The European X-Ray Laser Project XFEL and ILC

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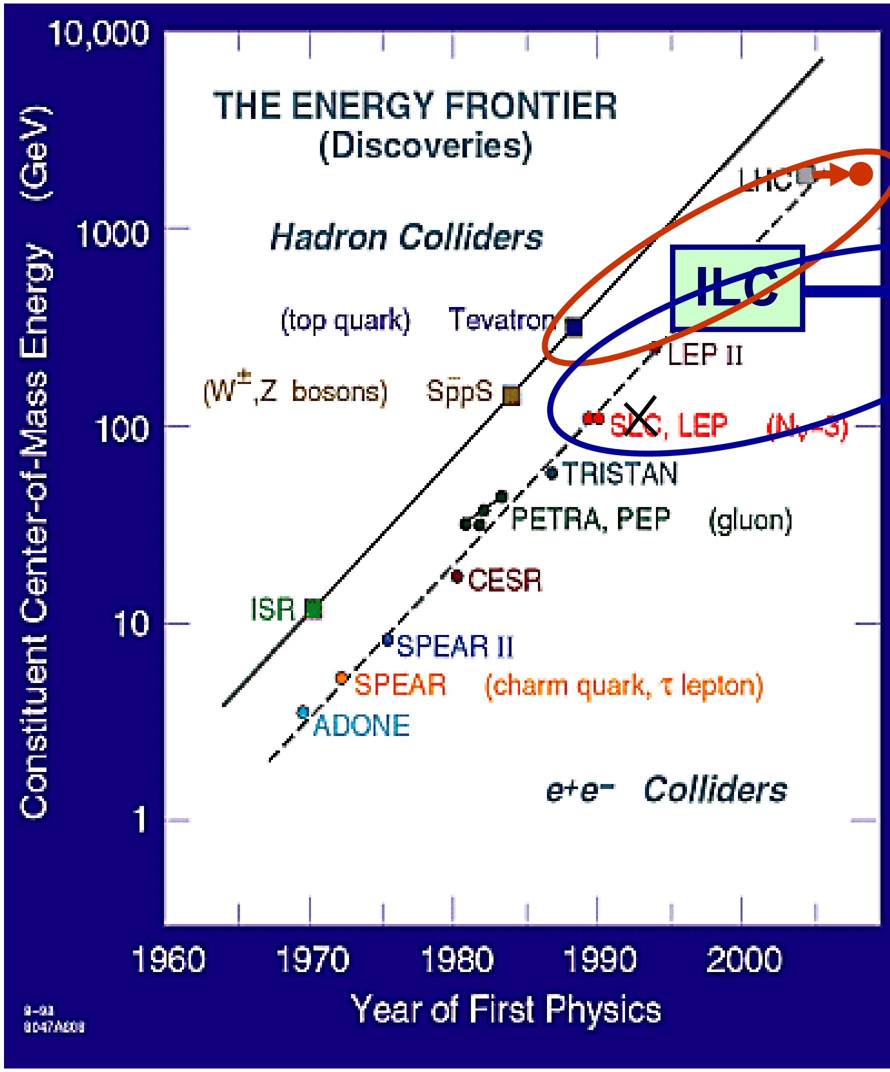
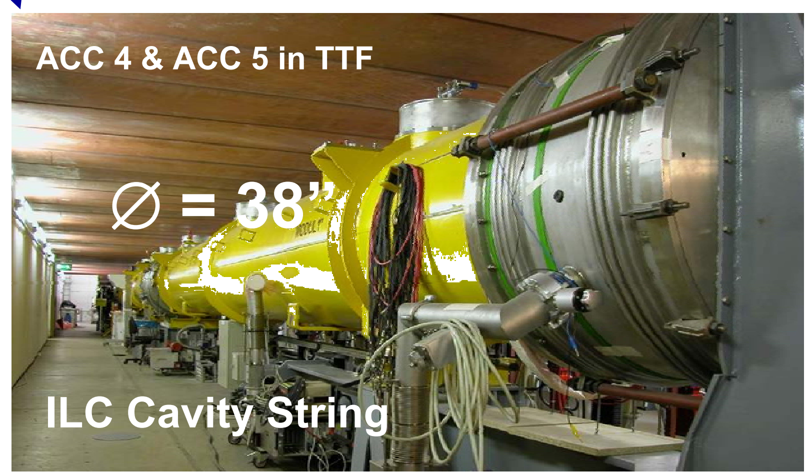
Energy Frontier and Accelerator Tech.



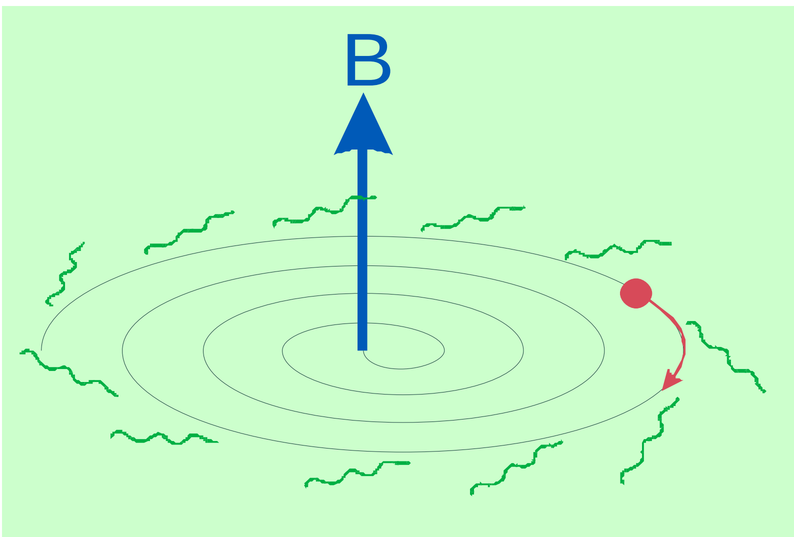
Superconducting Dipoles

Superconducting RF Cavities



No Circular e^+e^- Collider after LEP

Synchrotron Radiation:
charged particle in a magnetic field:



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

Energy loss dramatic for electrons

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

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

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**

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."

Technology Choice:
NLC/JLC or TESLA

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

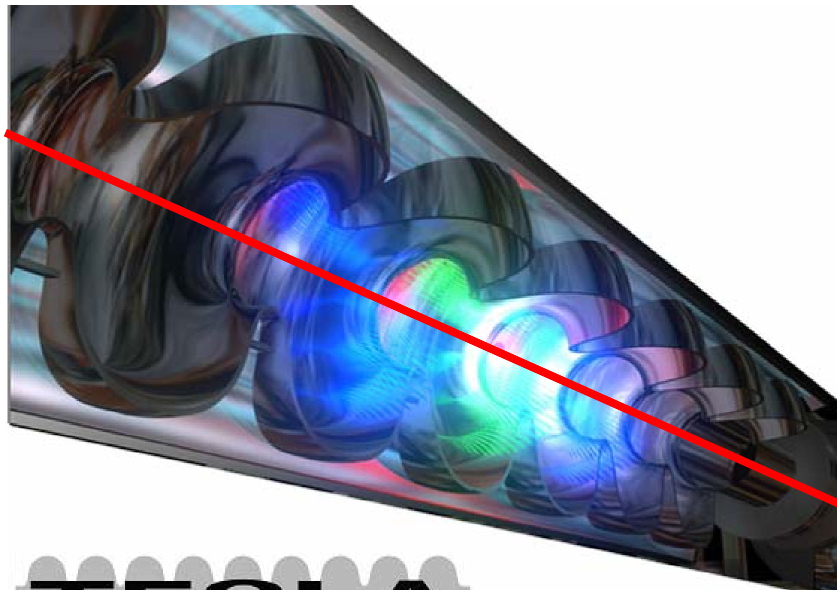
Asia:	**Europe:**	**North America:**
G.S. Lee	J-E Augustin	J. Bagger
A. Masaike	G. Bellettini	**B. Barish (Chair)**
K. Oide	G. Kalmus	P. Grannis
H. Sugawara	V. Soergel	N. Holtkamp

First meeting end of January 2004 at RAL

Mission: **one technology** by end 2004

Result: **recommendation** on 19 August 2004

Competing technologies for the ILC



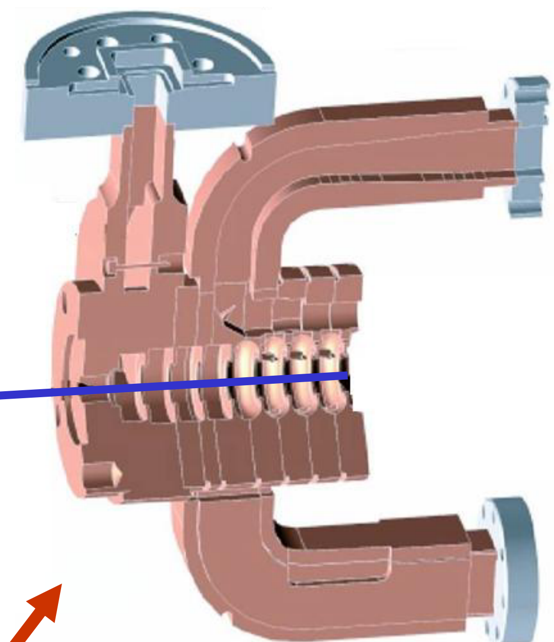
TESLA

1.3 GHz - Cold

Evolution from: CEBAF & LEPII

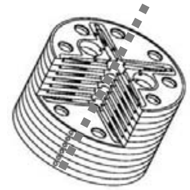
+ TRISTAN, HERA, etc.

Evolution from: SLAC & SLC



NLC JLC

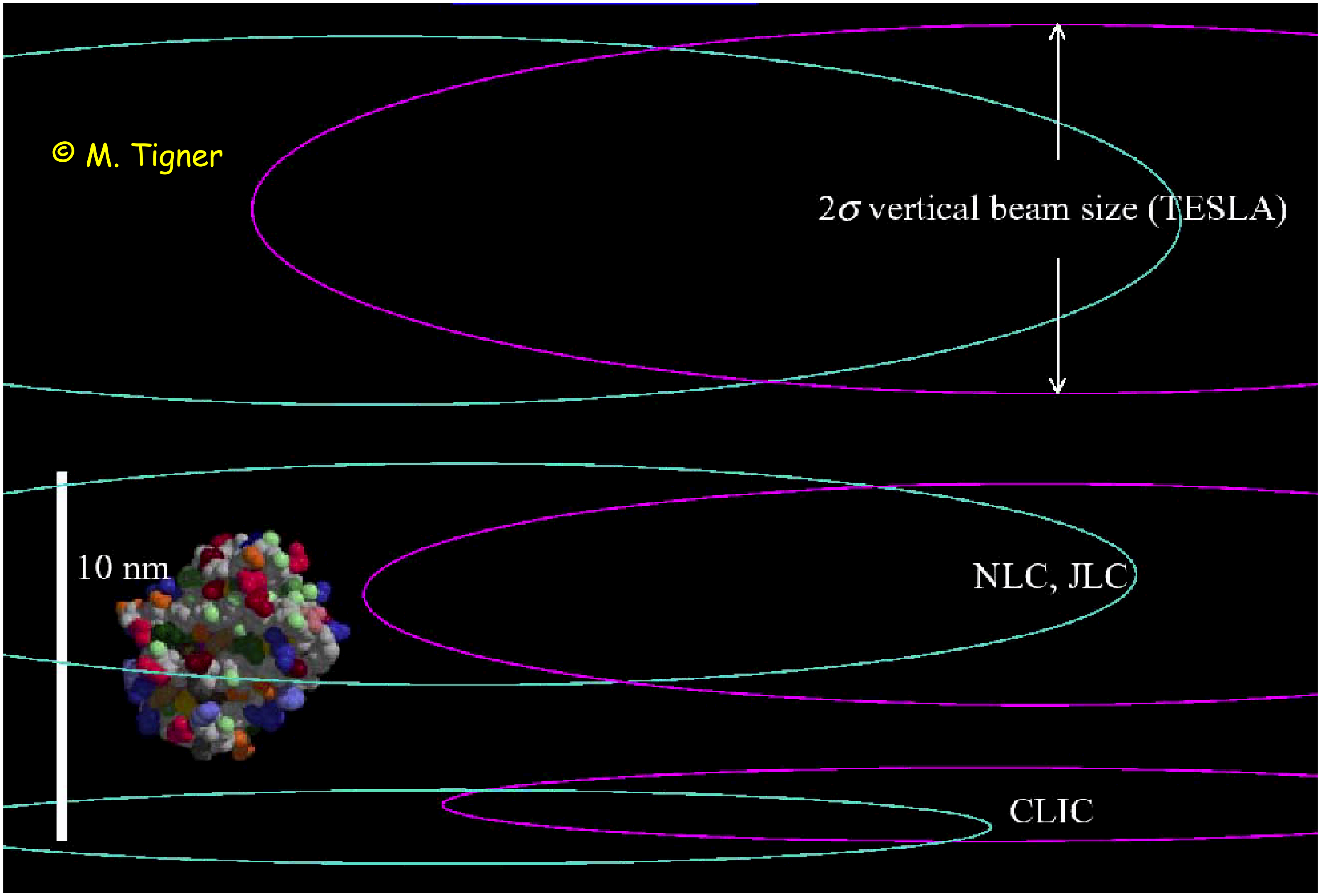
11.4 GHz - Warm



CLIC

12 GHz - Warm

Beam Sizes: Pictorial View



Basic parameters for the ILC

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%

Machine upgradeable to 1 TeV

Luminosity: Beam Size & Beam Power

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

- $f_{rep} \cdot n_b$ 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 and small betas:

$$\sigma_x = \mathrm{sqrt}\,(\beta_x\ \varepsilon_x)$$

From the ILC Birthday

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.

19-Aug-04 ITRP - LC Technology Recommendation 13

From the ILC Birthday

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.

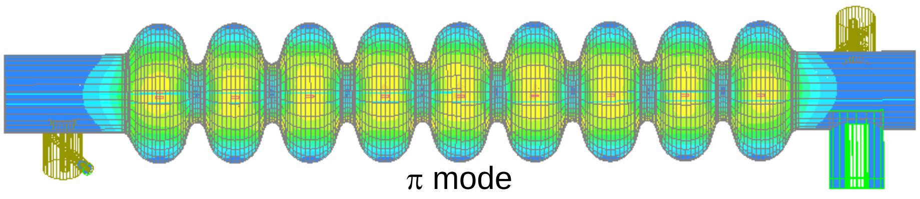
Both technologies have wider impact beyond particle physics. The superconducting rf technology has applications in other fields of accelerator-based research, while the X-band rf technology has applications in medicine and other areas.

19-Aug-04 ITRP - LC Technology Recommendation 14

The ILC technology choice

Standing wave: $V_{ph} = 0$ and $Vg = 0$

TESLA: f = 1.3 GHz



The power is deposited at the operating temperature of 2 K

We need to guarantee and preserve the 2 K environment

- Cavity is sensitive to pressure variations, only viable environment is sub-atmospheric vapor saturated He II bath

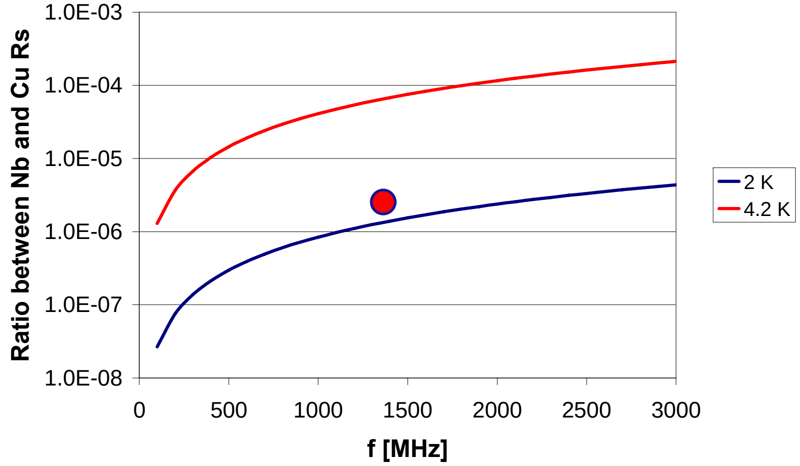
We need a thermal "machine" that performs work at room temperature to extract the heat deposited at cold

- We can't beat Carnot efficiency!

