深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 4

European XFEL as a byproduct of the Linear Collider effort

Shenzhen, 2 September 2022 / INFN LASA, 9 October 2024

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INFN LASA

Contents

1. The TESLA Collaboration Framework
2. TTF and the Free-Electro Laser
3. Parallel Development of TESLA and XFEL
4. XFEL Approval and TESLA going to the ILC

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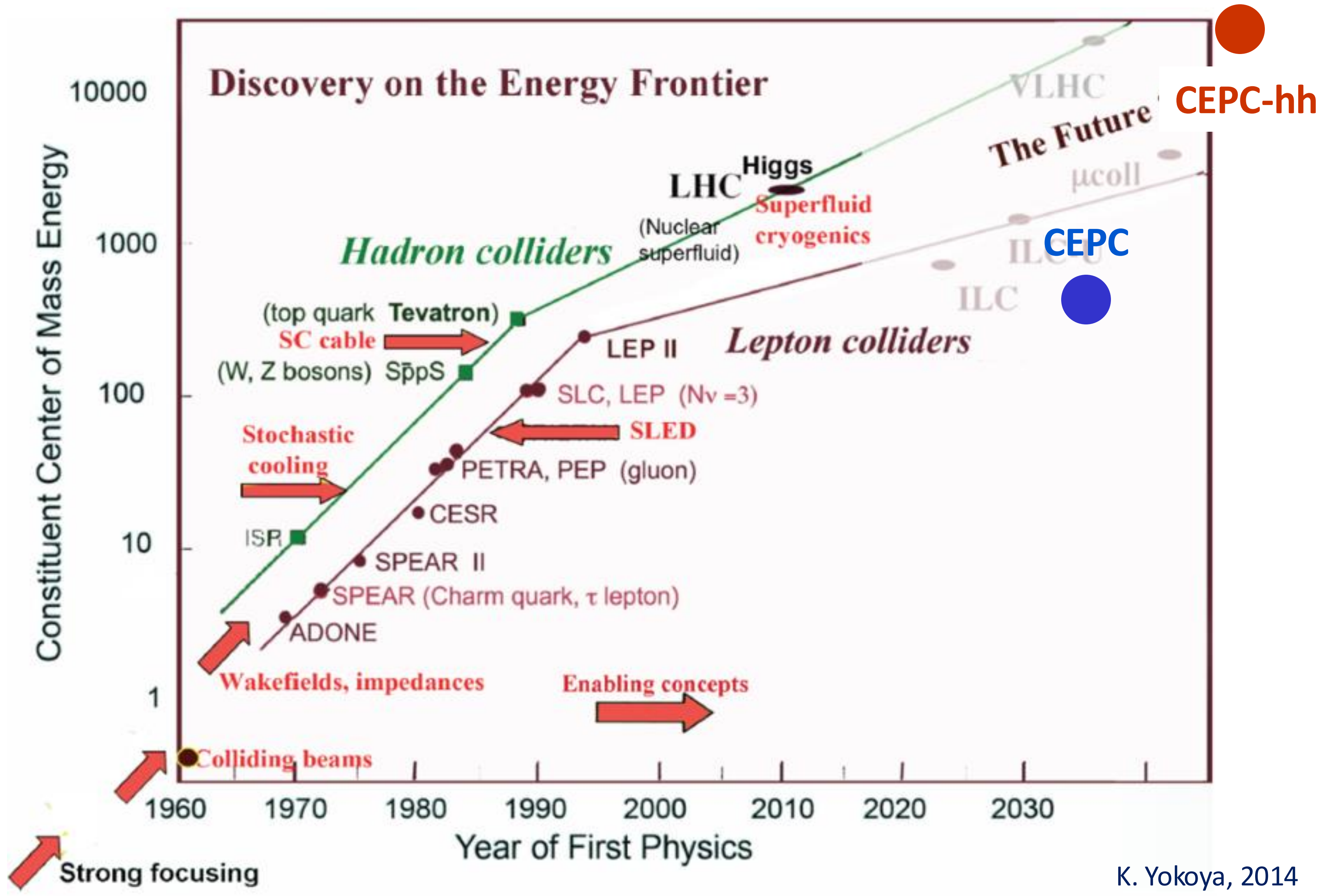
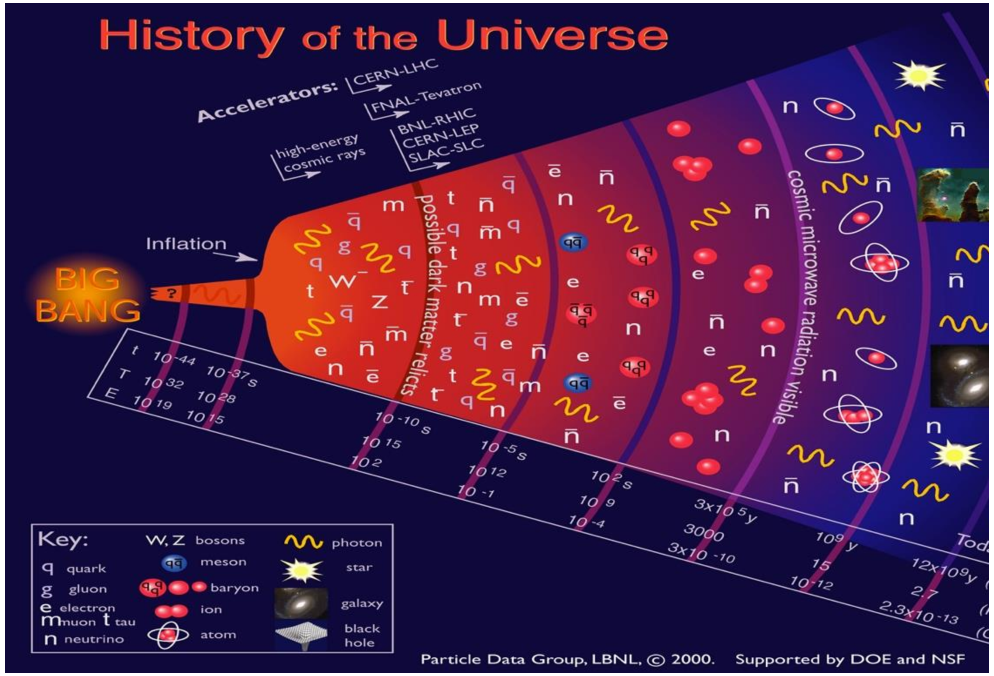
From 1979 HEP drives Accelerators R&D



K. Yokoya, 2014

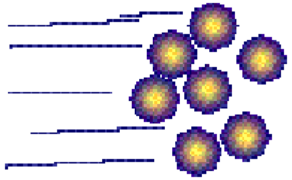
Colliders for center of mass Energy, $E_{c.m.}$

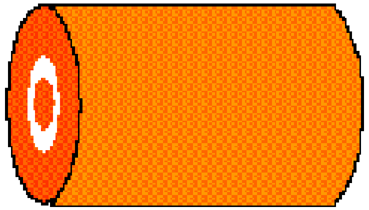
The center-of-mass Energy, $E_{c.m.}$, is the energy created at the center-of-mass of the collision point. This evolution of $E_{c.m.}$ creates particles, fermions and bosons, and through them we are looking deeper and deeper in the microscopic scale of space and time.



For fixed target :

$$E_{c.m} \cong \sqrt{2 m_T E_B}$$

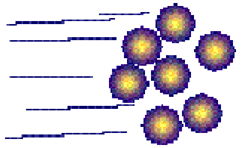


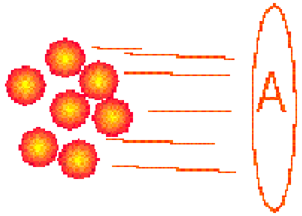


... and we rapidly run out of money trying to gain a factor 10 in c.m. energy

But a storage ring , colliding two beams, gives:

$$E_{c.m.} \cong 2\ E_B$$

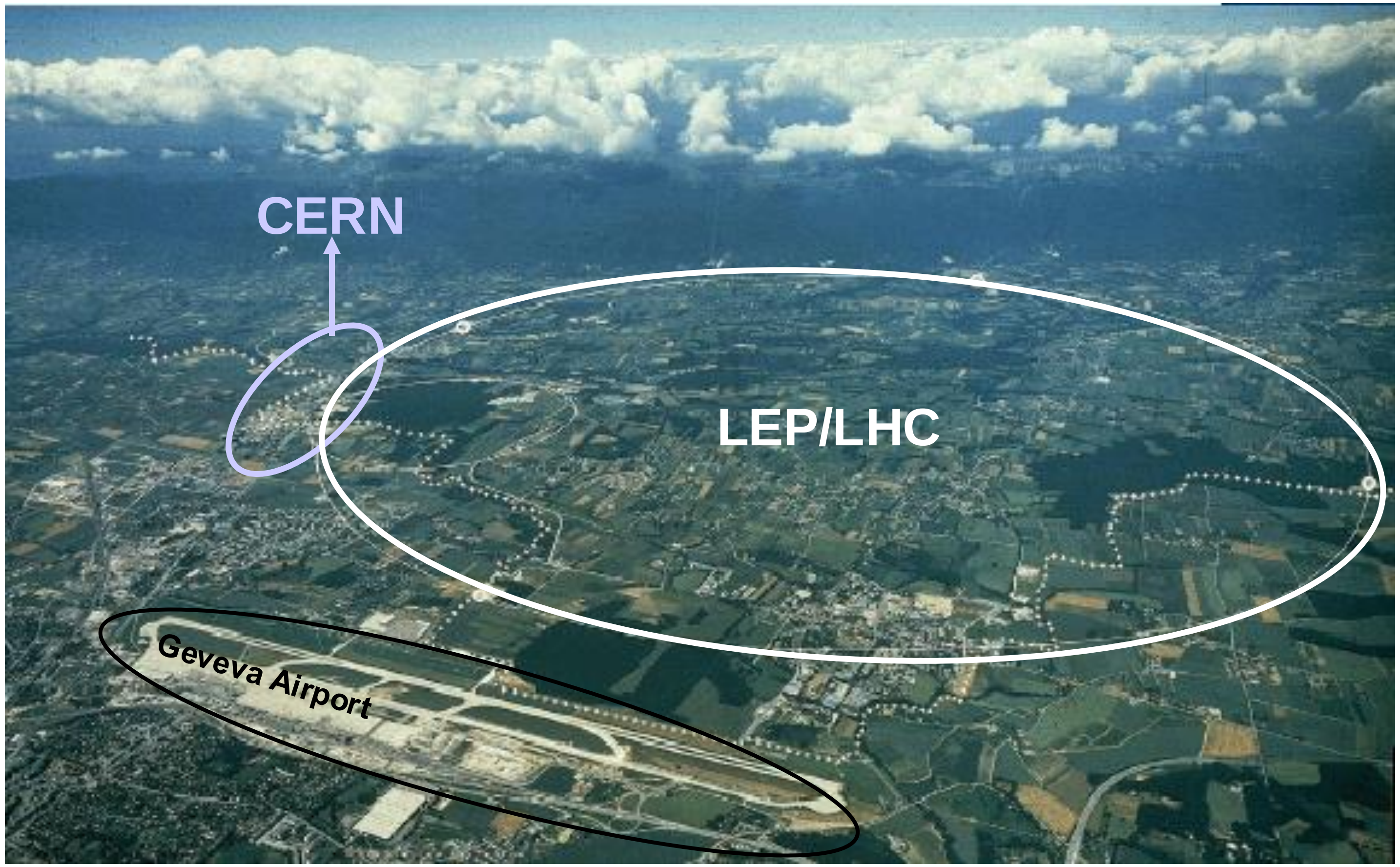




Problem: Smaller probability that accelerated particles collide .... "Luminosity" of a collider

From Ada to LEP & LHC in the CERN area

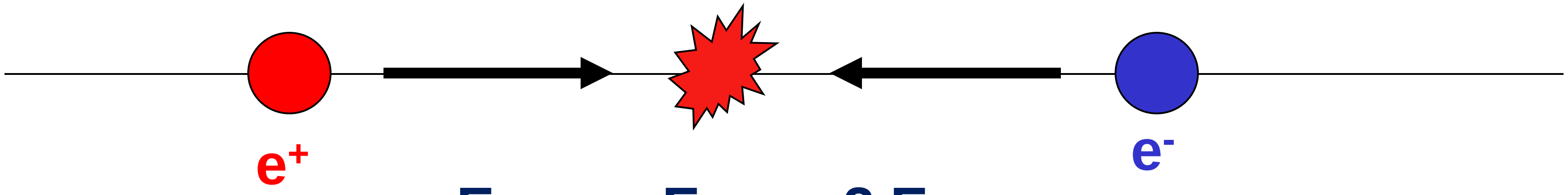
Ada, the first e^+e^- collider
Designed and built at Frascati in 1960



LEP-II	e^+e^- lepton collider	$E_{c.m.} = 200$ GeV
LHC	pp hadron collider	$E_{c.m.} = 14$ TeV

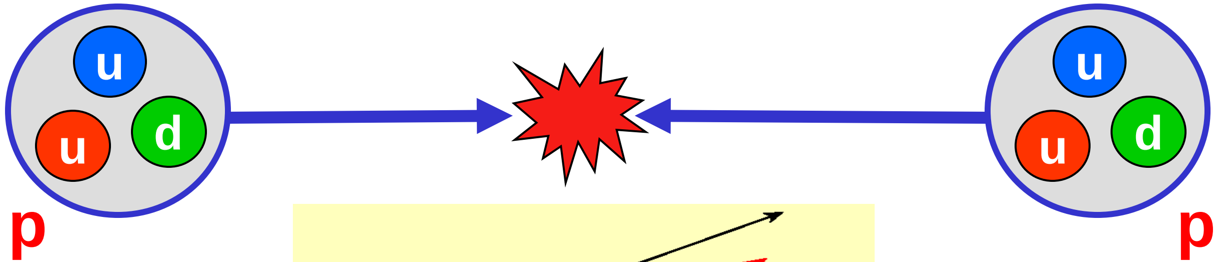
Why also leptons are needed?

