# The Energy Spectrometer at the ILC

DESY – Dubna - TU Berlin

Collaboration

# Outline

- Physics requirements
- Main parameters
- Magnets
- BPMs
- Survey, alignment
- Summary

# Physics requirements

- Mass of top quark:

  $\Delta M_{top} \simeq 40$ MeV
  (theor. uncertainty ~ 40 MeV)

  ➔ $\Delta E_b/E_b \simeq 10^{-4}$

- Mass of Higgs boson:

  $\Delta M_{Higgs} \simeq 40$ MeV
  (recoil mass technique ~ 40-50 MeV)

  ➔ $\Delta E_b/E_b \simeq 10^{-4}$

- Mass of W boson:

  $\Delta M_W \simeq 5\text{-}6$ MeV
  (LHC: $\Delta M_W \sim 15$ MeV)

  ➔ $\Delta E_b/E_b \simeq 5 \cdot 10^{-5}$

- Improve $\sin^2\theta_W$

  running at $M_Z$, from left-right asymmetry measurements
  improvements to

  $\Delta(\sin^2\theta_W) = \pm 0.00005$

  for $50 \cdot 10^6$ events, only electron polarization (90%)
  and $\Delta P_{eff}/P_{eff} = 0.25\%$

  ➔ $\Delta E_b/E_b = (1\text{-}2) \cdot 10^{-5}$

  or $\Delta(\sin^2\theta_W) = \pm 0.00002$

  for $100 \cdot 10^6$ events, electron and positron polarizations (90%,50%)
  and $\Delta P_{eff}/P_{eff} = 0.10\%$

  ➔ $\Delta E_b/E_b = (3\text{-}4) \cdot 10^{-5}$

- Desire to re-scan Z lineshape

  ➔ $\Delta E_b/E_b \leq 1 \cdot 10^{-5}$ $(1 \cdot 10^{-6})$

- Basic target

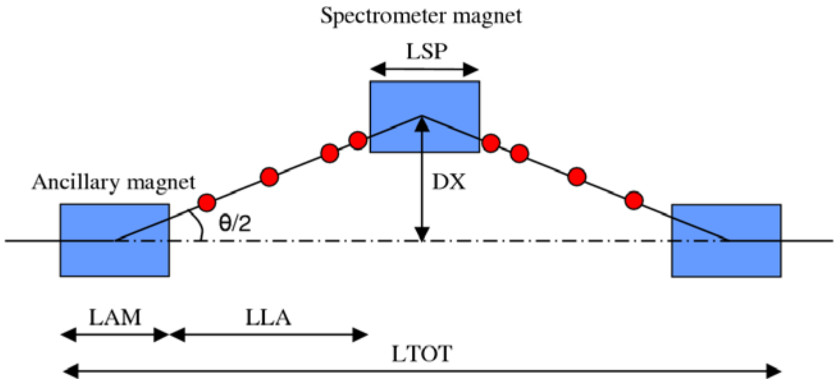
  for $2M_{top} \leq \sqrt{s} \leq 1\text{TeV}$

  ➔ $\Delta E_b/E_b = (1\text{-}2) \cdot 10^{-4}$

# Main parameters of the spectrometer

Concept:
determination of the bending angle Θ
of charged particles through a magnet

$$E_b = \frac{ce}{\Theta} \int_{magnet} B dl$$



**Θ= bending angle**
**B= magnetic field**

3 magnets (one analyzing, two ancillary)
and a series of BPMs

Measurements at different nominal LC energies are proposed to be performed at constant Θ by adjusting the power to the magnets.

Main parameters:
- length of lever arm, LA
- precision of B-field, $\Delta B/B$
- precision of the BPMs, $\sigma_{BPM}$
- # of BPMs

