TESLA Collaboration Meeting

DESY, Zeuthen, 21-23 January 2004

Status of LC Technologies

Carlo Pagani

INFN Milano and DESY

On leave from University of Milano

Talk Outline

- Introduction
- 1st ILC-TRC Status and Recommendations
- Outstanding Results from Test Facilities
- 2nd ILC-TRC Recommendations
- Rankings and Results
- Conclusions

Next e+e- collider must be linear

- Synchrotron Radiation (SR) becomes prohibitive for electrons in a circular machine above LEP energies:

$$U_{SR}[\mathrm{GeV}] = 6 \cdot 10^{-21} \cdot \gamma^4 \cdot 1/r[\mathrm{km}]$$

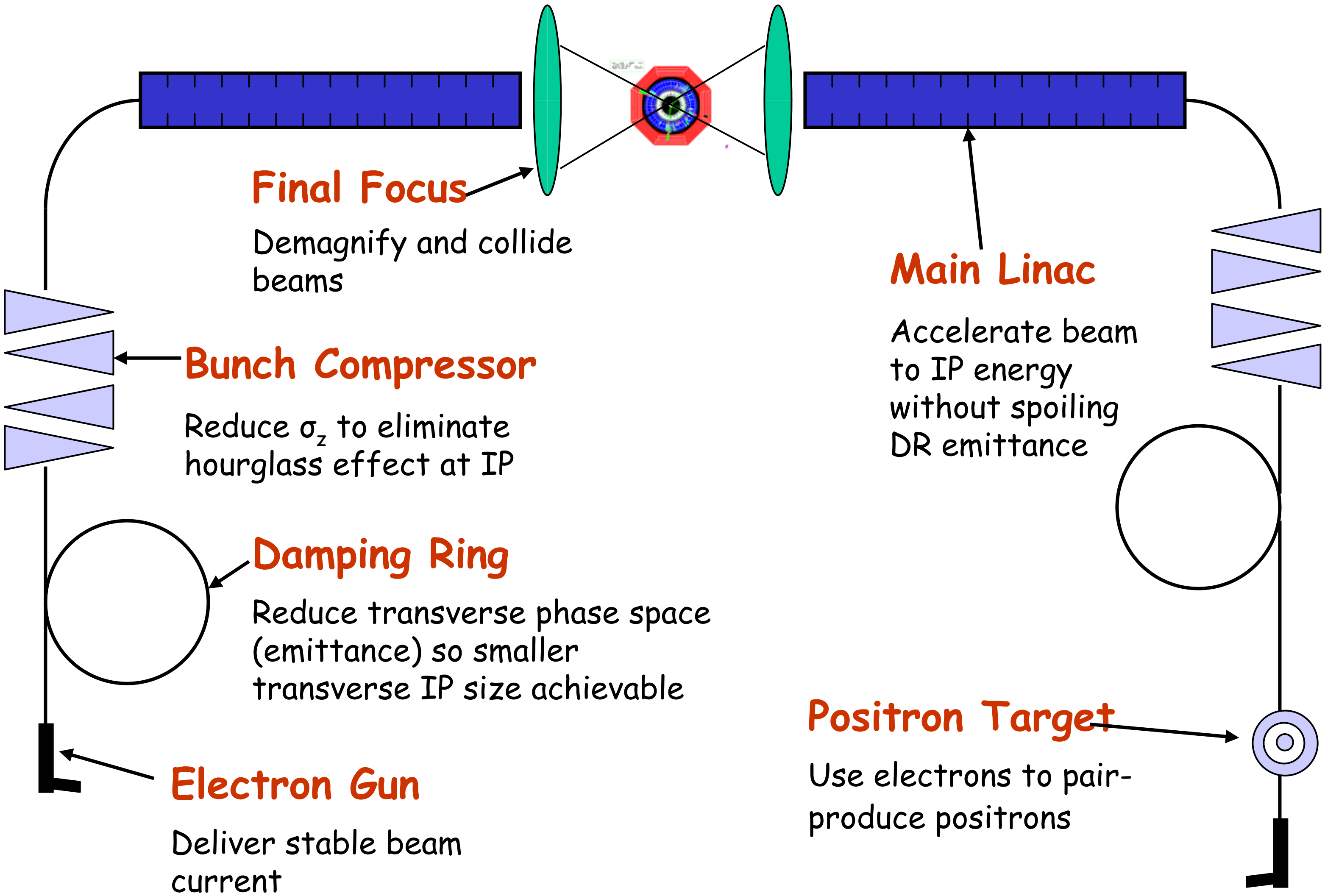
U_{SR} = energy loss per turn
γ = relativistic factor
r = machine radius

- RF system must replace this loss, and r scale as E^2
- LEP @ 100 GeV/beam: 27 km around, 2 GeV/turn lost
- Possible scale to 250 GeV/beam i.e. **E_{cm} = 500 GeV**:
  - **170 km** around
  - **13 GeV/turn** lost

$\gamma_{250GeV} = 4.9 \, . \, 10^5$

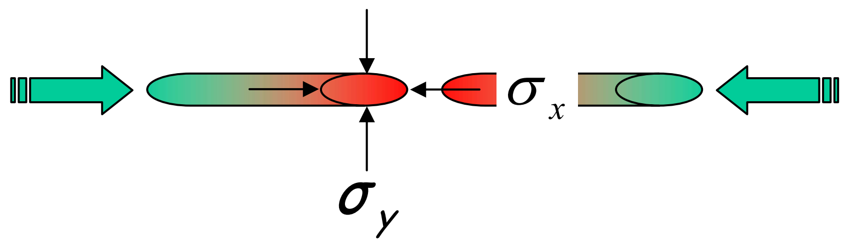
- Consider also the luminosity
  - For a **luminosity of ~ 10^{34}/cm^2/second**, scaling from b-factories gives ~ 1 Ampere of beam current
  - 13 GeV/turn x 2 amperes = **26 GW RF power**
  - Because of conversion efficiency, this collider would consume more power than the state of **California in summer: ~ 45 GW**
- Both size and power seem excessive

LC conceptual scheme



What to do 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

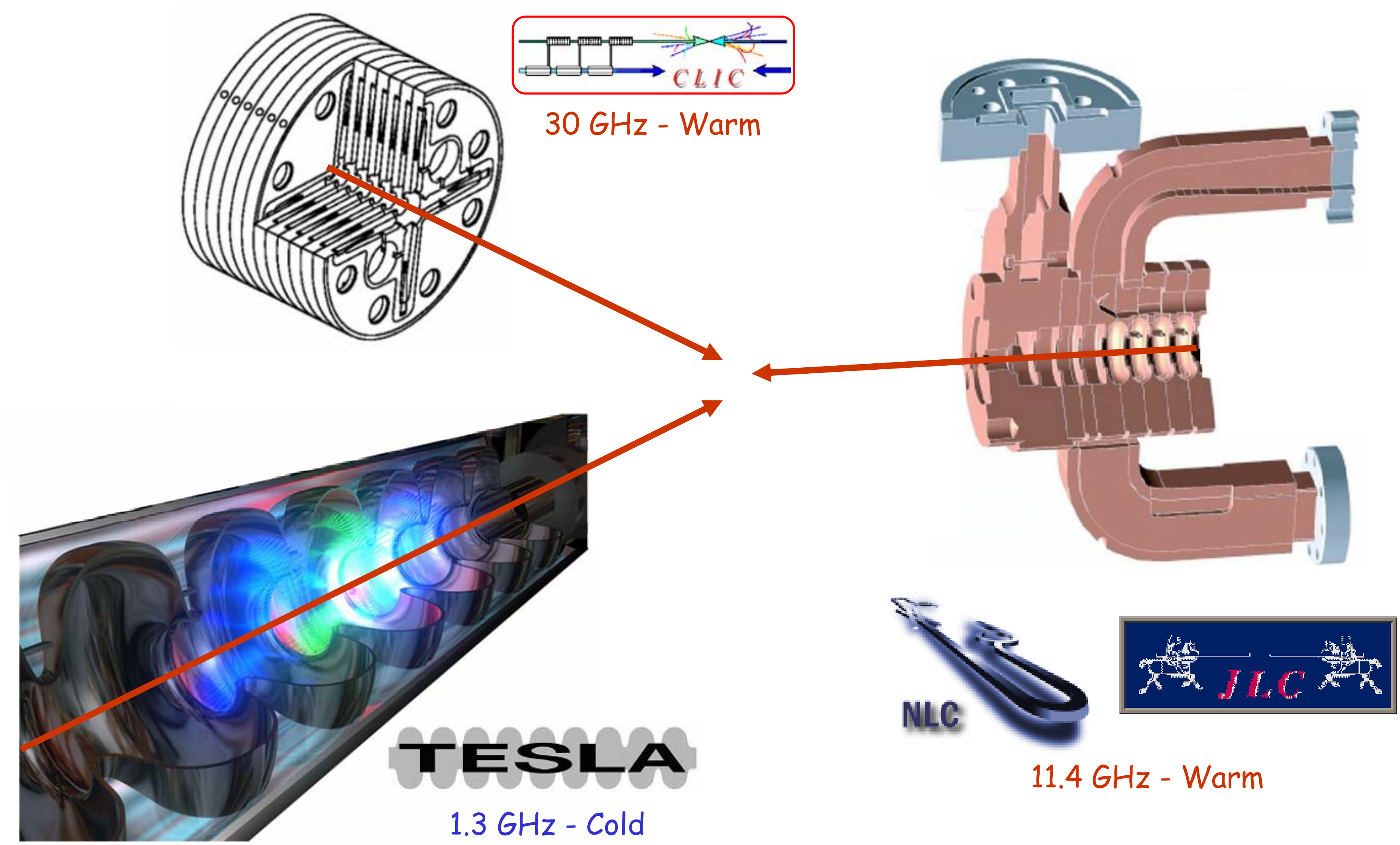
P_b = beam power

$E_{c.m.}$ = 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 ($P_b = N_e \cdot n_b \cdot f_{rep}$)
- ↑ Increase beam to-plug power efficiency for cost

