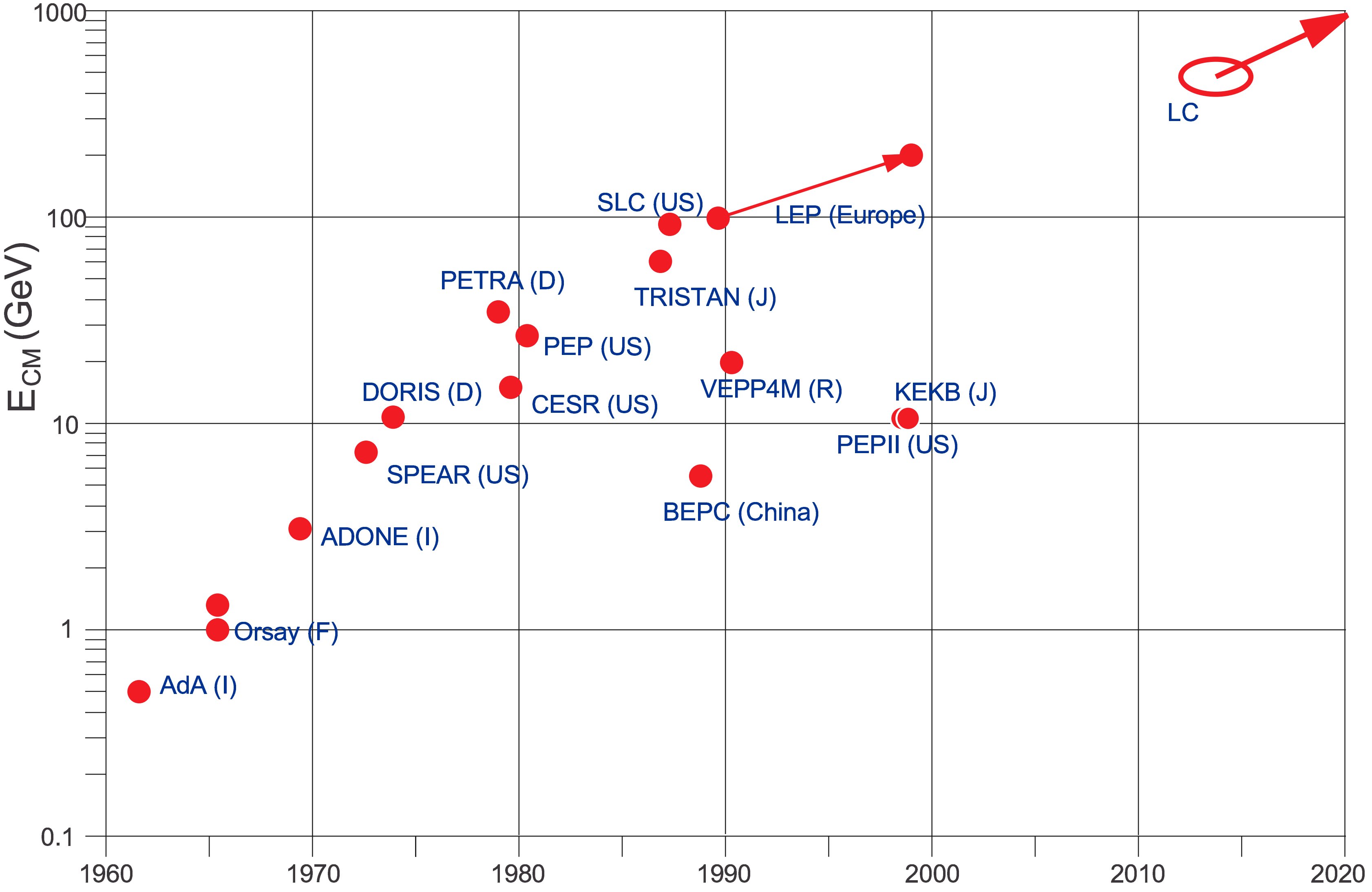
International Linear Collider
- after technology decision

Higgs Physics at Future Colliders workshop
2004/2005

A.F.Żarnecki
20 X 2004

e^+e^- Colliders



Lepton Colliders

- Ring collider is impossible beyond LEP200
  - (Though, some still propose e^+e^- rings in VLHC tunnel)
- Linear Colliders have been persued for $\gtrsim$20 years as the only candidate after LEP
  - Obviously, higher gradient is better for higher energy reach
  - Numerous exotic acceleration methods proposed: Wakefield accelerator, Inverse Cerenkov, Inverse FEL, Laser-Grating, Plasma accelerator, etc
  - Only conventional microwave methods survived for the next (SLC is the 1st) and 2nd next generation LC

Next Generation Linear Collider

- $E_{CM} \lesssim$ 1TeV
- 2 competing technologies

	TESLA	GLC/NLC	
Technology	SC	NC	
Frequency	1.3	11.4	GHz
Loaded gradient	35	53	MV/m
Max.energy	0.8	1-1.3	TeV
Site length	33	33	km
Lum(500GeV)	3.4	2.5	10^{34}cm^{-2}s^{-1}

- Similar level of technological maturity

The TeV ILC planned for 2015, overlaps with LHC.

Parameters defined by ILCSC scope-panel for ITRP

http://www.fnal.gov/directorate/icfa/LC_parameters.pdf

Baseline $\sqrt{s}$ = 200-500 GeV,

integrated Λuminosity 500 fb^{-1} over 1st 4 years

80% electron polarisation

2 interaction regions with easy switching

Upgrade Anticipate $\sqrt{s} \rightarrow$ 1 TeV, $\int\Lambda$ = 1 ab^{-1} over 4 years

ITRP wants highest possible

Options e$^-$e$^-$ collisions,

50% positron polarisation,

"GigaZ"; high Λ at Z and at WW threshold,

Laser backscatter for γγ and γe collisions,

Doubled Λ at 500 GeV.

Choice among options to be guided by physics needs.

Next e+e- collider must be linear

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

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

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

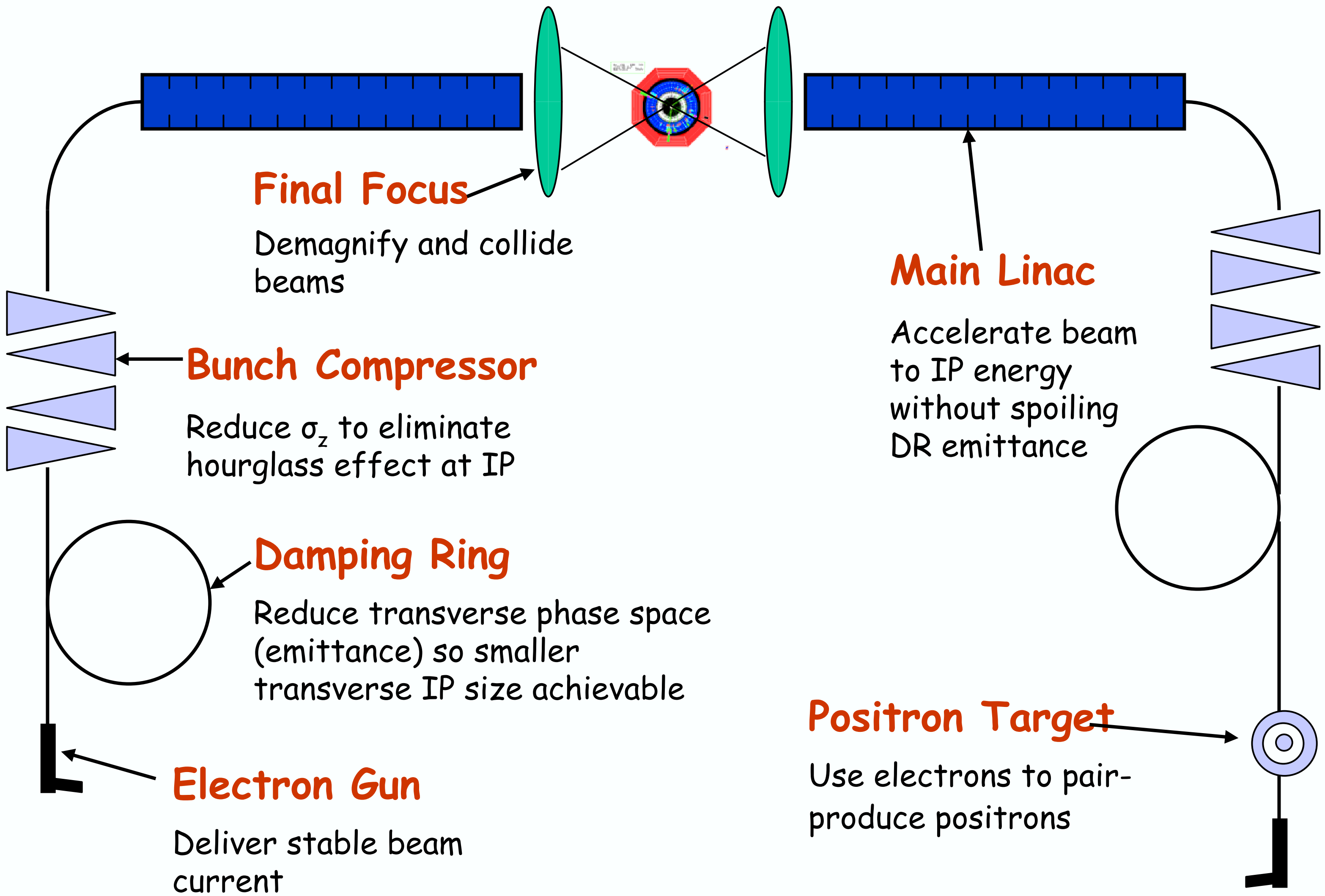
$\gamma_{250GeV} = 4.9\ .\ 10^{5}$

- Consider also the luminosity
  - For a **luminosity of ~ 10^{34}/cm²/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**

