03/01/00

All you ever wanted to know about CLIC: a cost-effective linear collider for multi-TeV energies

Frank Zimmermann for the CLIC study team:

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O. Napoly, Saclay

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LETTERE ALLA REDAZIONE

(La responsabilità scientifica degli scritti inseriti in questa rubrica è completamente lasciata dalla Direzione del periodico ai singoli autori)

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N.-Y.

(ricevuto il 2 Febbraio 1965)

While the storage ring technique for performing clashing-beam experiments (1) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant or superficially more complex may prove more tractable.

In order to be useful for clashing-beam work an acceleration device must produce beams of small cross-section or beams of high enough quality that they may be focused to a small spot in the interaction region or regions. Such beams are well known to be produced by linear radio-frequency accelerators. Figure 1 depicts a rudimentary type of arrangement for performing a clashing beam experiment with standard traveling wave linacs. For purposes of illustration let us consider two linacs having energy gains of 500 MeV each and producing continuous beam currents of 50 to 100 milliampere. (As we shall see currents of this order would be necessary to obtain useful interaction rates at this energy.) Under these conditions the rf power necessary to establish the accelerating field in the guides would be of the order of 100 megawatt in a standard

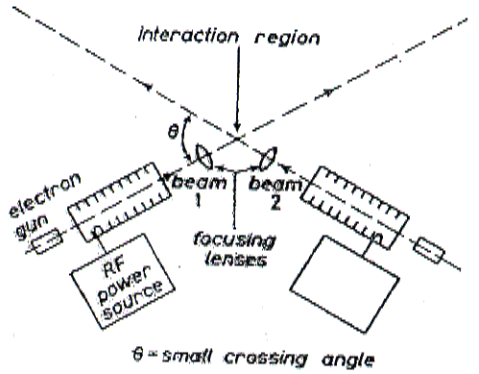


Fig. 1.

design while an additional 25 to 50 megawatt would be carried away by each beam. Although in principle it may be possible to produce and handle this large power the sheer brutishness of the scheme robs it of all appeal.

With some modification we may be able to retain the basic advantages of the linear device while avoiding the

(*) Work supported in part by the United States National Science Foundation.

(1) See for instance G. K. O'NEILL: *Phys. Rev.*, 102, 1418 (1956).

A POSSIBLE SCHEME TO OBTAIN e^-e^- AND e^+e^- COLLISIONS AT ENERGIES OF HUNDREDS OF GeV

U. AMALDI
CERN, Geneva, Switzerland

Received 18 December 1975

As a contribution to the discussion on very long term developments in the field of high energy physics, it is pointed out that it is possible to devise e^-e^- and e^+e^- colliding beam machines which are not affected by the large synchrotron losses typical of conventional storage rings. The scheme proposed here makes use of two collinear superconducting linacs which at the same time accelerate and recover the energy fed to the electron and positron beams.

The construction of a very large electron-positron storage ring (PETRA) has been recently approved in Western Germany and a similar project is under consideration in the United States (PEP). For these machines the maximum value of the centre-of-mass energy, about 50 GeV, is fixed mainly by the large power that must be supplied to the beams to compensate for the synchrotron radiation losses. Because of these losses, the storage ring scheme is today considered unrealistic for energies an order of magnitude larger than 50 GeV. It is therefore worth discussing alternative solutions, even if they cannot become practical in less than ten or fifteen years.

In presenting our argument, we consider a center-of-mass energy of 300 GeV, that corresponds to the so-called unitarity limit of weak interactions. It has to be understood that this choice does not imply that, already at these energies, the scheme we propose is today economically advantageous with respect to conventional storage rings. Anyway at energies of this order of magnitude, weak interactions dominate the cross-section and electron-electron collisions are almost as interesting as electron-positron collisions. We thus start by considering the simpler case of an *electron-electron colliding beam machine.*

The working principle of a conventional, very high energy, electron storage ring can be characterized as follows: "use" the same electron many times, by keeping it on a circular orbit, and accept to throw away energy through incoherent synchrotron radiation. The opposite possibility is considered here: "use" each electron only once, by having it moving on a straight path without radiation losses, and, after the interaction point, recover coherently a large fraction of its energy.

For e^-e^- collisions this can be achieved with the scheme shown in fig. 1. Two collinear, superconducting standing-wave linacs accelerate two continuous beams of electrons up to, say 150 GeV, and magnetic lenses focus them to very small transverse dimensions in one, or more, low β interaction regions. After crossing, the electron bunches give back their energy to the electromagnetic field of the opposite linac, since there the electric field will be given the opposite phase to decelerate them. Stationary conditions are thus achieved and in each linac the energy given back to the electromagnetic field by the decelerated electrons

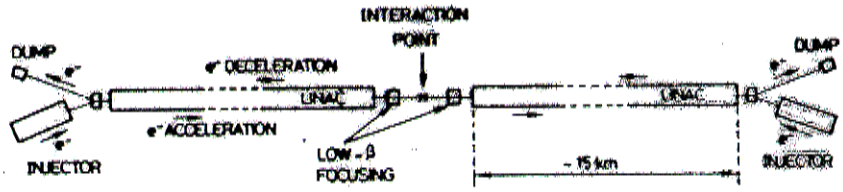
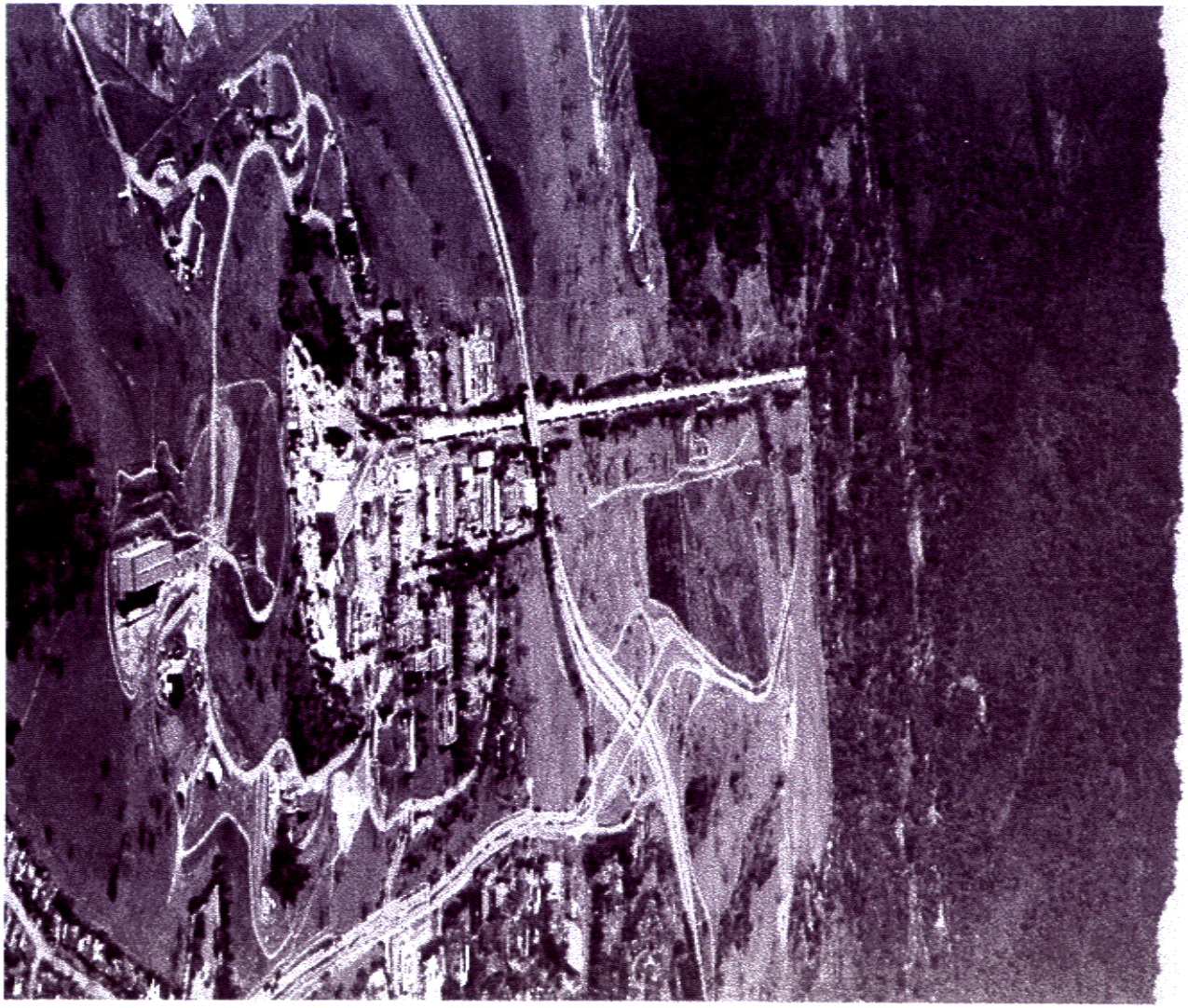
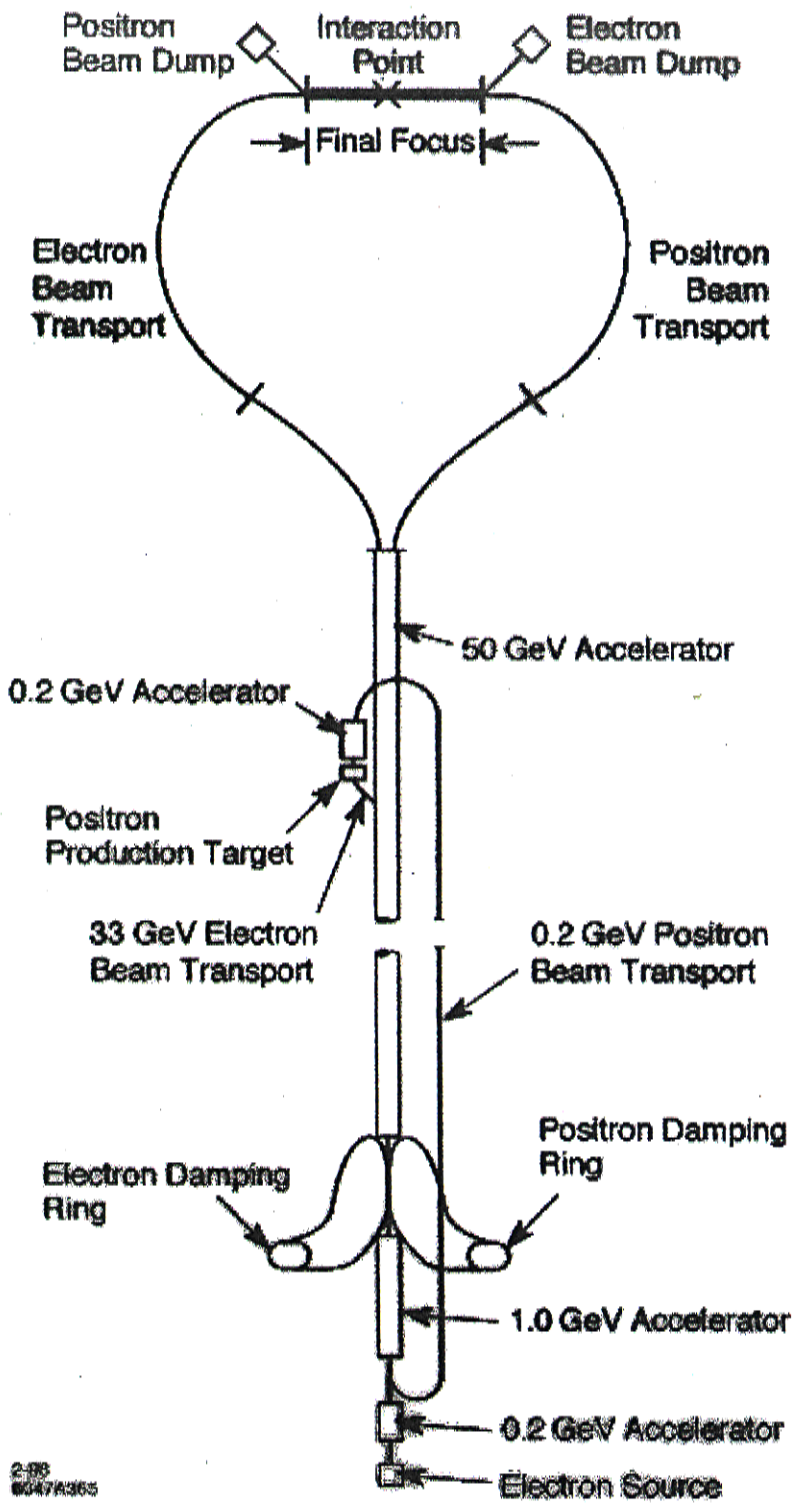


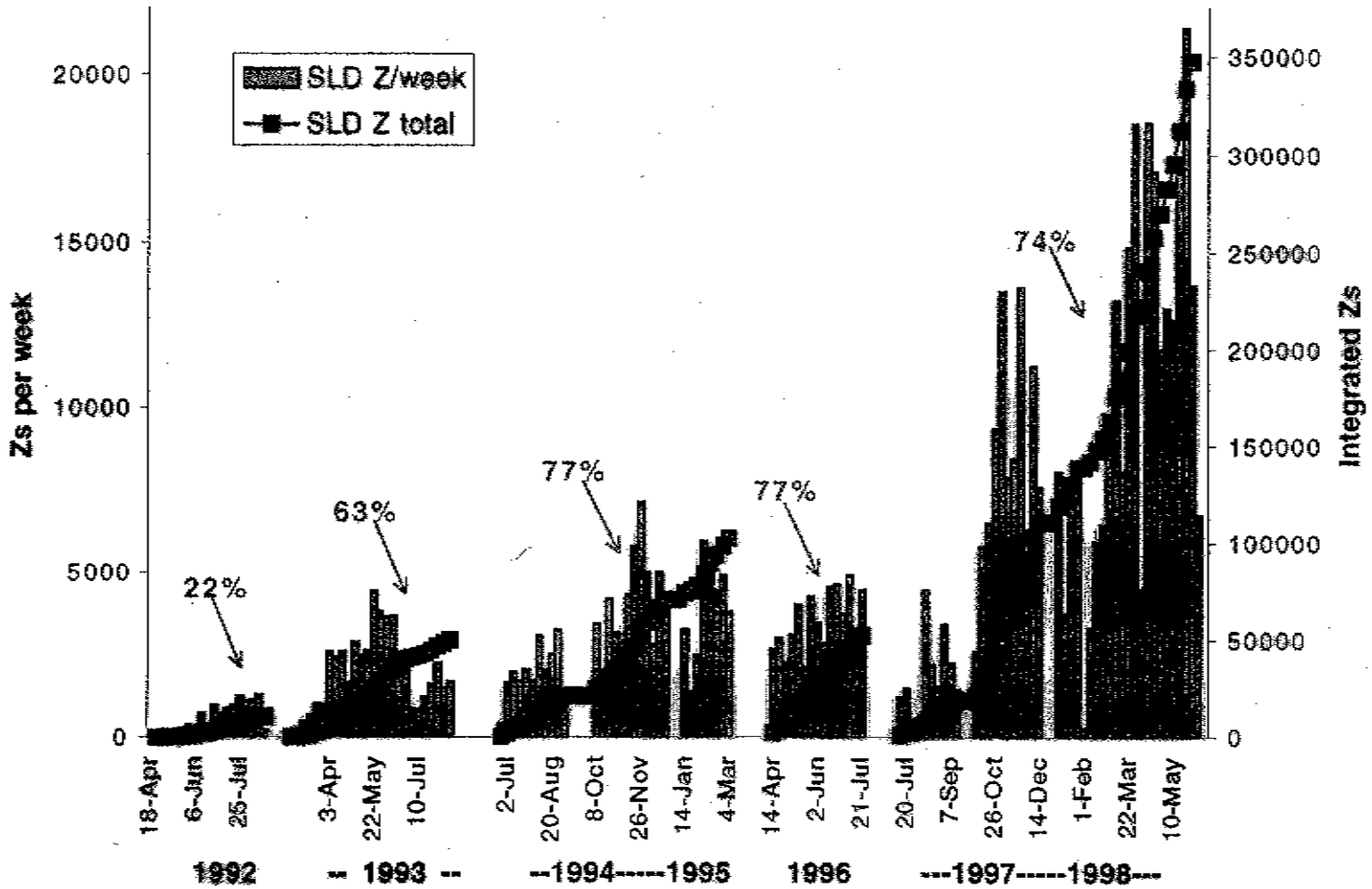
Fig. 1. Schematic drawing of the collinear electron-electron colliding beam machine. If accelerating fields of ~10 MV/m can be achieved, to obtain (150 + 150) GeV collisions the length of the superconducting linacs has to be ~15 km.



Stanford Linear Collider (SLC)

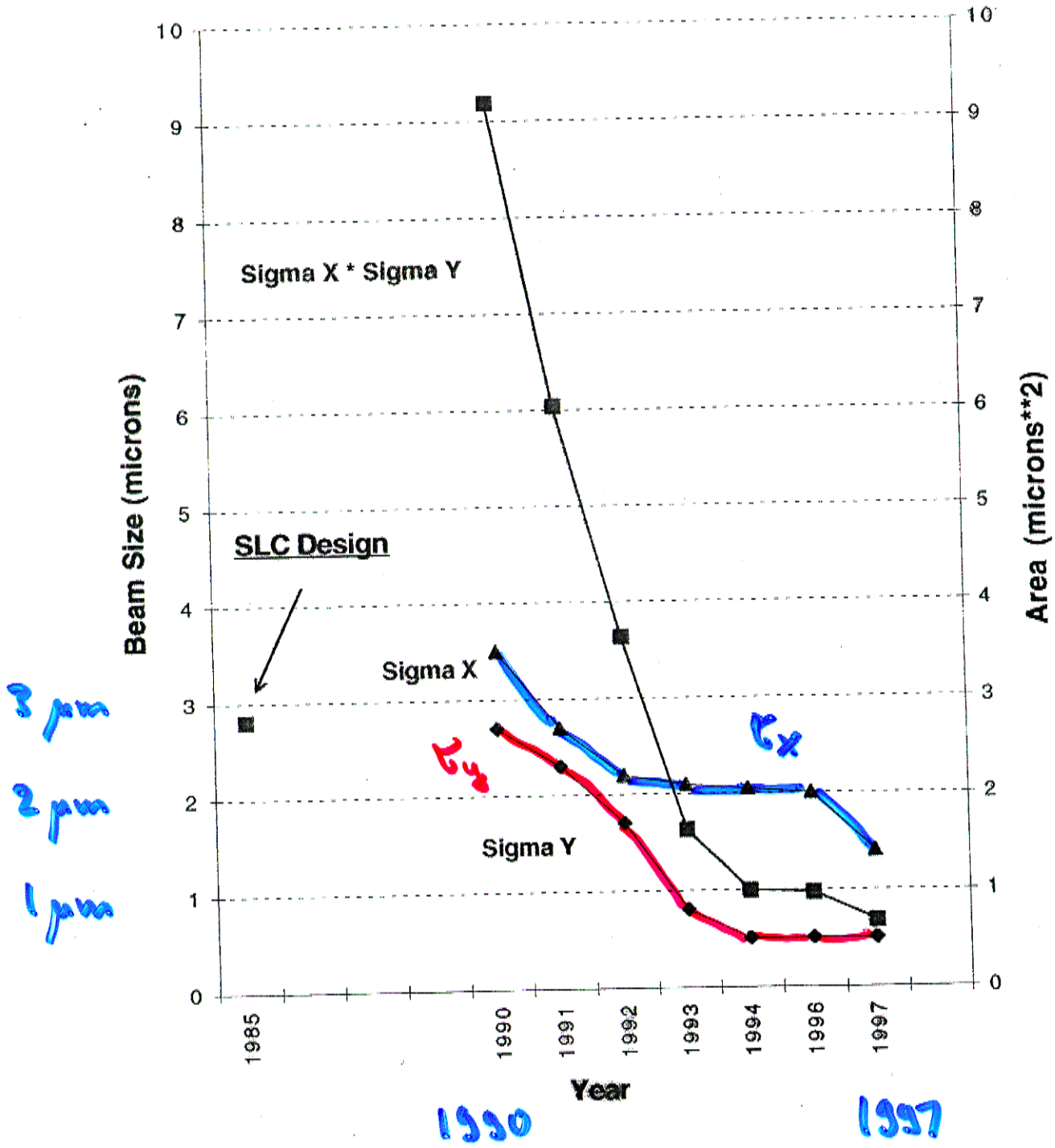


1992 - 1998 SLD Luminosity



N. Phinney 9/23/98

IP Beam Size vs Time



N. Phinney 12/12/97

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/98-03
CERN-SL 98-004 (AP)
CERN-TH/98-33

Options for Future Colliders at CERN

J. Ellis, E. Keil, G. Rolandi

POST-LHC SCENARIO

The priorities that emerge are therefore: (i) an $\ell^+\ell^-$ collider with a centre-of-mass energy comparable to the physics reach of the LHC, which means above 2 TeV and preferably capable of 4 or 5 TeV, and (ii) a pp collider able to make a first exploration of the next energy range beyond the LHC, say up to 10 TeV in the effective hard-scattering centre of mass.

