5th Zeuthen Workshop on Elementary Particle Theory

Loops and Legs in Quantum Field Theory

Bastei/Königstein, Germany

Sunday, April 09 - Friday, April 14

A. Wagner

New Frontiers in e+e- Collisions The Physics Potential of TESLA

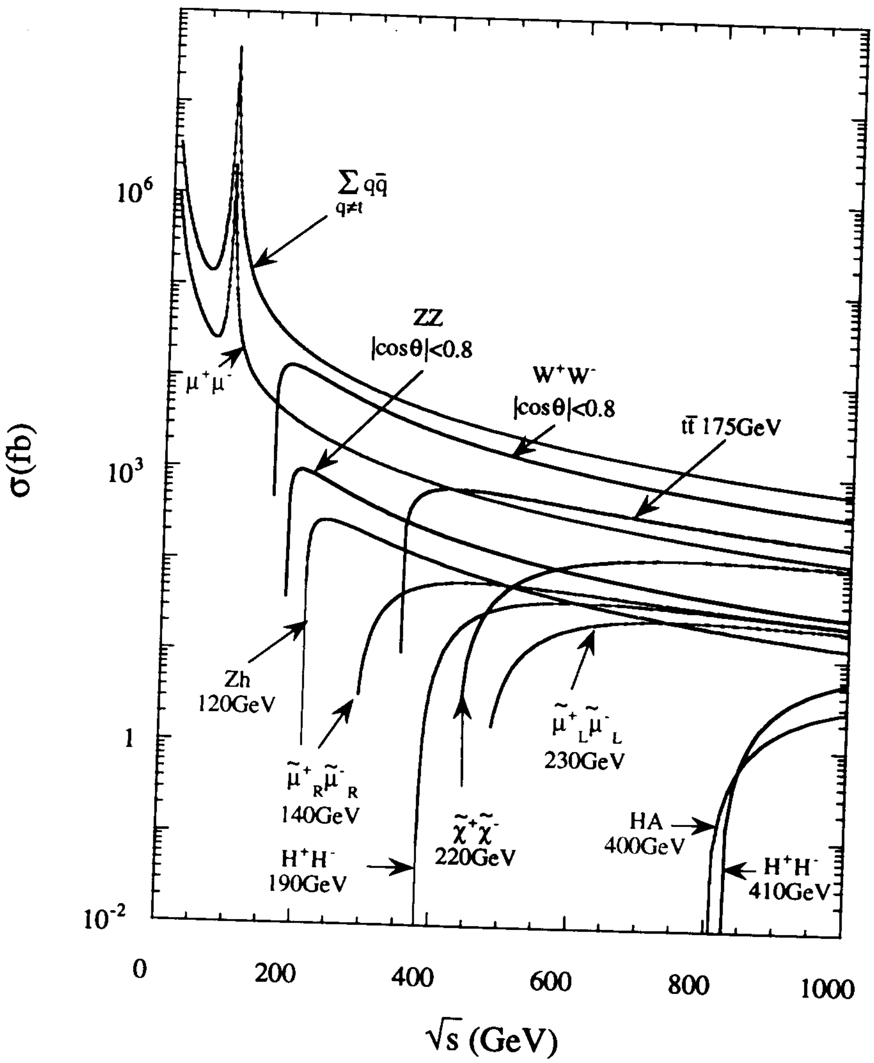
45.

New Frontiers in e+e- Physics
The Physics Potential of TESLA

Albrecht Wagner
University of Hamburg and DESY

Parameters of the LC

- e^+e^- Accelerator, $\sqrt{s} = 500 - (1000)$ GeV
- Luminosity $\mathcal{L} \approx 3 - 50 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- integrated luminosity per year: $50 - 500\mathrm{fb}^{-1}$



- $1 \cdot 10^5$ Higgs/ year
- $3 \cdot 10^5$ $\mathrm{t\bar{t}}$/ year
- $1 \cdot 10^6$ WW/ year

at $\sqrt{s} = 500$ GeV
at $500 fb^{-1}$/ year

- large amounts of data available
- precision physics!

Linear Collider:

Search for New Physics

high precision study of $200\,\mathrm{GeV} \lesssim E_{cm} \lesssim 1\,\mathrm{TeV}$

Precision Measurements

Forces and particles within the Standard Model are affected by new physics, therefore perform precision measurements of

- top quark
- gauge bosons
- (Higgs)

Search for and Study of New Particles

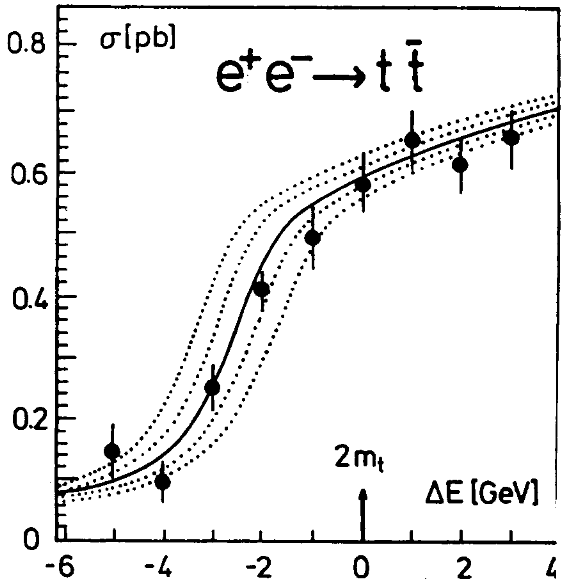
Search for new fundamental particles and study of their properties, when found

- (Higgs)
- Supersymmetric Particles
- The unexpected

TOP PHYSICS

- An LC(500) is a “TOP factory”
- allows precision physics in the top sector

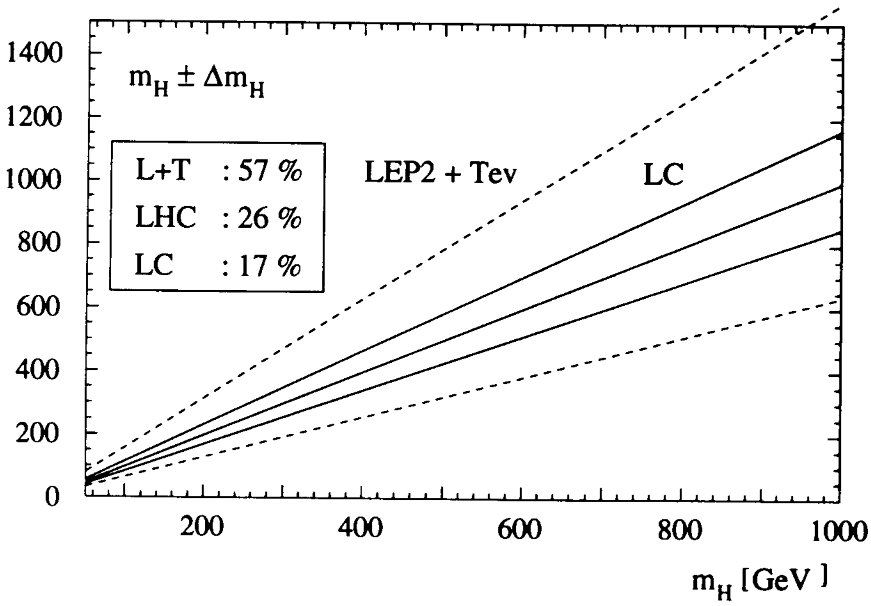
plot for 50 fb^{-1}



Excitation curve of the top quarks including initial-s

based on $500 fb^{-1}$ integrated luminosity = 1 year of running:

$$\Delta m_t = \pm 100(\mathrm{stat}) \pm (100 - 200)(\mathrm{theo})\mathrm{MeV}$$



The Top, being the heaviest known fermion, is expected to be most sensitive to deviations in the standard model

Precision Measurements at Lower Energies

By building a by-pass, TESLA can produce

10^9 Z/y

with $P_{e^-} = \pm 80\%$ and $P_{e^+} \approx \pm 60\%$

↳ precision measurements

quantity	Improvement w.r.t present error
Γ_Z	2
$\alpha_s(M_Z)^*$	2
R_b	5
$\sin^2\theta^{\ell}_{eff}$	~ 10 ($\Delta_{A_{LR}} = 4 \cdot 10^{-5}$)
M_W	~ 10
A_b	20

$\delta \sin^2\theta \approx 10^{-5}$

$\delta M_W \approx 6$ MeV

↳ M_H $\Delta M_H / M_H = 5\%$ → compare to direct measurement

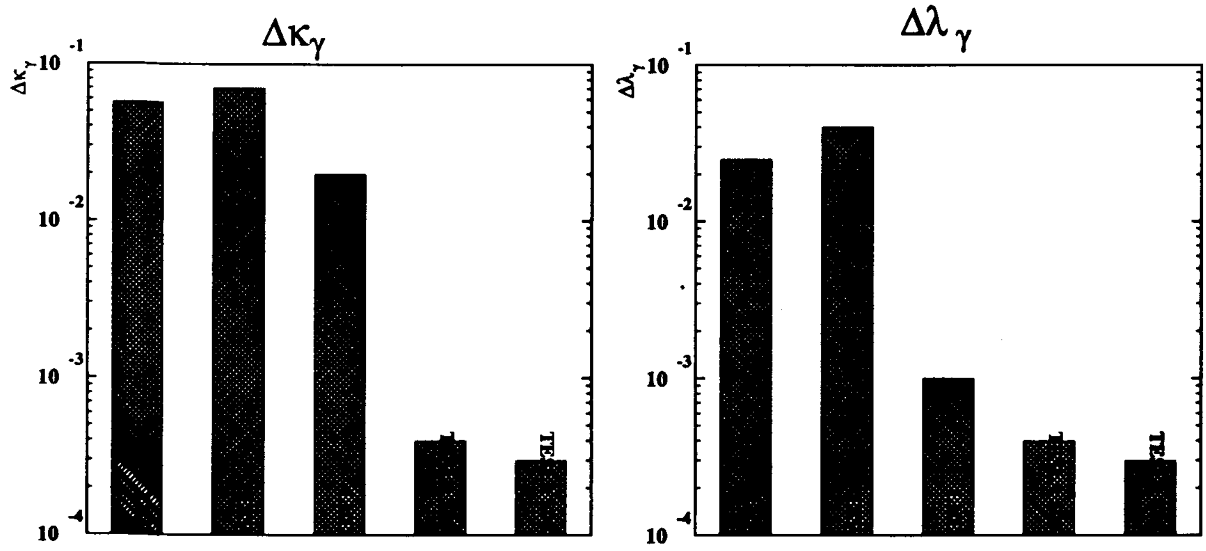
* from lineshape

The other quantities are limited by systematic errors.

Anomalous Couplings

- Important test of the Standard Model in general and of "no-Higgs" scenarios in particular
- Tripple gauge couplings open a window to possible new physics

- Comparison of sensitivity between LHC and LC



- LC has advantage for $\Delta\kappa_\gamma$
- LHC und LC comparable for $\Delta\lambda_\gamma$

  - LC has larger indirect reach (via $\Delta\kappa_\gamma$)
  - LHC has better direct discovery potential through reconstruction of resonances, if they exist

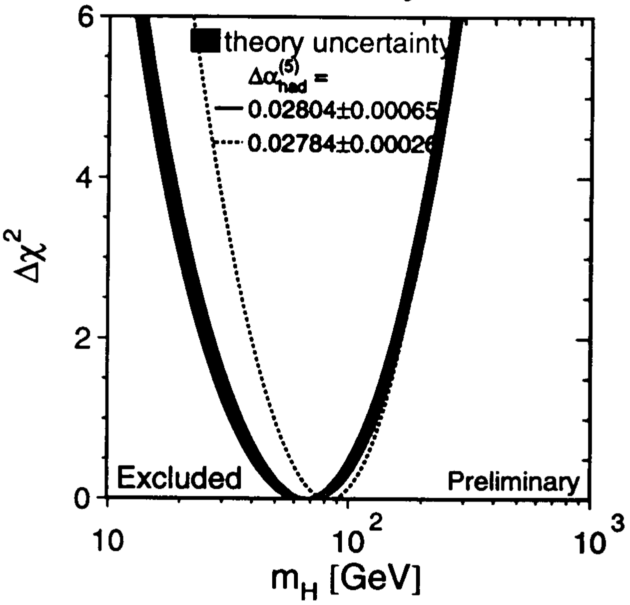
- high precision tests are possible

THE STANDARD MODEL

- SM experimentally enormously sucessful
- But:central question remains open:

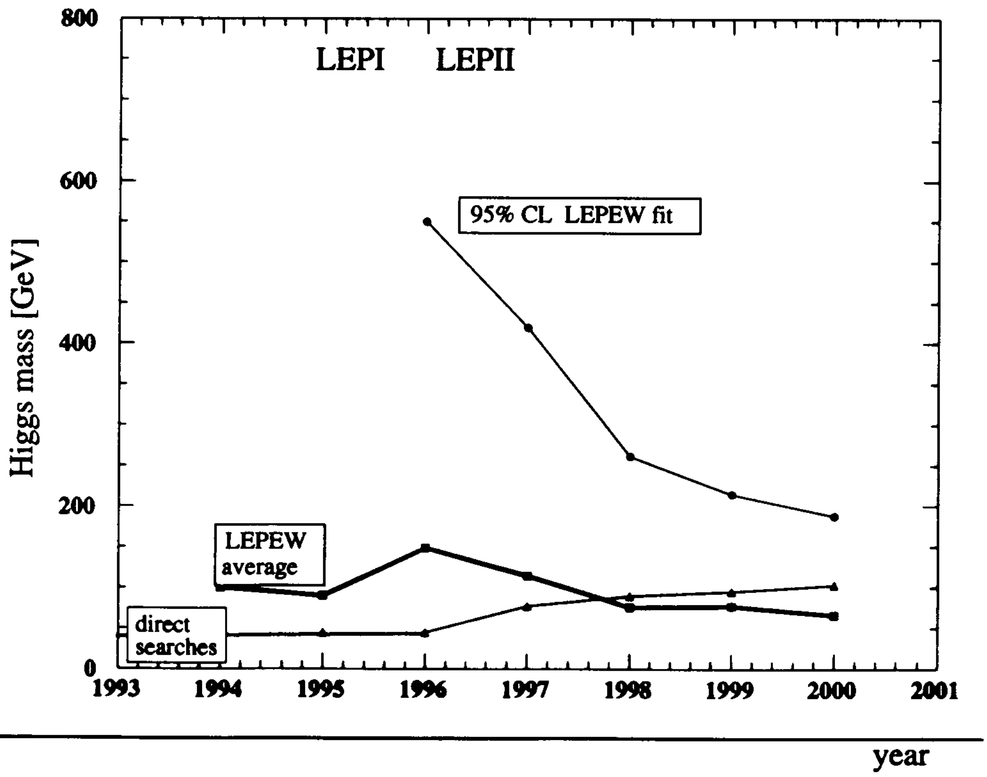
  breaking of the electroweak symmetry
- mechanism is not understood

- Where are we today?



