# Machine Parameters for Next Generation Linear Colliders

Steve Holmes
Fermilab LC Series
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## OUTLINE

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V. Upgrade Paths

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# PERFORMANCE LIMITATIONS IN ELECTRON-POSITRON LINEAR COLLIDERS

The performance of a high energy electron-positron collider is characterized by the energy and the luminosity.

Because of the inverse square relationship between reaction cross sections and center-of-mass energy, a next generation electron-positron collider **must target a luminosity in the range 5-50x$10^{33}$cm$^{-2}$sec$^{-1}$**.

**⇒Nearly all technical issues in electron colliders are related to the achievement of high luminosity.**

The luminosity in any collider is given by

$$L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y} F$$

where f is the frequency of collisions between bunches, $N_1$ and $N_2$ are the number of particles in the colliding bunches, $\sigma_x$ and $\sigma_y$ are the transverse beam dimensions, and F is a form factor (usually ~1) related to the specifics of the collision geometry.

Circular electron-positron colliders are limited by synchrotron radiation (total beam power):

$$L(10^{30}\,cm^{-2}sec^{-1}) = 1.5\times10^{6}\times\frac{P_b(MW)\times C(km)\times PF\times\Delta\nu_y}{\beta_y^*(m)\times E_{CM}^3(GeV)}$$

or

$$P_b(MW) = 6.4\times10^{-7}\times\frac{L(10^{30}cm^{-2}sec^{-1})\times\beta_y^*(m)\times E_{CM}^3(GeV)}{C(km)\times PF\times\Delta\nu_y}$$

| Examples: | R=4.2 km | R=100 km |
|---|---|---|
| | B=.075 Tesla | B=.008 Tesla |
| | U=3.0 GeV/turn | U=4.9 GeV/turn |
| | $\Delta\nu_y$=.075 | $\Delta\nu_y$=.075 |
| | $\beta^*_y$=0.1 m | $\beta^*_y$=0.1 m |
| | PF=0.7 | PF=0.7 |
| | L=1×10$^{32}$ | L=1×10$^{34}$ cm$^{-2}$sec$^{-1}$ |
| | $E_{CM}$=200 GeV | $E_{CM}$=500 GeV |
| | **⇒$P_b$=36 MW** | **⇒$P_b$=2400 MW** |

**L/P increased by increasing $\Delta\nu_y$ and decreasing $\beta y^*$.**

**However**, for a given luminosity, optical parameters, and footprint, **the power scales as E$^3$(!)**

Linear electron-positron colliders are also limited by (total) beam power:

$$L(10^{30}\,cm^{-2}sec^{-1}) = .05 \times \frac{P_b(MW) \times H_D}{\sigma_y(nm) \times E_{CM}(GeV)} \times \frac{N}{\sigma_x(nm)}$$

or

$$P_b(MW) = 20 \times \frac{L(10^{30}\,cm^{-2}sec^{-1}) \times \sigma_y(nm) \times E_{CM}(GeV)}{H_D} \times \frac{\sigma_x(nm)}{N}$$

| Example: | $H_D$=1 | $H_D$=1.4 |
|---|---|---|
| | $N=3.3\times10^{10}$ | $N=1.0\times10^{10}$ |
| | $\sigma_x$=1500 nm | $\sigma_x$=330 nm |
| | $\sigma_y$=700 nm | $\sigma_y$=5 nm |
| | $L=1.0\times10^{30}$ | $L=1\times10^{34}$ cm$^{-2}$sec$^{-1}$ |
| | $E_{CM}$=100 GeV | $E_{CM}$=500 GeV |
| | **$\Rightarrow P_b$=.063 MW** | **$\Rightarrow P_b$=12 MW** |

**L/P increased by decreasing $\sigma_y$.**

(Note $N\gamma \propto N/\sigma_x$, $\delta_B \propto \gamma N^2/\sigma_x^2$)

**However**, for a given luminosity and optical parameters, **the power scales as E.**

# PARAMETER SETS

| | NLC | NLC(H) | JLC(C) | TESLA | |
|---|---|---|---|---|---|
| Energy (CM) | 482 | 490 | 500 | 500 | GeV |
| Repetition Rate | 120 | 120 | 100 | 5 | Hz |
| Bunches/pulse | 95 | 190 | 72 | 2820 | |
| Bunch separation | 2.8 | 1.4 | 2.8 | 337 | ns |
| Particles/bunch | $1\times10^{10}$ | $7.5\times10^{9}$ | $1.1\times10^{10}$ | $2\times10^{10}$ | |
| Beam sigma at IP (H) | 365 | 245 | 318 | 553 | nm |
| Beam sigma at IP (V) | 6.2 | 2.7 | 4.3 | 5.0 | nm |
| $\delta_B$ | 3.0 | 4.6 | 3.4 | 3.3 | % |
| Luminosity Enhancement | 1.4 | 1.4 | 1.7 | 1.8 | |
| Luminosity | $5.5\times10^{33}$ | $22\times10^{33}$ | $8.6\times10^{33}$ | $29\times10^{33}$ | cm-2sec-1 |
| Beam power | 9 | 13 | 6 | 22 | MW |

