Linear $e^{\pm}$ Colliders
Comparing TESLA, JLC/NLC and CLIC

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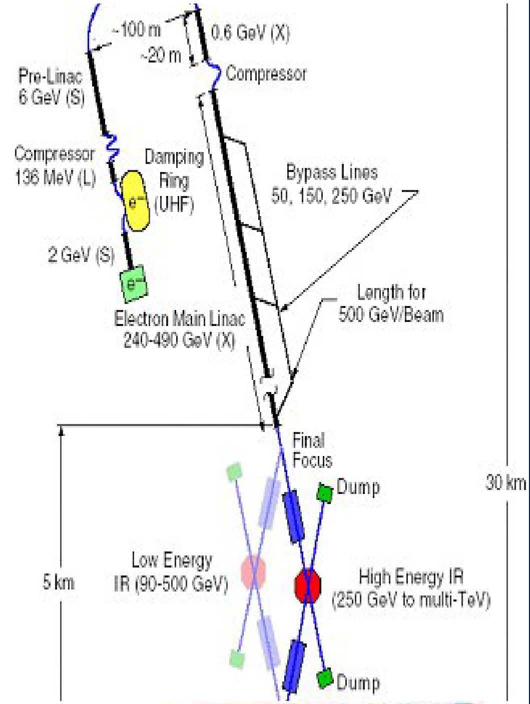
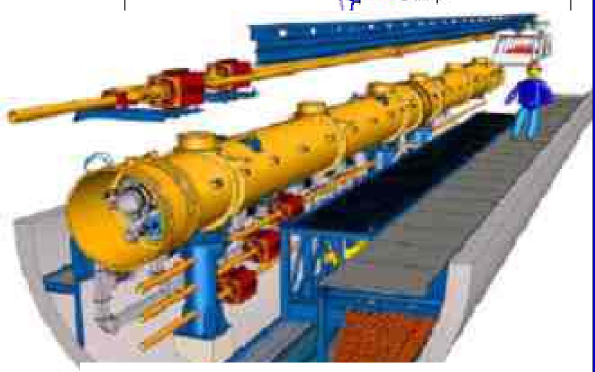
Summary

General Layout of Linear Colliders

NLC e^--linac layout





TESLA simulation

Photo-Injector

(ε_N<100 mm-mrad rms, l_b<10 mm, I_b= 10 mA)

↓

Damping Ring(s)

(ε_{yN}<0.015 mm-mrad rms, l_b<5 mm, P_{SR}= 2 MW)

↓

Bunch Compressor & PreLinac

($\Delta E/E$<3%, l_b<0.3 mm, E_b~10GeV)

↓

Main Linac

(E_b=250 GeV, $\Delta\varepsilon/\varepsilon$<100%, P_{AC}<200 MW, L<30 km)

↓

Final Focus

(σ_x<500 nm, σ_y<5 nm σ_z<300 µm, H_D=1-2, $L>2\cdot10^{34}$)

