CLIC Note N° 252

Brainstorming Session

on the Feasibility of Multibunching

for CLIC

Participants: U. Amaldi, H. Braun, J.P. Delahaye, G. Guignard,
K. Hübner, A. Millich, O. Napoly, W. Schnell, L. Thorndahl,
D. Warner, I. Wilson, W. Wuensch, B. Zotter

Geneva, 27 October 1994

The revised schedule for the,

Brainstorming Session on the Feasibility of Multibunching for CLIC

Date: Thursday and Friday the 13th and 14th of October.
Place: Novotel in Ferney Voltaire.
Participants: U. Amaldi, H. Braun, J. P. Delahaye, G. Guignard, K. Hubner, O. Napoly, W. Schnell, L. Thorndahl, D. Warner, I. Wilson, W. Wuensch, B. Zotter , A. Millich

THURSDAY

• Opening remarks	J.P. Delahaye	9:00	10'
• Physics requirements for linear colliders and the performances of current linear collider schemes.	O. Napoly	9:15	15'
• Interaction region crossing angles	B. Zotter	9:45	15'
• Present CLIC interaction region beam parameters.	G. Guignard	10:30	30'
• Lunch		12:00	
• Introducing multibunching	I. Wilson, W. Wuensch	13:30	1.5 h
• Multibunching and the drive beam	L. Thorndahl, J.P. Delahaye	16:30	30'

FRIDAY

• Ramifications of multibunching on hardware	W. Wuensch	9:00	10'
• An open discussion of what CLIC's attitude should be towards multibunching.	I. Wilson	9:30	
• Posssible parameter lists for 0.5 and 1 TeV	G. Guignard	10:45	20'
• Tentative conclusions	J.P. Delahaye	11:30	
• Lunch		12:30	
• Further discussions, if needed.		14:00	

J.P. Delahaye, W. Wuensch

JPD
13-14/10/95

WELCOME

Brainstorming Sessions
- overview of various aspects
- favour discussion and exchanges
- developp common culture and knowledge
- orientation of study and work priorities

Subjects for Brainstorming
- Multibunches
- Test Facilities
- General Parameters
- Drive Beam

Objectives for the session on "Multibunches":
- Strong and weak aspects of present beam par[ameters]
- CLIC as a single or multibunches collider?
- Improved(?) parameters for

  U_{cm} : 0.5 TeV — 1 TeV

  $\mathcal{L} \geq$ 1 to 3 10^{33} $cm^{-2} sec^{-1}$ — 10^{34} $cm^{-2} sec^{-1}$
- Work priorities

Organisation:
- Schedule
- Copies of transparencies

Scientific Secretary: W. Wuensch

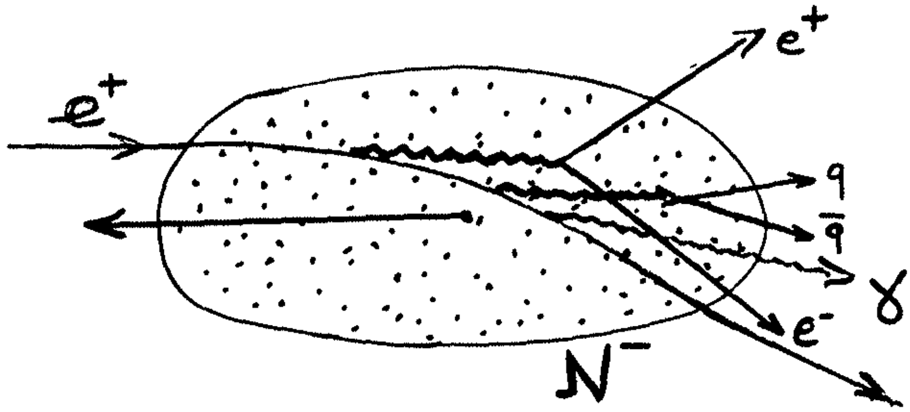
Table 1 Linear Colliders: Overall and Final Focus Parameters Available at the End of LC 93

	TESLA	SBLC	JLC-I(S)	JLC-I(C)	JLC-I(X)	NLC	VLEPP	CLIC
Initial energy (c. of m.) (GeV)	500	500	500	500	500	500	500	500
RF frequency of main linac (GHz)	1.3	3	2.8	5.7	11.4	11.4	14	30
Nominal luminosity ($10^{33}cm^{-2}s^{-1}$) @	2.6	2.22	2.8	4.3	3.7	6	12	0.7-2.7
Luminosity w/pinch ($10^{33}cm^{-2}s^{-1}$) @	6.5	3.65	4.4	6.5	6.3	8.2	15	2.2-8.9
Linac repetition rate (Hz)	10	50	50	100	150	180	300	1700
No. of particles/bunch at IP (10^{10})	5.15	2.9	1.30	1.0	0.63	.65	20	.6
No. of bunches/pulse	800	125	55	72	90	90	1	1-4
Bunch separation (nsec)	1000	16.0	5.6	2.8	1.4	1.4	--	.33
Beam power/beam (MW)	16.5	7.26	1.4	2.9	3.4	4.2	2.4	.4-1.6
Damping ring energy (GeV)	4.5	3.15	1.98	1.98	1.98	1.8	3.0	3
Total length (1.1 L_{RF}+3km)	25	35.3	33.8	21.4	22.5	18.4	10	10.3
$\gamma\epsilon_x/\gamma\epsilon_y$ (m-rad x 10^{-8})	2000/100	1000/50	330/4.5	330/4.5	330/4.5	500/5	2000/7.5	180/20
β_x^*/β_y^* (mm)	25/2	22/0.8	10/0.1	10/0.1	10/0.1	10/0.1	100/0.1	2.2/0.16
σ_x^*/σ_y^* (nm) before pinch	1000/64	670/28	300/3	260/3	260/3	300/3	2000/4	90/8
σ_z^* (μm)	1000	500	80	80	67	100	750	170
Crossing Angle at IP (mrad)	0	3	7.3	8	7.2	3	--	1
Disruptions D_x/D_y	0.54/8.5	.36/8.5	.13/13	.13/11.7	.07/6	.08/8.2	.4/215	1.3/15
H_D	2.3	1.64	1.60	1.50	1.72	1.37	1.26	3.3
Upsilon sub-zero	.021	.04	.24	.21	.16	.095	.059	.16
Upsilon effective	.029	.055	.24	.21	.16	.096	.074	.35
δ_B (%)	2.7	3.2	10.0	8.1	4.5	3	13.3	36
n_γ (no. of γ per e)	2.7	2.0	1.62	1.44	.95	.85	5.0	4.7
$N_{pair}(p_T^{min}$ = 20MeV/c, θ_{min}=0.15)	19.0	13.4	15.8	9.9	2.8	2.4	2028	27.0
$N_{hadrons}$	.17	.20	.44	.25	.07	.04	45.9	1.37
N_{jet} x 10^{-2} (p_T^{min} = 3.2GeV/c)	.16	.27	1.68	.90	.22	.1	56.4	5.77

@ The JLC machines include the luminosity reductions due to the hour glass effect and the crossing angles without crab (0.68, 0.60, 0.70 for S, C and X-Band respectively).

G.A. Loew / October 20, 1993

"Beamstrahlung"



- Paramètre $\Upsilon = \gamma \dfrac{\langle B \rangle}{B_c} \equiv \dfrac{2}{3} \dfrac{\langle E_c \rangle}{E_0}$

  - $\langle B \rangle$: champ magnétique moyen crée par le paquet opposé
  - $B_c = \dfrac{m^2c^2}{e\hbar} = 4.4 \times 10^9\,\mathrm{T}$
  - $\langle E_c \rangle$: énergie critique moyenne

- $$\Rightarrow \quad \Upsilon = \frac{5}{6} \cdot \frac{r_e^2 \gamma N}{\alpha \sigma_z (\sigma_x + \sigma_y)}$$

	E_0	σ_x	σ_y	σ_z	N	Υ	$\langle B \rangle$
LEP	50 GeV	200 μm	8 μm	12 mm	2×10^{11}	7×10^{-6}	.33 T
SLC	50 GeV	2 μm	2 μm	1 mm	5×10^{10}	3×10^{-4}	40 T
TESLA	250 GeV	1 μm	64 nm	1 mm	5×10^{10}	2×10^{-2}	185 T
NLC	250 GeV	300 nm	3 nm	100 μm	6.5×10^{9}	0.097	860 T
CLIC	250 GeV	90 nm	8 nm	170 μm	6×10^{9}	.16	1400 T

Energy Spread

2 Définitions:

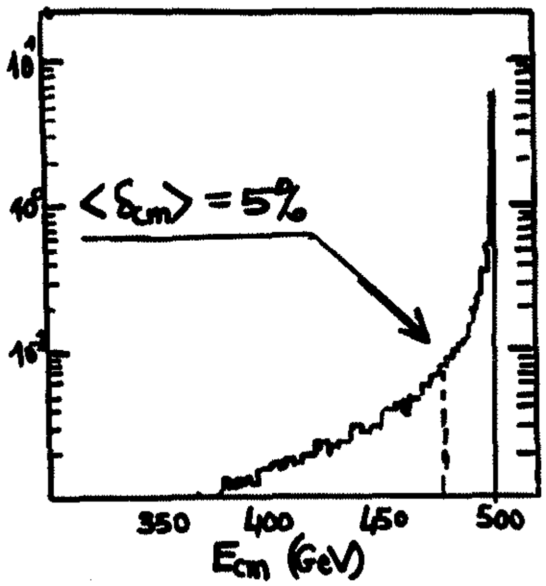
i) $\delta = \dfrac{\langle \delta E \rangle}{\langle E \rangle}$ averaged over the final electron distribution

ii) $\delta_{cm} = \dfrac{1}{\langle E_{cm} \rangle} \int \sqrt{s} \cdot \dfrac{d\mathcal{L}}{\mathcal{L}\, ds} \cdot ds$

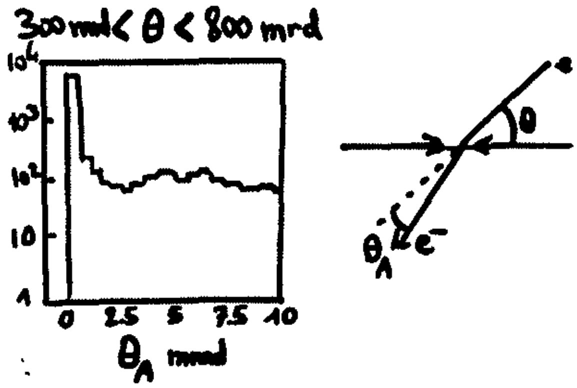
averaged over the luminosity spectrum

3 Contributions:

i) Initial State Radiation (ISR, or Bremstrahlung)



(K. Berkelman, CLIC Note 154
P. Chen, T. Barklow & W. Kozanecki)



acollinearity

(M. Frary and D. Mill

ii) Energy Spread at the end of the Linac:

$$E(z) = E_{RF}(z) + E_{Wake}(z)$$

iii) "Beamstrahlung"

Average energy loss of particles after collision [rigid bunch]

$$\left\langle \frac{\delta E}{E} \right\rangle_{B^{hg}} = \frac{r_e^3}{3\sqrt{\pi}} \times \frac{\gamma}{\sigma_z} \times \frac{N^2}{\sigma_x \sigma_y} \times g(R)$$

$(R = \sigma_x / \sigma_y)$ (Bassetti + LEP-TH, 1983)

$$\frac{8 r_e^3}{9} \times \frac{\gamma}{\sigma_z} \times \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

(R. Noble, 1987)

$$\simeq \frac{1}{2} \langle N_\gamma \rangle \Upsilon$$

$\langle N_\gamma \rangle$ → number of γ's / particle

•

		CLIC	TESLA
$\left\langle \frac{\delta E}{E} \right\rangle_{B^{hg}}$	$\simeq$	22 %	2.2 %
$\langle N_\gamma \rangle$	$\simeq$	2.8	2.2

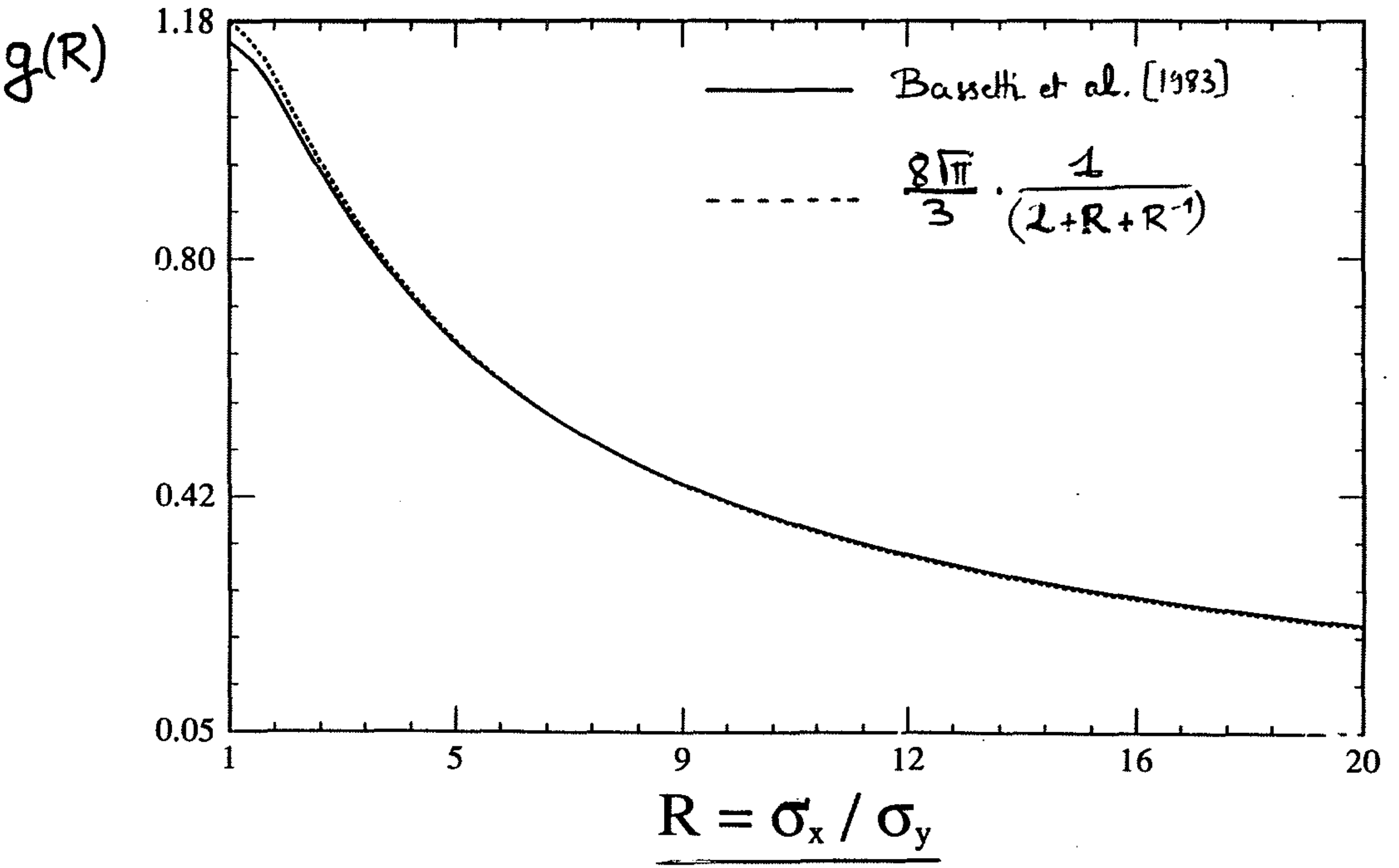
• $$\left\langle \frac{\delta E}{E} \right\rangle_{B^{hg}} = \frac{4\sqrt{\pi}\, r_e^3}{3} \cdot \gamma \cdot \overline{\mathcal{L}}_{1\,\text{collision}} \cdot \frac{g(R)}{\sigma_z}$$

$\overline{\mathcal{L}}_{1\,\text{collision}}$ → luminosity intégrated over one collision

Perte d'énergie moyenne pour $\mathcal{L} = 10^{33}\ cm^{-2}s^{-1}$

	TESLA	DLC Desy-D^{dt}	JLC-X KEK	NLC SLAC	CLIC CERN
σ_z	1 mm	500 µm	150 µm	100 µm	170 µm
$f_{Rep.}$	10 Hz	50 Hz	150 Hz	180 Hz	1.7 kHz
$\tau_{RF}\vert_\varphi$	0.8 ms	2 µs	28 ns	126 ns	11 ns
η_φ	8×10^{-3}	10^{-4}	4.2×10^{-6}	2.3×10^{-5}	2×10^{-5}
$n_{paquets}$	800	172	20	90	1
$\Delta\tau$	1 µs (300 m)	11 ns (3.2 m)	1.4 ns (42 cm)	1.4 ns (42 cm)	—
$R = \frac{\sigma_x}{\sigma_y}$	15.6	8	74	100	11
$g(R)$	.27	.47	6.2×10^{-2}	4.6×10^{-2}	.35
$\left\langle\frac{\delta E}{E}\right\rangle_{B\gamma}$	0.9%	2.9%	3.7%	0.8%	32%

↳ @ $\mathcal{L} = 10^{33}\ cm^{-2}s^{-1}$



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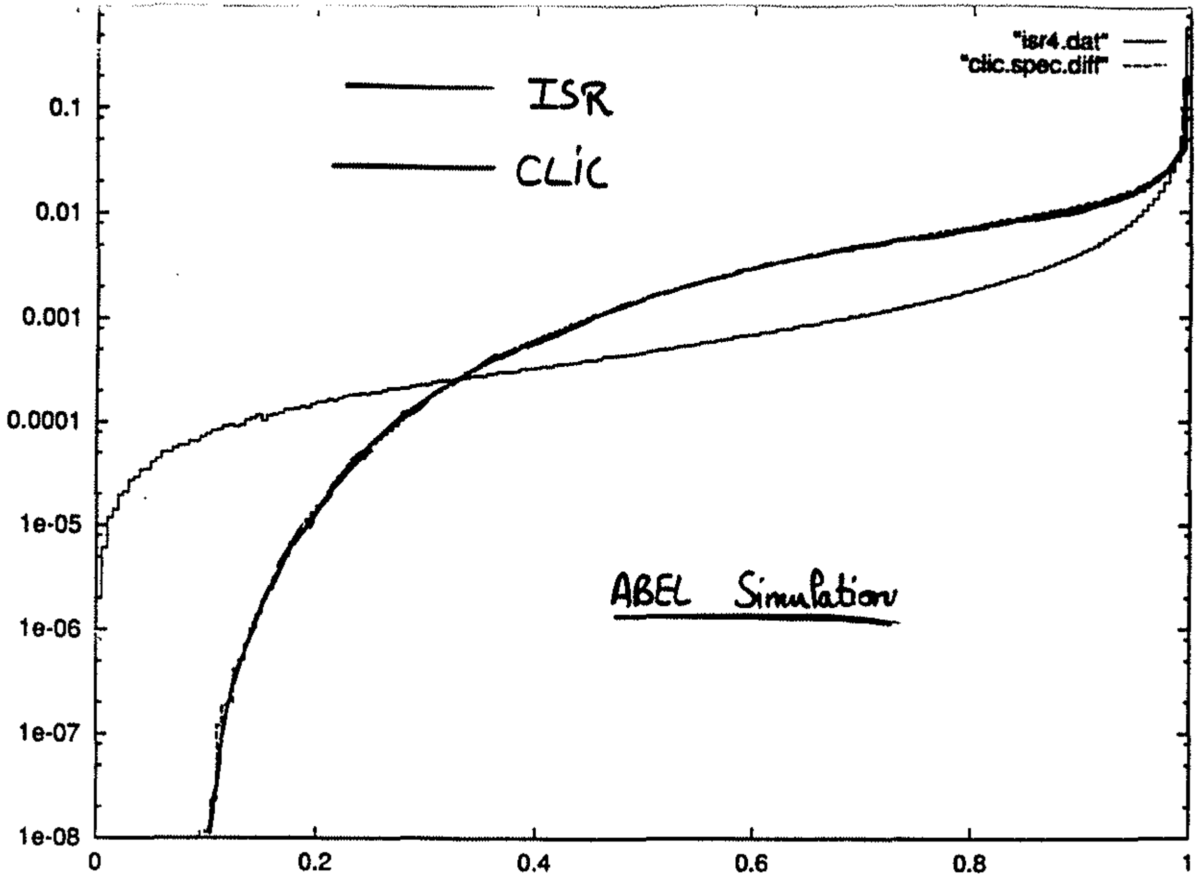
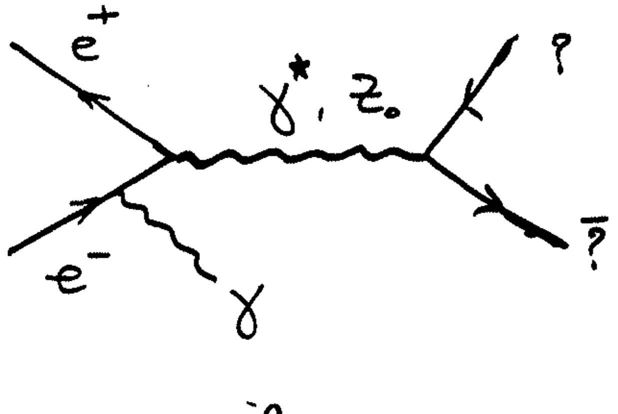
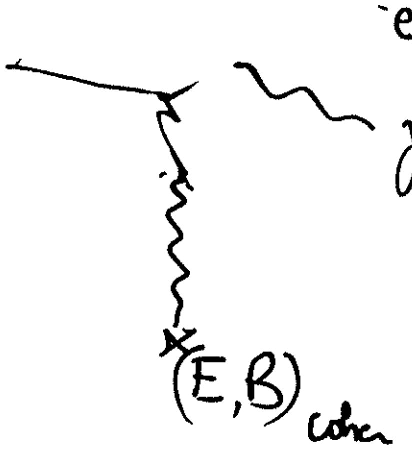


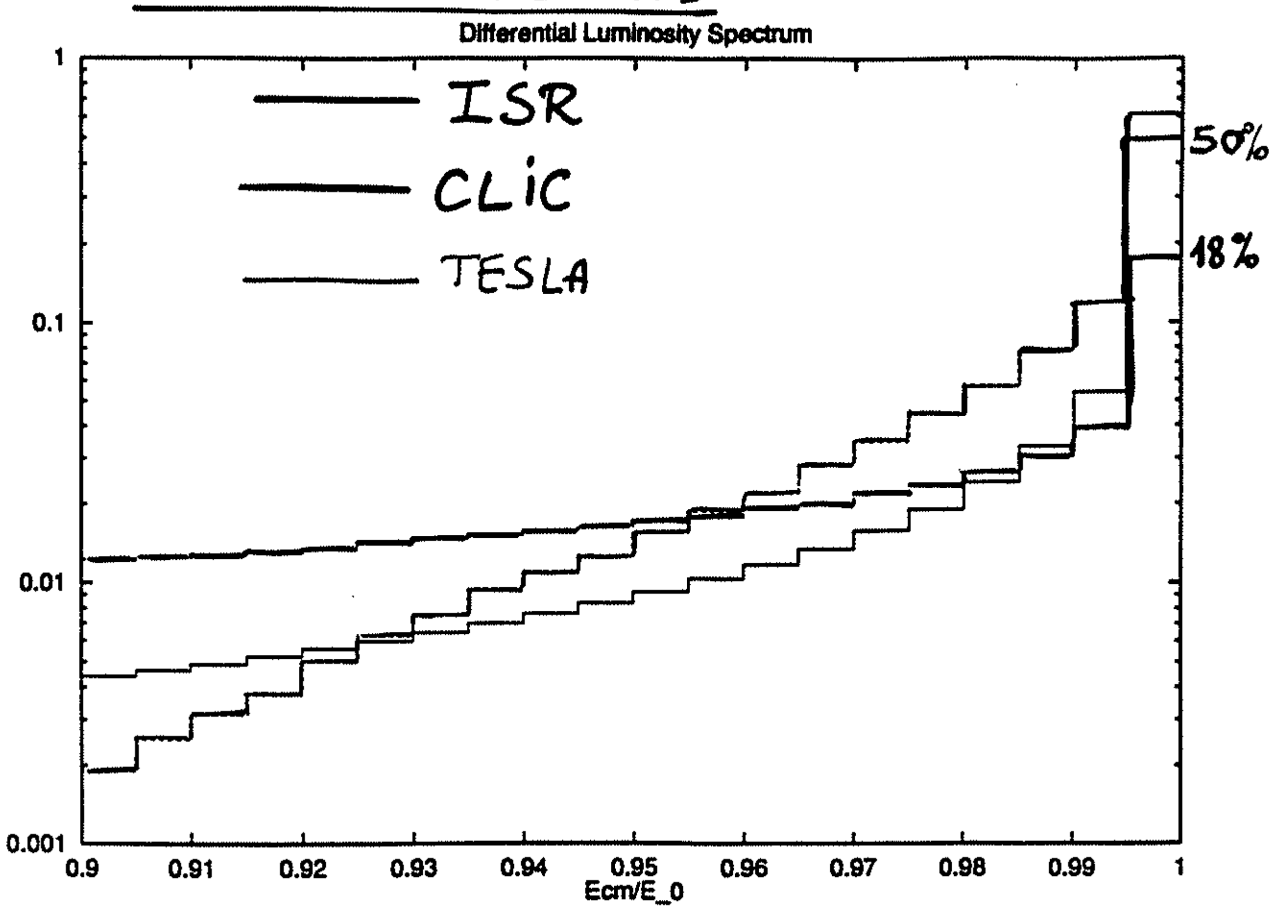
CLIC Luminosity Spectrum

vs. Initial State Radiation





SIMULATION RESULTS



$\delta_{cm} = 5\%$ for Initial State Radiation

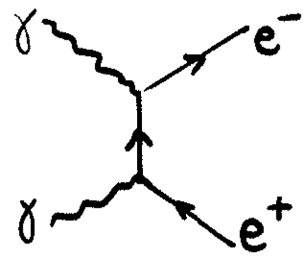
from ABEL:

$\delta = 19\%$, $\delta_{cm} = 12\%$ for CLIC

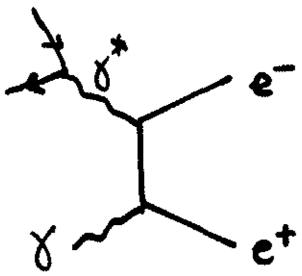
$\delta = 3.1\%$, $\delta_{cm} = 1.8\%$ for TESLA

Pair Production: e^+e^-

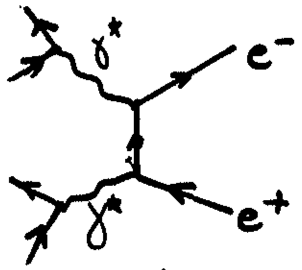
• Incoherent Production



Breit-Wheeler



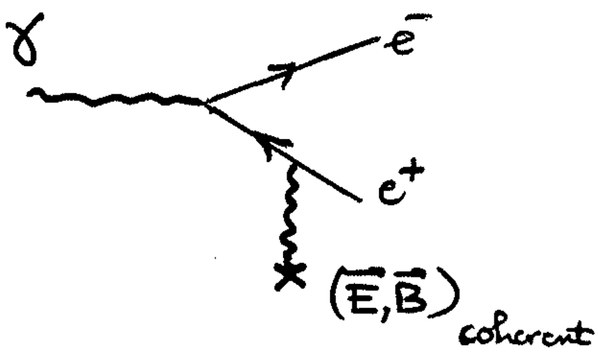
Bethe-Heitler



Landau-Lifshitz

BH $\geq$ LL $\geq$ BW

• Coherent Production



Very sensitive to Υ

$$N_{(e^+e^-)} = N_\gamma \cdot \left(\frac{\alpha\, \sigma_z}{\gamma\, \lambda\!\!\!^{-}_e} \Upsilon \right) \cdot \frac{7}{128}\, e^{-16/3\Upsilon}$$

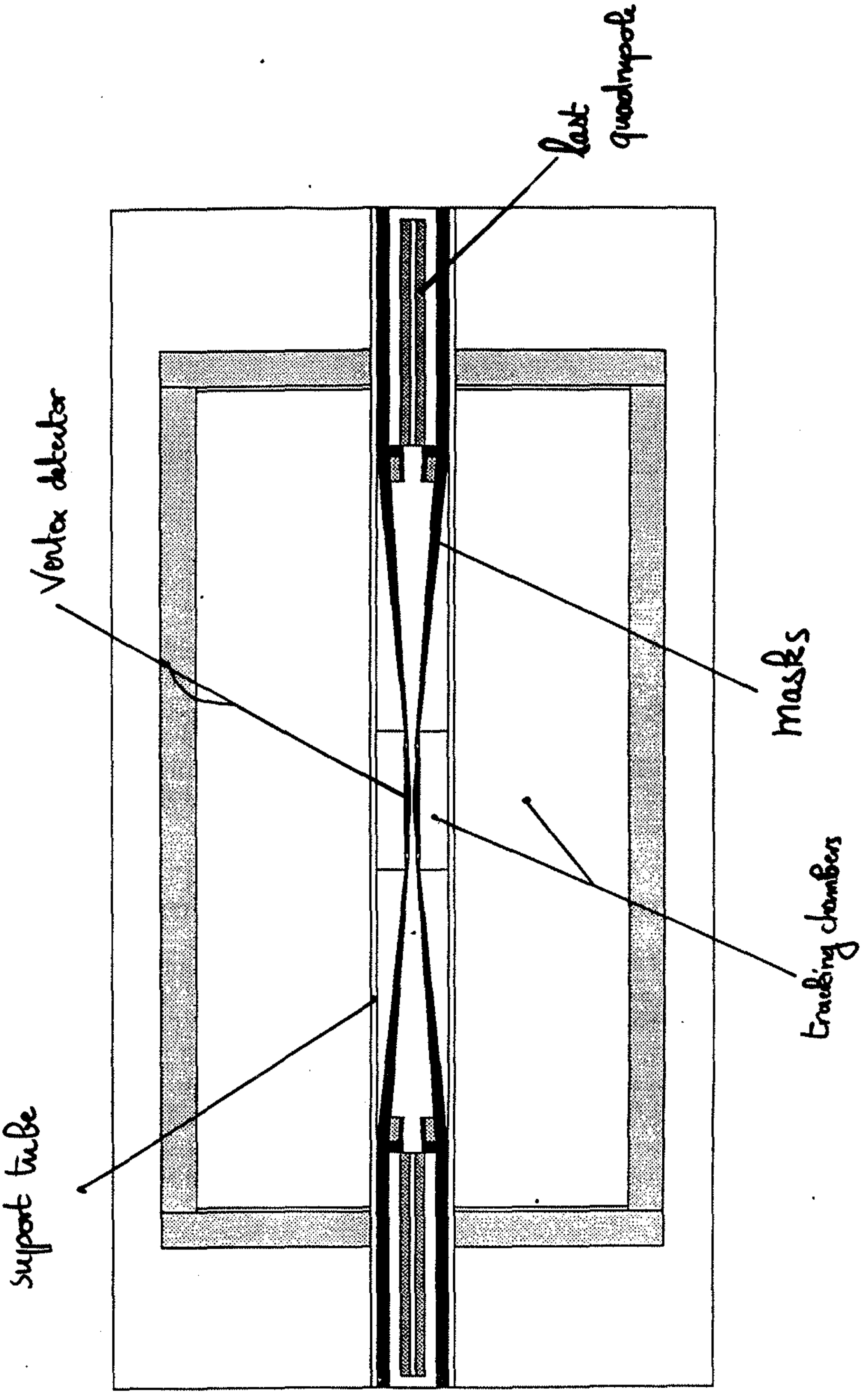


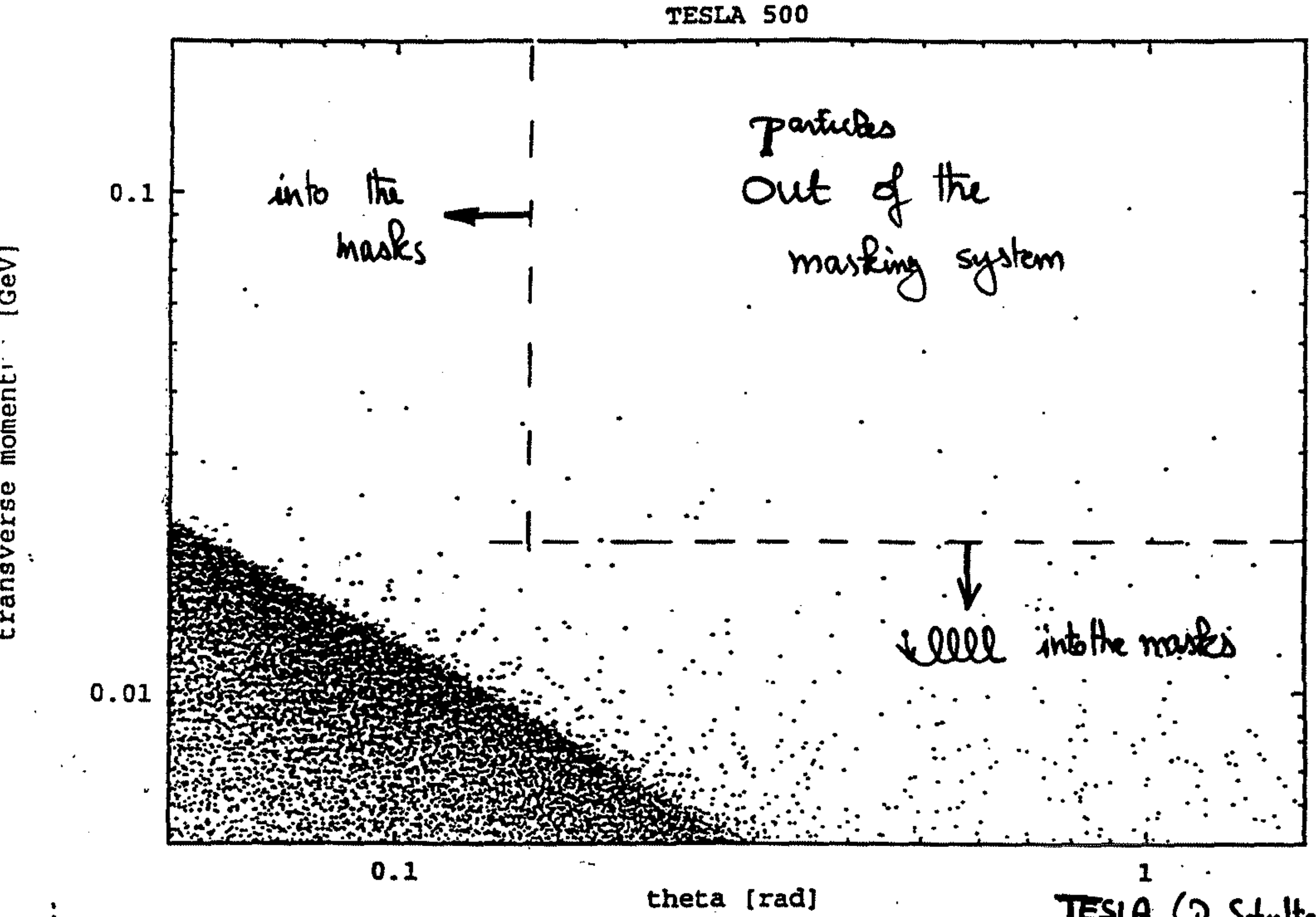
Figure 1: A rough sketch of the detector layout.