# FACILITY CONFIGURATIONS

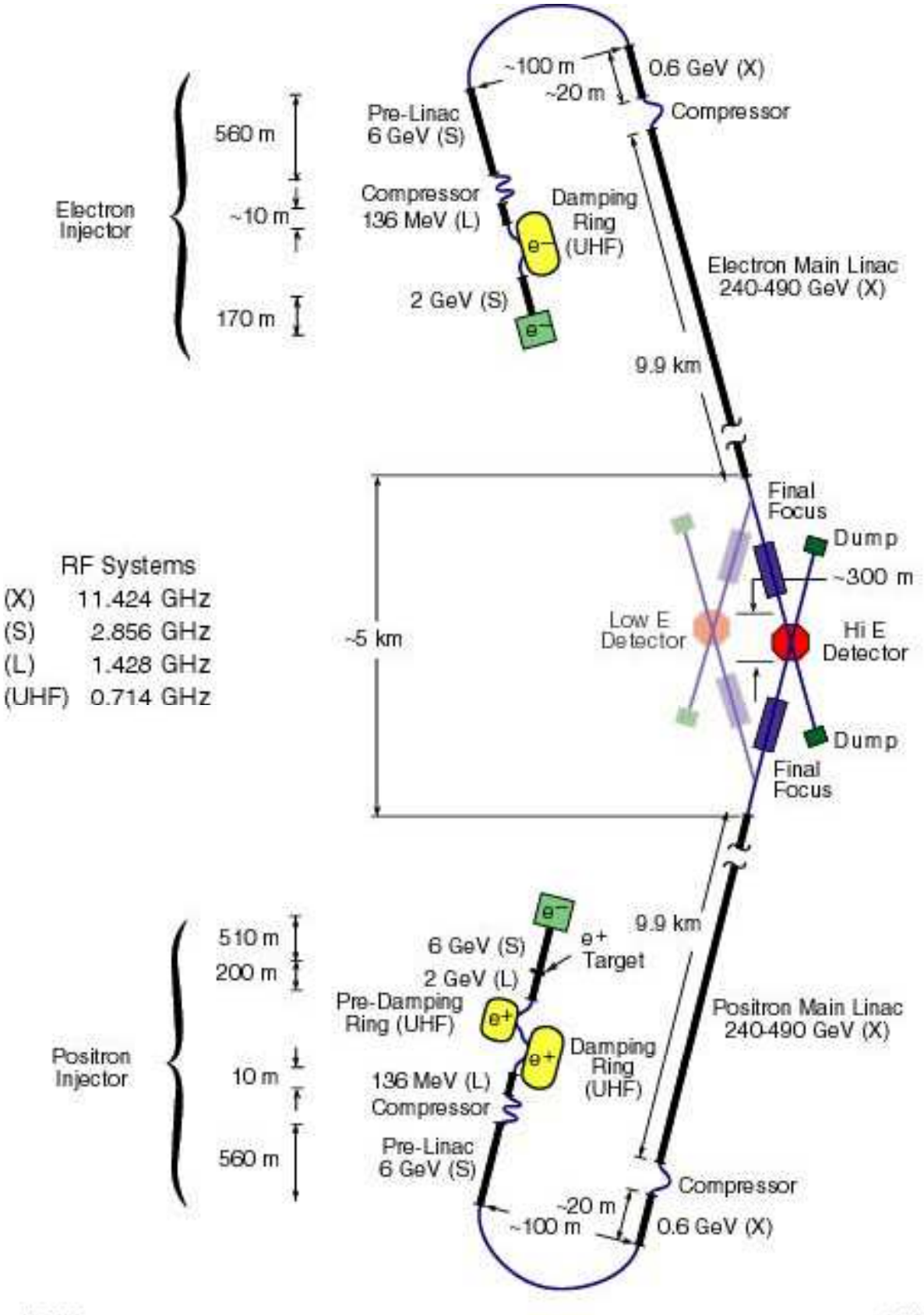
## NLC

The NLC configuration has changed over the past year in a number of ways:

- Each linac arm is still 10 km long, providing 1000 GeV (center of mass) if the entire length is filled with 50 MV/m accelerating structures.
- The beam delivery/final focus has been shortened by a factor of 2, to about 5 km, through a redesign of the optics and elimination of the "big bend".
- The two interaction areas are no longer symmetric. One is referred to as the "High Energy" area, the other as the "Low Energy" area.

| | Luminosity vs $E_{CM}$ | | | |
|---|---|---|---|---|
| | 90 | 250 | 350 | 500 GeV |
| Low Energy IR | 0.3 | 0.9 | 1.3 | 1.3 |
| Hi Energy IR | -- | 1 | 1.4 | 2 |

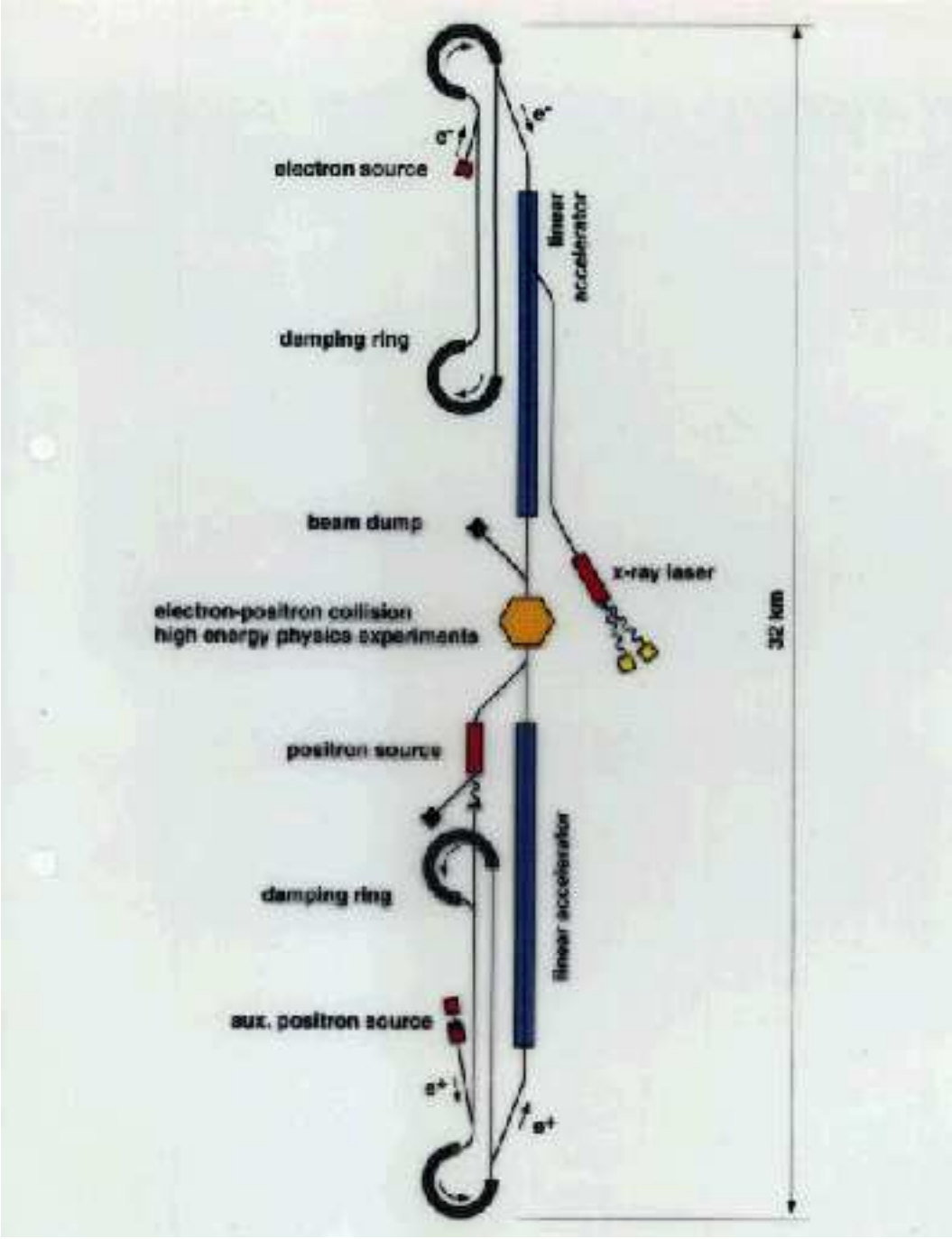
- Optimization energy of the low energy IR is still up for grabs.
- Simultaneous operations at different energies is not in the current configuration but is not precluded as an upgrade (180 Hz operations).


