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LCWS-2000

TESLA Linear Collider : Status Report

O. Napoly, CEA/Saclay

for the TESLA collaboration

OUTLINE

- Generalities
- SC Cavities and RF systems
- SASE-FEL
- Collider design
- Interaction Regions
- Conclusions

Members of the TESLA-Collaboration

IHEP
Academia Sinica, Beijing

Tsinghua-University, Beijing

SEFT
University of Helsinki

CEA/DSM
(DAPNIA, CE-Saclay)

IN2P3
(INP Orsay + LAL Orsay)

Max-Born-Institut,
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DESY, Hamburg und Zeuthen

GH Wuppertal
Fachbereich Physik

IAP, University of Frankfurt

GKSS, Geesthacht

FZ Karlsruhe

IfH, TU Darmstadt

ITE, TU Berlin

IKK, TU Dresden

RWTH Aachen III

Uni. Hamburg

Uni. Rostock

BESSY

Hahn-Meitner Inst., Berlin

INFN Legnaro

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Polish Academy of Science
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University of Warsaw,
Inst. of Exp. Physics

University of Cracow (INP)

Univ. of Mining & Metallurgy,
Cracow

Polish Atomic Energy
Agency, Cracow

Soltan Institute for Nuclear
Studies, Otwock-Swierk

JINR Dubna

INR Troitsk

IHEP Protvino

MEPhI Moscow

INP Novosibirsk

Cornell University
Newman Lab. Ithaca NY

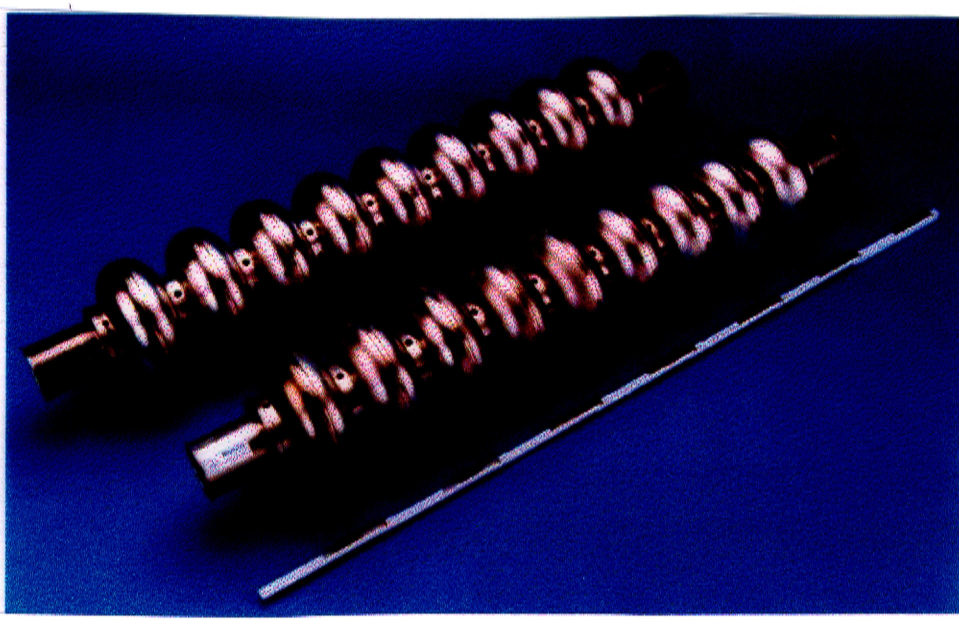
Fermilab
Batavia IL

UCLA
Los Angeles CA

ANL

Yerevan Physics Institute

TESLA Basic Concept

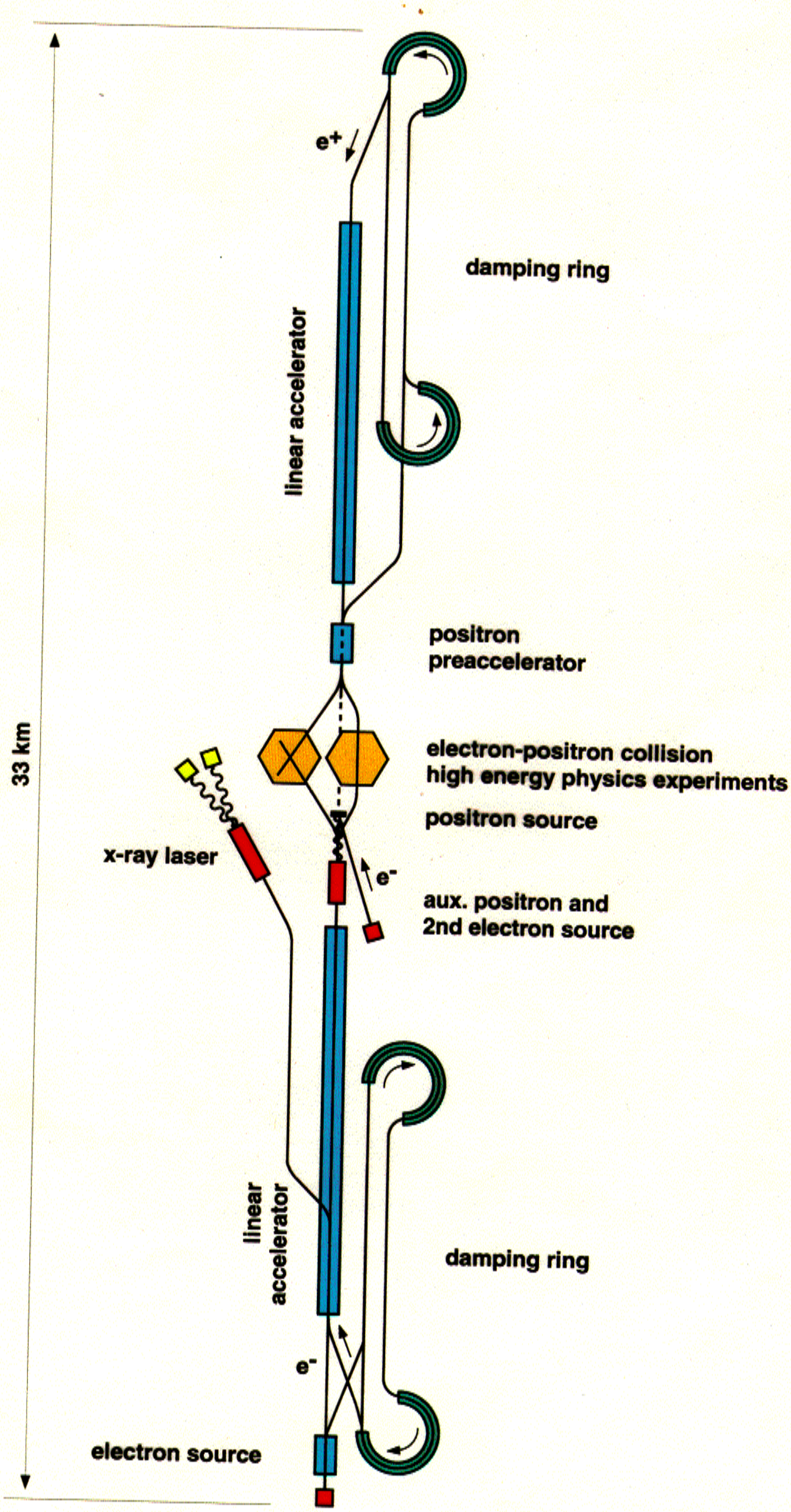


- Superconducting 9-cell Nb cavities
  Eacc ≈ 25 MV/m , T = 2K

- Long RF pulse (~ 1 ms)
  ⇒ low RF peak power (200 kW/m)
  ⇒ long bunch train with large spacing

- Low RF Frequency (1.3 GHz)
  ⇒ small wakefields

- Overall design compatible with
  $\sqrt{s}$ = 300-800 GeV



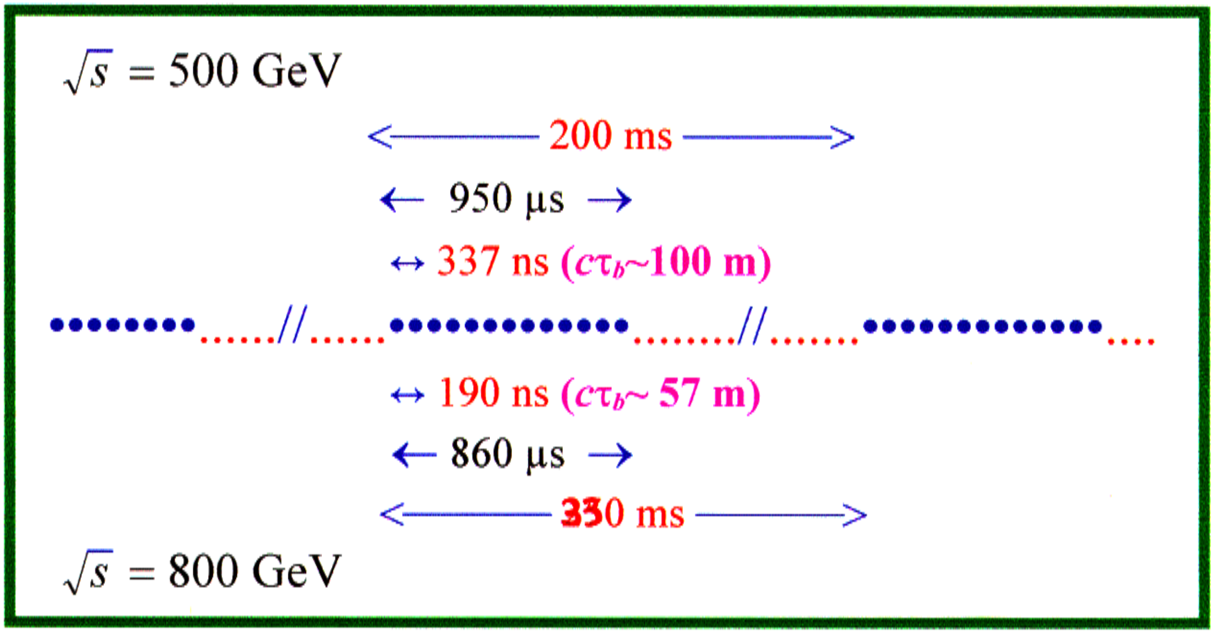
H.Weise 3/2000

TESLA Parameters

$\sqrt{s}$	GeV	**500**	**800**
Luminosity	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	3.4	5.8
RF-frequency	GHz	1.3	-
Accelerating gradient	MV/m	22	35
Quality factor Q_0	-	10^{10}	$5 \cdot 10^{9}$
Fill factor	%	76	76
Total site length	km	33	-
Repetition rate	Hz	5	4
Pulse length	µs	950	860
# bunches/pulse n_b	-	2 820	4 886
Bunch spacing τ_b	ns	337	~~190~~ 176
Bunch charge N_e	-	$2 \cdot 10^{10}$	$1.4 \cdot 10^{10}$
Spot sizes at IP $\sigma^*_{x,y}$	nm	553 , 5	391 , 2.8
Emittances at IP $\gamma\varepsilon_{x,y}$	µm	10 , 0.03	8 , 0.015
Betas at IP $\beta^*_{x,y}$	mm	15 , 0.4	15 , 0.4
Bunch length σ_z	µm	300	300
Beamstrahlung parameter δ_B	-	3.2	4.4
Beam current	mA	9.5	~~12~~ 13
Average current	µA	45	~~41~~ 44
Beam power ×2	MW	23	35
AC power	MW	100	160
Efficiency	%	23	20

TESLA Bunch Trains

Bunch Train
- 5 Hz × 2820 × 2.0 •10^{10} @ 500 GeV
- 3 Hz × 4568 × 1.4 •10^{10} @ 800 GeV



~1 ms long bunch trains provide:

- Many orbit corrections (fast feedback systems)
- Head-on Collisions (beam separation required before 1st parasitic collision @ $c\tau_b/2$)
- Bunch collisions well separated in the detector

SC Cavities and RF Systems

TESLA Test Facility (TTF) Goals

Phase I

- Accelerator modules: from R&D to Industry

1991 costs : 200 k$/m ÷ 5 MV/m = 40 k$/MV

↓ ↓ ↓

2000 costs : 50 k€/m ÷ 25 MV/m = 2 k€/MV

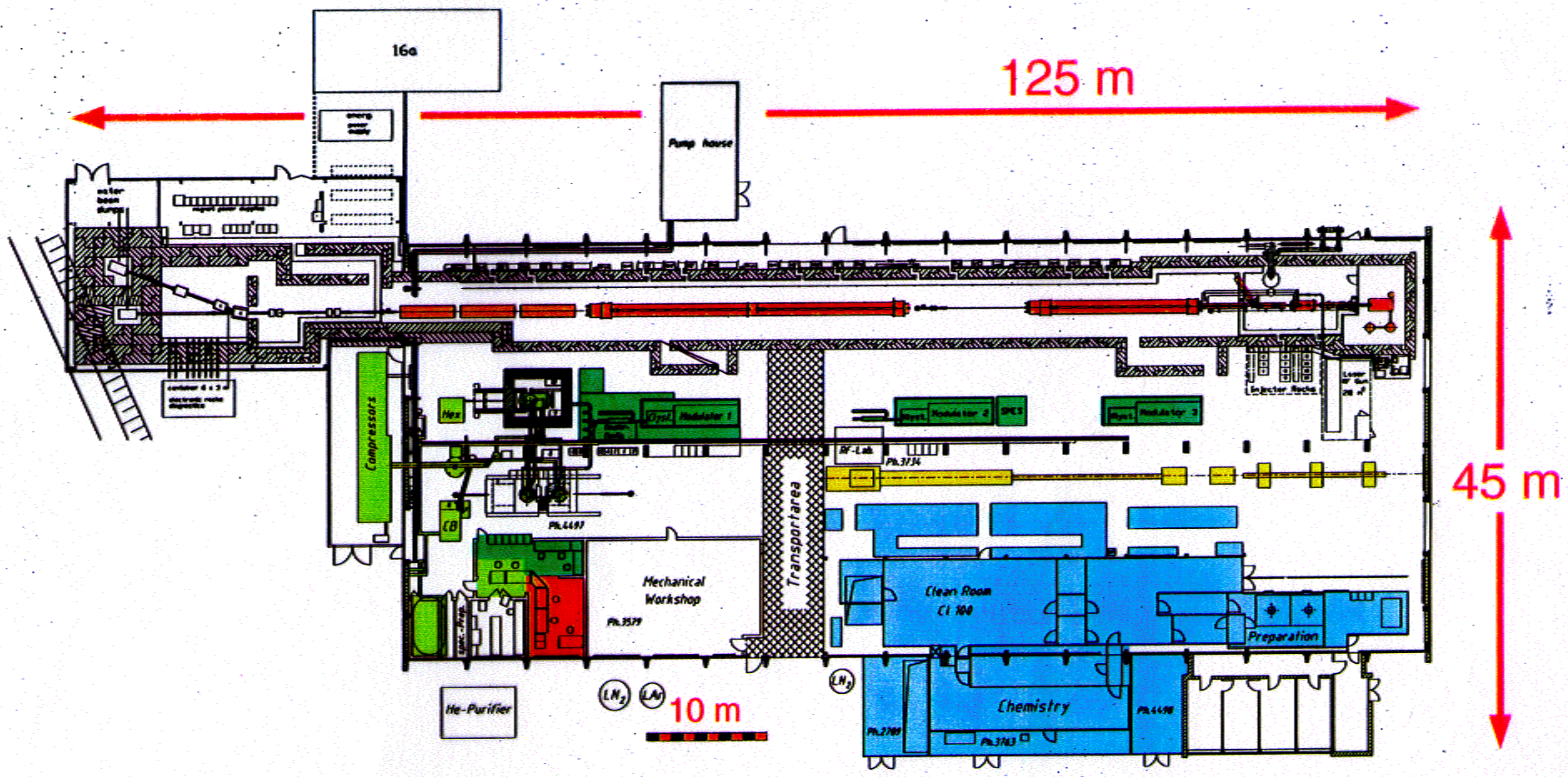
- SASE FEL at low wavelength (~ 60 nm)

Phase II

- SC Linac up to 1.2 GeV

- SASE FEL User Facility (6 nm)

TESLA TEST FACILITY (HALL 3)



Cavity Treatment and Assembly

Cavity Testing (RF System / He Plant)