There are over 10^5 particles from low-energy

e^+e^- pairs : CLIC ~ 4.4 10^5

TESLA ~ 1.5 10^5

Pairs e+e-

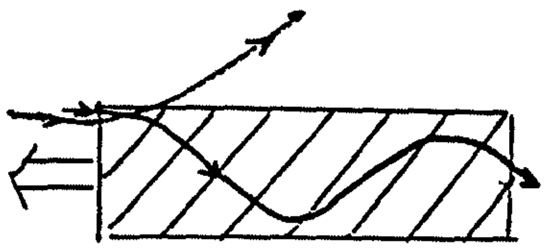


TESLA (D. Schulte)

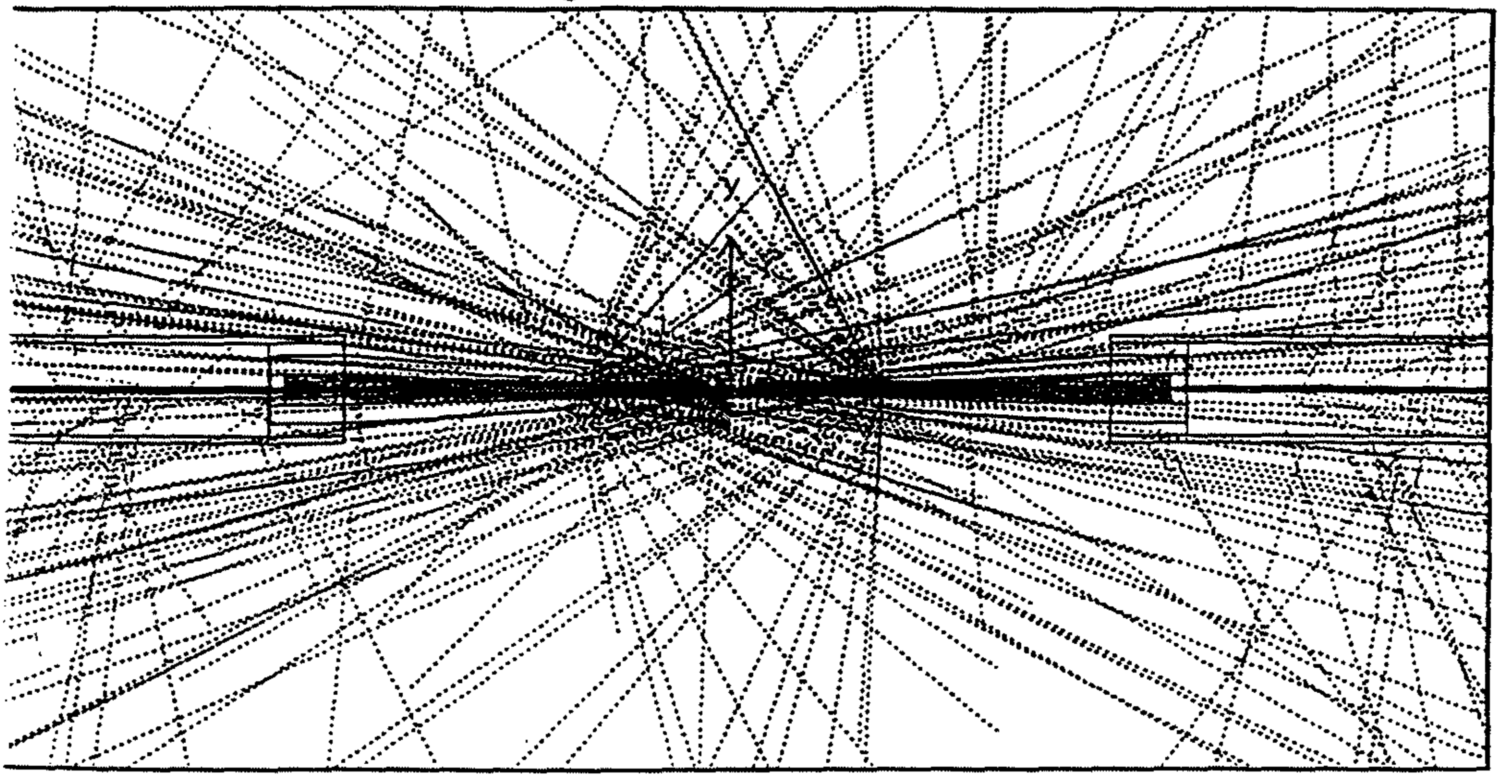
≈ 14 / crossing with p_t>20 MeV/c, θ>0.15 rad

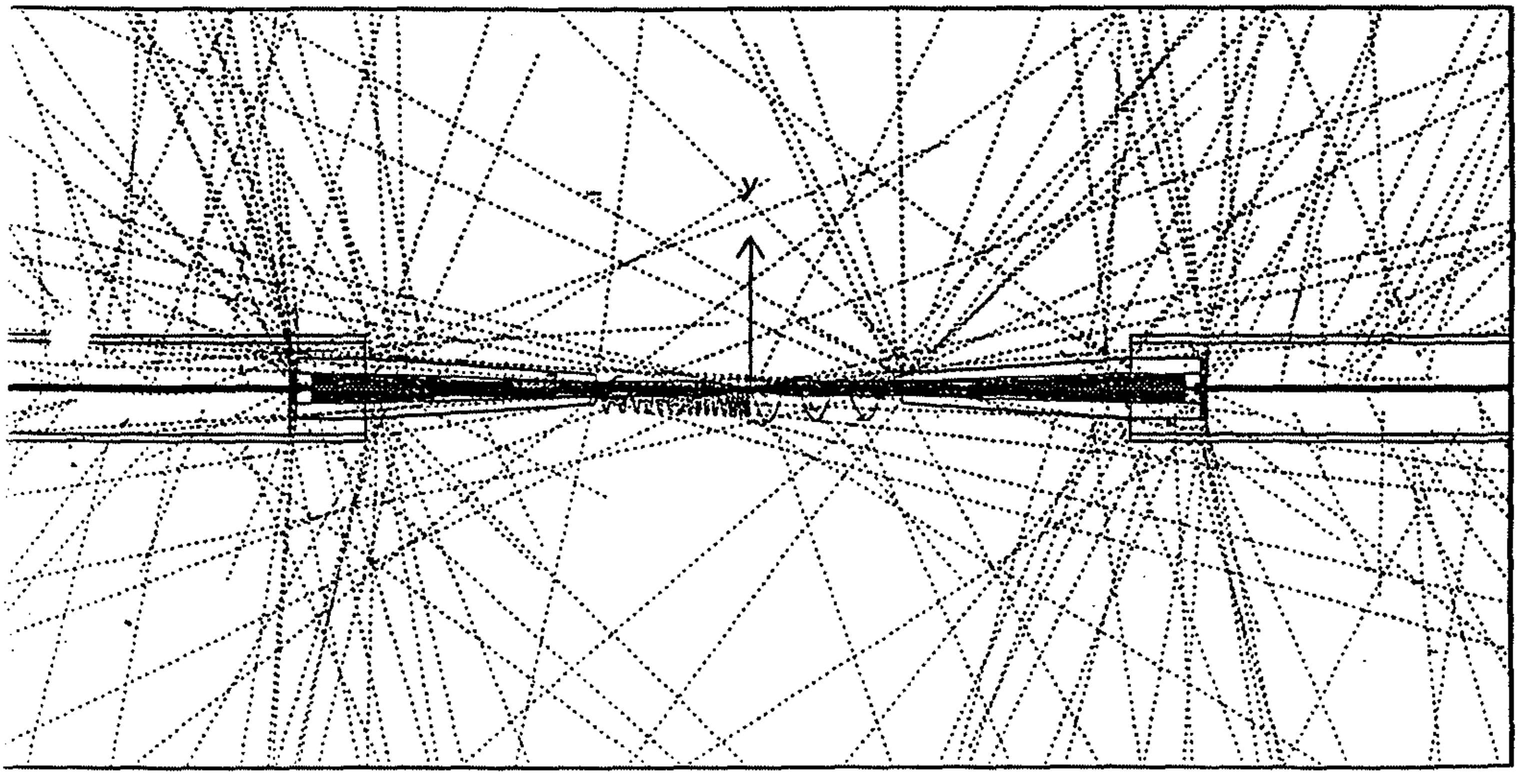
$$\theta_m = \sqrt{4\,\frac{\ln(D'/\varepsilon+1)\,D'\sigma_x'^2}{\sqrt{2}\,\varepsilon\,\sigma_z^2}} \qquad D' = \frac{N r_e \sigma_z}{\gamma\,\sigma_x'^2}$$

approximate maximum deflation angle

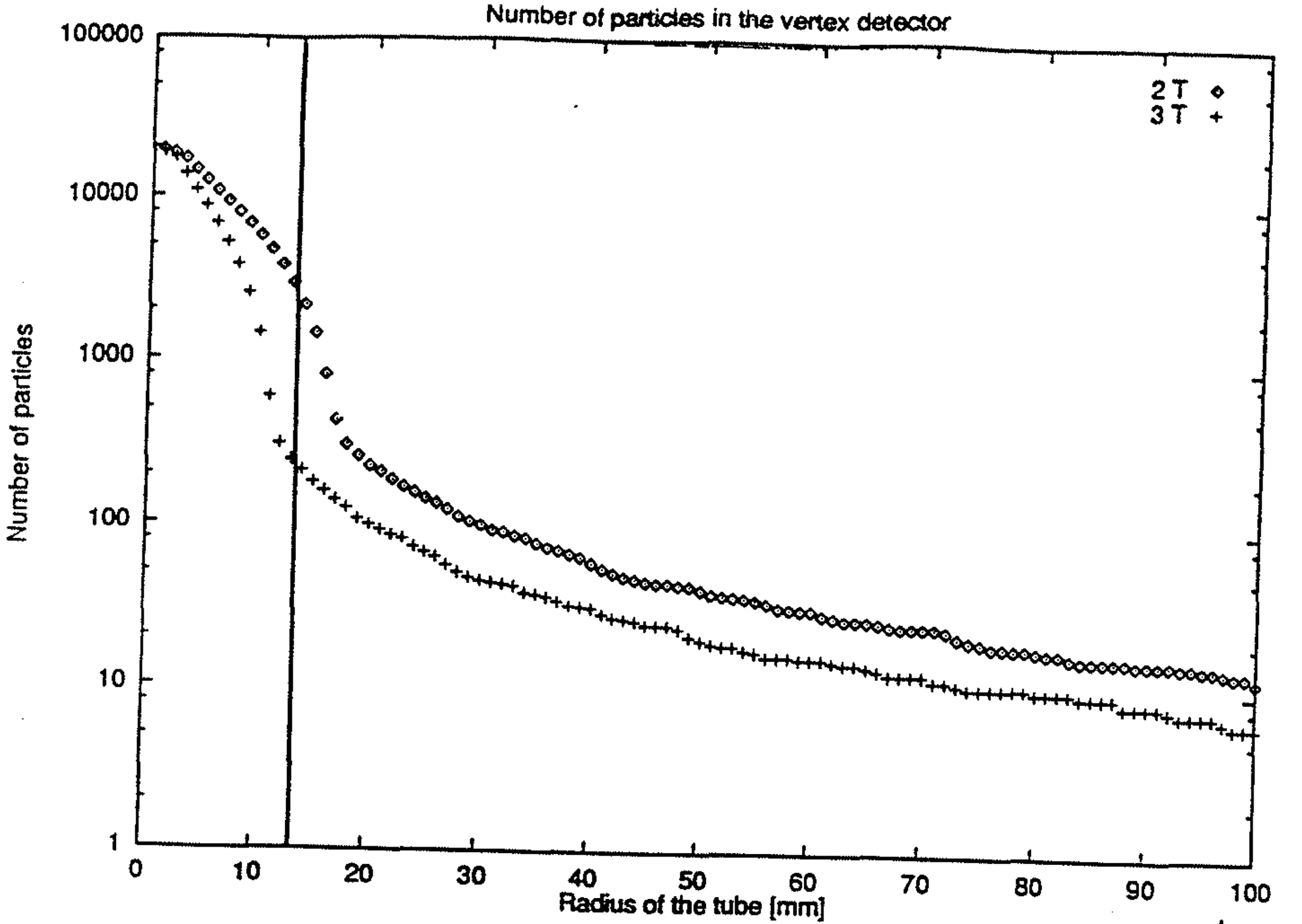


Photons from particles in the masking system hitting the detector



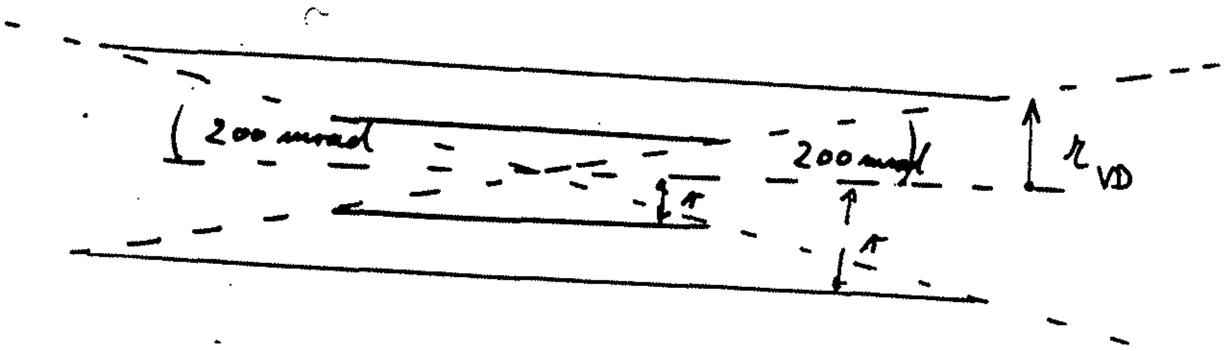


(D. Schulte)



r_{VD}

Number of Particles from e^+e^- pairs in the first layer of the silicon vertex detector



$\cos\theta = 0.98$

12.10.94

Interaction Regions for CLIC:

Comparison of Crossing-Angle and Head-on Collisions

Bruno Zotter

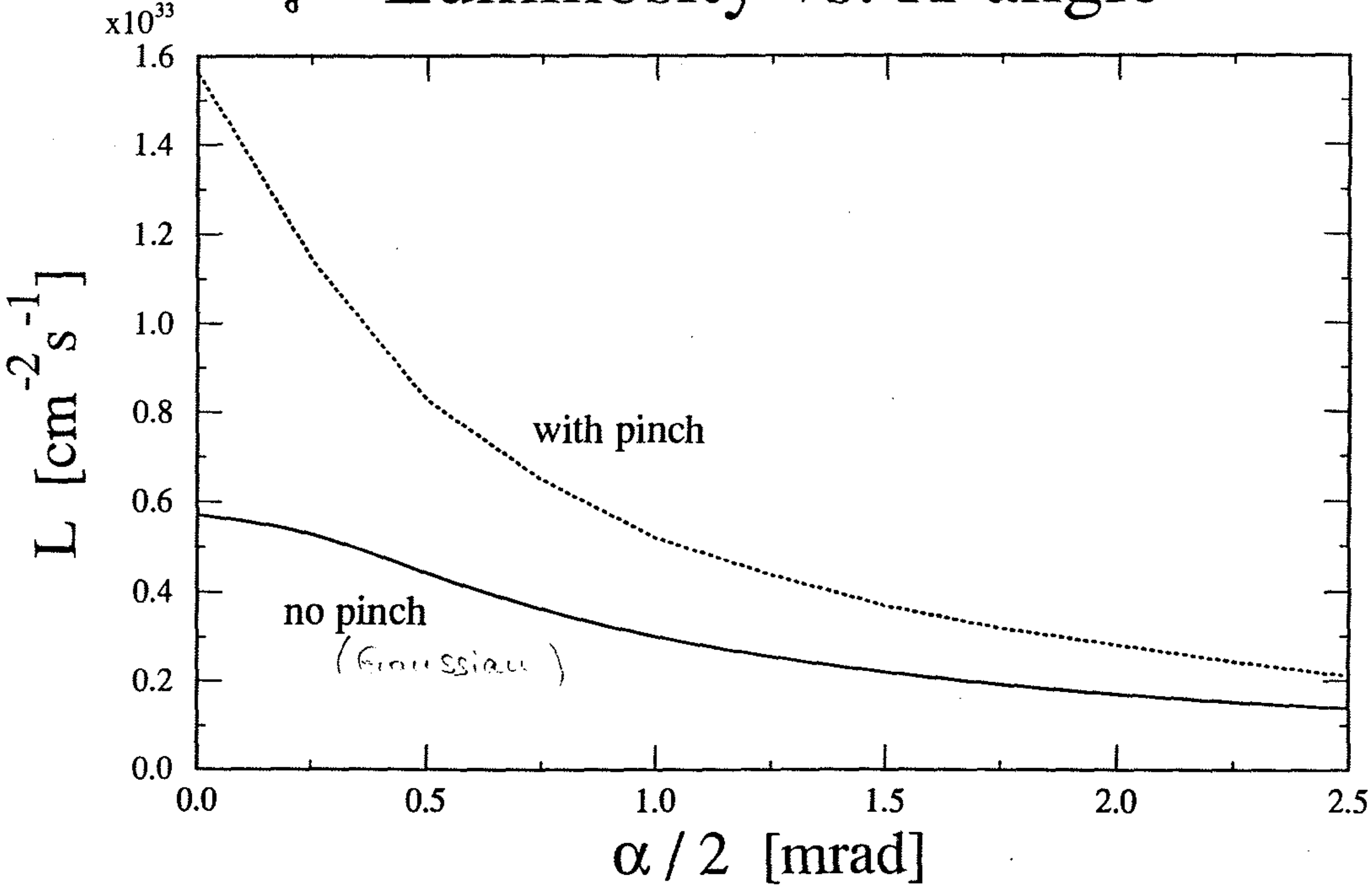
- Using 'old' CLIC Final Focus parameters - recent claims by Pisin Chen of excessive beam strahlung parameters ($\Upsilon = 0.35$ and $\delta = 20$ %) were unknown to me before the CLIC meeting last Friday;
- Olivier Napoly will discuss the various results obtained for these parameters with the program ABEL by Chen and by Schulte, as well as by using 'handy formulae' - all different - and the status of RBEAM which is being fixed by him and Paolo Pierini from Milano.

1. The problems related to a **crossing angle collision** for CLIC were already pointed out in the 1991 PAC - with a 'diagonal angle' of only 1/2 mrad horizontally (and much less vertically) a strong luminosity reduction sets in for crossing angles of the order of >1 mrad (Fig.1).

   In CLIC Note 210 (Sep.93) we then discussed the requirements for **'crabbing'** - in particular the very high phase stability of 0.04 degrees to keep the bunches rotated correctly. In addition, we found that an experimental solenoid - almost certainly desired by the experimenters - will introduce a vertical dispersion (for a horizontal crossing angle) and increase the beam size by a large factor (~5). Although compensation is possible in principle, it will interact with the two other (chromatic) correction sections and cause them to be less effective. Fig 2: Crabbing would very limited in CLIC

   An alternative method to avoid - or at least reduce - this vertical dispersion was by **shielding** the beam trajectory from the solenoid field. We used the program POISSON to design cylindrical or conical shields (see Fig.3) but found that the field distortion in the midplane was always rather large, and might complicate data analysis for experimenters. Also it appeared that the channeling of pair-created particles along magnetic field lines would no longer send them into the beam pipes, and additional shielding might be required.

Fig.1: Luminosity vs. X-angle



TempleGraph 2.5, Origin: napoly@seas67 - Thu Mar 18 16:21:54 1993 (data file was clic.xres)

12.10.94

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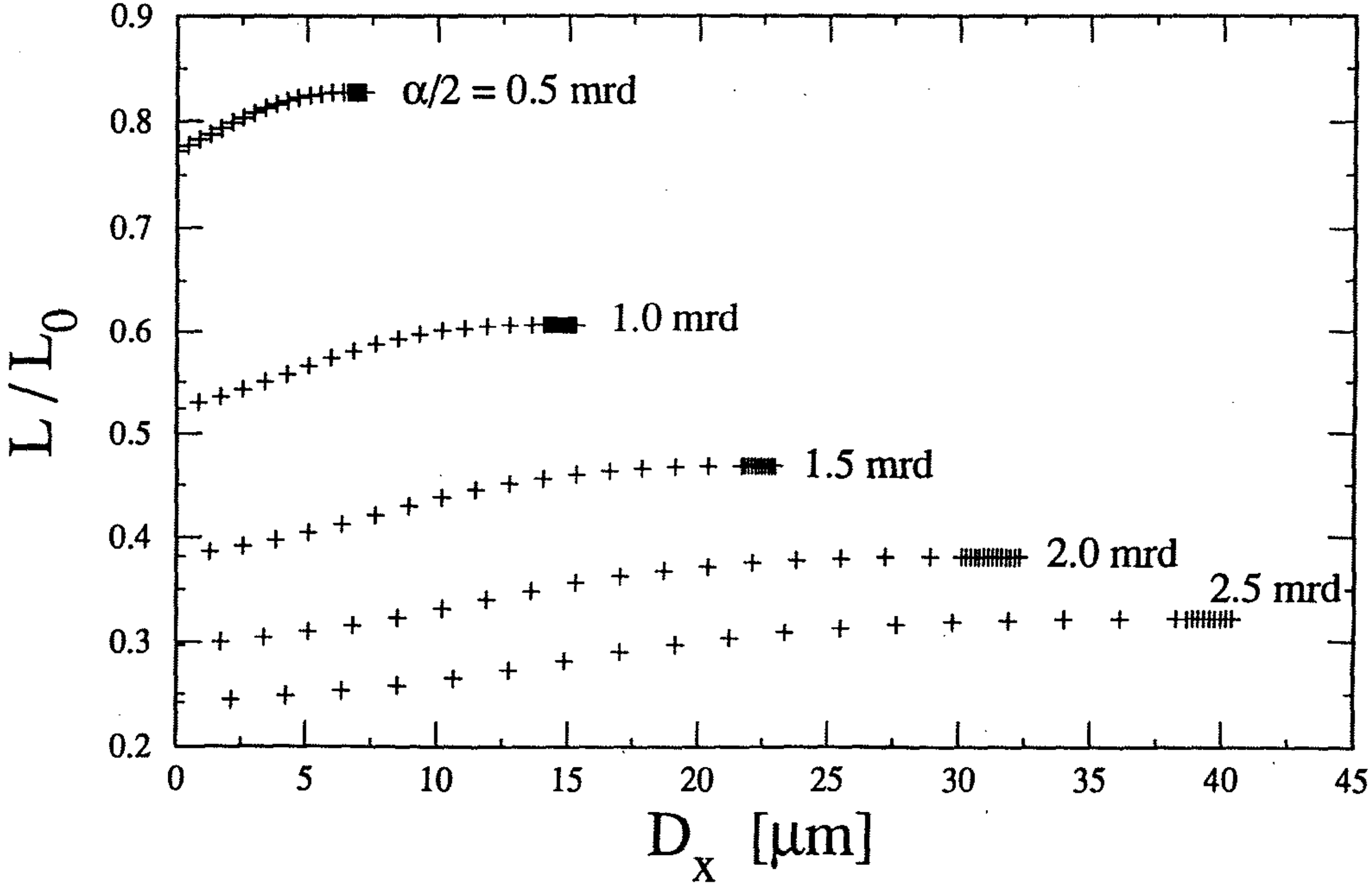
Fig.2: CLIC: "Crabbing" with Dispersion

improvement of luminosity with dispersion in IX



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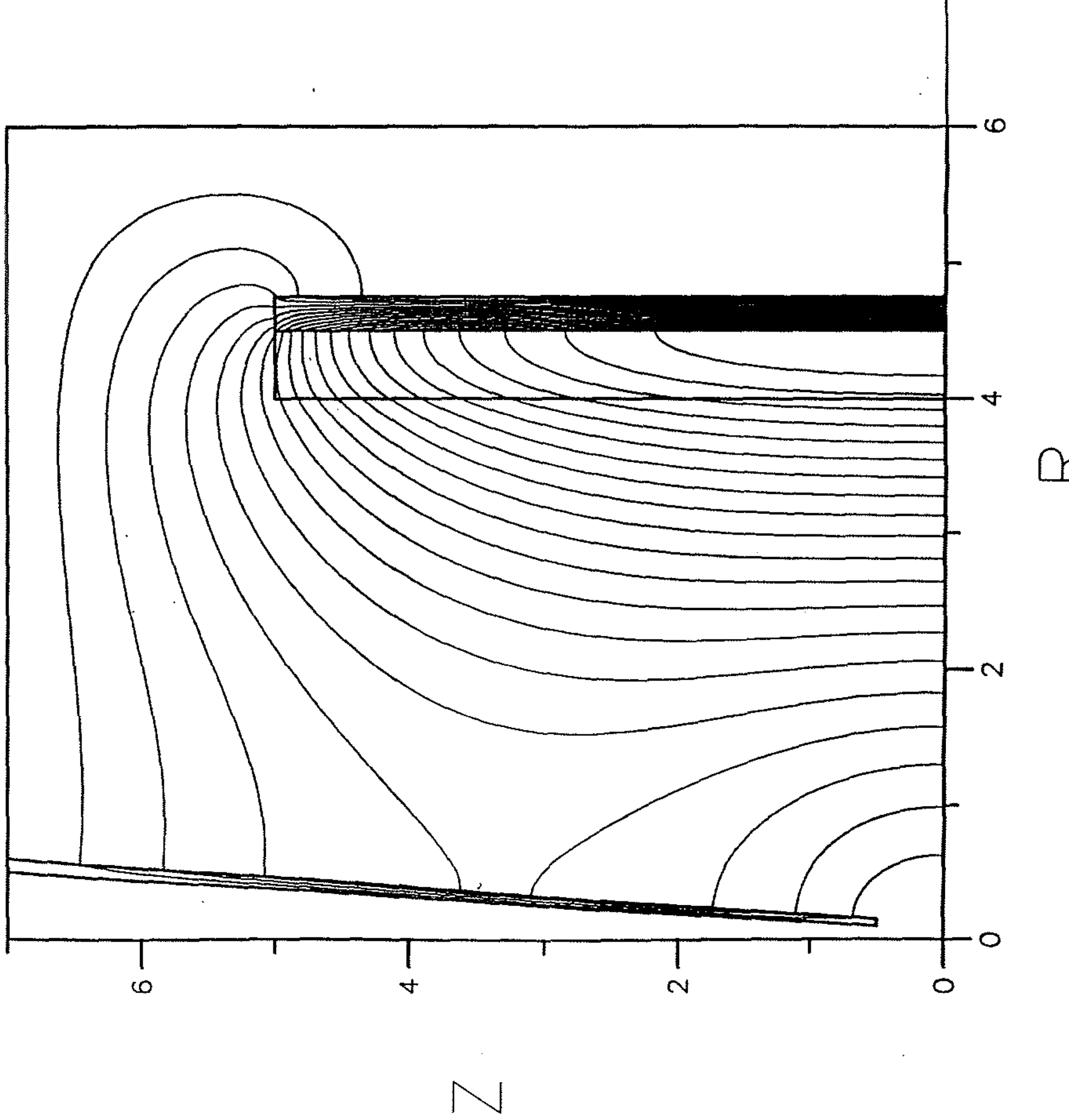


Fig. 3: Shielding of SC- solenoid (4m inner radius, 5m half length) with conical iron shield

2. **Head-on collisions** were studied earlier this year - a provisional CLIC note was written. Only single bunch operation was thought to be possible then, as parasitic collisions inside the interaction region would have been unavoidable with small bucnh spacings. CLIC would have required stronger bunches to achieve the desired luminosity of 10**33 , but the note was not published since linac designers wanted to explore their parameter options first. In a sense this was good, since now the idea of **'recirculation'** has been advanced (CLIC note 242) which permits much larger bunch spacing. By lengthening the (quite low loss) waveguides connecting the accelerating sections, the distance can be adjusted to push the parasitic collisions behind the last doublet (2x5 m).

   However, even more free space will be needed for separation of the two beams. **Electro-static separators** would bend the beams apart, but are rather inefficient at high energies. Even with highest fields of 3 MV/m, over 5 m length would be needed to get a separation of just 2σ in the vertical plane - still ignoring the emittance blow-up by disruption. **Magnetic separators** need to be **pulsed** - and rather short risetimes are required for more than 2 bunches/beam. Nevertheless, this possibility warrants further study.