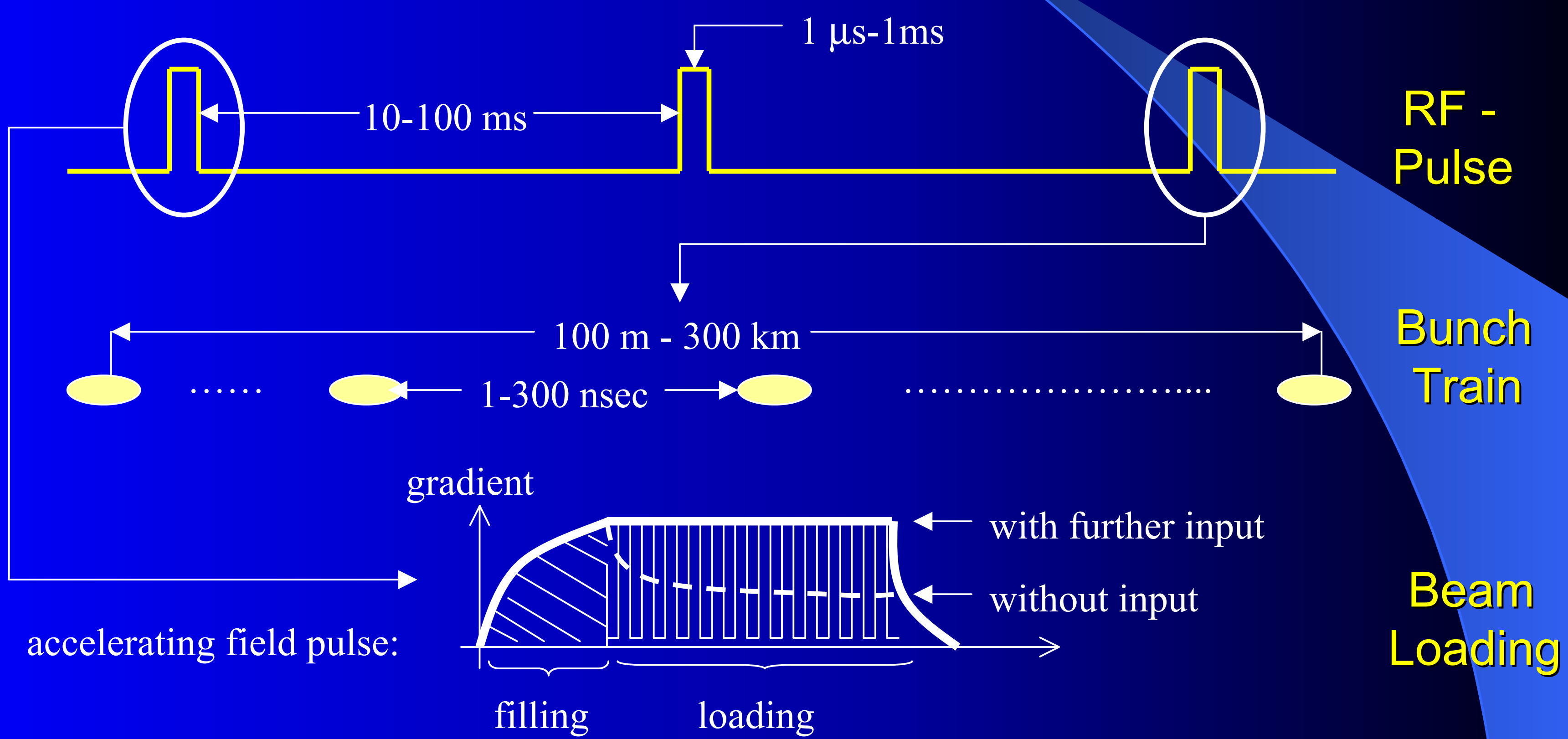
↓

Beam Dump

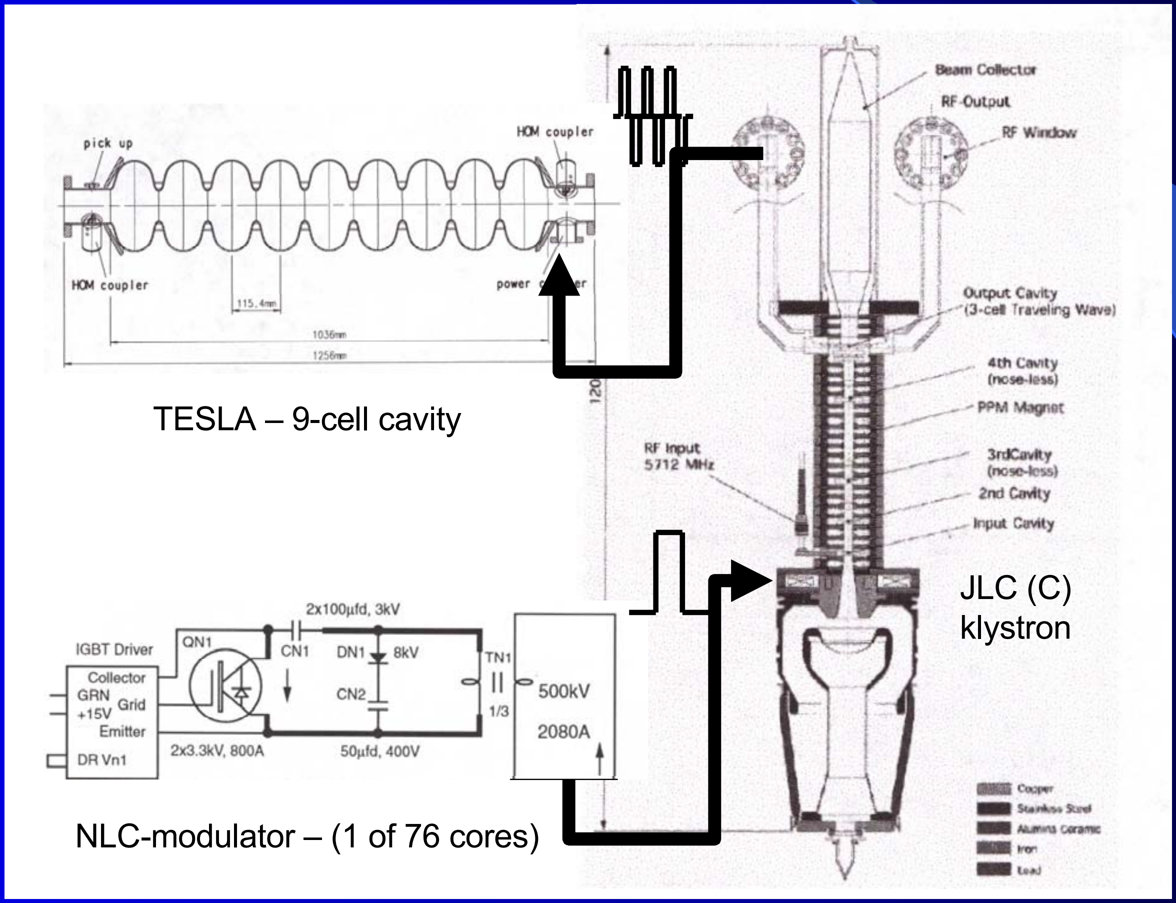
(P=10MW/beam)

Linear Collider Beam Structure

LCs are *pulsed* machines to improve efficiency. As a result the duty factors are small (e.g.: <0.1%) and the pulse peak powers can be very large (e.g.: 100 GW)!



Transfer of power from plug to beam is achieved through the following chain of devices: modulator → klystron → structure

