GLOBAL (0.5-1) TEV LINEAR COLLIDER

- Motivation - basic ideas
- LC accelerator physics
- Introduction to the machine(s)
- Procedure for technology choice (end-2004)
- Machine - detector interface

Reference material

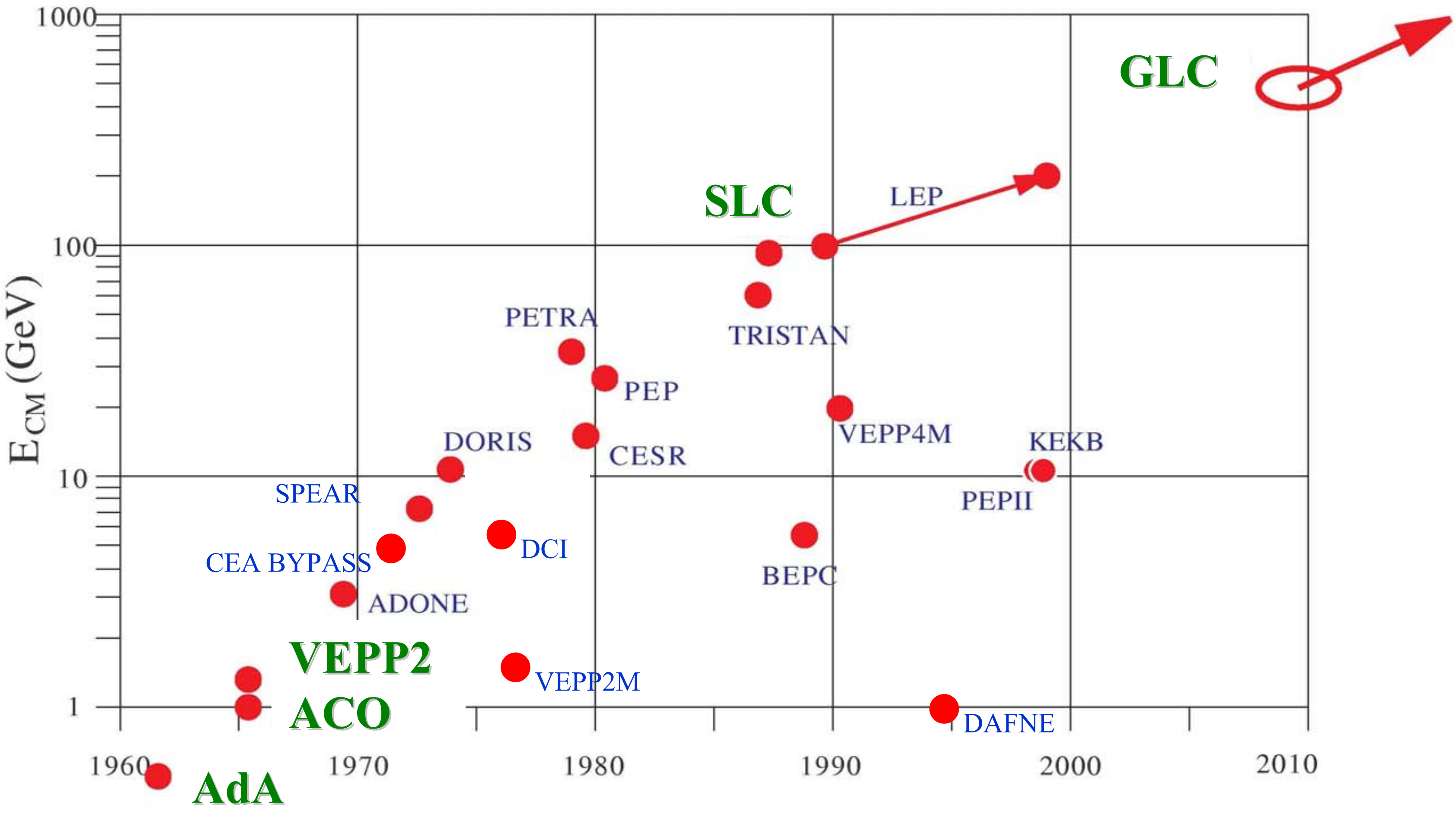
- US Particle Accelerator School, Santa Barbara, June 2003
  9 detailed lectures by A. Seryi, P. Tenenbaum, N. Walker and A. Wolski
  http://www.desy.de/~njwalker/uspas/

•• Int. LC Tech. Rev. Committee - Greg Loew 2003 Report
  http://www.slac.stanford.edu/xorg/ilc-trc/2002/2002/ report/03rep.htm

••• International Technology Recommendation Panel
  http://www.ligo.caltech.edu/~donna/ITRP_Home.htm

•••• Recent machine-detector interface activity
  http://www-flc.desy.de/bdir/BDIRtop.html
  http://www.slac.stanford.edu/xorg/lcd/ipbi/general.html
  http://acfahep.kek.jp/subg/ir/

Evolution of e^+e^- colliders



adapted from K. Yokoya and J.-E. Augustin

Why shift to linear collider ?

storage ring

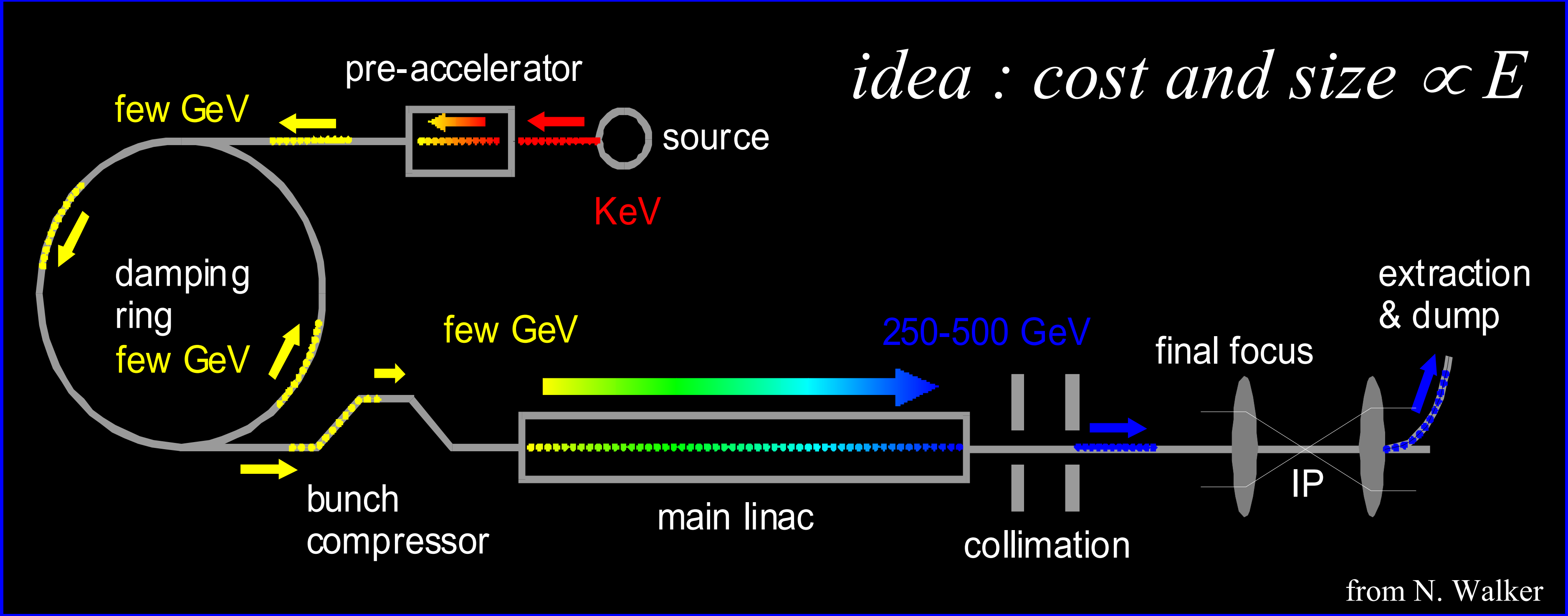
- tunnel, magnets,… $\propto \rho$
- synchrotron radiation losses (RF) $\propto E^4 / \rho$
- optimum : equate both costs

$\Rightarrow$ total cost & size $\propto E^2$

		LEP- II	Super-LEP	Hyper-LEP
E_{cm}	GeV	180	500	2000
L	km	27	200	3200
ΔE	GeV	1.5	12	240
$\$_{tot}$	10^9 SF	2	15	240

unacceptable scaling !

Linear collider concept



idea : cost and size $\propto E$

from N. Walker

focus $\left\{ \begin{array}{l} \text{RF technology (gradient, efficient power transfer)} \\ \text{beam phase-space control and stability} \end{array} \right.$

→ synchrotron radiation still drives design…

Linear collider luminosity (1)

$$L \sim \frac{n_b N_e^2 f}{4\pi\sigma_x\sigma_y} H_D$$

$$L \sim \frac{\eta P_{electrical} N_e}{4\pi\sigma_x\sigma_y E_{cm}} H_D$$

H_D = disruption enhancement
f = linac repetition rate
N_e = bunch population
n_b = bunches per train
σ = RMS bunch size
ε = emittance
η = power transfer efficiency

- linac rep. rate $f \ll$ ring frequency ⇒ need tiny IP size σ

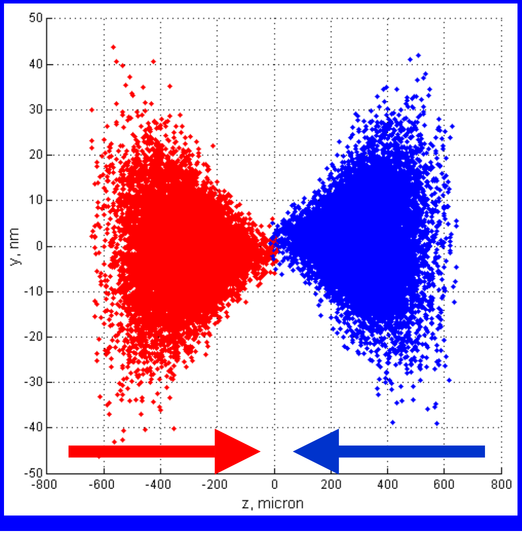
⇒ beam-beam mutual focusing : beamstrahlung, disruption…

- luminosity ~ available RF power for given E_{cm} and η

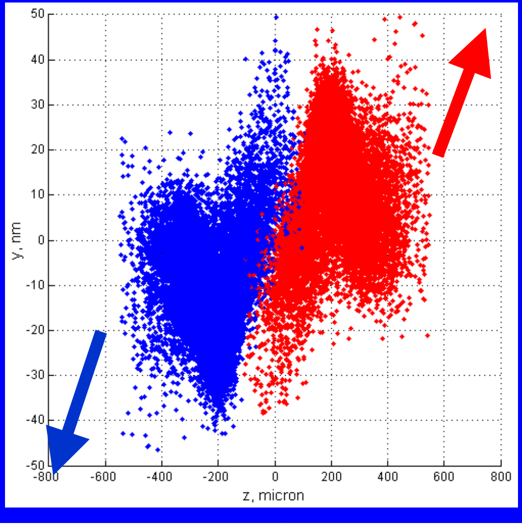
⇒ choice of linac technology

Beam-beam mutual focusing (1)

simulate
collision
with initial
Δy offset



detectable
post-IP
deflection



main tool
at SLC
(and LEP)

SLAC-PUB-6790

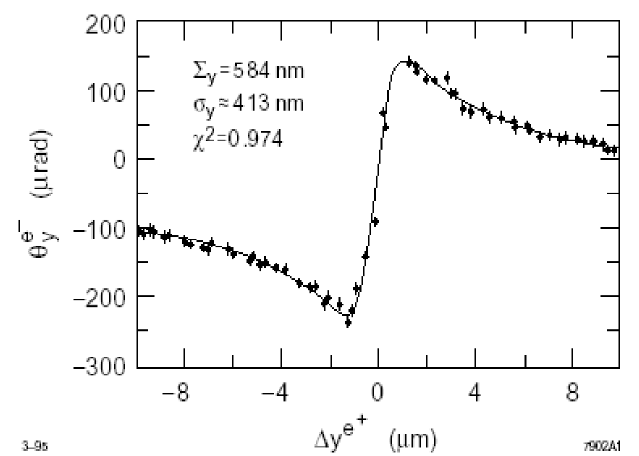
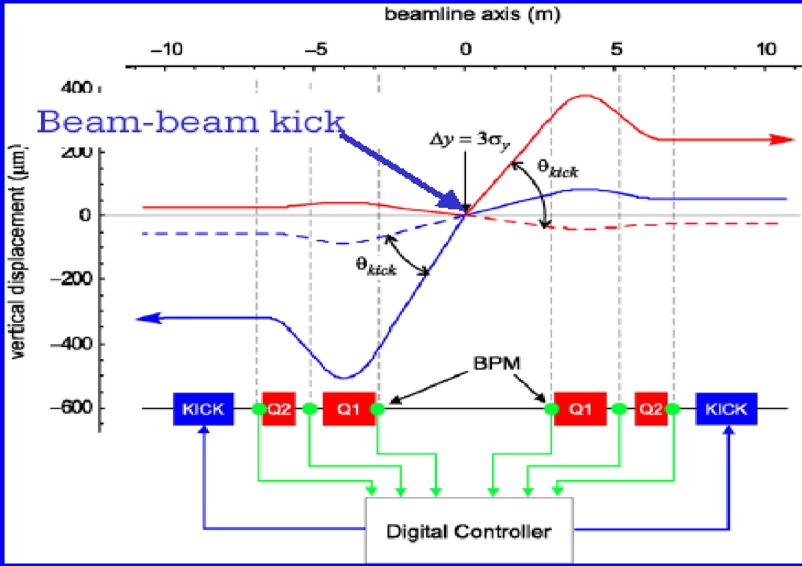


Figure. 1. Vertical beam-beam deflection scan at low current, demonstrating a single-beam size of about 410 nm.