3. A compromise solution might be a **very small crossing angle** - less than the bunch 'diagonal angle' - and large aperture quadrupoles which accept the increased 'effective' emittance created by such beams. A final focus system using **LHC super-conducting-dipoles** with 5 cm apertures has been obtained by Olivier already in spring, and might be the basis of such a solution.

   Indeed, it turns out that the crossing angle necessary to separate bunches does **not** depend on their spacing, but only on the divergence at the IP (i.e. on the square-root of emittance over beta function). Parasitic collisions with more than 10σ separation are probably acceptable, and for CLIC only +/- 0.2 mrad (horizontal X-ing) are needed for this. Nevertheless, the crossover of trajectories inside the quadrupoles need to be adjusted carefully like in a **Pretzel scheme**, which has not been done yet.

Search for CLIC Interaction Region Beam Parameters

13-14th/10/94 G Guignard

"Present" Parameters at 2 × 250 GeV
(CLIC Note 163, 19.5.92)
Concocted by O. Napoly w. tracked emittances and using RBEAM code

$N_b = 6\ 10^9$ $5\ 10^9$ in the acceptance

$\sigma_z = 0.17$ mm

$\gamma\varepsilon_x = 1.8\ 10^{-6}$ $\beta_x^* = 2.2$ mm

$\gamma\varepsilon_y = 2\ 10^{-7}$ $\beta_y^* = 0.16$ mm

$\sigma_x^* = 90$ nm $\sigma_y^* = 8$ nm

$\Upsilon = 0.15$ $\delta_B = 5.9$ %

Rationals: β_y^* fixed by σ_z
Oide limit gives σ_x^* and σ_y^*
Check aberrations
Keep $\delta_B \approx 5$ %

In the mean time, people used our parameters to produce different numbers for $\mathcal{L}$ (larger enhancement) and δ_B (much higher)

Ian and I tried to understand it, during summer. with the help of P. Chen and V. Telnov

Some Basic Formulae

"Old" Nominal

Luminosity

2x 250 GeV CLIC

$$L_0 = \frac{N_b^2 f_{rep}}{4\pi\, \sigma_x^* \sigma_y^*} H_D(\eta_L) \qquad L = L_0 k_b$$

$2.2\ 10^{33}$

$8.8\ 10^{33}$ for $K_b = 4$

$$\eta_L = \frac{2}{\sqrt{\pi}\,\sigma_z} \int_0^\infty \frac{\exp(-z^2/\sigma_z^2)}{[\beta_y^{*2} + z^2]^{1/2}} dz$$

η_L ~ 0.85

with $A_y = \frac{\sigma_z}{\beta_y^*}$ ~ 1

idem from A_x, but negligible $\sim .077$

Disruption Parameters

$$D_x = \frac{2 r_e N_b \sigma_z}{\gamma \sigma_x^* (\sigma_x^* + \sigma_y^*)}$$ 1.34

$$D_y = \frac{2 r_e N_b \sigma_z}{\gamma \sigma_y^* (\sigma_x^* + \sigma_y^*)}$$ 15.3

Pinch effect, Effective sizes

H_{D_x} — 5.1

$$H_{D(x,y)} = 1 + D^{1/4} \frac{D^3}{1+D^3} \left\{ \ln(\sqrt{D}+1) + 2 \ln \frac{0.8}{A} \right\}$$

H_{D_y} — 3.13

$$\bar{\sigma}_x^* = \frac{\sigma_x^*}{H_{D_x}^{1/2}}$$ 40 nm

$$\bar{\sigma}_y^* = \frac{\sigma_y^*}{H_{D_y}} f(R) \qquad R = \sigma_x^* / \sigma_y^*$$ 5.5 nm

$R = 90/8 = 11$

Luminosity enhancement

$$H_D = H_{D_x}^{1/2} \; H_{D_y}^{f(R)}$$ **3,3**

$$f(R) = \frac{1 + 2R^3}{6R^3}$$ 0,333

Critical γ-to-particle E-ratio

$$\Upsilon = \frac{5}{6} \frac{r_e^2 \, \gamma \, N_b}{\alpha \, \sigma_z \, (\bar{\sigma}_x^* + \bar{\sigma}_y^*)}$$ **0,35**

Average E-loss per unit time

$$\langle -\frac{1}{E}\frac{dE}{dt} \rangle = \frac{2}{3} \frac{\alpha}{\lambda_e} \frac{\Upsilon^2}{\gamma} \, U_1(\Upsilon)$$ 1118

$$U_1(\Upsilon) \approx \frac{1}{[1 + (1.5\Upsilon)^{2/3}]^2} \stackrel{\text{also}}{=} H_\Upsilon$$ 0,36

of emitted γ and relative E-loss

$$n_\gamma \cong 2{,}54 \, \frac{\alpha \, \sigma_z \Upsilon}{\lambda_e \gamma} \, U_0(\Upsilon)$$ **4,7**

$$U_0(\Upsilon) = \frac{1}{(1 + \Upsilon^{2/3})^{1/2}}$$ 0,81

$$\delta_B = \langle -\frac{\Delta E}{E} \rangle \approx 1{,}24 \, \frac{\alpha \, \sigma_z \Upsilon^2}{\lambda_e \gamma} \, U_1(\Upsilon)$$ **0.36**

References: Beam-beam Phenomena in LC
K. Yokoya, P. Chen, 1990
Lecture Notes in Physics
Disruption Effects from Collision in Quasi-flat beam
P. Chen

Discussion on formulae

Pisin's formulae are deduced from fitting results of his code ABEL simulating the collisions (large range of D and A)

⟹ Caution needed in their use

Still, it's a useful tool for scaling

Check: • Pisin ran ABEL w. "old" params

⟹ $H_D = 3$ $\delta_B \cong 0{,}20$

Pisin was disappointed by the discrepancy: H_D was 3,3 δ_B was 0.36 with his formulae.

But, he guesses the "errors" to $\gtrsim 10\%$

So taking $\overline{\sigma}_x \times \overline{\sigma}_y \approx 50 \times 5$ nm^2

Formulae give $\delta_B \cong 0{,}28$

not too good for "intermediate" (CLIC) aspect ratio.

• Valery Telnov visited us and ran its own code.

⟹ $H_D = 2.6$ $\delta_B \simeq 0{,}23$

Conclusion: CLIC old parameters give too high an horizontal disruption

⟹ too large energy loss δ_B

Where to go. How to optimize

Formulae tell us: $\mathcal{L} \sim \dfrac{N_b^2}{\sigma_x \sigma_y}$

$$\delta_B \sim \frac{N_b^2}{\sigma_z \sigma_x^2}$$

$\Rightarrow$ Three possibilities to decrease δ_B

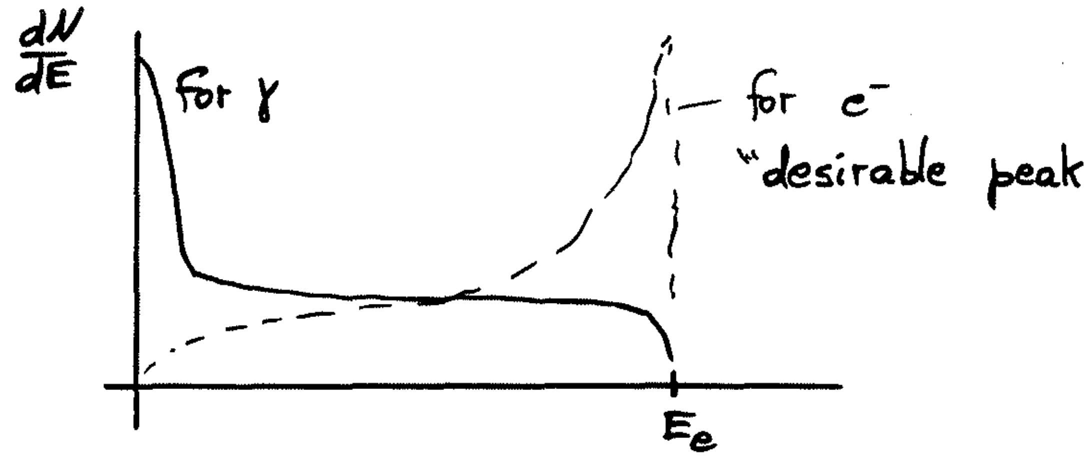
a) Decrease N_b, but $\mathcal{L}$ drops

b) Increase σ_z (see Curve)

Small sensitivity with σ_z unless we increase it by 3 or 4 $\rightarrow$ prohibited by wake fields.

N.B. the apparent gain when σ_z is small is not welcome for physics and $\mathcal{L}$- distribution.

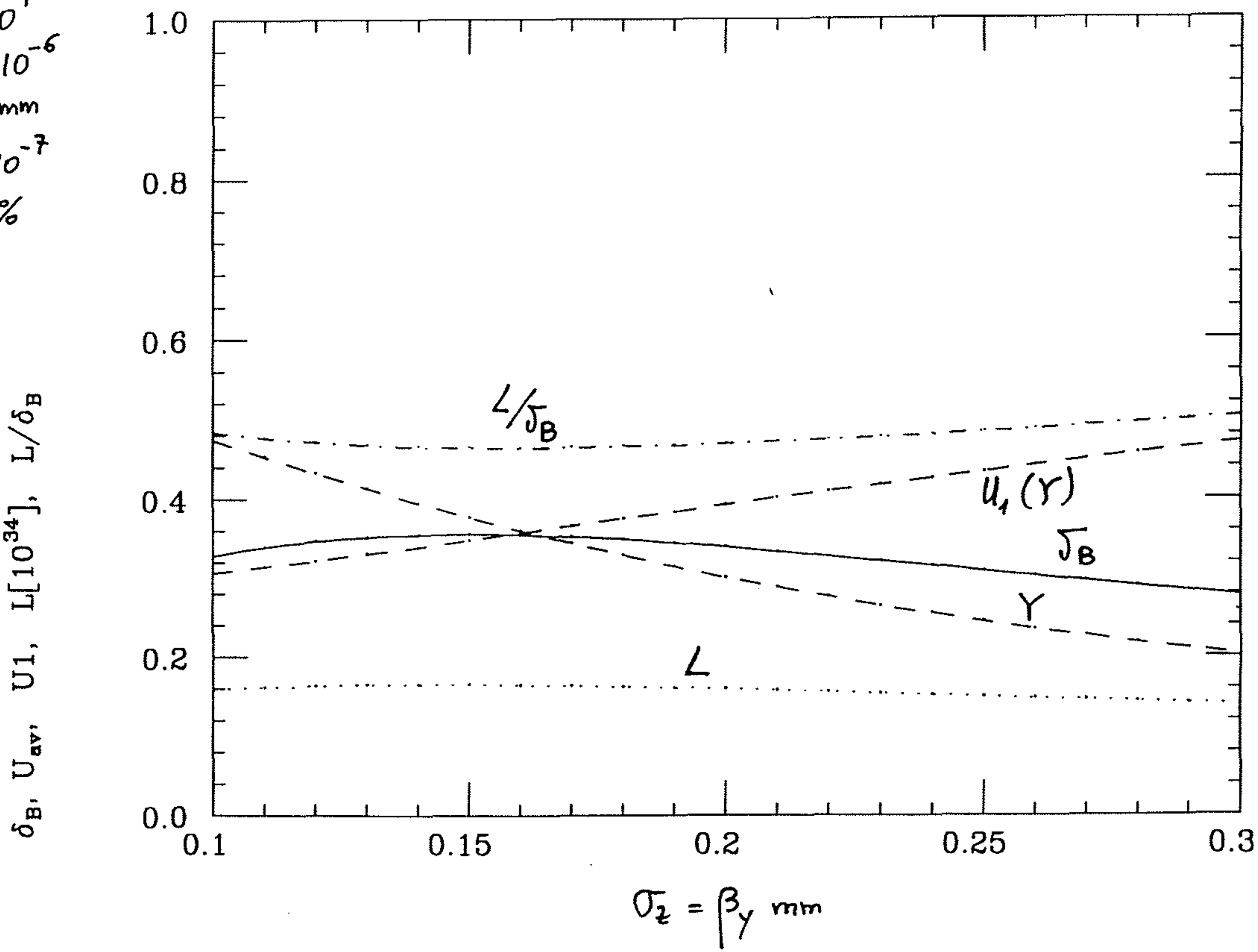
γ- Spectrum decreases with E + is truncated



$\sigma_z \searrow$ peak not narrower, spectrum spreads more $\rightarrow$ δ_B decreases apparently in a not desirable way

Conclusion: select $\sigma_z \cong 0{,}2\,mm$ $\rightarrow$ Min. $\delta E/E$ with "Bunch Shaping"

$N = 6\ 10^{9}$
$\gamma\varepsilon_x = 1.8\ 10^{-6}$
$\beta_x^* = 2.2$ mm
$\gamma\varepsilon_y = 2\ 10^{-7}$
$\eta_L = 75\%$



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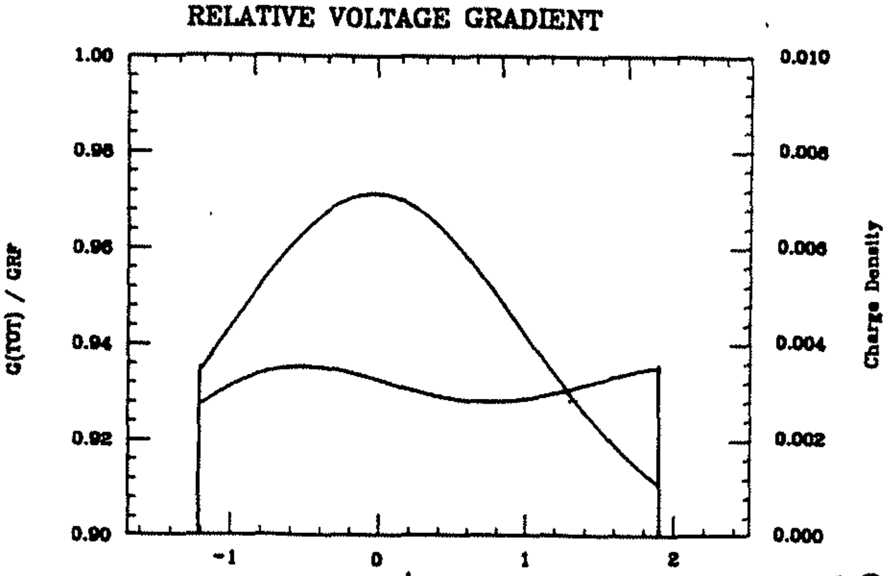
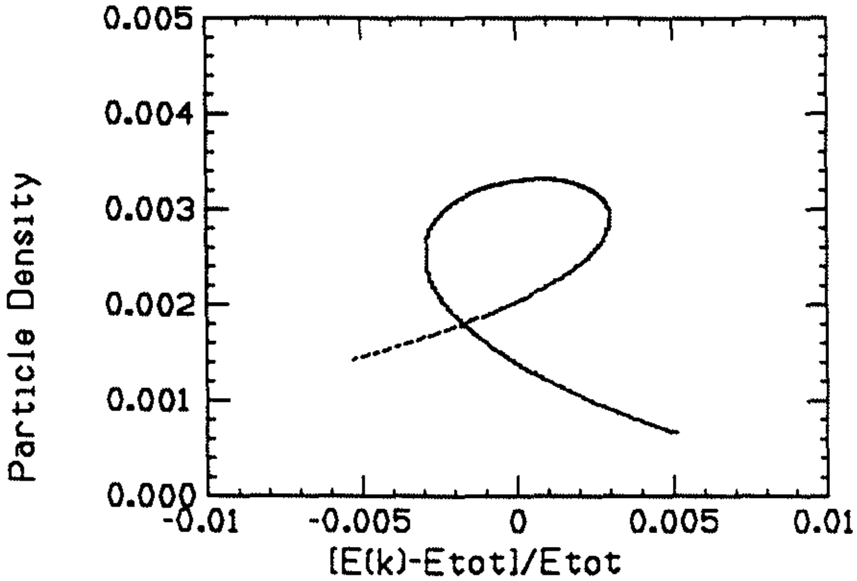
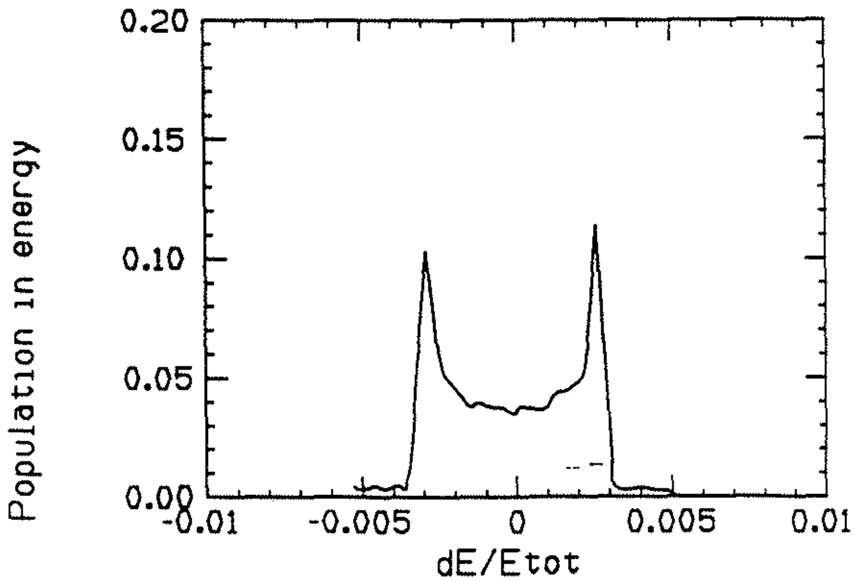


Truncated Gaussian $\sigma_z = 0.2\ mm$

" Shaping " $N = 8\ 10^9$



Optimisation at linac "exit" < ± 5‰ >



Distribution in energy $\sigma_E = 0.22\ \%$

c) Enlarge the beam size σ_x

Both δ_B and $\mathcal{L}$ drop, but not in the same way

$\Rightarrow$ For a same δ_B, one can adjust independently N_b and σ_x (See curves)

$\Rightarrow$ To get $\delta_B \simeq .065$ (formula) with $N = 6 \cdot 10^9$ $\Rightarrow$ $\sigma_x = 150$ nm

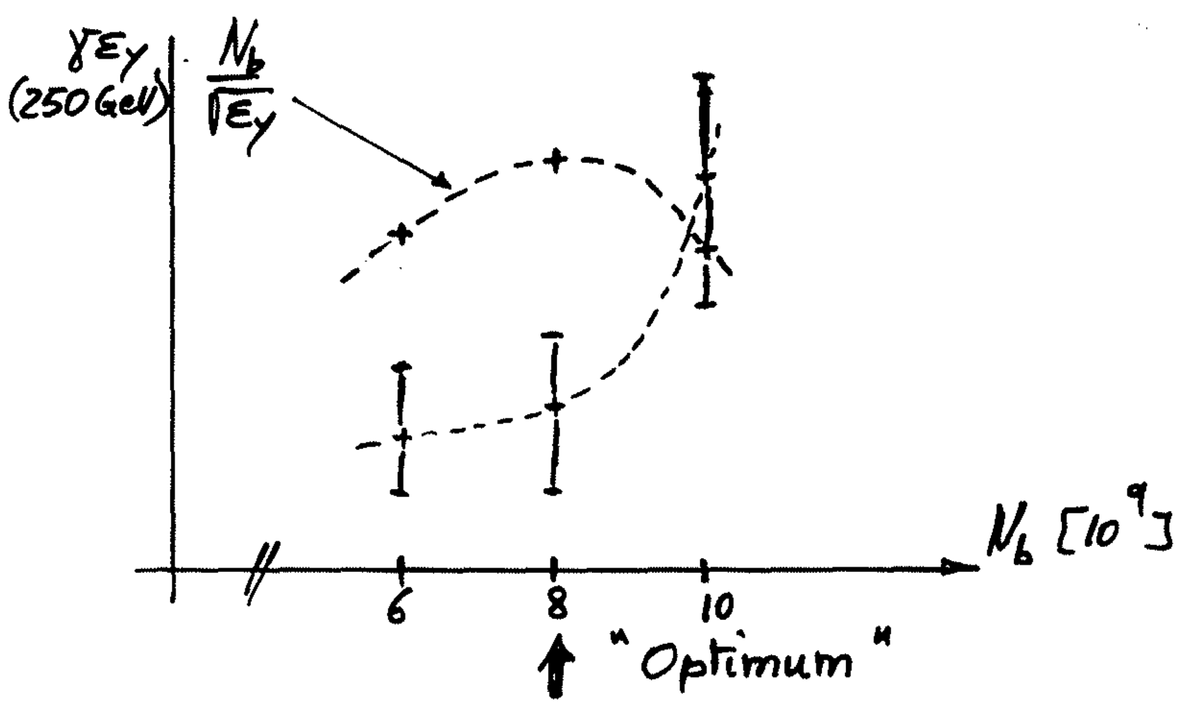
$\mathcal{L}$ is now in the $0.6\ 10^{33}$ range.

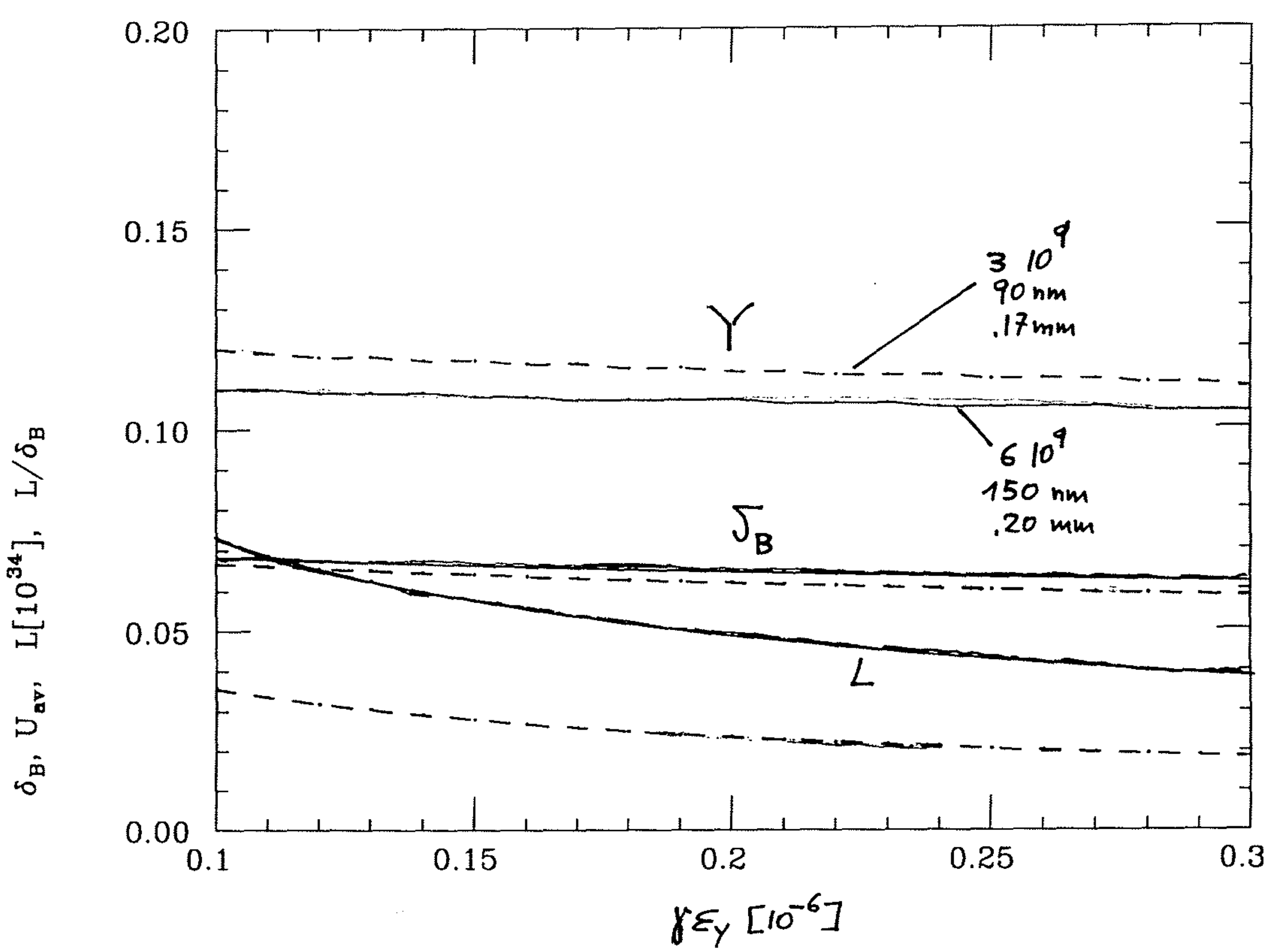
Telnov proposed to push N_b even further

Why? Combining the formulae gives

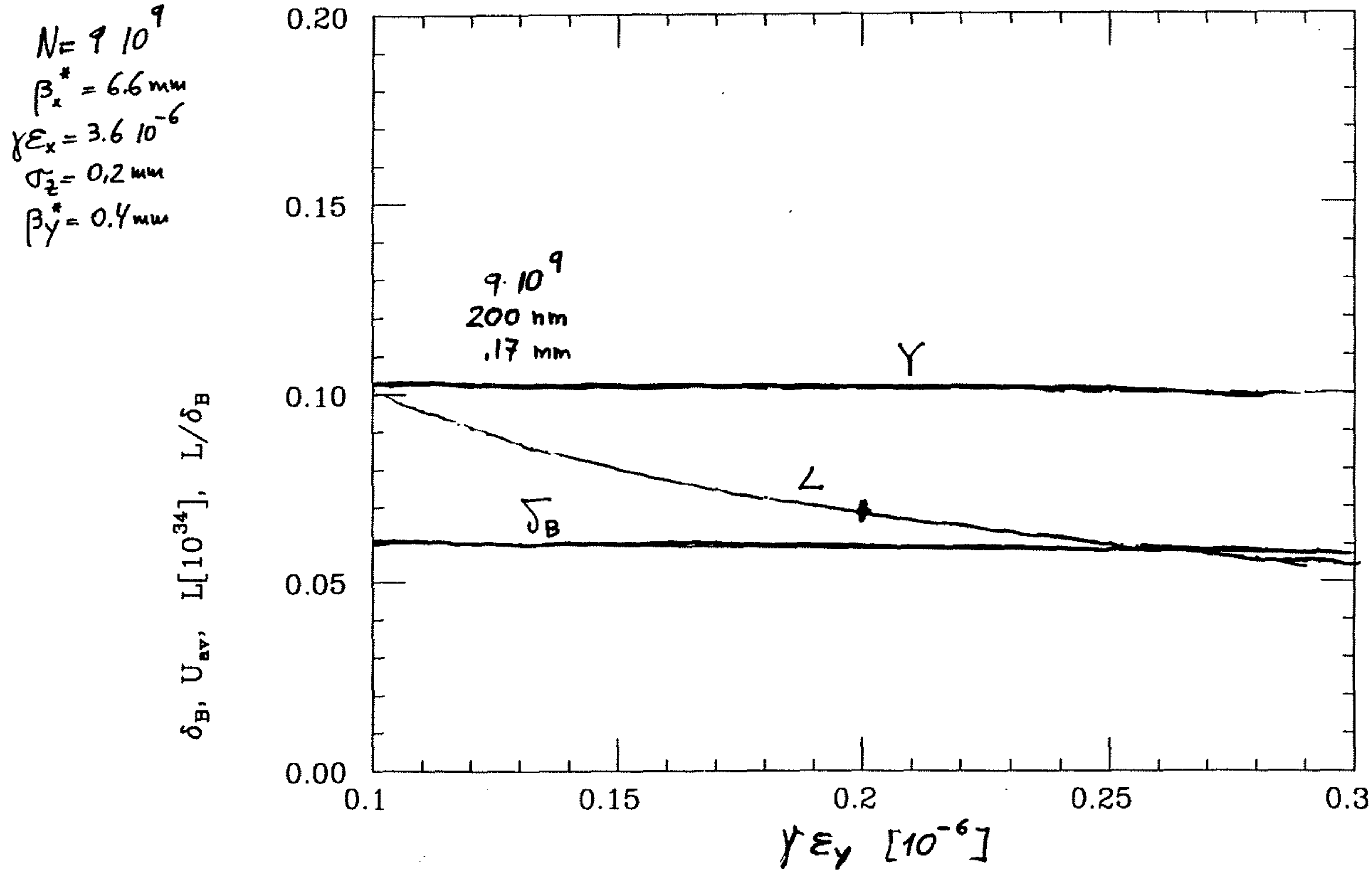
$$\mathcal{L} \sim N_b \sqrt{\frac{\delta_B}{\varepsilon_y}}$$

$\rightarrow$ At constant δ_B, push N_b and find out (by tracking in the LINAC) the maximum of $N_b / \sqrt{\varepsilon_y}$





0.20
0.15
0.10
0.05
0.00
0.1
0.15
0.2
0.25
0.3
δ_B, U_{av}, $L[10^{34}]$, L/δ_B
$\gamma \varepsilon_y$ [10^{-6}]
Y
δ_B
L
3 10^9
90 nm
.17 mm
6 10^9
150 nm
.20 mm


$N = 9\ 10^9$
$\beta_x^* = 6.6$ mm
$\gamma\varepsilon_x = 3.6\ 10^{-6}$
$\sigma_z = 0.2$ mm
$\beta_y^* = 0.4$ mm
$9 \cdot 10^9$
200 nm
.17 mm
Y
L
δ_B
δ_B, U_{av}, $L[10^{34}]$, L/δ_B
0.20
0.15
0.10
0.05
0.00
0.1
0.15
0.2
0.25
0.3
$\gamma\varepsilon_y$ $[10^{-6}]$

10

Simulations w. Telnov's Code

4 bunches, 1700 Hz   CLIC   2x 250 $\sigma_z = \beta_y^*$

	N $[10^9]$	σ_x^* [nm]	σ_y^* [nm]	σ_z [mm]	$\mathcal{L}$ $[10^{33}]$	$\mathcal{L}_{98}$ (>98%) $[10^{33}]$	$\mathcal{L}_{98}/\mathcal{L}$ [%]	δ_B	$1/\mathcal{L}\,(\mathcal{L}_{98}/\mathcal{L})^2$
"Old"	6	90	8	0,17	7	1,27	18	0,23	4,36
	idem, but 1,2/-2 σ_z truncation				4,8	1,13	23,5	0,207	3,77
	6	150	9	0,20	2,23	0,994	44,6	0,08	2,25
	idem, but 1,2/-2 σ_z truncation				1,76	0,85	48,3	0,08	2,44
	8	175	9	0,20	3,5	1,43	41	0,1	1,7
	truncated				2,7	1,18	44	0,1	1,9
"New"	8	200	13	0,2	2,5			<0,1 >0,06	

Can we hope to decrease $\gamma\varepsilon_y$

in keeping δ_B constant ($\sim 6\%$)

We tried : one to few corrections (more P.U.)
different scaling
D. F. algorithm
W. F. "

to get $\gamma\varepsilon_y = 2 \cdot 10^{-7}$ with $10\,\mu m$ tol.
on cavities + P.Us

Can we do better:

- Non Dispersive Bumps (G. Parisi)
  efficient in NLC, JLC, SLC
  closed traj. + closed dispersion
  Wake deflections in cavities add to globally counter-balance the wake perturbation
  No dispersive spread
  ↳ true only if Wakes are a perturbation
  In CLIC, strong Wakes
  Bumps never close for all $\Delta p/p$
  → dispersive spread, additional blow-up

- Beam-based correction of wake : (C. Fischer)
  Measure and correct a traj.-difference with "nominal" intensity (full wakes) and "minimum" intensity (no wakes)
  Work being carried on
  Promising : $\gamma\varepsilon_y \simeq 10^{-7}$ after 1 km
  (to be confirmed)

