2005 International Workshop-Summer School
on physics, detector and accelerator at the linear collider
July 15-20, 2005

Center for High Energy Physics
Tsinghua University, Beijing 100084, China

Lecture 2

Technology Competition Towards a Linear Collider

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INFN Milano and DESY

On leave from University of Milano

A Little History

M. Tigner,
Nuovo Cimento **37** (1965) 1228

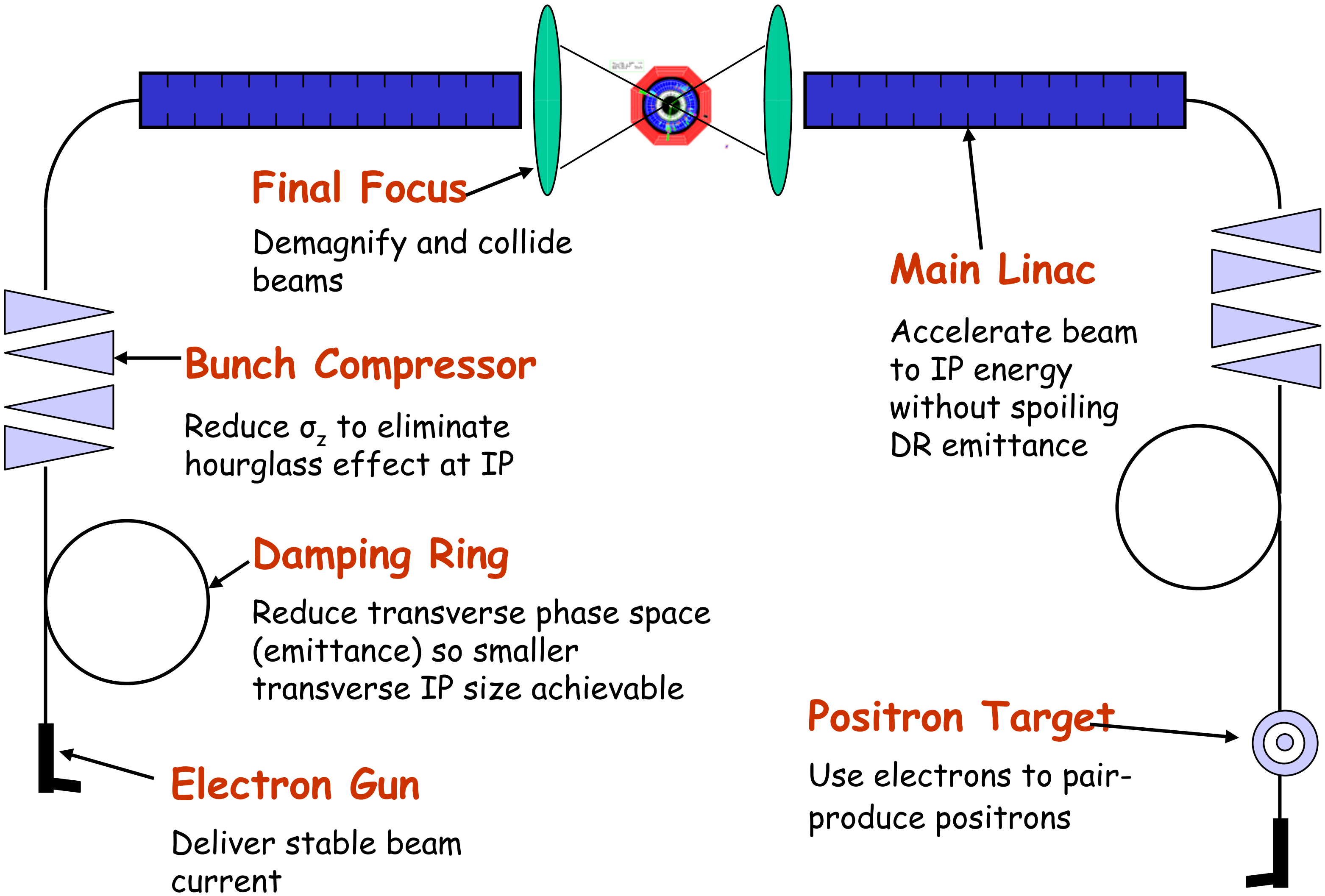
A Possible Apparatus for Electron-Clashing Experiments (*).

M. Tigner

Laboratory of Nuclear Studies. Cornell University - Ithaca, N.Y.

"While the storage ring concept for providing clashing-beam experiments ([1]) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant and superficially more complex may prove more tractable."

Linear Collider Conceptual Scheme



Competing Technology for the Linacs

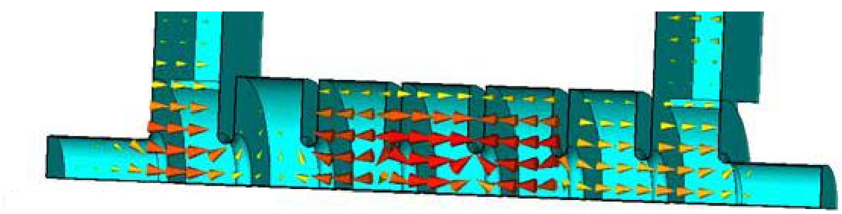
Traveling wave

$V_{ph} \approx c$ and $Vg < c$

NLC/GLC: f = 11.4 GHz

CLIC f = 30 GHz

Normal-Conducting

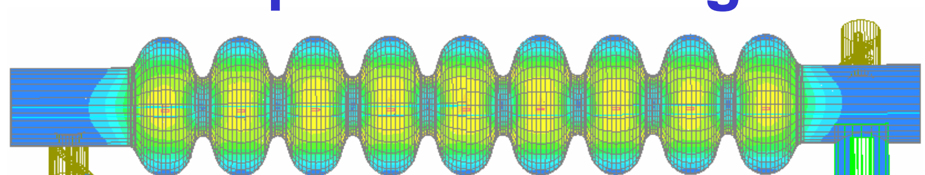


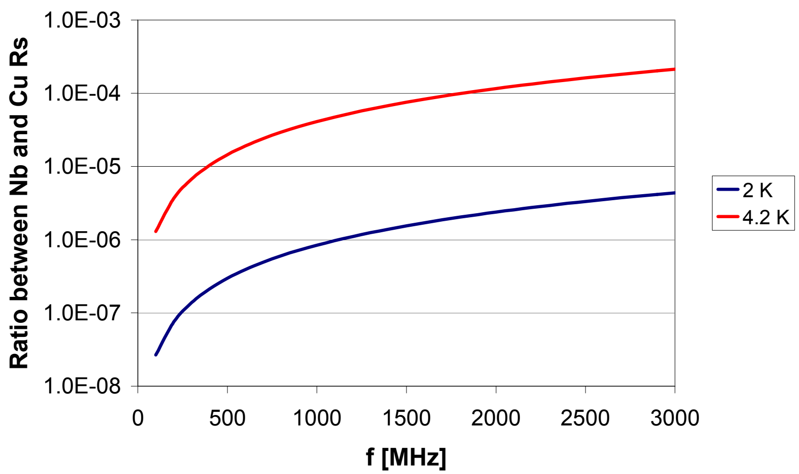
Standing wave

$V_{ph} = 0$ and $Vg = c$

TESLA: f = 1.3 GHz

Super-Conducting





Remembering that the power dissipated on the cavity walls to sustain a field is:

$$P_{diss} = \frac{R_s}{2} \int_S H^2 dS$$

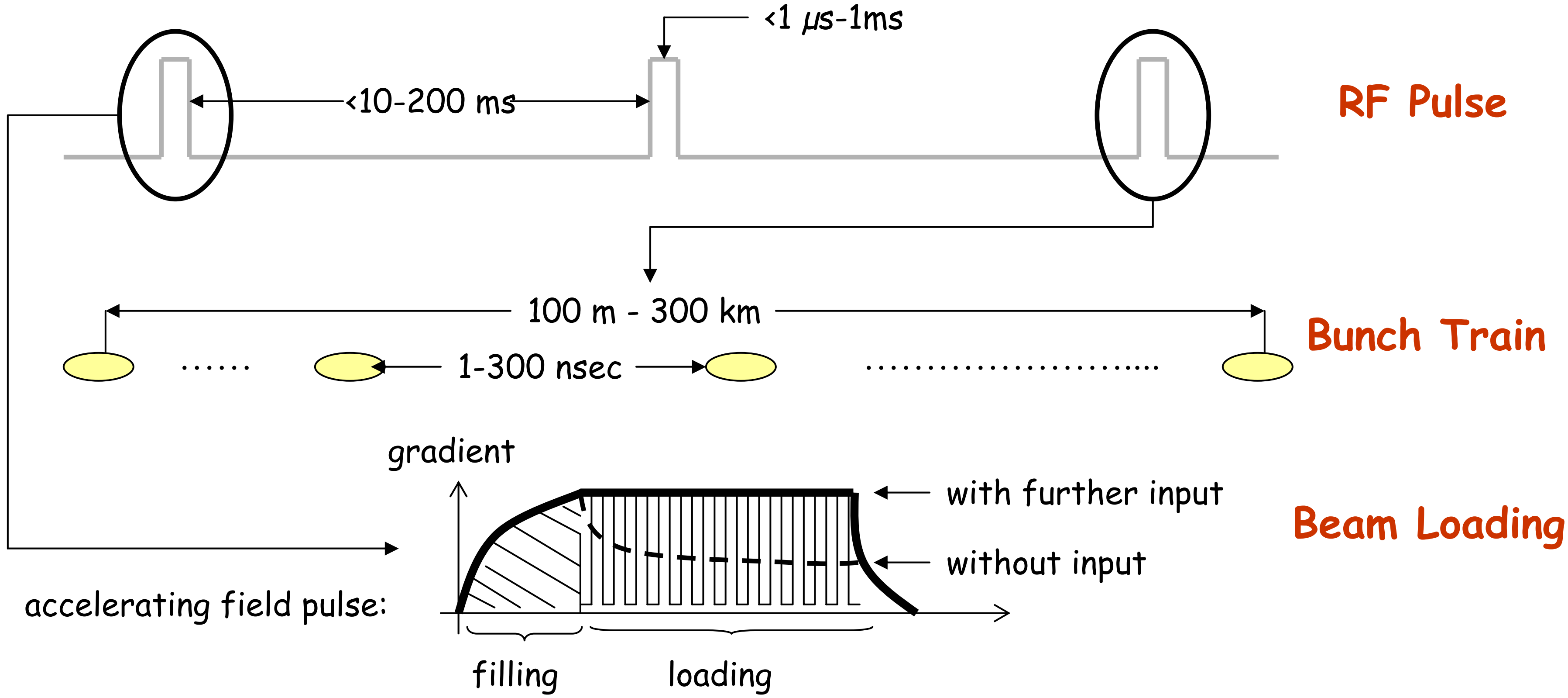
standing wave case

a pulsed operation is required to reduce the time in which the maximum allowable field is produced to accelerate the particles

Linear Colliders are pulsed

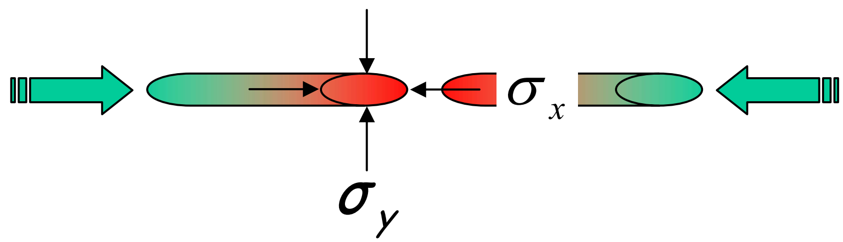
LCs are pulsed machines to improve efficiency. As a result:

- duty factors are small
- pulse peak powers can be very large



Fighting for Luminosity

$$L \propto \frac{N_e^2}{\sigma_x \sigma_y}$$



$$L \propto n_b \times f_{rep}$$

L = Luminosity

N_e = # of electron per bunch

$\sigma_{x,y}$ = beam sizes at IP

IP = interaction point

$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

n_b = # of bunches per pulse

f_{rep} = pulse repetition rate

P_b = beam power

$E_{c.m.}$ = center of mass energy

Parameters to play with

↓ Reduce **beam emittance** ($\varepsilon_x \cdot \varepsilon_y$) for smaller beam size ($\sigma_x \cdot \sigma_y$)

↑ Increase bunch population (N_e)

↑ Increase beam power $\left(P_b \propto N_e \times n_b \times f_{rep}\right)$

↑ Increase **beam to-plug power efficiency** for cost

ILC-TRC (Greg Loew Panel)