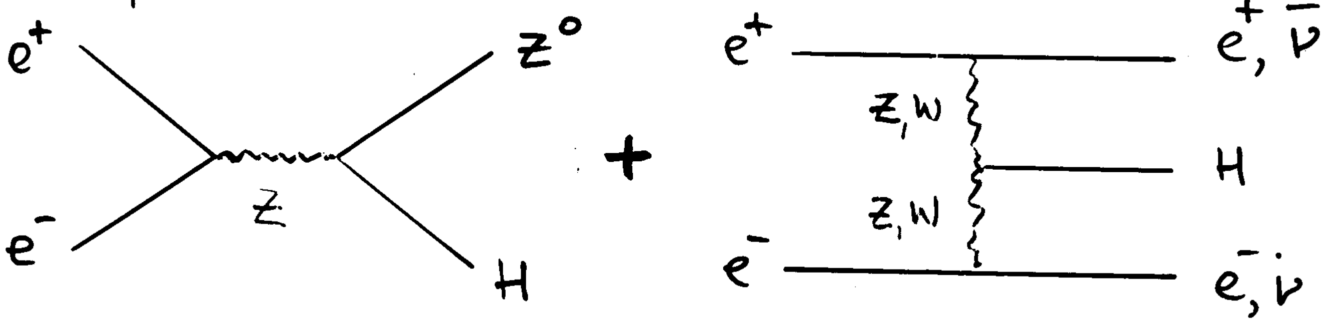
light Higgs favoured within the SM

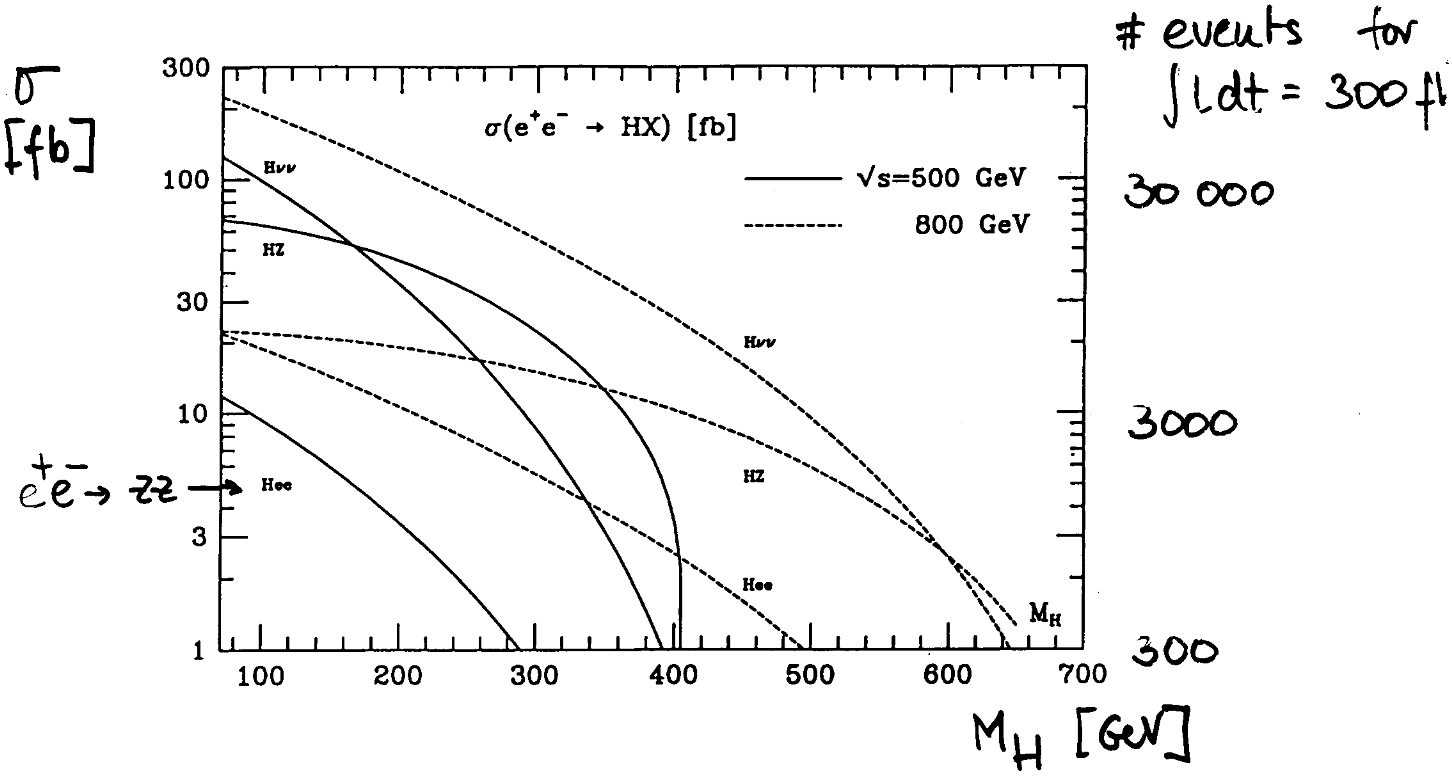
m_{Higgs}
$<$ 188 GeV
@ 95% CL



Standard Model Higgs

- production





- identify $Z \to \ell\ell, q\bar{q}$
- study recoiling system

measure either:

- mass recoiling against Z

or:

- invariant mass

} similar sensitivity

↳ unbiased study

Lohmann, Garcia-Abia

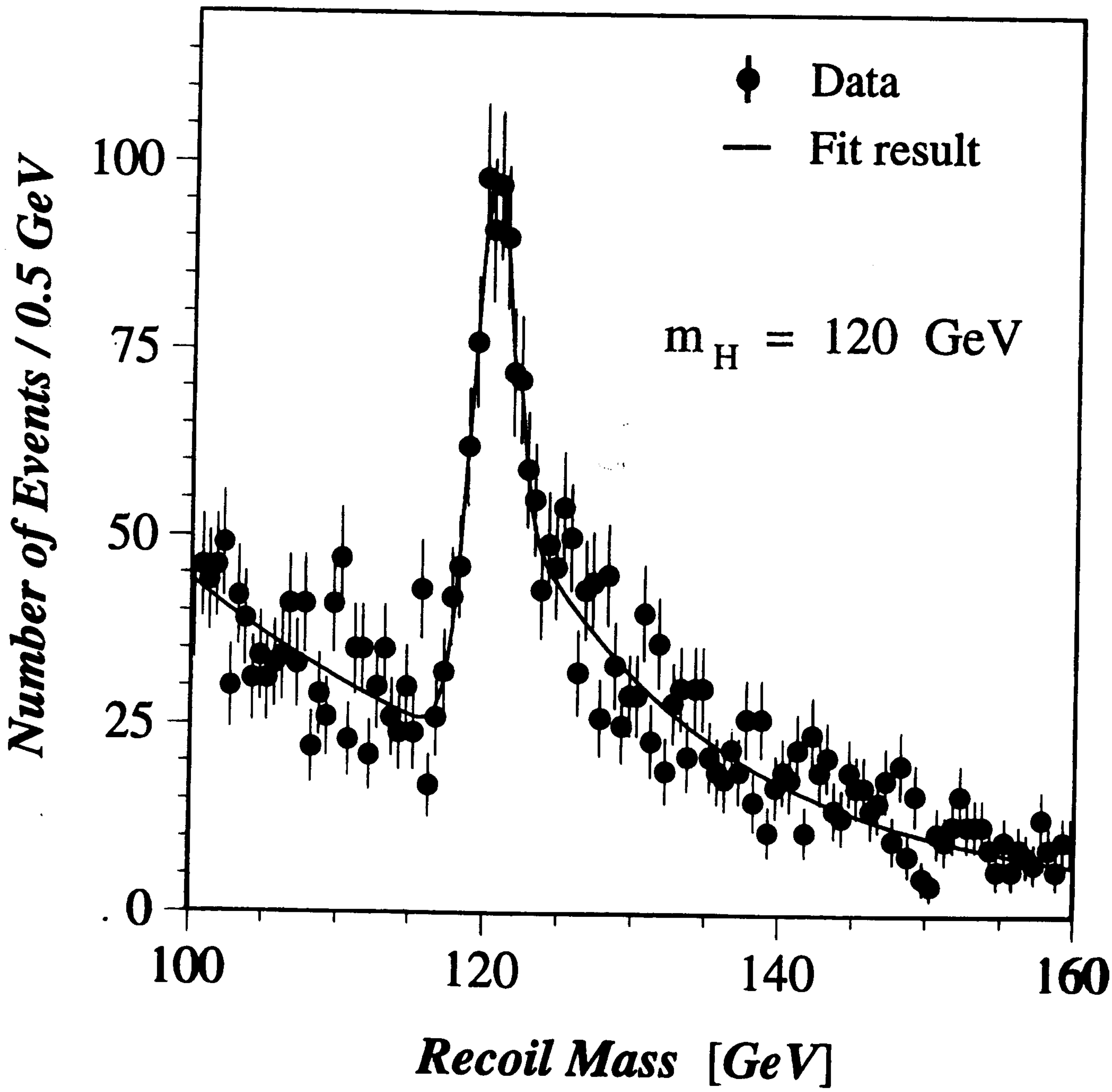
ECFA DESY Linear Collider Workshop

Recoil Mass Fit, e^+e^-

$$M_H = 120.48 \pm 0.14 \text{ GeV}$$

$$\sigma_H = 1.48 \pm 0.11 \text{ GeV}$$

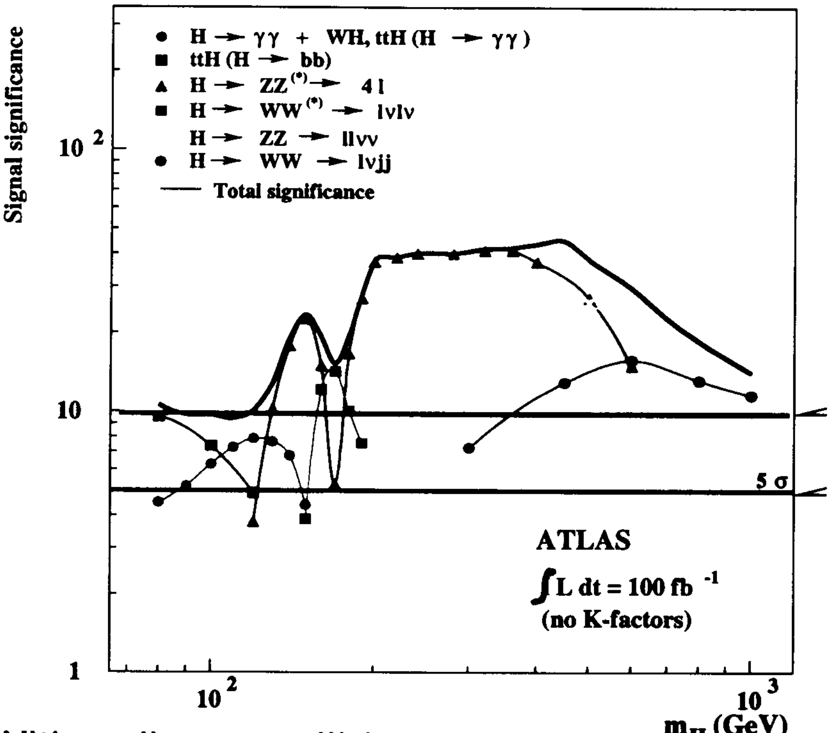
$$\sigma(ZH \rightarrow e^+e^-X) = 5.26 \pm 0.18 \pm 0.13 \text{ fb}$$



POSSIBLE HIGGS DISCOVERY

If nature has realised the Higgs:

Most probably the LHC will discover the Higgs



After three years convincing signals

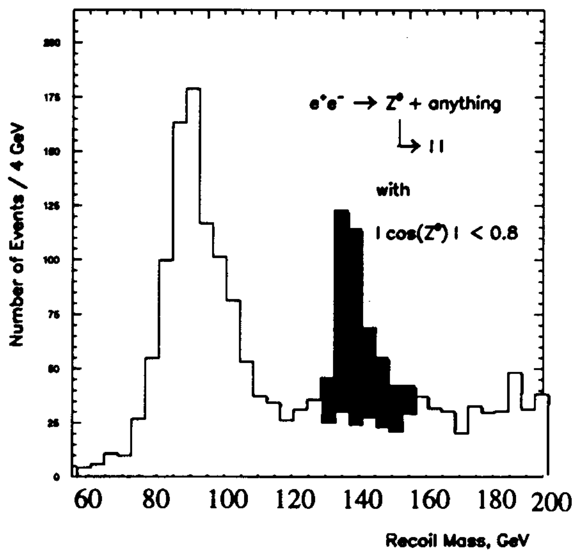
5 σ after 1 year

5 σ after 3 years

With a linear collider convincing signals will be seen after a short time

After one month at TESLA

mass to $\pm 1/10\%$ with 500 fb^{-1}

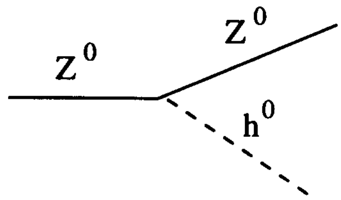


At high lumi $\approx 10^5$ Higgs bosons / year: precision measurements

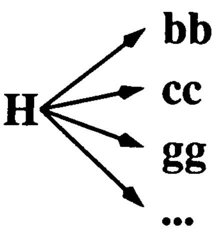
BEYOND A DISCOVERY

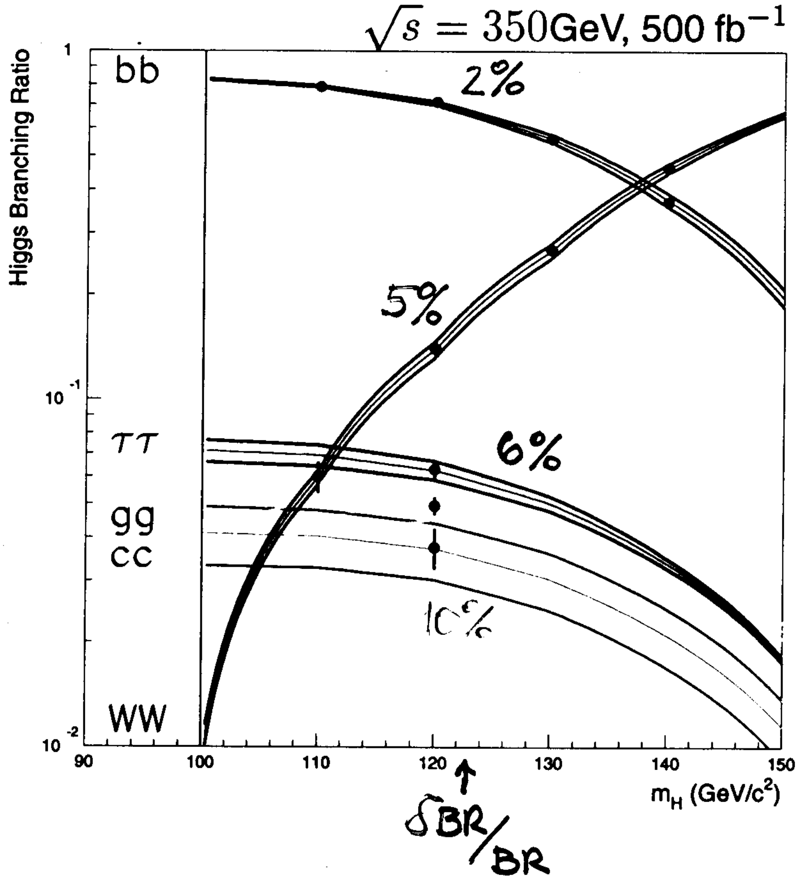
- Complete test of our understanding of mass

Does the Higgs explain the mass of the Z? $\sum W_i^2 = v^2$, where: $v = 246 GeV$

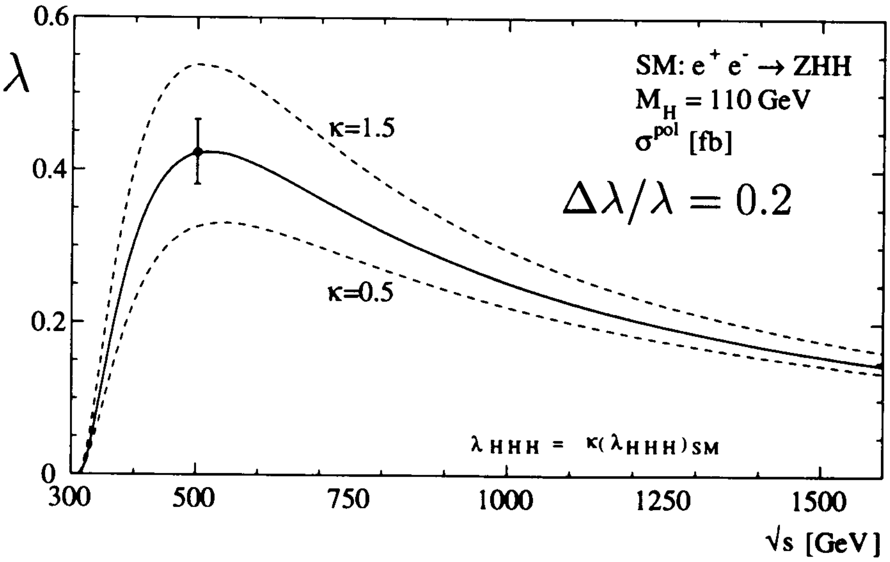


$$= \frac{M_Z^2}{v^2} W_i$$





precision measurements of Higgs decays on the percent level!



Higgs self-coupling:
Reconstruction of the Higgs potential
High Lumi is essential!

$$V = \lambda \left[|\varphi|^2 - \frac{1}{2} v^2 \right]^2$$

Minimal Supersymmetric Extension of the Standard Model

Why?

- eliminates divergence problems in SM
- unification of matter and forces

How?

- gauge interactions as in SM
- similar Yukawa interaction
- pairing of fermionic and bosonic particles - (each fermion gets a bosonic partner and vice versa)
- introduce two Higgs doublets, to give masses to all quarks and leptons

Arguments supporting SUSY

- SUSY predicts light Higgs
- SUSY predicts $\sin^2\theta_W \approx 0.234 \pm 0.002$ exp: $.2320 \pm .000$[illegible]
- unification of forces at 10^{16} GeV

Consequences:

- many new particles (SUSY particles)

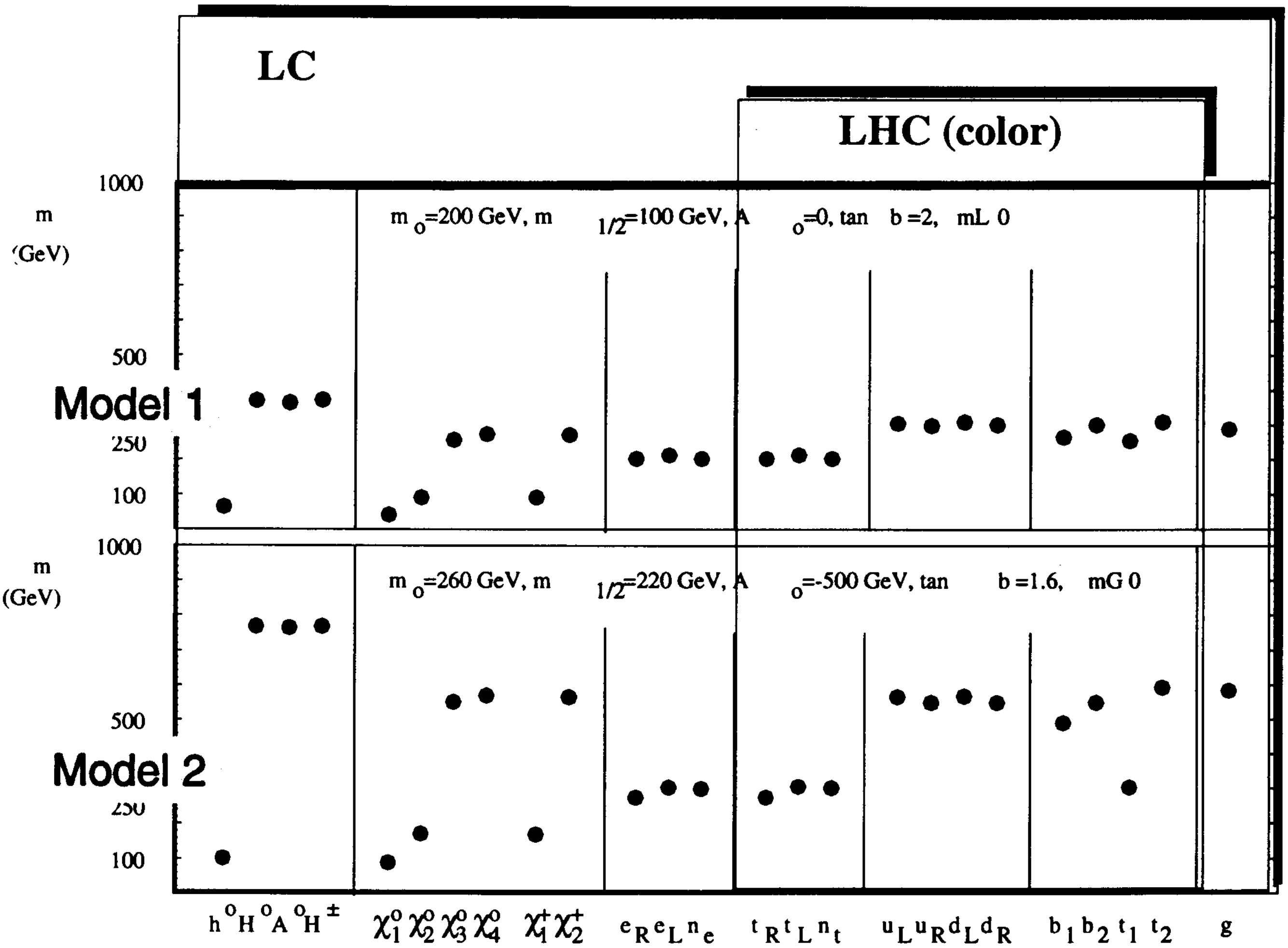
BUT......

- nothing seen so far

quantum theory of gravity

SUPERSYMMETRY

- Supersymmetrie: popular extension of the SM
- Different models predict widely different particle spectra:



- Linear Collider with high luminosity should be able to reconstruct and measure a large part of the spectrum.
- This is the only way to really understand the nature of supersymmetry (if it exists).

Precision Measurements will play a key role in this

The MSSM Higgs Sector

- <u>five states</u> : $h^0, H^0, A^0, H^\pm$

- <u>Masses</u>

  MSSM : $m_{h^0} \lesssim 140$ GeV

  $m_{H^0, A^0, H^\pm}$ depend on model parameters

- <u>production</u>

  Higgs strahlung : $e^+e^- \to Z + h/H$

  Pair production $e^+e^- \to A + h/H$

  $\to H^+H^-$

- <u>decays</u>

  for $m < 140$ GeV : $h \to f\bar{f}$ $(b\bar{b}, \tau^+\tau^-)$

  $H^0, A^0 \to f\bar{f}$

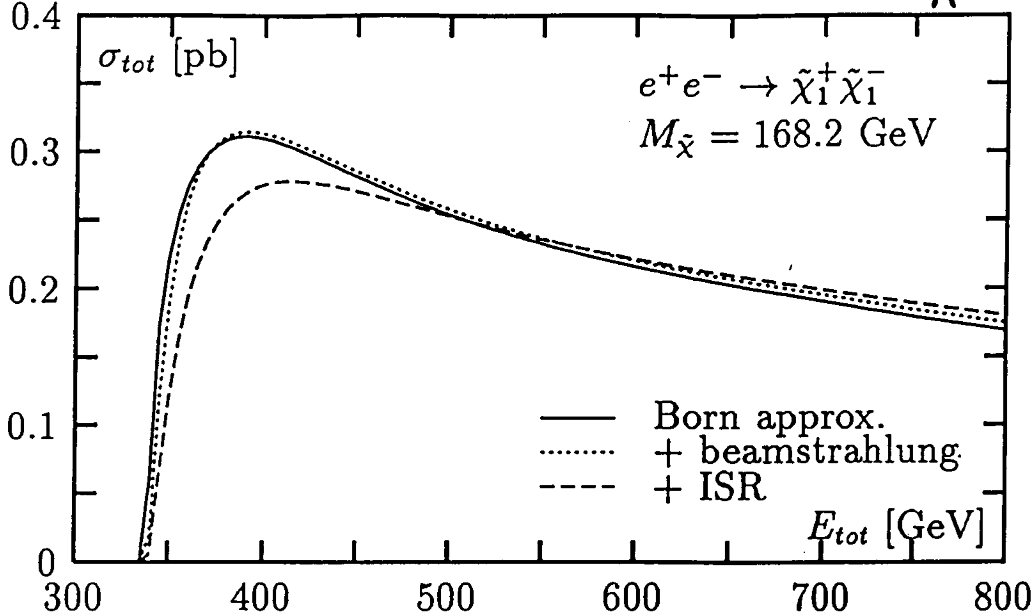
  for large masses : $H^0, A^0 \to t\bar{t}$

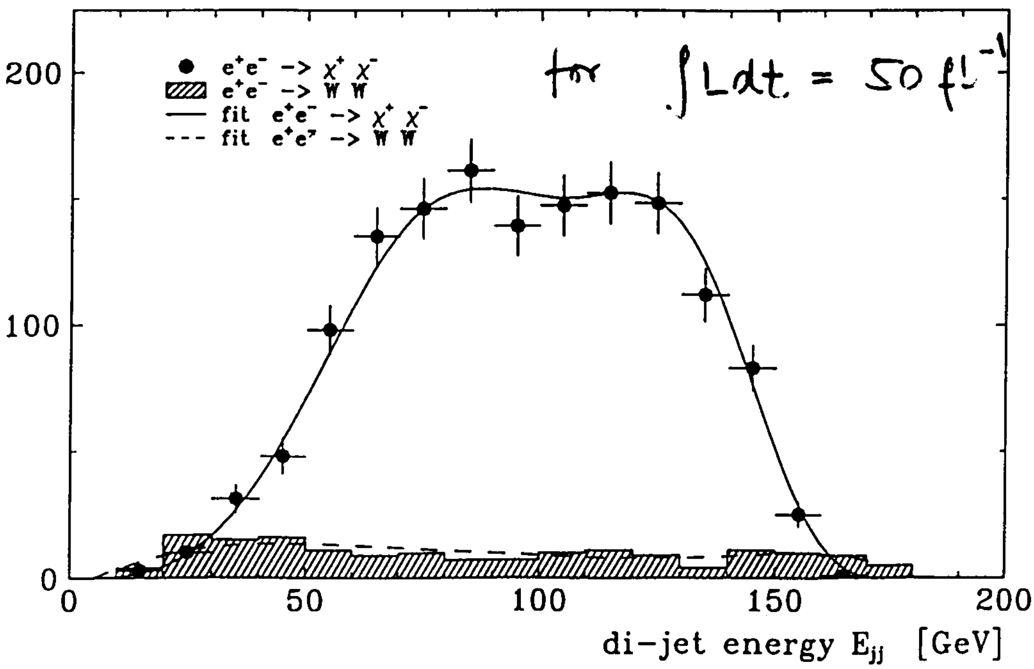
- from precise measurement of BRs :

  limit on M_A up to 800 GeV possible; independent of $\tan\beta$.