RECOMMENDATIONS

2. CERN should continue its current technical studies of linear e^+e^- colliders, centred on the CLIC programme, as planned. The central thrust of this programme should be a collider with a CoM energy of 2 TeV or more. Its scope and orientation after the currently approved programme should be reviewed soon.

CLIC : Compact Linear Collider

center-of-mass energy range
for e^+e^- collisions : 0.5 – 5 TeV

luminosity $\mathcal{L} \gtrsim 10^{34}\ cm^{-2}s^{-1}$ @ 1 TeV
increasing with energy

design optimisation for 3 TeV

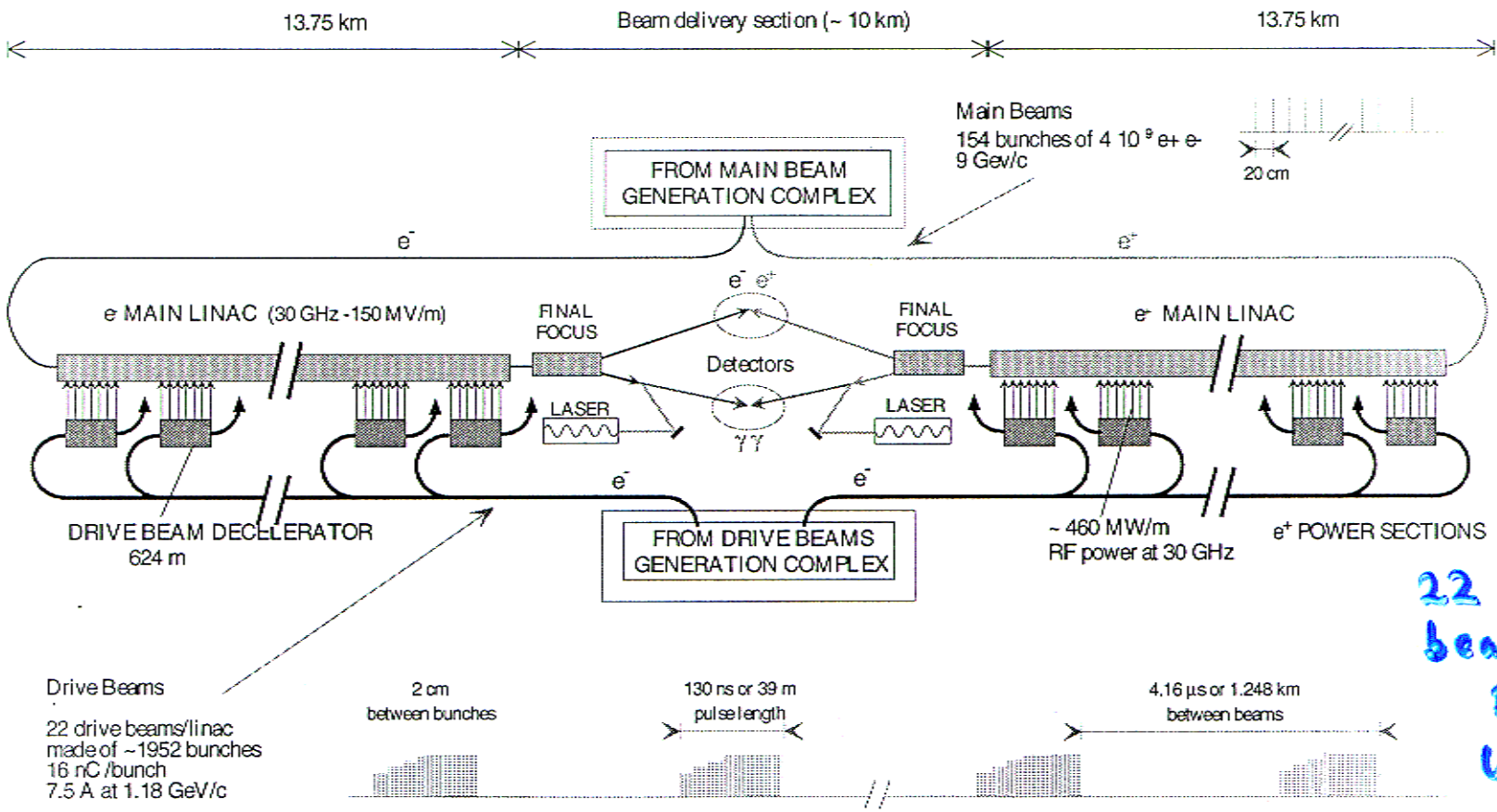
easy energy upgrade

rf power production by
Two-Beam Acceleration

high rf frequency (30 GHz)
→ high accelerating gradient

parameter choice, overall layout, rf power source, beam delivery, route to the CLIC collider

overall layout for 3 TeV cm. energy



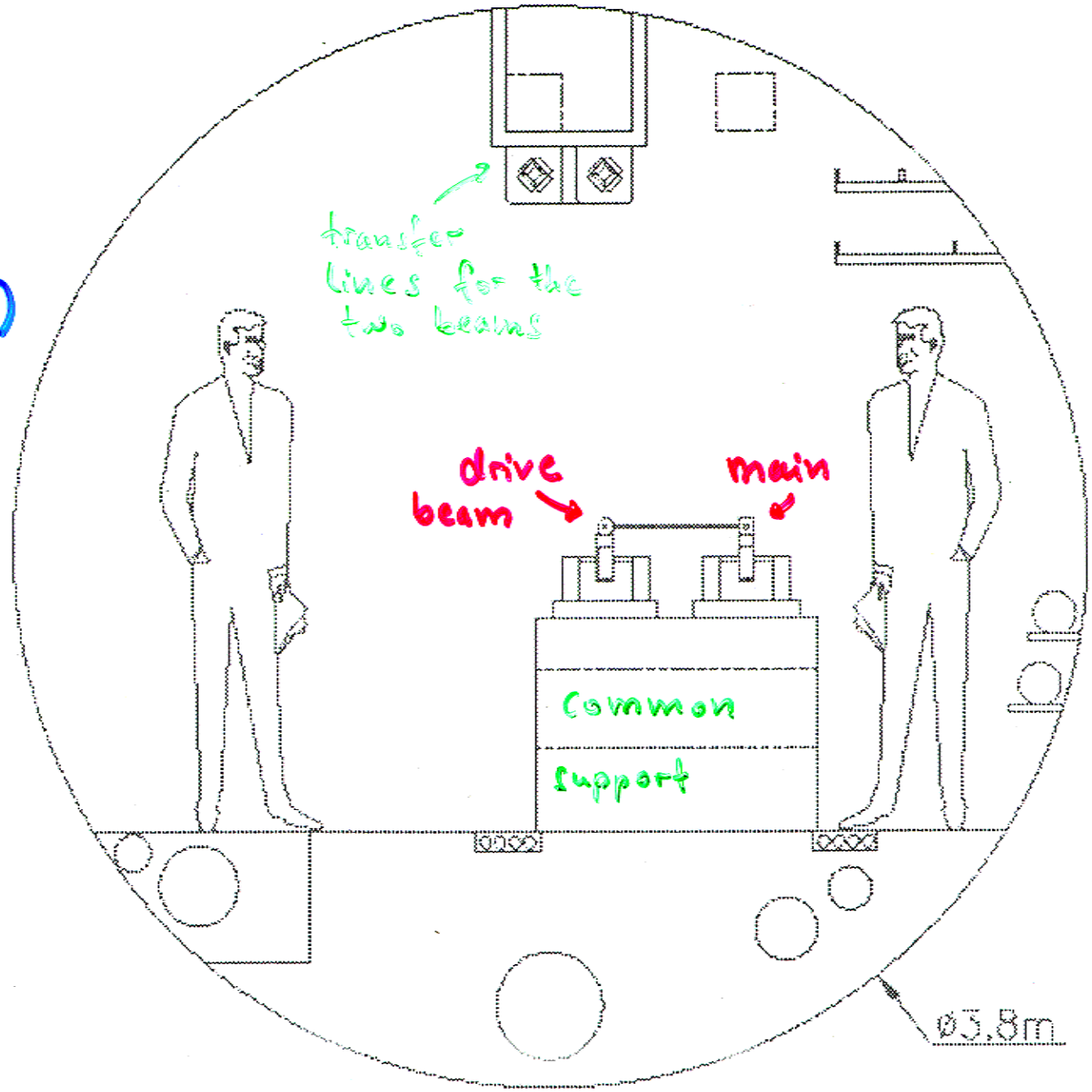
22 drive beams per linac

total length ~ 36 km

CLIC tunnel

no active components (modulators, klystrons, etc.)

simple, cost-effective extendable



Parameters

parameter	symbol	SLC	NLC	CLIC
c.m. energy [TeV]	E	**0.1**	1	**3**
luminosity [10^{34} cm^{-2} s^{-1}]	L	**0.0002**	1.3	**10**
repetition rate [Hz]	f_{rep}	120	120	100
bunch charge [10^{10}]	N_b	3.7	1	0.4
bunches/rf pulse	n_b	1	95	154
bunch separation [ns]	Δ_b	—	2.8/1.4	0.67
av. beam power [MW]	P_b	0.04	9	14.8

luminosity of a linear collider

$$\mathcal{L} = \frac{f_{rep} \cdot n_b \cdot N_b^2}{4\pi \sigma_x^* \sigma_y^*} \simeq \left(\frac{5}{r_e}\right) \frac{P_{wall}}{E_{beam}} N_\gamma \frac{\eta}{\sigma_y^*}$$

η : wall-plug power $\rightarrow$ beam power conversion efficiency (SLC $\ll 1\%$ NLC, CLIC $\sim 10\%$)

LC needs small $\sigma_y = \sqrt{\beta_y^* \varepsilon_y}$

$\rightarrow$ $\boxed{\text{small } \beta_y^* \quad \text{small } \varepsilon_y}$

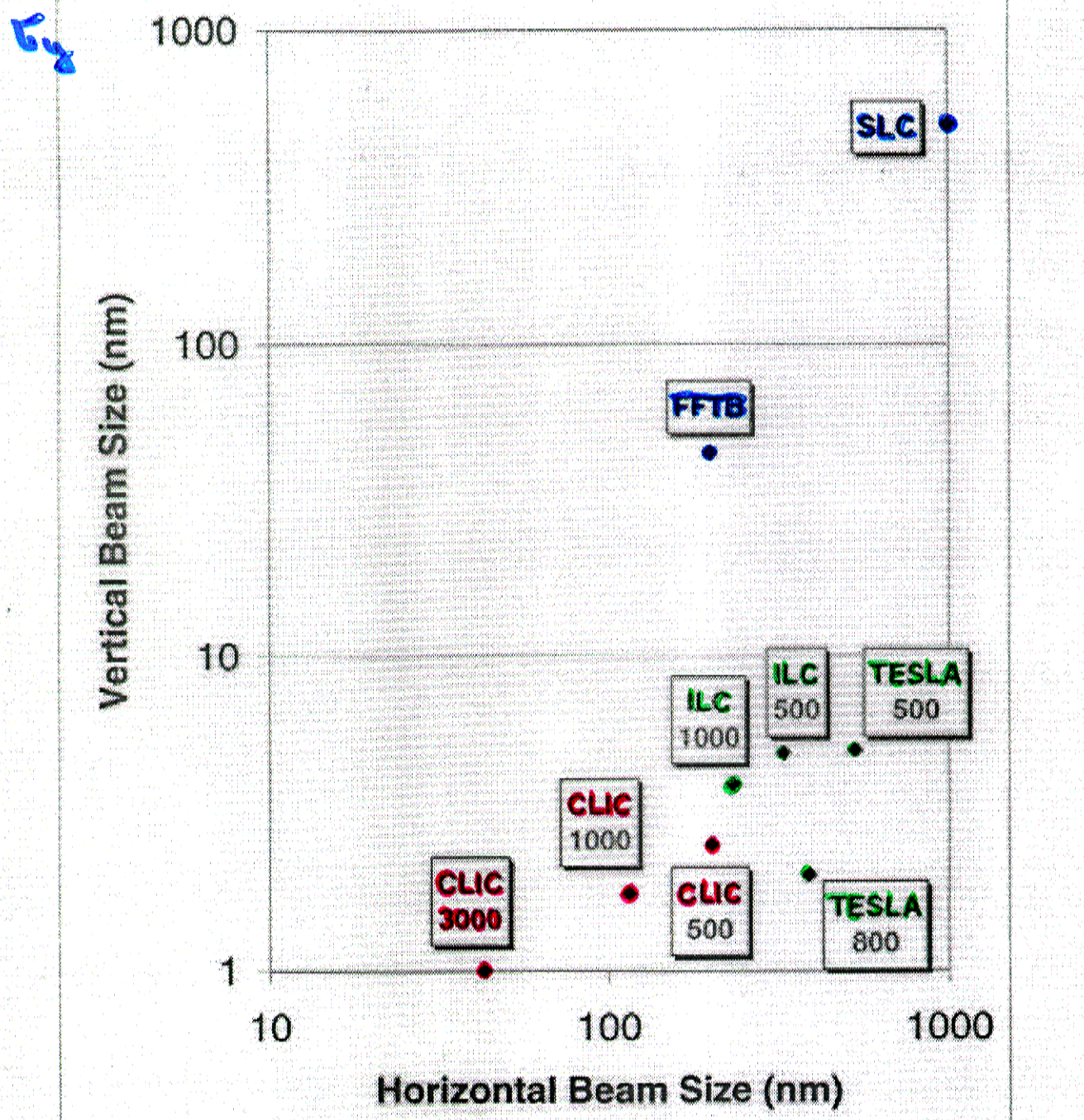
challenging final-focus optics, tolerances, chromatic aberrations, ...

challenging production and preservation of low-emittance beam

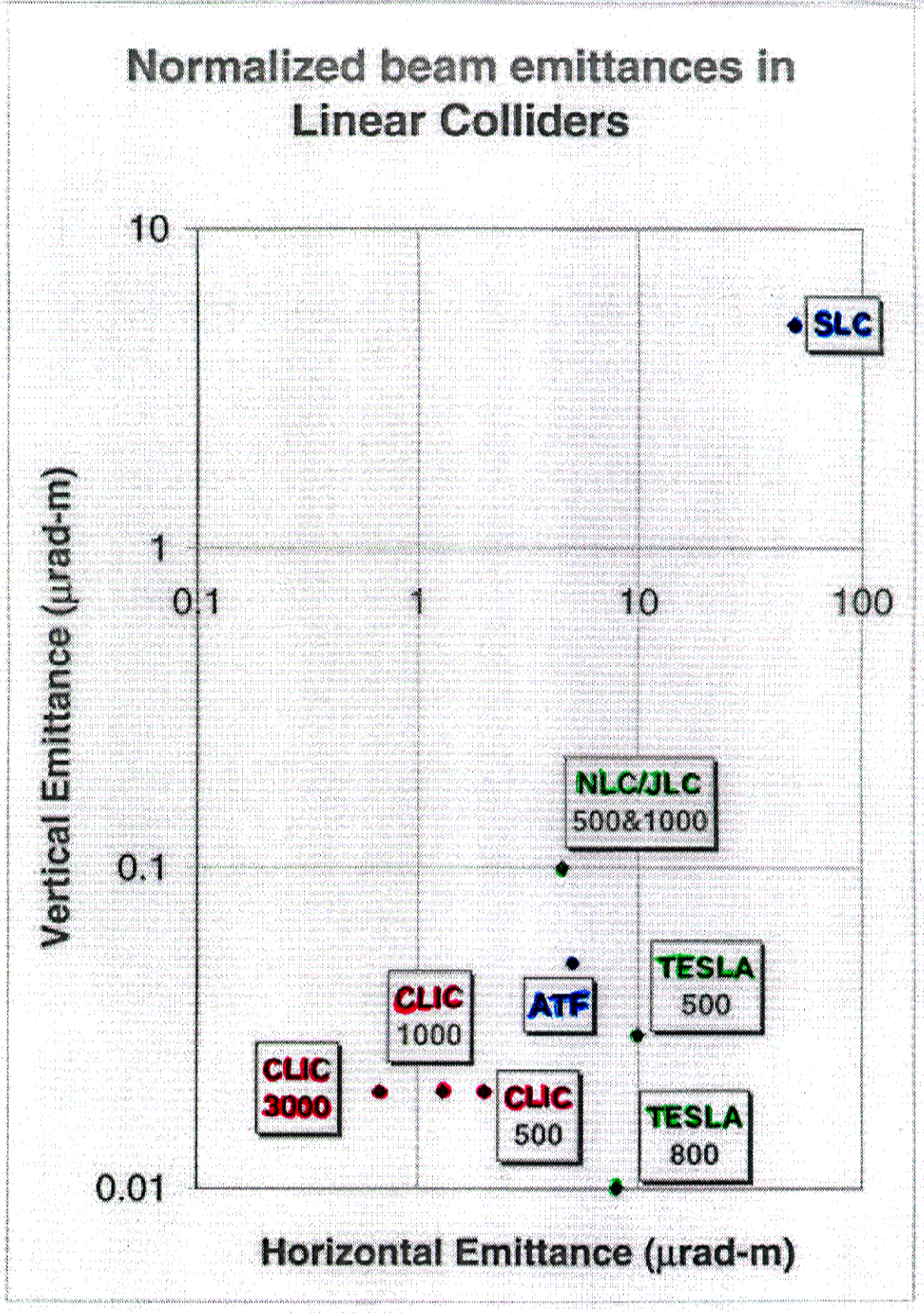
parameter	symbol	SLC	NLC	CLIC
IP hor. emittance [μm]	$\gamma\epsilon_x$	**50**	4.5	**0.68**
IP vert. emittance [μm]	$\gamma\epsilon_y$	**8**	0.1	**0.02**
hor. beta [mm]	β_x^*	2.8	12	8
vert. beta [mm]	β_y^*	1.5	0.15	0.15
hor. spot size [nm]	σ_x^*	**1700**†	235	**43**
vert. spot size [nm]	σ_y^*	**900**†	4	**1.0**
bunch length [mm]	σ_z	1	0.12	0.03
Upsilon	Υ	2×10^{-3}	0.3	**8.1**
pinch enhancement	H_D	2.0	1.45	2.24
beamstrahlung	δ_B [%]	**0.06**	10	**31**
photons per e^- (e^+)	N_γ	1	1.4	2.3