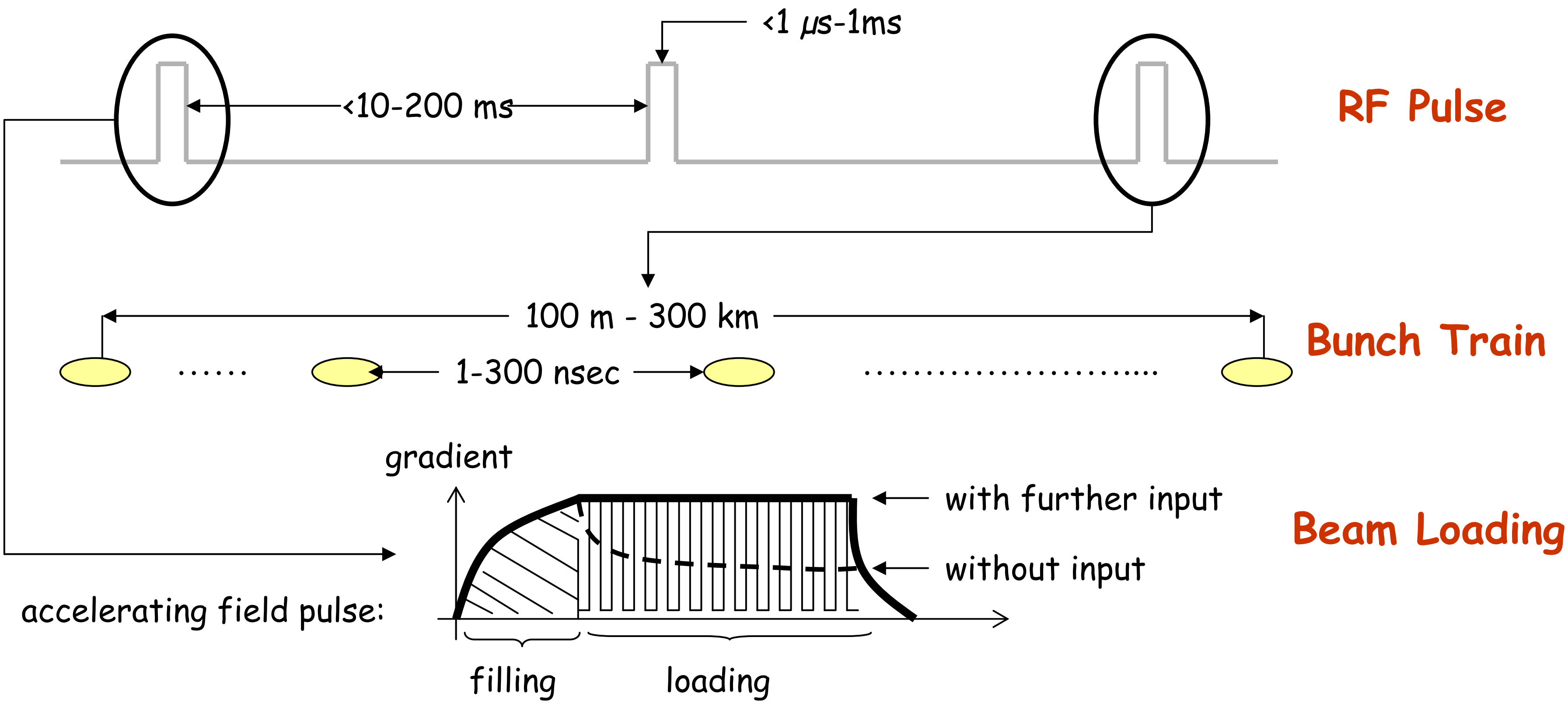
Competing technologies



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



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 1st 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 2nd report January 2003

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

LC status at 1st 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
$\mathcal{L}\times10^{33}$ [$cm^{-2}s^{-1}$]	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
$\gamma\varepsilon_y$ [$\times10^{-8}$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

1st ILC-TRC Recommendations

Baseline c.m. 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

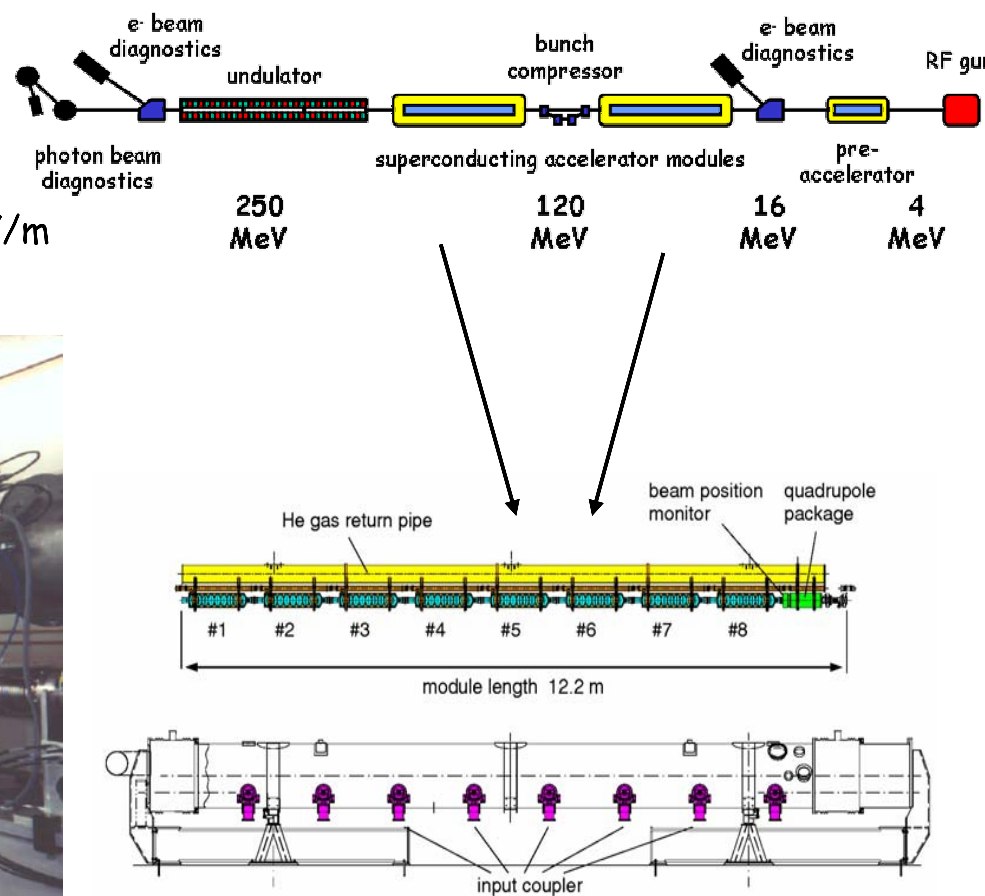
TTF for TESLA

TTF = TESLA Test Facility

TTF 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

TTF as operated for SASE FEL

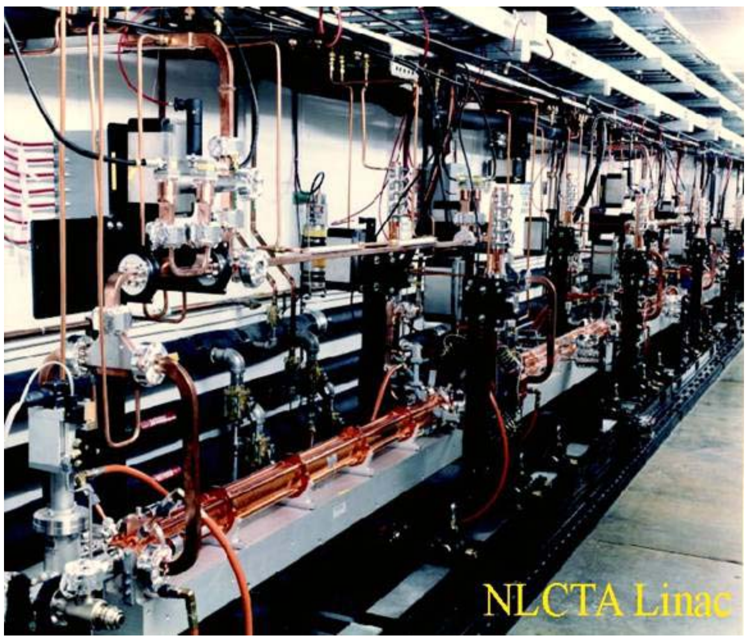


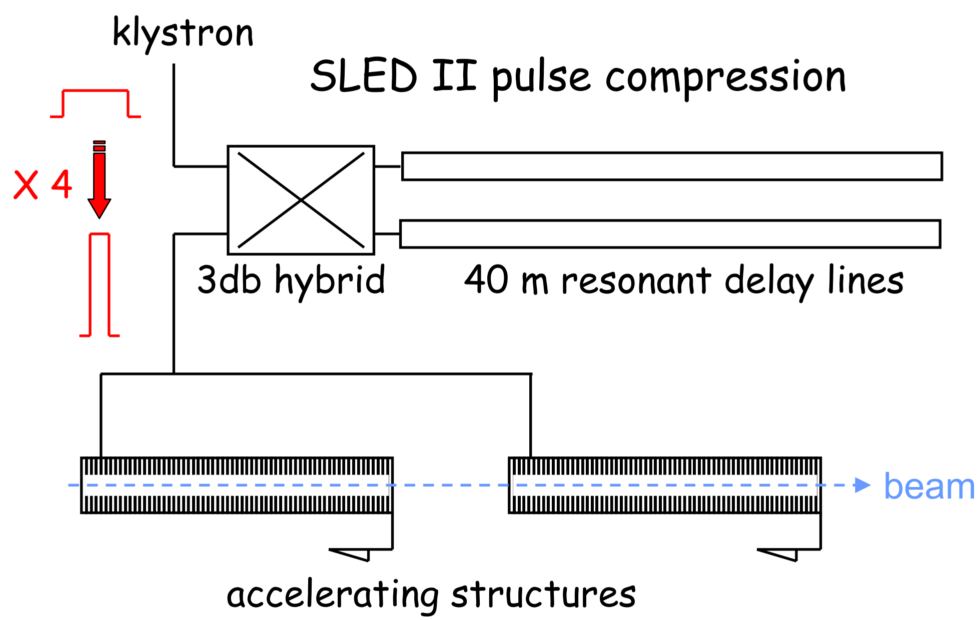
NLCTA for NLC

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





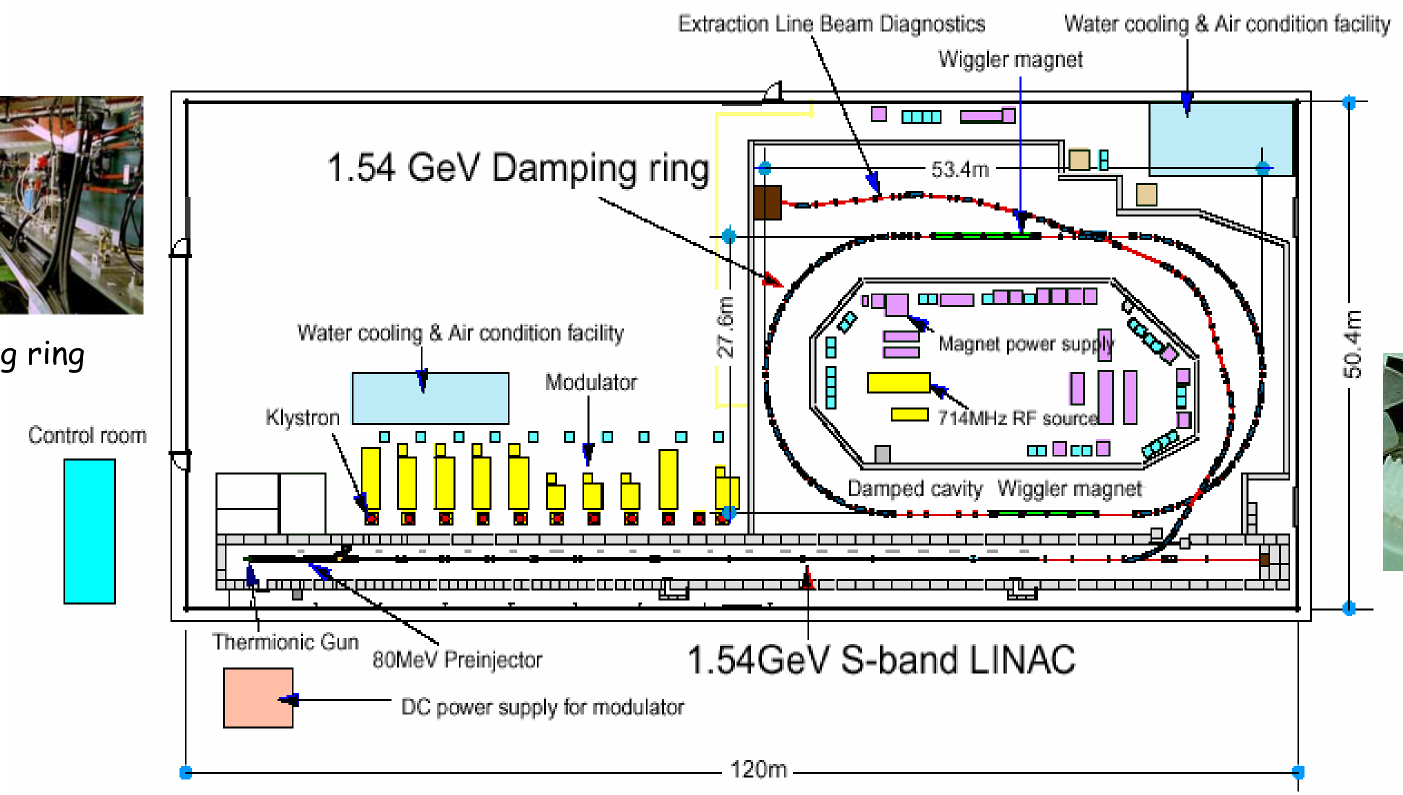
ATF for JLC

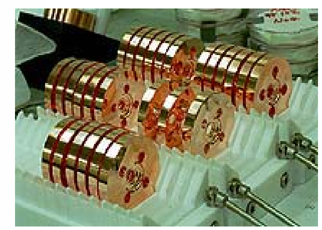
ATF = Accelerator Test Facility

ATF Goals:

