec. 1978

18 DEC 78 Linear Coll Bms

Can we use PEP or basis of linear coll bm system to get ~100 GEV cm?



1) e^+ & e^- accel during same linac pulse.
2) Time delay sets where coll occur.
3) Bend field increased to allow high energy particles to go around.

Ignore for now source of e^+

1st question — synch loss
2nd " energy spread
3rd " bm size

Q1. Energy loss $U_0 = 8.85 \times 10^{-5} \frac{E^4_{GeV}}{\rho_{meters}}$

at 15 GEV

Transp line

B	θ (mrad)	# of mags	ρ	$U_0(15)$
10.6	66	1	47	.0010
12.5	66	1	40	.0012
12.5	131	7	40	.0163
7.9	83	1	63	.0009
	1.13 radians			.019 GEV

Potential Big Problem with beam lines!

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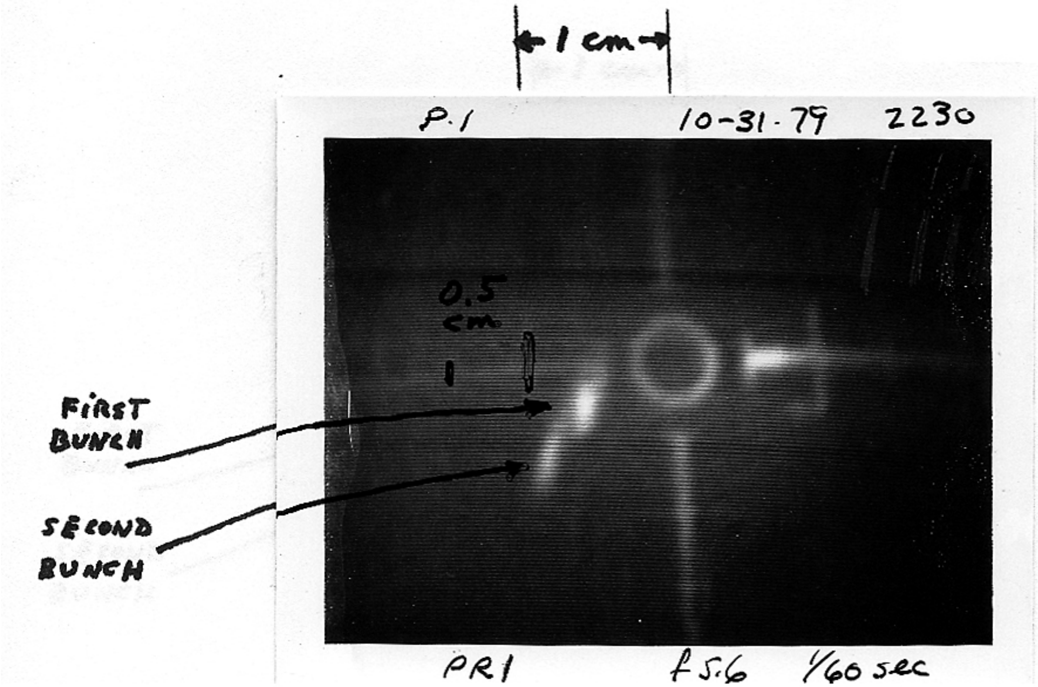
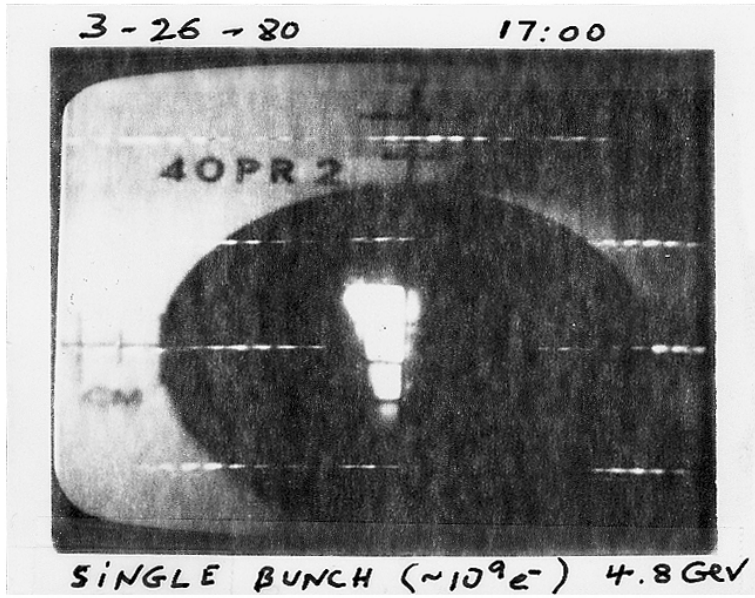
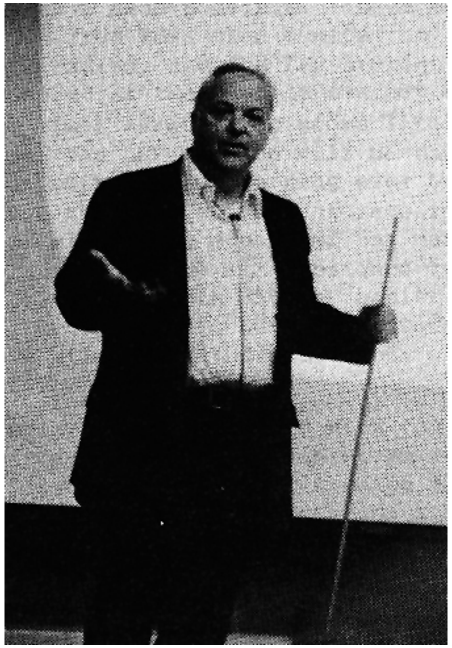


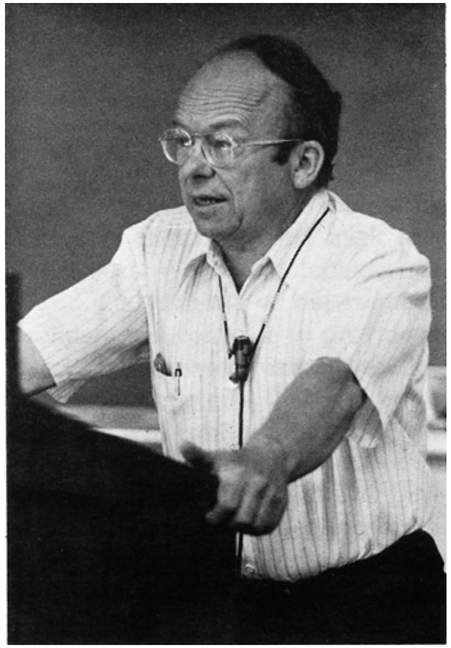


1979-1980 Transverse Wakefield Experiments

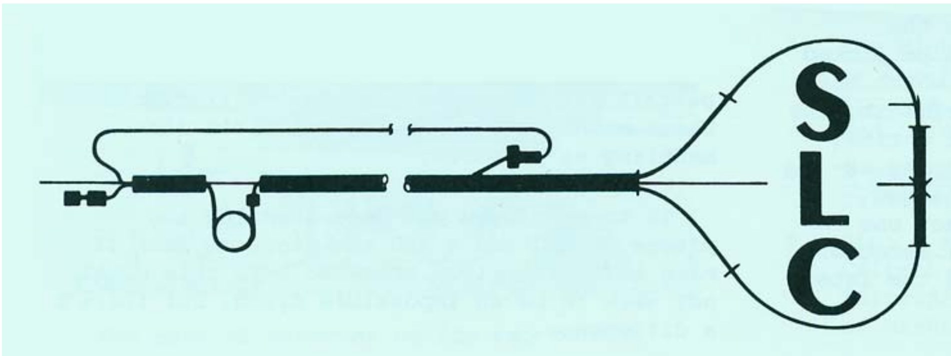
Stanford's Hope for Heavy Boson
Stanford Pulls Off a Novel Accelerator