† 1998 average value

R.M.S. Beam Sizes at Collision in Linear Colliders



- in operation
- test facility
- under study



• in operation

• test facility

• under study

CLIC rf power source

Two-Beam Acceleration scheme (A. Sessler, 1982)
Adaptation to CLIC single bunch (W. Schnell, 1986)
Novel TBA (CLIC study group, 1988-98)

deceleration of high-intensity low-energy drive beam running parallel to main linac

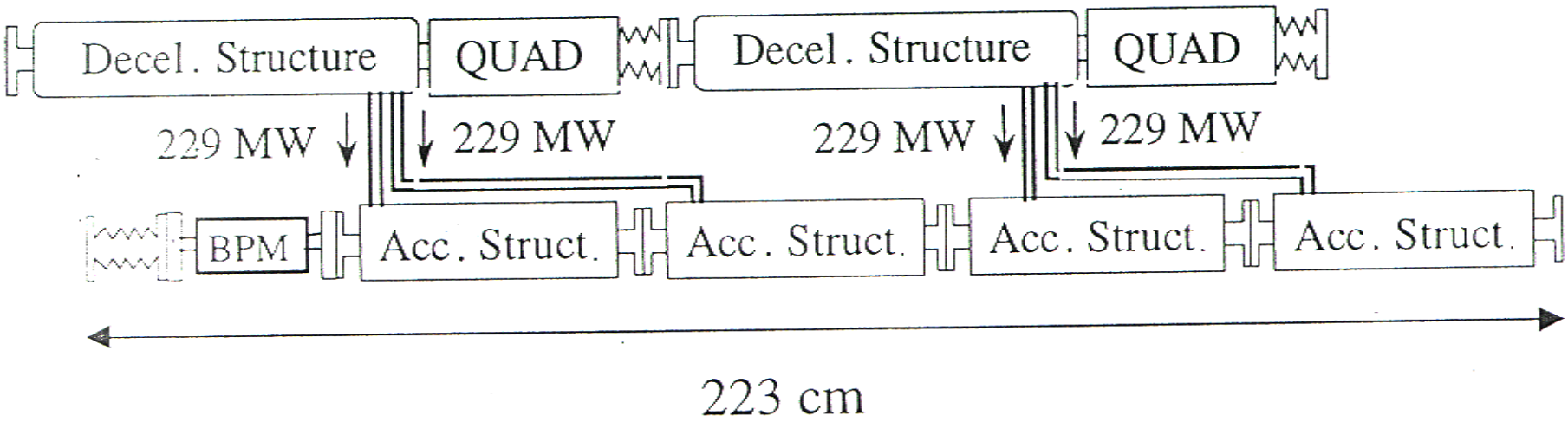
↳ rf power generation

drive beam pulse $\hat{=}$ rf pulse
(600 kJ rf power)

challenges:

(1) drive beam total energy 810 kJ / pulse
(2) generation & acceleration of high-charge beam
(3) overall efficiency & stability
(4) reliability & beam-power management

Drive Beam Decelerator



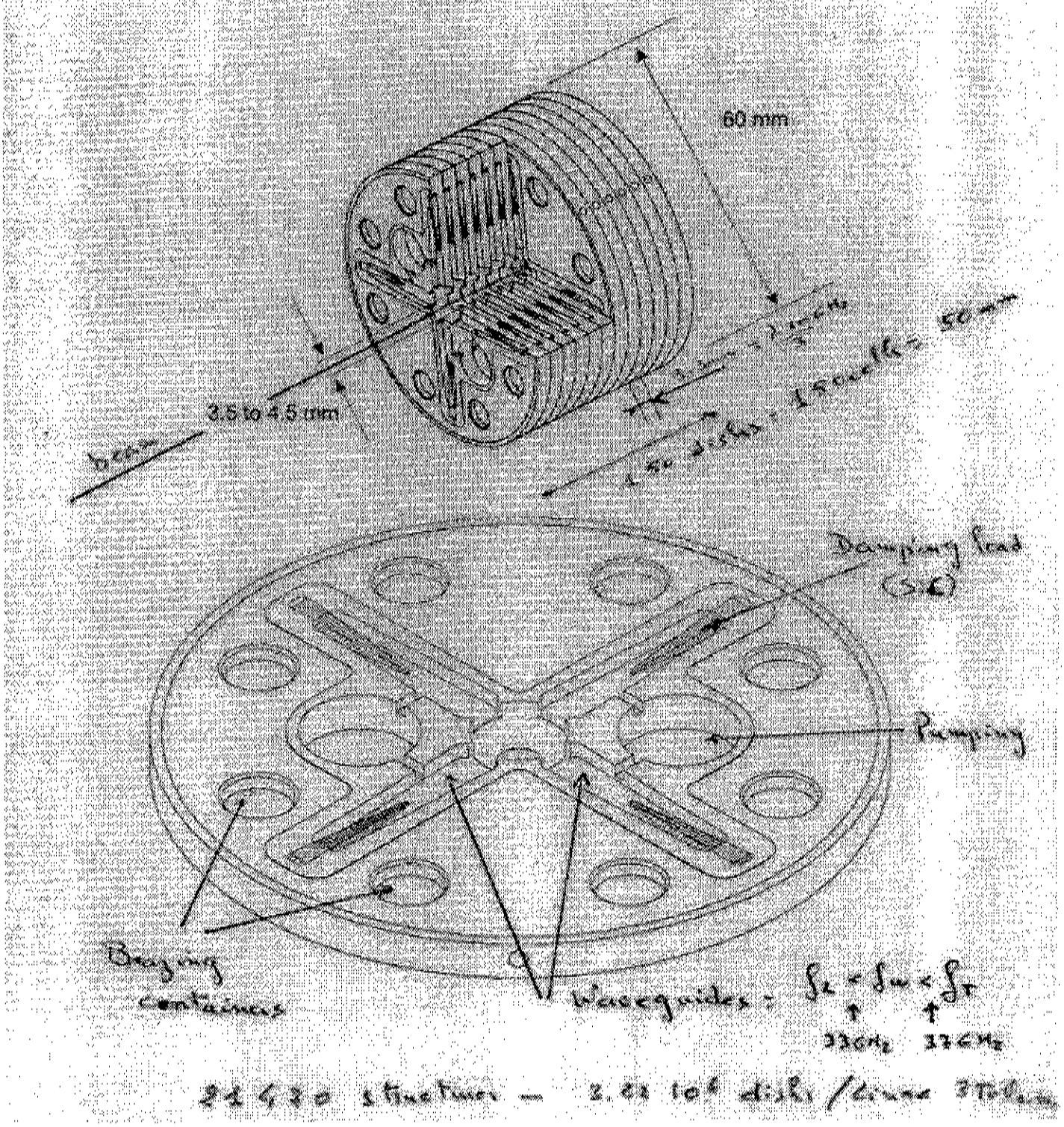
Main Linac Accelerator

basic linac module

W. Wuensch

CLIC MULTI-BUNCH ACCELERATING TAPERED DAMPED STRUCTURE (TDS)

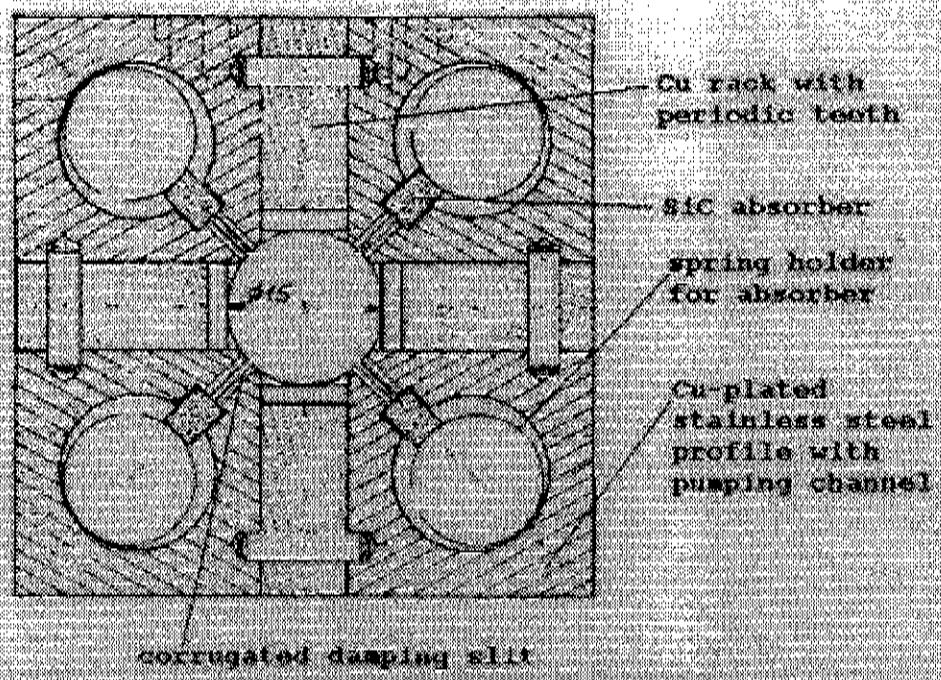
Damping by four radial waveguides per cell.
Discrete RF load in each waveguide.
Detuning by simple linear taper of beam-pipe (Δf detuning 2 GHz= 5.4 %)
First dipole mode damped to Q=16
Quasi-constant unloaded accelerating field

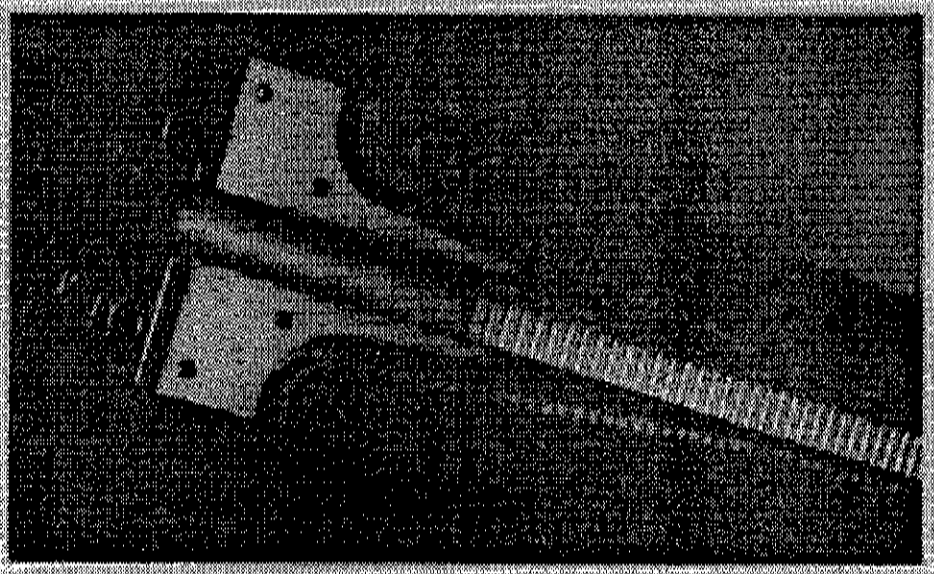


21 420 structures — 2.83 10^6 disks / linear 3 TeV

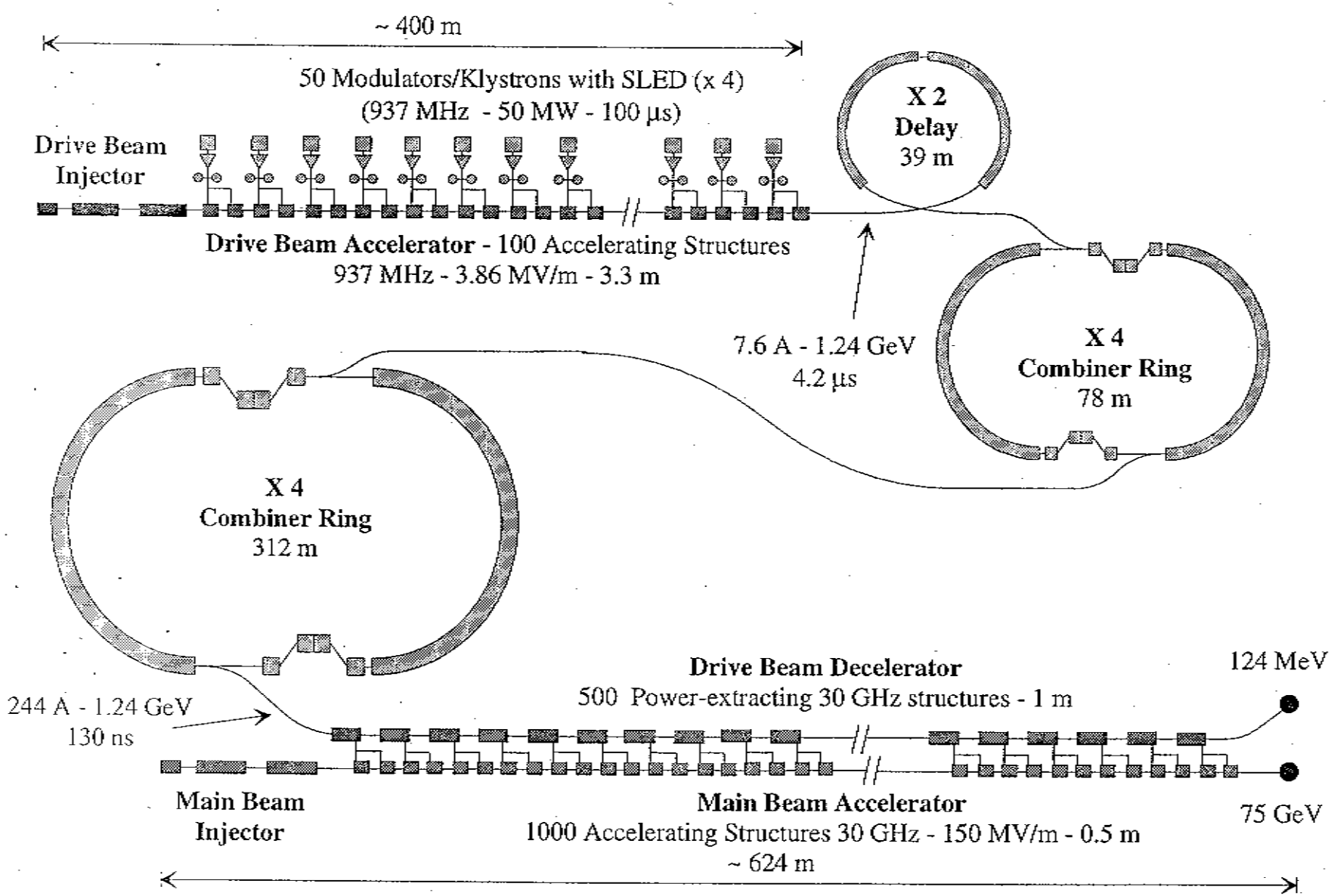
14.jpg

Prototype Power Extraction Structure





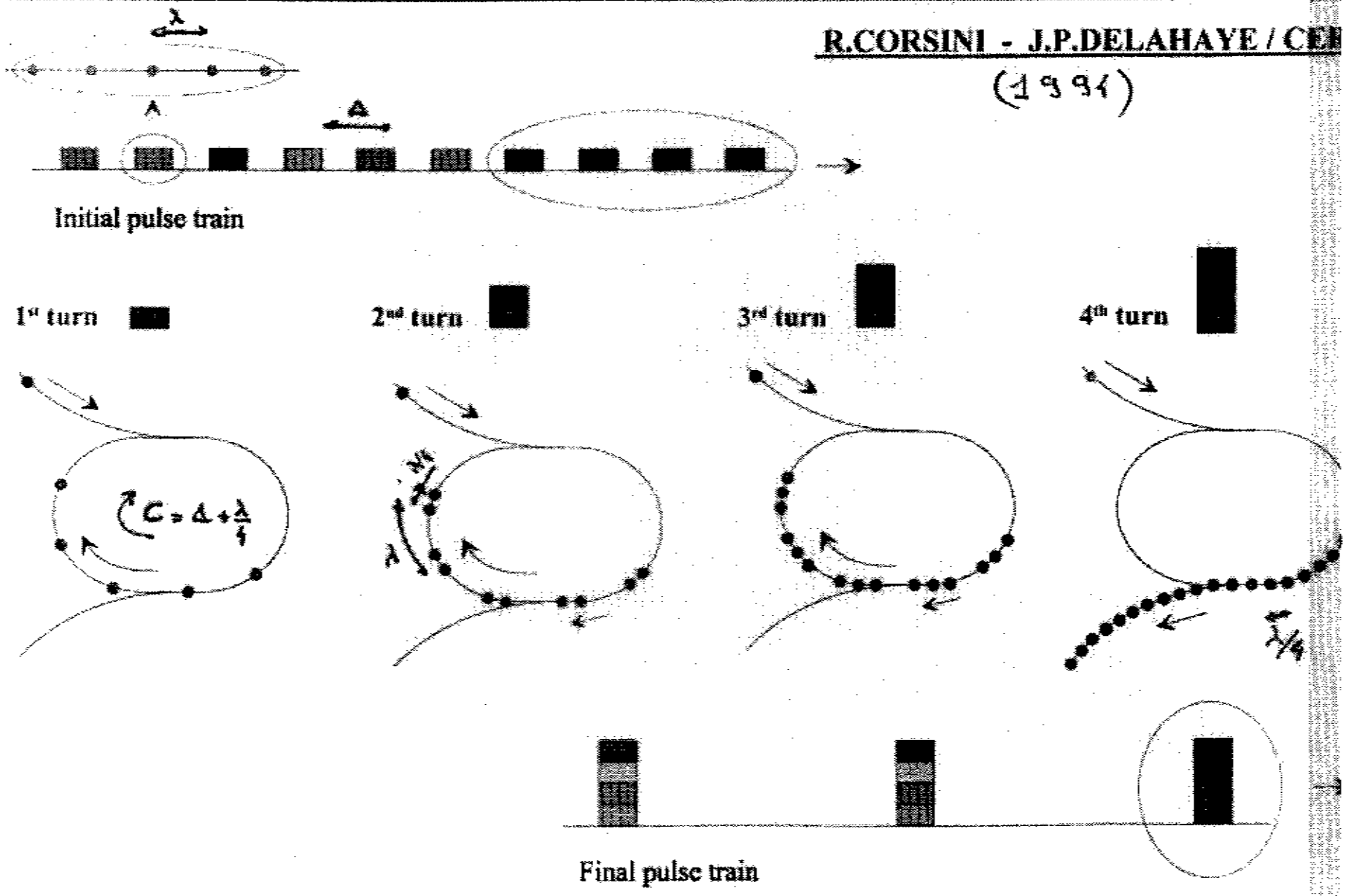
Consists essentially of 4 loaded WGs coupled to a circular beam pipe – recently generated 50 MW of 30 GHz RF power from this structure in the CTF from a 3 GHz bunched beam. Note damping is required to suppress $W_\perp$ effects on drive beam