International LC Technical Review Committee

- International Collaboration for R&D toward TeV-Scale e^+e^- LC asked for first ILC-TRC in June 1994
- ILC-TRC produced first report end of 1995
- 2001: ICFA requests that ILC-TRC reconvene to produce a second report with the following charge:
  - To assess the present technology status of the four LC designs at hand, and their potential for meeting the advertised parameters at 500 GeV c.m.
  - Use common criteria, definitions, computer codes, etc., for the assessments
  - To assess the potential of each design for reaching higher energies above 500 GeV c.m.
  - To establish, for each design, the R&D work that remains to be done in the next few years
  - To suggest future areas of collaboration
- ILC-TRC produced second report January 2003

  http://www.slac.stanford.edu/xorg/ilc-trc/2002/2002/report/03rep.htm

LC status at first ILC-TRC

End 1995 E_{cm}= 500 GeV

	TESLA	SBLC	JLC-S	JLC-C	JLC-X	NLC	VLEPP	CLIC
f [GHz]	1.3	3.0	2.8	5.7	11.4	11.4	14.0	30.0
$\mathcal{L}\times 10^{33}$ [$cm^{-2}s^{-1}$]	6	4	4	9	5	7	9	1-5
P_{beam} [MW]	16.5	7.3	1.3	4.3	3.2	4.2	2.4	1-4
P_{AC} [MW]	164	139	118	209	114	103	57	100
$\gamma\varepsilon_y$ [$\times 10^{-8}$m]	100	50	4.8	4.8	4.8	5	7.5	15
σ_y^* [nm]	64	28	3	3	3	3.2	4	7.4

Tasks to be addressed

Baseline cm Energy stays at 500 GeV

- Push Luminosity to the maximum value
- Technology:
  - Demonstrate that the proposed technology can be pushed to the limits required for a Linear Collider
  - Demonstrate that the proposed technology can be produced in large scale by industry with high reliability and reasonable cost
  - Find solution for all critical items
- Design issues:
  - Demonstrate that very small spot sizes ($\sigma_x \cdot \sigma_y < 1\ \mu m^2$) are possible
  - Investigate all beam physics critical issues
  - Support all design features with cross-checked simulations
  - Address reliability and availability issues
- Roadmap for energy upgrade
- Test Facilities

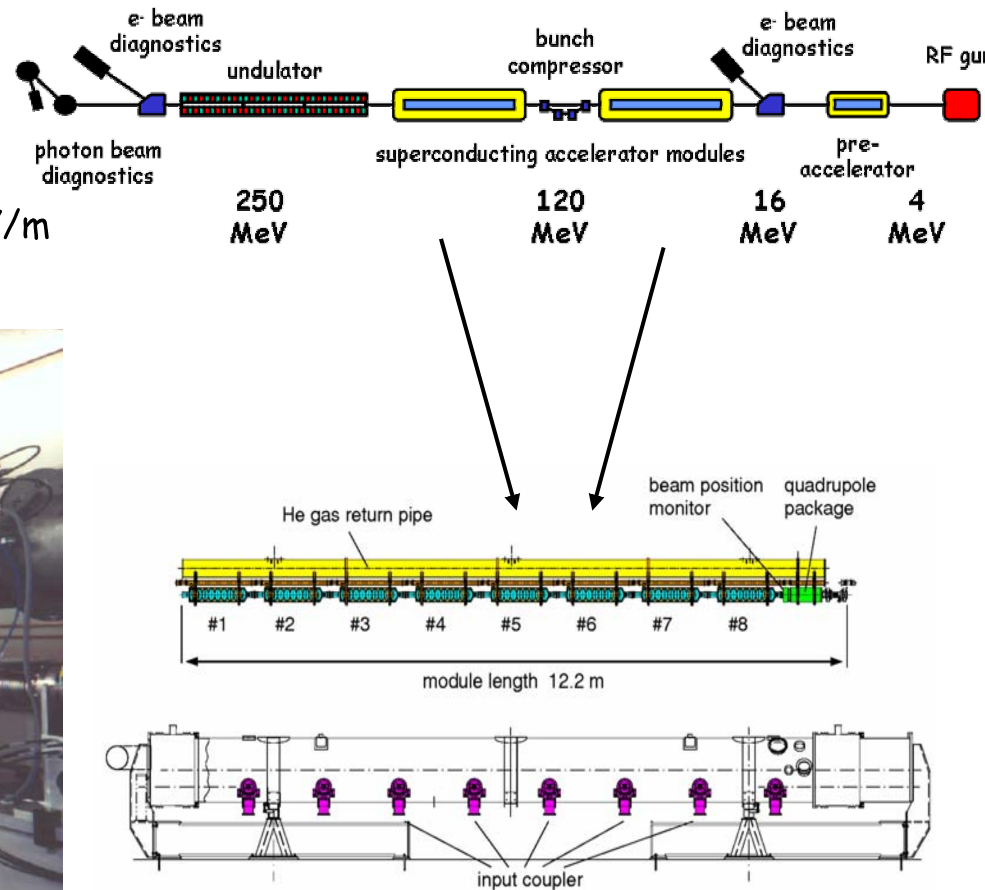
TTF for TESLA

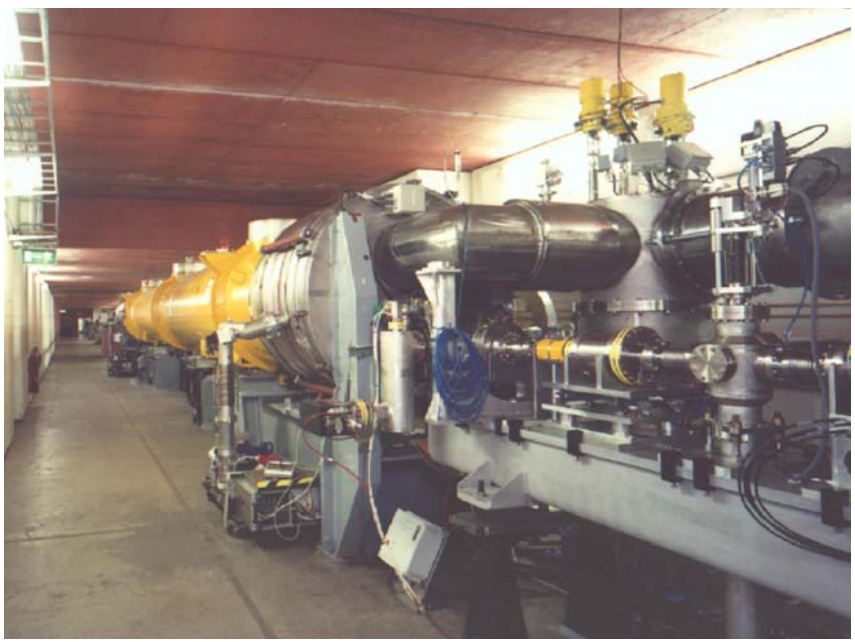
TTF = TESLA Test Facility

TTF as operated for SASE FEL

TTF Goals:

- Demonstrate that Superconducting RF technology is suitable for LC
- Operate TTF at E_{acc} > 15 MV/m
- Develop cavity technology for Eacc > 25 MV/m



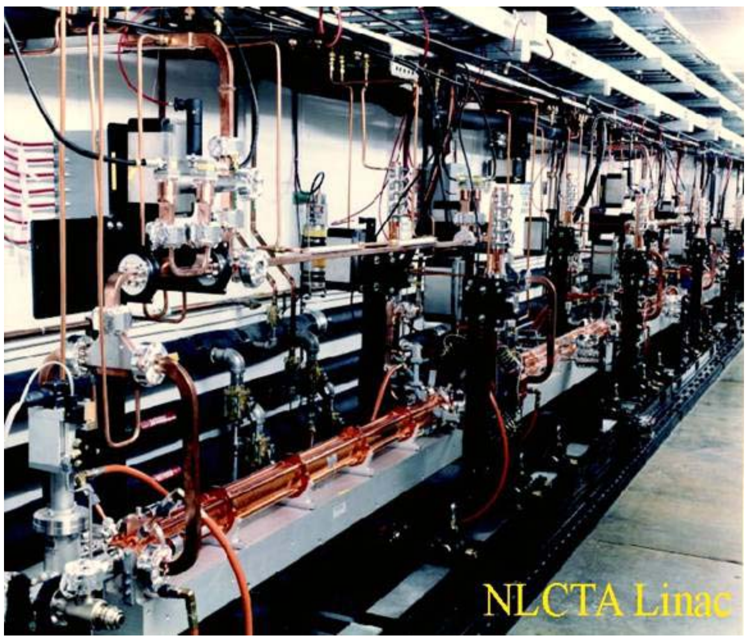


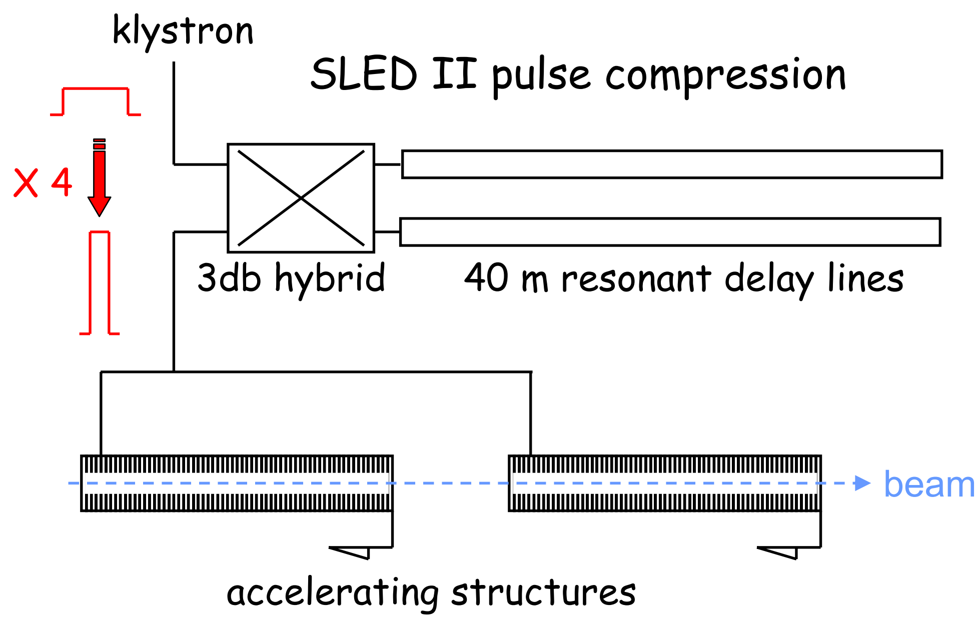
NLCTA for NLC

NLCTA = NLC Test Accelerator

NLCTA Goals:

- RF system integration test of a NLC linac section
- Test efficient, stable and uniform acceleration of a NLC-like bunch train





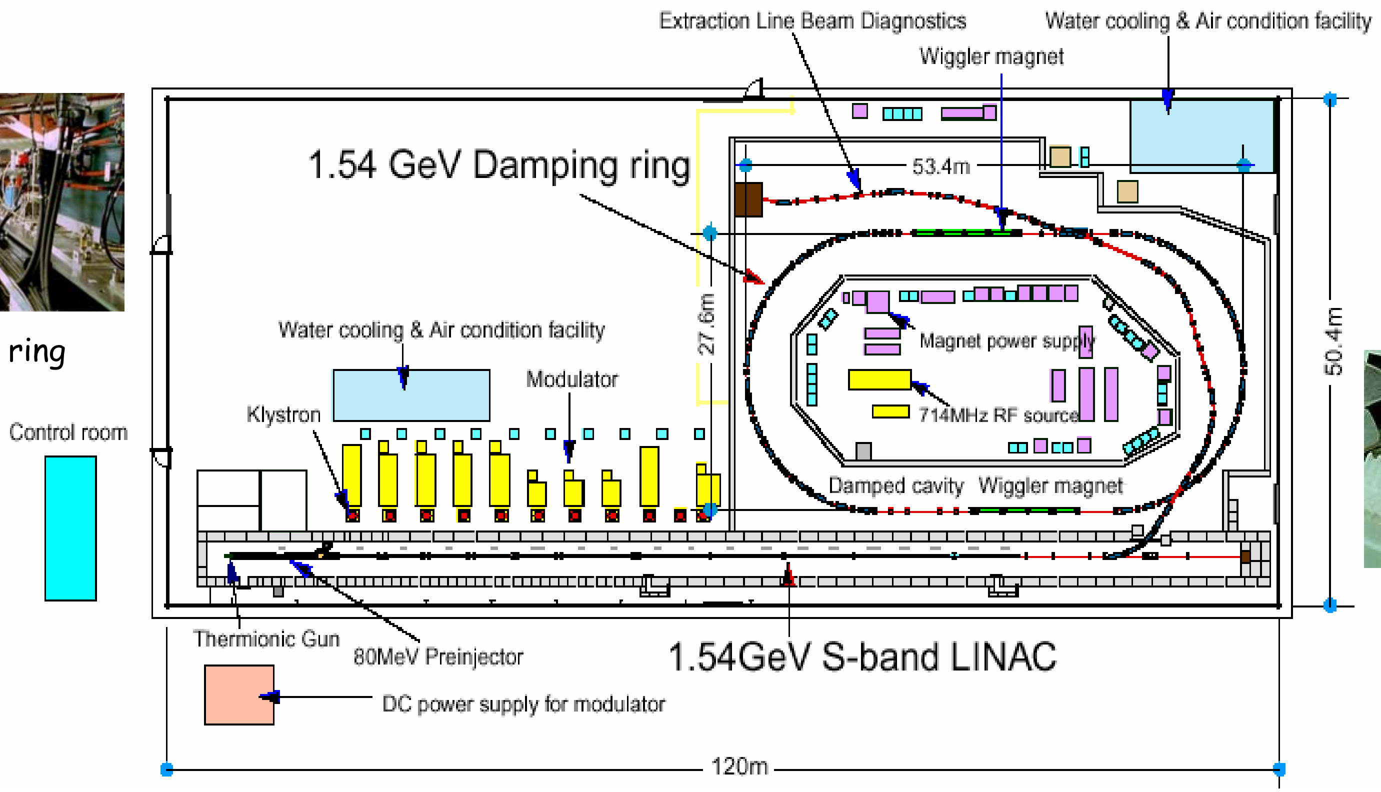
ATF for JLC

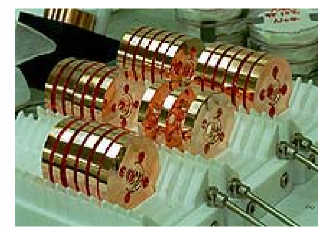
ATF = Accelerator Test Facility

ATF Goals:

- Demonstrate very low beam emittance
- Develop RF technology

Damping ring





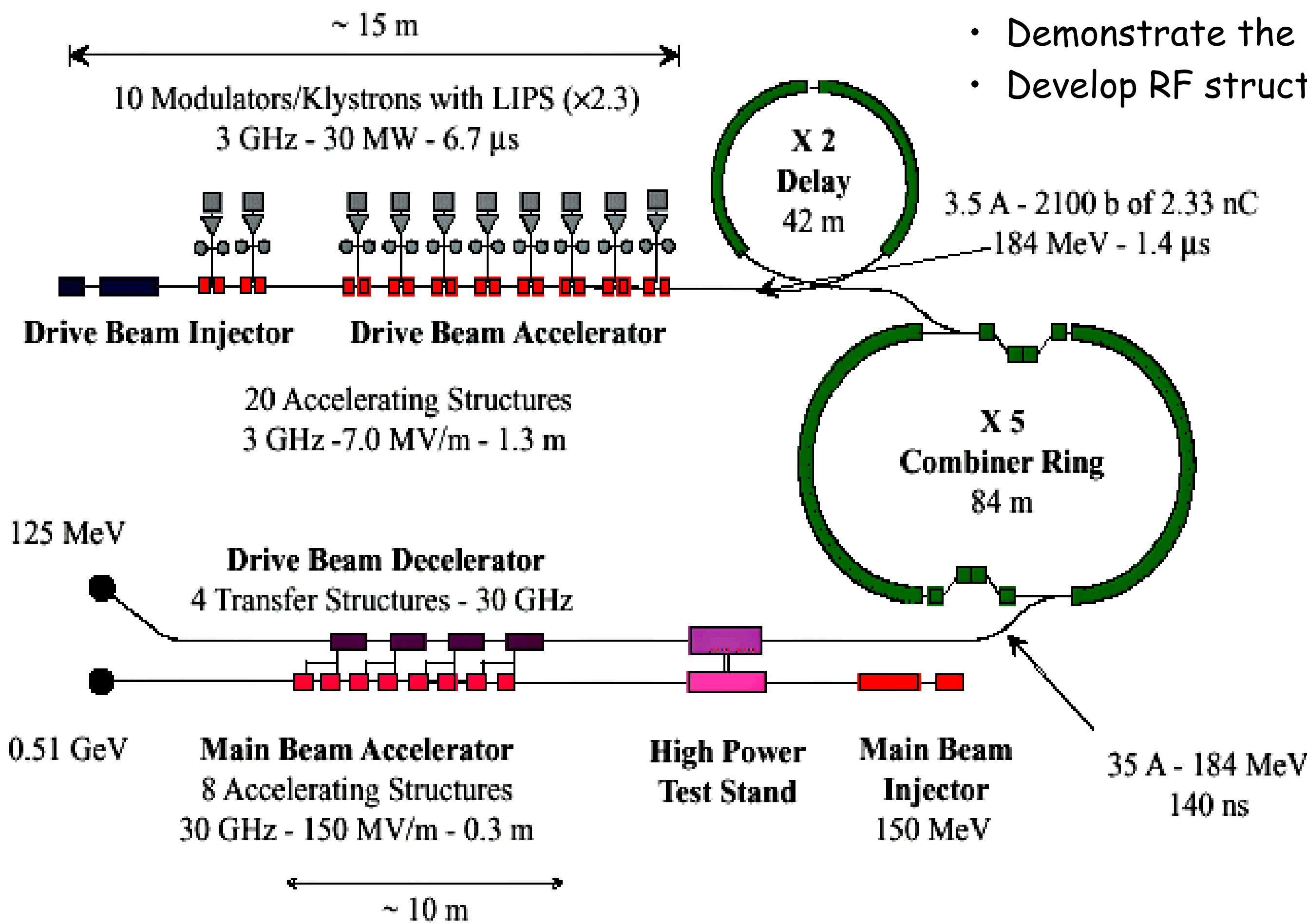
Cavity Production

CTF for CLIC

CTF3 = CLIC Test Facility #3 (Under construction after CTF1 and CTF2)

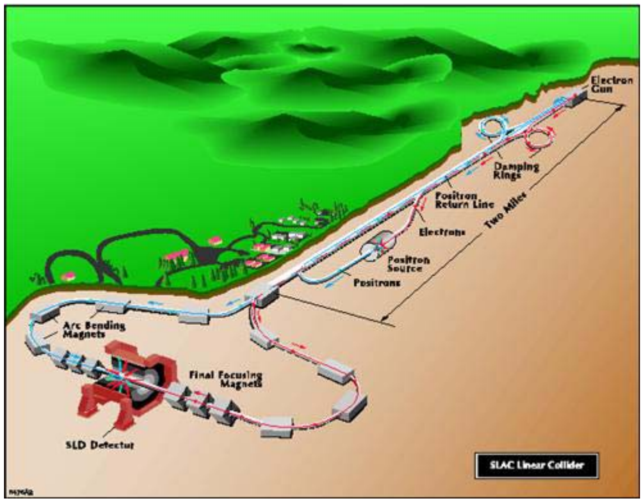
CTF3 Goals:

- Demonstrate the drive beam scheme
- Develop RF structures and technology

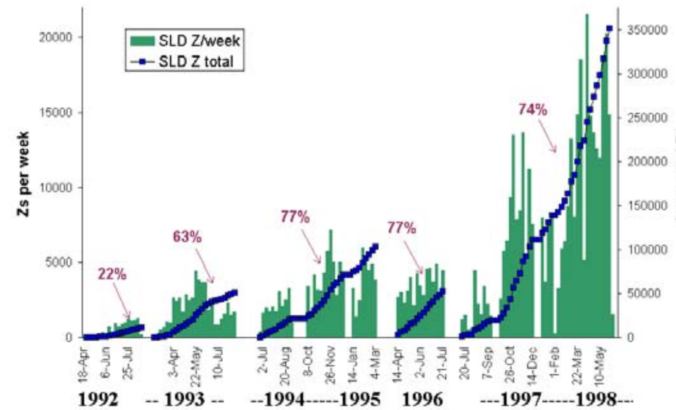


Lessons from the SLC

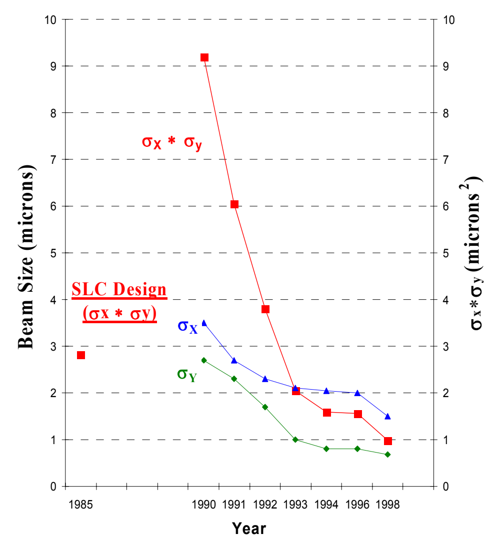
SLC = SLAC Linear Collider



1992 - 1998 SLD Luminosity



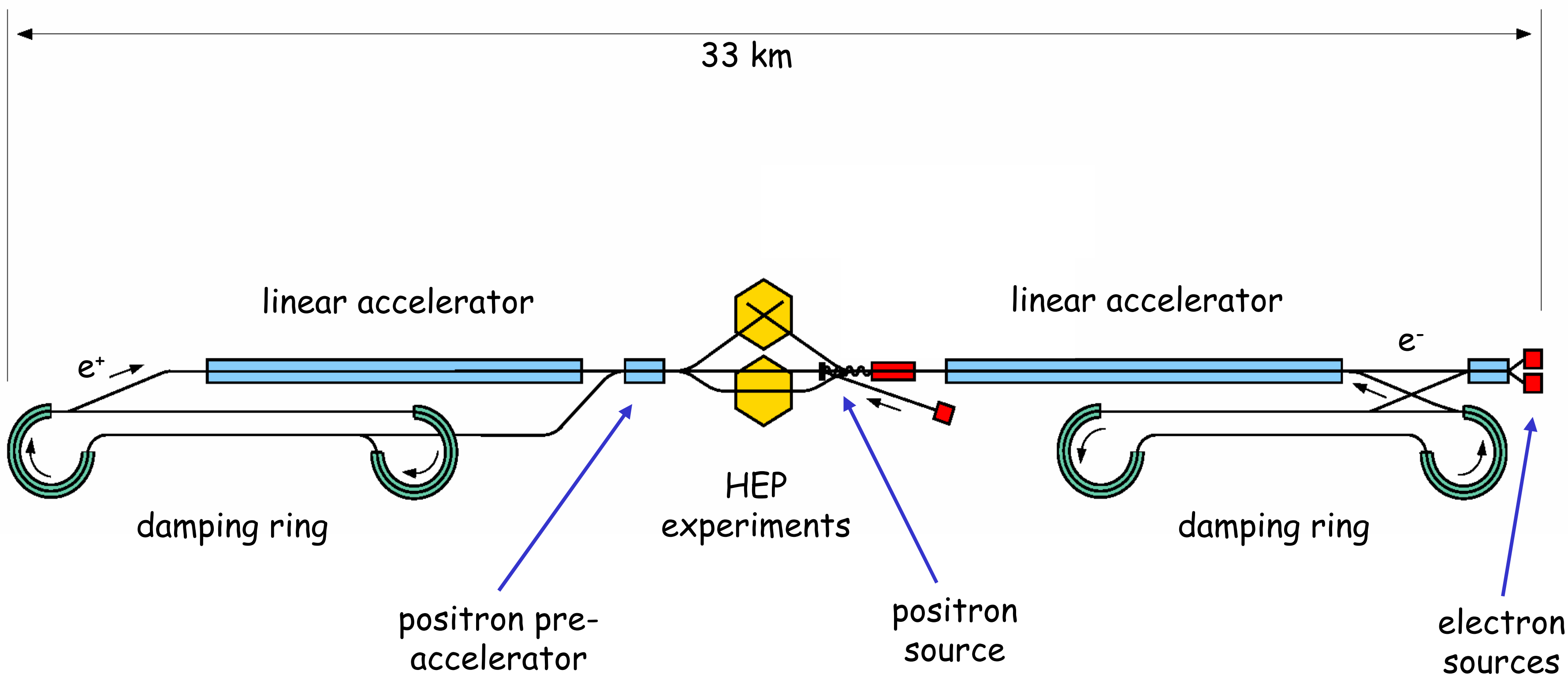
IP Beam Size vs Time



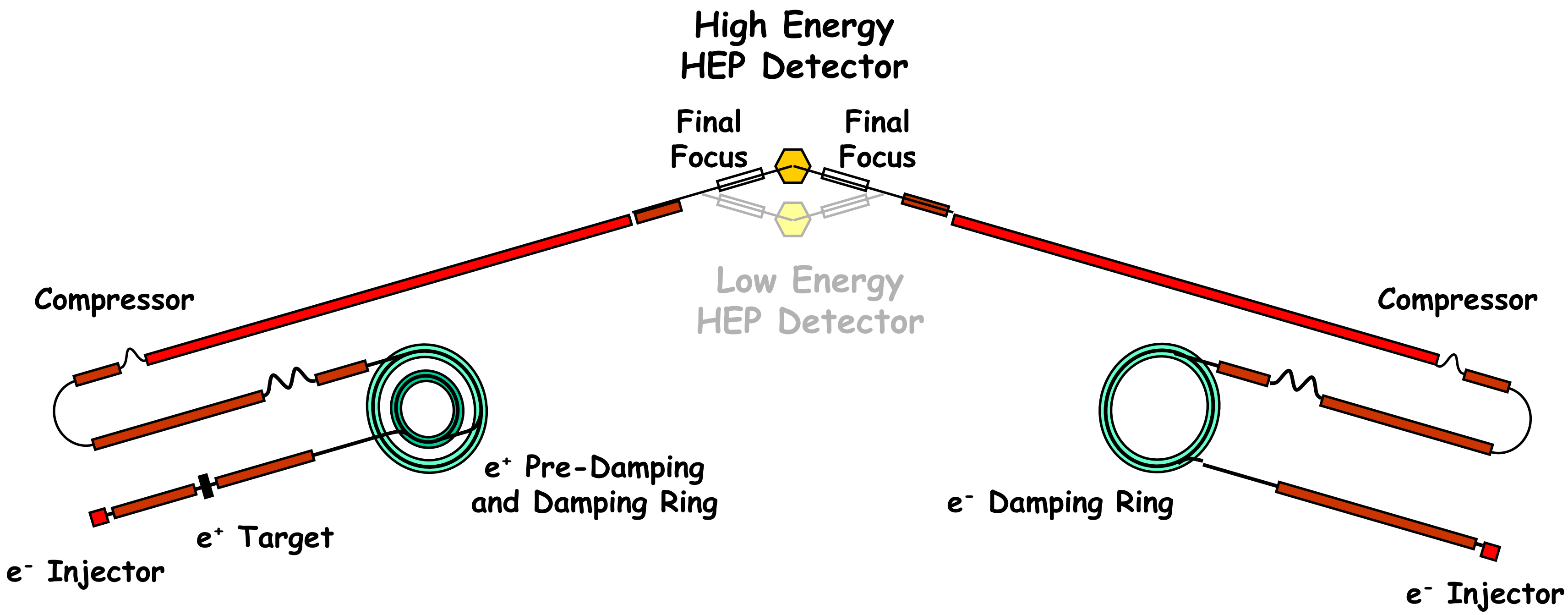
New Territory in Accelerator Design and Operation

- Sophisticated on-line modeling of non-linear beam physics.
- Correction techniques (trajectory and emittance), from hands-on by operators to fully automated control.
- Slow/fast feedback theory and practice.