aim to provide a parameter set for

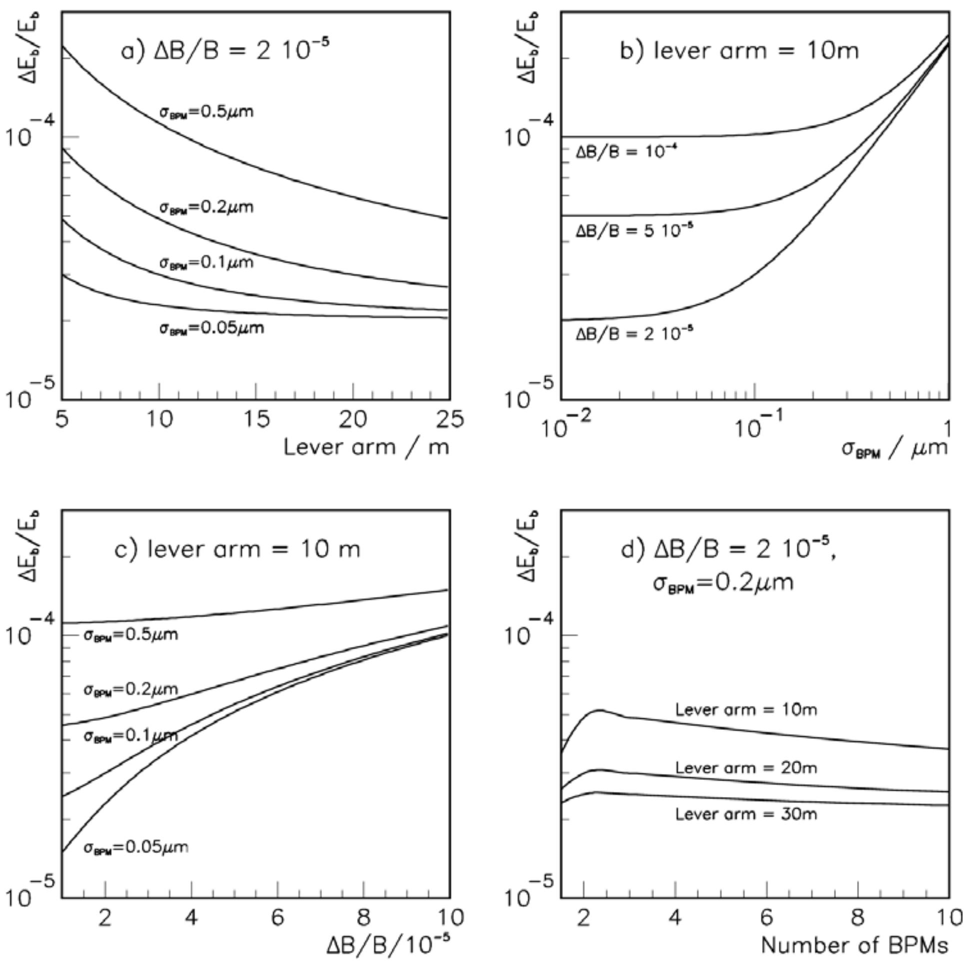
$\Delta E_b/E_b = 5\cdot10^{-5}$

Assuming LA = 10 m,

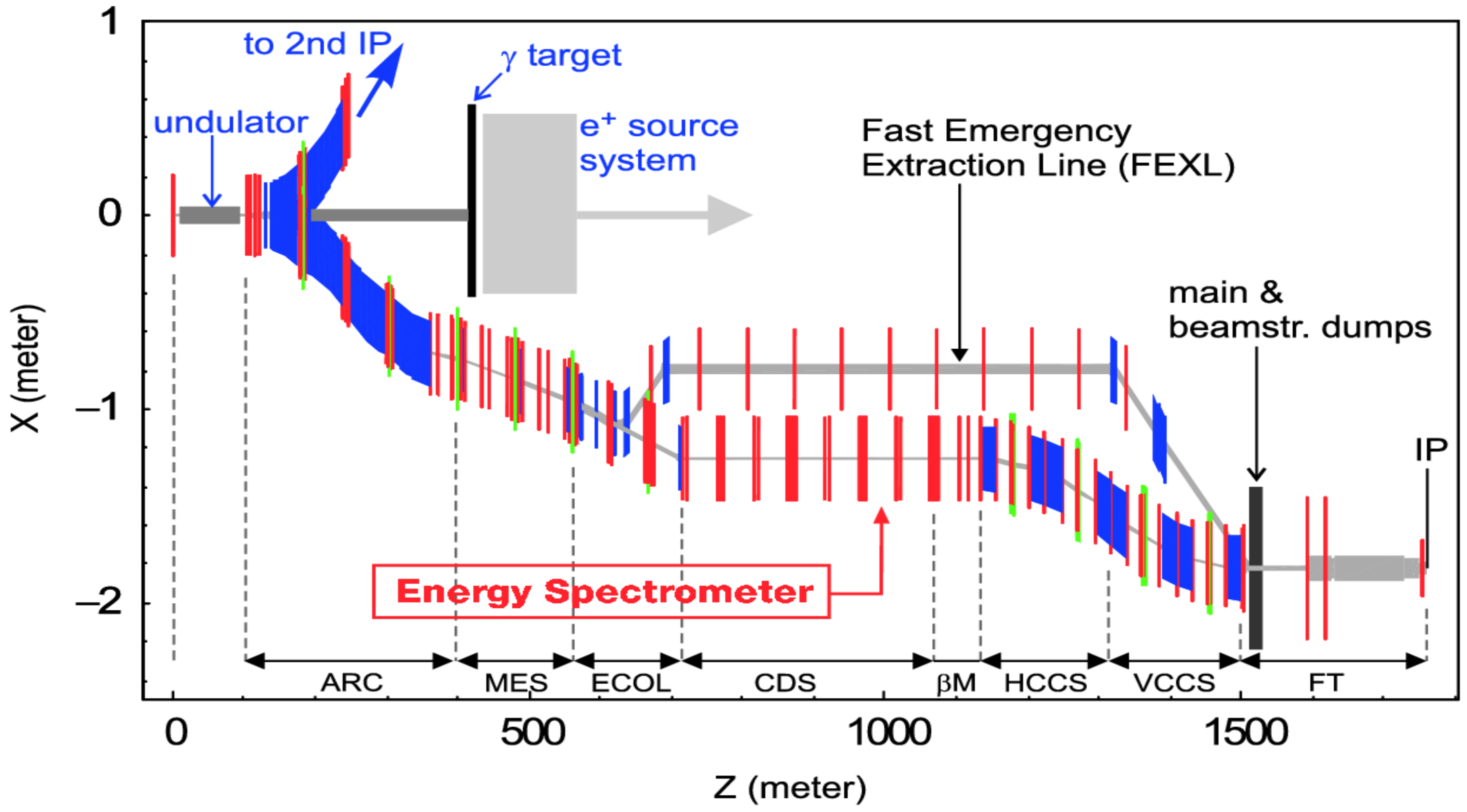
➔ $\Delta B/B = 2\cdot10^{-5}$
➔ $\sigma_{BPM}$ = 200 nm
➔ # of BPMs = 3-4

Advantages:

compact spectrometer $L_{tot}$ ~25 m, sufficient field free drift space, relaxed $\sigma_{BPM}$, B-field precision achievable with custom design devices, but bending angle of 1 mrad !


TESLA Energy Spectrometer Resolution

# Suitable spectrometer location within the BDS

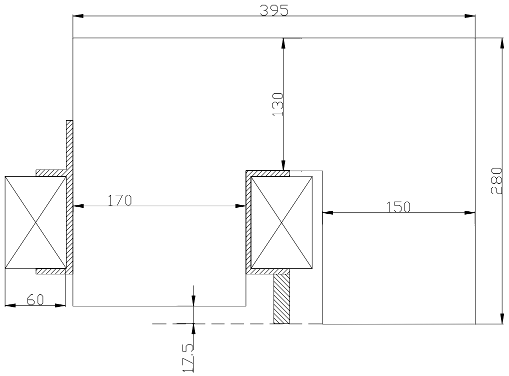


spectrometer located close to the end of collimation and diagnostic section (CDS), within free space of ~40 m; upstream of the polarimeter but also of the chromatic correction sections (HCCS and VCCS) **(IMPORTANT)**