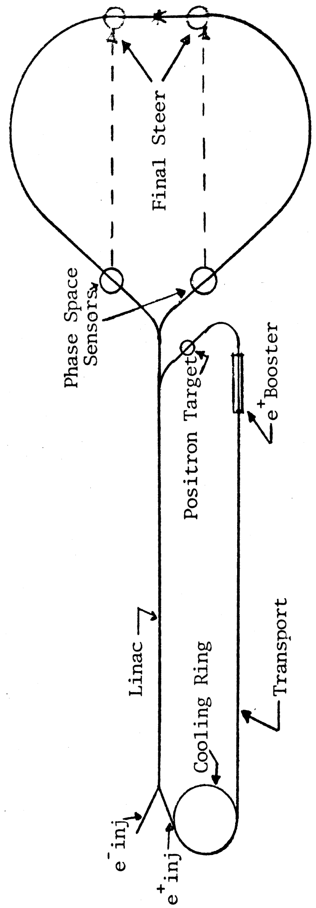


Burton Richter
1981

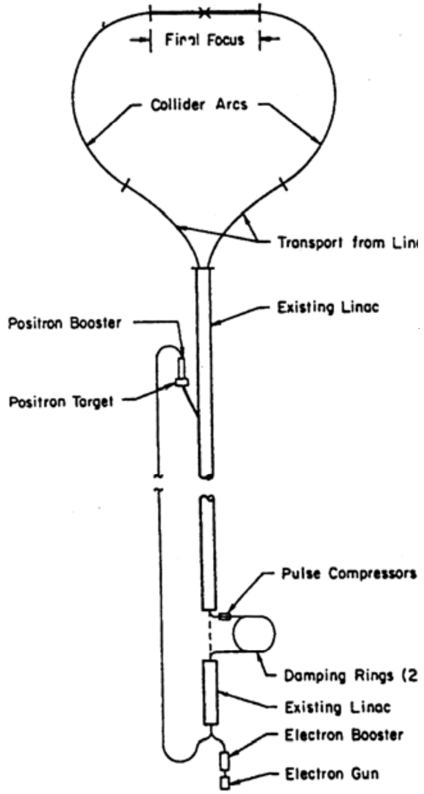


W.K.H. Panofsky
1983

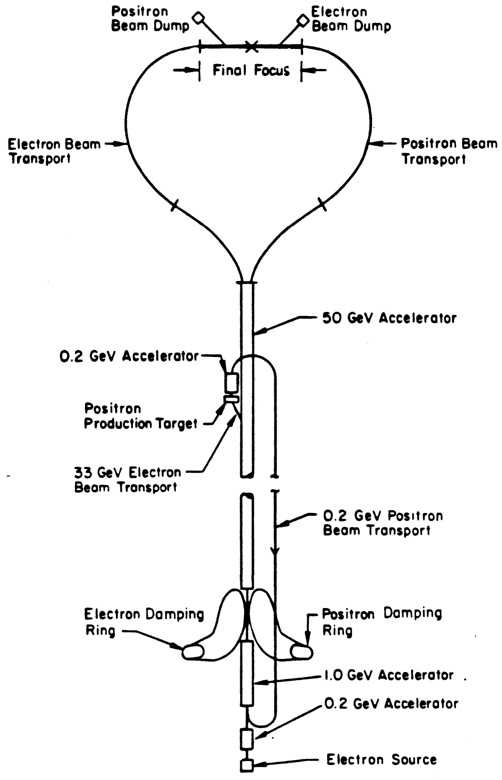




B. Richter
AATF Note 79/3
August 1979

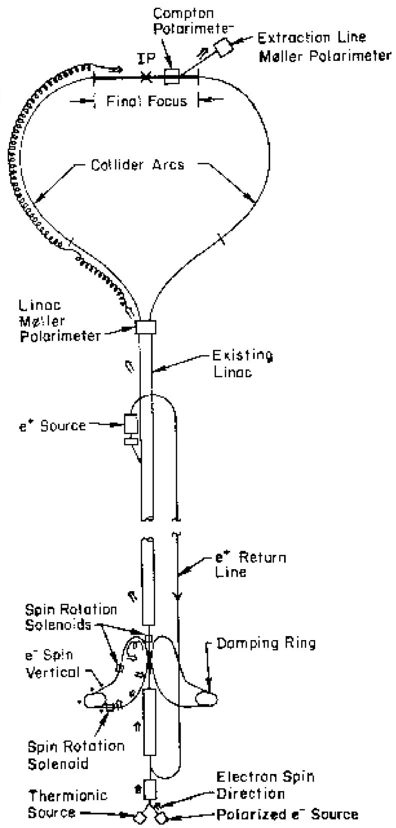


SLC CDR
June 1980



OVERALL SLC LAYOUT

SLC as completed
In 1987 with Mark II
First Z - 4/13/1989

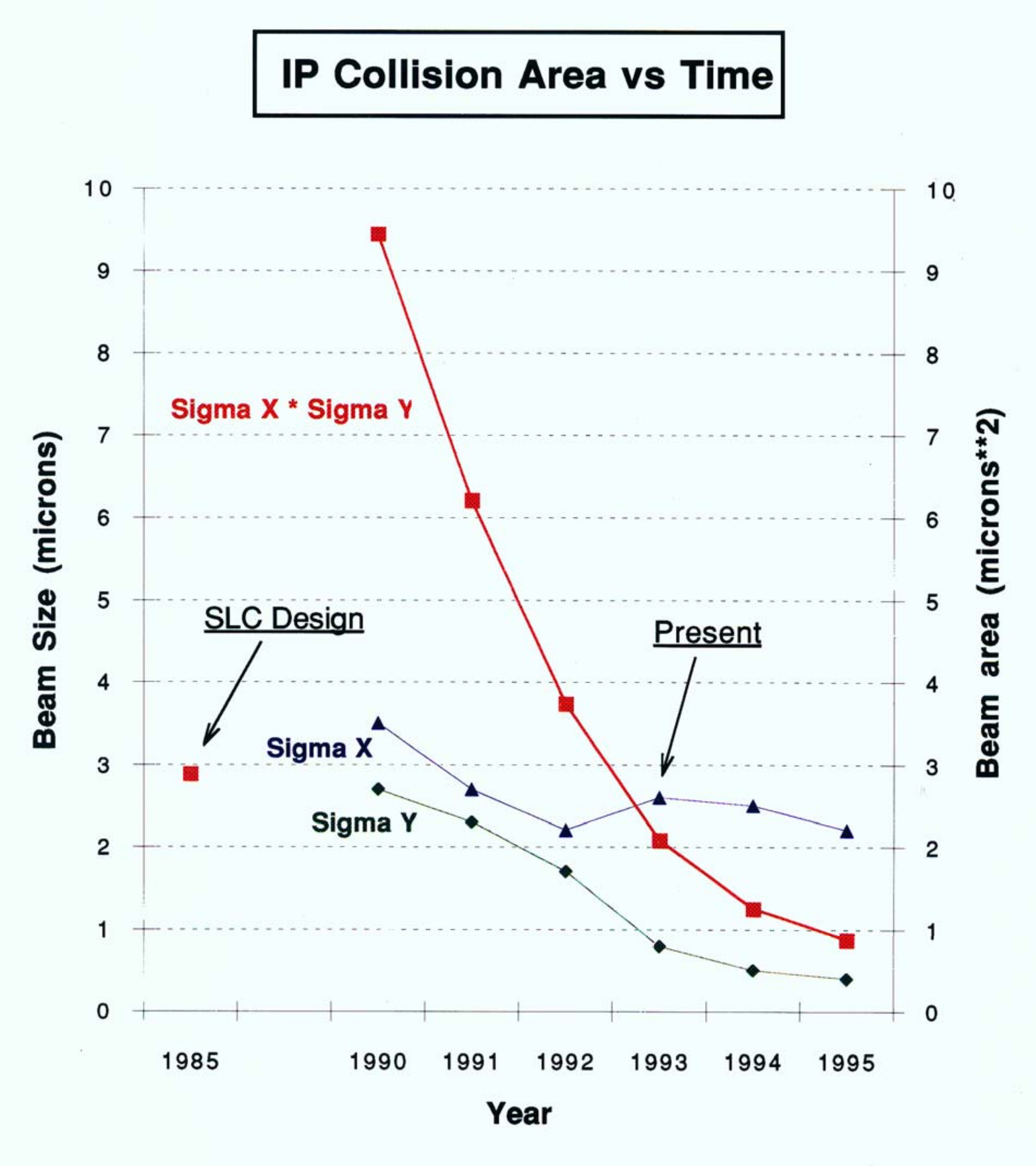


POLARIZATION IN THE OVERALL SLC LAYOUT

SLC with SLD
and e^- Polarization
1991 - 1998

Innovations Brought About by the SLC and FFTB

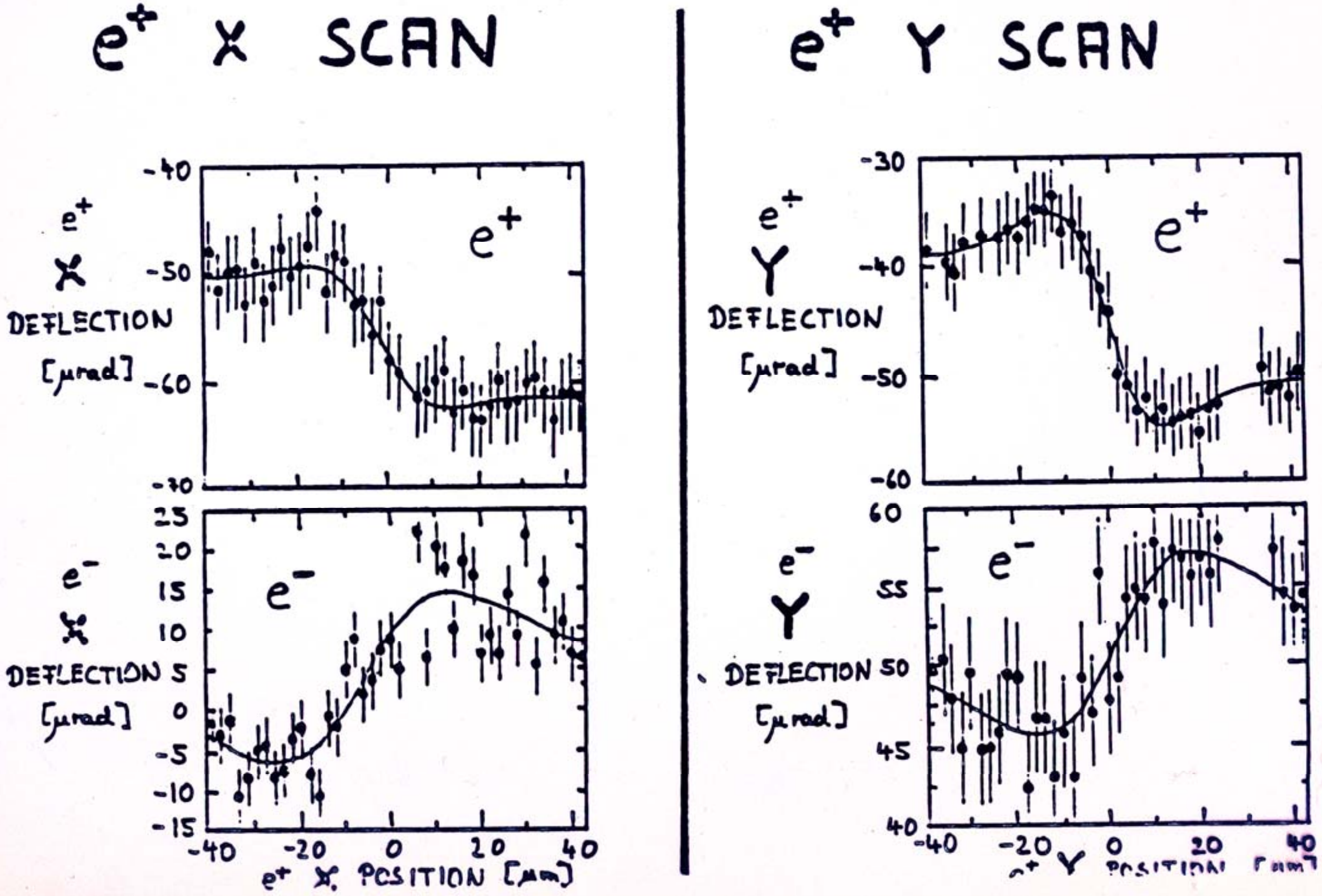
- New "5045" Klystrons and SLED II RF Pulse Compression
- New Positron Source
- Damping Rings and Fast Kickers, Instability Cures
- Measurements and Corrections of Wakefields (including ASSET Facility)
- Flat Beams
- Beam Based Alignment and Dispersion Free Steering (Raubenheimer Ph.D.)
- Modeling Effects of Ground Vibrations on Beam Properties, Magnet Movers
- Thermo-Mechanical Stability Controls
- BPM's, Wire Scanners and Laser Wires
- Smart Feedback and Feedforward Systems
- Combined Function Magnet Achromats for Arcs