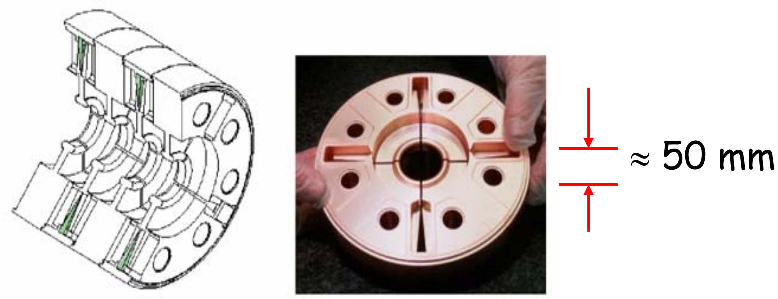
TESLA 0.5 - 0.8 TeV c.m.



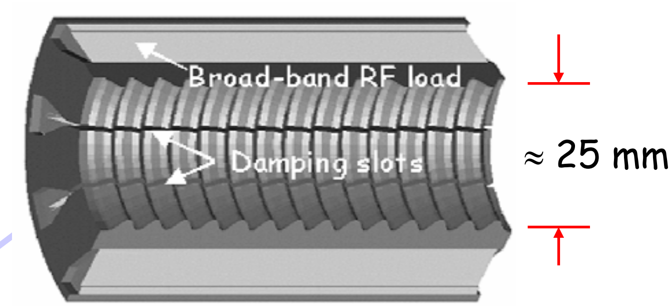
NLC/JLC   0.5 - 1.0 TeV c.m.



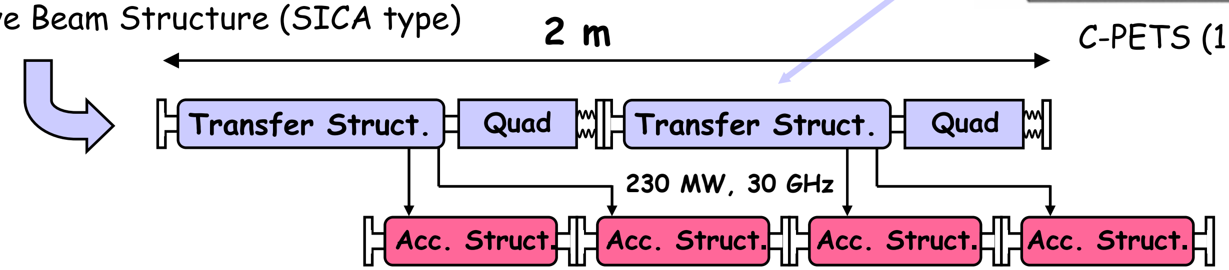
The CLIC Idea

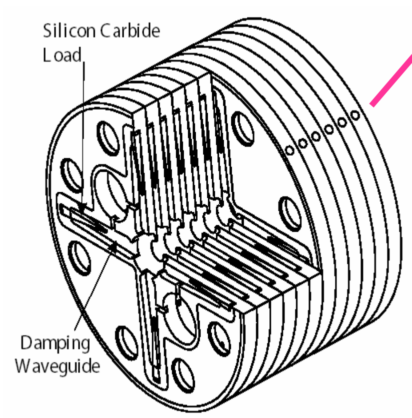


CLIC Drive Beam Structure (SICA type)

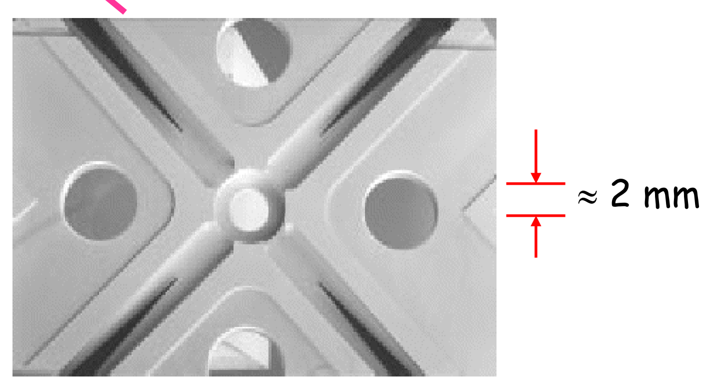


C-PETS (12 damping slots)

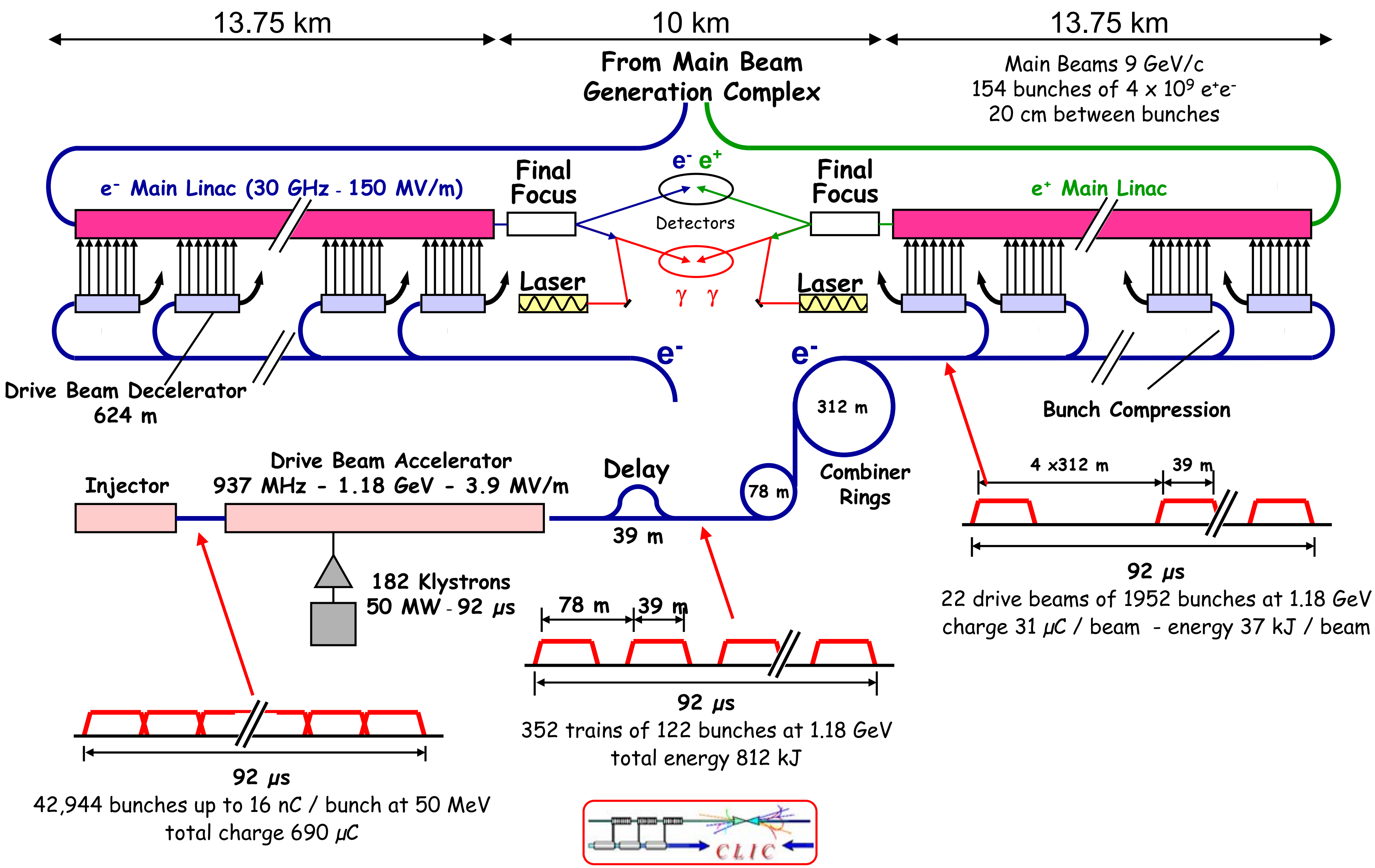




Tapered-Damped Structure (30 GHz)



CLIC 3 GeV c.m. Layout



2nd ILC-TRC Methodology and Rankings

Time-line
Summer 2001: ICFA requests a new report
January 2003: Report published

Methodology

- Review current designs and status (achievements) of R&D, particularly the test facilities
- Identify the positive aspects of the designs
- Identify those areas of 'concern' and
- identify R&D that needs to be done to address these issues
- Categorise (rank) the R&D items

Ranking Criteria

- **R1**: **R&D needed for feasibility demonstration of the machine.**
- **R2**: R&D needed to finalize design choices and ensure reliability of the machine.
- **R3**: R&D needed before starting production of systems and components.
- **R4**: R&D desirable for technical or cost optimization.

2^{nd} to 1^{st} ILC-TRC Comparison

2003 vs. 1995 E_{cm} = 500 GeV

	TESLA 2003	TESLA 1995	JLC/NLC 2003	<JLC/NLC> 1995	CLIC 2003	CLIC 1995
f [GHz]	1.3	1.3	11.4	11.4	30.0	30.0
$L \times 10^{33}$ [$cm^{-2}s^{-1}$]	34	6	20	6	21	1-5
P_{beam} [MW]	11.3	16.5	6.9	3.7	4.9	1-4
P_{AC} [MW]	140	164	195	110	175	100
$\gamma\varepsilon_y$ [$\times 10^{-8}$m]	3	100	4	5	1	15
σ_y^* [nm]	5	64	3	3	1.2	7.5

Ranking Score Sheet

	TESLA		JLC-C	JLC-X/NLC		CLIC		Common
E_{cm} [GeV]	500	800	500	500	1000	500	3000	
R1	0	1	2	2	0	5	2	0
R2	7	4	2	3	0	6	2	8
R3	10	3	3	11	0	5	0	19
R4	1	0	1	2	2	0	0	8

R1 Comparison

TESLA

E_{cm} = 500 GeV

- No feasibility demonstration is required for TESLA 500

E_{cm} = 800 GeV

- Building and testing of a cryomodule at 35 MV/m and measurements of dark current by end 2003

NLC/JLC

E_{cm} = 500 GeV & 1 TeV

- Test of complete accelerator structure at design gradient with detuning and damping, including study of breakdown and dark current
- Demonstration of SLED-II pulse compressor at full power

R1: feasibility demonstration required?

R1: R&D needed for feasibility demonstration of the machine.

	Modulators	Klystrons	RF Distribution	Accelerator Structures
TESLA	No	No	No	No (500 GeV) ~~Yes (800 GeV)~~
NLC/JLC-X	No	No	~~Yes~~	Yes
JLC-C	No	No	Yes	Yes
CLIC	Yes	Yes	Yes	Yes

From Chris Adolphsen talk at ALCW, Mumbai, July 2003

Common R2 Items

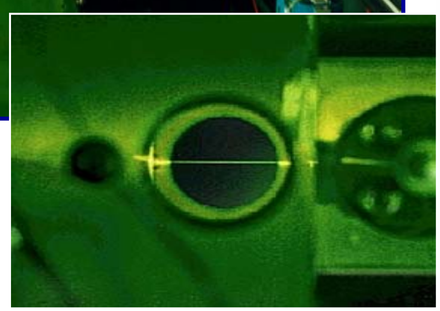
Common items related to all designs

- **Damping Rings**
  - Electron cloud effects
  - fast ion instabilities
  - Extraction kicker stability
  - Tuning simulations
- **LET: Low Emittance Transport**
  - Static tuning studies
  - girder/cryomodule prototypes to study stability (vibration)
  - Critical beam instrumentation
- **Reliability**
  - Detailed evaluation of critical sub-systems reliability