Beam-beam mutual focusing (2)

observed / calculated
luminosity

from measuring :

1. IP spot sizes & intensities
2. Z & Bhabha rates

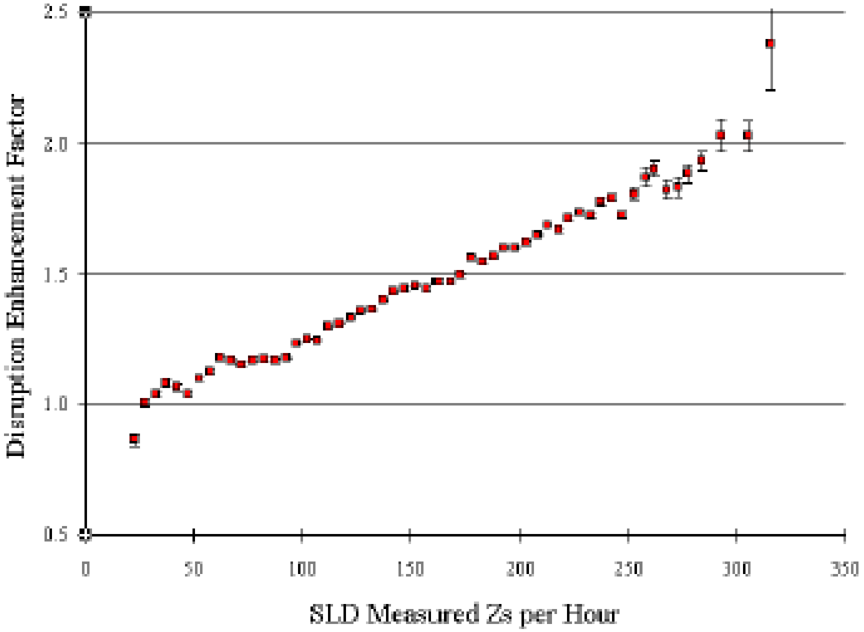


Figure 1: Measured disruption enhancement factor, H_D, plotted versus SLD measured Zs per hour.

beam-beam disruption evidence at SLC

T. Barklow et al., Proc. PAC, New York, 1999

Linear collider luminosity (2)

Beamstrahlung energy spread :

$$\delta_E \sim \frac{N_e^2 E_{cm}}{\sigma_z (\sigma_x + \sigma_y)^2}$$

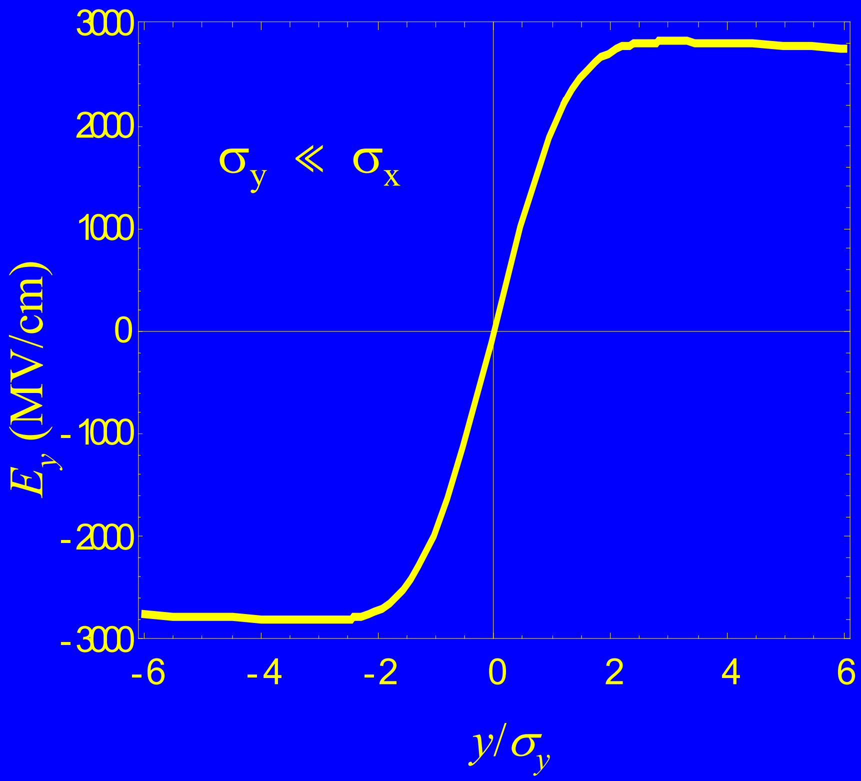
$$L \sim \frac{\eta P_{electrical} \; N_e}{4\pi\sigma_x\sigma_y E_{cm}} H_D$$

luminosity → small $\sigma_x\sigma_y$

energy spread → large $\sigma_x+\sigma_y$

$\Rightarrow$ trick : very flat beams

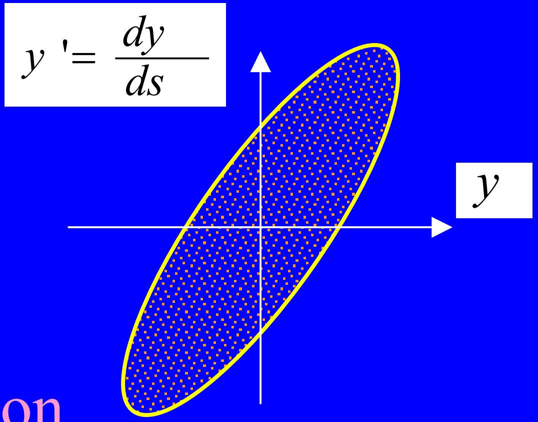
$\sigma_y \ll \sigma_x$



Linear collider luminosity (3)

Replacing δ_E for $\sigma_y \ll \sigma_x$:

$$L \sim \eta \frac{P_{\text{electrical}}}{E_{CM}^{3/2}} \frac{\sqrt{\delta_E \sigma_z}}{\sigma_y} H_D$$



1. Hamiltonian ("Courant-Snyder") invariant
2. obeys Liouville

Emittance = phase-space area   β = enveloppe function

$$(y\ y')\begin{pmatrix}\beta & -\alpha \\ -\alpha & \gamma\end{pmatrix}\begin{pmatrix}y \\ y'\end{pmatrix} = \pi\varepsilon_y$$

$$\begin{pmatrix}\langle y^2\rangle & \langle yy'\rangle \\ \langle yy'\rangle & \langle y'^2\rangle\end{pmatrix} = \begin{pmatrix}\beta_y\varepsilon_y & -\alpha_y\varepsilon_y \\ -\alpha_y\varepsilon_y & \gamma_y\varepsilon_y\end{pmatrix}$$

usual
error
matrix

Linear collider luminosity (4)

Replace $\sigma^2 = \varepsilon_n \beta$:

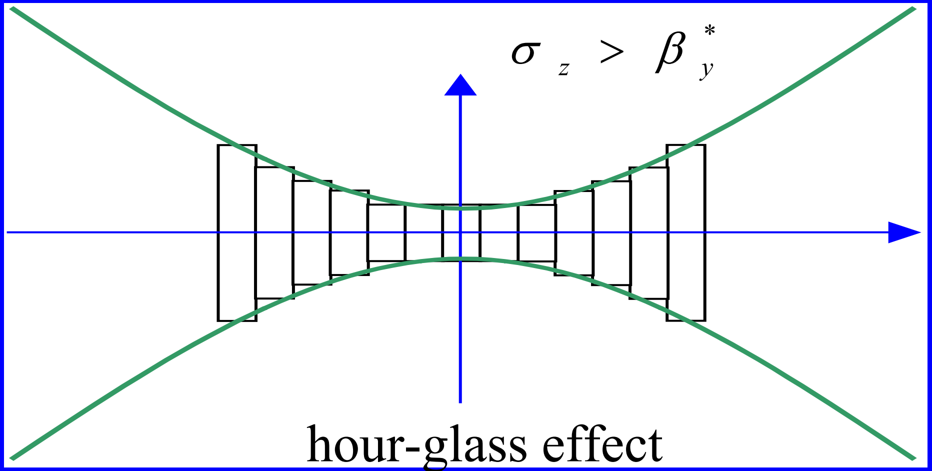
$$L \sim \eta \frac{P_{\text{electrical}}}{E_{CM}} \sqrt{\frac{\delta_E}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} H_D$$

at optical focus :

$\beta \equiv$ “depth of focus”

- want small β_y
- need $\sigma_z < \beta_y$

→ SET $\sigma_z = \beta_y$



$$L \sim \eta \frac{P_{\text{electrical}}}{E_{CM}} \sqrt{\frac{\delta_E}{\varepsilon_{n,y}}} H_D$$

$$\Rightarrow \quad \text{Merit} = \frac{L E_{CM}}{P_{\text{electrical}} \sqrt{\delta_E}} \sim \frac{\eta}{\sqrt{\varepsilon_{n,y}}}$$

LC machine : 2 design choices

$$\boxed{\text{Merit} = \frac{L E_{CM}}{P_{\text{electrical}} \sqrt{\delta_E}} \sim \frac{\eta}{\sqrt{\varepsilon_{n,y}}}}$$

A : efficient electrical power transfer from wall-plug to beam

B : small vertical beam emittance at collision point

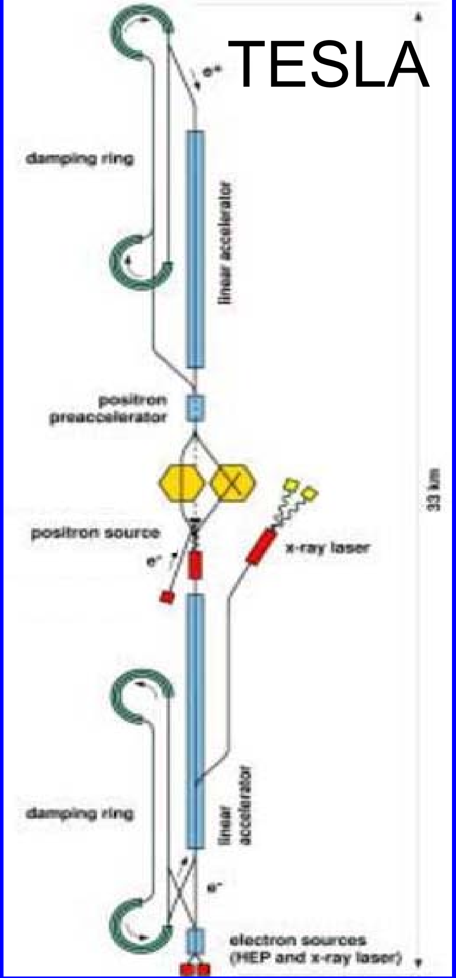
A & B essential

TESLA stresses A

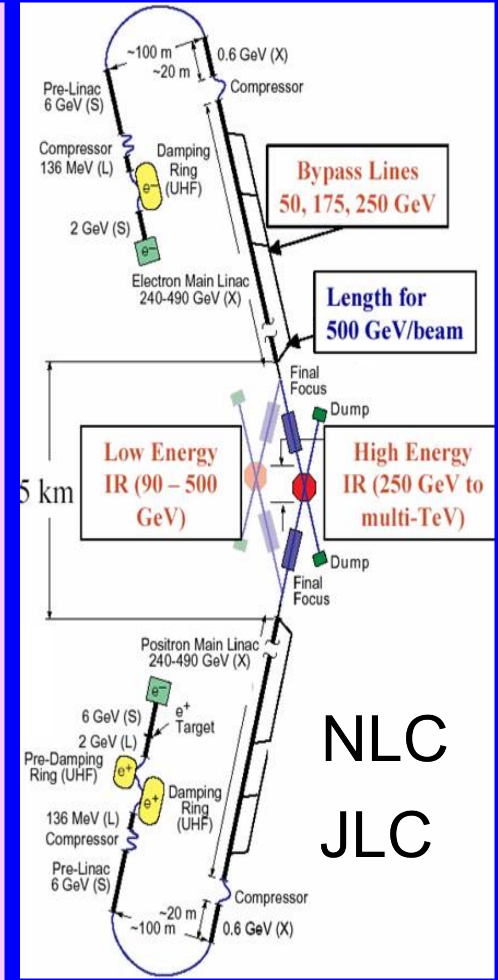
NLC / JLC always stressed B, now also TESLA does…

must consider also accelerating gradient ⇒ length & wake field ⇒ stability tolerances

cold (1.3 GHz) ↔ warm (11.4 GHz)



Parameters	TESLA	NLC / JLC-X
$\gamma\varepsilon_y$ (10^{-6}m-rad)	0.03 – 0.015	0.04
β_y (mm)	0.4	0.11
σ_z (mm)	0.3	0.11
σ_y (nm)	5 – 2.8	3 – 2.1
σ_x / σ_y	110 – 140	81 – 104
$\mathscr{L}$ (10^{34} cm^{-2}s^{-1})	3.4 - 5.8	2.0 - 3.4
$\sqrt{s}$(GeV)	500 - 800	500 – 1000
Beamstrahlung δ_E	3.2 - 4.3 %	4.6 – 7.5 %
gradient (MV/m)	23.4 – 35	50 (loaded)
frequency (GHz)	1.3	11.4
bunch / train	2820 – 4886	196
Δt bunch (ns)	337 – 176	1.4
beam power (MW)	11.3	6.9
AC power (MW)	140	195
combined efficiency	8 %	4 %

