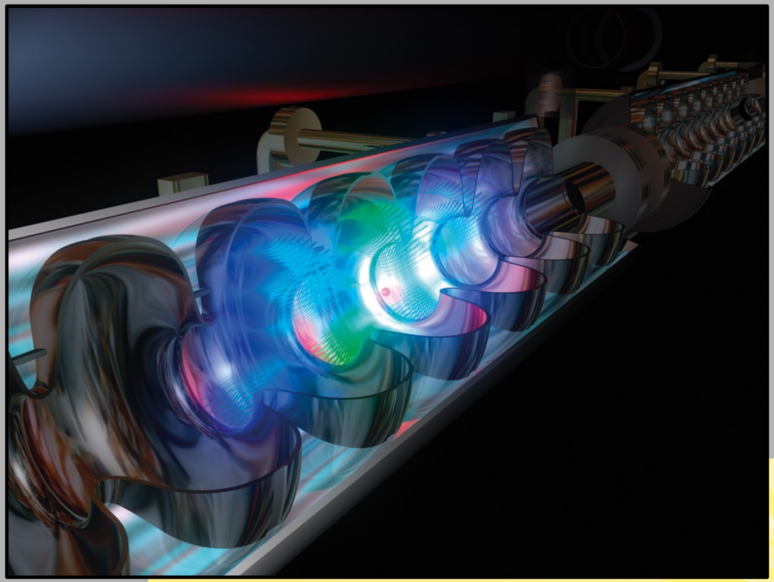
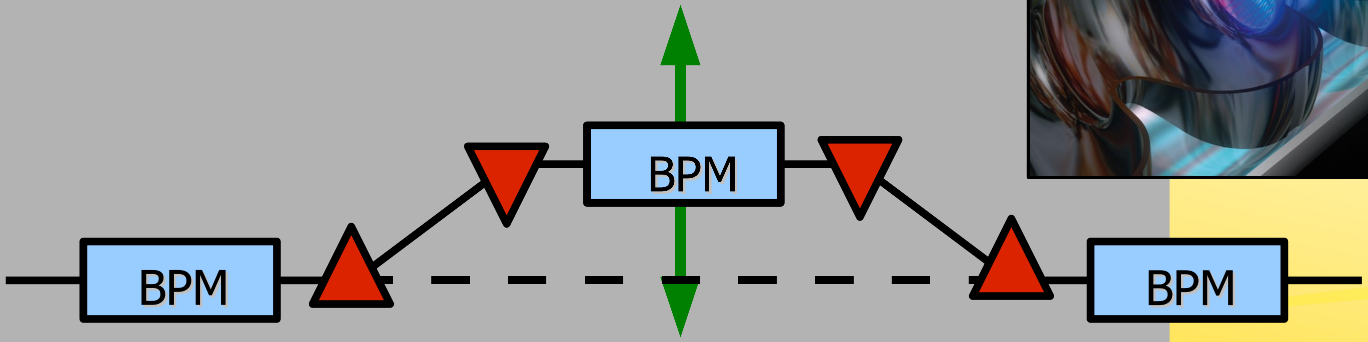
An Energy Spectrometer for the International Linear Collider

Reasons, challenges, test experiments and progress





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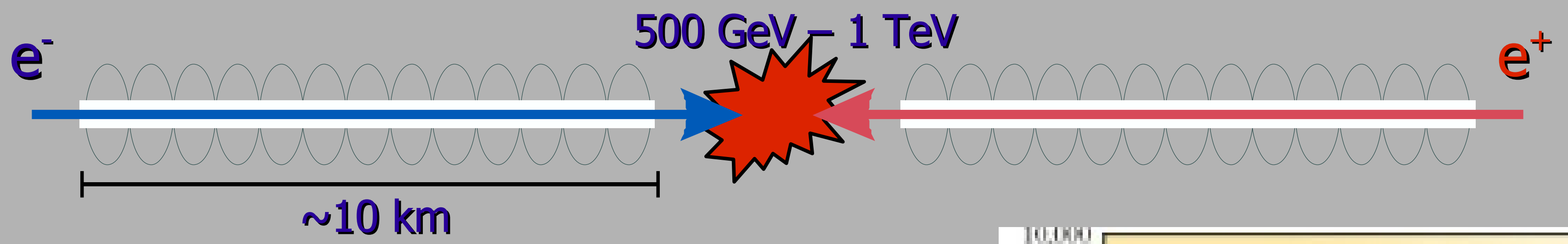
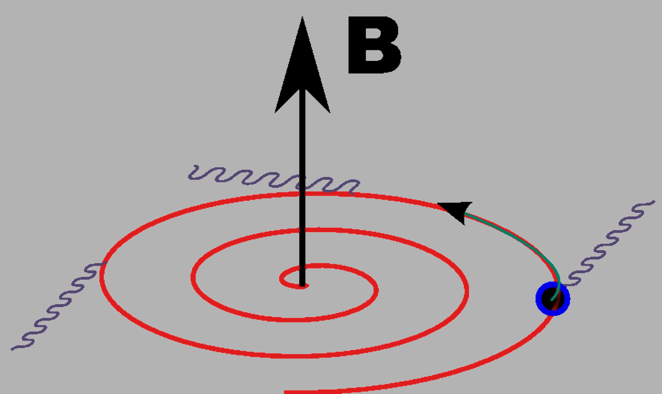
Seminar Outline

- Why build the linear collider, and what is it actually ?
- How does such a linear collider look like ?
- Importance of the beam energy measurement...
- Development of a magnetic chicane spectrometer based upon high resolution Beam Position Monitors (BPM)
  - Principles...
  - High resolution cavity beam position monitors...
- Test experiments, End Station A at SLAC...
- Outlook for our project...

What is the ILC and why build it ?

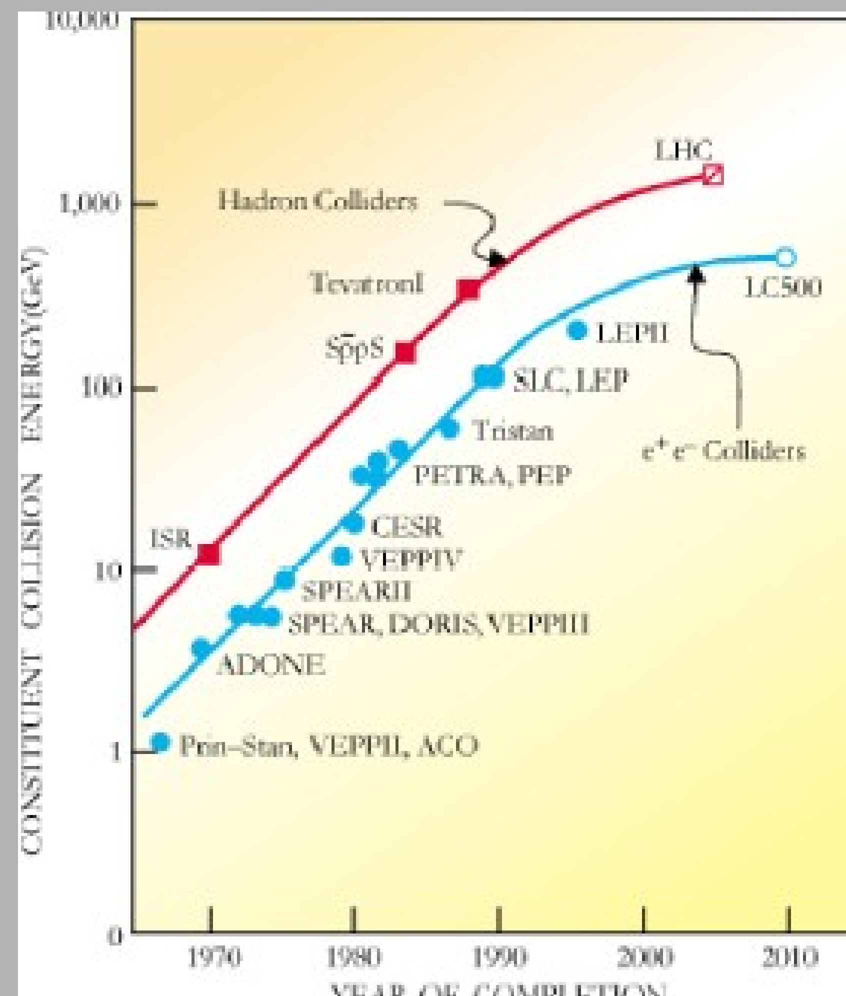


- Proposed ~30 km long linear e^+e^- collider
- CM energy up to 1 TeV
- International... obviously
- targeted completion around 2020



costs $\sim P_{RF}$

$\Delta E_{turn} \sim E^4 / \rho$

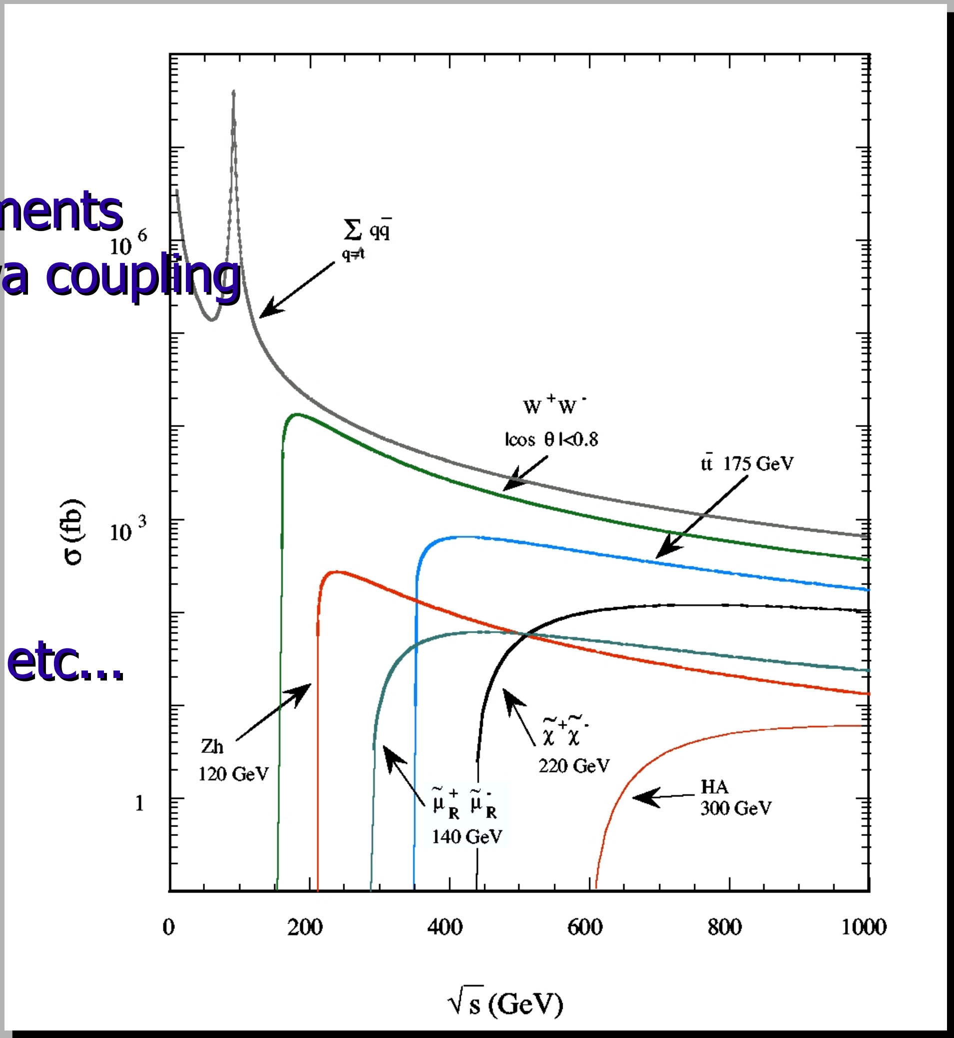


- e^+e^- : colliding elementary particles : clean !
- Precision measurements from discoveries made at hadron machines (eg. LHC)

Physics case for the ILC

- Standard model physics
  - Precision electroweak and QCD measurements
  - Top quark threshold, mass, width, yukawa coupling
  - Properties of (a) Higgs particle(s)
  - Giga Z, etc...

