Comparison of different approaches to Linear Collider

- LC development
- Beam-beam effects and Luminosity
- Damping Ring
- Emittance dilution in Main Linac
- Summary

Linear Collider Development

- R&D works on future LC started at the end of 70-s. (VLEPP-1978).

- Different approaches to LC:

TBA, CLIC,	-Two beam schemes
TESLA,	- SC
SBLC, JLC-S,	- S-band
JLC-C, JLC-X, NLC,	- C,X-band
VLEPP,	- single bunch
etc…	- wake-field, plasma, laser, W-band

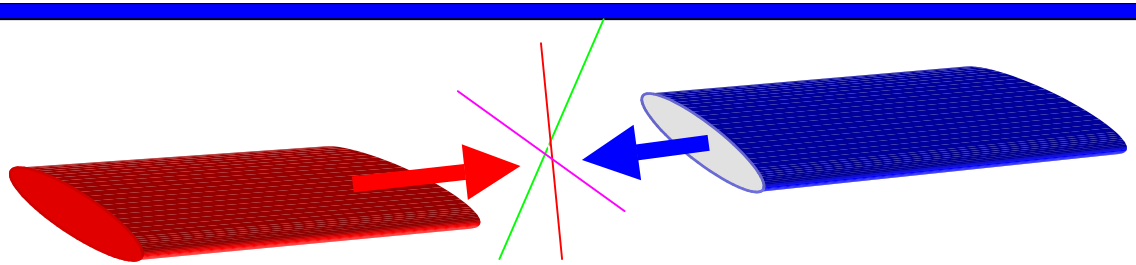
The main differences are: RF power production, SC or "warm" AS

- Wide Frequency range:
  L-band -1.3 GHz, TESLA
  K-band -30 GHz, CLIC, W-band -90 GHz.

- Not all of these LC projects survived - TBA, S-Band LCs, VLEPP,…

At Last LC'02 were presented : NLC/JLC, TESLA, CLIC, JLC-C

Beam-beam effects and Luminosity



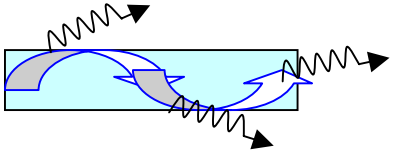
Geometrical Luminosity

$$L_0 = f \cdot \frac{n_b N^2}{4\pi\sigma_x\sigma_y} \cdot \eta(\theta, A_{x,y})$$

θ-cross angle,
A= σ_z /β -divergence

- Strong Magnetic field in IP $\mathscr{B}\partial > 10^5$ T (for round beams)

There are two strong-field beam-beam effects:



1. Beamstrahlung →(energy losses/spread, background) → flat beams

$$\delta_E = \frac{16}{27\sqrt{3}} \cdot \frac{r_e^3 \cdot N^2 \cdot \gamma}{\sigma_z \cdot (\sigma_x + \sigma_y)^2} \rightarrow \sigma_x = const \cdot N \sqrt{\frac{\gamma}{\sigma_z \delta_E}}$$ - *horizontal*

$$\sigma_y = \sqrt{\frac{\varepsilon_{ny}\beta_y}{\gamma}} \xrightarrow{\beta_y = \sigma_z} \sigma_y = \sqrt{\frac{\varepsilon_{ny}\sigma_z}{\gamma}}$$ - *vertical*

Luminosity (2)

- *Luminosity*

$$L \approx 4 \cdot 10^{31} \cdot \frac{P_{tot}(MW) \cdot \eta}{E_{cm}(TeV)} \cdot \sqrt{\frac{\delta(\%)}{\varepsilon_{ny}(mm \cdot mrad)}} \cdot H_D$$

- *LC requirements:*

Energy c.m.	$E_0 =$ 0.5 TeV → 1 TeV → 3-5 TeV
Luminosity	$L \geq 10^{34}\ cm^{-2}\ s^{-1}$ → ... → $10^{34}\ cm^{-2}\ s^{-1}$
Energy spread	$\delta_E \approx$ few % → ... → 20-30 %
Vertical emittance	$\varepsilon_{ny} \approx (3\text{-}5)10^{-8}\ m*rad$
AC Power	P_{tot}=100-200 MW

Efficiency (P_{beam}/P_{tot})	$\eta \approx$ 10-30 %
Enhancement parameter	$H_D \approx$ 1.5-2

Beam dynamics in IP

- 2. *Disruption and Luminosity Enhancement.*

Disruption parameter: $$D_{x,y} = \frac{\sigma_z}{F_{x,y}} = \frac{2r_e N\sigma_z}{\gamma\sigma_{x,y}\sigma_z}$$ $D_y >> D_x$

- *For small and intermediate* ***D ≤ 10*** → *pinch-effect (* ***H>1*** *)*

  (Maximum enhancement H_D = 2.4 for flat beams)

- *For large* ***D>>10*** → *Kick instability (Luminosity Losses H<1)*

- *Disruption angles* $$\theta = \frac{D_{x,y}\sigma_{x,y}}{\sigma_z} \cdot \frac{0.55}{(1+D_y^5)^{1/6}}$$

Beam parameters at IP

Energy = 0.5 TeV / 1TeV

	TESLA0.5/0.8	NLC/JLC	CLIC
Lumonosity $*10^{34}$	3.4 /5.8	2.0/3.4	1.7 /2.7
Energy loss (%)	3.2 /4.3	5.4 /10.2	3.8 /11.2
Frequency GHz	1.3	11.4	30
Rep. Rate (Hz)	5	120	200
Bunches in train	2820	192	154
N/bunch, 10^{10}	2	0.75	0.4
$\varepsilon_{ny}/\varepsilon_{ny}$, 10^{-8}m	1000/3	360/3.5	200/2 (130/2)
σ_{ny}/σ_{ny} nm	553/5	545/2.7	208/1.9
$\sigma_{z,}$ um	300	110	35
Enhamncement, H	2.1	1.43	1.4
Gradient, MV/m	23.4/35	48.5/55	150
RF to beam ef.,%	54	38	24.4
AC power, MW	97 /	139 /	100 /150
Total Length, km	33	6.3 /12.8	5 /10

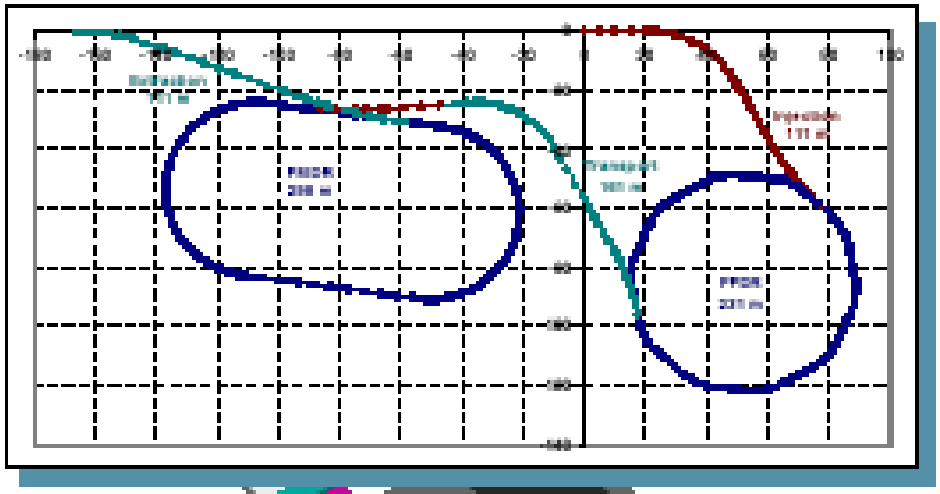
Vertical emittance

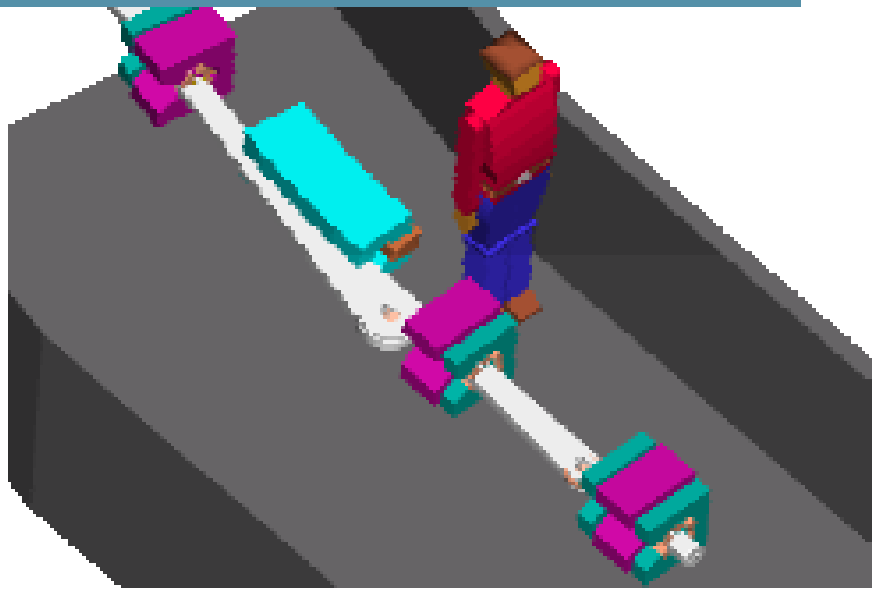
- Are vertical emittance goals realistic ?
  (0.01-0.002 mm*mrad)

- Can we receive small emittance in Damping Ring?