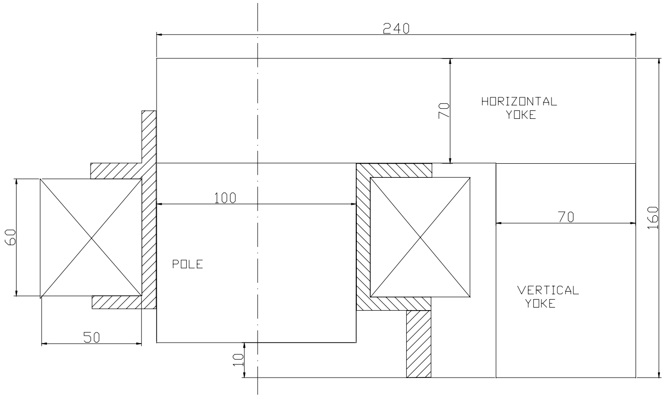
➔ small $\sigma_x$ and $\sigma_y$, well collimated beams, enough space and chance to avoid intolerable emittance grow

# The Magnets

Warm magnets with ferromagnetic core for the analyzing and ancillary magnets
Yoke type: **C core**



Cross-section of analyzing magnet
(1/2 part), 3m long)



Cross-section for ancillary magnet
(1/2) part, 1.5 m long)

Estimation and optimization were performed by a series of 2D and 3D simulations ➔ basic parameters of the magnets, issues for manufacturing, material requirements, temperature stabilization and position tolerances

➔ most critical issue: parallelism of pole gap for analyzing magnet to achieve an integrated field error of $\Delta B/B = 2\cdot10^{-5}$

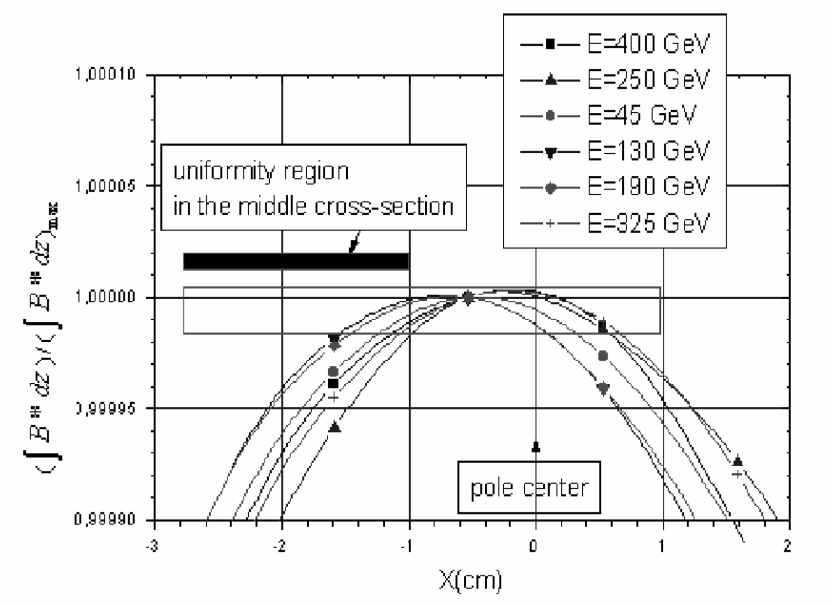
## one of the main concerns of simulations ➔ uniformity of B-field, normalized

### analyzing magnet:

- gap height: 35 mm
- uniformity region: ~10 mm (5-6 mm)
- use of magnetic end field screenings

- mechanical tolerances shift the uniformity region by few mm

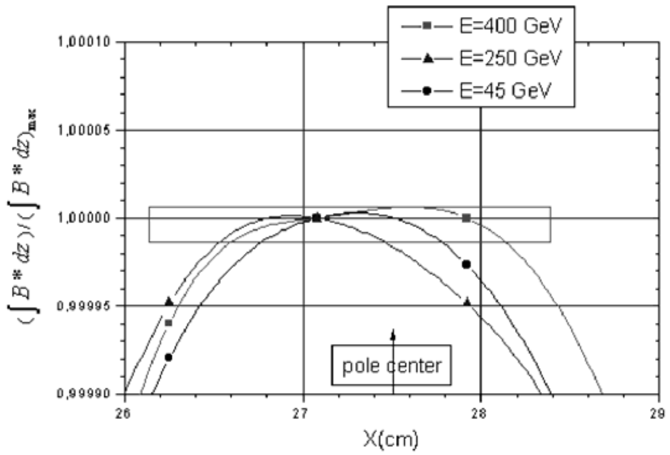
**➔ B-field measurements !**



### ancillary magnet:

- less stringent requirements
- simpler mechanical design
- gap height: 22 mm
- uniformity region: ~7 mm (3-4 mm)

  --> **rel. cheap**



# Other important aspects

- elimination of magnet hysteresis effects
- adjustment of zero B-field
- water cooling system (ΔT < 0.2° C)
- power supplies
- control system

solutions are proposed, mainly based on

experiences from CERN, SLAC and CEBAF

➔ B-field integral reproducibility of
15-20 ppm precision

# Magnetic Field Measurements

Basically, techniques with best precision for field integral determination should be chosen

## - Laboratory field measurements (mapping):

* Moving NMR probes in the main field region and Hall probes in the fringe regions (probes are mounted on a support device to be moved in beam and transverse directions; laser system (in beam direction) and linear encoder for precise transverse positioning)

➔ total error expected = 18 ppm

* two search coils (as used at CEBAF)