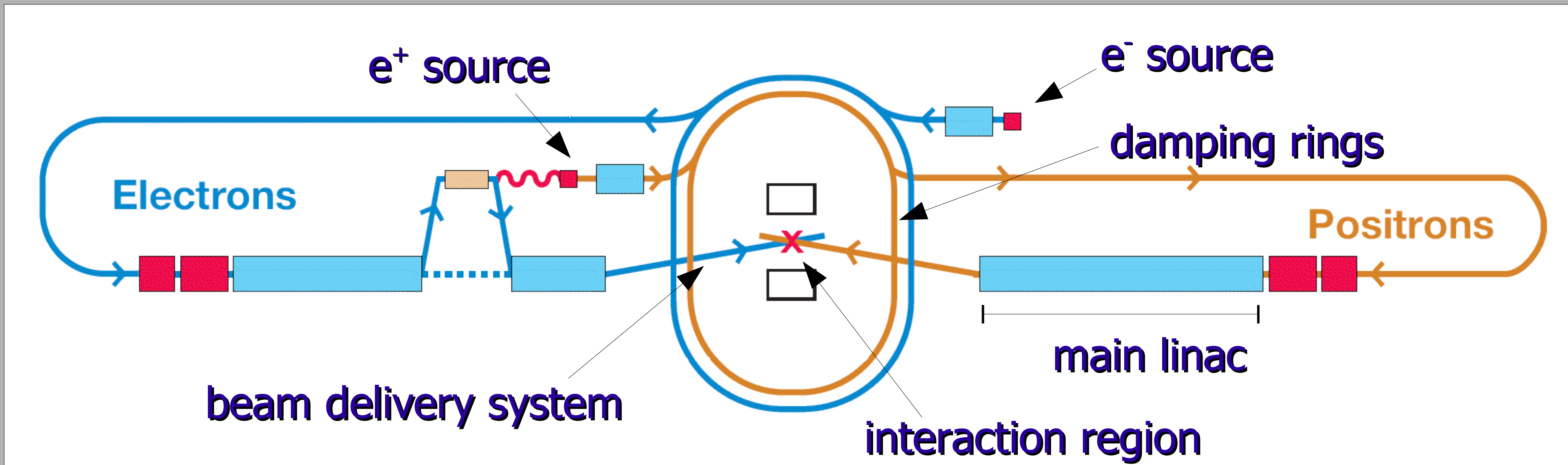
- Physics beyond the standard model.
- What is awaiting us at the Terascale ?
- SUSY, GUT, extra dimensions, dark matter, etc...



The energy scale and the physics program push present day technology to the limit...

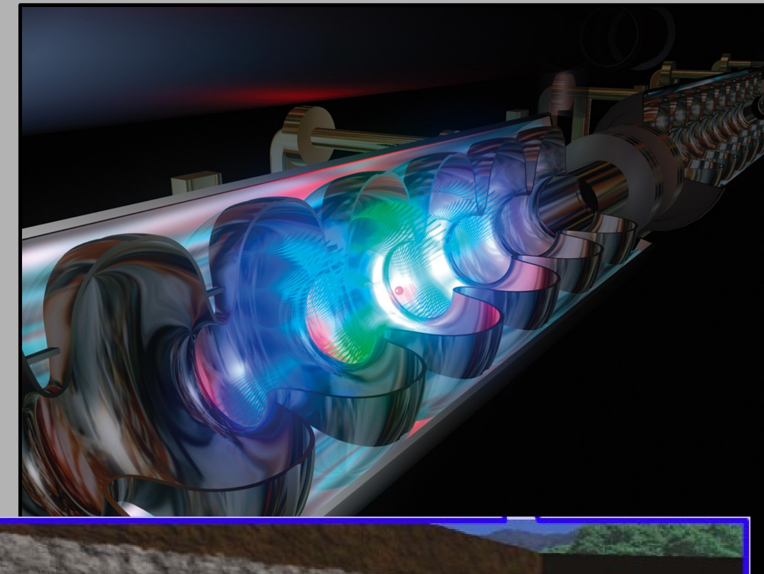
→ Lot of R&D programs actively trying to make the ILC feasible both on the detector and accelerator side

Proposed layout of the ILC... I hope :)



- Particle sources
  - electrons : pulsed laser
  - positrons : 150 GeV electrons through undulator
- Damping rings
  - reduce transverse beam size (emittance), establish bunch train structure, 2625/pulse
- Main linac :
  - Accelerate beam from about 5 GeV to 500 GeV, super conducting RF cavities
- Beam delivery system : beam diagnostics, focussing, collimation
- Interaction region : final focussing and beams into collision.
- Extraction line : safely dispose of heavily distorted beam + diagnostics
- 1 Experimental hall, 2 detectors in push-pull and 14 mrad crossing angle

Some of many challenges...



- Average accelerating gradient ~ 31.5 MeV/m
- Final focussing needed to get $2x10^{34}/cm^2/s$
  - Lumi ~ $f_{rep} / \sigma_x \sigma_y$
  - f_{rep} = 40 kHz (LEP), = 5 Hz (ILC)
  - Need vertical beam size of 5 nm + measure it !!

    (compare to $0.0003x10^{34}/cm^2/s$ and 500 nm beam size for SLC)
- Infrastructure :
  - 31 km main tunnel + 6.7 km damping ring
  - 230 MW power consumption
- Beam dump.. dispose of 18MW of beam power

  (compare to 0.04 MW for SLC)
- Beam Delivery System (e.g. energy measurement):
  - you only get 1 go, no averaging (LEP)

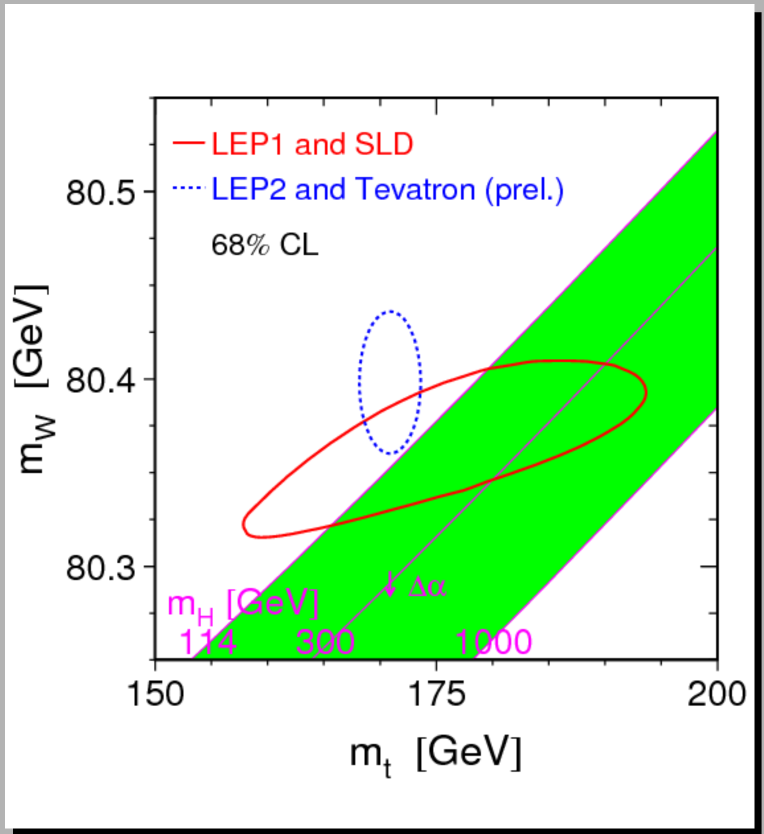
The ILC physics program requires an energy measurement uncertainty of $dE/E = 10^{-4}$

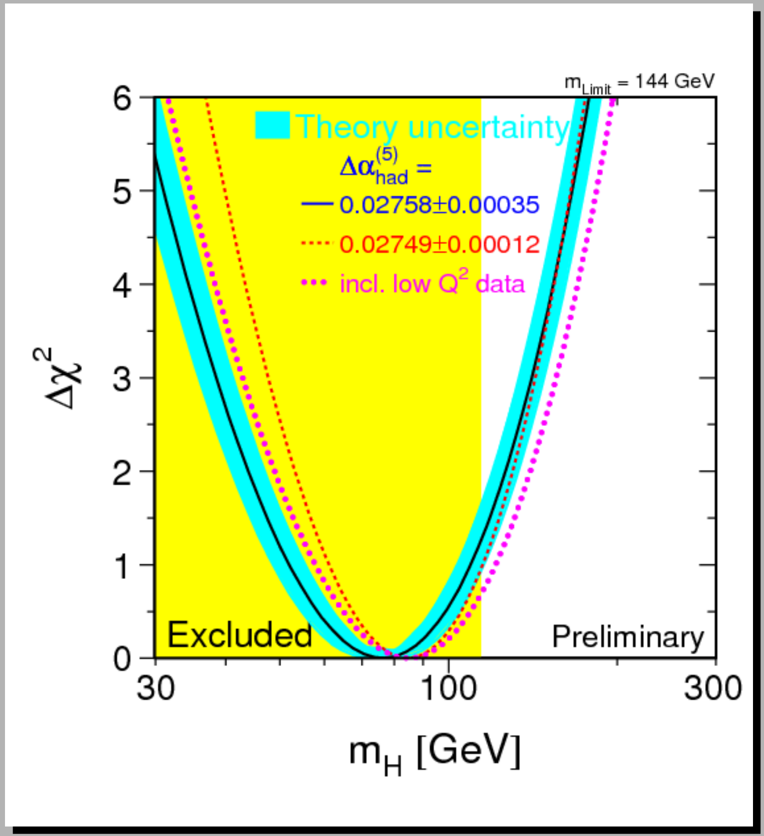
Let's have a look at the top quark to understand why...

Physics case for good energy measurement

Case study : the top quark

- Top quark : large decay width -> pQCD !!
- ILC = top quark factory, QCD precision tests
- Better precision on the top mass constrains Higgs & SUSY parameters better

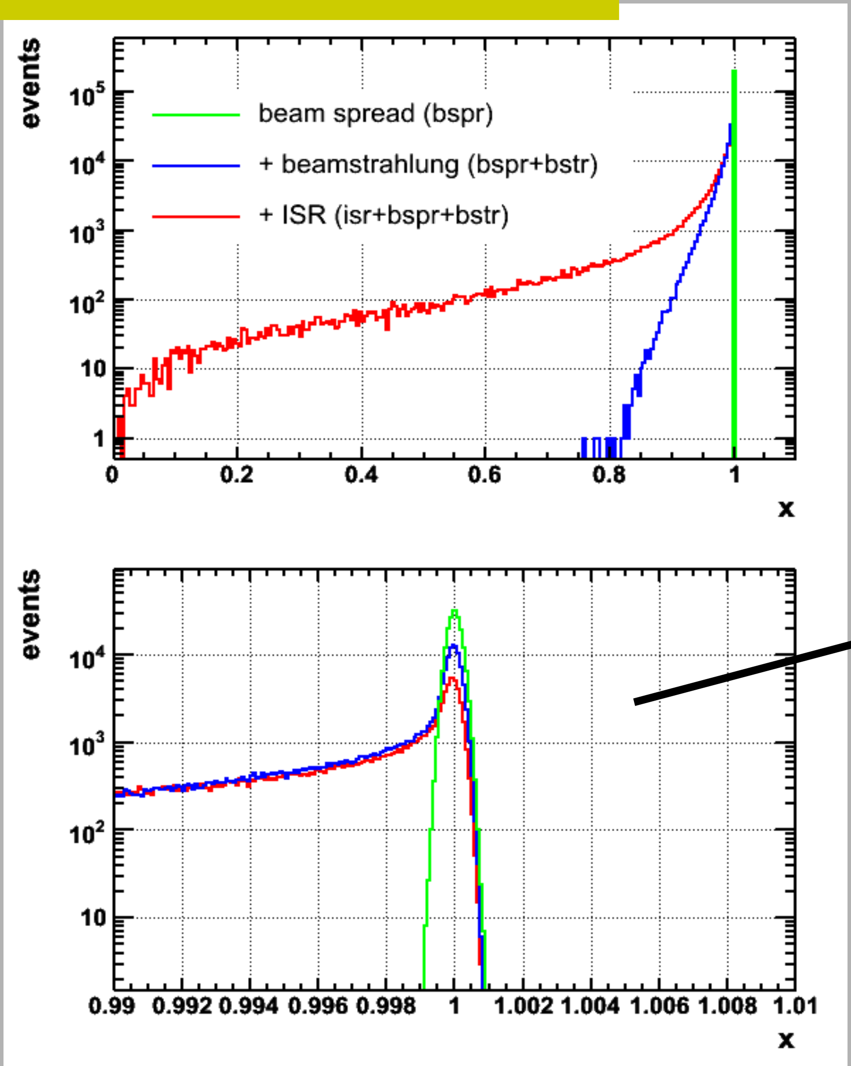




Beam energy determination is largest contribution of systematics...

Influence of energy spread on top threshold...

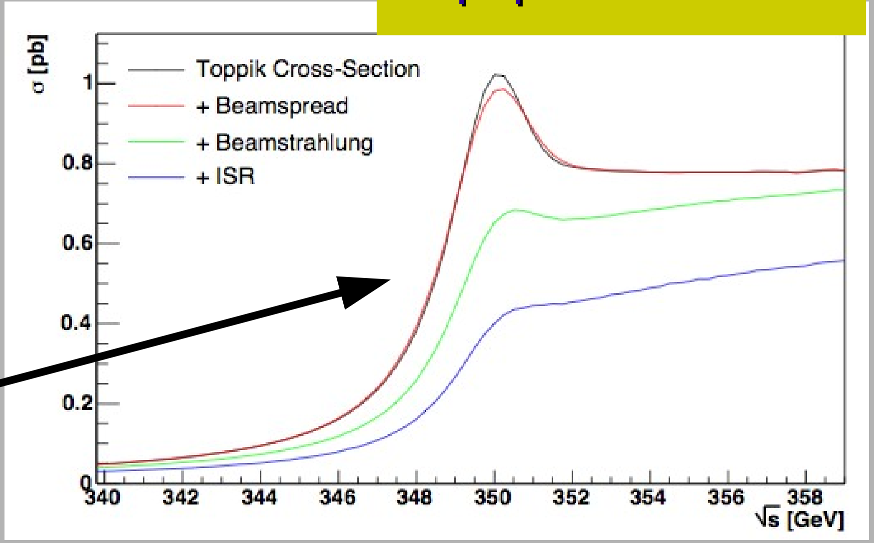
Luminosity spectrum dL/dE



Energy at collision is not delta function !!