Leptons (e^-, e^+, μ^-, μ^+) are Fermions, i.e. matter constituents

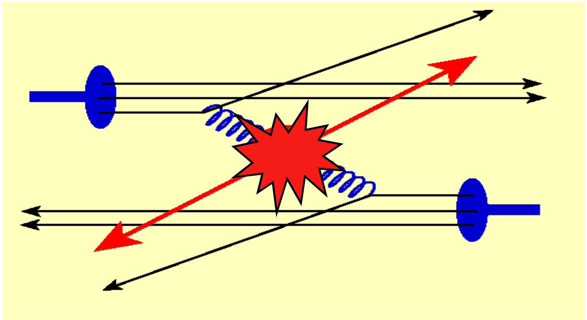


$$E_{react.} = E_{c.m.} = 2\ E_{beam}$$

Hadrons (p, $\bar{p}$, ions) are complex composite particles



$$E_{react.} << 2\ E_{beam}$$

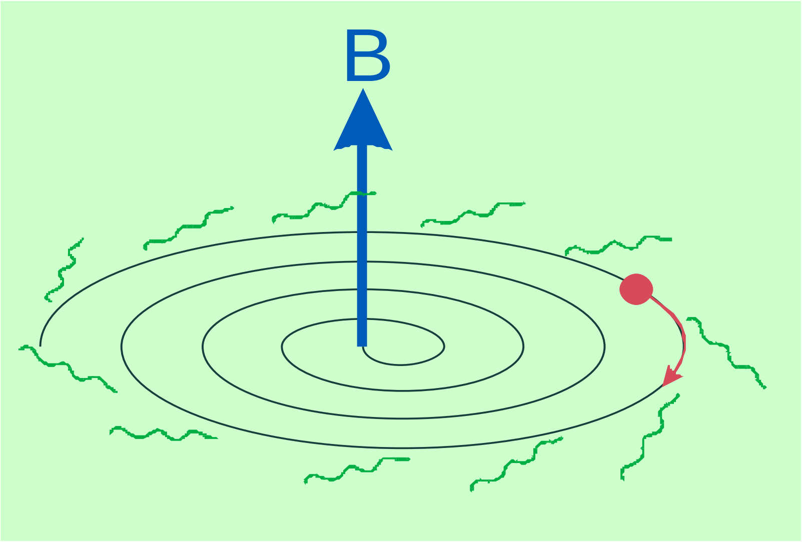


Gluon-Gluon Collision

$E_{react.}$ cannot be controlled and it is unknown

No Circular e^+e^- Collider after LEP

Synchrotron Radiation:
charged particle in a magnetic field:



Energy loss replaced by RF power
cost scaling $ $\propto E_{cm}^2$

Energy loss dramatic for electrons

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

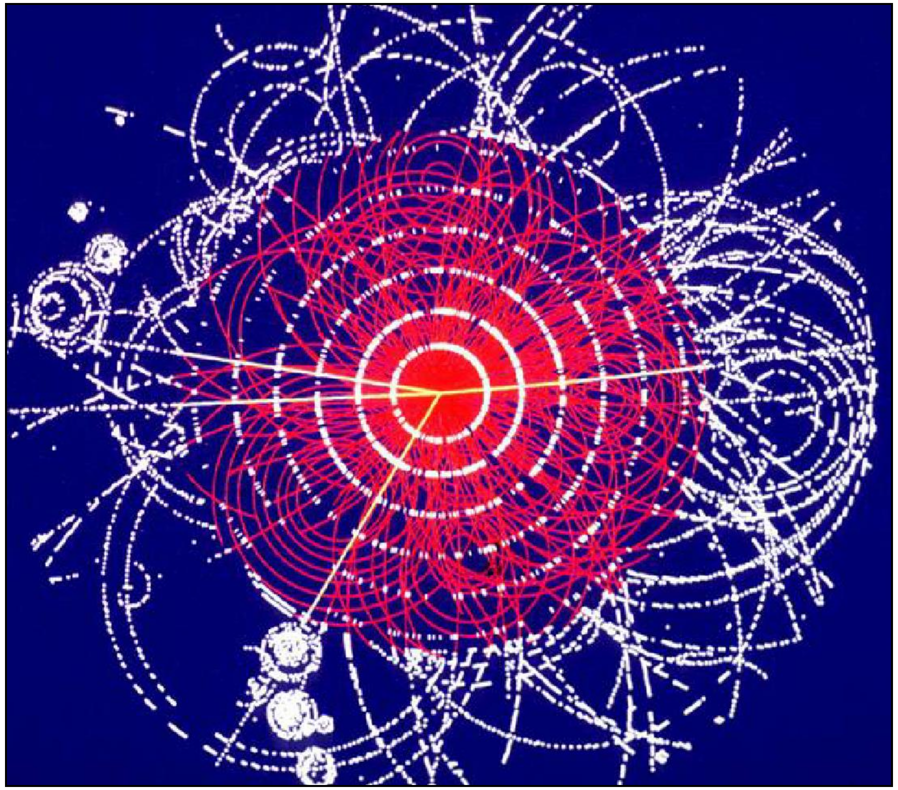
$$\gamma_{proton} / \gamma_{electron} \approx 2000$$

Impractical scaling of LEP II to E_{cm} = 500 GeV and $L = 2 \cdot 10^{34}$

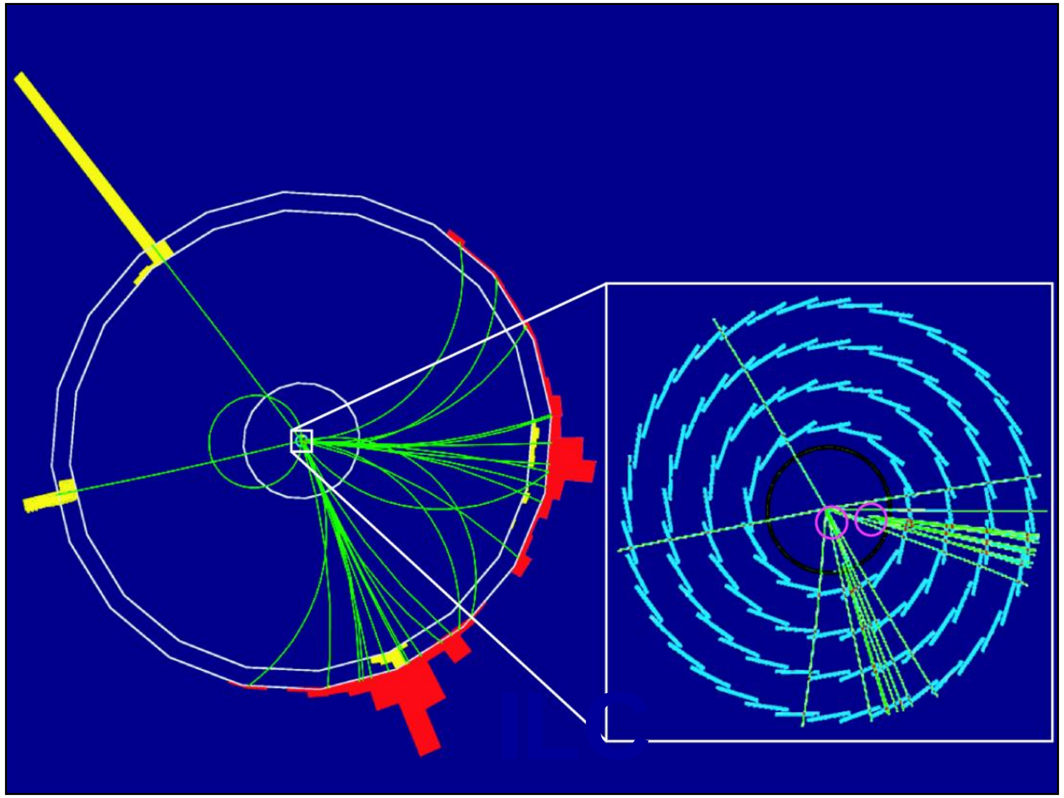
- 170 km around
- 13 GeV/turn lost
- 1 A current/beam
- 26 GW RF power
- Plug power request > Germany

Higgs event Simulation Comparison

LHC: hadron collision



ILC: lepton collision



$e^+ e^- \rightarrow ZH \quad Z \rightarrow e^+ e^-, H \rightarrow b\bar{b}$

Origin of the Linear Collider Idea

M. Tigner,
Nuovo Cimento 37 (1965) 1228

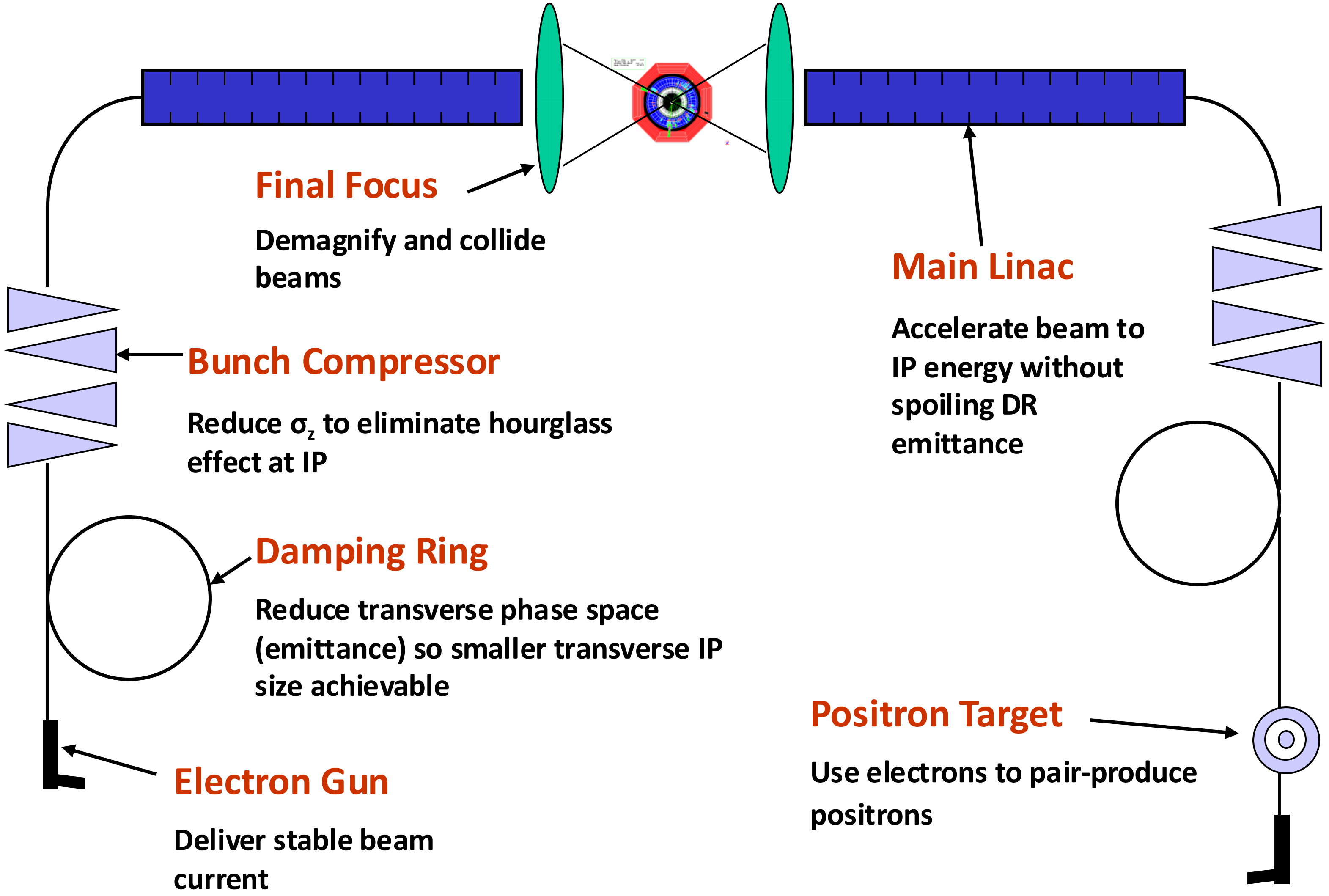
A Possible Apparatus for Electron-Clashing Experiments (*).

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."

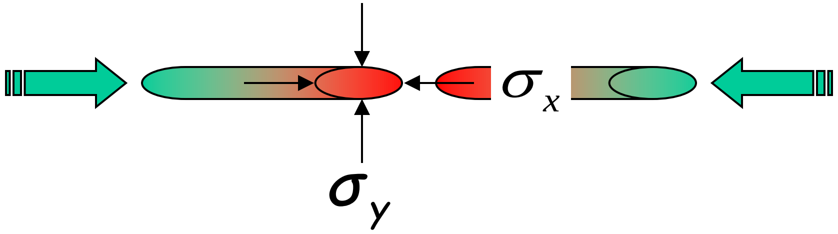
Linear Collider Conceptual Scheme



Fighting for Luminosity

C. Pagani - ISLC08 - Lecture 1
Oak Brook, October 20, 2008

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



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

L = Luminosity
N_e = # of electron per bunch
$\sigma_{x,y}$ = beam sizes at IP
IP = interaction point

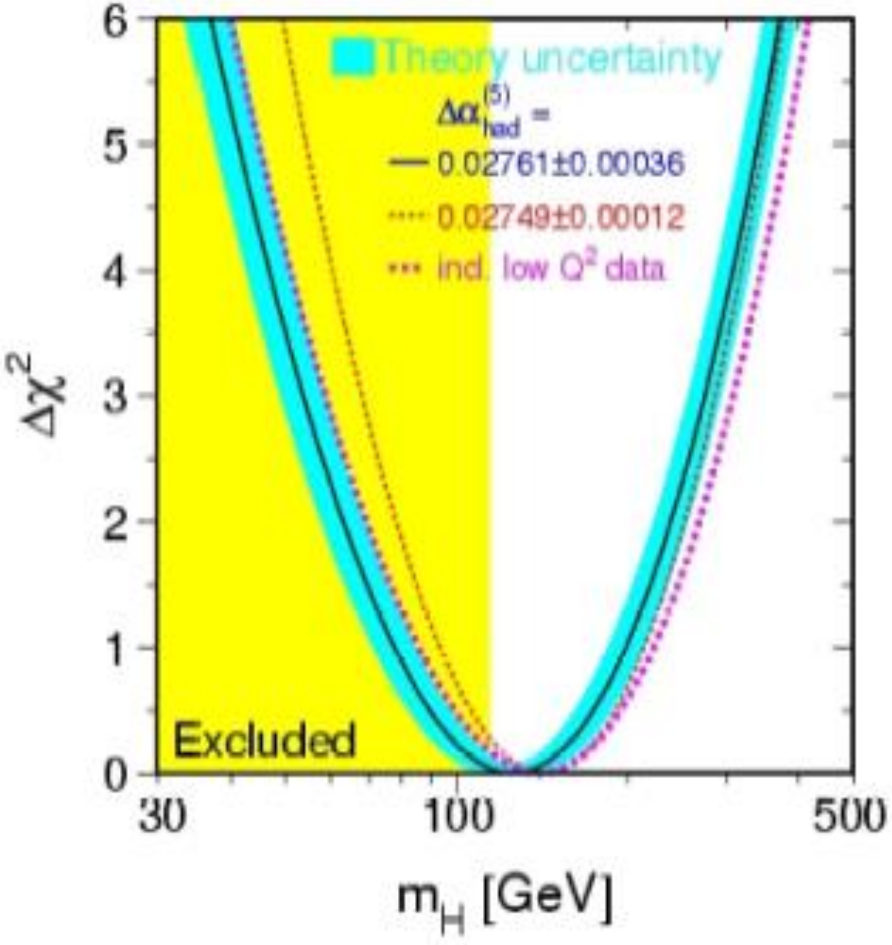
$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