Circulating beam power = 500 GW

- Both size and power seem excessive

LC conceptual scheme



Final Focus

Demagnify and collide beams

Main Linac

Accelerate beam to IP energy without spoiling DR emittance

Bunch Compressor

Reduce σ_z to eliminate hourglass effect at IP

Damping Ring

Reduce transverse phase space (emittance) so smaller transverse IP size achievable

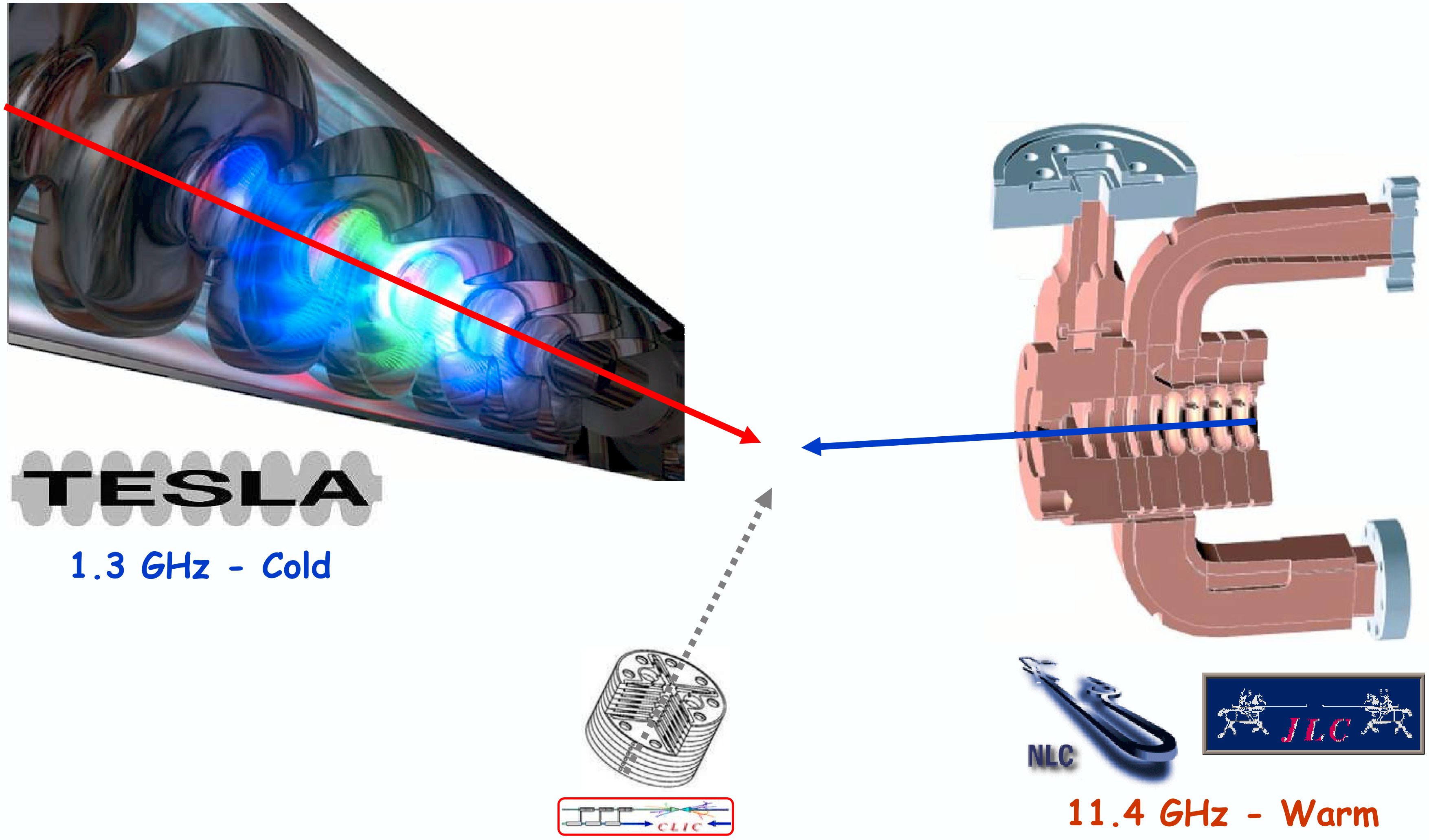
Positron Target

Use electrons to pair-produce positrons

Electron Gun

Deliver stable beam current

Competing technologies



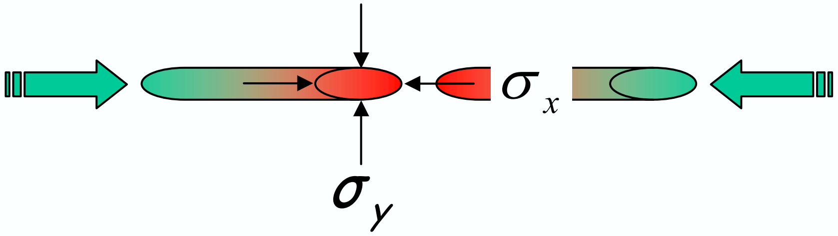
1.3 GHz - Cold

30 GHz-Warm

11.4 GHz - Warm

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

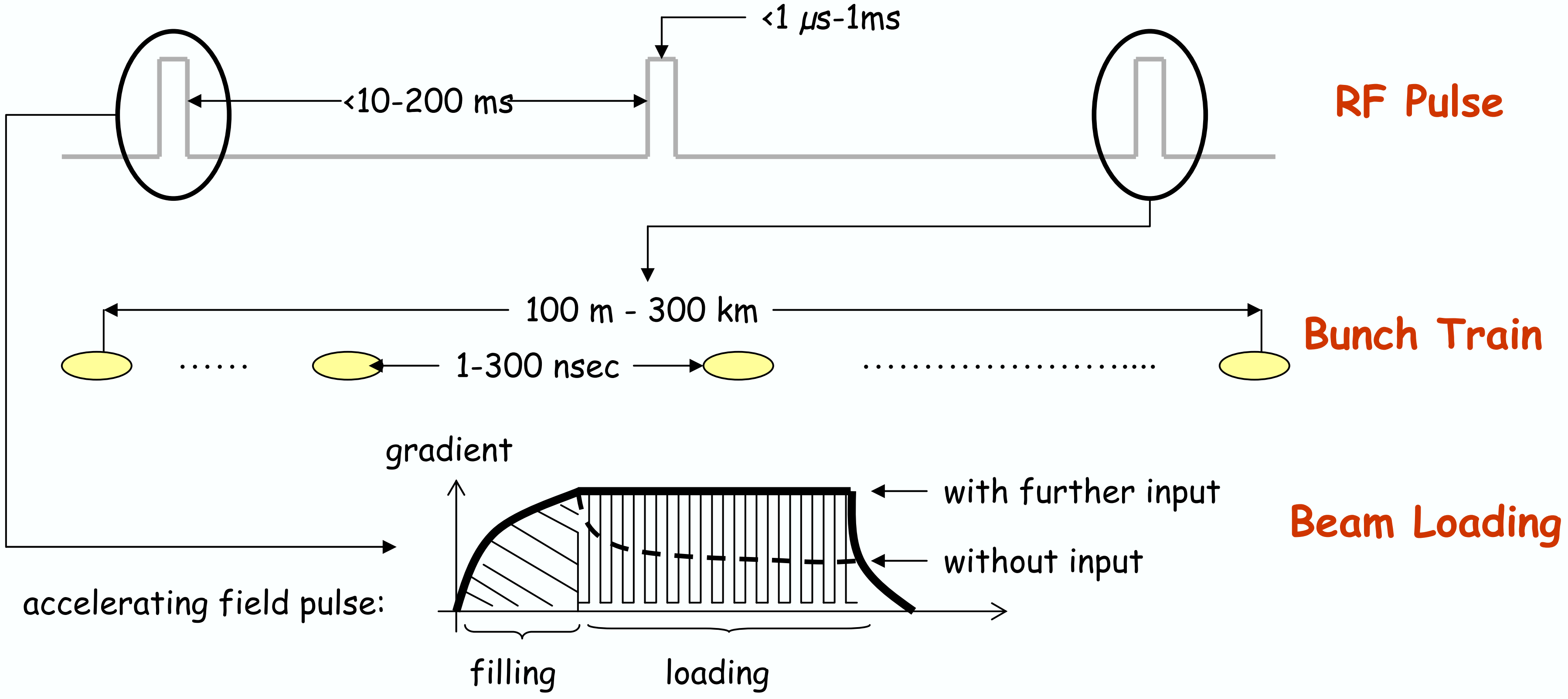
Parameters to play with

- ↓ 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 $\left(P_b \propto N_e \times n_b \times f_{rep}\right)$
- ↑ Increase **beam to-plug power efficiency** for cost

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



The TESLA challenge

Use Superconducting RF: **Higher Conversion Efficiency**
Smaller Emittance Dilution

Physical limit at 50 MV/m → ≥25 MV/m should be possible
→ Common R&D effort for TESLA