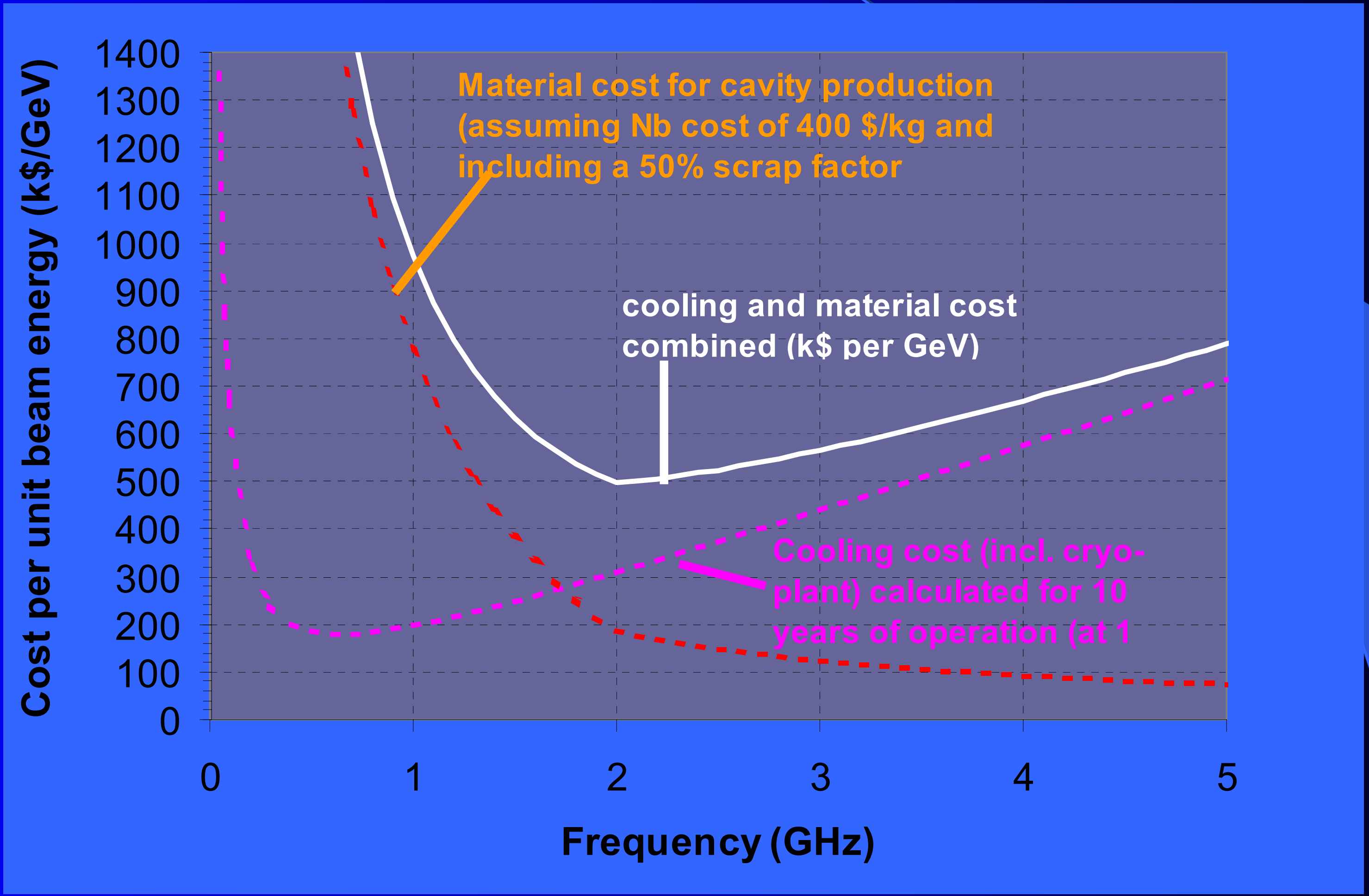


Superconducting Cavities for TESLA - introduction

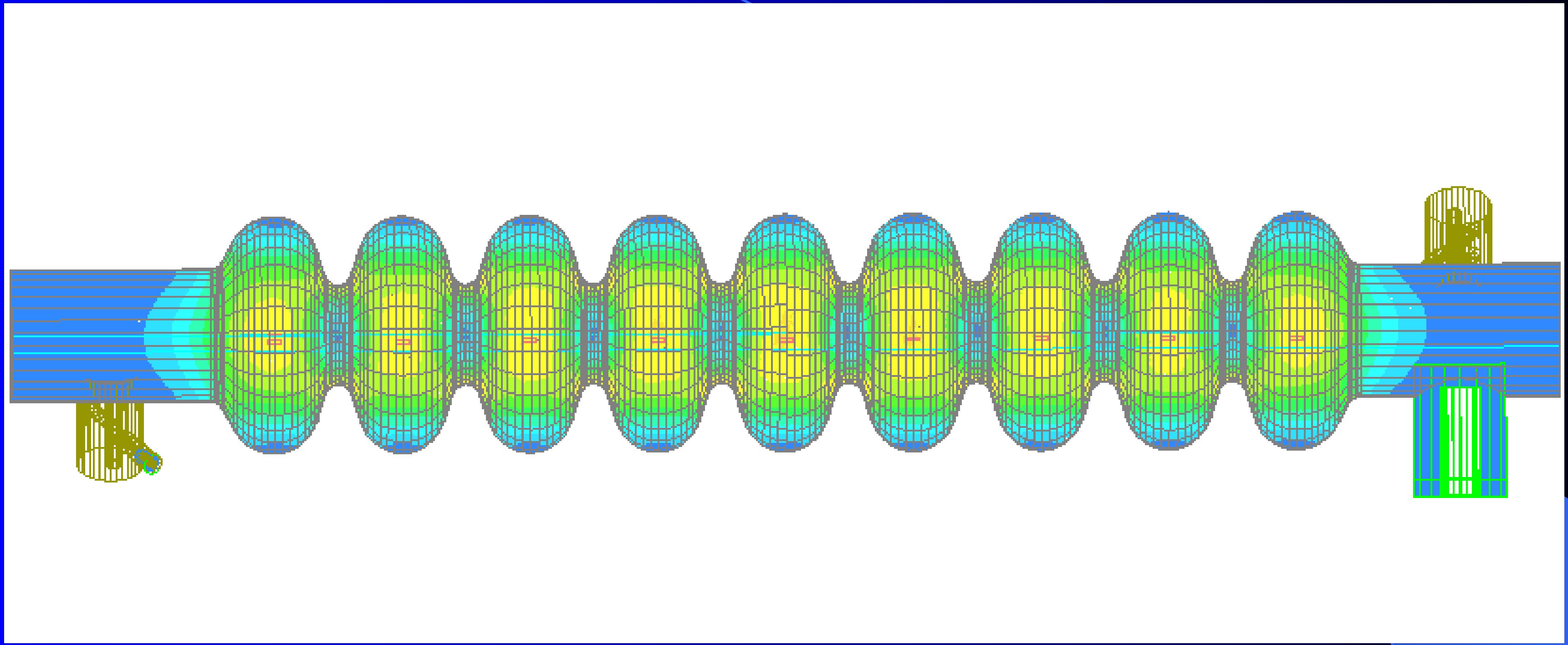
Extremely high Q (10^{10}) resonator because of superconducting, low resistivity surfaces → low dissipation in walls (~100 W/m). Long filling time (depends only on Q!) with low peak power preferred → commercial klystron technology (10 MW). Standing wave - π-mode. SC RF is optimized for longer pulses, limited by damping ring size, also limited in terms of minimum bunch spacing because of HOMs. The surface resistance is not entirely zero and this makes continuous operation impossible! 50 MV/m on axis gradient believed to be maximum achievable in Nb at 2 K (=~200 mT on equator). Cost now 100 k$/m! Frequency in Nb is optimal at ~1.5 GHz – multi-dimensional problem, involving material cost, cooling cost (dissipation in surface resistance), gradient and Q, operational temperature.