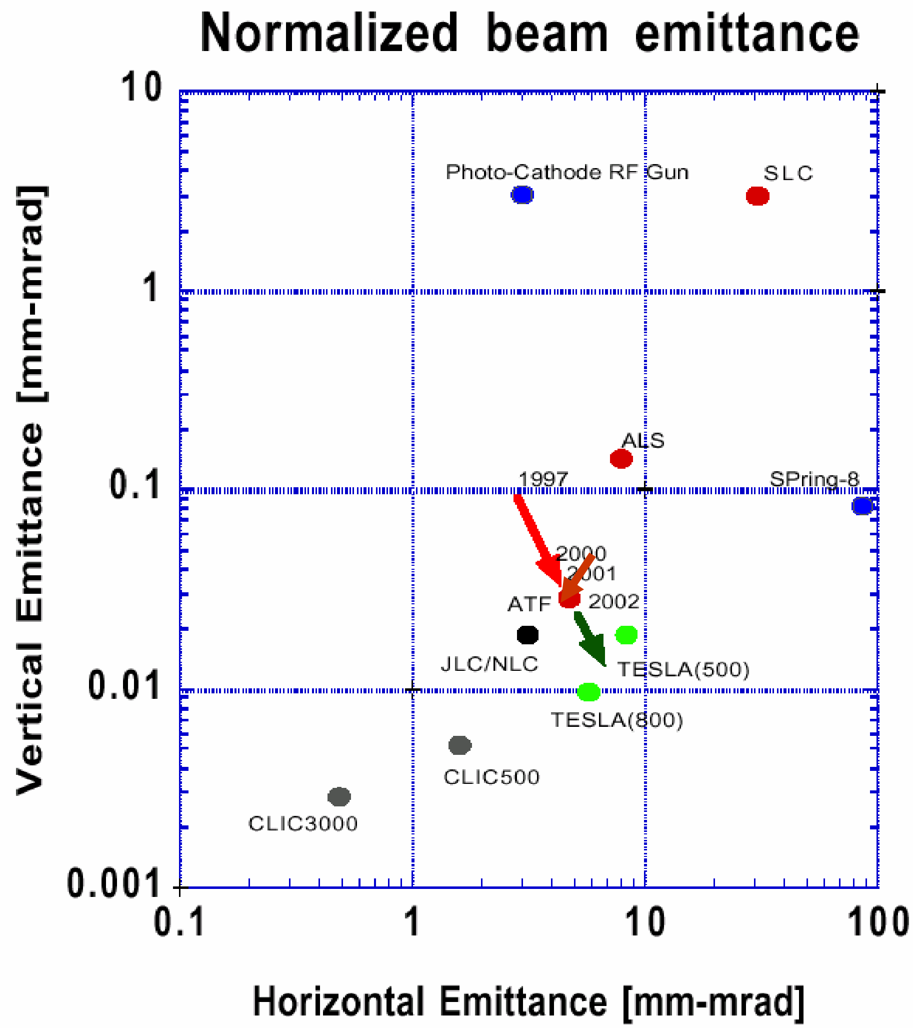
Damping Ring

Low emittance

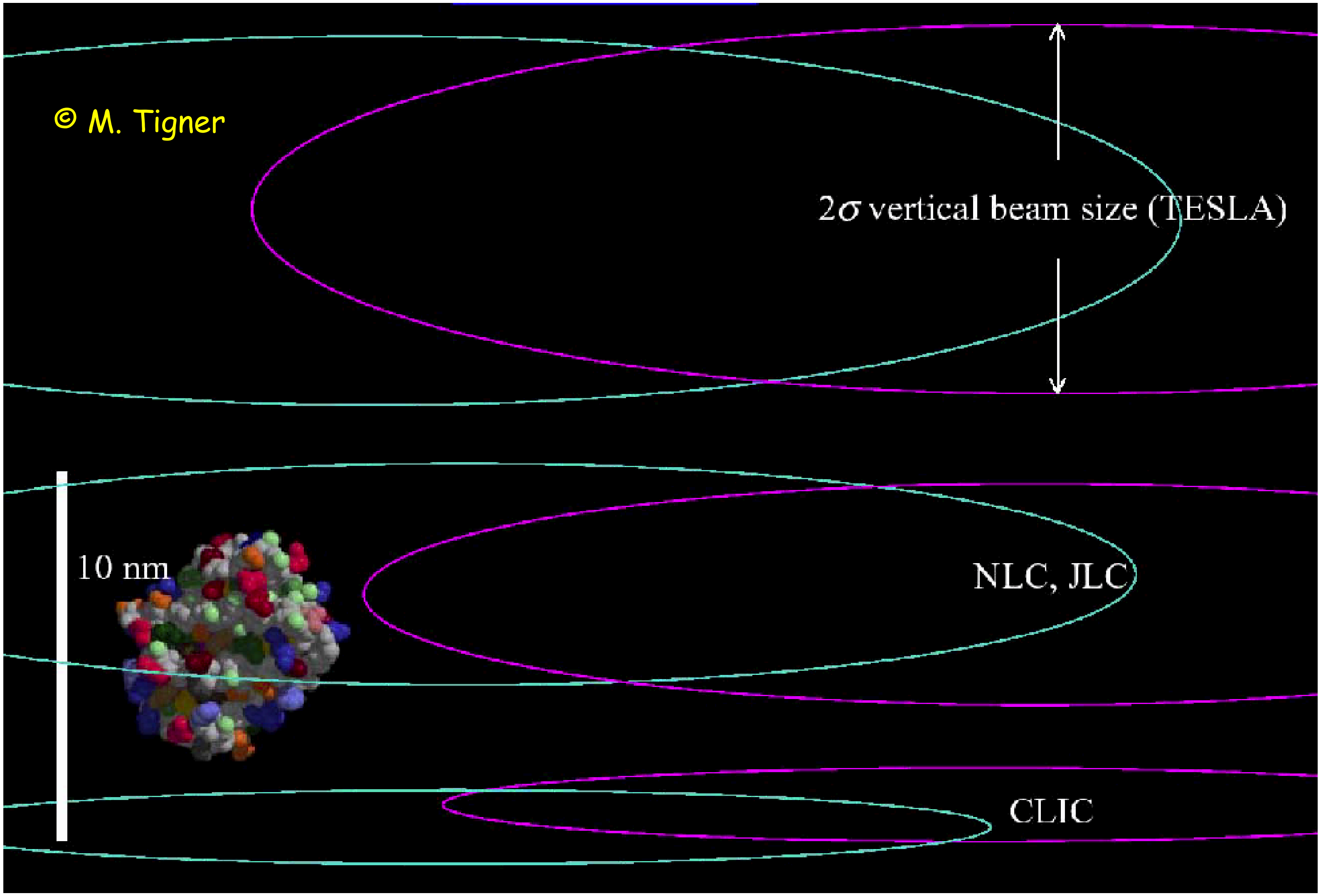
ATF Damping Ring at KEK



"Laser Wire"



Beam Sizes



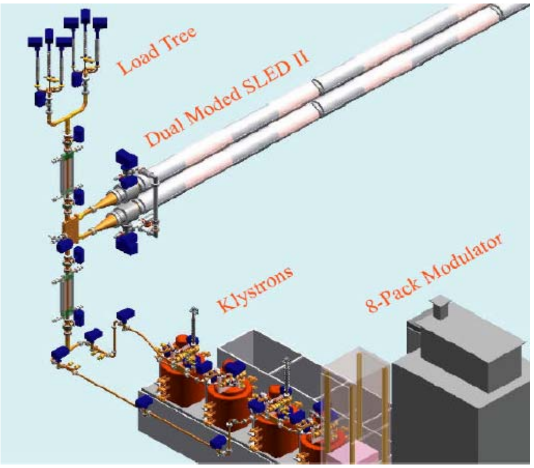
R2 Comparison

TESLA

- Test of complete main linac RF sub-unit (as in TDR) with beam
- Tests of several cryomodules running at gradient 23.4 MV/m for a prolonged period of time
  - quench rates, breakdowns, dark current
- One versus two tunnels (reliability)
- DR dynamic aperture
  - wiggler end fields
  - minimise injection losses (P_{inj}=220kW)
- DR kicker development
- Head-on versus crossing angle
  - extraction lines issues

NLC/JLC

- Test of complete X-band main linac RF sub-unit (as described in baseline design) with beam
- Full test of KEK 75 MW 1.6μs PPM klystron at 150/120 Hz
- Full test of SLAC induction modulator



SC vs NC Linac for LC

Advantages

- Low frequency – wakes weak, klystrons easy
- Low power loss in structures and high conversion efficiency
- Low input power (230 kW per structure)
- Low beam current (8 mA)
- Long bunch spacing (337 ns) so bunch-by-bunch control easy
- Standing-wave cavities have gradient uniform along length

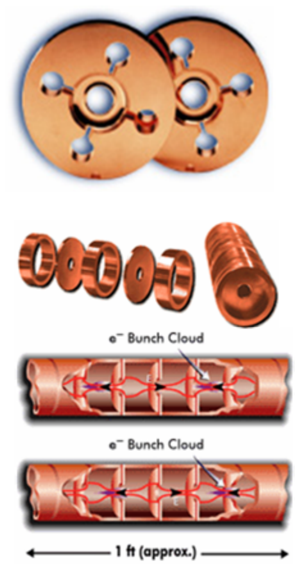
Disadvantages

- Small cavity band-width ask for a mechanical, piezo-assisted, tuner on each cavity
- Beam instrumentation design for larger aperture is needed
- Long bunch train requires long DR (17 km around)
- Low repetition rate (5 Hz) makes train-by-train control harder
- Lower gradients – Linac longer

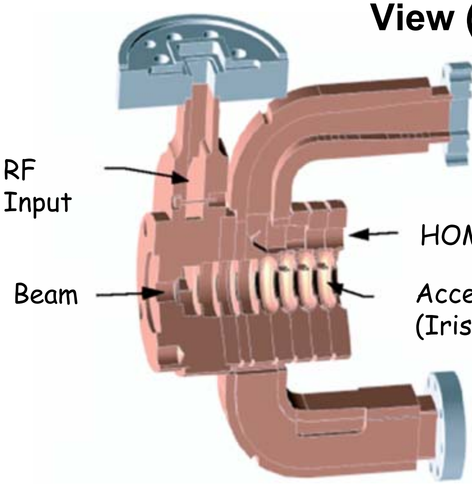
NLC/JLC RF Structures

Rounded Damped-Detuned Structure (RDDS)

Frequency	11.4	GHz
RF mode	$2\pi/3$	
Acc. Gradient	70	MV/m
Iris diameter	11.2–7.8	mm



RDDS Cutaway View (8 of 206 cells)



Made with Class 1 OFE **Copper**.

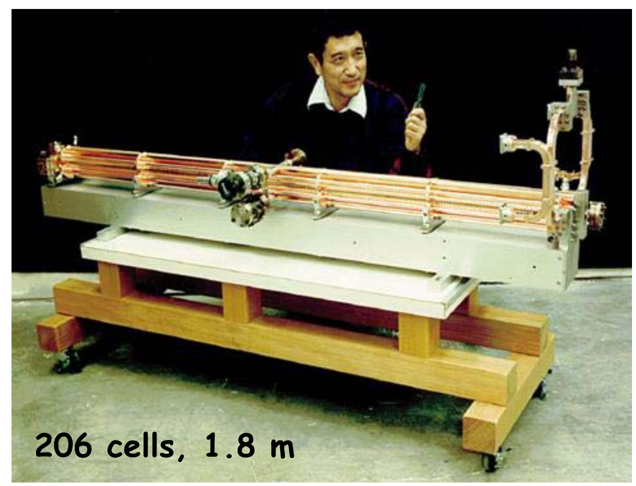
Cells are precision machined (few μm tolerances) and diffusion bonded to form structures.

Fill time ≈ attenuation time ≈ 100 ns, i.e. length 1.8 m.

Operated at 45°C with water cooling.

RF losses approx. 3 kW/m

RF ramped during filling to compensate beam loading (21%). In steady state ~ **50% input power goes into the beam.**

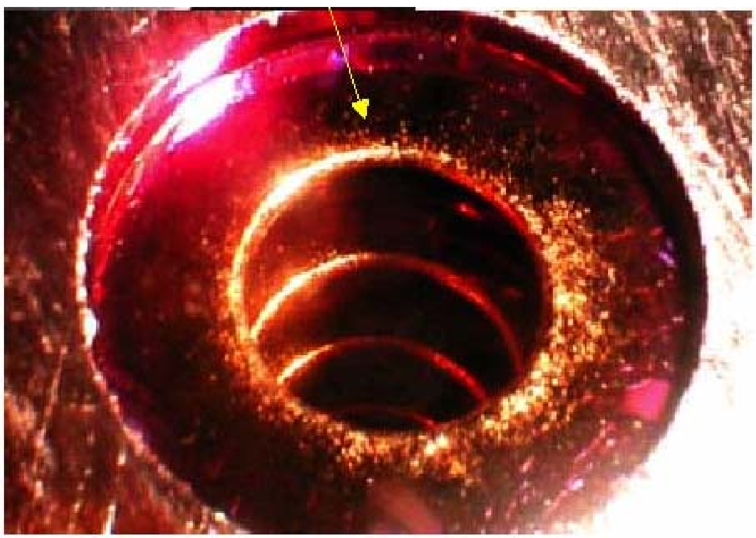


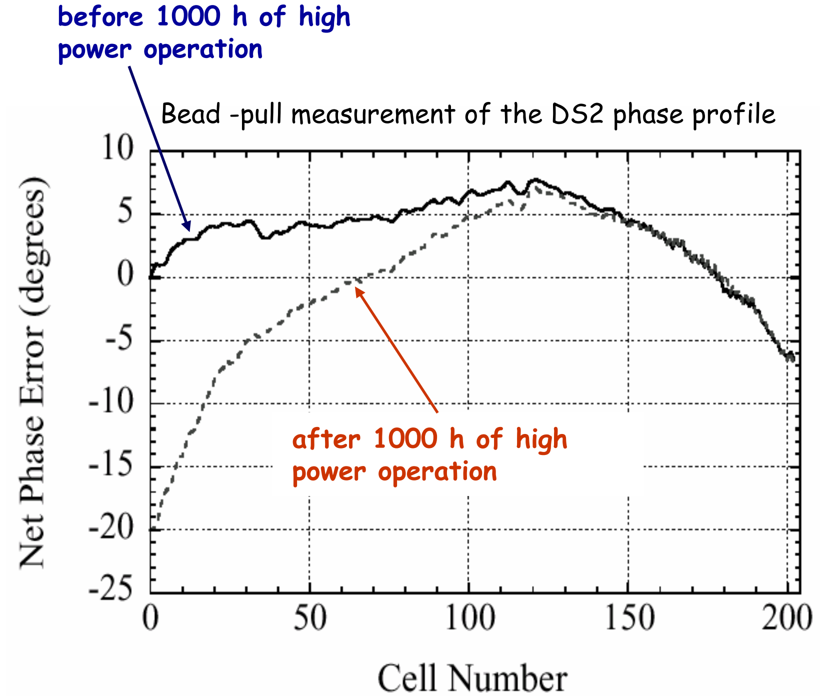
Surface damage problem

An unexpected problem...

