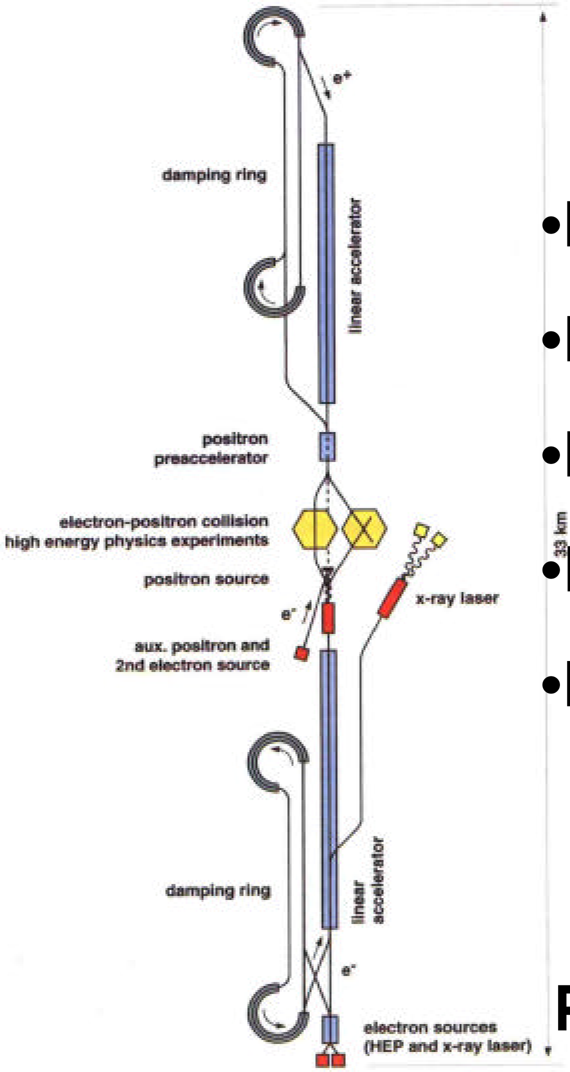
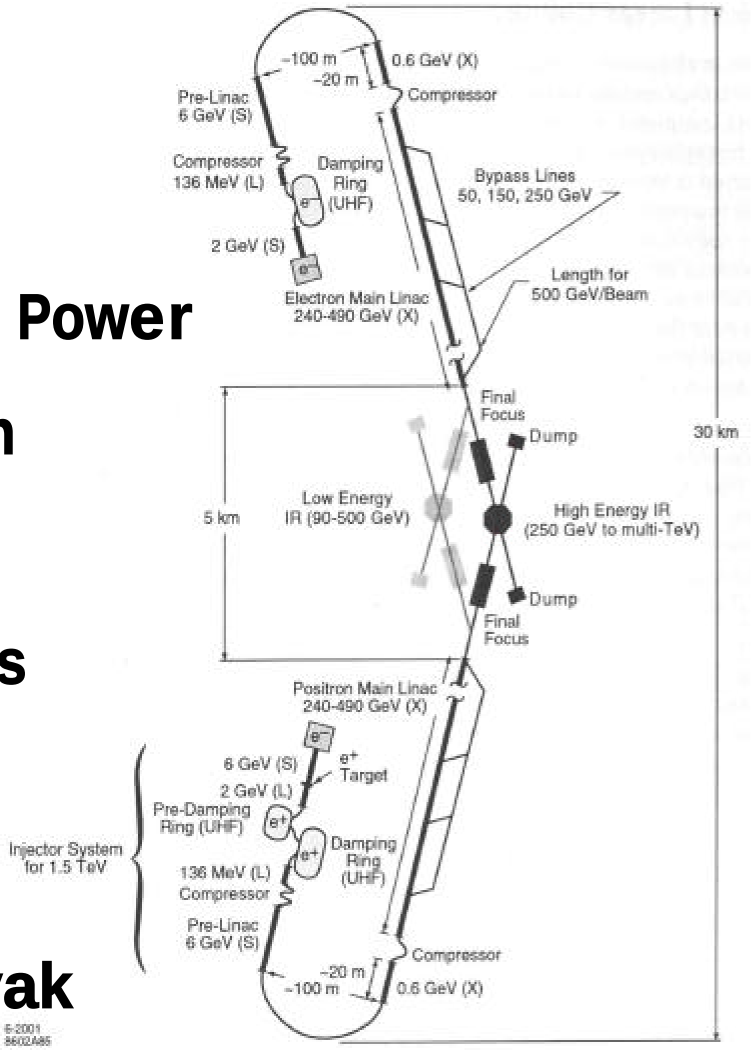
NLC-I – TESLA-500 COMPARISON