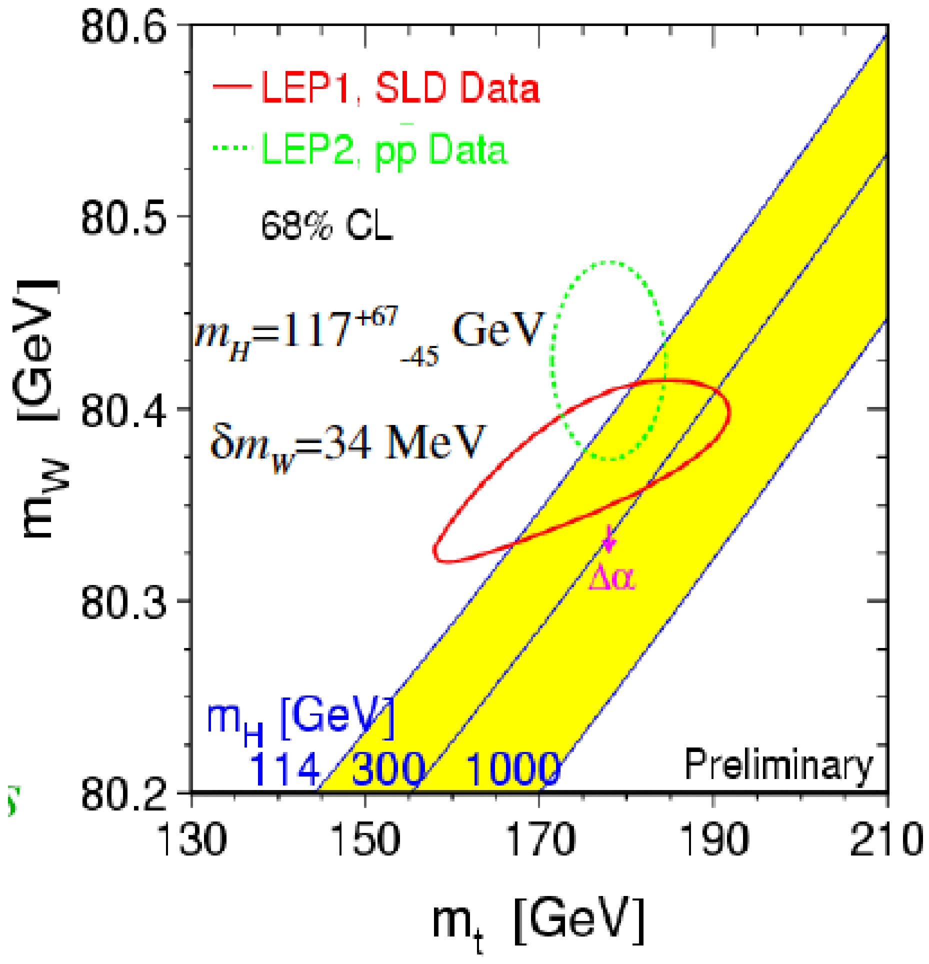
n_b = # of bunches per pulse
f_{rep} = pulse repetition rate
P_b = beam power
$E_{c.m.}$ = center of mass energy

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

Higgs mass from SM: 117-200 GeV





$$m_H = 125\ GeV$$

Measured at the LHC

Complementarity between LHC and ILC

Since the ILC will start after the start of LHC, it **must add significant amount of information**. **This is the case!**

Neither LC nor HC's can draw the whole picture alone. ILC will add new discoveries and precision of ILC will be essential for a better understanding of the underlying physics.

There are probably pieces which can only be explored by the LHC due to the higher mass reach. **Joint interpretation of the results** will improve the overall picture

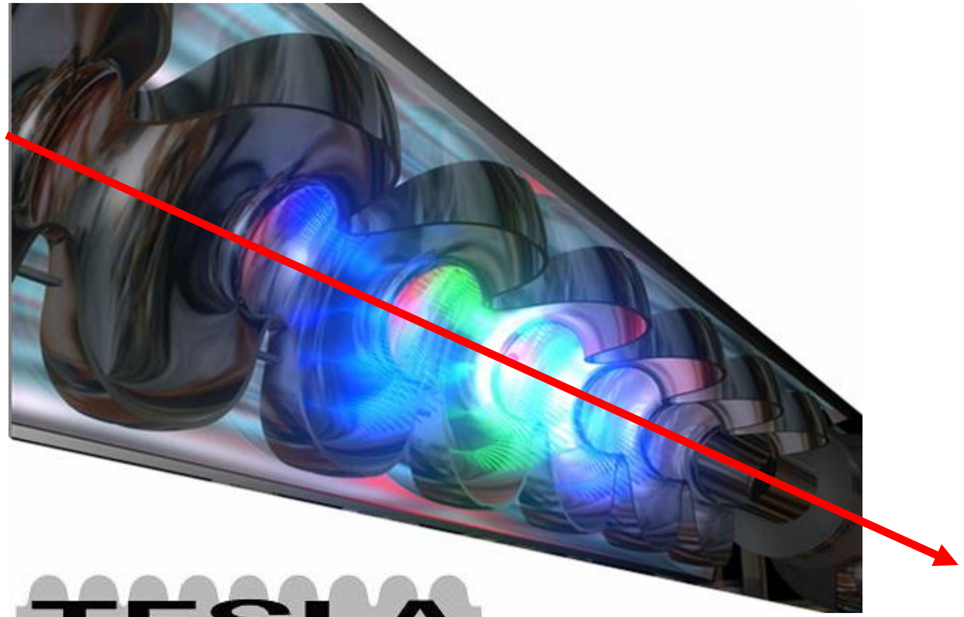
In the Higgs Boson Scenario

LHC will make the **discovery**

ILC will behave as a **Higgs Boson factory** to precisely determine its properties and the consequences for physics beyond the standard model

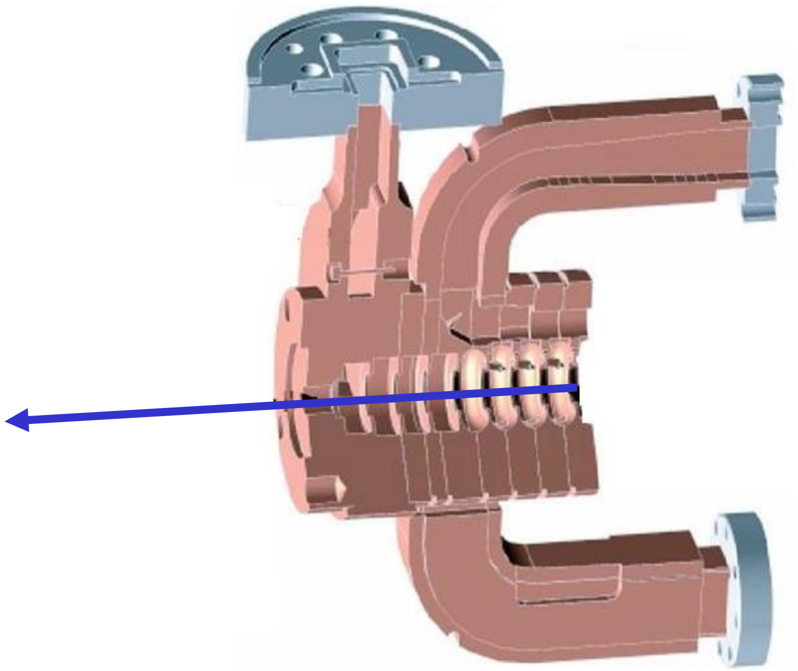
Competing technologies for the ILC Linac

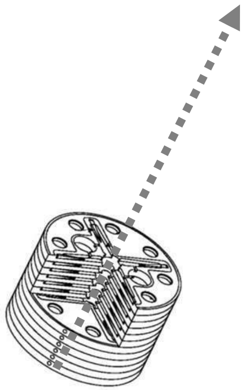
C. Pagani - ISLC08 - Lecture 1
Oak Brook, October 20, 2008



TESLA

1.3 GHz - Cold





CLIC

30 GHz-Warm

NLC

JLC

11.4 GHz - Warm

The TESLA Mission since 1990

Develop SRF Technology for the future Linear Collider

Basic goals on SRF Technology

- **Increase gradient by a factor of 5: from 5 to 25 MV/m**
  - Push cavity performances close to the physical limit, understanding practical limits
  - Set all the required quality control for reproducibility and industrial production
- **Make possible pulsed operation: Lorentz force detuning**
  - Combine SRF and mechanical engineering in cavity design
  - Develop efficient Modulators and Klystrons
  - Develop new ancillaries: slow and fast tuners, couplers
- **Reduce cost per MV by a factor 20: to make the LC feasible**
  - New cryomodule concept for cryolosses, cost and filling factor (for real estate gradient)
  - All subsystems designed for large scale production
  - Reliability and quality control as a general guideline

Basic goals on Machine Design

- Design a Linear Collider based on the Cold Linac peculiarities
- Maximize Luminosity and optimize cost for a given plug power
- Design and quote major subsystems: DR, Positron Source, BDS, etc.
- Put all together in a consistent TDR, including cost estimation

Contents

The origin of TTF: TESLA Test Facility

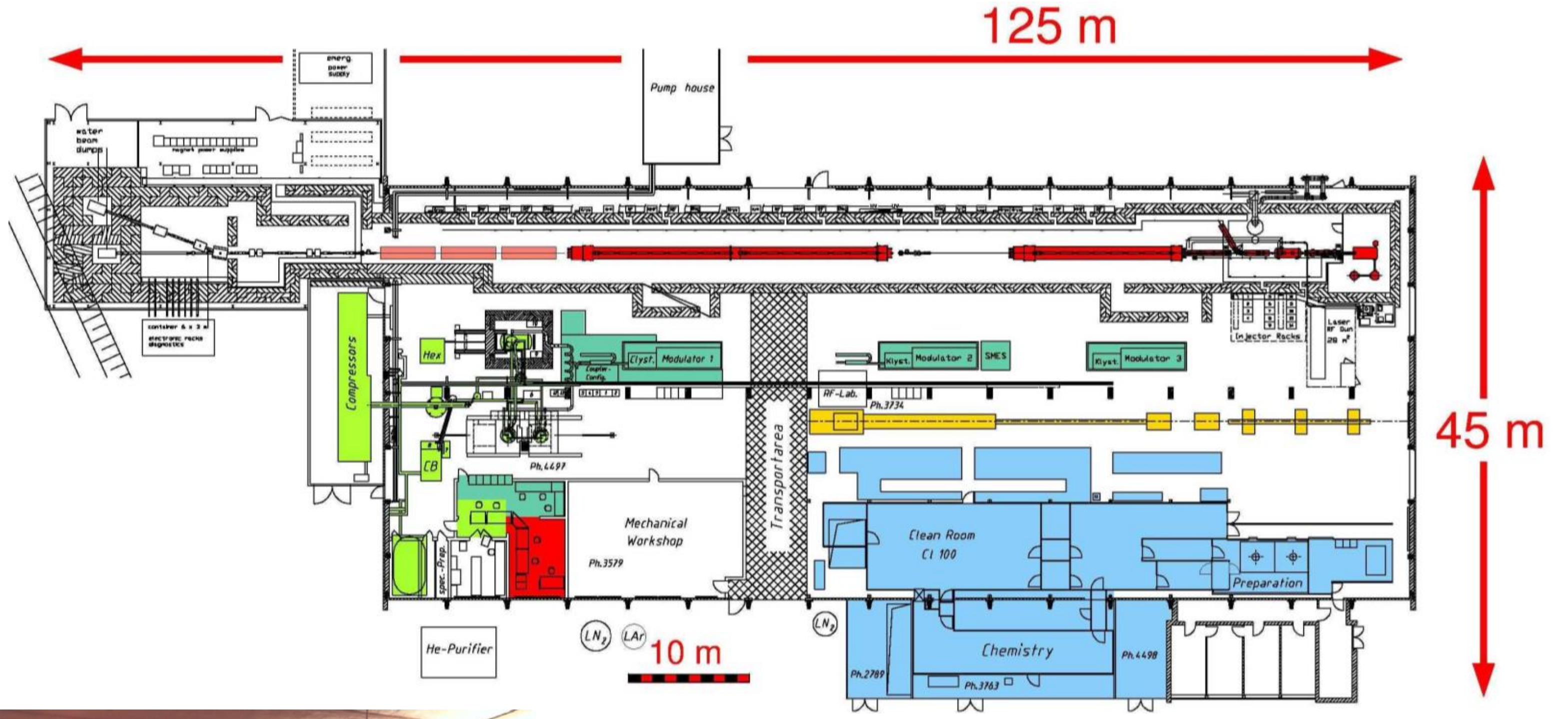
A Proposal to Construct and Test
Prototype Superconducting R.F. Structures
for Linear Colliders

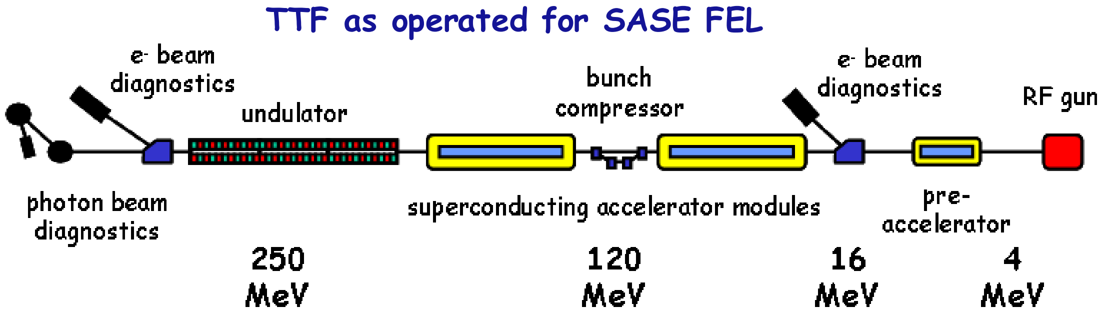
(April 1992)

DESY

March 1993, TESLA 93-01

TTF: a new infrastructure at DESY





The TTF Design Report

TESLA Test Facility Linac
Design Report

Editor: D. A. Edwards

Version 1.0
1 March 1995

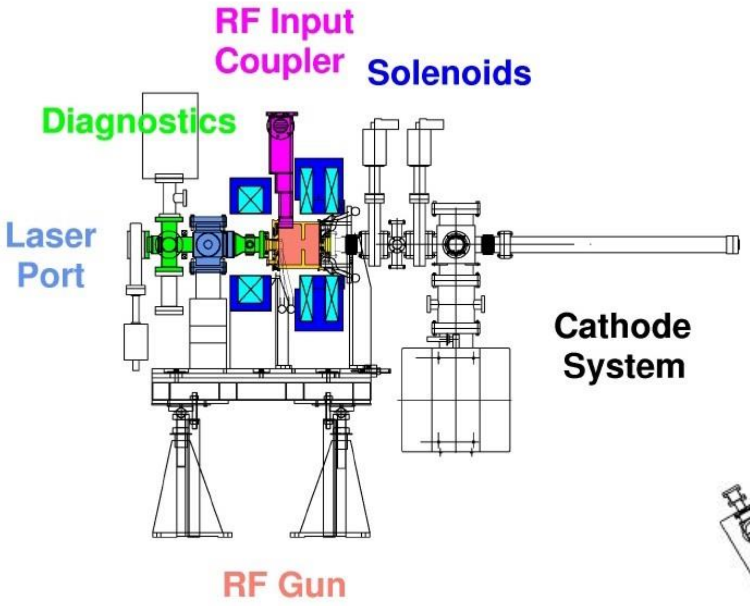
TTF: the RF Gun based Injector

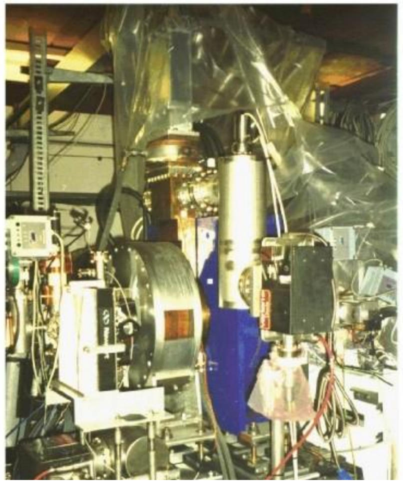
CEA/DSM DAPNIA, Saclay
IN2P3/LAL, Orsay
IN2P3/IPN, Orsay