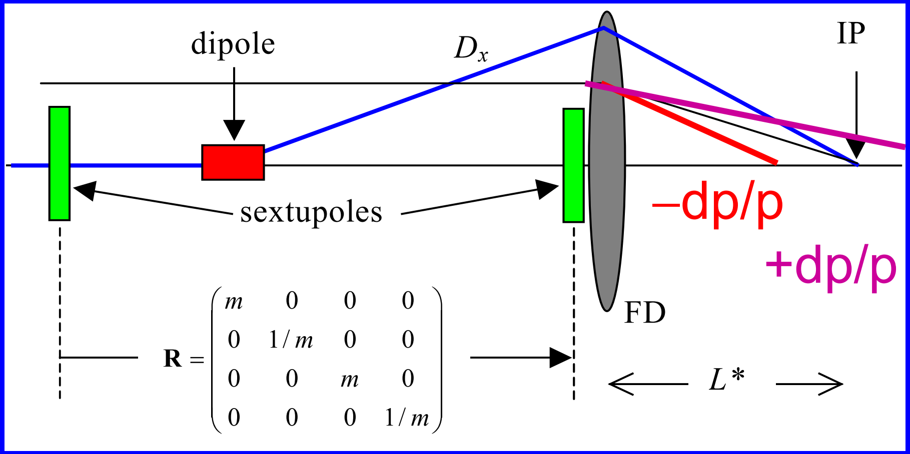


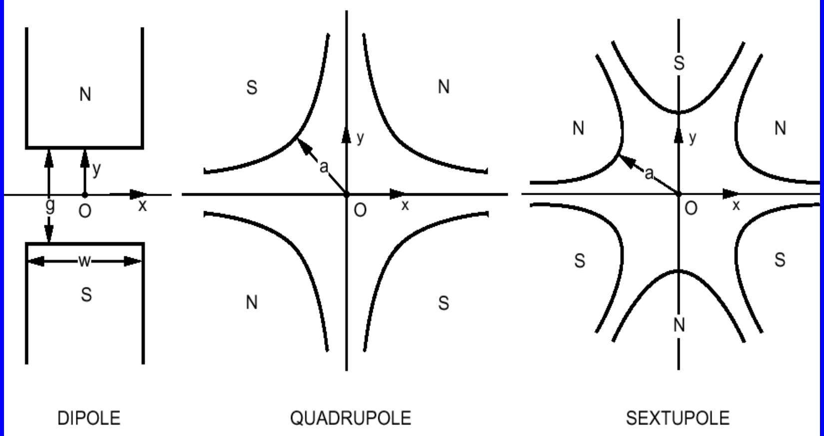
Superconductive linac
niobium cavities

$\mathscr{L} = 5.10^{34}$cm^{-2}s^{-1}
10^7s/year → 500 fb^{-1}/year

Conventional linac
(SLC) – Cu cavities

Optical telescope to minimize β*



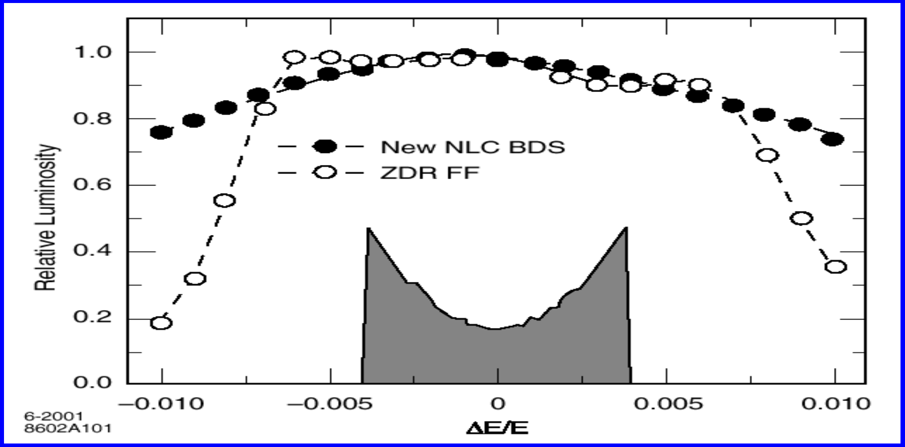


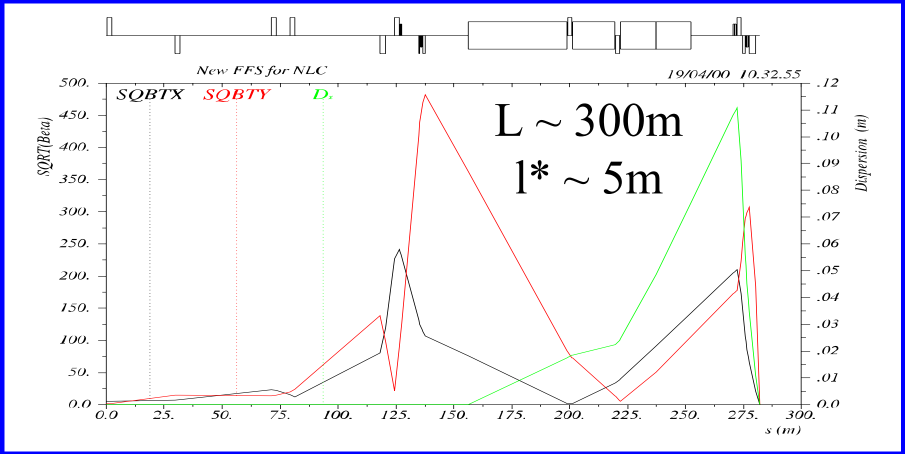
local chromaticity correction with pairs of sextupole doublets → optical bandpass

Just bends the trajectory

Focus in one plane, defocus in another:
$x' = x' + G\,x$
$y' = y' - G\,y$

Second order focusing
$x' = x' + S\,(x^2 - y^2)$
$y' = y' - S\,2xy$





L ~ 300m
l* ~ 5m

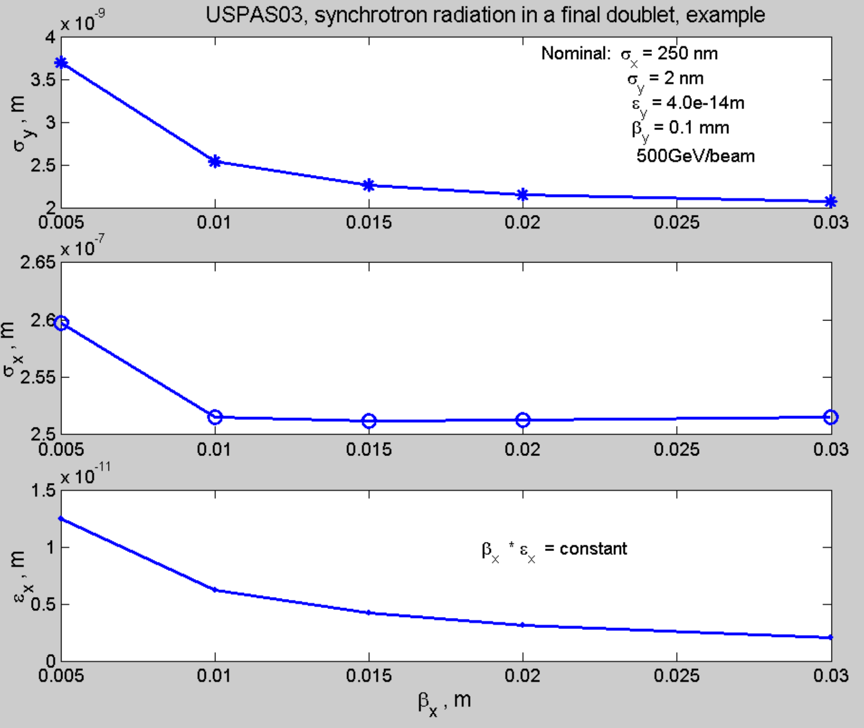
Minimum spot size : Oide effect

Ultimate limit : synchrotron radiation in last quadrupoles can generate large enough local energy spread to induce chromatic growth at the IP

minimum size : $\sigma \approx 1.83\left(r_e \bar{\lambda}_e F\right)^{1/7} \varepsilon_n^{5/7}$ when $\beta \approx 2.39\left(r_e \bar{\lambda}_e F\right)^{2/7} \varepsilon_n^{3/7}$

typically $F \sim 7$

independent of E!



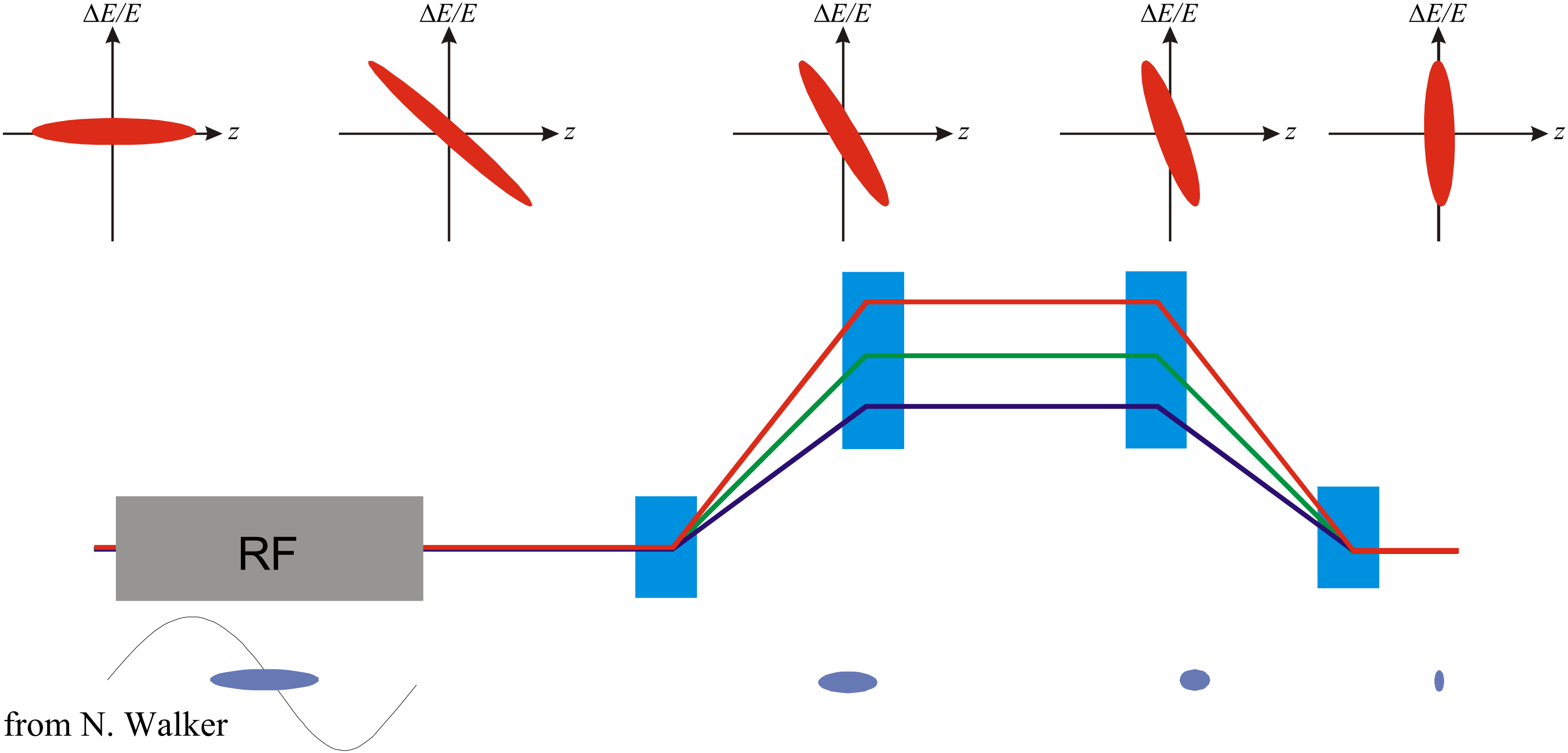
Horizontal design parameters :

$\beta_x \sim 10$ mm & $\varepsilon_{n,x} \sim 4\ 10^{-6}$ m-rad

are not that far from this limit

Longitudinal bunch compression

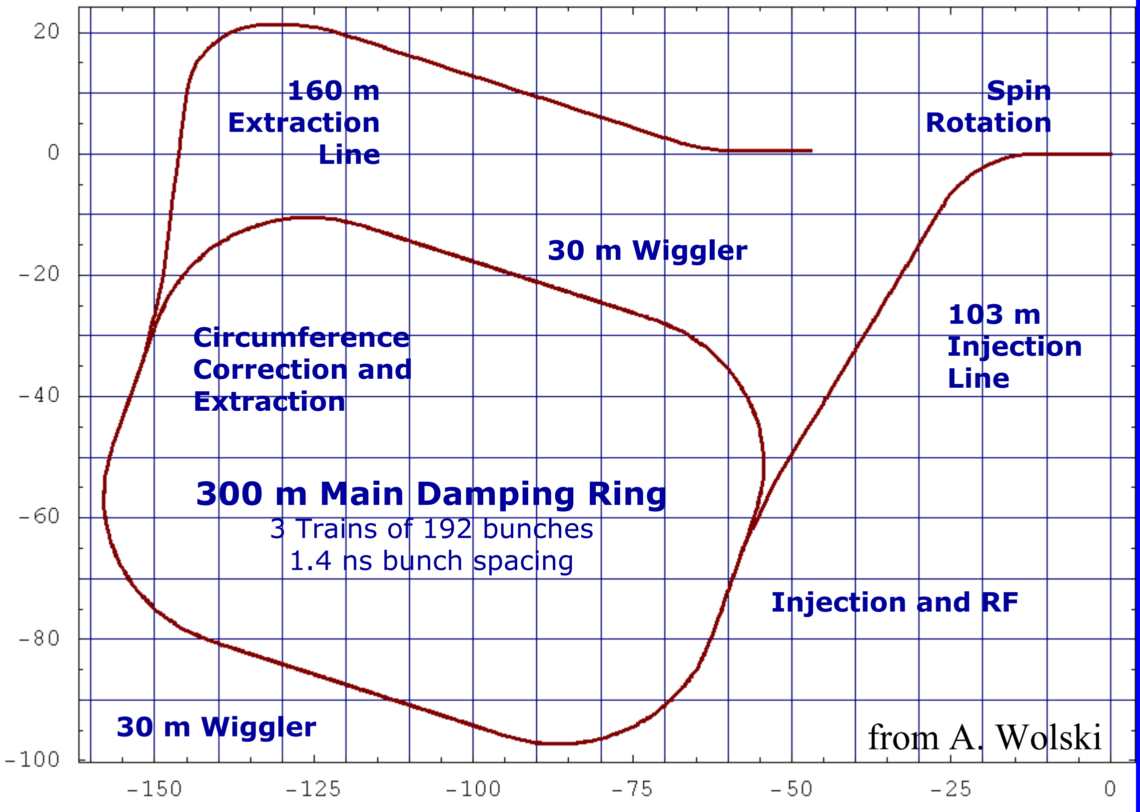
- bunch length from damping ring ~ few mm
- required at IP 100-300 μm ("depth of focus")



from N. Walker

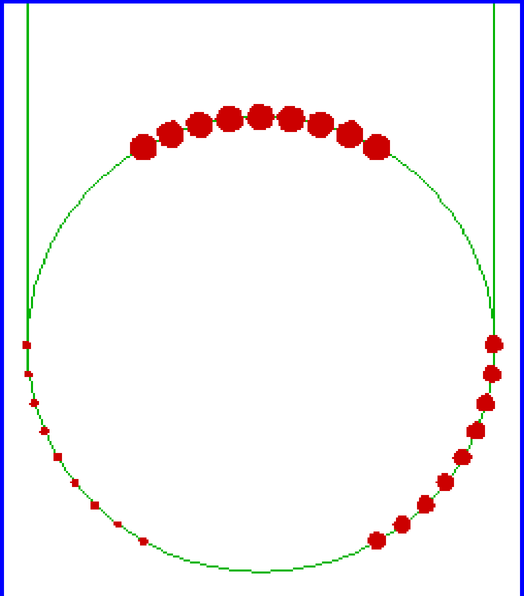
Damping ring (NLC/JLC)

- Each bunch train is stored for three machine cycles
  - 25 ms or 25,000 turns in NLC
- Transverse damping time ≈ 4 ms
- Horizontal emittance ×1/50, vertical ×1/7500