- How to prevent emittance growth in Main Linac, Beam Delivery System, Final Focus?

Damping Rings





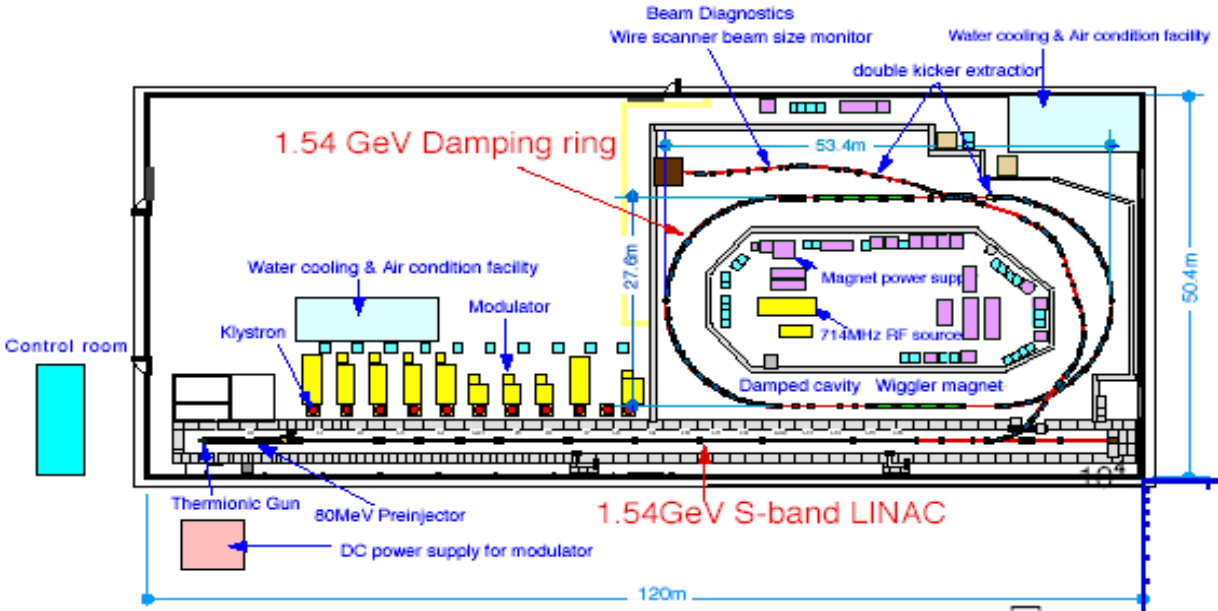
- **Main damping rings:**
  - similar to 3rd generation light sources
    - energy (1.98 GeV)
    - emittance ($\gamma\varepsilon$ = 3 x 0.02 mm.mrad)
  - Single-turn injection and extraction of bunch trains (challenging!)

- **Pre-damping ring**
  - positrons only
  - reduces huge emittance from target to level acceptable to MDR ($\gamma\varepsilon$ ~ 150 mm.mrad)

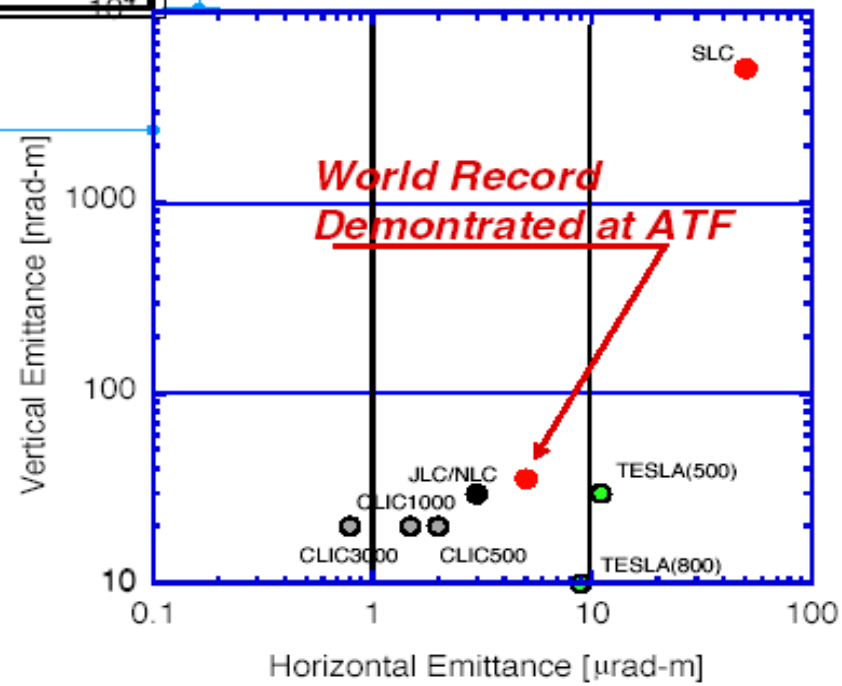
Images stolen from T. Raubenheimer and A. Wolski

KEK ATF: Ultra-Low Emittance Beam

N.Toge, KEK, LC'02



Beam emittance (normalized) required at Linear Colliders



International Collaboration

KEK, Tokyo Met. U.,
Tokyo Sci. U., Tohoku Gakuin U.,
Soken-Dai U.,
SLAC, LBNL, Postech, CERN,
BINP Protvino ...

ATF Vertical Emittance in Multi-bunch Operation

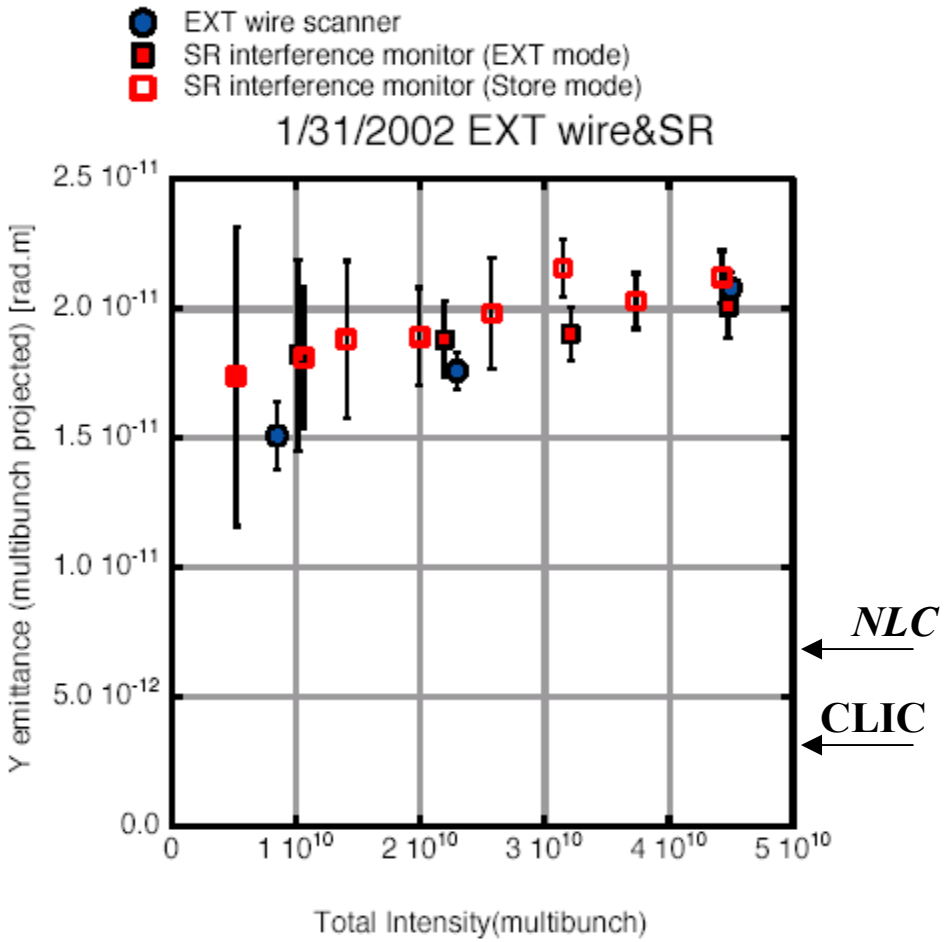
N.Toge, KEK, LC'02

- Typical # of bunches = 18/pulse
- Bunch spacing = 2.8 ns

- Instrumentation used:
  - SR interference monitor
  - Wire scanner in EXT line

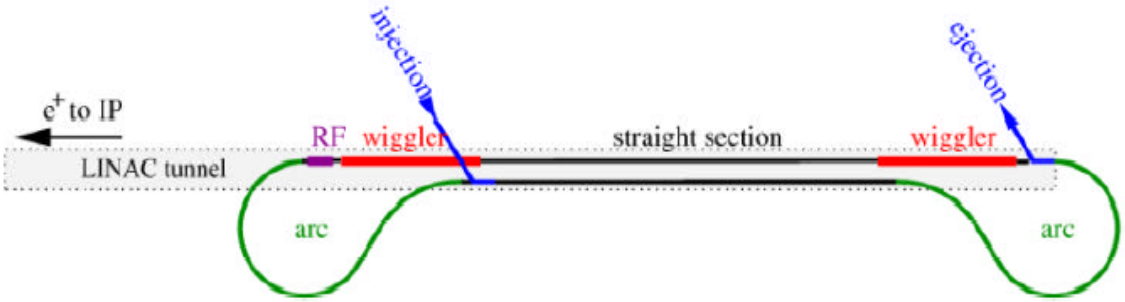
- Measured quantity:
  - Superposition of all bunches, including effects of possible bunch-to-bunch orbit variation.