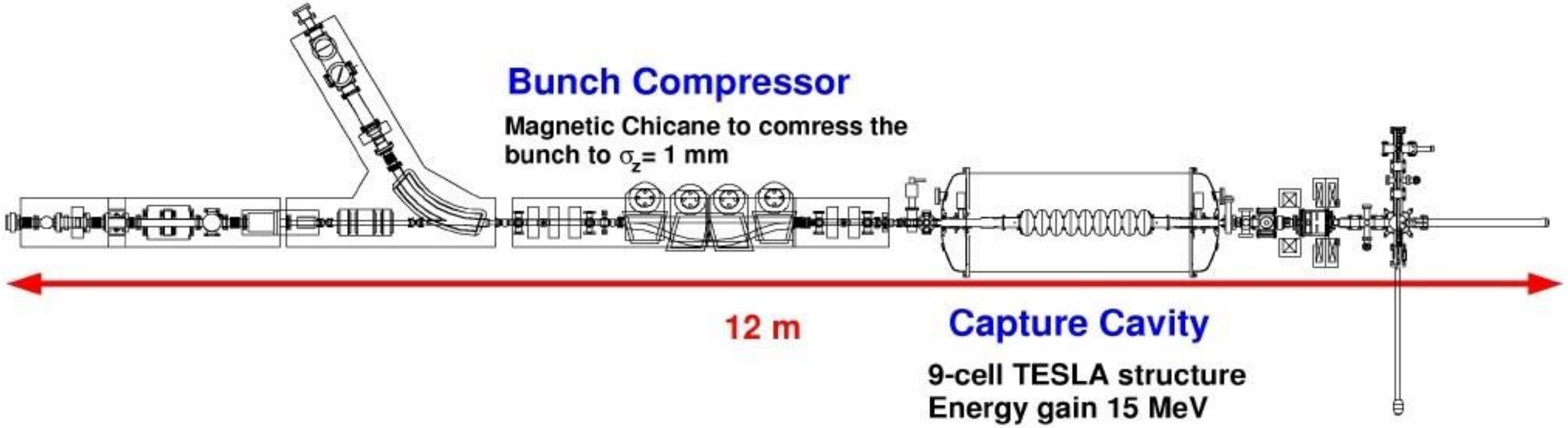
Max-Born Inst., Berlin
DESY Hamburg

INFN LASA, Milano
INFN Frascati
INFN and Univ. Roma 2

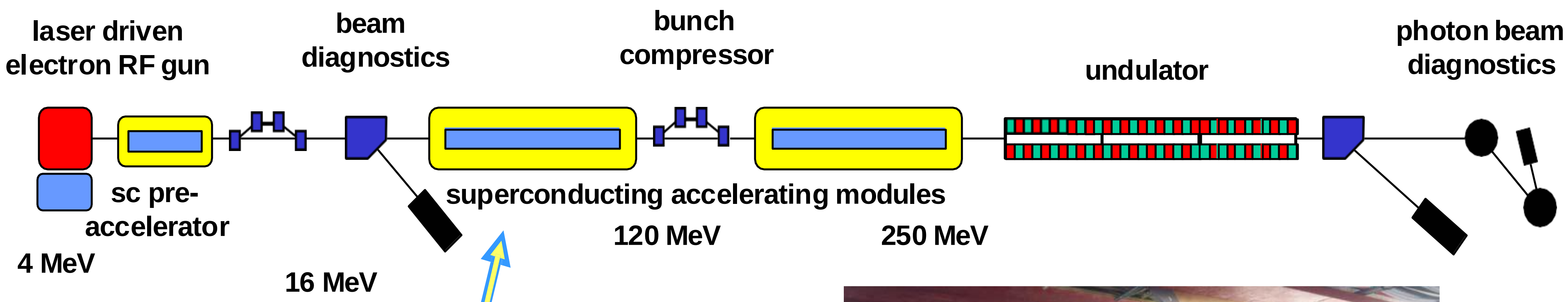
Fermilab, Batavia
Rochester Univ.
UCLA, Los Angeles
ANL, Argonne

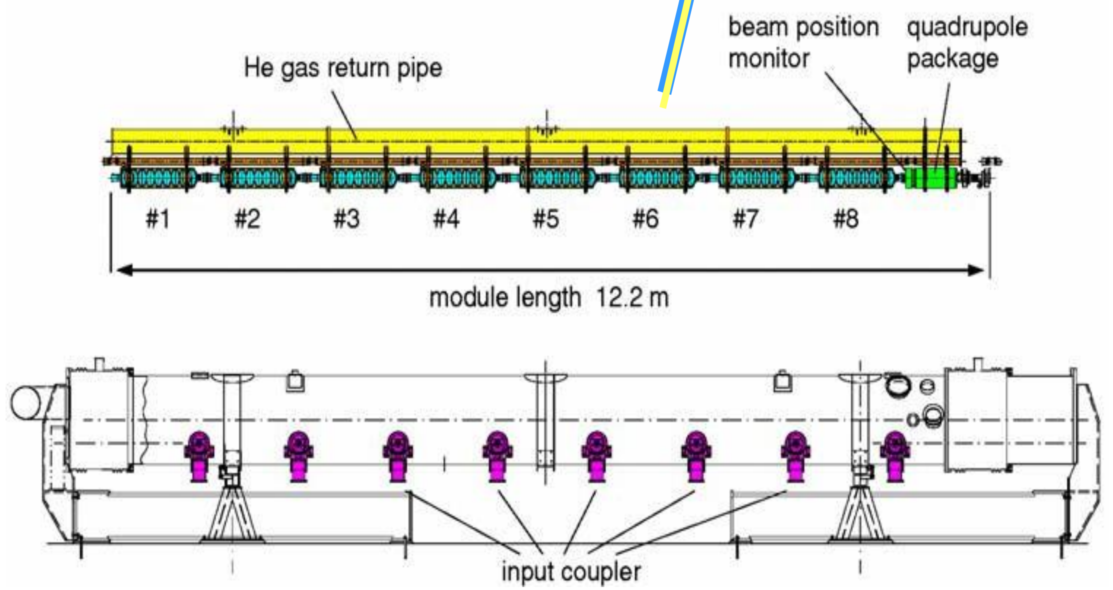


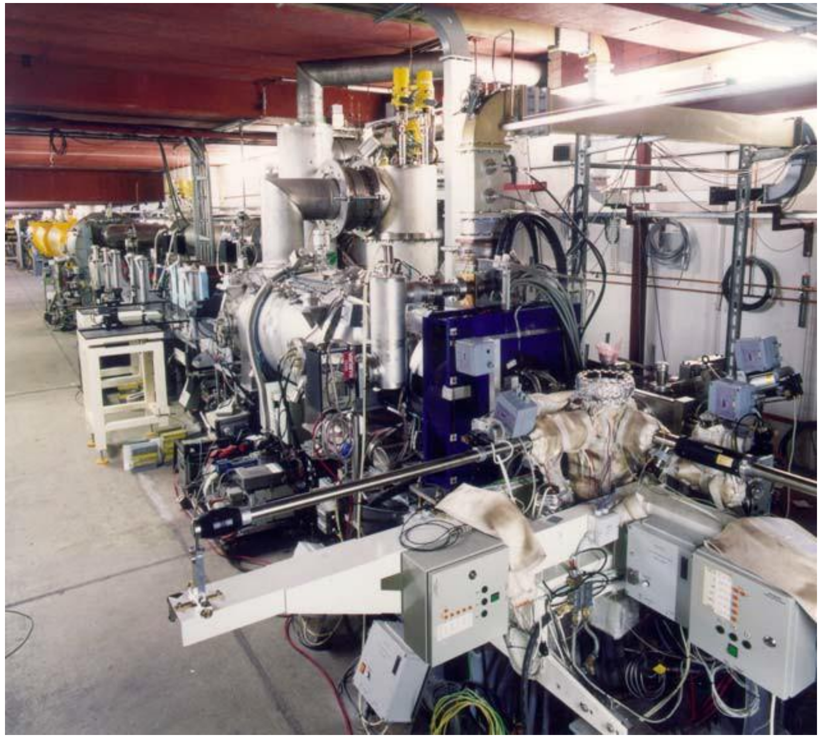




TESLA Test Facility Linac (TTF 1)







FEL is the 1° potential application

Chapter 11

Potential Applications

11.1 A Self-Amplified-Spontaneous-Emission Free-Electron Laser at 200 eV

The workshop on Fourth Generation Light Sources held at SLAC in 1992 focussed on X-ray lasers[1], and with the recent development of low emittance electron guns the construction of X-ray lasers at 1 Å wavelength at high energy linacs comes in reach. The scientific applications of such coherent X-rays have been discussed at SLAC in February 1994.[2]

11.1.1 The TESLA Option

At DESY the construction of a Self-Amplified-Spontaneous-Emission(SASE) FEL at the TESLA Test Facility (TTF) is under discussion. Due to its exceptional capability to maintain high electron beam quality during acceleration, a superconducting linac is the optimum choice to drive a SASE FEL at high energies. The goal is to produce coherent radiation tunable in the photon energy range up to 200 eV (6 nm).

Schematic Layout of SASE FEL @ TTF

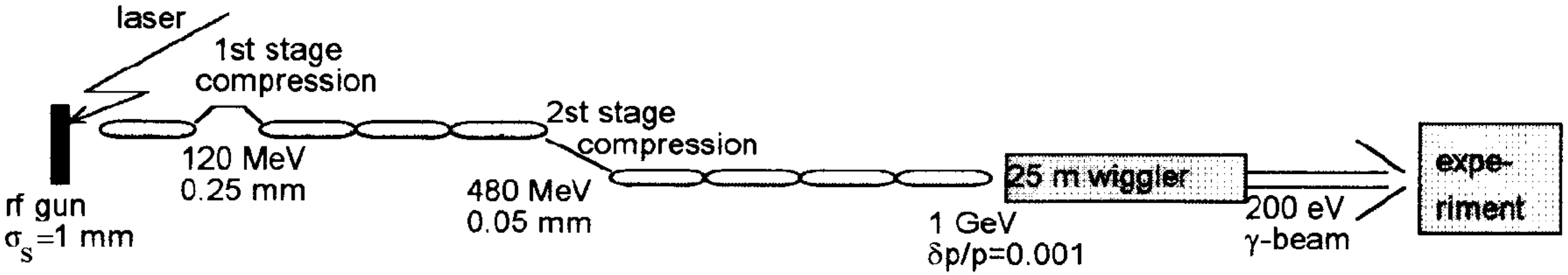


Figure 11.1: Schematic layout of a 1 GeV SASE FEL facility based on the TESLA Test Facility. The bunch length is reduced from 1mm to 50μm within two steps of bunch compression, the first of which is after the first superconducting RF module. Whether the first stage of bunch compression can, alternatively, be placed just after the RF gun, is not yet clear. The over-all length is some 160 meters.

Why TESLA and XFEL developed together?

With the enormous support from the HEP community **TESLA was develloping** an accelerator to efficiently produce **an high energy electron beam of unprecedented quallity**, **high brightness and low emittance**, i.e. the **ideal beam for a Free-Electron Laser**

This effort sustained by an international scientific community and with the interested collaboration of industry because of the perspective of the realization of a huge scientific infrastructure led to the **parallel developments of all the accelerator subcomponents**: RF, cryogenics, electronics, etc.

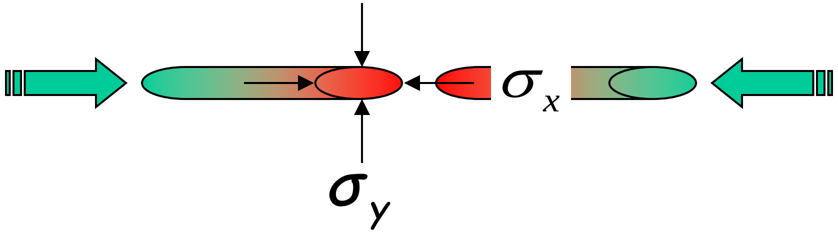
The **required development of a TESLA Test Facility** to combine the different components and experimentally qualify all the hardware and beam theory, created the condition of having an **unique infrastructure for FEL experiments** and applied physics.

Finally, the existance at DESY of a **consistent community of photon scientist at Hasylab**, suggessted the dual use of TTF, so extending the scientific interest for the TESLA mission

Emittance ad Brightness drive Luminosity

C. Pagani - ISLC08 - Lecture 1
Oak Brook, October 20, 2008

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



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

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

The Luminosity Issue: Aiming for $2x10^{34}$

Collider luminosity [$cm^{-2}\,s^{-1}$] is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{A} H_D$$

where:

n_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
A = beam cross-section at IP
H_D = beam-beam enhancement factor

For a Gaussian beam distribution luminosity is usually written

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D$$

The Luminosity Issue: RF Power - 1

Introducing the

centre of mass energy, E_{cm}

$$L = \frac{\left(E_{cm} n_b N f_{rep}\right) N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

$$n_b N f_{rep} E_{cm} = P_{beam}$$

$$= \eta_{RF \to beam} P_{RF}$$

η_{RF} Is the RF to beam Power Efficiency

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

i.e. for a given E_{cm}

Luminosity* is proportional to the *RF Power

The Luminosity Issue: RF Power - 2

Using some rough ILC numbers

$$L = \frac{\left(E_{cm} n_b N f_{rep}\right) N}{4\pi\sigma_x\sigma_y E_{cm}} H_D$$

E_{cm} = 500 GeV
N = 2 x 10^{10}
n_b = 3000
f_{rep} = 5 Hz

P_{beam} **~ 2 x 10 MW**

Taking into account conversion efficiencies

$\eta_{RF\rightarrow beam}$ **~ 60% (SCRF)**

$\eta_{PlugPower\rightarrow RF}$ **~ 50%**

It turns out that ~**70 MW** of average **AC Power** are required to accelerate the 2 beams to 250 GeV, achieving *Luminosity*

The Luminosity Issue: LEP vs ILC

LEP f_{rep} = 44 kHz

ILC f_{rep} = 5 Hz
(power limited)

$$L = \frac{(E_{cm} n_b N f_{rep}) N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

$\Rightarrow$ factor 8800 in L already lost!

Must push very hard on beam cross-section at collision:

LEP: $\sigma_x \sigma_y \approx 130 \times 6\ \mu m^2$

ILC: $\sigma_x \sigma_y \approx 500 \times (3\text{-}5)\ nm^2$

factor of 10^6 gain!