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



→ Cryogenics and cryomodules

How is spent the cold advantage?

The gain in RF power dissipation with respect to a normal-conducting structure is spent in different ways

$$W \geq Q \frac{T_h - T_c}{T_c}$$

- Paying the price of supplying coolant at 2K
  - This include ideal Carnot cycle efficiency
  - Mechanical efficiency of compressors and refrigeration items
  - Cryo-losses for supplying and transport of cryogenics coolants
  - Static losses to maintain the linac cold

- Increasing of the duty cycle (percentage of RF field on)
  - Longer beam pulses, larger bunch separation, but also
  - Larger and more challenging Damping Rings

- Increasing the beam power (for the same plug power)
  - Good for Luminosity

The TESLA Collaboration Mission

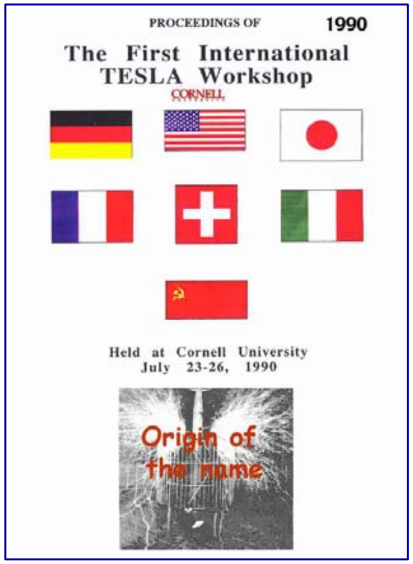
Develop SRF for the future TeV Linear Collider

Basic goals

- **Increase gradient by a factor of 5** (Physical limit for Nb at ~ 50 MV/m)
- **Reduce cost per MV by a factor 20** (New cryomodule concept and Industrialization)
- **Make possible pulsed operation** (Combine SRF and mechanical engineering)

Major advantages vs NC Technology

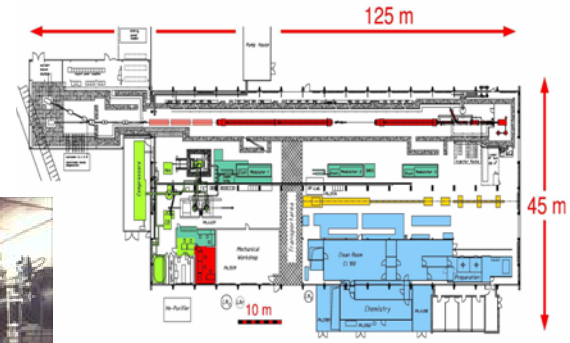
- **Higher conversion efficiency**: more beam power for less plug power consumption
- **Lower RF frequency**: relaxed tolerances and smaller emittance dilution



TESLA Collaboration Milestones

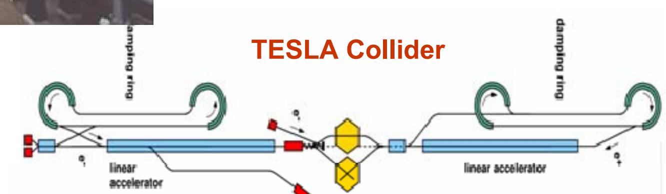
- February 1992 – 1° TESLA Collaboration Board Meeting @ DESY
- March 1993 - "A Proposal to Construct and Test Prototype Superconducting RF Structures for Linear Colliders"
- **1995 – 25 MV/m in multi-cell cavity**
- May 1996 – First beam at TTF
- March 2001 – First SASE-FEL Saturation at TTF
- March 2001 – TESLA Technical Design Report
- February 2003 –TESLA X-FEL proposed as an European Facility,
  50% funding from Germany
- 2004 – FLASH (TTF II) Commissioning start
- **April 2004 - 35 MV/m with beam**
- **August 2004 - TESLA Technology chosen for ILC**
- **June 2007 – Formal start of the XFEL Project**

Infrastructure @ DESY in Hall 3



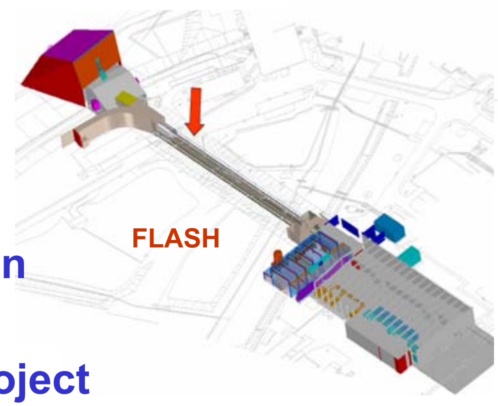
TTF I

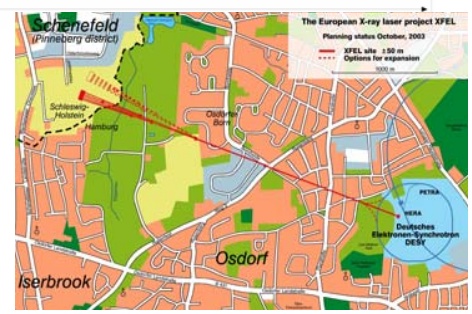
TESLA Collider



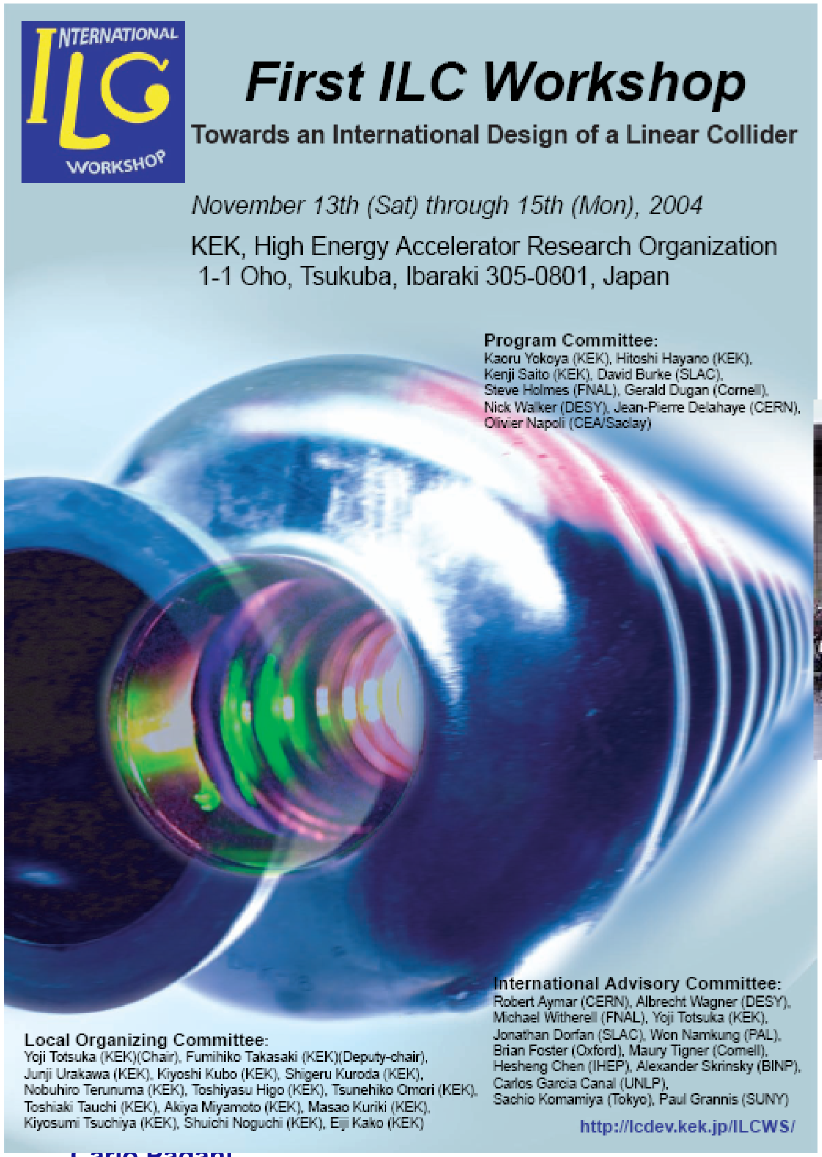
TESLA X-Ray FEL

FLASH





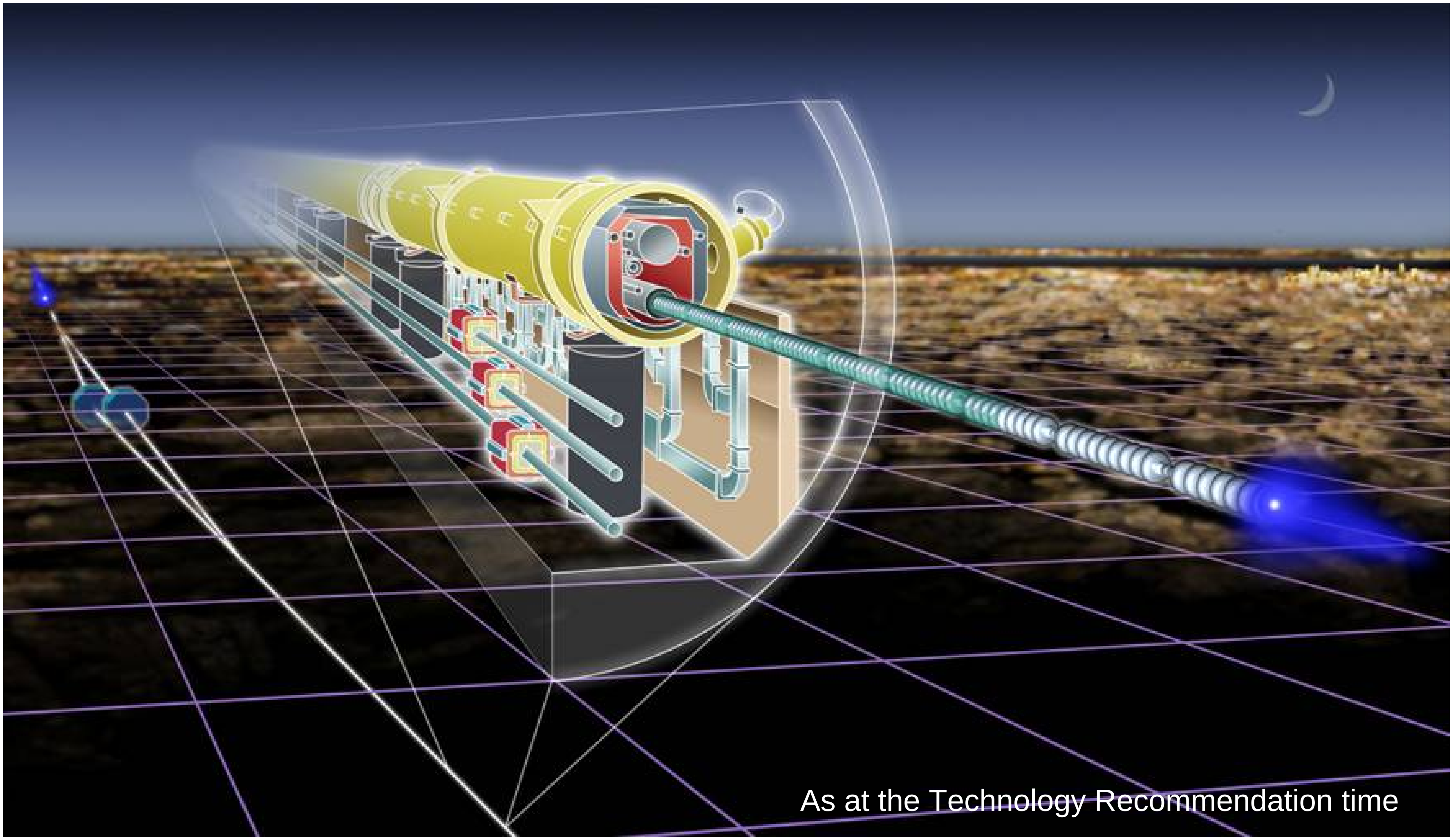
Start of the Global Design Initiative



~ 220 participants from 3 regions

most of them accelerator experts

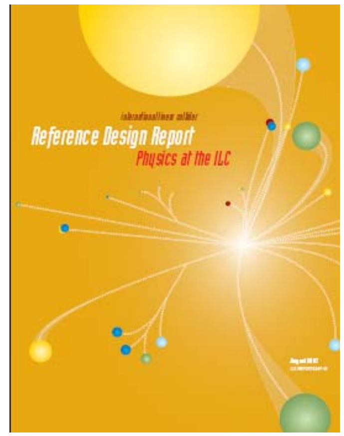
ILC Pictorial View (TESLA Like)



ILC Reference Design Report, Feb 2007

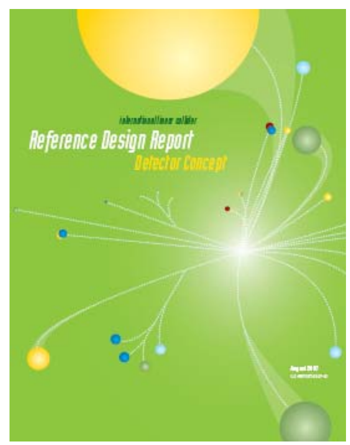
The 4 Volumes of the ILC Reference Design Report

Executive Summary



Physics at the ILC

Accelerator

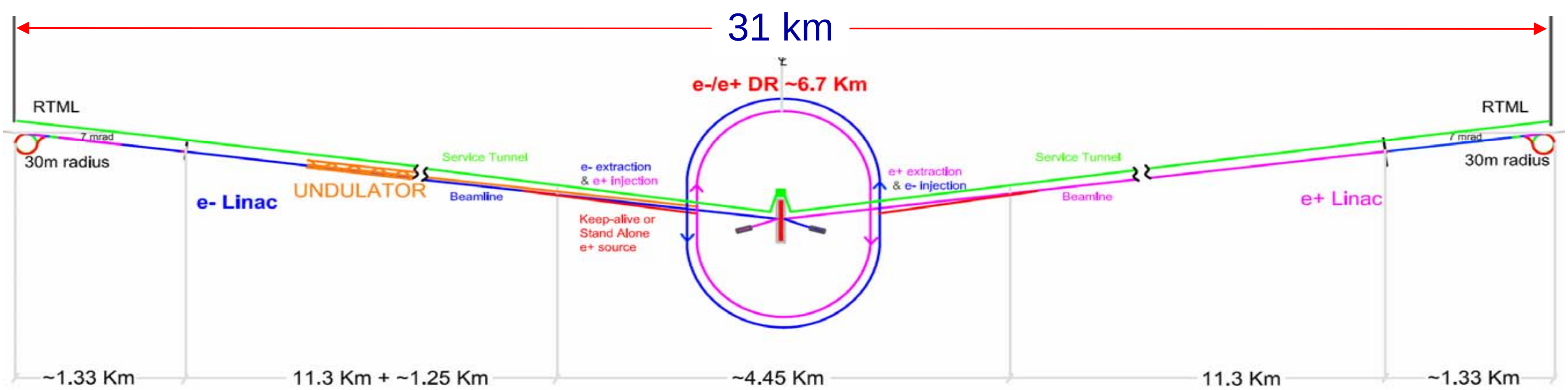


Detectors

ILC as in the Reference Design Report

- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - Circular damping rings for electrons and positrons
  - Undulator-based positron source
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability

ILC Reference Design – as in RDR, Feb 2007



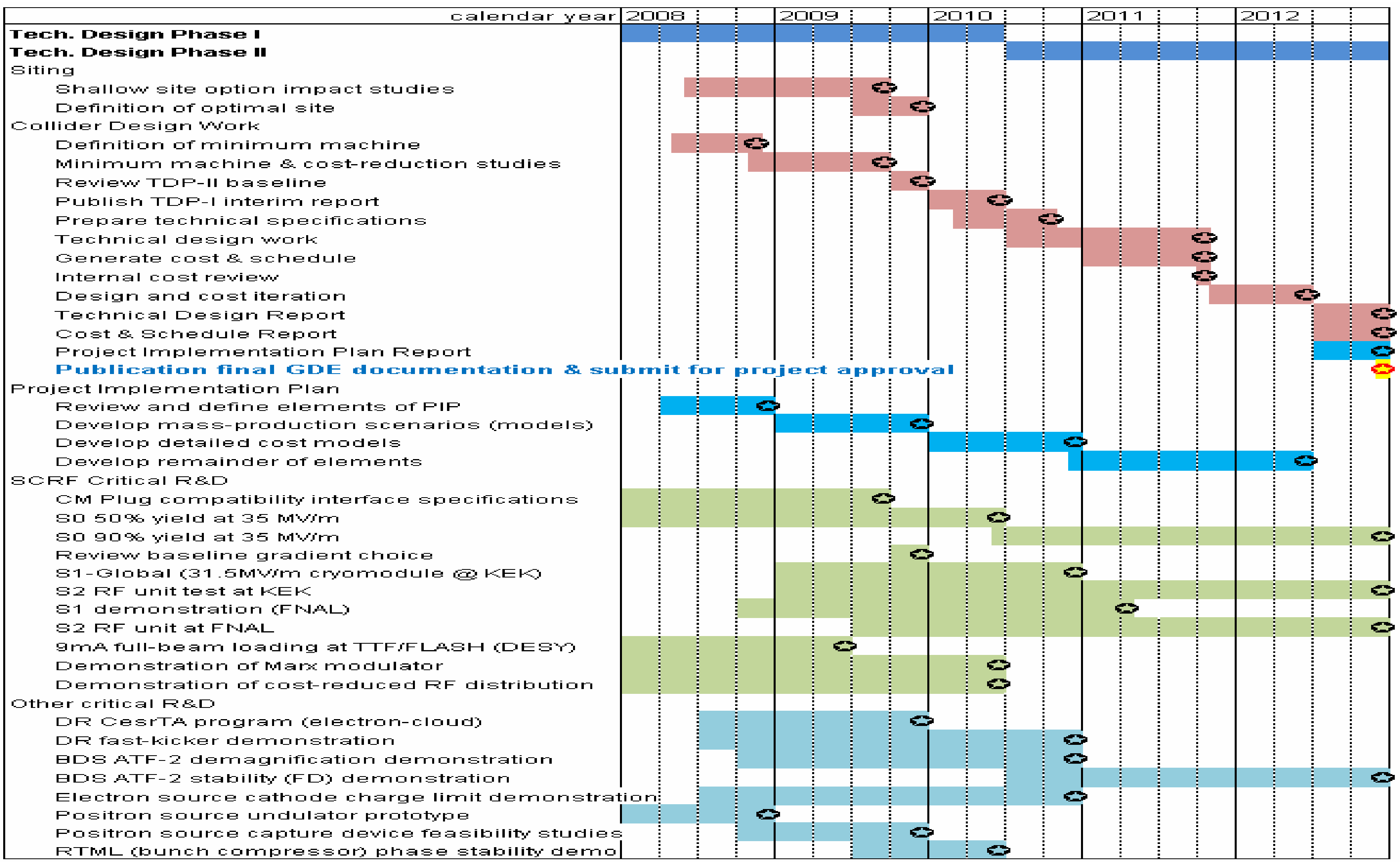
ILC RDR Design Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	~ 2×10^{34}	$1/cm^2s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

Some Context for ILC Re-planning

- Building close collaboration with XFEL. It will provide all SCRF development, except high gradient and ILC scale mass production, including a full systems test in 2013, industrialization, etc.
- We plan to take advantage of alignments and synergies where they will exist with US generic SCRF program, Project X development, etc.
- Undertaking steps to integrate linear collider (ILC and CLIC) R&D efforts, where beneficial to both efforts (meeting on 8-Feb, 13-May). Examples – sources, beam delivery, conventional facilities, detectors, costing, …..

TD Phase 1 & 2 Schedules



SCRF Global Cavity Program

Americas	US FY06 (actual)	US FY07 (actual)	US FY08	US FY09	US FY10	TDP-1 Totals*	US FY11	US FY12
Cavity orders	22	12		10	10	**52**	10	10
Total 'process and test' cycles		40	5	45	30	**113**	30	30
Asia	**JFY06 (actual)**	**JFY07 (actual)**	**JFY08**	**JFY09**	**JFY10**		**JFY11**	**JFY12**
Cavity orders	8	7	8	25	15	**44**	39	39
Total 'process and test' cycles		21	40	75	45	**147**	117	117
Europe	**CY06 (actual)**	**CY07 (actual)**	**CY08**	**CY09**	**CY10**		**CY11**	**CY12**
Cavity orders	60**	8		834*		**8**		
Total 'process and test' cycles		14	18	26	30	**73**	380	406
Global totals								
Global totals - cavity fabrication	90	27	8	869	25	103	49	49
Global totals - cavity tests		75	65	135	175	333	501	501

SCRF Major Goals

High-gradient cavity performance at 35 MV/m according to the specified chemical process with a yield of 50% in TDP1, and with a production yield of 90% in TDP2	2010 2012
Nominal Cryomodule design to be optimized: - plug-compatible design including tune-ability and maintainability - thermal balance and cryogenics operation - beam dynamics (addressing issues such as orientation and alignment)	2009
Cavity-string performance in one cryomodule with the average gradient 31.5 MV based on a global effort (S1 and S1-global)	2010
An ILC accelerator unit, consisting of three cryomodules powered by one RF unit, with achieving the average gradient 31.5 MV/m (S2)	2012

5 M€ from EU for the ILC Prep. Phase

SEVENTH FRAMEWORK PROGRAMME
RESEARCH INFRASTRUCTURES
Construction of new infrastructures – preparatory phase

Combination of Collaborative Project and
Coordination and Support Action

ILC-HiGrade

International Linear Collider and
High Gradient Superconducting RF-Cavities

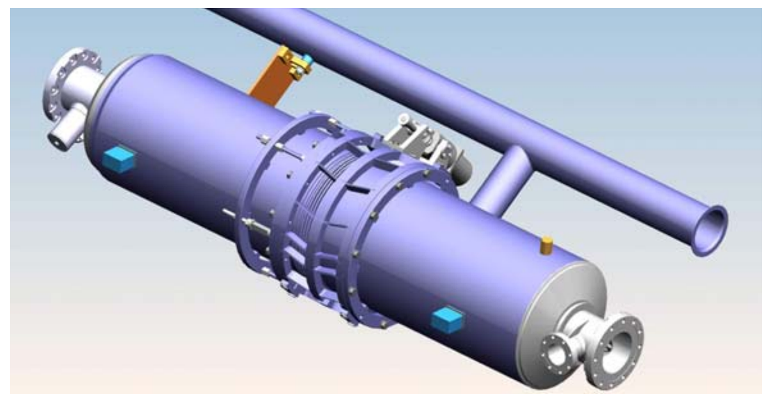
www.ilc-higrade.eu

Grant agreement number 206711

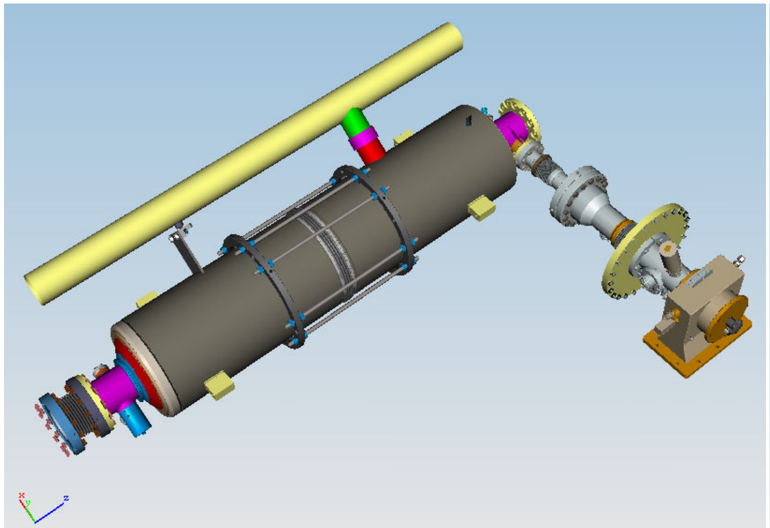
Annex I – "Description of Work"

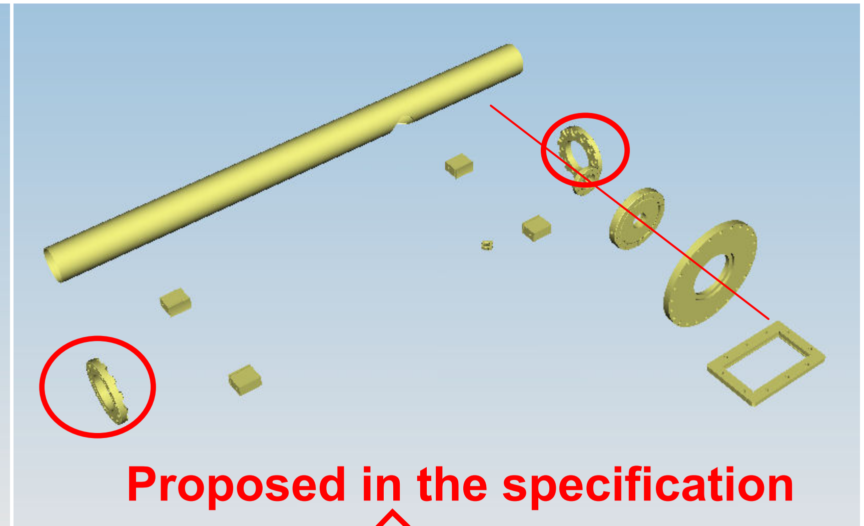
Deliverables by 2012

- 24 fully dressed TESLA-like cavities with all the ancillaries:
  - He Vessel
  - Coupler
  - Tuner
  - Mag. Shield
- **Performances as on ILC RDR**



Plug Compatibility Concept

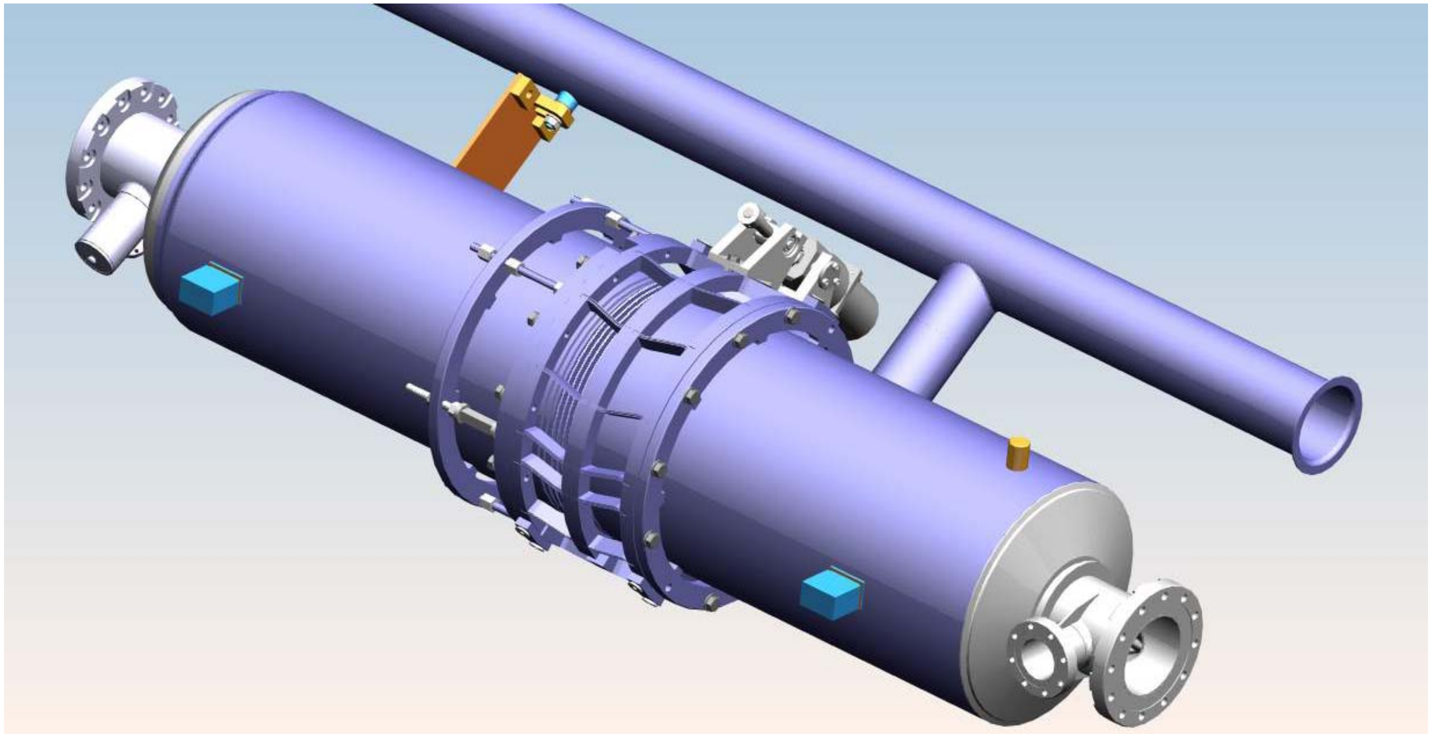




Helium Vessel Body		KEK-STF-BL	KEK-STF-LL	FNAL-T4CM	DESY-XFEL
Helium Jacket	Material	Ti	SUS	Ti	Ti
	Slot length, mm	1337	1337	1326.7	(1382:Type3)
	Distance between beam pipe flanges, m	1258.6	1254.5	1247.4	1283.4
	Distance between bellows flanges, mm	78.4	85.2	80.49 (cold)	
	Outer diameter, mm	242	236	240	240
Beam Pipe Flange	Material	NbTi	Ti	NbTi	NbTi
	Outer diameter, mm	130	140	140	140
	Inner diameter, mm	84	80	82.8	82.8
	Thickness, mm	14	17.5	17.5	17.5
	PCD, bolts	ϕ115, 16−ϕ9	ϕ120, 16−ϕ9	12, M8 SS studs	12, M8 SS studs
	Sealing	Helicoflex	M-O seal	Al Hex Seals	Hexagonal Al ring
	Distances between the connection				
	surface and input coupler axis	62, −1196.6	58.1, −1213.9	60.6, −1186.8	60.6, −1222.8

ILC-XFEL Plug Compatible Cavity

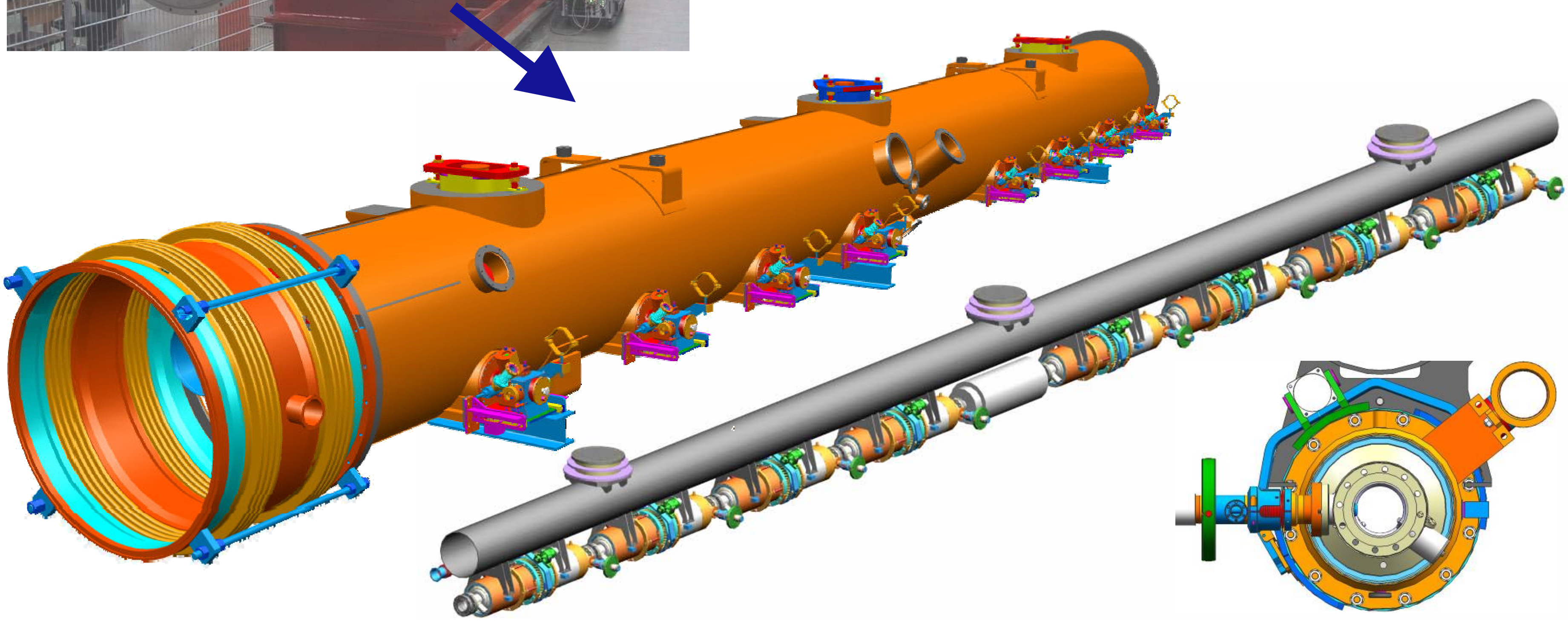
- Cavity with Helium Tank, Tuner and pipe connections
  - Plug Compatible with the 3 Regional Infrastructures
  - Plug Compatible with the FLASH and XFEL Cryomodules