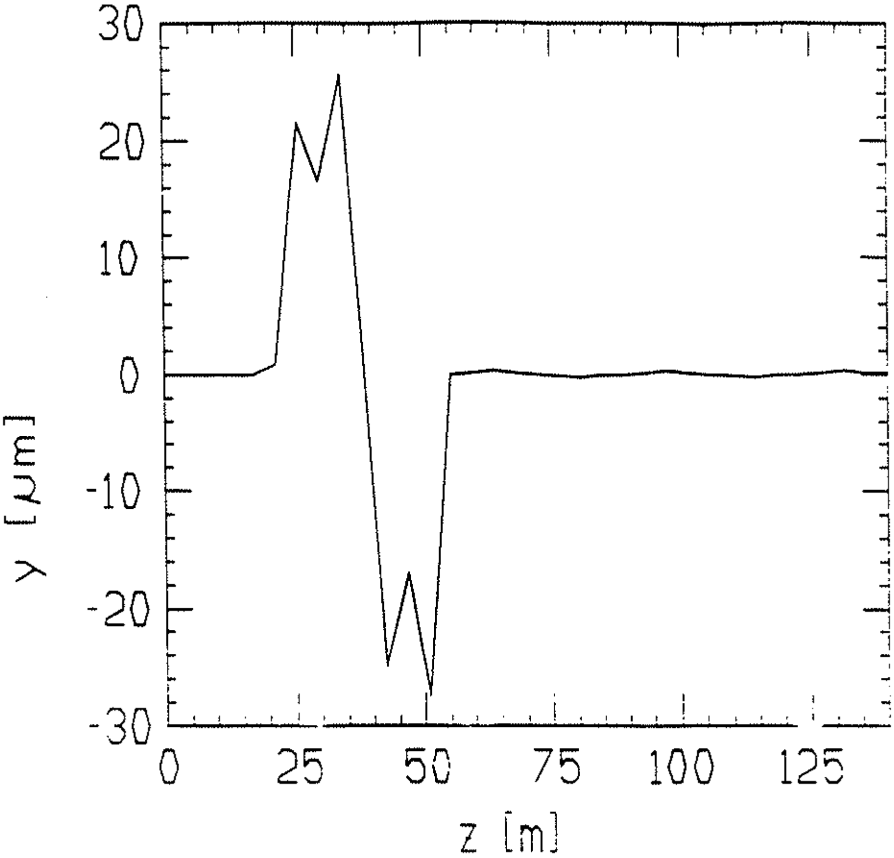
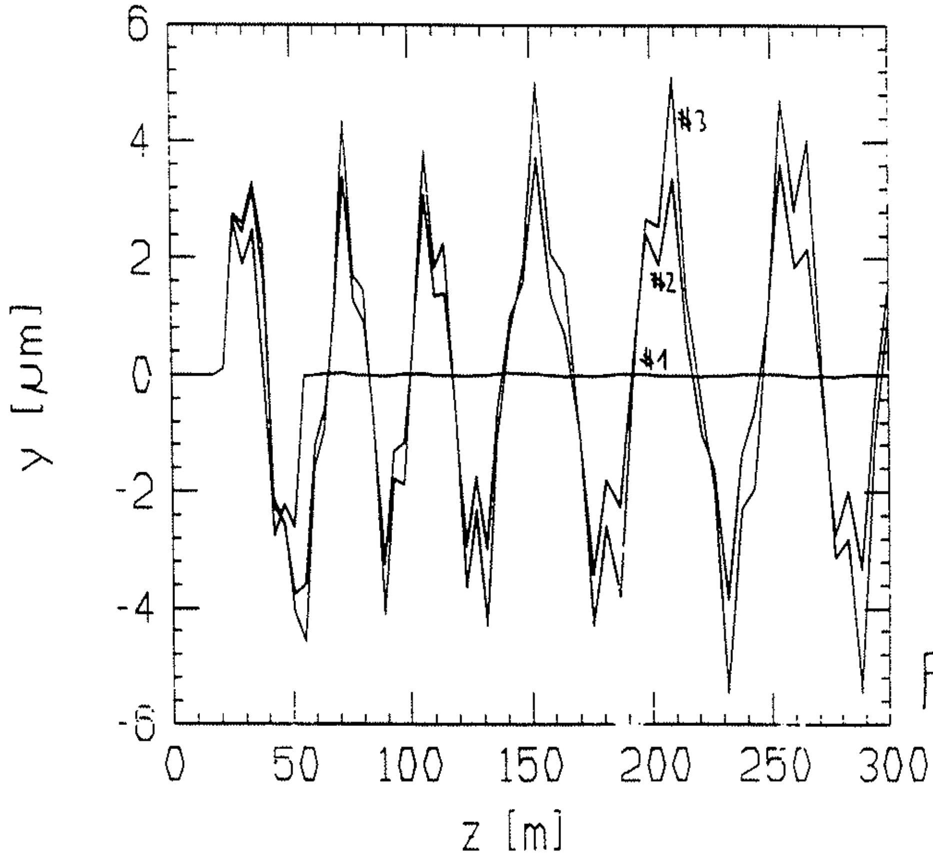


Fig. 5



accel. cavities ON

wake-fields ON

ampl = 10 %

3 slices

Fig. 6

Single Bunch possible Parameters

2 × 250 GeV "Optima" were around

$N = 8\ 10^9$ $\sigma_z = 0.2\,mm$ $\frac{\Delta p}{p} = 0.22\%$

$R \gtrsim 15$ by increasing $\gamma\varepsilon_x$ and/or β_x^*

⇒ e.g. $\gamma\varepsilon_x = 3\ 10^{-6}$ $\beta_x^* = 6.6\,mm$

$\gamma\varepsilon_y = 2\ 10^{-7}$ $\beta_z^* = 0.3\,mm$

$\sigma_z / \beta_y^* \simeq 1/1.5$ to increase η_L

⇒ See List of parameters (formulae)

$\mathcal{L} \simeq .72\ 10^{33}$ $\delta_B = 0.059$

Question for today: how to go beyond 10^{33}

- Increase (double) f_{rep}
  - → costs power, D. Ring limitations ?
  - $\mathcal{L}/P$ value ?
- Run with 4 bunches for instance
- Decrease the Vertical emittance ?
  - Bottom line seems to be 10^{-7}

2 × 500 GeV Grosso modo (to be checked)

$\gamma\varepsilon_x$ could be maintained at $3 \cdot 10^{-6}$

$\gamma\varepsilon_y$ will increase by factor 1,5 to 2.0

⇒ Gain of only ≈ 1,5 on $\mathcal{L}$

Not significant, a factor 10 is missing to get 10^{34}

⟹ Can we avoid multibunch mode?

Some Basic Formulae

"New" Possible

Luminosity

2x 250 GeV CLIC

$$L_0 = \frac{N_b^2 f_{rep}}{4\pi \sigma_x^* \sigma_y^*} H_D(\eta_L) \qquad L = L_0 k_b$$

$\underline{0.72\ 10^{33}}$

$2.9\ 10^{33}$ for $k_b = 4$

$$\eta_L = \frac{2}{\sqrt{\pi}\,\sigma_z} \int_0^{\infty} \frac{\exp(-z^2/\sigma_z^2)}{[\beta_y^{*2} + z^2]^{1/2}} dz$$

η_L ~ 0,93

with $A_y = \frac{\sigma_z}{\beta_y^*}$ ~ 1/1,5

idem from A_x, but negligible ~ 0,03

Disruption Parameters

$$D_x = \frac{2 r_e N_b \sigma_z}{\gamma \sigma_x^* (\sigma_x^* + \sigma_y^*)}$$ $\underline{0.43}$

$$D_y = \frac{2 r_e N_b \sigma_z}{\gamma \sigma_y^* (\sigma_x^* + \sigma_y^*)}$$ 7,8

Pinch effect, Effective sizes

H_{Dx} — $\underline{1,2}$

$$H_{D(x,y)} = 1 + D^{1/4} \frac{D^3}{1+D^3} \left\{ \ln(\sqrt{D}+1) + 2 \ln \frac{0.8}{A} \right\}$$

H_{Dy} — 1,56

$$\overline{\sigma_x}^* = \frac{\sigma_x^*}{H_{D_x}^{1/2}}$$ ~ $\underline{170}$ nm

$$\overline{\sigma_y}^* = \frac{\sigma_y^*}{H_{D_y}} f(R) \qquad R = \sigma_x^* / \sigma_y^*$$ 8,7 nm

Luminosity enhancement

$$H_D = H_{D_x}^{1/2} \; H_{D_y}^{f(R)}$$ **1.87**

$$f(R) = \frac{1 + 2R^3}{6R^3}$$ 0,333

Critical γ-to-particle E-ratio

$$\Upsilon = \frac{5}{6} \frac{r_e^2 \, \gamma \, N_b}{\alpha \, \sigma_z \, (\bar{\sigma}_x^* + \bar{\sigma}_y^*)}$$ **0,10**

Average E-loss per unit time

$$\left\langle -\frac{1}{E}\frac{dE}{dt} \right\rangle = \frac{2}{3} \frac{\alpha}{\lambda_e} \frac{\Upsilon^2}{\gamma} \, U_1(\Upsilon)$$ 158

$$U_1(\Upsilon) \approx \frac{1}{\left[1 + (1.5\,\Upsilon)^{2/3}\right]^2} \overset{\text{also}}{=} H_\Upsilon$$ 0.6

of emitted γ and relative E-loss

$$n_\gamma \cong 2{,}54 \, \frac{\alpha \, \sigma_z \, \Upsilon}{\lambda_e \gamma} \, U_0(\Upsilon)$$ **1,8**

$$U_0(\Upsilon) = \frac{1}{(1 + \Upsilon^{2/3})^{1/2}}$$ 0,91

$$\delta_B = \left\langle -\frac{\Delta E}{E} \right\rangle \approx 1{,}24 \, \frac{\alpha \, \sigma_z \, \Upsilon^2}{\lambda_e \gamma} \, U_1(\Upsilon)$$ **0,059**

Reference: Beam-beam Phenomena in LC
K. Yokoya, P. Chen, 1990
Lecture Notes in Physics

(Ian Wilson)

Introduction to Multibunching

Let's look first at single bunches

The maximum charge per bunch is limited by either
(a) δ_B parameter (beamstrahlung induced energy spread),
(b) W_T transverse wakefields,
(c) ΔE_b single bunch energy spread.

This charge determines
(a) RF to beam energy transfer efficiency,
(b) luminosity per bunch crossing.

From this we get two figures of merit for linear colliders.
(a) L/P, the luminsoity to power ratio,
(b) δ_B
Necessary condition : absolute L must of course be acheived
(Limitations : total power consumption, repetition rate, etc)

Present CLIC published parameters for 0.5 TeV c.m.
(Greg Loew LC93 - Pisin Chen Analytic Formulae)

N 6×10^9
δ_B 36%
L 2.2×10^{33}
P 170 MW

Broad consensus among experimental physicists $\delta_B \approx 5\%$
Can be achieved roughly by reducing charge per bunch by 2
Result - L/P down by a factor of at least 4

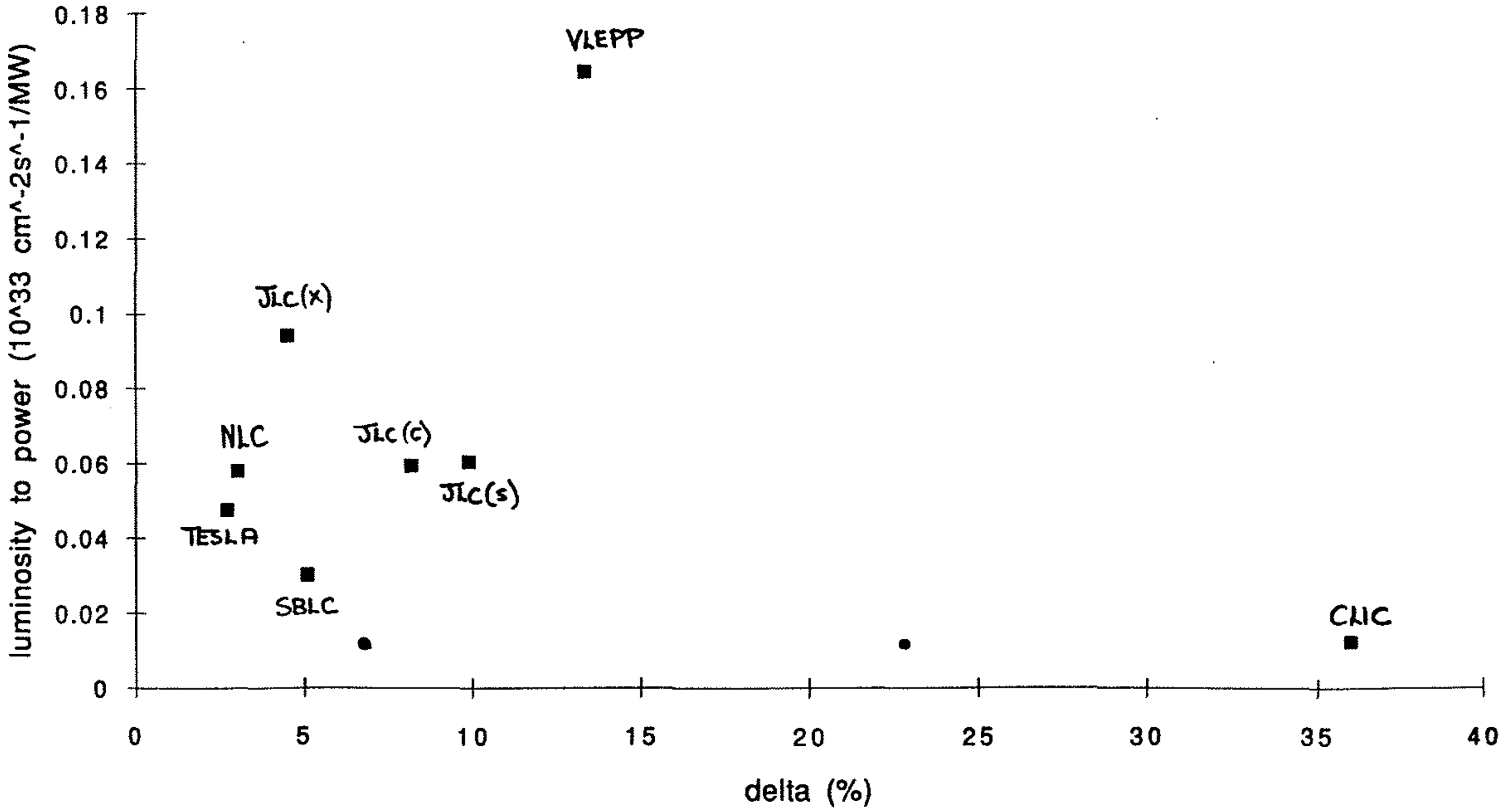
Possible remedies to maintain same absolute L and P
Certainly don't advocate first two (!) mentioned in passing

(i) reduce gradient by 4 - increase length by 4 - increase f_r by 4
(ii) increase R/Q by 4 (4 f_{RF} or drastic reduction in iris dia)
(iii) energy re-circulation (however only brings at most factor 2)
(iv) multi-bunching

Very recent news - a δ_B of 6% has been achieved without reducing the charge per bunch by re-optimising the final focus parameters albeit with a resulting lower L - so multiple bunches may still be an option rather than a necessity but still should be looked at

LC 93

Luminosity to power ratio versus delta



The question is - can CLIC improve its performance by operating in a multi-bunch mode ?

All but one of other LC studies have multi-bunching & have at least on paper higher L & lower δ_B values

Have to understand why the others multi-bunch
See to what extent if at all their reasoning is applicable to CLIC

Reason SBLC adopts multibunching - very clear.
Not an option - fundamental part of their design
At 3 GHz stored energy is high, a single bunch of 2.1×10^{10} takes out only a very small fraction of this energy

Comparison with CLIC for example
relative beam induced voltages for single bunches,
SBLC/CLIC(nominal)=(0.5%*17 MV/m)/(2.5%*78 MV/m) = 0.04

To obtain an acceptable L/P ratio SBLC choose
• low accelerating gradient
• multibunching (n_b=172)

Basically low frequency colliders which are limited in charge per bunch must multibunch to stay competitive

For CLIC at 30 GHz the motivation to multibunch is less obvious.

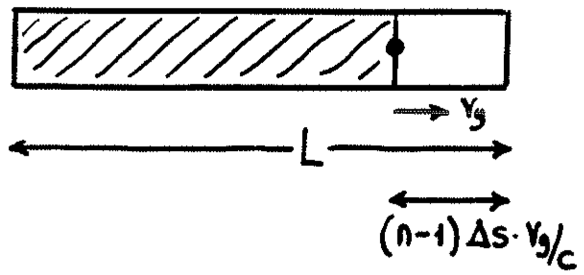
Two basic types of multibunching:

• short bunch trains << structure fill time
The idea here is to improve the L/P ratio by extracting a bit more energy from the fill by adding a few extra bunches since 90% of the energy is left in the section after passage of the first bunch.

• long bunch trains >> fill time
In this approach the trains have many bunches and are several fill times long. In the limit one can have 100% beam loading with low charges per bunch and no energy spread.

Multi-bunch Energy Compensation

Simplest scheme minimises energy spread by having section only partially filled when 1st bunch passes but completely filled when last bunch passes



There are two field contributions to be considered

(i) RF driving voltage
(ii) Beam-induced voltage

If you do analysis assuming

(i) n bunches equally spaced by distance Δs or time $\Delta t = \Delta s/c$
(ii) constant RF gradient E_0
(iii) no attenuation of beam-induced fields

we find the following

(not new - similar analyses by R. Ruth, K. Thomson, D. Farkas)

1st Bunch of n bunches sees a voltage

$$E_o\left[L-(n-1)\Delta s\cdot V_g/c\right] - 2k'qL(1/2)$$

RF driving voltage — Beam-induced voltage

2ND Bunch

$$E_o\left[L-(n-2)\Delta s\cdot V_g/c\right] - 2k'q\left[L-\Delta s\, V_g/c\right] - 2k'qL(1/2)$$

RF driving voltage — remaining beam induced voltage of 1ST — beam-induced voltage of 2ND

b th Bunch

$$E_o\left[L-(n-b)\Delta s\cdot V_g/c\right] - (b-1/2)2k'qL + 2k'q\Delta s\cdot V_g/c\cdot \frac{b}{2}(b-1)$$

Last bunch

$$E_oL - (n-1/2)2k'qL + 2k'q\Delta s\cdot V_g/c\cdot n(n-1)/2$$

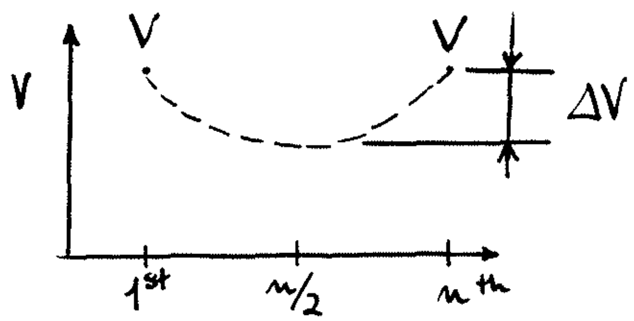
Now use $V_1 = V_n$ as energy compensation condition

$$\boxed{\frac{\Delta s}{L} = \frac{2k'q}{\left[E_o + n.k'q\right] V_g/c}}$$

There is an energy "sag" between the first & last bunch

Define $\Delta V = V_{(b=n)} - V_{(b=n/2)}$

$$\boxed{\frac{\Delta V}{V} = \frac{E_o\cdot n/2\cdot\Delta s\cdot V_g/c - nk'qL + 2k'q\Delta s\cdot V_g/c\cdot n(3n-2)/8}{E_oL - E_o(n-1)\Delta s\cdot V_g/c - k'qL}}$$



CLIC Parameters

$q = 4.24 \times 10^{9} \times 1.6 \times 10^{-19}$ C

$k' = 1.25 \times 10^{15}$ V/Cm

$E_0 = 80$ MV/m

$V_g/c = 6.3\%$

$n = 4$

$L = 0.273$ m

$\Delta s = 0.09$ m

$\equiv 9$ RF Cycles

$\equiv 0.3$ ns

$\frac{\Delta V}{V} = 0.13\%$ $(\pm 0.065\%)$

(FF energy acceptance $\pm 0.23\%$)

Will see in next section that 0.3 ns is very short time in which to attenuate transverse wakefield of 1st bunch to a level that is acceptable for following bunches

Short train multibunching.

As an example - analysed the case of four bunches with $\sqrt{2}$ reduced charge (4.2×10^9) the idea being to gain a factor of 2 in L and to reduce δ_B by 2.

• Beam loading compensation
Bunch-to-bunch energy spread has to be maintained within final focus acceptance of $\pm$ 0.5% (see beam loading analysis)

• Transverse wakefield levels
Beam tracking simulations with bunches of 4.2×10^9 show that the wakefield induced by the lead bunch must be reduced by a factor $\approx$ 250 by the time the following bunch comes along
This value varies linearly with charge.

• Transverse wakefield reduction

Excessively tight tolerances exclude solutions with following bunches sitting at zero crossings of (i) 38 GHz (approx) dipole wave (ii) envelope produced by beating two dipole frequencies

Cannot use our present CI structures
Obliged to go to damped and/or detuned structures

Let's look first at detuning - basic idea is to create a spread in the frequencies of the first (most damaging) dipole mode so that wakefields of individual cells decohere after some time and a substantial reduction of the total wakefield envelope is obtained.

The net wake in time is the Fourier transform of the frequency distribution. Gaussian frequency distributions are favoured because they transform to a Gaussian in the time domain. In reality however distributions have to be truncated introducing some "sin x / x" component in the time response.

For short train multibunching to be effective - require time between bunches to be short (0.3ns for easiest beam loading compensation) - determined by how fast the envelope of wakefield is reduced - this determined by total bandwidth of frequency distribution .

For 0.3 ns bunch spacing require Δf = 36%
this is much more than can be achieved.

Upper and lower detuning limits impose $\Delta f_{max} \approx 10\%$.
Lower limit - $2a_{min} = 3.5$mm - machining capability.
Upper limit - $2a_{min} = 5.0$mm - beyond sections become over-moded ! (lower edge of f_1 pass-band reaches f_0)

$\Delta f_{max} = 3.9$ GHz = 10.4%.

As a first step - continuous distributions have been used in the analysis - assumes we have infinite number of cells.

With $\Delta f_{max} = 10.4\%$ can achieve required attenuation factors but only for much longer bunch spacings (see figure).

Δf (%)	σ (%)	Attn	Δt (ns)
10.4	1.56	1000	1.0
10.4	2.0	200	0.8

Forced to $\Delta t \approx 1$ ns.

Above results however assume continuous spectrum
What is the effect of discreteness ?

Spectrum	n_c	Δf (%)	σ (%)	Attn
Continuous	100	10.4	1.56	1000
Discrete	101	(7.9)	1.56	100
Discrete	1001	(8.9)	1.56	1000

Discreteness with n_c=101 increases wake from 0.001 to 0.01.
Using n_c=1001 reduces wake to 0.001 level again.
Intuitively - baseline level $\approx 1/n_c$

Couplers must be included in distribution otherwise wakefield reduction limit $\approx 2/n_c$. Difficult - not circularly symmetric and both polarizations must be included in the frequency distribution! Same comment applies to RFQs.

Now let's look at the requirements for damped structures

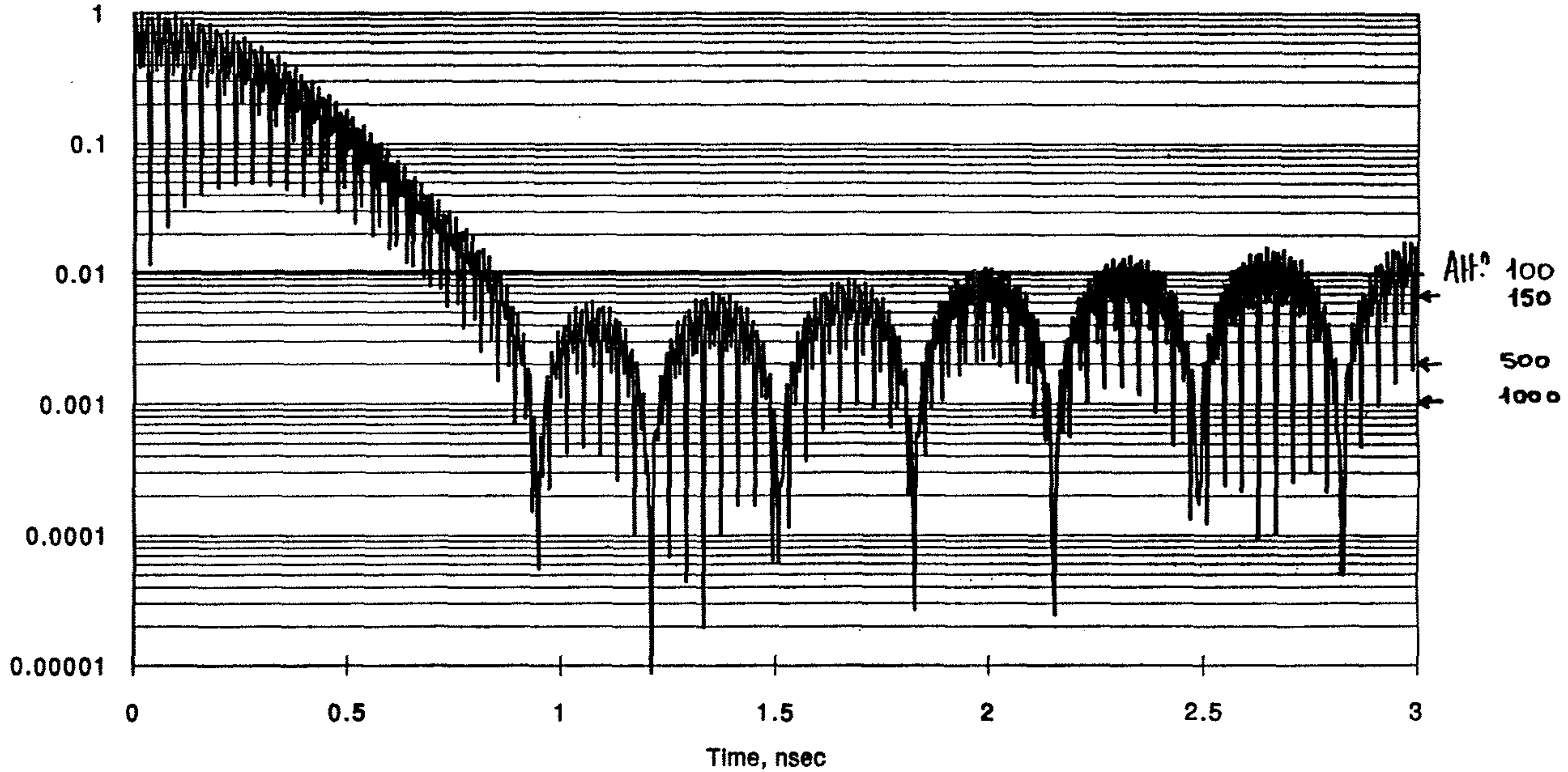
Damping by a factor 250 in field in 0.3 ns requires a Q=6 !!
$\Delta t \approx$ 1ns requires a Q=20.

Attn	Δt (ns)	n_{RF}	Q
50	0.33 (1)	10 (30)	8 (24)
100	0.33 (1)	10 (30)	7 (20)
250	0.33 (1)	10 (30)	6 (17)

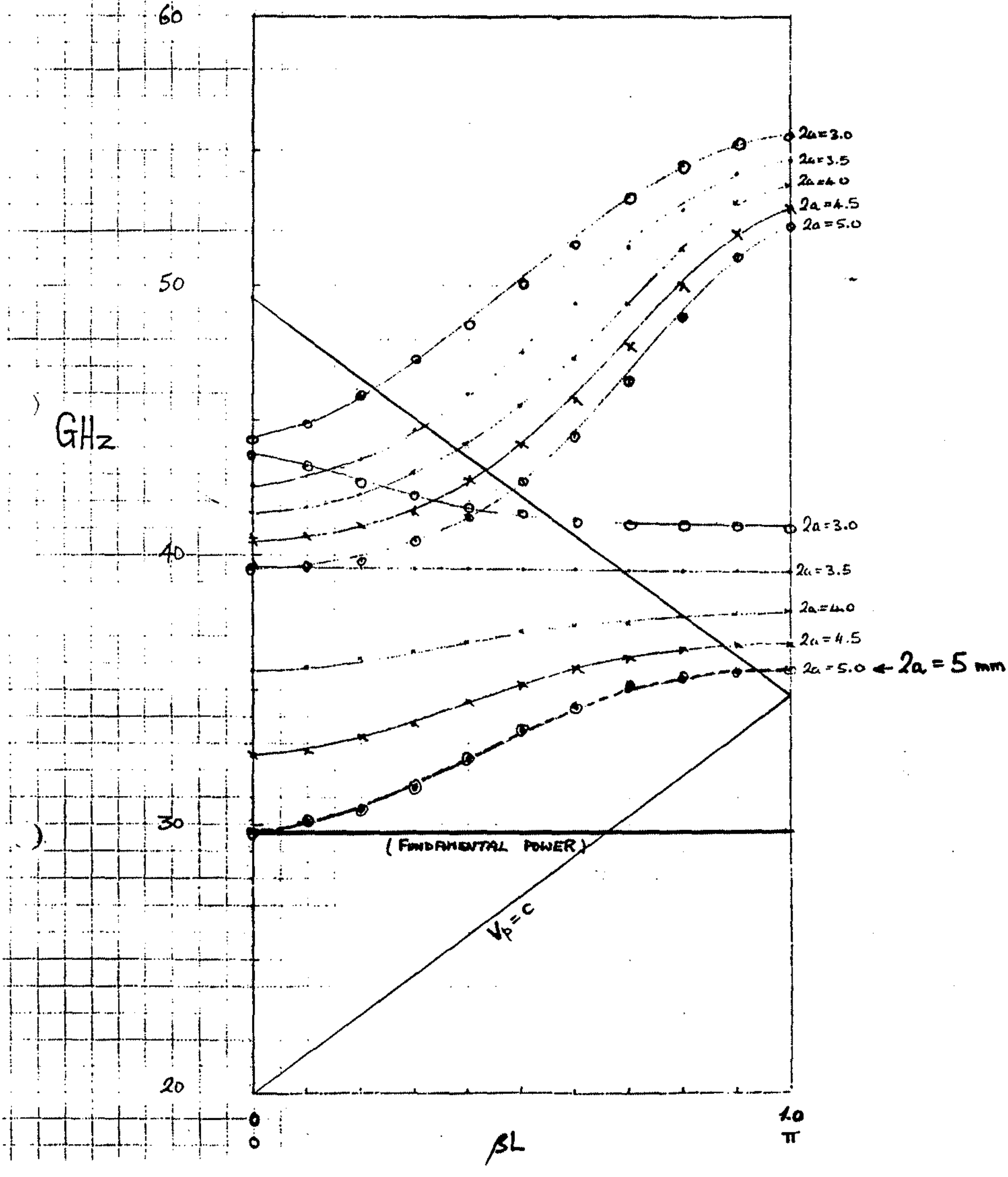
Δf σ

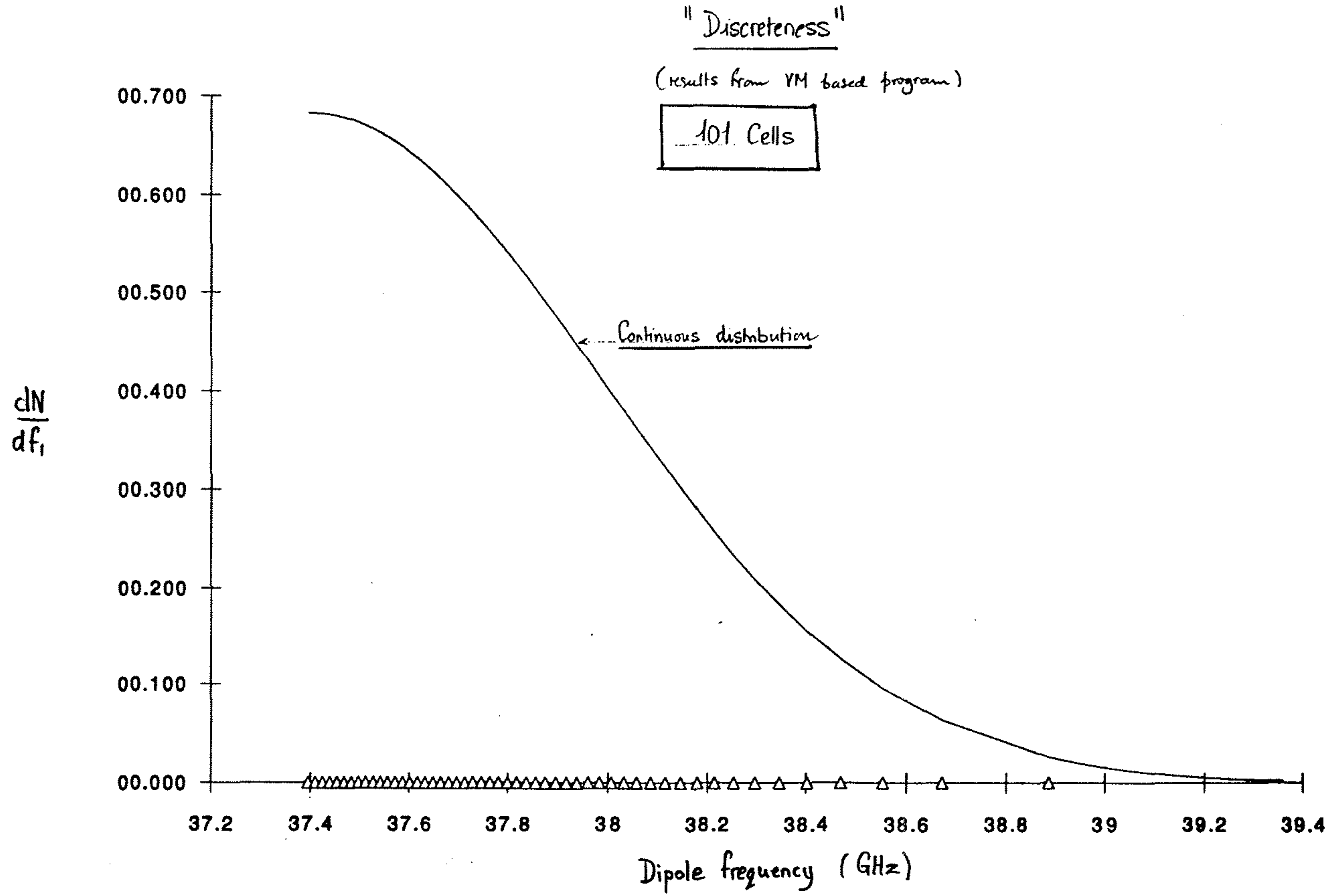
101 cells, 2.95, .58 (nom. 3.89, .58)

achieve 10.4% 1.56%



Dispersion curves obtained from TRANSV for square cornered geometries using dimensions obtained from URMEL with rounded corners for the fundamental 2π/3 accel. mode




"Discreteness"
(results from YM based program)
101 Cells
Continuous distribution
00.700
00.600
00.500
00.400
00.300
00.200
00.100
00.000
dN/df1
37.2
37.4
37.6
37.8
38
38.2
38.4
38.6
38.8
39
39.2
39.4
Dipole frequency (GHz)

• What about power ?