~ 400 m
50 Modulators/Klystrons with SLED (x 4)
(937 MHz - 50 MW - 100 μs)
Drive Beam
Injector
X 2
Delay
39 m
Drive Beam Accelerator - 100 Accelerating Structures
937 MHz - 3.86 MV/m - 3.3 m
7.6 A - 1.24 GeV
4.2 μs
X 4
Combiner Ring
78 m
X 4
Combiner Ring
312 m
Drive Beam Decelerator
500 Power-extracting 30 GHz structures - 1 m
124 MeV
244 A - 1.24 GeV
130 ns
Main Beam
Injector
Main Beam Accelerator
1000 Accelerating Structures 30 GHz - 150 MV/m - 0.5 m
~ 624 m
75 GeV

X4 PULSE COMPRESSION AND FREQUENCY MULTIPLICATION USING A COMBINER RF

R.CORSINI - J.P.DELAHAYE / CE

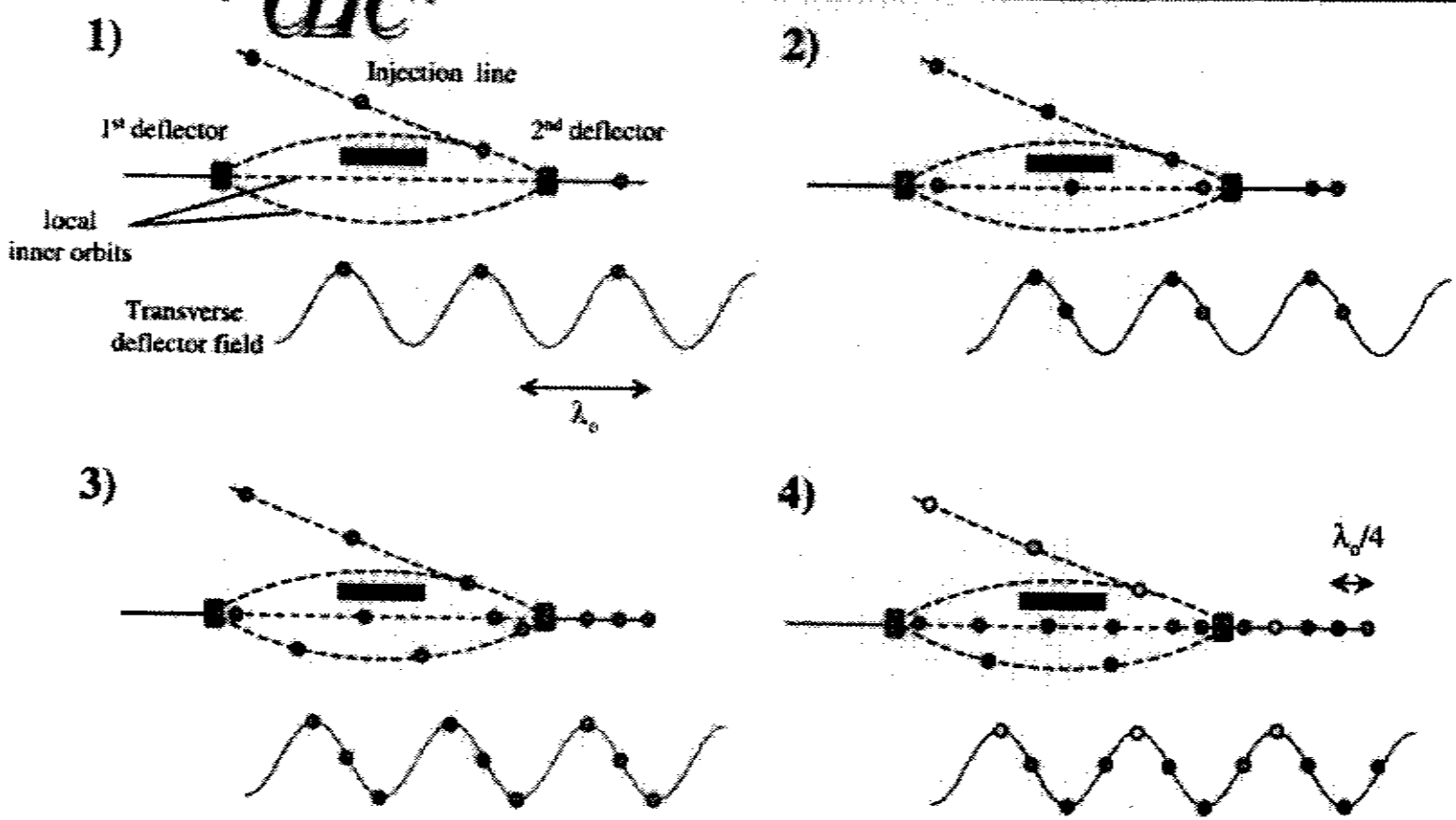
(1991)



28.jpg
298x419; 32bit; 54.9KB

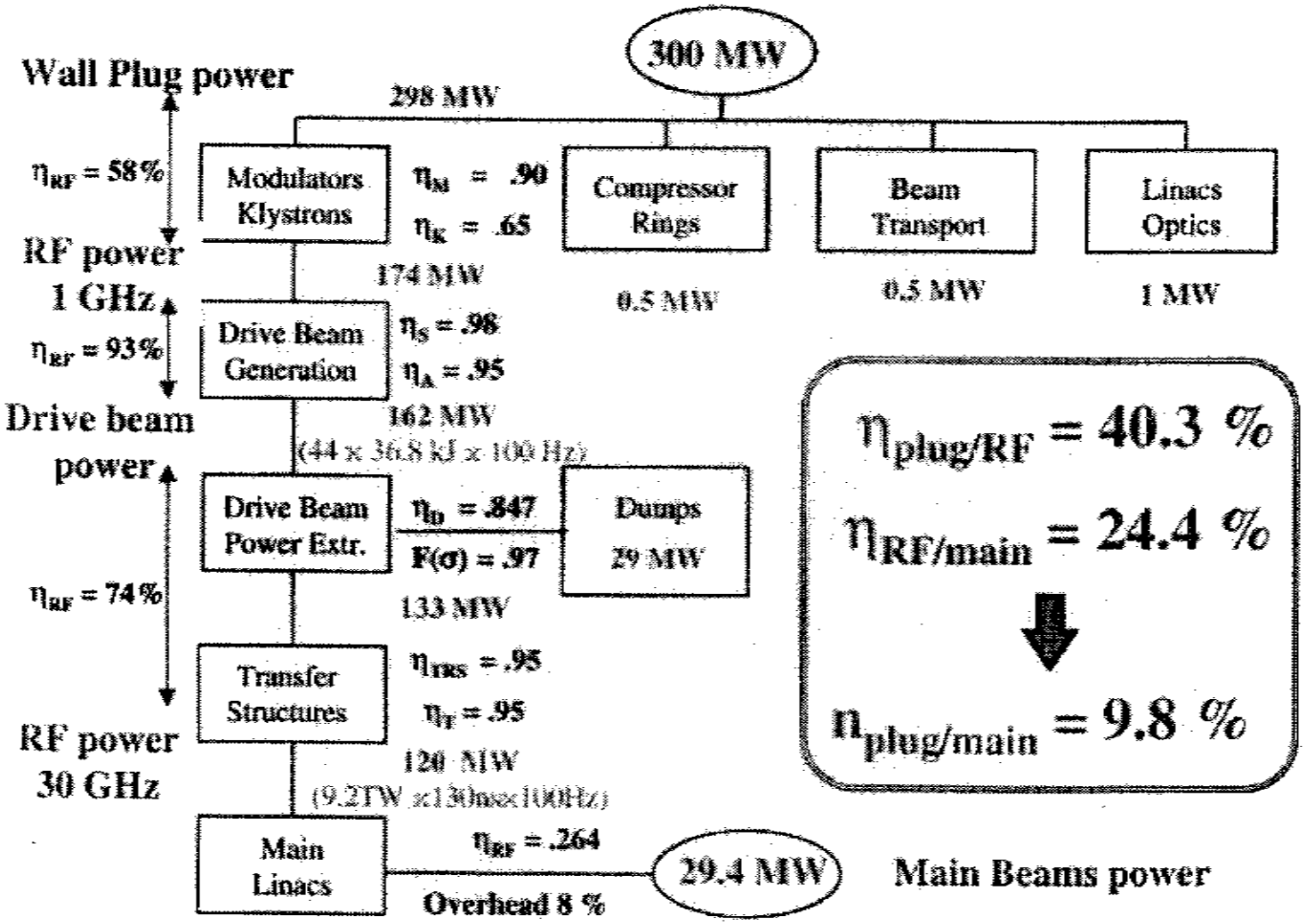
Injection in Combiner Rings

R.CORSINI - J.P.DELAHAYE / CERN (1994)



29.jpg
298x419; 32bit; 58.3KB

Power flow in a 3 TeV CLIC complex



31.jpg
298x419: 32bit: 64.2KB

TBA – ideal rf power source for LCs

all energy stored in e^- beam

reasonable number of klystrons

180 in total

low frequency, long pulse

efficient energy transfer in fully loaded conventional low-frequency linac

Compare: SLAC linac 240 klystrons

NLC 1TeV 10,000 klystrons

5,500 modulators

pulse compression syst.

distributed all along the linac!

rf power created locally where and when needed with excellent

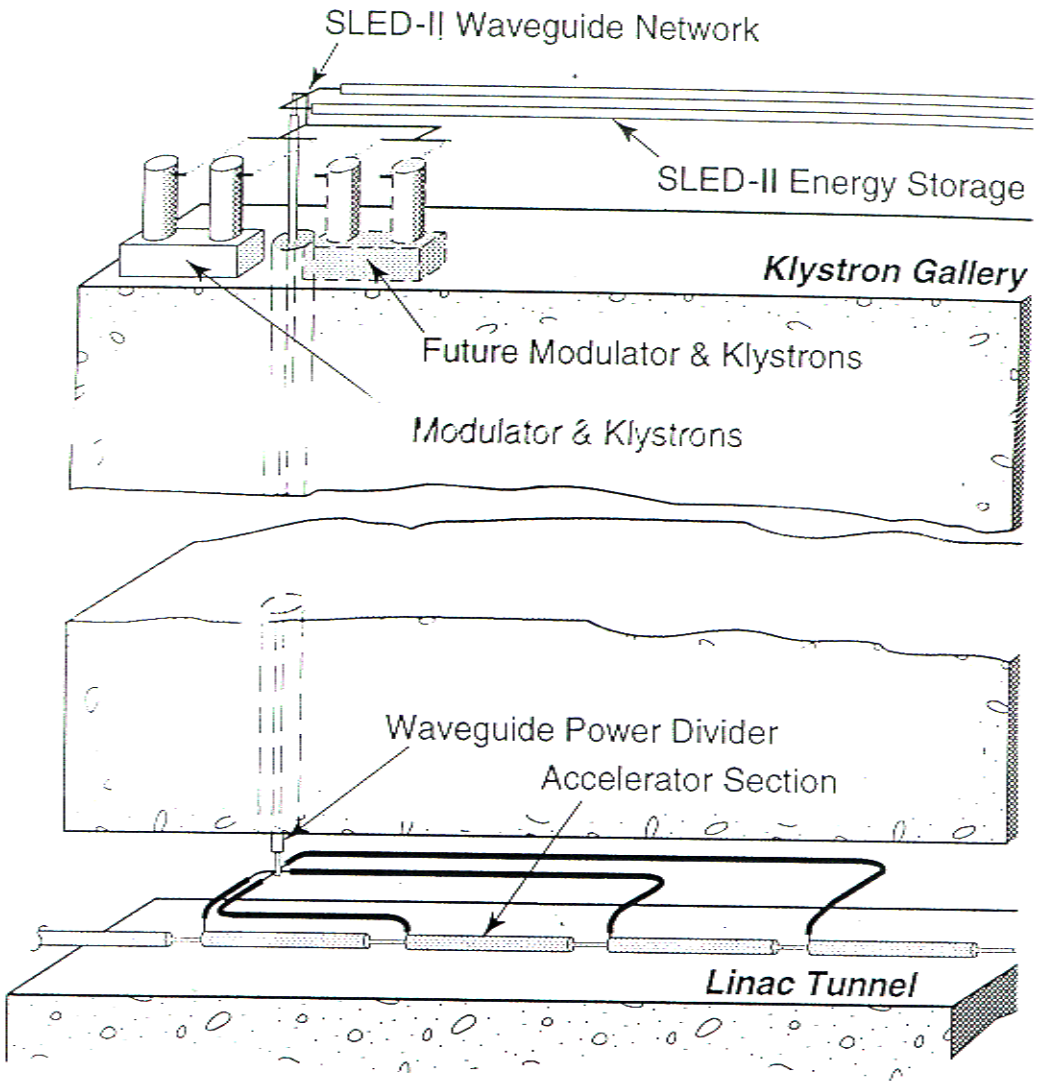
AC → RF efficiency ~ 40%

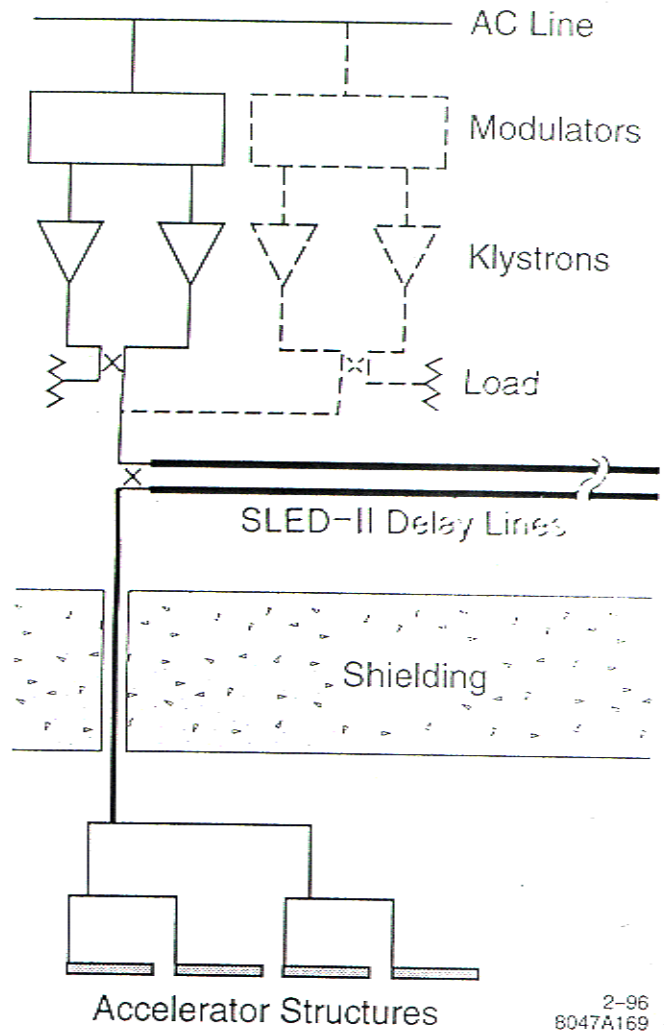
flexible (in acc. gradient, frequency, energy upgrades)

cost-effective (central facility, small # components)

Compare NLC :

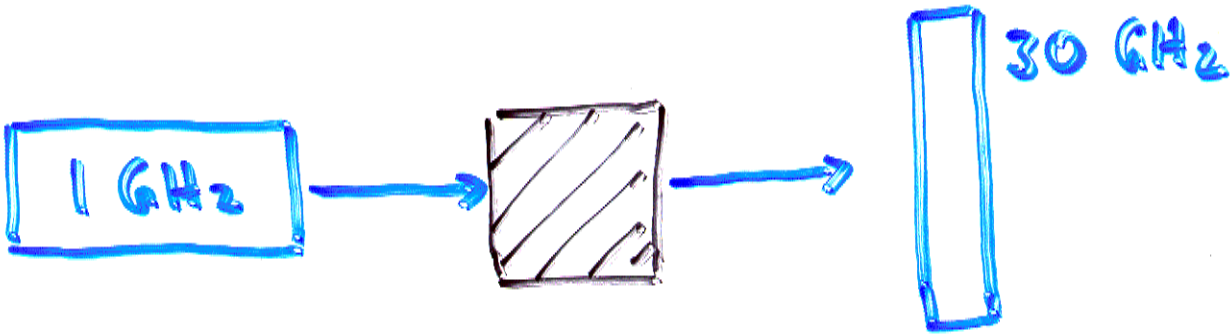
~ 2300 such units all along the linac





whole process is like

"black box" (J.P. Delahaye)