- Demonstrate very low beam emittance
- Develop RF technology

Damping ring

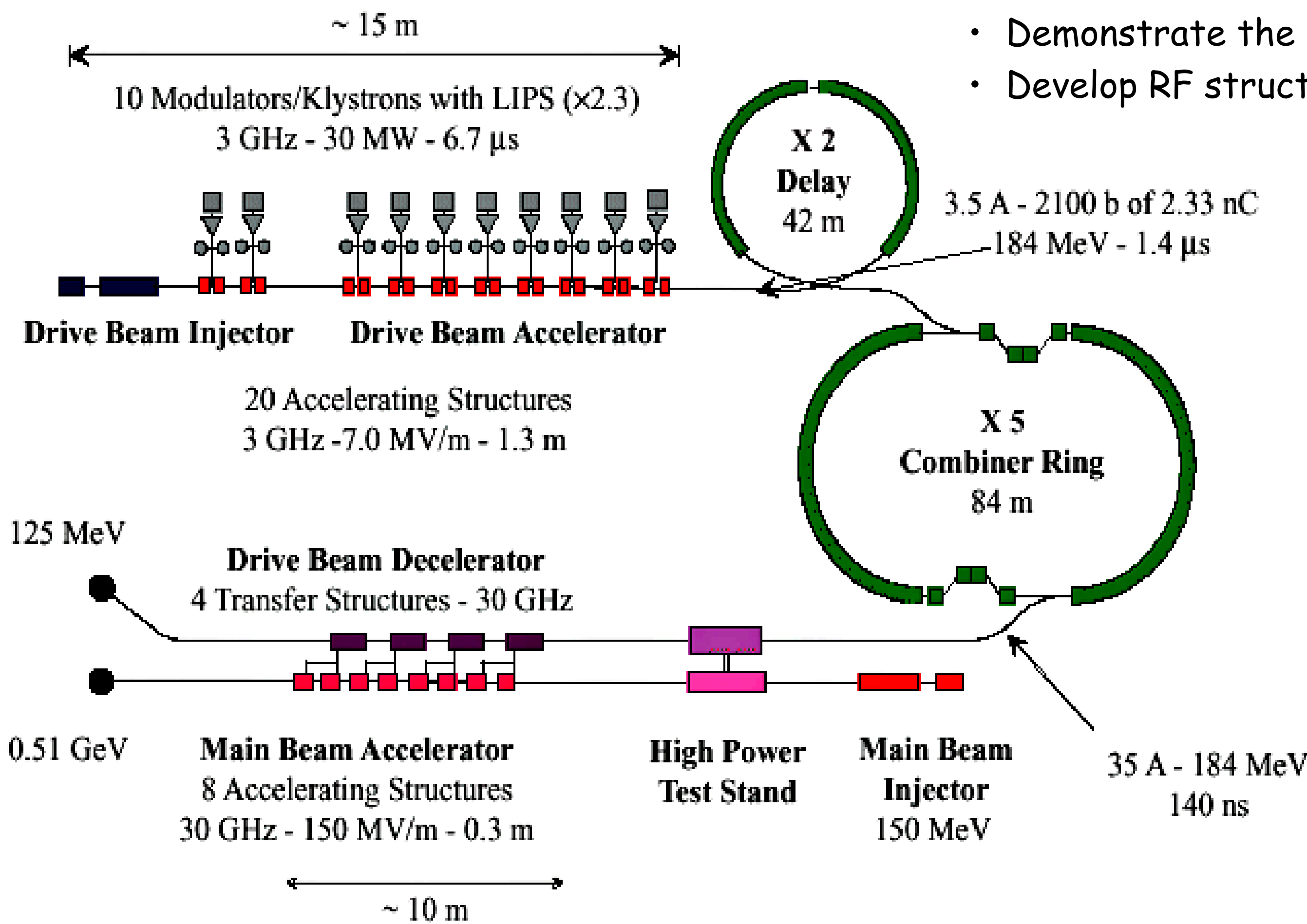




Cavity Production

CTF for CLIC

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

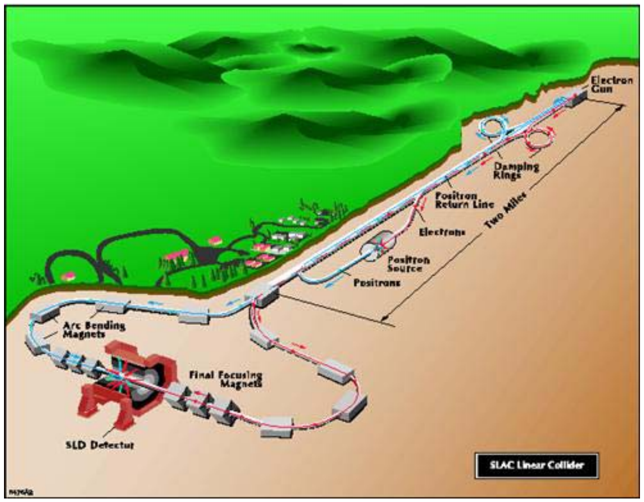


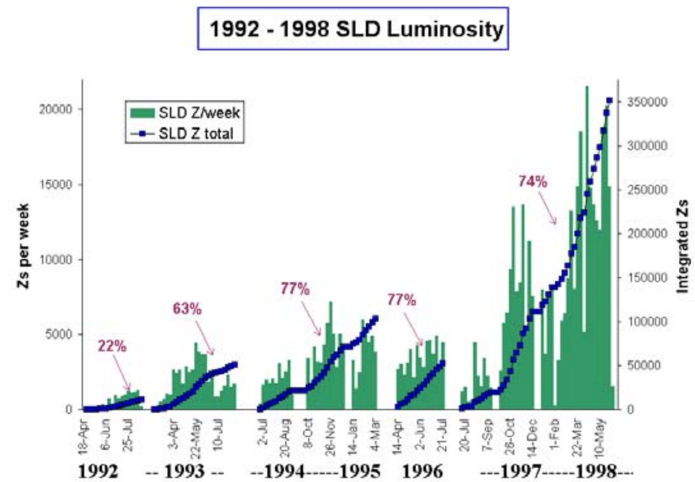
CTF3 Goals:

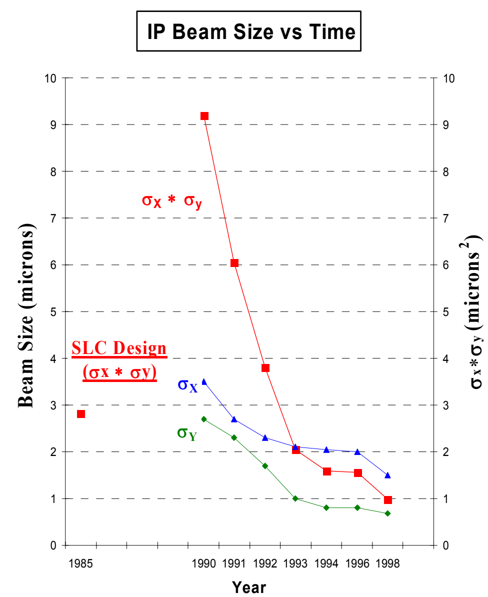
- Demonstrate the drive beam scheme
- Develop RF structures and technology

Lessons from the SLC

SLC = SLAC Linear Collider







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.

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
$\mathcal{L}\times 10^{33}$ [$cm^{-2}s^{-1}$]	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, 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

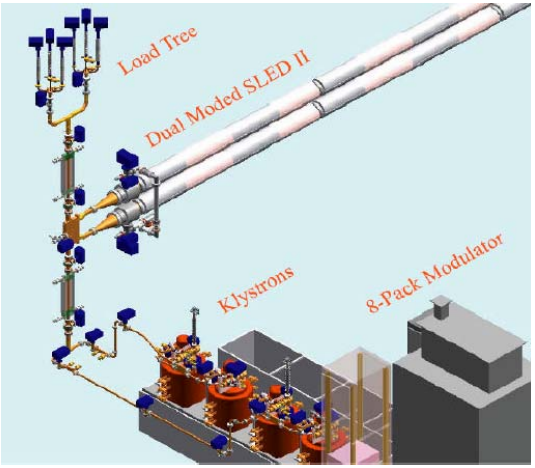
R2 Comparison

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

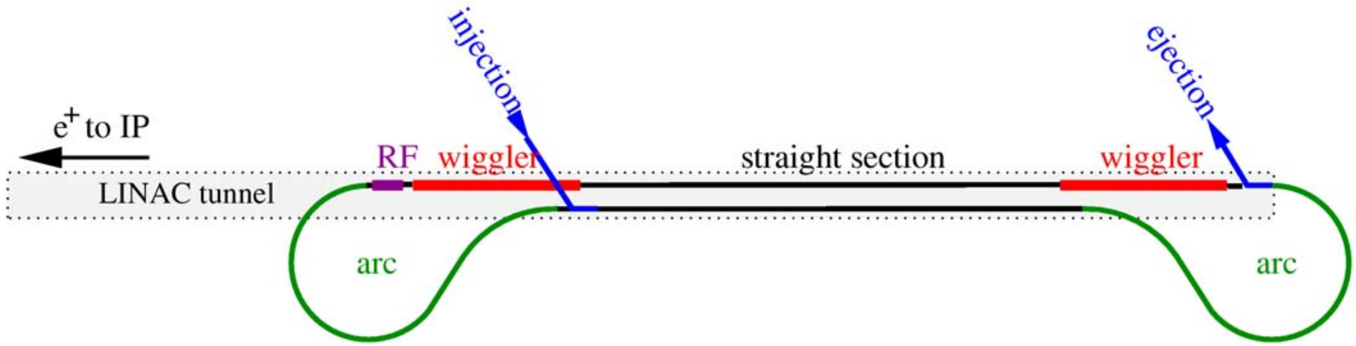
- Low frequency – wakes weak, klystrons easy
- Low power loss in structures and high conversion efficiency
- Low input power (230 kW per structure)
- Low beam current (8 mA)
- Long bunch spacing (337 ns) so bunch-by-bunch control easy
- Standing-wave cavities have gradient uniform along length