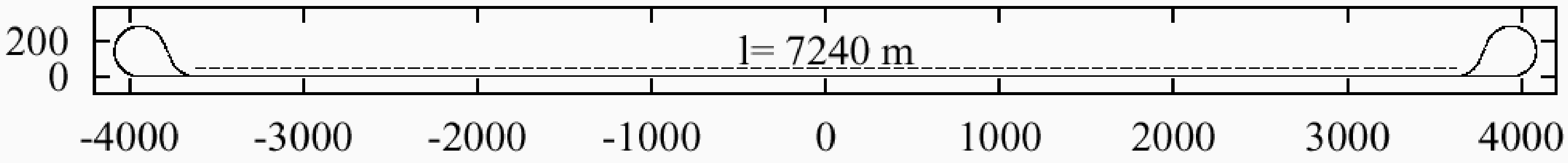


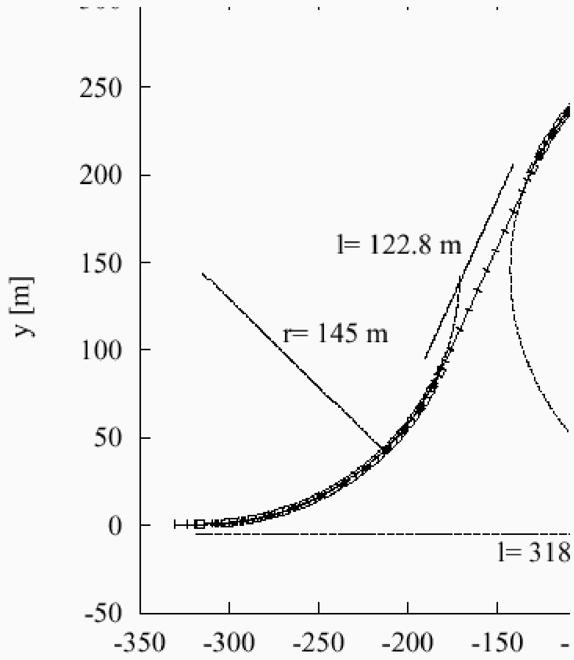
from A. Wolski

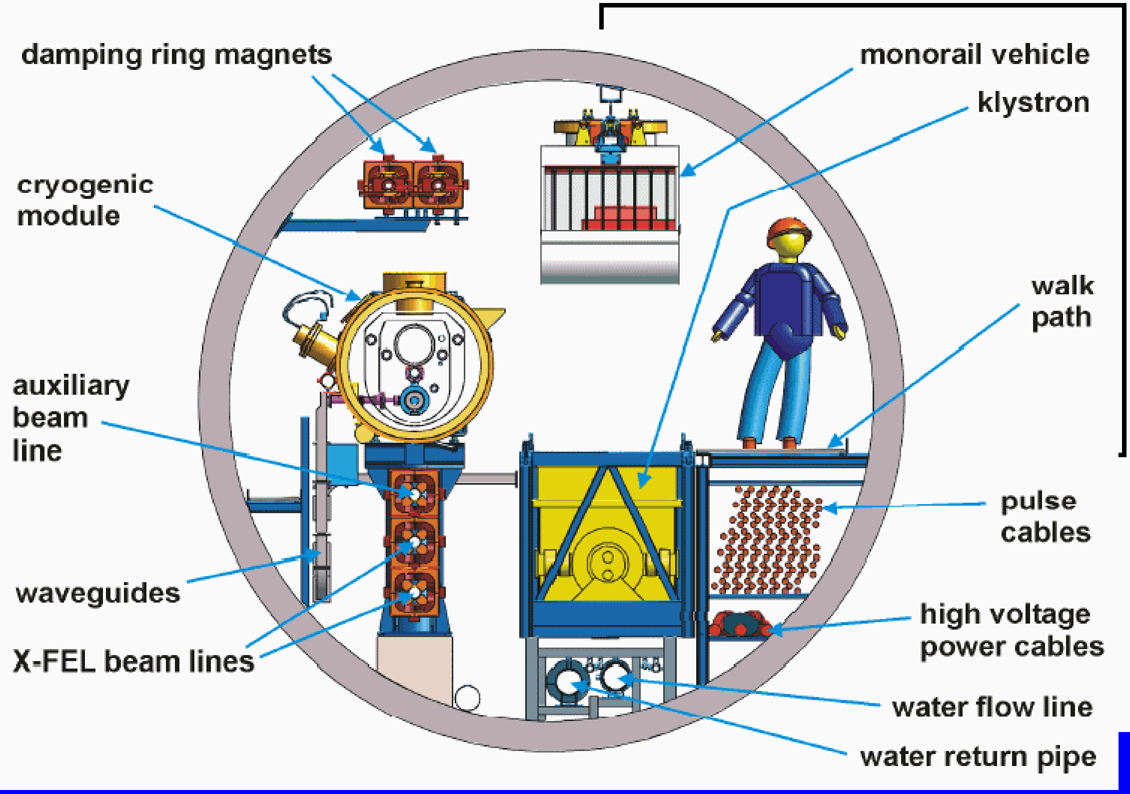
Cascade of 2 such damping rings needed



Damping ring (TESLA)

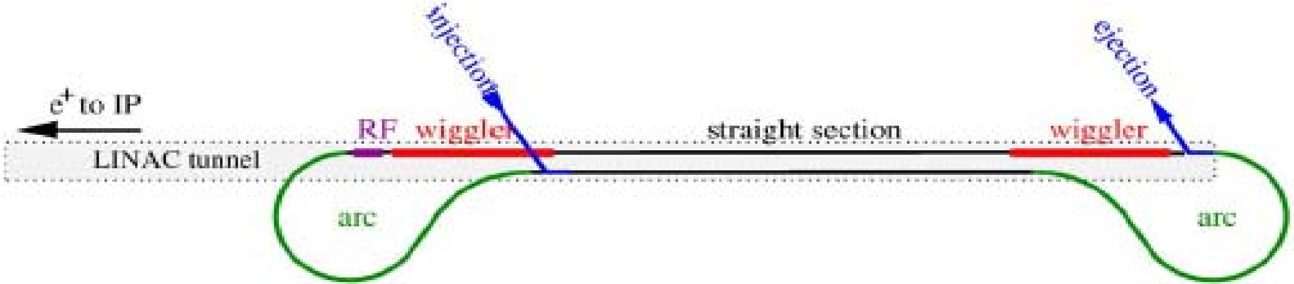






One TESLA design problem

Very long damping rings: at present 17 km



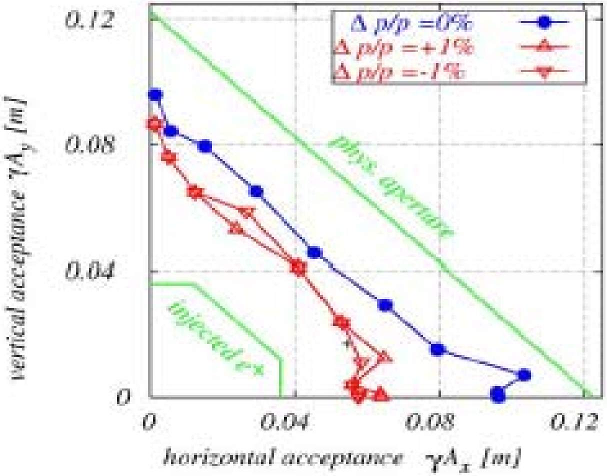
Electron cloud and beam-ion instability effects:

- more simulation effort required,

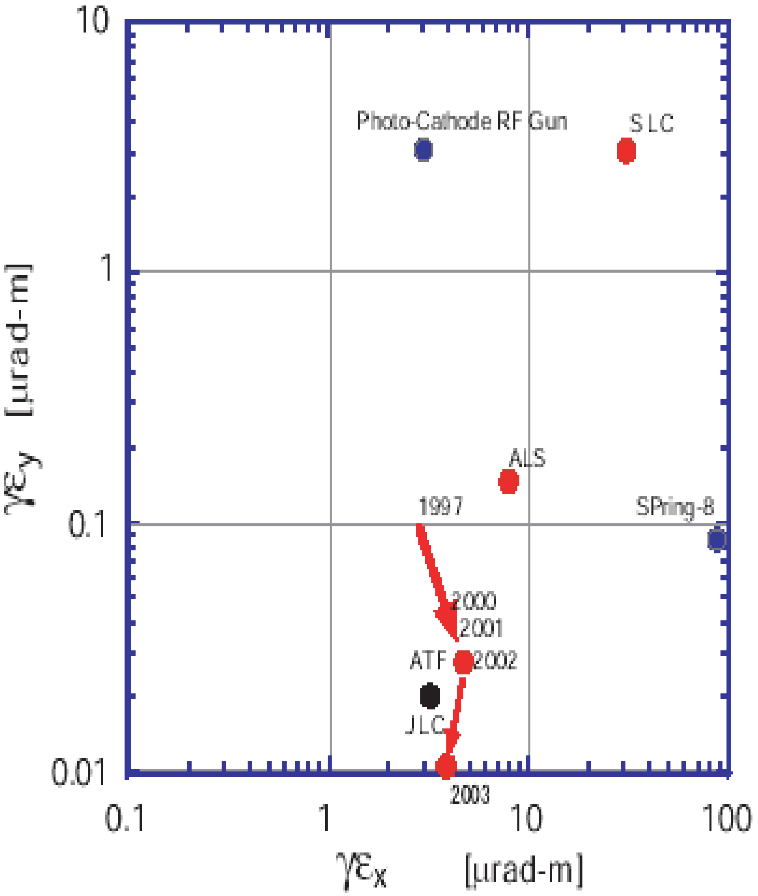
Dynamic aperture with sextupoles OK, but not yet sufficient with present wiggler model

Faster kickers would simplify DR design and reduce cost

present kickers : 20 nsec



ATF damping ring test @ KEK



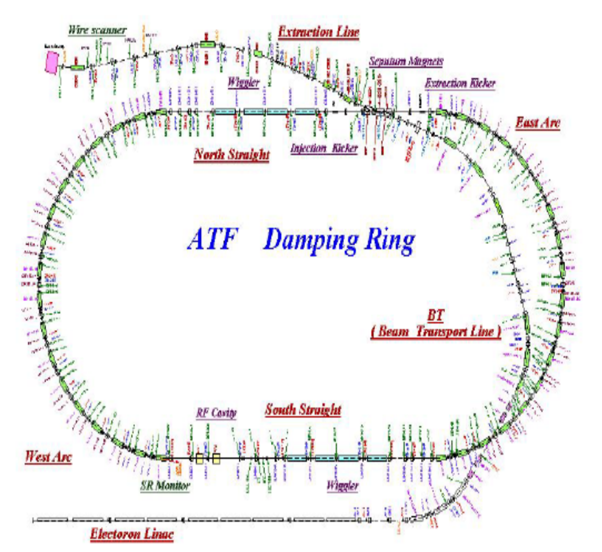
ATF Emittance

- World record of normalized emittance

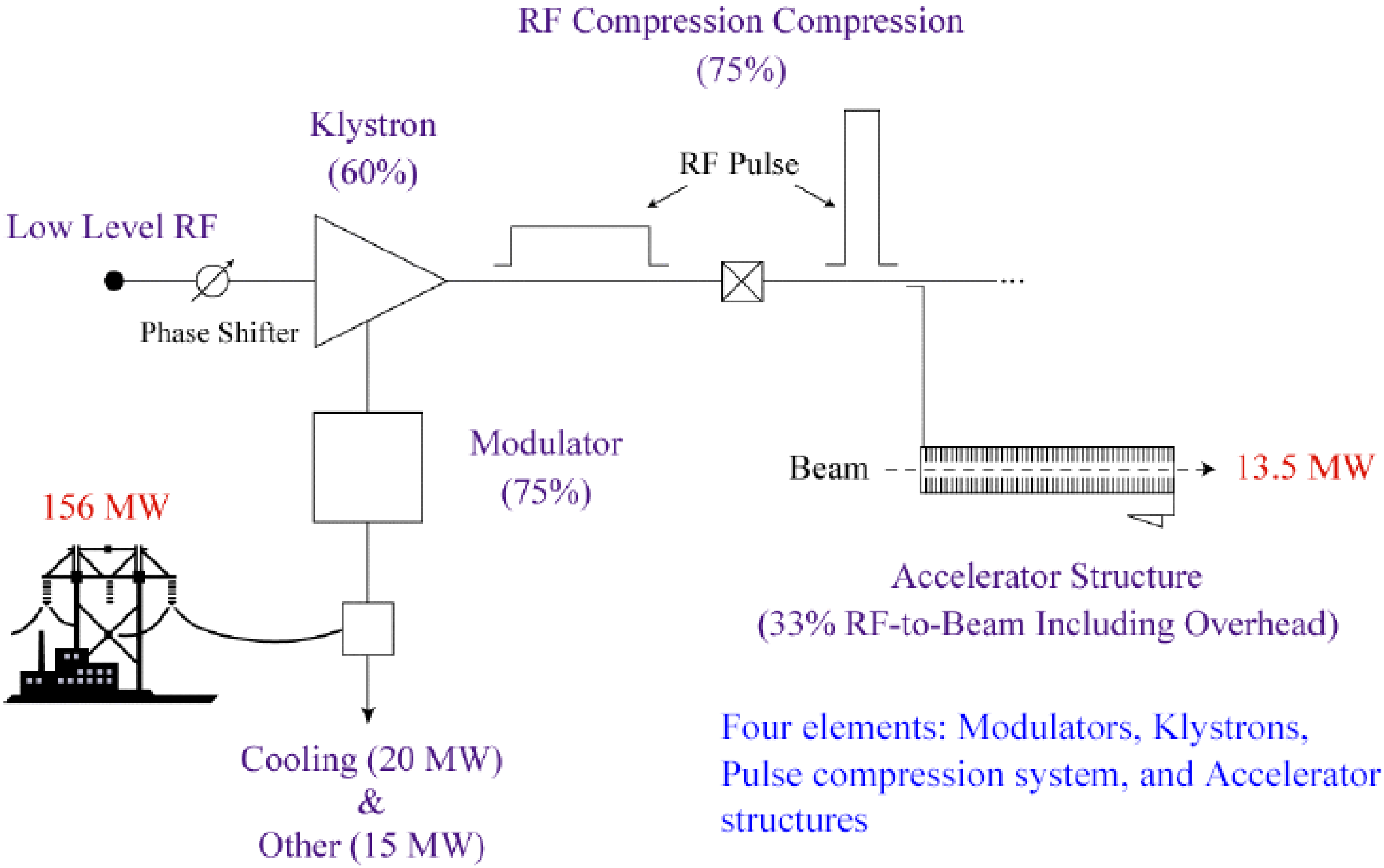
  $\gamma\epsilon_y \approx 1 \times 10^{-8}\text{rad}\cdot\text{m}$

- Already below the GLC requirement
  - single bunch
  - low current

from K. Yokoya



Normal conductive linac (NLC)



RF Compression Compression
(75%)

Klystron
(60%)

RF Pulse

Low Level RF

Phase Shifter

Modulator
(75%)

