CLIC Workshop 2009

Summary of WG5
Technical Systems

Hermann Schmickler – CERN
Grahame Blair –Physics Department

Subjects:

- Beam instrumentation
- Module design and integration
- Quadrupole (MB + FF) stability, BBF
  → partially treated in the summary of A.Seryi
- Machine Protection
- MB-DB phase alignment
- Many Others

It is impossible to mention in detail the contribution of everybody in this summary. I try to highlight new evolutions and I will point to problem areas that need follow up.

Beam Instrumentation, Presentations:

Drive Beam BPMs	SOBY, Lars
Laser-wire issues	DEACON, Lawrence
Instrumentation at ATF2 and relevance to CLIC	OKUGI, Toshiyuki
Instrumentation at CTF3 and relevance to CLIC	DABROWSKI, Anne
Longitudinal Profile	GILLESPIE, Allan
Polarimetry at CLIC	HARTIN, Anthony
Electronics Development	VILALTE, Sebastien
Summary of BI Workshop	LEFEVRE, Thibaut

CLIC 3TeV – Numbers of devices

Instrument	N° Devices
Intensity	386
Position	**49520**
Beam Size	**798**
Energy	166
Energy Spread	166
Bunch Length	384
Beam Loss/Halo	2968
Beam Phase	192

Drive Beam

54580 devices

Instrument	N° Devices
Intensity	311
Position	**7579**
Beam Size / Emittance	143
Energy	75
Energy Spread	23
Bunch Length	26
Beam Loss/Halo	4
Beam Polarization	23
Tune	8
Beam Phase	96
Luminosity	4
Wakefield monitor	**142812**

Main Beam

8292 devices

+ 142812 wakefield monitors

T. Lefevre

CLIC BPM overview

	Accuracy	Resolution	Stab.	BW	Φ	NB	FB	MPS
Injectors	100 µm	50 µm	?	1 GHz	40 mm	189	?	?
Pre damping rings	10 µm	10 µm	?	10MHz	20/9 mm	600	Yes	?
Damping rings	10 µm?	2 µm	?	10MHz	20/9 mm	600	Yes	?
BC1, Booster Linac, Transfer lines, BC2	100µm	10µm	?	10MHz?	?	1404	?	?
DBA, DL's, CR's and transfer lines	20µm	20µm	?	100MHz	40mm	900	?	?
DB long transfer lines	?	?	?	100MHz	200mm	848	?	?
DB Turn around's	20µm	20µm	?	100MHz	Var.	1920	?	?
DB decelerator's	20µm	2µm	2µm	10MHz	23mm	41576	Yes	Yes
MB Linac	5µm	50nm	5µm	10MHz	8mm	4776	Yes	Yes

A total of 52813 BPMs!!...or ~800MCHF

Summary of Cavity BPMs in ATF2 Beamline

The Thermal noise of the cavity BPMs corresponds to 4nm resolution for a 1e10 intensity electron beam.

But, we expect that the noises are amplified by the amplifier in the readout circuit up to 12nm resolution.

The < 20nm resolution is achieved in the ATF line with Homodyne and Heterodyne type electronics for very narrow dynamic range (10μm for the resolution test).

The cavity BPMs are used with the resolution of around 1μm in order to enlarge the dynamic range.

T. Okugi

Summary Longitudinal Devices & CTF3 CLIC

CLIC Drive Beam Complex and CTF3 have comparable bunch length and bunch spacing – provide test bed for CLIC Drive beam Devices

R&D should continue on cost effective, non-destructive techniques

- RF Pickup
- Coherent Diffraction Radiation (CDR)

Cross Calibrated against RF-Deflector and Streak Camera (bunches > 2ps)

Use Califes to to bench mark diagnostics for shorter bunches ?

- CLIC Bunch Form factor measurements
  - DB decelerator for RF production efficiency verification : 300fs resolution
  - MB for feedback : 30fs resolution

Difficult to test that @ CTF3 → will work on 300 fs resolution for RF-pickup and CDR by 2010

A. Dabrowski

So are all problems solved...?

Low time resolution (>1ps structure)

- spectral decoding offers explicit temporal characterisation
- relatively robust laser systems available
- diagnostic rep rate only limited by optical cameras

High time resolution (>60 fs rms structure)

- proven capability
- significant issues with laser complexity /robustness

Even higher time resolution (<60 fs rms structure)

- limited by EO material properties (& laser)

List of Critical Items

Collaboration with RHUL & Oxford

- **Very tight requirements** for measuring micrometer **beam size**, 40-75microns short **bunch length** and **beam position** with a 50nm resolution

Collaboration with U. Dundee, PSI & RHUL

Collaboration with Fermilab, CEA/Saclay, RHUL

- Need to study the **Machine Protection System** for both the Drive and Main beams and to develop a **Beam loss monitoring system along the CLIC linac** (both beams)

Collaboration with U. Liverpool

- **Reliability and availability** of roughly 5000 high resolution BPM's, 40000 BPM's for the Drive Beam Decelerator and 142812 **Wakefield monitors**, (+ beam loss monitors)

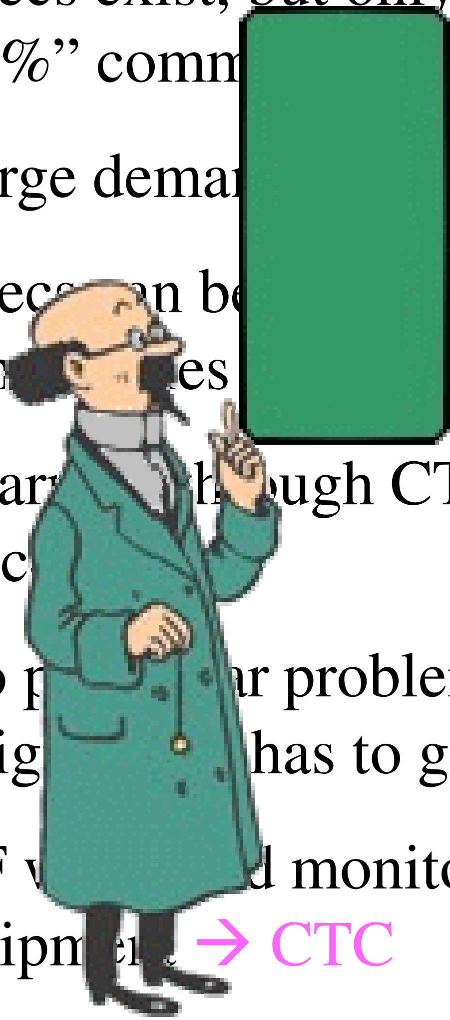
Activity covered by the RF Group - Collaboration with CEA &PSI

- Beam **synchronization** implies a **0.1deg at 12GHz phase measurement** with an adequate feed-forward system

Activity covered by RF group – FP7 – NCL activities

T. Lefevre

Beam Instrumentation, Summary

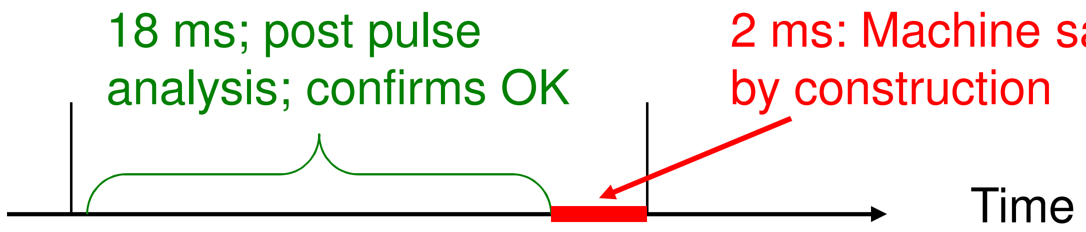


- Specs exist, but only for the nominal beams and a "10%" comm[illegible]g beam → MP&OP WG
- Large dema[illegible]strumentation, cost explosion
- Spec[illegible]n be[illegible]thin factors 2…3 with present tech[illegible]es
- Lear[illegible]ugh CTF3 and other facilities, not all fields are c[illegible]
- No p[illegible]ar problems for the CDR, but effort during the desig[illegible] has to grow by an impressive amount.
- RF [illegible]d monitors will be moved in PBS to RF equipm[illegible] → CTC