H.Weise 2000

- •Luminosity
- •Efficiency & Site Power
- •Emittance Dilution
- •Damping Rings
- •R&D Achievements



P. Bauer, N. Solyak

NLC-I – TESLA-500 COMPARISON

Parameter	TESLA		NLC/JLC	
Energy c.m. TeV	0.5	0.8	0.5	1.0
Luminosity $*10^{34}$ $cm^{-2}*s^{-1}$	3.4	5.8	2.0	3.4
Frequency GHz	1.3		11.424	
N/bunch, 10^{10}	2	1.4	0.75	
Bunches in train/ Rep. Rate	2820 /5	4886 /4	192 / 120 (JLC-150)	
Bunch spacing, ns	337	176	1.4	
Bunch train, μs	950		0.27	
Energy spread δ_E (%)	3.2	4.3	5.4	10.4
Photons per electron	1.5		1.2	
$\varepsilon_{ny}/\varepsilon_{ny}$, $*10^{-8}$ m	1000/3	800 / 1.5	360/3.5	
σ_{ny}/σ_{ny} nm	553/5	391 / 2.8	245 / 2.7	190 / 2.1
β_x/β_y, mm	15 / 0.4		8 / 0.11	13/0.11
σ_z, μm	300		110	
Disruption parameter, D	25		14	
Pinch factor H_D	2.1		1.43	1.5
Total Length, km	33		15	30
Gradient, MV/m	23.4	35	48.5	55
AC/beam power, MW	105 / 2x11.3	150/	140 / 2x6.9	(?)

NLC-I – TESLA-500 COMPARISON

Luminosity - I

	NLC-I	TESLA-500
Av. beam power (MW)	6.9	11.3
s^*_x / s^*_y at IP (nm)	245 / 2.7	553 / 5
s^*_z at IP (mm)	110	300
Hourglass s_z/b^*_y	1	0.75
Disruption D_x / D_y	0.16 / 14.2	0.22 / 24.8
Pinch Factors H_{Dx} / H_{Dy}	1.02 / 1.41	1.03 / 1.74
Total Pinch H_D	1.13	1.22
Luminosity (10^{34}cm^{-2}s^{-1})	1.75	2
BS phot / e^+/e^- pair	1.2	1.5
BS phot / cross (´10^{10})	0.9	3
d_E [%]	4.5	2.9

NLC-I – TESLA-500 COMPARISON

Luminosity - II

$$L = \frac{N_b N_{e-} N_{e+} f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D$$

Beam-power!

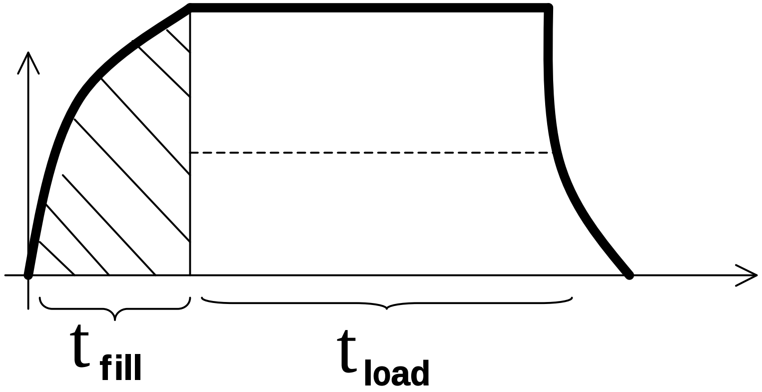
$$L \approx \frac{P_b}{E_{cm}} \sqrt{\frac{\delta_E \times HG}{\varepsilon_{Ny}}} \times H_D$$

$$\frac{L_{NLC}}{L_{TESLA}} \approx \left[\frac{0.61}{1}\right] \sqrt{\frac{1.55 \times 1.47}{1.17}} (0.93) = 0.75$$