~100 m
0.6 GeV (X)
~20 m
Compressor
Pre-Linac
6 GeV (S)
Compressor
136 MeV (L)
Damping
Ring
(UHF)
e−
2 GeV (S)
e−
Electron Main Linac
240-490 GeV (X)
9.9 km
560 m
~10 m
170 m
Electron
Injector
Final
Focus
Dump
~300 m
Low E
Detector
Hi E
Detector
Dump
Final
Focus
~5 km
RF Systems
(X) 11.424 GHz
(S) 2.856 GHz
(L) 1.428 GHz
(UHF) 0.714 GHz
e−
6 GeV (S)
e+
Target
2 GeV (L)
Pre-Damping
Ring (UHF)
e+
e+
Damping
Ring
(UHF)
136 MeV (L)
Compressor
Pre-Linac
6 GeV (S)
9.9 km
Positron Main Linac
240-490 GeV (X)
510 m
200 m
10 m
560 m
Positron
Injector
Compressor
~20 m
~100 m
0.6 GeV (X)
10-2000
8047A611

## TESLA

The TESLA configuration has been relatively stable although some of the changes adopted by NLC could also be adopted here:

- Each linac arm is 10 km long, providing 500 GeV (center of mass) when filled with 25 MV/m accelerating structures.
- Nothing precludes incorporation of the SLAC final focus optics and/or dual experimental areas.
- A fourth generation light source (FEL) is provided as part of the design.
- Luminosity performance as a function of (lower) energy is expected to be similar to NLC.
- I do not believe simultaneous operations of the linear collider and FEL is precluded.
- e+ production scheme lends itself to polarized e+.


electron source
damping ring
beam dump
x-ray laser
electron-positron collision
high energy physics experiments
positron source
damping ring
aux. positron source
32 km

# TECHNOLOGY REQUIREMENTS

The dominant technology requirements of course derive from the need to produce energy and luminosity.

⇒ **Energy is electric field x length**

⇒ **Luminosity is beam power/spot size**

## Energy/Accelerating Gradient

The NLC assumes an accelerating gradient of 50 MV/m, TESLA assumes half that. As a result TESLA has twice the length of accelerating structures for the same beam energy.

Electric field gradients are generated by supplying rf power to a conducting structure. The translation between gradient and power dissipated in a structure (in the absence of beam) is:

$$\frac{P}{l} = \frac{G^2}{R_S'}$$

where $R_S'$ is called the shunt impedance (per unit length).

- Shunt impedance increases with frequency.
- Shunt impedance is effectively infinite for superconducting structures.

If we add up over the entire length of a linear accelerator we get:

$$P = \frac{E_{CM}^2}{R_S' L}$$

where L is the total length of the linac. Note that this implies that for a given $R_S'$ the power, and hence number of klystrons/modulators, goes down as the length increases (i.e. gradient decreases).

Of course if we have a fixed power source, the gradient decreases once beam is introduced because some of the energy that was going into the cavity walls now has to go into the beam. We say the "loaded gradient" is less than the "unloaded gradient".

The gradient in the **NLC**, as designed, is limited by power:

- Unloaded gradient = 75 MV/m
- Loaded gradient = 53 MV/m

  (Of course beam loading also implies that energy goes down as beam current goes up)

The gradient in the **TESLA**, as designed, is limited by material characteristics:

- Gradient = 25 MV/m

  (Beam loading is not really a gradient issue)

## *Fundamental Gradient Limitations*

- Fundamental limits seem to be related to breakdown (for whatever reason) in room temperature structures.
  - Single cells can support up to a few x 100 MV/m at 11 GHz.
  - Multi-cells are showing evidence of copper erosion after ~1000 hours operation at ~50 MV/m (unloaded).