Disadvantages

- Tight frequency tolerances, mechanical, piezo-assisted, tuners needed on all cavities
- Beam instrumentation more demanding (large apertures)
- Long bunch train requires long DR (17 km around)
- Low repetition rate (5 Hz) makes train-by-train control harder
- Lower gradients – Linac longer

One TESLA design problem

Very long damping rings: at present 17 km

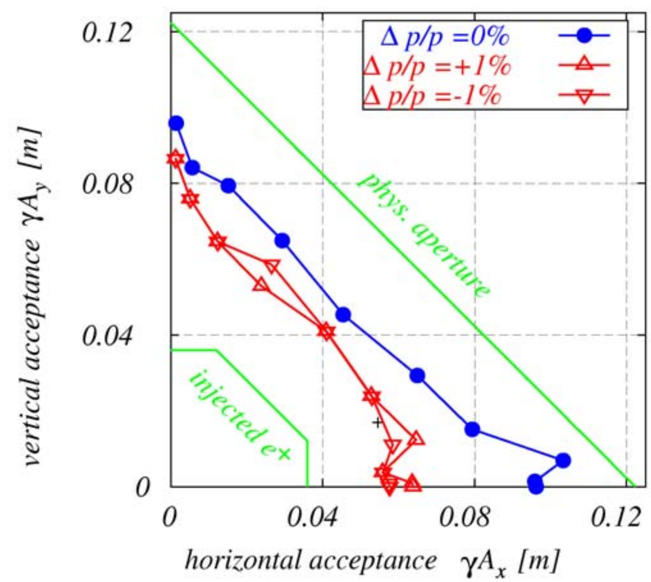


Electron cloud and beam-ion instability effects:

- more simulation effort required,

Dynamic aperture with sextupoles OK, but not yet sufficient with present wiggler model

Faster kickers would simplify DR design and reduce cost



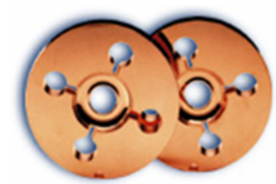
A few comments on ILC-TRC

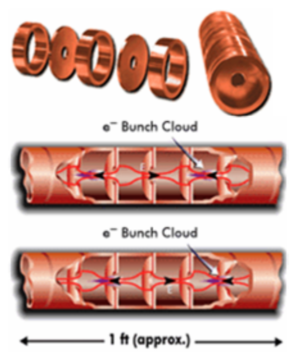
- Rankings reflect the concerns of the working groups, but ILC-TRC overall findings were extremely positive
- “did not find any insurmountable obstacle to building TESLA, JLC-C, JLC-X/NLC within the next few years…”
- “also noted that the TESLA linac RF technology for 500 GeV c.m. is the most mature.”
- Assuming the R1s are demonstrated, the RF systems of the two machines will be on an equal footing…
- The ILC-TRC is a excellent example of what we can achieve when the LC accelerator communities work together
- Attempts to maintain the ‘momentum’ post ILC-TRC are dwindling

NLC/JLC RF Structures

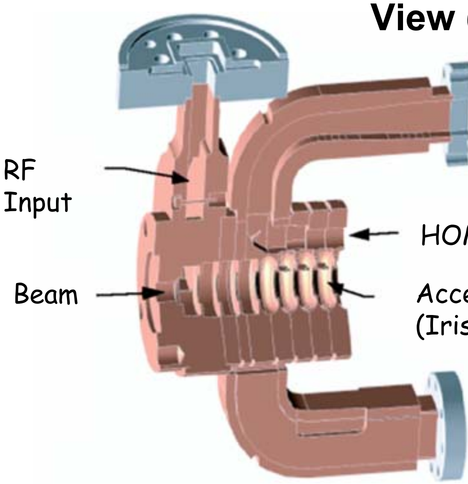
Rounded Damped-Detuned Structure (RDDS)

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**.

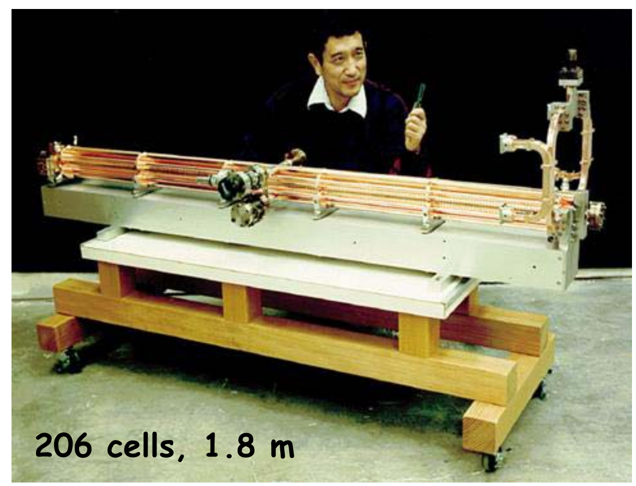
Cells are precision machined (few μm tolerances) and diffusion bonded to form structures.

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

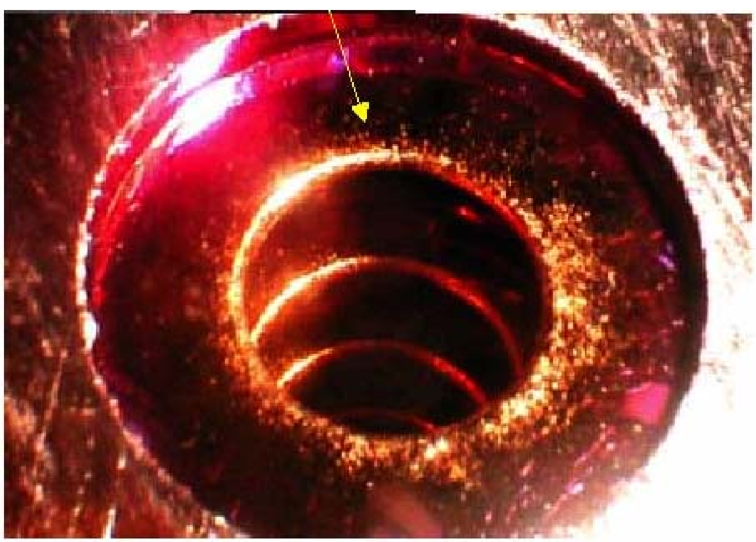
An unexpected problem...

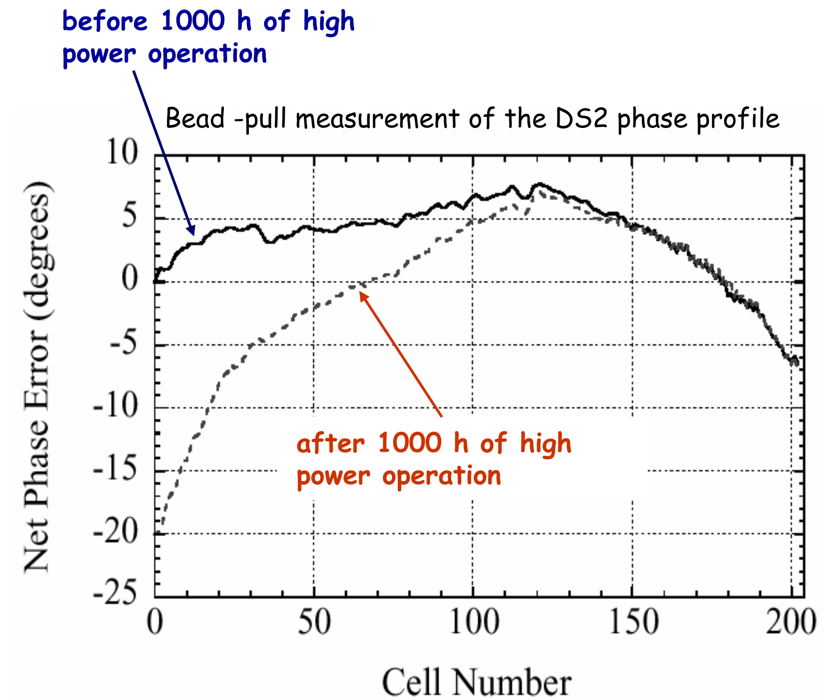
During conditioning of the first long NLC structures changes in the field profile were observed.

- 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

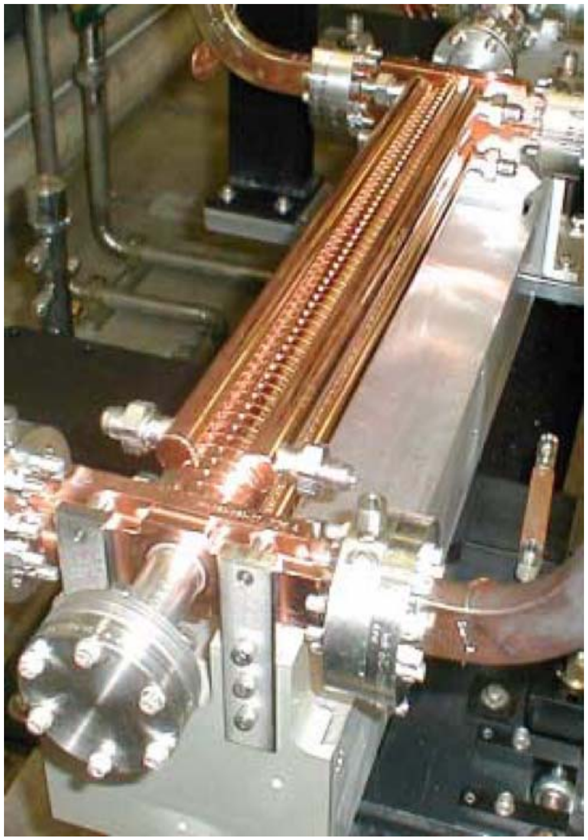




C. Adolphson et al., RF Processing of X-Band Accelerator Structures at the NLCTA, LINAC 2000 Conference

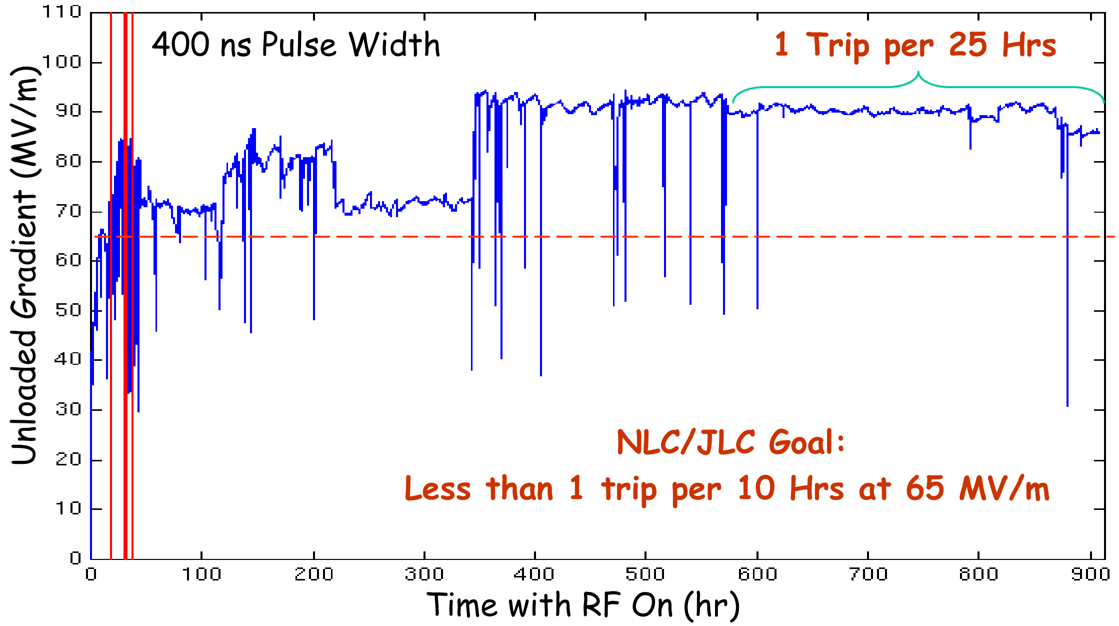
Shorter structures required

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.