- Inherent energy spread
- Beamstrahlung
- Initial state radiation

Top quark mass scan



Uncertainty on beam energy measurement contributes directly to the uncertainty on the ILC physics output...

→ Magnetic chicane with high resolution BPMs

BPM Spectrometry

$E \sim \int B.dl/\Theta$

Study & design magnetic chicane for beam energy measurement using Beam Position Monitors (BPMs) :

so... reduce energy measurement to beam position measurement

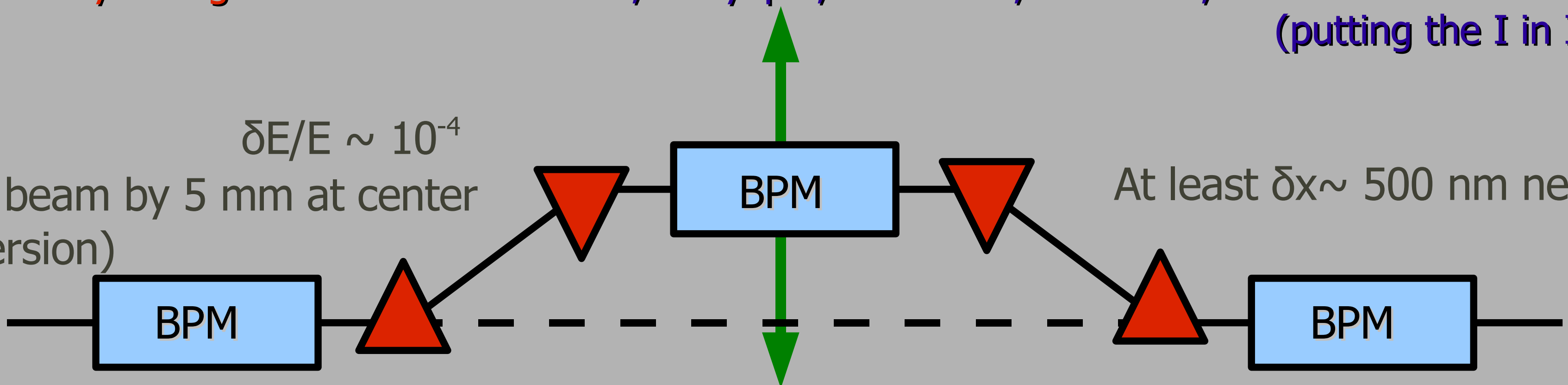
Royal Holloway University London: S. Boogert
Cambridge : M. Slater, M. Thomson and D. Ward
University College London: F. Gournaris, A. Lyapin, B. Maiheu, S. Malton, D. Miller and M. Wing
(putting the I in ILC :)

Different aspects of the project...

$\delta E/E \sim 10^{-4}$

Move beam by 5 mm at center (dispersion)

At least $\delta x \sim 500$ nm needed



NanoBPM@ATF (KEK) : test resolution, try different analysis methods, BPM stability tests, multi bunch operation, advanced electronics techniques, inclination of beam in BPMs.

-> spectrometer aspects of BPMs can be tested

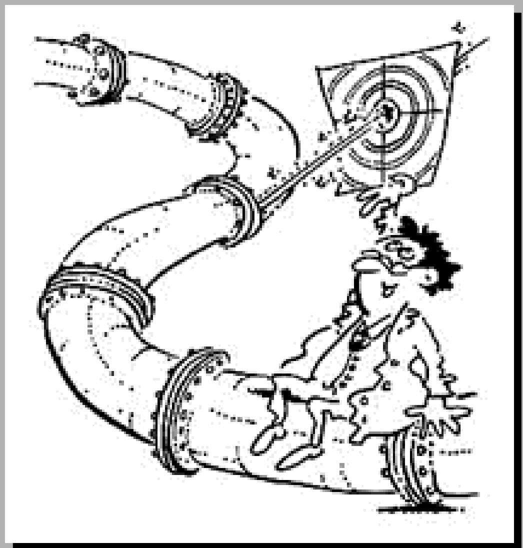
ESA@SLAC : test stability and operational issues with a full implementation of 4 magnet chicane and 3 BPM stations

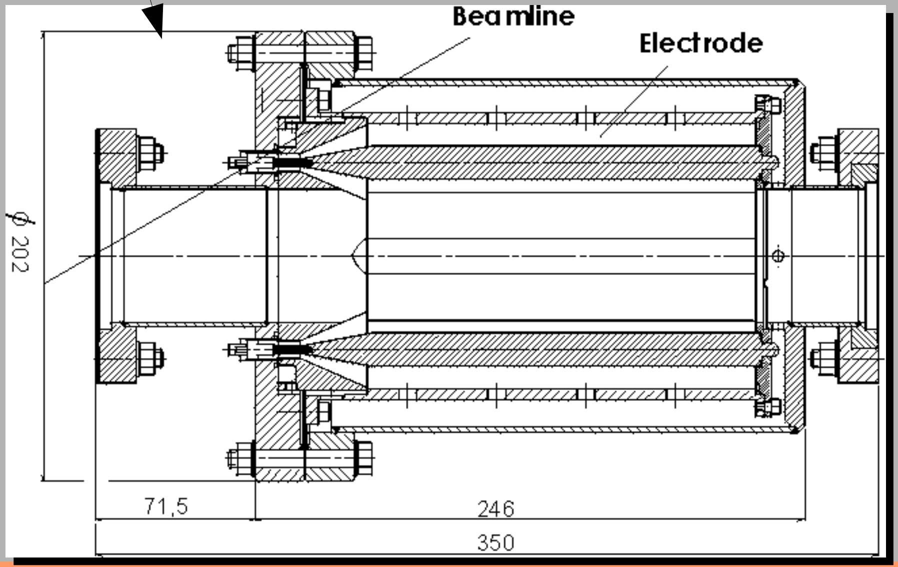
-> test of real chicane prototype

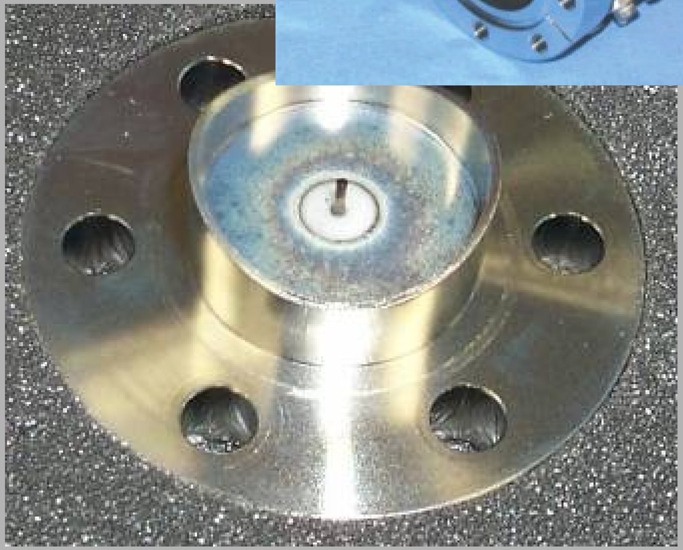
will talk about ESA later on...

What kind of BPMs to use ?

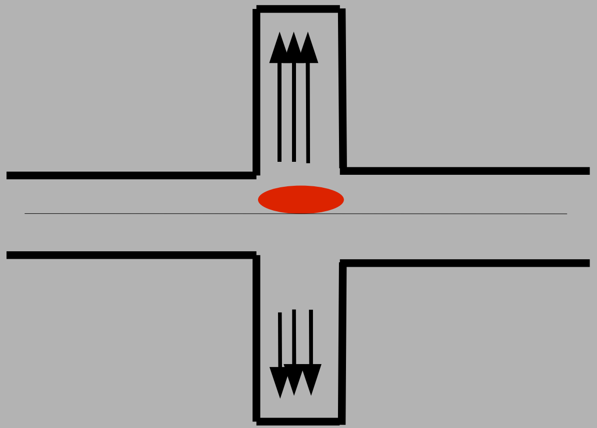
- Beam position monitors essential diagnostic for accelerators
  - Beam orbit in accelerator : steering, alignment, energy
  - Specialist applications such as energy spectrometer
- Many different varieties exist
  - Operate via electromagnetic interaction with structure placed around the beam
  - Button (1 mm – 10 um)
  - Stripline (100 um - 1 um)
  - Resonant cavity (1 um - 20 nm)
  - ...





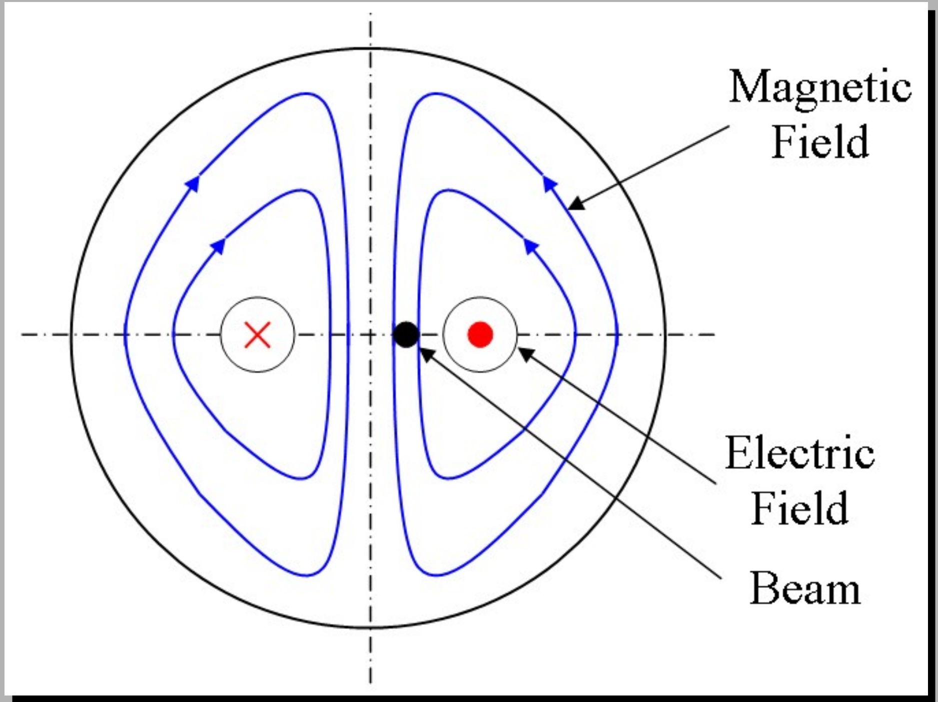


Introducing resonant cavity beam position monitors...



Solution of the EM wave equations taking into account the boundary conditions of the conducting walls leads to certain eigenmodes of cavity excitation by the beam...

Configuration of first dipole mode : TM110



For the interested :) :

$$
\begin{aligned}
E_z &= C J_1\left(\frac{j_{11} r}{R}\right) \cos\phi \, e^{i\omega t} \\
H_r &= -iC \frac{\omega \epsilon_0 R^2}{j_{11}^2} \frac{J_1\left(\frac{j_{11} r}{R}\right)}{r} \sin\phi \, e^{i\omega t} \\
H_\phi &= -iC \frac{\omega \epsilon_0 R}{j_{11}} J_1'\left(\frac{j_{11} r}{R}\right) \cos\phi \, e^{i\omega t}
\end{aligned}
$$

Excitation voltage for TM110 mode :

$$V_{ex} = E_0 \, T_{tr} \, L \, r / a$$

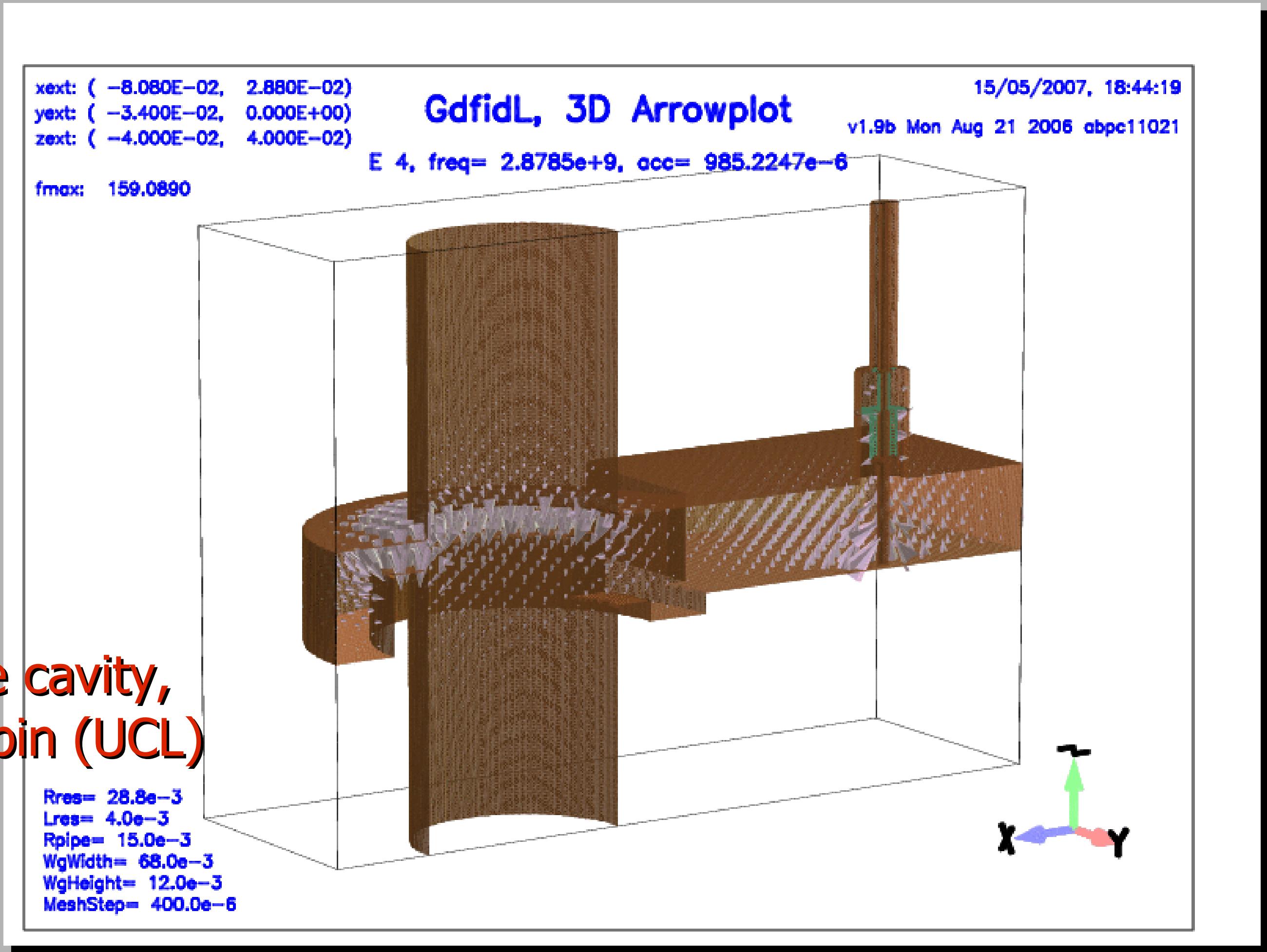
Offset w.r.t. electrical center

Total electrical field (bunch charge)

Of course in real life...