Cryomodule Assembly

TTF Linac

H.Weise / June 24th, 1996

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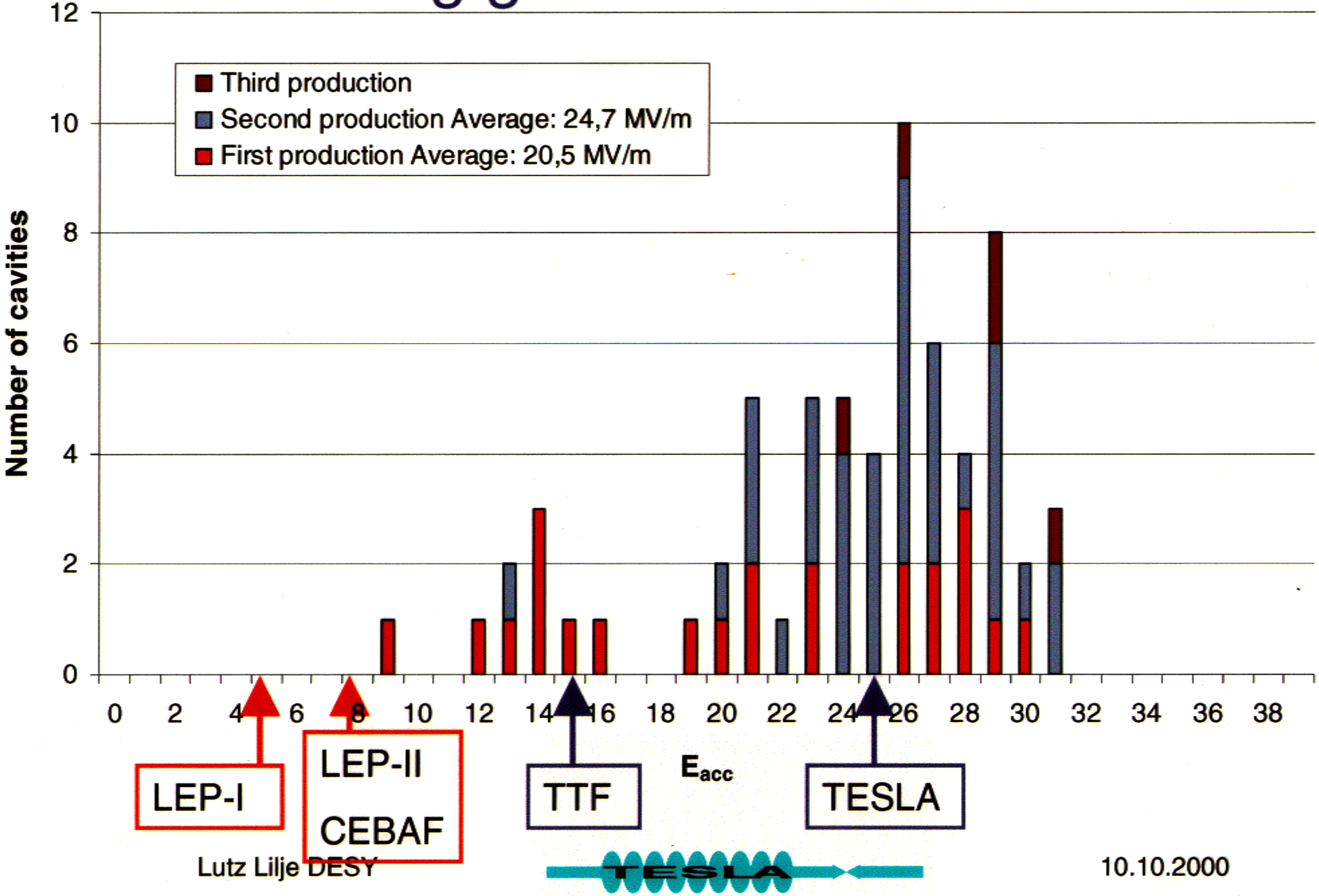
TESLA Cavities

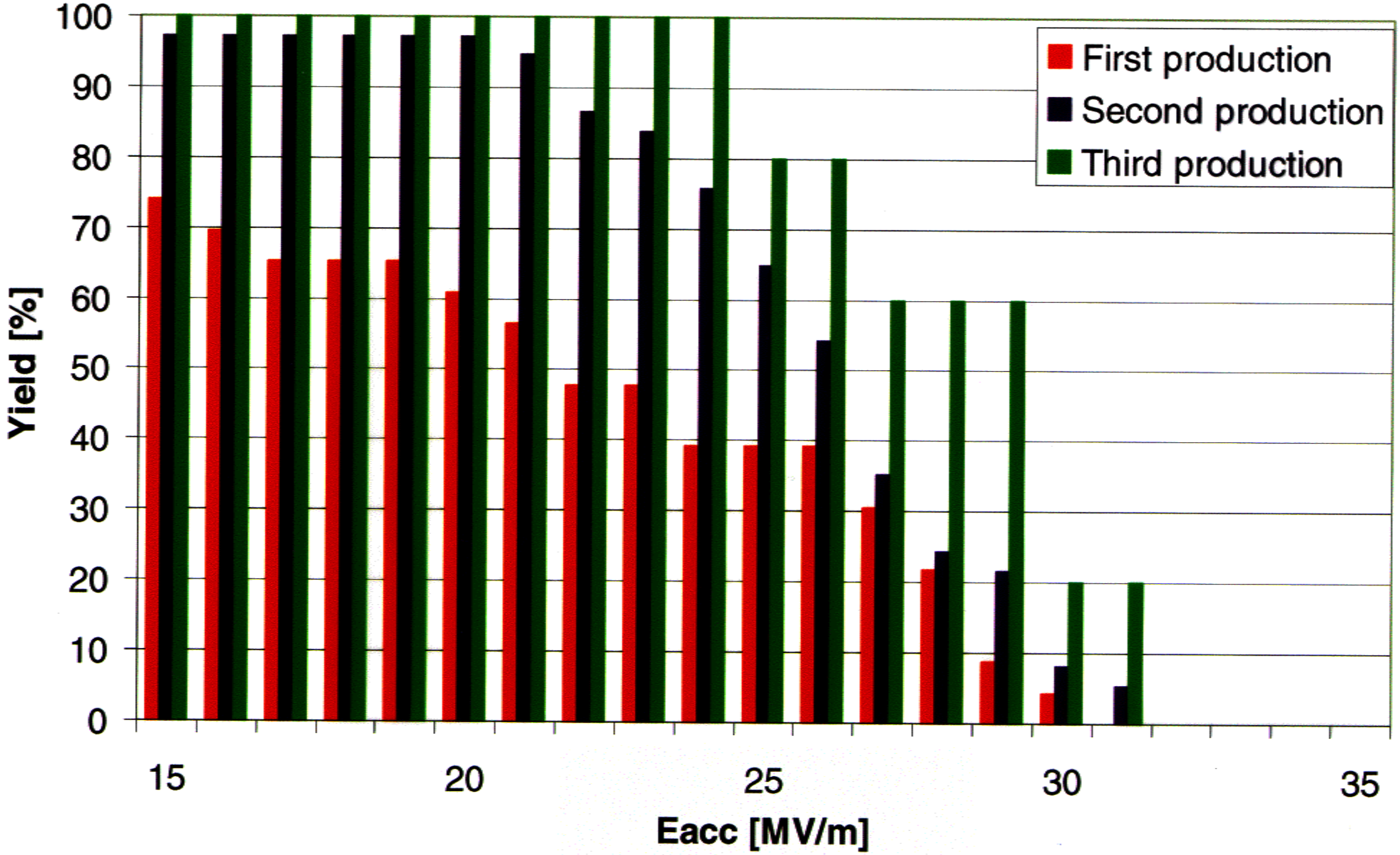
Accelerating gradients of 9-cell cavities



Lutz Lilje DESY

10.10.2000

Yield of cavities from CW test



Lutz Lilje DESY

TESLA

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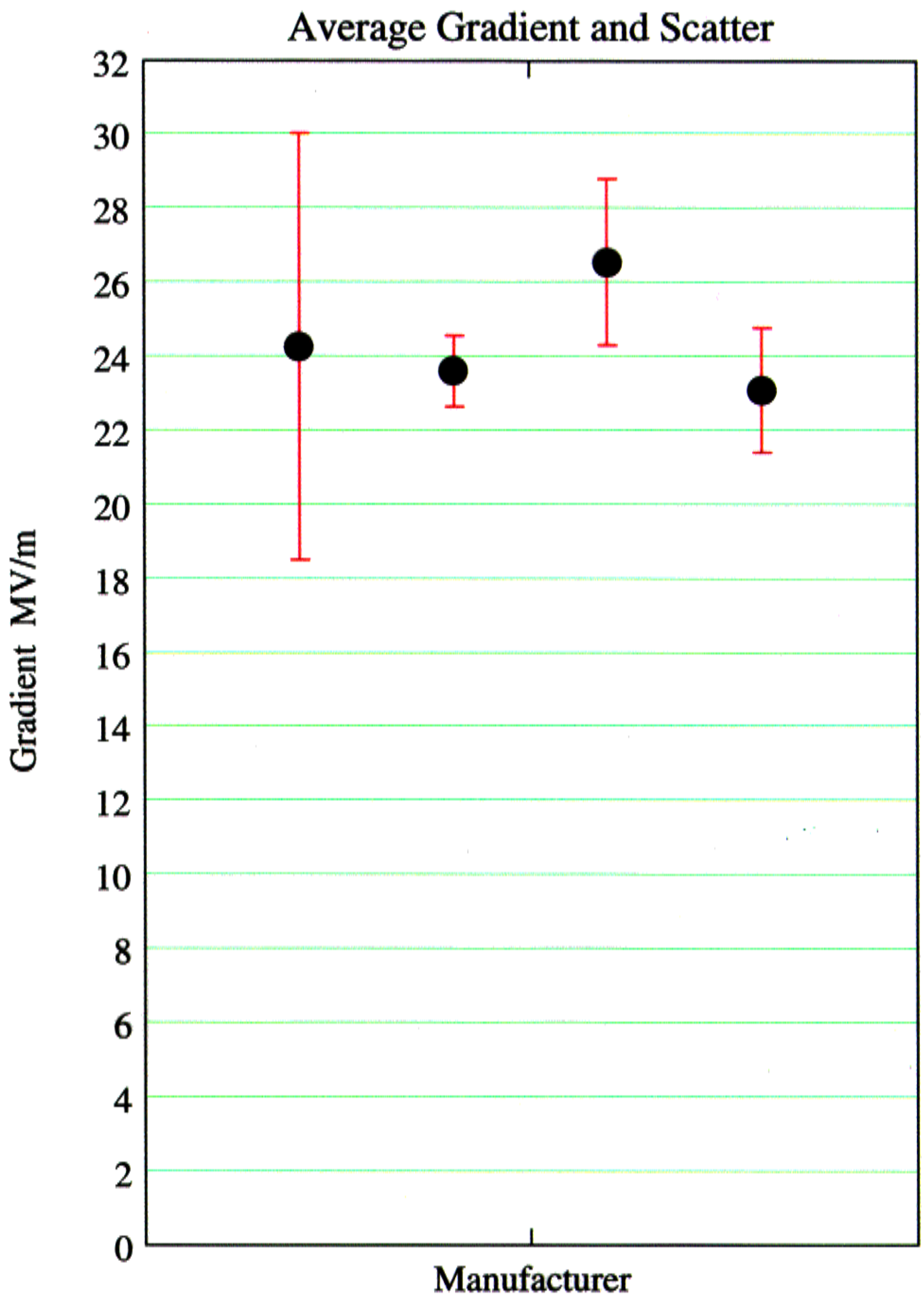
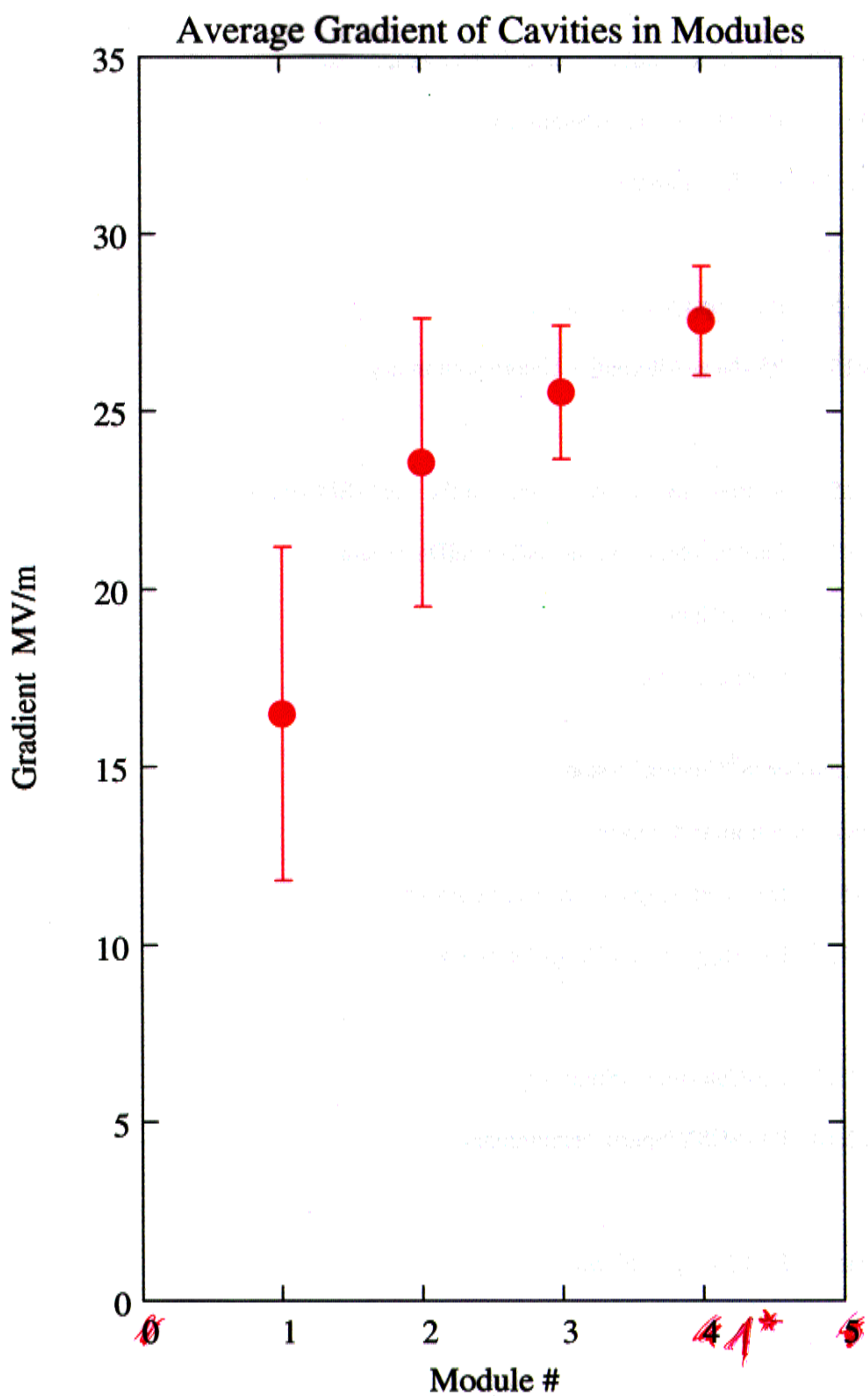
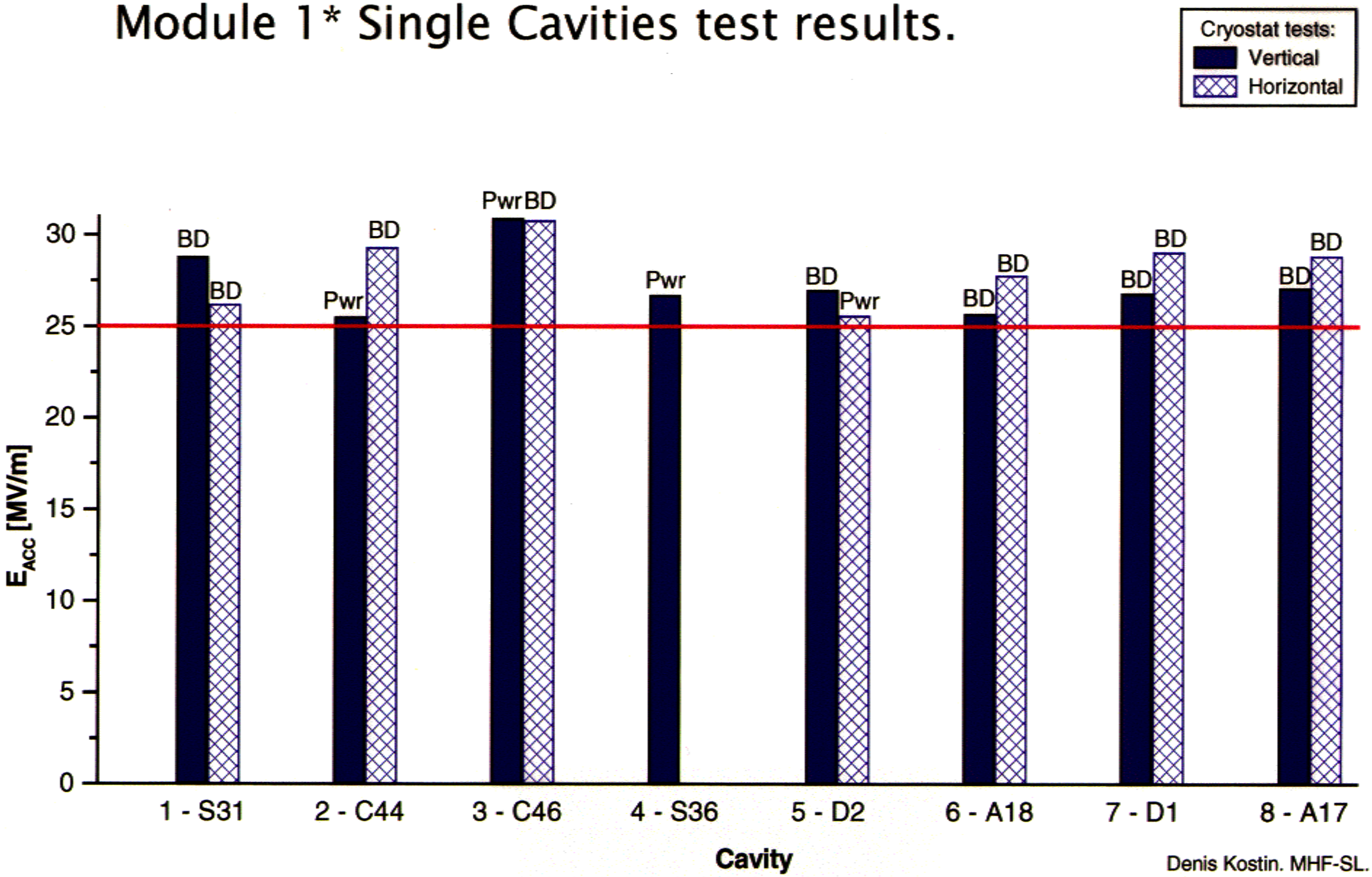


Average Gradient and Scatter
Gradient MV/m
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Manufacturer



Average Gradient of Cavities in Modules
Gradient MV/m
Module #
0
5
10
15
20
25
30
35
1
2
3
4
5
1*

Module 1* Single Cavities test results.