➔ total error expected = 14 ppm

Note, special designed probe holders inside the vacuum chamber are needed

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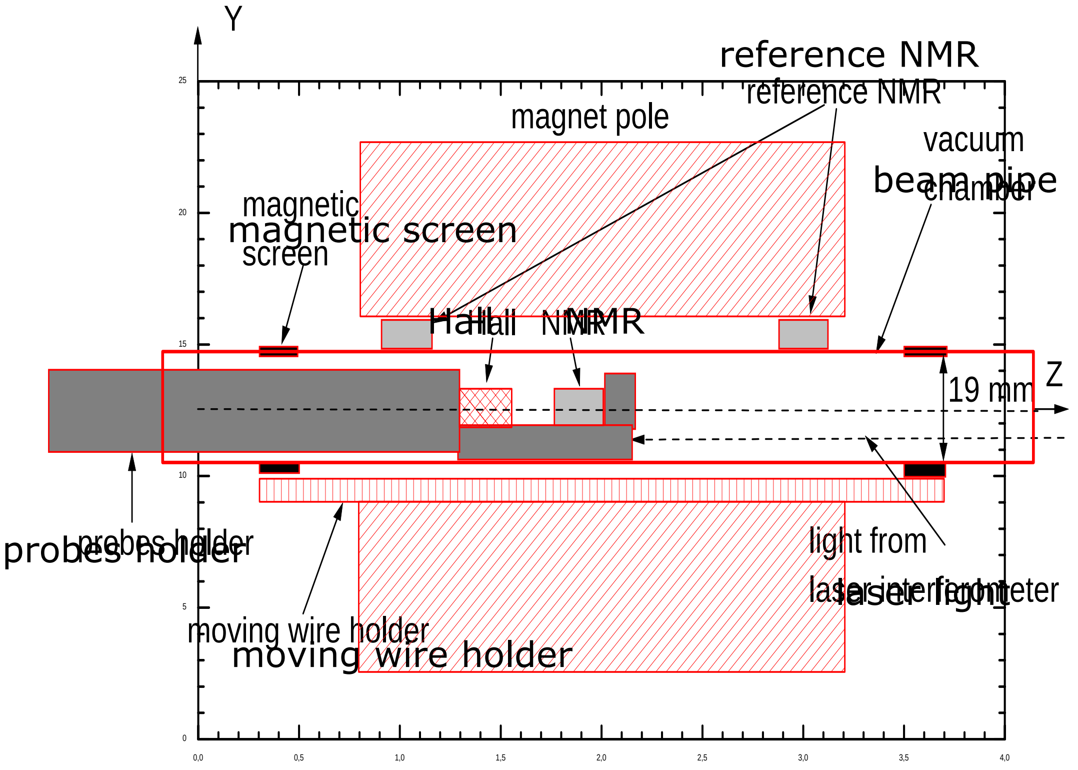
## - Field measurements in situ:

* reference NMR probes at two fixed points, which achieved
at LEP a relative field integral precision of 15-20 ppm

* moving wire technique

➔ **systematic uncertainty**
**$\Delta B/B$ = 19 ppm**



B-field range = 0.05 - 0.44 T
for $E_b$ = 45 – 400 GeV

# The Beam Position Monitors

Requirements:
- transverse beam position measurements within nm range and with excellent stability over large range
- bunch-to-bunch measurement
- simple mechanical design with µm production tolerances

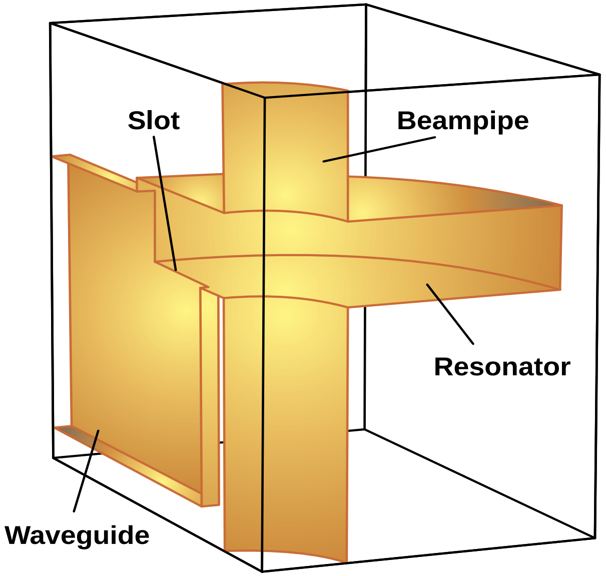
→ **VERY STRINGENT DEMANDS**

Solution: RF cavity BPM (at 5.5 GHz)

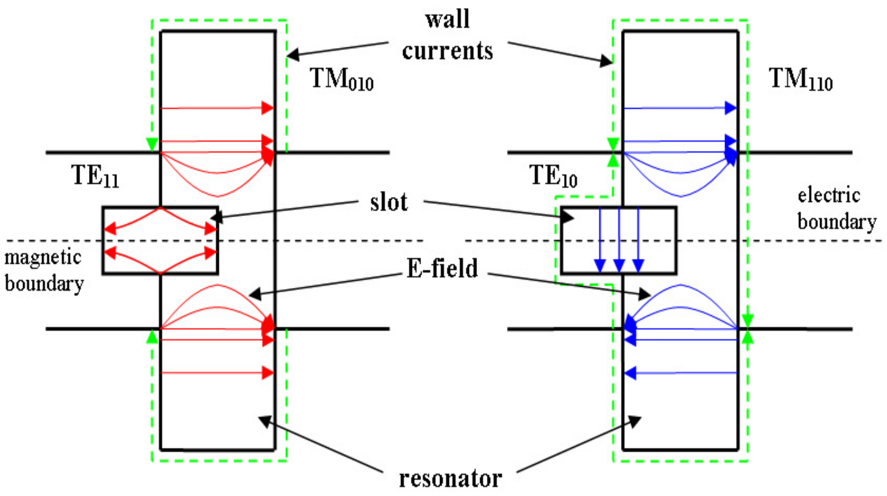
(as far as we know, only this type of BPM has the potential to achieve the requirements)

Our particular choice: cavity BPM with a novel slotted coupling scheme to waveguides