- Issues:
  - Subtraction of y-dispersion
  - Vacuum levels in DR
  - Intra-beam effects
  - x-y tilts



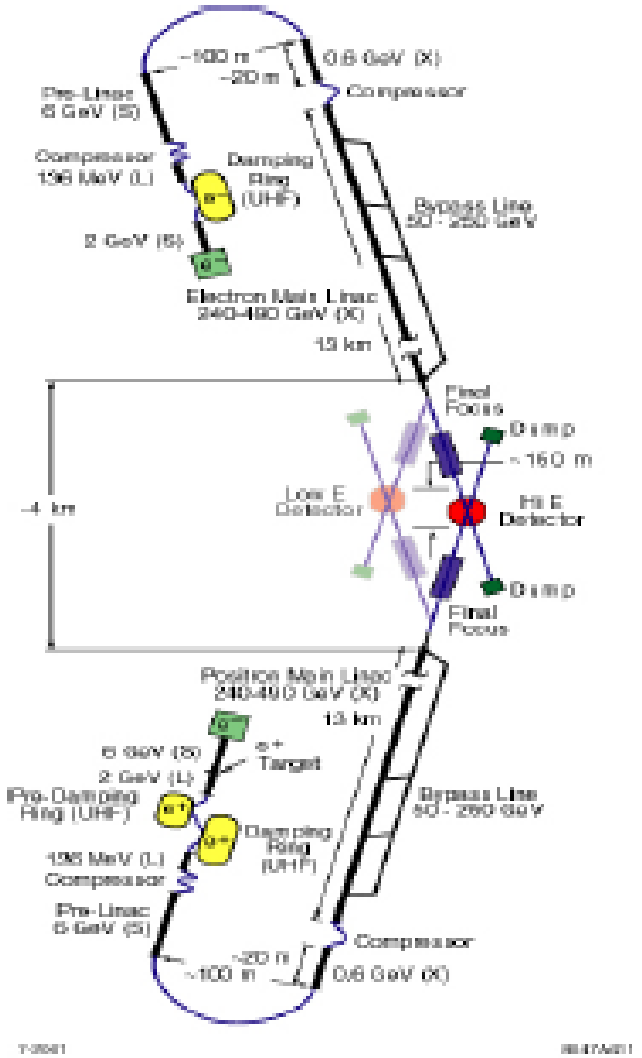
TESLA Damping Ring

Damping Ring



- 17 km long to accommodate TESLA bunch train
- Looks unconventional, but major 'new' issue is space charge, cured by local coupling
- Needs a 20 ns rise/fall-time injection kicker system

Layout



- Two interaction regions (sequential, not simultaneous, operation)
  - HEIR: minimal bending, 20 mrad crossing angle (set by linac lines)
    - up to 3-5 TeV CM (someday!)
  - LEIR: more bending, 25-30 mrad crossing angle
    - Luminosity okay up to about 1 TeV CM
- Bypass lines for running below max energy
  - Most flexible for operation and installation
- Linac tunnels sized for 1 TeV CM
  - stage 1: fill 50%, run thru bypass lines to beam delivery system
  - populate 2nd half of each linac over time to reach 1 TeV CM

NLC/JLC project

NLC - The Next Linear Collider Project

The Basics

- JLC/NLC linear collider design uses:
  - 11.424 GHz ("X-Band") RF acceleration...
  - 70 MeV/m unloaded gradient...
  - 0.75×10^{10} e^+/e^- per bunch...
  - 192 bunches per RF pulse with 1.4 nsec spacing (268 nsec total train length)...
  - 120 RF pulses per second...
  - IP spot sizes approx. 250 nm x 2.5 nm...
- To achieve 2.0 – 3.5 x 10^{34} luminosity @ 0.5 – 1.0 TeV CM

P. Tenenbaum

NLC RF Distribution System

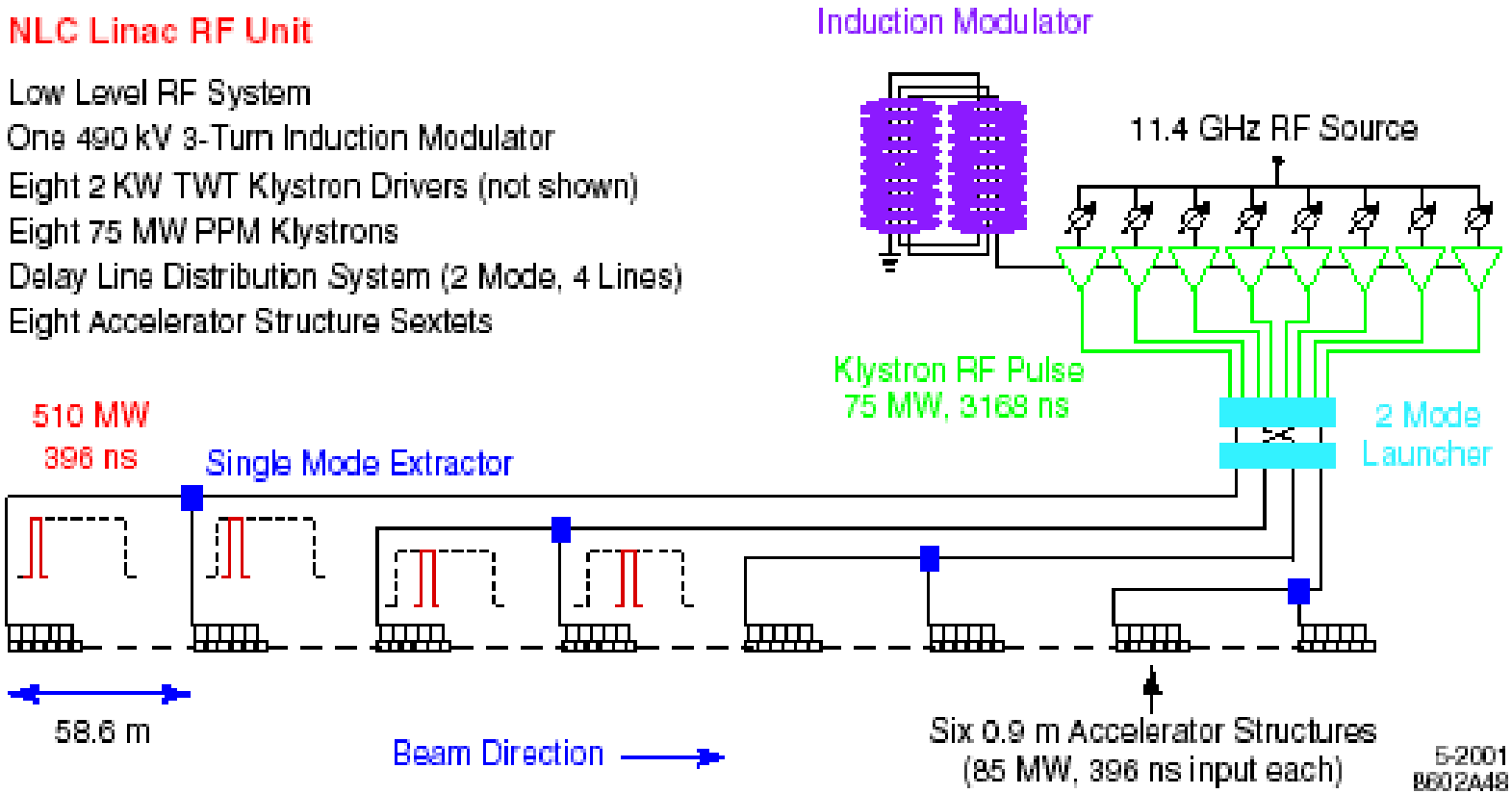
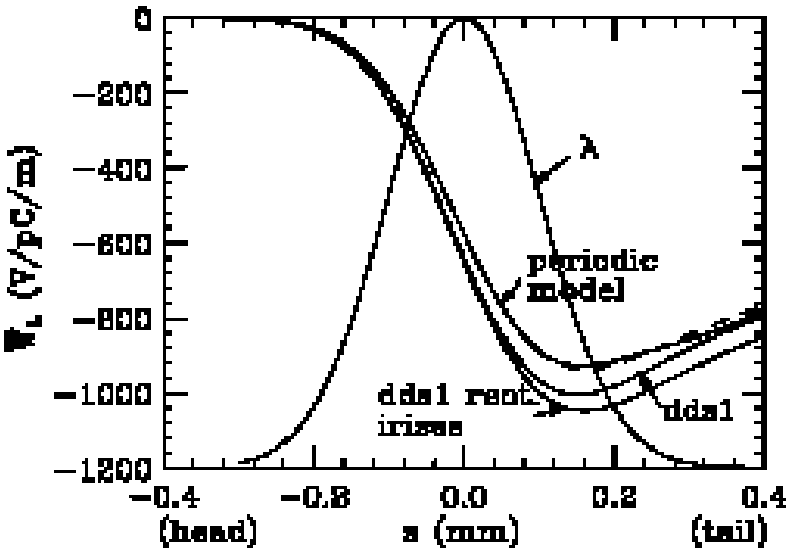
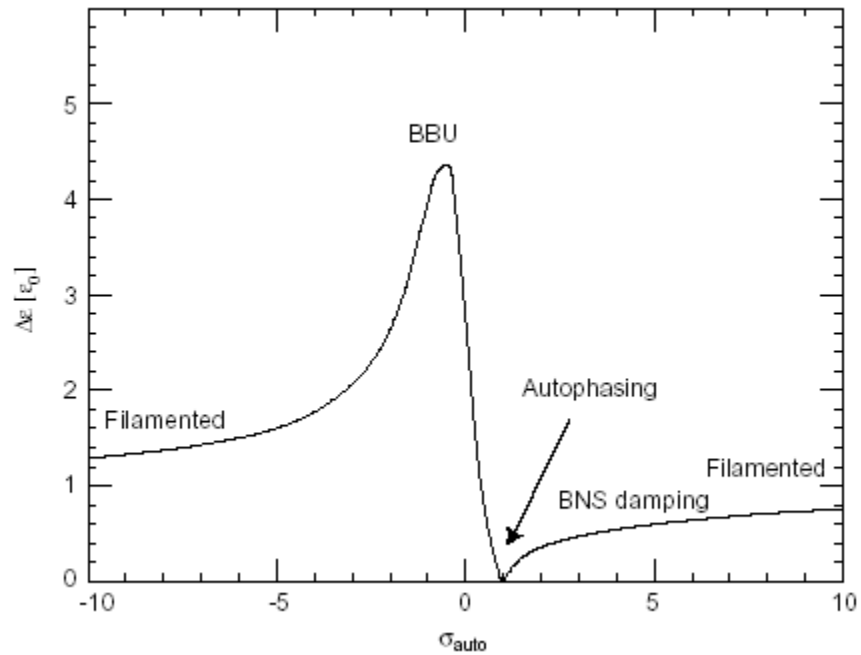