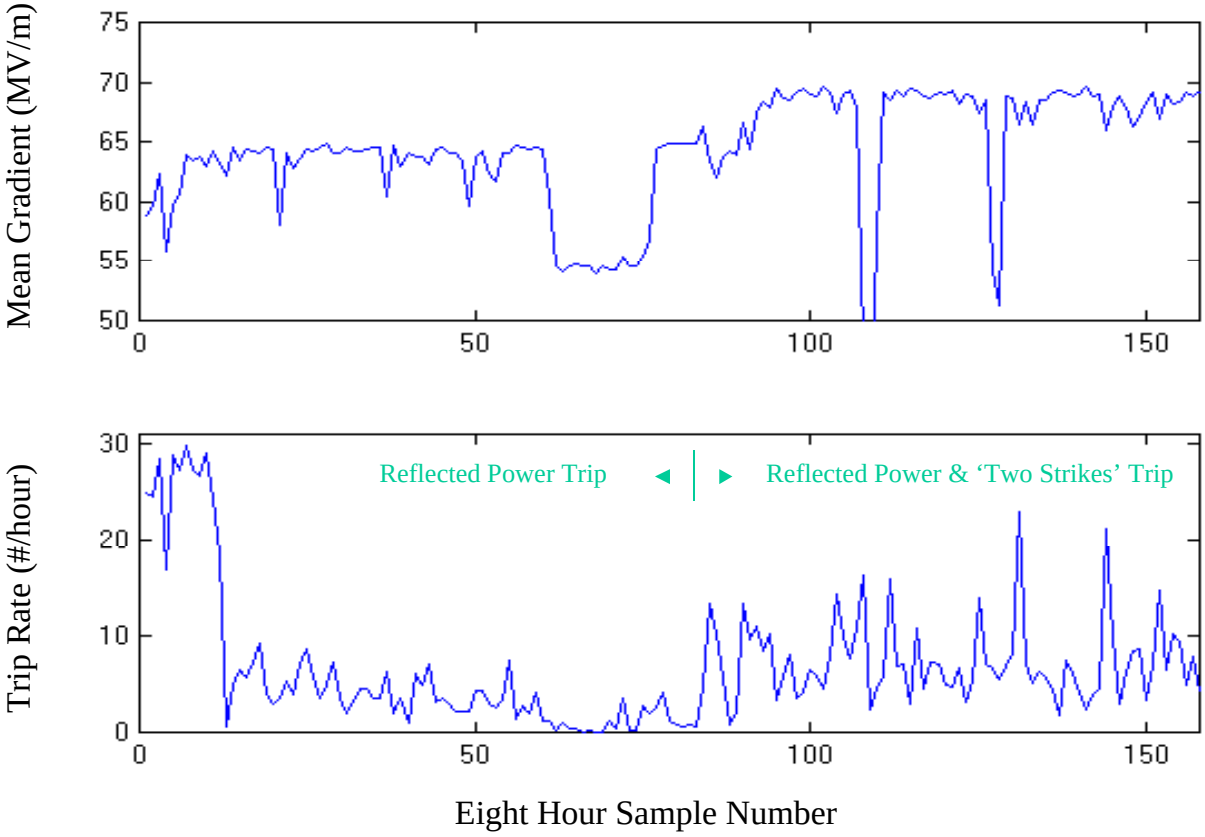
  ⇒R&D initiated on different design/fabrication approaches. Current parameters assume success, but fallback is backing off gradient by 15%.

- Fundamental limits in superconducting structures are related to loss of superconductivity (either materials properties or surface impurities).
  - Single cells can support up to 40 MV/m at 1.3 GHz.
  - Achieving ~25 MV/m in multi(9)-cell structures (~70% yield).

## ***Implications***

NLC has a short pulse length so that they don't put all the power into the walls. TESLA is not so constrained and so are happy to run a much longer beam pulse which has a number of additional advantages.

# DS2S Operation History with 250 ns Pulses




- Pre-processing at 70 MV/m resulted in 2-3 degree change/cell in first 5-6 cells.
  =>change in processing protocols
- No subsequent degradation seen over period covered by this figure
  =>but this particular structure is not robust in the sense that need 1 trip per hour for operational NLC.
- T20VG5N and T105VG5N being prepared for February installation into NLCTA.

## Luminosity/Beam Current/Wakefields

Achieving high luminosity at manageable beam power requires very small spot sizes.

- Small beam emittances are produced in state-of-the-art damping rings.
- Emittance preservation depends on controlling wakefields.
  - Wakefields tend to scale as $N_e f^3$.

$\Rightarrow$ Wakes are inherently smaller at TESLA. This may provide an advantage in producing the small spot sizes required, if they can get the small emittance out of the damping ring.

***Bottom Line***

- Accelerating gradient

  Warm structures support inherently higher gradients, but RF power distribution is more complicated because of short pulses.
- Creation/preservation of very small emittance/high brightness beams

  Damping rings are more difficult at TESLA because of the long pulses, but wakefields are higher at NLC.