Mass measurement of $\chi^{\pm}, \chi^{0}$

1. Di-jet energy spectra — $\Delta m_{\chi^{\pm}} \approx 1$ GeV
2. Threshold scan — $\Delta m_{\chi^{\pm}} \sim 0.1$ GeV, $\Delta m_{\chi^{0}} \sim 0.6$ GeV

② 

① 

$\tilde{\chi}^+ \to \tilde{\chi}^0 + W^+$

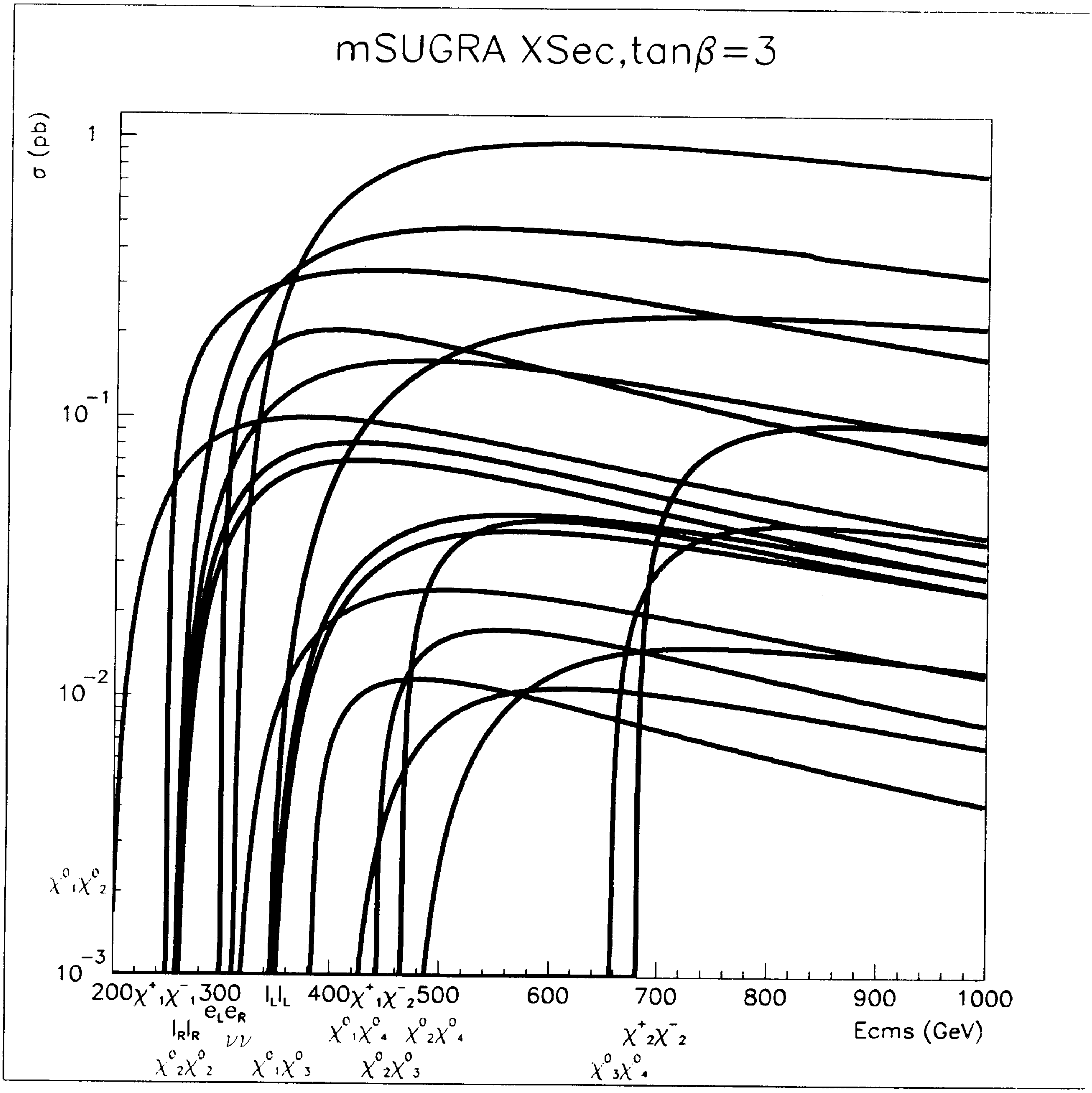


Figure 1: Cross sections of processes for $\tan\beta=3$. The cross sections were obtained using Pythia and SUSYGEN interfaced to separate private codes of S.Ambrosanio and W.Porod

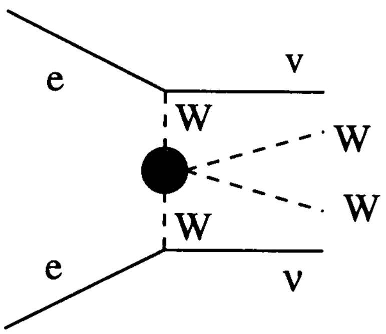
THE HIGGS DOES NOT EXIST.....

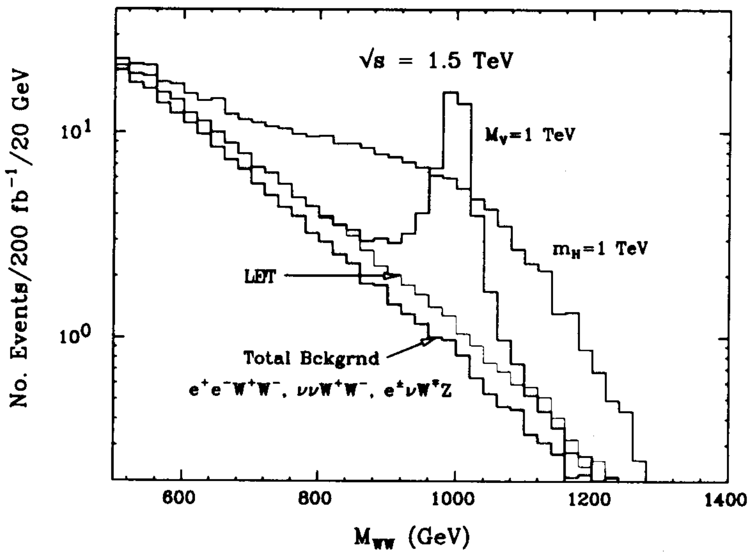
THE STRONG WAY

- If the Higgs does not exist....

  Introduce a new strong interaction (WW Re-scattering...)

- The role of the Higgs is played by non-elementary objects which acquire a non-zero vacuum expectation value
- Such an object should be visible in WW scattering



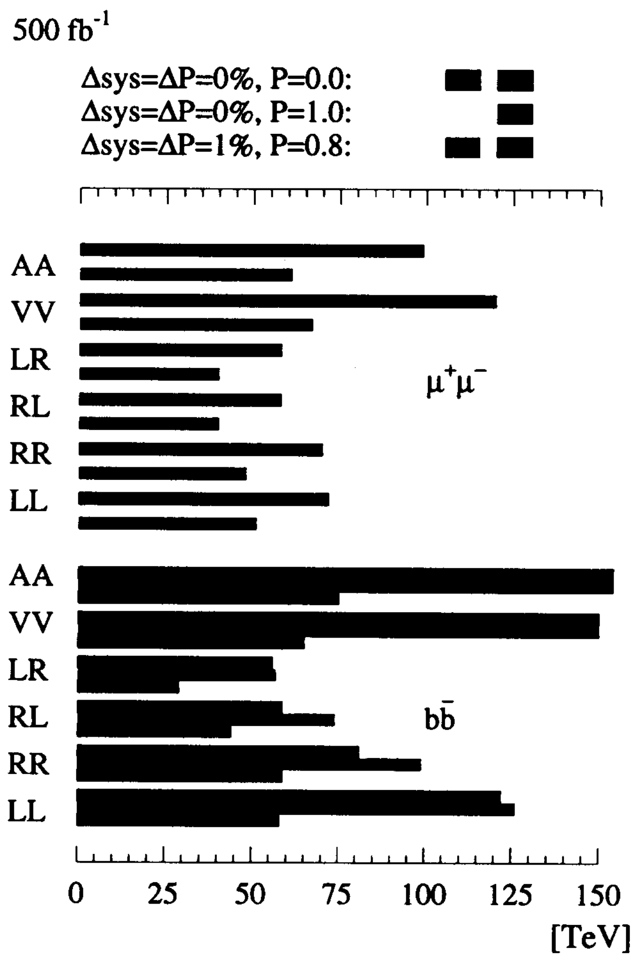


- typical mass scales for such theories (constrained by existing data) are $\mathcal{O}(1 - 1.5)$ TeV
- Study of WW scattering allows the investigation of these effects at energies below 1 TeV

THE HIGGS DOES NOT EXIST...

SUBSTRUCTUR

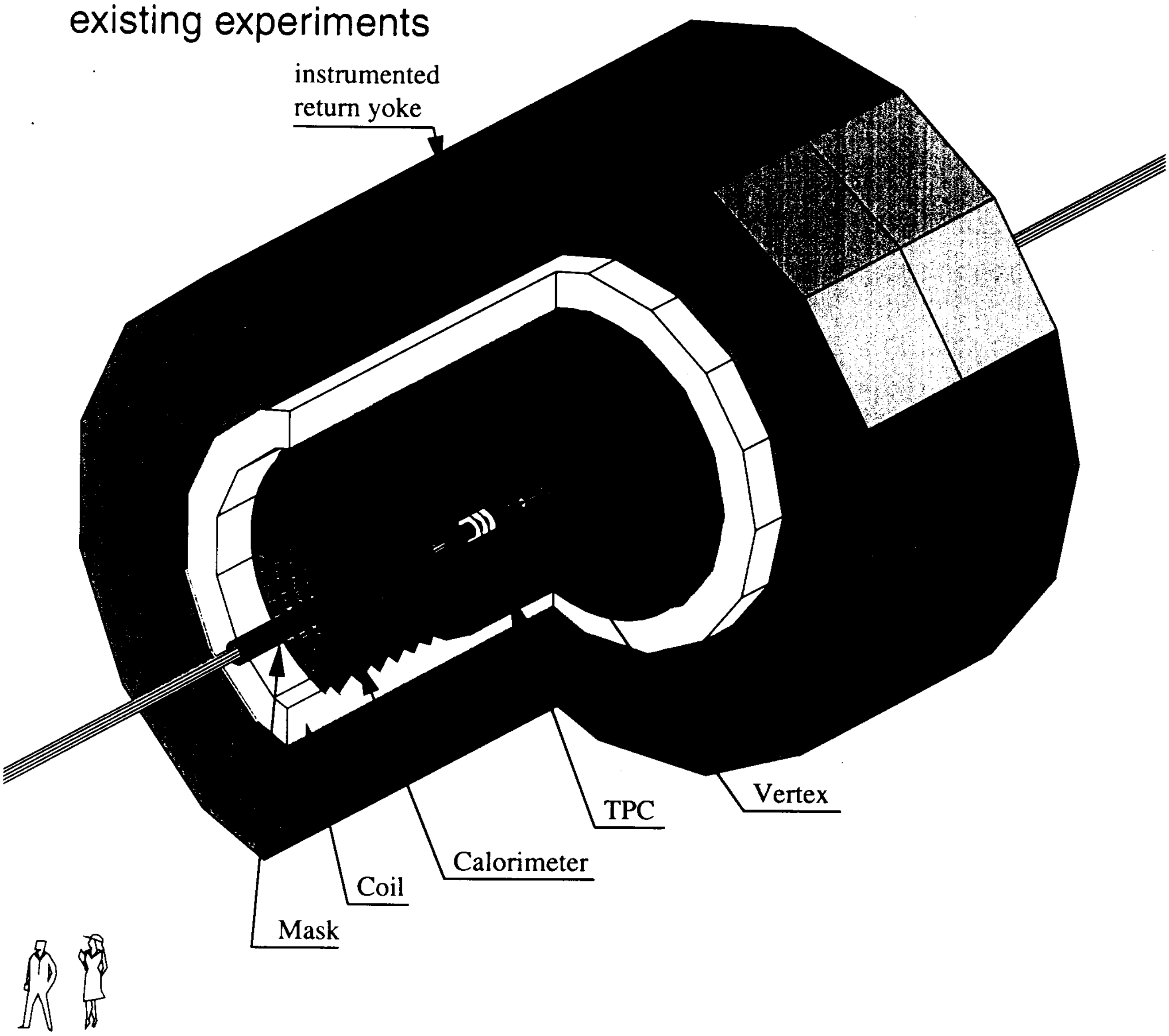
- Is there a structure below the known one?
  - new heavier $Z^{0\prime}$ bosons?
  - contact interactions? Leptoquarks?
  - more exotic scenarios? Spin 2 exchange particles?
  - ....
- Best studied in the reaction: $e^+e^- \to f\bar{f}$