Figure 4.1: Schematic of a linac rf unit (one of 117 per linac).

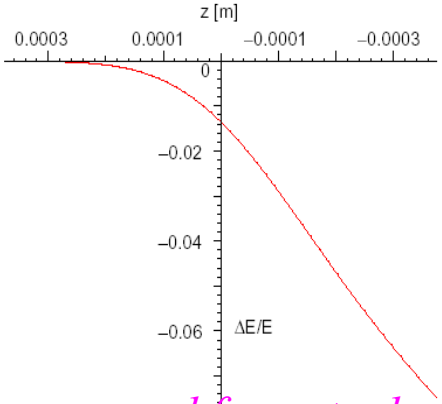
Short-range Wakes and BNS damping



Longitudinal short range wake-fields in structure



Autophasing condition

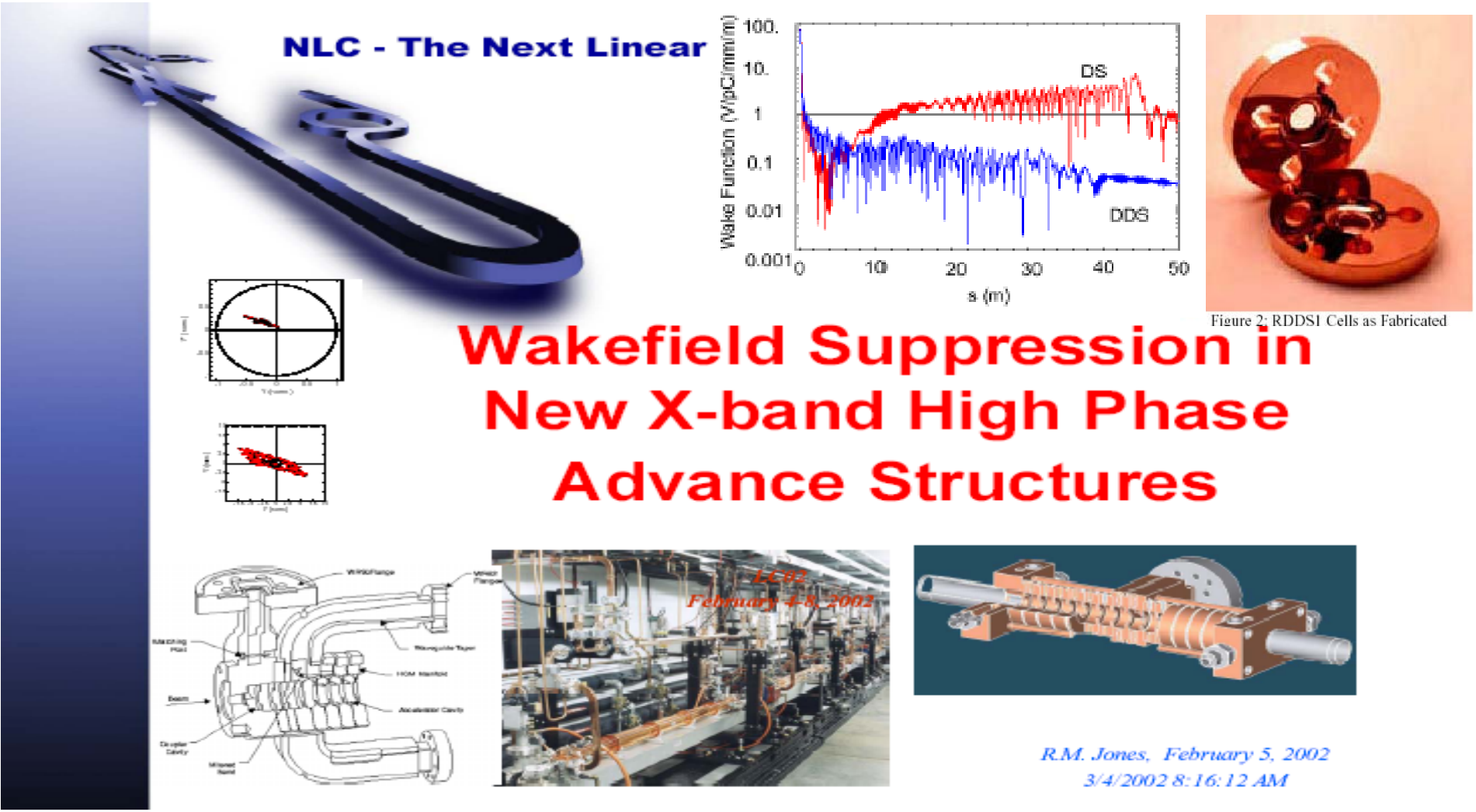


Energy spread for autophasing

$$\delta_{wake}(z) = \frac{4\pi\varepsilon_0 N r_e}{K\gamma_0}\int_z^{\infty} W_\perp(z'-z)\rho(z')dz'$$

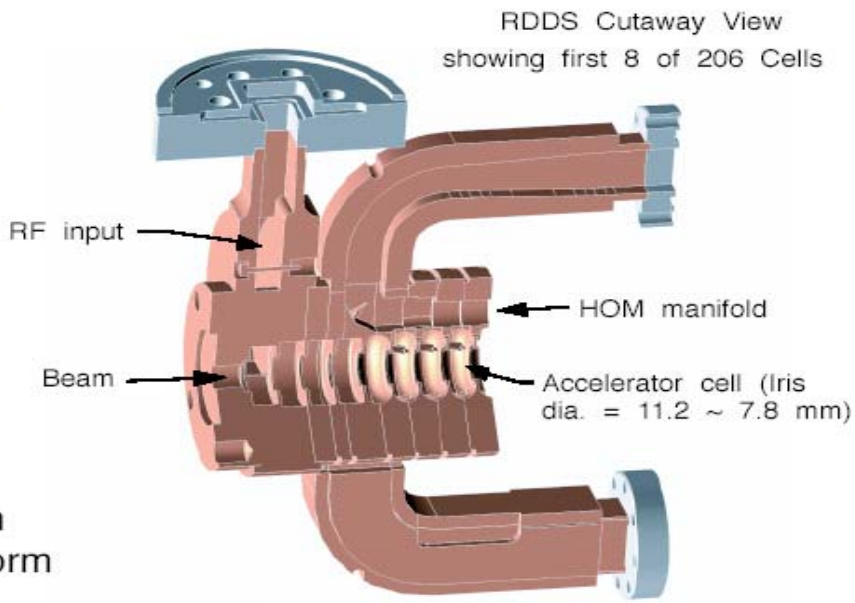
Energy spread = 0.8%, Klystron phase = -14°,