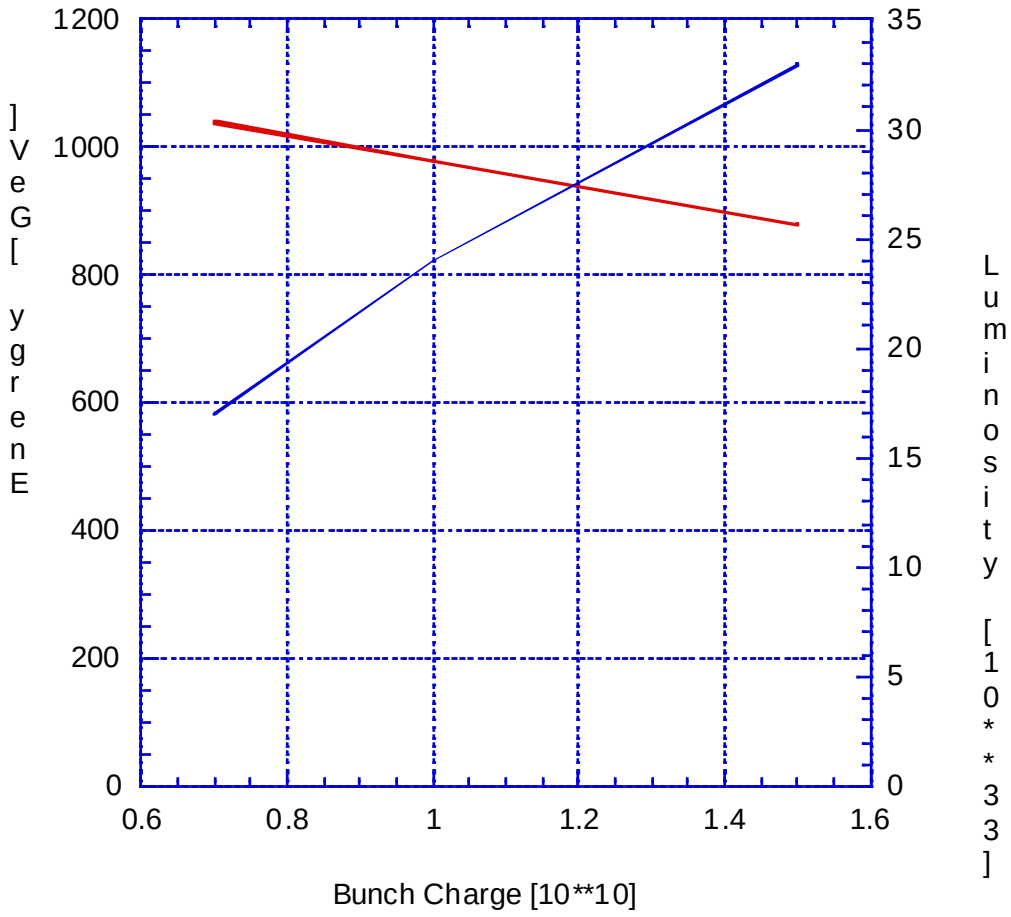
# UPGRADE PATHS

NLC injector and beam delivery/final focus are designed for 1500 GeV operation. Initial configuration only has 500 GeV of installed accelerating structures/power sources with room for another 500 GeV at 50 MV/m.

- lack of bending in high energy area maintains compatibility with several TeV beam delivery

TESLA injector and beam delivery/final focus are designed for 800 GeV operation (I believe).

| | NLC | TESLA | CLIC | |
|---|---|---|---|---|
| ***Phase 1*** | | | | |
| **Energy** | **500** | **500** | **3000** | **GeV** |
| Luminosity | 0.5-2E33 | 3E34 | 1E35 | $cm^{-2}sec^{-1}$ |
| | ⇓ Length × 2 | ⇓ Gradient × 1.6 | | |
| ***Phase 2*** | | | | |
| **Energy** | **1000** | **800** | **--** | **GeV** |
| Luminosity | 1-4E34 | 5E34 (?) | -- | $cm^{-2}sec^{-1}$ |
| | ⇓ Gradient × 1.5(technology unspecified) | | | |
| ***Phase 3*** | | | | |
| **Energy** | **1500** | **--** | **--** | **GeV** |
| Luminosity | 5E34 (?) | -- | -- | $cm^{-2}sec^{-1}$ |
| **Physical Length** | **20 km + Beam Delivery and Final Focus** | | | |


1200
1000
800
600
400
200
0
35
30
25
20
15
10
5
0
0.6
0.8
1
1.2
1.4
1.6
Bunch Charge [10**10]
]VeG[ ygreneE
Luminosity [10**33]