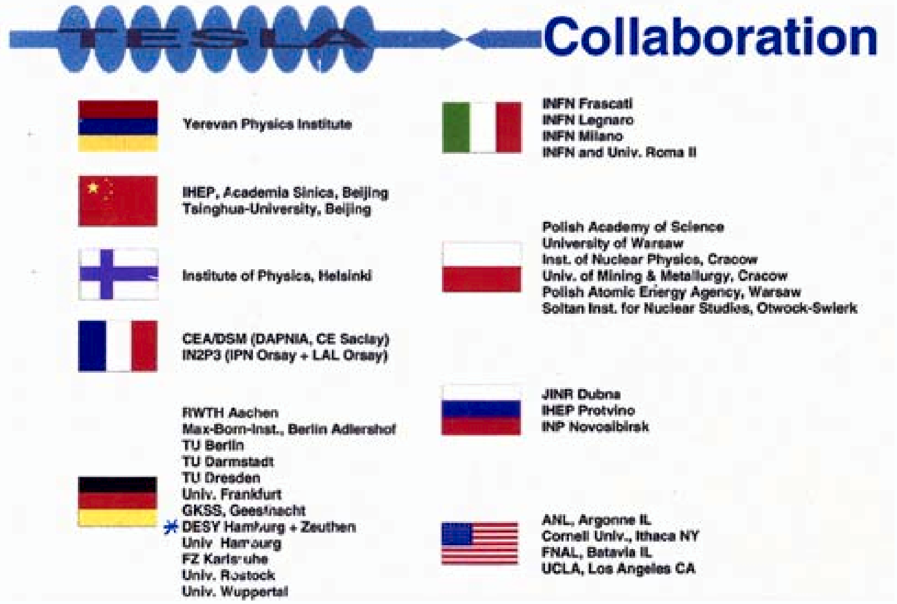

PROCEEDINGS OF 1990

The First International
TESLA Workshop
CORNELL

Held at Cornell University
July 23-26, 1990


Origin of the name

1992 - TESLA Collaboration set up at DESY


TESLA Collaboration

Yerevan Physics Institute

IHEP, Academia Sinica, Beijing
Tsinghua-University, Beijing

Institute of Physics, Helsinki

CEA/DSM (DAPNIA, CE Saclay)
IN2P3 (IPN Orsay + LAL Orsay)

RWTH Aachen
Max-Born-Inst., Berlin Adlershof
TU Berlin
TU Darmstadt
TU Dresden
Univ. Frankfurt
GKSS, Geesthacht
DESY Hamburg + Zeuthen
Univ. Hamburg
FZ Karlsruhe
Univ. Rostock
Univ. Wuppertal

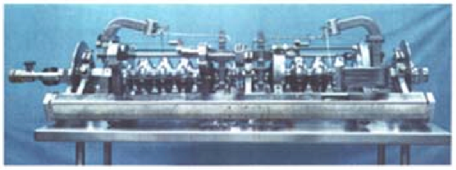
INFN Frascati
INFN Legnaro
INFN Milano
INFN and Univ. Roma II

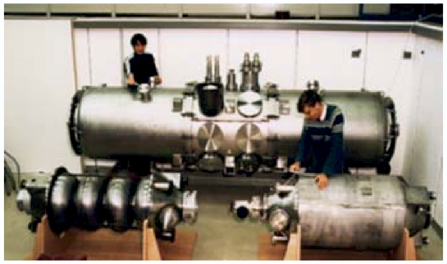
Polish Academy of Science
University of Warsaw
Inst. of Nuclear Physics, Cracow
Univ. of Mining & Metallurgy, Cracow
Polish Atomic Energy Agency, Warsaw
Soltan Inst. for Nuclear Studies, Otwock-Swierk

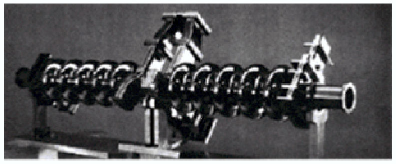
JINR Dubna
IHEP Protvino
INP Novosibirsk

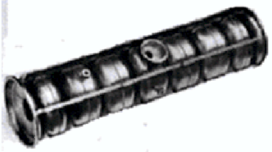
ANL, Argonne IL
Cornell Univ., Ithaca NY
FNAL, Batavia IL
UCLA, Los Angeles CA