- LC: expand the range significantly relative to currently known limits

EXPERIMENTS 500 GEV

- International group - ECFA/DESY Workshop works on physics and detector for TESLA
  - Detector must be able to
    - do precision physics
    - handle large amounts of data
  - comparatively simple extrapolation of existing experiments



Detector picture.
Scale: 4 story building
(comparable HERA Detector × 1.5)

Conclusion Physics

Linear Collider

Higgs	mass:	$1/10\%$
	width	$5-10\%$
	BR's	few %
	HHH	20%
SUSY	many states accessible	
	distinguish between different models	
	GUT/Planck Extrapolation	
Z,W	Giga-Z	10^{-5}
Z'	mass range	10 TeV indirect
WW	mass scale	up to 3 TeV indirect
$t\bar{t}$	mass	± 200 MeV

Design criteria for a high energy e^+e^- collider

- Very high luminosity

  @ 500 GeV : $L \geq 3 \cdot 10^{34}\ cm^{-2} s^{-1} \rightarrow 300\ fb^{-1}/y$

  @ 1000 GeV $L \geq 5 \cdot 10^{34}$

- Energy

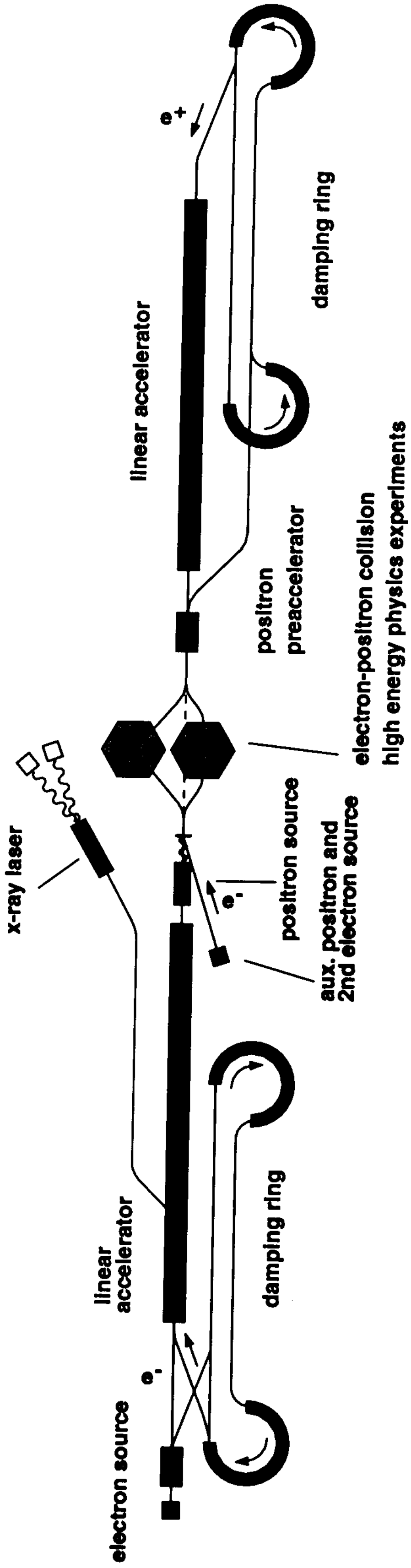
  initially: $E \geq 500$ GeV

  upgradable to: $E \approx 1000$ GeV

- beam polarisation e^- and e^+

- options e^-e^-, $e\gamma$, $\gamma\gamma$

The TESLA accelerator



TESLA Concept

superconducting (2K) Nb resonators at 1.3 GHz

- high AC-to-beam efficiency (~20%)
- long (~1ms), low peak-power (200kW/m) RF-pulses
- very small wakefields ($\propto f_{RF}^{2\ldots3}$) •
- fast orbit feedback on bunch-to-bunch basis possible

Challenge:

reduction of cost (per unit beam energy) by large factor compared to existing s.c. RF installations

goal: **2k€ / MeV** by

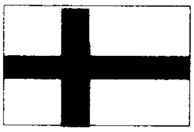
- increasing $g_{acc} = 5\ldots6 \rightarrow 25$ MV/m
- reducing cost per unit length /factor four

Members of the TESLA Collaboration

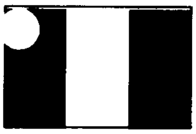
Yerevan Physics Institute

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-Institut,
Berlin-Adlershof

BESSY Berlin

Hahn-Meitner-Institut, Berlin

TU Berlin

TU Darmstadt

TU Dresden

Universität Frankfurt

GKSS, Geesthacht

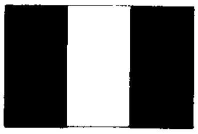
DESY, Hamburg und Zeuthen

Universität Hamburg

FZ Karlsruhe

Universität Rostock

Universität Wuppertal

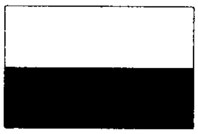


INFN Frascati

INFN Legnaro

INFN Milano

INFN and Univ. Roma II



Polish Academy of Science

Institute of Physics, Warsaw

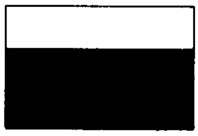
University of Warsaw

Institute of Nuclear Physics,
Cracow

Univ. of Mining & Metallurgy

Polish Atomic Energy
Agency

Soltan Inst. for Nuclear
Studies, Otwock-Swierk



JINR Dubna

IHEP Protvino

MEPhI, Moscow

INP Novosibirsk

INR Troitsk

ANL
Argonne IL

Cornell University,
Ithaca NY

FNAL,
Batavia IL

UCLA
Los Angeles CA

März 2000

R&D program in the framework of the TESLA Collaboration

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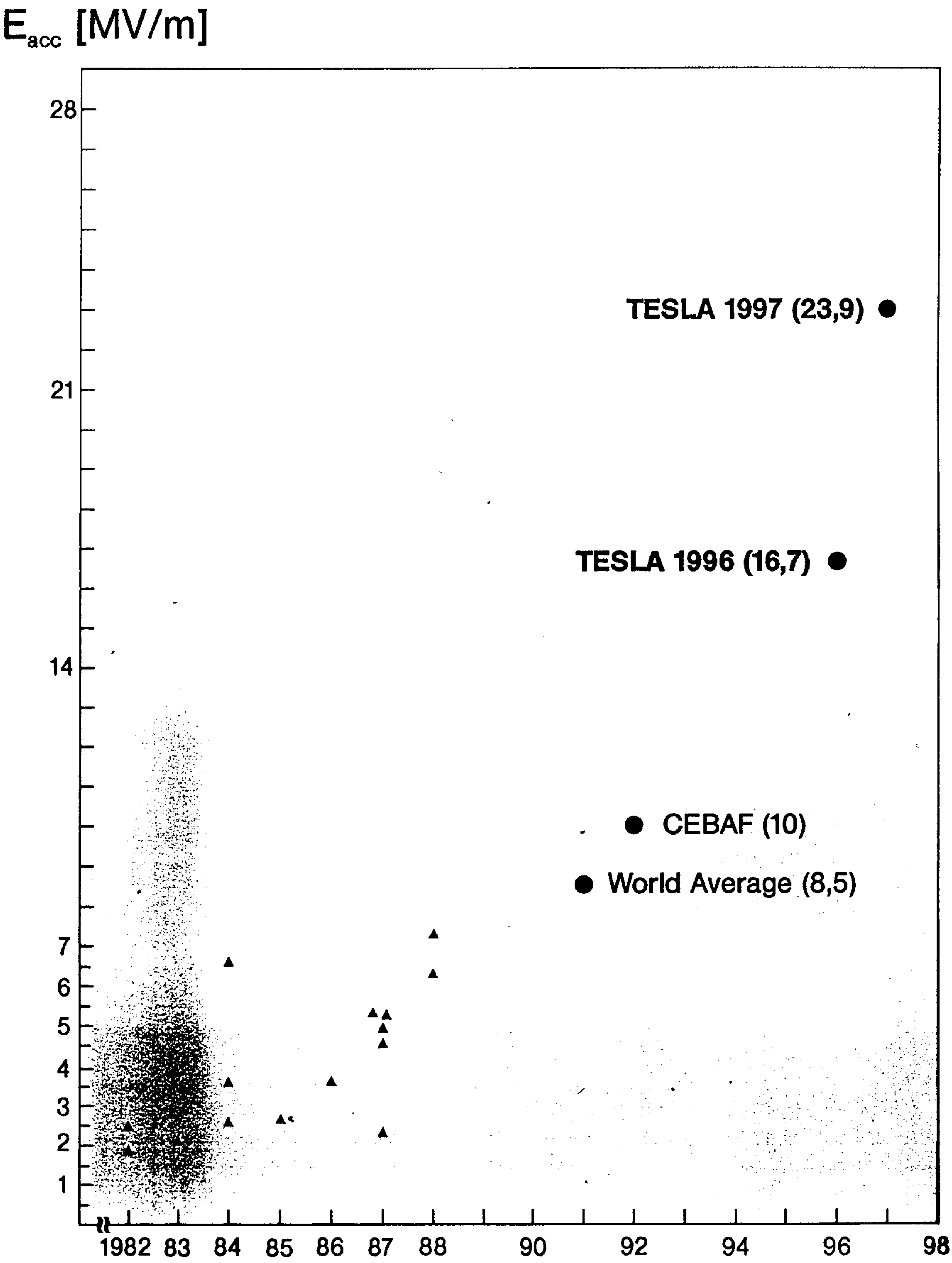
goals:

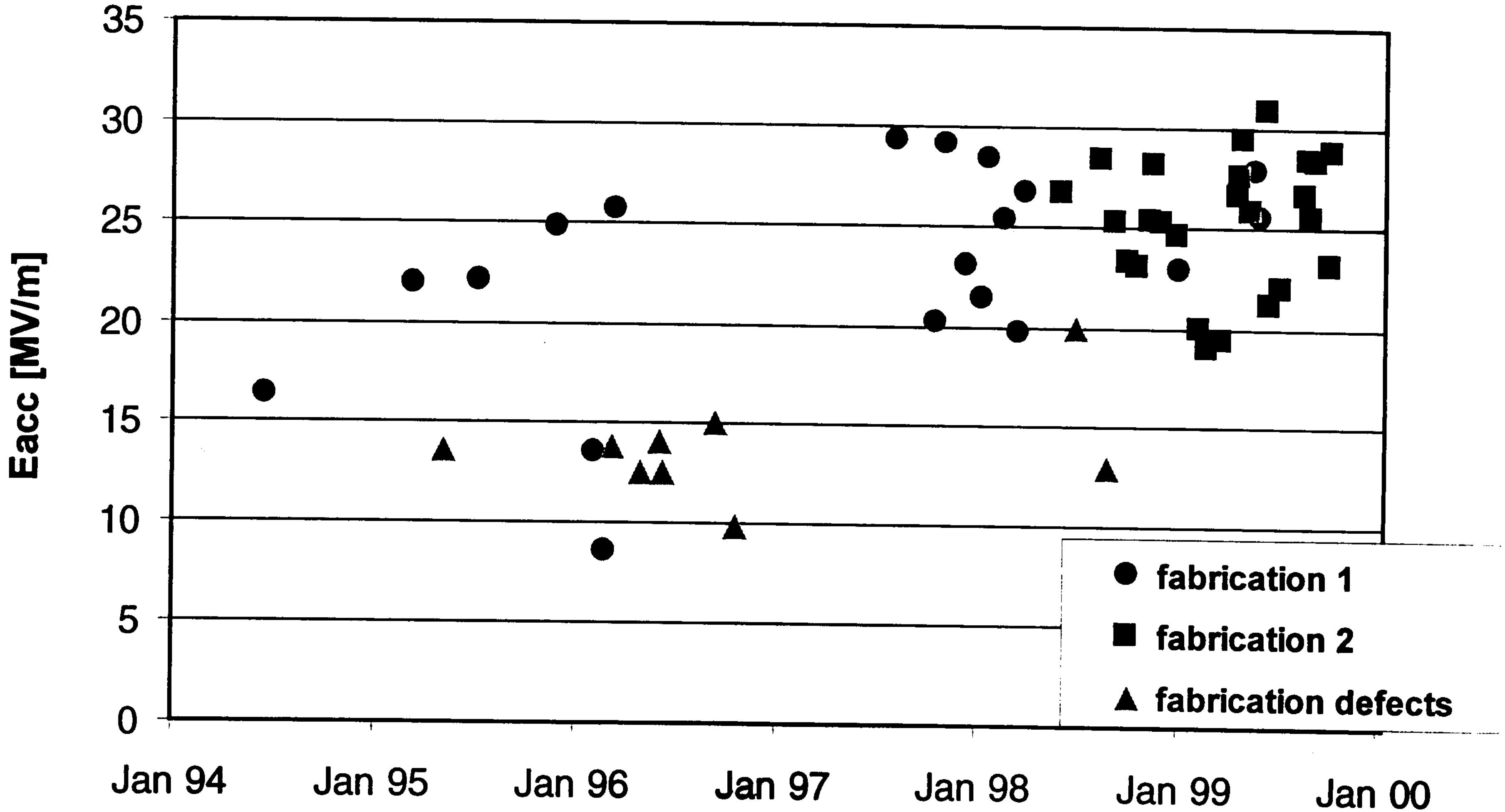
- improve gradients in SC cavities
- build cost effective structures
- build test facility (TTF)
- prove SASE principle
- gain operating experience through VUV-FEL user facility

- design of overall facility
- CDR (May 1997)
- TDR (Spring 2001)



Entwicklung der Beschleunigungsgradienten in supraleitenden Hochfrequenz-Resonatoren