Beam

13.5 MW

156 MW

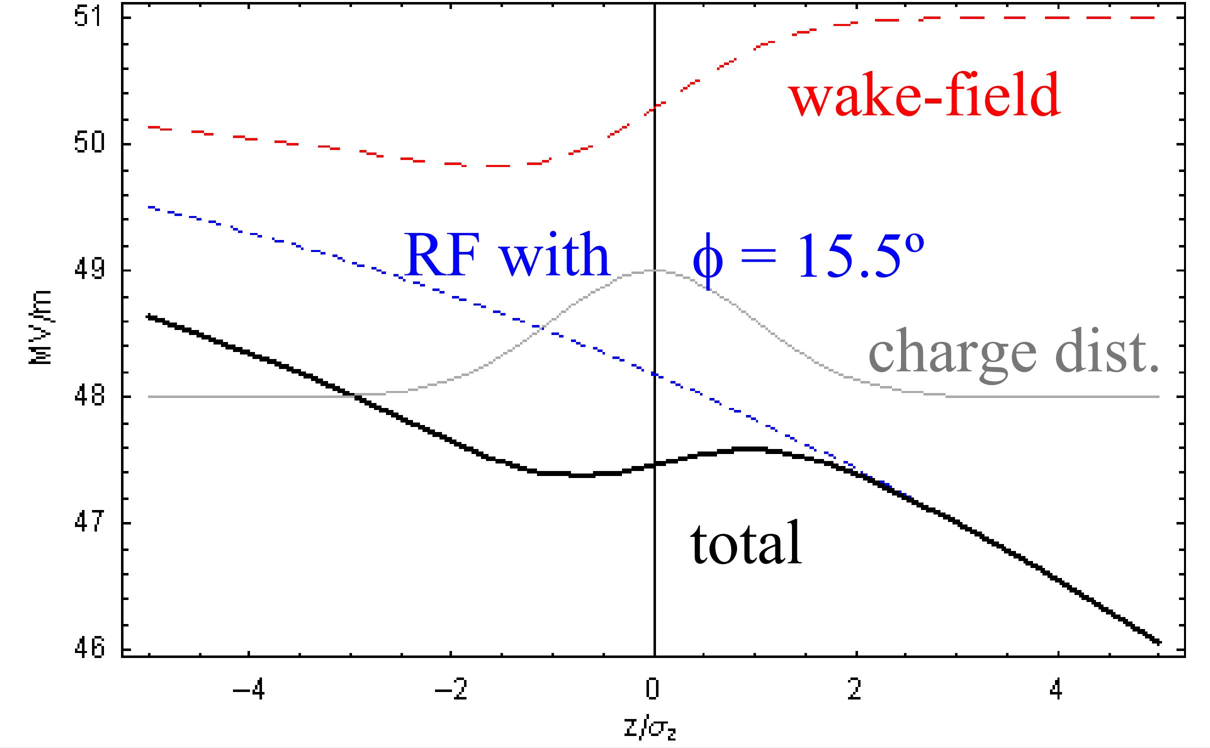
Accelerator Structure
(33% RF-to-Beam Including Overhead)

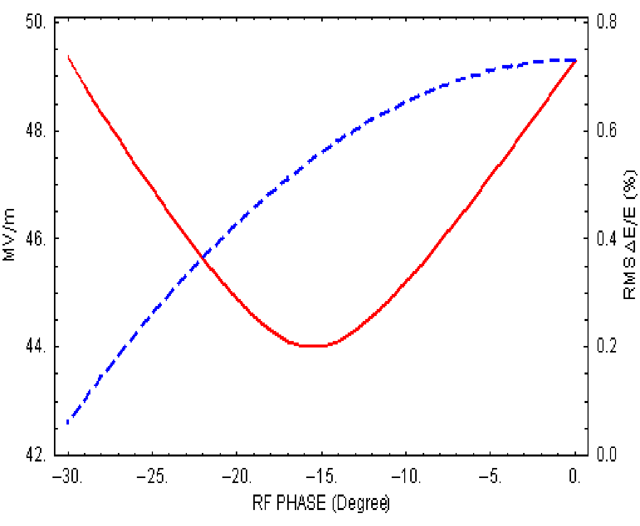
Cooling (20 MW)
&
Other (15 MW)

Four elements: Modulators, Klystrons, Pulse compression system, and Accelerator structures

from T. Raubenheimer

Beam-loading from longitudinal wake-field





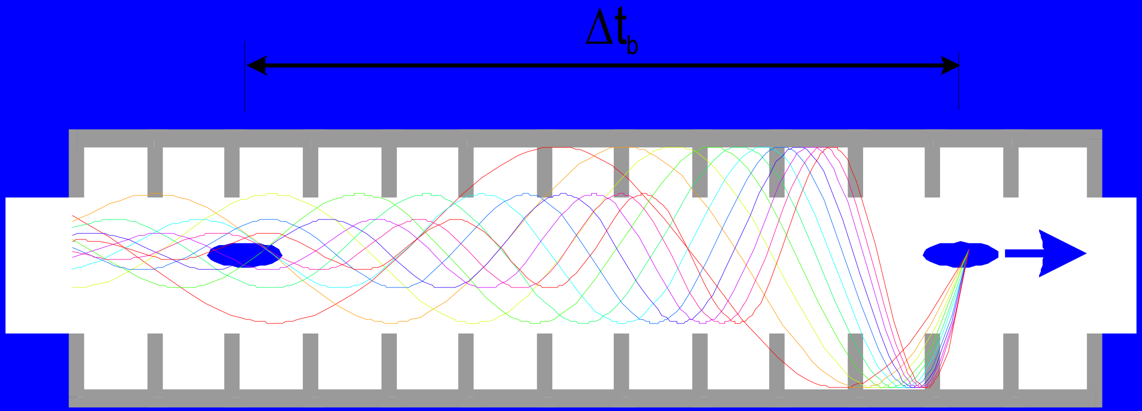
Some energy loss

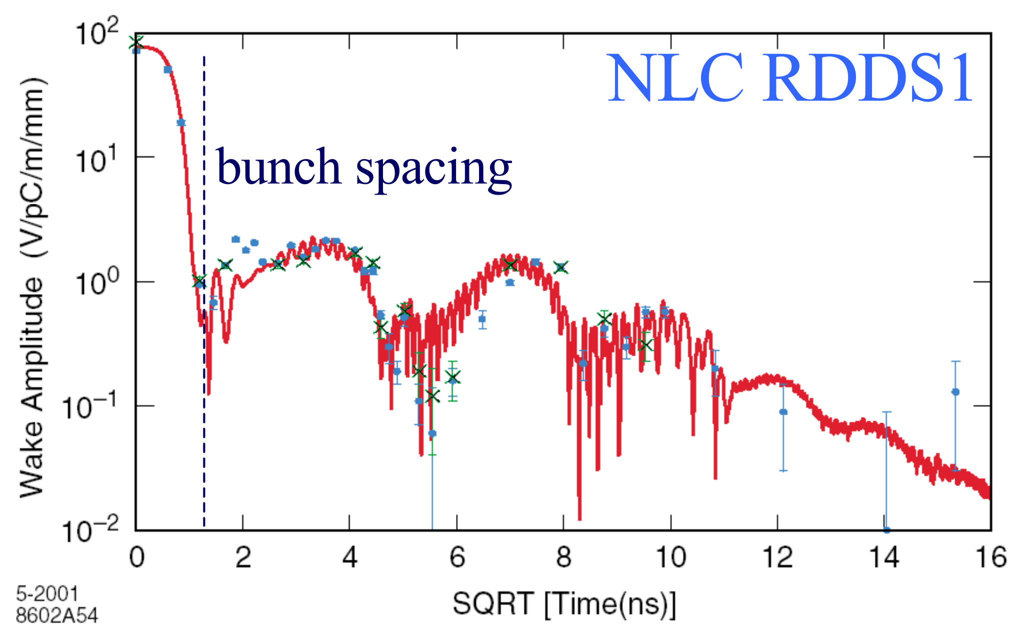
Compensation by running off the RF crest

Energy spread remains after optimizing

Transverse wake-fields : within train

Deflecting modes are excited when bunches off axis





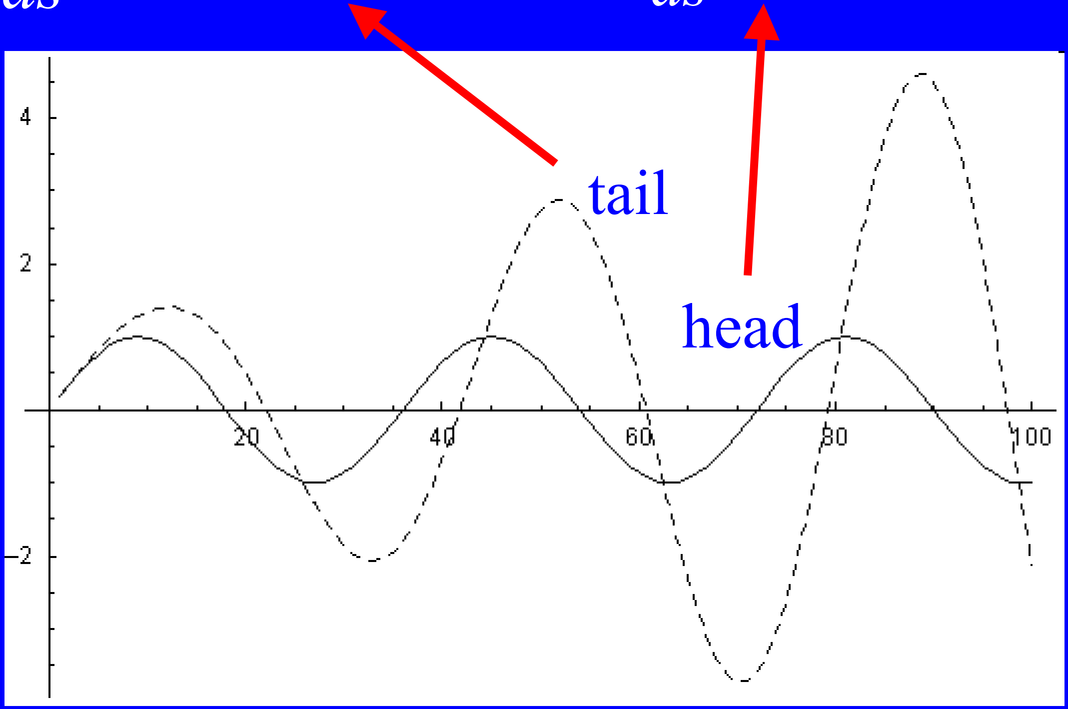
Slight random detuning between cells causes HOMs to decohere.

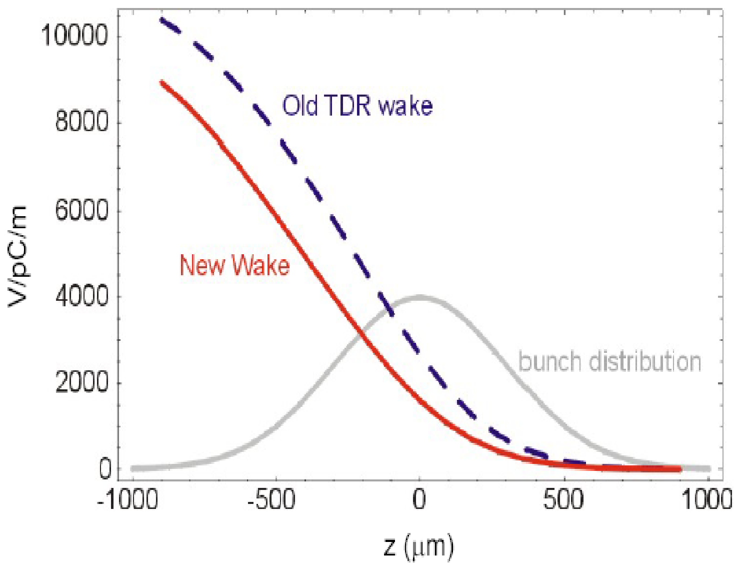
Will recohere later: needs to be damped (HOM dampers)

Transverse wake-fields : within bunch

head of bunch resonantly drives the tail if coherent betatron oscillation

$$\frac{d^2 y_t}{ds} + k^2 y_t = k_{wf}\, y_h \qquad \frac{d^2 y_h}{ds} + k^2 y_y = 0$$





Cures

1. lower charge (limiting)
2. stronger focusing ($)
3. higher gradient (anyway)
4. lower freq. (f ^{3} scaling)
5. BNS damping

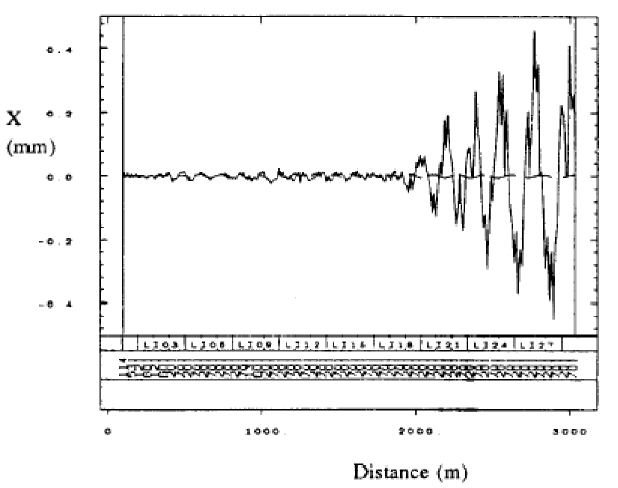
BNS damping in SLC (Balakin, Novakhatsky, Smirnov)

Turn off or reverse beam-loading compensation to introduce large energy spread correlated with z along bunch in first part of linac,

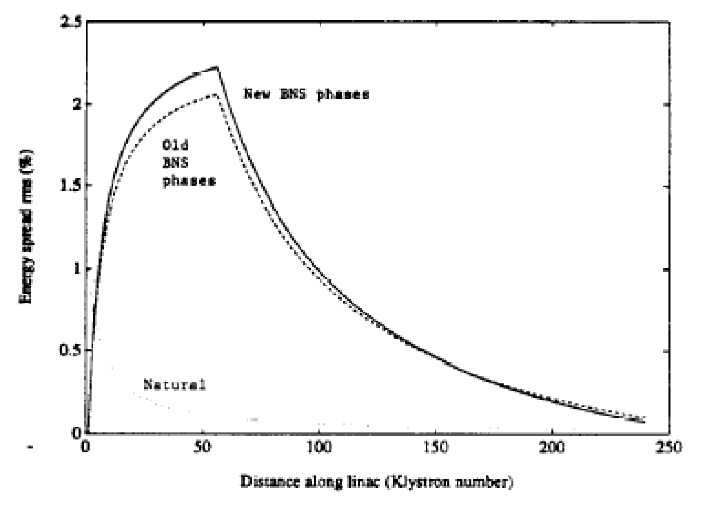
⇒ Deflected tail more strongly focused than head → partial correction

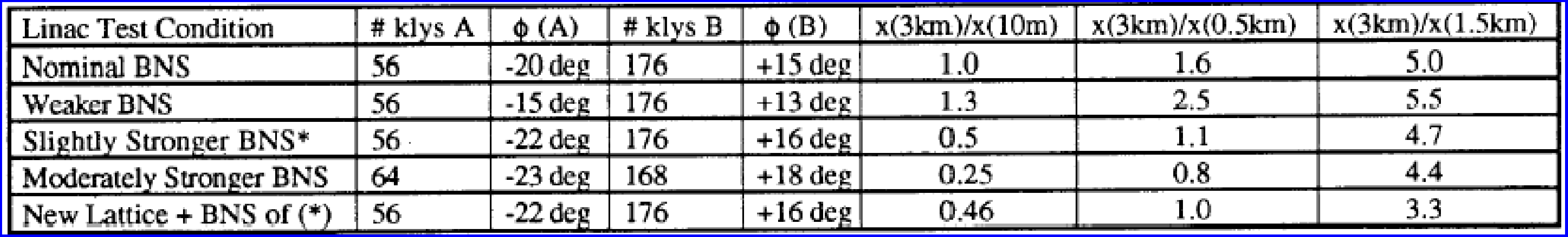
⇒ Later remove energy spread at linac end via stronger RF phase offset