- Innovative Final Focus Systems, including Muon Suppression, Collimators, and SC Final Quadrupoles
- Beamstrahlung and Pinch Observations, Beam-Beam Collision Optimization via Deflection Scans
- Control of Backgrounds
- Pulse-to-Pulse Electron Polarization
- Compton Polarimeter and Energy Spectrometer at FF
- High Precision Bend and Focusing Magnets
- RF BPM's
- Laser-Compton Spot Size (Shintake) Monitor



IP Collision Area vs Time
Sigma X * Sigma Y
SLC Design
Present
Sigma X
Sigma Y
Beam Size (microns)
Beam area (microns**2)
Year
1985
1990
1991
1992
1993
1994
1995

OBSERVATION OF SIMULTANEOUS DEFLECTION OF BOTH BEAMS:

BEAMS INITIALLY WELL CENTERED
(NO DEFLECTION PERPENDICULAR TO SCAN DIRECTION)

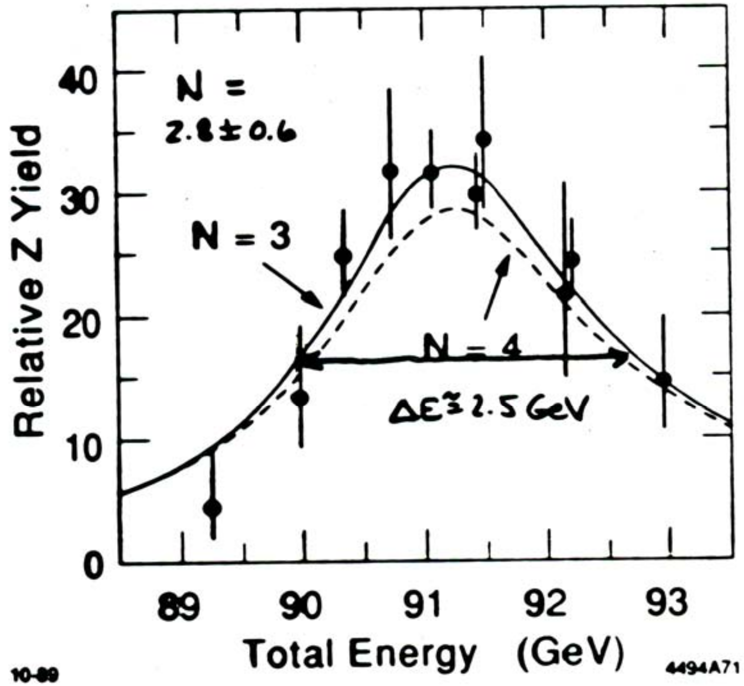


Only 3 Neutrinos!

Data from 1989 SLC Run

April - October 1989

~500 events



Lifetime of Z particle:

Heisenberg U.P. $\Delta E \, \Delta t \approx \frac{h}{2\pi} = 6.6 \times 10^{-25}$ GeV-sec

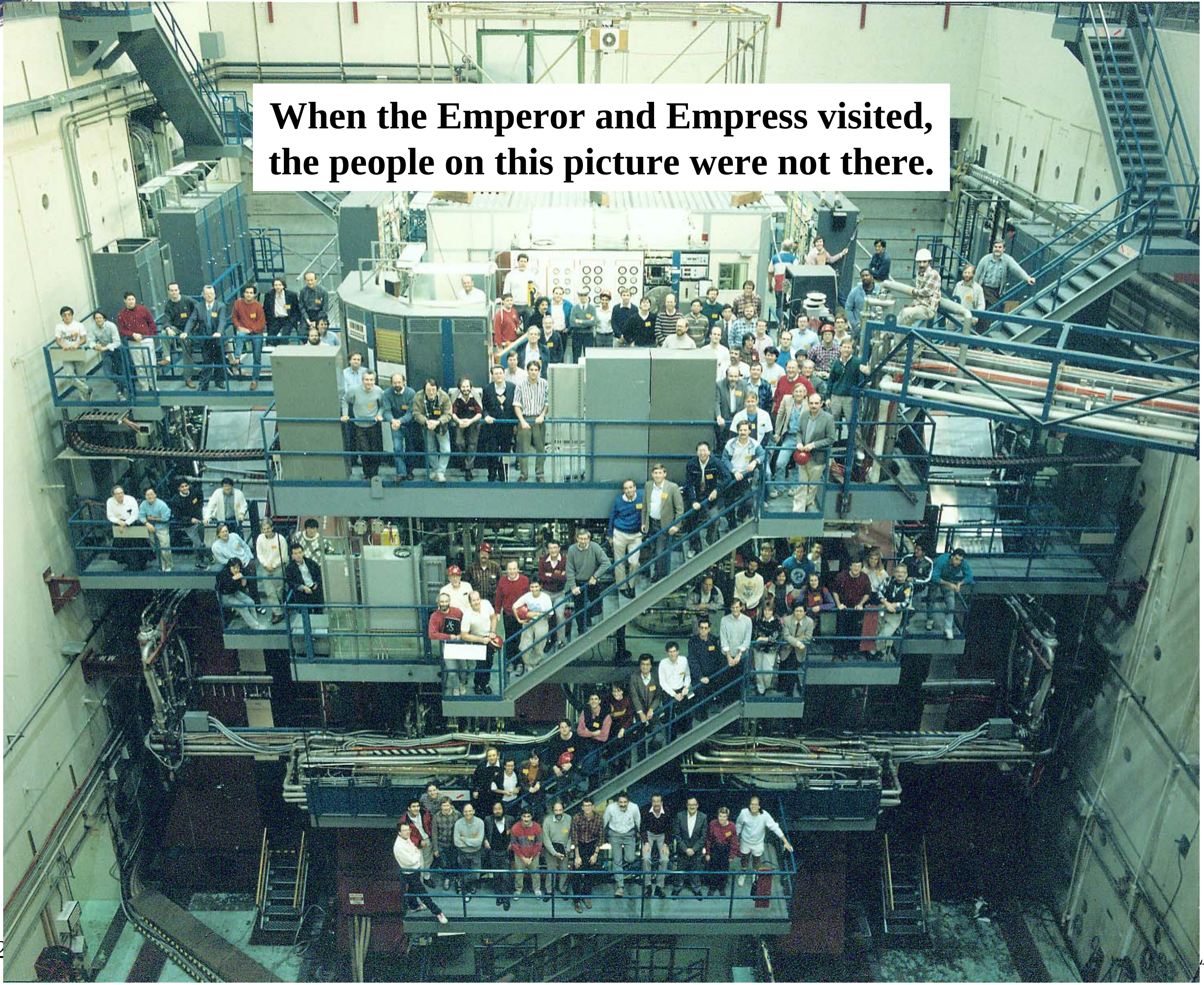
$\therefore \Delta t \approx \frac{6.6}{2.5} \times 10^{-25}$ sec