# Monitor Design and Basics:



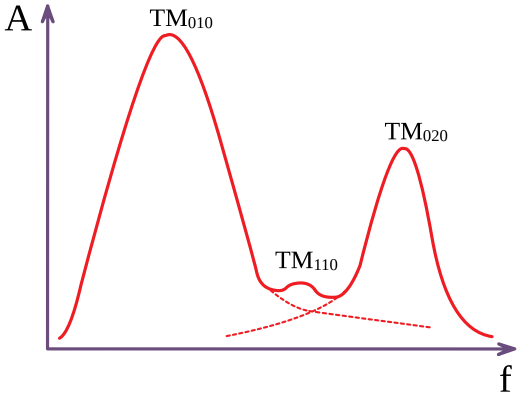
Cavity geometry with coupling slot scheme and waveguide



principle of coupling

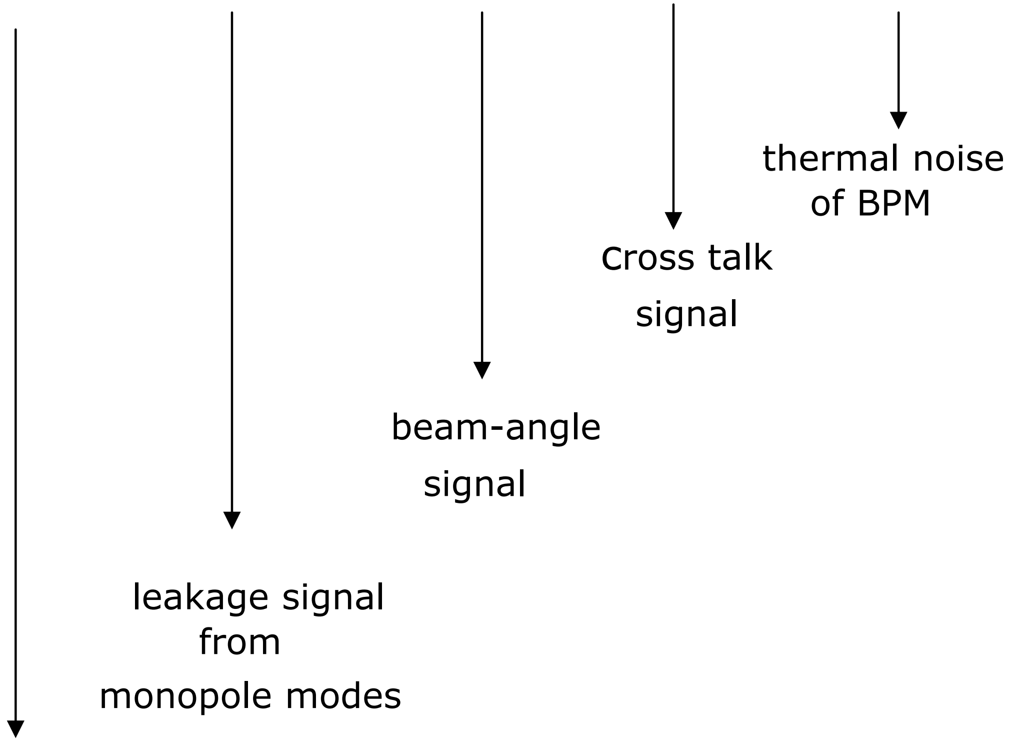
Most important waves excited are

monopole modes $TM_{010}$ and $TM_{020}$,
dipole mode $TM_{110}$ (**offset information !**),
with by orders of magnitude
different strengths



# Beam induced signal (at 5.5 GHz):

$$\boxed{V = V_{110}(x) + V_{010} + V_{110}(x') + V_{110}^{T} + V_{noise}}$$



thermal noise
of BPM

cross talk

signal

beam-angle

signal

leakage signal
from

monopole modes

beam displacement

signal : ~ (beam offset)*(bunch charge)

**Way out:**

**slotted RF cavity with**

**proper designed**

**waveguides:**

**> 100 dB suppression of monopole leakage signal**

In our case : most important noise signals are the

**$V_{010}$ and $V_{110}(x')$ with the leakage signal orders of magnitude larger than the beam displacement signal**

# Practical solution:


Prototype assambled


position cavity disasambled

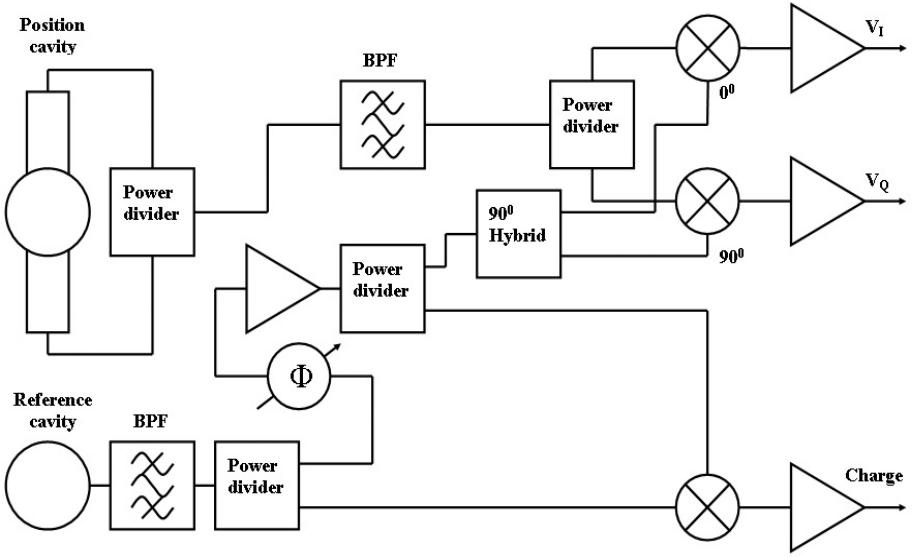

reference cavity disassembled

In addition to the position BMP, a reference cavity with the common mode frequency of 5.5 GHz **(!)** was designed to provide