NLC-I – TESLA-500 COMPARISON

Efficiency and Site Power – I – Pulse Duration

Quality Factor Q_0: 10^{10} (TESLA) / 7500 (NLC)



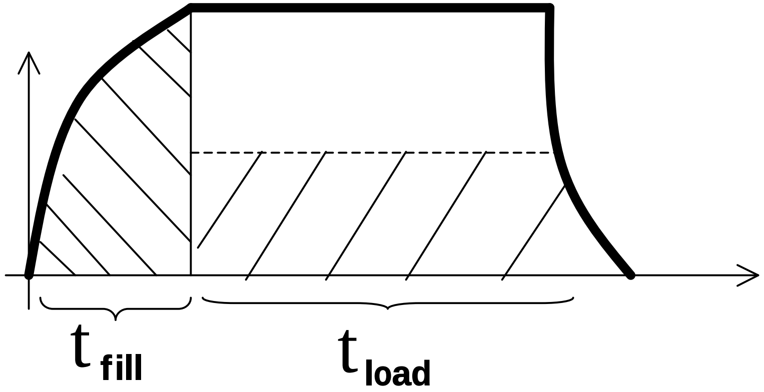
t_{fill} « f/Q / P_{peak} in NLC / TESLA

t_{load} « T / DR in NLC TESLA

	NLC-I	TESLA-500
RF pulse flat-top duration, t_{flat} (ms)	0.293	880
RF pulse total duration, t_{tot} (ms)	0.396	1300
RF pulse efficiency, t_{flat}/t_{tot}	0.75	0.61

NLC-I – TESLA-500 COMPARISON

Efficiency and Site Power – II – Wall Loss



$$p_w = \frac{2G_{UL}^2}{z_c\,Q_0} \quad (W/m)$$

$\downarrow$

R/Q (shape fact.– indep.of R_{surf})

1.036 kW/m (TESLA) / 13 kW /m (NLC)

	NLC-I	TESLA-500
Loaded gradient (MV/m)	48	23.4
Bunch train current (mA)	858	9.5
Peak RF power /m at beam (kW/m)	41184	222
Peak RF power loss /m in wall (kW/m)	46000	0.1
Wall power loss factor h_{wall}	~0.5	~1

NLC-I – TESLA-500 COMPARISON

Efficiency and Site Power – III – Auxiliary Power

TESLA cavities operate at 2 K, where the Carnot factor is 500. The additional cryo efficiency factor is therefore:

$$\eta_{cryo} = \frac{p_{beam}^{peak}}{p_{beam}^{peak} + p_{cryo}^{peak} \times f_{Carnot}}$$

The cryo-efficiency can be generalized to include as well the static cryo- and other auxiliary power loads (modulator regulation, klystron solenoid..)

	NLC-I	TESLA-500
Peak RF power /m at beam (kW/m)	41184	222
Aux. peak dyn. RF plug power /m (kW/m)	-	60
Aux. av. stat. plug power /m (kW/m)	0.58*	0.27*+0.295*
Duty Factor (%)	0.0048	0.65
Auxiliary efficiency, η_{aux}	0.77	0.6

NLC-I – TESLA-500 COMPARISON

Efficiency and Site Power – IV – RF Efficiency

The NLC and TESLA RF systems are characterized by different frequencies. The NLC, X-band technology is still in development.

	NLC-I	TESLA-500
Modulator efficiency (%)	80	85
Klystron efficiency (%)	55	65
Transmission line efficiency, (%)	85	98
RF system efficiency, η_{RF}	0.38	0.54