$\Delta t \approx 2.6 \times 10^{-25}$

Anxious Workers

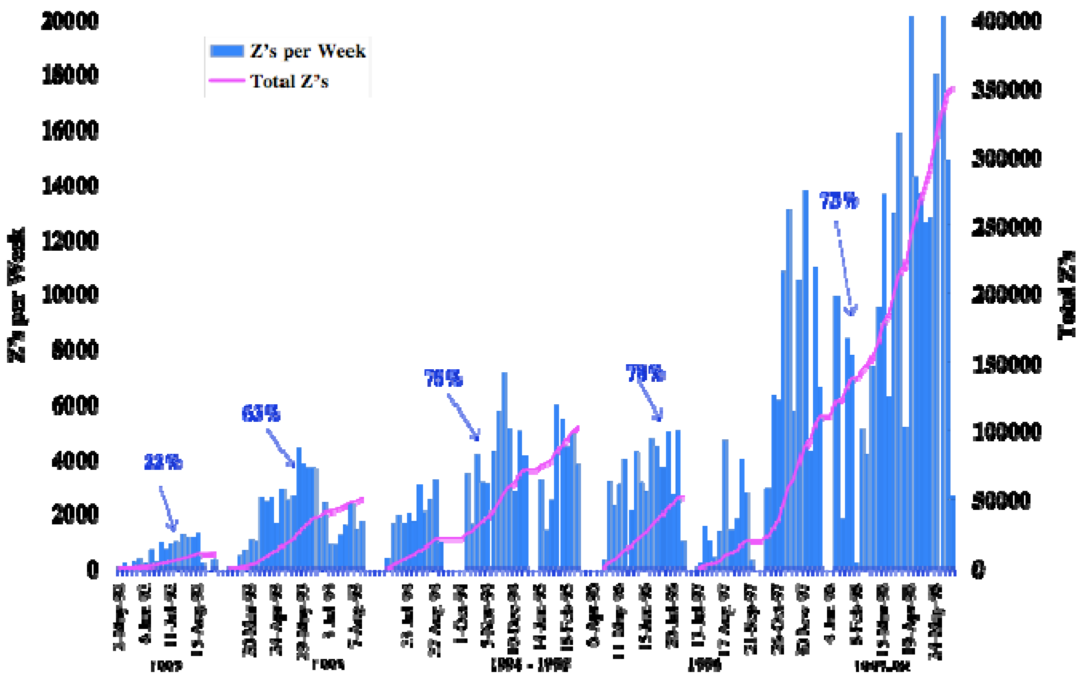
The Emperor and Empress With Guides

SLD – in the Early Days



The Empress Leaving

1992/8 SLD Run



- Proposed 1986:
- Luminosity: 6×10^{30} cm^{-2}s^{-1}
- Z events: $>10^6$
- Polarization: 40-50%
- $\Delta P/P$: 3-5%
- ΔA_{LR}: 0.005

- Achieved 1998:
- Luminosity: 4×10^{30} cm^{-2}s^{-1}
- Z events: 0.5×10^6
- Polarization: 72%
- $\Delta P/P$: 0.5%
- ΔA_{LR}: 0.002

1980-2000: Toward the Large Linear Colliders

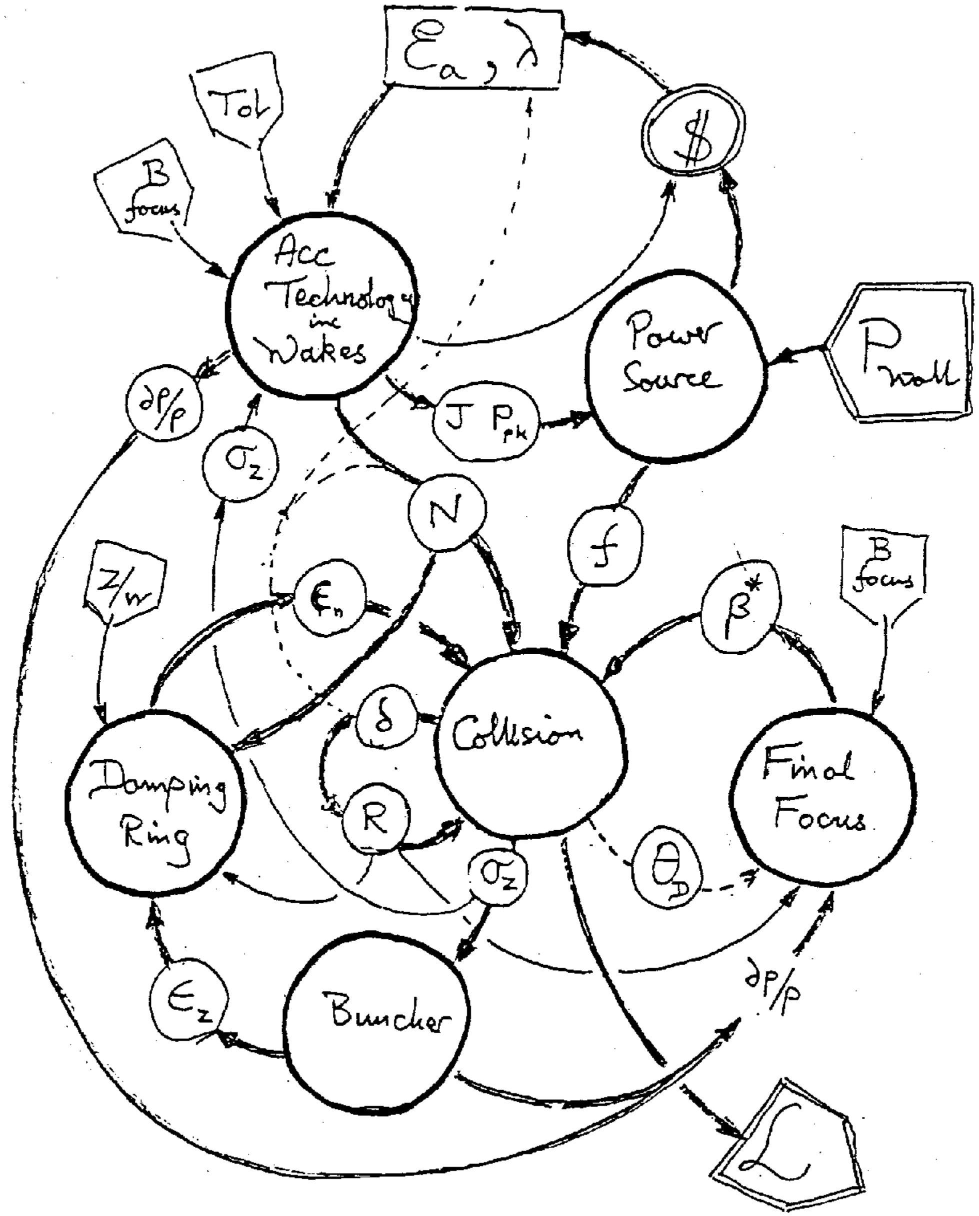
- Seminal LC papers with parameter sets explore all potential technologies including conventional RF , lasertron driver, SC RF, two-beam, wakefield driver, FEL driver, switched power radial driver and others

- Various Interlab Collaborations with MOU's are formed (KEK-SLAC, TESLA, SBLC, VLEPP, CLIC, etc.)