Long range wake-fields



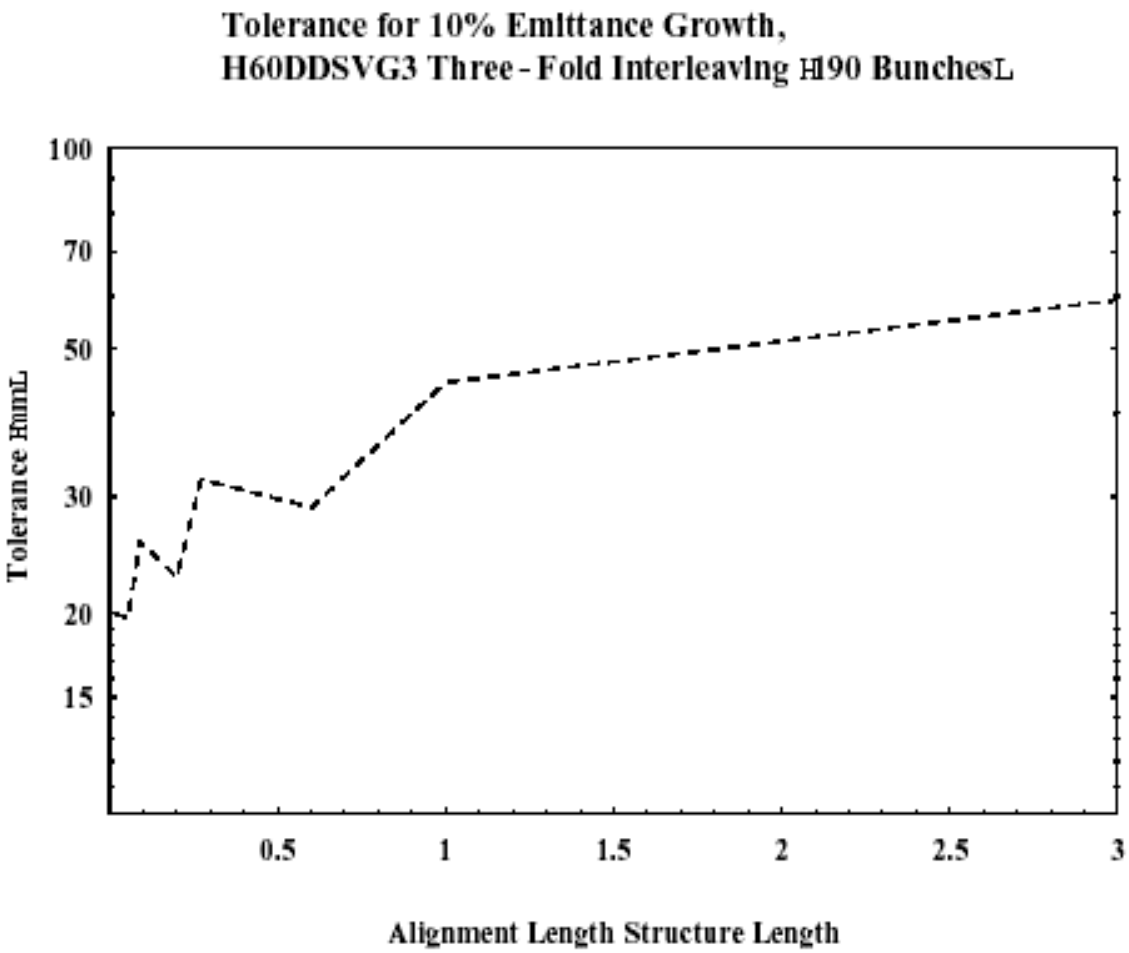
Multi-bunch Wake Suppression

NLC/JLC Rounded Damped-Detuned Structure (RDDS)



- Made with Class 1 OFE copper.
- Cells are precision-machined (few μm tolerances) and diffusion-bonded to form structures.
- 1.8 m length chosen so fill time ~ attenuation time ~ 100 ns.
- Operated at 45 deg C with water cooling. RF losses are about 3 kW/m.
- RF ramped during fill to compensate beam loading (21%). In steady state, 50% of the 170 MW input power goes into the beam.

2. Alignment Tolerances for H60VG3



Cell-to-cell and structure-to-stucture alignment tolerances for a MANIFOLD DAMPED 60 cm structure with 3-fold interleaving of adjacent structure frequencies.

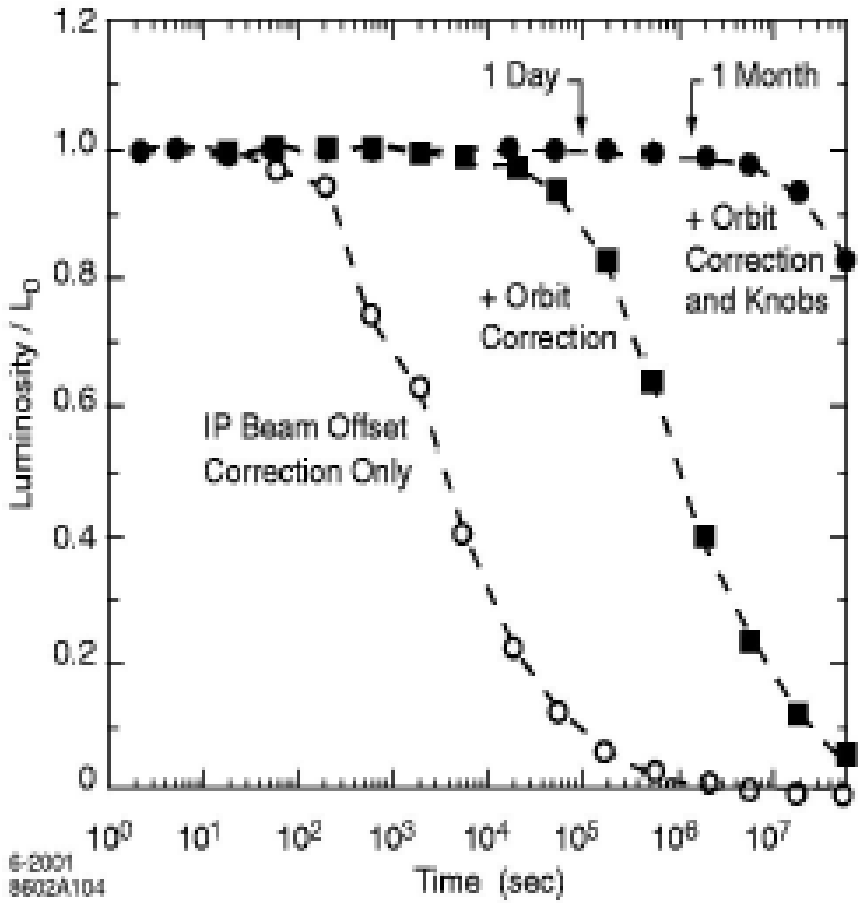
The line is obtained via a semi-analytical/statistical model.