NLC-I – TESLA-500 COMPARISON

Efficiency and Site Power – V – Total Efficiency

$$h_{tot} = h_{struct} \times h_{wall} \times h_{RF} \times h_{aux}$$

$$h_{NLC} = 0.75 \times 0.5 \times 0.38 \times 0.77 = 0.11$$

$$h_{TESLA} = 0.61 \times 1 \times 0.54 \times 0.6 = 0.2$$

	NLC-I	TESLA-500
RF pulse, total duration (fill+flat), (ms)	0.396	1300
RF pulse, flat-top duration, (ms)	0.293	880
RF structure efficiency, h_{struct} (%)	75	61
Wall loss factor, h_{wall} (%)	50	100
Modulator efficiency (%)	80	85
Klystron efficiency (%)	55	65
Transmission line efficiency, (%)	85	98
RF system efficiency, h_{RF} (%)	38	54
Aux. peak dyn. RF plug power /m (kW/m)	-	60**
Aux. av. stat. plug power /m (kW/m)	0.58	0.27+0.295**
Auxiliary efficiency, h_{aux} (%)	77	60
Plug-to-beam power efficiency, h_{tot} (%)	11.6	24.4

NLC-I – TESLA-500 COMPARISON

Efficiency and Site Power – Summary

$$p_{site} = h_{tot} \times 2 p^{beam}_{av} = h_{tot} \times 2 p^{beam}_{peak} \times DF$$

	NLC-I	TESLA-500
Loaded gradient (MV/m)	48	23.4
Bunch train current (mA)	858	9.5
Peak RF power /m at beam (kW/m)	41184	222
Active 2-linac length, (m)	2´5208	2´10680
Beam duty factor, DF, $t_{load} f_{rep}$ (%)	0.0035	0.44
Average Beam power (MW)	6.9	11.5
Av. 2-linac site power (RF+cryo), (MW)	124.2	85.7
Plug-to-beam power efficiency, (%)	11.6	24.4

* including RF overhead

With a two times lower plug-to-beam power efficiency NLC-I requires ~50% more site-power to operate at ~50% less average beam-power than TESLA-500.

NLC-I – TESLA-500 COMPARISON

Emittance Dilution I

Transverse wake-potential $W_{\wedge} \sim a^{-3}$:
NLC/TESLA $\rightarrow (4.6/35)^{-3} \sim 440$

Transverse kick $\sim W_{\wedge}$N:
NLC/TESLA $\rightarrow (2/0.75)440 \sim 165$

Emittance dilution $\sim (W_{\wedge}\text{N})^2$:
NLC/TESLA $\rightarrow 165$

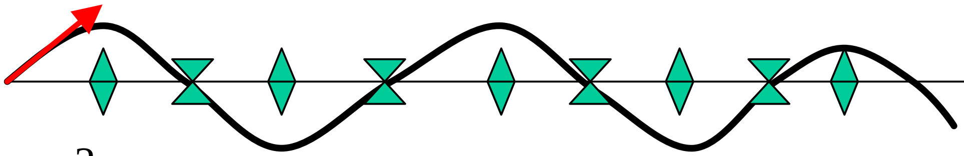
Transv. Wake Control	NLC-I	TESLA 500
Single-Bunch	BNS	-
Multi-Bunch	D&D	D&D

+ Beam Based Alignment!

NLC-I – TESLA-500 COMPARISON

Emittance Dilution – IIa - Model

By K. Bane / SLAC:



kick-angle: $$q_{kick,m} = \frac{e^2 N W_\perp L_s}{E_m} \Delta y_{s,m}$$

Displacement at end of linac after one kick in structure m:

$$\Delta y_{f,m} = q_{kick,m} b_m \sqrt{\frac{b_f}{b_m}} \sqrt{\frac{E_m}{E_f}} \sin\left(m_{f,m}\right)$$

Phase-diff:

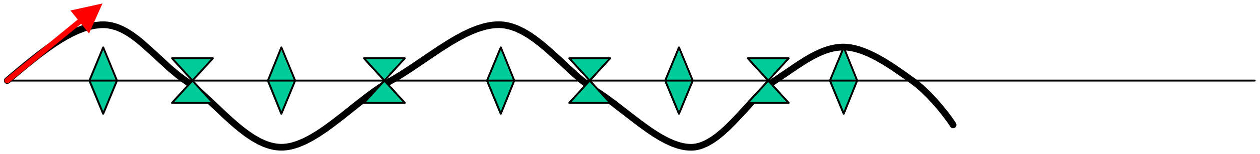
Optical magn. adiab. damping

Sum of kicks from all structures, with : $\beta \sim E^{1/2}$

$$y_f = \sum_{m=1}^{N_s} \Delta y_{f,m} = e^2 N L_s \left\langle W_\perp \right\rangle \sqrt{\frac{b_f}{E_f}} \sum_{m=1}^{N_s} \Delta y_{s,m} \sin\left(m_{f,m}\right) \sqrt{\frac{b_m}{E_m}}$$