- In 1987, Burt Richter proposes that a true international collaboration on future LC R&D be formed

- In response, starting in 1988, regular LC workshops begin

- In 1994 Dave Burke prompts Interlaboratory LC Council to create ILC-TRC which produces first TRC Report in December 1995



Bob Palmer's 1988 Simple LC Parameter Model


1988 KEK/SLAC LC Workshop


US/Japan Collaboration after Global Warming

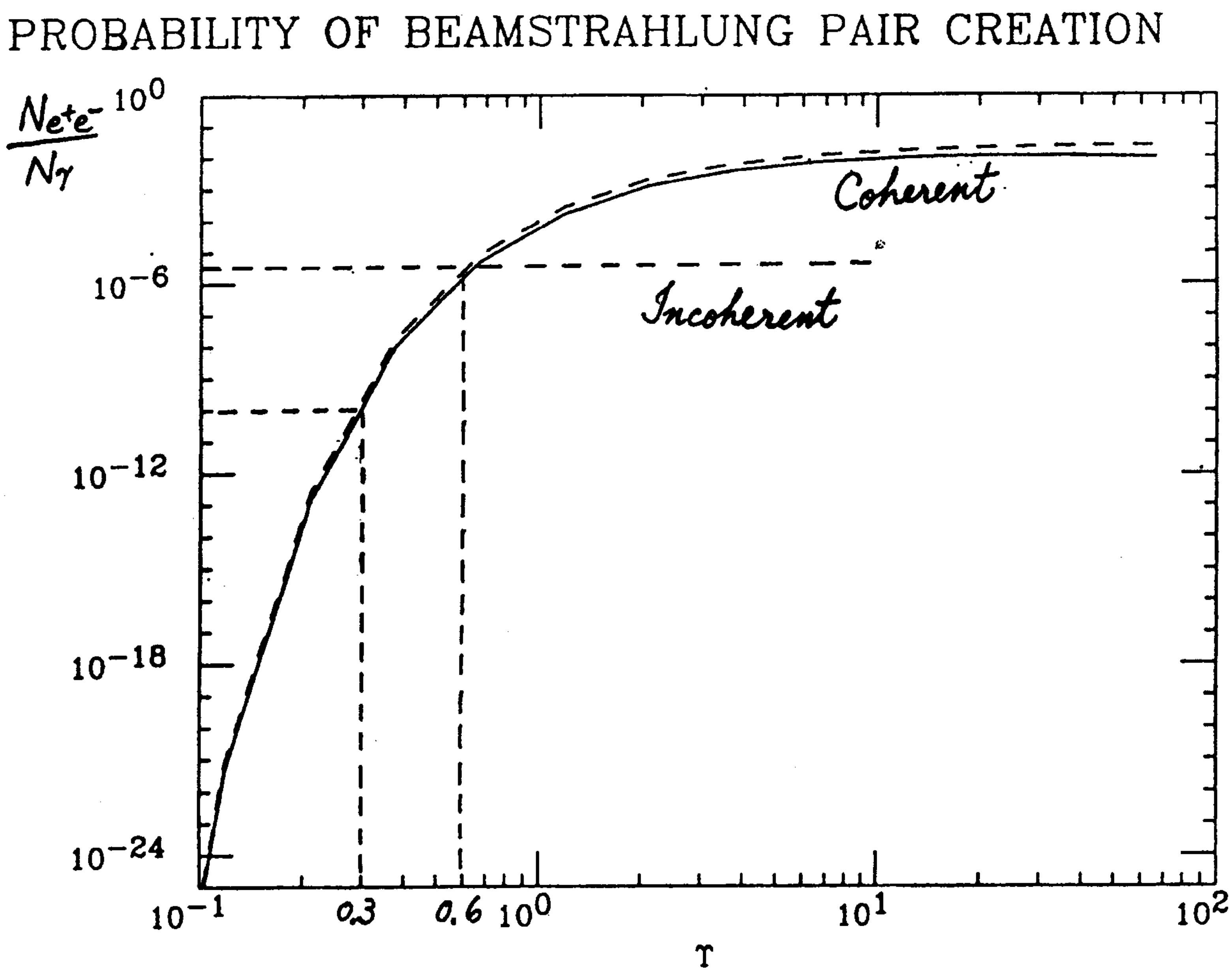
International Linear Collider Workshops

Accelerator Physics

Year	Workshop	Location
1988	LC88	SLAC
1990	LC90	KEK
1991	LC91	Protvino
1992	LC92	Garmisch
1993	LC93	SLAC
1995	LC95	KEK
1997	LC97	BINP, Zvenigorod
1999	LC99	INFN, Frascati
2002	LC02	SLAC
2004	1st ILC Workshop	KEK
2005	2nd ILC Workshop	Snowmass

Particle Physics

Year	Workshop	Location
1991	LCWS91	Saariselkä, Finland
1993	LCWS93	Waikoloa, HI
1995	LCWS95	Morioka-Appi, Japan
1999	LCWS99	Sitges, Barcelona, Spain
2000	LCWS00	Fermilab Batavia, IL USA
2002	LCWS02	Jeju, Korea
2004	LCWS04	Paris, France
2005	LCWS05	Stanford, USA
2006	LCWS06	Bangalore, India



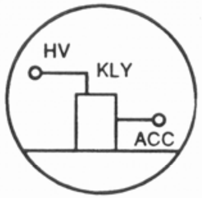
The Big Scare of LC88 at SLAC (Chen – Telnov – Yokoya)

Table 6
Tunnel Models and Costs

LC 92 (GARMISCH)

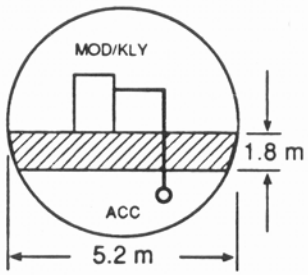
LC92 (Garmisch)

VLEPP-TYPE
(Single Tunnel)



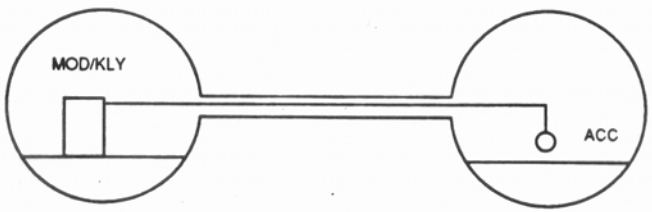
~ 6 k$/m in West
(much cheaper in Russia)

DESY-TYPE
(Like Hera Tunnel)



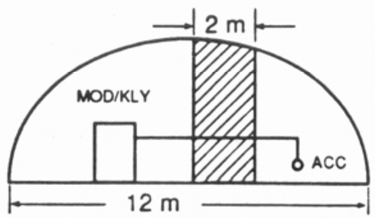
~ 8 k$/m

SLAC-TYPE
(Two Connected
Tunnels)