TTF Type III Refenence Cryomodule

Developed by INFN for TTF-TESLA

- 3rd generation of improvements
- Many years of successful operation
- Baseline for XFEL and ILC
- Reference for others (Project X, etc)



Path to the European XFEL

sc linac

2001 XFEL Proposal

2002 XFEL Supplement

2006 XFEL Final TDR

- **1997 1st electron beam accelerated at TTF**
- **2000 1st lasing at TTF-FEL (80-120 nm)**
- **2005 1st lasing at TTF (VUV-FEL) 30 nm**
- **2006 13 nm and saturation**
- **many happy photon beam users**
- **2007 energy upgrade to 1 GeV,**
- **i.e. 6 nm reached**

FLASH

- **2003 German Science Council recommends**
- **building the XFEL**
- **2004 Project Preparation Phase**
- **MoU between European Partners**
- **(project preparation)**
- **2006 Final TDR incl. detailed technical layout**
- **and experiments**
- **2007 June 5, Formal Project Approval**
- **2008 Autumm: XFEL Company being created in Berlin**

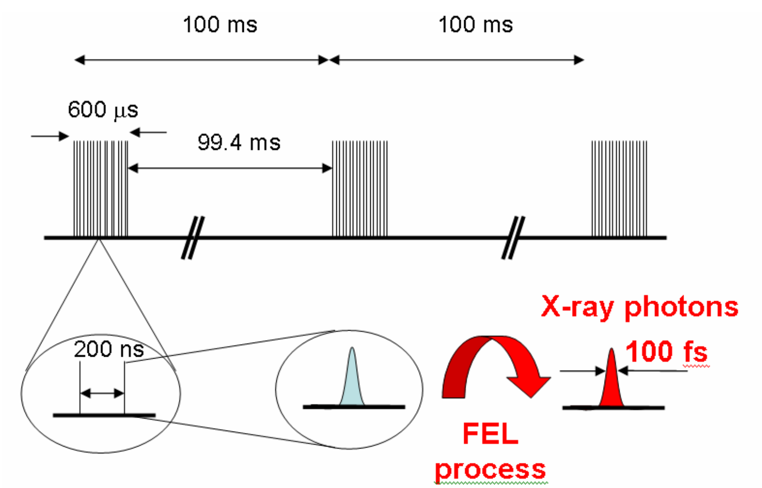
XFEL

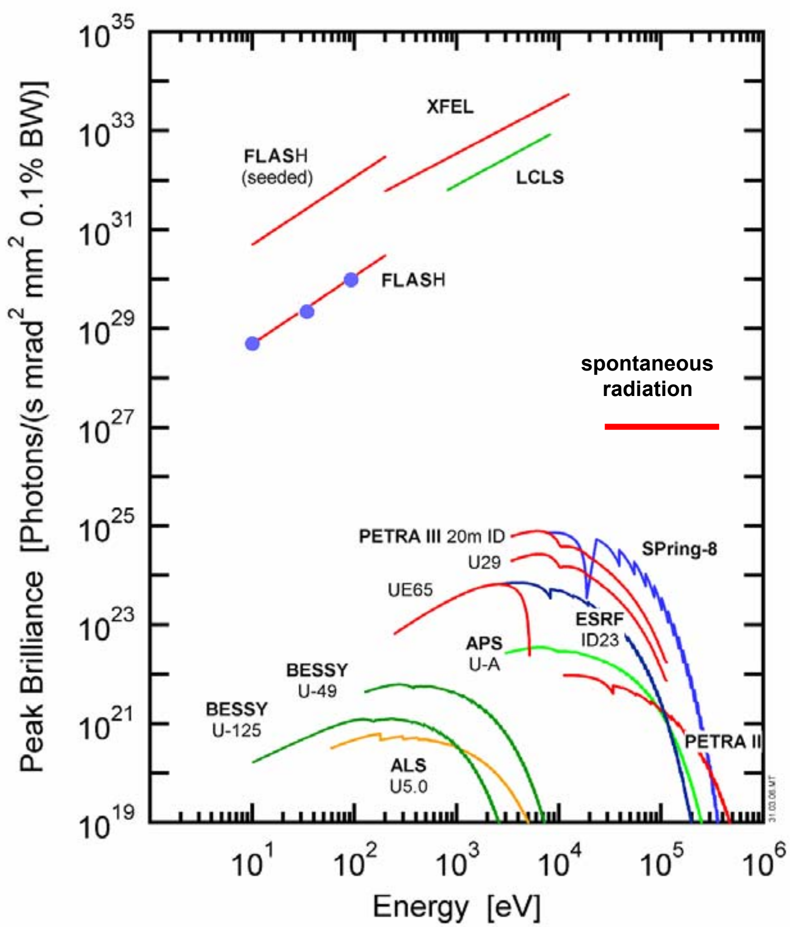
The European XFEL

- Proposal Oct. 2002 – X-ray FEL user facility with 20 GeV superconducting linear accelerator from TESLA technology
- Approval by German government Feb. 2003 as European Project
- **Formal starting on June 5, 2007**
- Negotiations close to conclusion: Convention, Articles of Association and Final Act have been finalized.
- **Creation of the XFEL Company expected in early Autumn 2008**

Properties of XFEL radiation

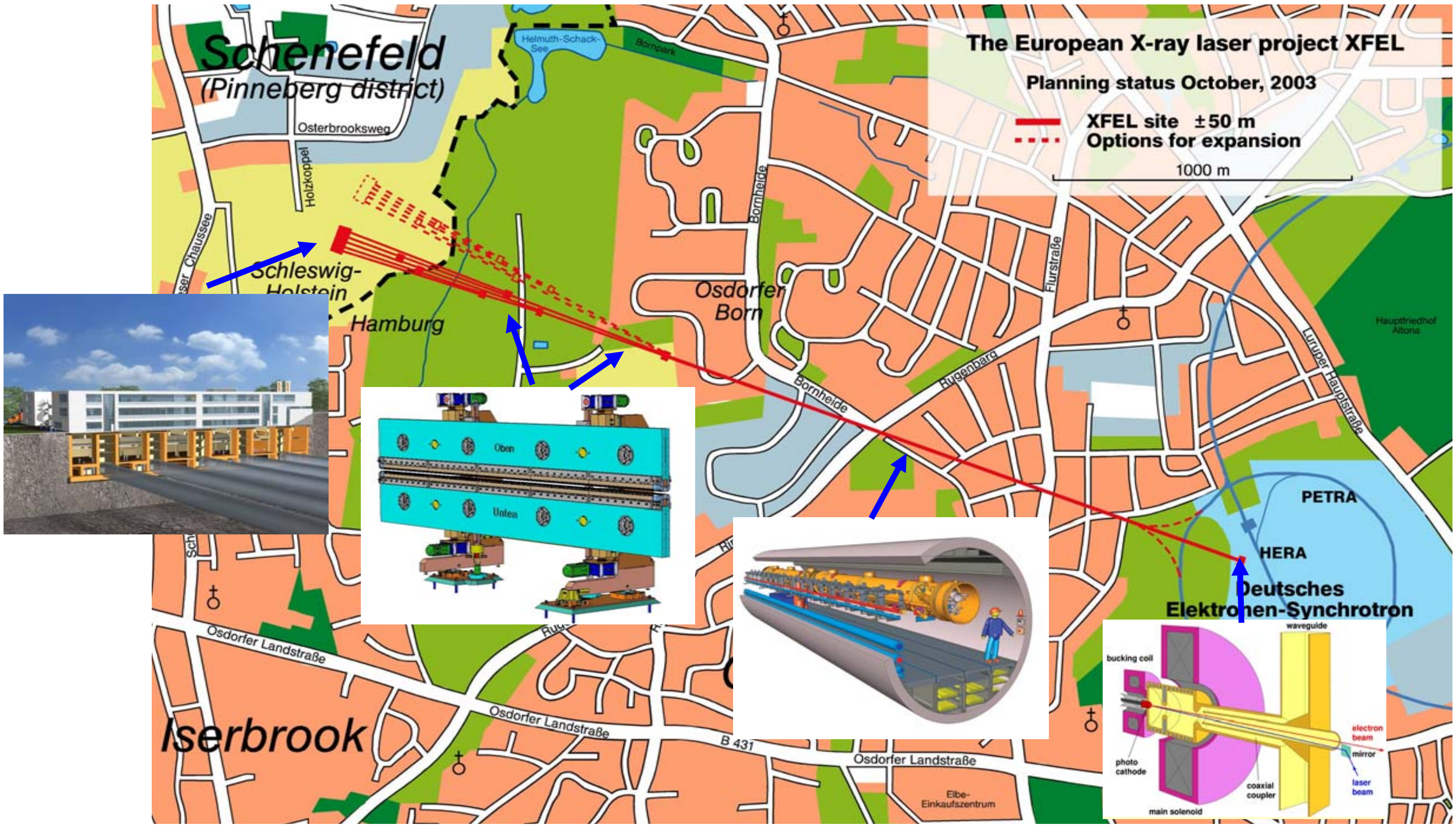
- X-ray FEL radiation (0.2 - 14.4 keV)
  - ultrashort pulse duration <100 fs (rms)
  - extreme pulse intensities 10^{12}-10^{14} ph
  - coherent radiation x10^9
  - average brilliance x10^4
- Spontaneous radiation (20-100 keV)
  - ultrashort pulse duration <100 fs (rms)
  - high brilliance