Using partial filling scheme with Δt=1ns and $n_b = 4$ have 3ns/11ns reduction in total accelerating field per section requires $1/(1-{}^{3}/_{11})^2 = 1.89$ increase in P to maintain energy gain per section const. (1.94 in fact since $R'_{gauss} \approx 0.95\ R'_{CI}$)

[Main linac average gradient higher by factor $1/(1-{}^{3}/_{11})$
$\langle E_4\rangle = 1.37 \langle E_1\rangle = 110$ MV/m]
q/bunch of drive beam higher by same factor - must also incidently also increase the drive beam energy (energy lost $\alpha\ q^2$)

Δt	P	<E> & q
0.3	1.19	1.09
1	1.89	1.37

• Luminosity gain (or loss)
Main question now - what fraction of the single bunch charge can be handled in multibunch mode ?
Determines whether you gain or lose luminosity.
example: if N goes to N/2 in multibunch with nb=4, $L_4/L_1=1$

Now let's go back to our beam simulation results

Simulation : A=250, N= 4.2×10^9 (two bunches)
- W_t directly proportional to charge
- For n_b bunches - max wake increased by $\sqrt{(n_b-1)}$

Using only detuning - cannot do better than A=100

For 4 bunches with A=100, N must therefore be reduced to $(4.2/2.5/\sqrt{3})\times10^9 = 1\times10^9$
$N_1/N_4 = 6 \Rightarrow L_4/L_1 \approx 4/36 = 1/9$

Very recently detected error in simulation program - maybe more realistic value for N= 4.2×10^9 is A=50-100 (needs checking!)

Let's be very optimistic and take A=50
$N_4 = (4.2*2/\sqrt{3})\times10^9 = 4.8\times10^9$
$N_1/N_4 = 1.25 \Rightarrow L_4/L_1 \approx 4/1.56 = 2.6$

• Luminosity to power ratio L/P

n_b=4, Δt=1ns

N_1/N_4	L_4/L_1	P_4/P_1	$(L/P)_{4/1}$
6	1/9	1.89	1/17
√2	2	1.89	1.06
1	4	1.89	2.1

n_b=4, Δt=0.3ns

N_1/N_4	L_4/L_1	P_4/P_1	$(L/P)_{4/1}$
6	1/9	1.19	1/11
√2	2	1.19	1.7
1	4	1.19	3.4

Very important at this stage to have an accurate value for A

Scaling from NLC (require A=100 at short distances)

factor of 18 up - $(30/11.4)^3$
factor of 15 down - CLIC tolerates 15 x emittance blow-up
(NLC 1⇒ 1.2 : CLIC 1 ⇒ 4)

would suggest A at least 100

• Additional remarks

For Δt > 0.3ns simple energy compensation scheme no longer works - must now taper input power pulse during time of bunch passage because rate at which energy flows into section is too fast to compensate beam loading - situation aggravated further by reducing charge per bunch.

Schemes and difficulties of modulating power pulse - Lars.

(W. Wuensch)

LONG TRAIN MULTIBUNCHING

13-10-94

Trains have many bunches and are several fill times long. Potentially very efficient.

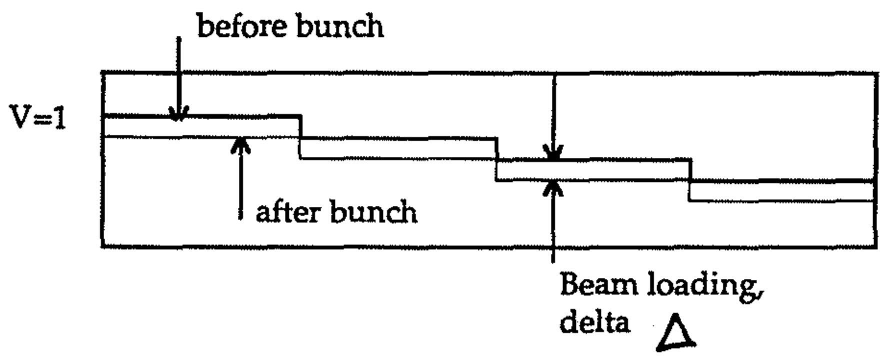
How does long train multibunching bring efficiency?

Consider the question: What does the field in an accelerating section look like with multibunching?

(Ignore transverse wakefields, assume no losses in a constant impedance accelerating section)

Consider the equilibrium condition first so we can make all arguments refer to a single fill time.

The voltage in an accelerating section,



Voltage flowing out of the structure is down by $n\Delta$. The lower the voltage flowing out, the better the RF to beam energy transfer.

By adding more bunches per fill time - energy transfer can go to 100%

- OR -

Increase the charge per bunch and get 100% energy transfer.

Multibunch advantage: charge per bunch is lower by a factor n.

- Energy spread within a bunch is down by n (for the same bunch length and level of beam shaping gymnastics)
- Beamstahlung induced energy spread is down by roughly n^2.

With 100% RF to beam energy transfer - no advantage to using higher frequencies (no thrown away power to minimize). Of course there are peak power, gradient considerations etc.

BEAM LOADING: Average voltage in a section just before the arrival of a bunch is down by,

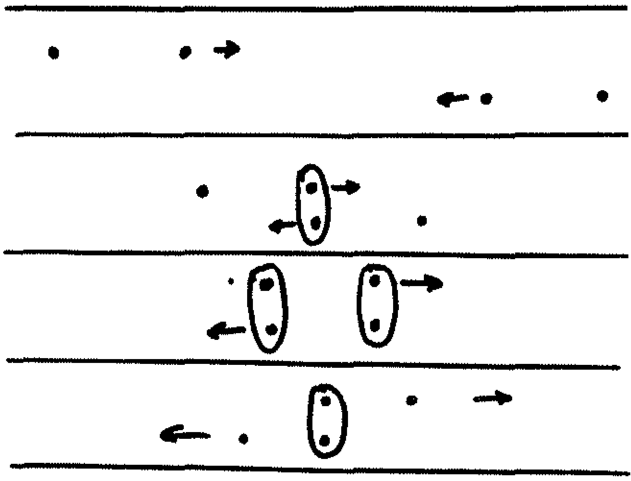
$$V_{drop} = \frac{(n-1)\Delta}{2}$$

The power in must be raised by adding the voltage drop to maintain average accelerating gradient,

$$P' = \left(1 + \frac{(n-1)\Delta}{2}\right)^2$$

The luminosity is increased by only a factor n when multibunching (most 'collisions' are occurring outside the final focus).

$$\left(\frac{L}{P}\right)' = n\left(1+\frac{(n-1)\Delta}{2}\right)^{-2}$$



Maximum at approximately,

$$n = \frac{2}{\Delta}$$

Input voltage of 2 and an output voltage of 0 (100% beam loading)! The luminosity to power improvement is,

$$\left(\frac{L}{P}\right)_{\max}' = \frac{1}{2\Delta}$$

Most improvement when the beam loading per bunch is low.

For CLIC, n per fill time is limited to 12 because of the minimum bunch spacing of 1 nsec determined by maximum detuning.

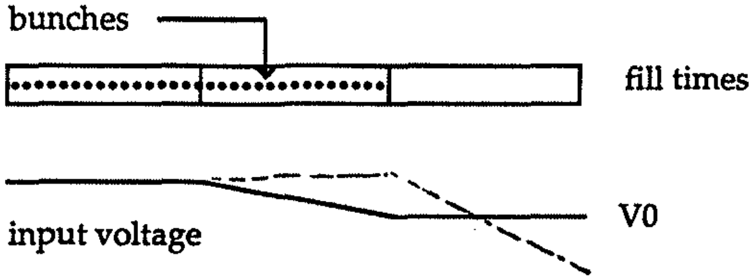
Bunch population	$6x10^9$	$3x10^9$	$6x10^9$
Δ	.025	.0125	.025
time between bunches	1 nsec	1 nsec	.3 nsec
bunches per fill	12	12	36
L/P improvement	9.2	10.5	17

L/P improvement realized during equilibrium.

The power during the initial fill time is always wasted.

The lost fill time is directly an inefficiency.

Need to ramp voltage to compensate for varying beam loading or dump beam with wrong energy.



For CLIC with 60 bunches (RF power for 6 fill times) 1/6 of the power is thrown away. This brings us down to

Bunch population	$6x10^9$	$3x10^9$
L/P improvement	7.7	8.7

MULTIBUNCHING PARAMETERS

	DLC	NLC	CLIC
RF pulse length to section	2800 nsec	250 nsec	
Section fill time	790 nsec	100 nsec	12 nsec
Number of fills	3.5	2.5	
Number of bunches per train	172	90	
Time between bunches	11 nsec	1.4 nsec	1 nsec
Number of bunches/fill	70	60	12
Fractional voltage drop per bunch	.005	.004	.025/.0125
Charge per bunch	21×10^9,	6.5×10^9	$6/3 \times 10^9$
Gradient [MV/m]	17	38	~~80~~ 78
unloaded	(21)	(50)	

DETUNING

Way of getting the wakefield down quickly and that is why we used it for short bunch trains.

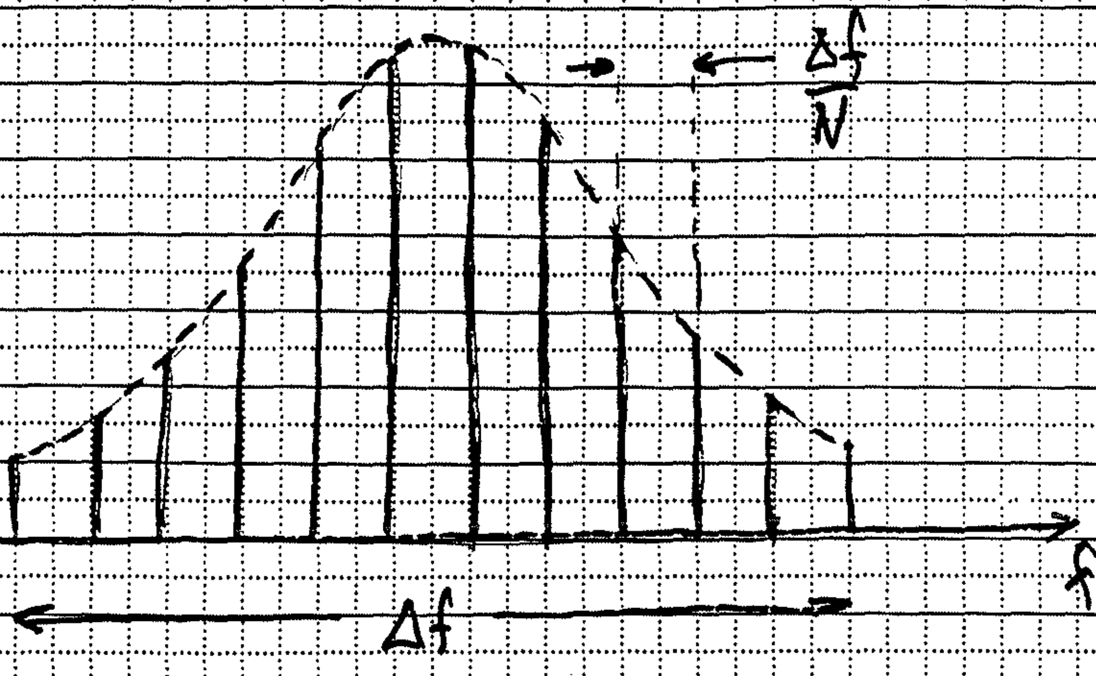
Wakefield rises again in a time typical of the inverse of the frequency spacing between cells. Limits the number of bunches which can be used and motivates denser frequency distributions by detuning over many sections.
Number of bunches is about 1/2 to 2/3 the number of cells in the frequency distribution (the bunch spacing is $1/\Delta f$ (width of the frequency distribution) and the time the wake repeats its maximum is 1/frequency spacing=$N/\Delta f$.

State of the art detuning calculations, (includes the effects of coupling between cells): double band model. Detuned X-band section tested at ASSET .

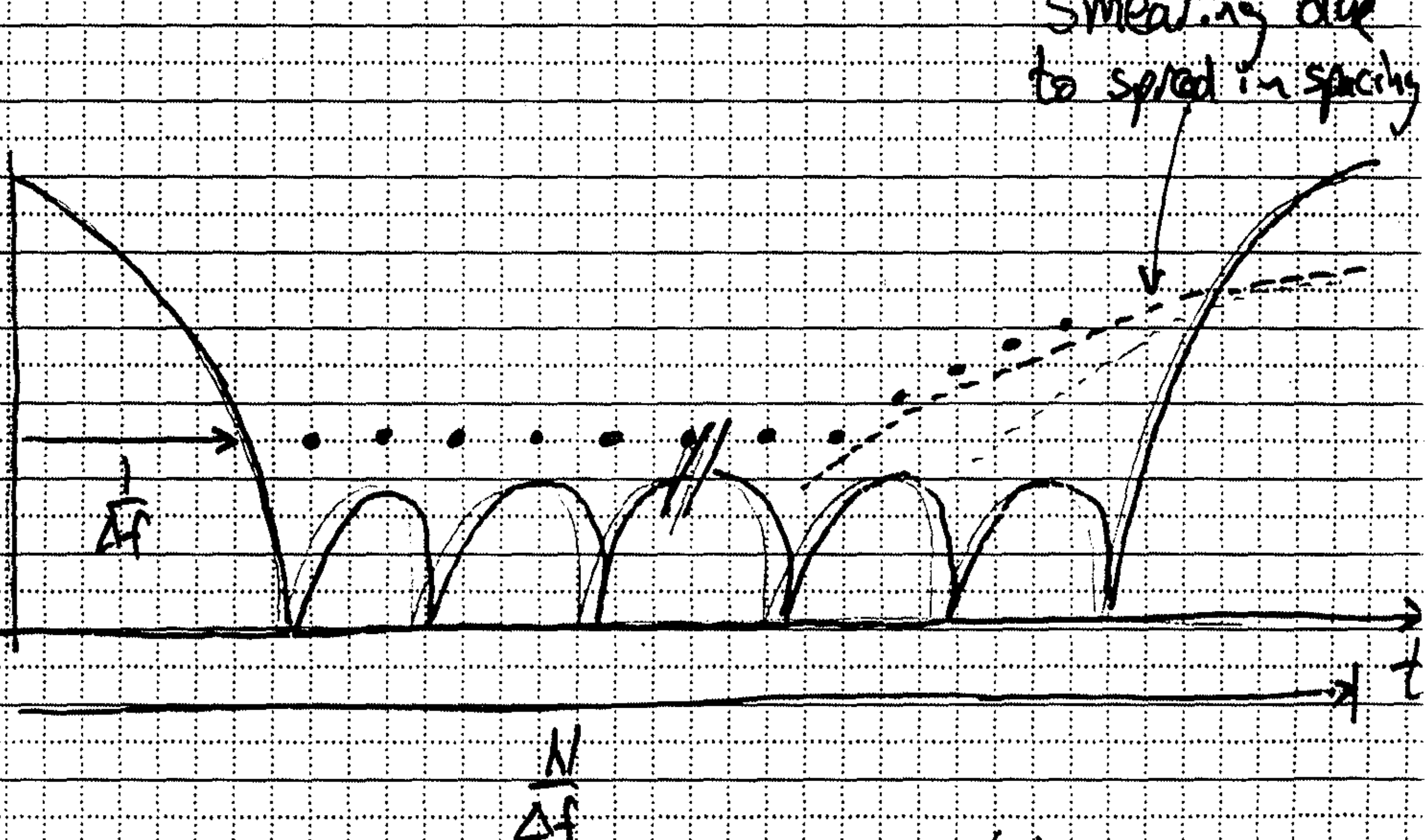
Varying iris thickness detunes all higher deflecting modes.
ASSET section - contribution from all higher deflecting modes was 1%, would have been 10% without iris thickness variations.
The section achieved a total wakefield reduction of the order 2-3%.

Detuning does not seem to drastically complicate accelerating section design, but the achievable performance seems to be limited.

Frequency Distribution



Wakefield



DAMPING

Realistic levels of damping produce slower wakefield reductions than detuning but the wakefield stays down.

One class of damping uses waveguide couplings to take deflecting mode power out. There are various schemes with 2, 3 and 4 outputs per cell. Both polarizations of the fundamental dipole mode must be taken out. Theoretically, low Q's can be achieved (like 10 or even less on the computer).

A choke mode, Shintake, structure may be a possibility as well. Are total residual wakefields low enough from damped cavities? Are Q's low enough for enough deflecting modes?

Damping inevitably complicates fabrication and loads are a problem.

THE SUM FROM MANY BUNCHES

Wakes from successive bunches add incoherently - an additional factor of $\sqrt{n}$ in wakefield reduction is required at long times with many bunches.

Assume CLIC has 90 bunches like NLC, wakefield reductions need to be of the order of 500-10,000 at longer times.

NLC has frequency distributions over 4 sections. Tolerances become quite severe because the frequency spacing is small.

They reconsider detuning over a single section + medium damping (like DLC). Detuning is used to get the wakefields down fast, and damping to keep going down.

THE BOTTOM LINE

Multibunching with 6×10^9 bunch population we could get a L/P improvement of a factor of 8. What do we really think we could do?

- We don't want to detune over more than one section + we have the effects higher modes at the 1% level with iris thickness variations so the best wakefield attenuation is,

$$\frac{1}{\sqrt{\frac{1}{86^2}+\frac{1}{100^2}}}=65$$

- With past beam simulations this means a maximum bunch charge of $4.2 \times 65/250 \times 10^9 = 1.1 \times 10^9$. Performance might be better than that, need to do beam simulations.

- reoptimise $\sigma/\Delta f$ for less attenuation so we can have a bunch spacing of .8 nsec, 14 bunches per fill.

- *assume* we can put in medium damping so we can have longer bunch trains. For 60 bunches, $\alpha=65$,

$$Q=\frac{\omega_0 t}{2\ln\alpha}\frac{1}{\sqrt{n}}=160$$

NLC detuning/damping $Q \approx 300\text{-}500$.

- we get a luminosity to power ratio compared to single bunch ($6x10^9$),

$$\frac{L}{P} = \left(\frac{1.1}{6}\right)^2 (13)(.83) = .36$$

Lousy L/P but great δ parameter.

Single bunch alternative with same L/P is

$$N = 6 \times 10^9 \sqrt{.36} = 3.6 \times 10^9$$

δ parameter is not so bad.

(A. Millich)

Wakefields excited in the 30 GHz CLIC Disk Loaded Structure by a train of four equidistant bunches.

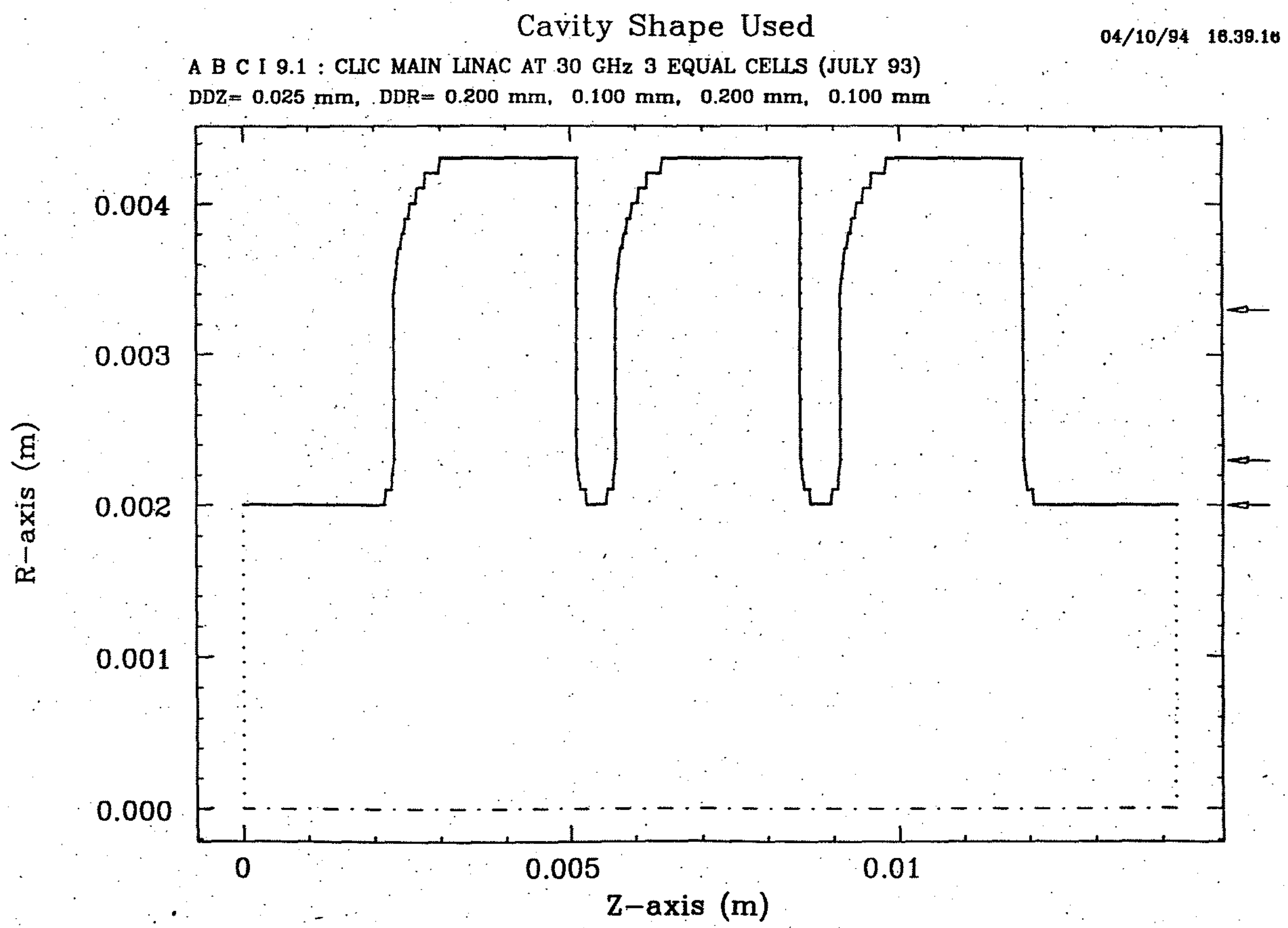
Single bunch results from ABCI.

We have used the code ABCI to repeat the computations with the single bunch with the aim of establishing a reference point for the multibunch calculations. Fig 1 shows the CLIC DLW geometry used in ABCI. Fig. 2 shows the longitudinal wake potential together with the bunch envelope. The bunch length is $\sigma = 0.2$ mm and the charge is 1 pC.

The peak negative wake potential is 35.29 V/pC

The longitudinal loss factor is 25.4 V/pC for three cells or 2.54 KV/pC per meter of structure.

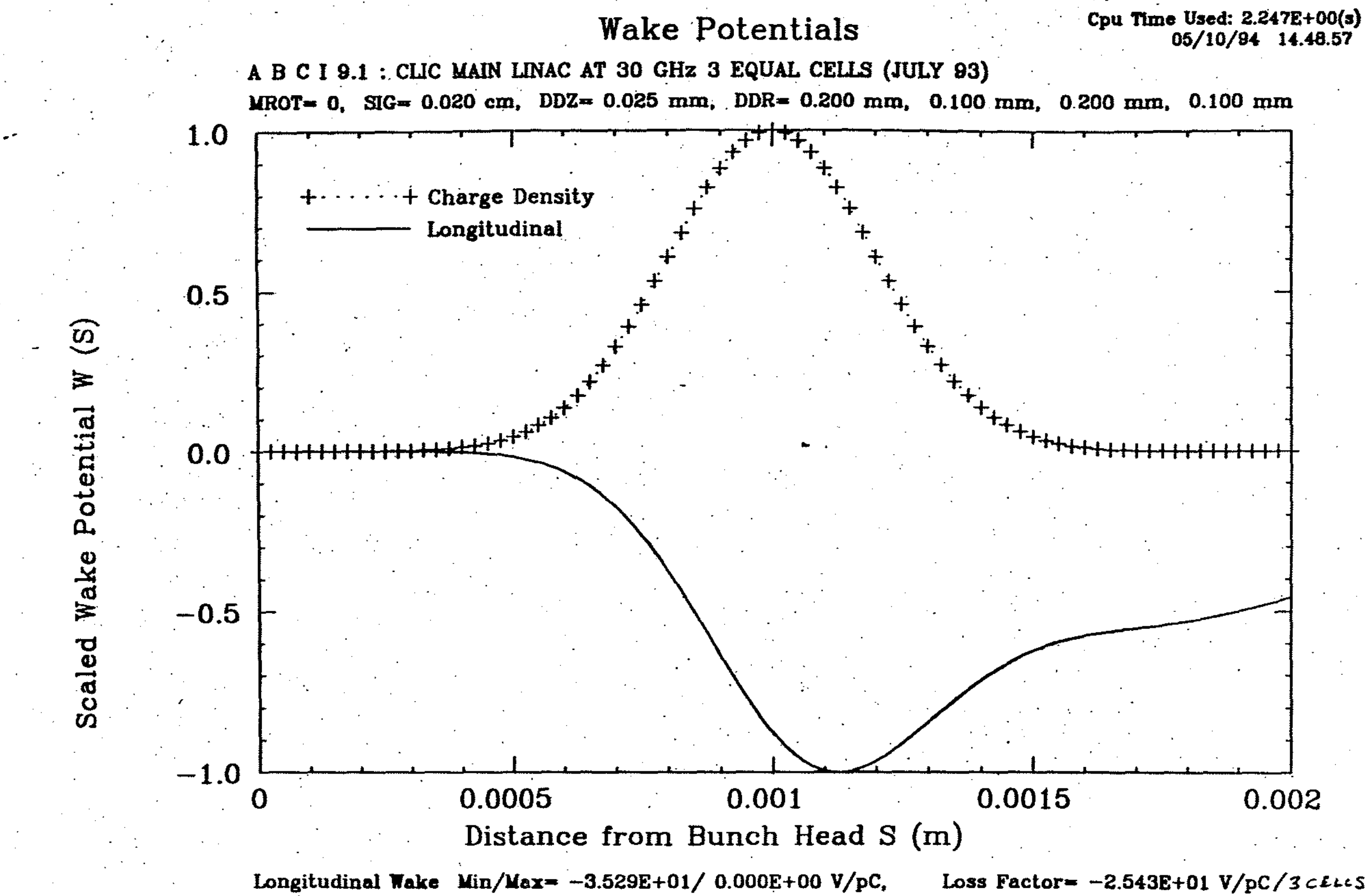
The transverse wake potential for the single bunch is shown in Fig. 3. The transverse kick factor is 3.35 V/pC per mm transverse displacement, or 335 V/pC/mm per meter of structure.