R.M. Jones LC02, February 2002, #32

Main Linac Emittance Budget

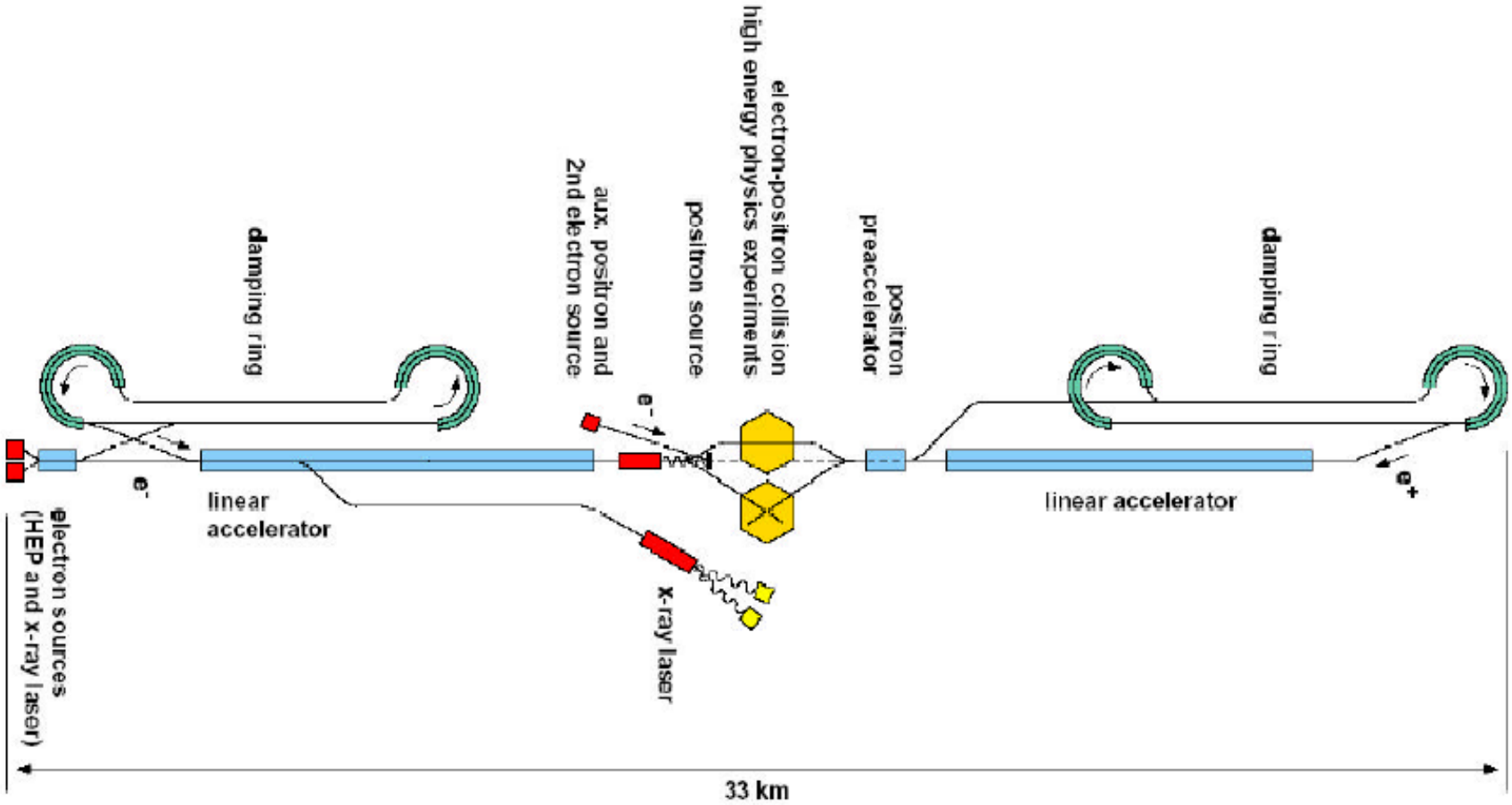
Effect	Tolerance	$\Delta\gamma\varepsilon_y$, mm.mrad	
Beam-to-Quad Offsets	2.0 μm	0.005	*25%*
Quad Strength Errors	0.1%	0.0001	*0.5%*
Struc-to-Girder Misalignments	30 μm	0.0014 (single-bunch) 0.0002 (multi-bunch)*	*7%* *1%*
Struc-to-Girder Tilts	30 μrad	0.0008	*4%*
Struc BPM Resolution	5 μm	0.0006	*3%*
Quad Rotations	200 μrad	0.0008	*4%*
Mover Steering Interval	30 minutes	0.0004	*2%*
Structure Bow	50 μm	0.0002*	*1%*
Cell-to-Cell Errors	3.5 μm	0.0002*	*!%*
HOM Freq Errors	1 MHz	0.0002*	*1%*
Total		0.0099 (50%)	

Stabilization of BDS (2)

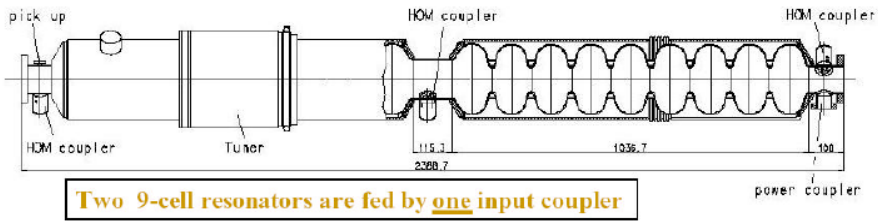


- Longer term: driven by diffusive ground motion
- Tools to preserve luminosity
  - IP collide feedback
  - steering feedback through sextupoles
  - Adjust aberrations via dither feedbacks
- Only 1 overall realign needed per year

TESLA


damping ring
e-
linear
accelerator
electron sources
(HEP and x-ray laser)
aux. positron and
2nd electron source
e-
positron source
electron-positron collision
high energy physics experiments
x-ray laser
positron
preaccelerator
damping ring
linear accelerator
e+
33 km

TESLA RF Distribution System



K

RF Unit : 1 klystron
3 cryomodules
36 cavities

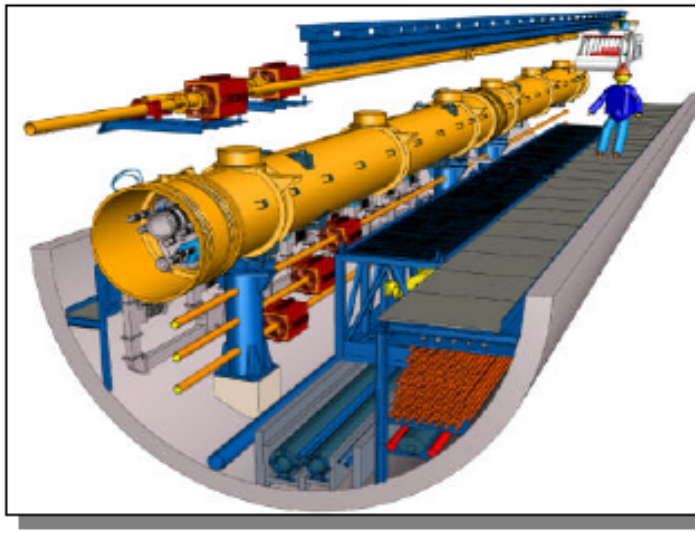
286 RF Units per LINAC :

10,296 Cavities

858 Cryomodules

286 Klystrons

(10MW, 1.5ms, 5Hz, 65%)



TESLA wake-fields

Single-bunch (short range) wake-fields

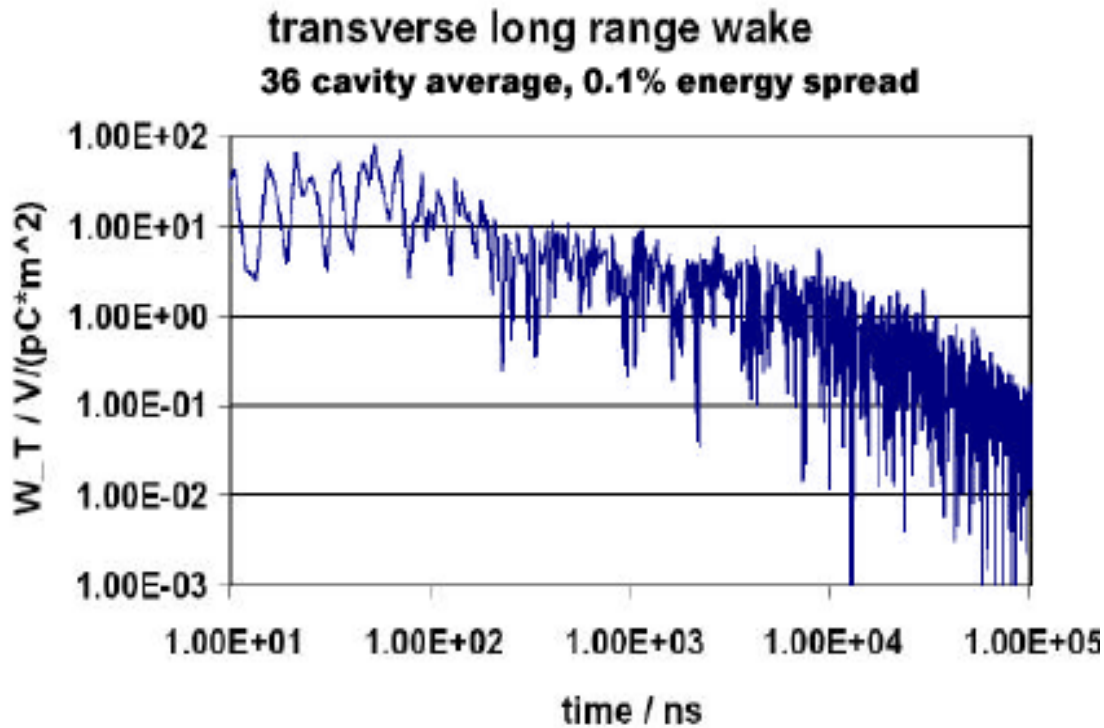
- Longitudinal wake is small (induced energy spread $<10^{-3}$, can be minimize to $3\cdot10^{-4}$ by running at the optimal RF phase +5°)
- More serious 2.5% energy spread at injection energy (chromatic effects)
- Transverse wake $\propto 1/a^3$ → no BNS damping necessary, only 2.5% emittance growth due to wake-field & 7% - due to 0.5mm cavity misalignment.

Multi-bunch (long range) wake-fields

- Longitudinal wake is almost negligible due to natural frequency spread longitudinal HOM. Bunch-to-bunch energy spread after feed-back suppression (Lorentz force) $< 5\cdot10^{-4}$.
- Transverse wakes should be detuned and dumped to suppress BBU instability. Natural HOM frequency spread due to fabrication errors helps. For damping needs $Q< 10^5$. In TTF found dipole mode 2.58 GHz with high $Q> 10^6$ (need redesign HOM coupler).
- Fast intra-train orbit correction system can remove BBU effects.
- Jitter due to ground motion has to be corrected by fast intra-beam correction. Slow drift (diffusive ground motion) → re-alignment once/month.