Denis Kostin. MHF-SL.

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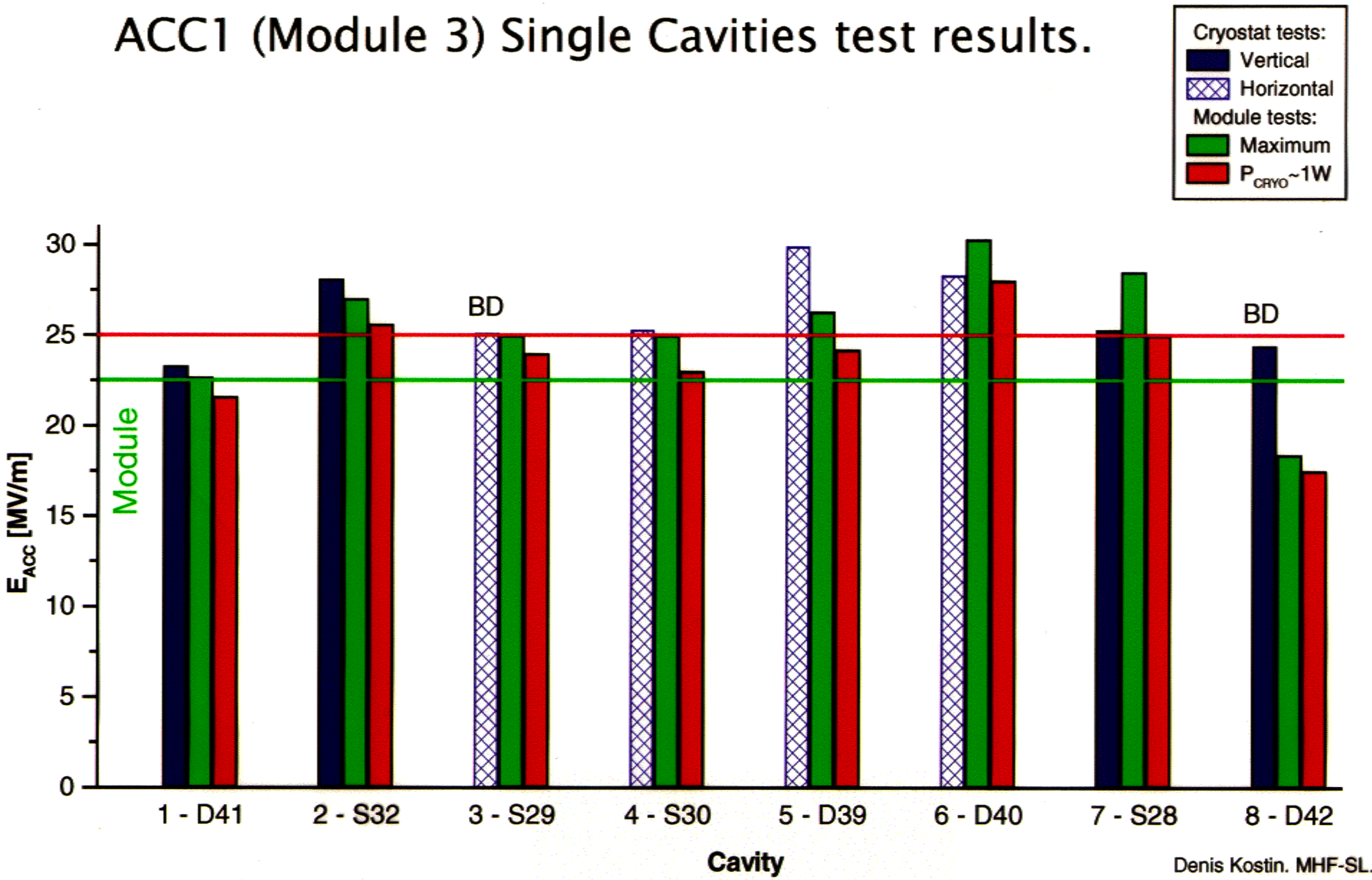
→ 32 cavities / klystron → RF control

ACC1 (Module 3) Single Cavities test results.



Denis Kostin. MHF-SL.

Lutz Lilje DESY

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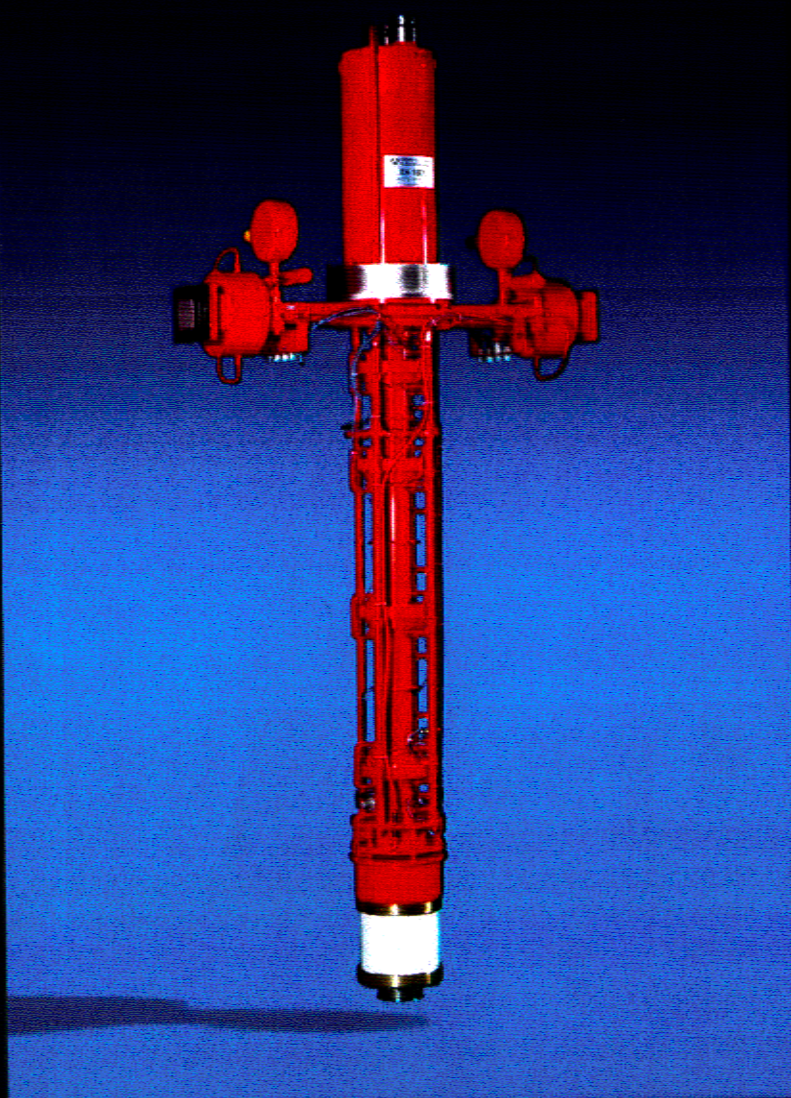
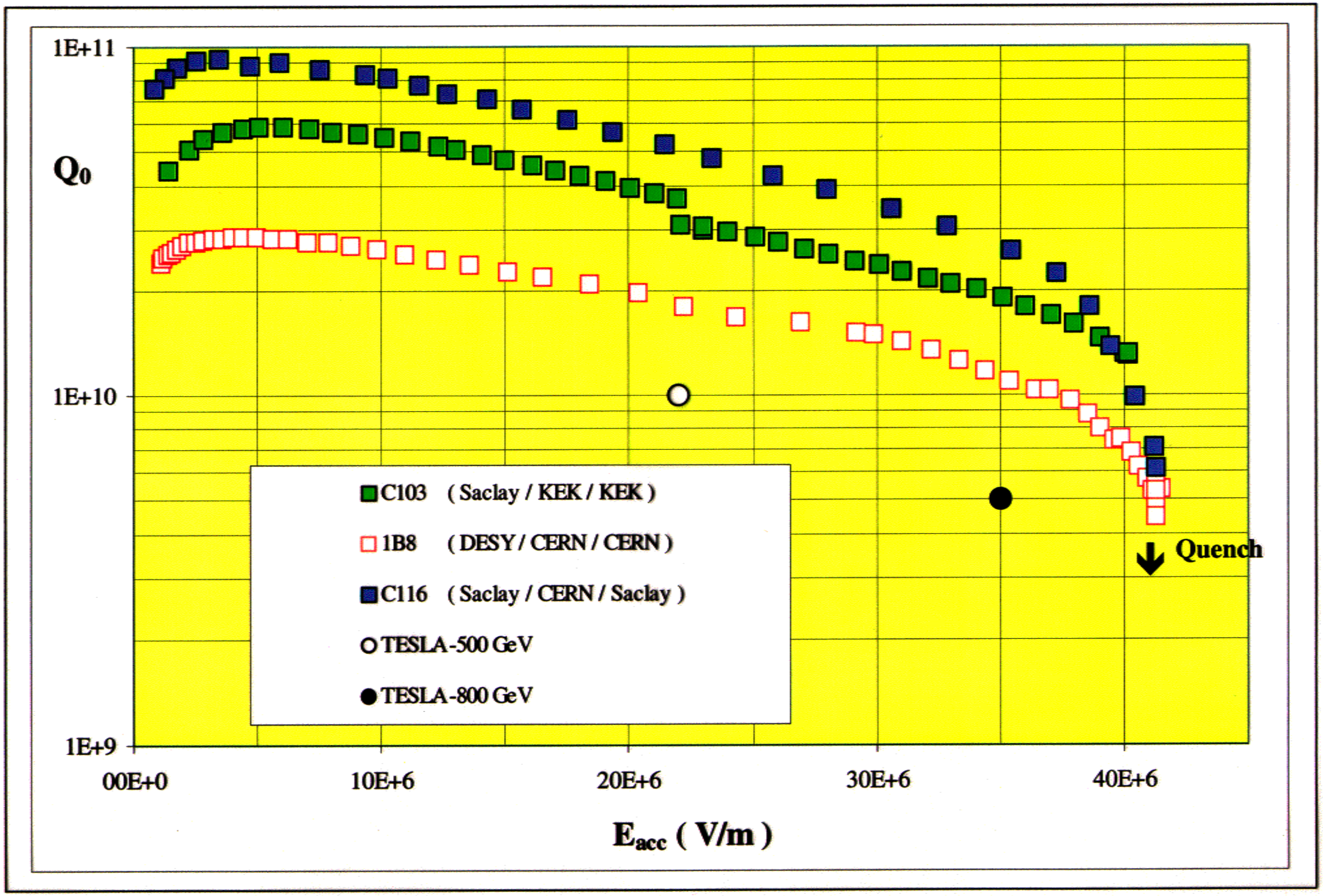
TH 1801 multi beam klystron



High power	10 MW peak at 1300 MHz
Low voltage	117 kV
High efficiency	65 %
Long pulse	1.5 ms

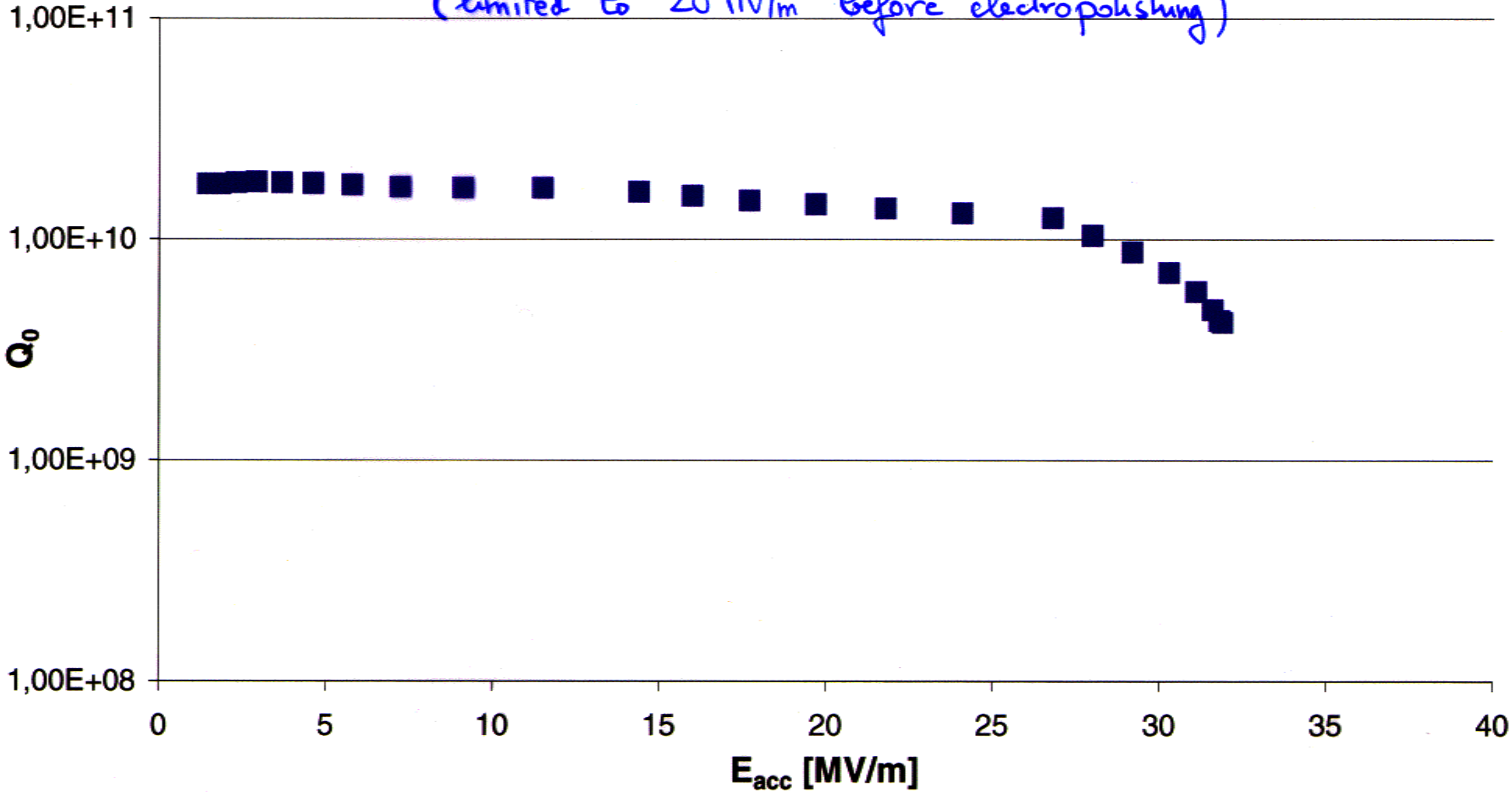
Single Cell Cavities : Electropolishing + Baking (120°C)