Needed to obtain high luminosity of a few $10^{34}\ cm^{-2}s^{-1}$

Luminosity: Beam Size & Beam Power

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D$$

$f_{rep} \cdot n_b$ tends to be low in a linear collider

	L [cm^{-2} s^{-1}]	f_{rep} [s^{-1}]	n_b	N [10^{10}]	σ_x [μm]	σ_y [μm]
ILC	**$2 \cdot 10^{34}$**	**5**	**3000**	**2**	**0.5**	**0.005**
SLC	$2 \cdot 10^{30}$	120	1	4	1.5	0.5
LEP II	$5 \cdot 10^{31}$	10,000	8	30	240	4
PEP II	$1 \cdot 10^{34}$	140,000	1700	6	155	4

The beam-beam tune shift limit is much looser in a linear collider than a storage rings → achieve luminosity with spot size and bunch charge

- **Small spots mean small emittances, $\varepsilon_{x,y}$ and small β-functions, $\beta_{x,y}$**

$$\sigma_{x,y} = \sqrt{\beta_{x,y} \cdot \varepsilon_{x,y}}$$

Emittance and Phase Space

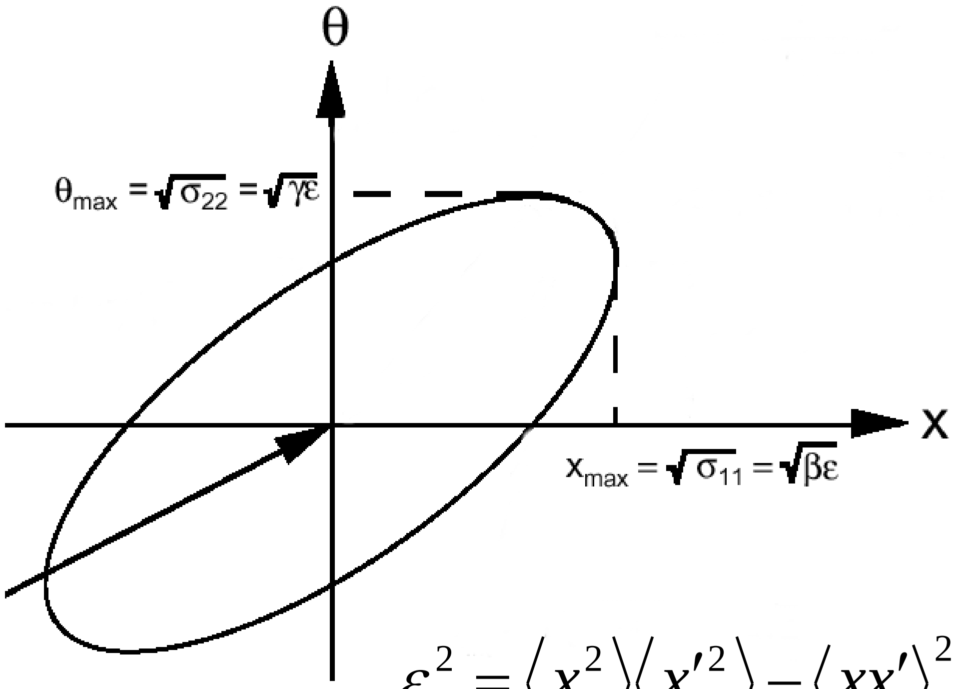
Beta function β characterize optics

Emittance ε is phase space volume of the beam – optics analogy is the wavelength

Tilt is parameterized with α

Beam size: $(\varepsilon\ \beta)^{1/2}$

Divergence: $(\varepsilon\ /\beta)^{1/2}$



$$\varepsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

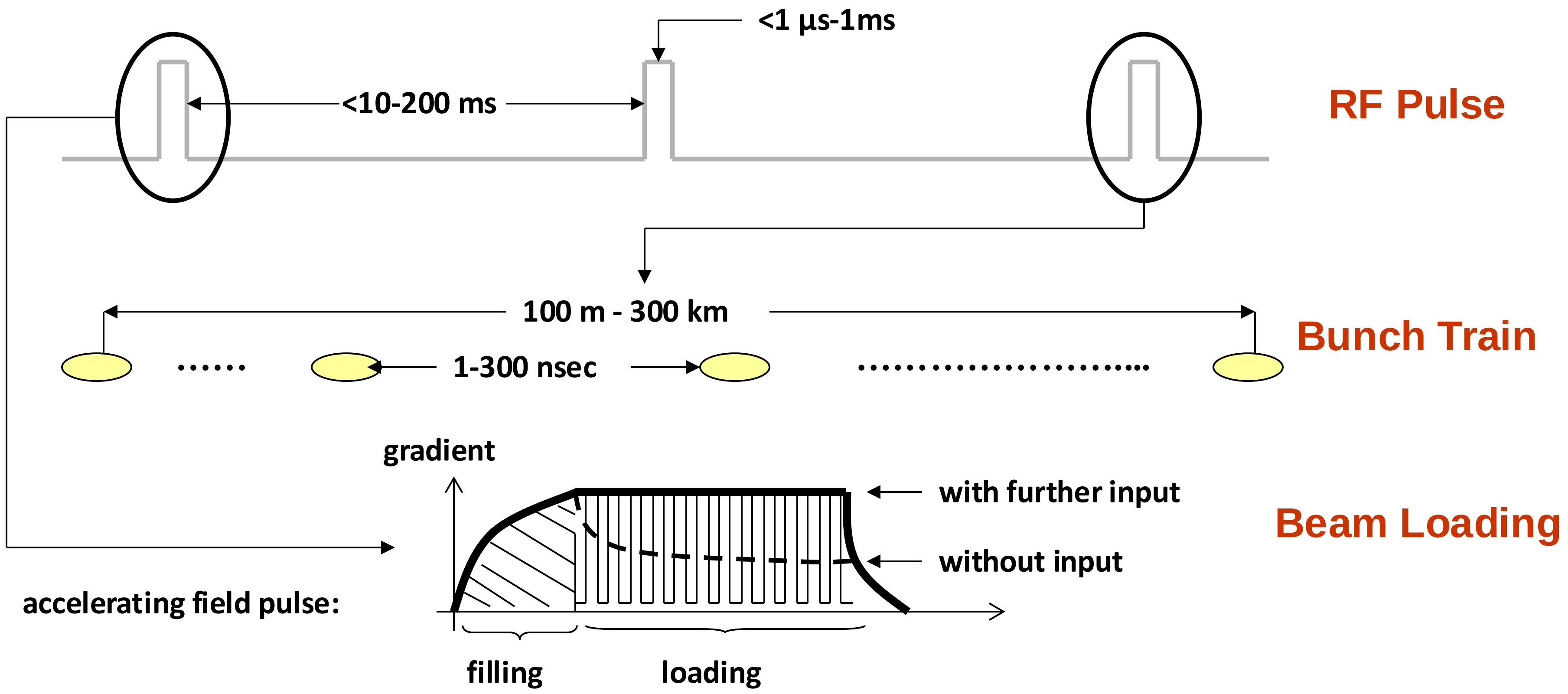
Squeeze on beam size → increase angular divergence

Beam emittance is not conserved during acceleration → normalized emittance should be γε

Drawback: all Linear Colliders are pulsed

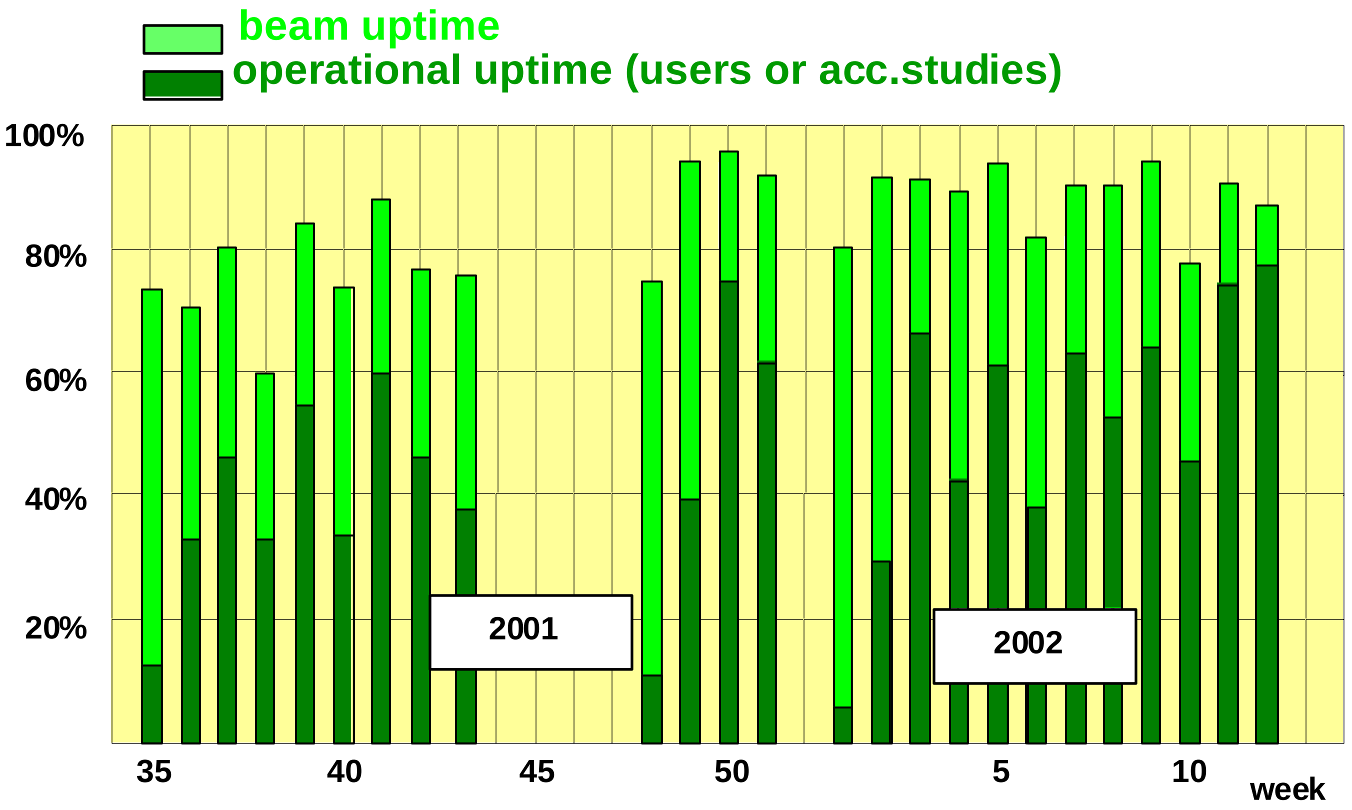
All the LCs must be pulsed machines to improve efficiency. As a result:

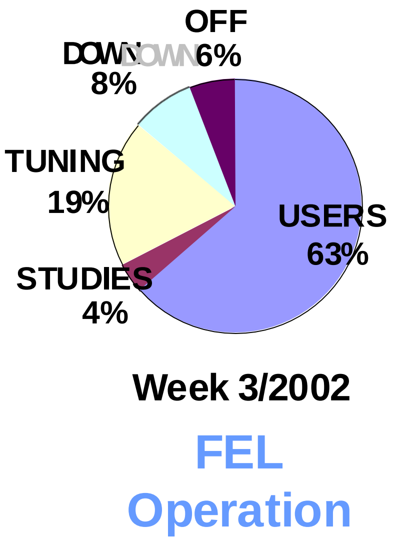
- duty factors are small
- pulse peak powers can be very large

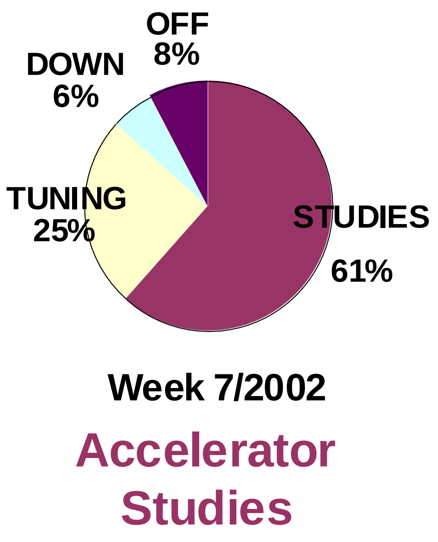


TTF 1 Operational Statistics

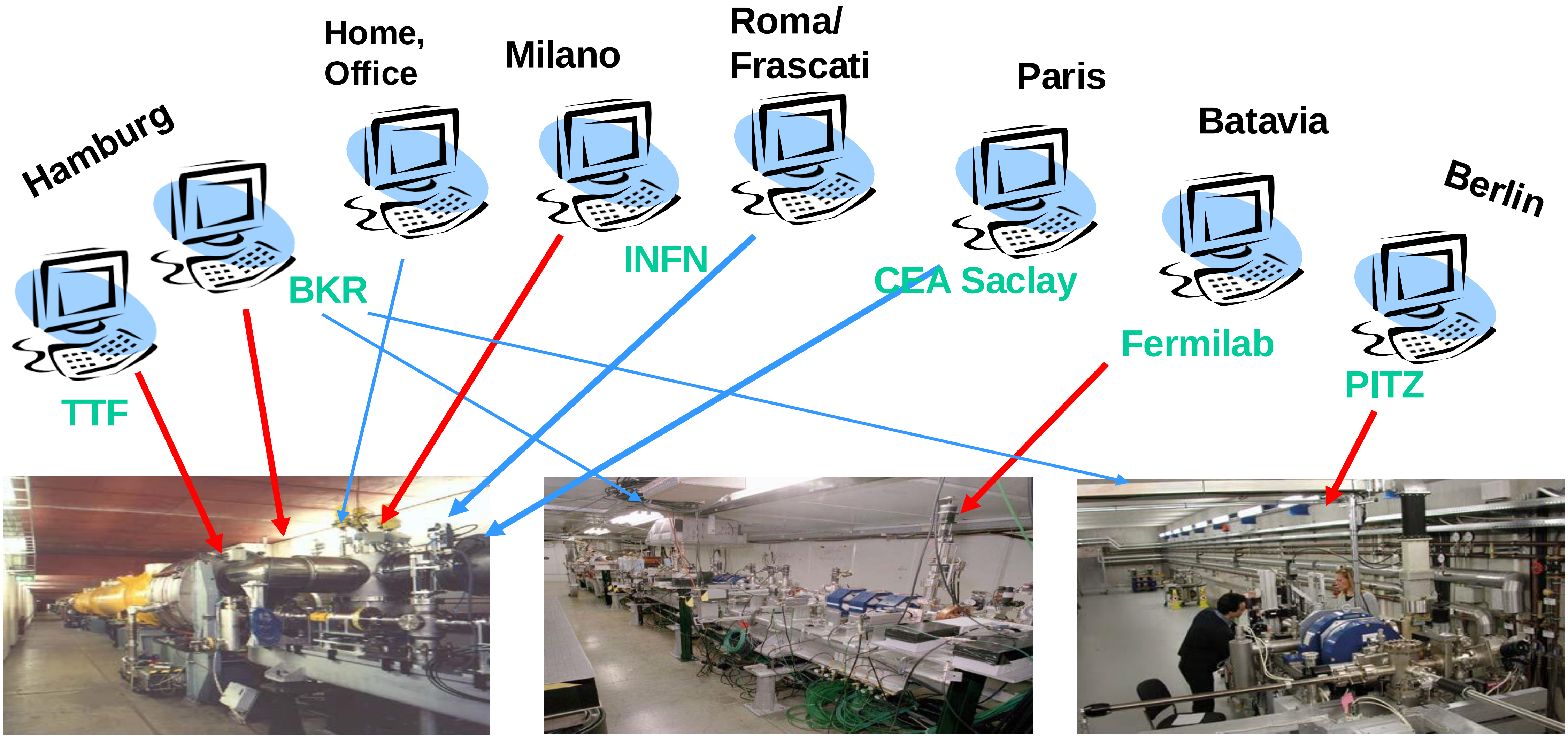
- Operated 7 days per week, 24 hours per day, since 1997
- 15,000 hours of beam delivered since November 2002
- About 50 % of the time was allocated to FEL operation including a large percentage of user time.