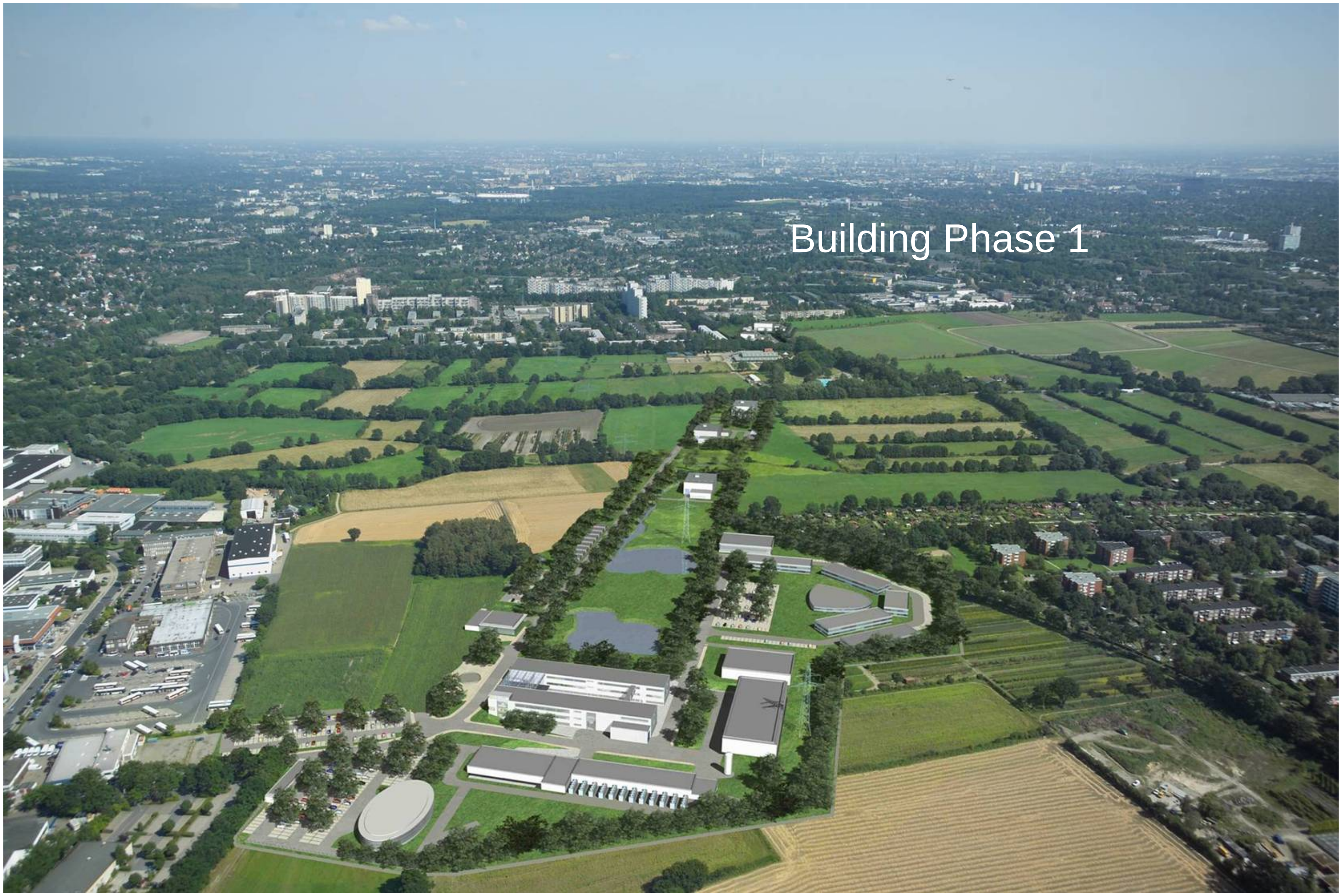
Overall layout of the European XFEL

3.4km

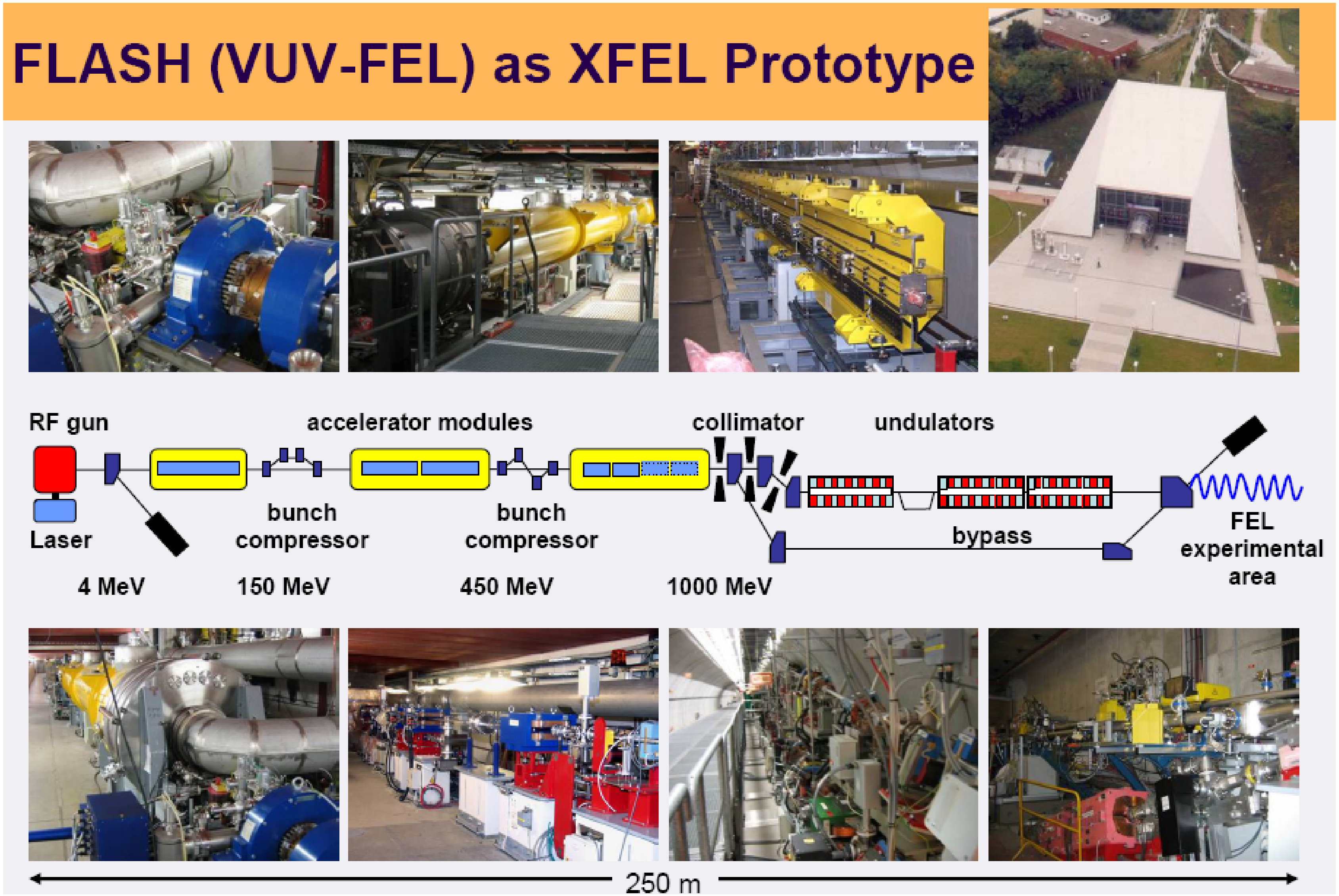


XFEL site in Hamburg/Schenefeld

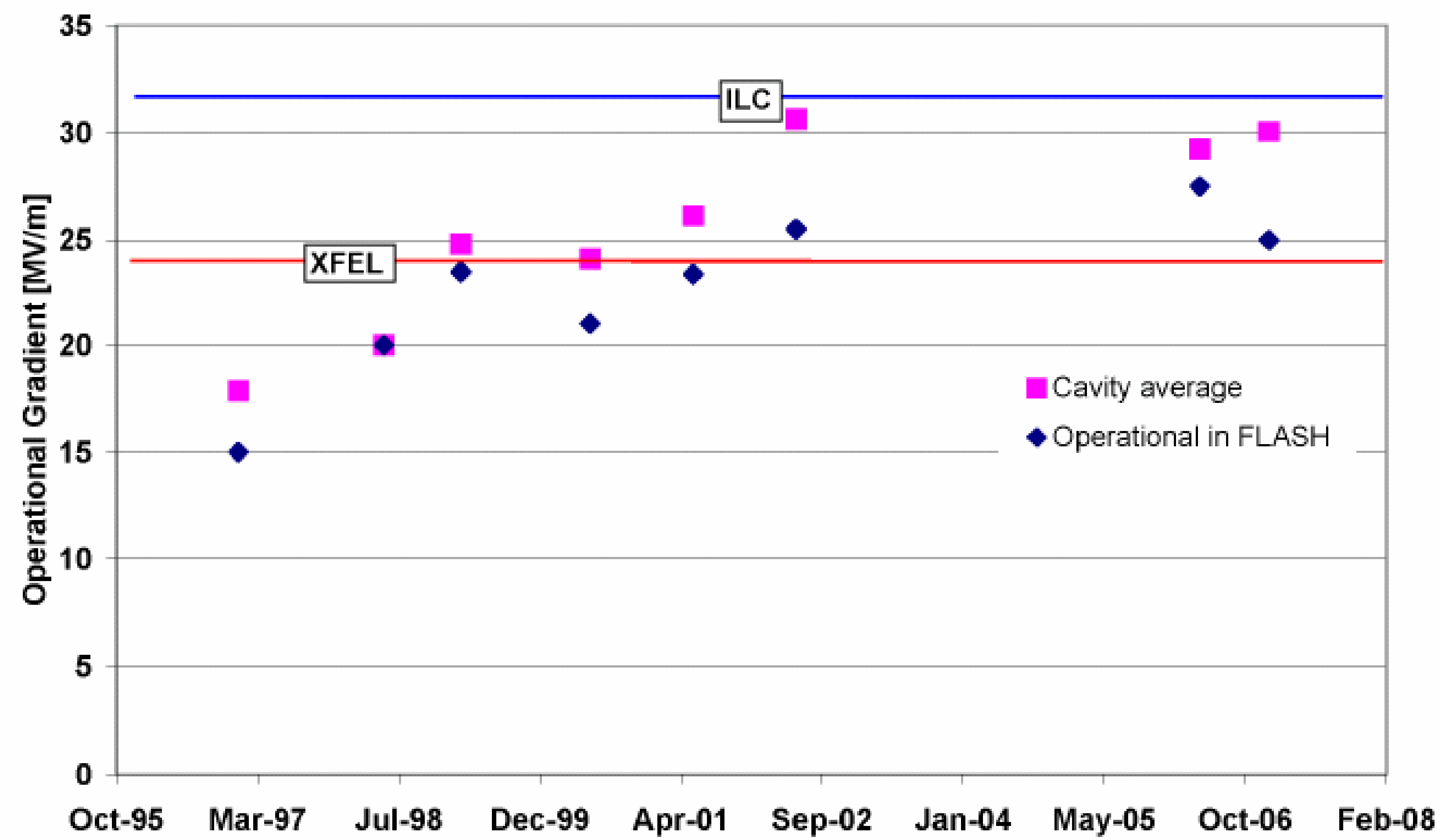
… after construction (computer simulation)



The Existing FLASH @ DESY



TTF-FLASH Cryomodule Performances

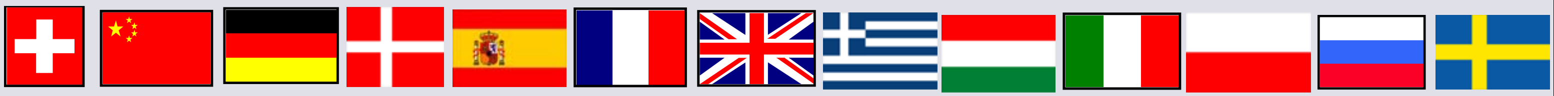


A more flexible RF Distribution System will allow higher operation gradient

XFEL International Project Preparation

XFEL Steering Committee ISC (Chair: John Wood, UK)

- Representatives of all countries intending to contribute to the XFEL facility
- ***13 countries have signed MoU (project preparation phase) in 2004***



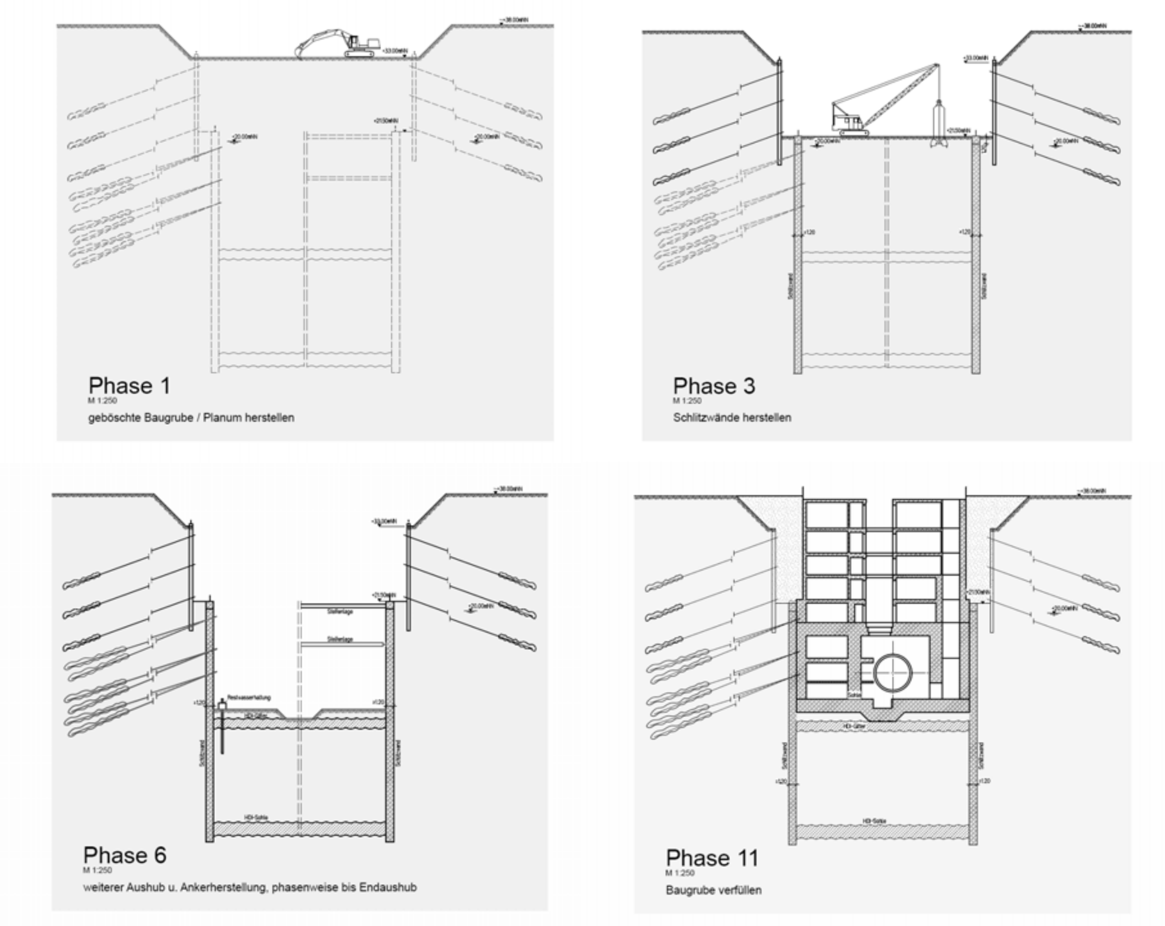
CH	CN	DE	DK	ES	FR	GB	GR	HU	IT	PL	RU	SE

- ***European Project Team (Leader: Massimo Altarelli)***

WG on Scientific and Technical issues STI (chair: F. Sette, ESRF)

WG on Administrative and Funding issues AFI (chair: H.F. Wagner, Germany)

XFEL Ground Breaking started

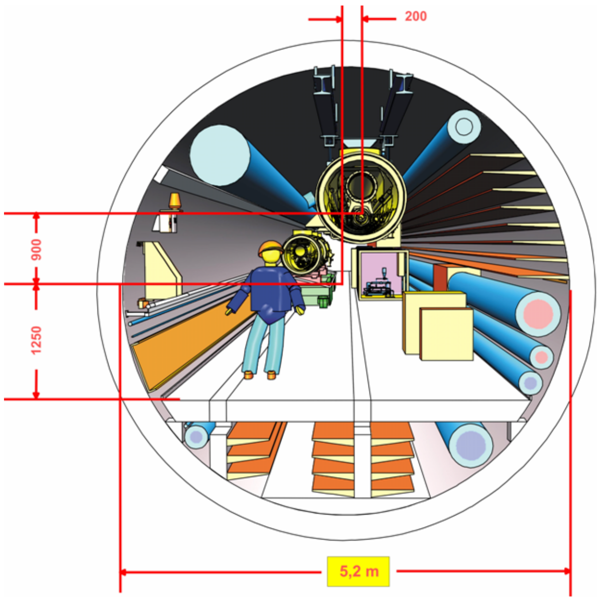


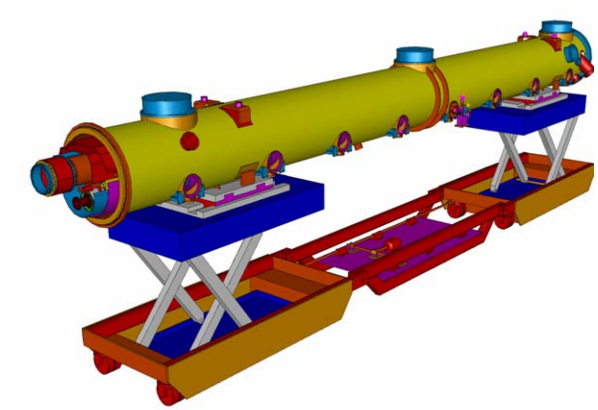
Ground-breaking started in 2008

The tunnel and shaft buildings will be realized in a depth from 12 m up to 44 m below the surface.

The **foundation** of the buildings will thus be situated **below the groundwater table** and the buildings will lie up to 20 m inside the groundwater.

The XFEL Tunnel - will start on 2009

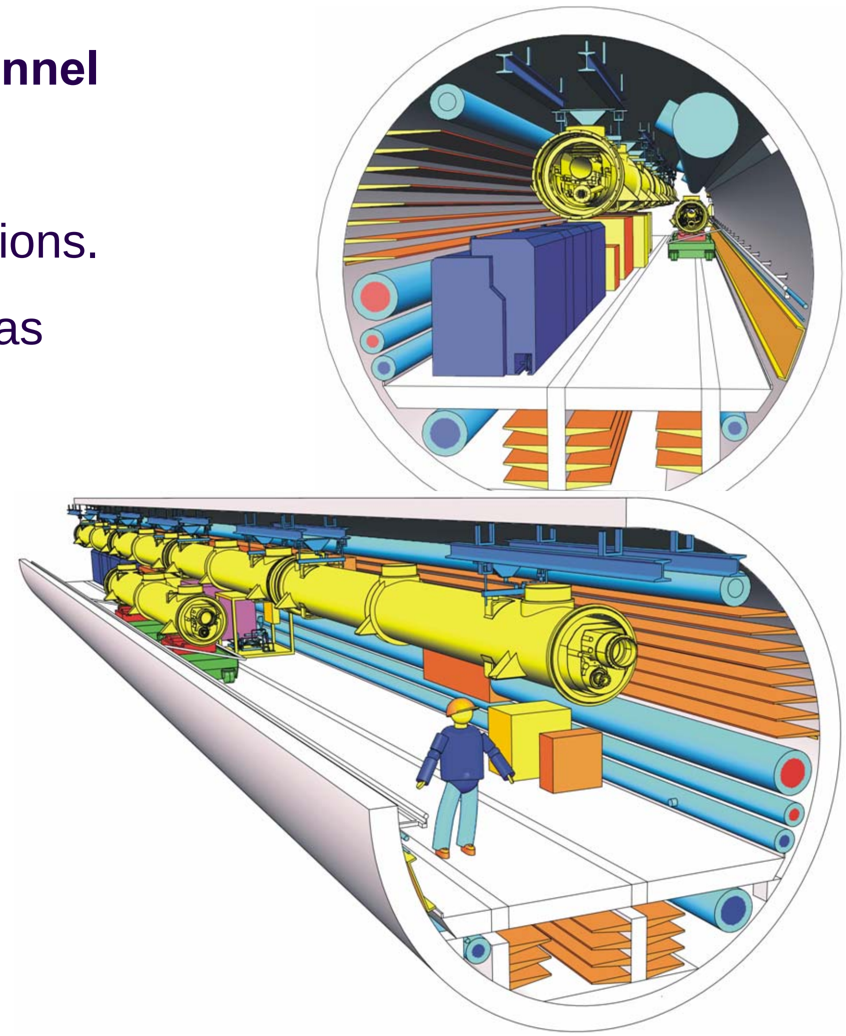




The **XFEL tunnel layout** was developed in several iterations.

A **mockup** has been built.

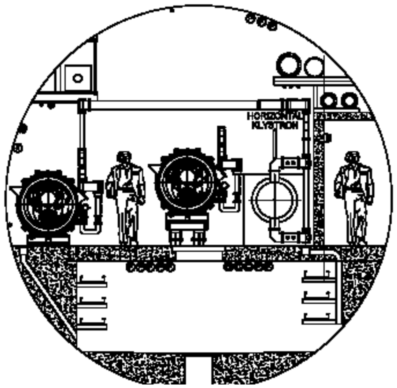
Installation procedures are under study.