- the LO-signal
- the phase reference
- the bunch charge

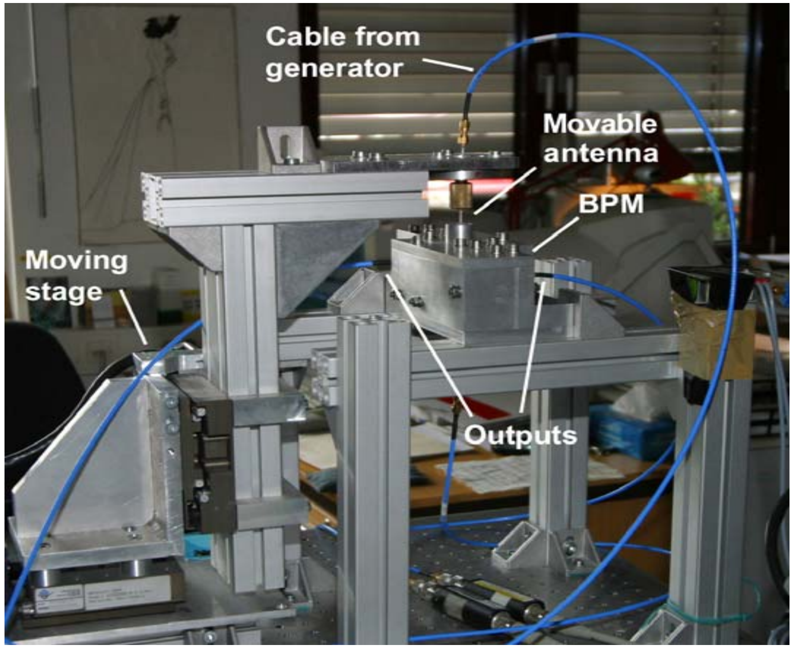
Both cavities and the waveguides were machined out of a single aluminum (copper [UHV !]) block.

The (first) read-out electronics provides two signal, I and Q, resp. amplitude and phase, as well as the bunch charge

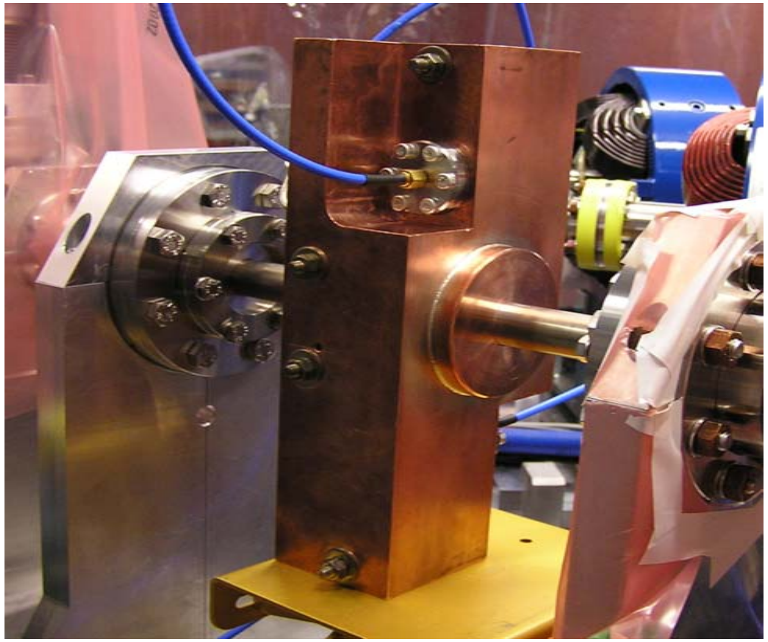


# Measurement results

Test bench measurements were performed in the laboratory, while tests with beam at the linac ELBE (Rossendorf/Dresden)



Test bench for the BPM



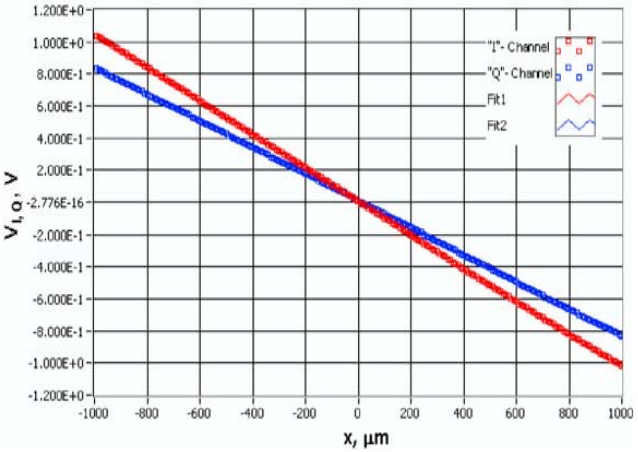
copper BPM in the ELBE beam line

Aluminum model; beam was simulated by an antenna driven from a signal generator; antenna could be precisely moved to simulate beam offsets; signals were down-converted with an electronics and digitized.

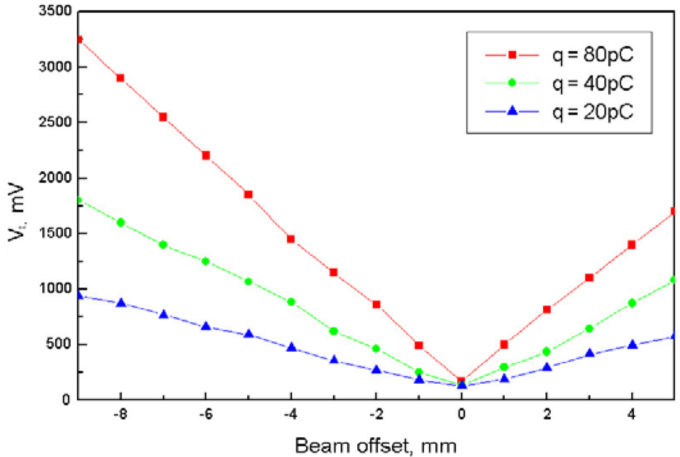
Copper prototype (UHV); beam could be moved transversally with a steerer; two view screens provided rough beam position; bunch charge=20-80 nC, bunch spacing was either 20 μsec (single bunch regime) or 308 nsec (multi bunch regime, similar to TESLA) ; a LabVIEW application was used to control the scope and to transfer the data to disk; usually signals were averaged over at least 10 bunches