GAN: TTF Practiced Remote Operation

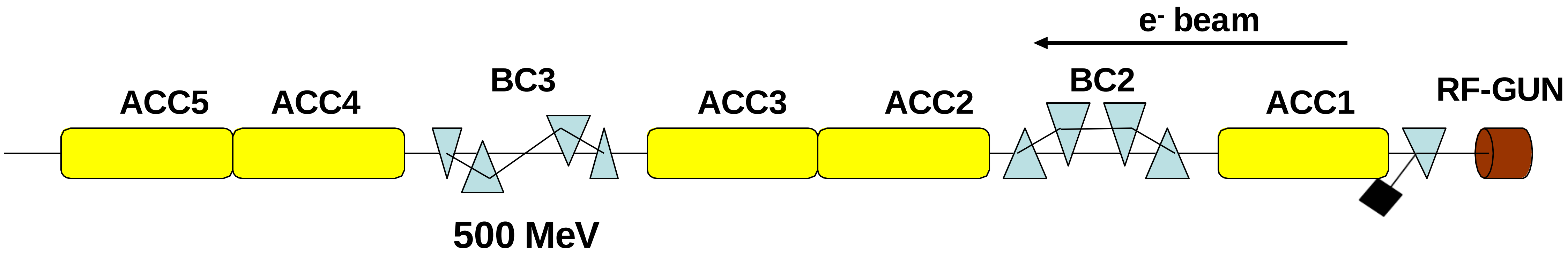


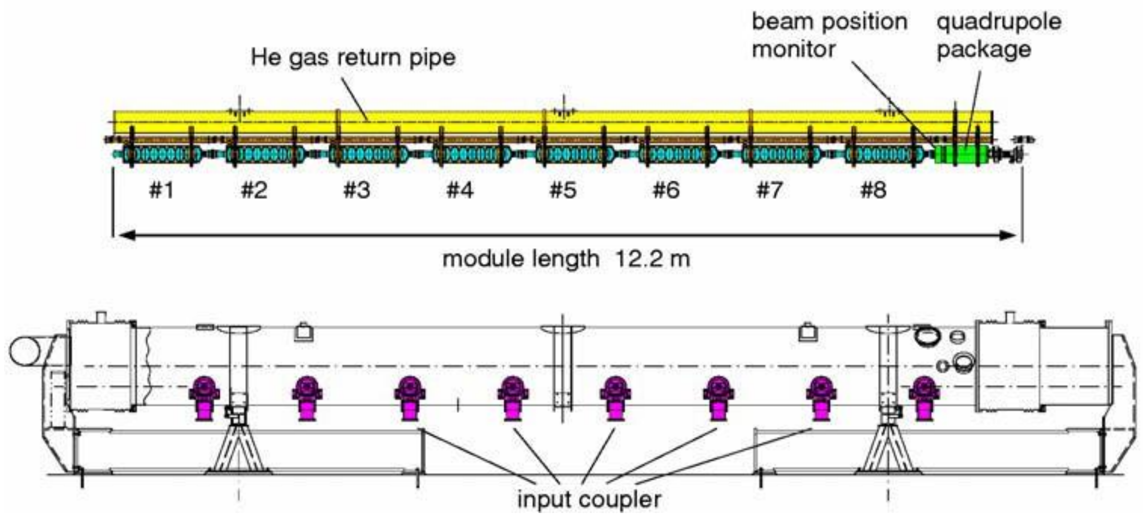
TTF @ DESY | Photoinjector @ Fermilab | PITZ @ Zeuthen

From TTF1 to TTF2/FLESH

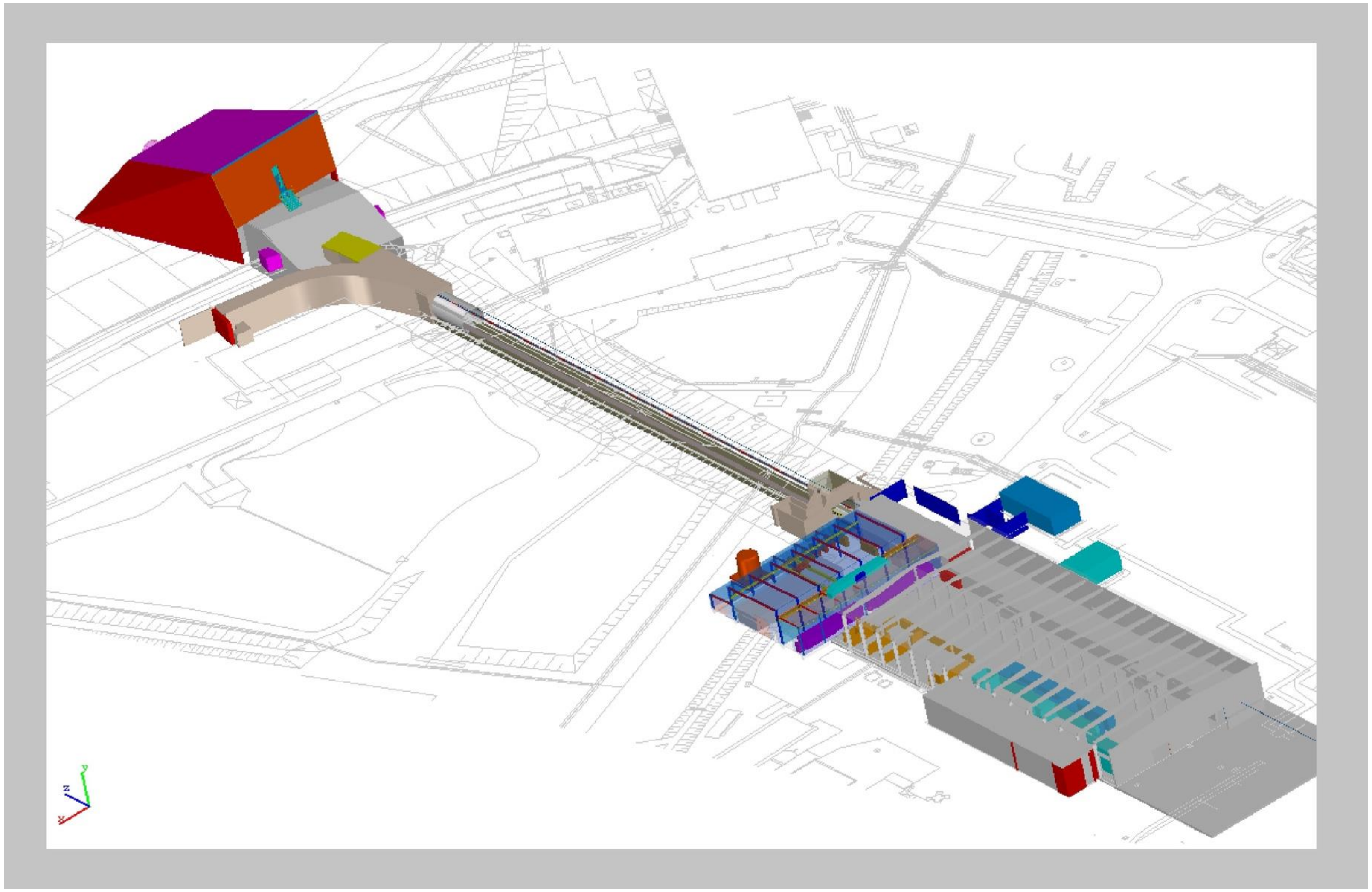
Contents

TTF2 as XFEL Injector Prototype





TTF2: SASE FEL @ TTF



TESLA/XFEL Milestones

July 1990 – 1° International TESLA Workshop @ Cornell University

February 1992 – 1° TESLA Collaboration Board Meeting @ DESY

March 1993 - **“A Proposal to Construct and Test Prototype Superconducting RF Structures for Linear Colliders”**

March 1995 -TESLA Test Facility Linac Design Report

SASE FEL included in TESLA → TTF 2

May 1996 – **first beam at TTF1**

March 2001 – **TESLA Technical Design Report with XFEL**
First SASE-FEL Saturation at TTF

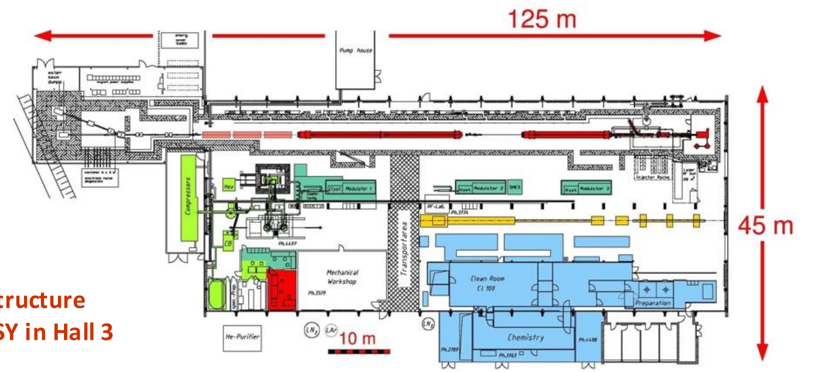
July 2002 – from the German Science Council: **Two independent projects: TESLA X-FEL** and **TESLA LC**

February 2003 –**TESLA X-FEL proposed** as an European Facility, **50% funding from Germany**

June 2004 – TTF II: First beam accelerated

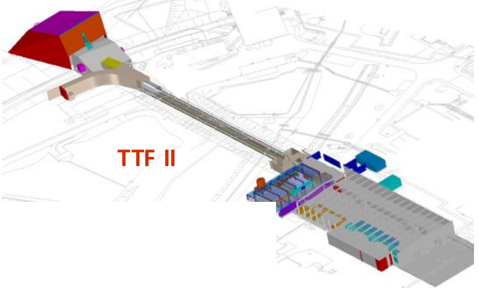
August 2004 – **TESLA Technology chosen for ILC**