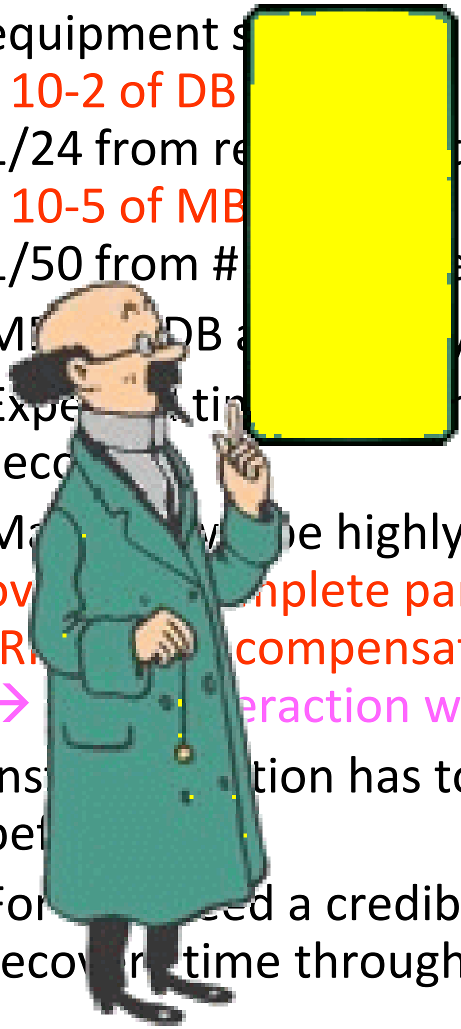
Machine Protection WG

- Presenters:
  General Concept of MP : M.Jonker
  BLM specs: B.Holzer, M.Sapinski
  Implications for power converters: S.Pittet, Y.Thurel
  First look at beam scenarios: G.Morpurgo

Concept:
Protected against Slow losses by (20-x, x) next pulse permit
Protected aginst fast losses by masks and absorbers



...the concept sounds OK, but the devil is in the detail:



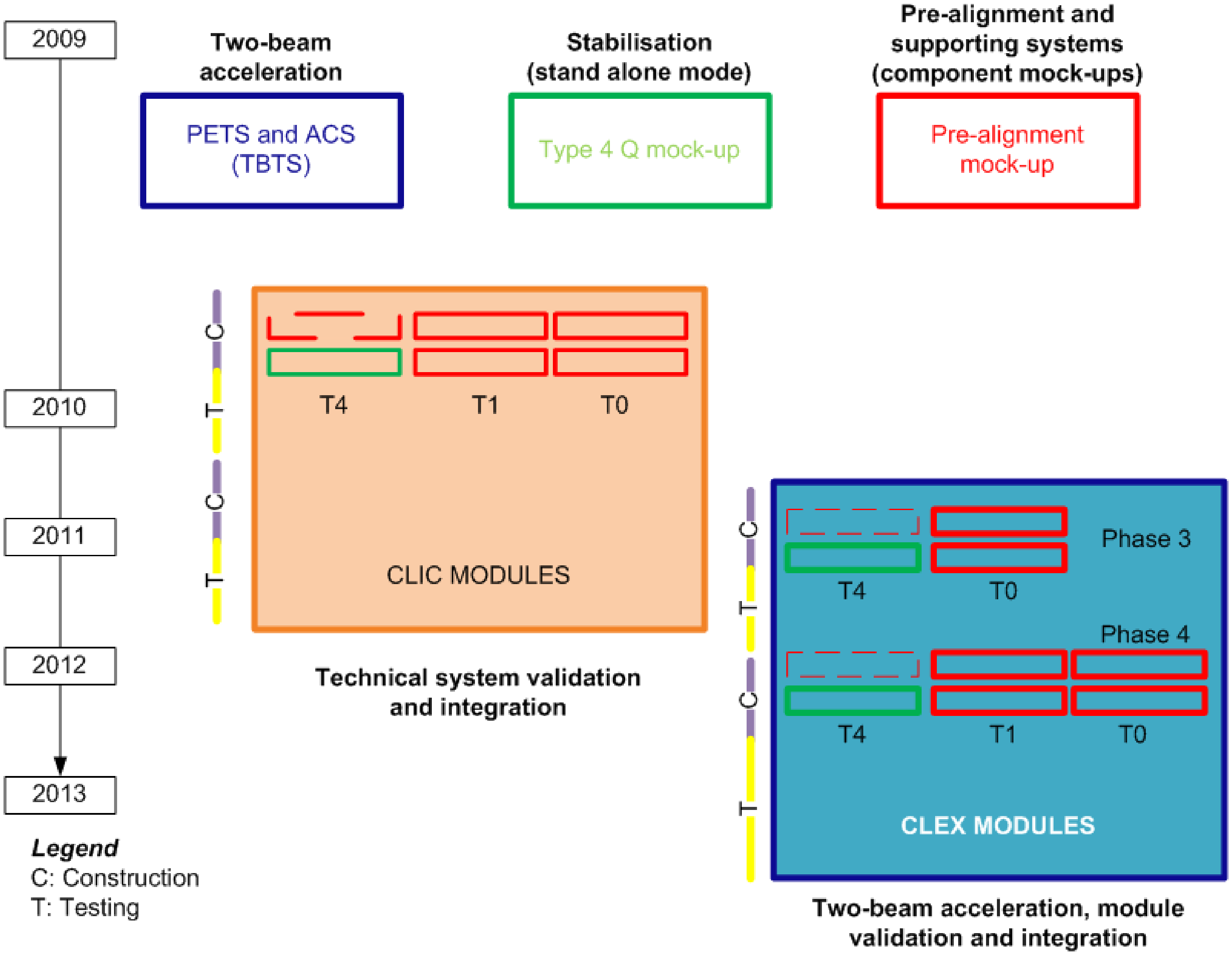
- We need “save” beams, which can be injected without worries for equipment s
  - 10-2 of DB
  1/24 from re tion + ¼ by shortening
  - 10-5 of MB
  1/50 from # es, 1/3 from bunch intensity, 1/(3x20) from size
- M DB a y coupled
- Expe ti nts short in order to stay in thermal equilibrium (10 secc
- Ma be highly optimized for nominal beams. Automatic switch ov nplete parameter set for 10-2 resp. 10-5 beams? (R compensation, feedbacks..)
  → eraction with CTF3 and RF team
- Ins tion has to follow → need specs for intermediate beams bet
- For ed a credible scenario of overall uptime (expected failure rate, recov r time through automatic controler)