# Main results:

- Voltages at the output ports I and Q versus position of the antenna →



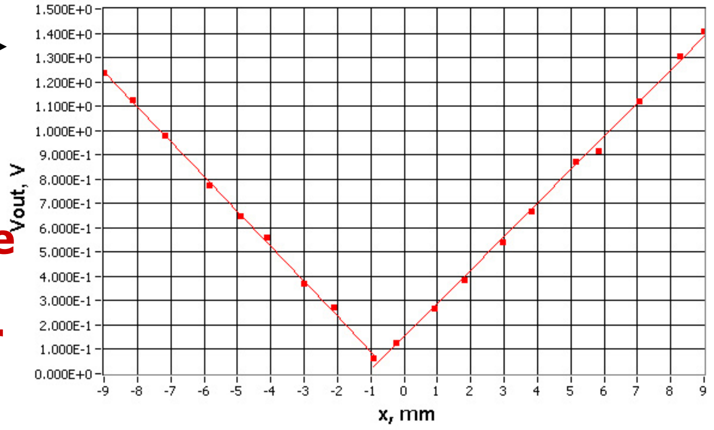
- ➔ **basic behaviour of the system (BPM and electronics) is ok**
- ➔ position resolution **~300** nm r.m.s. within ±100 µm offset range
- ➔ linearity range **±0.7** mm



← I-port voltage (after averaging over 10 bunches) against beam offset for several bunch charges Q:

- linear dependence of the signal on Q is evident;
- almost linear displacement range over ±4 mm (!),
- which allows for ~70 µm position uncertainty for ±4 mm offset range

Beam signal vs. displacement → over very large range of ± 9 mm; position resolution of ~100 µm



**Conclusion: position resolution and linear range worse than anticipated, due to the use of broad-band components and the low-level mixer and bad beam conditions**

## Further R&D

- include system to stabilize electronics
  (as realized in e.g. NIM A 572 (2004) 240; here a corresponding reference signal is introduced by a directional coupler)

- improve dynamic range of BPM system from ±1.3 mm to ±(2.5-3) mm
  (by improving the dynamic range of the I/Q mixer, basically possible)

- reduce the beam-angle signal (it fakes a beam offset)
  * by a slight modified design of the cavity
  * and/or change read-out electronics (90° phase difference between position and beam-angle signals) *** **IMPERATIVE ?**

- temperature stabilization system for each BPM station ($\Delta T \leq 0.2$°C)
  (remind that a 10 cm long piece of aluminum changes its length by about 2 μm if $\Delta T = 1$°C)

- dumping time should be reduced (by a factor of two) to ~36 nsec
  to maintain 100 μm internal position resolution for single-bunch measurements

- fast 18 bit ADC with on-board memory, not (yet) commercially available

# Alignment, stability, control system

- BPM drift (electronics, thermal effects, ground motion)

- Magnet drift (power, thermal effects)

- Beam trajectory (ground motion, tuning, feedback, etc.)

## Solutions and proposals

- construct the spectrometer on a **single girder** (grounded to the floor, ~25 m long, control its stability)
  ➔ relative movements of the components strongly eliminated

- BPM electronic drift
  ➔ control and stabilize of read-out electronics by **reference signal** generated by a dedicated circuit

- BPM thermal effects
  ➔ **cooling system**

- **BPM positioning**, needed in long. (trans.) direction: ~50 µm (~50 nm !)
  - ➔ laser interferometer resp. piezoelectrical devices or flexible bearings

- **BPM calibration**
  - ➔ B-field off: use ballistic path of beam
  - ➔ operate on Z pole, with B-field on, use precise Z mass ($\Delta M$=2.2 MeV)
  - ➔ in each lever arm, use two BPMs to calibrate the third (continuously possible)
- **B-field stability and control**
  - ➔ power and temperature control
  - ➔ permanent field measurements with two complementary methods
  - ➔ moderate positioning of magnets (few mm field uniformity)

- **Synchrotron radiation loss** (in e.g. the analyzing magnet at 250 (400) GeV beam energy: 18 (105) MeV, corresponding to $\Delta E_b/E_b = 7\cdot10^{-5}$ $(2.6\cdot10^{-4})$ )
  - ➔ live with loss and compensate (otherwise 3 times less B-field resp. 3 times better BPM resolution or increase spectrometer length by a factor 10 !)

**Stability will be a key issue**

→ **clever engineering solutions (in iterations) needed**

# Control of the System

**Main tasks:**

- stabilization and alignment control of components
- control of magnetic fields and BPM electronics
- remote control of all relevant instrumentations
- transfer of data to detector DAQ system
- access to data from other systems

The total information flow rate is not critical for modern systems;

network protocol IEEE 488 possess properties as needed;

for file transfer Ethernet (and related network) using TCP/IP protocol ok;

modular design of software advantageous

➔ reliable control is important for successful commissioning and operation of the spectrometer

# Cost Estimates

-- Magnets (2 ancillary, 1 analyzing): ~180 kEUR /spectrometer

-- 10 BPMs (with electronics): ~320 kEUR /spectrometer

-- Stabilization, alignment and control system: ~200 kEUR /spectrometer

In total, ~1.4 million EUR for two BPM-based spectrometers

But - possible price evolution between now and the time of construction is not accounted for

- we assumed , manpower required for the project will be supplied by existing manpower in the collaborating institutions

→ rough estimation !

# Summary

- a compact, large angle (1 mrad) energy spectrometer is proposed

  ➔ $\Delta E_b/E_b = 5\cdot10^{-5}$ possible, but challenging

  in accordance with most physical requirements
  (if no Higgs/SUSI ⟶ $\Delta E_b/E_b = 10^{-5} \ldots 10^{-6}$
  may be needed)