June 2007 – **European XFEL Project Starts**



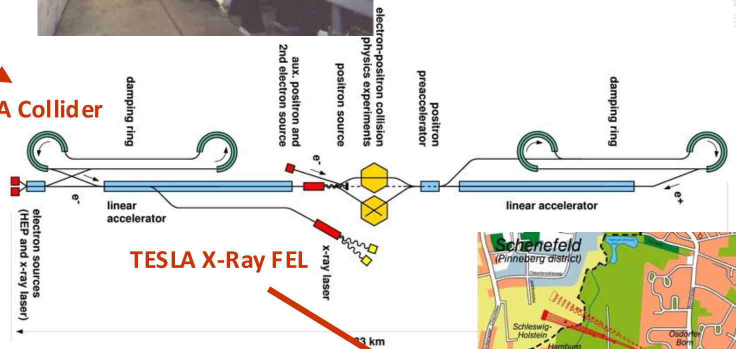
Infrastructure
@ DESY in Hall 3

TTF I

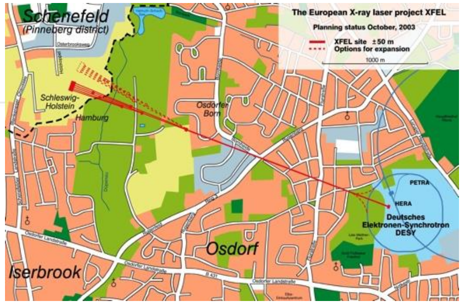


TTF II

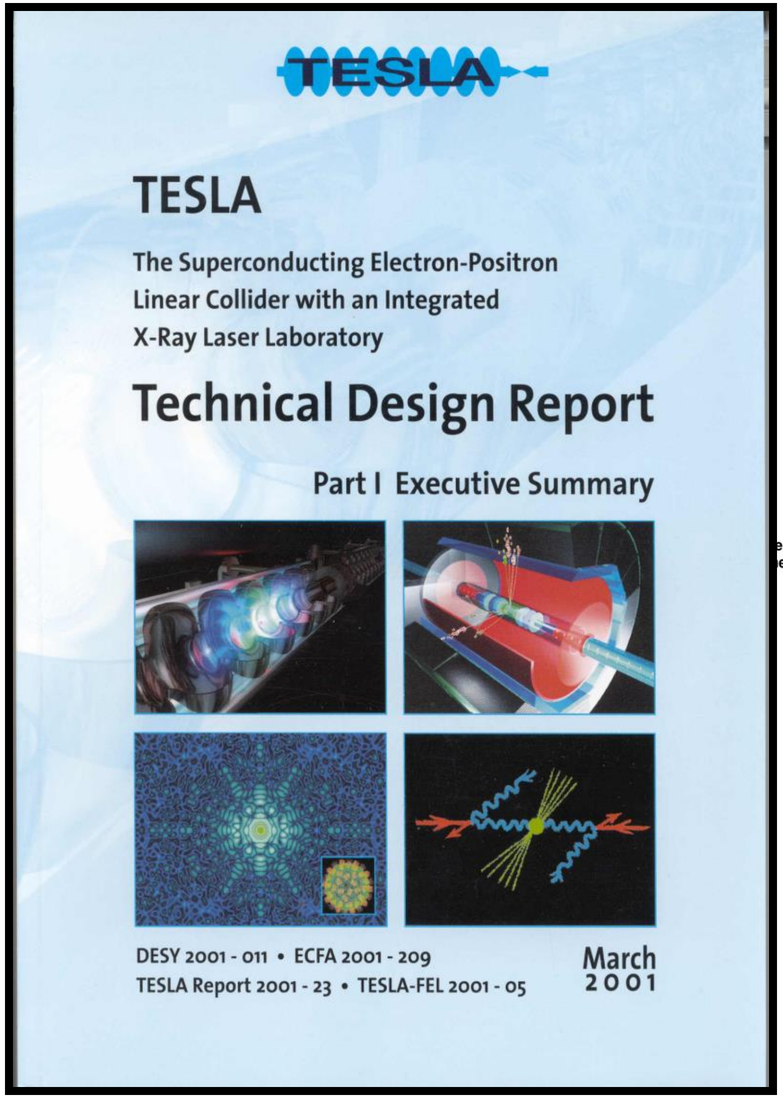
TESLA Collider

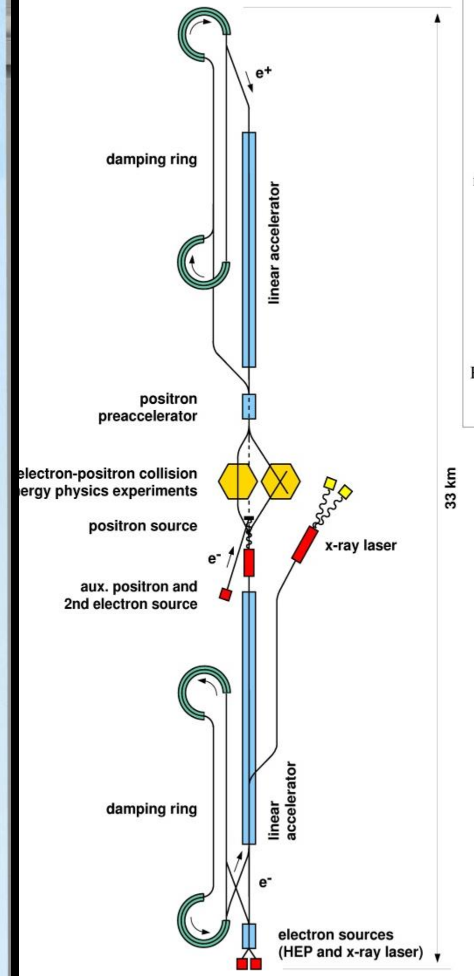


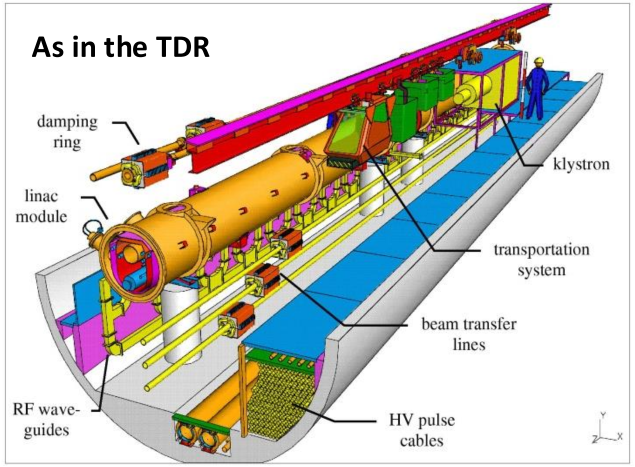
TESLA X-Ray FEL

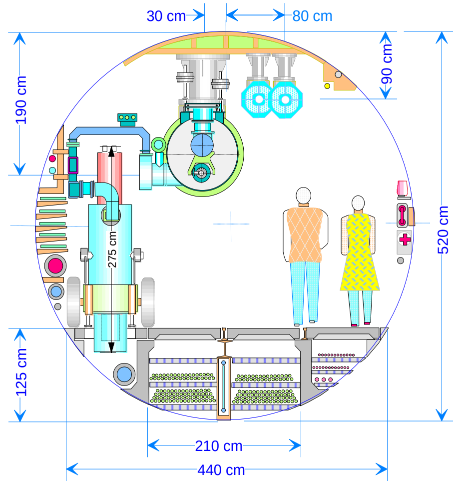


TESLA Technical Design Report 2001









Updated tunnel cross section

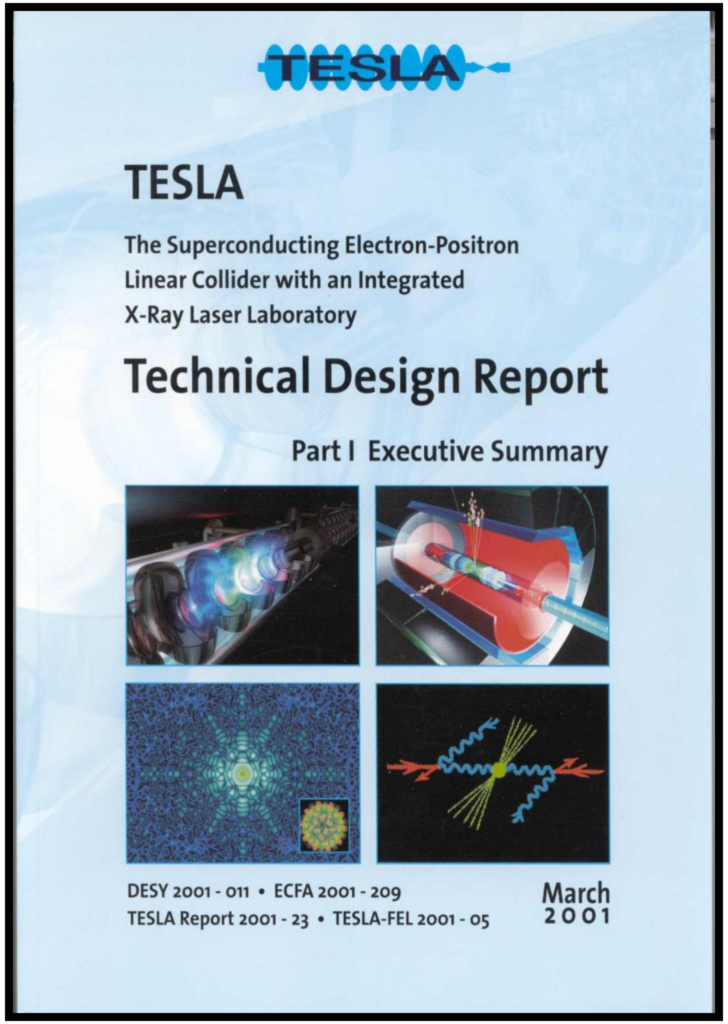
TESLA TDR: Presentation and Reactions

TESLA TDR kick-off meeting March 2001

1000 participants, 40% from abroad

- Cold reaction from German Government to the proposal to host the TESLA inear collider
- Insufficient momentum from the HEP international community, inspired by CERN
- Understanding of the potentiality opened by the TESLA driven SRF technology
- Endorsement of the science prospectives coming from the realization of an X-Ray Free-Electron Laser
- Interest for a stand alone X-Ray FEL

From TESLA TDR to an independent XFEL



On request of German Science Council

Feb 2003 - **Decision by German Government:**

Germany will cover half of the cost of the free-electron laser facility proposed by DESY, which has to be **realized in a European collaboration**.

TESLA package in 2003

In 2003 TESLA is the combination of: 3 independent Projects:

C. Pagani: TCM May 2003

TESLA LC, **TESLA X-FEL** and **TTF2**

All based on the outstanding SC linac technology

Created by the TESLA Collaboration effort

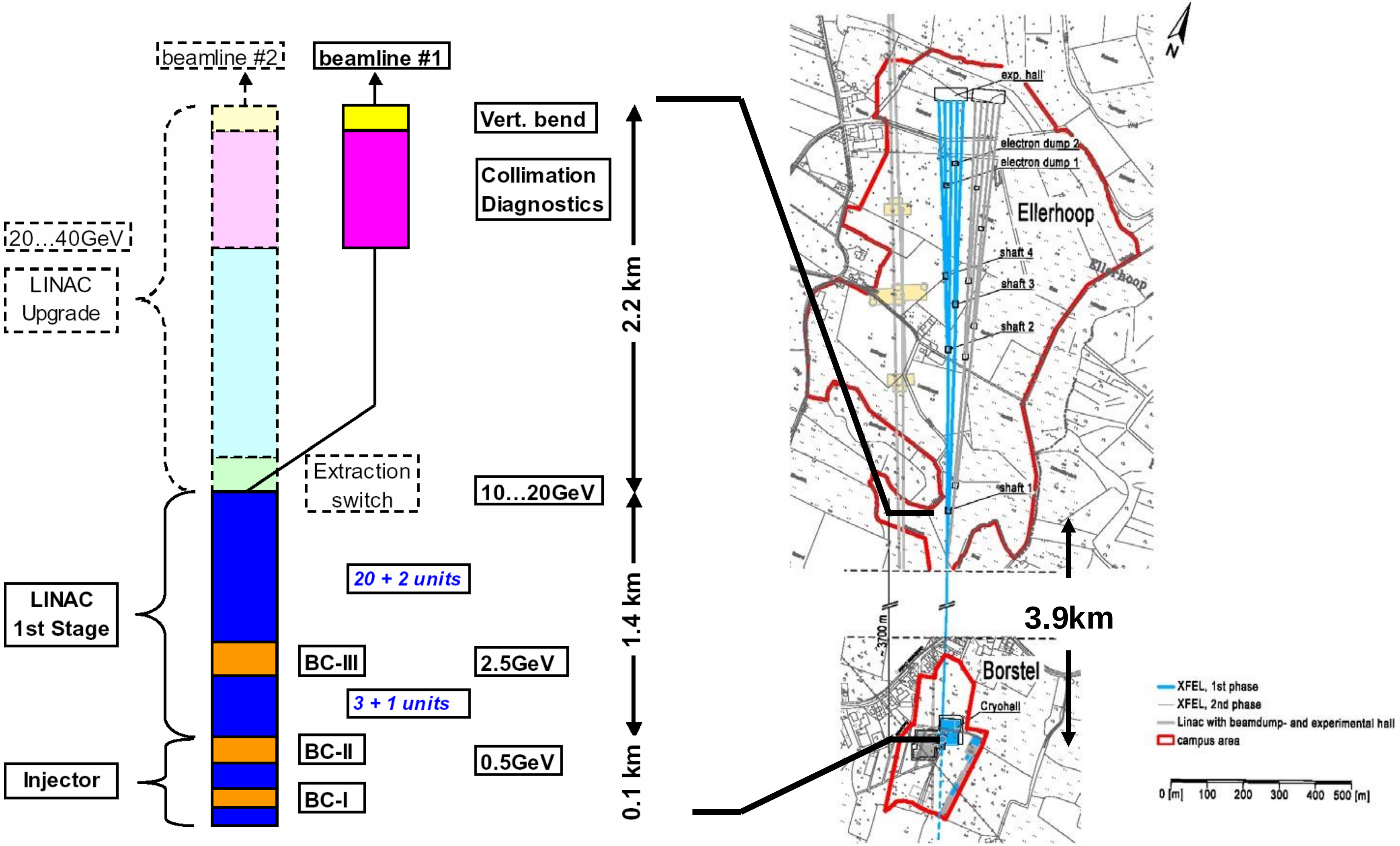
TESLA LC is one of the two remaining competitors for the next HEP large accelerator facility

TESLA X-FEL is the core of a proposal for an European Laboratory of Excellence for fundamental and applied research with ultra-bright and coherent X-Ray photons

TTF2 will be the first user facility for VUV and soft x-ray coherent light experiments with impressive peak and average brilliance.

It will be also the test facility to further implement the TESLA SC Linac technology in view of the construction of a large and reliable accelerator

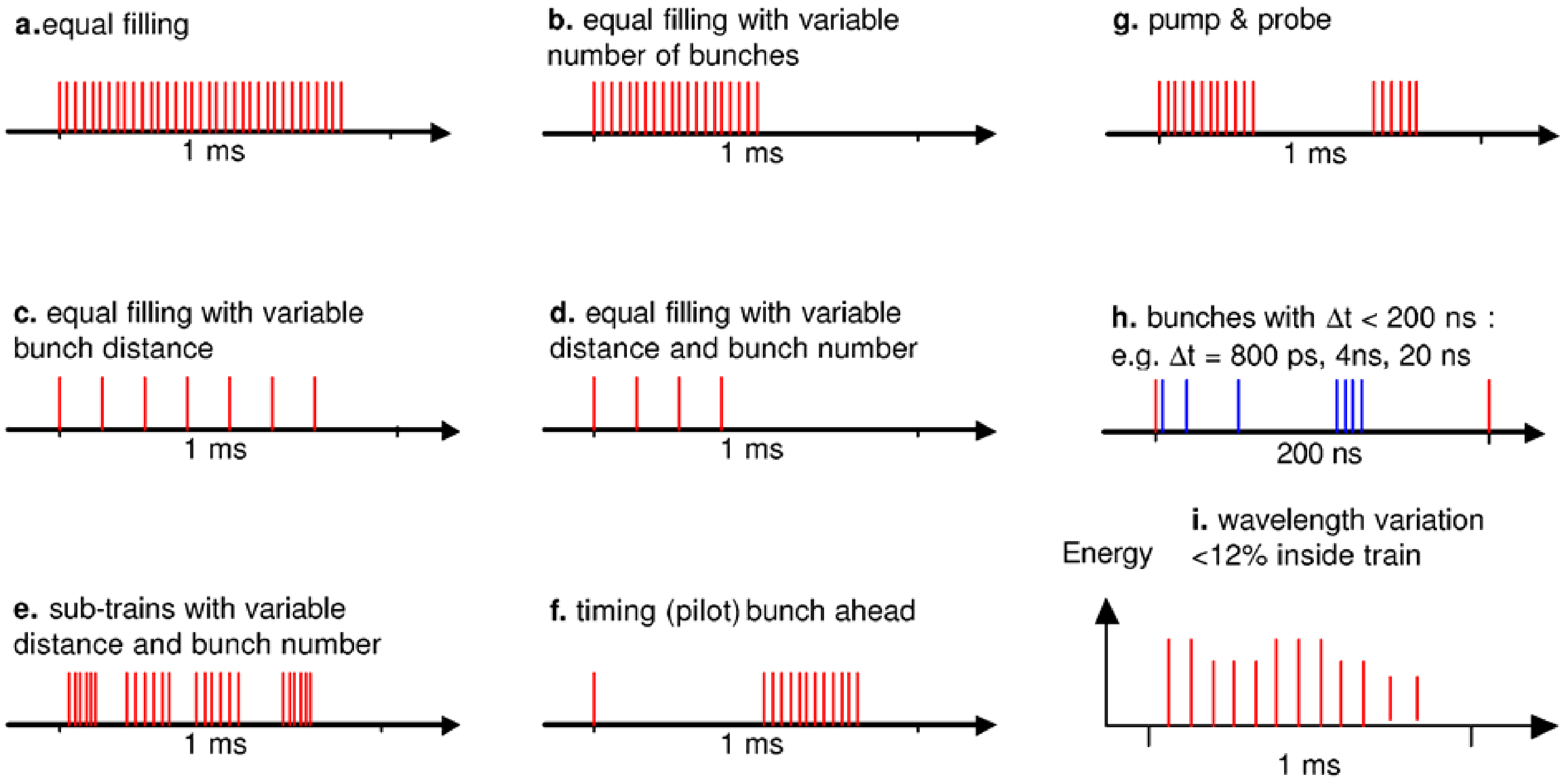
TDR Update 2002: XFEL Layout



Parameter Flexibility and Limitations

Some flexibility aloowed on bunch distribution inside the 1 ms macropulse

Macropulse reprate and linac enegy limited by the existing DESY cryoplant



Contents

Path to the European XFEL

- 2001 – TESLA Proposal and Science Council Eval.
- Oct. 2002 – X-ray FEL with 20 GeV superconducting accelerator (TESLA-technology)
- Feb. 2003 - Approval by Federal Government as European project
- Nine countries signed MoU for the Preparatory Phase of the XFEL in January 2005
- July 2006 – Technical Design Report
- July 2006: Plan Approval Process completed
- **Sept/Nov 2009: XFEL Construction Starts**

A. Wagner, Jan 2009

DESY Role in the XFEL

- **Central Element of DESY Strategy**: Participation in all phases of the XFEL (construction, operation, science und development)
- DESY **leads the international accelerator consortium** for the construction of the SC accelerator and its infrastructure, delivering the majority of components and technical systems as in-kind contributions
  - Up to 300 FTEs from DESY will work on the XFEL
- DESY is ready to **operate** the **accelerator system** on behalf of the XFEL GmbH
- DESY will **develop** the XFEL further, together with the XFEL GmbH
- A Centre for FEL science has been established together with MPG und Uni HH to become a **main user** of the XFEL