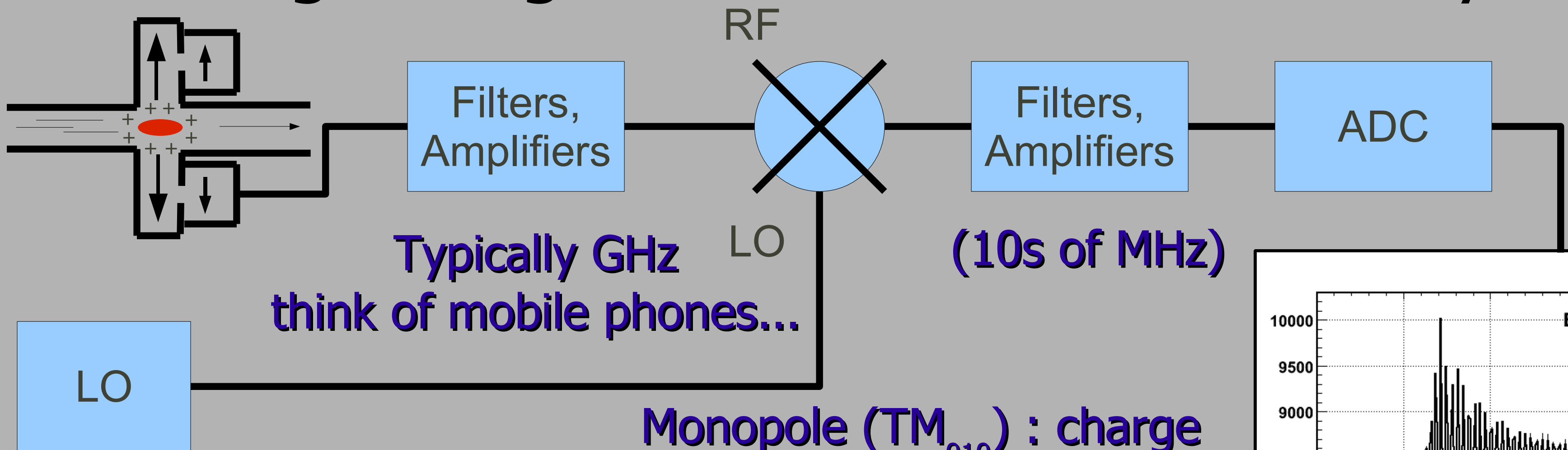
... it's a little bit more complicated... as usual :)

- Accurate geometrical design of cavity and manufacturing of cavity is critical
  - Cavity size determines frequency
  - Positioning of antennae to couple out the RF power (typically couple of GHz)
- Dipole mode depends on :
  - bunch charge
  - beam offset
  - but also beam tilt
- need reference cavity :
  - monopole mode TM010
  - sensitive to charge only



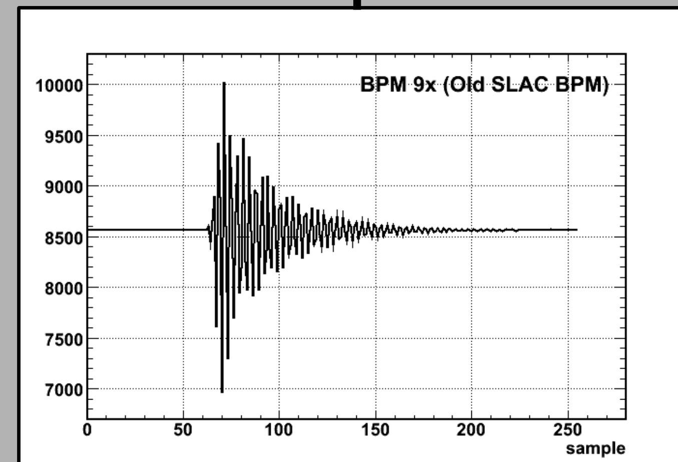
Prototype reference cavity, designed by A. Lyapin (UCL)

Handling RF signals from a resonant cavity BPM...



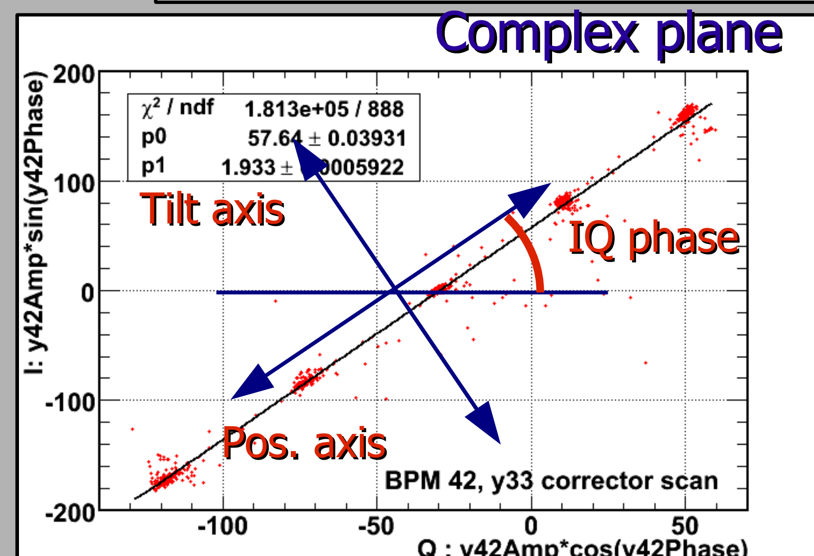
Monopole (TM_{010}) : charge

Dipole (TM_{110}) : charge + offset + tilt



Determine Amplitude & Phase

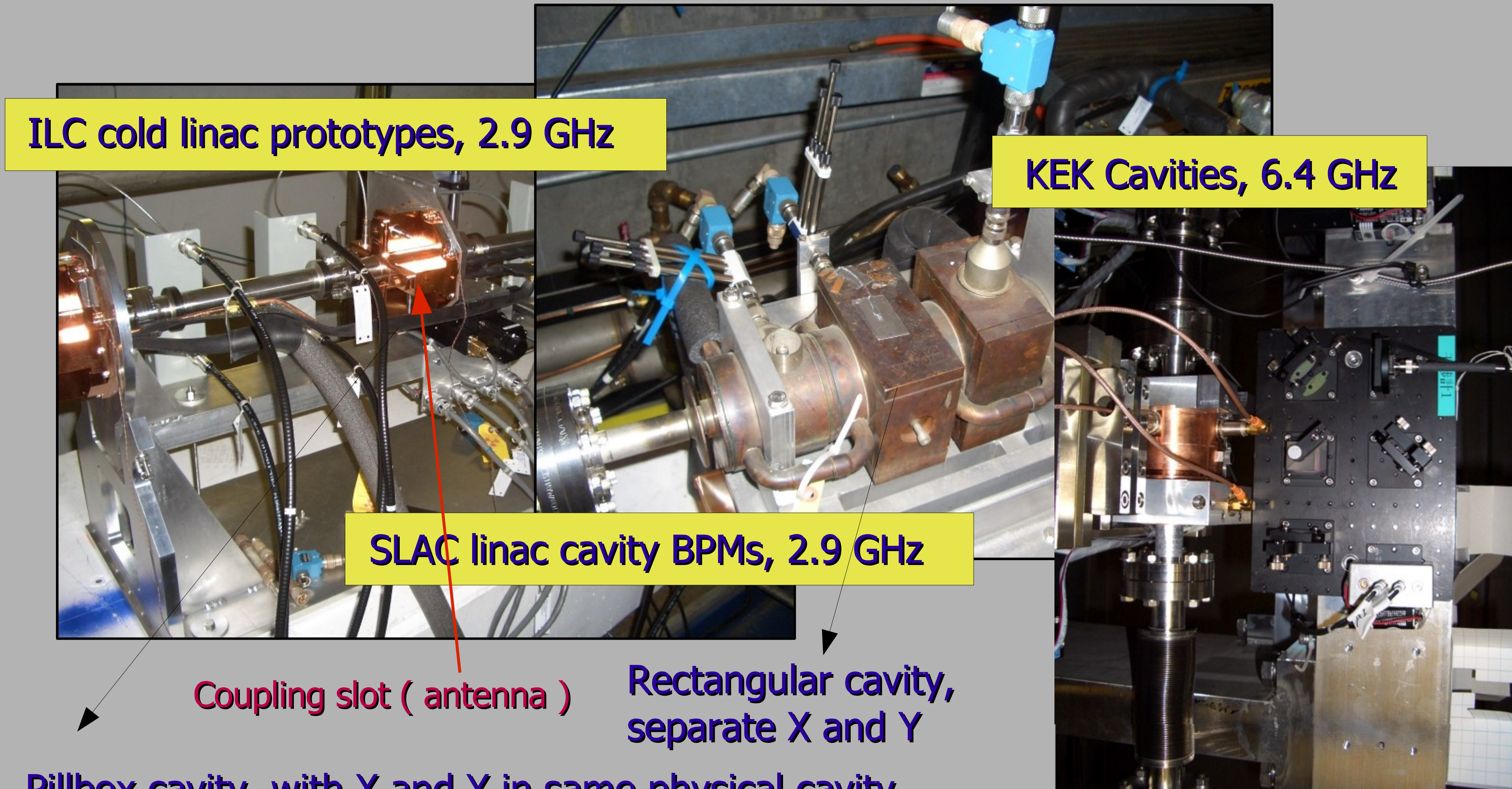
- Fit waveform : $V = V_0 + A\, e^{-\Gamma(t-t0)} \sin[\omega(t-t_0) + \varphi]$
- Digital Down Conversion (DDC) :
  - Multiply waveform with $e^{i\omega t}$
  - Filter out 2ω component
  - Sample waveform at fixed point for linearity -> A, φ



Disentangle charge, offset and tilt :

1. Normalize signal to Ref (Q) Cavity
2. IQ rotation ($\pi/2$ tilt phase difference)
3. Calibrate

Some examples of resonant RF cavities...