Module Design and Alignment

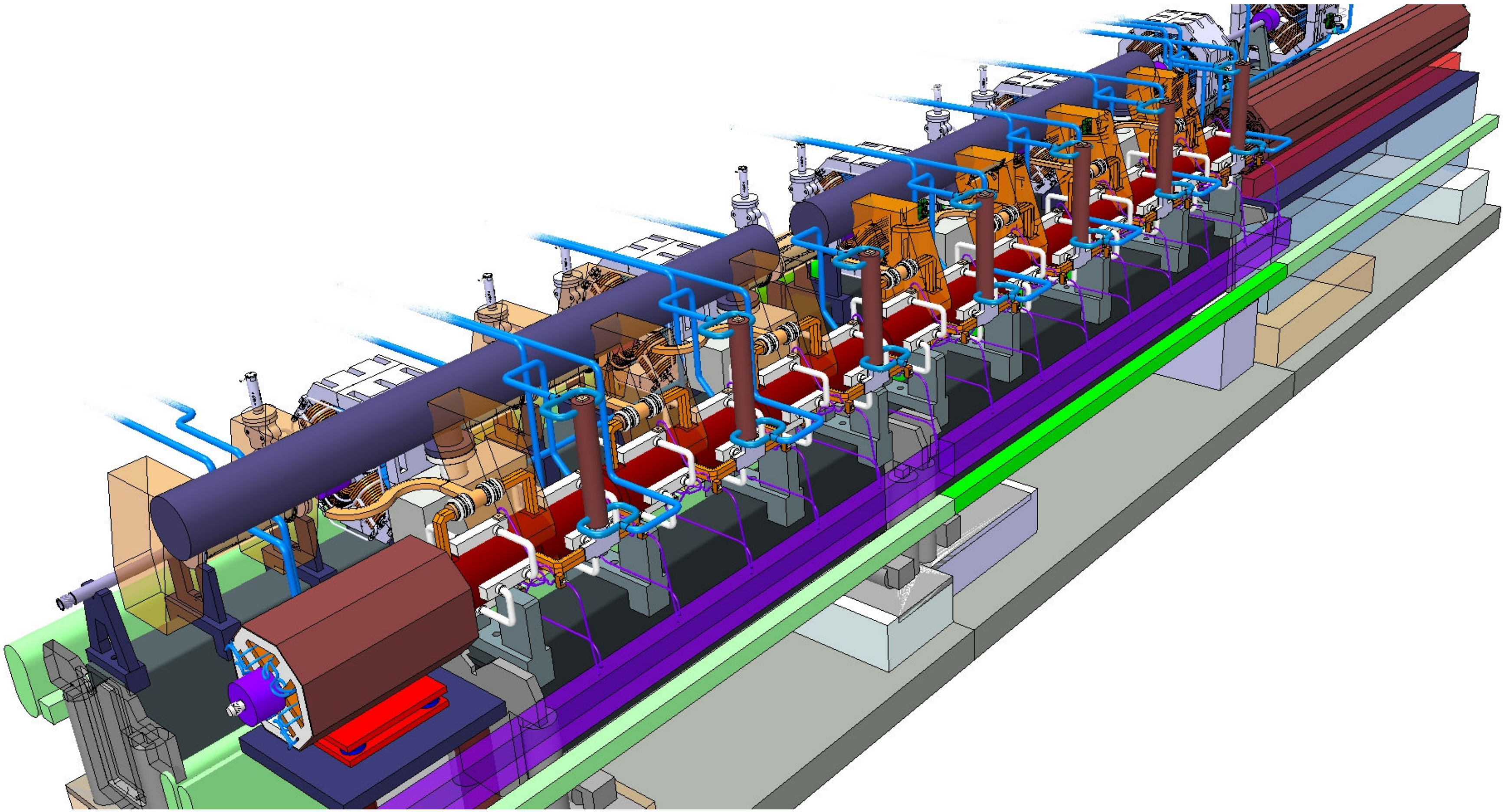
- Present State of Designs & Integration Studies
- Some details on Alignment strategy
- Thermo-mechanical simulations
- Conclusions

Presenters:
G.Riddone (CERN), A.Samoshkin (JINR),
R.Nousiainen (HIP), H.Mainaud-Durand (CERN)
T.Touze (PhD@CERN)

Strategy for main linac two-beam module validation

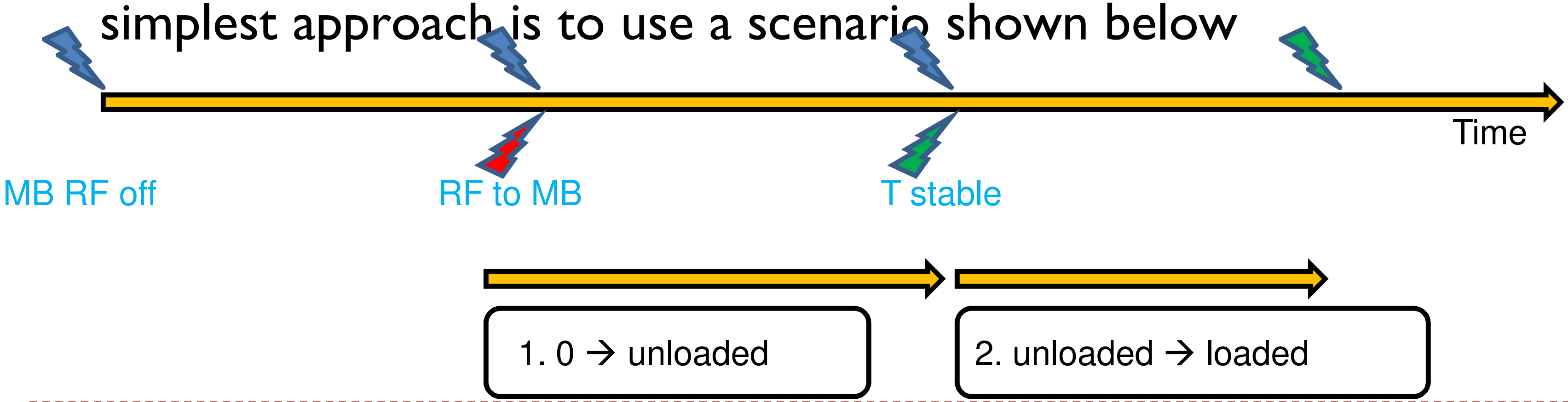


TEST MODULES INTEGRATION STUDY



Overview of thermal model

- Our current approach
  - Currently preliminary work is done with ANSYS
    - Incrementally from smaller to larger (some technical details there)
    - Selection of software is not written on stone… (Multi-physics simulations)
  - Extension of existing model via including new subsystems and boundary conditions
- Time constants between stable thermal conditions are being simulated
- Operation ramp up sequence of the accelerator can be looked also from the thermal dissipation point of view. At this stage the simplest approach is to use a scenario shown below



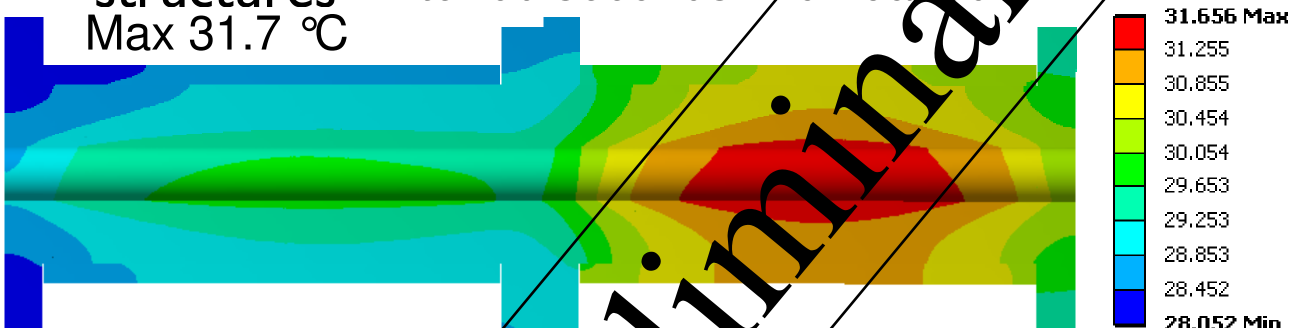
0 → Unloaded

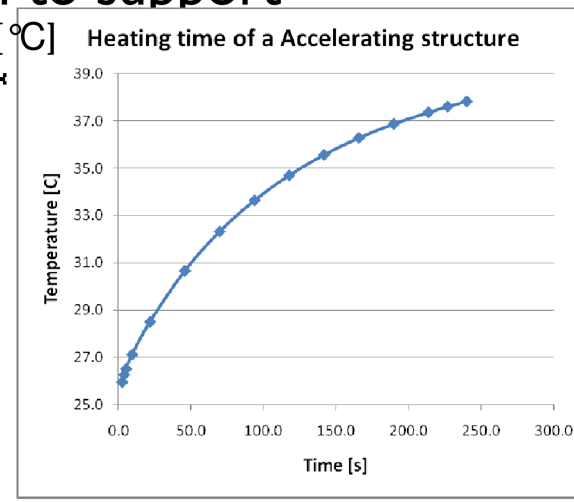
- Accelerating structure heating in unloaded condition
  - Initial temperature 25°C
- According to results ramp up time to stable condition is 8 minutes
- The model does not take into account conduction to support structures