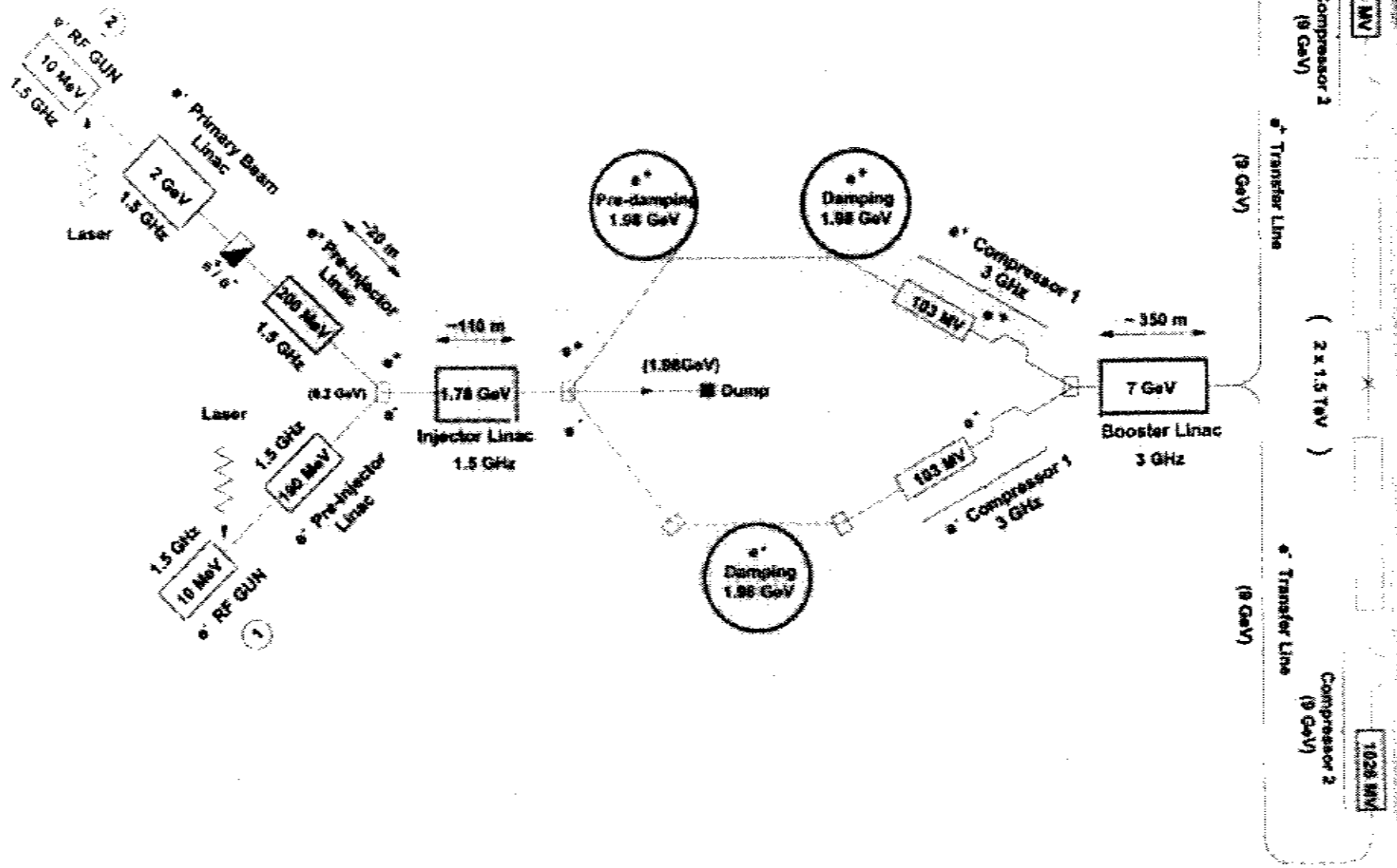


rf pulse compression

frequency multiplication !

loss free transport over long distance

L. Rinolfi



CLIC INJECTOR COMPLEX FOR THE e+ and e- MAIN BEAMS

October 1999

21.jpg
298x419; 32bit; 55.7KB

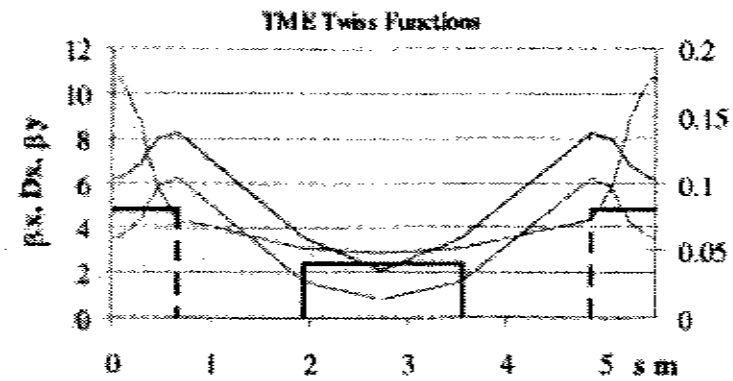
J.P. Potier

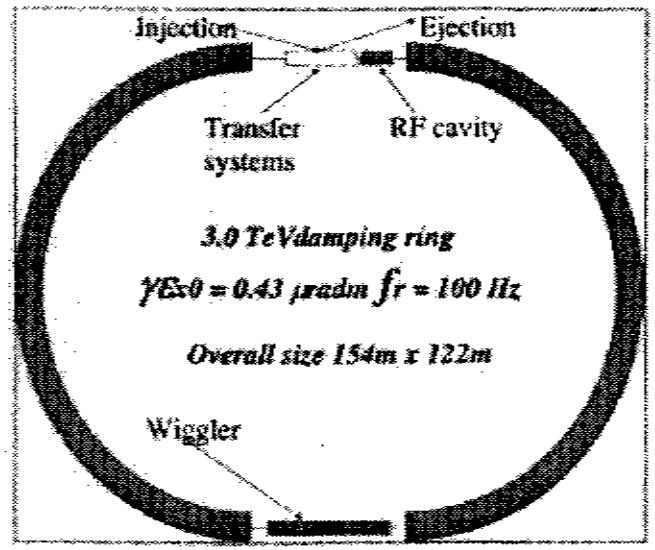
LC '99 CLIC Damping Rings

CLIC

*Tentative parameters for a CLIC Positron Damping Ring for the 3.0 TeV case $\gamma\varepsilon_{x0}$ = 0.43 μrad*m / 100 Hz*

Parameter	Symbol	Units	Value
Momentum	E	GeV/c	1.98
Number of cells	-	-	54
Ring length	L	m	448
Arc cell length	L_C	m	7.12
Charge per bunch	N_C	10^9 e	4.2
Beam current		A	0.82
Injection rpetition frequency	f_r	Hz	100
Normalised Ring equilibrium emittance H/V	$\gamma\varepsilon_{eqH,V}$	10^{-9} radm	430/ 3
Momentum spread	σ_ε	10^{-4}	6.9
Damping time	$\tau_{x,y}$	ms	23.7/
Bending magnet field	B	T	0.3
Horizontal tunes per cell	μ_x	2π	0.608
Momentum compaction	α_p	10^{-4}	5.4
Wiggler bending peak field	B_w	T	1.6
Wiggler length	L_w	m	29.5
Impedance threshold	Z/n	Ω	0.12
Energy loss per turn	U_0	MV	0.249
Bunch length (assumed with an harmonic RF system)	σ_z	mm	3.0





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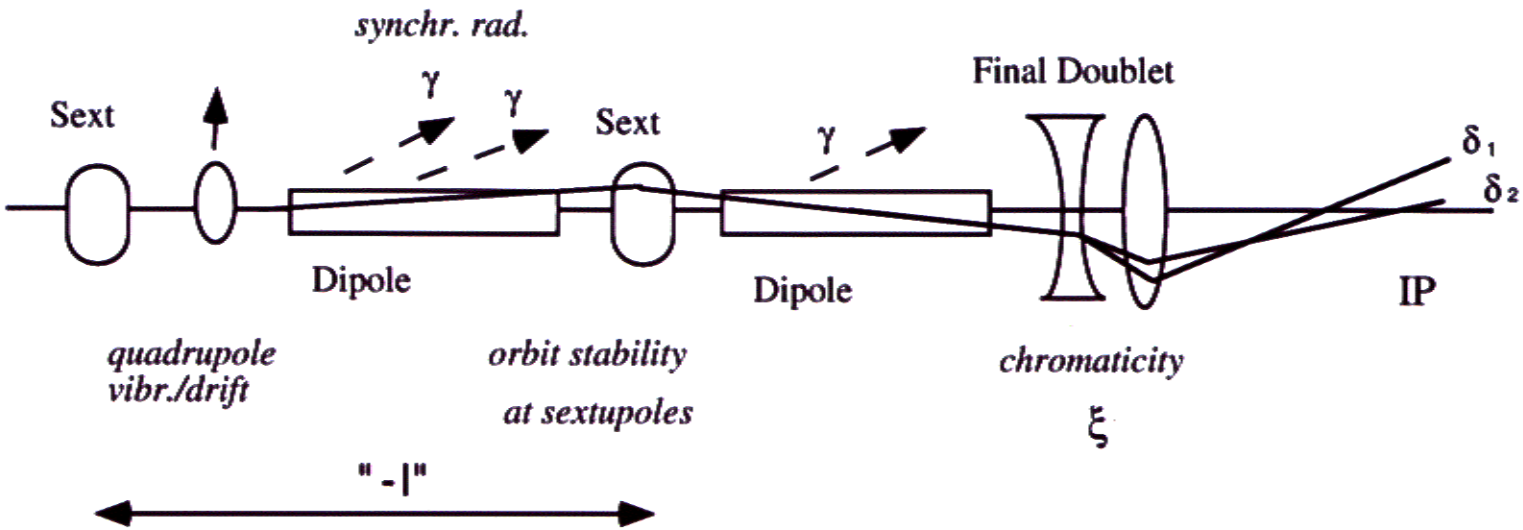
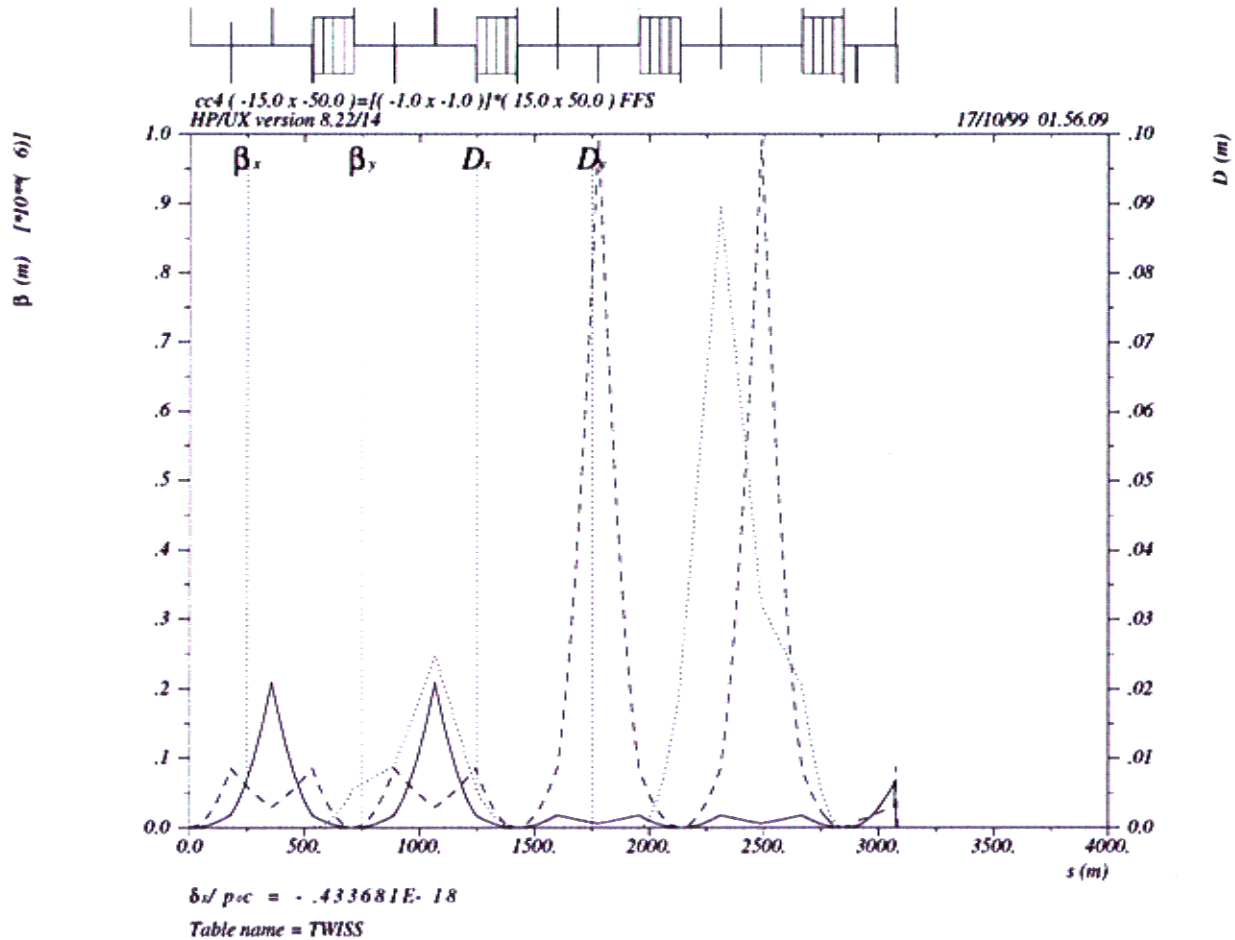


Schematic of a conventional final focus.

Final Focus

Optics

- baseline design aided by FFADA code and O. Napoly
- chromatic correction (CCX, CCY) and final transformer with demagnification factor 15/50, initial $\beta_{x,y} \sim 1$ m
- odd-dispersion scheme à la Oide $\rightarrow$ fewer dipoles, larger bandwidth
- final-quadrupole gradient: 450 T/m, extrapolating from LHC magnet design: 320 T/m & 35 mm 1/2 inner radius
- trade-off between Oide effect ($\rightarrow$ large ξ_x) and chromatic bandwidth ($\rightarrow$ small ξ_x)
- vary bending/drift lengths, ratio vertical/horizontal bending angle, strength of final-doublet quadrupoles, Brinkmann sextupoles,... for optimum luminosity with 1% flat energy spread

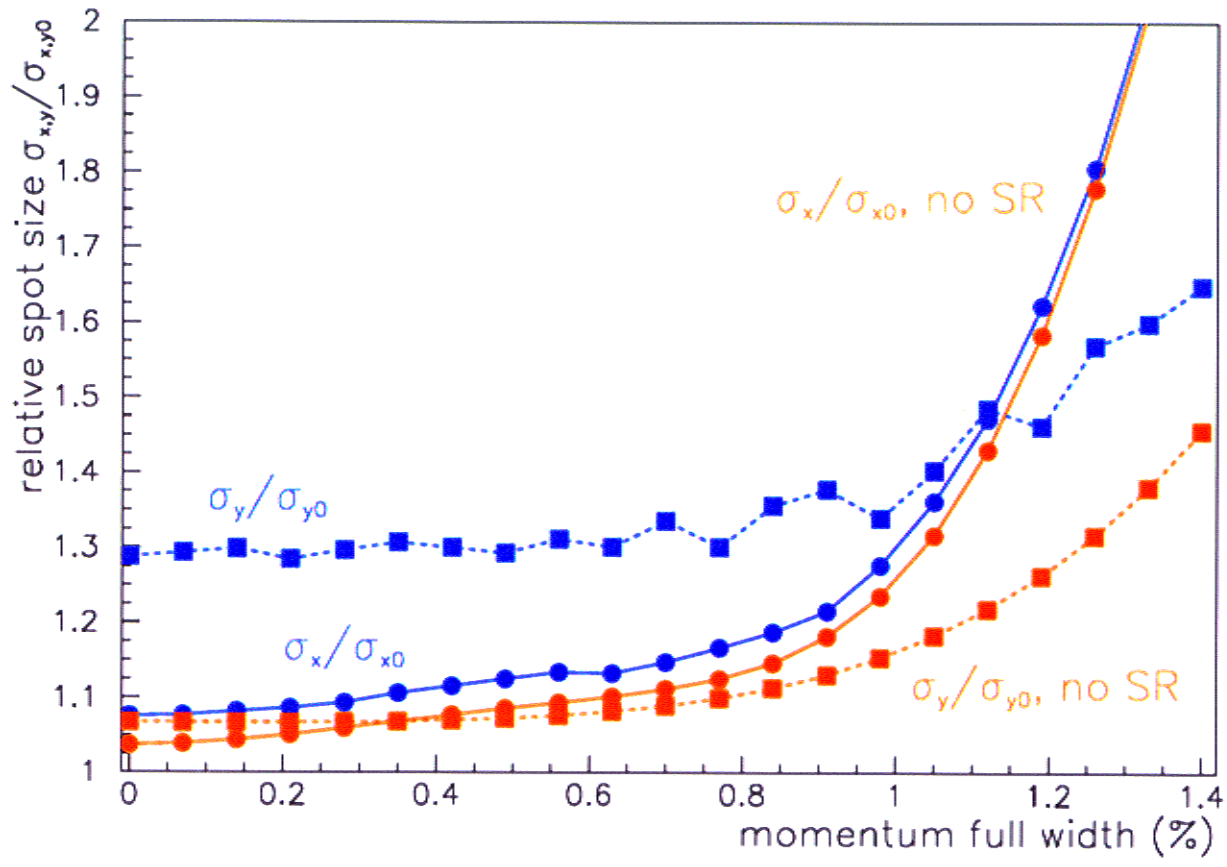


Final-focus optics: beta functions and (odd) dispersion.

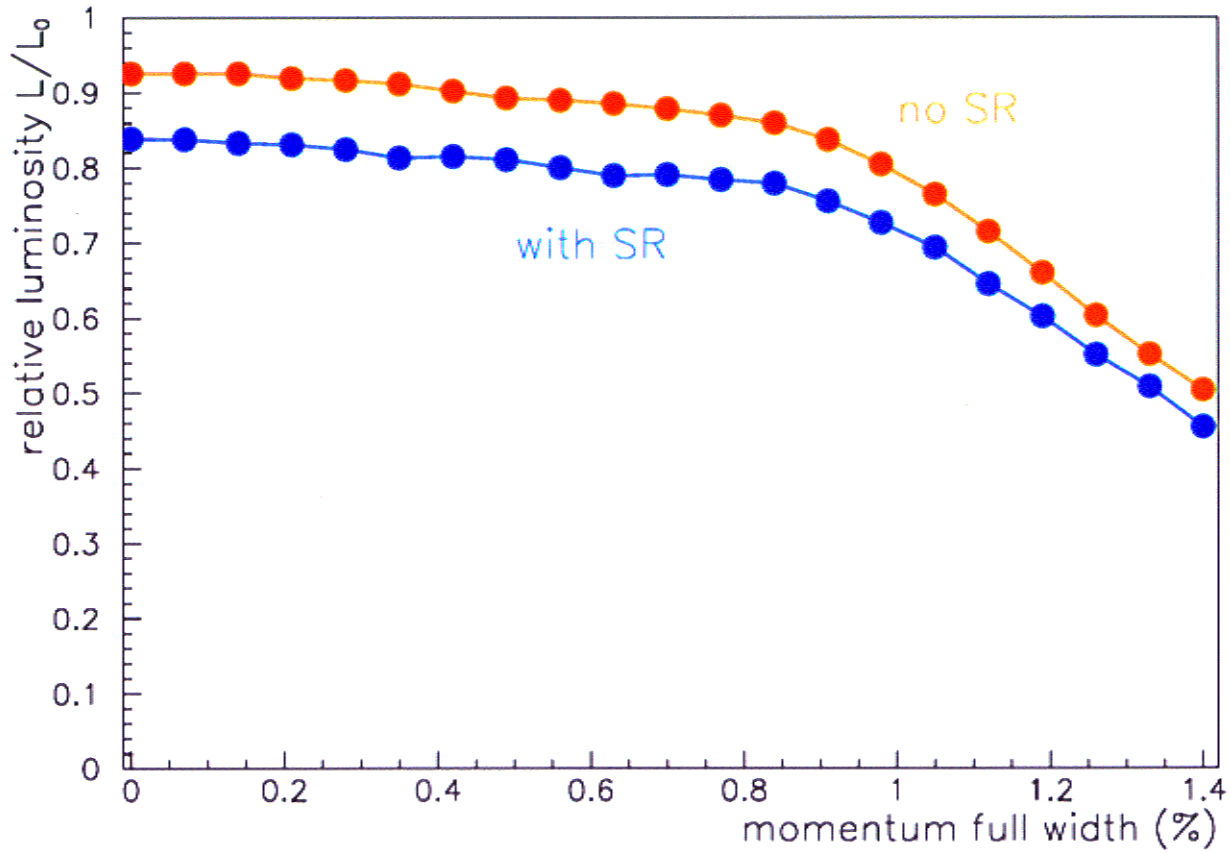
Final-focus characteristics

total length (per side)	3080 m
demagnification factor $M_{x,y}$	15, 50
IP beta functions $\beta^*_{x,y}$	8, 0.15 mm
chromaticity $\xi_{x,y}$	6900, 27000†
bending length	4×176 m
angle per dipole section	63, 230 μrad
final quadrupole gradient	450 T/m
beta function $\hat{\beta}_y$ at CCY sextupoles	1000 km†
peak dispersion η_x in CCY	0.1 m†
beta functions $\beta_{x,y}$ at entrance to final quad	15, 88 km