~ 14 k$/m

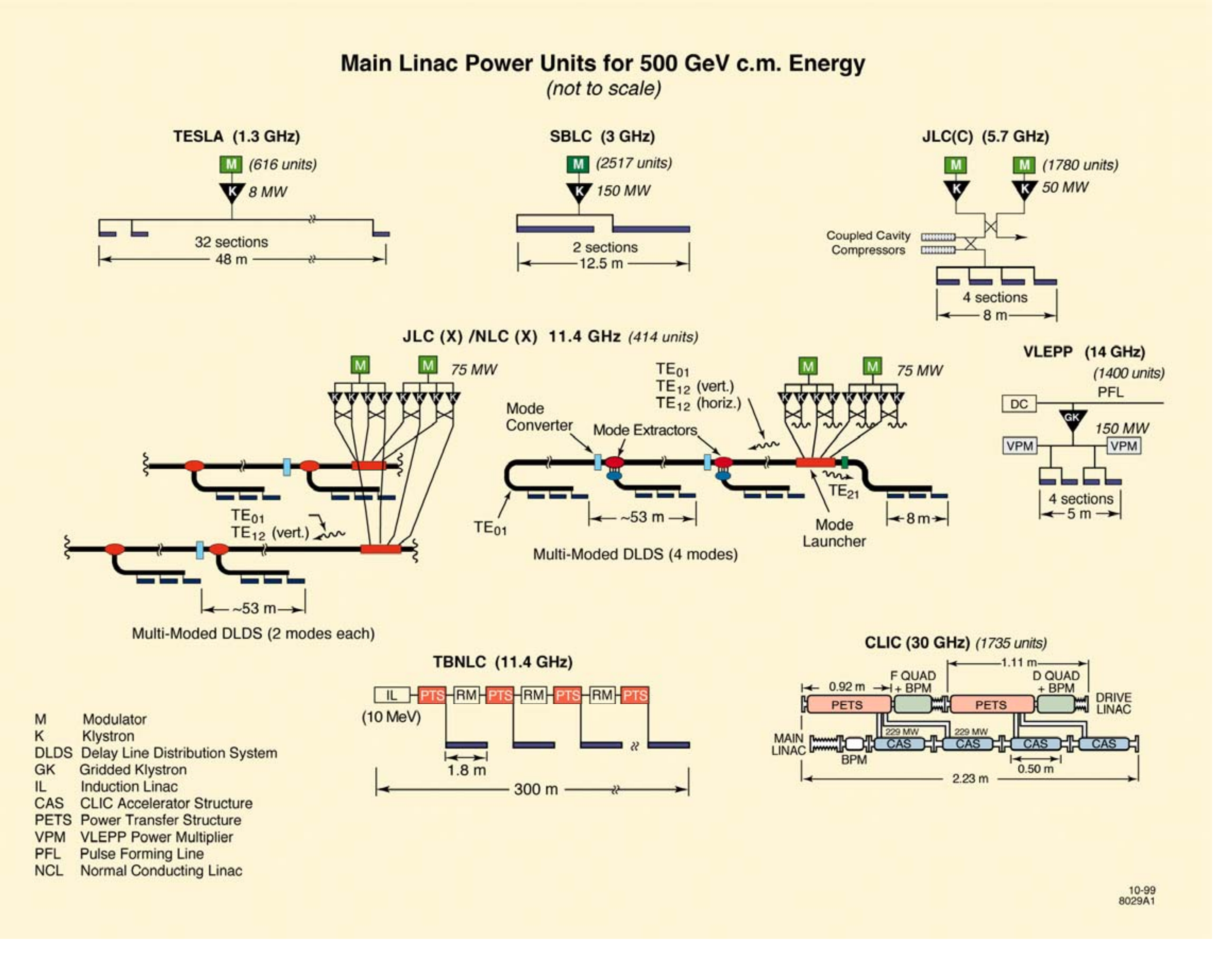
KEK-TYPE



~ 20 k$/m

10-92
7227A10

ILC-TRC 1995


Main Linac Power Units for 500 GeV c.m. Energy
(not to scale)
TESLA (1.3 GHz)
(616 units)
8 MW
32 sections
48 m
SBLC (3 GHz)
(2517 units)
150 MW
2 sections
12.5 m
JLC(C) (5.7 GHz)
(1780 units)
50 MW
Coupled Cavity Compressors
4 sections
8 m
JLC (X) /NLC (X) 11.4 GHz (414 units)
75 MW
Mode Converter
Mode Extractors
Mode Launcher
~53 m
8 m
Multi-Moded DLDS (4 modes)
Multi-Moded DLDS (2 modes each)
VLEPP (14 GHz)
(1400 units)
PFL
DC
GK
150 MW
VPM
4 sections
5 m
TBNLC (11.4 GHz)
IL
PTS
RM
(10 MeV)
1.8 m
300 m
CLIC (30 GHz) (1735 units)
1.11 m
0.92 m
F QUAD + BPM
D QUAD + BPM
PETS
DRIVE LINAC
MAIN LINAC
CAS
BPM
229 MW
0.50 m
2.23 m
M Modulator
K Klystron
DLDS Delay Line Distribution System
GK Gridded Klystron
IL Induction Linac
CAS CLIC Accelerator Structure
PETS Power Transfer Structure
VPM VLEPP Power Multiplier
PFL Pulse Forming Line
NCL Normal Conducting Linac
10-99
8029A1

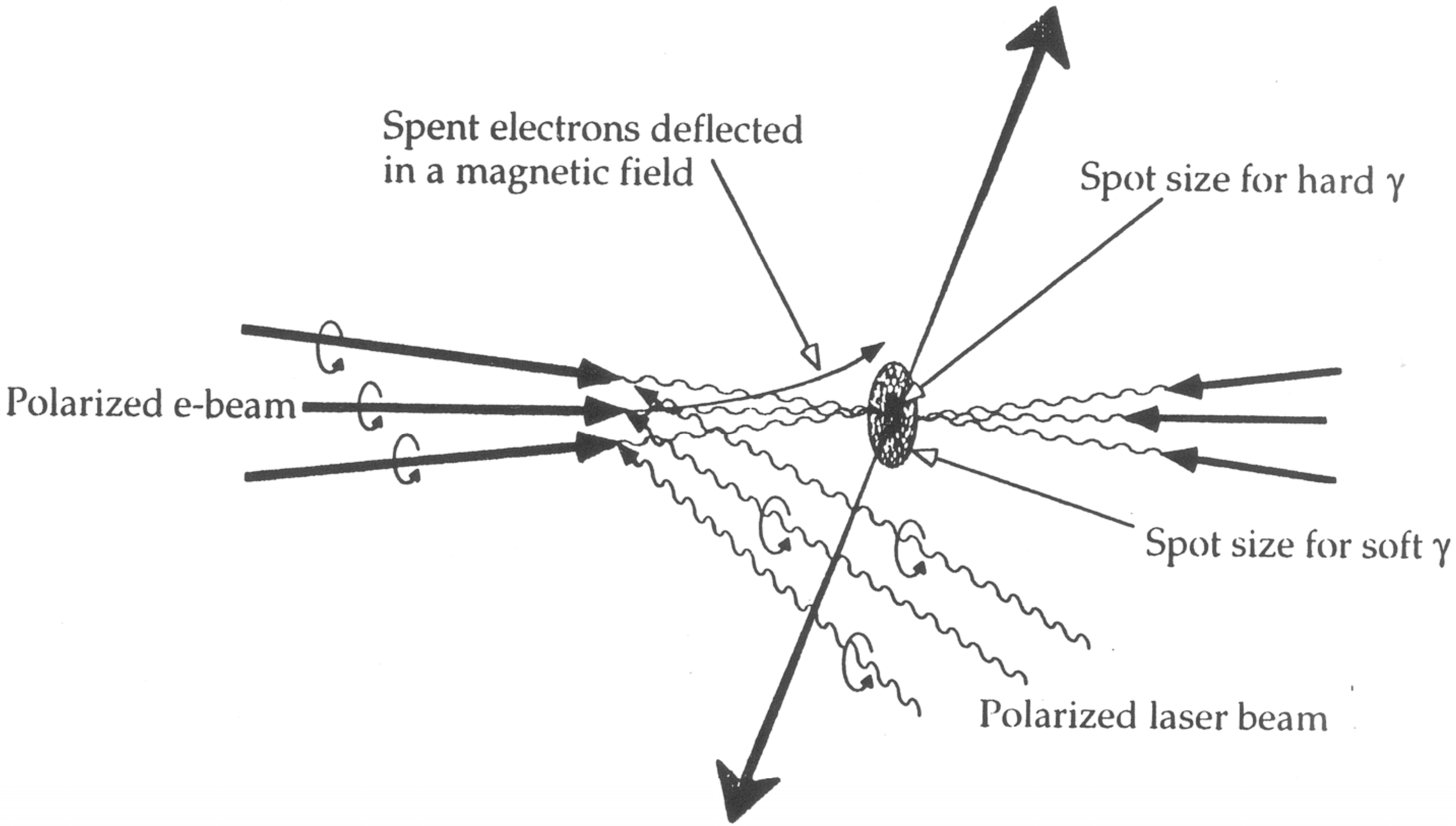


Fig.3.2.1 General schematic of a $\gamma\gamma$ collider interaction point.

Gamma-Gamma

Linear Collider Test Facilities

FACILITY	LOCATION	GOAL	OPERATIONS STARTED
FFTB	SLAC	Final Focus Interaction Region	1993
ASTA (rf) ASSET (wakes) NLCTA (linac)	SLAC	X-Band Tests	1995
ATF	KEK	Injector Damping Ring	1995 1996
SBTF	DESY	S-Band Linac	1996
CTF	CERN	2-Beam Linac	1996
TTF	DESY	SC Linac	1996
VLEPP	BINP	Various Prototypes	1966

FFTB Collaboration

BINP (Novosibirsk/Protvino)

DESY

Fermilab

IBM

Kawasaki

KEK

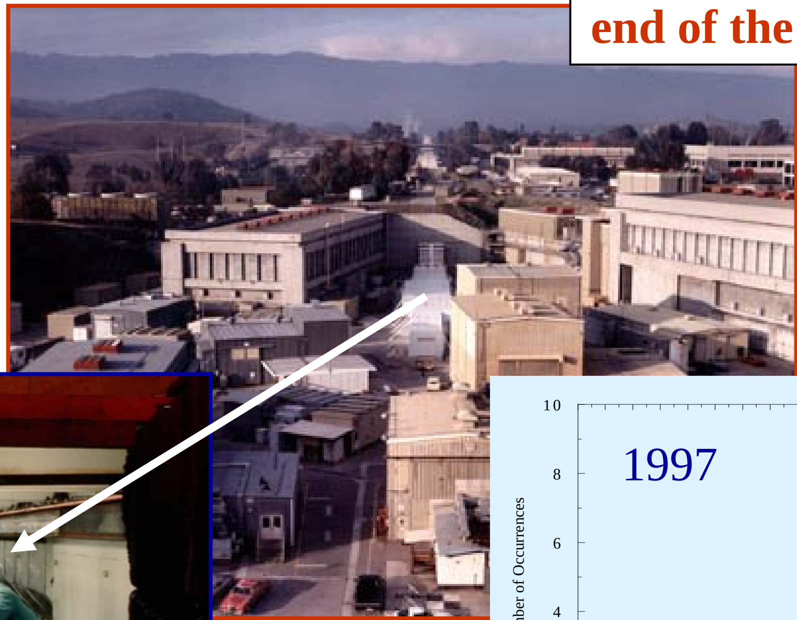
LAL (Orsay)

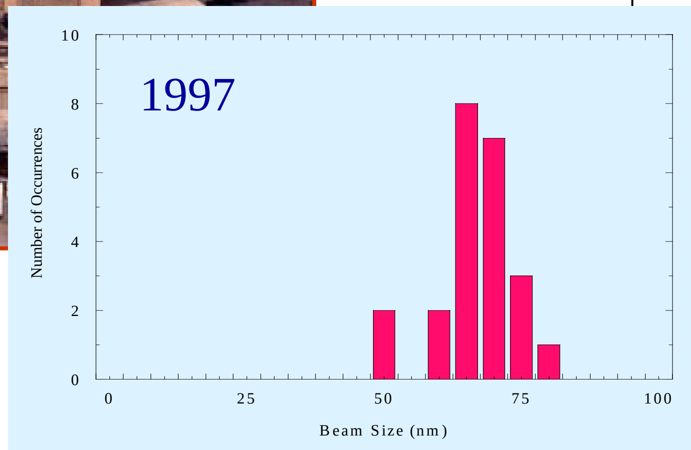
MPI(Munich)