Superconducting Cavities for TESLA – Optimum Frequency

Optimum frequency calculation for TESLA type cavity incl. cooling cost ($\sim R_s(f^2)A_{cell}(f^{-2})N_{cell}(f)$) and material cost ($\sim A_{cell}(f^{-2})N_{cell}(f)Th(f^{-1})$). Calculation performed for fixed gradient of 23.4 MV/m, fixed T=2K, fixed residual resistance of 3 nΩ!



Superconducting Cavities for TESLA - Fields



Standing wave pattern is produced due to cut-off reflection in beam tubes at both ends. The smaller the tube diameter the higher the cut-off frequency. Also the cell-to-cell coupling (~1.78%) is regulated through cut-off.

Structures for NLC - Characteristics

average loaded/unloaded gradient: ~50/70 MV/m

cost per disc in R&D-/mass-production: ~300$ / 10$

structure length / a/λ: 0.9 m (90 cells) / ~0.18

variation of group velocity / iris $\varnothing$: 5-1% / 11-8 mm

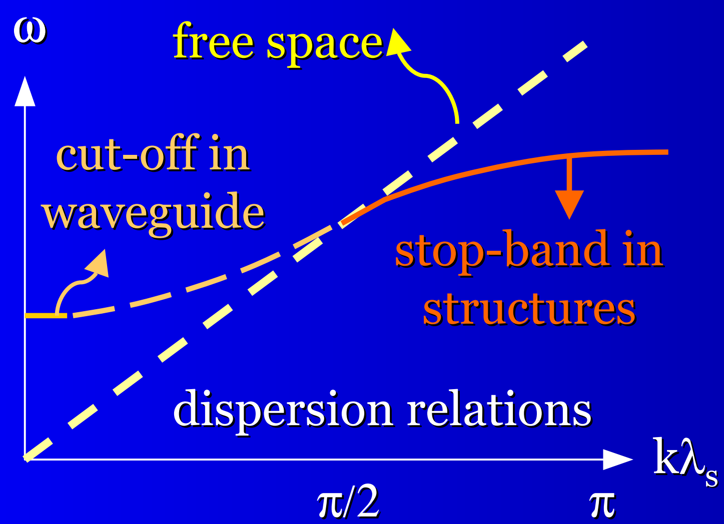
phase advance: $5\pi/6$ (150°)

Detuning frequency spread / damping: 8% / 4 damping manifolds

disc machining / disc-to-disc alignment precision: 5 μm / 10 μm

Total of more than 10^6 discs required for a 500 GeV cm NLC !

Structures for NLC Linac - Basics



"Structures" → derivative of waveguide. Obstructions induce reflections →"stop-bands". Phase velocity ω/k always >c in wave-guide and possibly <c in structures. Group-velocity dω/dk is 0 at $\Delta\phi_{cell}$=0 and π. The control of group- and phase velocities is the major aspect of structure design. Each structure geometry (a/λ) and mode have a characteristic dispersion relation.

stored energy – damage → max L

cost – # of couplers → min L

1) large Δφ → v_g↓, L ↓, E_{stored} ↓, a/λ ↑, $E_{surface}$ ↑, standing wave, G_L, N_{cell} ↓;

2) small Δφ → v_g ↑, L ↑, E_{stored} ↑, a/λ ↓, $E_{surface}$ ↓, traveling wave, G_{UL}, N_{cell} ↑;

structure design parameters:

L, a, b, N_{cells} (v_g, dv_g/dz, Δφ)