After 60 seconds in unloaded

Temperature [°C]

Max 31.7 °C



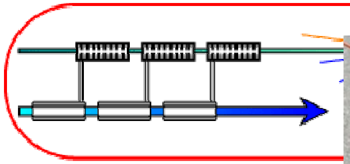


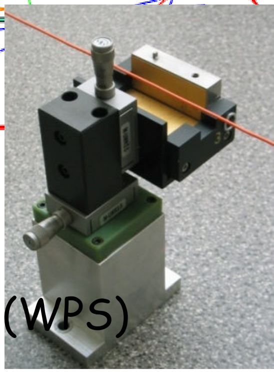
After 480 seconds in unloaded

Max 39.5 °C

Configurations
0. Boundary conditions
1. Unloaded
1. Loaded
1. 0 → Unloaded
1. Unloaded → Loaded
2. Nominal
3. Unloaded

Favoured pre-alignment concept

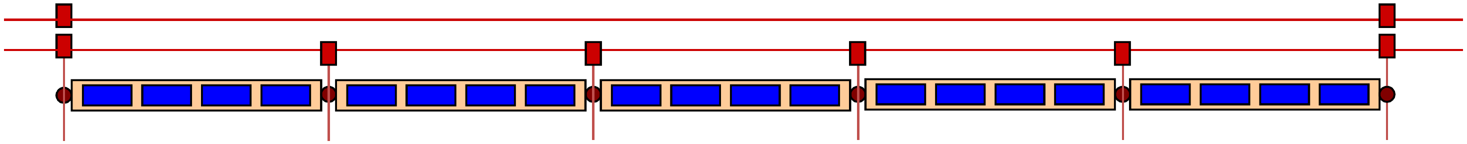




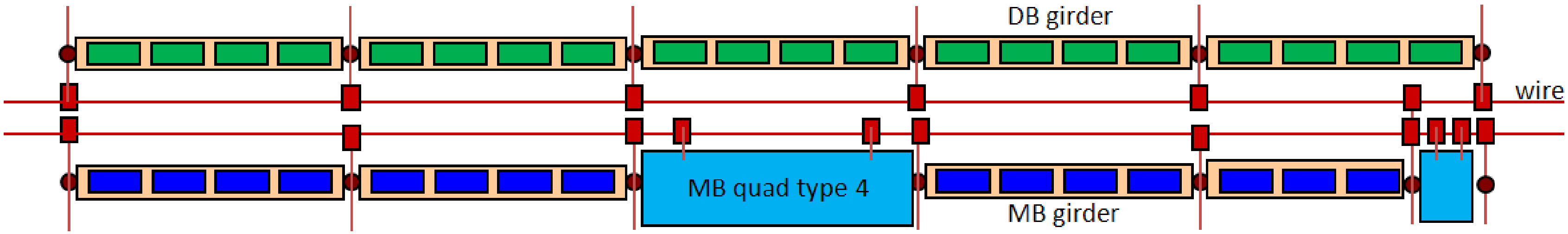
- ✓ straight reference = stretched wire
- ✓ vertical & transverse position measured thanks to Wire Positioning Sensors (WPS)

Accelerating structures
PETS + DB quad } pre-aligned on independent girders

- ✓ DB and MB girders pre-aligned with 3+1 DOF (« snake system » / "articulation point")



- ✓ MB quad pre-aligned independently with 5+1 DOF



Feasibility of the concept

STEPS → **ISSUES**

Active pre-alignment

STEPS	ISSUES
Determination of the propagation network	Stable alignment reference, known at the micron level
Determination of the position of each sensor w.r.t propagation network	Submicrometric sensors providing « absolute » measurements
Fiducialisation: determination of the zero of each component w.r.t the sensor (external alignment reference)	Stable determination of 2m long objects within a few microns
Repositionning: displacement of the component supporting structure according to the sensor readings	Submicrometric displacements along 3/5 DOF

Other issues:

- Compatibility with the general strategy of installation and operation
- Compatibility with other accelerator equipment or services

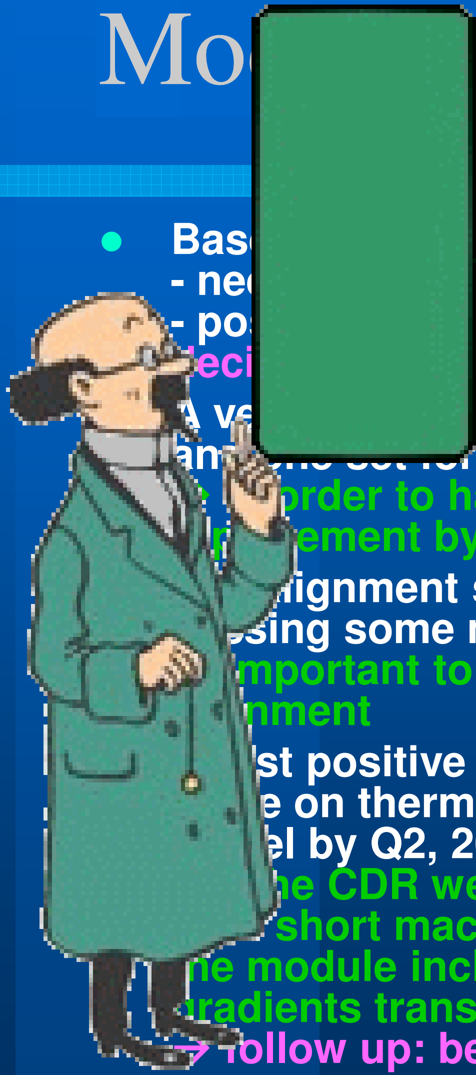
Conclusion

The propagation network seems to enable a micrometric precision. 2 µm of precision along 140 m has been reached in the TT1 facility during 33 days of measurements, even with huge meteorological variations.

It is a significant step in the CLIC prealignment feasibility. The next one is the accuracy. When the WPS are calibrated, it will be possible to check the reliability of the wires and hydrostatic networks. This will be particularly delicate for the HLS which require a geoide and tides models. It will be linked to the PhDs of Julien Boerez & Sébastien Guillaume.

When this new model is validated, it will possible to simulate the whole CLIC propagation network in order to study the error propagation and its effects on the beam physics.

Mo[illegible] & Alignment conclusions



- Bas[illegible] well defined for CDR: open questions:
  - ne[illegible]rate alignment of DB and MB → monogirder vs 2 girders
  - po[illegible]add small electro magnets for BB feedback?