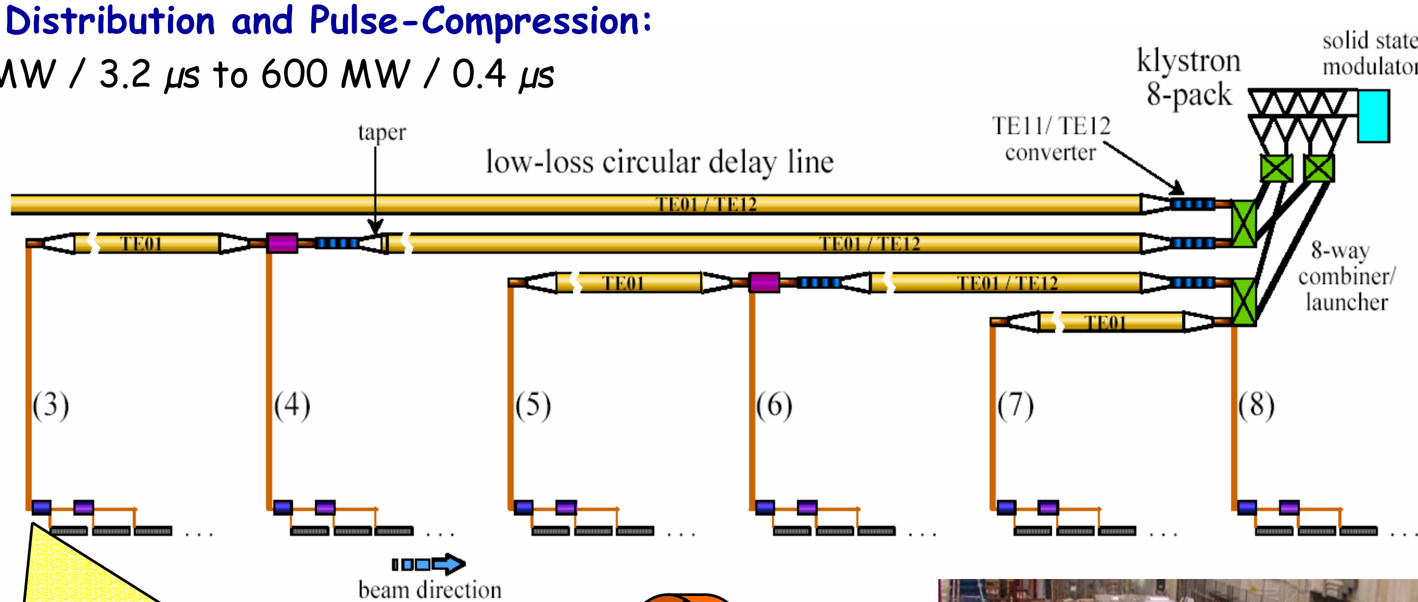
Tests of 60 cm structures reach 65 MV/m, little overhead.
Designs with higher shunt impedance in fabrication and test.

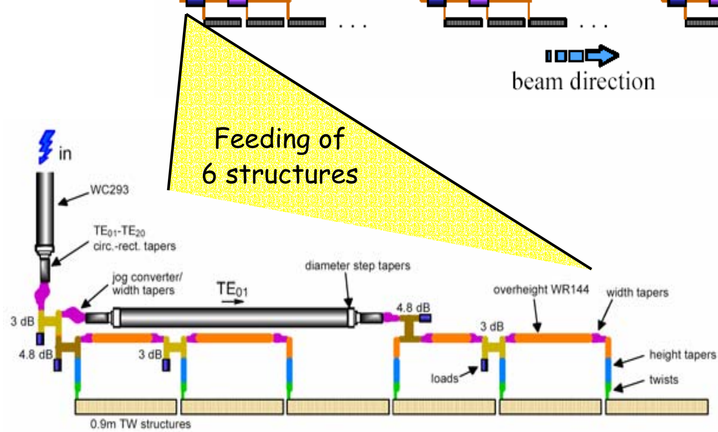
NLC/JLC RF Unit and DLDS

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

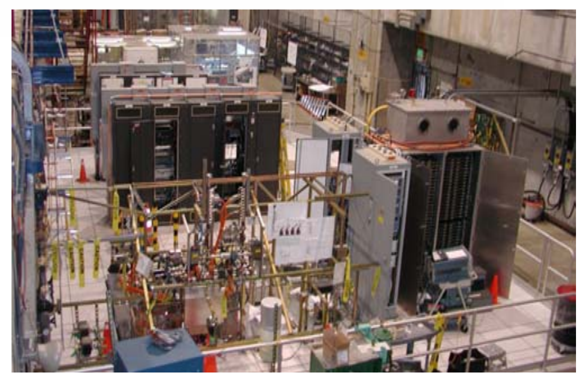
RF Power Distribution and Pulse-Compression:

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





in 2004



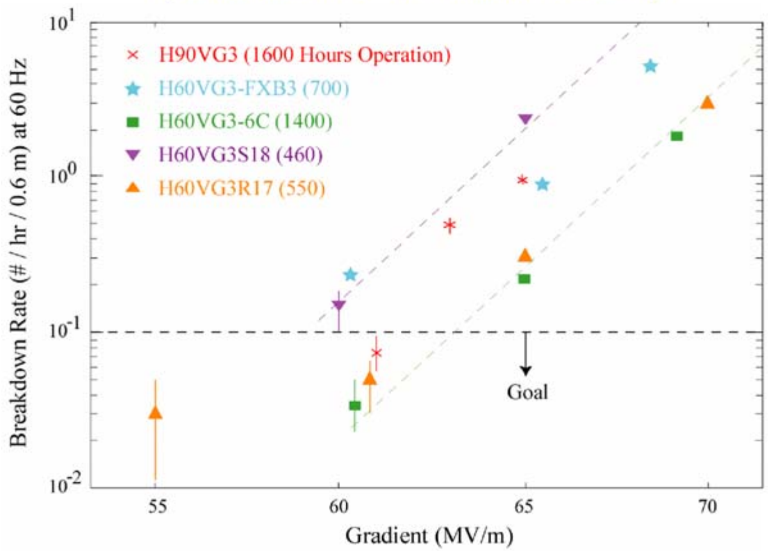
JLC-NLC TeV SLED-II Test

Recent Promissing Results

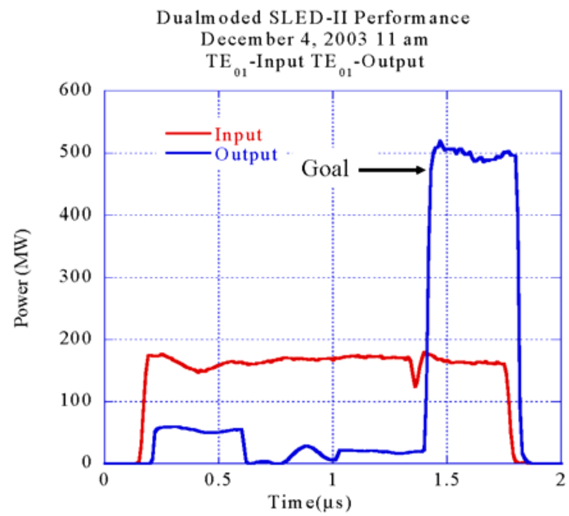
Still some problem for 65 MV/m
But 60 MV/m should work fine

Major R1 goal for Power Distribution achieved in December 2003

Structure High Gradient Performance
(Breakdown Rate -vs- Unloaded Gradient)



Dual Moded SLED-II High Power Test

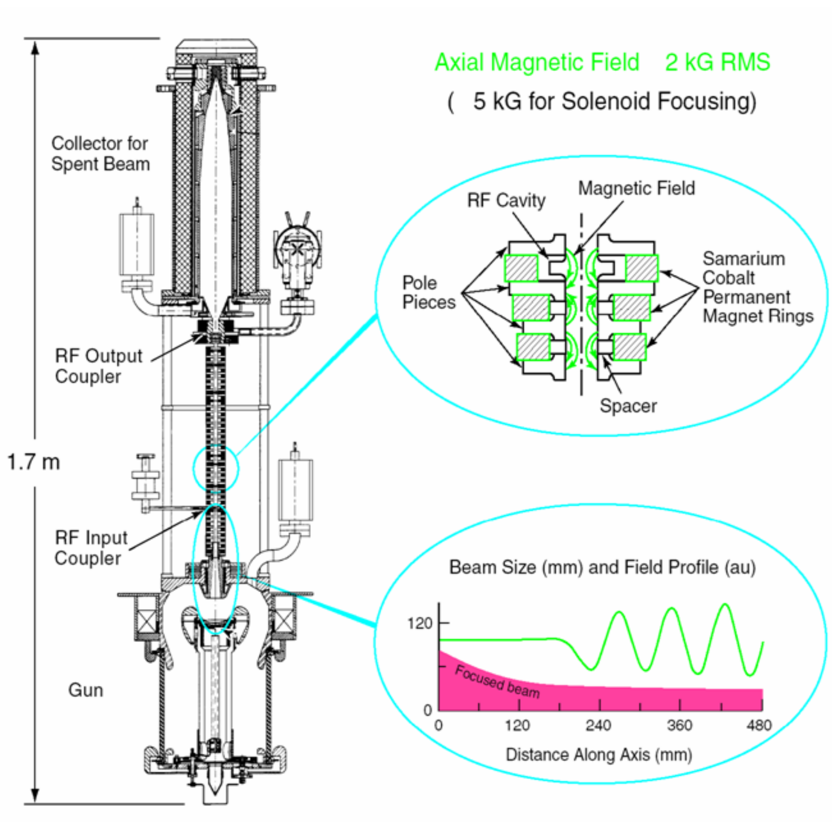


Have since achieved 580 MW, limited only by klystron power.