wake-fields → min a/λ

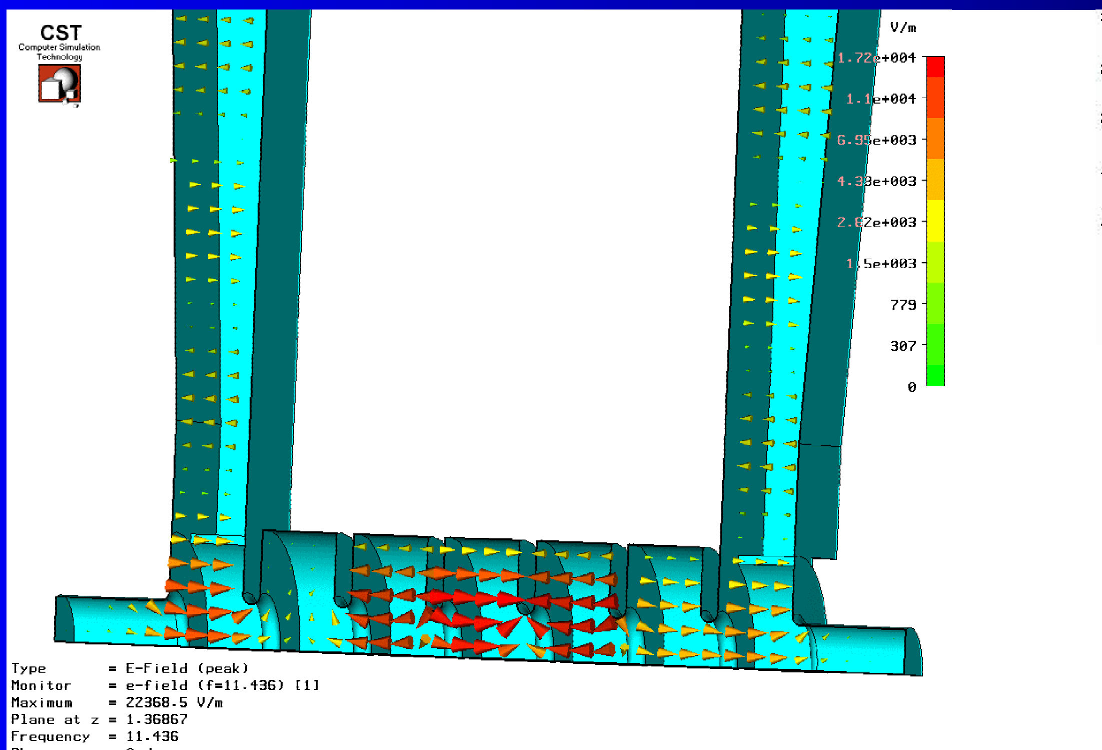
break-down → surface fields → max a/λ

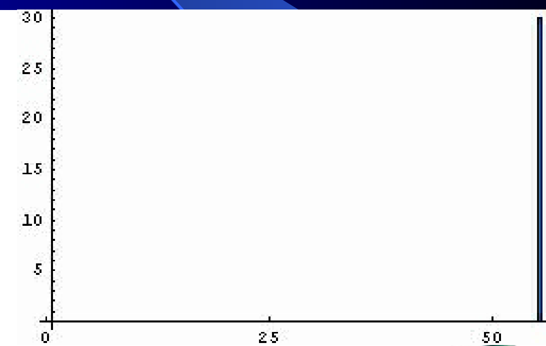
efficiency → fill time → max Q, min v_g

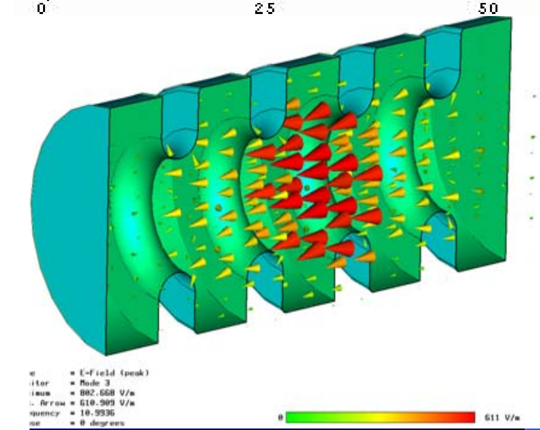
dv_g/dz for G= const.

Traveling Wave Structures for NLC - Fields

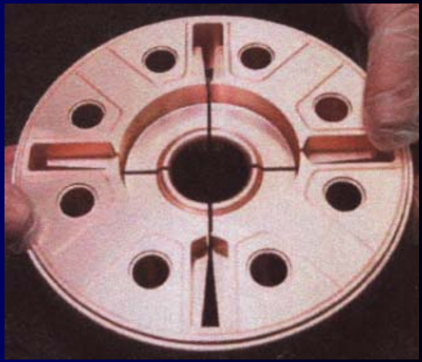
Pulsed EM fields (TE110 mode) are sent down rectangular waveguides (2 in symmetric arrangement) and couple into structure (TM01 mode). The pulse has to be short because of the high wall loss (~100 MW/m). Promise of higher gradients. Decreasing iris diameter along the structure introduces group velocity gradient to obtain constant gradient structure (under beam loading conditions, however, the gradient is not constant – the quoted gradients are averages along the structure). Damping and detuning to cope with wake-fields.







CLIC – 2 Beam Acceleration - Basics



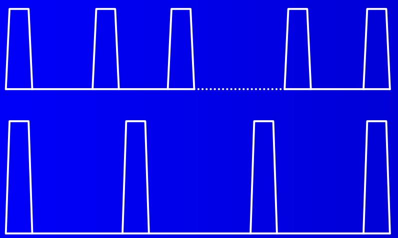
Higher RF frequency →higher gradient; 2-beam acceleration scheme = high frequency (e,g, 30 GHz) RF power generator: deceleration of 2 GeV, high charge drive-beam in low impedance structures (each drive beam bunch induces a pulse, such that a ~1 cm bunch spacing gives a 30 GHz first harmonic RF signal)

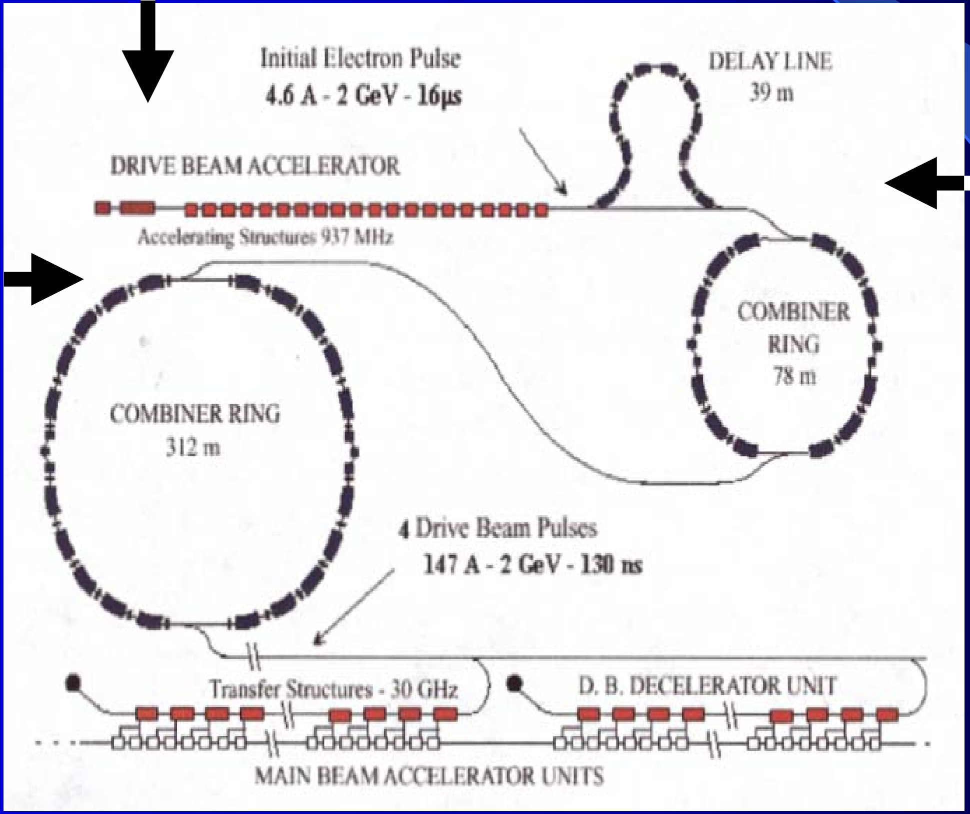
RF power and pulse-shape given by drive beam charge, bunch length / spacing and decelerating structure impedance; Current CLIC design: 625 m long, 70 GeV unit with 909 0.5 m long structures (made from 150 cells each) and 455 PETS; Main advantage of 2 beam scheme: RF pulse parameters (frequency, timing, power,..) are obtained through manipulation of drive beam, which can be transported with little loss. The huge drive beam charge is accumulated with long moderate power pulses and compressed 32 fold to produce large peak power (460 MW/m). 2-beam acceleration also promises higher efficiency because of its low frequency, moderate power drive beam RF system. Structure design: TW, $3\pi/2$ mode, damped (SiC absorber) and detuned (3.5 – 4.5 mm iris ∅). Small bunch population, short bunches to reduce wake-fields. Tungsten irises!