Cavity Shape Used
04/10/94 16.39.16
A B C I 9.1 : CLIC MAIN LINAC AT 30 GHz 3 EQUAL CELLS (JULY 93)
DDZ= 0.025 mm, DDR= 0.200 mm, 0.100 mm, 0.200 mm, 0.100 mm
R−axis (m)
0.004
0.003
0.002
0.001
0.000
0
0.005
0.01
Z−axis (m)

FIG. 1

M



Wake Potentials
Cpu Time Used: 2.247E+00(s)
05/10/94 14.48.57
A B C I 9.1 : CLIC MAIN LINAC AT 30 GHz 3 EQUAL CELLS (JULY 93)
MROT= 0, SIG= 0.020 cm, DDZ= 0.025 mm, DDR= 0.200 mm, 0.100 mm, 0.200 mm, 0.100 mm
Charge Density
Longitudinal
Scaled Wake Potential W (S)
1.0
0.5
0.0
−0.5
−1.0
0
0.0005
0.001
0.0015
0.002
Distance from Bunch Head S (m)
Longitudinal Wake Min/Max= −3.529E+01/ 0.000E+00 V/pC, Loss Factor= −2.543E+01 V/pC/3 CELLS

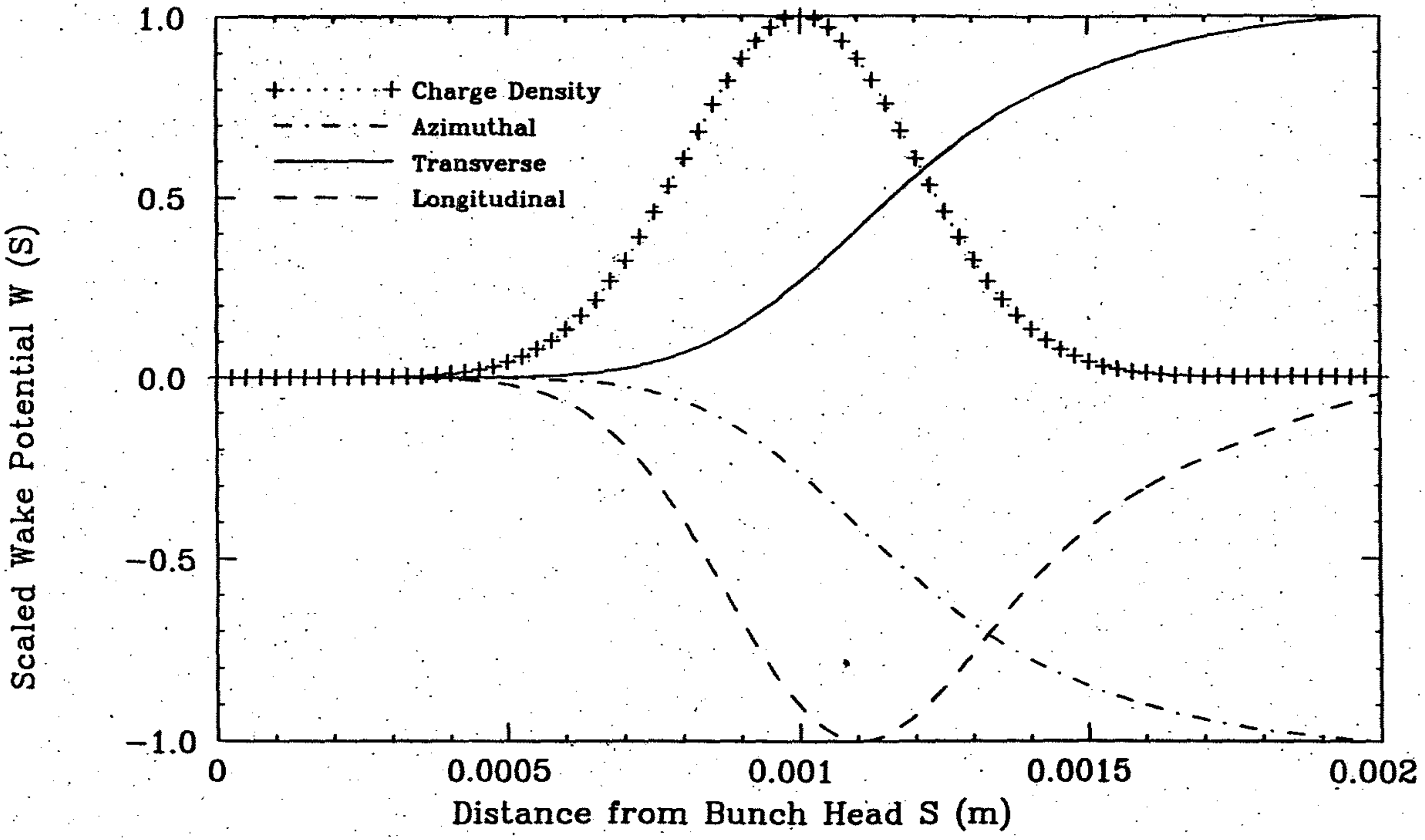
FIG. 2

Cpu Time Used: 4.401E+00(s)
05/10/94 14.48.57

Wake Potentials

A B C I 9.1 : CLIC MAIN LINAC AT 30 GHz 3 EQUAL CELLS (JULY 93)

MROT= 1, SIG= 0.020 cm, DDZ= 0.025 mm, DDR= 0.200 mm, 0.100 mm, 0.200 mm, 0.100 mm



Azimuthal Wake Min/Max= −1.105E+04/ 9.078E−03 V/pC/m, Loss Factor= −3.357E+03 V/pC/m
Transverse Wake Min/Max= 0.000E+00/ 1.103E+04 V/pC/m, Loss Factor= 3.351E+03 V/pC/m = 3.35 V/pC/m
Longitudinal Wake Min/Max= −1.641E+07/ 0.000E+00 V/pC/m², Loss Factor= −1.178E+07 V/pC/m²

FIG. 3

Longitudinal wakes in multibunch mode:

In the simulation we have used a train of four gaussian bunches separated by one 30 GHz period or 10 mm in space. This is not the usual spacing of bunches foreseen in multibunch schemes, but we are limited in computation time.

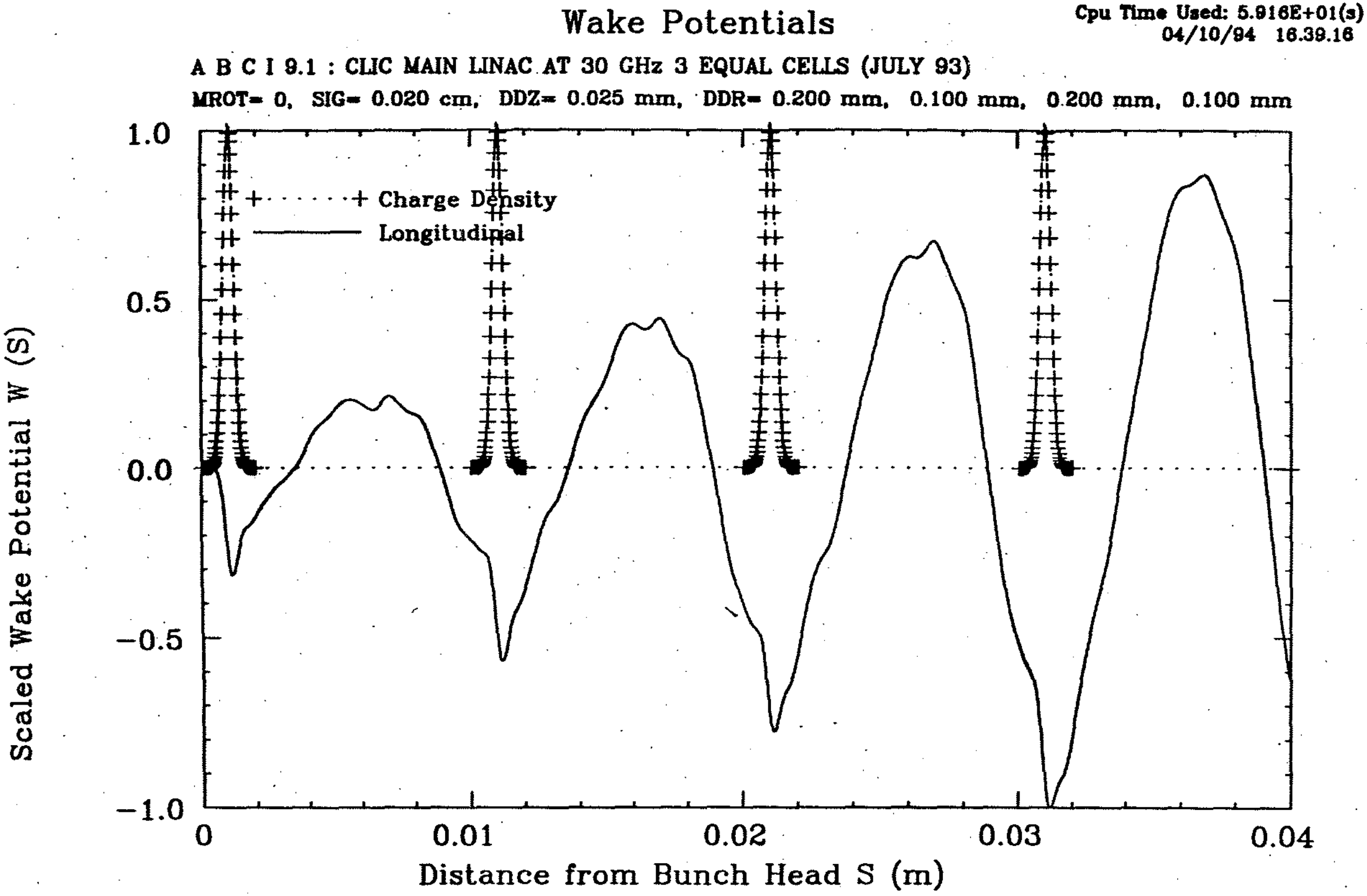
Fig.4 shows the resultant wake potential and the computed loss factor. Since ABCI divides the total charge by the number of bunches in the train, all wake potentials must be multiplied by four and all loss factors by sixteen as the charge is integrated twice in the loss factor calculation.

The peak negative wake potential is then 111.2 V/pC.

The total longitudinal loss factor (four bunches) is 16 x 15.9 = 254.4 V/pC.

It is almost linearly distributed so that we have:

first bunch	Kl = 25.4 V/pC
second bunch	Kl = 50.8 V/pC
third bunch	Kl = 76.2 V/pC
fourth bunch	Kl = 101.6 V/pC



Longitudinal Wake Min/Max= −2.783E+01/ 2.412E+01 V/pC, Loss Factor= −1.590E+01 V/pC

16x 15.9 = 254.4 V/pC

FIG. 4

Transverse wakes in multibunch mode.

The transverse wake potential for a train of four gaussian bunches of σ = .2 mm and spaced by 10 mm is shown in Fig. 5. The two median bunches in the train experience a much higher wake than the first and fourth ones.

The total transverse kick factor found is 29.1 V/pC/mm, divided as follows:

first bunch	Kt = 3.35 V/pC/mm
second bunch	Kt = 13.70 V/pC/mm
third bunch	Kt = 9.24 V/pC/mm
fourth bunch	Kt = 2.84 V/pC/mm

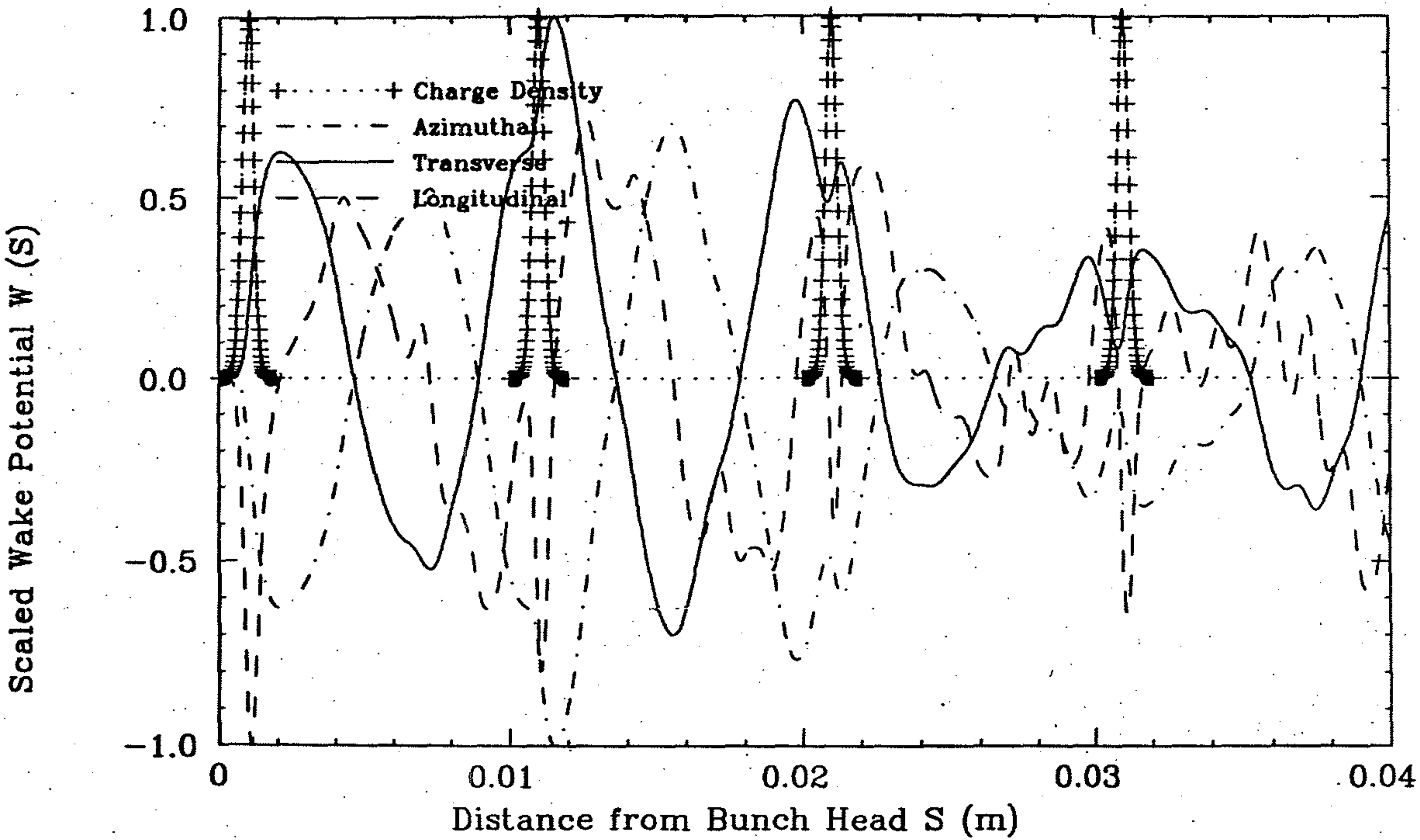
The detailed distribution of the kick factor was found by performing the computation successively with two, three and four bunches and taking the differences.

Wake Potentials

Cpu Time Used: 8.936E+01(s)
04/10/94 16.39.16

A B C I 9.1 : CLIC MAIN LINAC AT 30 GHz 3 EQUAL CELLS (JULY 93)

MROT= 1, SIG= 0.020 cm, DDZ= 0.025 mm, DDR= 0.200 mm, 0.100 mm, 0.200 mm, 0.100 mm



Azimuthal Wake	Min/Max= −4.414E+03/ 3.089E+03 V/pC/m,	Loss Factor= −1.818E+03 V/pC/m
Transverse Wake	Min/Max= −3.088E+03/ 4.415E+03 V/pC/m,	Loss Factor= 1.817E+03 V/pC/m
Longitudinal Wake	Min/Max= −4.102E+06/ 2.941E+06 V/pC/m²,	Loss Factor= −1.800E+06 V/pC/m²

FIG. 5

$K_T = 16 \times 1.82 = 29.1$ V/pC/mm

A possible scheme to improve the situation.

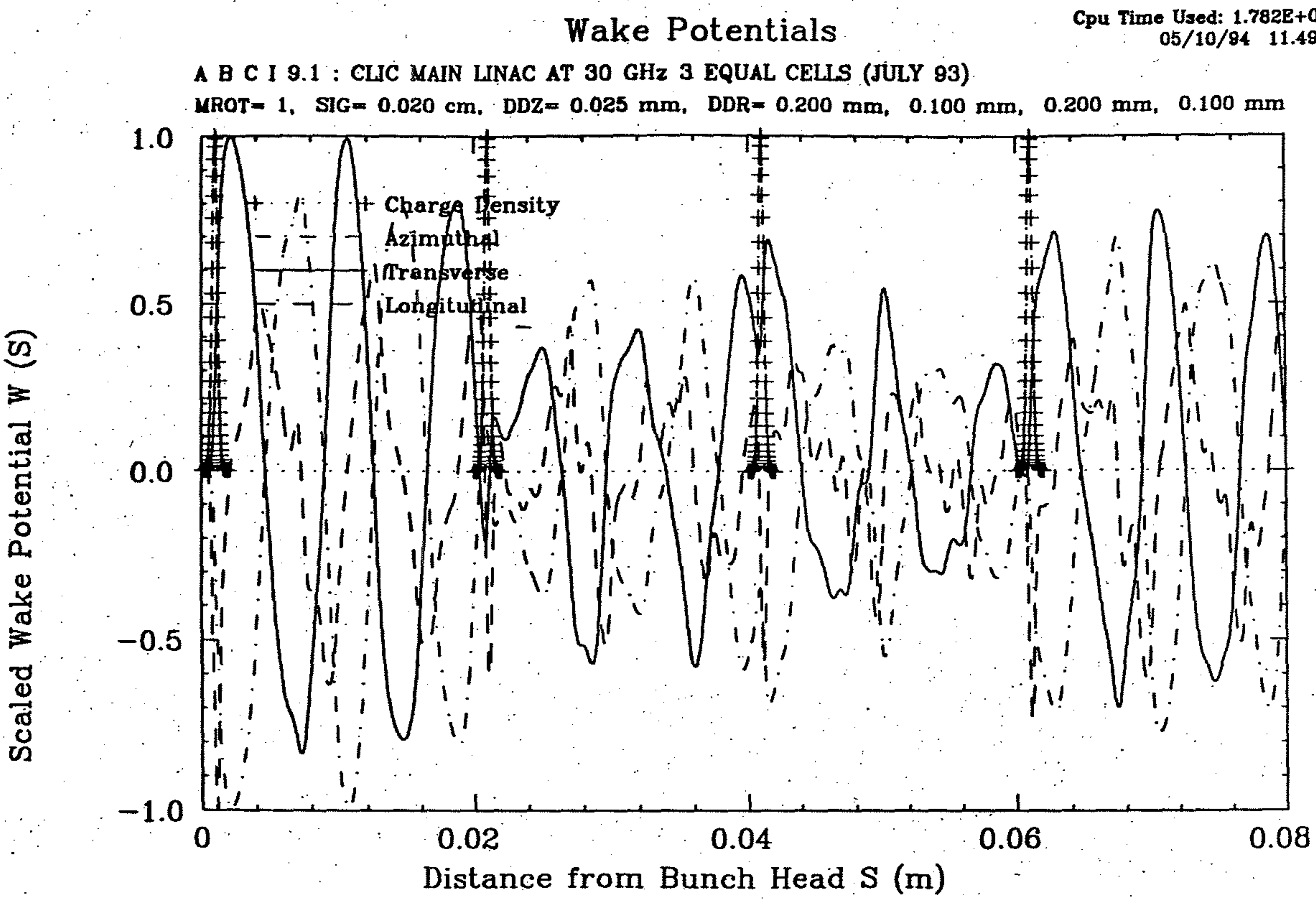
We know from the frequency domain computations that the main component of the transverse wake potential is at about 38 GHz and has therefore a period 22% shorter than the fundamental period at 30 GHz. Indeed we see in Fig. 5 that the second bunch arrives at the peak of the second period of the wake or $(2+1/4)\pi$ phase delay at 38 GHz. By increasing the bunch spacing a factor two, we can make the second bunch arrive in phase opposition to the wake potential generated by the first one.

Fig. 6 shows the transverse wake for a train of four bunches spaced by 20 mm. The total kick factor is 16 x 0.577 =9 .23 V/pC/mm distributed as follows:

first bunch	Kt = 3.35 V/pC/mm
second bunch	Kt =-1.05 "
third bunch	Kt = 5.08 "
fourth bunch	Kt = 1.86 "

The negative value for the second bunch is due to the fact that the wake potential changes sign just before the bunch head. If we consider the absolute value of the wake potential, then the kick factor for the second bunch can be estimated at about 2 V/pC/mm.

Cpu Time Used: 1.782E+02(s)
05/10/94 11.49.10



Azimuthal Wake Min/Max= −2.769E+03/ 2.309E+03 V/pC/m, Loss Factor= −5.781E+02 V/pC/m
Transverse Wake Min/Max= −2.308E+03/ 2.769E+03 V/pC/m, Loss Factor= 5.772E+02 V/pC/m
Longitudinal Wake Min/Max= −4.102E+06/ 2.557E+06 V/pC/m², Loss Factor= −1.870E+06 V/pC/m²

FIG. 6

$K_T = 16 \times 0.58 = 9.23$ V/pC/mm

Longitudinal wakes for the train of four bunches spaced 20 mm.

This is shown in Fig. 7. Since the bunch repetition is now a sub harmonic of the fundamental 30 GHz mode, no major improvement can be expected in the longitudinal case. Higher order harmonics however play a role in reducing the total loss factor by about 15%.

Conclusion.

The reported results show that for the train of four bunches spaced 10 mm the longitudinal wake potential increases linearly along the train so that the fourth bunch experiences a loss factor almost four times higher than the first. The transverse wake potential affects mostly the second bunch for which the kick factor is four times higher than that of the first bunch.

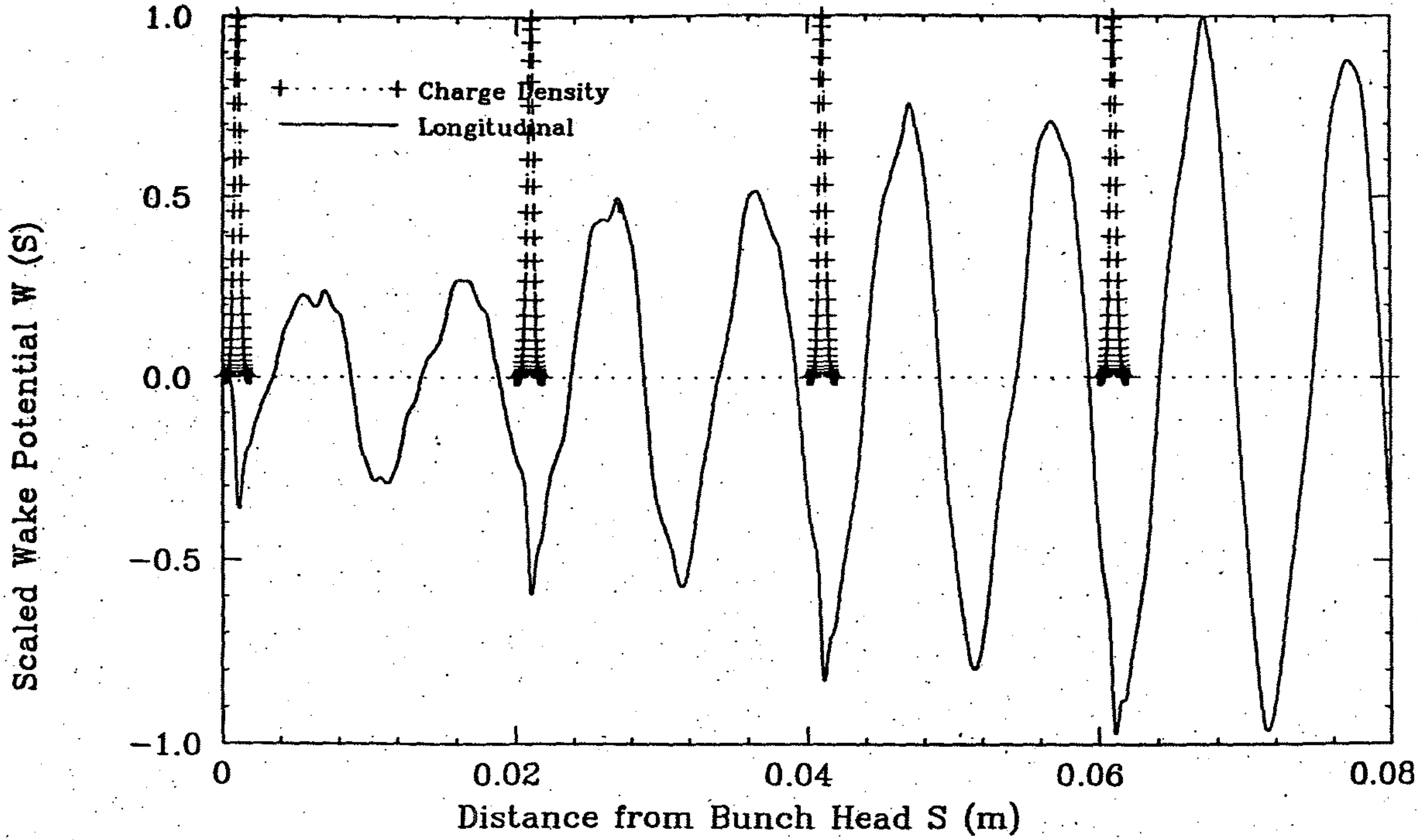
By increasing the bunch spacing to 20 mm the transverse kick factors of the trailing bunches are strongly reduced. In particular for the second and the fourth bunch there is partial cancellation of the transverse wake potential which leads to a kick factor lower than that of the first bunch.

Cpu Time Used: 1.163E+02(s)
05/10/94 11.49.10

Wake Potentials

A B C I 9.1 : CLIC MAIN LINAC AT 30 GHz 3 EQUAL CELLS (JULY 93)

MROT= 0, SIG= 0.020 cm, DDZ= 0.025 mm, DDR= 0.200 mm, 0.100 mm, 0.200 mm, 0.100 mm



Longitudinal Wake Min/Max= −2.385E+01/ 2.454E+01 V/pC, Loss Factor= −1.446E+01 V/pC

$K_L = 16 \times 14.46 = 231.4$ V/pC

FIG. 7

(L. Thorndahl)

Beam to 30 GHZ efficiency

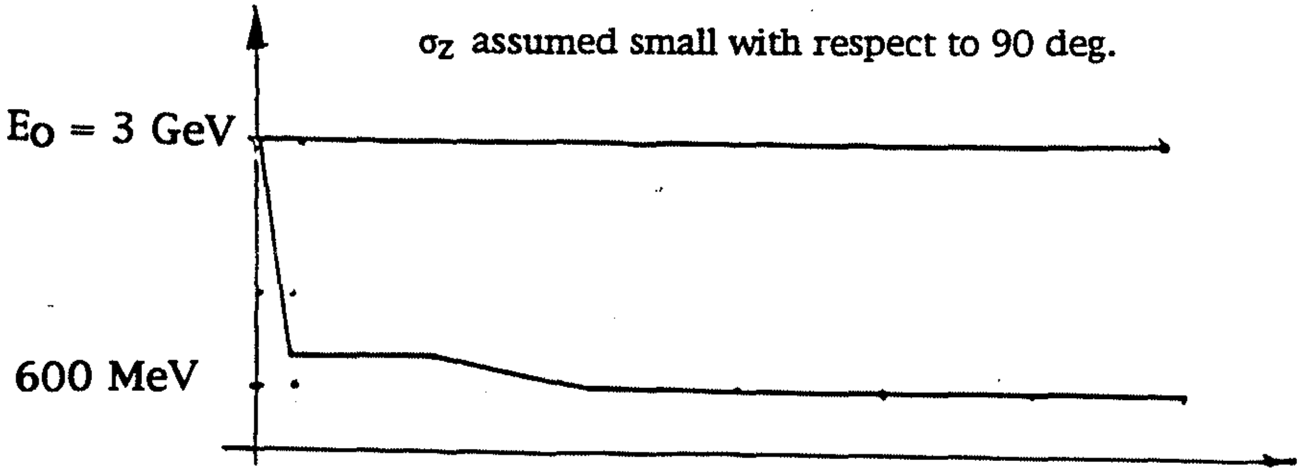
6 main linac structure fills

Max. rel. energy spread acceptable for betatron stability in the drive linac:

$$E_{max.} / E_{min.} = 5$$

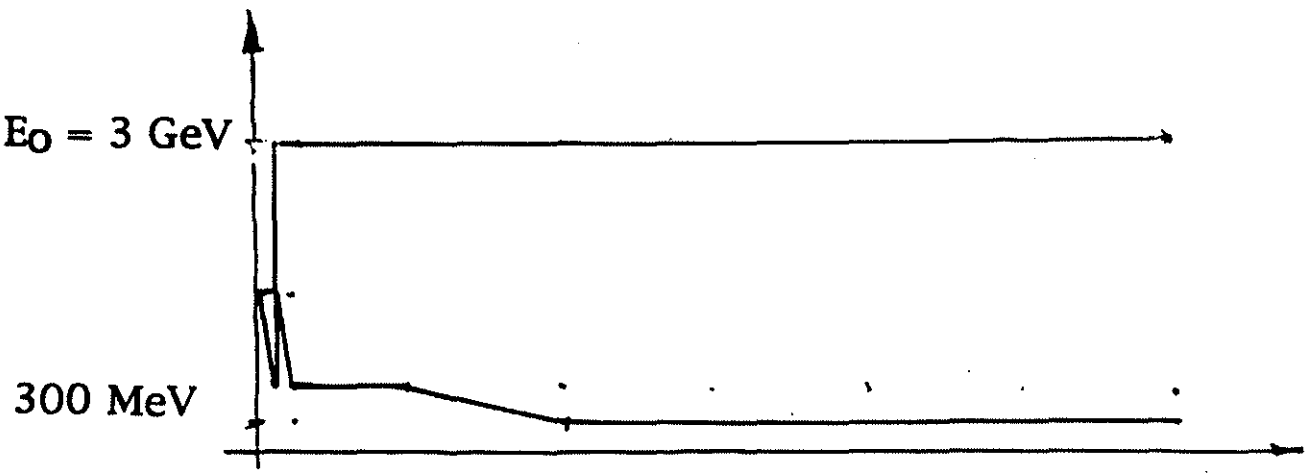
(result of tracking by G. Guignard)

σ_Z assumed small with respect to 90 deg.