Rochester

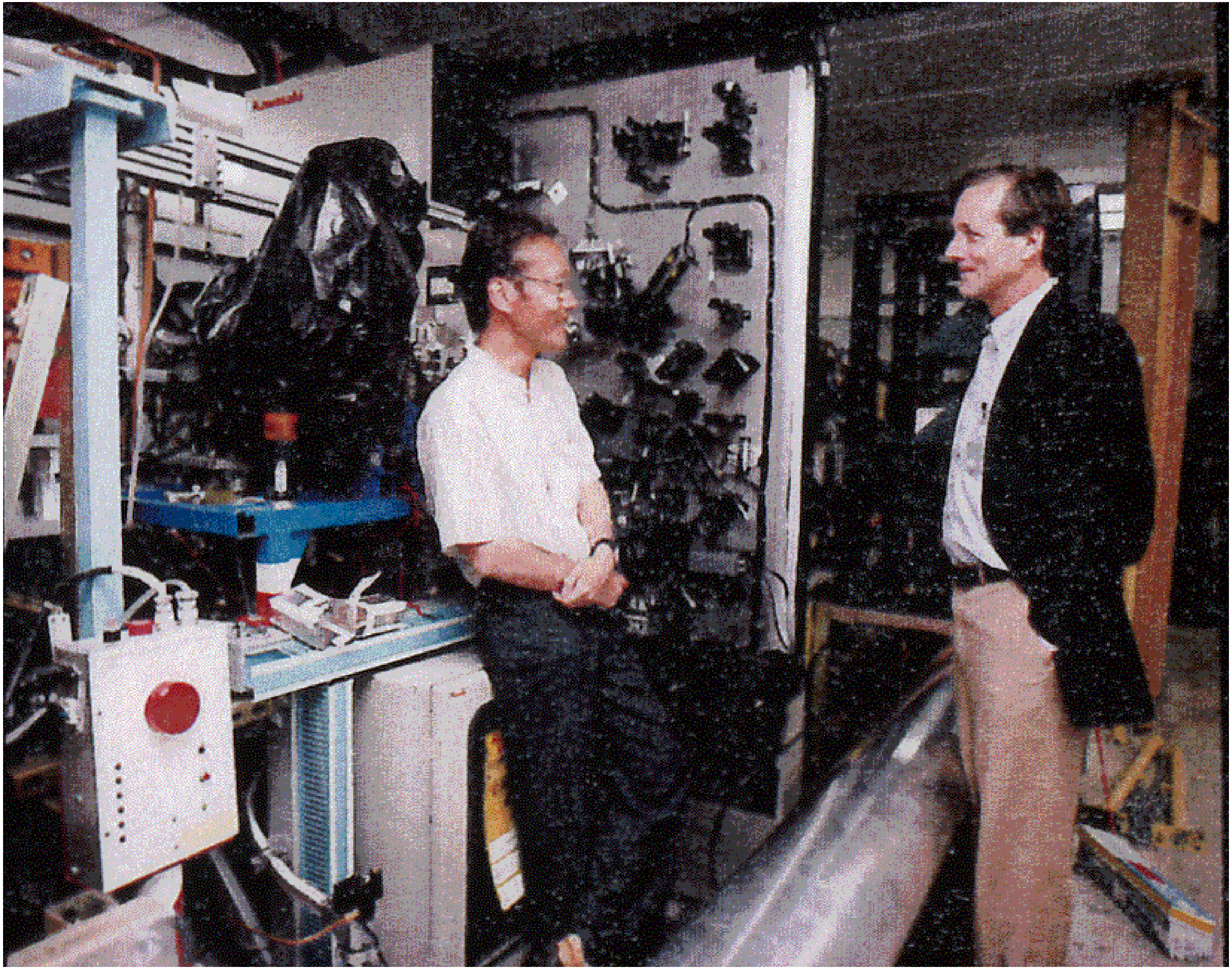
SLAC

FFTB beamline at the end of the SLAC linac.





Vertical beam size of 60-70 nm … demagnification needed for any linear collider.



Zvenigorod (LC97)

3/9-12/06

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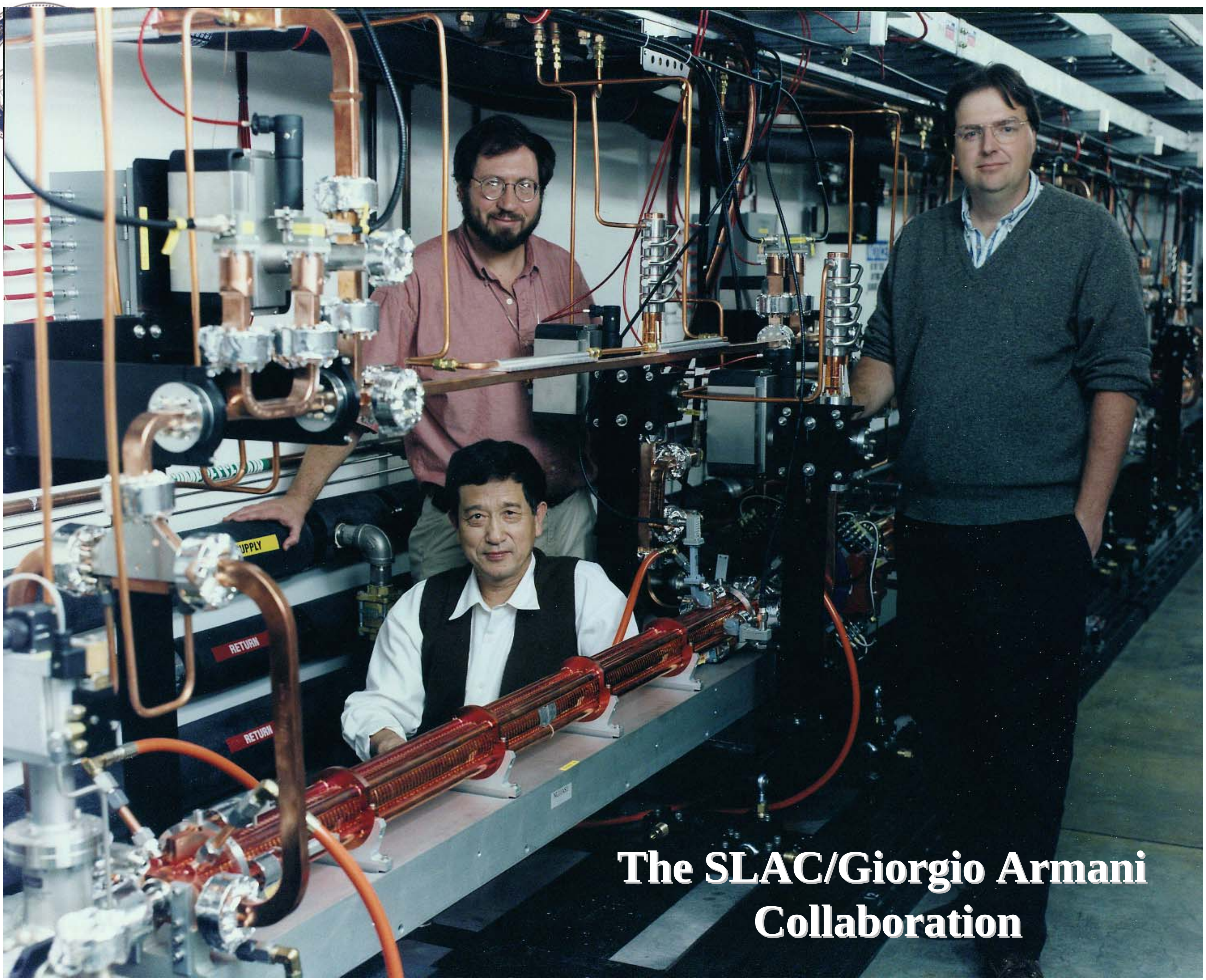
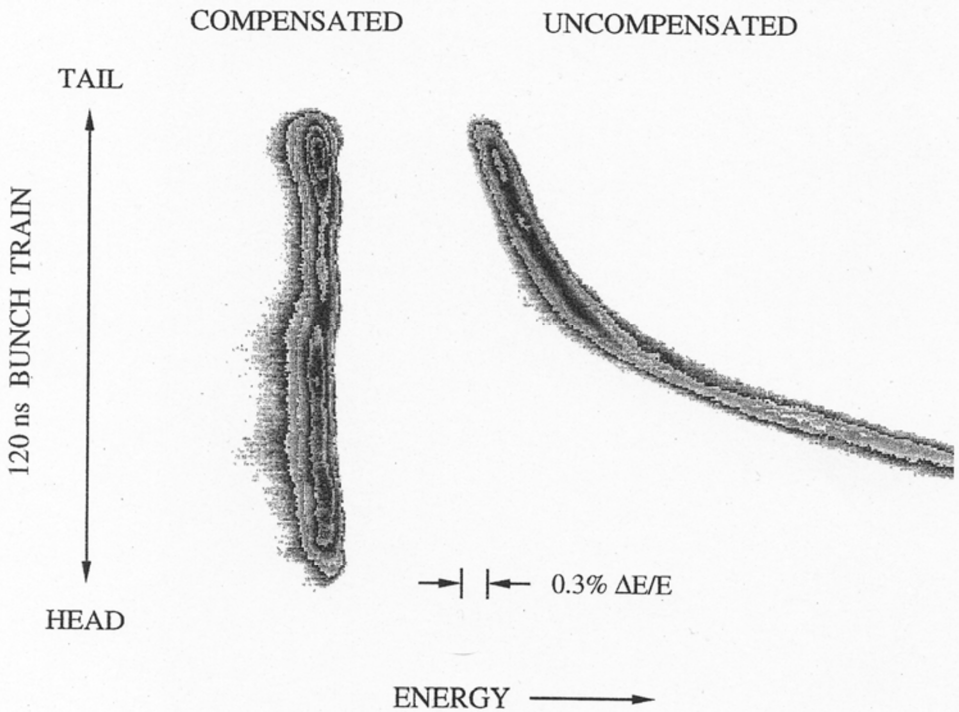