Development of cavity gradient



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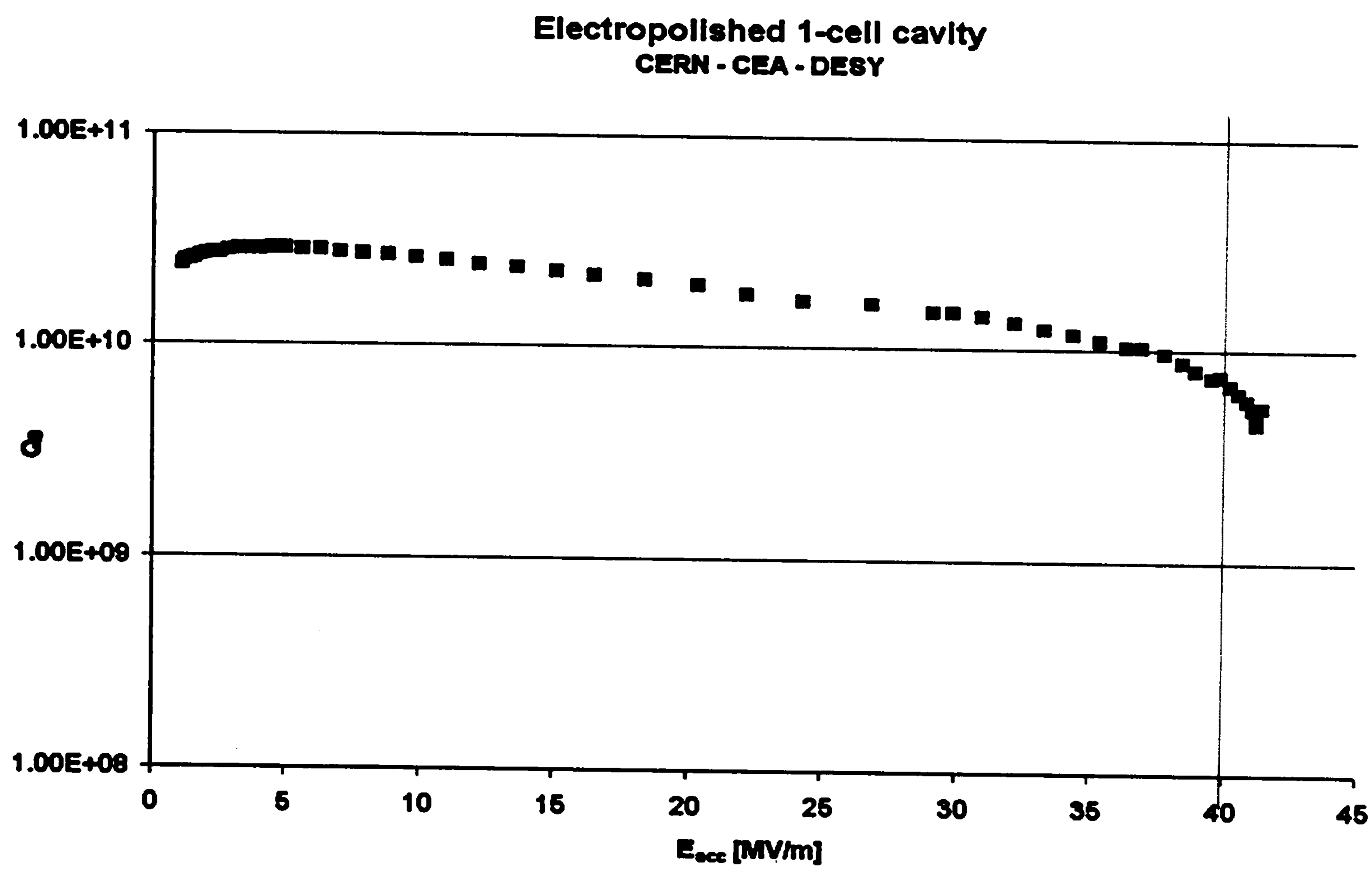
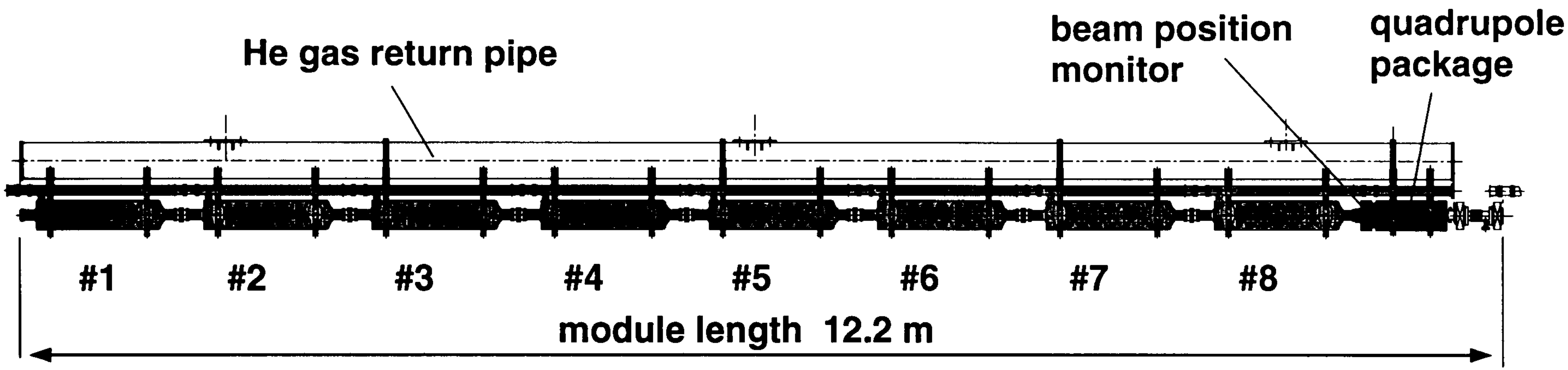
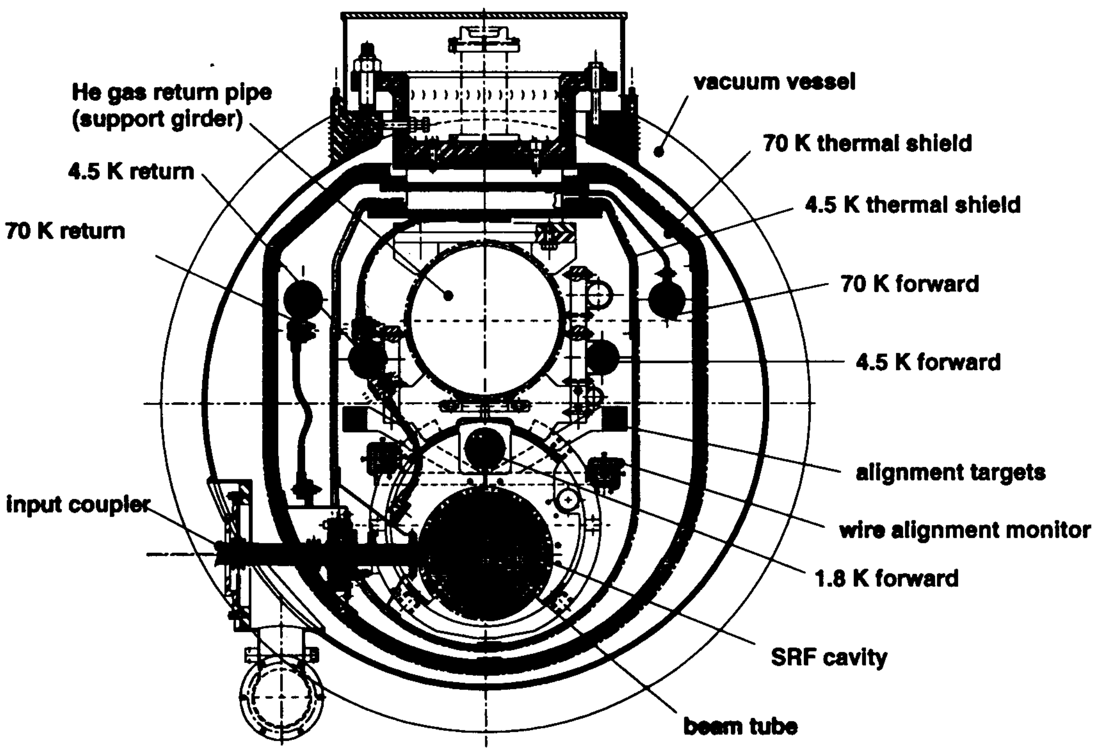


Electropolished 1-cell cavity
CERN - CEA - DESY
1.00E+11
1.00E+10
1.00E+09
1.00E+08
Q0
0
5
10
15
20
25
30
35
40
45
Eacc [MV/m]