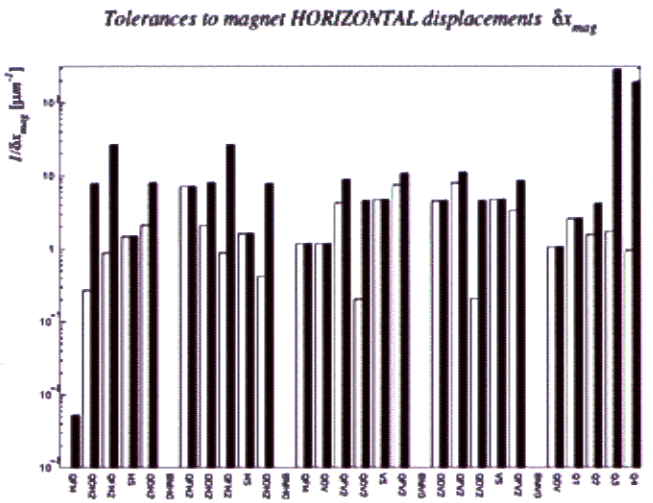
† NLC: $\xi_x \approx 7000$, $\xi_y \approx 30000$, $\hat{\beta}_y \approx 200$ km, $\eta_x \approx 0.1$ m

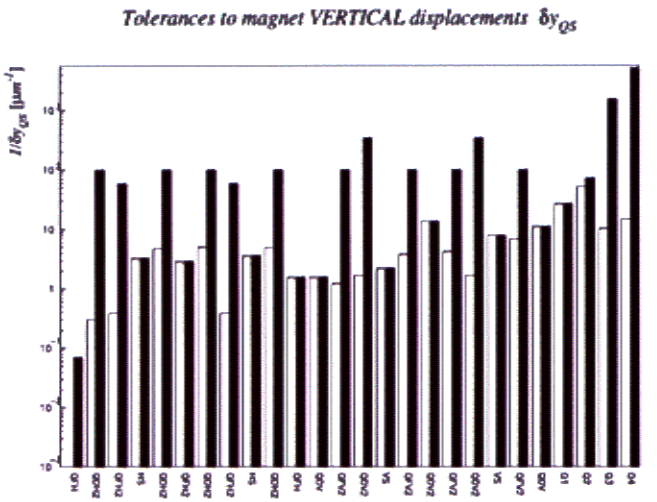


Relative rms spot sizes versus the full energy spread for a flat distribution. Design spot sizes: $\sigma_{x0} = 43$ nm, $\sigma_{y0} = 1.0$ nm.

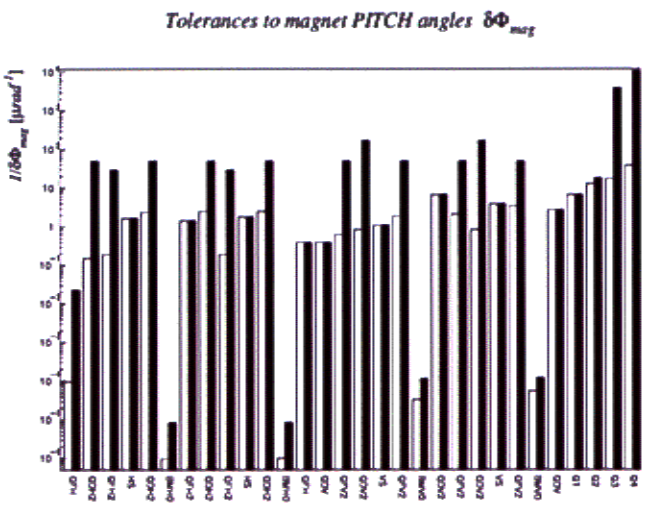


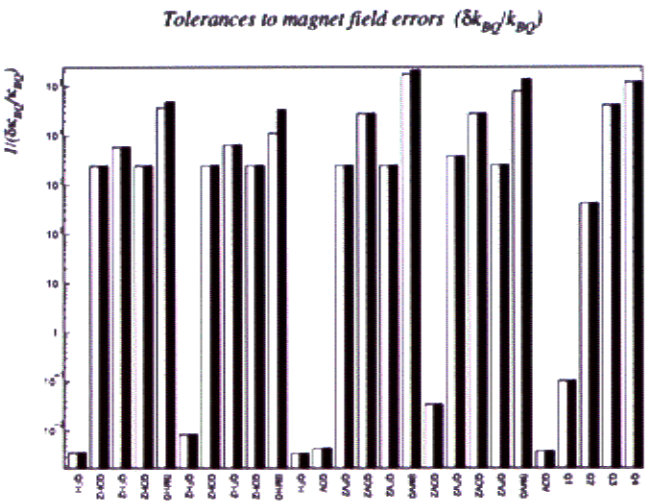
Relative luminosity (from tracking & convolving) vs. energy spread.
Ideal luminosity w/o pinch: $L_0 = 4.6 \times 10^{34}$ cm^{-2}s^{-1}.





Displacement sensitivities for 2% luminosity loss, calc. with FFADA. The tightest jitter tolerances are about 3 nm (x) and 0.2 nm (y). Drift tolerances are of the order of 100 nm.





Sensitivities to pitch angle (left) and relative field change $\Delta k_{BQ}/k_{BQ}$ (right), again calculated with FFADA. The tightest pitch angle tolerance is 0.1 nrad for the final quadrupole. Field stability tolerances are about 10^{-5}.

Collimation System

2 functions: halo removal & machine protection

major problem: collimator survival for bunch train impact

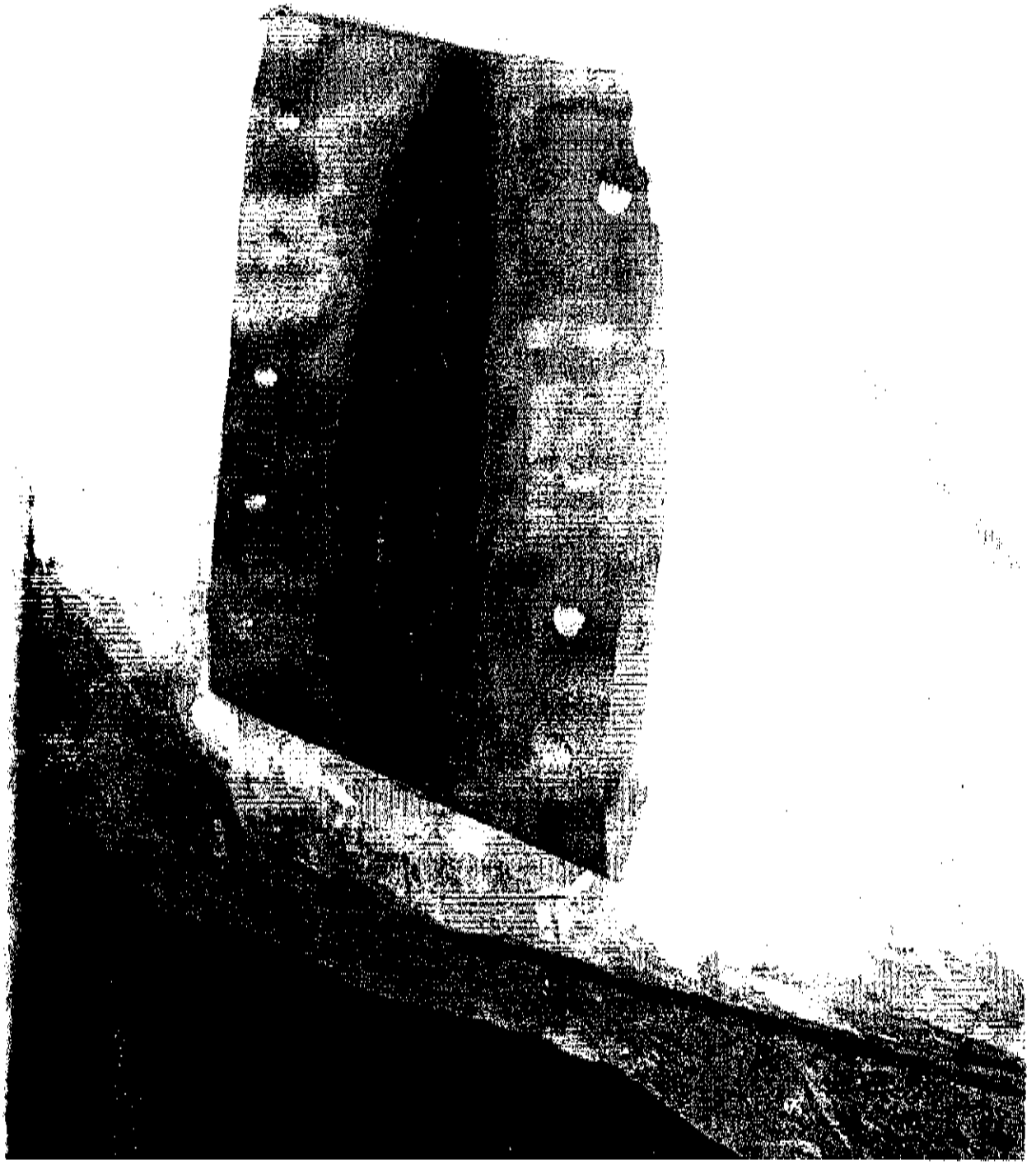
$$\sigma_{UTS} > \frac{\alpha E}{C_p}\frac{d\mathcal{E}}{dm}$$

with σ_{UTS} ultimate tensile strength, α linear thermal expansion coefficient, C heat capacity, E elastic modulus, $d\mathcal{E}/dm$ energy loss per g material. Rewrite this as

$$\sigma_x\sigma_y > \frac{\alpha E}{\sigma_{UTS}C_p}\frac{d\mathcal{E}}{dx}\left(\frac{n_b N_b}{2\pi}\right)$$

E.g., copper, $\alpha = 1.7\times 10^{-5}$ K^{-1}, $E = 120$ GPa, $C_p = 0.385$ Jg^{-1}K^{-1}, $d\mathcal{E}/dx \approx 1.44$ MeV cm^2/g, $\sigma_{UTS} = 300$ MPa:

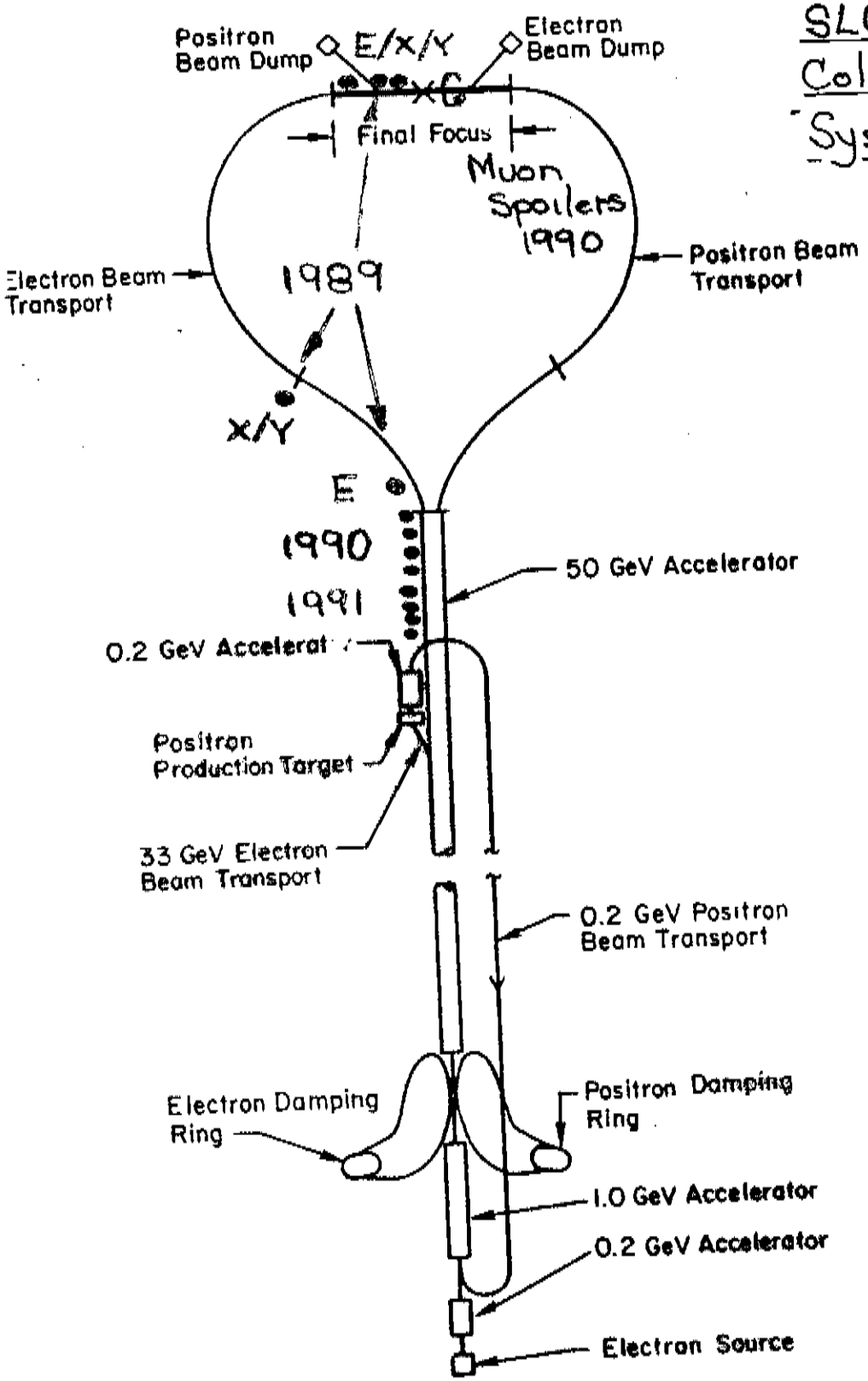
$$(\sigma_x\sigma_y)^{1/2} > 200\ \mu\text{m} \quad \text{or} \quad \beta_{x,y} \geq 1000\ \text{km}$$



At the SLC beam-halo collimation was found to be essential for acceptable background; many sets of collimators were added over the years (in the final focus proper, the beam switchyard, sectors 29 and 30 of the linac, muon spoilers in the final focus,....)

There was little quantitave understanding or modeling of the observed halo. At times, 10% or more of the beam had to be collimated, much more than expected from beam-gas scattering. The suspected culprits included magnet nonlinearities in the bunch compressor, longitudinal microwave instability in the damping rings, beam dynamics in the linac, and higher-order dispersion...

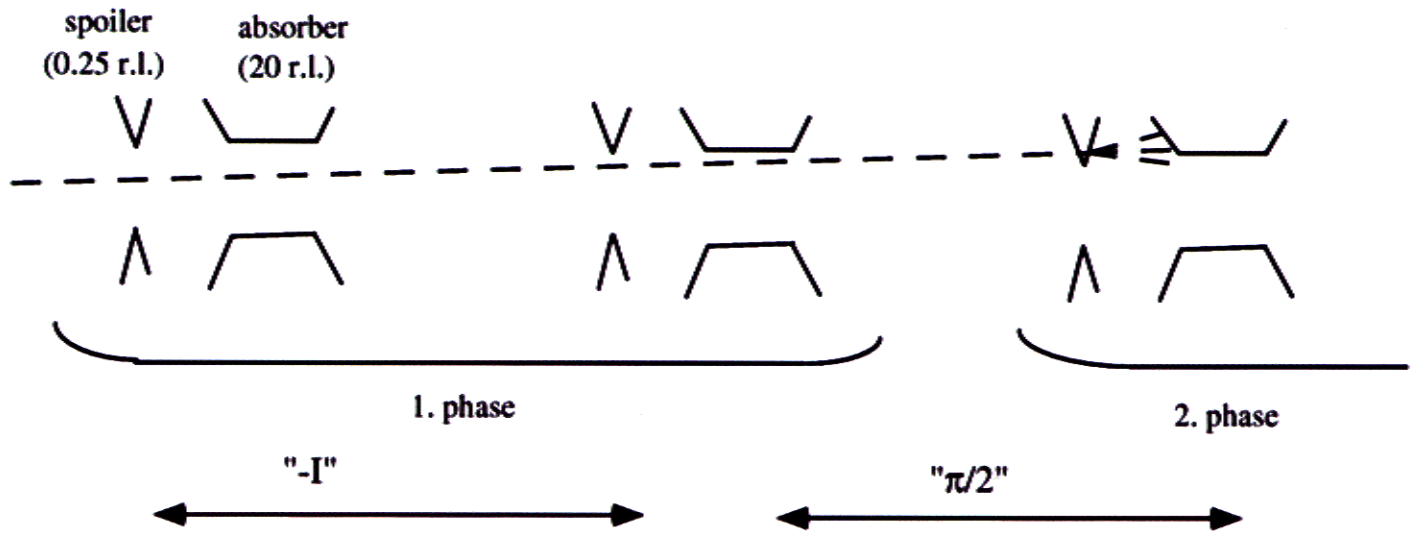
SLC Collimator Systems



OVERALL SLC LAYOUT

5722A7

3-87



Schematic of a conventional collimation system, as for the NLC, consisting of a series of Ti spoilers and Cu (and W) absorbers. The size of the spoilers and absorbers is approximately 1/4 and 20 radiation lengths, respectively.