Betatron oscillation without BNS



Energy spread

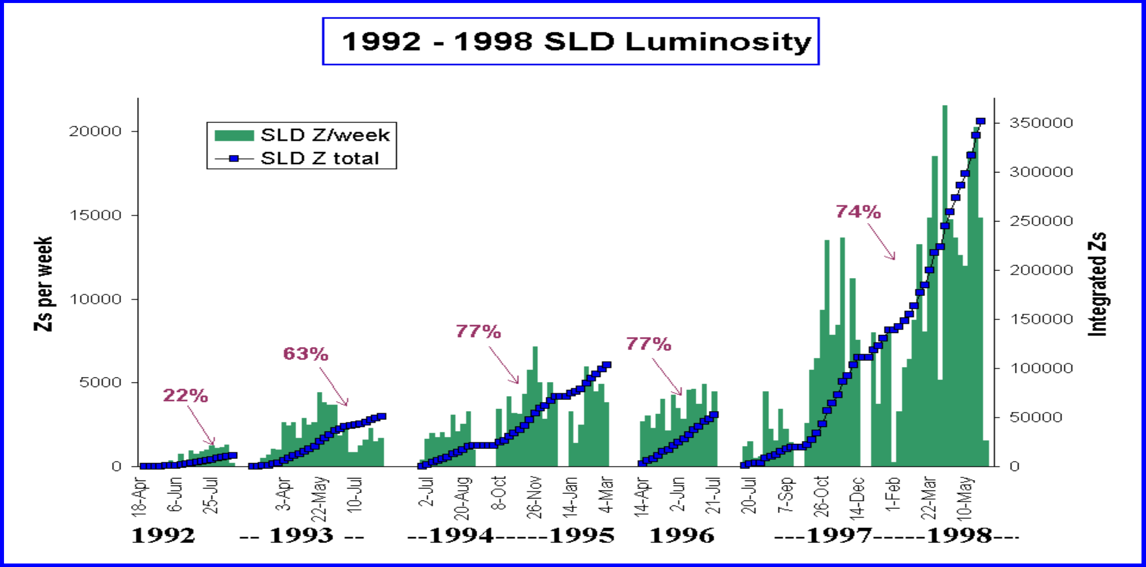


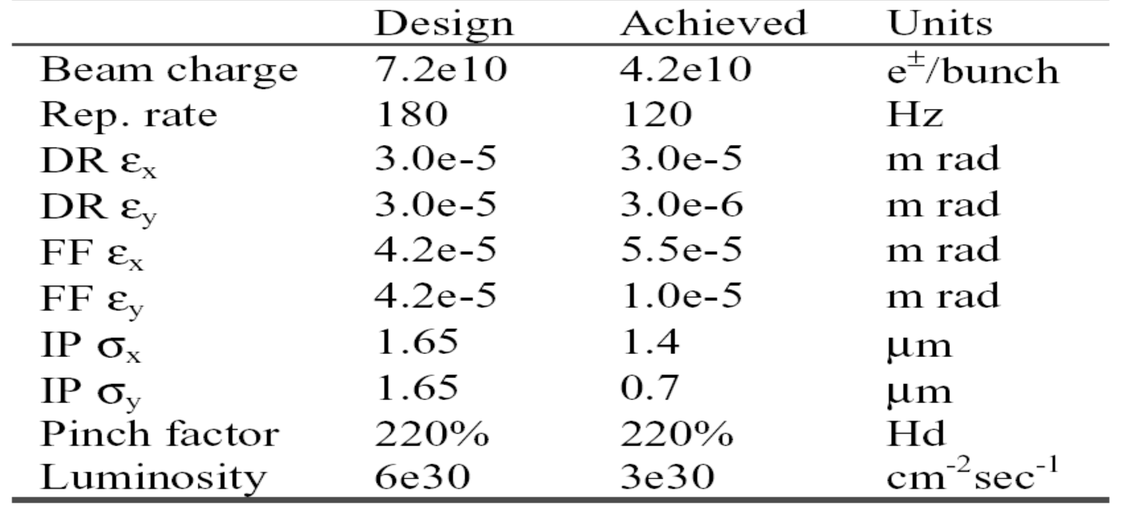


Linac Test Condition	# klys A	ϕ (A)	# klys B	ϕ (B)	x(3km)/x(10m)	x(3km)/x(0.5km)	x(3km)/x(1.5km)
Nominal BNS	56	-20 deg	176	+15 deg	1.0	1.6	5.0
Weaker BNS	56	-15 deg	176	+13 deg	1.3	2.5	5.5
Slightly Stronger BNS*	56	-22 deg	176	+16 deg	0.5	1.1	4.7
Moderately Stronger BNS	64	-23 deg	168	+18 deg	0.25	0.8	4.4
New Lattice + BNS of (*)	56	-22 deg	176	+16 deg	0.46	1.0	3.3

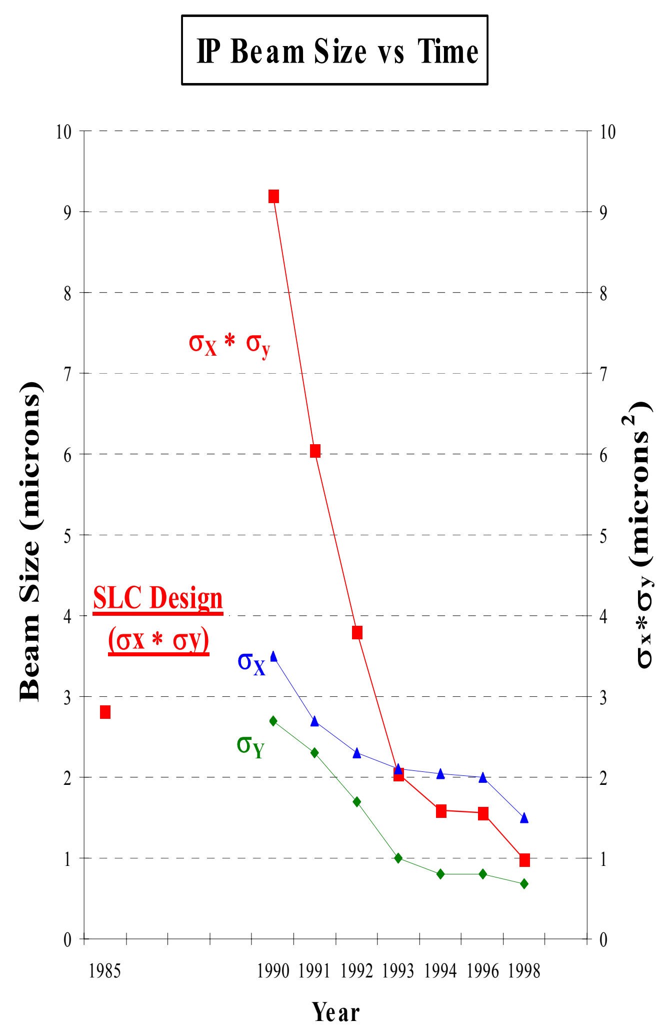
SLAC-PUB-6204

Successful SLC (warm / 3 GHz) experience

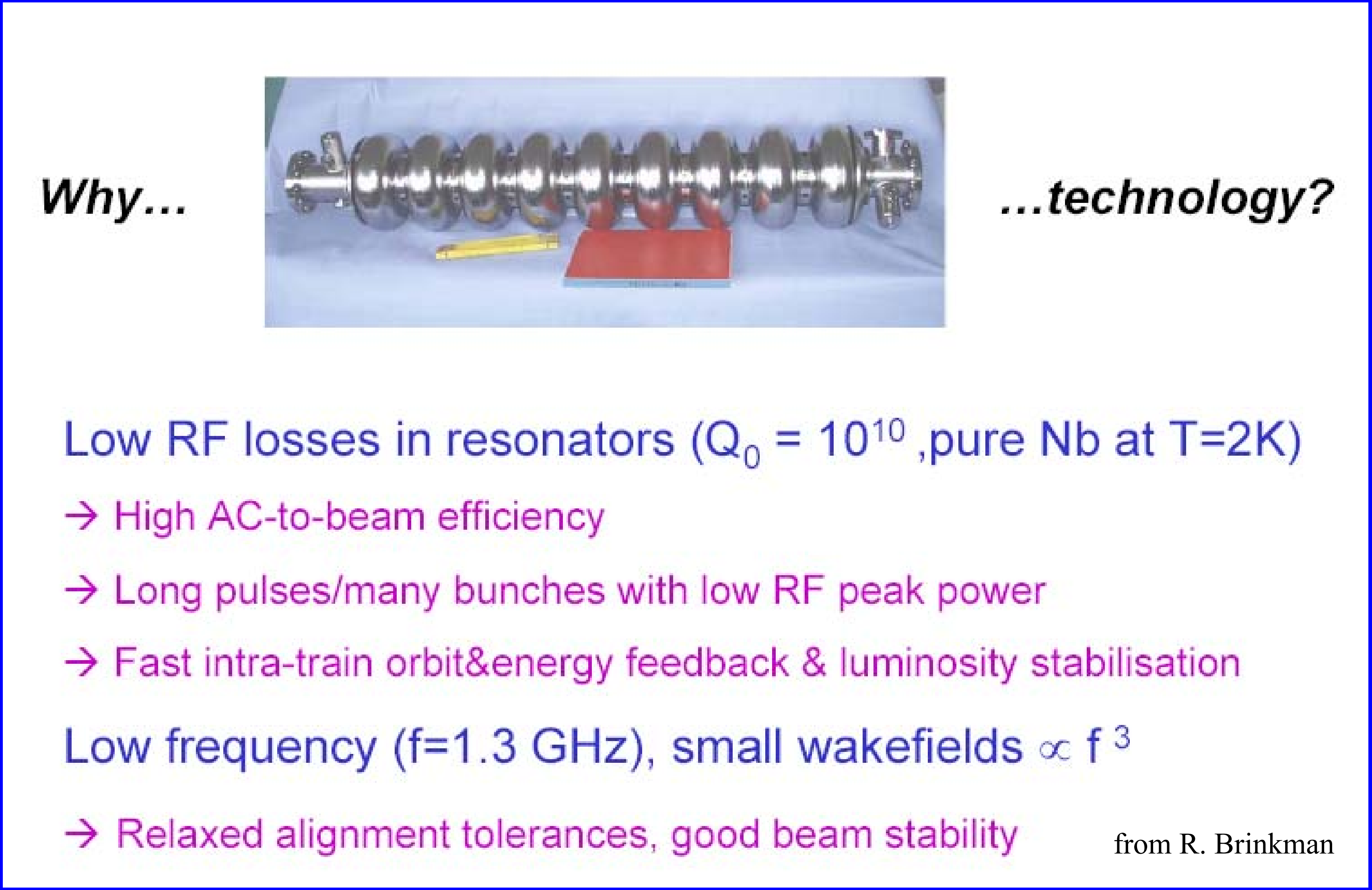




	Design	Achieved	Units
Beam charge	7.2e10	4.2e10	$e^{\pm}$/bunch
Rep. rate	180	120	Hz
DR ε_x	3.0e-5	3.0e-5	m rad
DR ε_y	3.0e-5	3.0e-6	m rad
FF ε_x	4.2e-5	5.5e-5	m rad
FF ε_y	4.2e-5	1.0e-5	m rad
IP σ_x	1.65	1.4	µm
IP σ_y	1.65	0.7	µm
Pinch factor	220%	220%	Hd
Luminosity	6e30	3e30	$cm^{-2}sec^{-1}$



Superconductive linac (TESLA)



Why… ***…technology?***

Low RF losses in resonators ($Q_0 = 10^{10}$,pure Nb at T=2K)

→ High AC-to-beam efficiency

→ Long pulses/many bunches with low RF peak power

→ Fast intra-train orbit&energy feedback & luminosity stabilisation

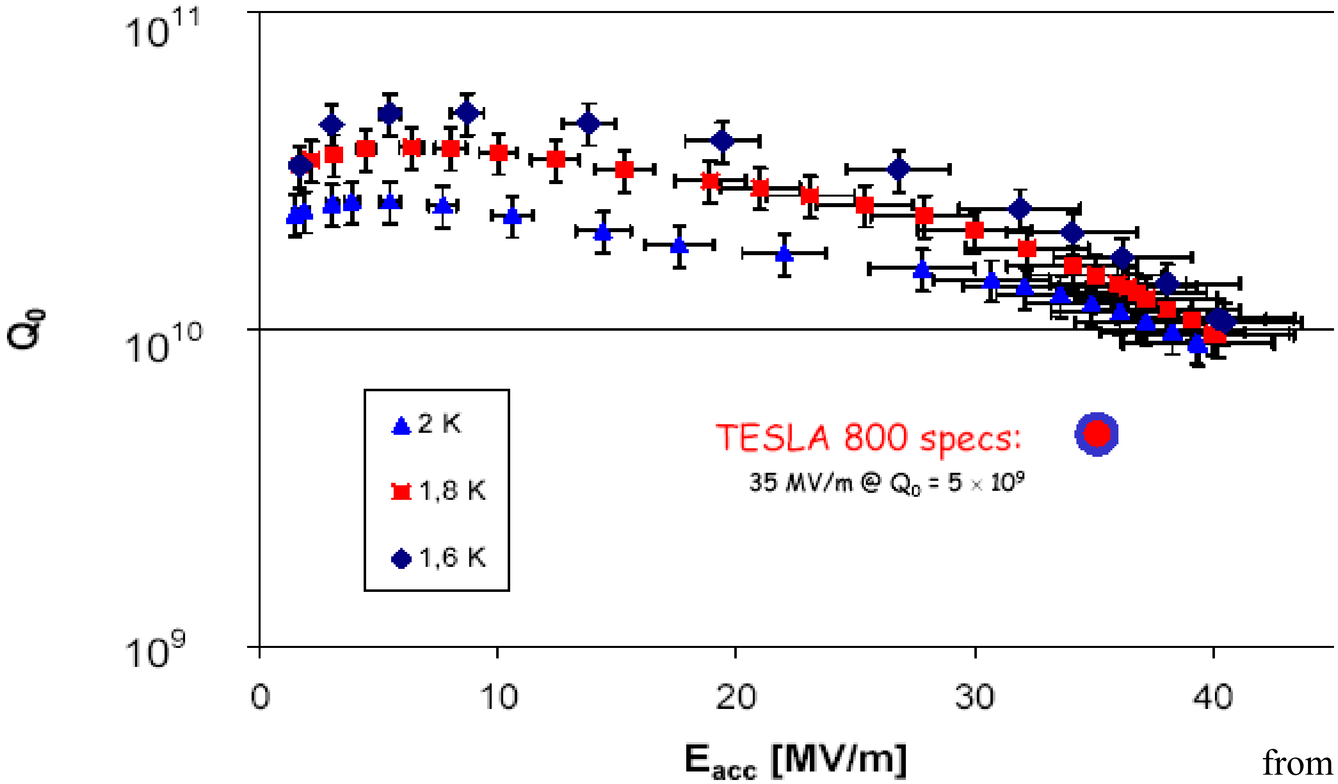
Low frequency (f=1.3 GHz), small wakefields $\propto f^{3}$