# CLIC (3 TeV)

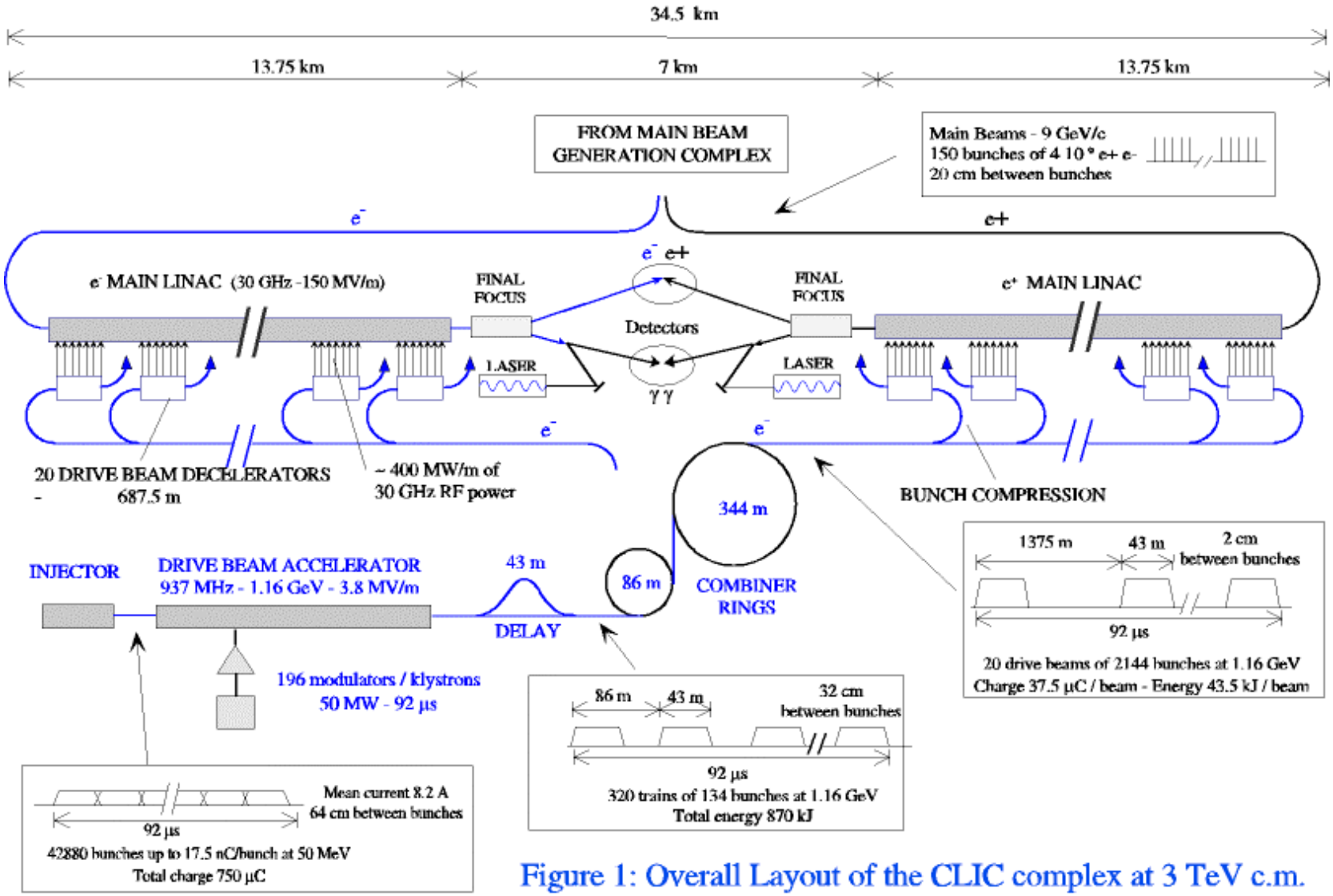



Figure 1: Overall Layout of the CLIC complex at 3 TeV c.m.

## Technical Viability

There was significant discussion last week on the topic of whether one should even discuss physics reach of a machine before its technical viability had been established. I would suggest that the real question is what standard should a facility be held to at various steps in the decision making process, and that at the moment the question to ask is:

**Is it plausible that a 500 GeV and beyond linear collider could be built? Is it plausible it could be upgraded?**

I believe the answer is **yes, it is certainly plausible—**

- We have an existence proof of a linear collider.
- We have multiple technological implementations being developed, each embedded in a fairly mature concept, and with different strengths and weaknesses.
- We have R&D efforts targeting all critical issues with significant achievements to date (NLCTA, FFTB, ATF, TTF).
- We have longer term R&D programs aimed at multi-TeV machines.