Strategies for Collimation System

- remove halo upstream of linac, *e.g.*, via resonant nonlinear collimation in CLIC transfer lines (G. Guignard)
- combine collimation and final focus; this reduces overall system length and can profit from large beta functions (A. Verdier)
- look for more suitable collimator materials, *e.g.*, carbon composites (F. Caspers)
- study nonlinear collimation system à la JLC or TESLA, e.g. utilizing FF sextupoles
- explore wake-field based passive machine protection schemes, exploiting dipole, quadrupole, or higher-order wakes (S. Fartoukh, F. Ruggiero,...)

beamstrahlung

synchrotron radiation in the field of the opposing bunch

critical energy:

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E} = \frac{5}{6}\frac{\gamma r_e^2 N}{\alpha\sigma_z(\sigma_x+\sigma_y)}$$

$\Upsilon \approx 2 \times 10^{-3}$ for SLC

$\Upsilon \approx 9$ for CLIC at 3 TeV

number of beamstrahlung photons affects 'purity' of luminosity spectrum

$$N_\gamma \approx \frac{5}{2}\frac{\alpha\sigma_z}{\gamma\lambda_e}\Upsilon\frac{1}{(1+\Upsilon^{2/3})^{1/2}}$$

fraction of luminosity at E_{cm}:

$$\frac{\Delta L}{L} = \frac{1}{N_\gamma^2}(1-e^{-N_\gamma})^2$$

D. Schulte

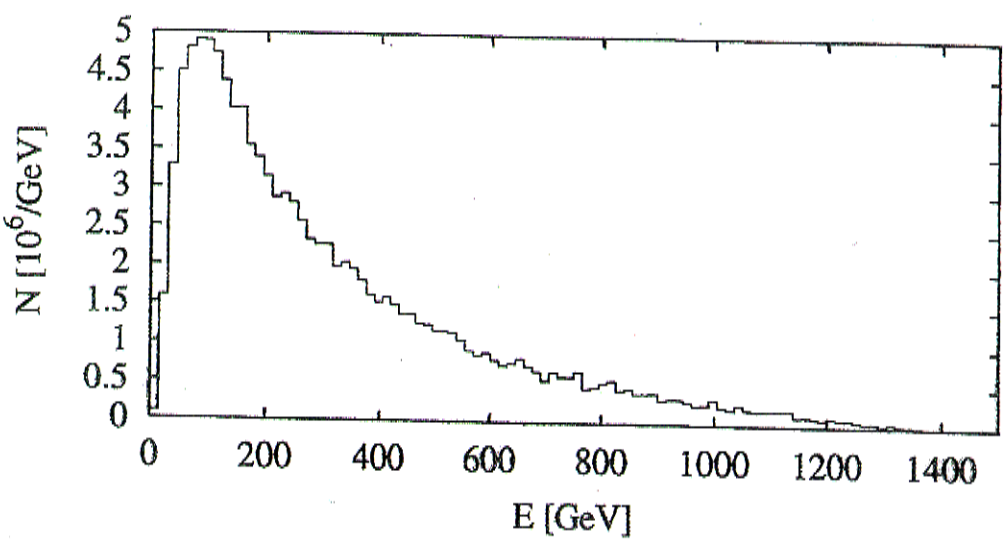
Coherent Pair Creation

A photon can turn into a e^+e^- pair in a strong external field

$$\frac{dN}{ds} \propto \frac{\exp(-8/(3\kappa))}{(1+0.22\kappa)^{\frac{1}{3}}}$$

$$\kappa = \frac{\hbar\omega}{mc^2}\frac{B}{B_c} = \frac{\hbar\omega}{E_0}\Upsilon$$

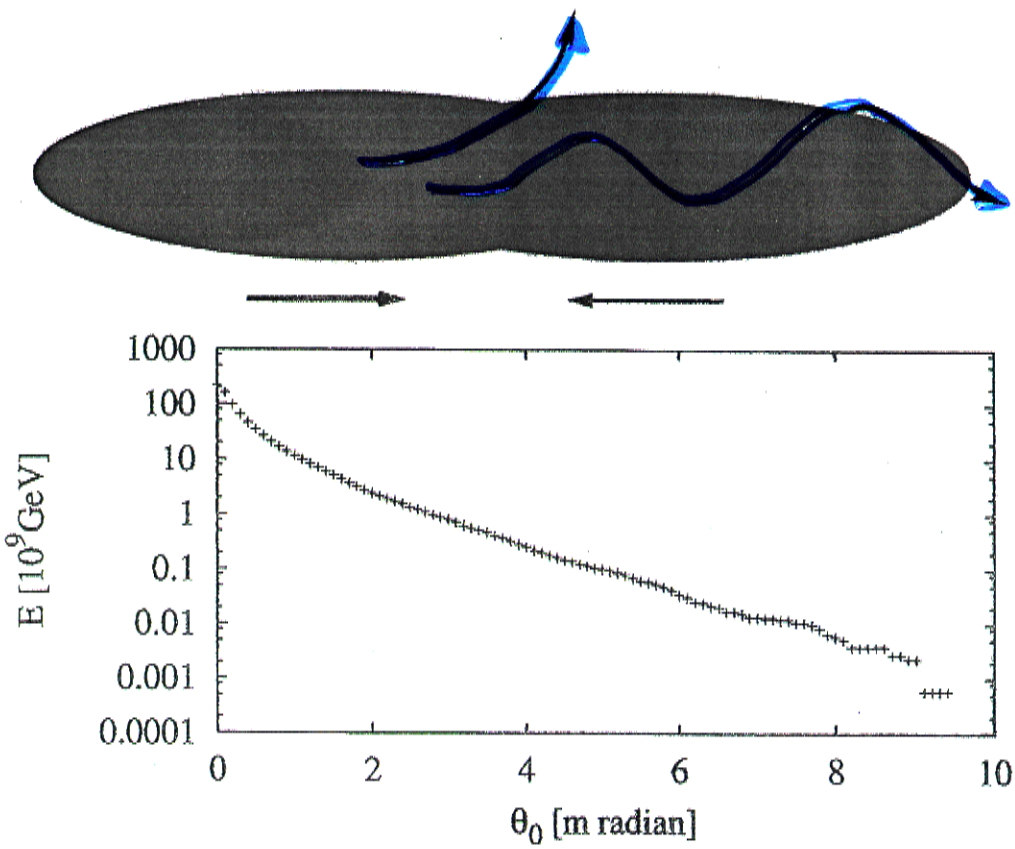
CLIC at E_{CM} [TeV]	n_c
0.5	3.4
1	$2 \cdot 10^5$
3	$8 \cdot 10^8$
5	$2.9 \cdot 10^9$



at 3 TeV almost $n_{pair} \approx n_{beam}$

D. Schulte

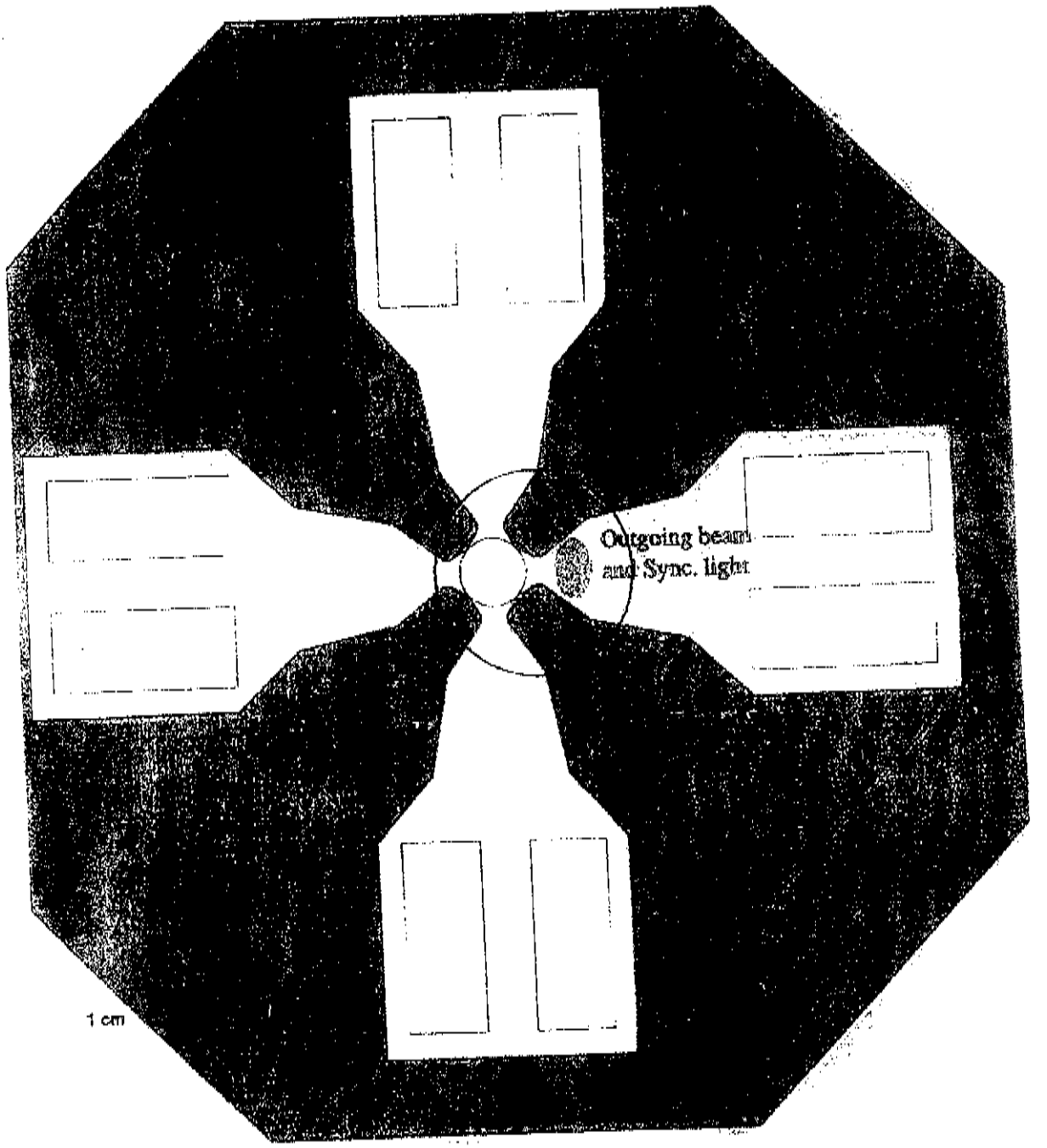
Pairs after Bunch Crossing



- significant power in pairs
- particles can be focused or defocused
- integrated energy above θ_0
- need exit hole of $> 10\,\mathrm{mradian}$

pairs are confined to $\leq$ 10 mrad

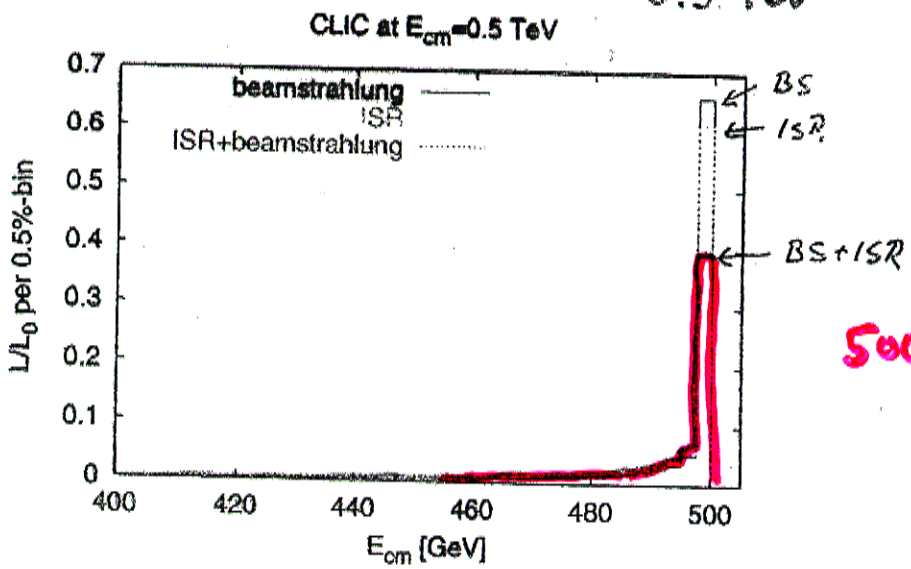
D. Schulte



D. Schulte

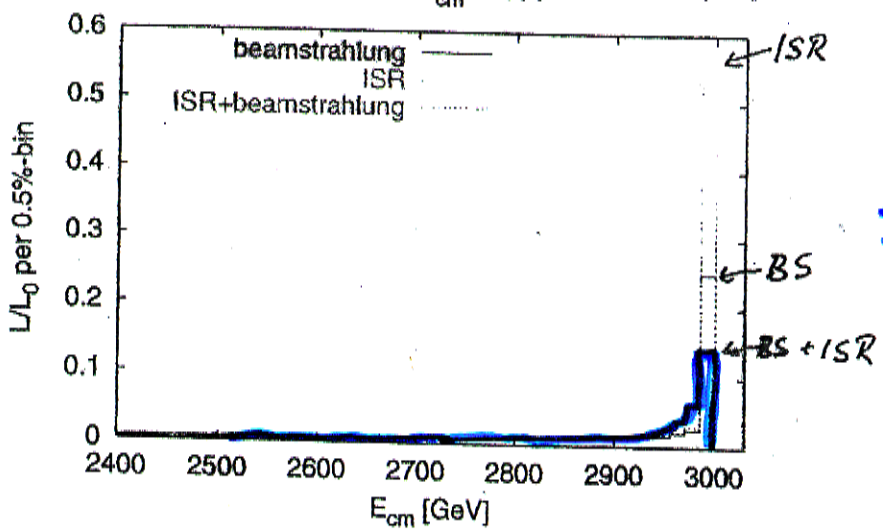
Luminosity Spectra

0.5 TeV



500 GeV

3 TeV

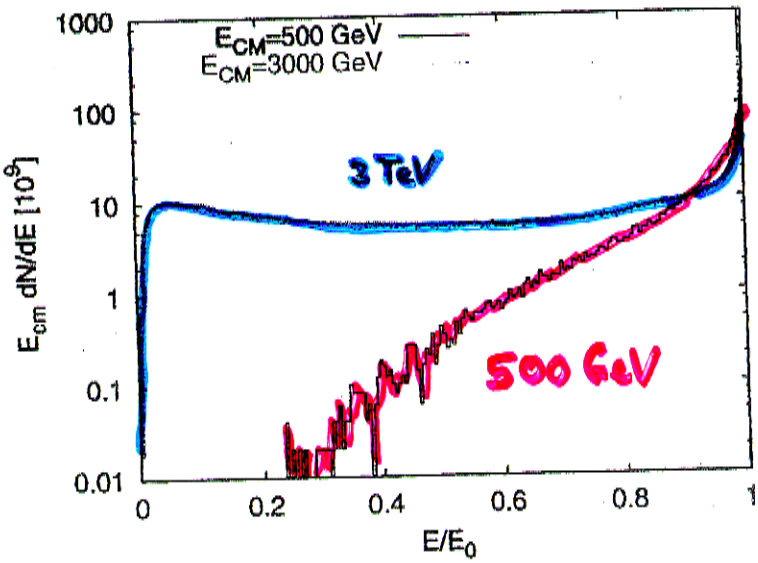


3 TeV

energy spread of spent beam

D. Schulte

Spent Beam

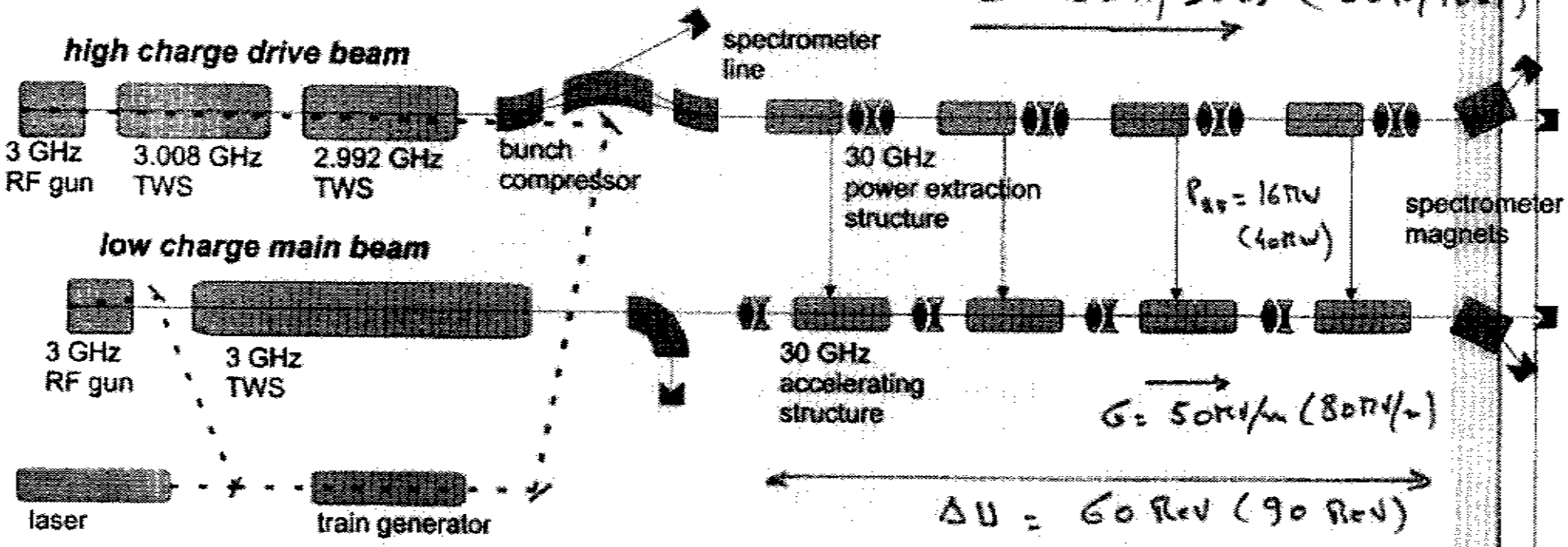


- beam has large transverse emittance after collision
- energy spread is very large

- OPTICS EXIST FOR NLC (20% - 100%) AND TESLA

H. Braun

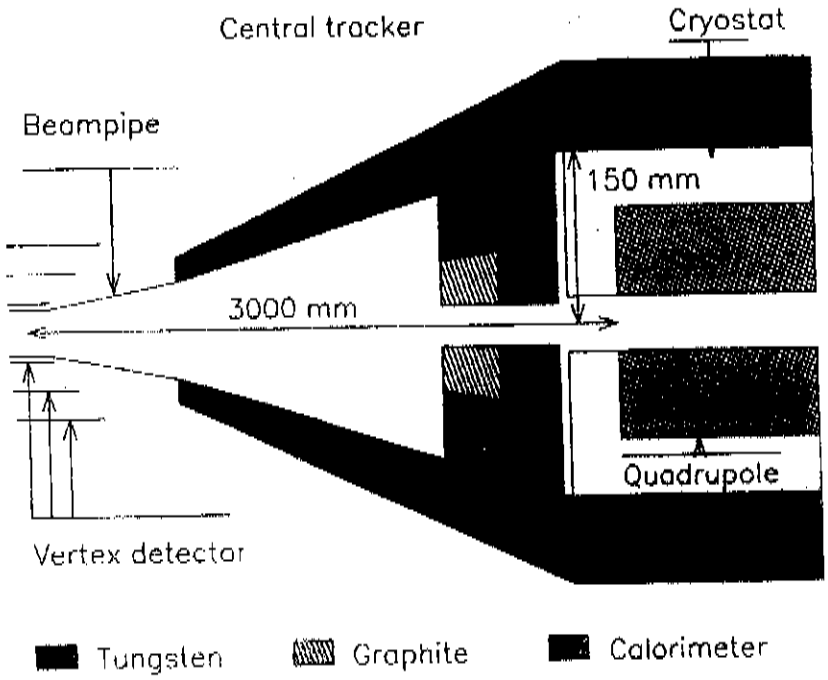
CTF2 performances achieved (design)