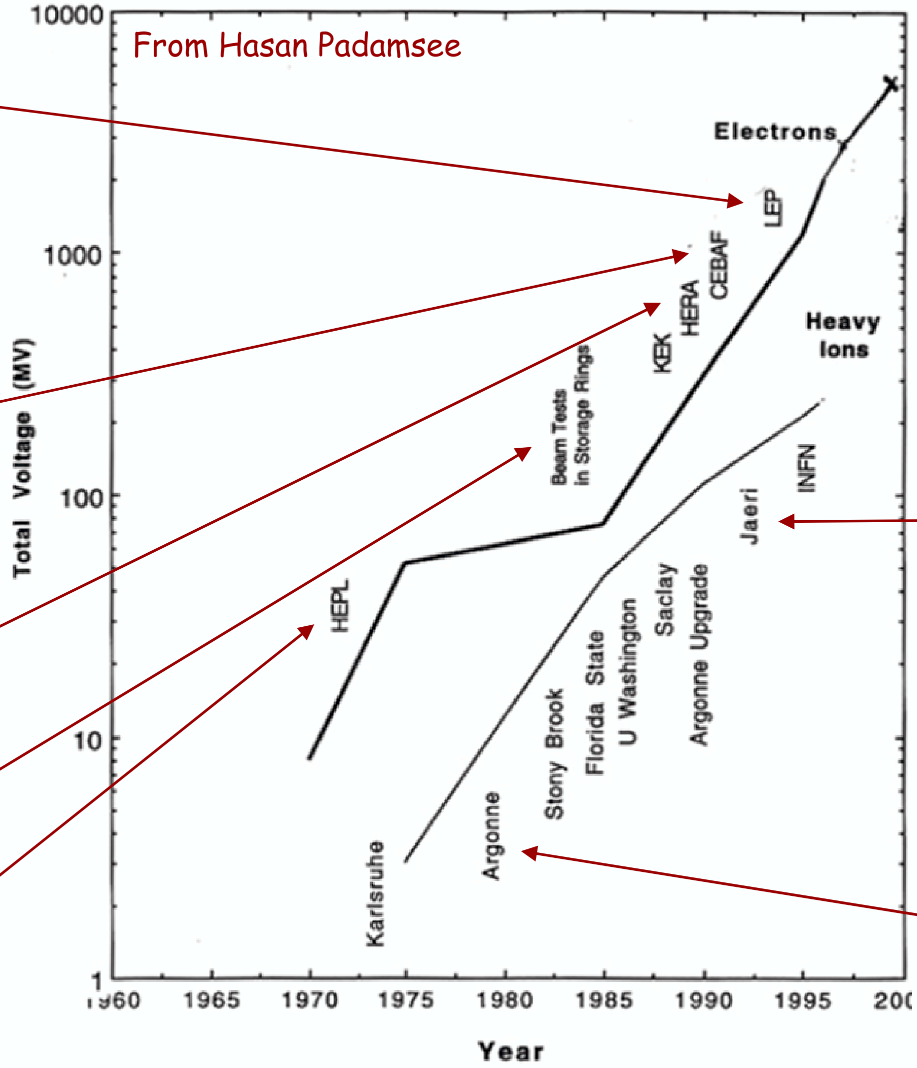
SRF before TESLA





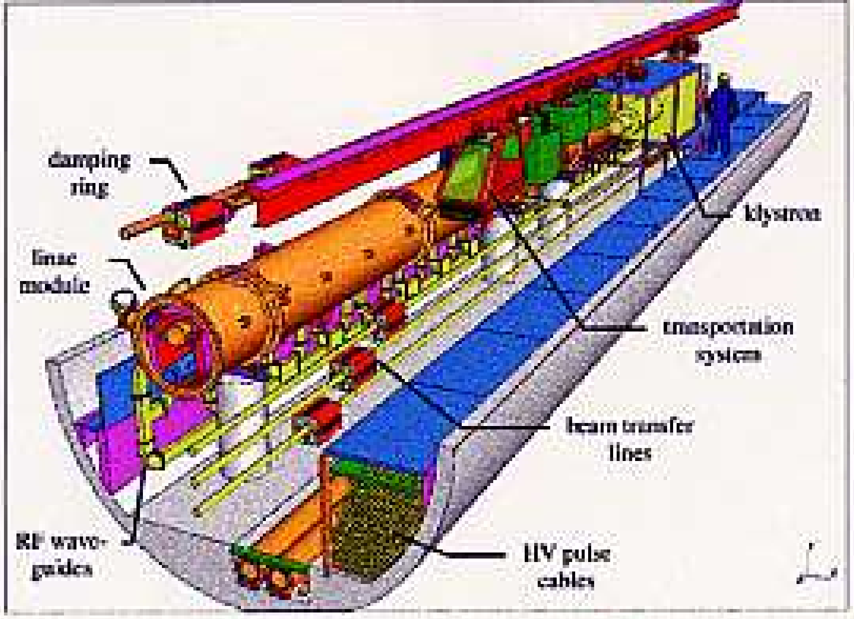






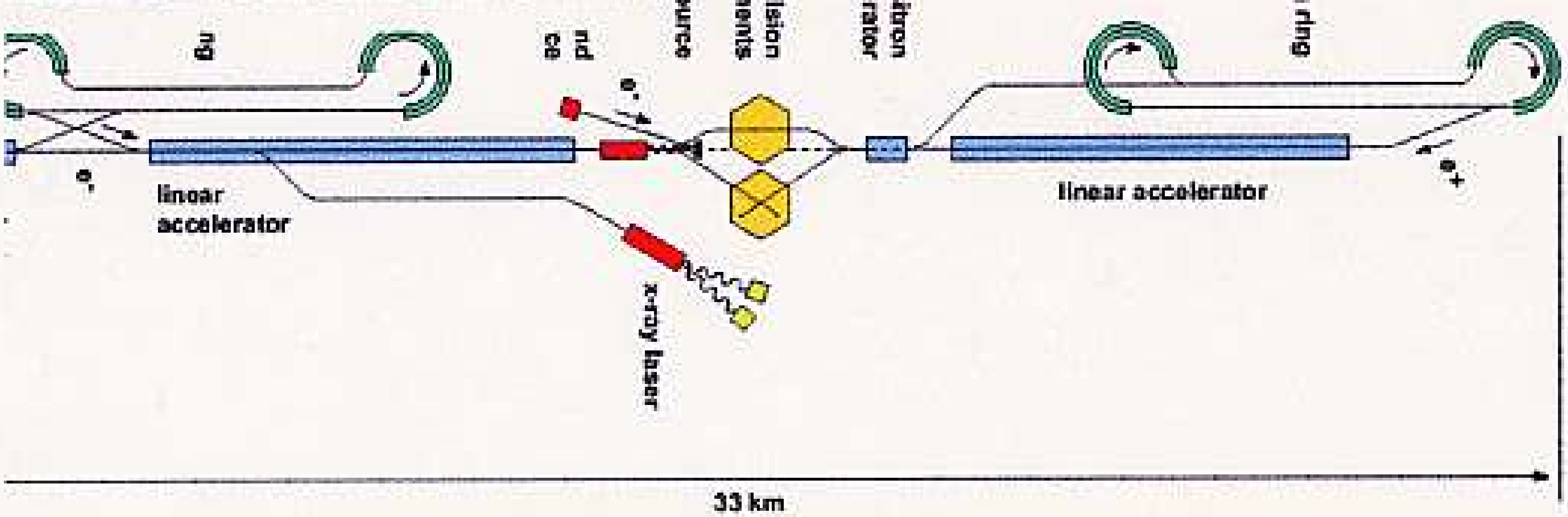
From Hasan Padamsee

Total >1000 meters
> 5 GV



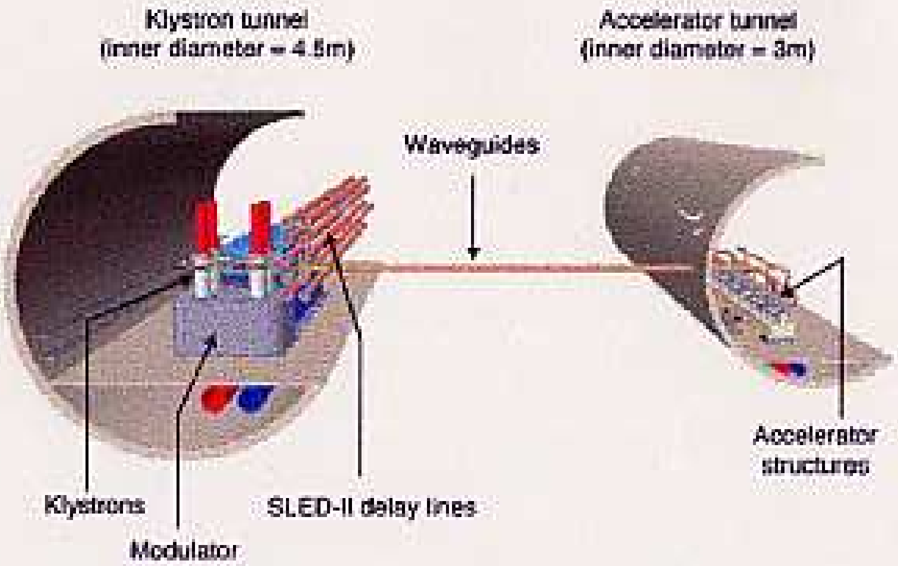
TESLA Linear Collider

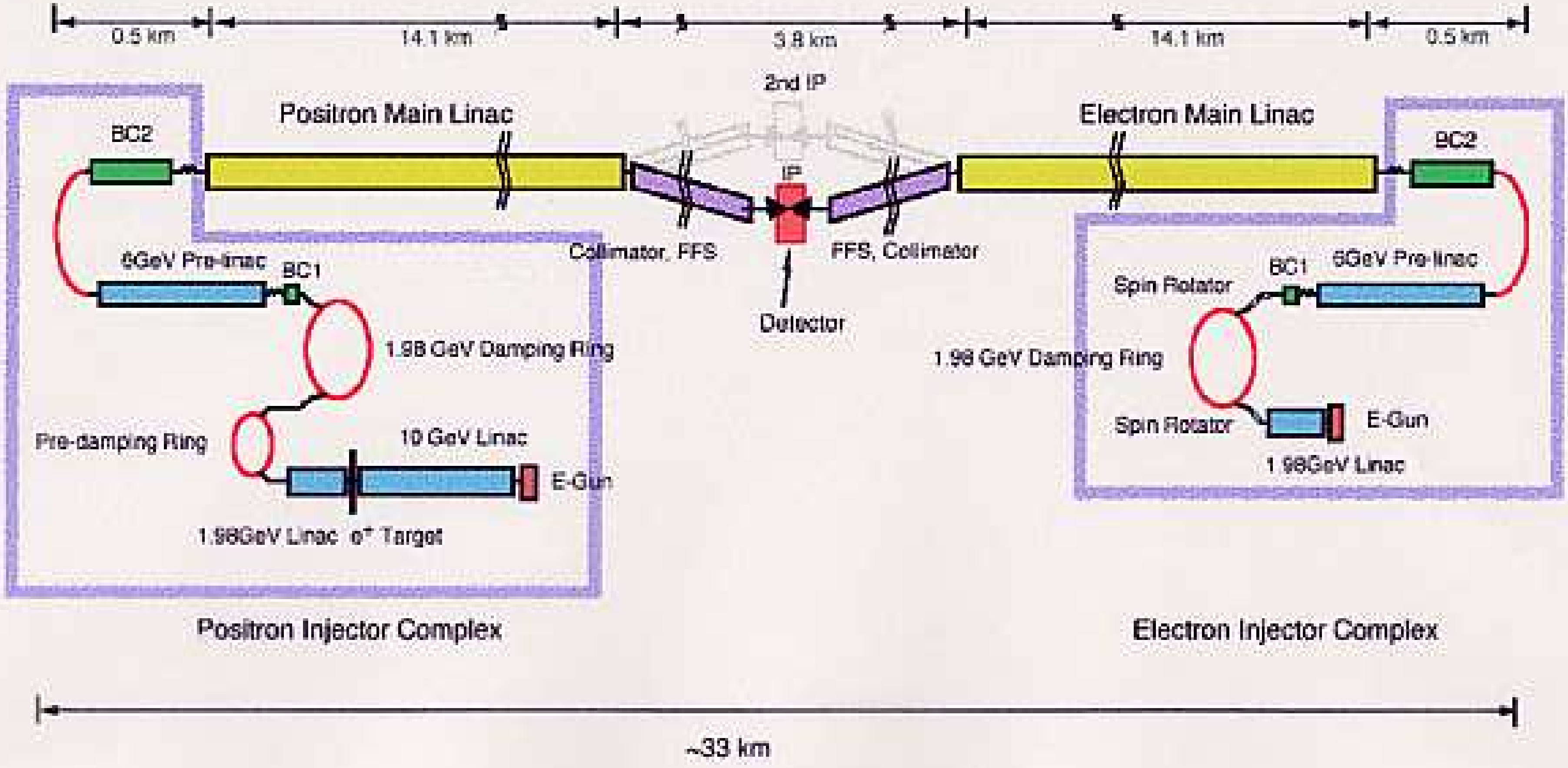
Superconducting RF, 1.3 GHz, loaded gradient=35 MV/m, site~33 km=>E_{max}(cm)=0.8 TeV

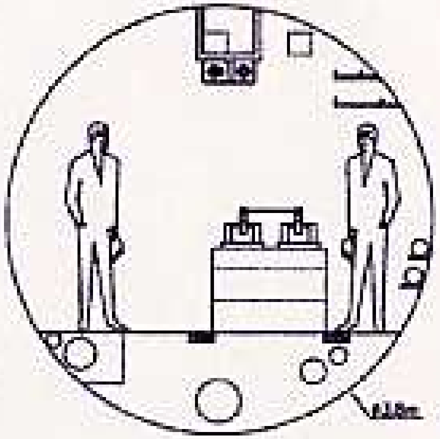


JLC/NLC Linear Collider

Warm RF, 11.4 GHz, Loaded gradient=50 MV/m, site ~33 km=>E_{max}(cm)=1.0-1.3 TeV







CLIC Linear Collider Warm RF, 30 GHz, loaded gradient=150 MV/m, site~36km=>E_{max}(cm)=3 TeV