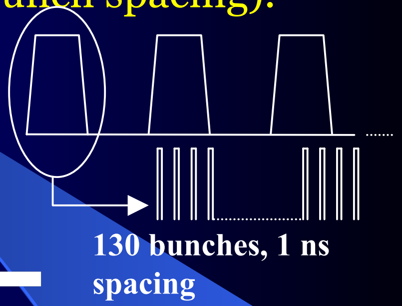
CLIC – 2 Beam Acceleration Principle

32-fold frequency and pulse power multiplication!

1GHz DBA - 16.7 µs pulse - ~8000 bunches (10 nC), hundred-twenty-eight 130 ns sub-pulses a 65 bunches with even (E) or odd (O) buckets occupied (~2ns bunch spacing).







4 pulses combined in 1st combiner ring (78 m, 260 ns) → sixteen 130 ns pulses a ~520 bunches, 0.25 ns bunch spacing, 520 ns gaps. 2nd combiner ring (312 m, ~1ms) → four 130 ns pulses with ~2000 bunches (63 ps bunch spacing) 2 ms gaps → four 625 m long decelerating units.

Every 2nd sub-pulse is folded back into the next sub-pulse with a 39 m (130 ns) delay line → sixty-four 130 ns sub-pulses a 130 bunches, with 1 ns bunch spacing and 130 ns gaps between the pulses.

LC General Parameter Table – 500 GeV cm Version

	TESLA	JLC (C)	JLC/NLC	CLIC
RF Frequency in Main Linac (GHz)	1.3	5.7	11.4	30
Design Luminosity ($\cdot 10^{34} cm^{-2} sec^{-1}$)	3.4	1.4	2.5/2	2.1
Linac Repetition Rate (Hz)	5	100	150/120	200
No. of Particles per Bunch ($\cdot 10^{10}$)	2	0.75	0.75	0.4
No. of Bunches per Pulse	2820	192	192	154
Bunch Separation (nsec)	337	1.4	1.4	0.67
Bunch Train Length (μsec)	950	0.267	0.267	0.102
Beam Power per Beam (MW)	11.3	5.8	8.7/6.9	4.9
Unloaded Gradient (MV/m)	23.4	41.8	70/65	172
Loaded Gradient (MV/m)	23.4	31.5	55/50	150
Norm Emitt, ε_{Nx},ε_{Ny}, after DR (10^{-6}m-rad)	8/0.02	3/0.02	3/0.02	1.6/0.005
Two-Linac-Length (km)	30	17.1	12.6/13.8	5
Total Site AC Power (MW)	140	235	215/195	175

LC Linac Parameter Table – 500 GeV cm Version

	TESLA	JLC (C)	JLC/NLC	CLIC
RF Frequency in Main Linac (GHz)	1.3	5.7	11.4	30
Loaded Gradient (MV/m)	23.4	31.5	55/50	150
Q Unloaded	10^{10}	9772	~9024	~3625
Shunt Impedance (MΩ/m)	10^{7}	54.1	81.2	~83
Klystron Peak Power (MW)	9.7	50	75	50
RF Pulse – before/after compr. (µs)	1370/1370	2.8/0.55	1.6/0.4	18/0.13
Filling Time (µs)	420	0.285	0.120	0.03
Total No. of Modulators	572	4276	468/508	432
Total No. of Klystrons	572	4276	3744/4064	432
Cavity/Structure Length (m)	1.04	1.8	0.9	0.5
Total No. of Structures/Cavities	20592	8552	11232/12192	7272
Plug to Beam Efficiency (%)	23.3	6.2	9.6/8.8	8.6

Efficiency of Structures/ Cavities

Beam power and size are the main ingredients for the luminosity of a linear collider:

$$L \sim P_b/\sigma_y$$

Efficiency and site power limitations are driving the beam power of the LC design. The main difference between the NC and SC designs lies in their plug-to-beam power efficiency. The difference in efficiency is related in part to the amount of losses in the wall. The wall loss can be calculated from the unloaded gradient and the shunt impedance. A wall loss factor, η_{wall}, can be derived from the beam power (beam-current x accelerating voltage/m) and the wall loss.

$$P_W = \frac{(E_{acc})^2}{z_S} \quad \left(\frac{W}{m}\right)$$

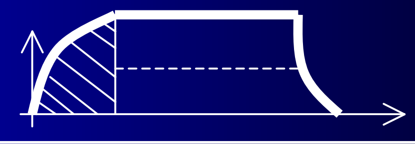
$$\eta_{wall} = \frac{P_{beam}}{P_{beam} + P_W f_C}$$

Wall Loss Factor at 500 GeV cm	TESLA**	NLC	CLIC
Loaded, Average Gradient (MV/m)	23.4	50	150
Average Bunch Train Current (mA)	9.5	868	972
Peak RF Power/m at Beam (kW/m)	222	42900	145757
Peak RF Power Loss in Wall (kW/m)	0.1	30790	270000
Wall Power Loss Factor η_{wall}	0.88*	0.58	0.35

*The Carnot "penalty" factor of 500 for the 2K operation is included. ** Shunt Imp. def. for TESLA incl.2.