  [illegible]eci[illegible]ed this year → CTC (input from beam physics needed)
- A ve[illegible]e production of test-modules with one set for lab studies an[illegible] beam measurements in CLEX is defined.

  → [illegible]order to have the lab system ready for the CDR the designs (or [illegible]p[illegible]ement by dummies) must be ready in Q1-2010
- [illegible]lignment strategy is well defined. First measurements in TT1 (still [illegible]sing some metrology results) confirm requested performance.

  [illegible]mportant to pursue the work on cam movers for the quad pre-[illegible]nment
- [illegible]st positive step (from module review mid September to now) has been [illegible]e on thermo-mechanical simulations. The aim is to have the complete [illegible]el by Q2, 2010.

  [illegible]he CDR we need a clear definition of beam cycles (set-up+ recovery [illegible] short machine stop → MPWG) and the complete heat simulation of [illegible]he module including supports and forces, such that temperature [illegible]radients translate into mechanical displacements.

  → follow up: beam physics WG and CMWG (CTC)

Quadrupole Stability (MB + FF), BBF

- Stability
- MB Quad stabilization
- MDI: new options for QD0 support
- MB stabilization and BBF: common simulation?
- Conclusions

Presenters:
C.Collette (CERN), J.Pfingstner (PhD@CERN), H.Gerwig (CERN), A.Jeremie (LAPP), A.Herve (ETH Zuerich), M.Modena (CERN), B.Dalena (CERN)

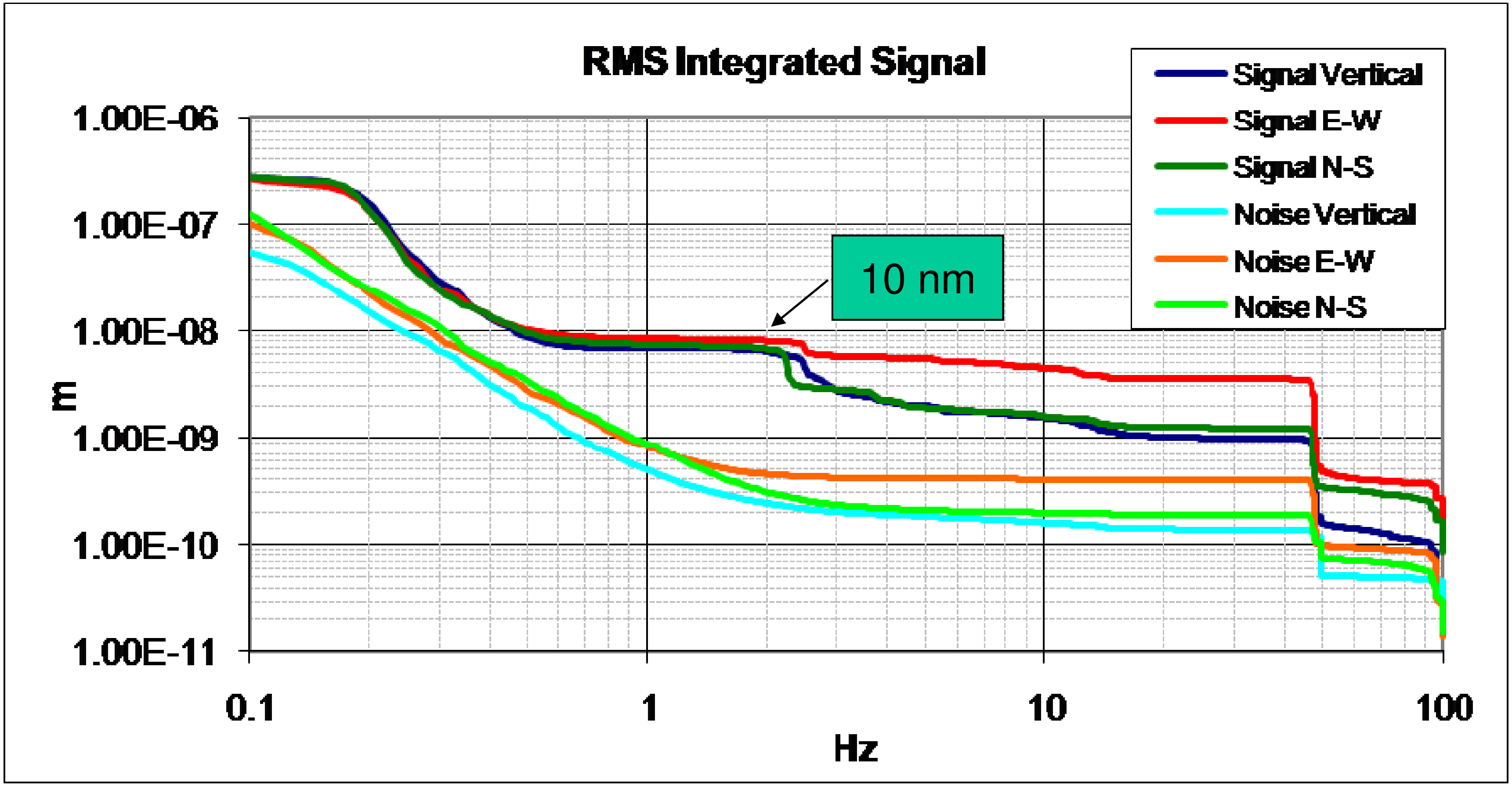
What can active stabilisation do?

Since the isolation systems don't isolate 100%, but only reduce the vibrations by a given factor (x10 for common systems, x100 VERY difficult, x1000 "impossible")

- The initial vibration background has to be as low as possible => if we want
  - MB stab of 1nm, the ground should not be higher than10nm
  - 0.15nm for the FF, the support should not be subjected to more than 2nm.
- Vibration measurements have shown:
  - Ground measurements at 1Hz vary from 2nm (LEP) to 150nm (ATF2).
  - Common detectors move already by 30nm to more than 100nm!

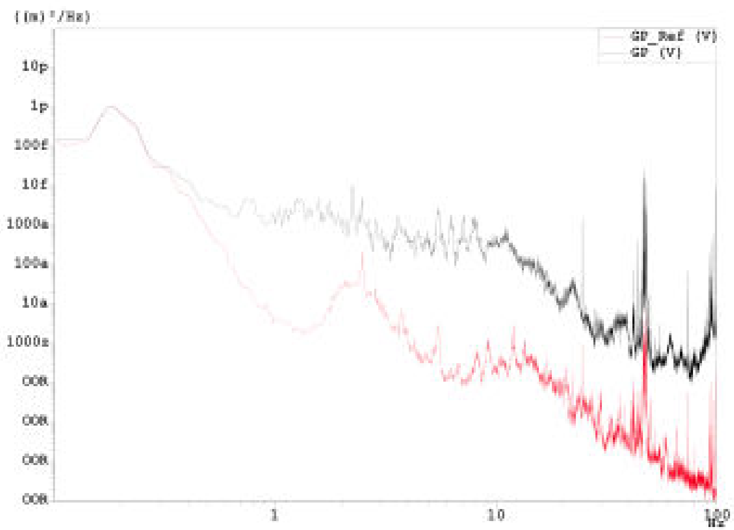
Ground motion measurement in CMS

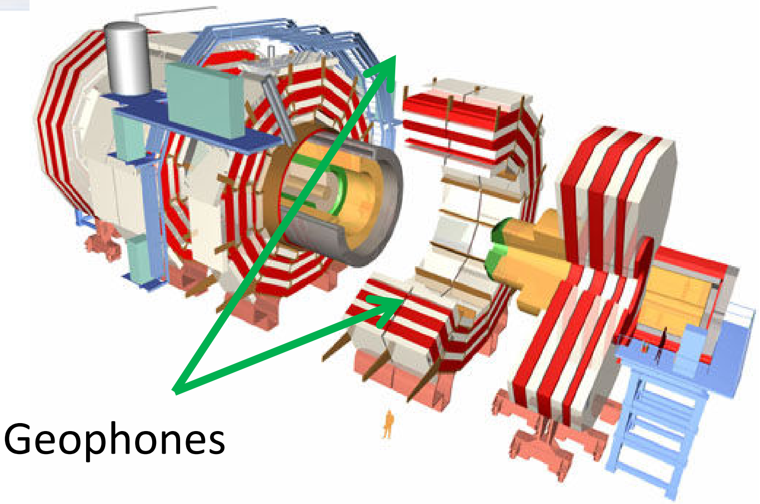
- To measure the ground vibration, two geophones were placed close together on the floor under YB0.
- The measurements were provided while the **cooling systems were off.**