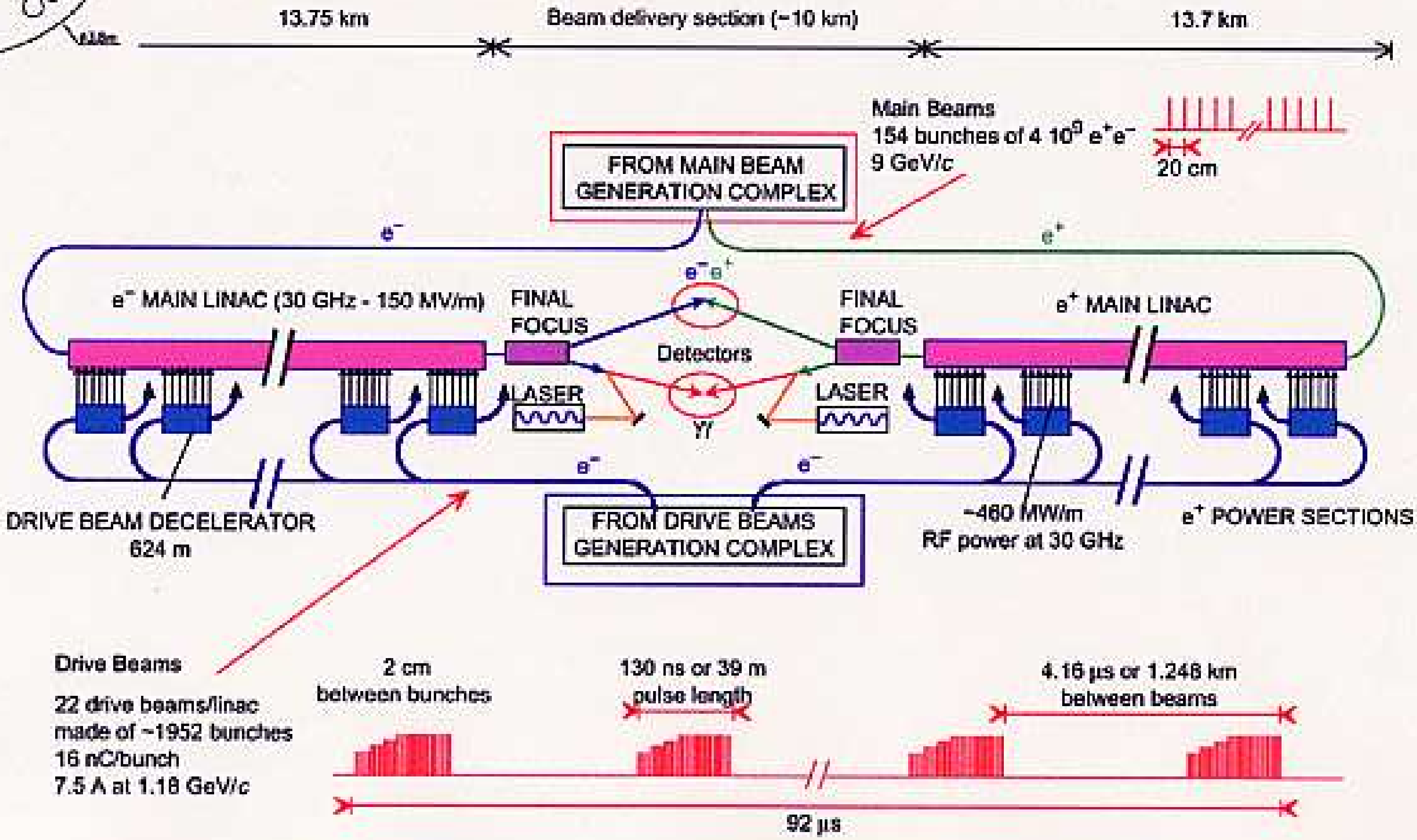
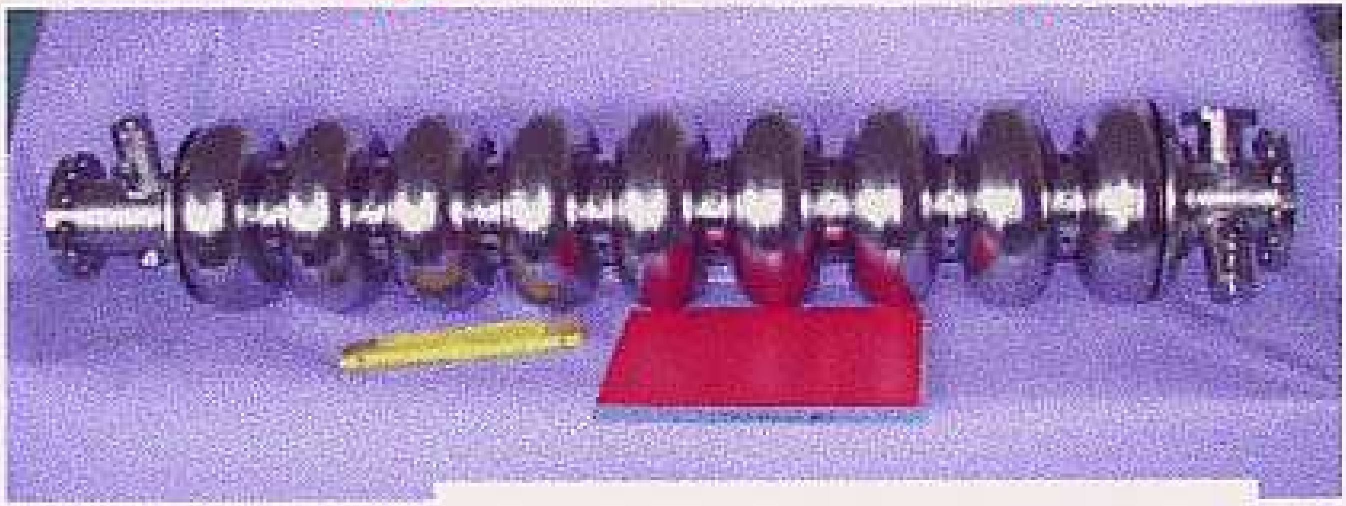
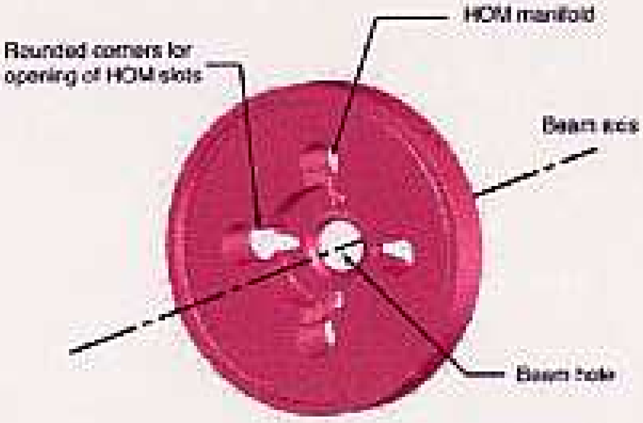


Fig. 1.1: Overall layout of CLIC for a centre-of-mass energy of 3 TeV.

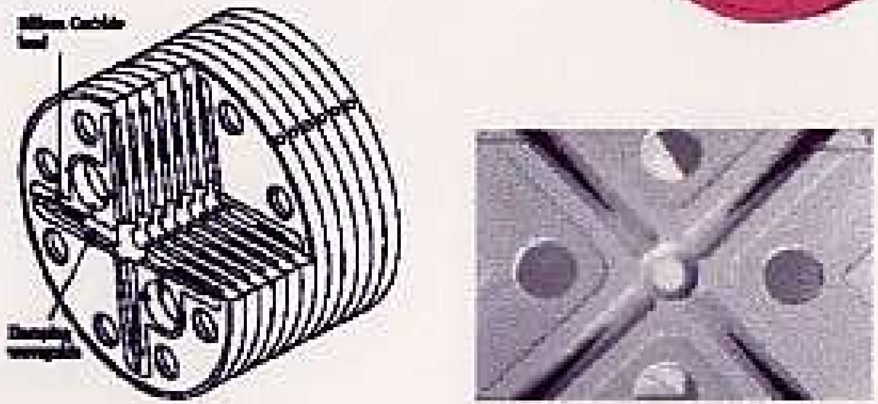
Accelerating structure components



TESLA 9-cell L-band
Pure Nb cavity,
Iris diameter 70 mm



JLC/NLC DDS X-band
Copper cell,
Iris diameter 9 mm



CLIC TDS W-band
Copper cell, Iris
diameter 4 mm

Why ITRP?

- Two parallel developments over the past few years (the science & the technology)
- The precision information from LEP and other data have pointed to a low mass Higgs; Understanding electroweak symmetry breaking, whether supersymmetry or an alternative, will require precision measurements.
- There are strong arguments for the complementarity between a ~0.5-1.0 TeV LC and the LHC science.
- Designs and technology demonstrations have matured on two technical approaches for an e^+e^- collider that are well matched to our present understanding of the physics. (We note that a C-band option could have been adequate for a 500 GeV machine, if NLC/GLC and TESLA were not deemed mature designs).

Why Decide Technology Now?

- **We have an embarrassment of riches !!!!**
  - **Two alternate designs -- “warm” and “cold” have come to the stage where the show stoppers have been eliminated and the concepts are well understood.**
  - **R & D is very expensive (especially D) and to move to the “next step” (being ready to construct such a machine within about 5 years) will require more money and a concentration of resources, organization and a worldwide effort.**
  - **It is too expensive and too wasteful to try to do this for both technologies.**
  - **A major step toward a decision to construct a new machine will be enabled by uniting behind one technology, followed by a making a final global design based on the recommended technology.**
  - **The final construction decision in ~5 years will be able to fully take into account early LHC and other physics developments.**

The ITRP Members

Jean-Eudes Augustin (FRANCE)

Jonathan Bagger (USA)

Barry Barish (USA) - Chair

Giorgio Bellettini (ITALY)

Paul Grannis (USA)

Norbert Holtkamp (USA)

George Kalmus (UK)

Gyung-Su Lee (KOREA)

Akira Masaike (JAPAN)

Katsunobu Oide (JAPAN)

Volker Soergel (GERMANY)

Hirotaka Sugawara (JAPAN)

David Plane - Scientific Secretary

Departing from Korea

International Technology Recommendation Panel Meeting
August 11 ~ 13, 2004. Republic of Korea

The Charge to the International Technology Recommendation Panel

General Considerations

The International Technology Recommendation Panel (the Panel) should recommend a Linear Collider (LC) technology to the International Linear Collider Steering Committee (ILCSC).

On the assumption that a linear collider construction commences before 2010 and given the assessment by the ITRC that both TESLA and JLC-X/NLC have rather mature conceptual designs, the choice should be between these two designs. If necessary, a solution incorporating C-band technology should be evaluated.