TRC R1 Met

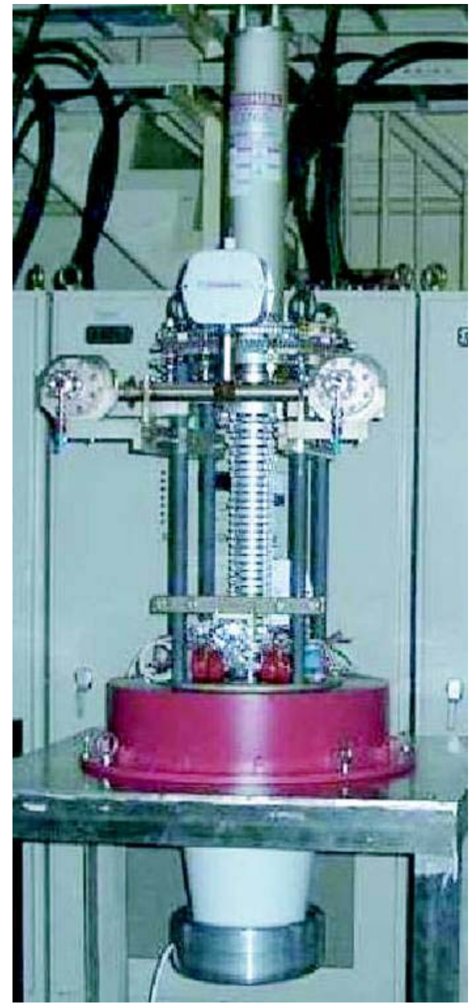
NLC/JLC Klystron Programs

NLC XP-Klystron



Major concern is 150 Hz repetition rate:
Average power handling for both Klystron and Modulator is still insufficient, but improving.

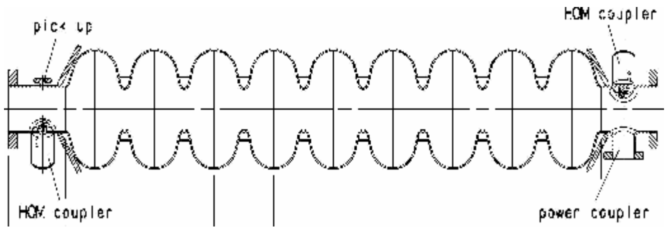
JLC PPM



The 9-cell TESLA cavity

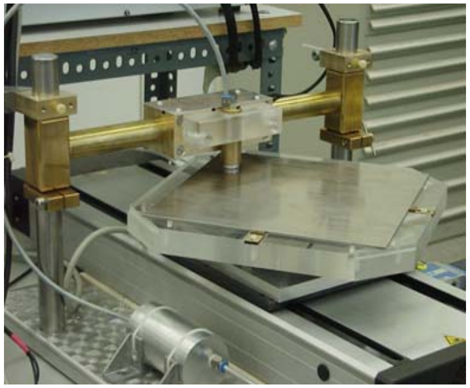
Major contributions from: CERN, Cornell, DESY, CEA-Saclay

- **9-cell, 1.3 GHz**



TESLA cavity parameters

R/Q	1036	Ω
E_{peak}/E_{acc}	2.0	
B_{peak}/E_{acc}	4.26	mT/(MV/m)
Δf/Δl	315	kHz/mm
$K_{Lorentz}$	≈ -1	$Hz/(MV/m)^2$



Eddy-current scanning system for niobium sheets

Cleanroom handling of niobium cavities

Preparation Sequence

- Niobium sheets (RRR=300) are scanned by eddy-currents to detect avoid foreign material inclusions like tantalum and iron
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Cleanroom handling:
  - Chemical etching to remove damage layer and titanium getter layer
  - High pressure water rinsing as final treatment to avoid particle contamination

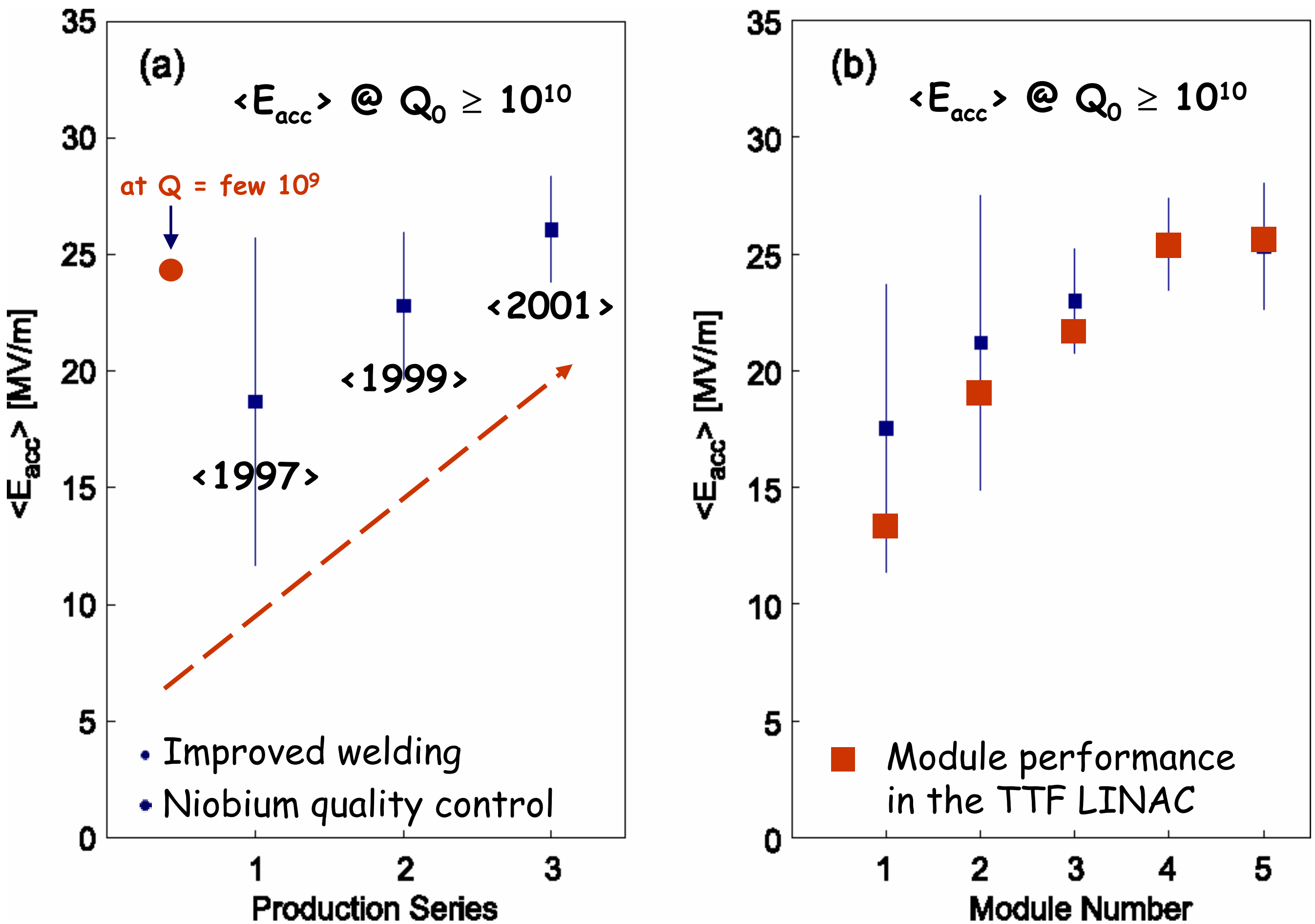
TESLA Learning curve with BCP

BCP = Buffered Chemical Polishing

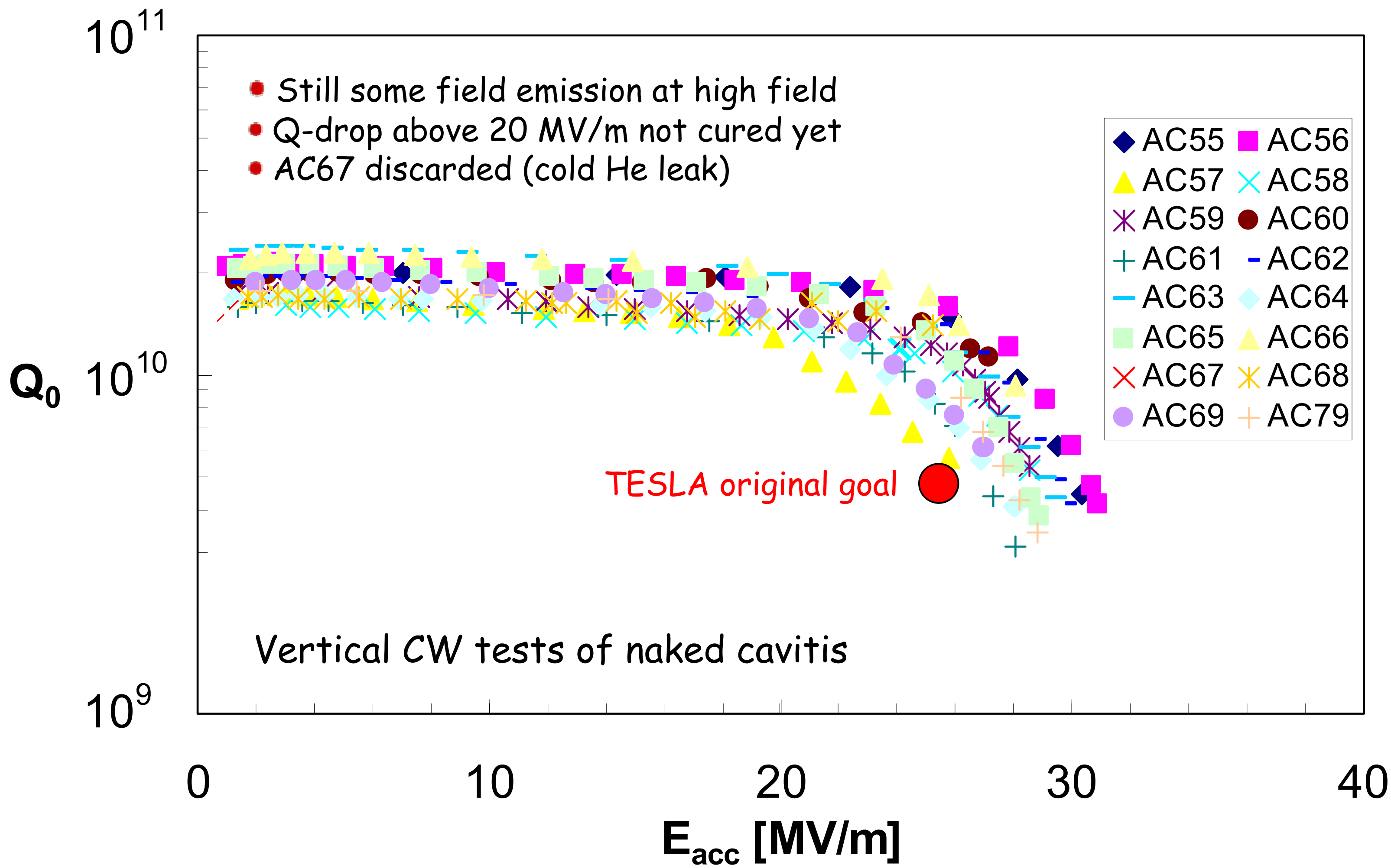
3 cavity productions from 4 European industries: Accel, Cerca, Dornier, Zanon