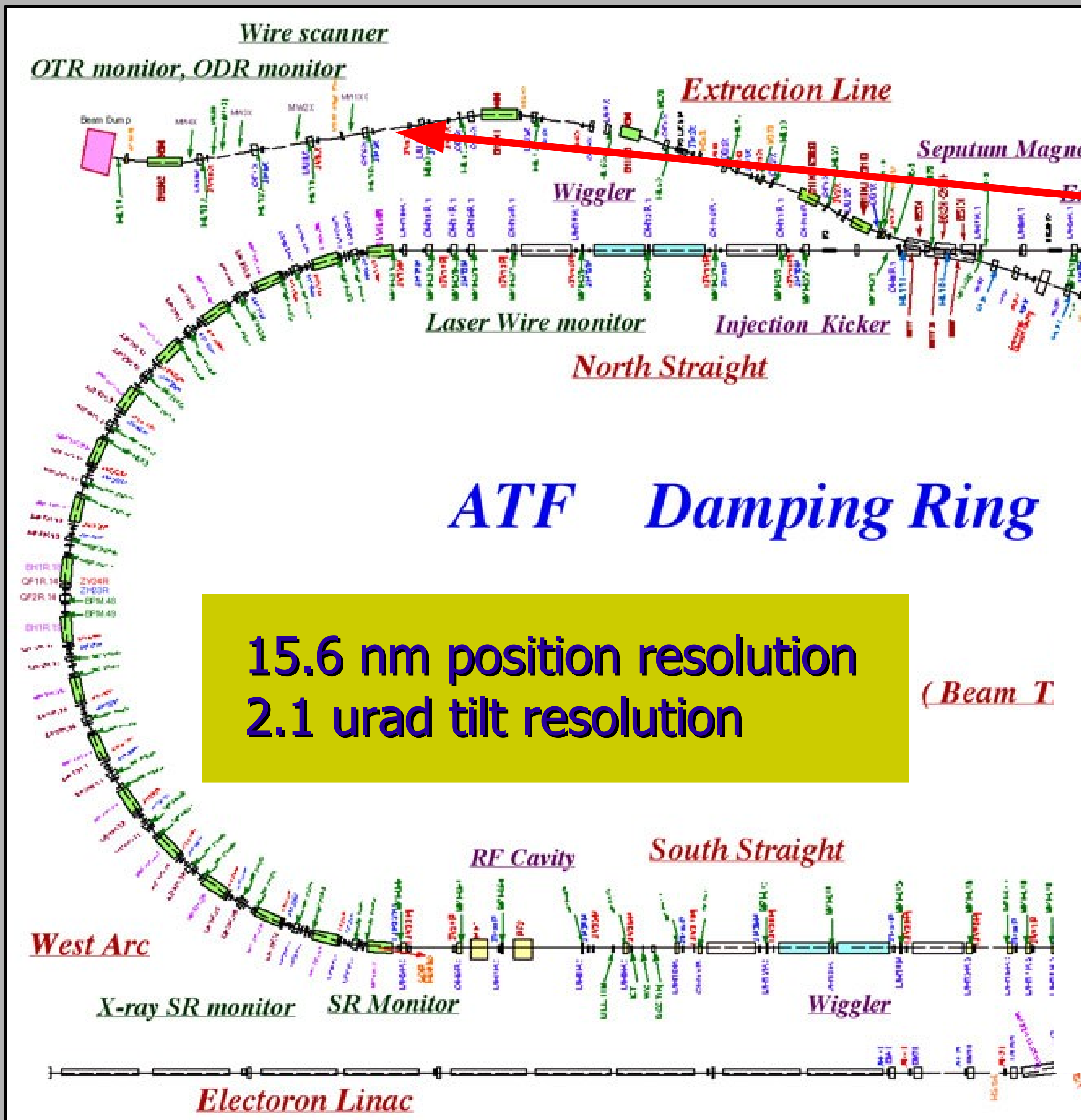


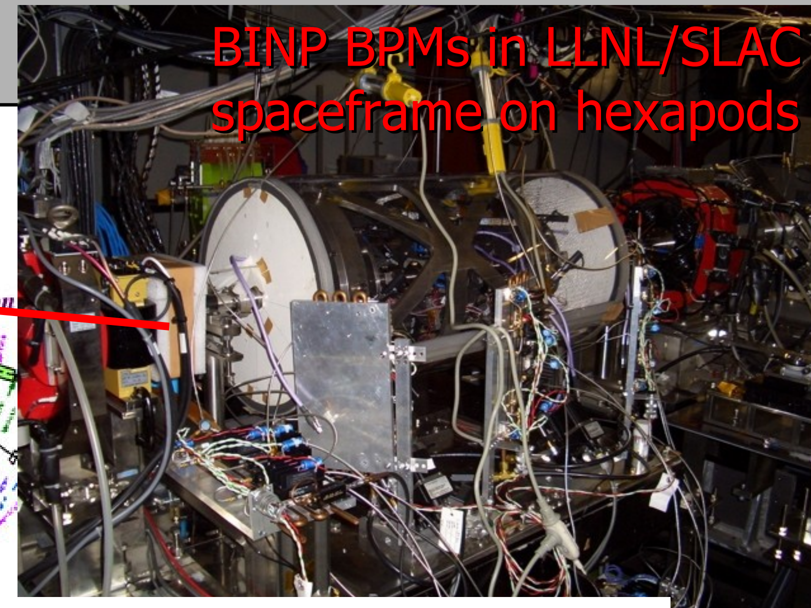
Pillbox cavity, with X and Y in same physical cavity
optimised for short ILC bunch spacing (300 ns) and cleaning for use in cold LINAC

Z. Li and C.Adolfson et al.

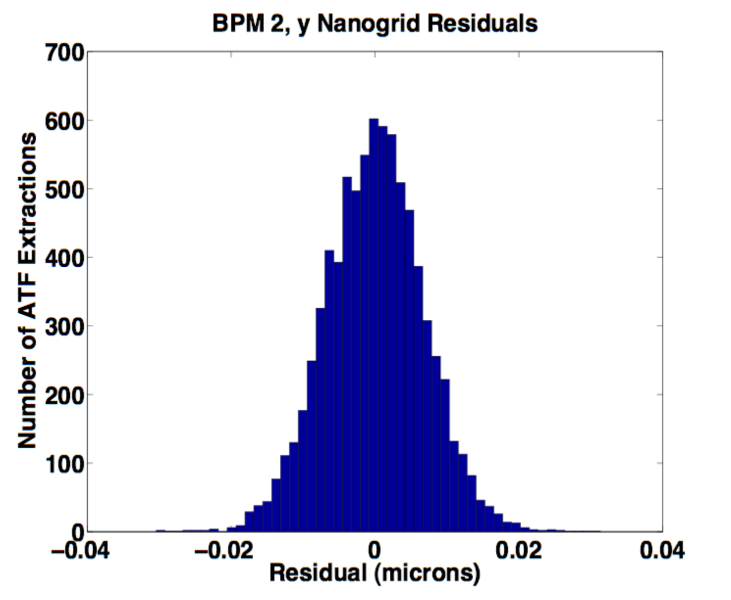
What precision can we reach with these BPMs ?

NanoBPM Collaboration: LBNL, LLNL, SLAC, KEK, BINP





15.6 nm position resolution
2.1 urad tilt resolution



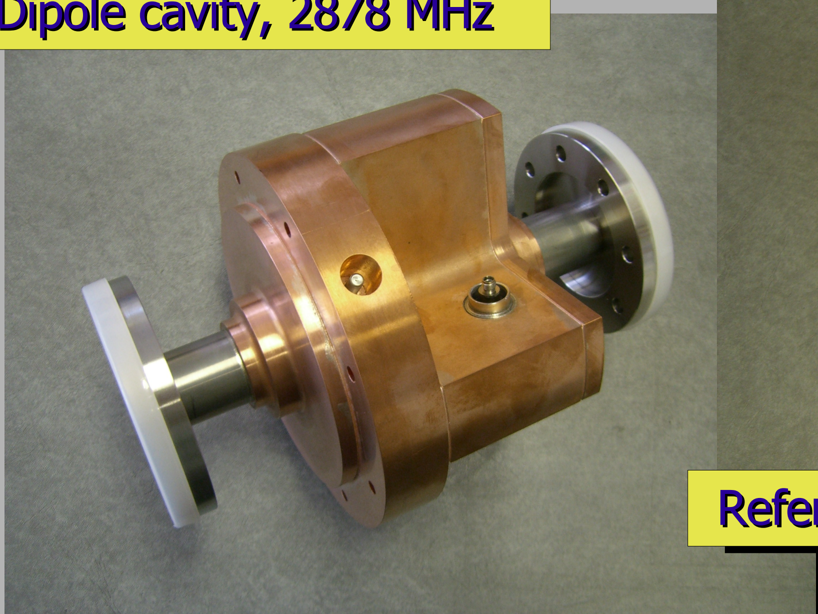
However, current BPM designs not optimal for ILC purposes...

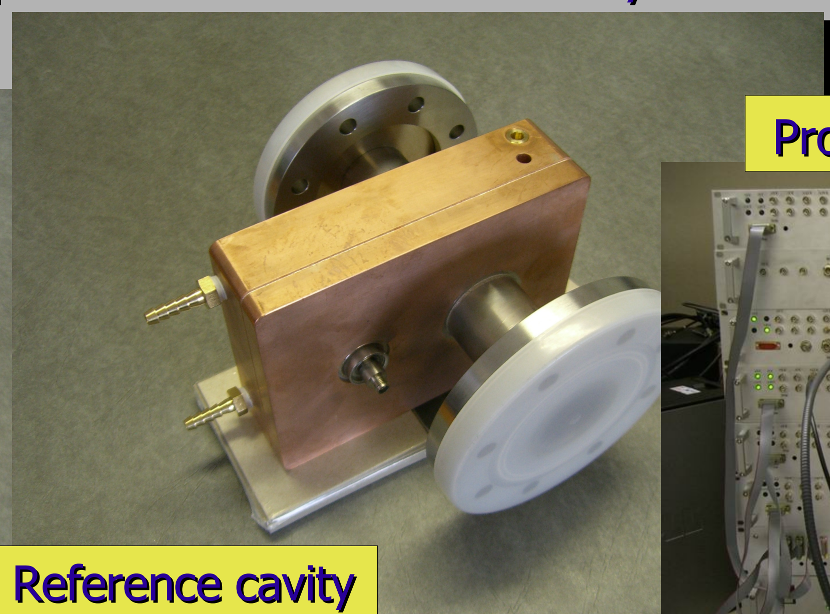
So far a good ILC spectrometer BPM prototype in itself hasn't been built yet...

- aperture (machine protection, resolution)
- resolution, stability
- monopole rejection : distortion of decaying waveform
- coupling -> decay time (multi bunch studies)

Our collaboration is developing a new prototype together with processing electronics exactly for this purpose... beam test underway at ESA in SLAC.