Note -- We have interpreted our charge as being to recommend a technology, rather than choose a design

Our Process

- We studied and evaluated a large amount of available materials
- We made site visits to DESY, KEK and SLAC to listen to presentations on the competing technologies and to see the test facilities first-hand.
- We have also heard presentations on both C-band and CLIC technologies
- We interacted with the community at LC workshops, individually and through various communications we received
- We developed a set of evaluation criteria (a matrix) and had each proponent answer a related set of questions to facilitate our evaluations.
- We assigned lots of internal homework to help guide our discussions and evaluations

Can be found at:
http://www.ligo.caltech.edu/~donna/ITRP_Home.htm

Evaluating the Criteria Matrix

- **We analyzed the technology choice through studying a matrix having six general categories with specific items under each:**
  - **the scope and parameters specified by the ILCSC;**
  - **technical issues;**
  - **cost issues;**
  - **schedule issues;**
  - **physics operation issues;**
  - **and more general considerations that reflect the impact of the LC on science, technology and society**

- **We evaluated each of these categories with the help of answers to our "questions to the proponents," internal assignments and reviews, plus our own discussions**

Accelerator System Reference Designs

- Two options were developed: a warm option, following the design of the GLC/NLC Collaboration, and a cold option, similar to the TESLA design at DESY.

- Both options have been developed and evaluated in concert, using, as much as possible, similar approaches in technical design for similar accelerator systems, and a common approach to cost and schedule estimation methodology, and to risk/reliability assessments.

- For each option, the accelerator design task force has prepared a reference design configuration description. The reference designs for both options satisfy the physics-based machine requirements specified in the USLCSG Scope Document prepared by the American Linear Collider Physics Group (ALCPG).

USLCSG/ALCPG Key Physics Requirements

- initial energy E_{cm} = 500 GeV
- upgrade energy: at least E_{cm} = 1000 GeV
- integrated luminosity 500 fb^{-1} in the first 4 years of physics running, corresponding to a design luminosity of 2×10^{34} $cm^{-2}s^{-1}$
- electron beam polarization 80%
- an upgrade option for positron polarization
- crossing angle at the collision point
- site consistent with two interaction regions, with one capable of γ-γ and e^--γ collisions

These requirements are consistent with those specified by the Parameters Subcommittee of the International Linear Collider Steering Committee.

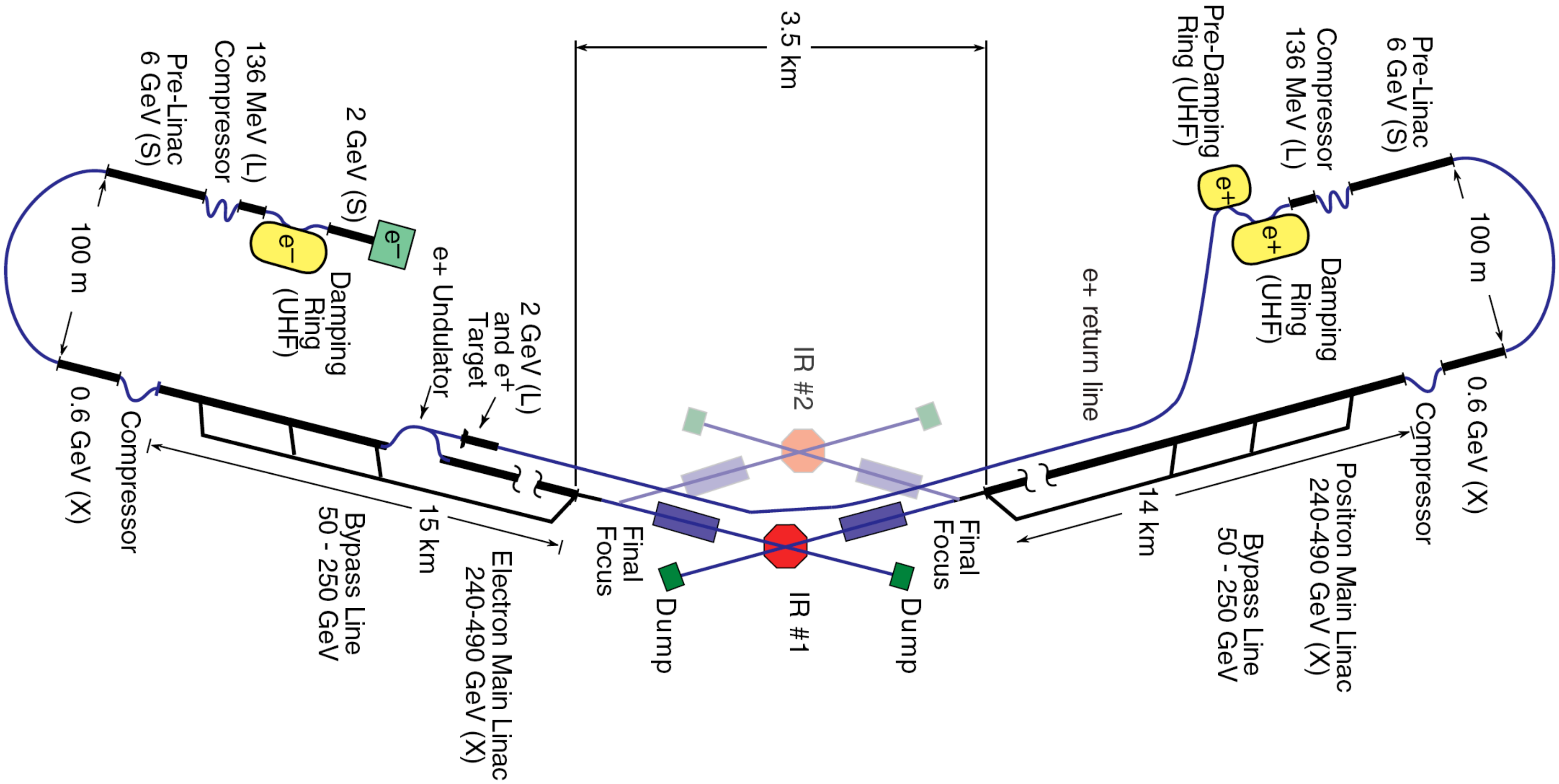
Accelerator Systems Reference Designs

In order to facilitate the comparison between the two linear collider technology options, the designs have been crafted with as much commonality as possible. Thus, both designs

- use an undulator-based positron source, capable of being upgraded to provide polarized positrons, driven by a 150 GeV electron beam
- have almost identical beam delivery systems and IR configurations;
- have the same initial stage energy reach, up to about 625 GeV;
- are upgradeable to 1 TeV without additional underground construction;
- require no change to the injector parameters for the upgrade to 1 TeV.