The SLAC/Giorgio Armani Collaboration

BEAM LOADING COMPENSATION

Method: Ramp RF Amplitude During Fill

Verification: Observe ΔE Variation Along Bunch Train



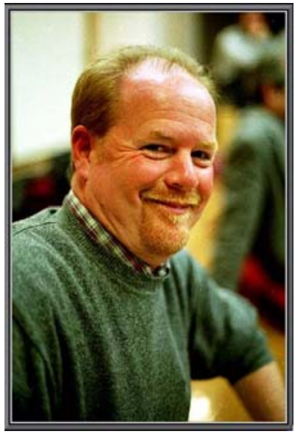
RF Station	Unloaded Gradient (MeV/m)	% Loading
0	47	14
1	44	17
2	37	17

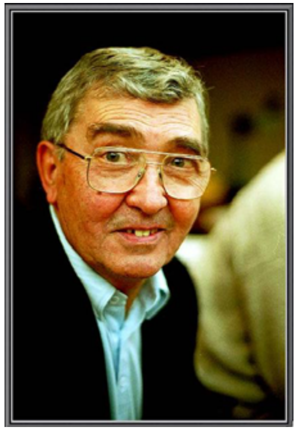
2001-2006: Globalization of the ILC

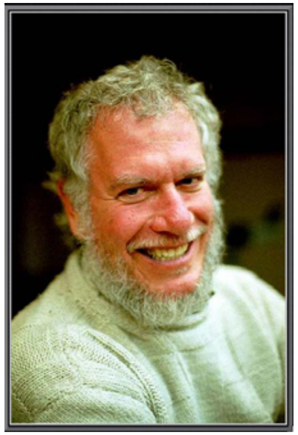
Feb. 2001	ICFA requests Second ILC-TRC Report
Mar. 2001	TESLA Design Report is presented in Hamburg
June 2001	NLC Report is submitted to Snowmass 01
Feb. 2001	Second ILC-TRC Report is published
May 27, 2003	GLC Project-Report is issued by ACFA
Jan.-Aug. 2004	ITRP is formed in late 2003 under Jonathan Dorfan's ICFA chairmanship and Maury Tigner's ILCSC chairmanship. The 12-member ITRP under Barry Barish meets six times
Aug. 20, 2004	ICFA in Beijing receives and accepts the ITRP's final recommendations that SC technology be selected for the ILC linacs
Mar. 2006	Here we are!

7th International ATF Collaboration Meeting

Nikko, March 31 – April 2, 2001







G. A. Loew, SLAC

ILC-TRC 2003

TABLE 1
Second ILC-TRC Overall Organization

Chair	Gregory Loew
Steering Committee	Reinhard Brinkmann Kaoru Yokoya Tor Raubenheimer Gilbert Guignard
Working Groups	
Technology, RF Power, and Energy Performance Assessments	Daniel Boussard
Luminosity Performance Assessments	Gerry Dugan
Reliability, Availability and Operability	Nan Phinney Ralph Pasquinelli

TABLE 2: Summary of Machine Parameters

	TESLA		**JLC-C**		**JLC-X/NLC**[a]		**CLIC**	
Center of mass energy [GeV]	500	800	500	1000	500	1000	500	3000
RF frequency of main linac [GHz]	1.3		5.7	5.7/11.4[b]	11.4		30	
Design luminosity [10^{33} cm^{-2}s^{-1}]	34.0	58.0	14.1	25.0	25.0 (20.0)	25.0 (30.0)	21.0	80.0
Linac repetition rate [Hz]	5	4	100		150 (120)	100 (120)	200	100
Number of particles/bunch at IP [10^{10}]	2	1.4	0.75		0.75		0.4	
$\gamma\varepsilon_x^*$ / $\gamma\varepsilon_y^*$ emit. at IP [m·rad × 10^{-6}]	10 / 0.03	8 / 0.015	3.6 / 0.04		3.6 / 0.04		2.0 / 0.01	0.68 / 0.01
β_x^* / β_y^* at IP [mm]	15 / 0.40	15 / 0.40	8 / 0.20	13 / 0.11	8 / 0.11	13 / 0.11	10 / 0.05	16 / 0.07
σ_x^* / σ_y^* at IP before pinch[c] [nm]	554 / 5.0	392 / 2.8	243 / 4.0	219 / 2.1	243 / 3.0	219 / 2.1	202 / 1.2	60 / 0.7
σ_z^* at IP [μm]	300		200	110	110		35	
Number of bunches/pulse	2820	4886	192		192		154	
Bunch separation [nsec]	337	176	1.4		1.4		0.67	
Bunch train length [μsec]	950	860	0.267		0.267		0.102	
Beam power/beam [MW]	11.3	17.5	5.8	11.5	8.7 (6.9)	11.5 (13.8)	4.9	14.8
Unloaded/loaded gradient[d] [MV/m]	23.8 / 23.8[e]	35 / 35	41.8/31.5	41.8/31.5 / 70/55	65 / 50		172 / 150	
Total number of klystrons	572	1212	4276	3392/4640	4064	8256	448	
Number of sections	20592	21816	8552	6784/13920	12192	24768	7272	44000
Total two-linac length [km]	30	30	17.1	29.2	13.8	27.6	5.0	28.0
Total beam delivery length [km]	3		3.7		3.7		5.2	
Proposed site length [km]	33		33		32		10.2	33.2
Total site AC power[f] [MW]	140	200	233	300	243 (195)	292 (350)	175	410
Tunnel configuration[g]	Single		Double		Double		Single	

ILC-TRC Methodology and Recommendations

The TRC examined about 120 outstanding R&D issues relevant to the four machines under review and ranked its relevant concerns according to the following criteria:

- **Ranking 1:** R&D needed for feasibility demonstration of the machine

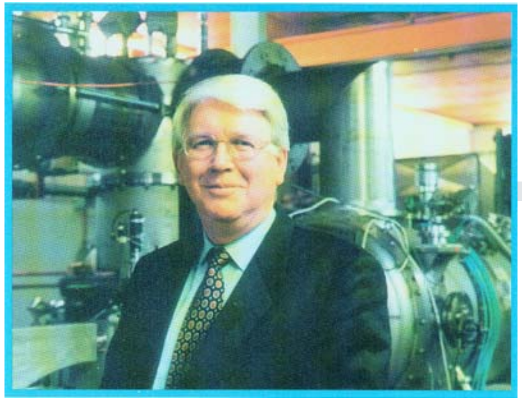
- **Ranking 2:** R&D needed to finalize design choices and ensure reliability of the machine

- **Ranking 3:** R&D needed before starting production of systems and components

- **Ranking 4:** R&D desirable for technical or cost optimization

Some of these R&D issues are still with us today.

International Technology Recommendation Panel Meeting
August 11 ~ 13, 2004. Republic of Korea



Bjorn Wiik's Final Words at LCWS 91 (Saariselkä)

- **It is clear that a 500-GeV, high luminosity e^+e^- collider has a unique physics programme and can be justified even if it starts operation several years after the turn on of the large hadron colliders. This justification is based on present knowledge and does not need input from the hadron colliders.**

- **The complexity and the cost of this collider makes it unlikely that more than one such facility will be constructed. An interregional collaboration will not only allow us to pool technical and financial resources, but it may also serve as a model for other large scientific or technical enterprises.**

Bjorn Wiik's Final Words at LCWS 91 (Saariselkä), cont.

- Within the high energy community we must discuss how such a linear collider facility could be organized. Should it only make use of the facilities of an existing laboratory but be independently organized, or should it be a new laboratory? At some stage these discussions must clearly involve the funding agencies.

- The final and most difficult question is one of site. This is clearly a political and financial question …

- To conclude: the collider project is not only based on a new technology granting us a unique physics programme, but if may also lead to a new kind of interregional collaboration. This in itself is both a challenge and a goal.