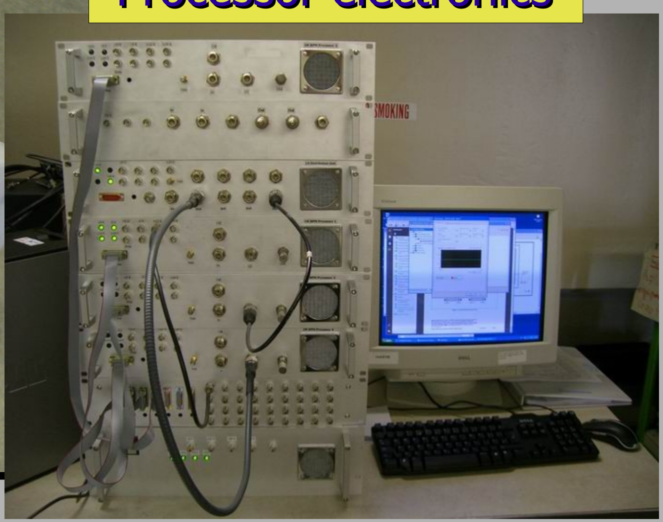
Dipole cavity, 2878 MHz



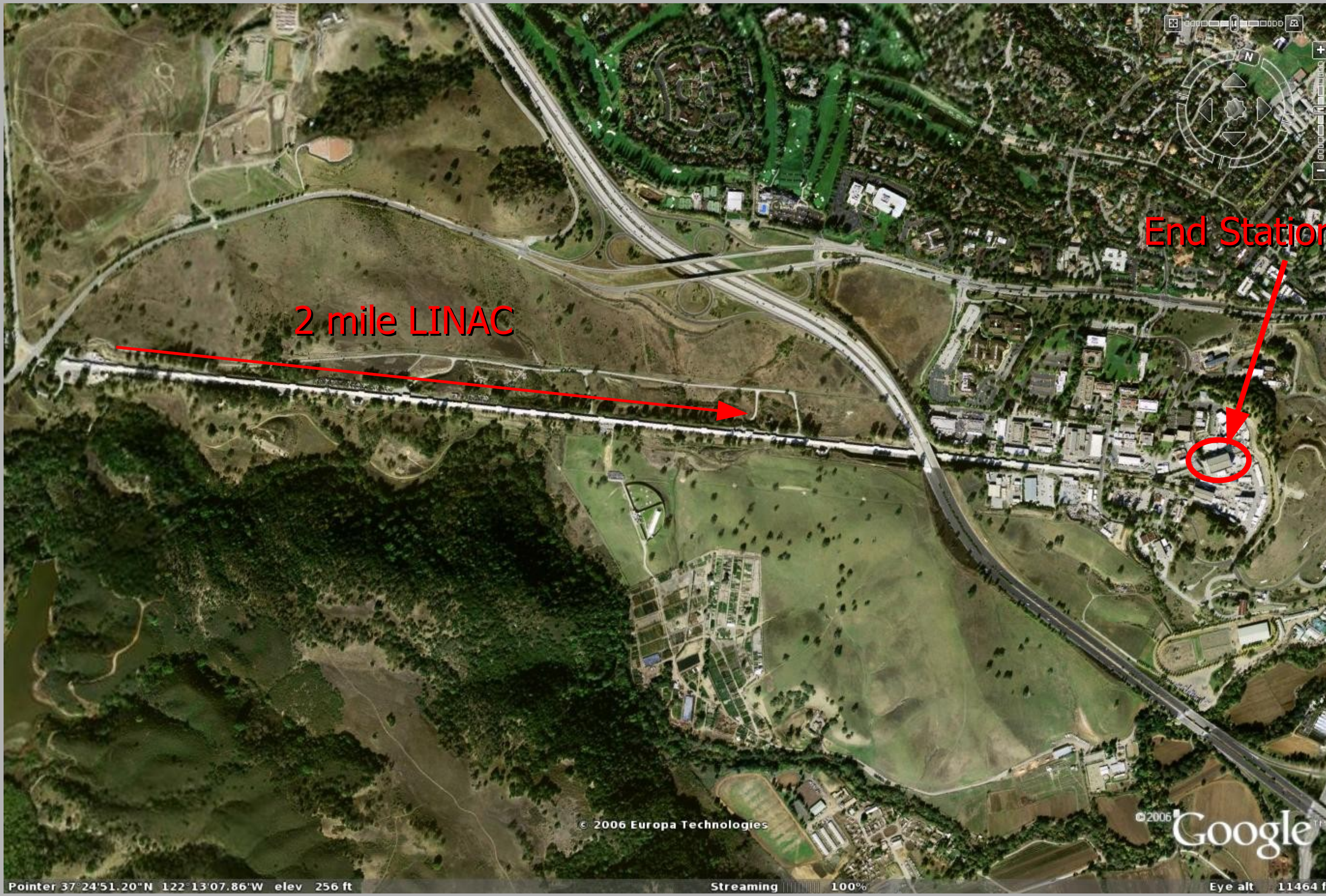


Reference cavity

Processor electronics



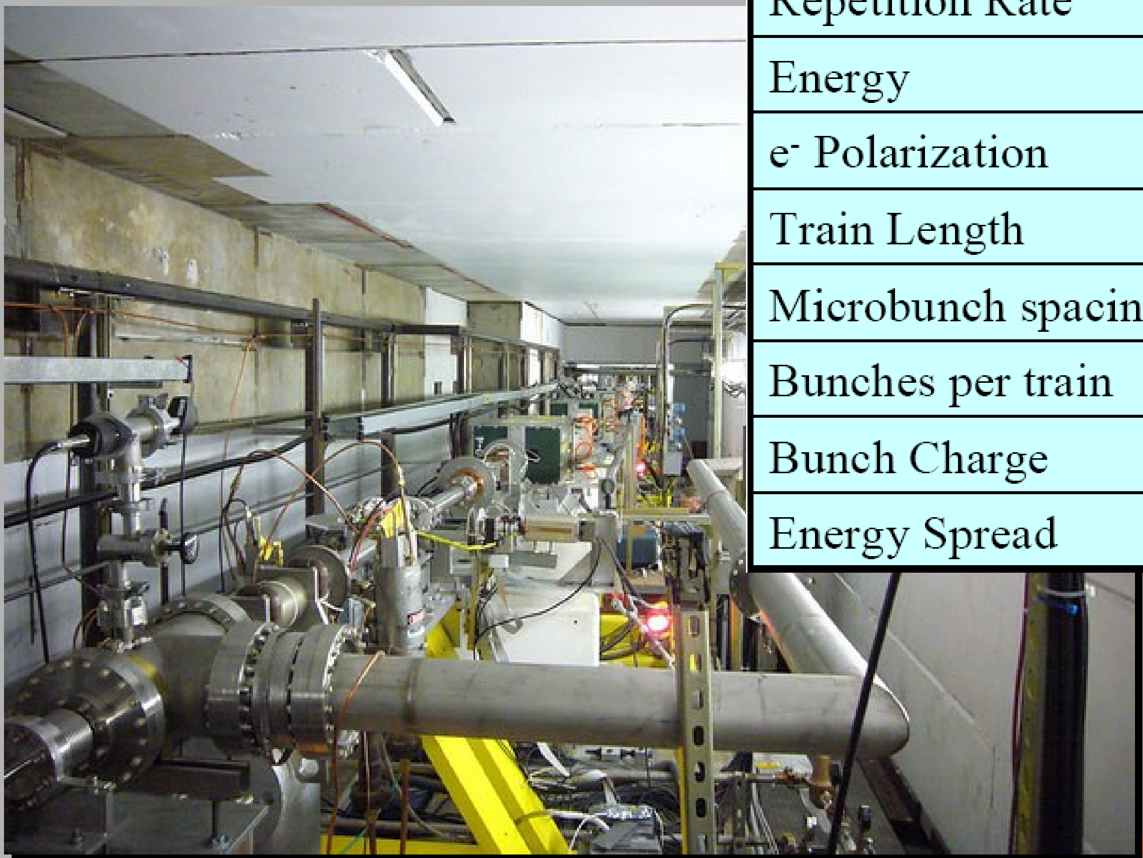
Putting it all together : T474 at ESA (SLAC)



End Station A at SLAC as ILC testfacility

- ESA is well suited for ILC test experiments, among others :
  - collimator wakefields (N. Watson, S. Molloy et al.)
  - bunch length diagnostics,
  - synchrotron light detector
  - magnetic chicane spectrometer (T-474)

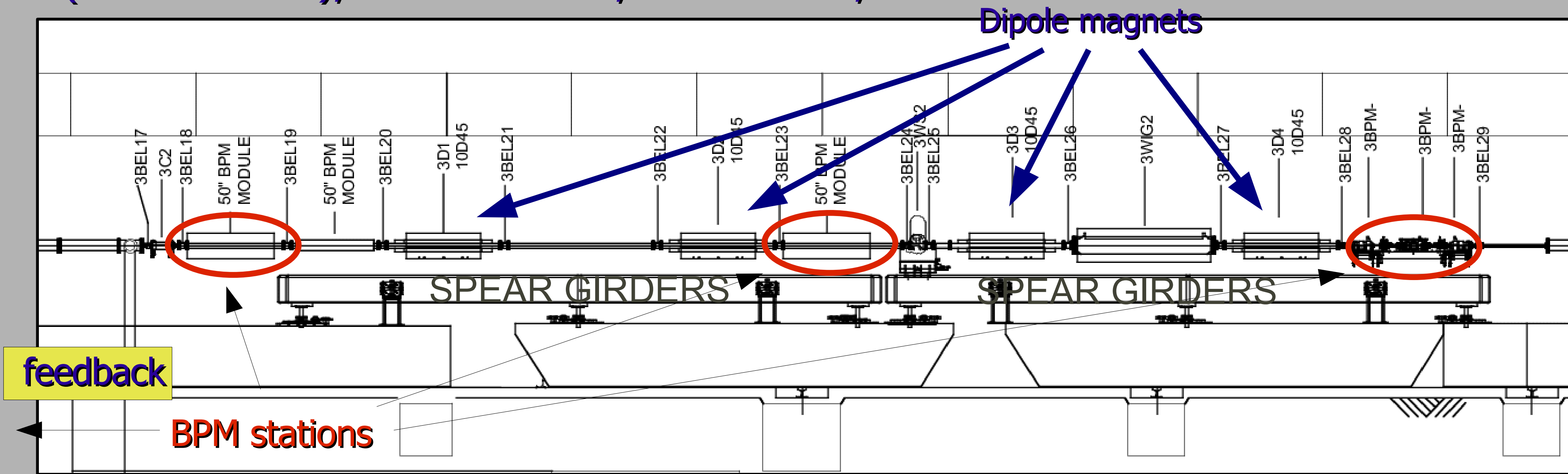
Parameter	SLAC ESA	ILC-500
Repetition Rate	10 Hz	5 Hz
Energy	28.5 GeV	250 GeV
e^- Polarization	(85%)	>80%
Train Length	up to 400 ns	1 ms
Microbunch spacing	20-400 ns	337 ns
Bunches per train	1 or 2	2820
Bunch Charge	2.0×10^{10}	2.0×10^{10}
Energy Spread	0.15%	0.1%



Possibility to vary energy, bunch charge bunch length etc.. systematic studies !

T474 at ESA (SLAC)

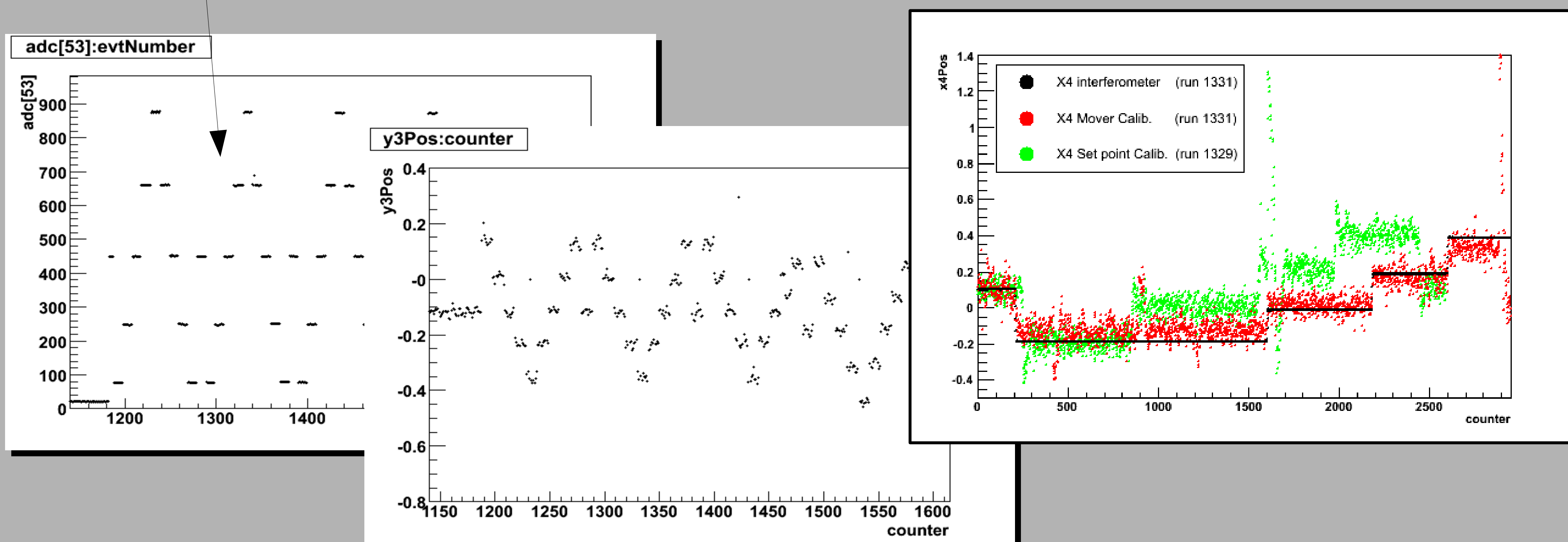
Collaboration with LBNL (Y. Kolomensky et al.), SLAC (M. Woods et al.), Notre Dame (M. Hildreth et al.), DESY Zeuthen, JINR Dubna, ...



- April run 2006 (2 weeks) :
  - Commissioning of new cold linac prototype triplet (BPM 3,4,5), where BPM4 on x,y mover system
  - Commissioning of old SLAC BPMs (9,10,11)
  - Digitisation/signal processing optimization
- July run 2006 (2 weeks) :
  - Commissioning of interferometer system (BPMs 3,4,5) + energy BPM24 upstream
  - Stability data taking with 10 BPMs, frequent calibrations
- March 2007 (2 weeks) :
  - Commissioning of calibration tone system and new UK BPM processor hardware
  - Commissioning of 4 chicane magnets and first full spectrometer data

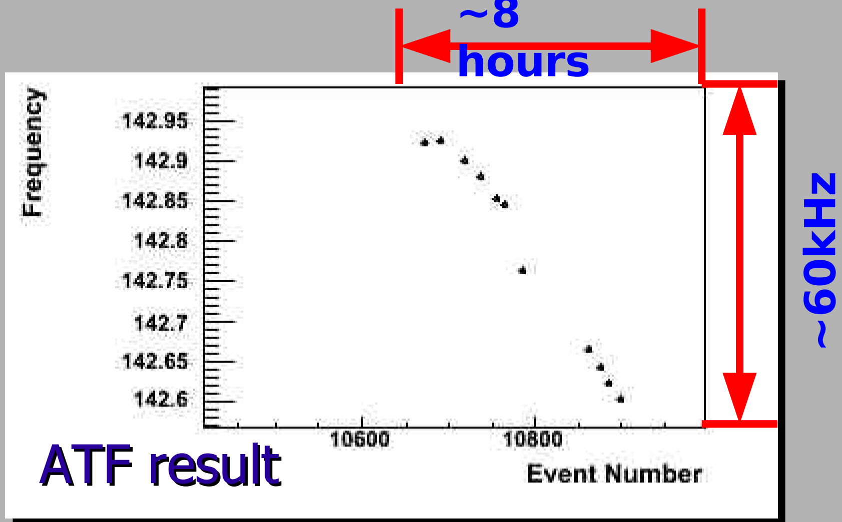
BPM Calibration at ESA...