TESLA HOM dumping (HOM couplers)

Frequency (ave. meas.) [GHz]	Loss factor (simulation) [V/pC/m²]	R/Q (simulation) [Ω/cm²]	Q (meas.)
TE_{111}-like			
1.6936	19.98	0.76	$7.0\cdot10^4$
1.6991	301.86	11.21	$5.0\cdot10^4$
1.7252	423.41	15.51	$2.0\cdot10^4$
1.7545	59.86	2.16	$2.0\cdot10^4$
1.7831	49.20	1.75	$7.5\cdot10^3$
TM_{110}-like			
1.7949	21.70	0.77	$1.0\cdot10^4$
1.8342	13.28	0.46	$5.0\cdot10^4$
1.8509	11.26	0.39	$2.5\cdot10^4$
1.8643	191.56	6.54	$5.0\cdot10^4$
1.8731	255.71	8.69	$7.0\cdot10^4$
1.8795	50.80	1.72	$1.0\cdot10^5$
TE-like			
2.5630	42.41	1.05	$1.0\cdot10^5$
2.5704	20.05	0.50	$1.0\cdot10^5$
2.5751	961.28	23.80	$5.0\cdot10^4$



all modes damped below 1×10^5, but …

HOM with High Q

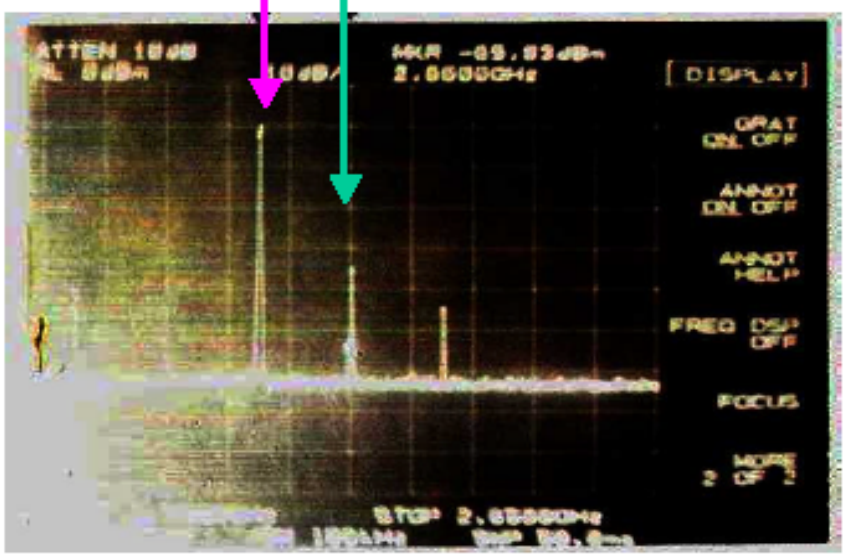
- Measured with intensity modulated beam with position offset
- Detected in HOM coupler and broadband BPM