Total Linac Efficiency

$$\eta_{tot} = \eta_{struct} \times \eta_{RF} \times \eta_{aux}$$



Total Efficiency at 500 GeV cm	TESLA	NLC	CLIC
RF Pulse (total/total-filling) (μs)	1370/950	0.4/0.28	0.13/0.1
Structure Efficiency (wout wall-loss&load) (%)	70	70	77
Struct.Eff. (incl. wall-loss and 8% load) η_{struct} (%)	57*	38	~25
Modulator Efficiency (%)	85	80	85
Klystron Efficiency (%)	65	55	65
Pulse-Transmission / Compression Eff. (%)	98	75	72
RF System Efficiency η_{RF} (%)	54	33	40
Auxiliary Average Static Plug Power (kW/m)	0.3	0.58	~0.4
Beam Duty Factor ($f_{rep}\tau_{flat}$), (%)	0.48	0.0034	0.002
Auxiliary System Efficiency η_{aux} (%)	78	72	~90
Total Efficiency η_{tot} (%)	24	9	10

*Includes 332 W/m at the plug of dynamic RF loss in couplers and HOM absorbers.

Average Linac Power Distribution

Average RF Power Distribution in Linac Components in 500 GeV cm LC:

Total average per linac (MW)	TESLA	NLC	CLIC
Beam	11.3	6.9	4.9
Structure	10 (4)	8	11.7
Load[3]	0	3.8	2
Transmission	0.3	6.4	9 (2)
Klystrons	8.5	21	14.9
Modulators	4.3	11.6	7.5
Total per Linac[1]	34.4	57.7	50

1) Only RF linac power requirements (does not include cooling water, RF overhead, power for movers, instrumentation, magnets..).

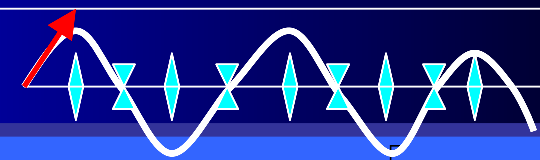
2) In CLIC most of the transmission/compression loss is assumed to occur when the drive beams are dumped. (0.72=0.93 (drive beam transportation)x0.82(drive beam beam dumps)x0.95(PETS→TDS)).

3) 8% in load for NLC, 10% in load for CLIC, no load assumed in TESLA.

4) Structure power in TESLA is dynamic (530 W/(m of active linac) average (0.65% DF) RF loss at the plug) and static (400 W/(m of active linac) at the plug) cryo plug power.

Wake-Fields and Emittance Dilution

Bane/Adolphsen/Kubo/Thompson model:



$$\Delta\varepsilon_s = e^4 N e^2 L_s^2 \langle S\rangle_{rms}^2 \langle\Delta\rangle_{rms}^2 N_s \beta_0 \left[\frac{1-\sqrt{E_0/E_f}}{\sqrt{E_0}\,E_f^{3/2}}\right]$$

$$\Delta\varepsilon_q = e^4 N_e^2 \beta_0 N_q \frac{L_{FODO}}{2} N_s L_s \langle\Delta_q\rangle_{rms}^2 \langle S\rangle_{rms}^2 \left[\frac{1-\sqrt{E_0/E_f}}{\sqrt{E_0}\,E_f^{3/2}}\right] \quad (m-rad)$$

Emitt. growth due to system. struct.& quad mis-alignment in 500 GeV LC accord. to Bane model	TESLA	NLC	CLIC
Linac injection/final energy, E_i/E_f (GeV)	5/250	2/250	2.4/250
Bunch Charge N_e (nC)	3.2	1.2	0.64
# structures/quads per linac, N_s / N_q	10296/365	6096/233	3636/300
Length of structures, L_s (m)	1.036	0.9	0.5
Initial, av.β / av. FODO length, β_0 / L_{FODO} (m)	64/80	12/48	5/15
Trans. m-bunch Σ wake-pot. <S> (V/pC/m/mm)	0.003	0.7	1.4
Struct.-to-struct. misalign for 1% Δε (μm-rms)	250	12	20
Quad-to-beam offset for 25% Δε (μm-rms)	15.2	0.74	1.5

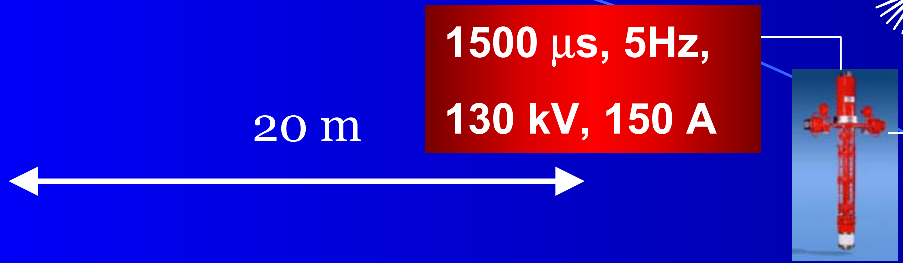
500 GeV LC Table – Beam Emittances and Alignment Tolerances

rms beam size parameters at IP	TESLA	JLC/NLC	CLIC
Horizontal/vertical ε_N in IP (mm-mrad)	10/0.03	3.6/0.04	2.0/0.01
Hor./vert. rms IP beam size bef. pinch (nm)	554/5	243/3	202/1.5
Longitudinal rms beam-size σ_z* at IP (μm)	300	110	35
rms alignment tolerances to remain within ~ 50-100% emittance budget			
Quadrupole to beam offset (μm)	20	2	10
Structure to structure offset (μm)	300	30	10
Structure tilt (μrad)	240	30	?
Quad BPM offset / resolution (μm)*	?/10	10/0.3	10/0.1

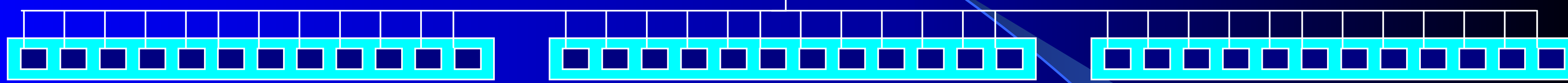
Unprecedented level of alignment precision required for all LCs! Damping and detuning of structures to reduce wake-field effects! TESLA uses realignment every several months using DFS and steering dipoles. The warm designs use global re-alignment every several months of of structures, quads & BPMs using ballistic methods (moving structure girders and quads separately). In addition all LCs use fast feedback systems in IP to compensate for beam jitter and ground-motion effects (in linac and FF). Finally the warm designs require (damping manifold signal based) realignment of structures and quads every ~1/2hrs!