→ Relaxed alignment tolerances, good beam stability

from R. Brinkman

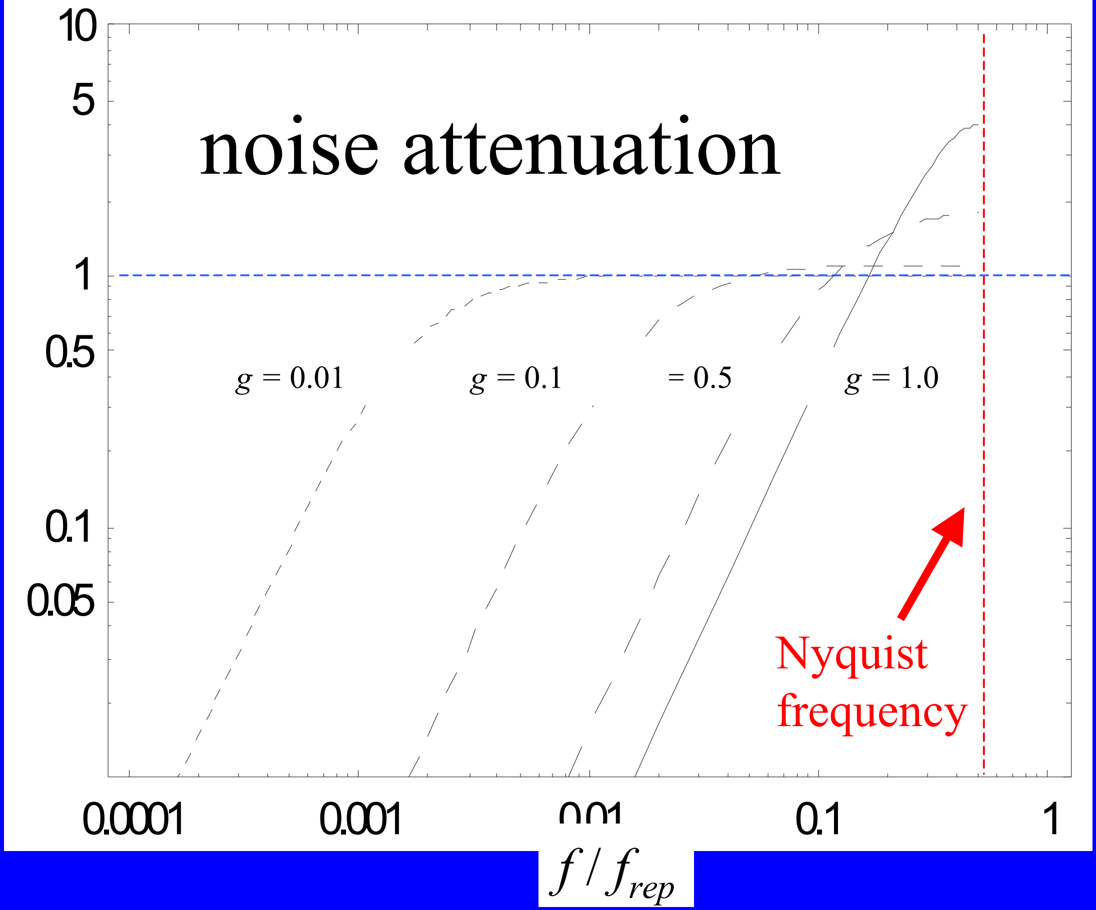
Continuous & outstanding progress

CW test of best 9-cell EP-treated (at DESY) cavity
note: no 1400 C titanisation treatment!

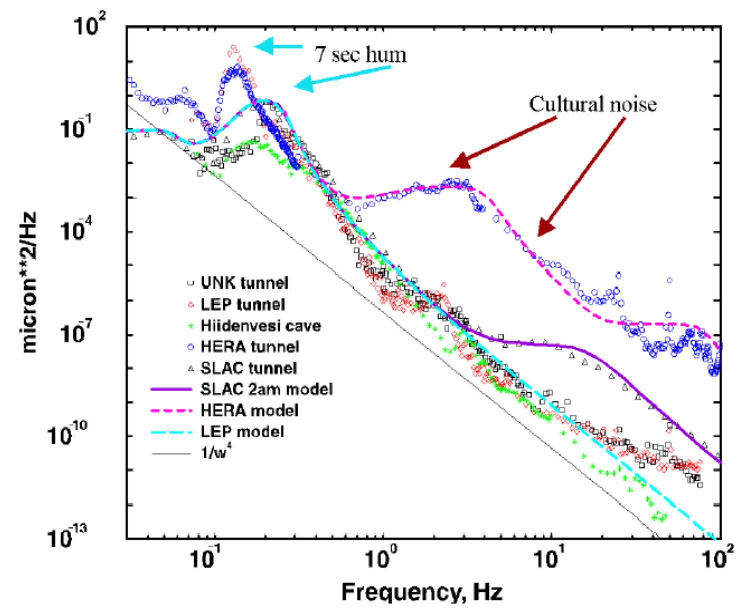


from R. Brinkman

Feedback bandwidth



vibration spectra



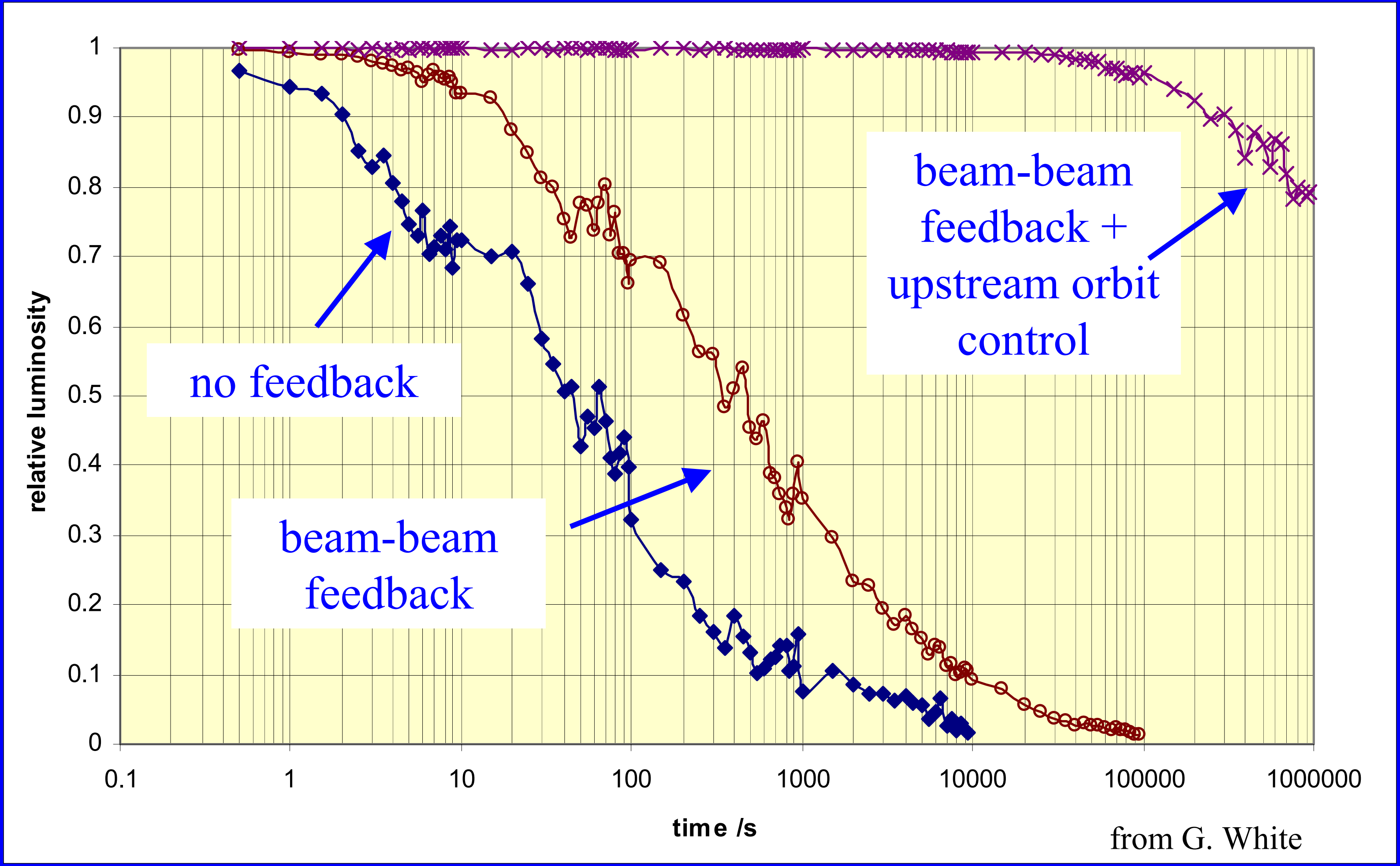
NLC : $f_{\text{inter-train}} = 120$ Hz

TESLA : $f_{\text{inter-train}} = 5$ Hz

TESLA : $f_{\text{intra-train}} = 300$ kHz

Typically attenuate noise with $f < f_{rep}/20$

Long term stabilization : nested loops



from G. White

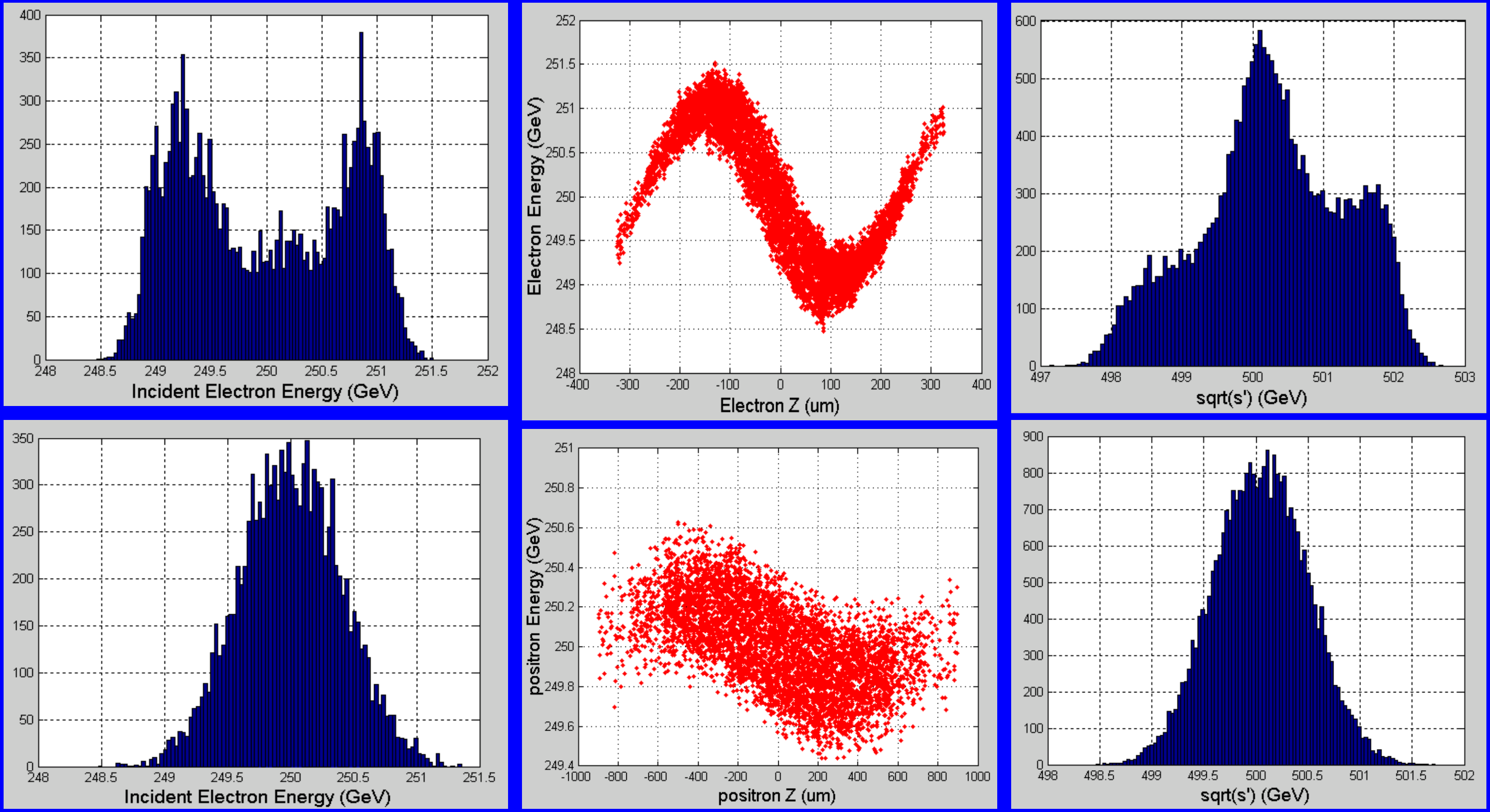
simulated response : ex. of slow diffusion ground motion (ATL model)

Biases from LC energy spread on E_{CM} reconstruction

from M. Woods

NLC

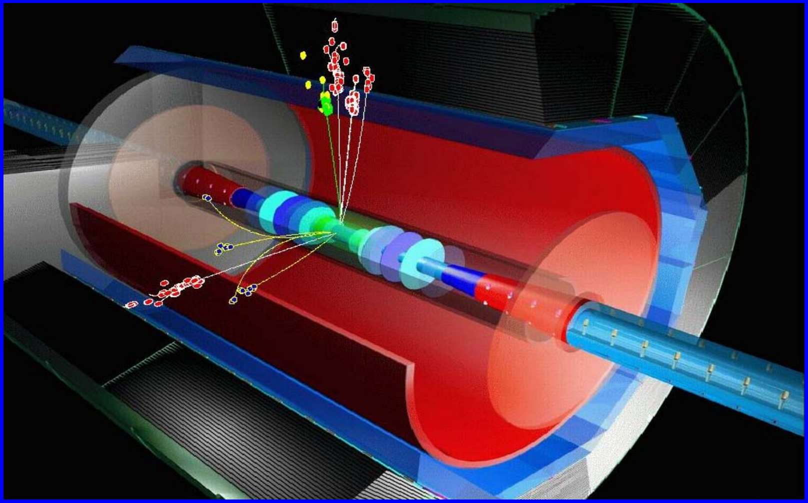
TESLA

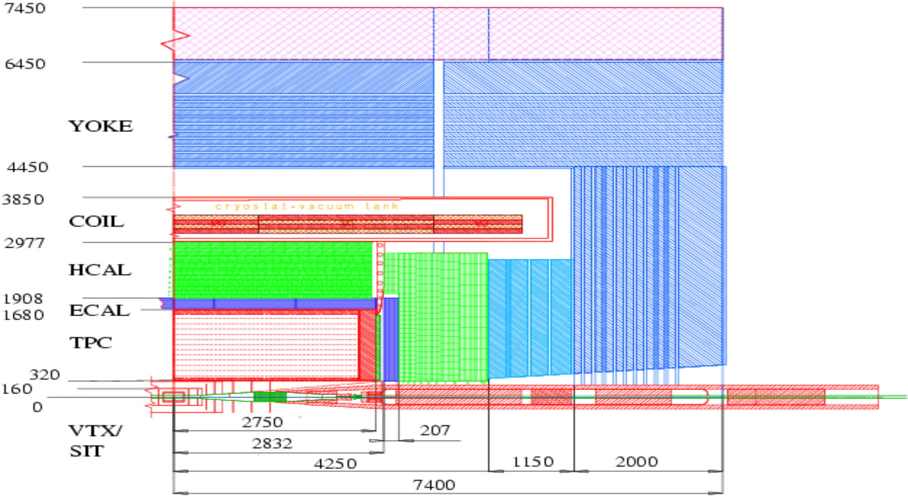


Simulating machine misalignments and associated correction schemes :