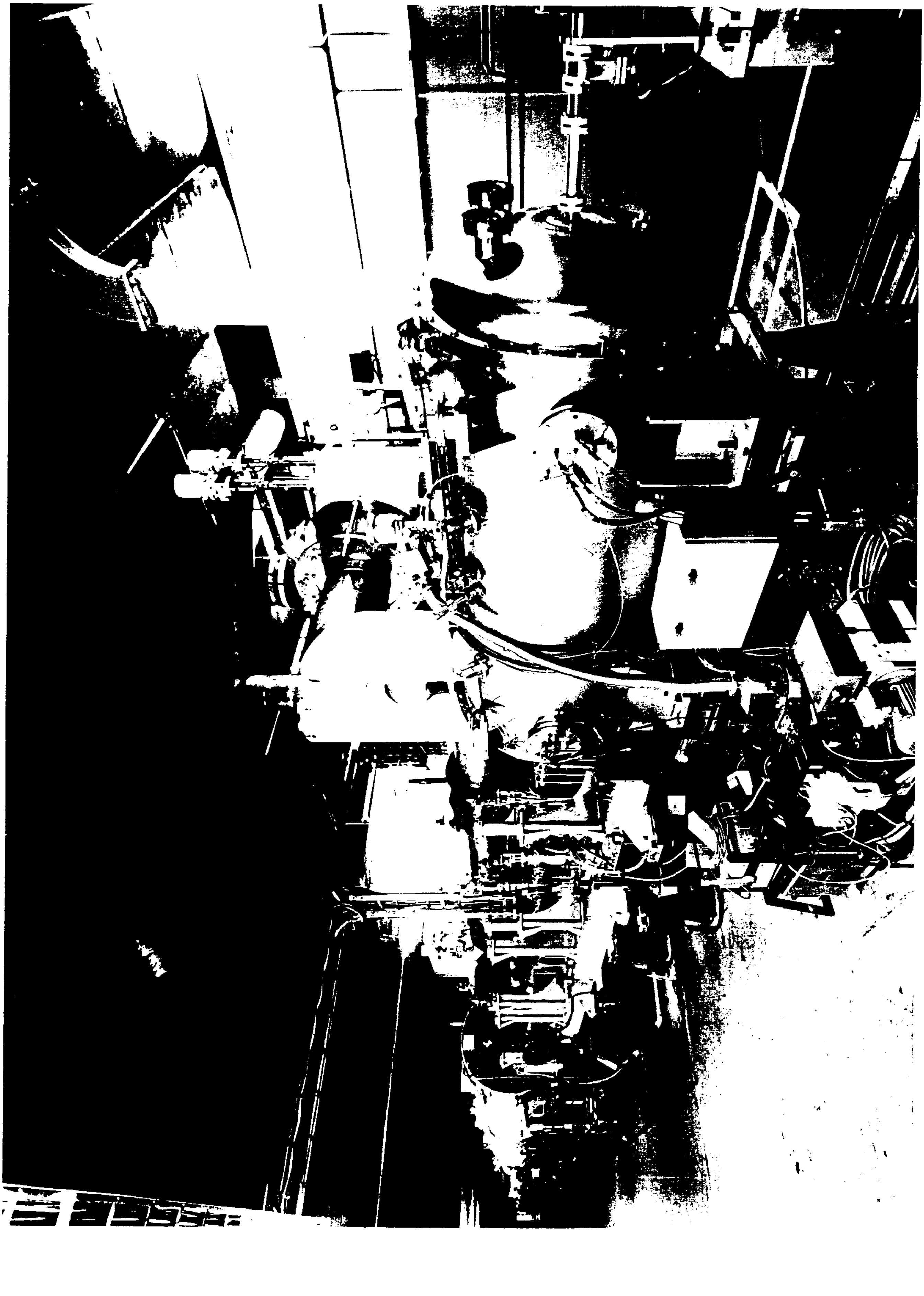


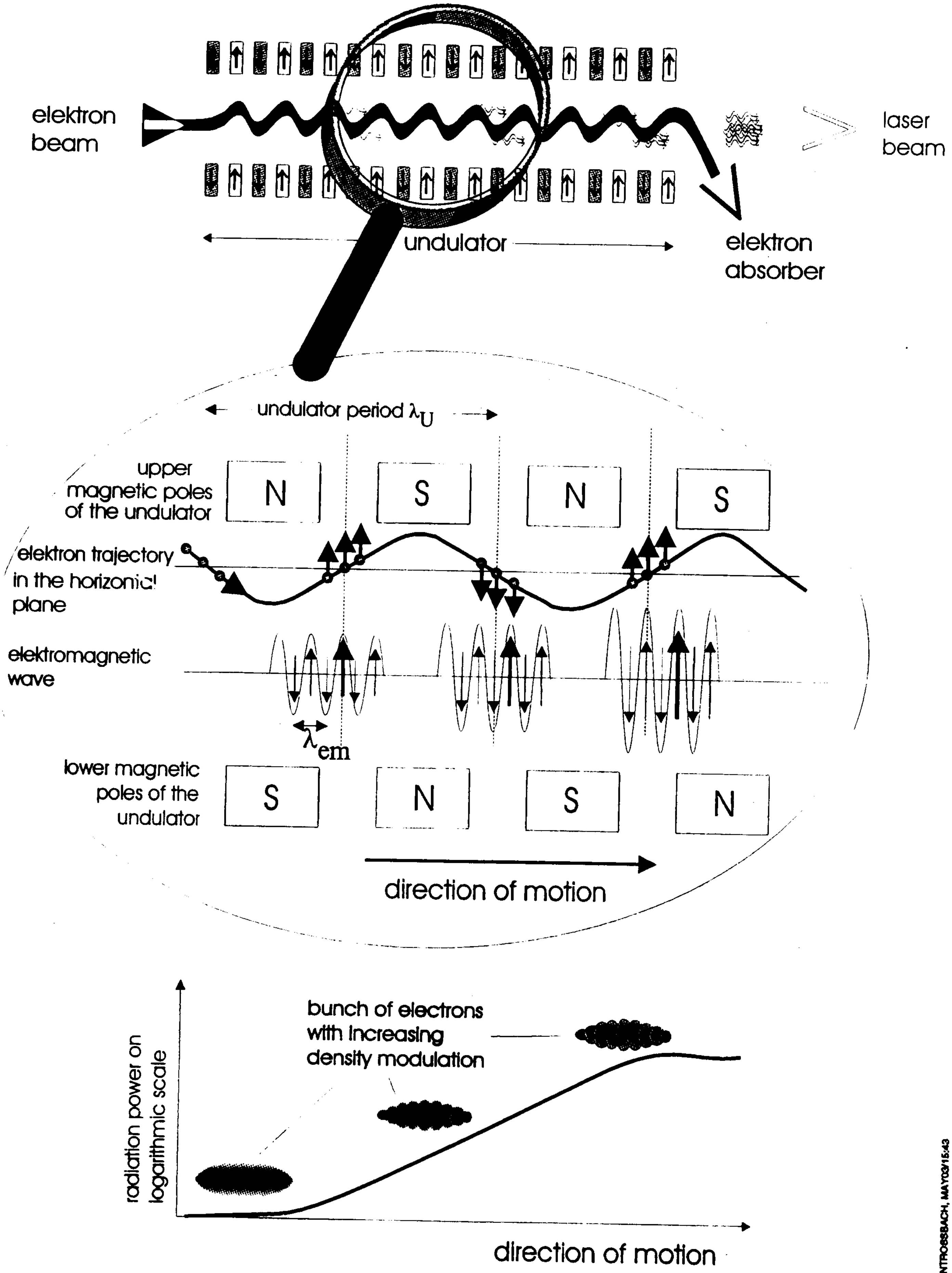


- He gas return pipe (HeGRP) is supported from above by three support posts (fiberglas pipe); it acts as a girder and is used for alignment
- the 8 cavities, the quadrupole package, and auxiliary equipement are attached to the HeGRP by means of stainless steel collars
- two aluminum radiation shields are at intermediate nominal temperature of 4.5 K and 70 K; they are cooled by means of flexible copper braids connected to the centerline of the shield upper section
- the input coupler penetrate both shields and have special radiation shield 'cones'
- approx. 128 temperature sensors and 2 accelerometers are mounted on the prototype module
- the measured static heat load for cryomodule #1 is

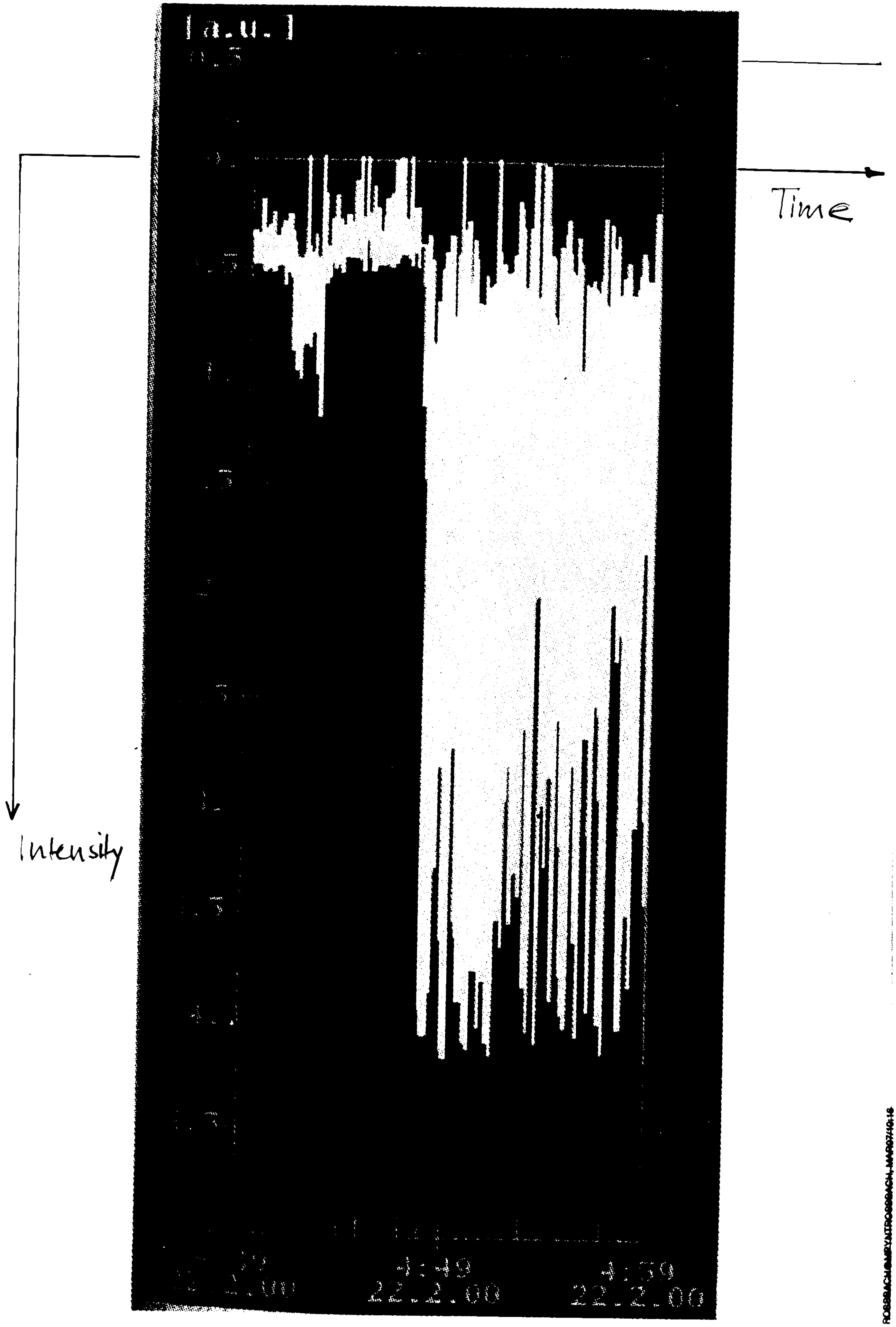
6 W @ 1.8 K
23 W @ 4.5 K
90 W @ 70 K

H. Weise 30/10/97





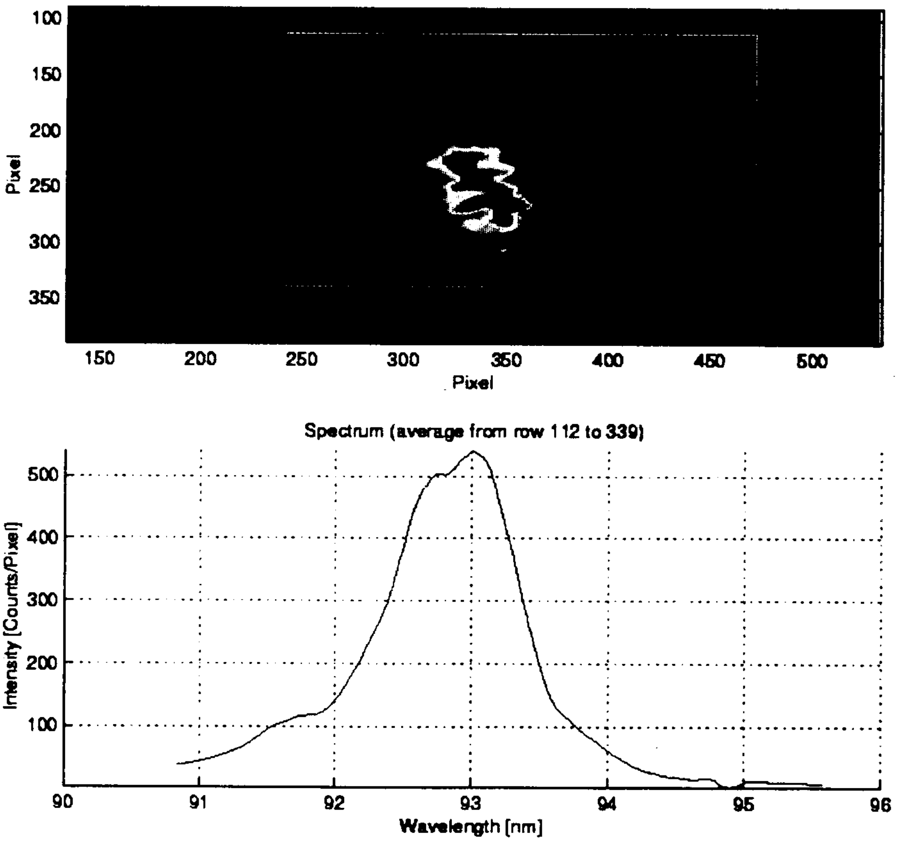
elektron beam
laser beam
undulator
elektron absorber
undulator period λ_U
upper magnetic poles of the undulator
N
S
N
S
elektron trajectory in the horizontal plane
elektromagnetic wave
λ_{em}
lower magnetic poles of the undulator
S
N
S
N
direction of motion
radiation power on logarithmic scale
bunch of electrons with increasing density modulation
direction of motion



[a.u.]
4:49
22.2.00
4:59
22.2.00
Time
Intensity

TESLA ist eine supraleitende Beschleunigeranlage für Energien bis zu Tera-Elektronenvolt, das sind 1000 Milliarden Elektronenvolt. Das Besondere an dieser geplanten Anlage ist ihre parallele Nutzung sowohl für die Elementarteilchenphysik als auch für auf Anwendung ausgerichtete Forschungen mit Röntgenstrahlung. In einem 33 Kilometer langen Tunnel stehen zwei Linearbeschleuniger, in denen Elektronen und ihre Antiteilchen, die Positronen, auf höchste Energien gegeneinander beschleunigt und zum Zusammenstoß gebracht werden sollen. Außerdem soll der Elektronenstrahl für die in TESLA integrierten Röntgenlaser verwendet werden. Mit einer Entscheidung über das TESLA-Projekt wird 2002/2003 gerechnet. Die Bauzeit ist mit sechs bis acht Jahren veranschlagt.

Die 300 m lange TESLA-Pilotanlage wird der weltweit erste und einzige Laser dieser Art sein. Vom 1. Juni bis zum 31. Oktober 2000 wird DESY dieses Projekt im Rahmen der Erlebnisausstellung „Licht der Zukunft - Ein 300 m langes supraleitendes Röntgenlaser-Mikroskop" als Weltweites Projekt der EXPO 2000 der Öffentlichkeit vorstellen - „greifbar", spannend und allgemein verständlich. Geöffnet ist täglich von 10 bis 19 Uhr, Donnerstag bis Mitternacht; der Eintritt ist frei.



Wellenlängen-Spektrum des neuen Freie-Elektronen-Lasers bei DESY

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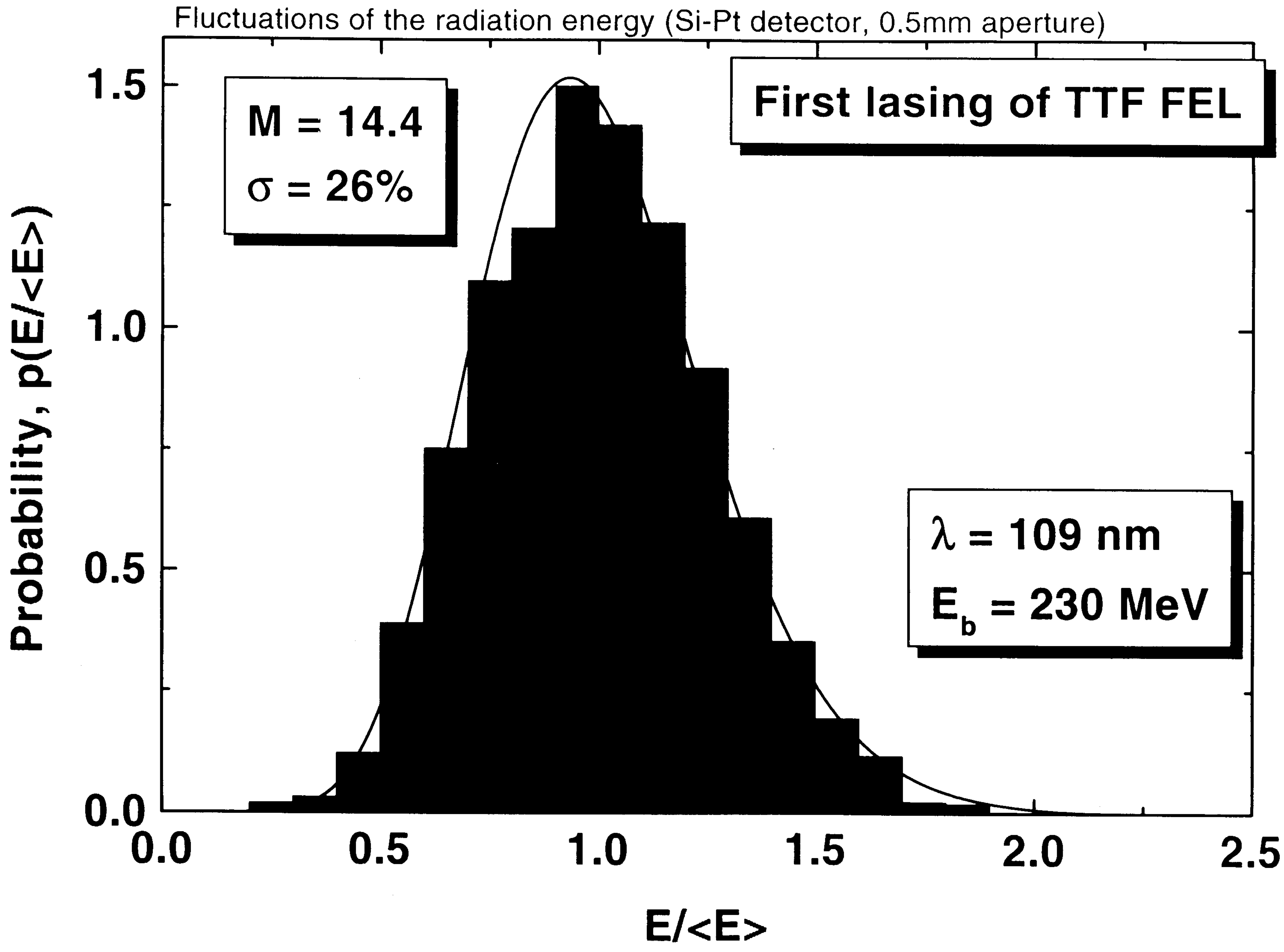

Fluctuations of the radiation energy (Si-Pt detector, 0.5mm aperture)
M = 14.4
σ = 26%
First lasing of TTF FEL
λ = 109 nm
E_b = 230 MeV
Probability, p(E/<E>)
E/<E>
0.0
0.5
1.0
1.5
2.0
2.5

TTF II

The tunnel will be extended to accumulate 5 + 2 additional modules, a third longitudinal bunch compressor and two undulators. A Hall for laser beam experiments in the VUV region will also be added.