74 %

Two-energy bunchlet train:



86 %

$$q_{tot} : \frac{E_{RF}}{\eta \cdot 3 GeV} = 17 \mu C / \text{drive beam}$$

switchyard: (8.5 mC) per linac

$$q_{bunchlet} \simeq 8 nC$$ — 4 drive beams

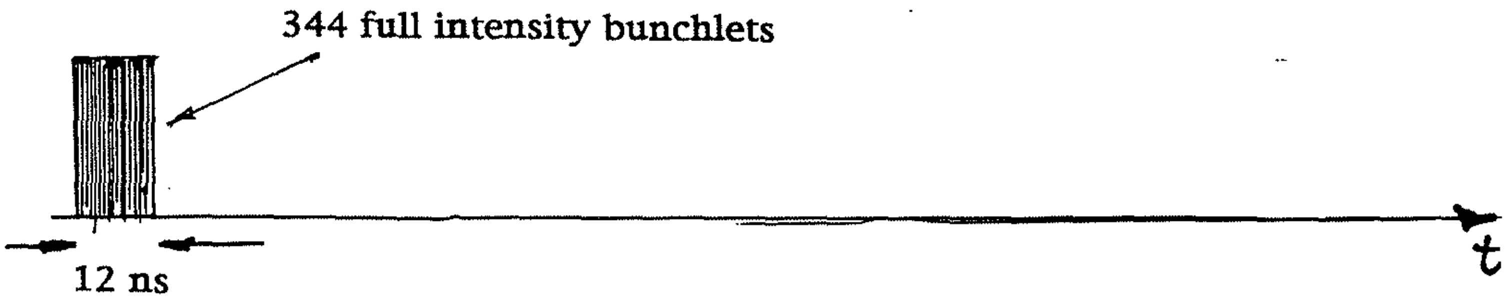
→ 2 nC/bunchlet

(← Thorndahl)

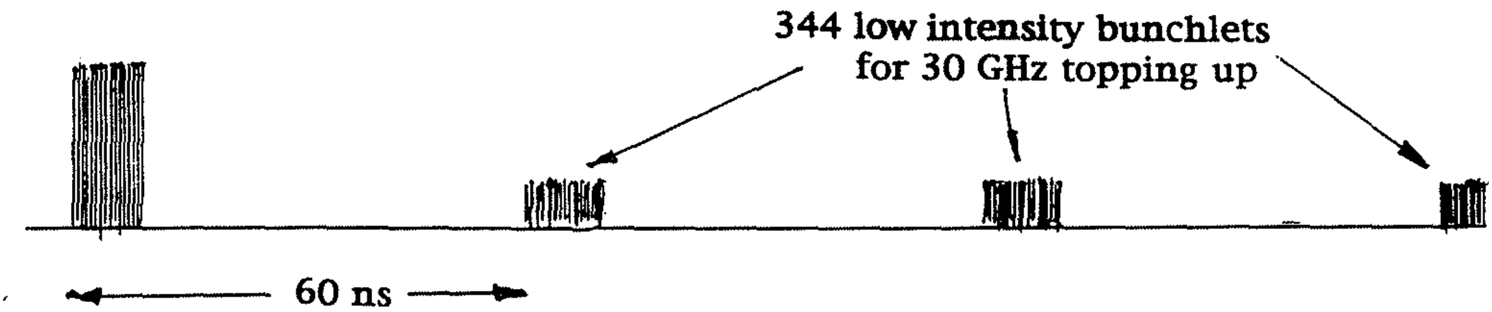
30 GHz Power Recirculation

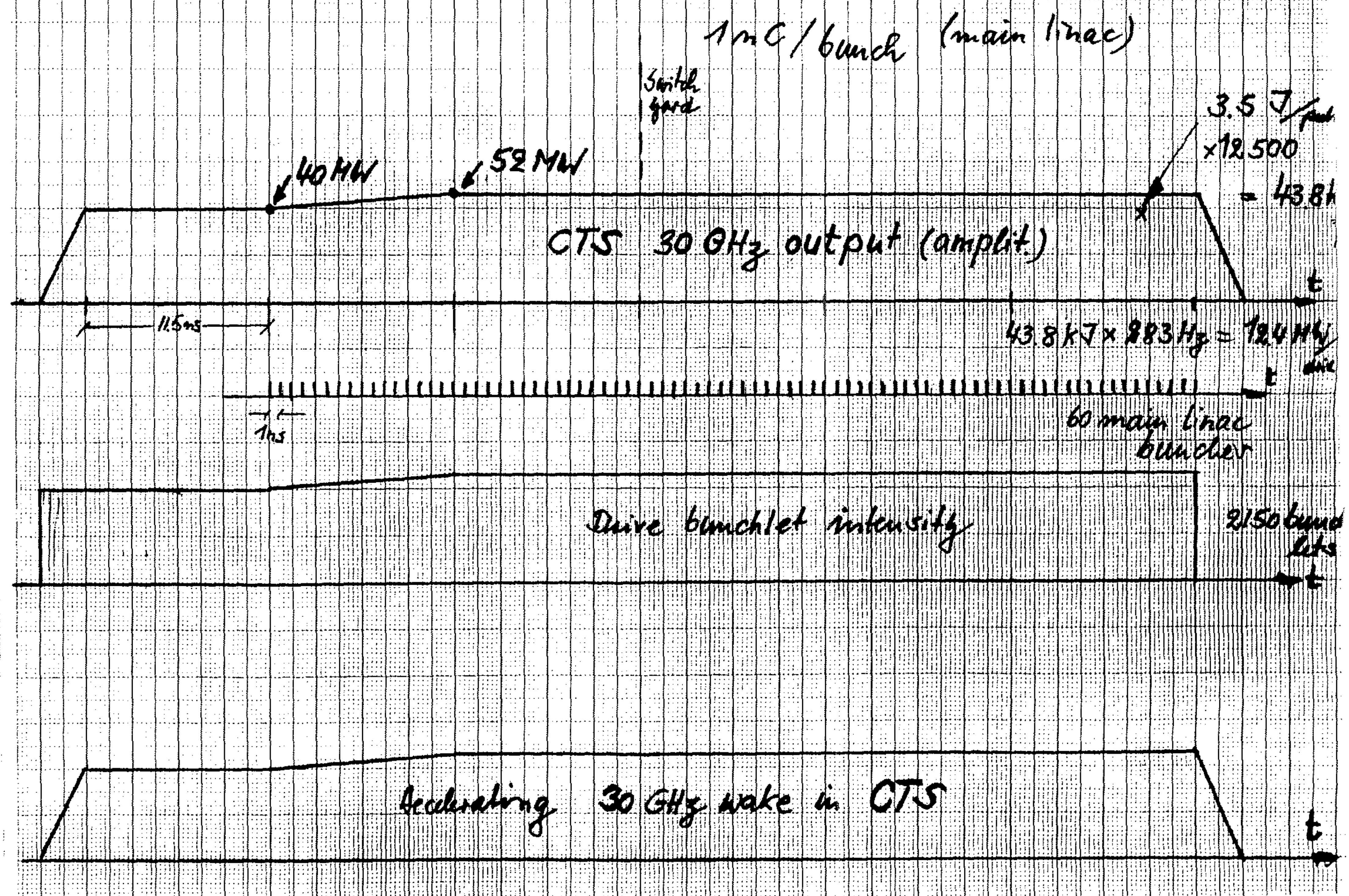
with long delay line (~ 20ms), see fig 3c of previous transparency

Drive bunchlets without recirculation:



Drive bunchlets with recirculation:



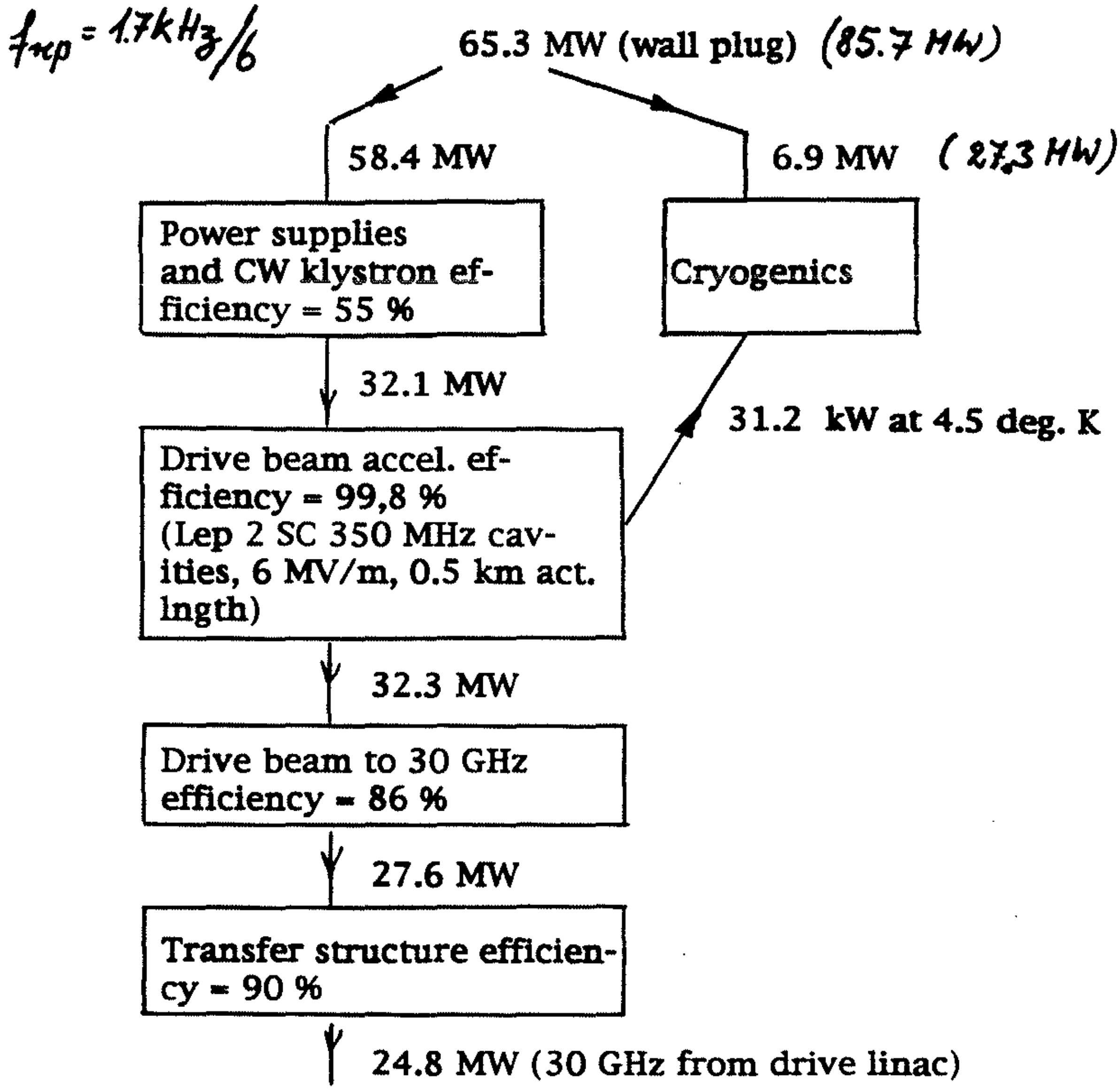

1 nC / bunch (main linac)
Switch gard
40 MW
52 MW
3.5 J/puls ×12 500 = 43.8 k
CTS 30 GHz output (amplit.)
t
11.5 ns
43.8 kJ × 283 Hz = 12.4 MW
1 ns
60 main linac buncher
Drive bunchlet intensity
2150 bunchlets
Accelerating 30 GHz wake in CTS

switchyard values $f_{rep} = 1.7$ kHz

Wall plug to 30 GHz efficiency

24.8 MW av. 30 GHz power required for acceleration in the 2 main linacs(250 GV/linac, 3.1 km active lngth each, 80 MV/m). Mag. lattices' power is neglected!

a) Continuous train of 2150 bunchlets(via isochronous ring):

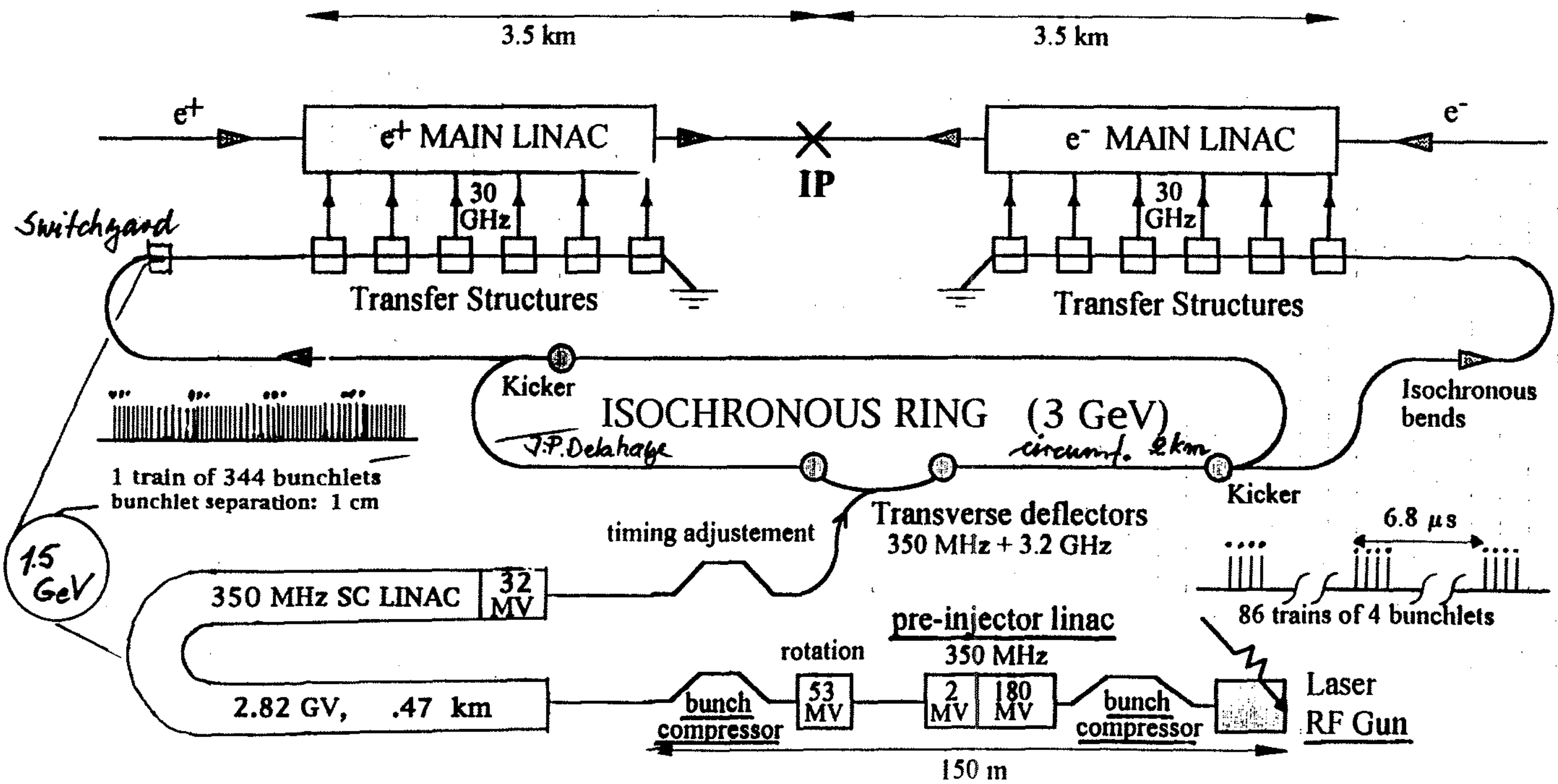


Drive linac efficiency (wall to 30 GHz) = **38 %** 29%

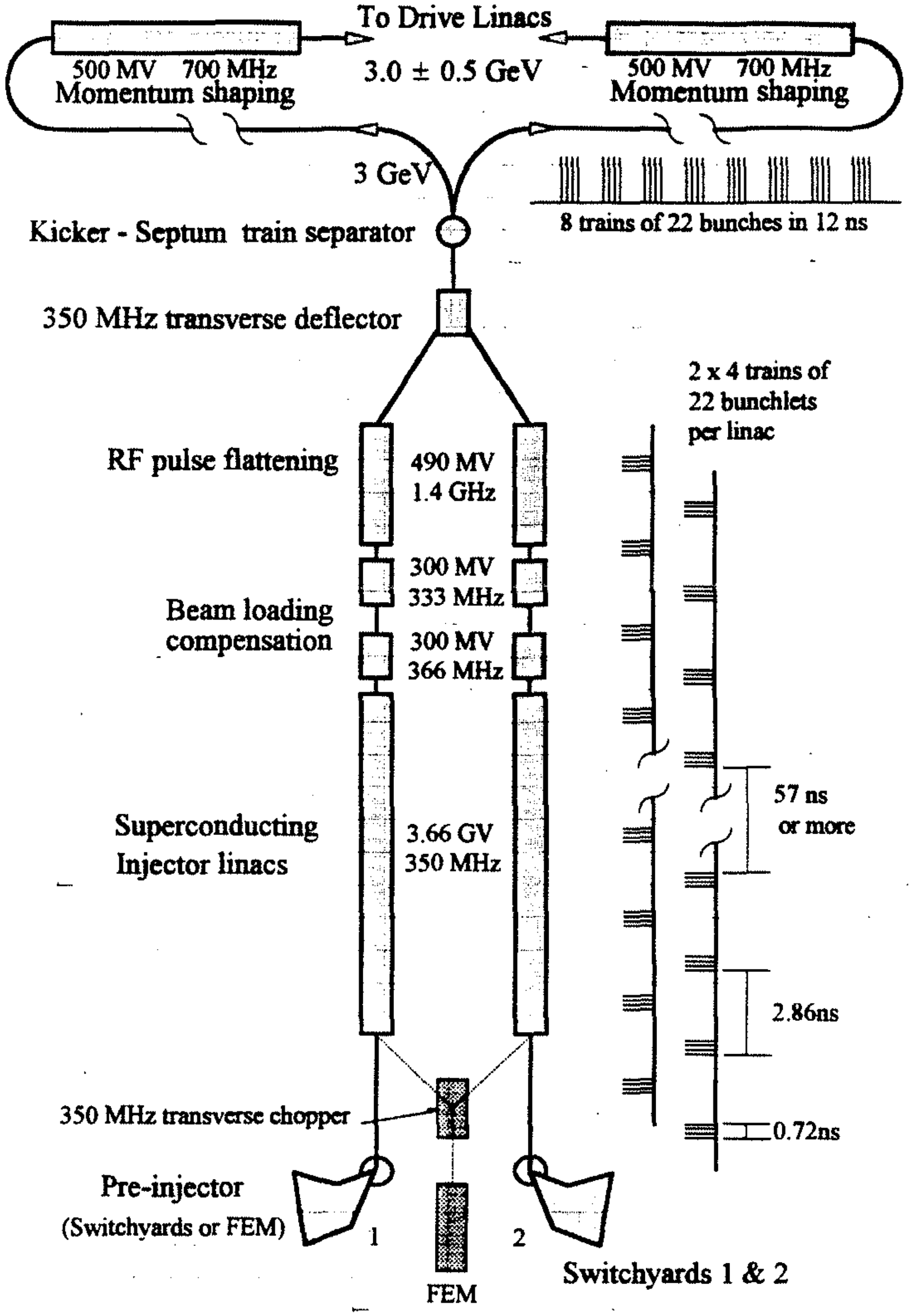
Overall efficiency (wall to main beams) = **13 %** 8%

(2 times 60 bunches of 1 nC at 250 GeV)

$\mathcal{L}_{mb} = 12 \times \mathcal{L}_{sb}$ $\mathcal{L}_{mb} = 8 \times \mathcal{L}_{sb}$



Drive Beam generation using an isochronous ring to stack and thereby compress bunchlets into 30 Ghz trains.



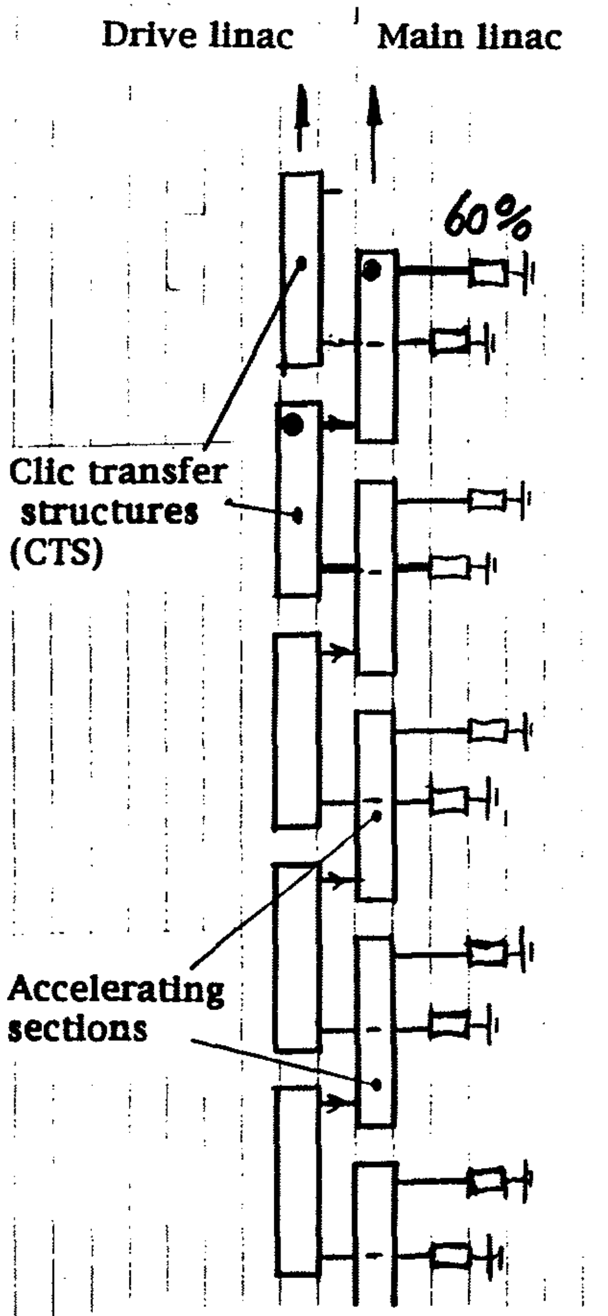
350 MHz: 1.32 km, 7.92 GV
(including beam load. comp)

700 MHz: 338 m, 2.7 GV

1400 MHz: 96 m, 0.96 GV

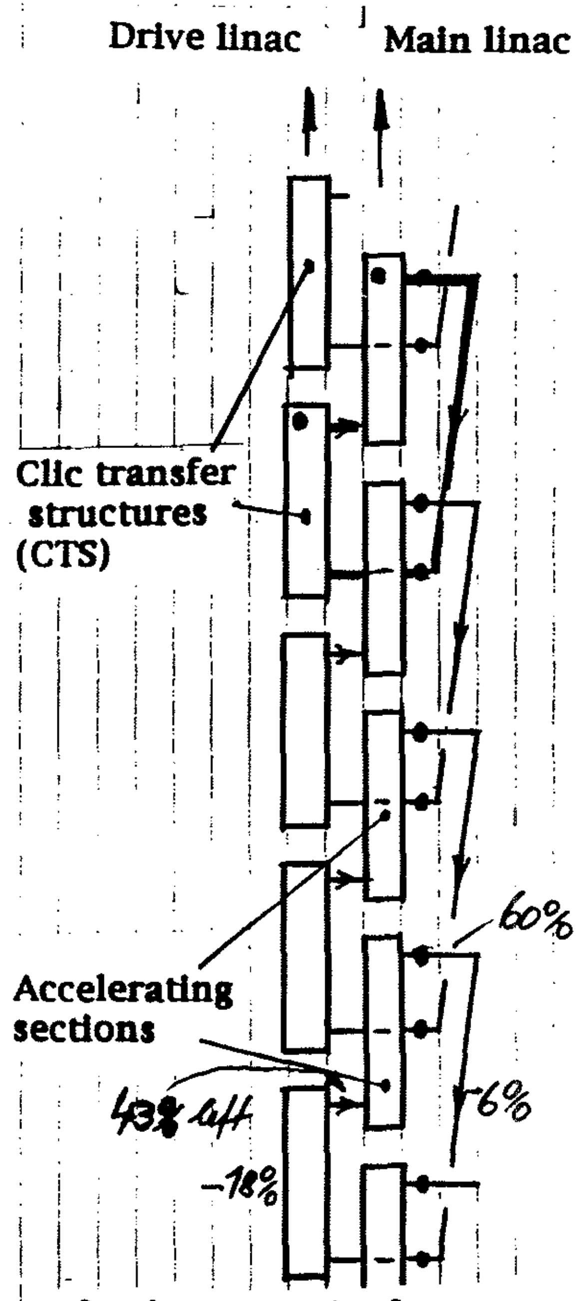
Power Recirculation Scheme (L. Thorndahl)

Fig. 1a



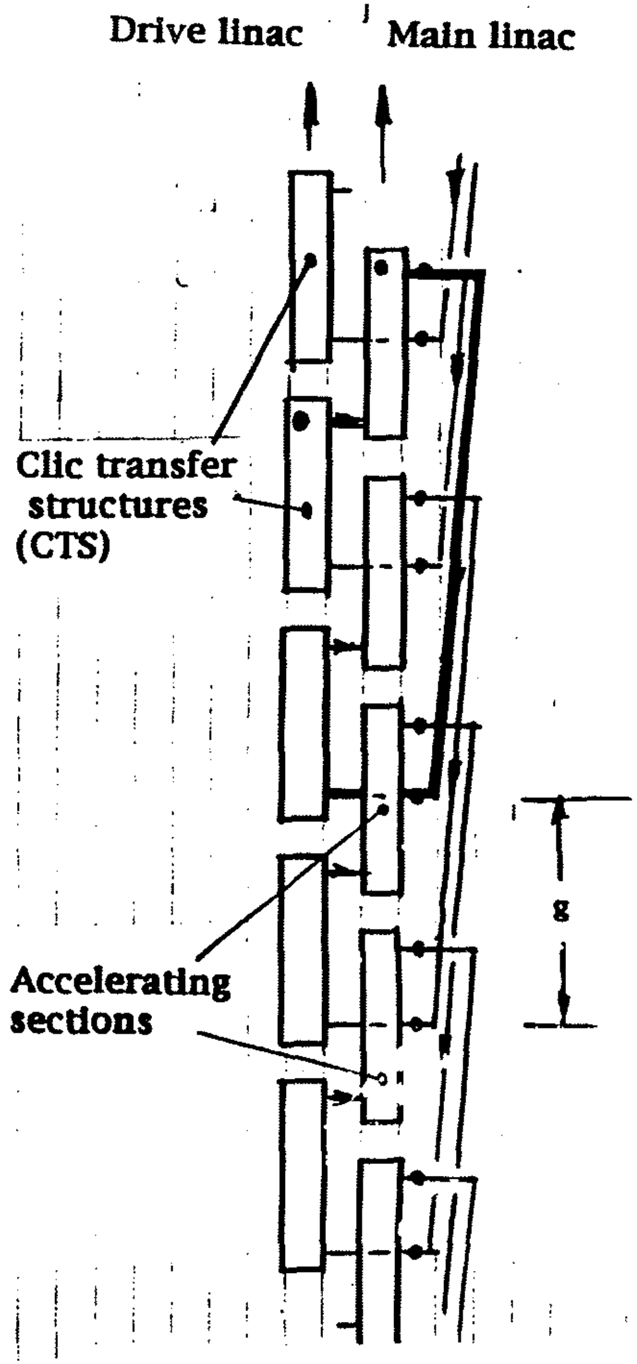
Terminated CTS input and terminated main section output ports

Fig. 1b



Low-loss connection for power recirculation
and petal mode converters

Fig. 1c



Power recirculation to an upstream by g CTS

Main problems:

- First bunchlets stacked in iso-ring travel 1059 km instead of 176 km, longitud. blow ups?.
- Energy losses via synchr. radiation. at 3 GeV probably not acceptable any more.
- R/Q ~ 300 Ω/m (CTS) 2 nC/bunch

Advantages:

- Only 2 nC per drive bunchlet
- 30 GHz energy recirculation seems posssible(electricity economy 15 to 20 %). (as indicated by Fig. 1b of the following transparency)

Main features of the proposal are summed up as follows:

a) The obtained main linac bunch spacing of 60 ns would be sufficient to avoid drastic changes(compared with the single-bunch mode) in the final focus lay-out[4] .

b) The spacing is most likely also sufficient to separate physics events from neighbouring bunches.

c) More time is available to decohere/damp transverse modes in the accelerating sections(than in previous CLIC multibunching schemes).

d) Better wall plug to beam efficiency than for single bunch mode.

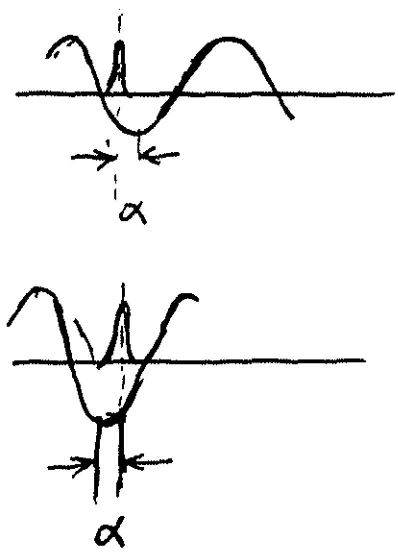
e) Beam-loading compensation for the individual main linac bunches can be obtained simply by intensity adjustments of the topping-up bunchlets.

f) No SLED II-type power pulse compression seems possible.

The recirculated wave is outphased by α with respect to the topping-up wave. Both the nominal output amplitude condition(output power = P_o) and the normal bunchlet deceleration condition(voltage) are satisfied if $\cos(\alpha)$ equals half the square root of the recirculated power divided by the nominal power(see fig. 2c):

$$|\alpha| = \arccos\left(\frac{1}{2}\sqrt{P/P_o}\right)$$

Alternately plus and minus signs should be used in the CTSs for α to cancel unwanted additional accelerations/decelerations of bunchlet heads/tails now situated on sloping waves of the recirculated pulse.