NLC biases ~ 10^{-4} - 10^{-3} TESLA biases ~ 10^{-5} - $3\ 10^{-4}$

Detector : basic concepts & specs (TESLA)





- Momentum resolution : $\sigma_{1/p} < 7x10^{-5}/\text{GeV}$ (1/10 × LEP)

⇒ recoil mass in Higgs Z → leptons

- Impact parameter : $\sigma_{ip} < 5\ \mu m \oplus 5\mu m/p(\text{GeV}$ (1/3 x SLD)

⇒ b & c quark tagging → Higgs BR measurements

- Jet energy flow : $\delta E/E = 0.3/E$ (GeV) (1/2 x LEP)

⇒ multi-jet masses events with few/no kinematic constraints

- Hermeticity : $\theta > 5$ mrad

⇒ SUSY signatures with small mass differences

Large TPC +
$B_{MAG} = 4$ T
2-track resolution
Ecal (SiW) + Hcal
high granularity
inside coil
Si microvertex
NO TRIGGER
RADIATION OK

physics ↔ detector ↔ machine

LC is open system ⇒ “the experiment starts at the gun”

diagnostics

extraction

final focus

controls

linac

damping ring

compression

injection

detector

(diagnostics)

backgrounds

collimation

masks

- LC design & operation : new challenges !
  - ➡ HEP community strongly involved → **SLAC model**
- special needs for some physics topics :

energy calibration – polarization – correlations – **forward region** – background

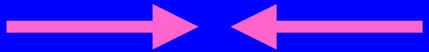
very forward region ↔ technology choice (1)

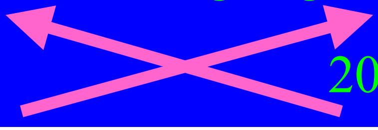
TESLA | NLC / JLC-X

bunch separation: 337 ns | 1.4 ns

head-on or crossing angle | crossing angle

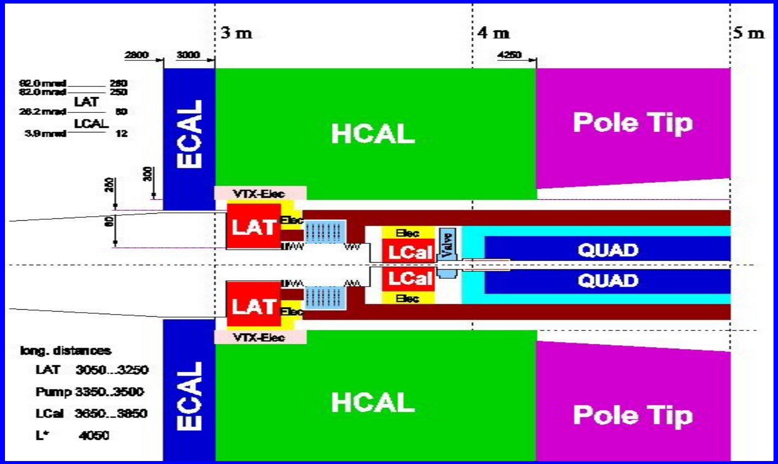
IP geometry

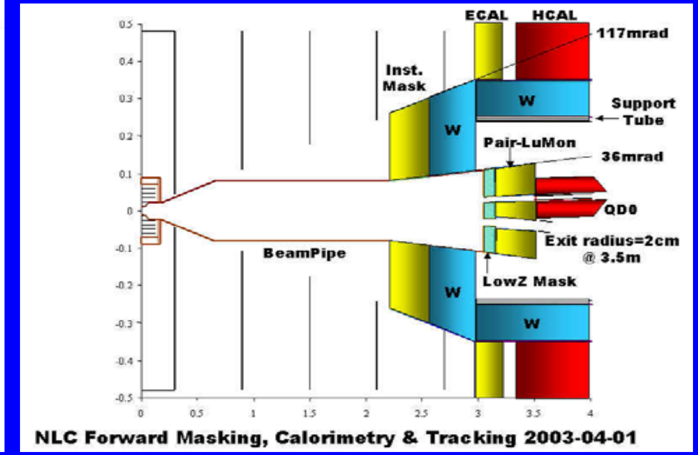




20(7) mrad

forward region

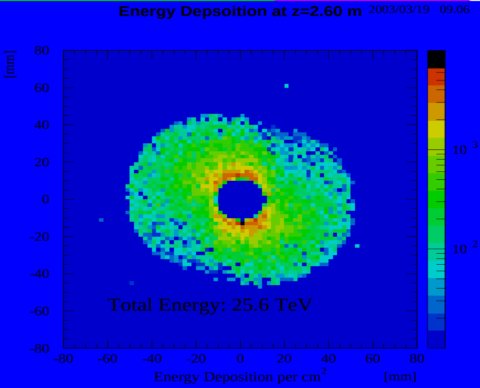




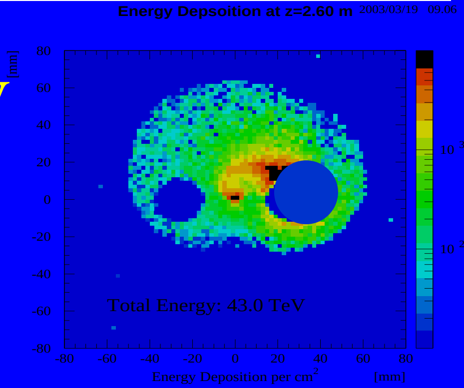
NLC Forward Masking, Calorimetry & Tracking 2003-04-01

calorimetry
at low angle
1. luminosity
2. veto

~ 25 TeV
from e^+e^-
pairs
(~ 3 GeV)



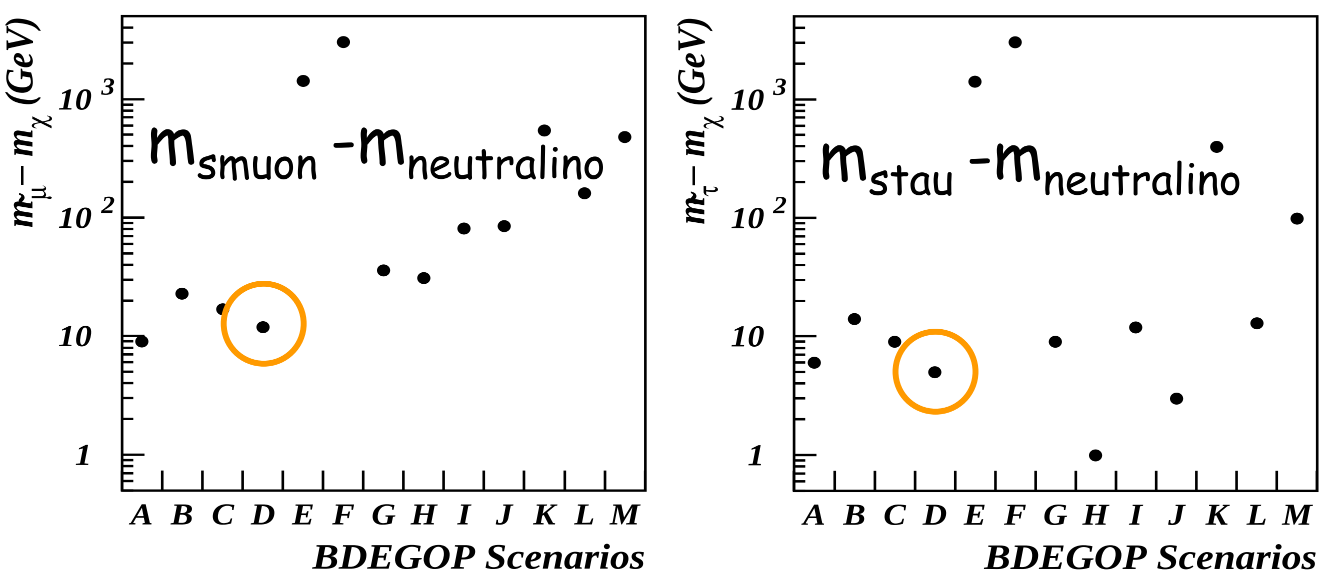
~ 43 TeV
× n
bunches
$\Delta t_{readout}$?



very forward region ↔ technology choice (2)

- Some popular dark matter SUSY explanations need the LSP χ^0 to be quasi mass-degenerate with the lightest sleptons $\tilde{\tau}$, $\tilde{\mu}$,…

  → co-annihilation mechanism
- mSUGRA + new dark matter constraints from WMAP cosmic microwave background measurements point in this direction
- Scenario considered also relevant more generally in the MSSM



Acceptable solutions in mSUGRA

M. Battaglia et al.
hep-ph/0306219

very forward region ↔ technology choice (3)

signal

$ee \to \tau\, \chi^0\, \tau\, \chi^0$

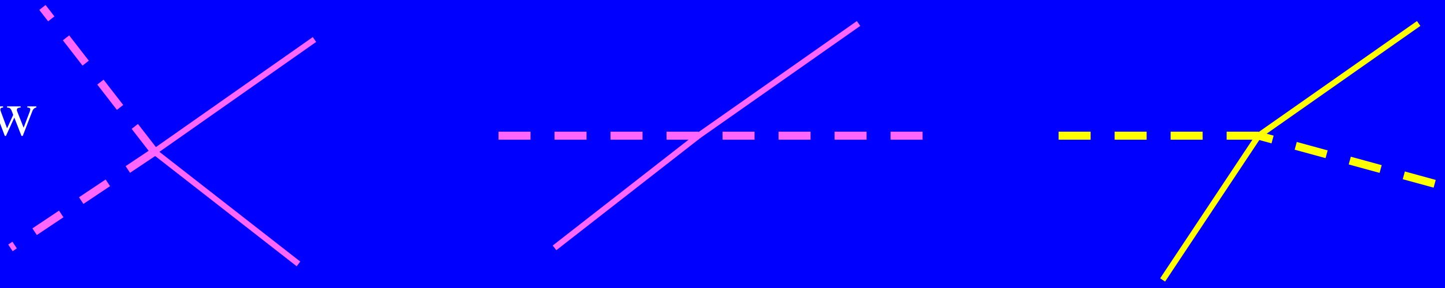
$\sigma \sim 10$ fb

main background

$ee \to (e)(e)\, \tau\, \tau$

$\sigma \sim 10^4$ fb

Transverse view



efficient / hermetic γγ veto crucial to detect sleptons in highly mass-degenerate SUSY scenarios

- Important LC channel, complementary to LHC
- Precise slepton masses ↔ dark matter ↔ constraints from Planck

(luminosity & energy strategy) (LC / LHC ↔ cosmology)

Road-map for choices & decision (ITER model)

- Technical review committee : E_{cm} = 0.5-1 TeV with L = 10^{34} cm^{-2} s^{-1}

R1 feasibility demonstration → at 0.5 TeV only TESLA has no R1 !

R2 R&D to finalize design & reliability

R3 R&D before begin large-scale production end 2002

R4 R&D desirable to optimize technical aspects and costs…

- Technology choice : 4 "wise persons" × 3 regions end 2004
- World LC community united → form international design team

  ⇒ detailed costed technical design by ~ end 2006
- Concerted political actions + outreach + site selection 2004 - 2006
- Decision (optimistic) when LHC starts ~ end 2007
- Construction ~ 6 years → commissioning → physics 2013 – 2015

form European team for relevant participation to GLC

Instruments & connections : detector(s)

- Regional meeting ~ 6 months : *attendance strong & young*
- International ~ 18 months : technology choice end-2004 → integration
- Sub-detector collaboration already → international (CALICE, very forward region, polarization,…)
- National funding + INTAS + bilateral collaborations + FP6 ? + …

ECFA Study
Physics and Detectors
for a Linear Collider

ACFA Joint Linear Collider
Physics and Detector Working Group

American Linear Collider
Physics Group

International Conference on Linear Colliders
Colloque international sur les collisionneurs linéaires

LCWS 2004
Paris, April 19-23, 2004
http://polywww.in2p3.fr/LCWS2004

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Instruments & connections : machine(s)

integrate & extend community on the model of HEP experiments

- FP6/Research Infrastructure/Esgard/Integrating Activity/ http://esgard.lal.in2p3.fr/ Kick-off CERN 11/03
  approved 2003-2007 with 15 Meur (60% → LC)
- FP6/Research Infrastructure/Esgard/Design Study/LC
  bid 03/2004 for 10 Meur for 2005-2007 ⟶ European LC team
- UK/PPARC/Design Study/LC Beam Delivery : ↑
  approved 2004-2006 with 7 M£ (mainly PhD & postdoc)
- FP6/Marie Curie/RTN ? ⟶ *next call for bid in* 2005
- Existing specific US DOE funding (FNAL, SLAC & university groups) ↗ ~ 100 M$ for 2005-2006 after technology choice (?)
- German Wissenschaftsrat 02/2003 : support multilateral LC process

decision to fund 50% of XFEL (673 Meur) ⟶ 20 GeV TESLA demo

EC to fund remaining 50% via investment bank → “quick-start” (?)

CONCLUSIONS

- ~ 20 years of R&D

  ⇒ sub-TeV LC technology now mature
- other more futuristic acc. project not at same level
- recognized scientific case for sub-TeV LC

  sub-TeV LC ↔ LHC programs
- organize internationally for truly global project

  ⇒ *good time to get involved !*

SPAIN

0.5-1 TeV LC ↔ LHC ↔ 0.5-3 TeV CLIC

(partly personal views)

- LHC answers soon : why sub-TeV LC ?
  - full interpretation & consistency via precise measurements (e.g. reveal EWSB scenario,…)

overlap → complementary

- historical : LHC last HEP collider ?
- wait : multi-TeV CLIC ↔ LHC ?
  - much R&D needed to reach LC-level maturity
  - would likely start with 0.5 TeV demonstration
  - surely relevant as second generation or phase