- Calibrate the measured BPM position against a well known beam offset.
- Important to minimize impact for this on physics data taking...
- At ESA :
  - feedback setpoint calibrations : do we trust the setpoint calibration ?
  - corrector calibrations : feedback off, drifts !
  - mover calibrations : correct with interferometer, correction factor, however be careful for fake interferometer drifts !
  - helmholtz coil calibrations : fast, averaging slopes (march 2007 run)
- Automation of the process is an important operational issue for the ILC

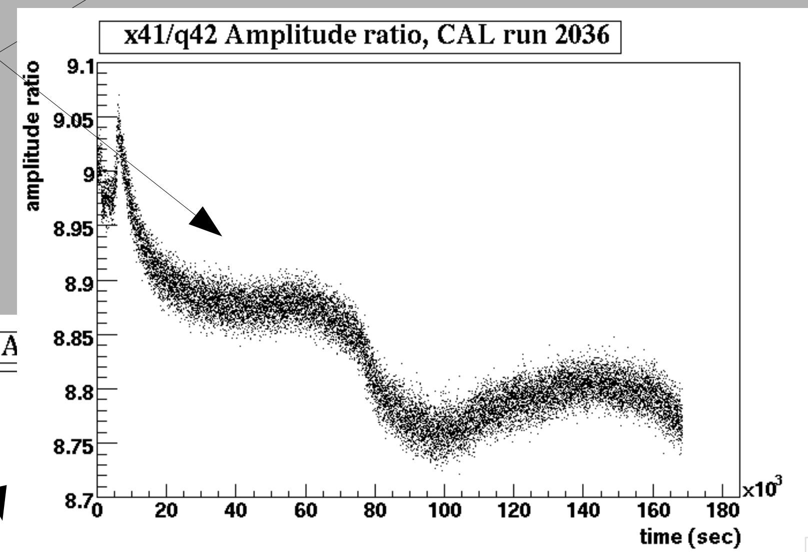


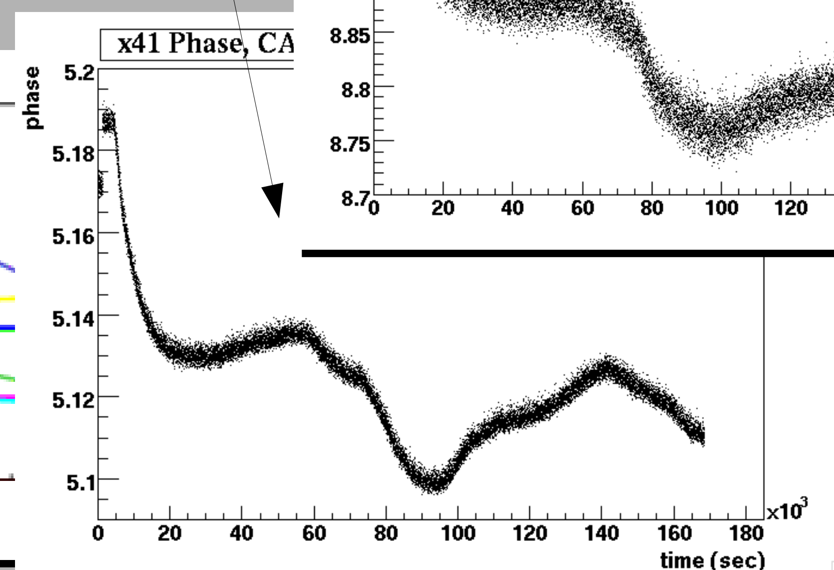
Stability issues : degradation of resolution over time

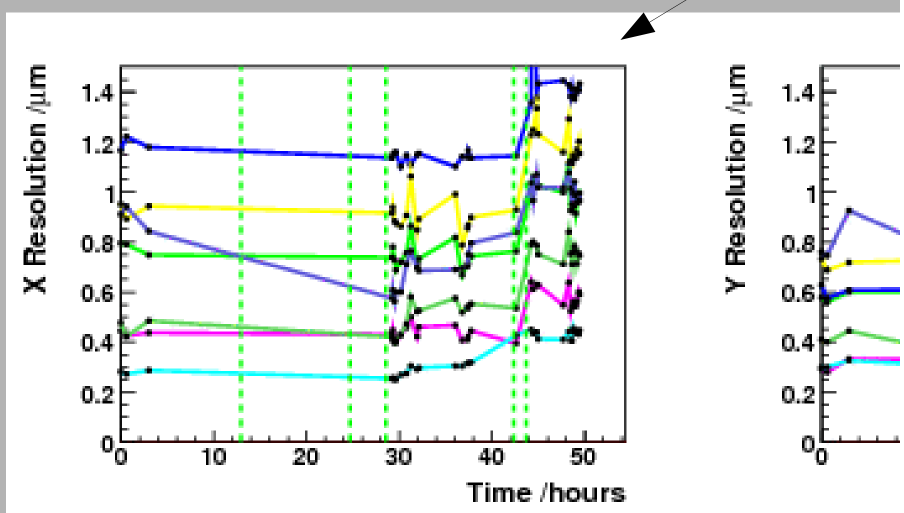
First of all... let's define resolution :)



- Mainly temperature difts cause degradation of the system
  - gain drifts
  - cavity shape changes : frequency changes
- Constant calibration tone !!

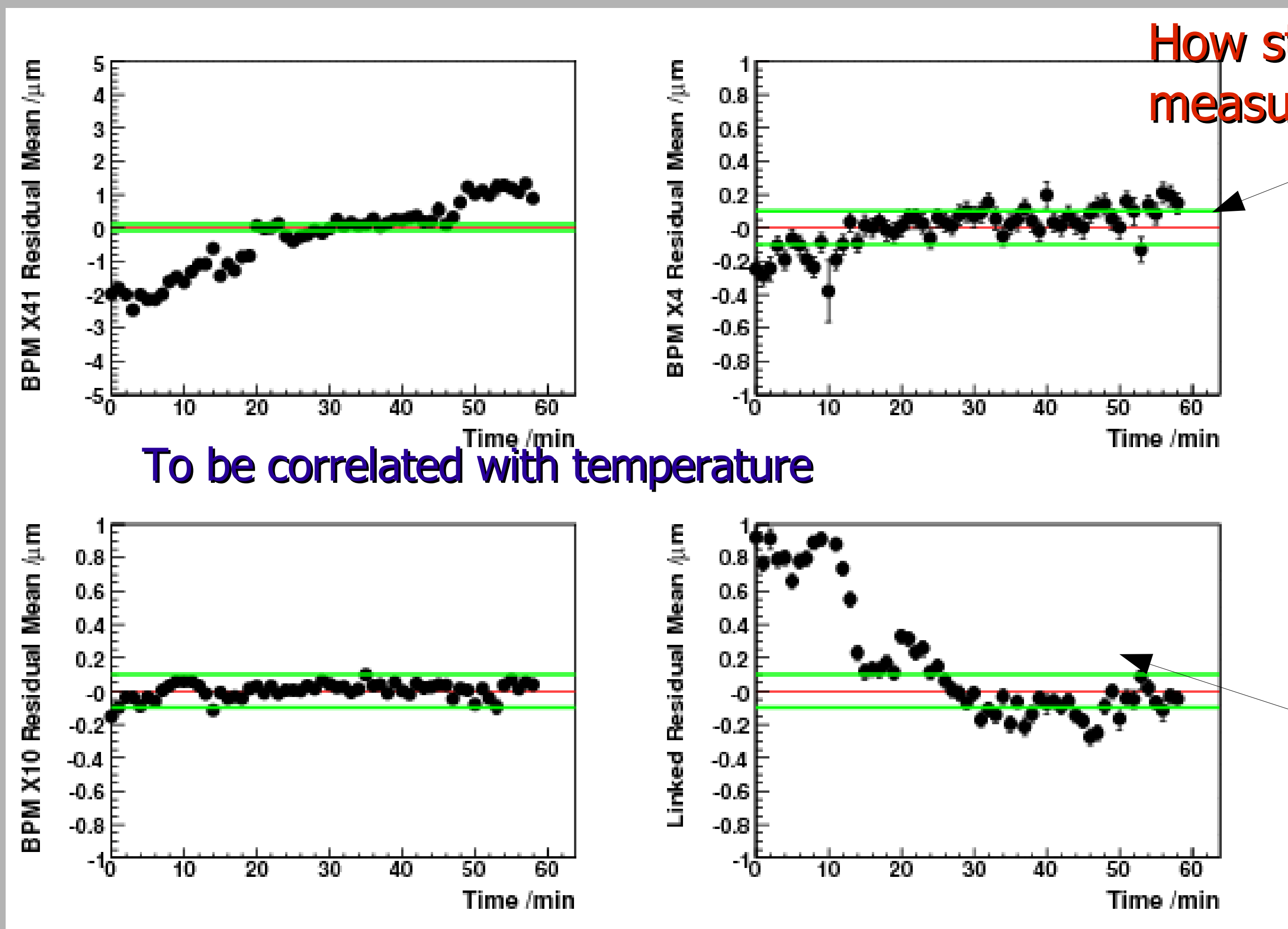






Drift of residual means...

- Monitors the relative gain drifts between the stations in terms of position measurement
- Direct impact on the stability of the energy measurement



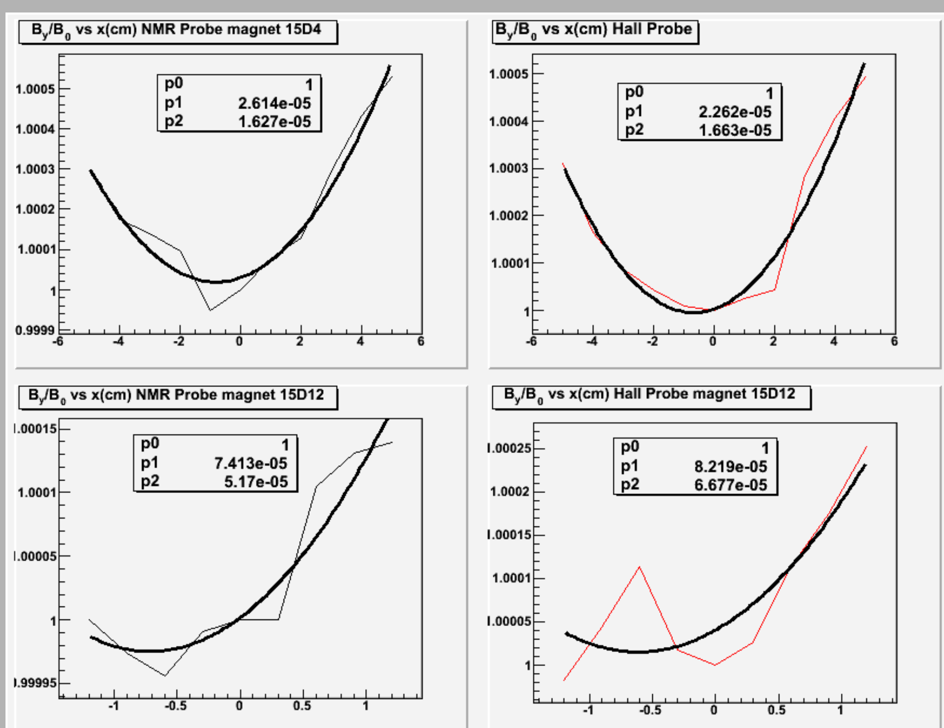
How stable is our position measurement in 1 BPM station

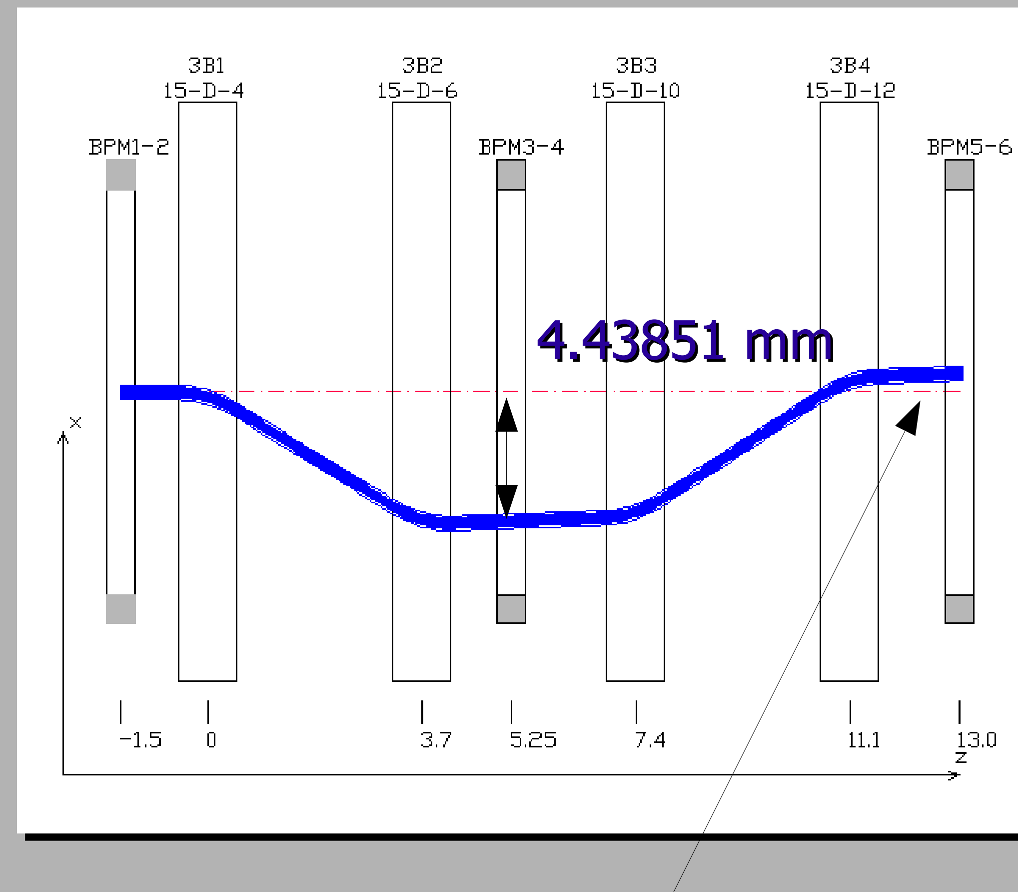
To be correlated with temperature

How stable is our measurement of the entire orbit ?