NLC-I – TESLA-500 COMPARISON

Emittance Dilution – IIb - Model



With:

$$\Delta e = \frac{\left\langle Y_f \right\rangle^2}{b_f}$$

and statistics

one obtains:

$$\Delta e_s = e^4 N_e^2 \overline{b}_i N_s L_s^2 \left\langle \Delta_{s-rms} \right\rangle^2 \left\langle S_{rms} \right\rangle^2 \left[\frac{1 - \sqrt{E_i / E_f}}{\sqrt{E_i}\, E_f^{3/2}} \right]$$

NLC-I – TESLA-500 COMPARISON

Emittance Dilution II

Alignment specs as calculated with Bane model:

Parameter	NLC-I	TESLA 500
Linac injection energy, E_i (GeV)	8	5
Linac collision energy, E_f (GeV)	250	250
Bunch charge, (nC)	1.2	3.2
Number of structures / linac, N_s	5602	10296
Length of structure, L_s (m)	0.9	1.038
Number of quads / linac, N_q	233	365
Typical FODO cell length, L_c (m	48	80
Initial average b-function, b_i (m)	12	64
FODO cell phase adv., m (deg)	90	60
Transverse multi-bunch sum wake-potential (V/pC/m/mm)	0.7	0.003
Struct.-to-struct. misalign. rms (mm) for 1% emitt. dil.	44	940
Quad to beam. offset. rms (mm) for 25% emitt. dilution	1.3	18

TESLA/NLC~20

NLC-I – TESLA-500 COMPARISON

System Alignment Specs according to design reports:

Parameter	NLC-I	TESLA 500
e_N, injection linac (mm-mrad)	3/0.02	8/0.02
e_N, final focus (mm-mrad)	3.6/0.035	10/0.03
Transverse multi bunch e dilution objective (%)	< 40	< 50
Struct.-to-struct. misalign. rms (mm) / emitt. dil. (%)	30 / 1%	500 / 3%
Quad to beam offset rms (mm) / emittance dilution (%)	2 / 25%	300 / ?
Quad rotation. rms (mrad) / emittance dilution (%)	200 / 4%	200 / ?
BPM resolution rms (mm) / emittance dilution (%)	5 / 3%	100 / ?

NLC-I – TESLA-500 COMPARISON

Damping Rings

Of the 10^6 ratio in quality factors between state of the art superconducting cavities and conventional RF structures, only 3 orders in magnitude difference remain in bunch train length. This is, in part, the result of constraints set by damping. The damping cannot be accomplished on-line (e.g. using linear damping) because the specified (normalized) emittance reduction is 2-3 orders of magnitude. The damping time in the TESLA e^- damping ring, for example, is 50 ms, which corresponds to ~10^3 revolutions (each time crossing through ~400 m of wiggler). The unfolded TESLA bunch train is 285 km long. With a maximum bunch train compression of 17 set by the limit in kicker technology at ~20 ns, this bunch train fits into a 17 km ring. The bunch train has to be unfolded into the main linac kicking out a bunch every 337 ns, which is the long bunch spacing necessary to allow for sufficient HOM damping (as discussed in 5). Therefore the damping ring has been identified as the major limitation of the TESLA design.

NLC-I – TESLA-500 COMPARISON

R&D Achievements

Experiment	Achievement	
ATF (1.3 GeV NLC-MDR prototype)	vert. emitt. ε_{Ny}	$3 \cdot 10^{-8}$ m-rad (single bunch only!)
FFTB (FF experiment in SLC)	Demagnification σ_y(linac)/σ_y(IP)	~600
TTF1 (DESY TESLA TEST FACILITY)	Bunch charge q_b Gradient	4 nC (0.8 ms bunch train, 1 Hz) 25 MV/m
NLCTA ASSET	Gradient Damping and detuning	70 MV/m for 400 ns Good agreement with wakefield prediction