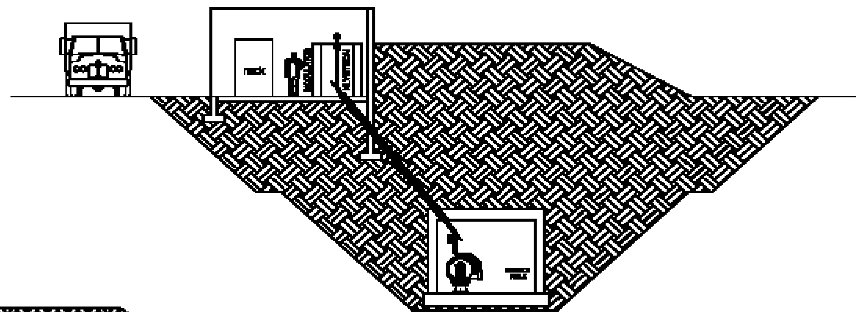
XFEL Tunnel Mockup at DESY

Mockup Module and Tunnel

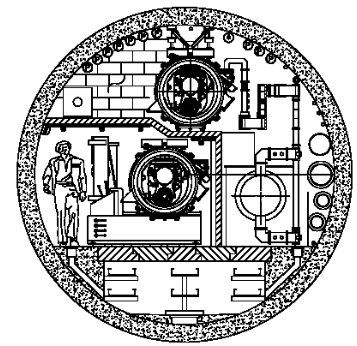
New ILC Potential Cross-Sections



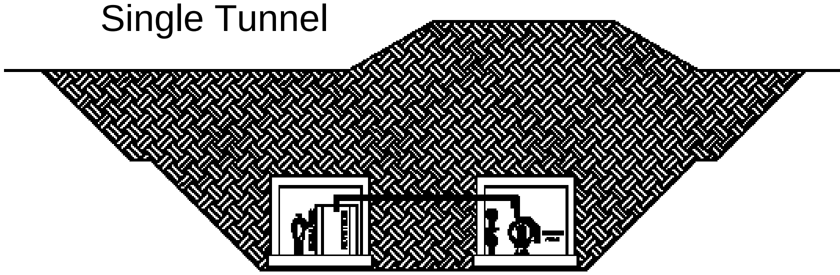
Single Tunnel



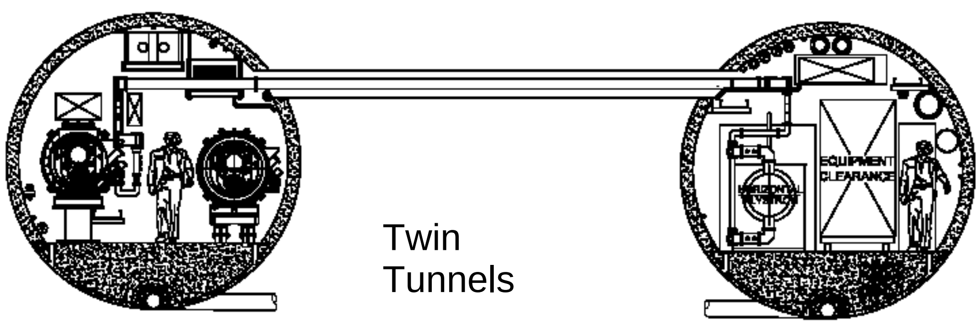
Open Cut



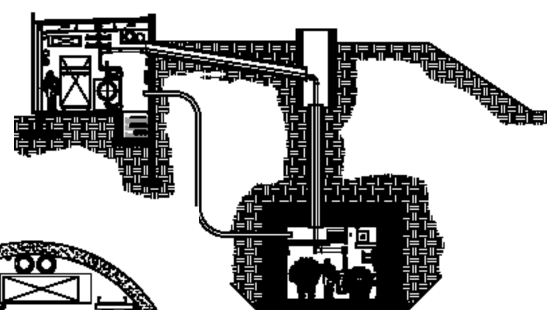
Single Tunnel



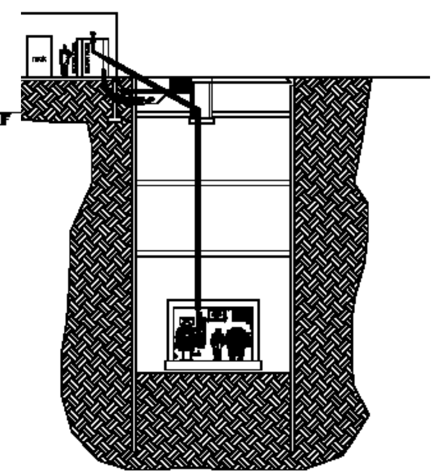
Open Cut Twin Enclosures



Twin
Tunnels

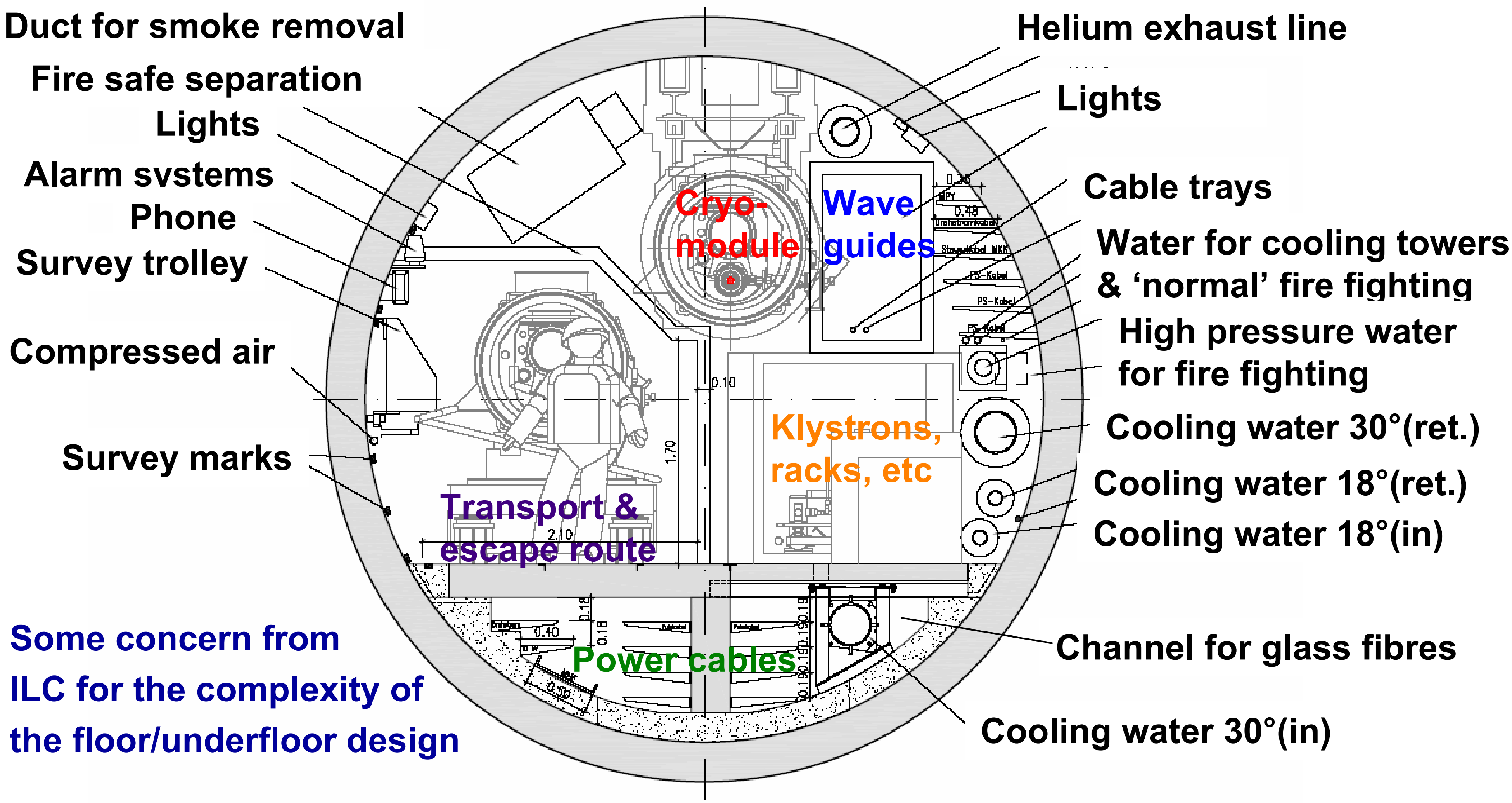


Open Cut



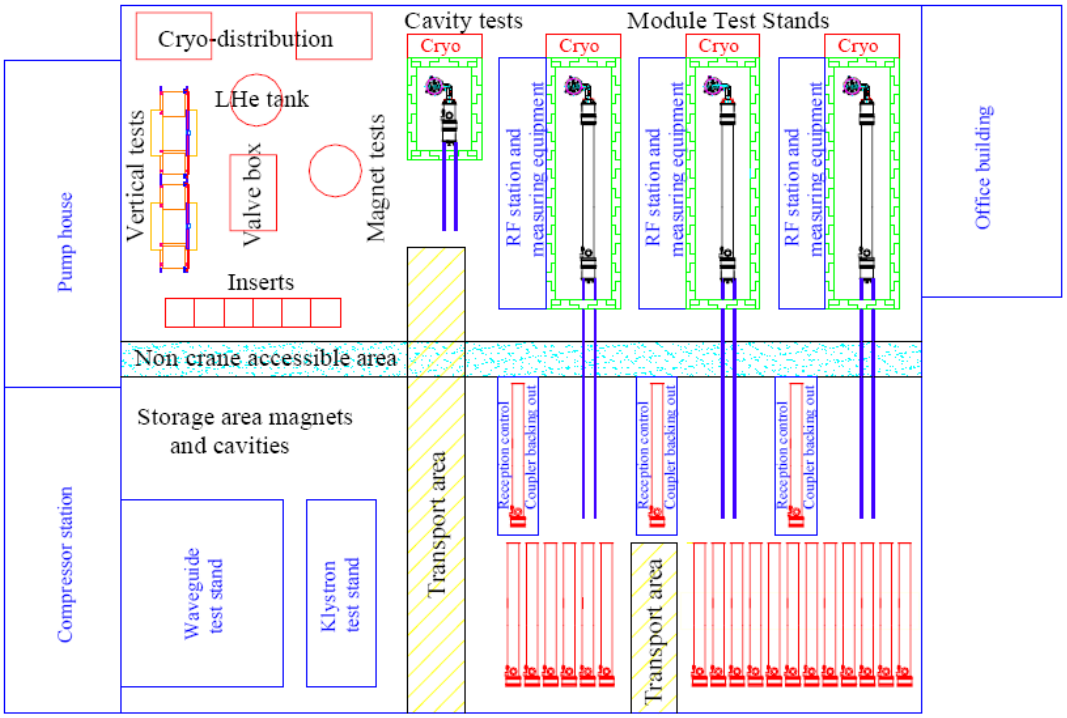
Braced Excavation

XFEL Tunnel cross-section



Some concern from
ILC for the complexity of
the floor/underfloor design

XFEL Accelerator Module Test Facility



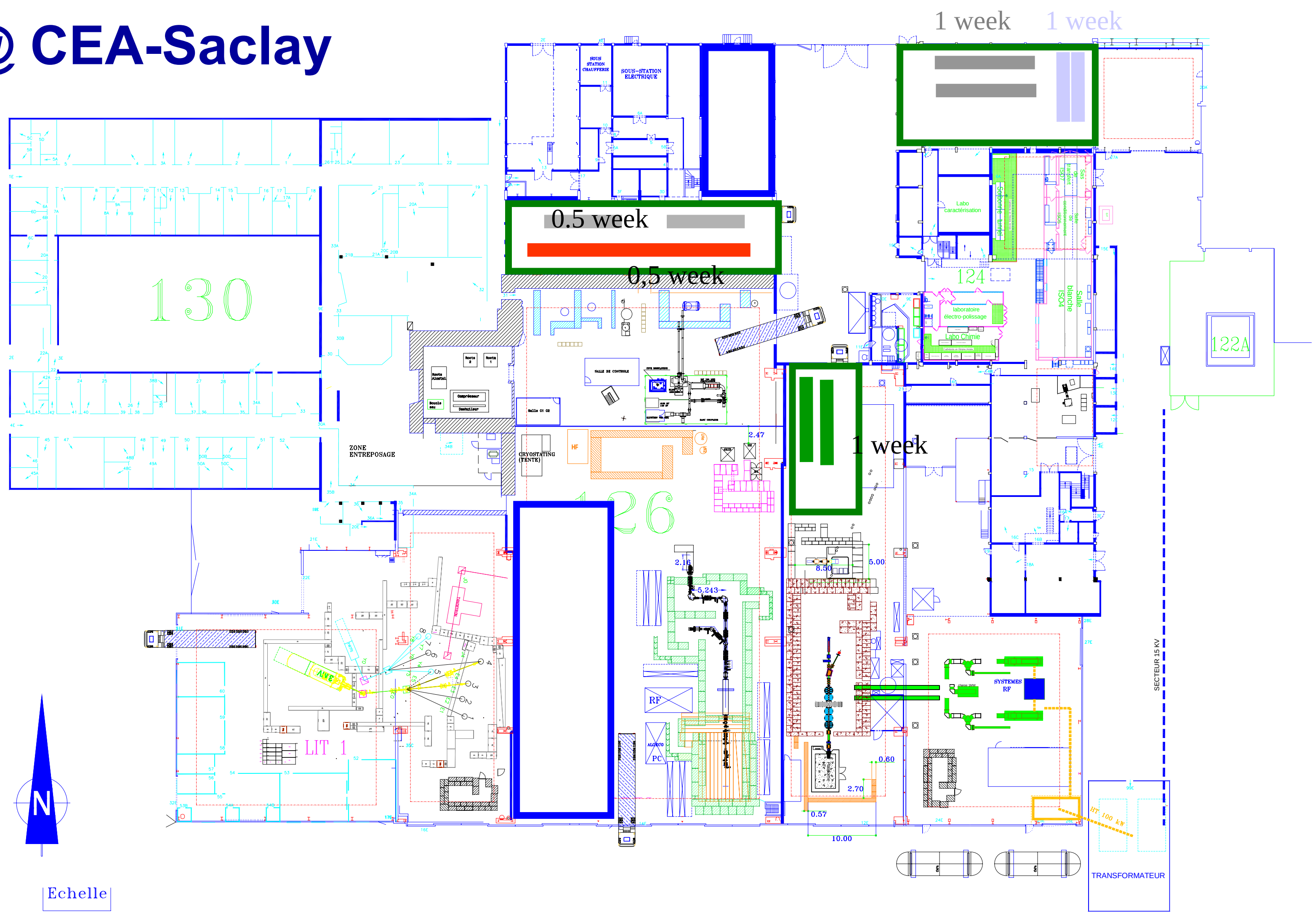
@ DESY

TDR version of the AMTF. After some iterations (costs, practicability) the final version to be built until 2009 will look slightly different.

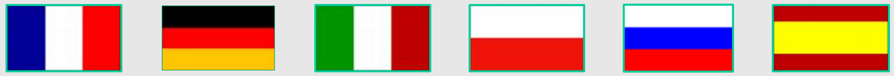
The XFEL requires an **Accelerator Module Test** of all 101 individual modules. The test rate is 1 module/week corresponding to the envisaged assembly rate. In order to be most efficient, the **vertical test** of bunches of cavities is integrated. Othee issues are **waveguides and cold magnets**.