Electropolished TESLA nine-cell cavity

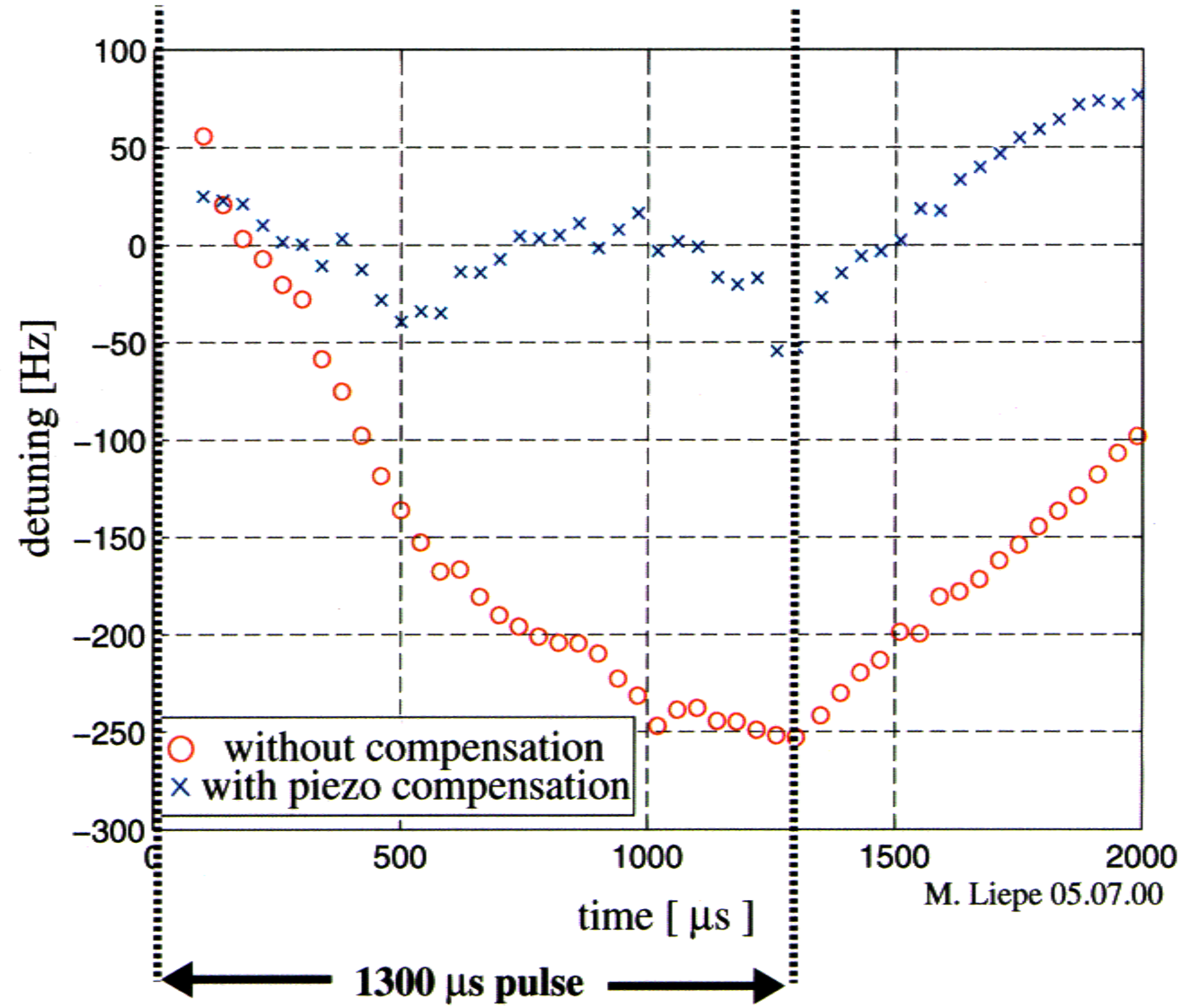
Electropolishing at Nomura Plating and KEK, Test at DESY

(limited to 20 MV/m before electropolishing)



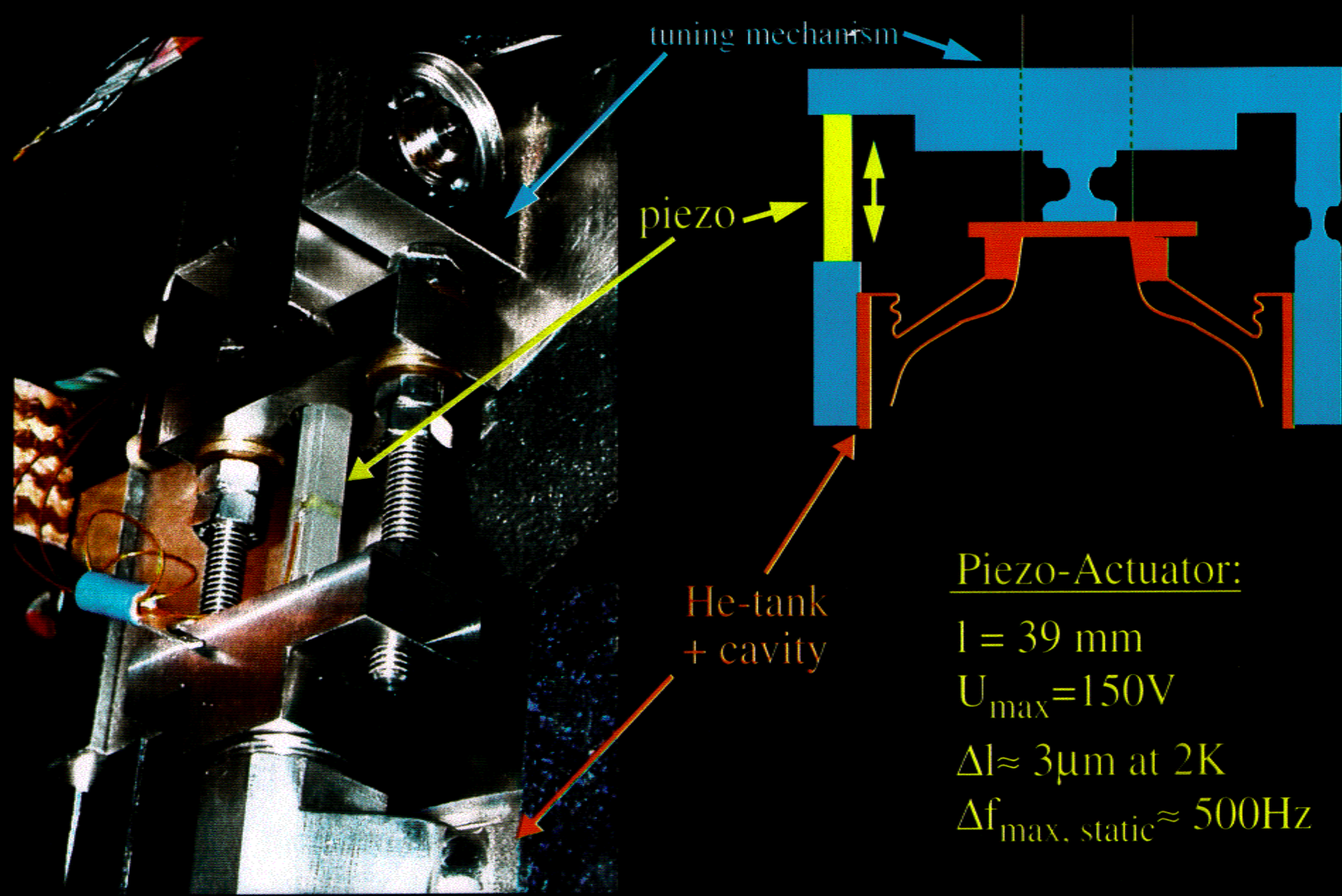
Active Lorentz-Force Compensation during the RF pulse

First *Successful Test on* Cavity C45 at 20 MV/m



⇒ 200 to 250 Hz detuning compensated!

Fast Piezo-Tuner for active Lorentz-force compensation



Piezo-Actuator:

$l = 39$ mm

$U_{max}=150V$

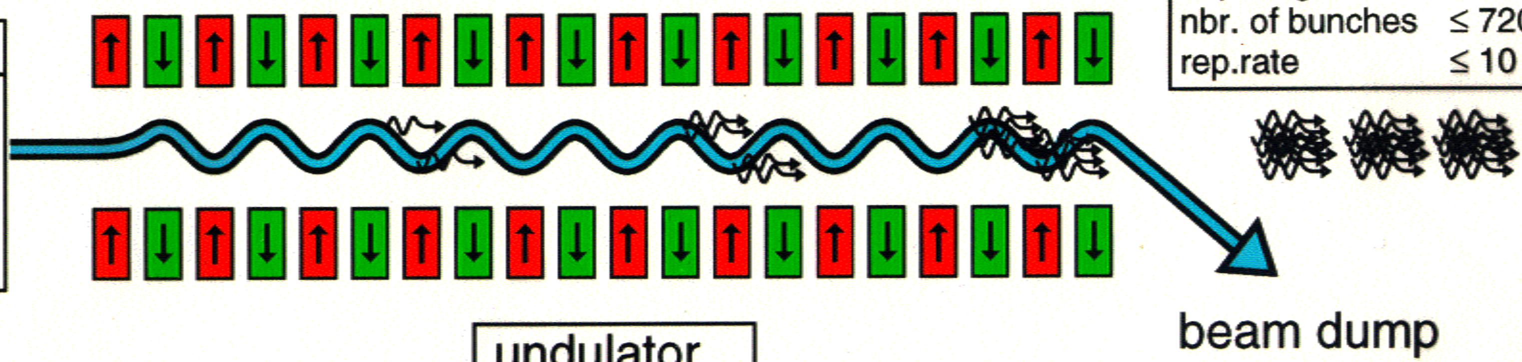
$\Delta l \approx 3\mu m$ at 2K

$\Delta f_{max,\ static} \approx 500Hz$

SASE FEL at the TESLA Test Facility

electron beam

I_{peak} = 2.5 kA
ε_n = 2 π mm mrad
σ_z = 0.05 mm
σ_γ/γ = 1.0 ‰
γ = 2000

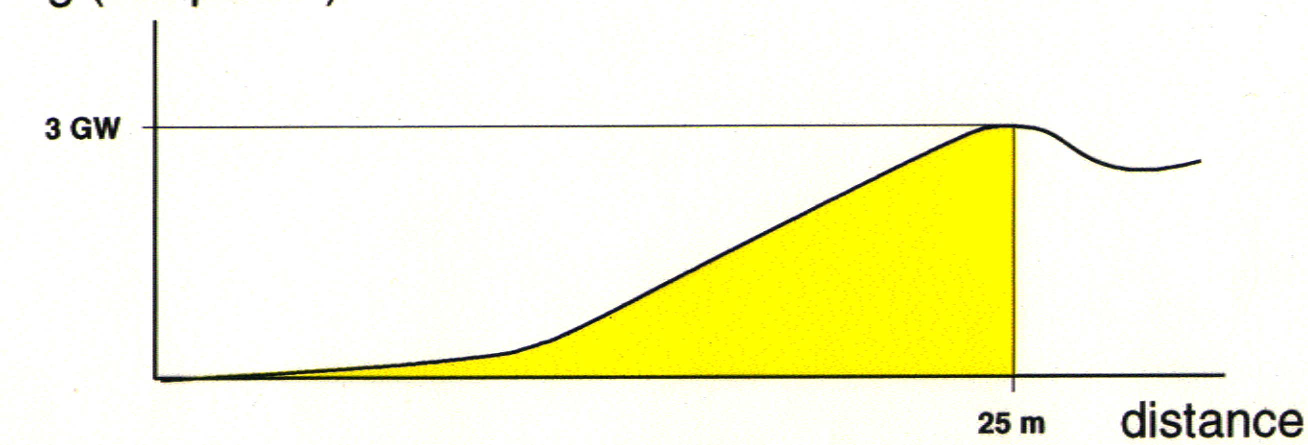


photon beam

λ_{ph} = 6.4 nm (193 eV)
P_{sat} = 3 GW
av.brill. > 10^{21} $\frac{\text{photons}}{\text{s (mm mrad)}^2\text{0.1\% bw}}$
pk.brill. > 10^{29} $\frac{\text{photons}}{\text{s (mm mrad)}^2\text{0.1\% bw}}$
m.p.length = 800 μs
nbr. of bunches ≤ 7200
rep.rate ≤ 10 Hz