Cornell ● 1995

5-cell

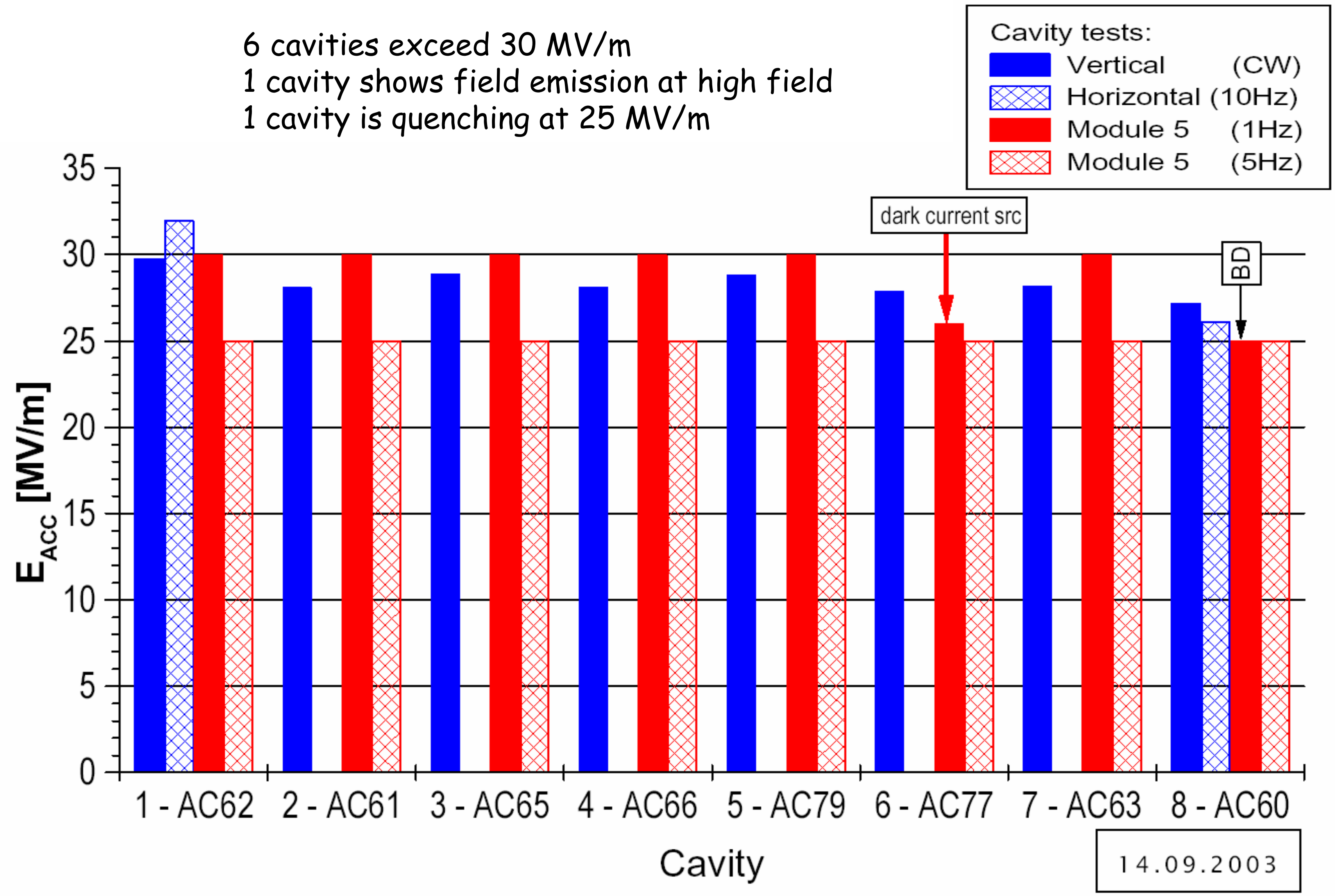


3rd cavity production with BCP



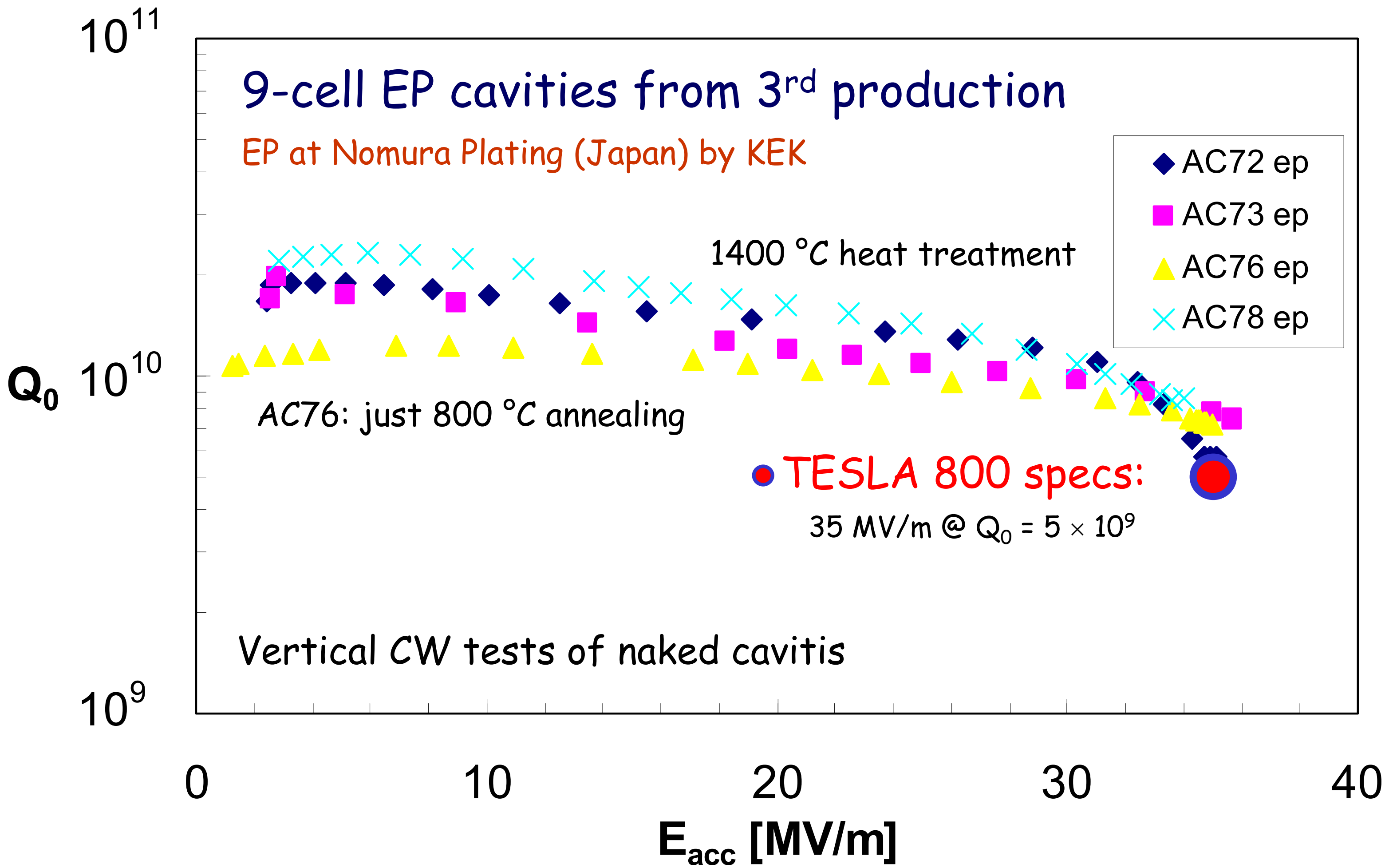
Recent results in module # 5

6 cavities exceed 30 MV/m
1 cavity shows field emission at high field
1 cavity is quenching at 25 MV/m



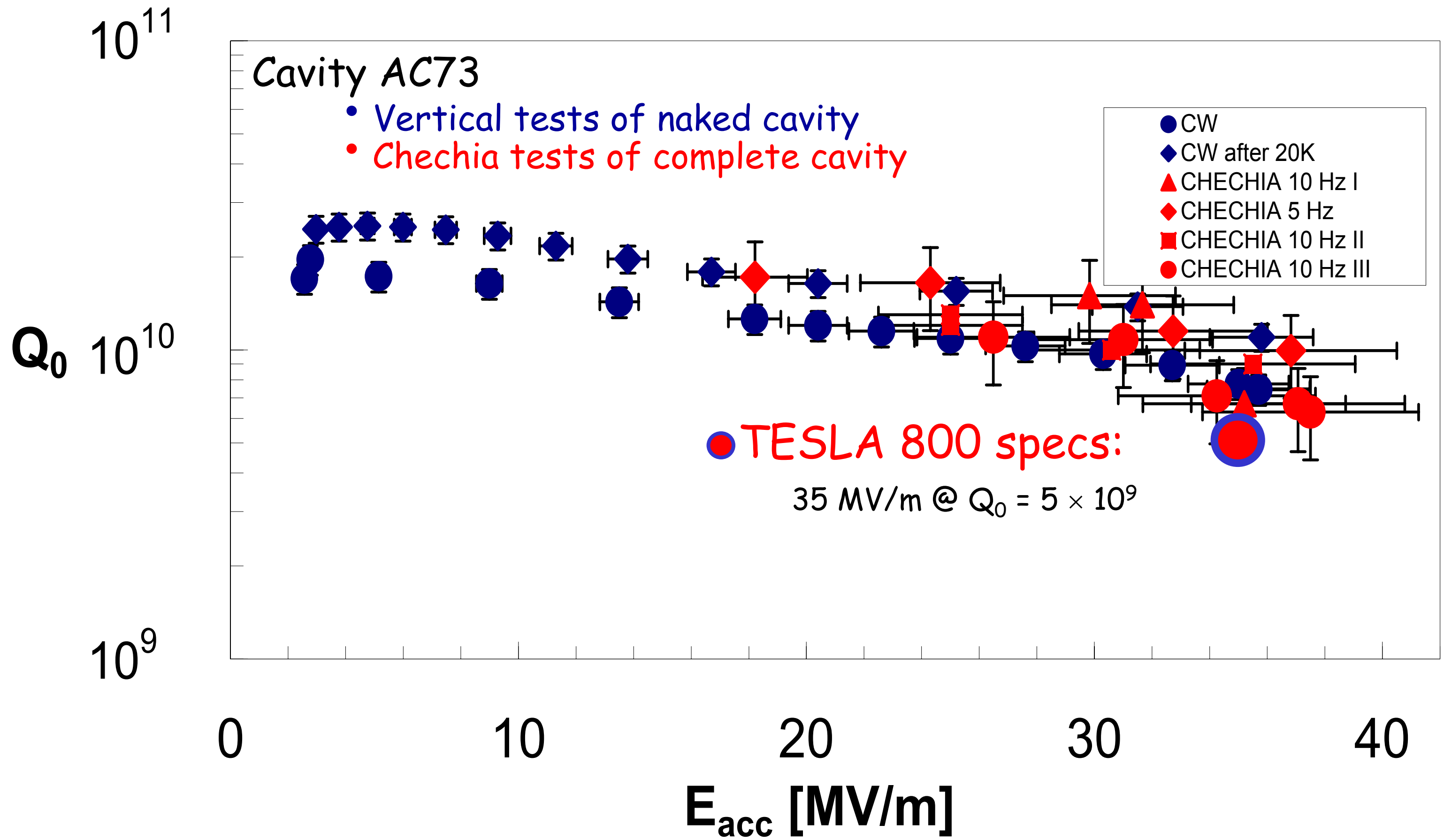
TESLA 800 Performances with EP

EP (Electro-Polishing) developed at KEK by Kenji Saito (originally by Siemens)
Coordinated R&D effort: DESY, KEK, CERN and Saclay