During conditioning of the first long NLC structures changes in the field profile were observed.

- surface damage due to field emission
- crater with approx. 30 μm diameter
- after 1000 h high power operation a 20 deg. phase error was measured

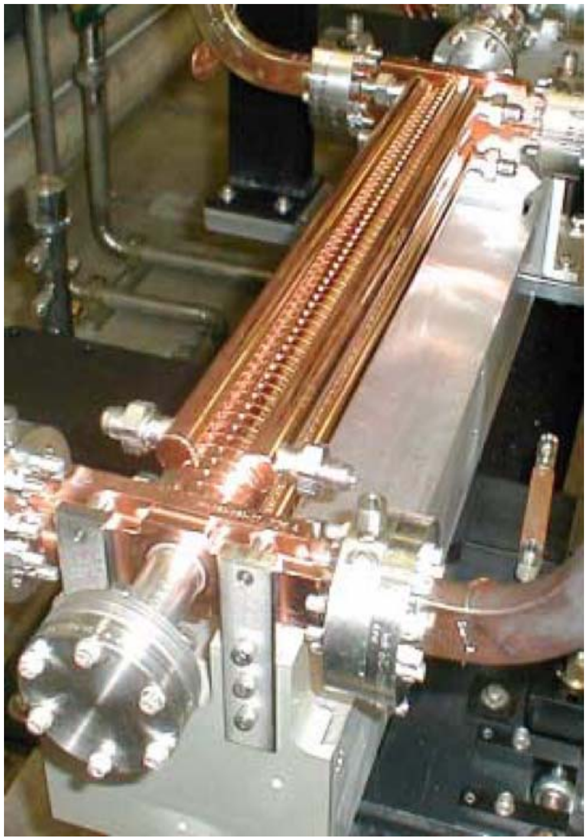




C. Adolphson et al., RF Processing of X-Band Accelerator Structures at the NLCTA, LINAC 2000 Conference

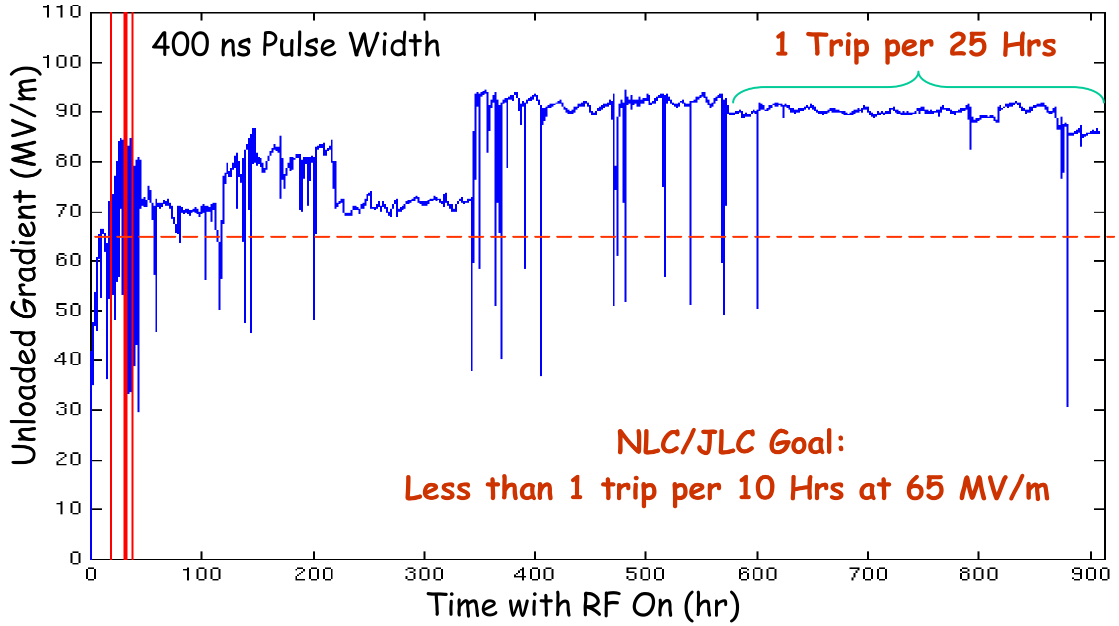
Shorter structures required

New designs with lower v_g



53 cm Traveling-Wave Structure
Group velocity 3.3% ↘ 1.6% c

Type T structure results: No Change in MW Properties



But

The T-Series design cannot be used in the NLC/JLC.

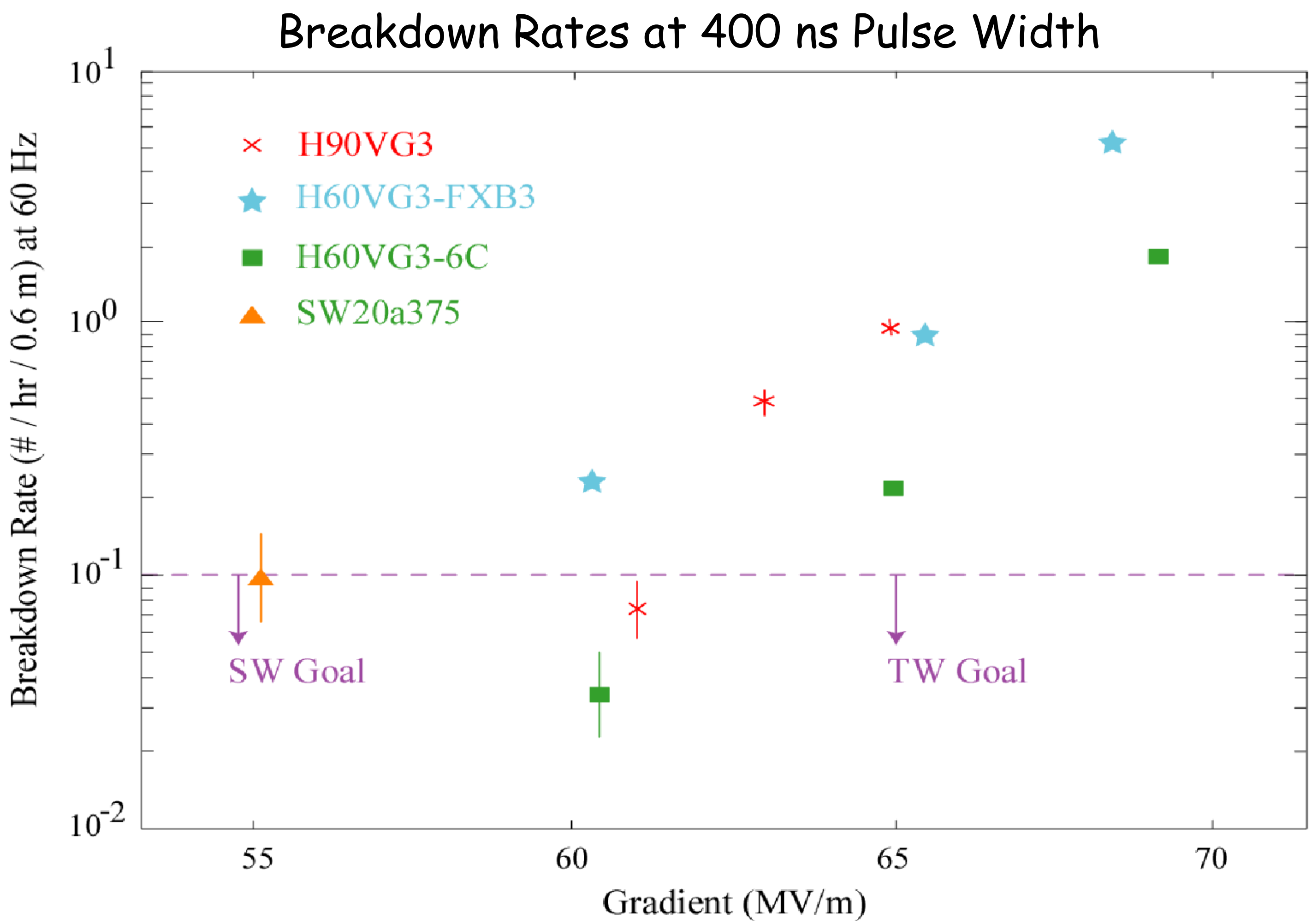
- average iris radius, <a/l> smaller (0.13) than desired (0.17-0.18),
- transverse wakefield 3 times larger than acceptable.

Structures with <a/l> = 0.17- 0.18 and with full damping.

Tests of 60 cm structures reach 65 MV/m, little overhead.
Designs with higher shunt impedance in fabrication and test.

Actual High Gradient performance

Still problems for 65 MV/m But 60 MV/m should work fine

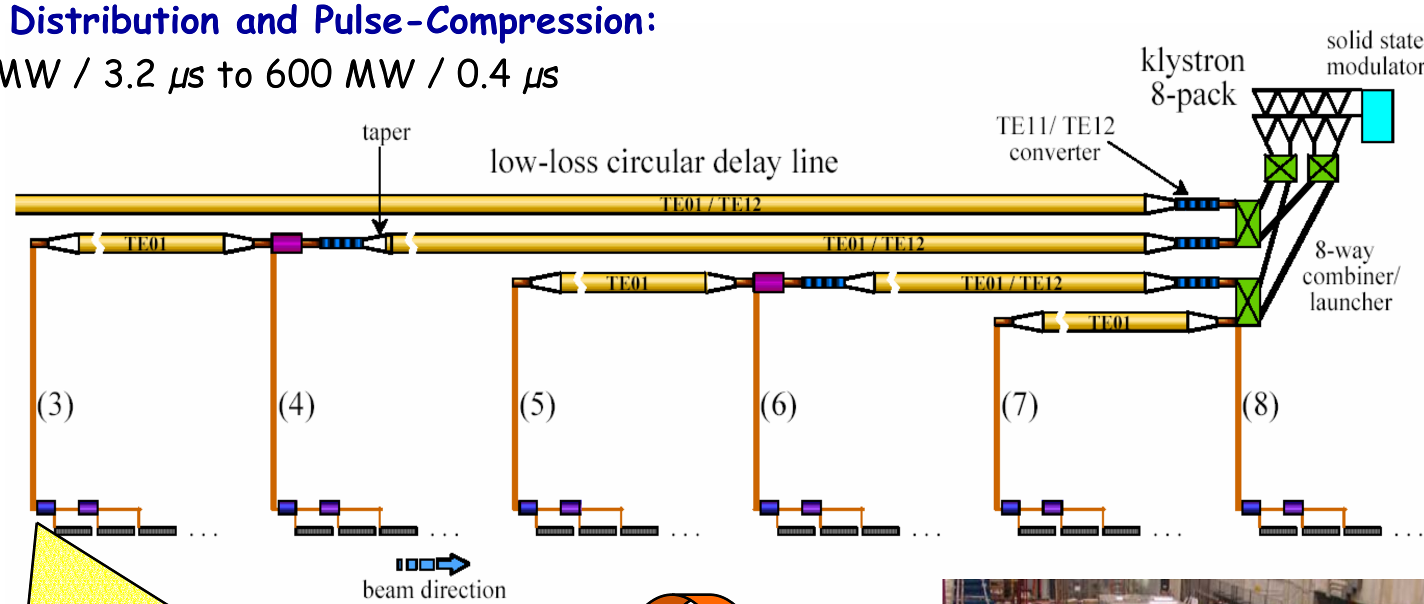


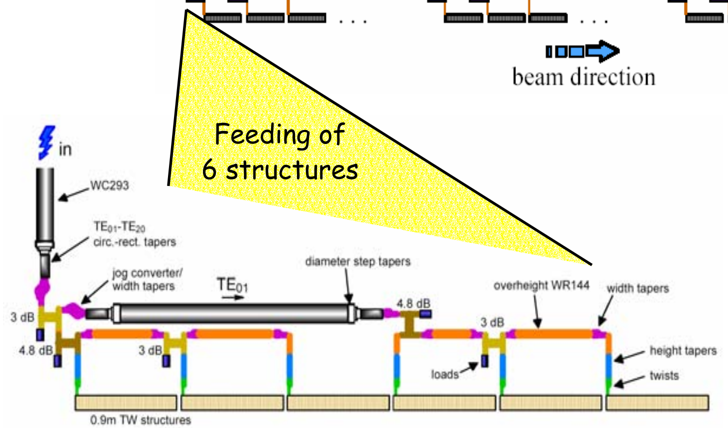
NLC/JLC RF Unit and DLDS

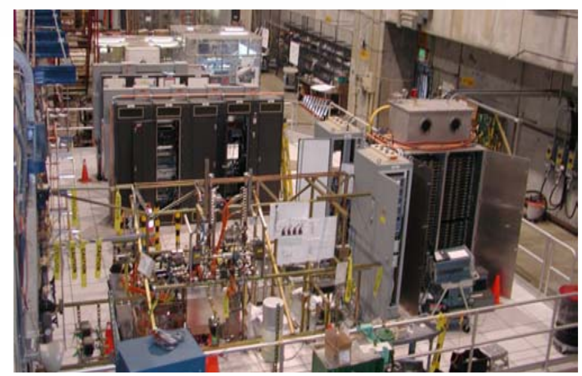
DLDS = Delay Line Distribution System (2 Mode, 4 Lines)