undulator

λ_u = 27.3 mm
B_{max} = 0.497 T
N ≈ 1000
gap = 12 mm



H.Weise 04/07

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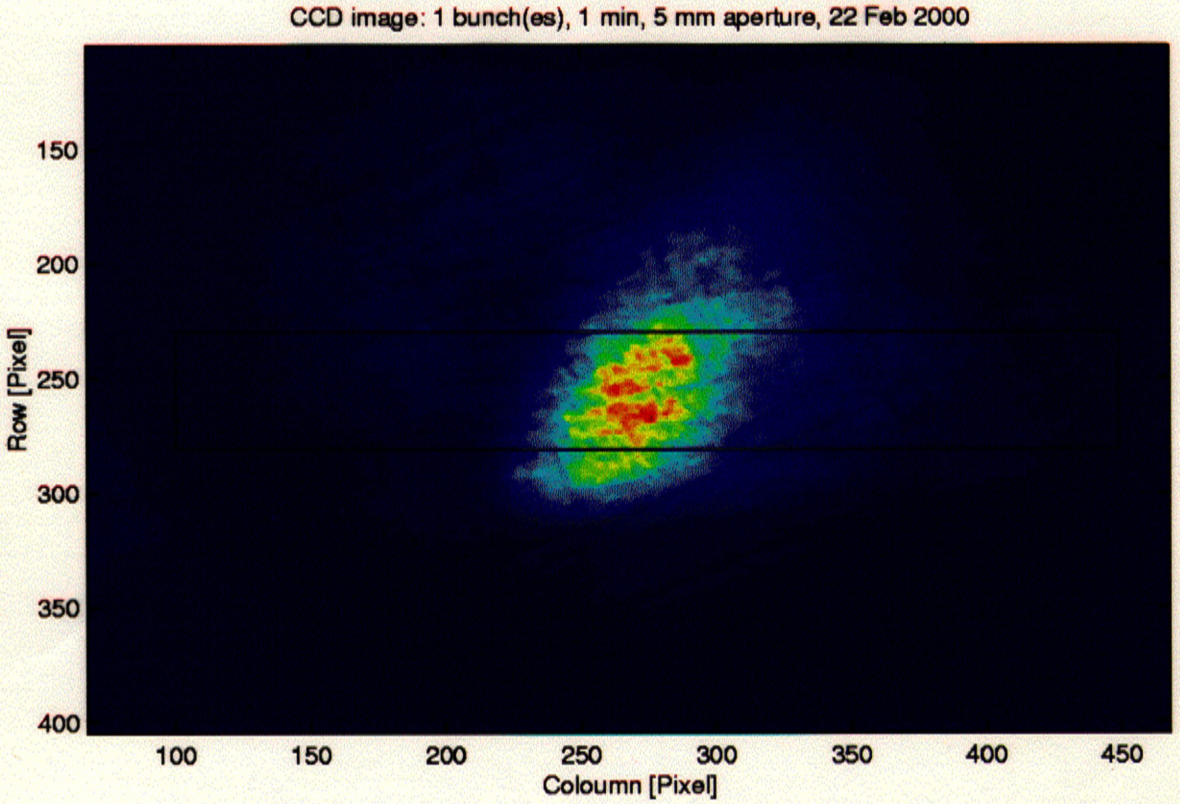
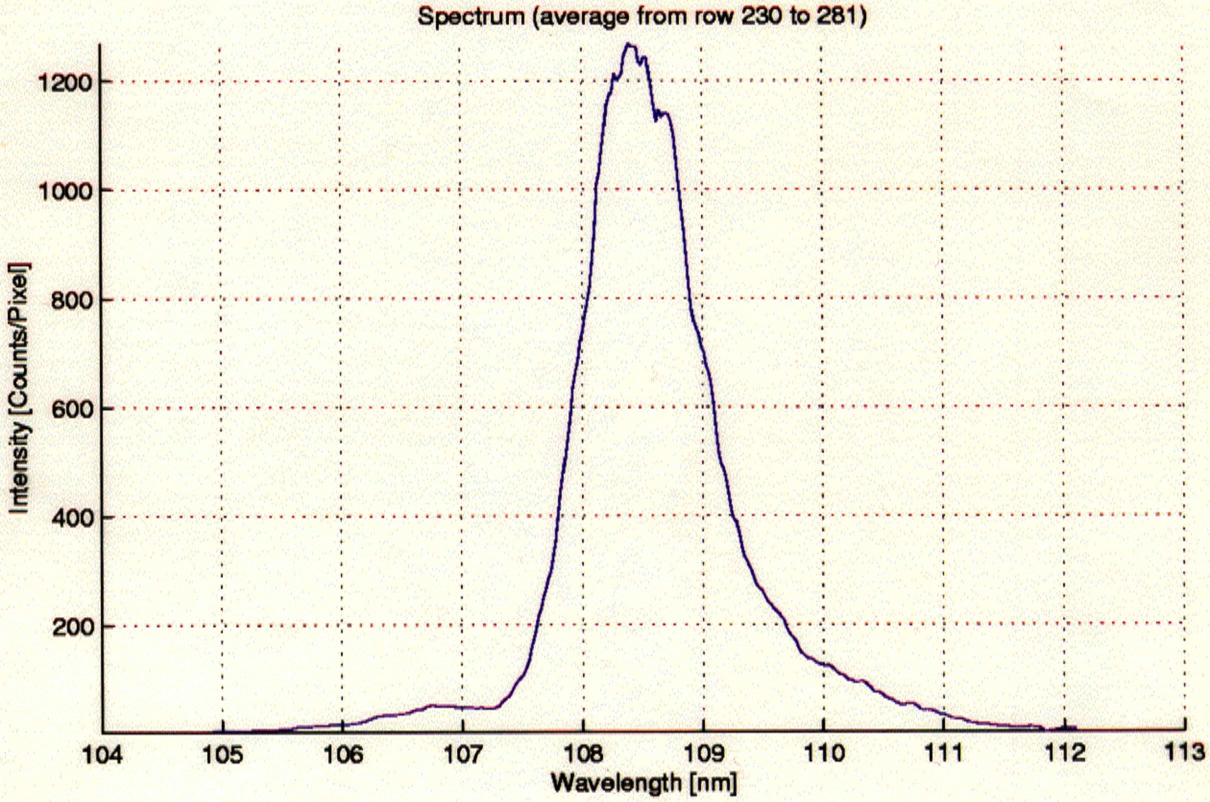
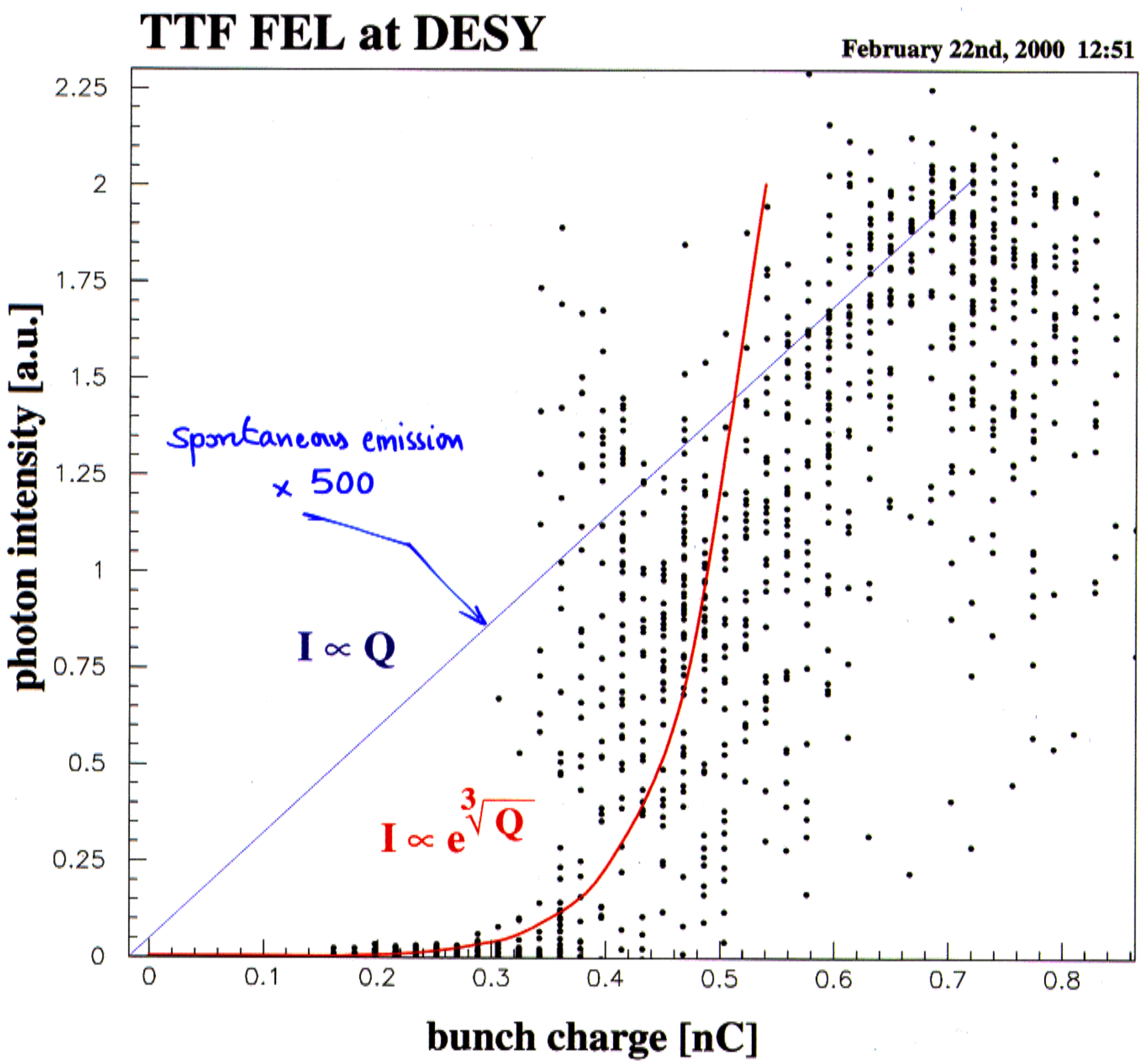
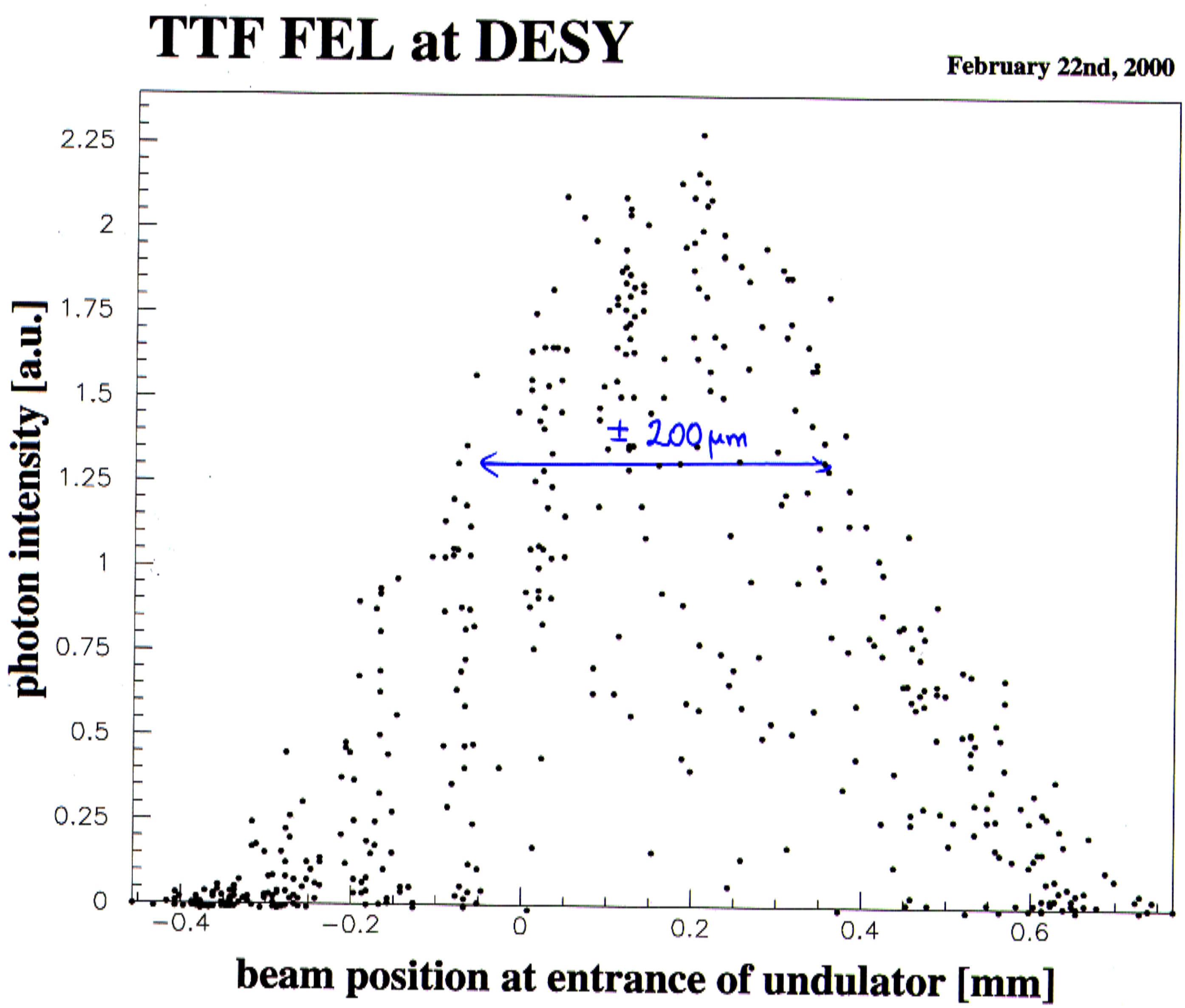




$\lambda_{ph} \simeq 108.5$ nm

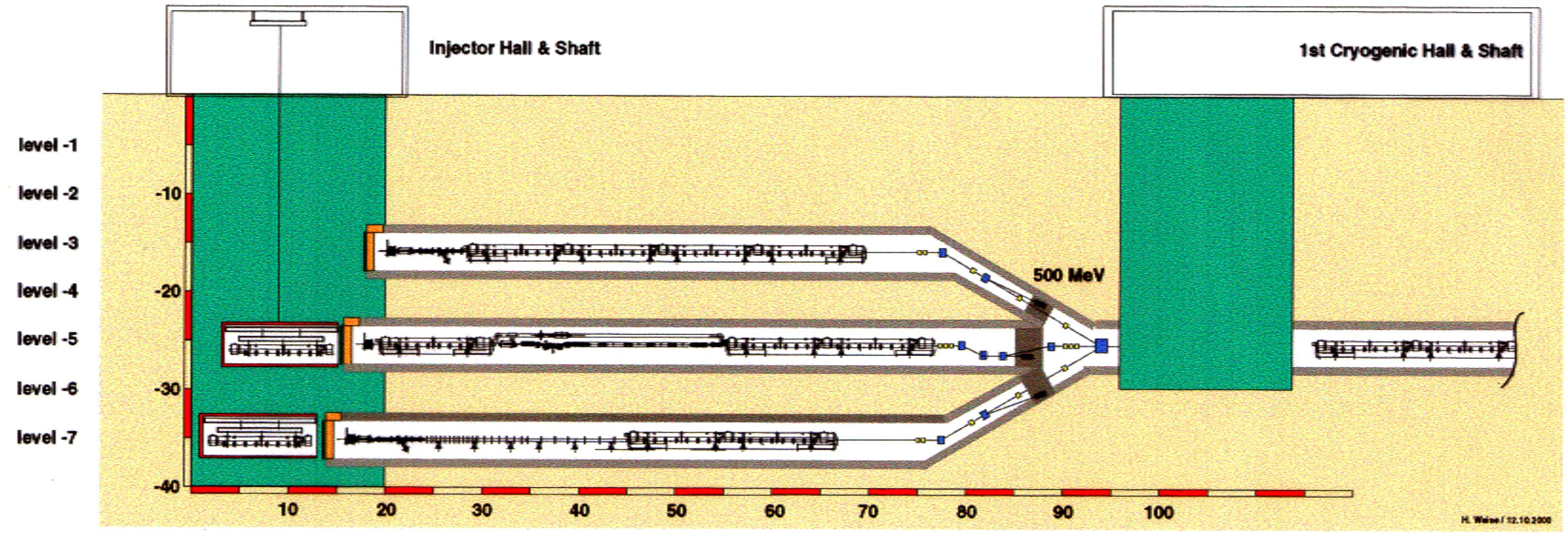

TTF FEL at DESY
February 22nd, 2000 12:51
photon intensity [a.u.]
bunch charge [nC]
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Spontaneous emission
x 500
I ∝ Q
I ∝ e∛Q

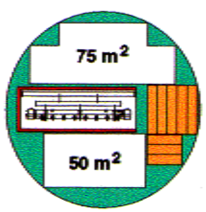

TTF FEL at DESY
February 22nd, 2000
photon intensity [a.u.]
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
± 200µm
−0.4
−0.2
0
0.2
0.4
0.6
beam position at entrance of undulator [mm]

Collider Design

- Source and Injectors
- Damping Rings
- SC Linacs
- ~~Beam Delivery System~~

The TESLA Injector Complex





level -3 High Energy Physics HEP Injector
level -5 Free-Electron Laser FEL Injector
level -7 polarized HEP Injector

level -4 laser room for all three injectors

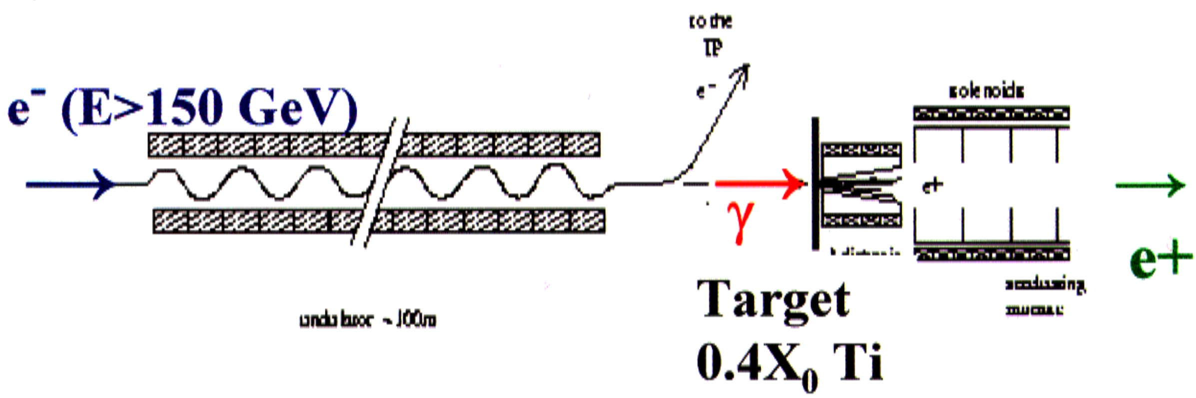
level ?? spare modulator(s) / klystron(s)
spare and conditioned rf gun(s)
spare and conditioned booster cavities
cathode preparation lab.