X-band Reference Design

X-band reference = 2003 NLC configuration with undulator e+ source

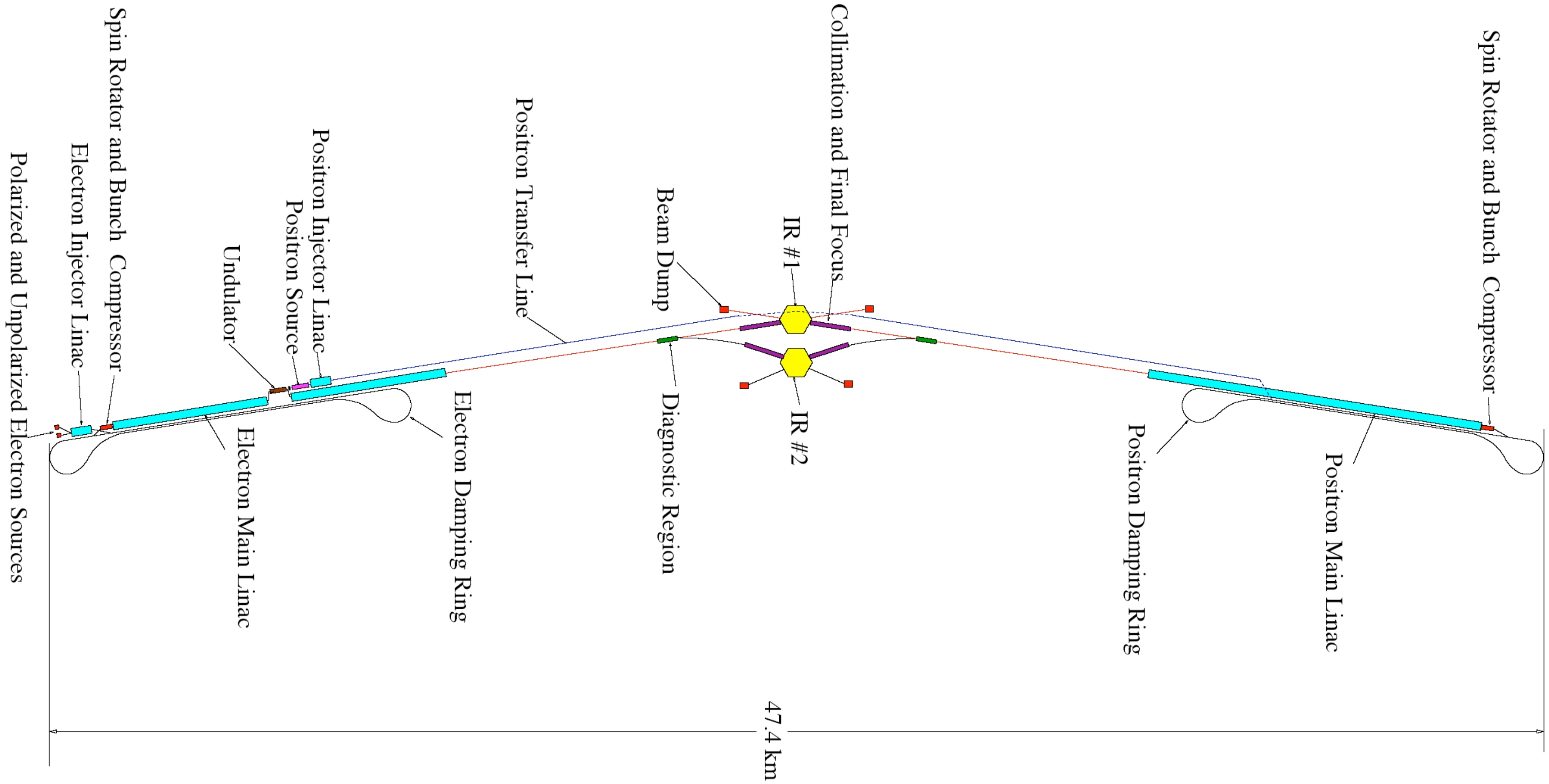


L-band Reference Design

- The L-band reference design follows, for the most part, the design outlined in the TESLA TDR. Major changes made to the TESLA design are:
  - An increase in the upgrade energy to 1 TeV (c.m.), with a tunnel of sufficient length to accommodate this in the initial reference design, assuming a gradient of 35 MV/m.
  - Improvements to the wigglers and vacuum systems of the damping rings,
  - The choice of 28 MV/m as the main linac design gradient for the 500 GeV (c.m.) machine.
  - The use of a two-parallel-tunnel architecture for the linac facilities.
  - NLC-style beam delivery system and IP configuration.
  - Vertical emittance at the IP = 40 nm-rad, vs. 30 nm-rad in the TESLA TDR. This change reflects recent simulations both in the U.S. and Europe, which indicate larger emittance growth in the cold main linacs than originally anticipated.

USLCSG

L-band Reference Design



Comparison of reference design key parameters

Parameter	**X**	**L**	**X**	**L**
C. M. Energy/Energy Reach [TeV]	0.5/0.625	0.5/0.625	1/1.3	1/1
Loaded rf gradient [MV/m]	52	28	52	35
2-linac total length [km]	13.4	27.0	26.8	42.5
$\gamma\varepsilon_x$(IP) [μm-rad]	3.6	9.6	3.6	9.6
$\gamma\varepsilon_y$(IP) [μm-rad]	0.04	0.04	0.04	0.04
$\mathcal{L}_g$ [10^{33}cm^{-2}s^{-1}]	14.2	14.5	22.2	22.7
D_y	12.9	22.0	10.1	17.3
H_D	1.46	1.77	1.41	1.68
$\mathcal{L}$[10^{33}cm^{-2}s^{-1}]	20.8	25.6	31.3	38.1
Number of main linac klystrons	4520	603	8984	1211
Number of main linac RF structures	18080	18096	35936	29064
Peak RF power per structure [MW]	56	0.28	56	0.35
Average power per beam [MW]	6.9	11.3	13.8	22.6
Linac AC to beam efficiency [%]	6.6	17.0	7.1	15.3
Site Operating AC power [MW]	260	179	454	356

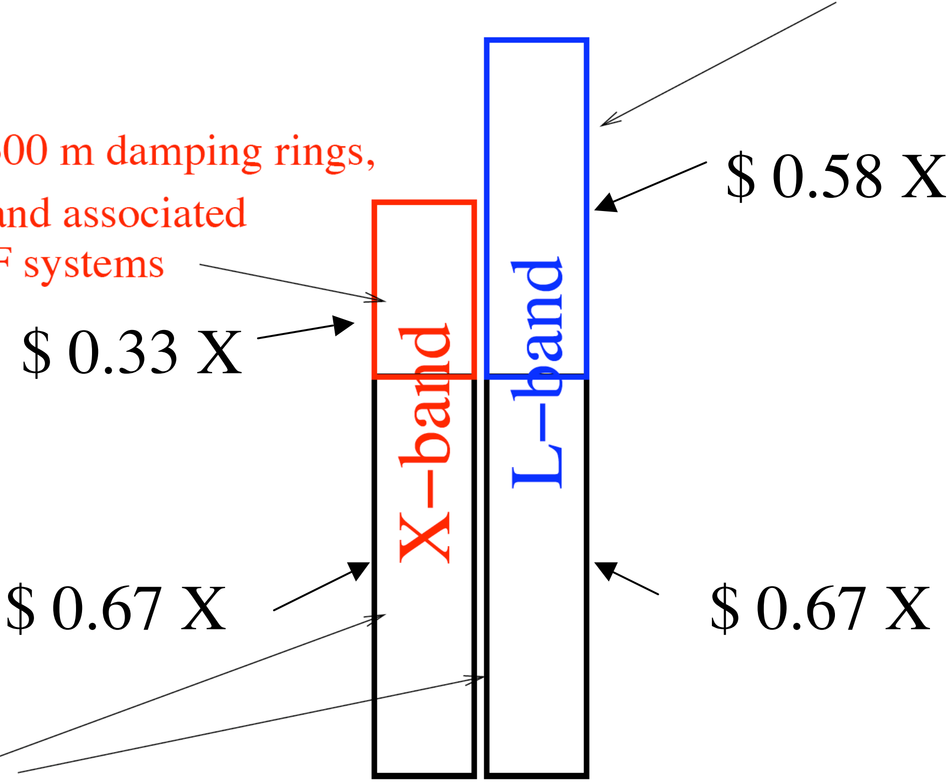
Warm option upgrade energy reach is 30% higher than warm

500 GeV cold linacs are x2 longer than warm linacs

Cold option $\mathcal{L}$ is 25% higher than warm

Baseline cold option AC power is 30% less than warm

Cost and schedule estimates-Cost comparisons

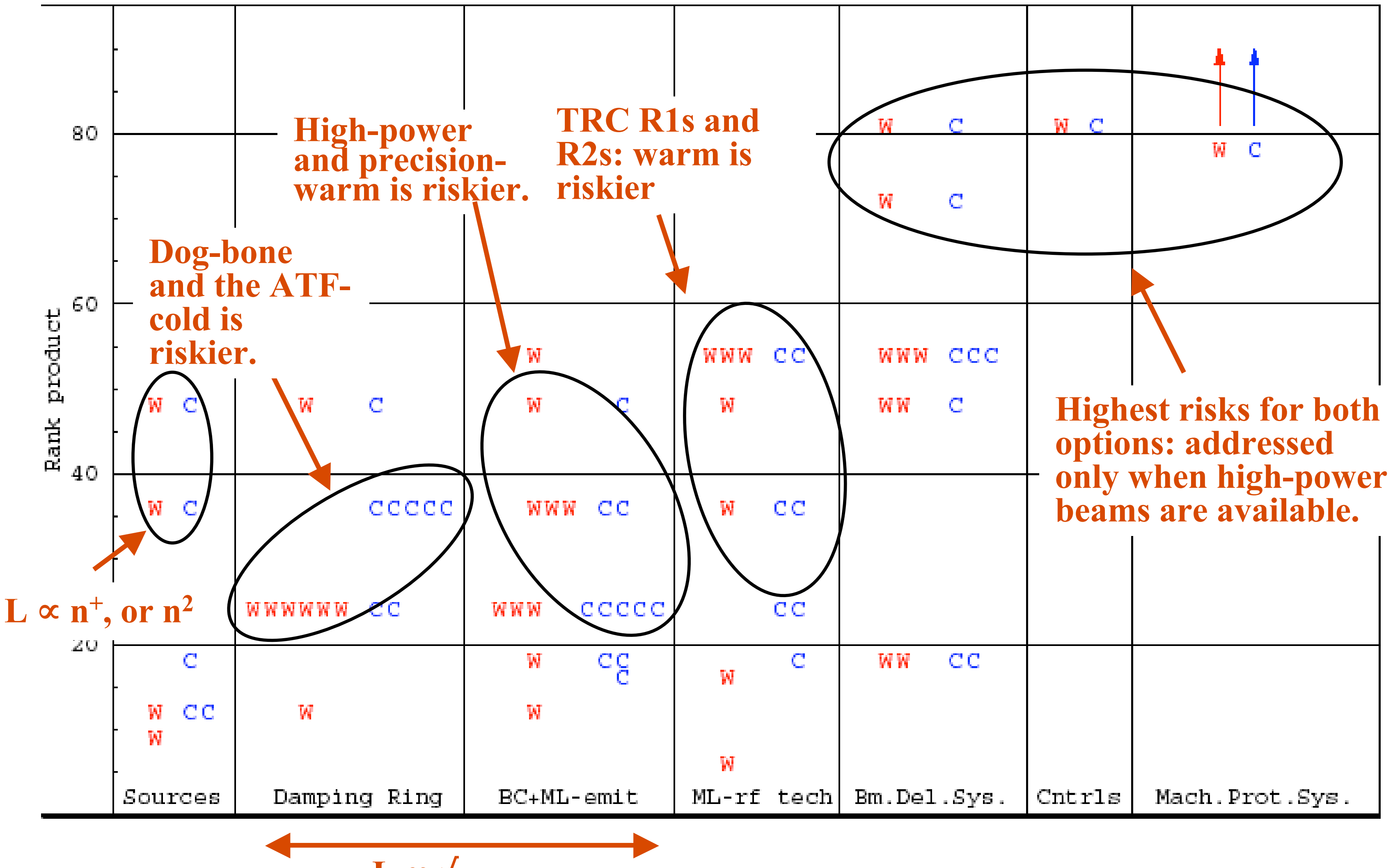


Costs specific to cold option: Extra 14 km of tunnel, cryogenics, 2x17 km damping rings, superconducting main linacs and associated L–band RF systems

Costs specific to warm option: 3x300 m damping rings, X–band main linacs and associated X–band RF systems

Common costs: Injectors, beam delivery systems, civil construction of 27 km of linac tunnel, site facilities, overheads, controls, system engineering, installation, pre–operations

Risk Assessment Rank Product Summary



High-power and precision-warm is riskier.