Magnetic measurements…

- 4 Magnets were mapped during summer 2006 in SLAC measurement lab (SLAC, DESY, JINR)
- Operating current of 150 A
- Integrated Bdl of 1.1 kG.m
- Long term stability analysis in progress



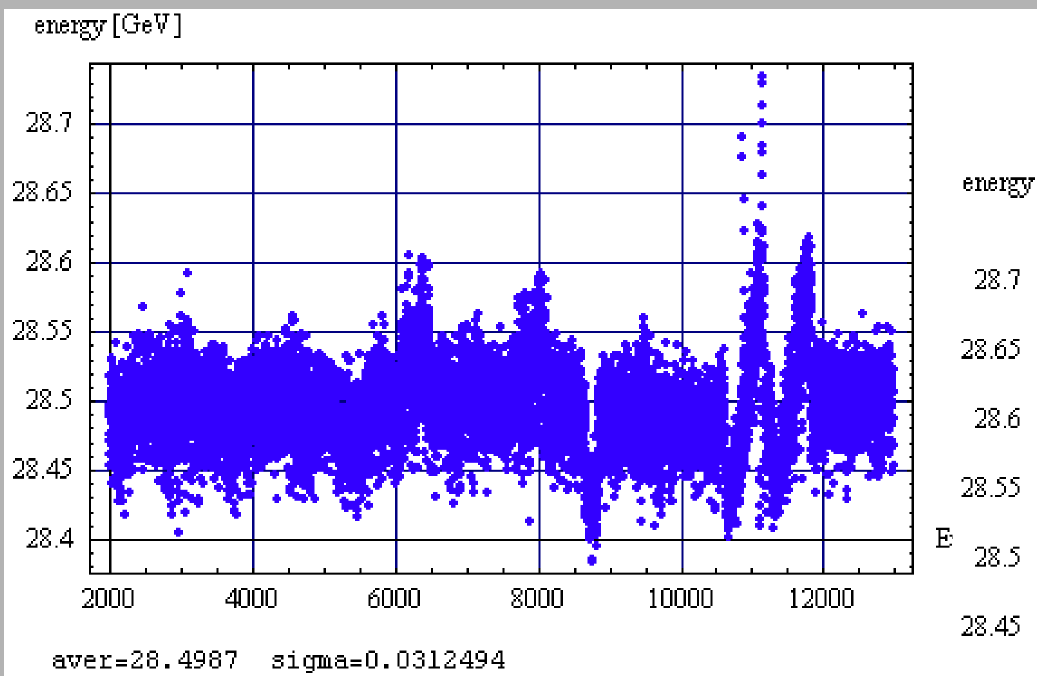


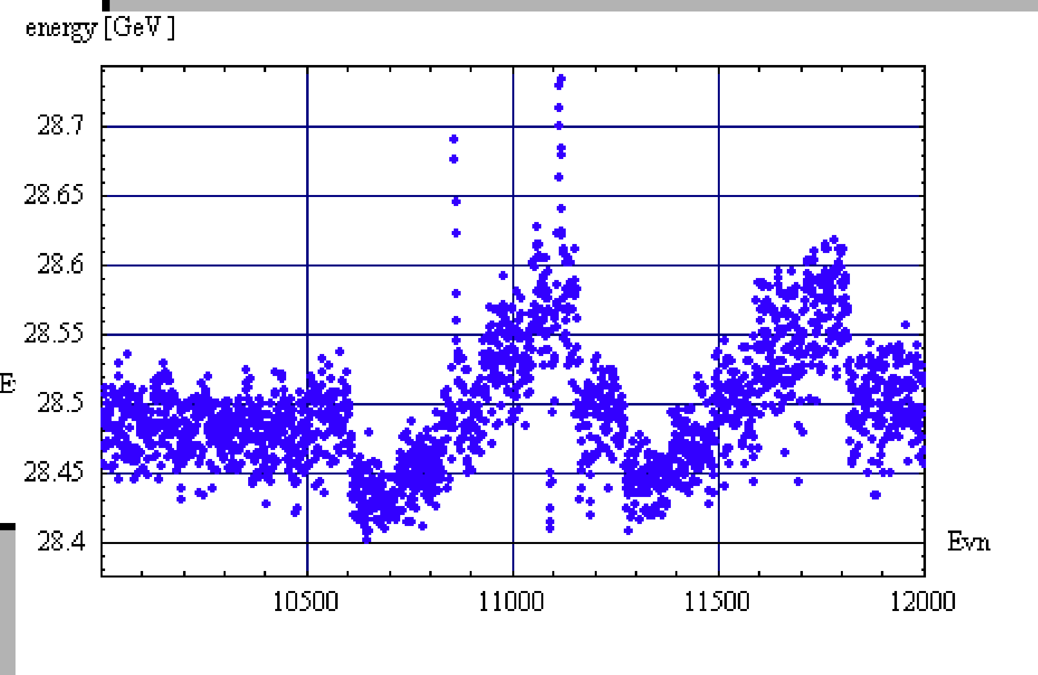
Small inhomogeneity in magnets

Important to understand for future ILC operation : beam disruption after chicane

Chicane results, first beam energy measurements

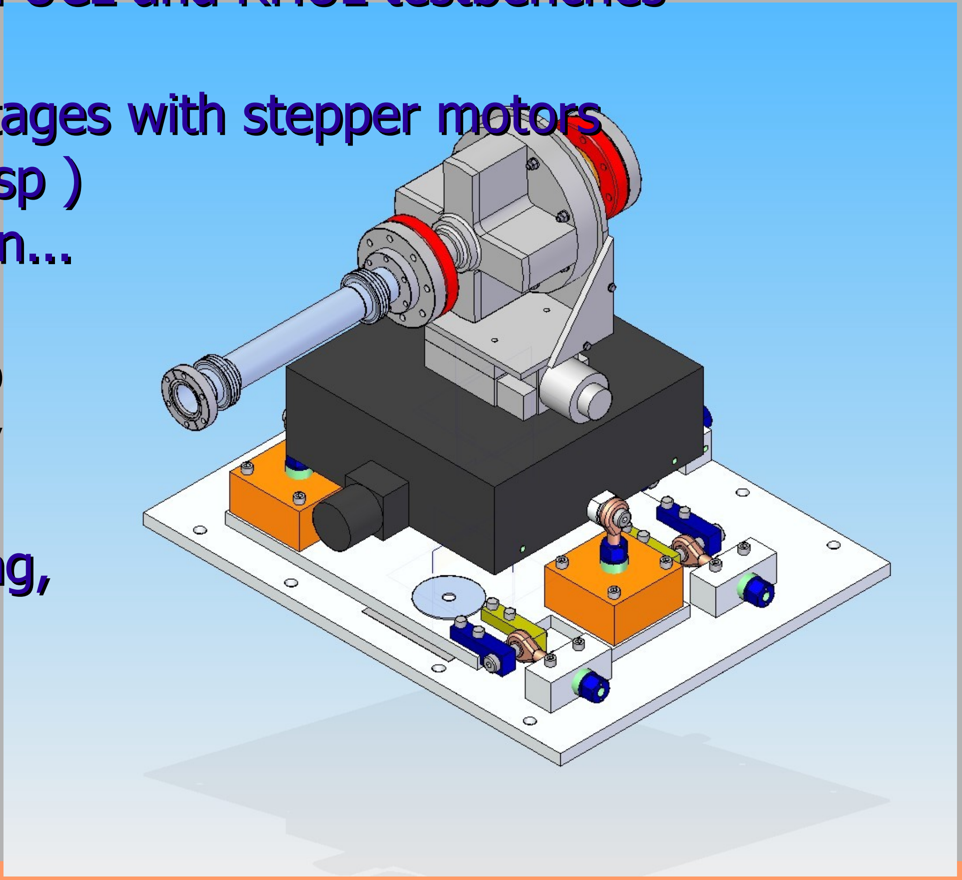
- Taking into account integral B.dl and deflection at center of chicane, can compute correct beam energy
- Have to subtract incoming orbit in each event
- Total error in energy calculation 2.5e-4 (~7 MeV) (preliminary!)
- Further detailed analysis stability studies underway...
- More and better data to come in July...





Future plans for ESA

- Had 3 successful runs so far
- Upcoming run in July 9th until the 22th 2007.
- Install and commission the new spectrometer BPM prototype complete with mover system
  - cavities are currently being measured on UCL and RHUL testbenches
  - mover system is being commissioned
    vertical elevation stage and horizontal stages with stepper motors and linear encoders (0.5 and 0.1 um resp)
  - Improve processor electronics in long run…
- Continue taking data with chicane, need to understand better systematics and stability
- Couple of papers underway : commissioning, Spectrometer BPM prototype and full T-474 ESA paper

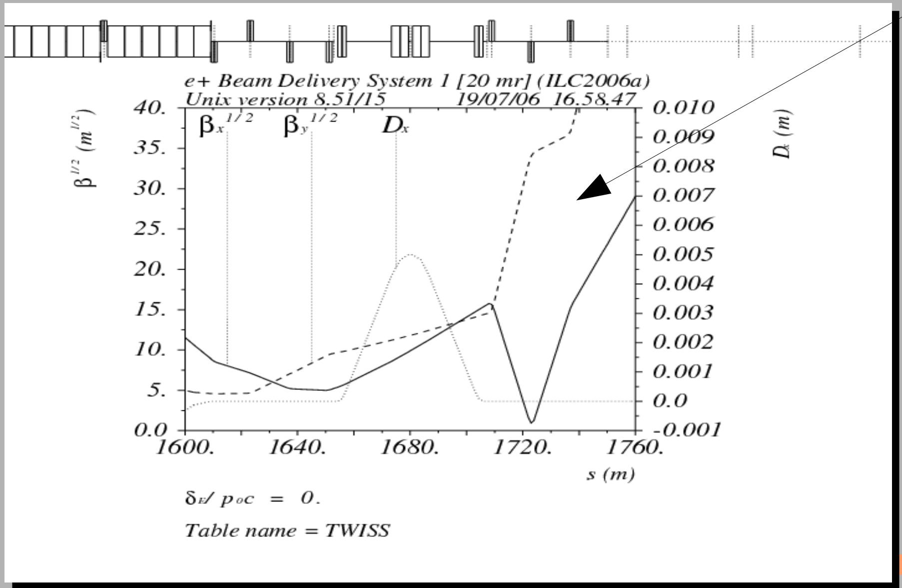


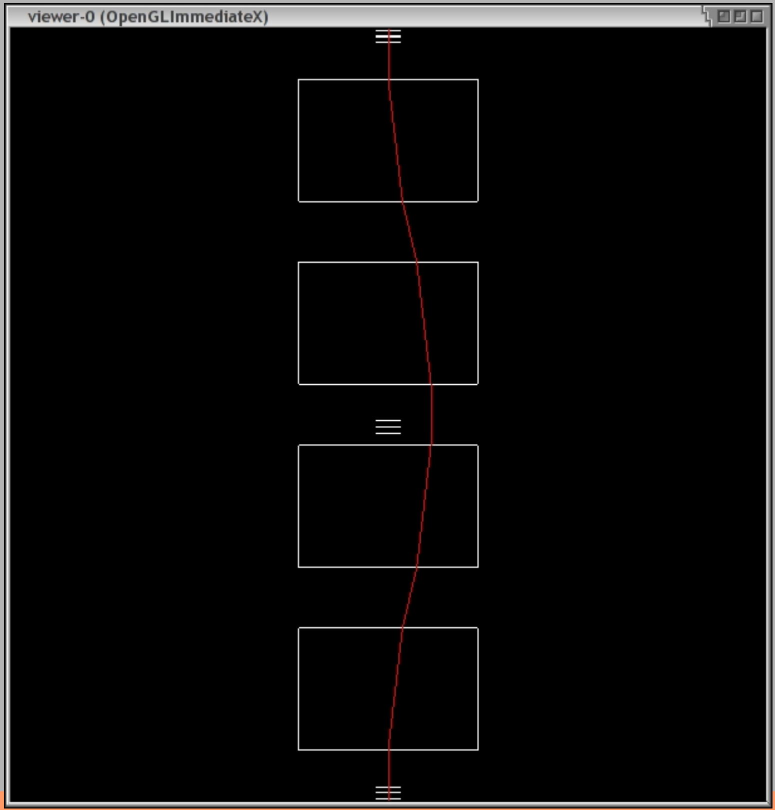
Simulation....

Of course.. one final issue... It's all fine to study stability and operational issues at 28.5 GeV, but we really need it at 500 GeV : simulation !

Currently developing :

- GEANT4 simulation of simple spectrometer chicane
  - beam distortion, track halo, synchrotron radiation
  - interface with core BPM processing library and simulation library to have a full simulation of the entire system
- Transport beam down to IP through rest of BDS
- Make studies for optimal chicane design, update baseline document eventually





Summary

- Physics case for an a 1 TeV linear e+e- collider is clear !
- Importance of the energy measurement, direct contribution to systematics on threshold studies (e.g. Top quark)
- Proposed magnetic chicane for single pass energy measurement
- Based upon high resolution resonant cavity beam position monitors
- Operational principles of these devices
- Full chicane prototype test experiment is commissioned at ESA in SLAC
- First results, data analysis ongoing + next run planned for this summer...
- Simulation studies...

Thanks for listening...

...and for the interested :

Some links at UCL

http://www.hep.ucl.ac.uk/lc/
http://www.hep.ucl.ac.uk/~bino/T474/
http://www.hep.ucl.ac.uk/~liapine/
http://www.hep.ucl.ac.uk/~sboogert/

SLAC ILC page

http://www-project.slac.stanford.edu/ilc/default.htm

SLAC ESA page

http://www-project.slac.stanford.edu/ilc/testfac/ESA/esa.html

Central ILC page

http://www.linearcollider.org