RF Power Distribution and Pulse-Compression:

from 75 MW / 3.2 μs to 600 MW / 0.4 μs







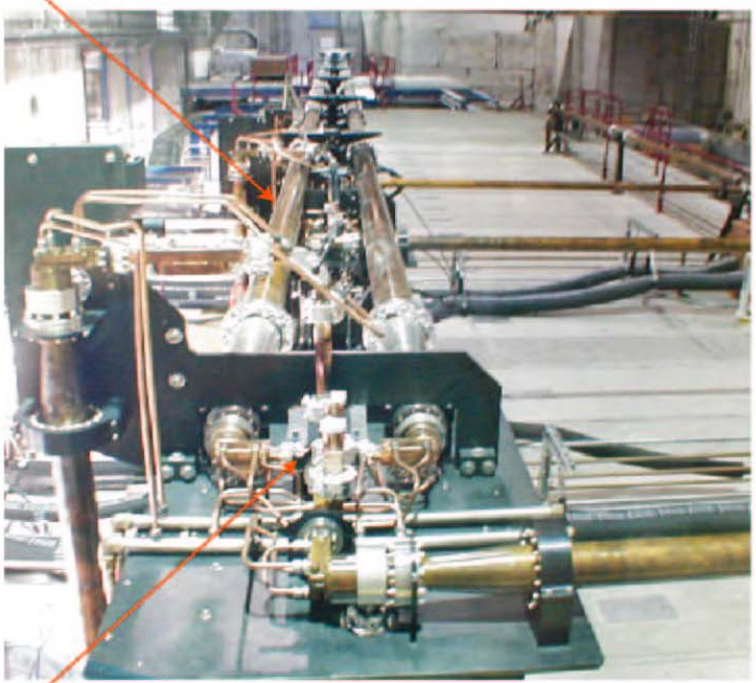
JLC-NLC TeV SLED-II Test

Recent Promissing Results for DLDS

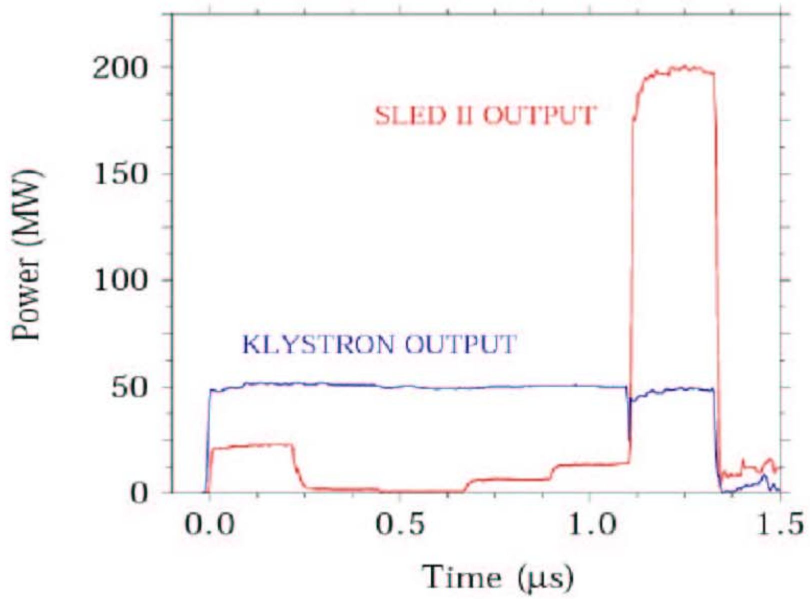
Major R1 goal for Power Distribution achieved in December 2003

At NLCTA:

40 m Long, 12 cm Dia. Circular Waveguide



3 dB Hybrid Using a 'Magic Tee'



Have Generated 240 ns, 250 MW Pulses at NLCTA and 150 ns, 485 MW Pulses in an Experimental Test Facilty

NLC/JLC Klystron Development

(75 MW, 1.6 μs, 120/150 Hz, 55% Efficiency Required)

KEK/Toshiba

PPM2: Tested at 75 MW with pulses of 1.6 μsec duration at 60 Hz. Efficiency = 56%

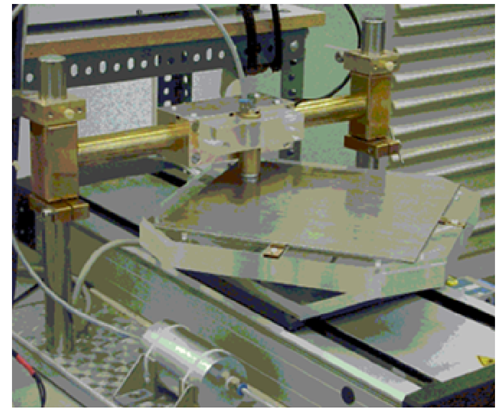
PPM4: Tested at 75 MW with pulses of 1.6 μsec duration at 50 Hz.

SLAC

XP3-3
Tested at 75 MW with pulses of 1.6 μsec duration at 120 Hz. Efficiency = 53%

The TESLA Superconducting Cavity

Niobium buck, 9-cell, 1.3 GHz



Nb Eddy current scanning

Cavity parameters

R/Q	1036	Ω
E_{peak}/E_{acc}	2.0	
B_{peak}/E_{acc}	4.26	mT/(MV/m)
$\Delta f/\Delta l$	315	kHz/mm
$K_{Lorentz}$	$\approx$ -1	$Hz/(MV/m)^2$