- basic layout of spectrometer

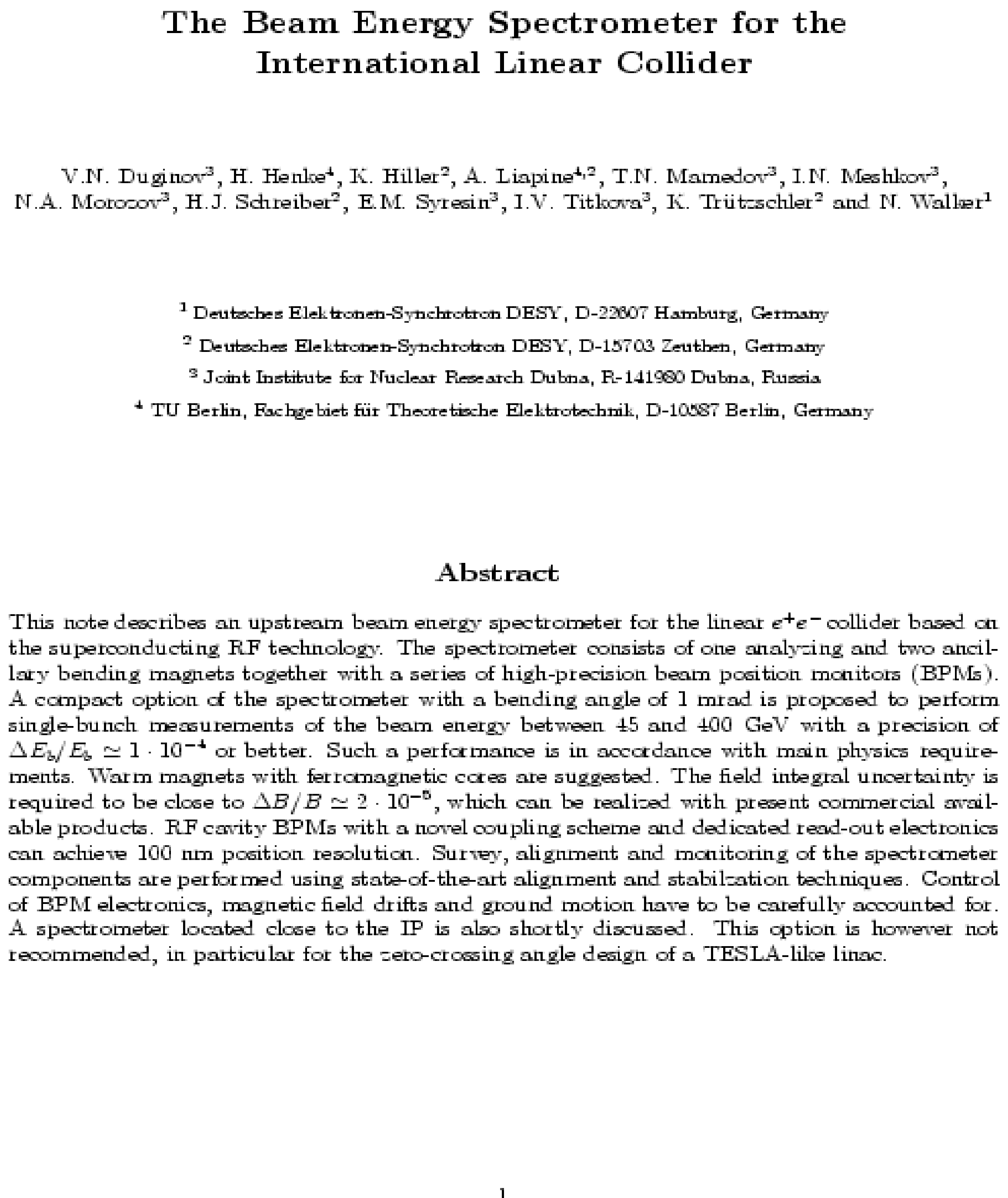
  - one analyzing magnet and two ancillary magnets (warm !)
  - 3 (4) high precision (100 nm) BPMs in each lever arm
    (additional BPMs should constrain the beam trajectory
    outside of the spectrometer)

- analyzing magnet ➔ field integral uncertainty **$\Delta B/B = 2\cdot10^{-5}$** is achievable;
  it needs control of power supply, temperature stabilization,
  control of hysteresis and zero-field adjustment,
  careful B-field measurement in lab and in situ using
  standard devices (NMR, Hall probes, search coils
  and moving wire techniques)

- RF cavity BPMs (5.5 GHz) with novel slot couplings to waveguides are proposed
  - ➔ allow for ~100 nm (internal) position resolution,
    further investment in electronics is needed,
    calibration procedures rely on
    - running with B-field off
    - running on Z-pole
- stability is a key issue, with the following suggestions
  - use a common (25 m long) girder
  - check drift of BPM electronics
  - account for temperature and power stabilization of magnets
- include the spectrometer during design of BDS,
  in particular for compensation of emittance grow
  by chromatic correction section (HCCS and VCCS)
- consider also complementary methods for beam energy determination
  - SR produced in magnets of the spectrometer
  - Møller scattering
  - polarization rotation measurements
  - resonance absorption of laser light
  - radiative return using e.g. $e^+e^- \longrightarrow \mu^+\mu^-\gamma$

***CROSS-CHECKS needed***

➔ which method(s) is promising ? **arrive a consensus** (over next years)



# The Beam Energy Spectrometer for the International Linear Collider

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## Abstract

This note describes an upstream beam energy spectrometer for the linear $e^+e^-$ collider based on the superconducting RF technology. The spectrometer consists of one analyzing and two ancillary bending magnets together with a series of high-precision beam position monitors (BPMs). A compact option of the spectrometer with a bending angle of 1 mrad is proposed to perform single-bunch measurements of the beam energy between 45 and 400 GeV with a precision of $\Delta E_b/E_b \simeq 1 \cdot 10^{-4}$ or better. Such a performance is in accordance with main physics requirements. Warm magnets with ferromagnetic cores are suggested. The field integral uncertainty is required to be close to $\Delta B/B \simeq 2 \cdot 10^{-5}$, which can be realized with present commercial available products. RF cavity BPMs with a novel coupling scheme and dedicated read-out electronics can achieve 100 nm position resolution. Survey, alignment and monitoring of the spectrometer components are performed using state-of-the-art alignment and stabilization techniques. Control of BPM electronics, magnetic field drifts and ground motion have to be carefully accounted for. A spectrometer located close to the IP is also shortly discussed. This option is however not recommended, in particular for the zero-crossing angle design of a TESLA-like linac.

# Many thanks to all my colleagues for very fruitful cooperation