Cryomodule Assembly Infrastructure

@ CEA-Saclay

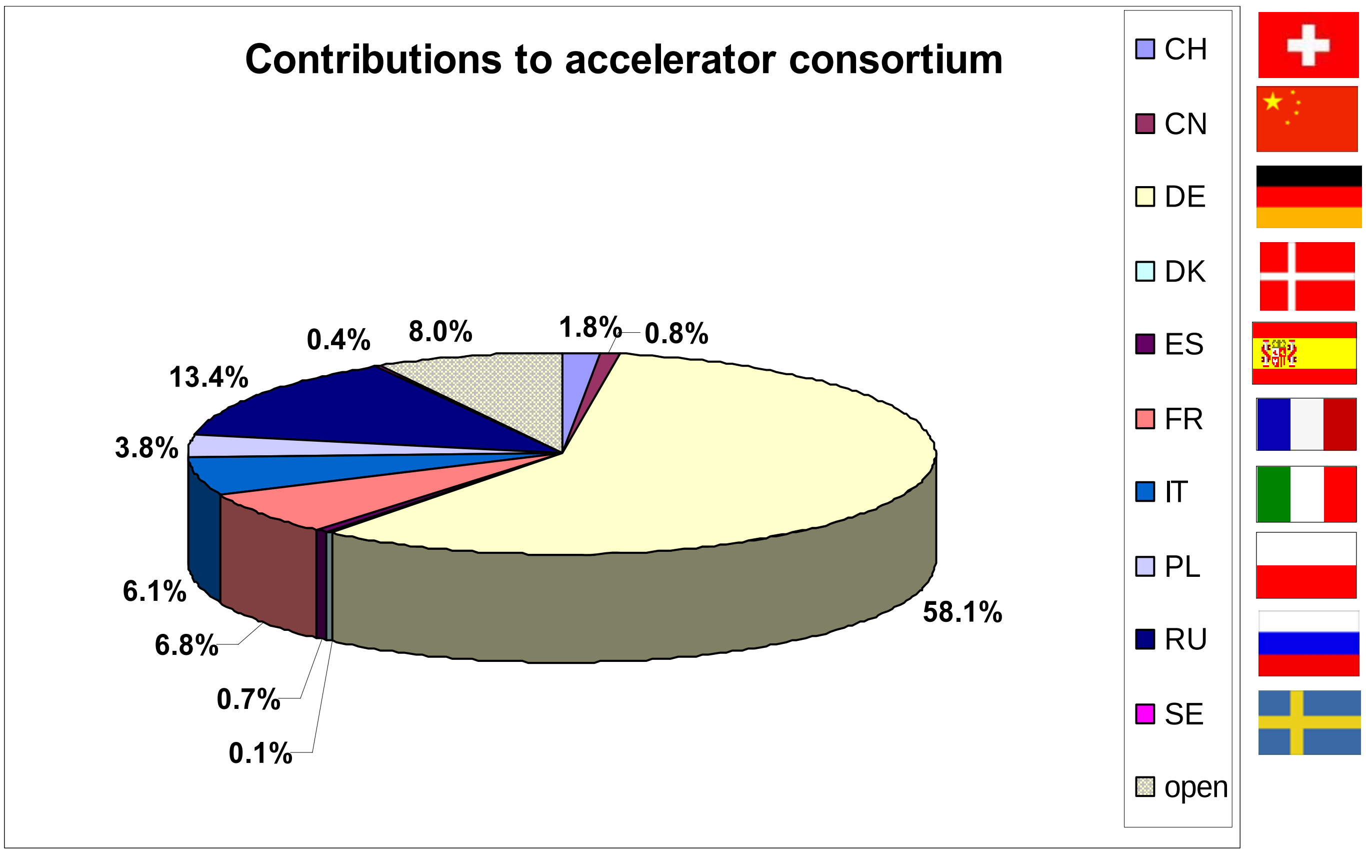


International Consortium for the Linac

	
WP 01: Power RF	DESY & RU
WP 02: LLRF	DESY & Lodz
WP 03: Module	CEA & DESY & INFN
WP 04: Cavities	DESY & INFN
WP 05: Coupler	DESY & LAL
WP 06: HOM	DESY & Swierk
WP 07: Tuner	DESY & INFN
WP 08: Cold Vacuum	DESY & BINP
WP 09: String Assembly	CEA & DESY
WP 11: Cold Magnets	CIEMAT & DESY
WP 46: 3.9 GHz	DESY & INFN

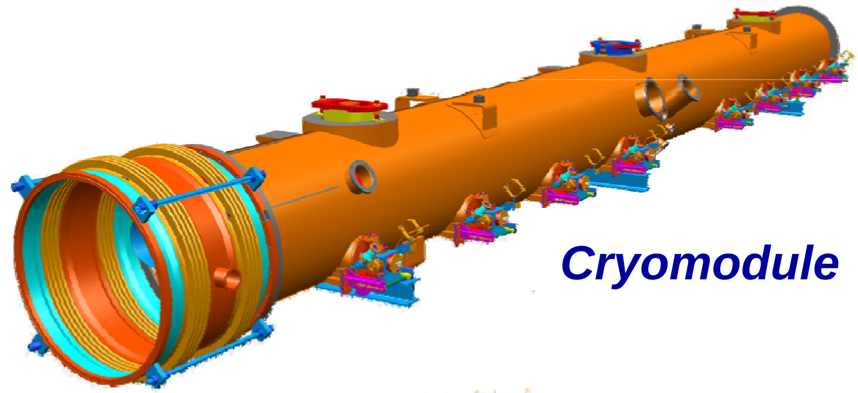
In-kind Contributions Picture

Preliminary picture – Final numbers at the end of negotiations

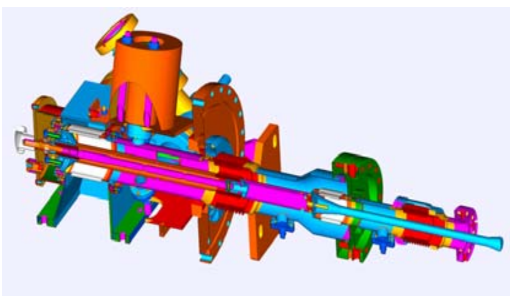


XFEL / ILC Accelerator Components

cavities

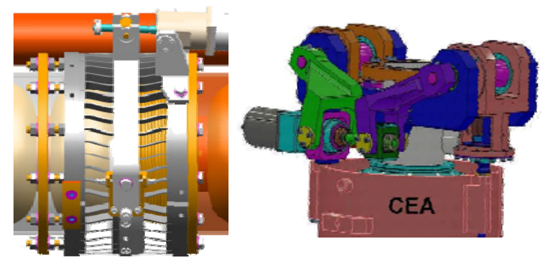


Cryomodule



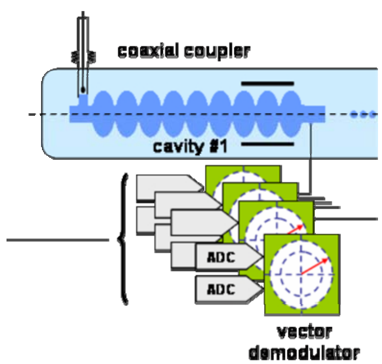
coupler

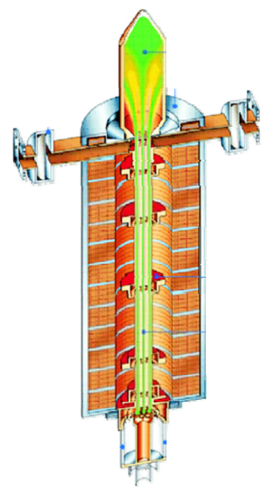
TESLA Technology



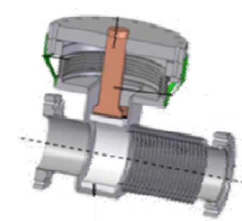
Tuners

LLRF





RF



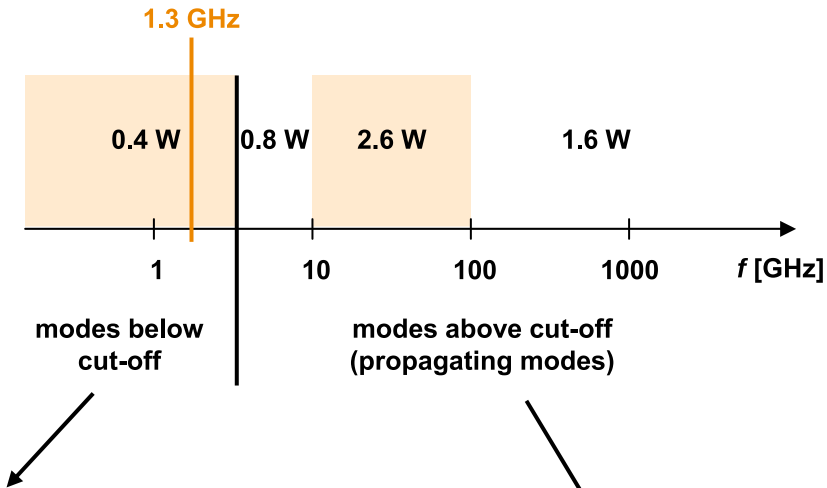
HOMs

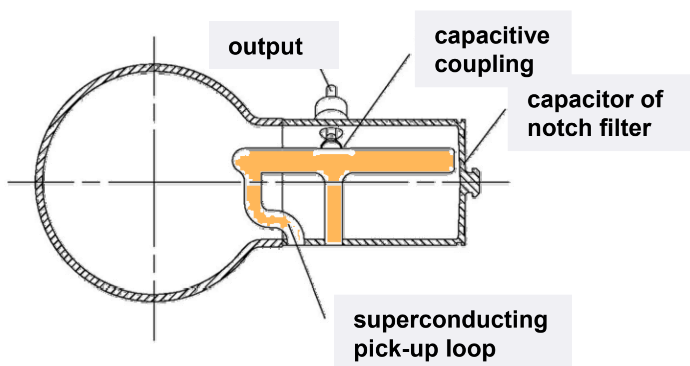
Damping of Higher Order Modes

The spectrum of the XFEL electron bunch (σ_z = 25 µm) reaches high frequencies up to 5 THz.

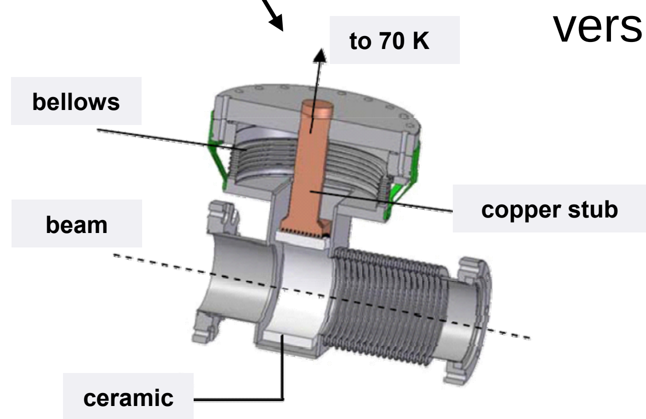
The standard accelerator module has an integrated loss factor of 135 V/pC.

The total power deposited by the nominal beam is 5.4 W per module.





HOM coupler

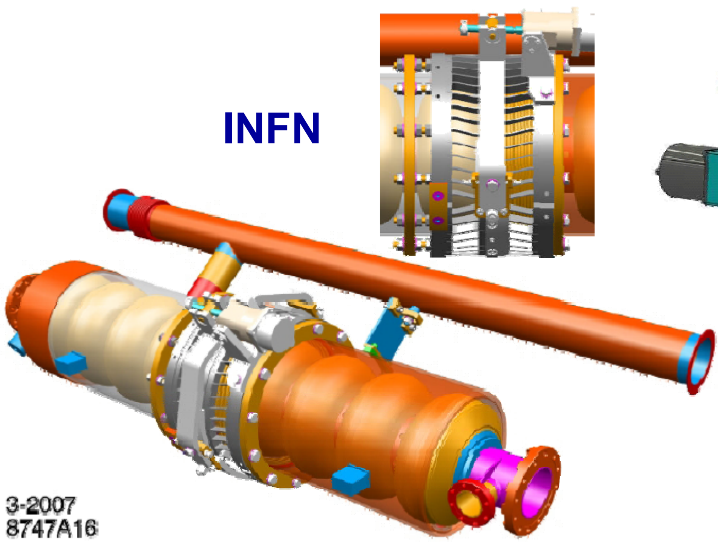


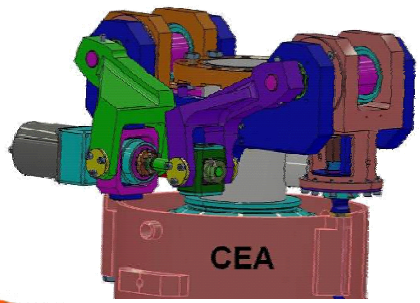
beam pipe absorber

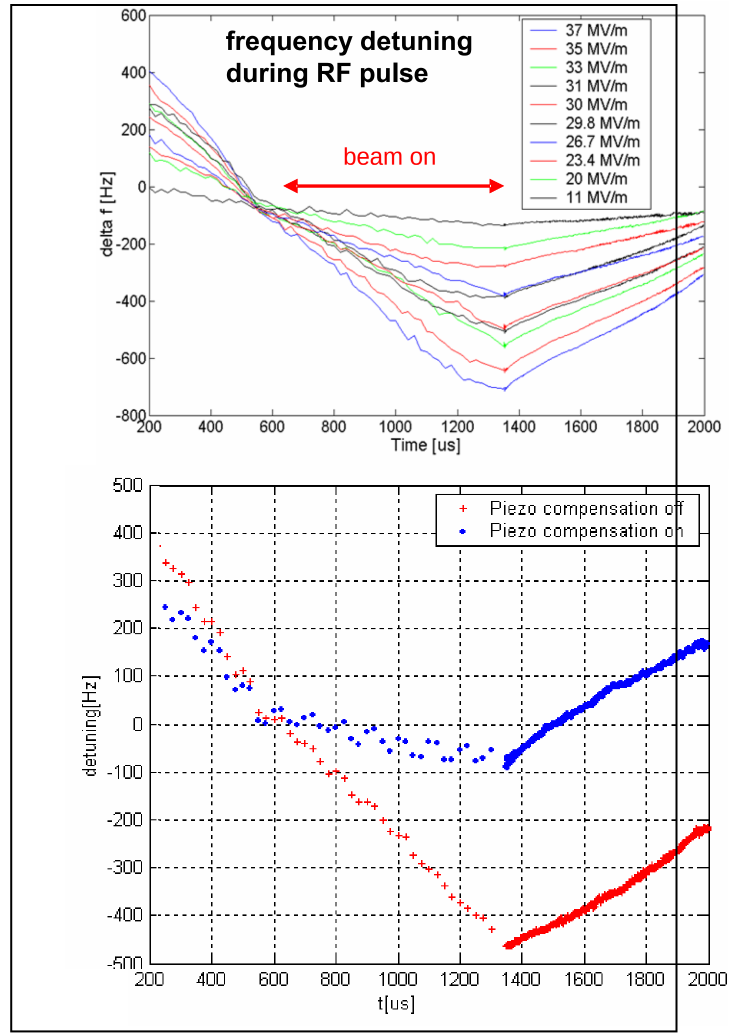
The ILC should have a little less HOM power at high frequencies.

Nevertheless, **HOM couples and absorbers are required.** The XFEL version is available.