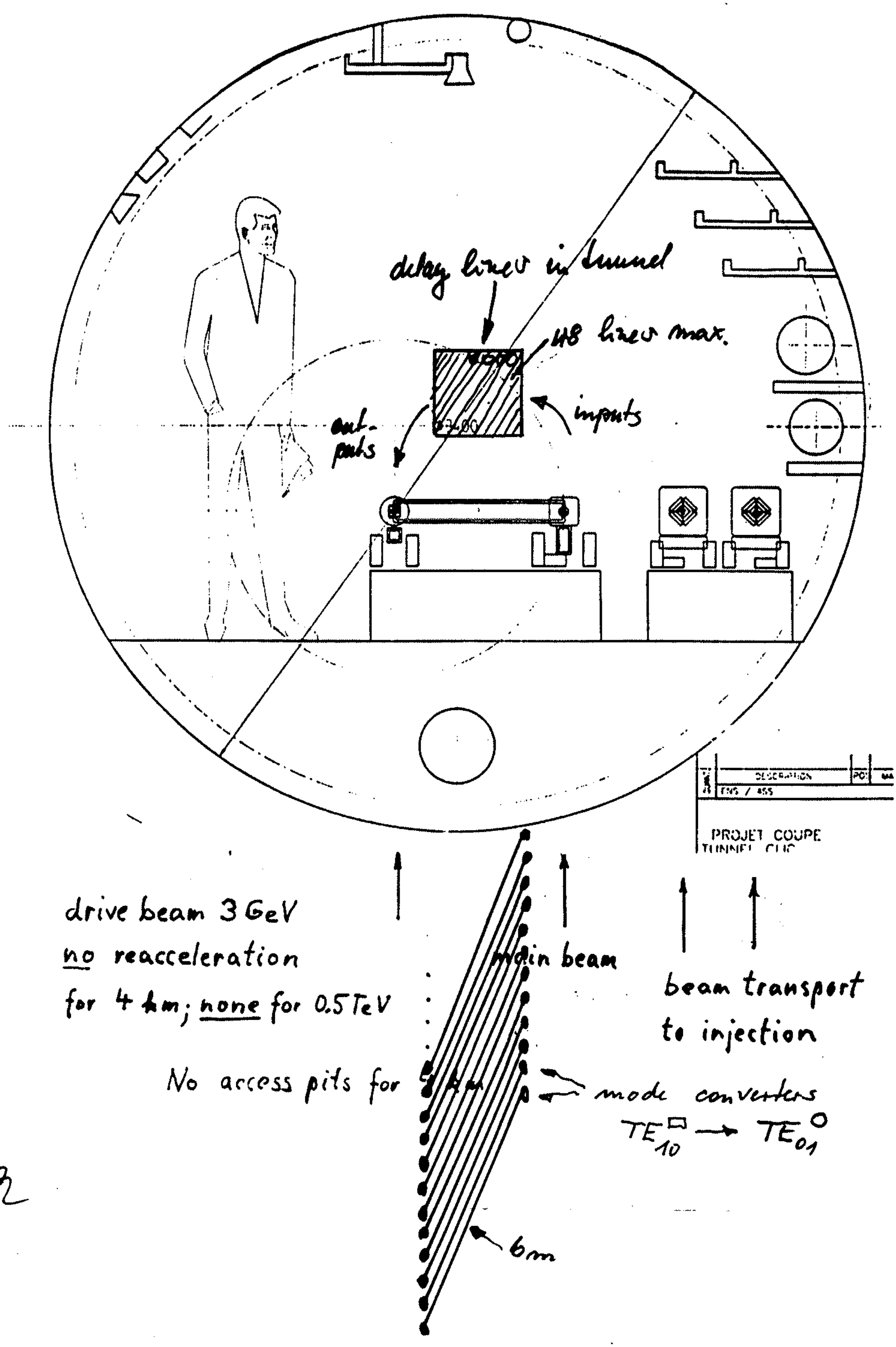


The **overall economy**(in mean accelerated drive linac charge per main linac bunch) with respect to the **full-length structure single-bunch case** can be summed up as follows(beam-loading neglected):

Number of **injected** main linac bunches per main linac train	1	2	3	4	5	6	infinite
Economy in % for full-length structures	0	21.5	28.7	32.3	34.4	35.8	43
Economy in % for half-length structures	12	39.1	48.2	52.7	55.4	57.2	66.3

Above half-length structure case requires bunchlets for the **first** pulse with **76 % higher** intensity(than in the full-length single-bunch case), causing an increase in **bunchlet charge** that could be problematical. - By accepting to reach the nominal acceleration only for the second main linac pulse(omitting the first main linac bunch, useless, because it would be too low in energy) and applying drive bunchlet intensities only increased by 18 % for the **first** two pulses, interesting overall economies can still be obtained:

Economy in % for half-length structures with one dummy drive pulse	-18	24.2	38.2	45.1	49.4	52.3	66.3


delay lines in tunnel
48 lines max.
out-puts
inputs
DESCRIPTION
PROJET COUPE TUNNEL CLIC
drive beam 3 GeV
no reacceleration
for 4 km; none for 0.5 TeV
main beam
beam transport
to injection
No access pits for
mode converters
$TE_{10}^{\square} \rightarrow TE_{01}^{\circ}$
6 m

Luminosity / RF power

(J.P. Delahaye)

Luminosity:

$$\mathcal{L} = \frac{f_{rep}\, n\, N^2}{4\pi\, \sigma_x \sigma_y} = \frac{f_{rep}\, R\, n\, N^2}{4\pi\, \sigma_x^2} \qquad \left(R = \frac{\sigma_x}{\sigma_y}\right)$$

Υ parameter:

$$\Upsilon = K \frac{U_2\, N}{\sigma_s (\sigma_x^* + \sigma_y^*)} = 1.78\, 10^{-33} \frac{U_2\, N}{\sigma_s\, \sigma_x\, (1 + R^{-1})}$$

RF power:

$$\underset{(2\ \text{Linacs})}{P_{RF}} = 2\, P_2\, (\tau_2 + n\Delta)\, f_{rep} \qquad (\Delta = \text{distance between bunches})$$

$$= 3.65\ \frac{E_2\, U_2}{g_2^2\, f_2^2} \left[1 + (n-1)\frac{\Delta}{\tau_2}\right] f_{rep}$$

$$\boxed{\mathcal{L} = 6.84\, 10^{54}\ \frac{g_2\, f_2^2}{E_2}\ \frac{\Upsilon^2 \sigma_s^2}{U_2^3}\ \frac{n\, R\, (1 + R^{-1})}{\left[1 + (n-1)\Delta/\tau_2\right]}\ P_{RF}}$$

Application :

$U_c = 250$ GeV $\qquad E_c = 80$ MeV/m

$g_c^2 = 0.783$ ($\alpha = 0.5$) $\qquad R \gg 1$ (flat beam)

$\Upsilon \leq 0.1$ ($\sim$ NLC)

$P_{wall\ plug} \leq 100$ MWatts (Total 2 linacs AC power)

$\hookrightarrow P_{RF\ (2\ linacs)} \leq 33$ MWatts

$\eta \simeq 33\%$

$$\mathcal{L}(cm^{-2} sec^{-1}) = 1.4\ 10^{30} \frac{n\ R\ \sigma_s^2 (mm)}{(1 + n\ \Delta/\delta_c)} f_c^2 (GHz)$$

$f_c \nearrow \Rightarrow$ high frequency

$R \nearrow \Rightarrow$ flat beams

$\sigma_s \nearrow \Rightarrow$ long bunches

$n \nearrow \Rightarrow$ multibunches

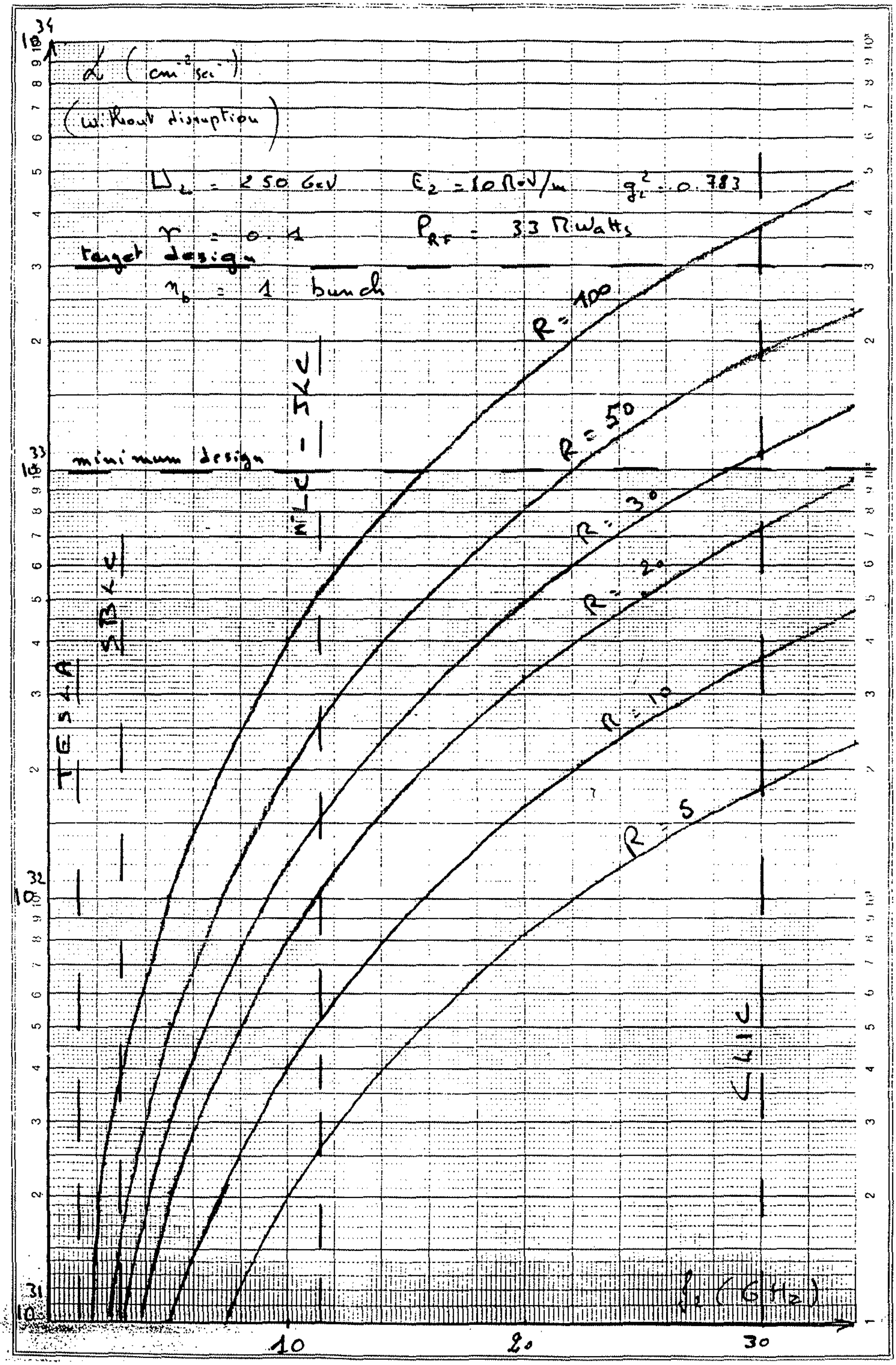
Compatibility ?

$\Downarrow$

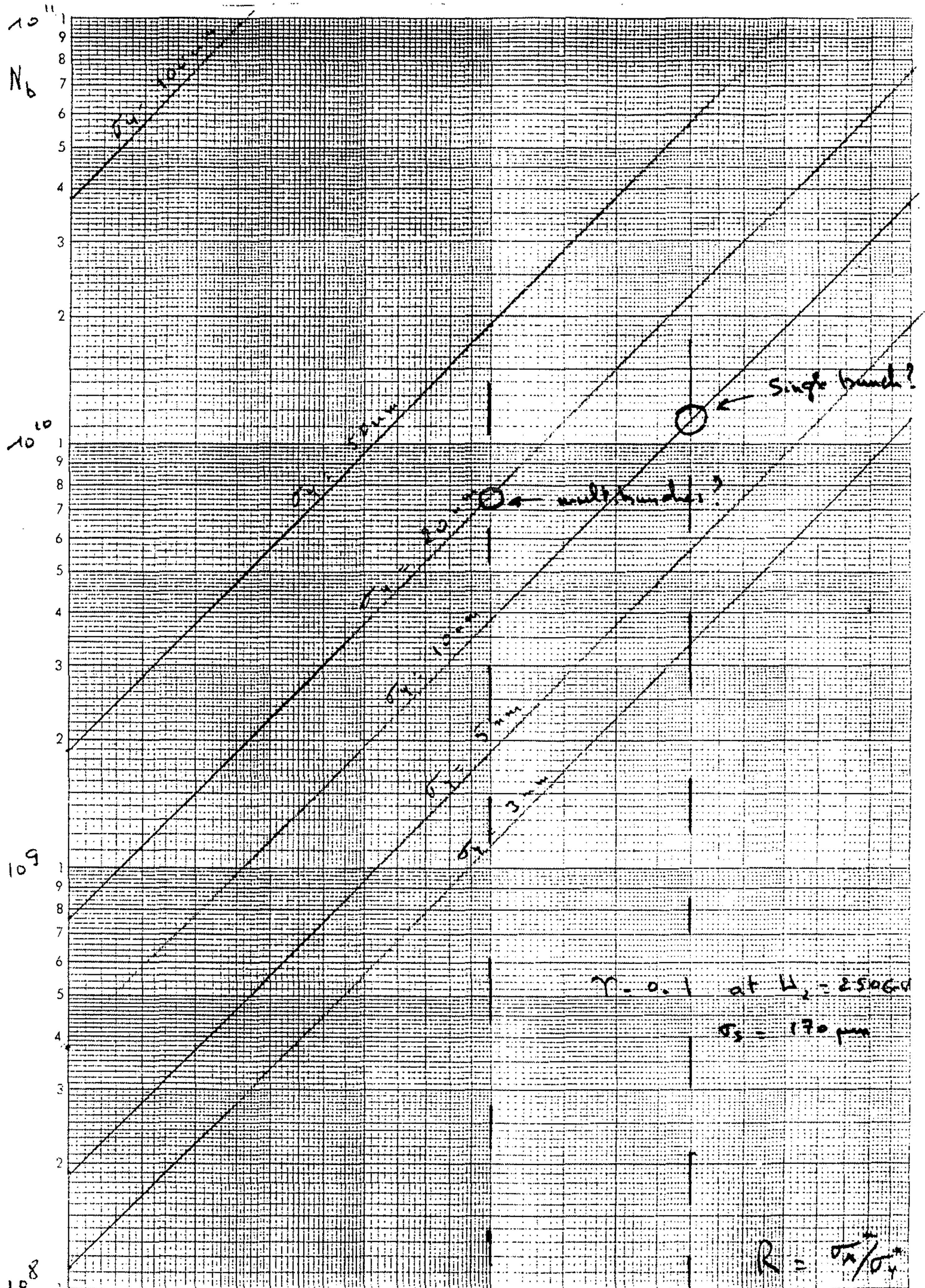
compromise

$$N_b = \frac{\Upsilon \sigma_s (\sigma_x^* + \sigma_y^*)}{K\ U_c} = 2.24\ 10^{16}\ R\ \sigma_y \sigma_s$$

$$f_{rep} = 0.107 \frac{f_c^2 (GHz)\ P_{RF} (MW)}{1 + n\ \Delta/\delta_c}$$



$\mathcal{L}$ (cm^{-2} sec^{-1})
(without disruption)
E_L = 250 GeV
E_z = 10 MeV/m
g_L^2 = 0.783
r = 0.1
P_{RF} = 33 MWatts
target design
n_b = 1 bunch
R = 100
R = 50
R = 30
R = 20
R = 10
R = 5
minimum design
TESLA
SBLC
NLC - JLC
CLIC
f_L (GHz)
10^{34}
10^{33}
10^{32}
10^{31}
10
20
30



10^{11}
N_b
10^{10}
10^{9}
10^{8}
5 nm
3 nm
Single bunch?
multibunches?
σ_z = 170 μm
$R = \sigma_x^* / \sigma_y^*$
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100

Linear Collider designs

Low frequency $\Longrightarrow$ { Multibunches; Low repetition rate

High frequency $\Longrightarrow$ { Single bunch possible!; High repetition rate

CLIC design: ($\mathcal{L} \geq 10^{33}$ at 0.5 TeV$_{c.m.}$)

* Single bunch if

$$R = \frac{\sigma_x}{\sigma_y} = 30 \quad \text{possible ?}$$

$$\begin{cases} \sigma_y = 10\ \text{nm} \\ \sigma_x = 300\ \text{nm} \\ N_b = 1.15\ 10^{10} \end{cases} \quad \text{or} \quad \begin{cases} \sigma_y = 20\ \text{nm} \\ \sigma_x = 600\ \text{nm} \\ N_b = 2.3\ 10^{10} \end{cases}$$

$P_{RF} = 33\ \text{MWatts} \Longleftrightarrow f_{rep} = 3.2\ \text{kHz}$

* Multibunches if R limited to ≈ 10

$n \geq 4$ bunches

$$\begin{cases} \sigma_y = 10\ \text{nm} \\ \sigma_x = 100\ \text{nm} \\ N_b = 3.8\ 10^{9} \end{cases} \quad \text{or} \quad \begin{cases} \sigma_y = 20\ \text{nm} \\ \sigma_x = 200\ \text{nm} \\ N_b = 7.6\ 10^{9} \end{cases}$$

$n \Delta \approx T_z \Longleftrightarrow f_{rep} = 1.6\ \text{kHz}$

* Gain in luminosity by disruption? longer σ_z ?

Table 1: Parameters for E_{CM} = 0.5 TeV Linear Colliders from LC-92[1,2]

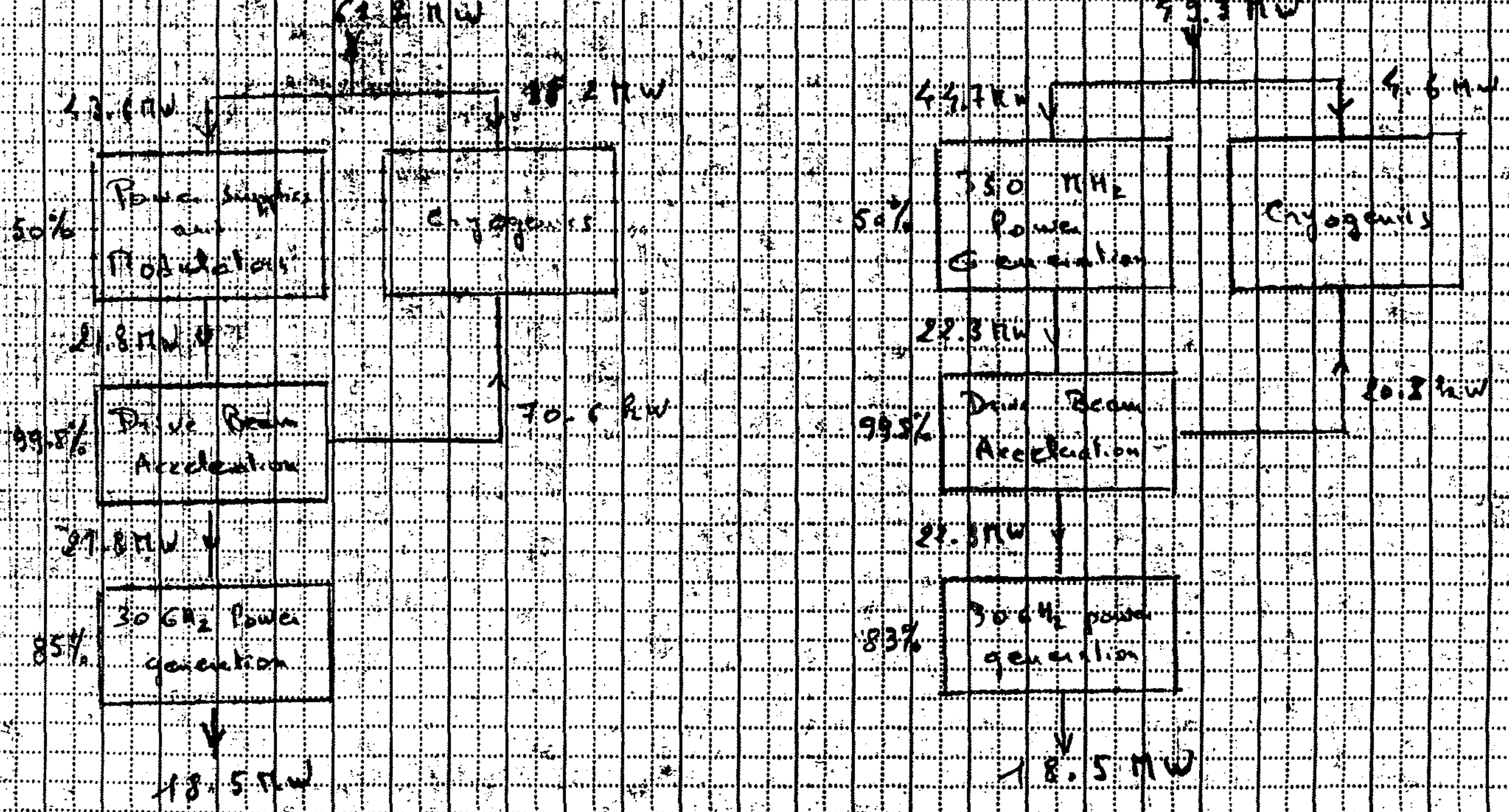
	TESLA	DLC	JLC-I(S)	JLC-I(C)	JLC-I(X)	NLC	VLEPP	CLIC
Linac RF Frequency (GHz)	1.3	3.	2.8	5.7	11.4	11.4	14.	30.
Beam Loaded Gradient (MV/m) [3]	25.	17.	18.4	32.5	28.	37.6	96.	78. - 73
Repetition Rate (Hz)	10.	50.	50.	100.	150.	180.	300.	1700.
Bunches/RF Pulse	800	172	55	72	90	90	1	1 - 4
σ_x/σ_y (nm) (with Disruption)*	310/50	250/190	300/1.9	260/1.9	260/2.0	300/2.2	1590/4	40/5.5
Beam Power/Beam (MW)	16.5	7.5	1.6	3.6	3.8	4.2	2.4	0.4 - 1.6
[redacted]	0.063	0.070	0.24	0.21	0.16	0.096	0.076	[redacted]
n_y [4]	5.7	3.1	1.6	1.4	0.9	0.8	5.1	4.6
Beam Posit. Monitor Precision (μm) [5]*	10.	10.	NA	NA	1.	1.	0.1	0.1
[redacted]	11.3	6.5	4.4	6.5	6.3	8.2	15.	[redacted]
[redacted]	5.15	2.1	1.3	1.0	0.63	0.65	20.	0.6
Bunch Separation (nsec)	1000.	10.7	5.6	2.8	1.4	1.4	-	0.33
Unloaded Gradient (MV/m)	25.	21.	22.	40.	40.	50.	108.	80.
Active Two-Linac RF Length (km)	20.	30.	28.	16.7	17	14	6.4	6.6
Section Length (m)	1.04	6.	3.6	2.	1.3	1.8	1.01	0.273
Two-Linac Number of Sections	19232	4900	7776	8360	13600	7778	5200	24000
Two-Linac Number of Klystrons	1202	2450	1944	4180	3400	1945	1300	2
Sections/Klystron	16	2	4	2	4	4	4	"12000"
Klystron Peak Power (MW)	3.25	150.	85.	45.	70.	94.	150.	700.
Klystron Pulse Length (μsec)	1300.	2.8	4.5	3.6	0.84	1.5	0.7	0.011
Pulse Length to Section (μsec)	1300.	2.8	1.2	0.6	0.21	0.25	0.11	0.011
Pulse Compression Ratio			3.7	6.	4.	6.	6.3	-
Pulse Compression Gain			2.4	4.2	3.2	4.	4.22	-
a/λ Ratio (Input/Output Cavity)	0.15	.154/.108	0.13	.160/.120	.236/.138	.210/.147	0.140	0.2
[redacted] [6]	137.	114.	106.	193.	86.	152.	91.	[redacted]
Damping Ring Energy (GeV)	3. or 14.	3.13	1.98	1.98	1.98	1.8	3.0	3.0
[redacted]	1000.	500.	80.	80.	67.	100.	750.	[redacted]
$\gamma\epsilon_x/\gamma\epsilon_y$ (10^{-8} m)	2000/100	500/50	330/4.5	330/4.5	330/4.5	500/5	2000/7.5	180/20
β_x^*/β_y^* (mm)	10/5	16/1	10/0.1	10/0.1	10/0.1	10/0.1	100/0.1	2.2/0.16
[redacted]m) (no Disruption)	640/100	400/32	300/3	260/3	260/3	300/3	2000/4	[redacted]
Disruptions, D_x/D_y	1.2/7.9	0.69/8.6	0.13/13	0.13/11.5	0.07/6.	0.08/8.3	0.4/- [7]	1.3/15.
H_D*	4.1	2.7	1.6	1.6	1.5	1.4	1.3	3.2
δ_B [4]*	0.13	0.078	0.098	0.081	0.043	0.027	0.14	0.35
Crossing Angle (mrad)	1. - 2.	2.	7.3	8.	7.2	3.	NA	1.

Notes

1) Based on a compilation made by Gregory A. Loew for LC92, ref. [1]. Modifications of and additions to his original table are indicated with a *.
2) Symbols are defined in the text.
3) Before applying further gradient reductions for off-crest running, BNS damping, etc (VLEPP excepted).
4) Including the effects of disruption, ref. [7].
5) From ref. [8].
6) DLC bases its number on a combined klystron-modulator efficiency of 45%. JLC and NLC have assumed this number to be closer to 35%. In addition, SLED-I (used for JLC-I(S)) and SLED-II (used for JLC-I(C), JLC-I(X), NLC and VLEPP) are assumed to be about 65% efficient. Power for klystron focusing is not included.
7) VLEPP employs a "traveling focus".

Fig 10: 30 GHz RF Power Production Efficiency
(Proposal)

FEL Bunching or Switchyard scheme | Continuous stream from Isochronous Ring



Net efficiency 29.5 % | Net efficiency 37.5 %

Variation with the frequency, f_2

$E_2 = 250$ GeV $E_2 \approx 80$ MV/m $g_2 \approx$ [illegible]

$P_{\text{Kl Lines}} = 100$ MWatts $\Rightarrow P_{RF} \approx 33$ MWatts

$r = 0.1 \Rightarrow \delta_B \sim 3\%$

$f_2 = 30$ GHz, single bunch ($n = 1$)

$$\left.\begin{matrix}\sigma_y = 10 \text{ nm} \\ \sigma_x = 200 \text{ nm}\end{matrix}\right\} R = 20 \quad \left.\begin{matrix} \\ \\ \sigma_z \approx 200 \ \mu\text{m}\end{matrix}\right\} N_b = 8.90 \ 10^{9}$$

$f_{rep} = 3.2$ KHz

$\mathcal{L} = 1.0 \ 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

$f_2 = 15$ GHz multi bunches ($n = 25$)

Transverse Wake fields / 8

$$\left.\begin{matrix}\sigma_y = 10 \text{ nm} \\ \sigma_x = 300 \text{ nm}\end{matrix}\right\} R = 30 \quad \left.\begin{matrix} \\ \\ \sigma_z = 150 \text{ nm}\end{matrix}\right\} N_b = 1.00 \ 10^{10}$$

$n\Delta \sim \tau_2 \Rightarrow f_{rep} = 400$ Hz

25 × 1.4 nsec $= \propto Q/\pi f_2 \propto f^{3/2} = 322$ nsec

$\mathcal{L}/\text{bunch} = 1.3 \ 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$

$n = 25$ bunches at 1.4 nsec distance

$\mathcal{L} = 3.40 \ 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

Drive Beam

$$W_2 = P_2 (\tau_2 + n\Delta)$$

$$W_2 = \eta_{12} W_{RF} \Rightarrow \boxed{q_1 \Delta U_1 = \frac{E_2 \; U_2 (1 + n\Delta/\tau_2)}{2\pi \eta_{12} f_2^2 a_0'^2 g_2^2 F(\ldots}}$$

$$n_{b\,drive} = \tau_2 f_2 \cdot \frac{\alpha_2 Q_2 f_2}{2\pi f_1} \qquad \boxed{q_b = \frac{q_1}{n_b} = \frac{E_2 \; U_2}{\Delta U_1 \tau_2 Q_2 \eta_{12} f_2^2 a_0'^2 g_2^2}}$$

Scaling with frequency:

$$q_1 \Delta U_1 \propto f^{-2}$$

$$q_b \propto \frac{1}{Q_2 f_2^2} \propto f^{-3/2}$$

$$n_b \propto Q_2 \propto f^{-1/2}$$

At 30 GHz:

$$q_1 (\mu C) \, \Delta U_1 (GeV) = 5.9$$

$$n_b = \tau_2 f_2 = 344 \text{ bunches}$$

$$\Delta U_1 = 2 \, GeV \Rightarrow q_b = 8.6 \, nC$$

At 15 GHz:

$$q_1 (\mu C) \, \Delta U_1 (GeV) = 5.9 \times \left(\tfrac{1}{2}\right)^{-2} \times 2 = 47.2$$

$$n_b \propto f^{-1/2} (1 + n\Delta/\tau_2) = 2 \times 344 \times \left(\tfrac{1}{2}\right)^{-1/2} = 973 \text{ bun}$$

$$\Delta U_1 = 4 \, GeV \Rightarrow q_b = 12.1 \, nC$$

Changing the RF frequency

G.G. CLIC Note 188

Considering 3 frequencies 15 24 30 GHz

Making 3 different assumptions

1) Same average power per unit length

$G \sim \omega_0 \longrightarrow$ 64 MV/m at 24

2) Same average power per section $\ell \sim \omega^{-1}$

$G \sim \omega_0^{3/2} \longrightarrow$ 57 MV/m at 24

$\Delta E_b \sim \omega_0^2$ decelerating field / unit length

3) Same total average power

$G \sim \omega_0^2 \longrightarrow$ 51 MV/m at 24

Tracking (statistics on 10 samples):

f	15 GHz	24 GHz	30 GHz
$\langle \gamma \varepsilon_y \rangle$	$2\ 10^{-7}$	$1.5\ 10^{-7}$	$2\ 10^{-7}$

~ indep. of G

$\Longrightarrow$ Gain of 25 - 30 % on $\gamma\varepsilon$

i.e. 15 % on $\mathcal{L}$!

Gain on the E-spread of drive beam

$\Delta E_{max} = 1.5$ instead of 2.3 GeV

10% reduction of the injection D.B. energy

(W. Wuensch)

Ramifications of Multibunching on Diverse CLIC Hardware

14-10-94

Adopting multibunching in CLIC will require major changes in a number of accelerator components and diagnostic devices.

Alignment system:	Repetition rate is probably lower to keep total power constant. This increases the sensitivity of the machine to ground movements.
BPMs:	Current BPMs are resonant and are tailored for single bunches. The BPMs could be adapted to 2 or 3 bunches with tricks. BPMs could give the average position of longer trains: is this sufficient? Transverse wakefields would be roughly .25% assuming one BPM per 4 sections.
Crab cavities:	Cavities plus a local power source must be developed.
Damping rings:	Are multibunch effects important?

Emmitance measure:	Doesn't exist even for single bunches. Will corrections of single bunch effects automatically be applied correctly on successive bunches (compensation for short range wakefields for example)?
Experiment:	A bunch spacing between .1 and 1 nsec is very fast.
Final focus Quads:	Must pass disrupted beam.
Positron production:	Need between 2 and 50?! times the positron flux.
RFQs:	Horizontal and vertical dipole modes must be detuned separately. Are computation and machining - milling - accurate enough? Do the damping schemes proposed by others work for non circular geometries - 3 output guides and chokes in particular?
Vacuum	Desorbed ions may cause emmitance blow up with trains, irrelevant for single bunches.

Possible parameters for 0,5 TeV cm ?

2 x 250 GeV — Resulting from re-optimization

$N = 8\ 10^{9}$

$\sigma_z = 0.2$ mm — $\Delta p/p)_{linac} = 0.22$ % — < 10 μm > tol.

$\gamma\varepsilon_x = 3 \cdot 10^{-6}$ — $\beta_x^* = 6.6$ mm

$\gamma\varepsilon_y = 2 \cdot 10^{-7}$ — $\beta_z^* = 0.3$ mm (?)

$\sigma_x^* = 200$ nm — $R \cong 15$

$\Longrightarrow \mathcal{L} = .72\ 10^{33}$

$\delta_B = .06$

$\Upsilon = 0.10$

$\mathcal{L}_{38\%}/\mathcal{L} \cong 50\%$

All single bunch values.

How to reach the target defined by "physics" and/or "review committee" ?

a) Double the repetition rate

$\Longrightarrow \mathcal{L} = 1.4\ 10^{33}$ — $f_{rep} = 34$ kHz, 1 bunch

b) Push the control of emittance with beam-based correction ($\gamma\varepsilon_y \cong 10^{-7}$)

$\Longrightarrow$ factor $\sqrt{2}$ — idem

$\mathcal{L} = 2\ 10^{33}$

c) Use the recirculation scheme to get another factor 2

$\Longrightarrow \mathcal{L} = 4\ 10^{33}$ — $f_{rep} = 1.7$ kHz, 4 bunches, 10 ns sep.

Possible parameters for 1 TeV cm ?

2 × 500 GeV

Can we start with $8\ 10^9$ and $4\ 10^{33}$
per bunch ? multibunch ?

Probably too optimistic and let us take $6\ 10^9$ with (assuming attenuation O.K.)

$\sigma_x^* = 150$ nm $\quad \delta_B \approx .06 \quad \Upsilon \approx 0.1$

$\Rightarrow \mathcal{L} = 0.5\ 10^{33}$

With same tricks as before: $2 \times 2 \times \sqrt{2}$

$\rightarrow \mathcal{L} \approx 3\ 10^{33}$

To reach the "review committee" target, we miss a factor <u>3~~4~~ to 5</u>.

No hope to get it from
- the emittance
- the injection energy
- a 20% reduction of f_{RF}

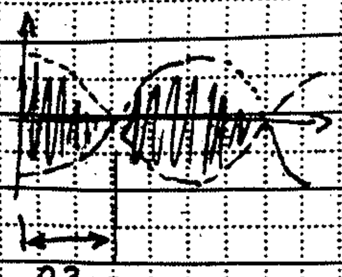
Only one way out ?

Multibunch w. at least 5 bunches or many more with same charge

→ Do nothing in first option to prevent multibunch ? $\mathcal{L}_{mb} = 8\mathcal{L}_{sb}$

→ Define the required attenuation !

MULTI-BUNCH (I.W. W.W)



RESUME

Reference value for single bunch

$N = 6 \times 10^9$

$L = ~~0.7~~\ 0.5 \times 10^{33}$ $P \simeq 70$ MW

Key no.

Short trains

$A_s = ?$ for 4.2×10^9 for 2 bunches

A=100

$f_{rb} = 2$ (f beating)
$\Delta f = 1$ GHz
tol. ≃ 8 MHz

simple b.l.c

$n_b = 4$, $\Delta t = 0.3$ns ?

N_4	A_s	N_1/N_4	L_4/L_1	P_4/P_1	$(L/P)_{4/1}$	
1×10^9	250	6	1/9	1.19	1/11	
4.2×10^9	(60)	√2	2	1.19	1.7	← 2.0
6×10^9	40	1	4	1.19	3.4	

$n_b = 4$, $\Delta t = 1$ns O.K.

N_4	A_s	N_1/N_4	L_4/L_1	P_4/P_1	$(L/P)_{4/1}$
1×10^9	250	6	1/9	1.89	1/17
4.2×10^9	60	√2	2	1.89	1.06
6×10^9	40	1	4	1.89	2.1

Long trains

$A_s = ?$ for 4.2×10^9 for 2 bunches
Damped/Detuned structures
A=65
60 bunches in 5+1 fill times
√60 wake increase assumed to be compensated
by damping (Q=160) for long times

$\Delta t \simeq 0.8$ns

A_s	N ($\times 10^9$)	$(L/P)_{n/1}$	$\Delta t \simeq 0.3$ns
250	1.1	0.36	0.58
100	2.73	2.23	3.60
60	4.2	5.3	8.5

Without better estimate of As
difficult at this moment
to take a decision !