HEP Injector:
RF gun
booster cavity
module #1 9-cell struct. / 8 input couplers
module #2 - #4 9-cell or superstructure

FEL Injector
RF gun
module #1 9-cell struct. / 8 input coupl.
3rd harmonic cavity
bunch compressor
module #2 - #3 9-cell or superstructure
operation at 80% of max. gradient

pol. HEP Inj.
SLC type gun
normal cond. linac to about 100 MeV
because of solenoidal focusing
supercond. modules until 500 MeV

TESLA e^+ Source Concept



- Undulator
  - L = 100 m, B = 0.6 T, 1.35 cm period

- Electrons (E=250 GeV)
  - $\delta E / E = 1.2\ \%$, $\sigma_E / E = 0.14\ \%$

- Photons (Nγ = 370 * Ne)
  - Eγ = 25 MeV , Pγ = 135 kW

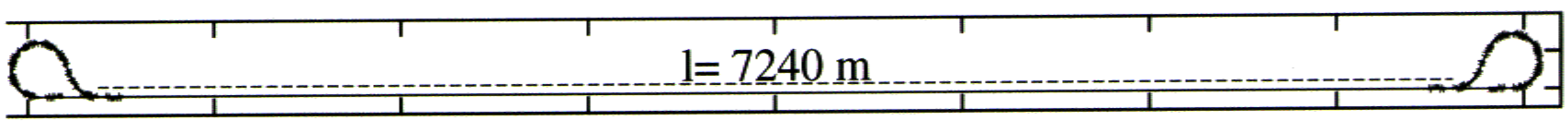
Damping Ring Concept

- Long TESLA bunch train (2820 bunches, 337 ns bunch-spacing) would require a 280 km circumference damping ring
  → compress bunch train with smaller bunch spacing in damping ring

  Circumference is now given by the achievable kicker raise/fall time

- Assume kicker raise/fall time of 20 ns ⟶ circumference $> 2820 * 20ns * c \approx 17$ km
- To avoid excessive additional tunnel cost build most part of the ring in the linac tunnel :

  DOG-BONE



- Note: Because of the TESLA positron source scheme the position of an ejected bunch is filled again after ≈ 1.5 turns

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Main DR Parameters

energy	5.0 GeV
circumference	17 km
hor. emittance $\gamma\varepsilon_x$	9×10^{-6} m
ver. emittance $\gamma\varepsilon_y$	2×10^{-8} m
transverse damping time $\tau_{D;x,y}$	28×10^{-3} s
equilibrium bunch length σ_z	6 mm
equilibrium momentum spread σ_p/P_0	0.13 %
longitudinal damping time $\tau_{D;s}$	14×10^{-3} s
energy loss per turn U_0	20.3 MeV
beam current I	160 mA
radiated power P_{rad}	3.25 MW
rf-voltage U_{rf}	50 MV
wiggler field integral $\int B^2_{wiggler} ds$	1.4 Tm/m
wiggler period length $\lambda_{wiggler}$	0.4 m
total wiggler length	464 m

Incoherent Space Charge Tune Shift

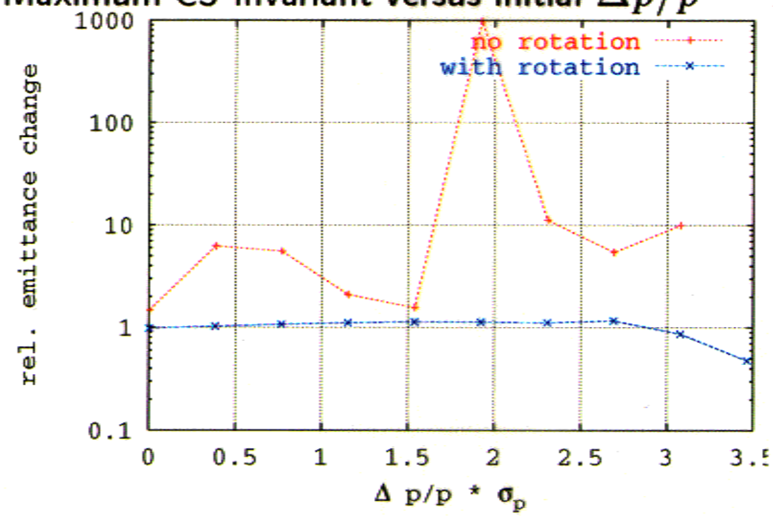
- Large ring length and low energy leads to huge incoherent space charge tune shift:

$$\Delta Q_{y;incoh} \approx -\frac{r_e N_e C}{(2\pi)^{3/2}\sqrt{\varepsilon_x \varepsilon_y}\sigma_z \gamma^2}$$

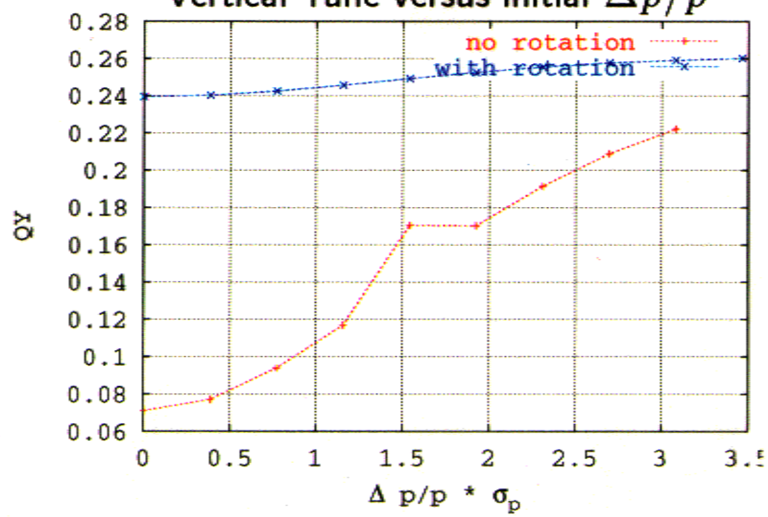
- Cures: Increase ring energy $\Delta Q_{y;incoh} \lesssim 0.2 \rightarrow \gamma \approx 10000$

  Increase bunch volume through local coupling and/or dispersion

Maximum CS Invariant versus initial $\Delta p/p$



Vertical Tune versus initial $\Delta p/p$



red: no vertical emittance increase in straight sections

blue: vertical emittance increased in straight sections with local coupling bump

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SC Linacs

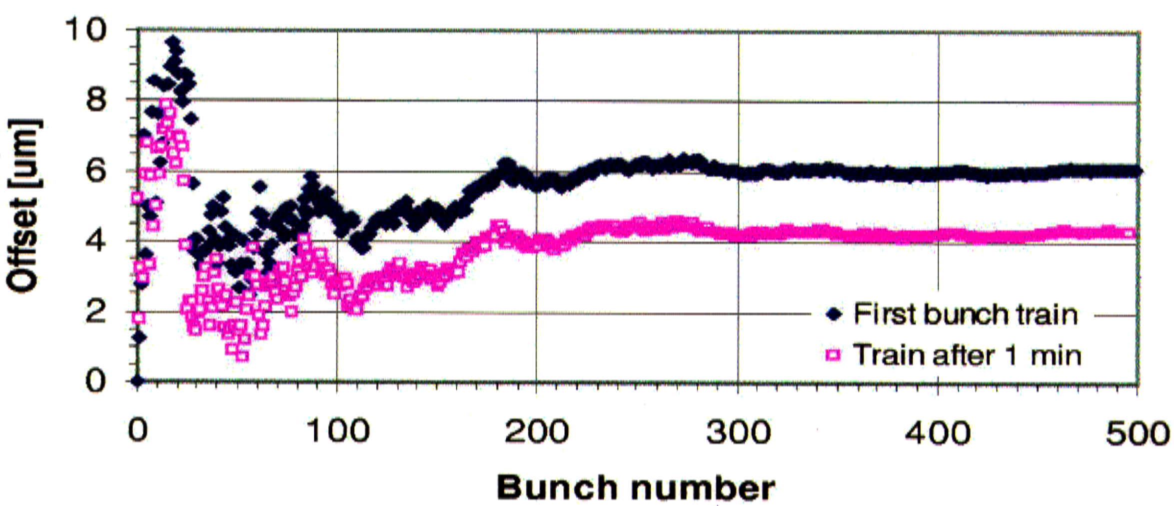
Per Linac :

- 860 RF modules (16 m, 12×9-cell cavities)
- 290 Klystrons (10 MW ⇒ 3 modules)

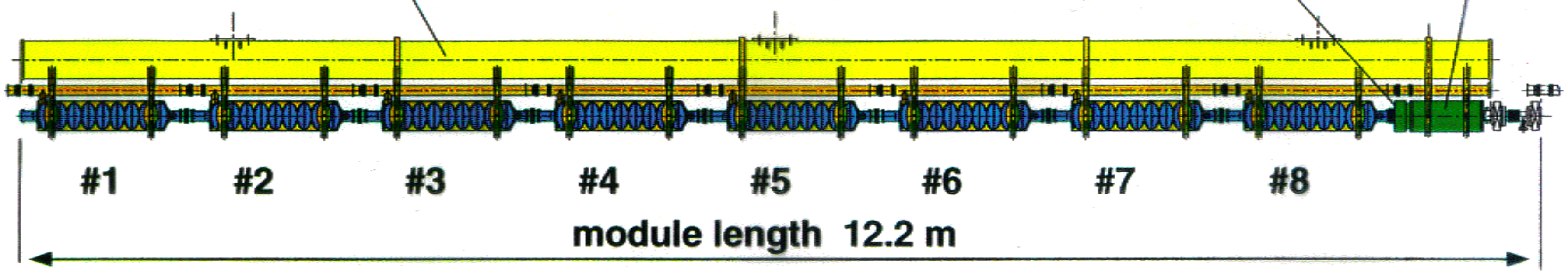
Alignment Tolerances :

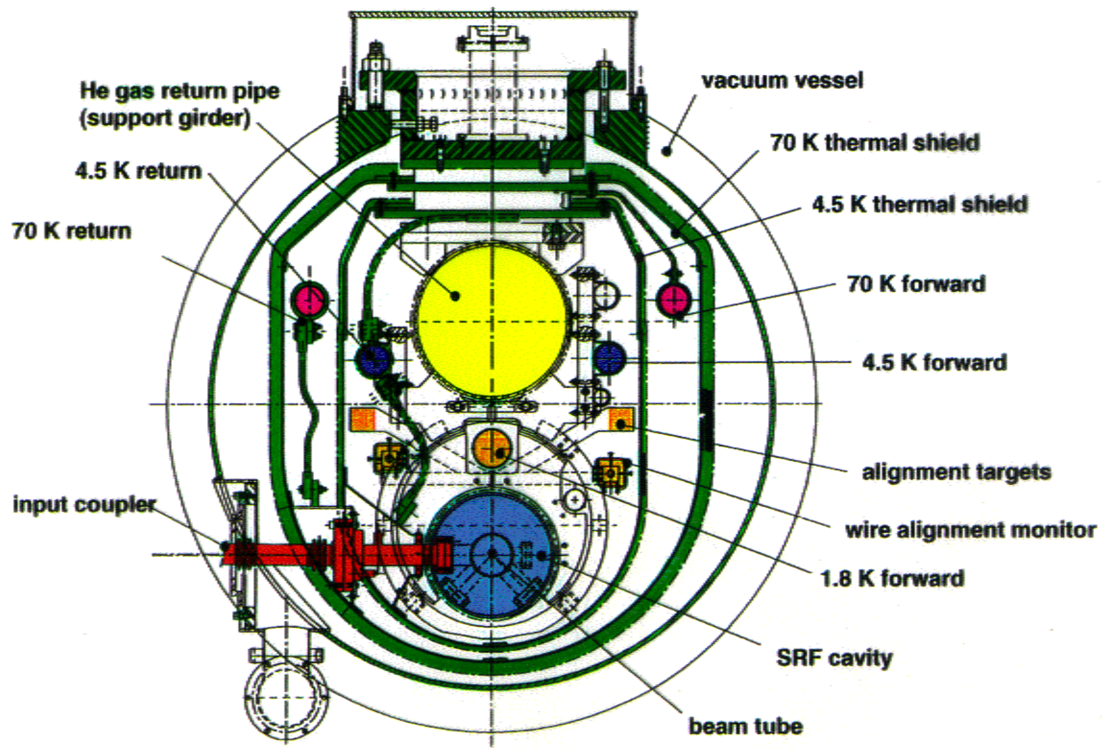
- 0.5 mm for cavities
- 0.3 mm for quads ⇒ ~ 10% $\delta\varepsilon_y/\varepsilon_y$
- 10 μm BPM/Quad single bunch

Multi-bunch instabilityis Static :



⇒ can be removed by fast kickers





- 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

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Interaction Regions

- Beam Switch Yard
- Fast IP Feedback
- Mask Region

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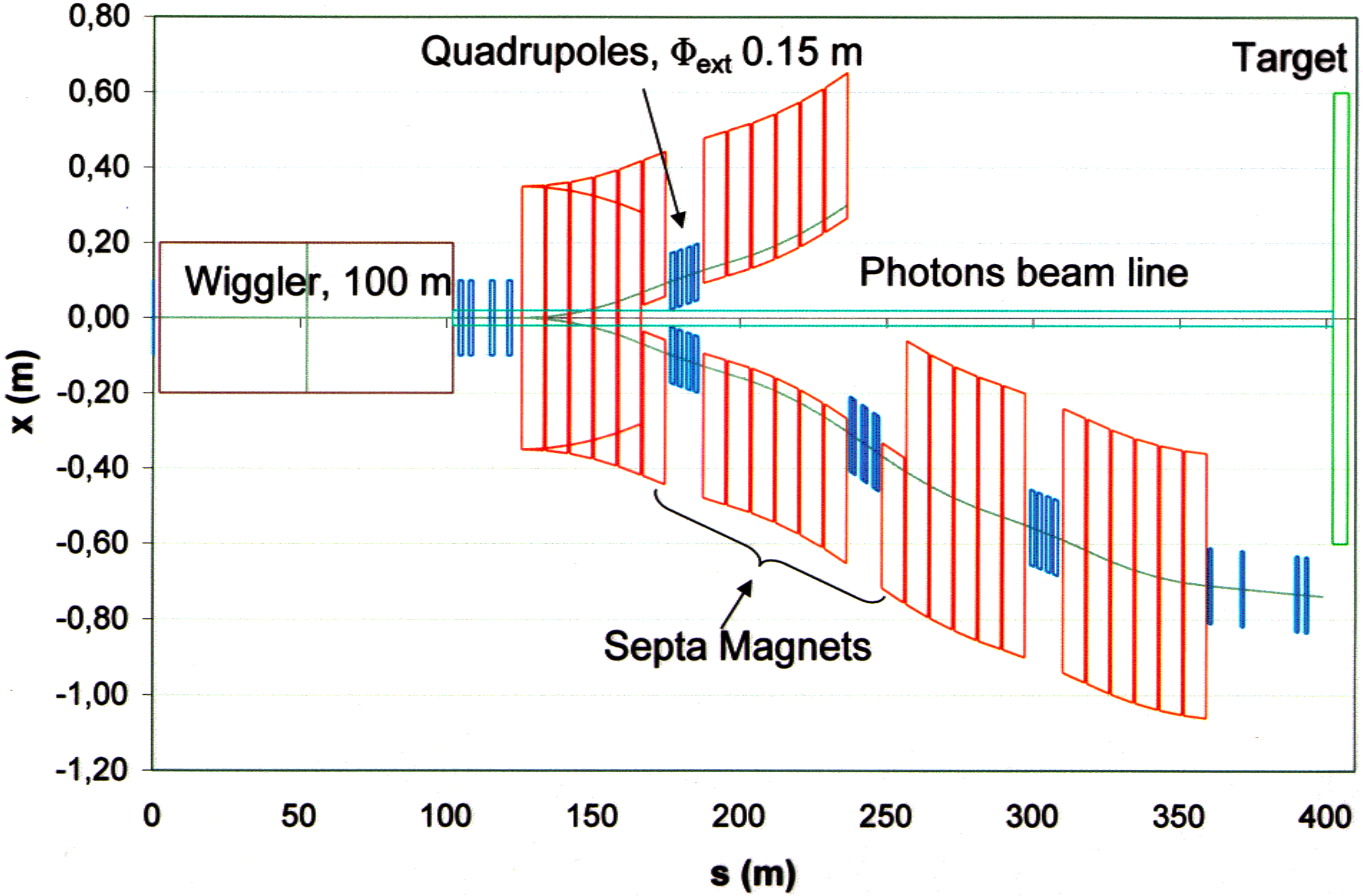
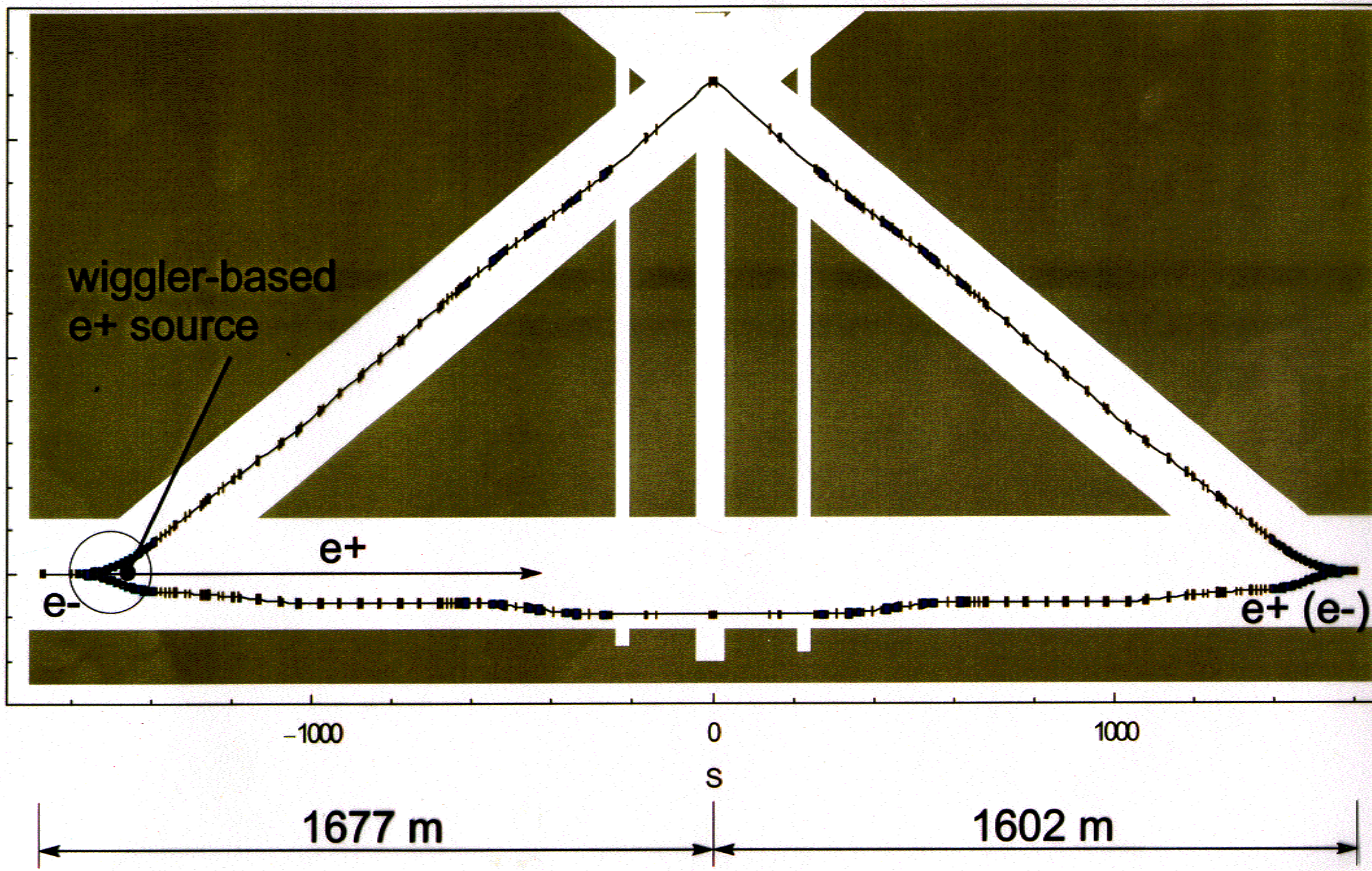
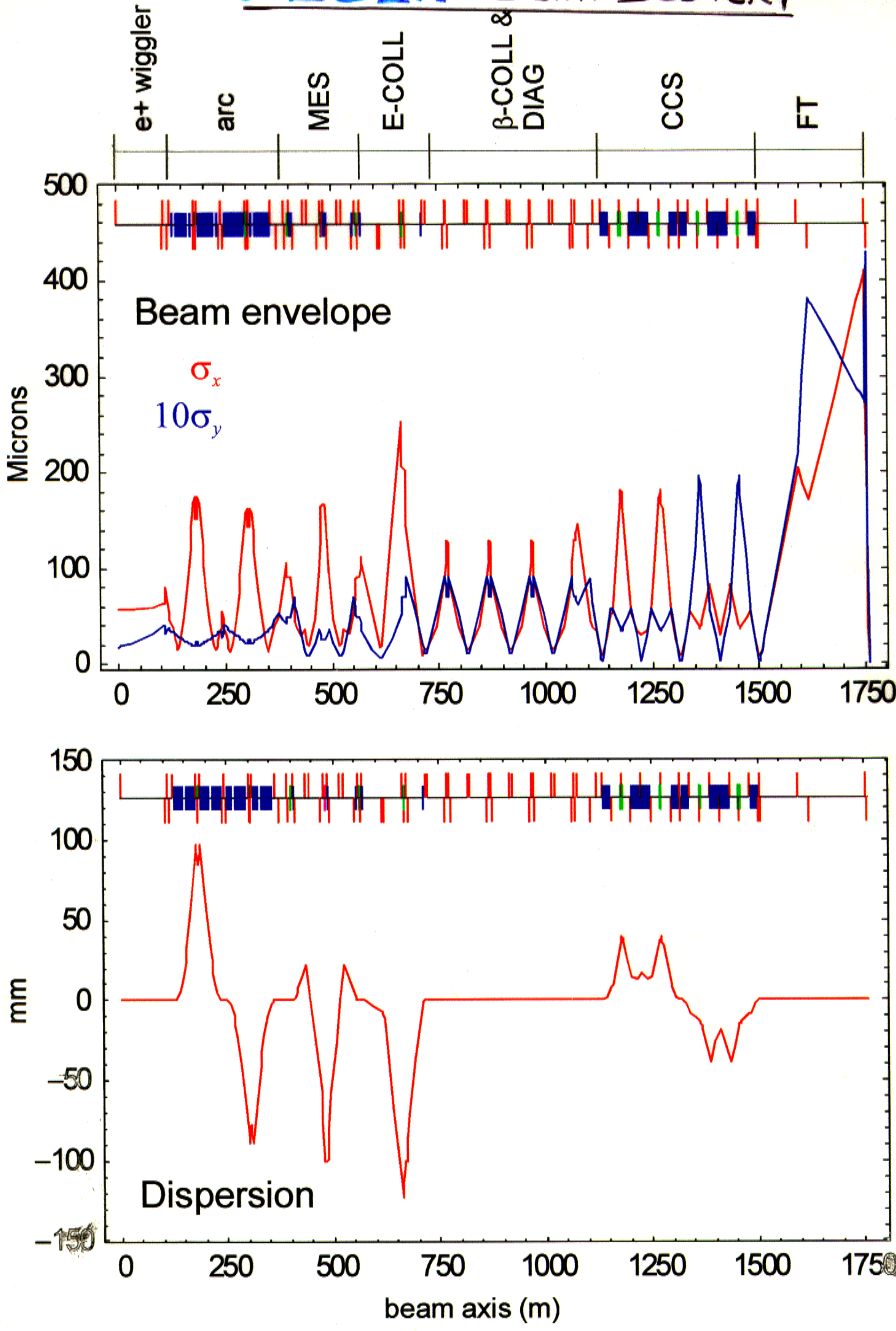
TESLA Beam Switch Yard
Double Bend Achromat