TRC R1s and R2s: warm is riskier

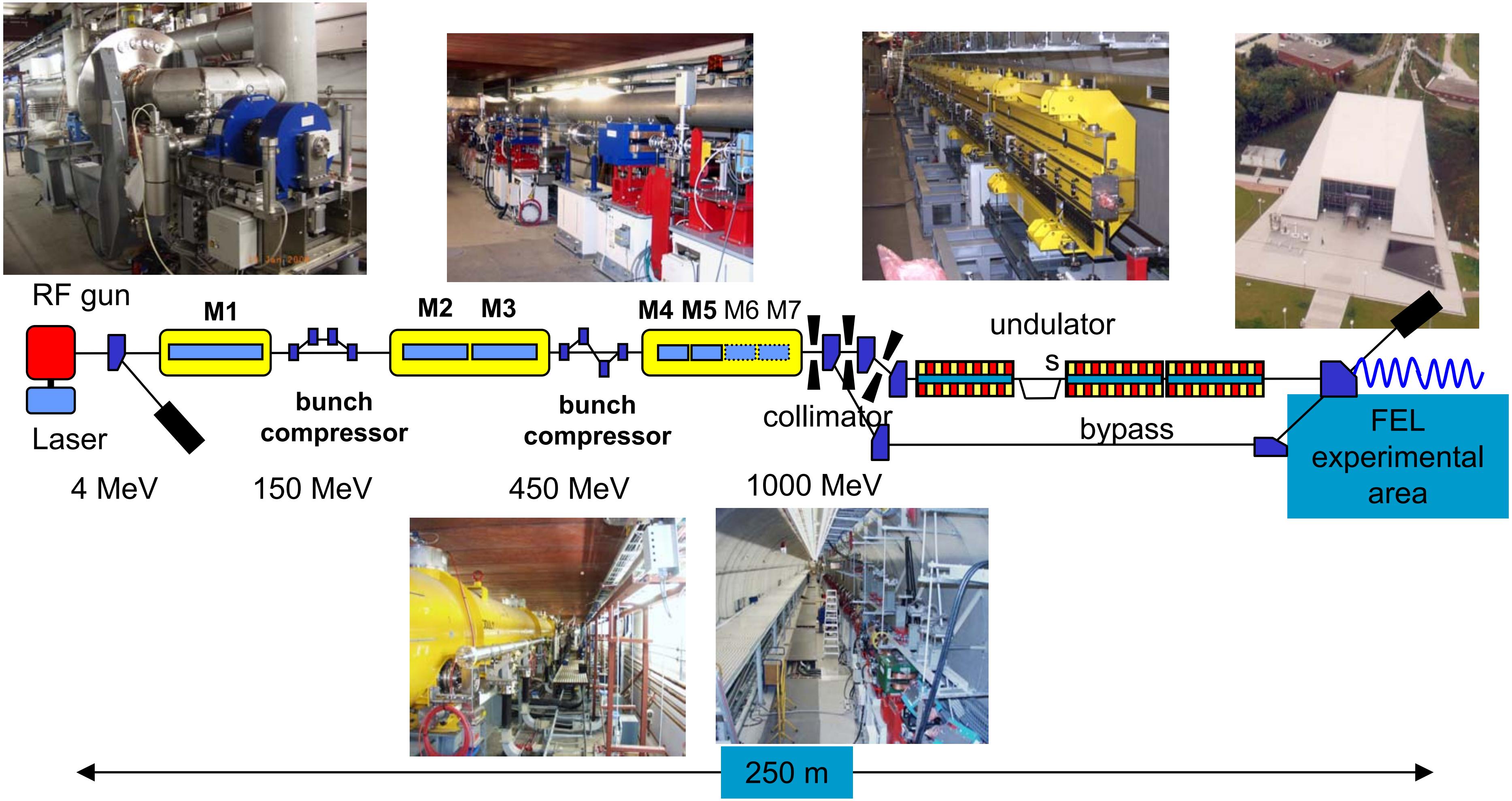
Dog-bone and the ATF-cold is riskier.

Highest risks for both options: addressed only when high-power beams are available.

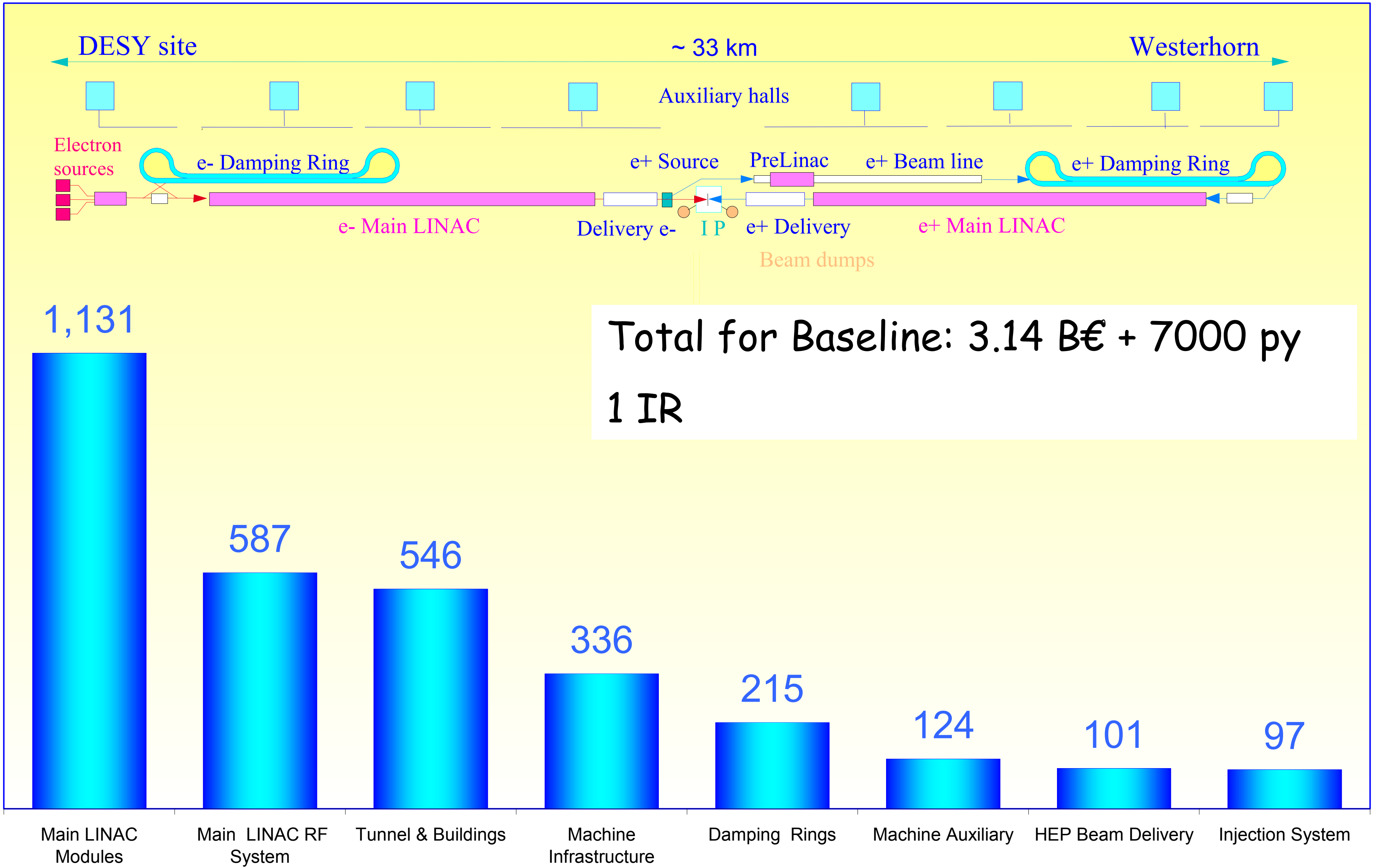
$L \propto n^+$, or n^2

$L \propto \sqrt{\varepsilon}$

The Basis for the TESLA Costing



TESLA Cost Distribution



Total for Baseline: 3.14 B€ + 7000 py

1 IR

Conclusion on US Study

Important work, will be useful in future optimisation

The quoted cost differential of 1.25 is a product of many few % differences and depends on many detailed assumptions, on large cost extrapolations for the warm machine and has an error which is probably larger than the quoted 10%

The luminosity is > 1.3 times higher in a cold machine

The TESLA collaboration is impressed by the amount of effort that this study has put into trying to understand the TESLA design. However, a more equal and wider participation of cold experts would have led to a more balanced report

The operating cost is definitely lower in the cold machine

Again, as in previous studies, no major errors/cost discrepancies have been found in the TESLA case

If cost were to play an important role in the technology choice, a fully co-ordinated international cost estimate must be made

The Recommendation

- **We recommend that the linear collider be based on superconducting rf technology (from Exec. Summary)**
  - **This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both (from the Executive Summary).**
  - **We submit the Executive Summary today to ILCSC & ICFA**
  - **Details of the assessment will be presented in the body of the ITRP report to be published around mid September**
  - **The superconducting technology has features that tipped the balance in its favor. They follow in part from the low rf frequency.**

Some of the Features of SC Technology

- **The large cavity aperture and long bunch interval reduce the complexity of operations, reduce the sensitivity to ground motion, permit inter-bunch feedback and may enable increased beam current.**
- **The main linac rf systems, the single largest technical cost elements, are of comparatively lower risk.**
- **The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.**
- **The industrialization of most major components of the linac is underway.**
- **The use of superconducting cavities significantly reduces power consumption.**

Both technologies have wider impact beyond particle physics. The superconducting rf technology has applications in other fields of accelerator-based research, while the X-band rf technology has applications in medicine and other areas.