HOM Pickup Signal

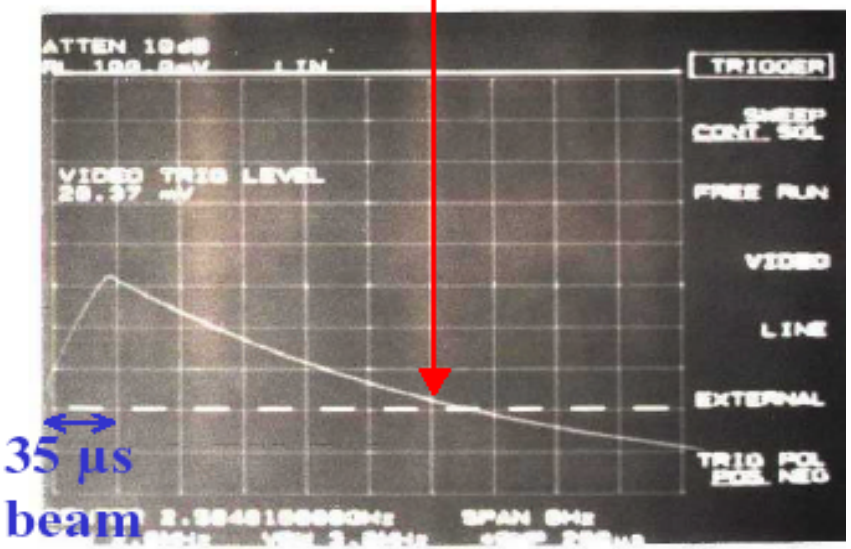
HOM at 2.585 GHz

Beam at 2.6 GHz

Decay time $\Rightarrow Q = 10^6$

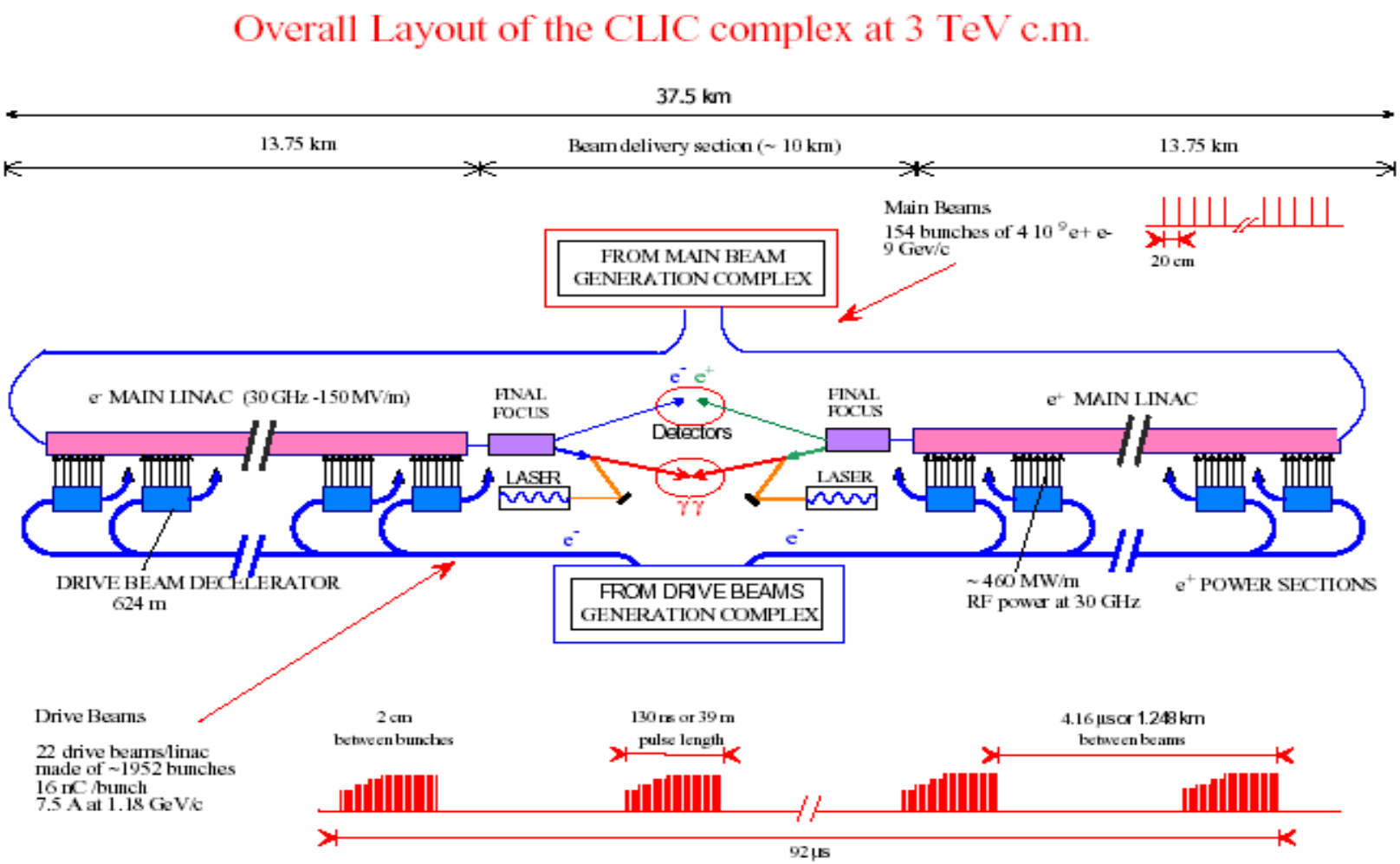


frequency domain

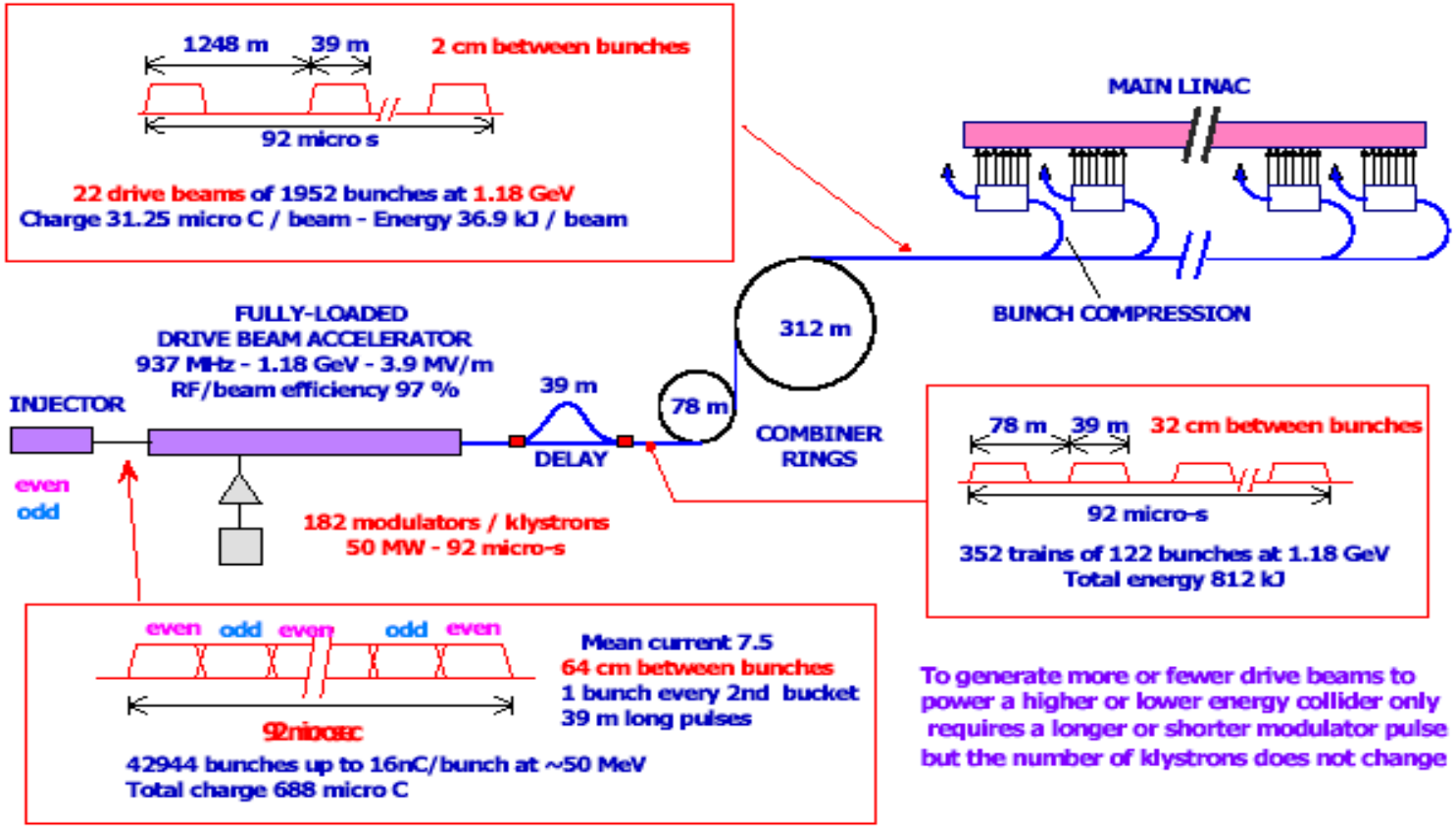


time domain

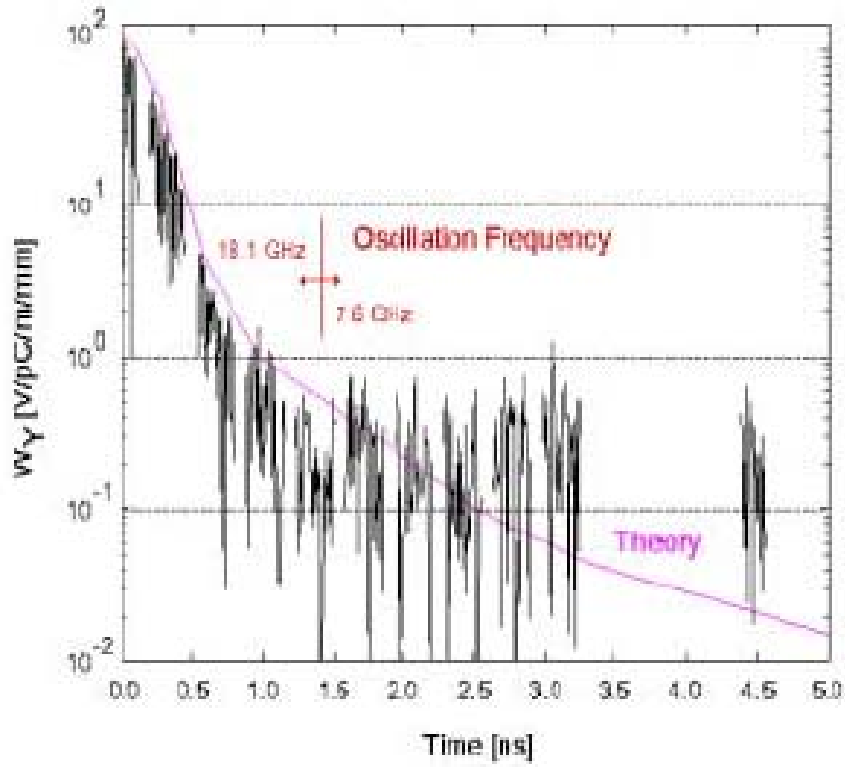
CLIC Layout


Overall Layout of the CLIC complex at 3 TeV c.m.
37.5 km
13.75 km
Beam delivery section (~ 10 km)
13.75 km
Main Beams
154 bunches of 4 10 9 e+ e-
9 Gev/c
20 cm
FROM MAIN BEAM GENERATION COMPLEX
e- MAIN LINAC (30 GHz -150 MV/m)
FINAL FOCUS
e- e+
Detectors
FINAL FOCUS
e+ MAIN LINAC
LASER
γγ
LASER
e-
e-
DRIVE BEAM DECELERATOR
624 m
FROM DRIVE BEAMS GENERATION COMPLEX
~460 MW/m
RF power at 30 GHz
e+ POWER SECTIONS
Drive Beams
22 drive beams/linac
made of ~1952 bunches
16 nC /bunch
7.5 A at 1.18 GeV/c
2 cm
between bunches
130 ns or 39 m
pulse length
4.16 µs or 1.248 km
between beams
92 µs

CLIC RF POWER SOURCE FOR 3 TeV COLLIDER



CLIC Damping structure



For suppression of Wt - work still being focused on WG damped structures of type shown here. Each cell is damped by 4 radial WGs terminated by discrete SiC RF loads.

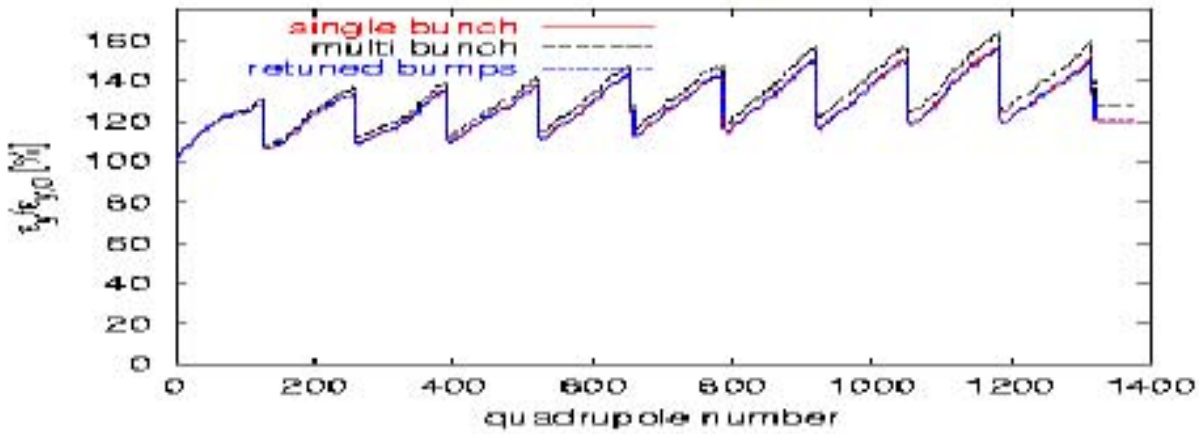
Photo shows 15 GHz model tested in ASSET. Excellent agreement between theory and experiment.

LC'02, Ian Wilson

Emittance Blow-Up

How are we doing on limiting the blow-up in the linac ?

In parameter list - budgeted for 100% blow-up.
Our beam simulations however predict only 20%.
(so for moment have some margin - at least on paper)



Pre-align cavities and BPMs in linac to 10 microns .
Use ballistic method to align BPMs with greater precision
Correct beam position by moving quads ("few-to-few" correction)
Re-align structures to new beam position by moving girders.
Use 10 emittance bumps (as in SLC) to locally reduce blow-up
(uses a few RF structures and a few quadrupoles).

Summary

- All LCs require beams with extremely low vertical emittances (1-2) $\bullet 10^{-8}$ m*rad. (For TESLA probably more difficult ?)
- Wake fields (and tolerances) for TESLA seems less problem than for NLC, CLIC (except HOM high Q ?)
- Luminosity for TESLA distributed in time.
- TESLA has high charge in train (collimation system, dump,…)