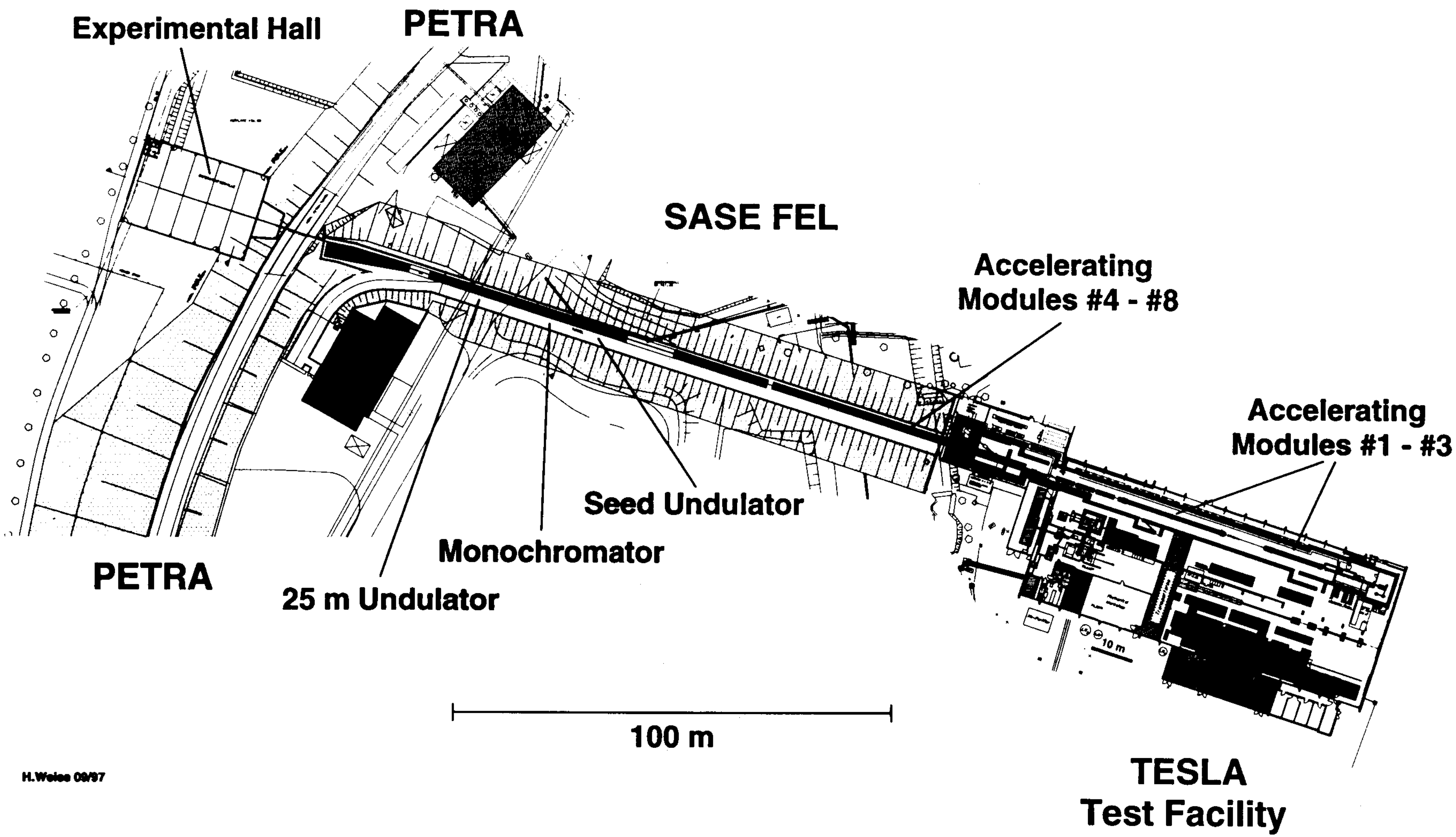
Dual use:

Driver of a SASE-FEL to produce intense, coherent VUV light, tunable for wavelengths between 2 nm and 30 nm.

Final integrated TESLA system test with some novel components

- multibeam klystron
- new type of modulator
- new cryostat
- in part seamless, densly packed cavities with final design of tuners, HOM couplers and power couplers

Start of construction:	10/1997
Tunnel and service buildings	12/1998
Experimental Hall	12/1999
Start commissioning	12/2001


Experimental Hall
PETRA
SASE FEL
Accelerating
Modules #4 - #8
Accelerating
Modules #1 - #3
Seed Undulator
Monochromator
PETRA
25 m Undulator
10 m
100 m
TESLA
Test Facility
H.Weise 09/97

Scientific Applications of

The 1Å Laser

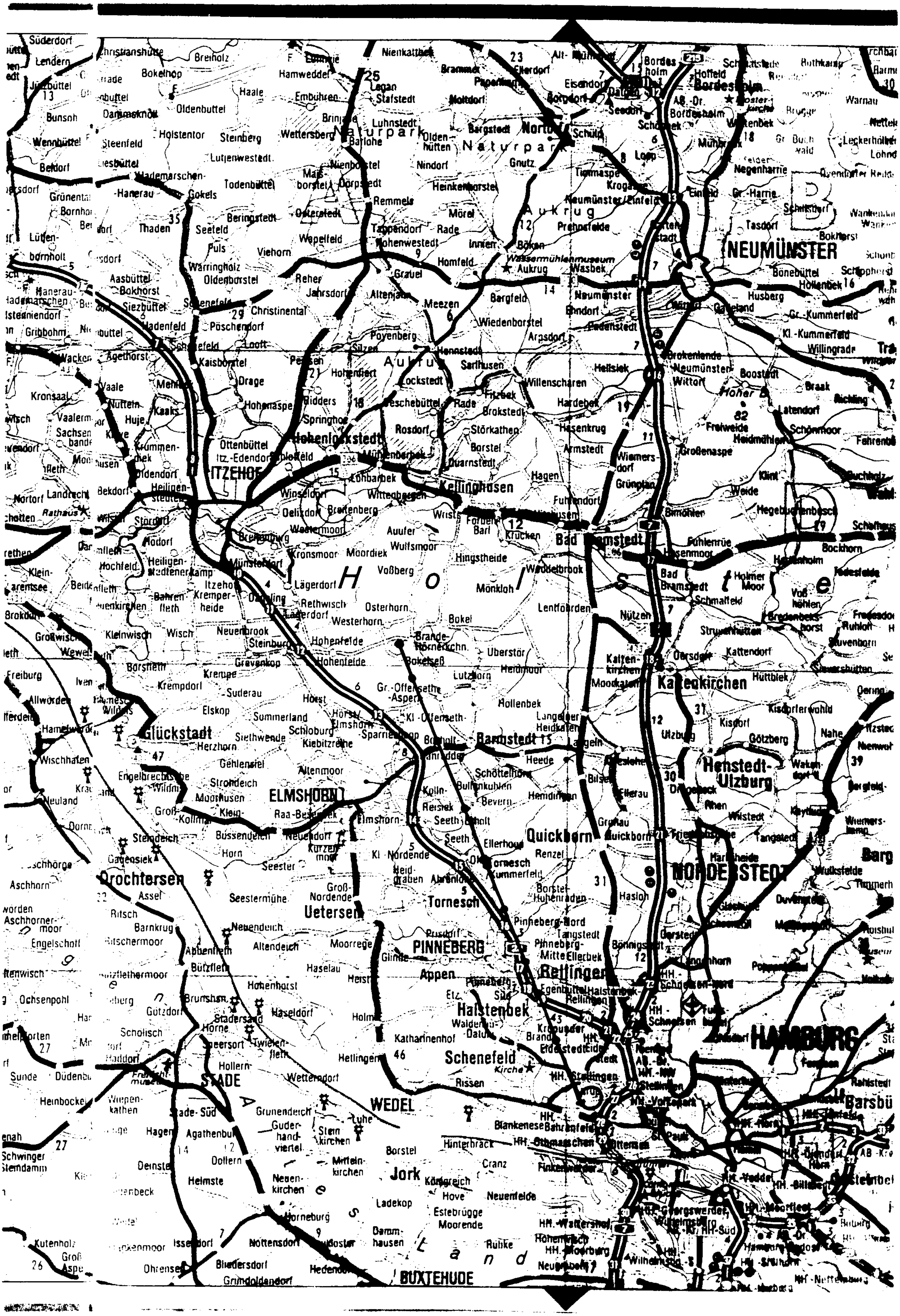
- **High Intensity Short Pulselength: 10^{13} photons/s in 100 fs 10^{18} - 10^{19} photons per second** → Instantaneous snapshot of physical, chemical or biological processes with atomic resolution and timescale. Study of nonlinear processes.
  $\downarrow$
  10^{16} W/cm² on 1 µm²

- **Tuneable:** → Spectroscopic measurements of electronic properties of molecules and condensed matter. Snapshots of atoms in an excited state.

$$\lambda_\gamma = \frac{\lambda_u}{2\gamma^2}\left(1 + k^2/2\right)$$

  $\downarrow$

- **Temporal and spatial:** coherent → Measure the dynamic of condensed matter. 3-D pictures (holograms) of molecules with atomic resolution.


NEUMÜNSTER
Bordesholm
Naturpark
Aukrug
Wassermühlenmuseum
Nortorf
Hohenwestedt
ITZEHOE
Kellinghusen
Bad Bramstedt
Hohenlockstedt
Glückstadt
ELMSHORN
Barmstedt
Kaltenkirchen
Henstedt-Ulzburg
Quickborn
NORDERSTEDT
Uetersen
PINNEBERG
Tornesch
Rellingen
Halstenbek
Schenefeld
Appen
WEDEL
HAMBURG
Drochtersen
STADE
Jork
BUXTEHUDE
Holstein
Altes Land
Hoher Busch
Lägerdorf
Wrist
Krempe
Horst
Elmshorn
Nützen
Hasloh
Bönningstedt
Blankenese
Altona
St. Pauli
Wilhelmsburg
Neuenfelde
Cranz
Borstel
Hollern
Agathenburg
Dollern
Horneburg
Helmste

TESLA_ Further Developments

- Formal Proposal (TDR) including Schedule and Cost (March 2001)
- Evaluation of TDR by German Science Council (2001/2002)
- ECFA Study on Long-term Perspectives of Particle Physics in Europe (2000/2001)
- ICFA Study of the Global Accelerator Network (2000/2001)
- Global Science Forum on HEP and Astroparticle Physics ? (2001/2002)
- How to achieve a Technical Comparison between different LC Proposals ?

Global Accelerator Network

- build and operate accelerators in the same way as HEP experiments
- network: → pull together world-wide competence, ideas, resources
- capital investment in home countries
- put accelerator into an existing lab
  - make optimal use of available experience, manpower, infrastructure
  - special financial obligation for Host country
- maintain & run accelerator from home labs, only small crew on-site
- maintain scientific & technical culture in home labs, remain attractive for young scientists, yet contribute to and participate in large, unique projects
- requirement: remote operation & diagnostics

  ↘ ICFA study

THE TESLA ROAD MAP

now	TTF R&D
spring 1998	"II. DESY / ECFA study on physics and detector at future linear colliders"
spring 1999	"scoping date" at DESY: start the environmental impact study for TESLA
april 1999	german government agrees to evaluation by the german "Wissenschaftsrat" in 2001
spring 1999	Installation and test of a second module in TTF
february 2000	"proof-of-principle" of the FEL
spring 2000	Workshop in Padua in preparation of the technical design report
spring 2001	TDR (machine and experiment) ready and handed over to "Wissenschaftsrat"
2002-2003	decision by german government
2003	project is establised as an international project
2003...	cosntruction begins
2008-[illegible]	first colliding beams

- Linear collider projects have made tremendous progress in the past few years
- A LC has a rich and interesting physics program
- The LC physics is in many respects complementary to the LHC physics program

Conclusion

The TESLA project offers

- a unique scientific potential
  - e^+e^- physics rich & complementary to LHC
  - huge scientific potential of X-FEL

  simultaneous multidisciplinary use

- technology for - high luminosity
  - low emittance

  linear accelerator using sc cavities very well advanced

  thanks to large international effort

- TDR in 2001

  a lot more work to be done until then

- Completion in 6/7 years

  fits also LHC schedule