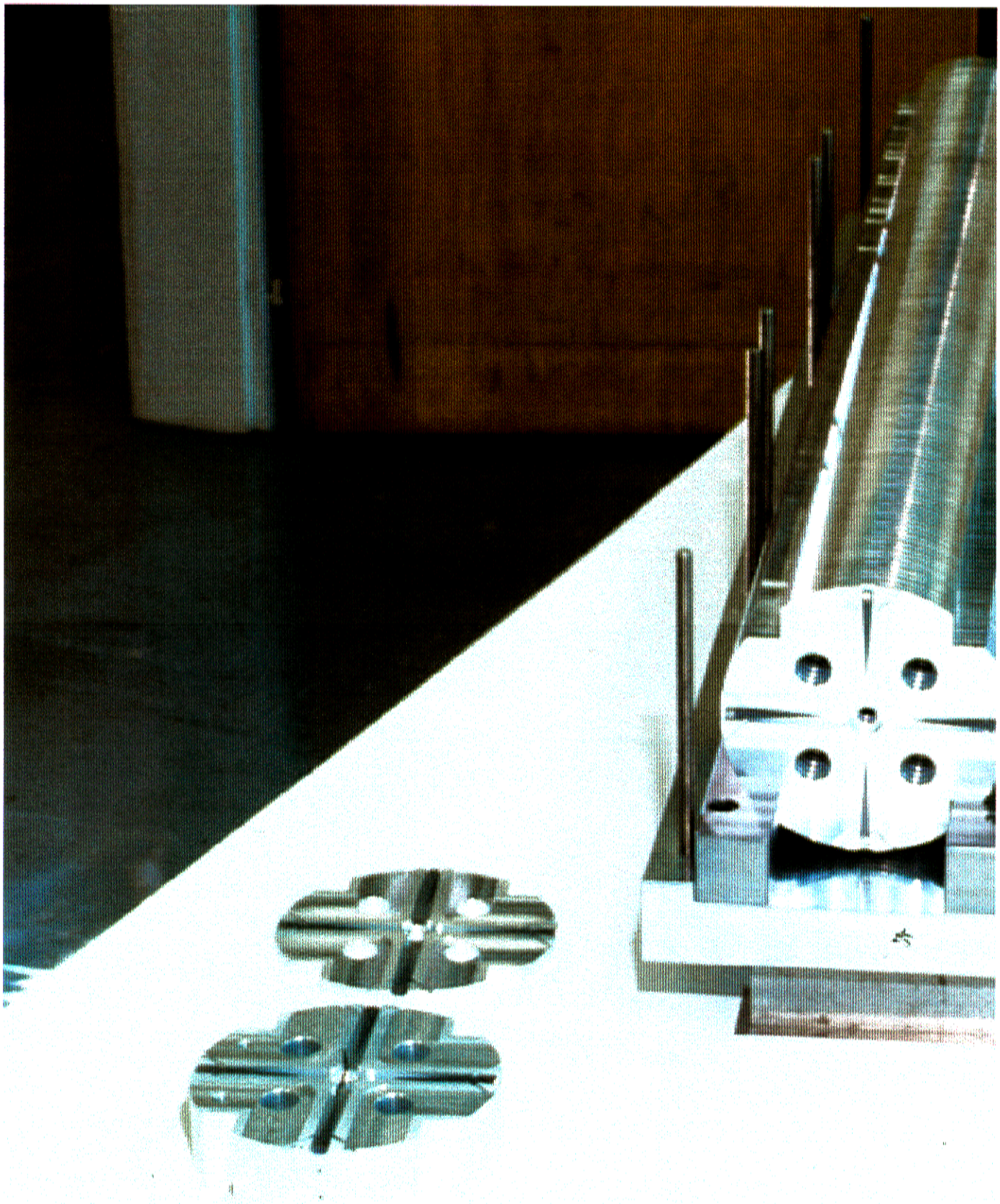
Record performances
- Total RF power 30 GHz = 60 MW (40 MW)
- Accelerating field = 70 MV/m (80 MV/m)

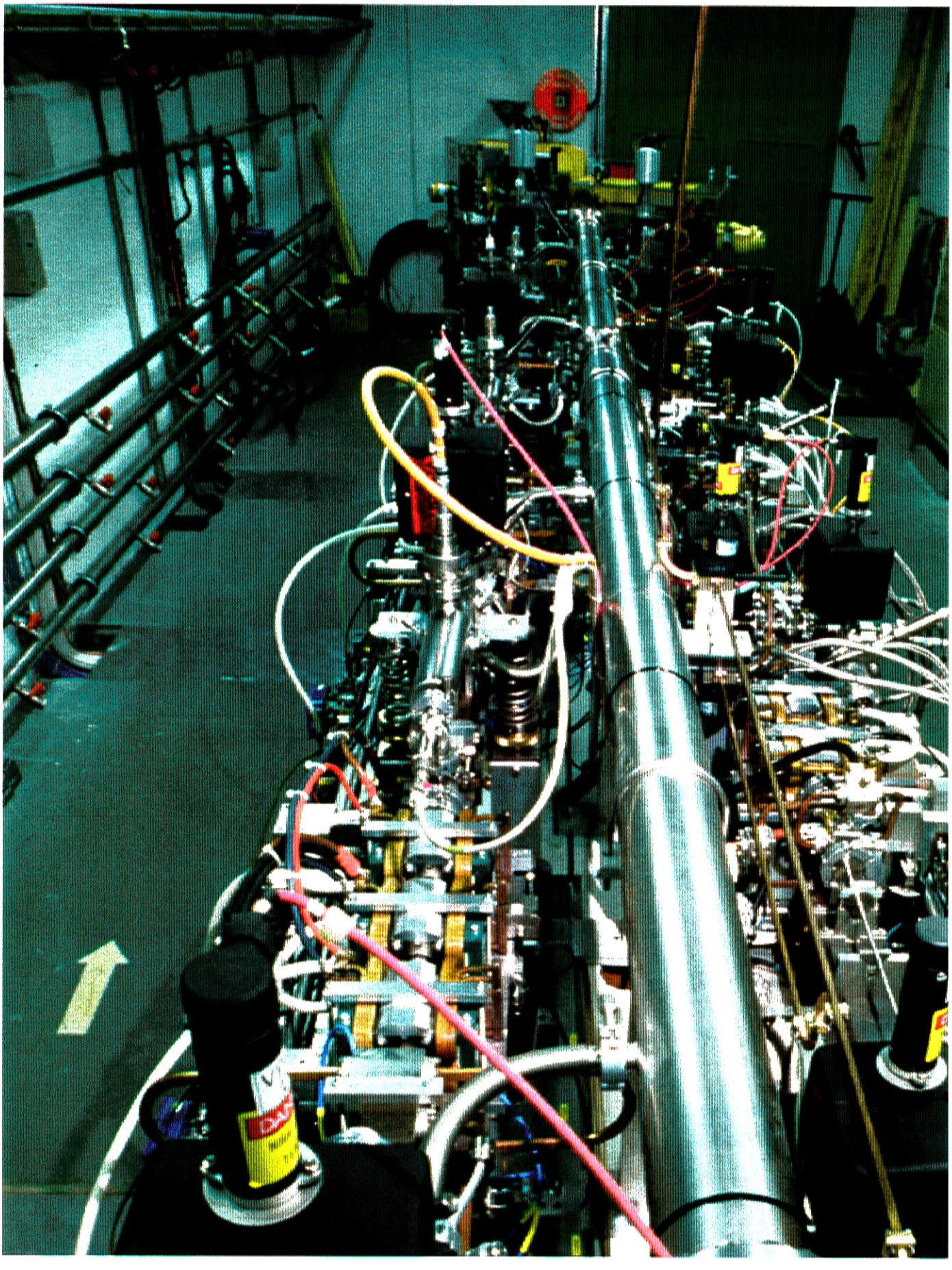
D. Schulte

Mask (TESLA)



- outer mask prevents backscattering of photons
- inner mask prevents backscattering of charged particles
- mask outer angle $83\,\mathrm{mradian}$
- inner mask hit by $12\,\mathrm{TeV}$ per bunch crossing
- almost all of this has $\theta < 20\,\mathrm{mradian}$



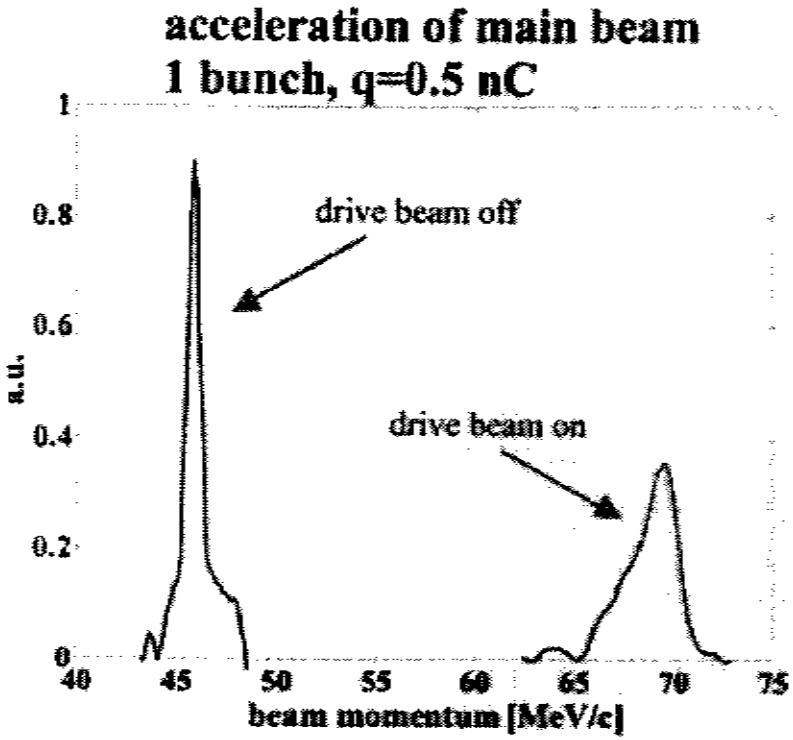


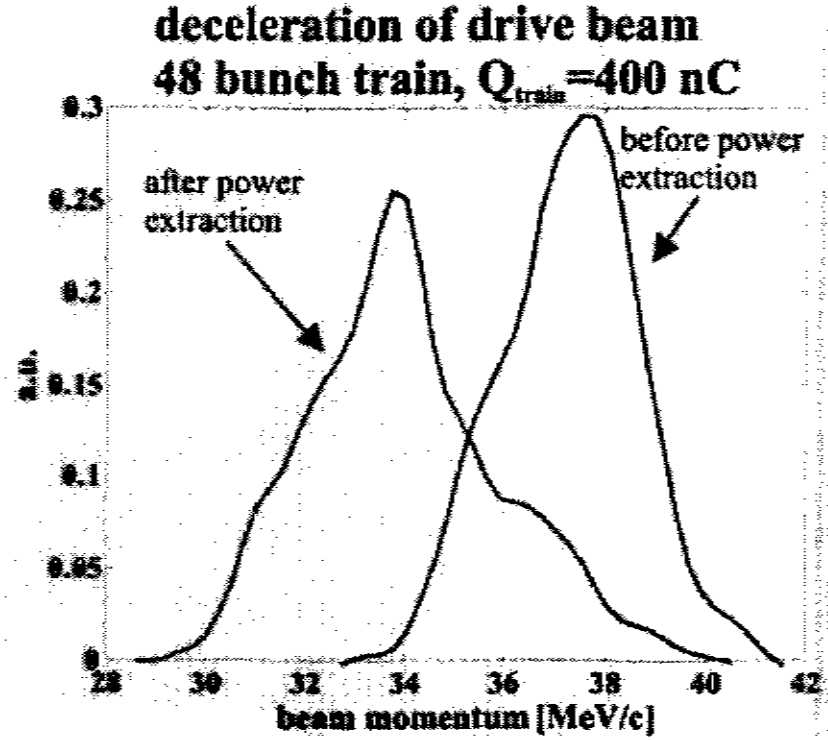
J.P. Delahaye

Key issues of the CLIC scheme

Specific to CLIC technology:	tested in
1. 30 GHz components development and integration in modules:	CTF2
• Two Beam Acceleration feasibility	CTF1, CTF2
• High accelerating fields (150 MV/m) during long pulses (130 nsec)	NLCTA/CTF 3
2. Multibunch beam emittance preservation during acceleration in strong wake-fields environment:	
• Accurate pre-alignment of components	CTF2
• RF structures with damping of transverse higher order modes	ASSET/CTF3
• Beam loading compensation	CTF3
• Beam based trajectory correction	CLIC1
3. RF power production by TBA:	
• Drive beam generation and acceleration	CTF3
• Beam power compression and frequency multiplication at high intensity	CTF3
• Operability, high energy beam operation	CLIC1
• Beam loss management and HW protection	CLIC1
• Power production efficiency	CTF2,3
• Drive beam stability during deceleration	CLIC1
4. Cost, Cost, Cost.....	CLIC1

two beam acceleration at 30 GHz





		design	achieved
drive beam	maximum accelerated charge	640 nC	755 nC
	acc. charge giving max. 30GHz power	640 nC	475 nC
	max. charge through decelerator	640 nC	480 nC
	number of bunches	48	48
	bunch length fwhm	5 ps	5 ps
$P_{30\ GHz}$ at input of accelerating structure		40 MW	36 MW
30 GHz power pulse length		14 ns	14 ns
mean acceleration in 30GHz acc. structure		80 MV/m	69 MV/m

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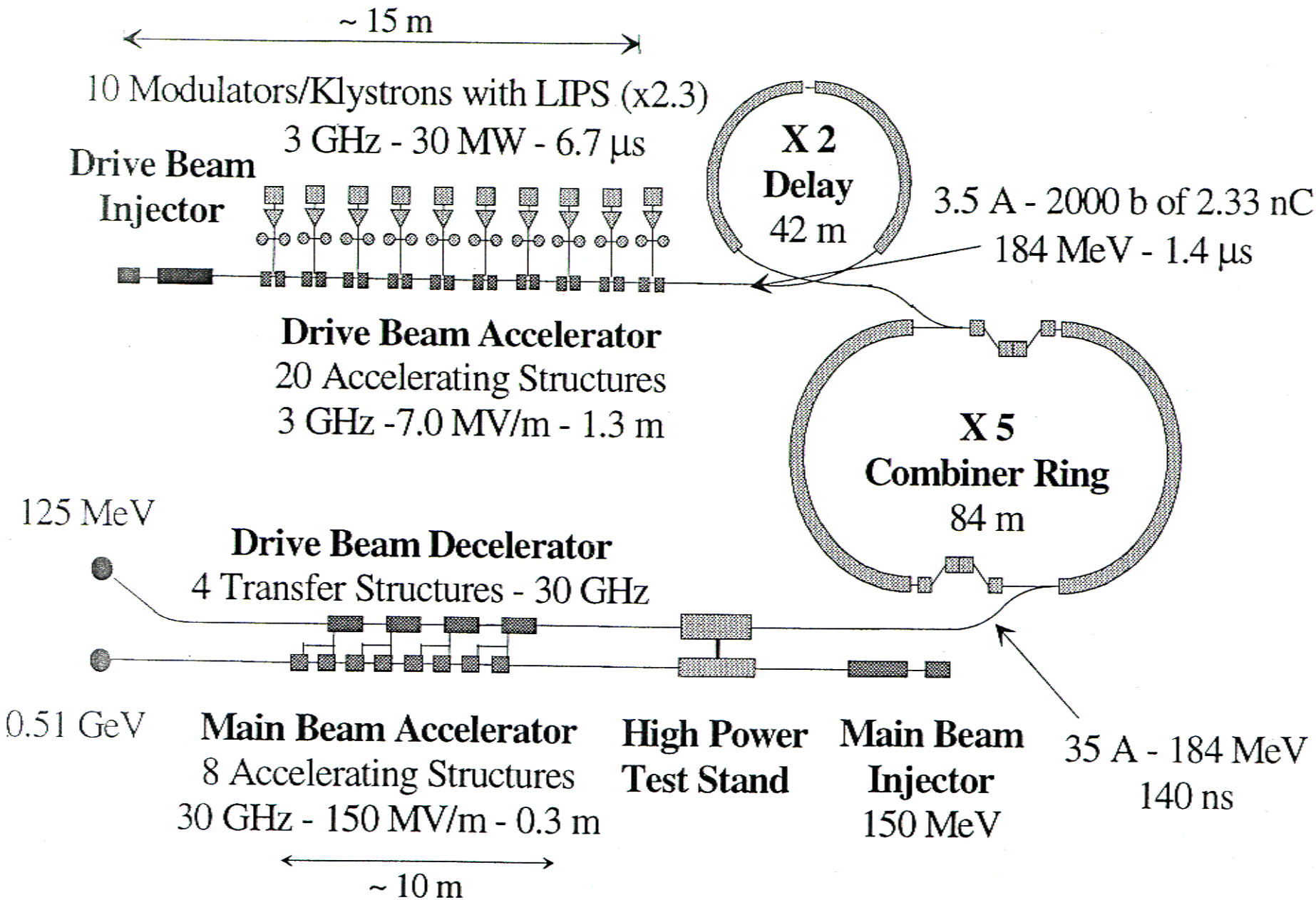
CTF 3 (approved project) 2000 →



J.P. Delahaye

Towards CLIC Parameters

	1995 1999 CTF2	2000 2004 CTF3	2005 2008 CLIC1	2009 → CLIC
Main beam				
Accelerating frequency (GHz)	30	30	30	30
Accelerating field (MV/m)	80	150	150	150
RF pulse length (nsec)	16	140	120	120
Number of bunches (-)	1	30	150	150
Particles /bunch (10^9 e^+)	4	4	4	4
Bunch length/spacing (mm)	1/-	0.2/200	0.05/200	0.05/200
Drive beam				
Number of drive beams (-)	1	1	1	20
Current (A) / Energy (GeV)	40/0.05	40/0.2	264/1.2	264/1.2
Bunch charge(nC)/spacing(cm)	12/10	2.75/2	17.5/2	17.5/2
Cur. (A)/Freq.(GHz) acc. Linac	40/3	4/3	8/0.937	8/0.937
Frequency multiplication (-)	-	10	32	32
Two Beam Acceleration				
Number of modules (PETS)	4	4	1*550	20*550
Number of accel. Struct. (-)	4	8	1*1100	20*1100
RF power(MW)/duration(ns)	40/16	462/140	462/120	462/120
Main beam accel./drive (GeV)	0.2	0.6	75	75
Drive beam energy/pulse (kJ)	0.032	1	40	800
Repetition frequency (Hz)	5	5	75	75
Power in drive beams (MW)	0.00016	0.005	3.0	60

Conclusions

- promising scheme for multi-TeV high-luminosity LC: 3 TeV, $10^{35}\,cm^{-2}s^{-1}$
  wide energy range

- major breakthroughs
- existence proof of final focus
- feasibility of TBA at 30 GHz
  demonstrated in CTF 1 and CTF 2;
  prototypes of all components built and tested with beam
- high accelerating gradient ~ 150 MV/m
- TBA: efficient, low cost,
  1 tunnel w/o active elements
  test facility CTF 3 (bunch combination + frequency multiplication)

the ideal power source for any future linear collider!