Class 10 clean room assembly

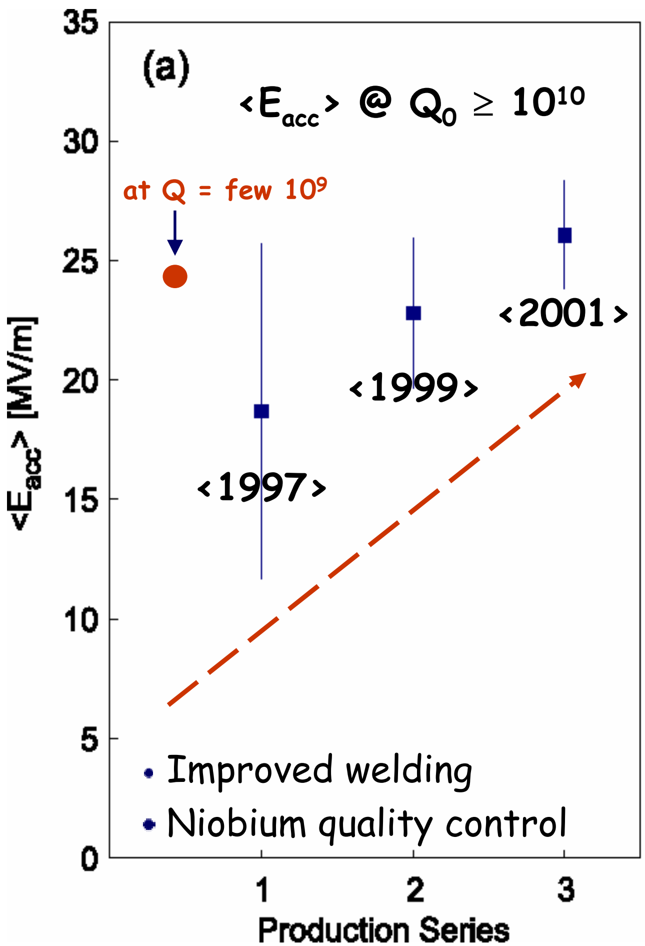
TESLA Learning curve with BCP

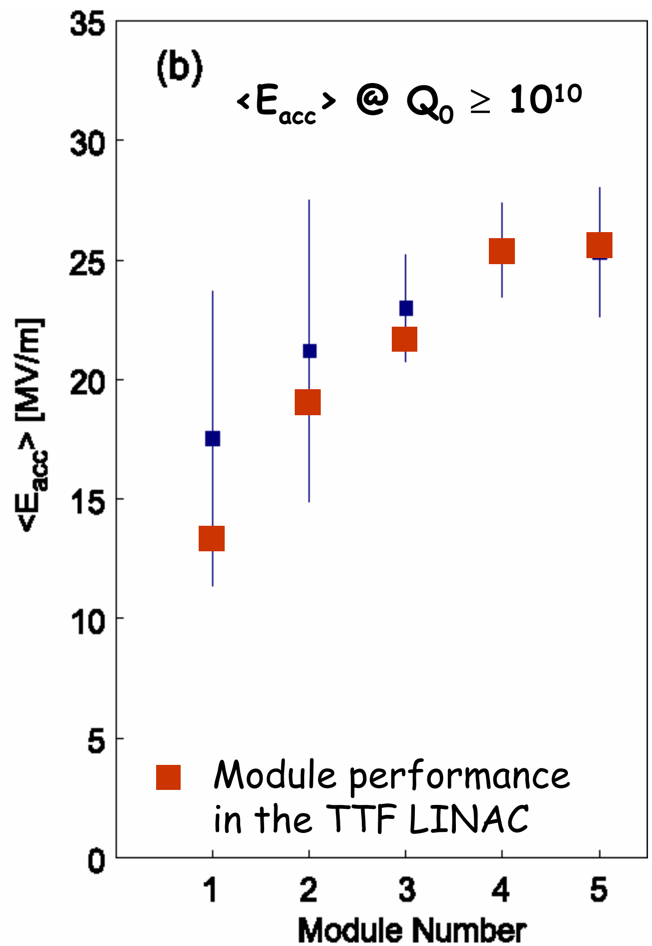
BCP = Buffered Chemical Polishing

3 cavity productions from 4 European industries: Accel, Cerca, Dornier, Zanon

Cornell 1995

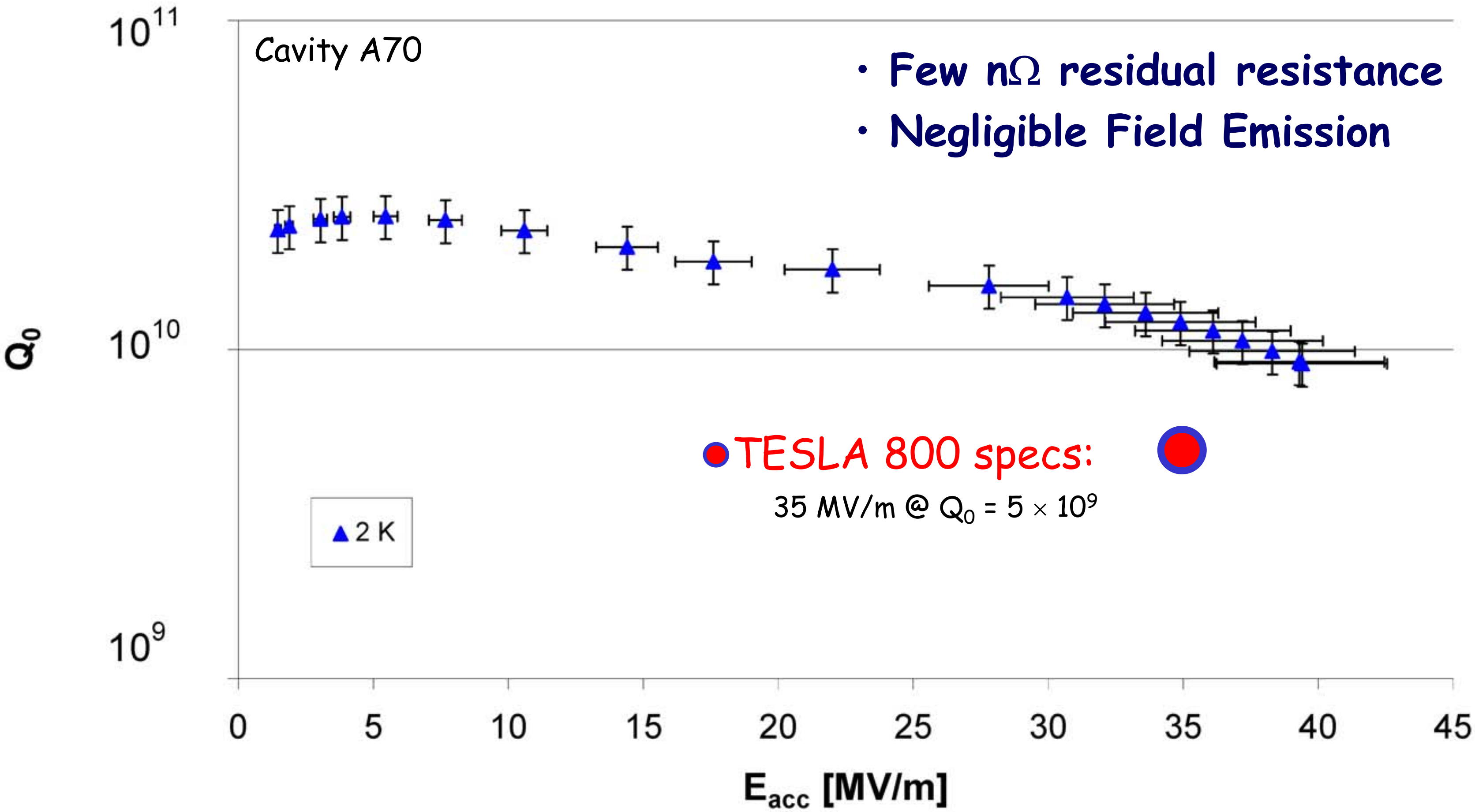
5-cell



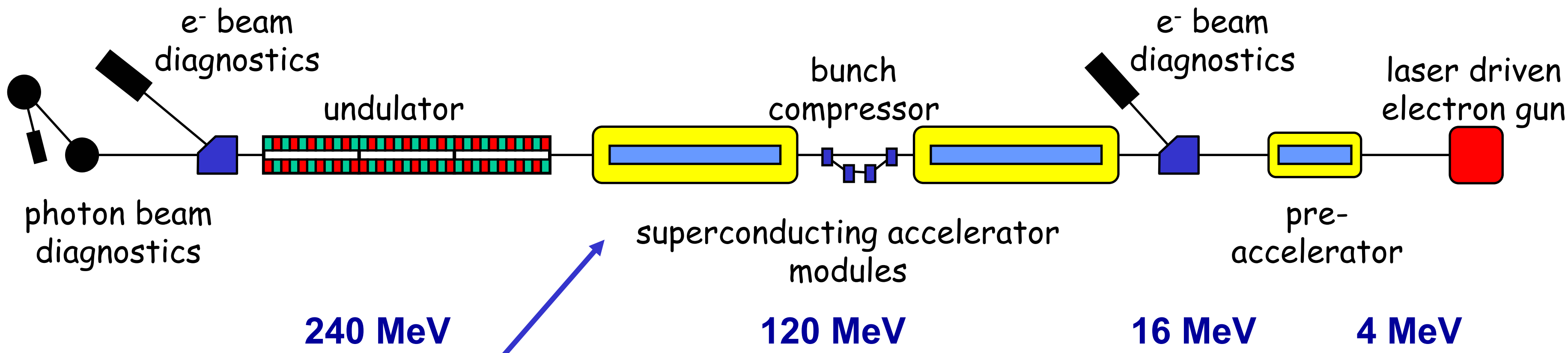


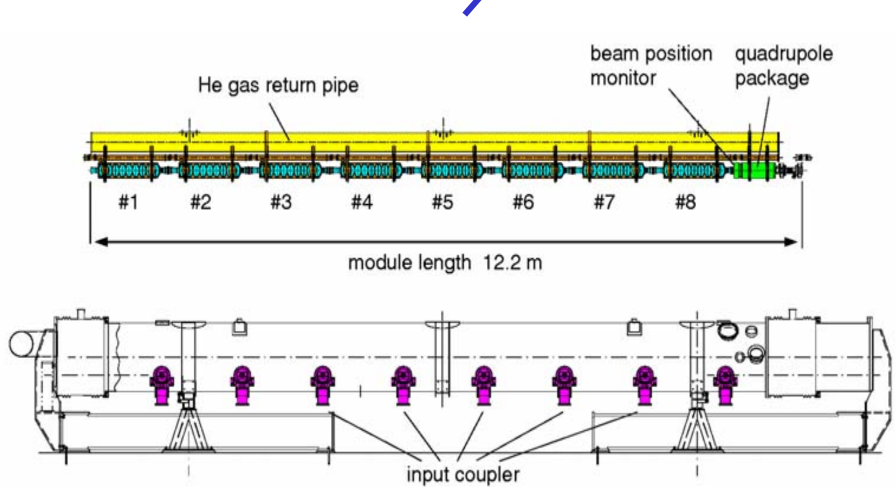
Outstanding Results with EP

EP at the new DESY plan 800°C annealing 120°C Backing



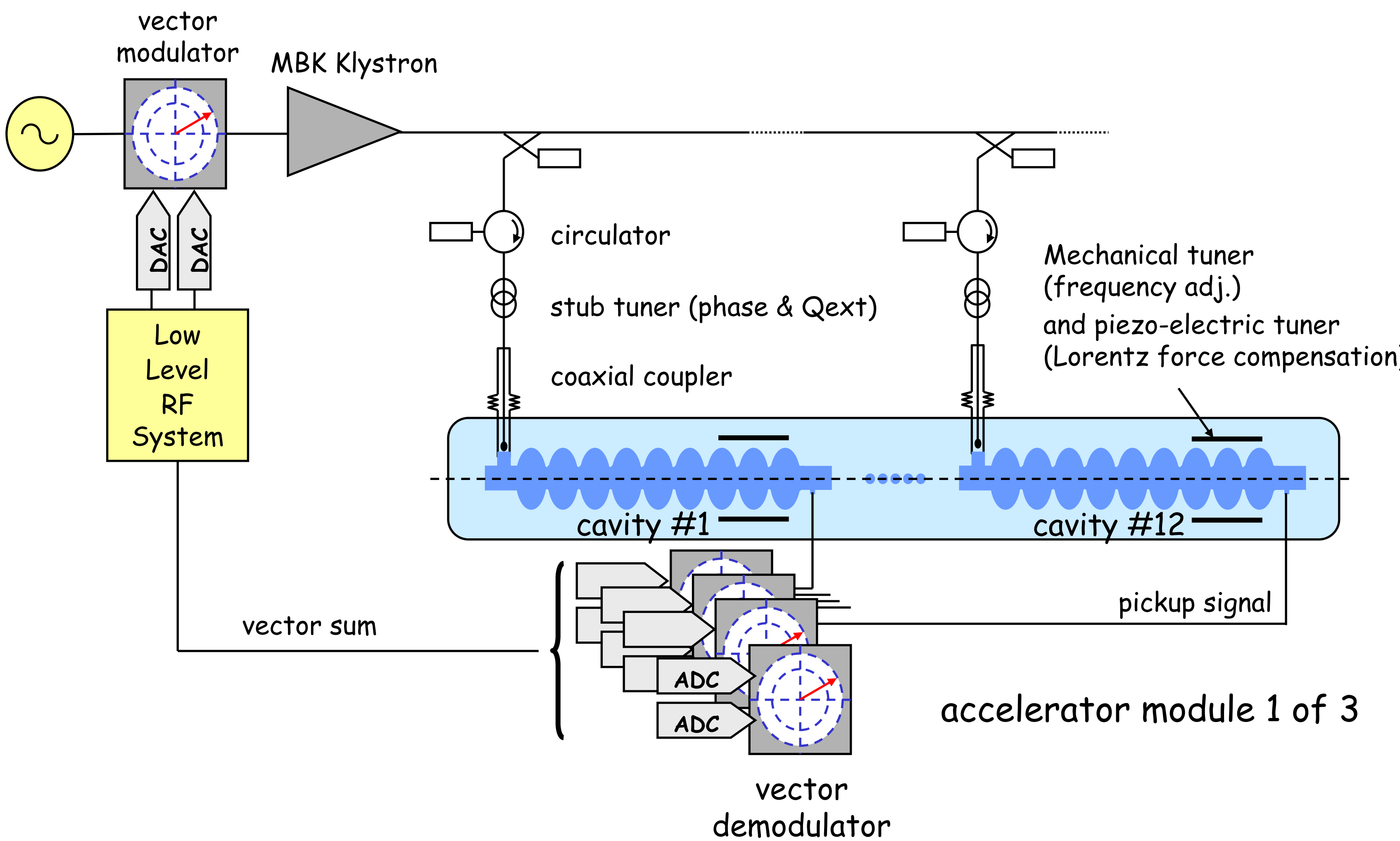
TTF I Linac – 6 Year Experience





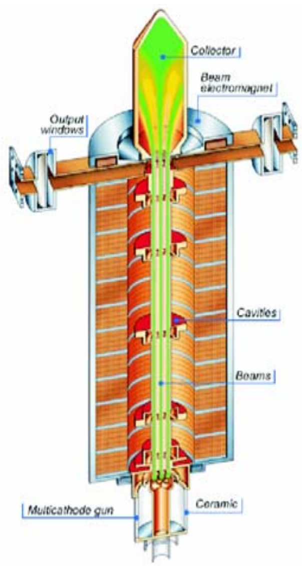
Standard TESLA RF Unit

1 klystron for 3 accelerating modules, 12 nine-cell cavities each



TESLA Multi Beam Klystrons

Three Thales TH1801 Multi Beam Klystrons produced and tested



Achieved efficiency	65%
RF pulse width	1.5 ms
Repetition rate	5 Hz
Operation experience	> 5000 h

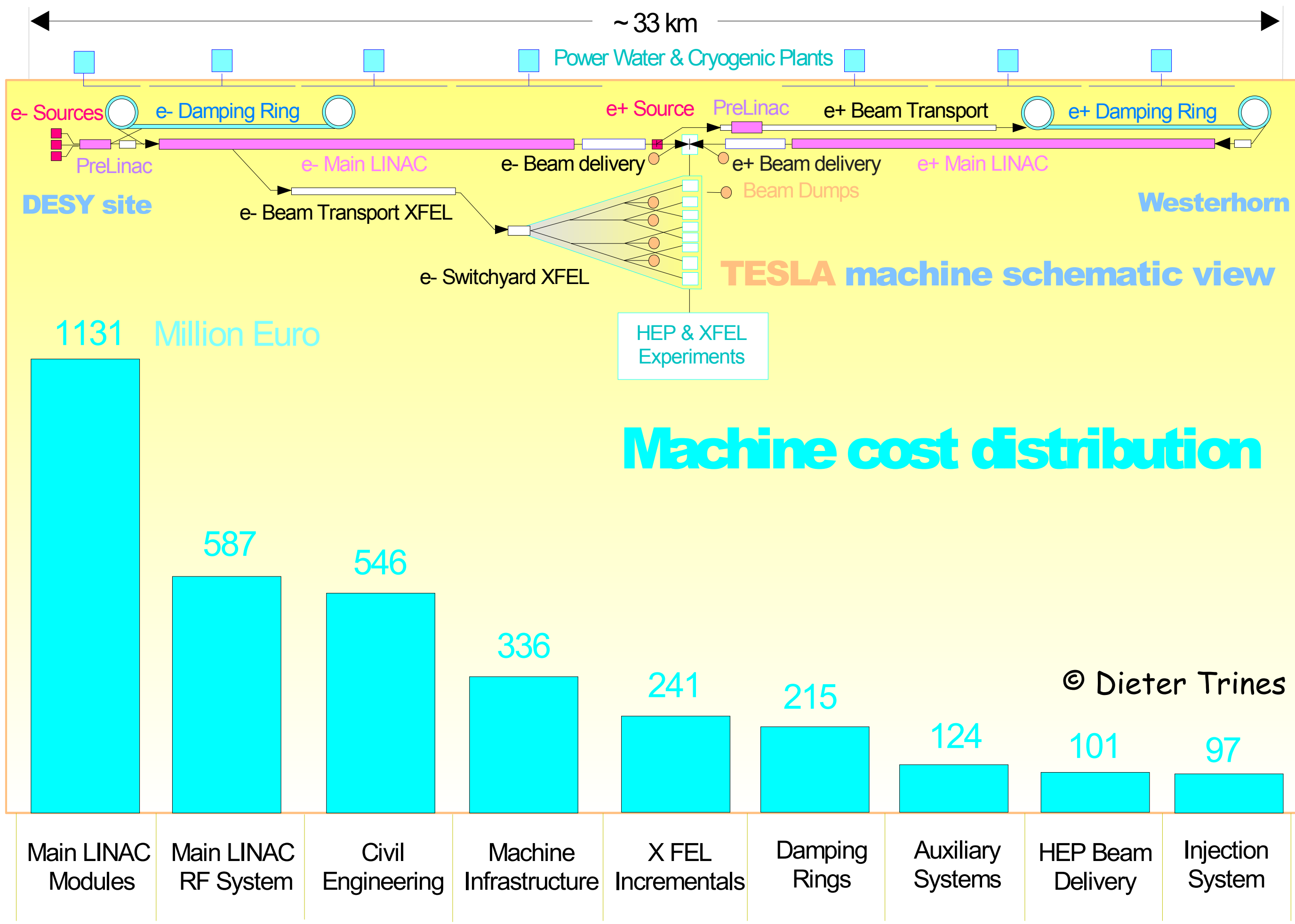
10% of operation time at full spec's

Indipendent beam design proposed and built by CPI.

A new design proposed by Toshiba looks robust and should reach 75% efficiency

Consistent Cost Estimation for TESLA

3,136 M€ (year 2000 - no contingency) **+ ~ 7,000 persons • years**



High synergy with the European XFEL

- 50% funded by the German Government - European consensus growing
- Great opportunity for TESLA
  - Machine reliability according to SRL standards
  - Industrial mass production of cavities (~ 1000) and modules (> 120)