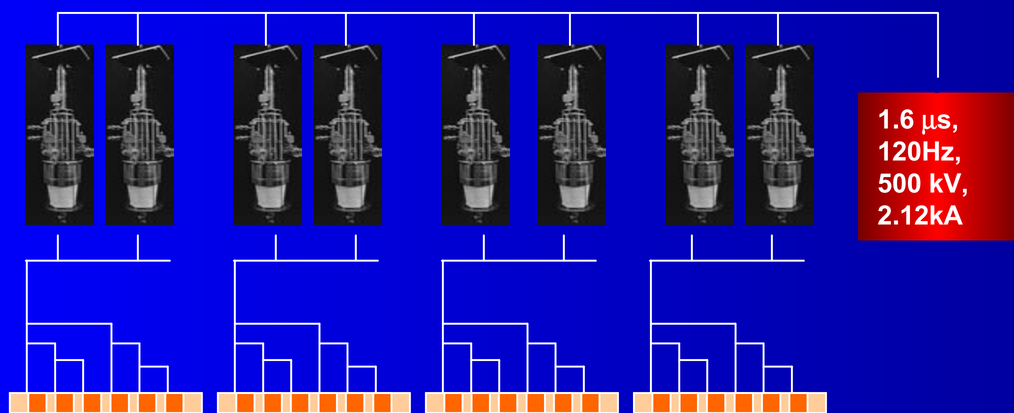
*Important for beam-based and ballistic alignment.

Summary : Linac Layout for ~1 GV Acceleration

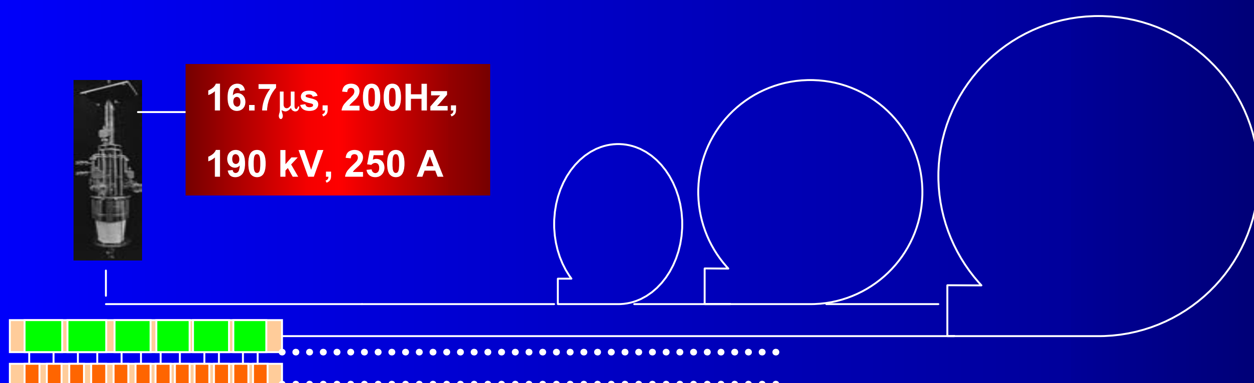


TESLA: 850 MV accelerating voltage: one 10 MW klystron driving 36 one meter long cavities (= 3 cryo-modules a 12 cavities) with 230 kW/m.





NLC: 1000 MV accelerating voltage: 8 x 75 MW klystrons, supplying (after pulse compression) a peak power of ~100 MW/m.



CLIC: ~1000 MV accelerating voltage: ~2 x 50 MW klystrons, supplying (after 32 fold pulse compression) a peak power of ~400 MW/m.

Summary: Alignment Tolerances

Transverse wake-potentials are $\sim a^{-3}$. The transverse kick-factors depend on the transverse wake and the bunch population: $\sim Na^{-3}$. On the basis of this (simplistic) argument the single bunch wakefield effects are expected to be 150 / 1000 times more pronounced in the NLC / CLIC designs as in TESLA. This, however, is only the beginning: the details and the cost of the alignment strategies and technologies proposed to cope with the wakefield effects in all linear collider options are the real issue: Unprecedented alignment precision required for all designs (order of 10-100 μm). There is a factor ~10 difference between warm and cold designs in what refers to the alignment requirements. In the current proposal TESLA is a traditional, static machine (except for a required alignment every several months that is common to all LCs). This is presently under discussion! Continuous re-alignment of all structures and quads is required in warm machines to cope with ground-motion effects. Luminosity stabilization (beam jitter, FF vibration, IP beam size) will be very challenging in all designs – Feedback systems!

Summary: Linear Collider Prototypes

TESLA: TTF = linac demonstrated ✓, average gradient: 25MV/m, HOMs?, alignment?, Issues: damping rings, alignment, upgrade path ..?

JLC/NLC: linac demonstration expected soon, break-down issues in structures, RF power sources not yet demonstrated: 8-pack test? Best results: 500 MW 250 ns, 90 MV/m unloaded with 1 breakdown /structure /10hrs (damage?, structure without damping), good progress in sub-system design (damping rings, diagnostics & controls, source to IP simulations, wake-field measurements in ASSET, Final Focus simulation in FFTB, ground-motion studies, ATF damping ring prototype, collimator wakefield test);

CLIC: feasibility of drive beam scheme not yet demonstrated → CTF3? Break-down issues in structures, RF power source not demonstrated, Best results: 150 MV/m unloaded for 15 nsec in structure with Tungsten iris (wout damping slots) → damage in couplers was observed starting at gradients of 60 MV/m! 2nd generation LC?