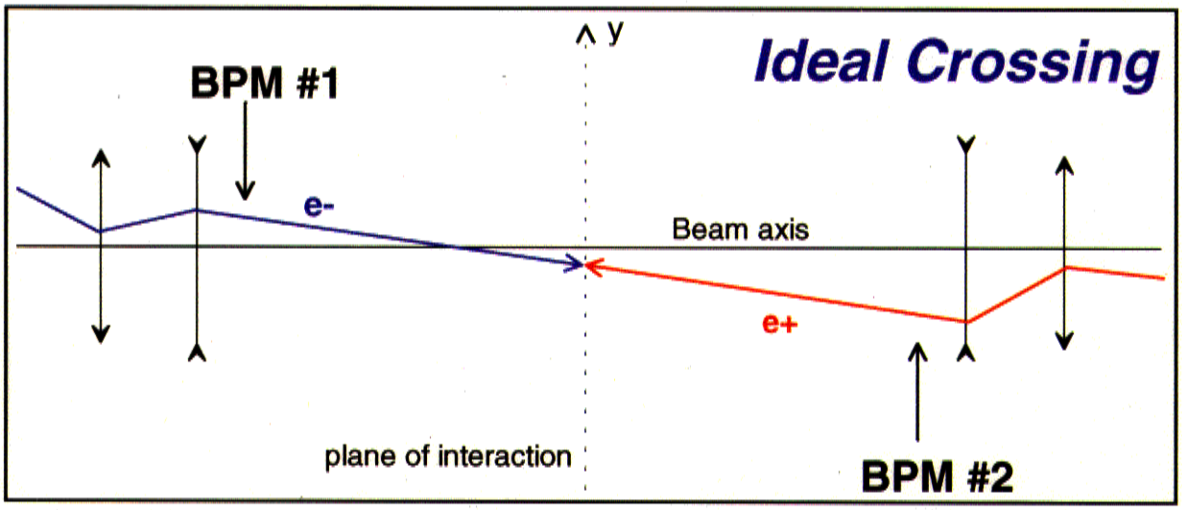


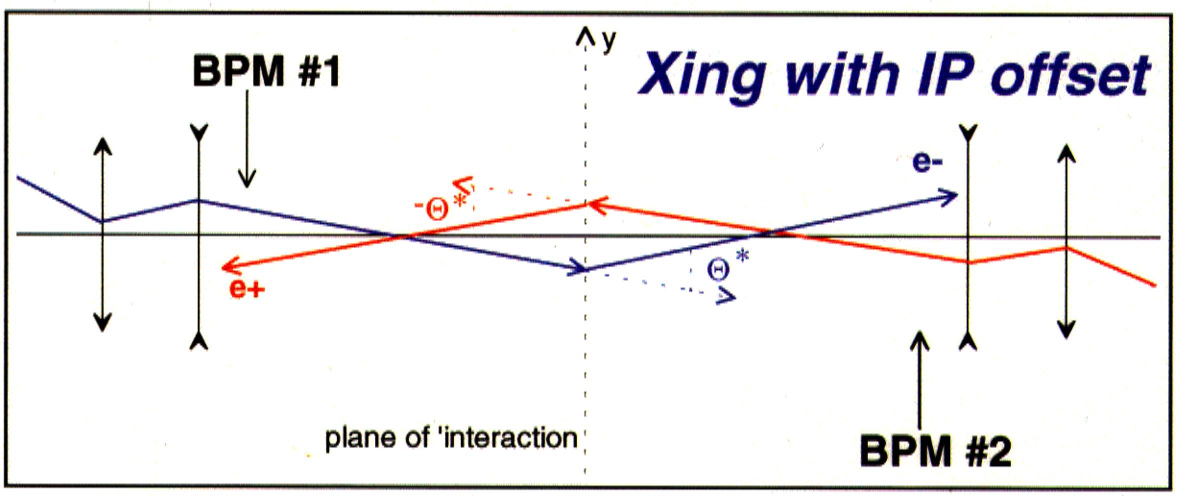

wiggler-based
e+ source
e+
e-
e+ (e-)
X
20
10
0
-1000
0
1000
s
1677 m
1602 m

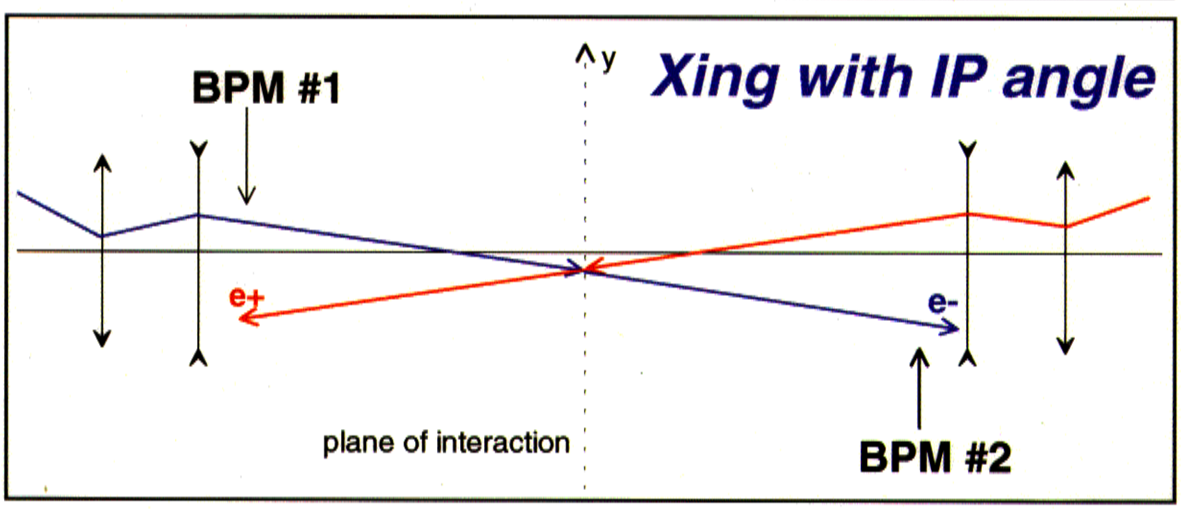
TESLA Beam Delivery



TESLA Feedback for IP Offset & Angle



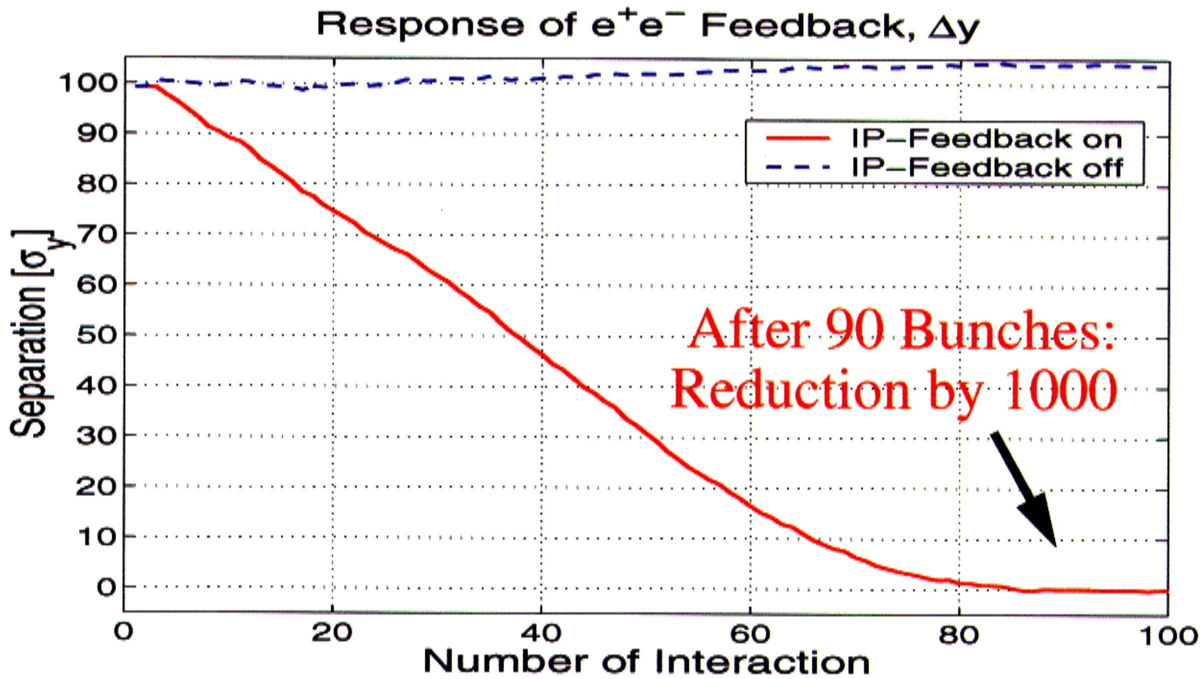


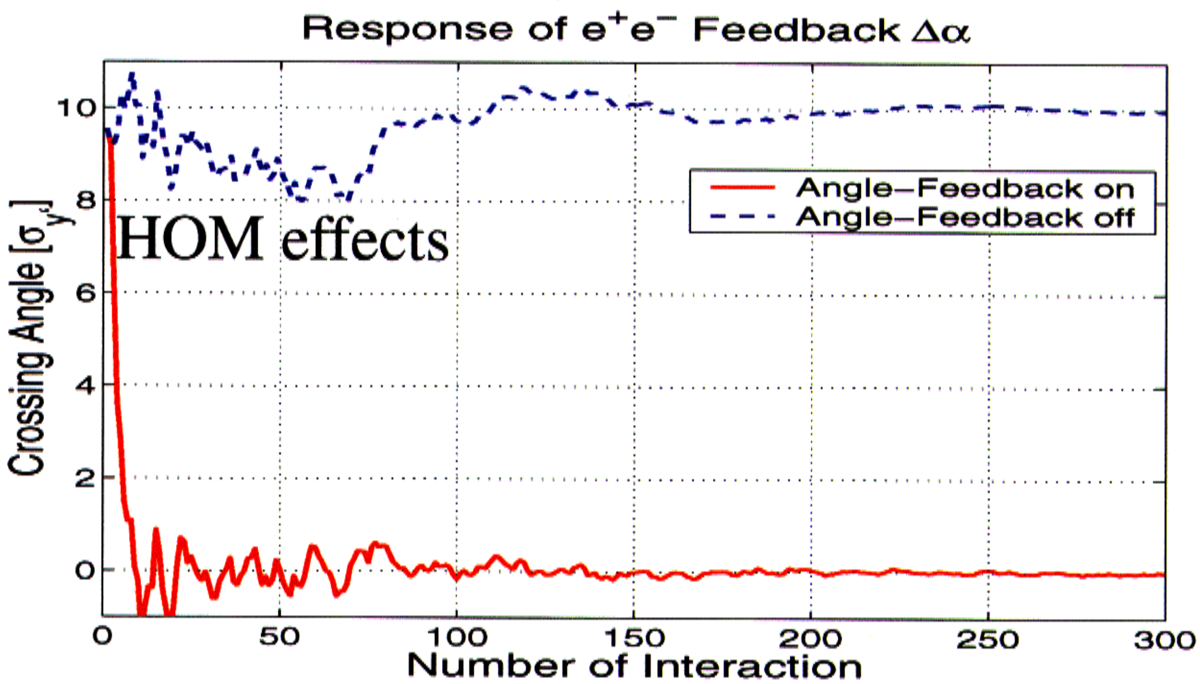


Head-on collision allow BPMs to read (y_{IN}-y_{OUT}) orbits

Δy and Δα Feedback in series

Add. disturbance $\Delta y=100\sigma_y$, $\Delta\alpha=10\sigma_{y'}$: **91.7%L**