A. Wagner, Jan 2009

Also TESLA is growing

The International **Linear Collider Steering Committee** (**ILCSC**) selected the twelve members of the **International Technology Recommendation Panel** (**ITRP**) at the end of 2003:

Asia:	Europe:	North America:
G.S. Lee	J-E Augustin	J. Bagger
A. Masaike	G. Bellettini	B. Barish (Chair)
K. Oide	G. Kalmus	P. Grannis
H. Sugawara	V. Soergel	N. Holtkamp

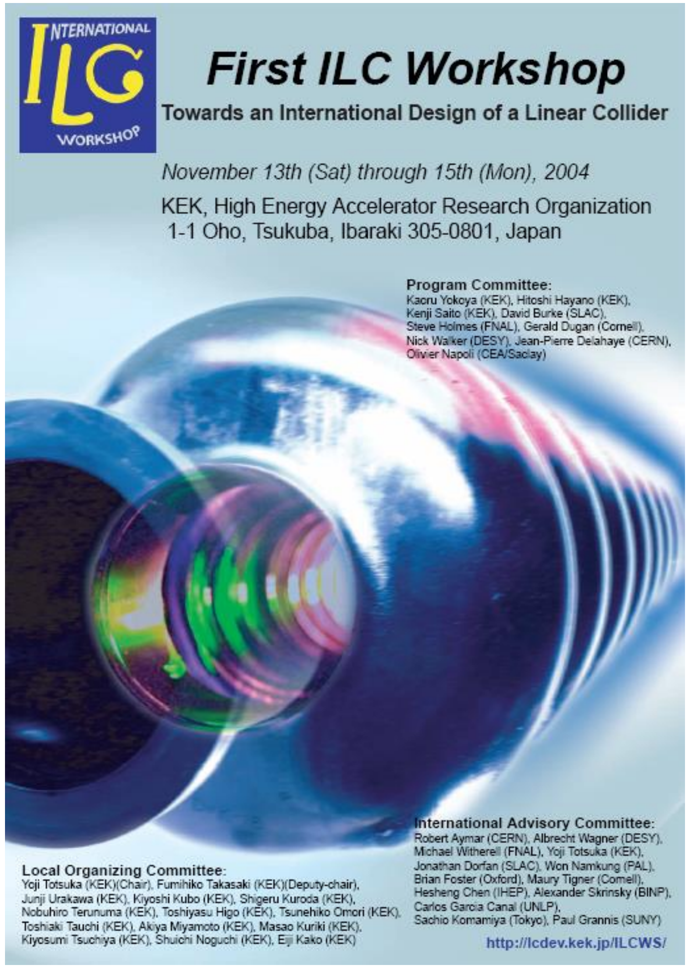
Mission: one technology by end 2004

The 3 Project Leaders were asked to follow the ITRP process as “Technology Experts”:
Dave Burke (NLC), Kaoru Yokoya (GLC) & Carlo Pagani (TESLA)

Result: recommendation on 19 August 2004

Cold that is **TESLA** like

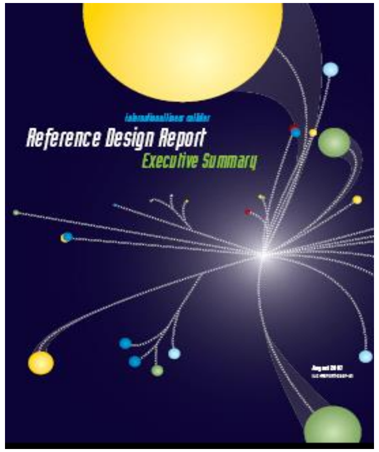
Start of the Global Design Initiative in 2004



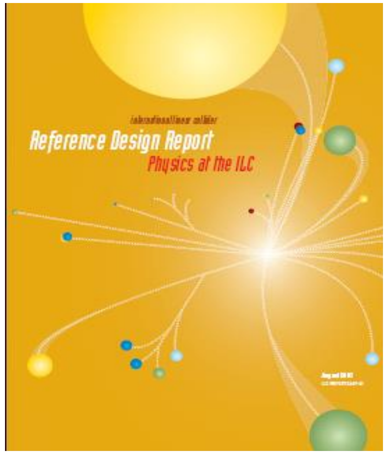
~ 220 participants from 3 regions

most of them accelerator experts

The 4 Volumes of the ILC Reference Design Report

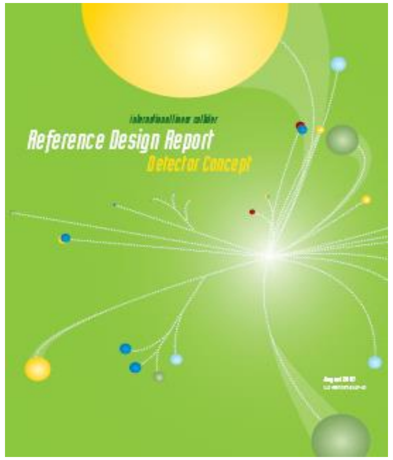


Executive Summary



Physics at the ILC

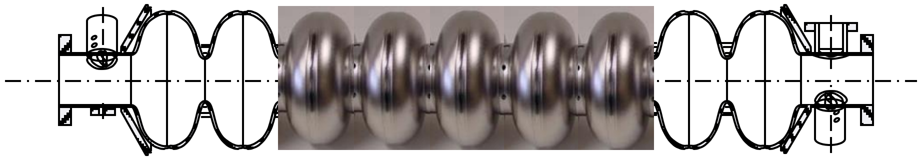
Accelerator

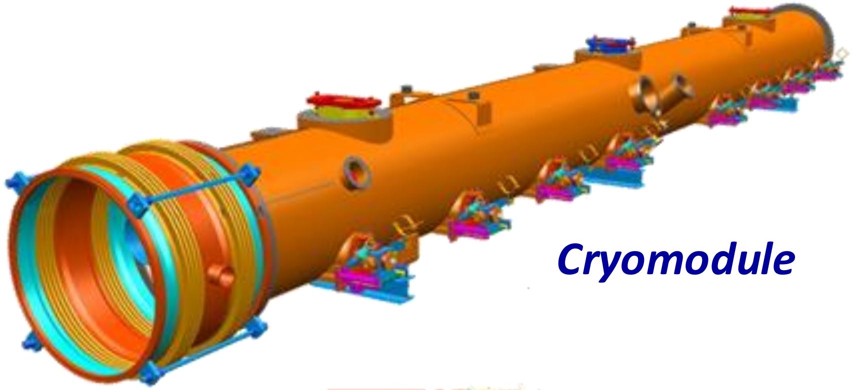


Detectors

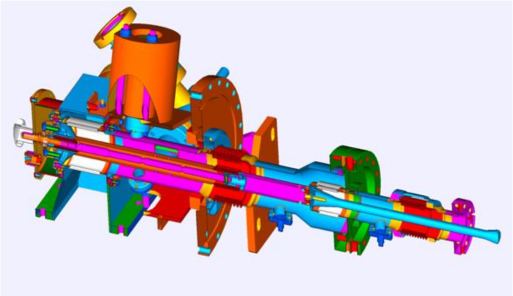
XFEL / ILC Accelerator Shared Components

cavities



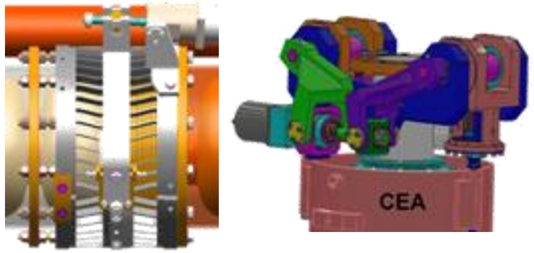


Cryomodule



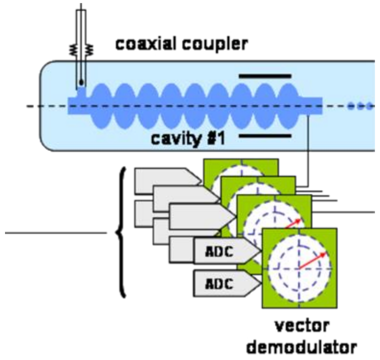
coupler

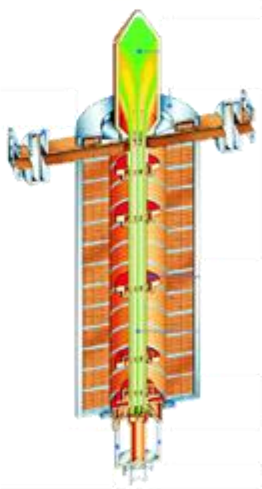
TESLA Technology



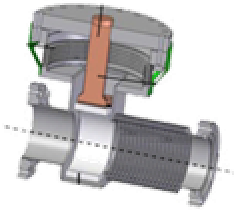
Tuners

LLRF





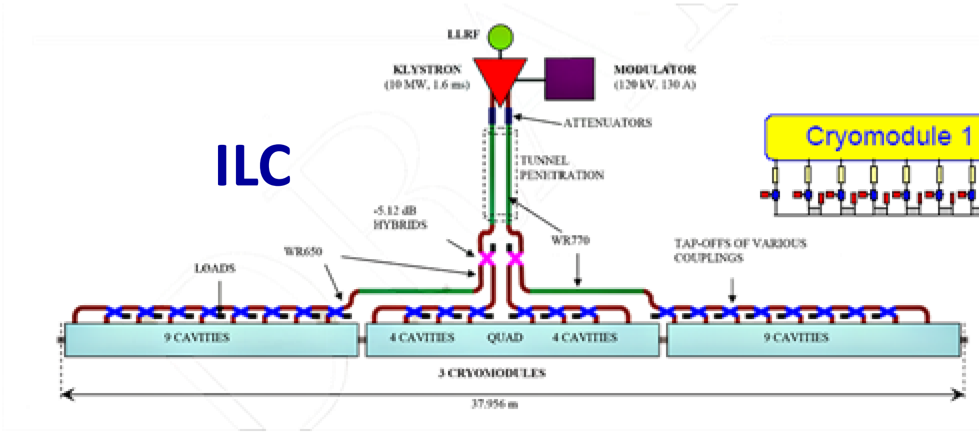
RF



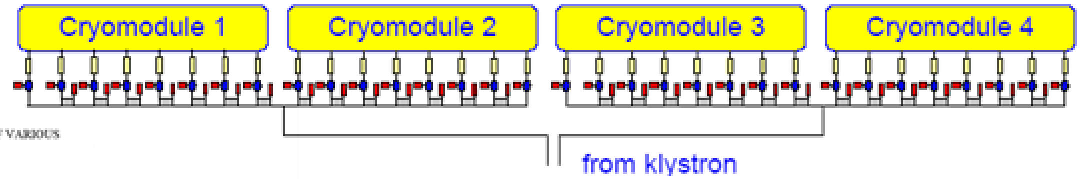
HOMs

XFEL–ILC Shared High Power RF Systems

ILC



XFEL



Minor Differences

XFEL has 32 cav. per klystron, ILC 26.

Due to the higher gradient, the ILC beam absorbs 7.6 MW instead of 3.9 MW. A margin of ca. 30 % is still available for wave guide and regulation reserve.

The XFEL will install the klystrons in the tunnel while ILC has chosen to put the klystrons & modulators in the 2nd tunnel.


Toshiba E3736

XFEL needs

31 RF stations

10 MW peak

150 kW average.

3.9 MW are needed for the beam at 20 GeV and nominal current.

5.2 MW. Including waveguide losses (6%) and regulation reserve (15%)

XFEL Low Level RF taken from TTF

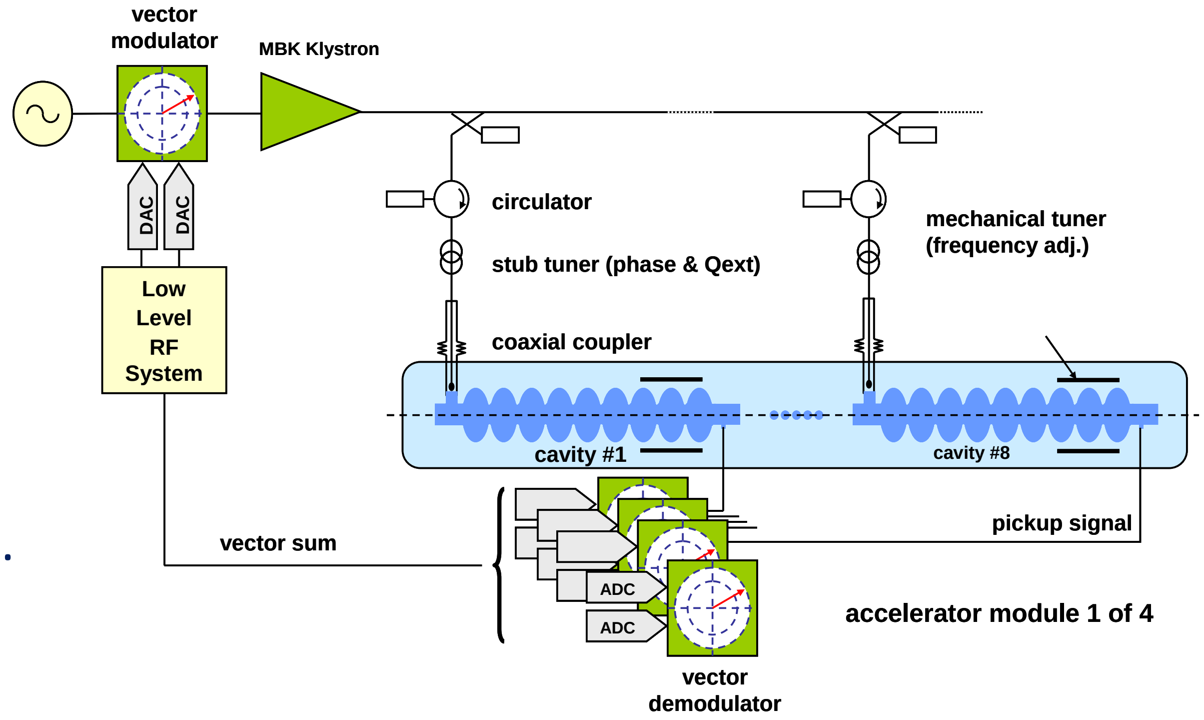
XFEL needs on RF

0.01% amplitude stability
0.01° phase stability!!!

Challenging phase and amplitude stability required by the FEL process

Successful tests already performed at TTF/FLASH.

The ILC numbers are more relaxed: 0.35% amplitude and 0.07° phase stability. XFEL development will be beneficial in any case



The operational requirements are probably different but similar to handle. Here the number of spare RF stations as well as the aimed up-time defines the 'rules of the game'.

Coclusions

Pro

The European XFEL, **EuXFEL**, is **based on** the achievements of the big international effort established through the **TESLA** Collaboration to develop the best possible linear collider for particle physics.

The success of the TESLA Mission made the **realization of the EuXFEL smooth**, being all the competences available for the task.

Scientists and technicians were **available and trained**.

Industrial partners already **qualified and prepared** for the series production thank to the prototypes successfully built already.

Cons

No further improvements allowed. All major components based on the last design of the prototypes developed for TTF.

Pulsed beam mandatory because at the basis of the TESLA design

Maximum energy and duty cycle **limited by the existing Cryo-plant at DESY**

Thank you for your attention