⇒ **The real question is what luminosity it will reach.**

Fermilab is starting to develop a view on the critical issues in such machines through our engagement in the NLC R&D program over the last year, and our longer term connection with TESLA (which, while diminished is still existent).

The make or break issues (as we see them):

- RF power distribution (warm)
- How to manufacture the hardware in a finite period of time? (warm and cold)
- Creation of very small emittance beams (cold more so than warm)
- Preservation of very small emittance beams (warm more so than cold)
- Public support/acceptance (U.S. more than Europe)
- Cost (warm and cold)

⇒**These issues are not yet resolved, although some are further along than others. The issues we are trying to attack and understand at Fermilab are all embedded in here.**

## The Fermilab LC R&D Program

### Goals/generic

1. Assist the national Next Linear Collider Collaboration in executing the R&D required to establish a technical basis for an x-band linear collider.

2. Become informed on the full range of technologies that might serve as a basis for a next generation linear collider.

3. Assess the viability of Fermilab as a site for a linear collider.

### Goals/specific

- Structures facility
  - capacity for production of one structure/month by end of CY02.
  - production of 24 accelerating structures, supported on girders with associated vacuum systems, controls, and focusing magnets and diagnostics for utilization in ETF in the summer of 2004.
  - development of an industrial capability for manufacturing structures.
- Engineering Test Facility
  - investigation of engineering aspects of the DLDS including assembly/installation, vacuum performance, (low power) microwave transmission performance, tolerances, environmental control, maintenance. 2001-2003.
  - Complete DLDS system driven by klystron 8-pack available for high power testing in the summer of 2004.
  - Beam tests demonstrating operations with the NLC bunch structure (bunch population, bunch spacing, pulse length) later in 2004 or into 2005.
- Permanent Magnets
  - investigation of design options and construction of prototypes FY01-02.
  - Construction of magnets for the ETF
- Accelerator Physics
  - development of simulation tools and support for the design of beam experiments in the ETF by the May MAC meeting.
  - application of these tools to more general investigation of linac wakes, tolerances, countermeasures especially in the context of a 25% emittance growth budget.
- Civil Construction.
  - completion of an optimized design on an identifiable Northern Illinois site or sites by the end of the CDR prior (summer of 2003? 2004?).
- Alternate Technologies
  - development of a Fermilab viewpoint on the pluses and minuses of technology options for a linear collider.
  - operation of the A-0 photoinjector with DESY as a collaborating institution.
  - bi-weekly internal technology discussion.

So what would the accelerator folks like to hear?

- Energy/luminosity requirements
  - Map out a physics program as a function of energy and luminosity. From this define the minimum energy that provides a program that people can get excited about.
  - Do not assume that luminosities in excess of $1x10^{34}$ will be available from day 1 (or day 365). Is there a physics program at somethingx$10^{33}$?
    ⇒Please let us know.

- Configuration
  - Is there a case for two IR's that do not run simultaneously (at different energies)?
  - If so should they be optimized at the same or at separate energies?
  - If not, is there a compelling case for two IR's that can run simultaneously (recognizing that this will increase the construction and operating costs)?
  - Positron polarization — I didn't talk about this but is it something that would really enhance performance?

- Luminosity packaging
  - The luminosity in the room temperature and superconducting linear collider is packaged very differently. Does it make any difference?
  - Do large beam energy spreads due to varying the beamstrahlung parameter matter? What levels of background photons can be tolerated?

- Upgradability
  - It appears highly unlikely that a 1 TeV or greater linear collider could be built as an initial step. Assuming a first step of 500 GeV what would be the minimal useful energy upgrade following several years of operations? What is the associated luminosity required?

# SUMMARY

I would suggest that you assume at least one technology will exist to support linear collider operating at 500 GeV and 5-20x$10^{33}$ $cm^{-2}sec^{-1}$ on the timescale of the current decade.

⇒ Figure out if there is a **physics program** that excites you and define the associated **performance parameters**.

⇒ Understand what kind of **upgrade paths** would be desirable for a **multi-decade program**.

⇒ Don't necessarily assume that >1x$10^{34}$ is available on day 1. Examine **physics opportunities at lower initial luminosities**.

⇒ Don't get hung up on the technology arguments. A **technology evaluation** will have to be done, but it **is not a prerequisite to the physics decision**. It is a prerequisite to a construction decision.