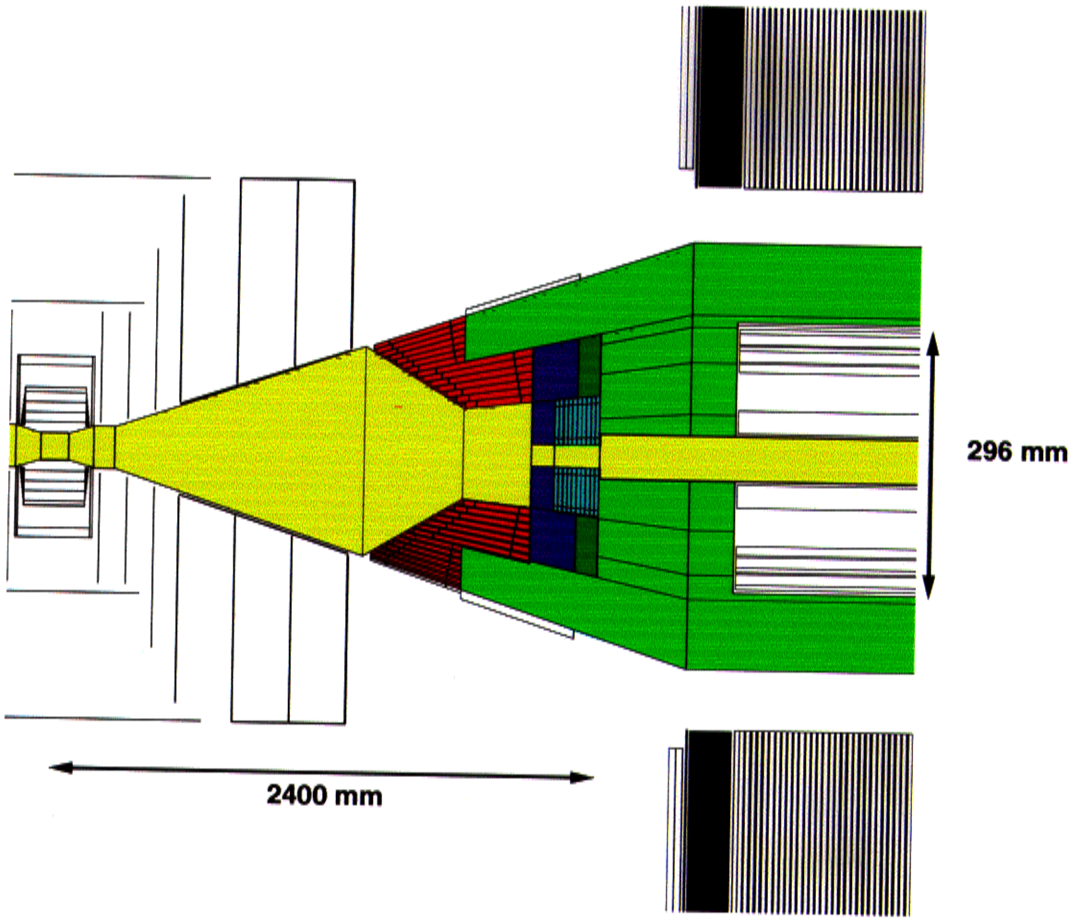


Train-to-Train Tolerance (5Hz) of Final Doublet limiting Luminosity Loss to 10% : 200nm

The Mask Region

Design of the mask region

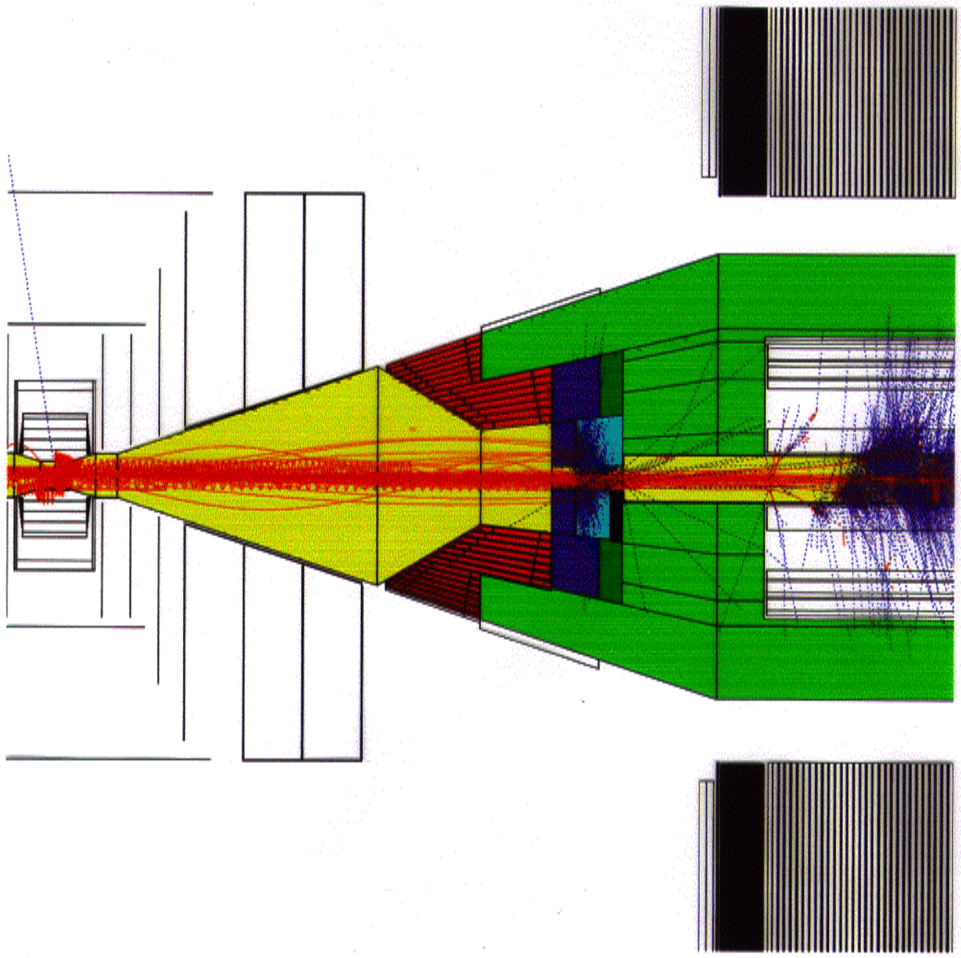
- Tungsten shield for backscattered pairs and secondaries
- Neutron shield (graphite absorbers)
- Shield for synchrotron radiation



- Instrumentation for small angles
  - Low Angle Tagger (LAT) $30\ \mathrm{mrad} < \theta < 83\ \mathrm{mrad}$
  - Luminosity CALorimeter (LCAL) : $6\ \mathrm{mrad} < \theta < 30\ \mathrm{mrad}$

Background: Pairs in the Mask

$\approx 0.1\%$ of one bunchcrossing @ 500 GeV , 3T



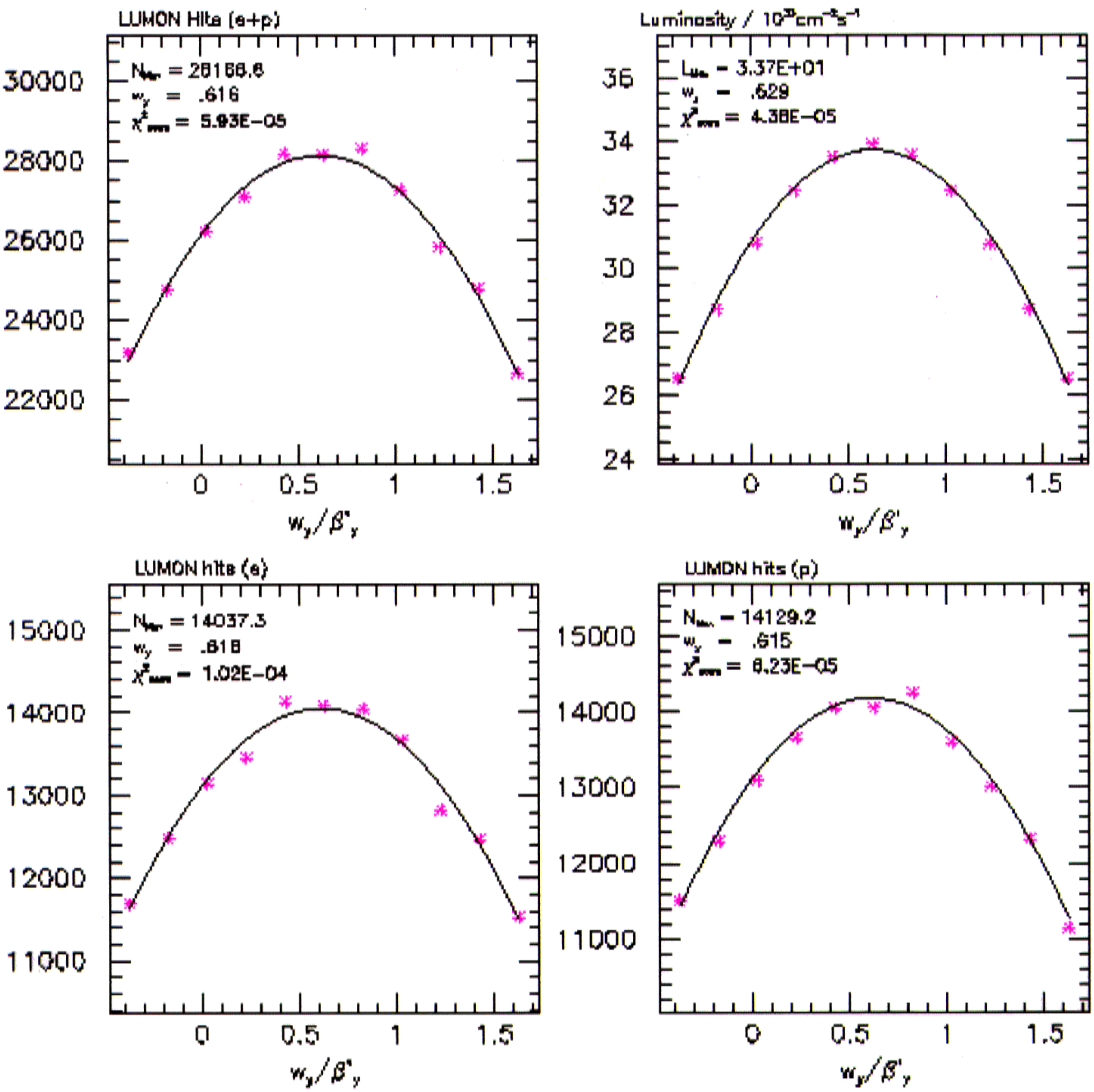
Pairs on one side ($z \geq 0$) for one full BX

Energy	# produced	Total E	# on LCAL	E on LCAL
500	60000	150 TeV	110000	21 TeV
800	90000	490 TeV	170000	35.5 TeV

Every channel of LCAL fires !!

Waist Optimisation with Pair Luminosity Monitor

Electron beam vertical waist–scan



'BANANA' EFFECT and HIGH DISRUPTION

Wakefields generate *(y,y')* vs. *z* correlations
⇒ Correlated emittance growth @ IP

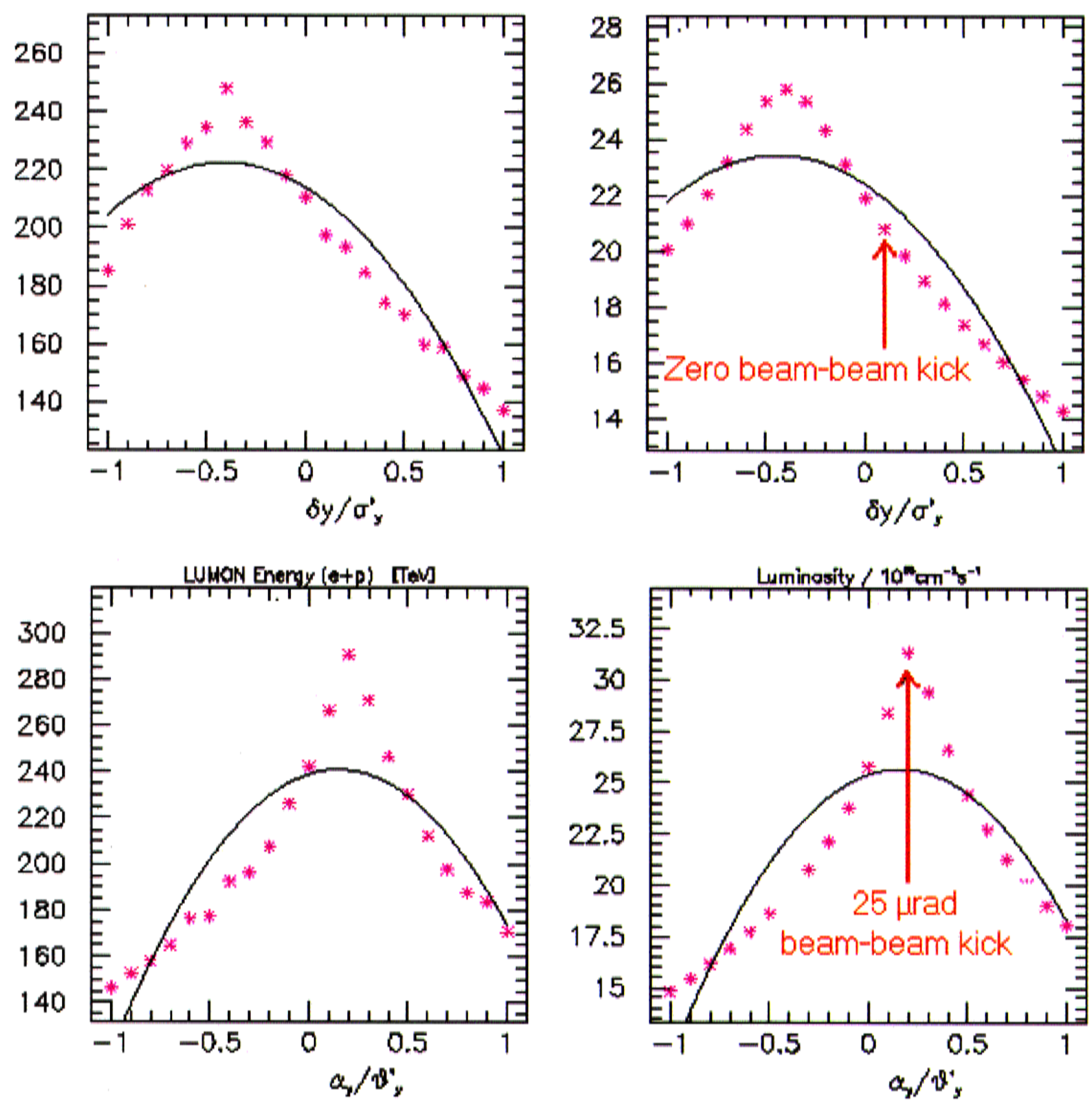
Example of TESLA: collisions with $\delta\varepsilon_y/\varepsilon_y = 10\%$ of electrons with $\langle y\rangle(z) > 0 \leftrightarrow$ positrons with $\langle y'\rangle(z) > 0$

Pair Energy [TeV] **Luminosity** [GUINEA-PIG]

Offset Scan

\+

Angle Scan



Conclusions

- TESLA Linear Collider designed for
  - **$\sqrt{s}$ = 500-800 GeV and L = 3-5 10^{34} $cm^{-2}s^{-1}$**
- TTF has overcome 2 major challenges:
  - **Accelerating Module for 500 GeV with present level of technology from industry**
  - **SASE-FEL demonstrated below 100 nm**
- R&D programme toward higher gradients is progressing :
  - **Eacc > 35 MV/m, Q>5x10^9 by *electropolishing***
  - **800 GeV LC requires better *stiffening* and *filling factor* (superstructure)**
- Technical Design Report (TDR) due in Spring 2001, incl^g cost & schedule
- Evaluation/German Wissenschaftrat in 2001
  - **Aim for start of construction as international project in 2003**

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Christiansholm
Eider
Nortorf
Naturpark
Aukrug
Bordesholm
Neumünster
NEUMÜNSTER
Hohenlockstedt
ITZEHOE
Kellinghusen
Bad Bramstedt
Holstein
Glückstadt
Barmstedt
Kaltenkirchen
Henstedt-Ulzburg
ELMSHORN
Quickborn
NORDERSTEDT
Drochtersen
Uetersen
Tornesch
PINNEBERG
Rellingen
Halstenbek
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STADE
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Blankenese
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Finkenwerder
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