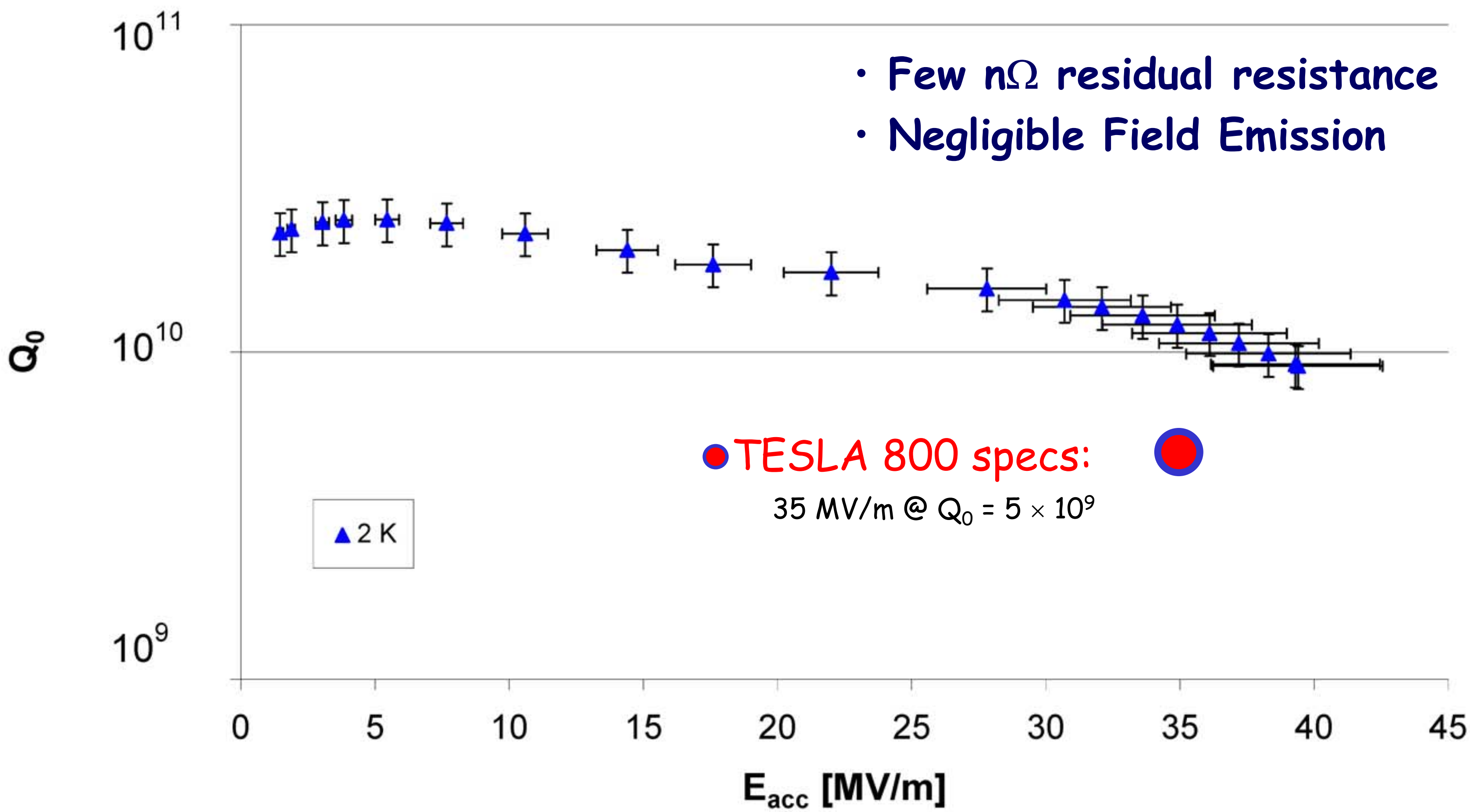
TESLA 800 in "Chechia"

- Long Term (> 1000 h) Horizontal Test
- In Chechia the cavity has all its ancillaries
- Chechia behaves as 1/8th (1/12th) of a TESLA cryomodule



Recent results on AC70

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



Important results for TESLA LC

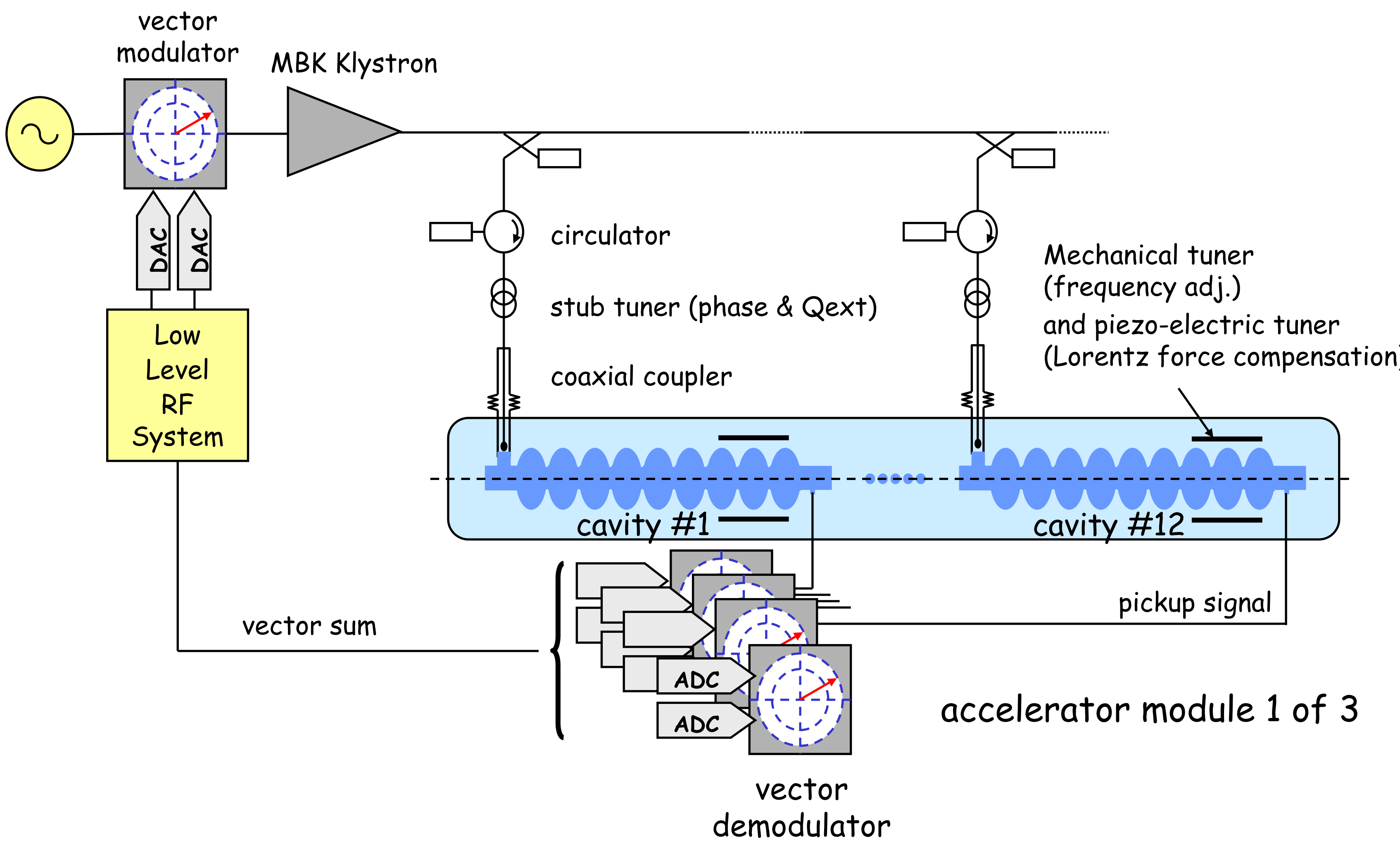
EP & 120°C backing are the key steps of the recipe

Field Emission and Q-drop cured

- Maximum **field is still slowly improving**
- Negligible Field Emission detected, that is
- **Negligible dark current expected** at this field level
- Cavity can be **operated close to its quench limit**
- Induced **quenches are not affecting cavity** performances

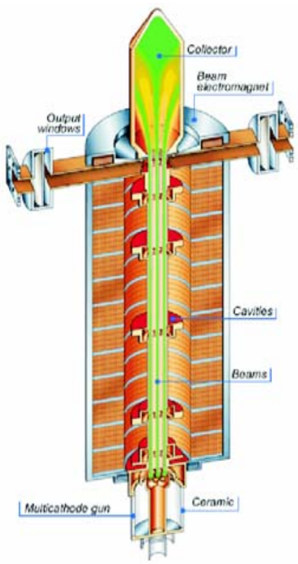
TESLA RF Unit

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

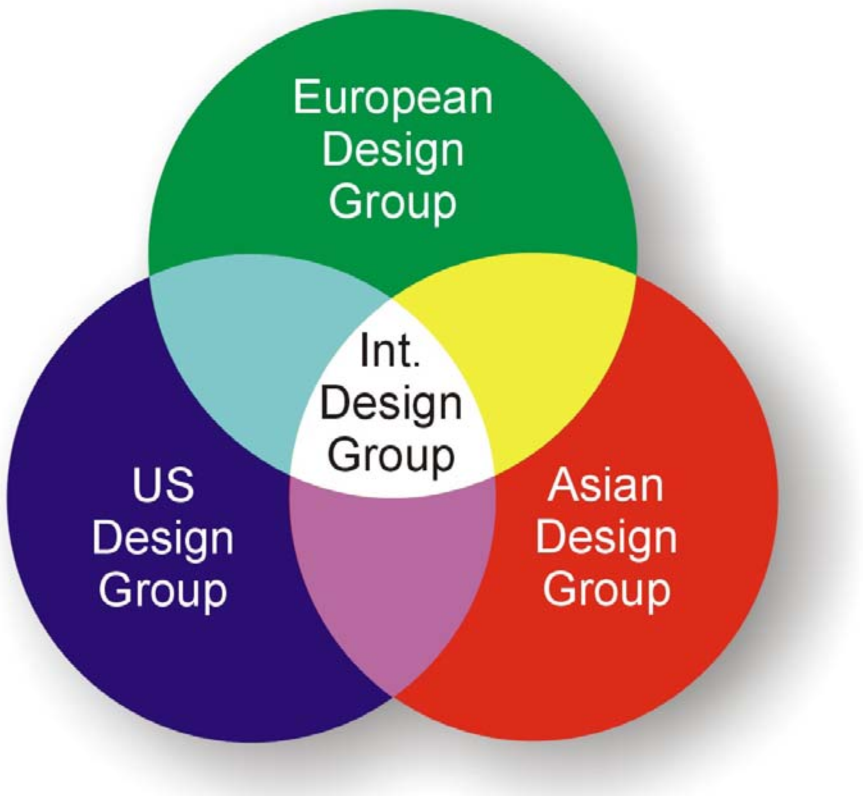
Indipendent beam design proposed and built by CPI. Tests from February.

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

First prototype tests expected on April this year

Concluding remarks

- Priority on LC worldwide accepted and agreement on fundamental parameters converging
- International Linear Collider Steering Group, ILCSG, and associated panels, are working
- 12 "wise men" for technology choice have been nominated
- Technology choice expected by end 2004
- Regional and international design groups are being formed
- Globally coordinated R&D and design work, on a common chosen technology, is expected from beginning 2005
- Overlap with LHC is conceivable



A global LC can now be built
Let's work together