Slow and Fast Frequency Tuner



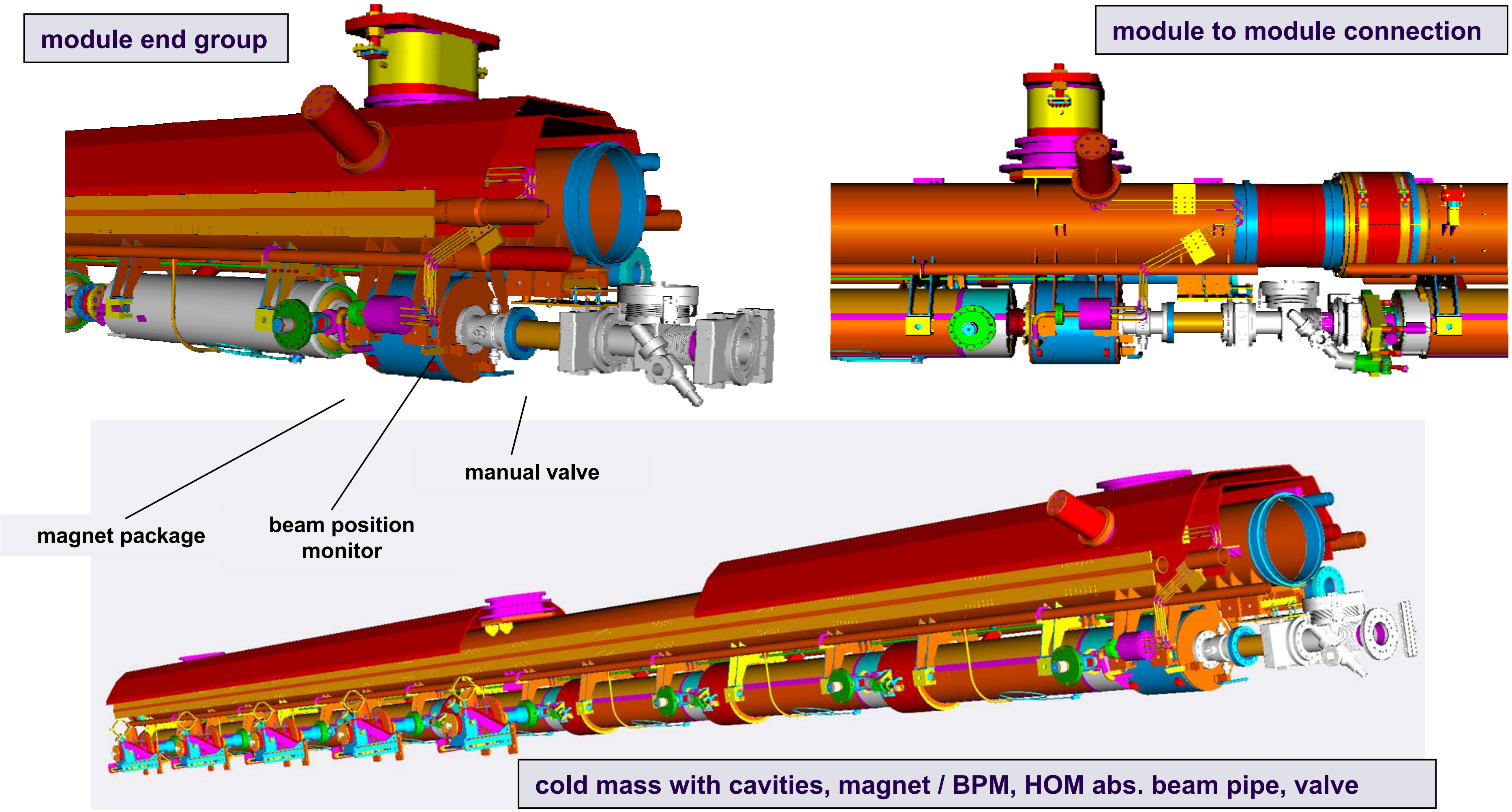




XFEL and ILC tuners look different, but **critical parts are identical**. DESY and INFN are co-leading the XFEL Tuner Working Package

- The slow tuner compensates for drifts; 400 kHz range, 1 Hz resolution.
- The fast tuner compensates the Lorentz-Force detuning during the RF pulse.
- **Blade Tuner option still open for the XFEL**

Accelerator Module (Cryomodule)



XFEL-ILC Cryomodules

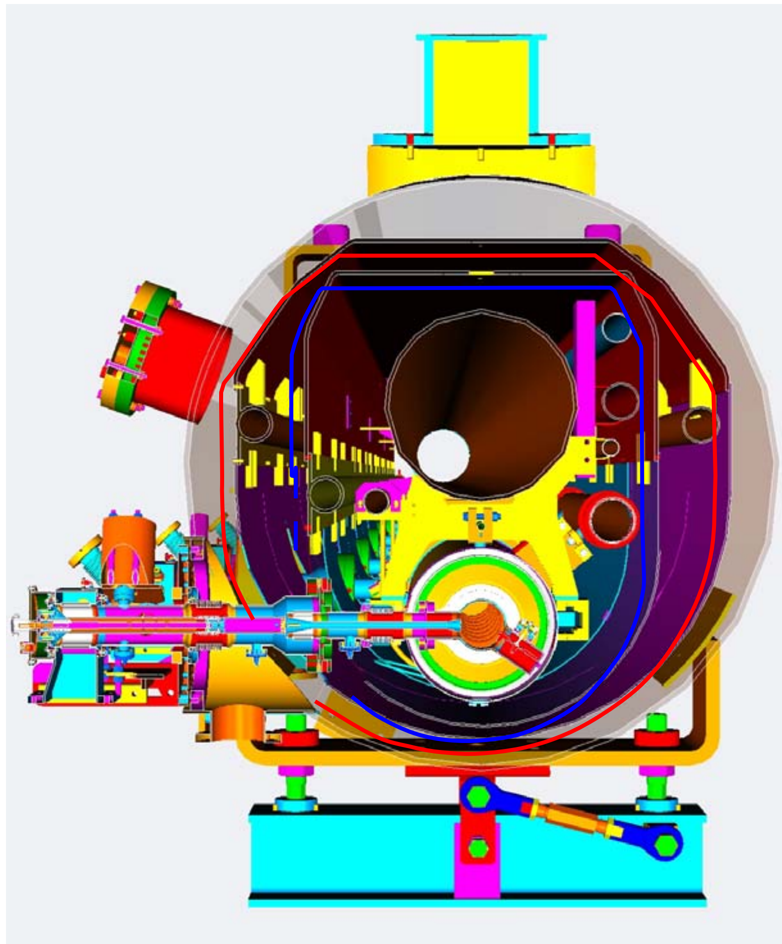
The XFEL accelerator module is based on the 3rd cryomodule generation of the TESLA Test Facility All designed by INFN.

Already 10 cryomodules have been built and commissioned for the TTF Linac.

Module 6 and Module 7 (repl. ACC3) are installed at TTF/FLASH.

Additional cryostats were available in 2007:

- Module 8
  spare for FLASH or ACC7
- Module 9
  assembled at Fermilab
- 3 additional cold masses under construction in 2008 by 3 new vendors (from France, Spain and China)

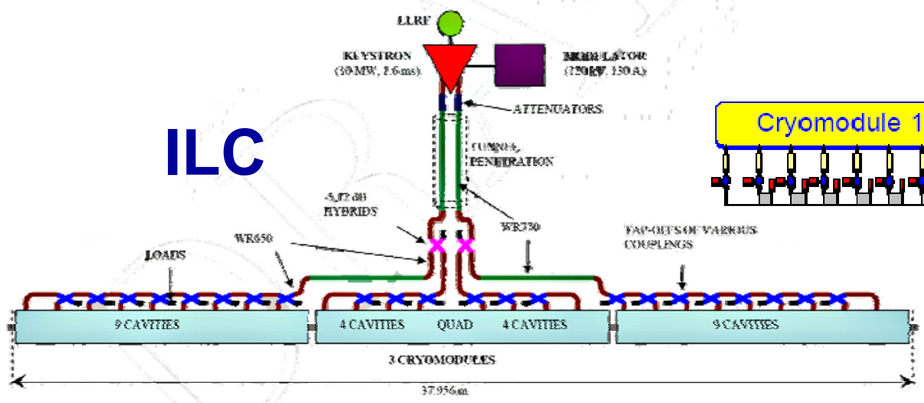


The **same baseline design** is used for XFEL and ILC.

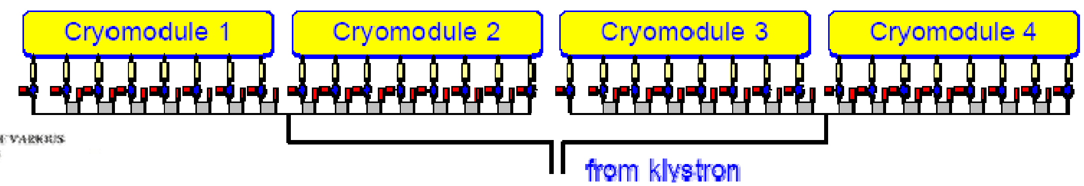
Minor modifications (quads, BPM, nbr. of cavities, overall length) should have almost no impact on industrialization.

Open issue: **vibration sensitivity** in the ILC case. The XFEL requirements are fulfilled.

XFEL–ILC High Power RF Systems



XFEL



Toshiba E3736

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.

XFEL needs

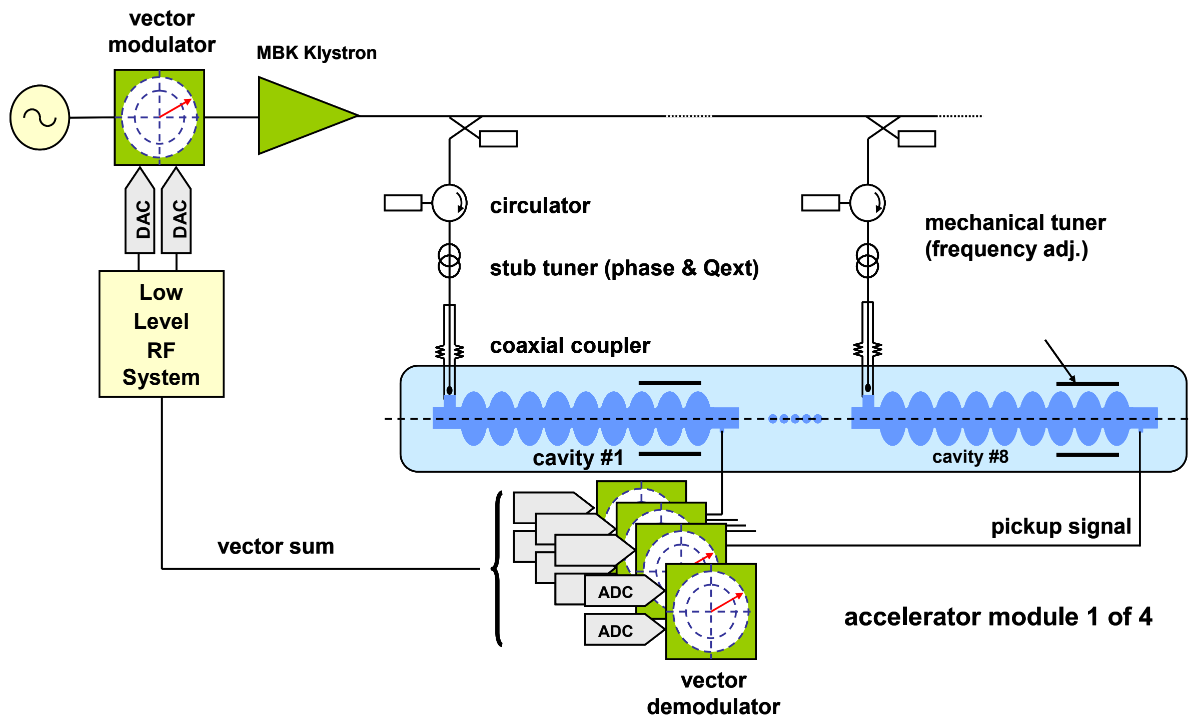
31 RF stations

- **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



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.

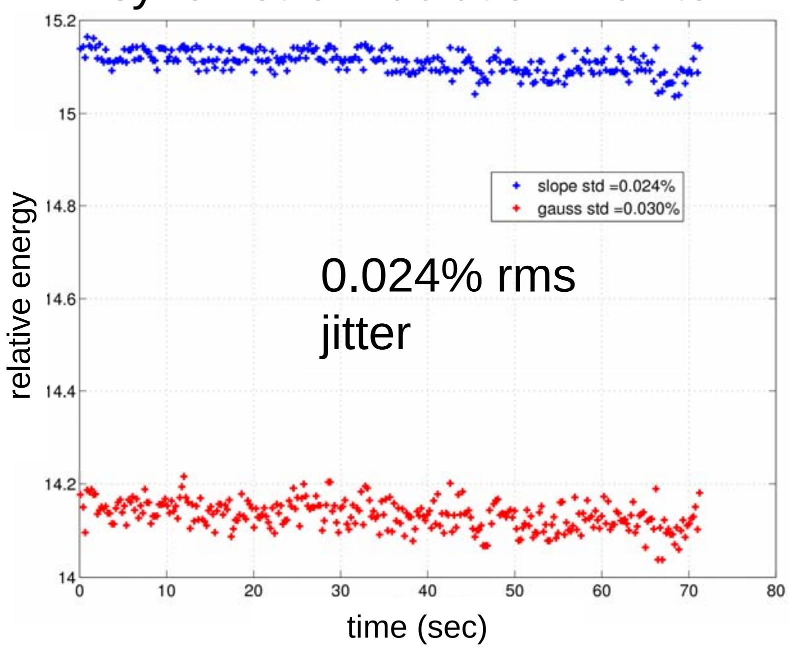
The **ILC numbers are more relaxed:** 0.35% amplitude and 0.07° phase stability. XFEL development will be beneficial in any case

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'.

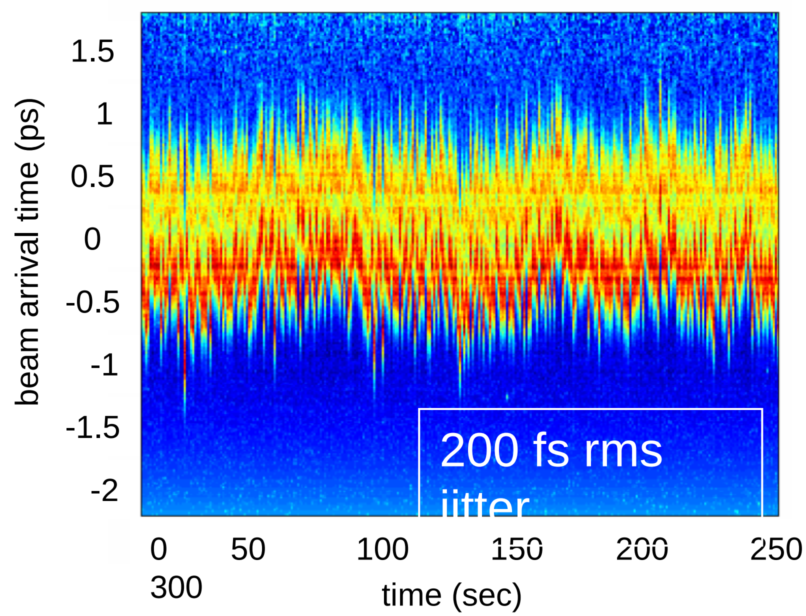
Progress on LLRF/energy stabilisation

- dE/E = 2.4 10^{-4} measured at 127 MeV
- electron and FEL beam arrival time jitter 200 fs rms

Energy jitter measured with synchrotron radiation monitor



Beam arrival time measure with electro-optical decoding



*Crash-Tests Performed with M3**

CMBT-Test 08.01.2008 – 16.05.2008

Test 1 venting isovac. slow with He (He-leak) - 2K operation

Measurement:cavity.performance.and cryoloses / Max. pressure isovac.: 10-5mbar up to 2 mbar

Test 2 venting couplervac. slow with N2 - 2K operation

Measurement: cavity.performance.and cryoloses / Max pressure couplervac. < 600 mbar

Test 3 venting beampipevac. slow with N2 – 2 K operation

Measurement: cavity.performance.and cryoloses / Max. pressure beampipevac. 6*10-6 mbar

-First warm up 300K

Test 4 and 5 venting isovac. fast / air – 2 K operation > 1bar

-Second warm up 300K

Measurement: cavity.performance.and cryoloses / we have to repair he-leak 2k-area / isovac.

Test 6 venting beampipevac. fast / air – 2 K operation > 1 bar

-Third warm up 300K

Measurement: cavity.performance.and mech. detuning of cavity´s

Test 7 venting beampipevac. fast / air – 4,5 K operation > 1 bar

Measurement: cavity.performance.and mech. detuning of cavity´s

Test 8 venting isovac. fast / air – 4,0 K operation < 1 bar

Measurement: Diff.-pressure isovac. / Temp. development of vac.vessel

- Fourth warm up 300K, end of Mod.3-Star test

M3* on CMTB after crash tests

Major XFEL Contributions to the ILC

XFEL is a factor 20 extrapolation of **TTF-FLASH**
ILC is a factor 20 extrapolation of **XFEL**

- **The experience of the construction of a 1/20 scale ILC will**
  - Prove the technology transfer to Industry
  - Prove the cost reduction through industrial competing contribution
  - Prove the learning curve parameters
  - Prove the effect of industrial QA and QC methods
  - Set the limits of an industrially based TESLA technology
  - Set numbers for cavity and ancillaries performances and yields
- **The experience of the operation of a 1/20 scale ILC will**
  - Prove MTBF and MTTR of components and systems
  - Prove and improve operation and setting strategies
- **XFEL is a pilot experience** for creating and organizing an **International Project** based on **in-kind contributions**