CMS top of Yoke measurement

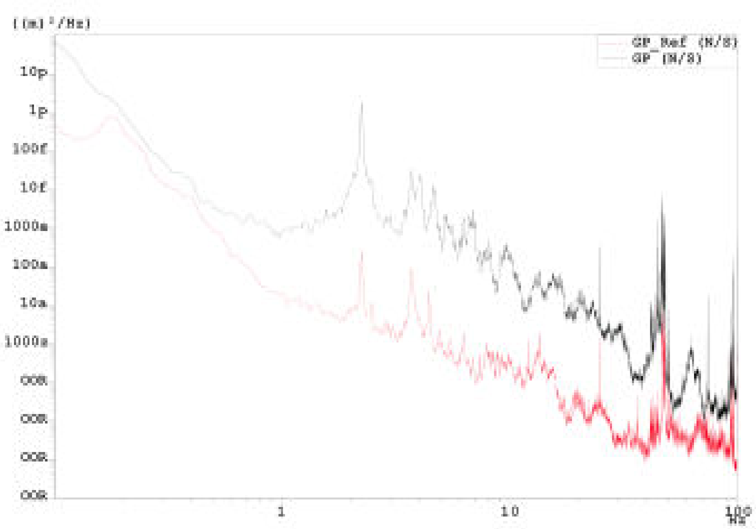
PSD of the signals Vertical direction

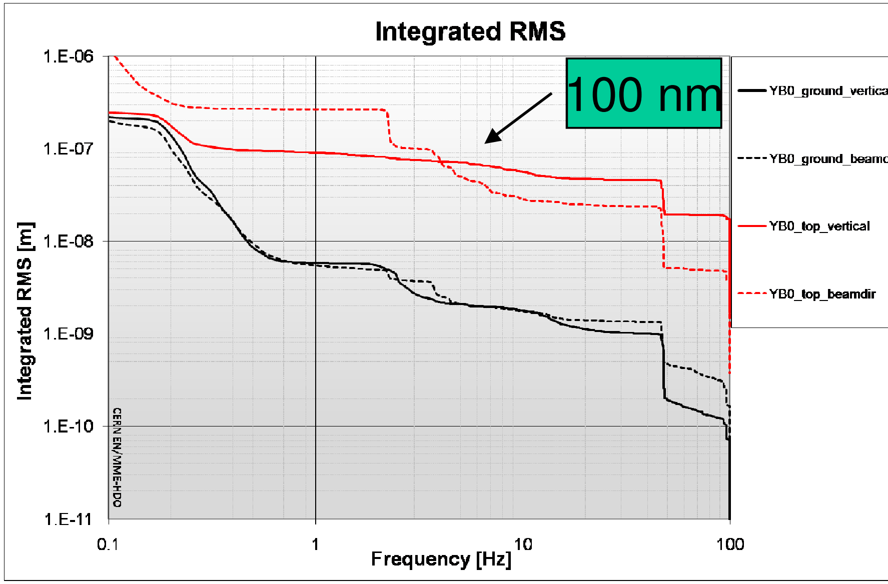




Cooling system OFF

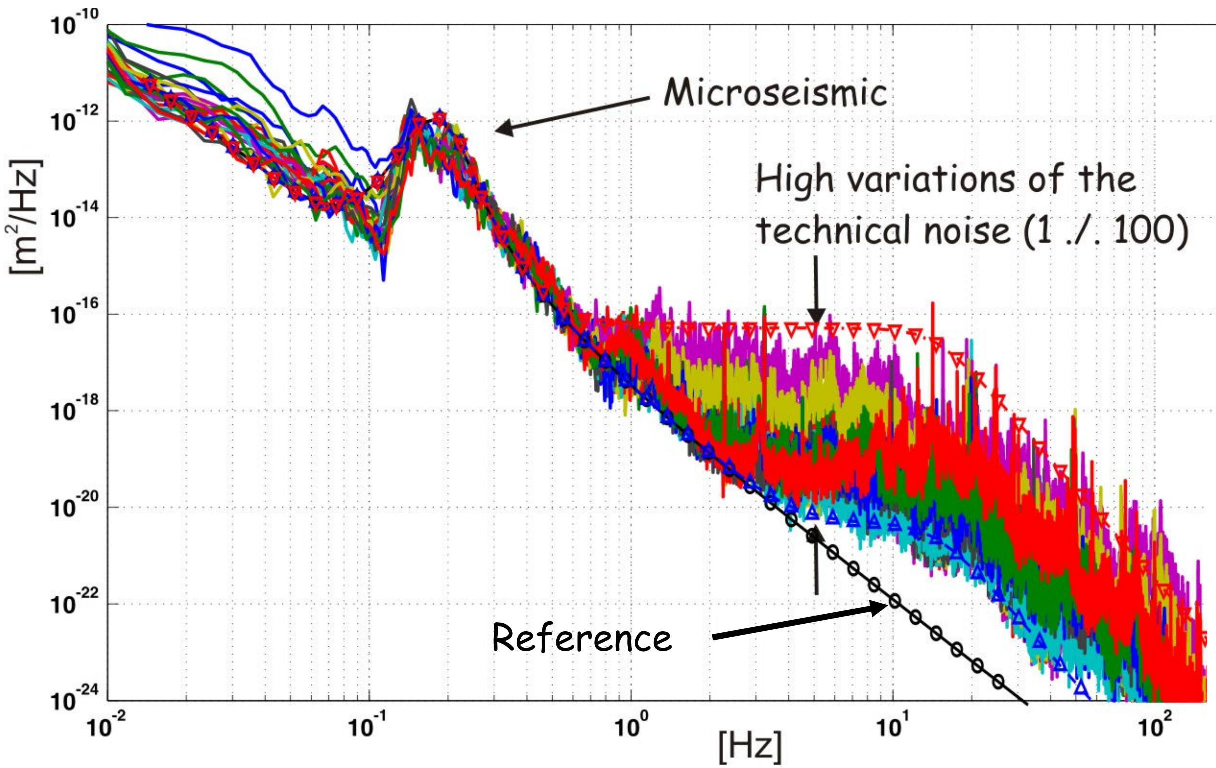
PSD of the signals Beam direction





Local excitations

Vertical ground motion



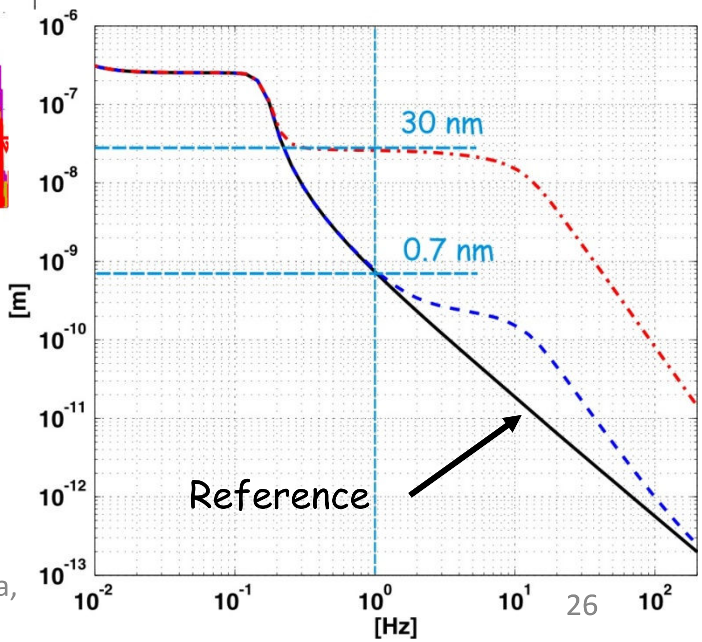
Additional technical noise:

$$N(\omega) = \frac{N_0}{1 + (\frac{\omega}{\omega_0})^6}$$

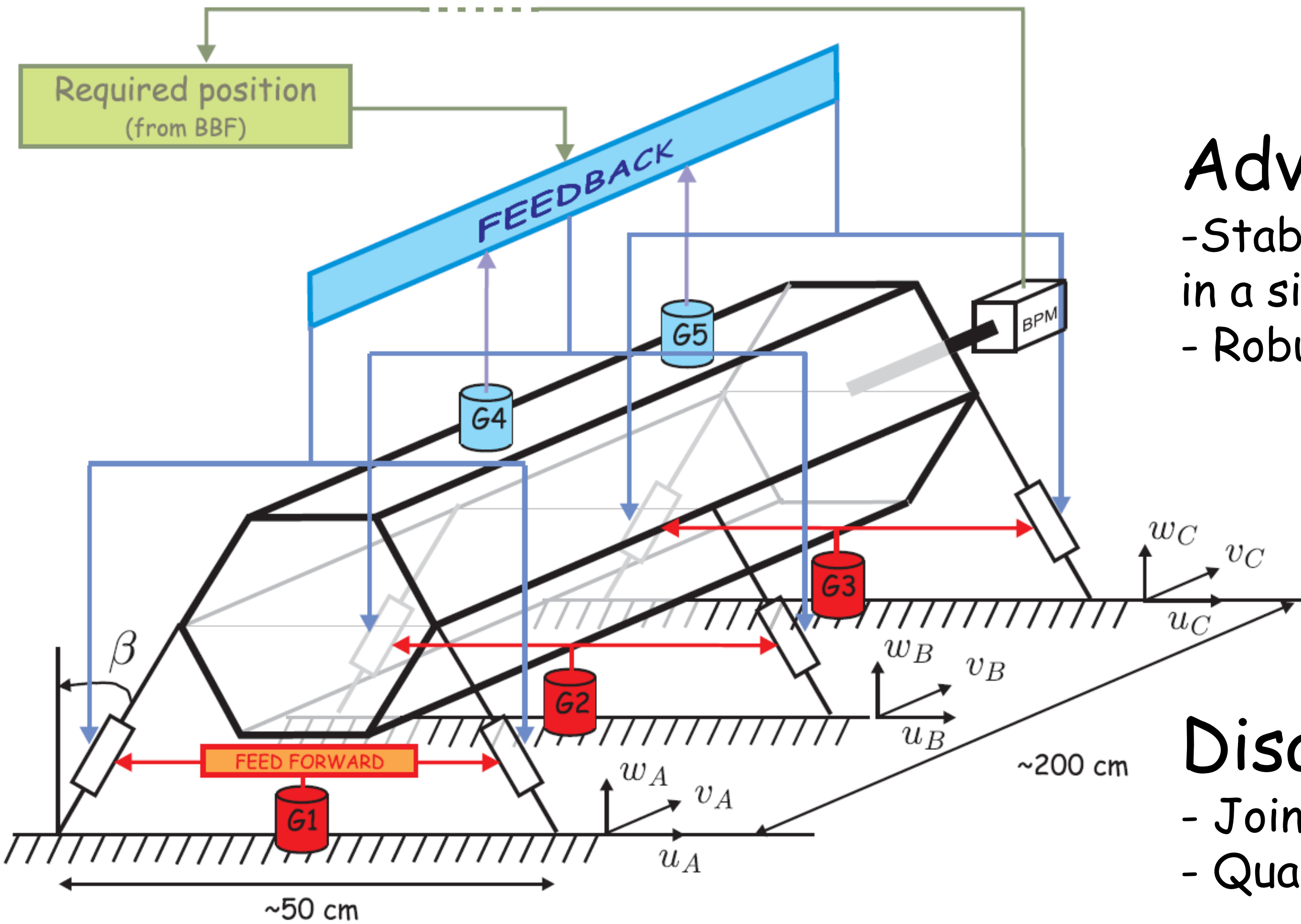
$$f_0 = 2\pi(Hz)$$

Low technical noise: $N_0 = 5*10^{-3}(nm^2/Hz)$

High technical noise: $N_0 = 50(nm^2/Hz)$



Hexapod concept

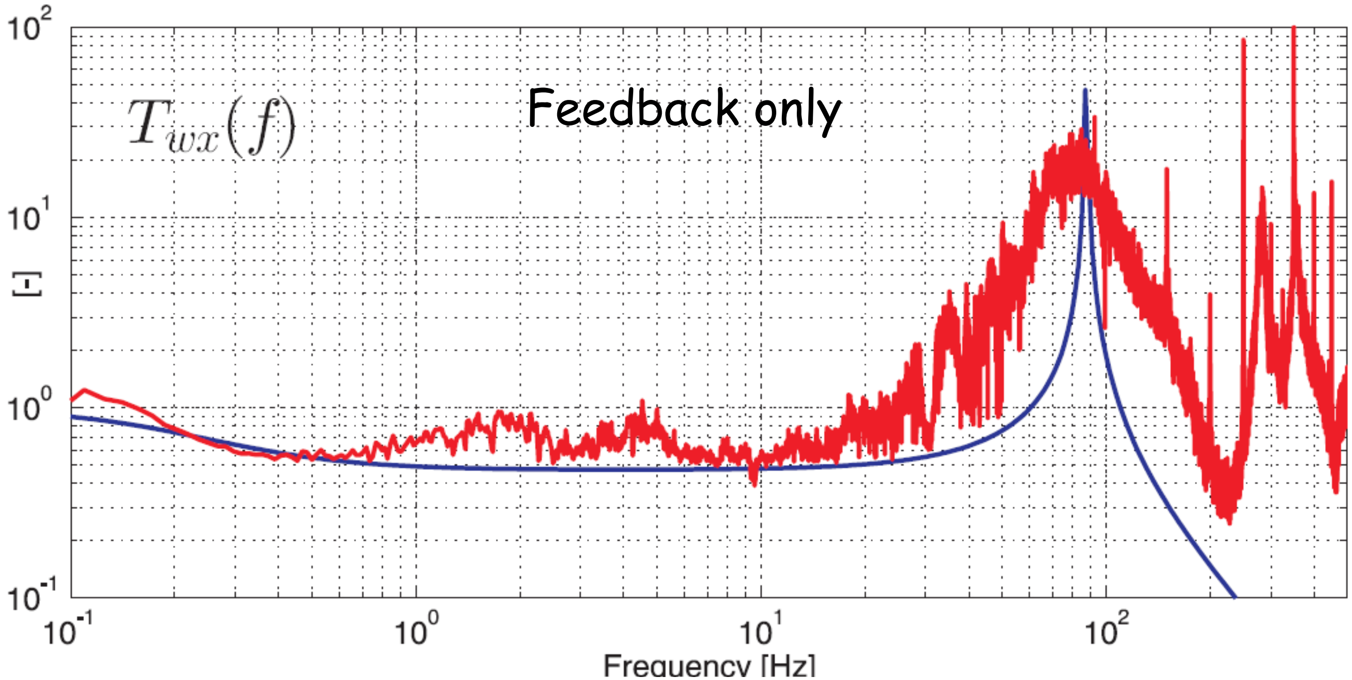


Advantages:

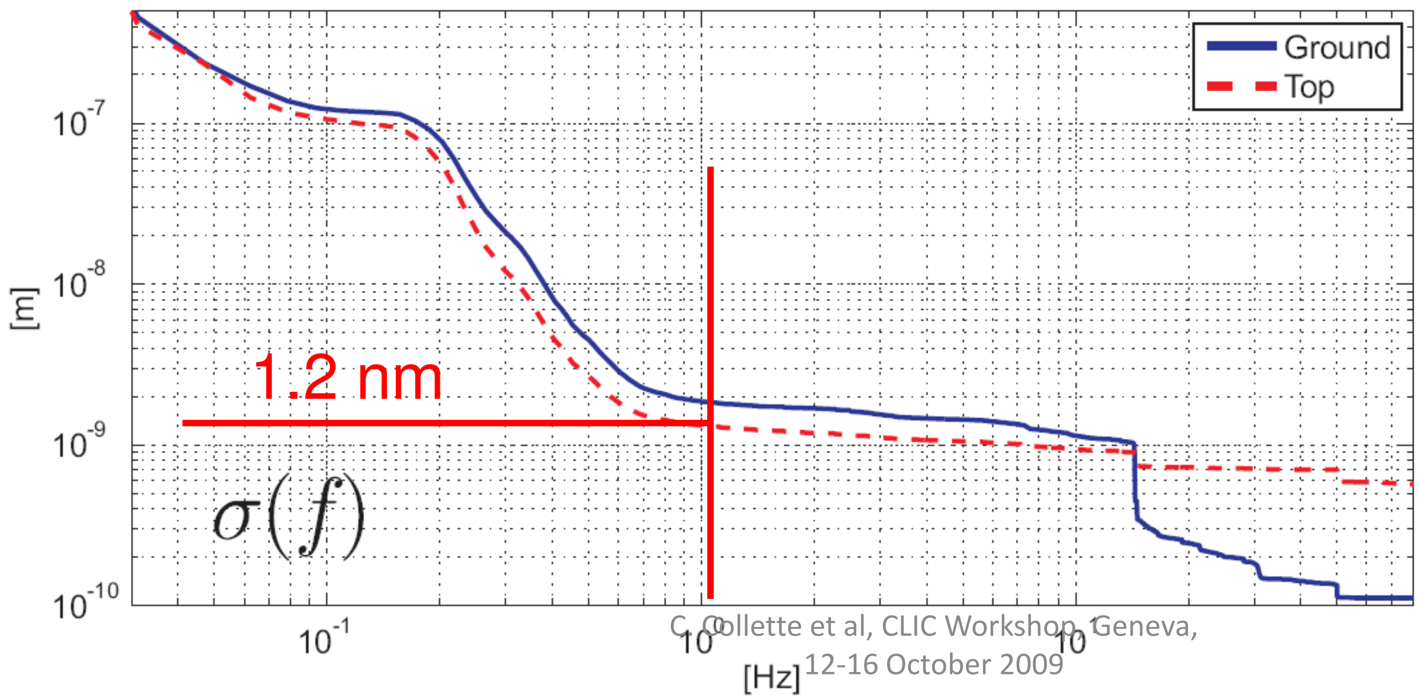
-Stabilization & Positioning in a single stage
- Robust to external forces

Disadvantages:

- Jointure issues
- Quadrupole flexibility



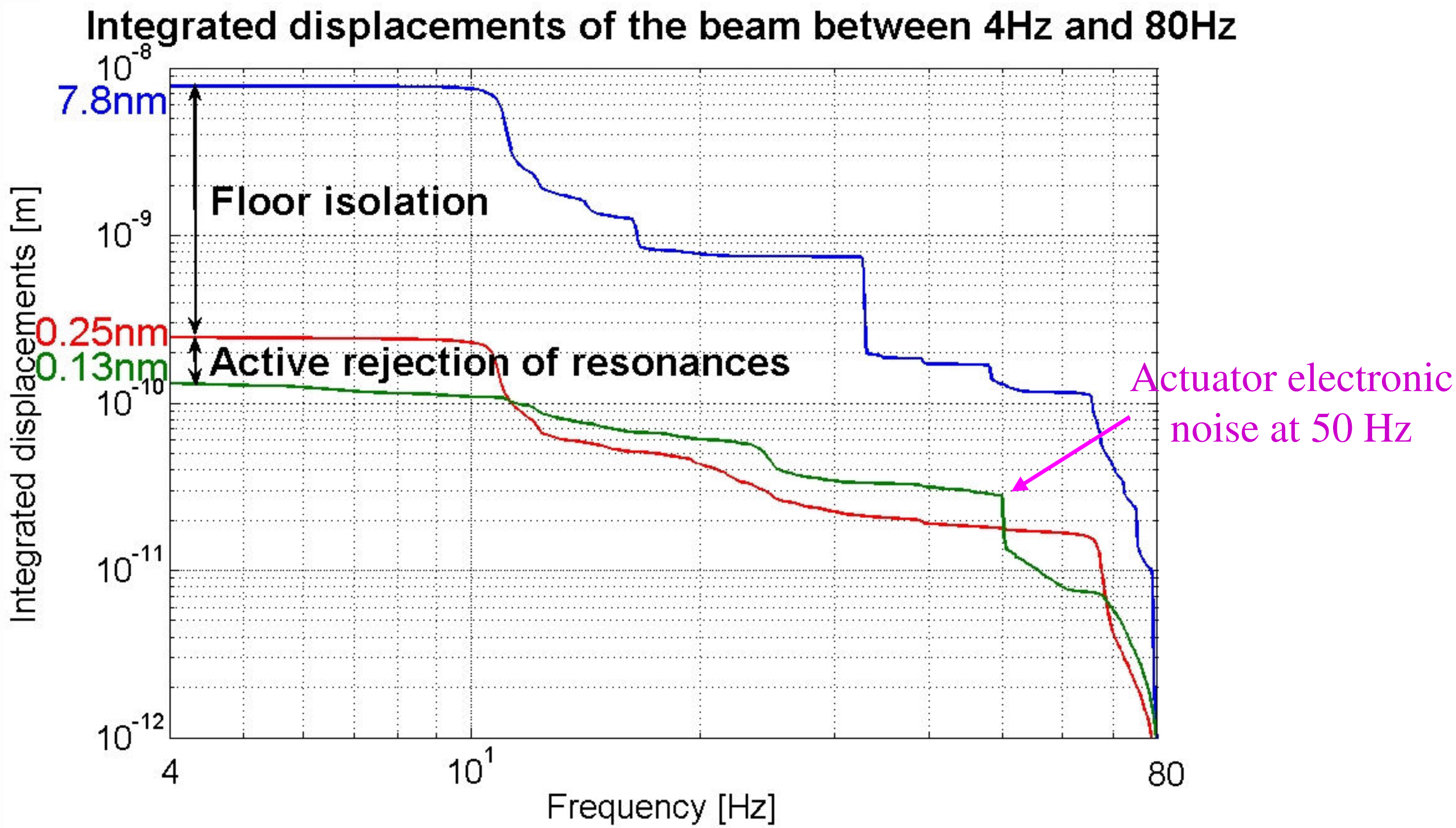
Results obtained in a quiet place (TT1)



Better results are expected with a more adapted hardware (resolution, noise…)

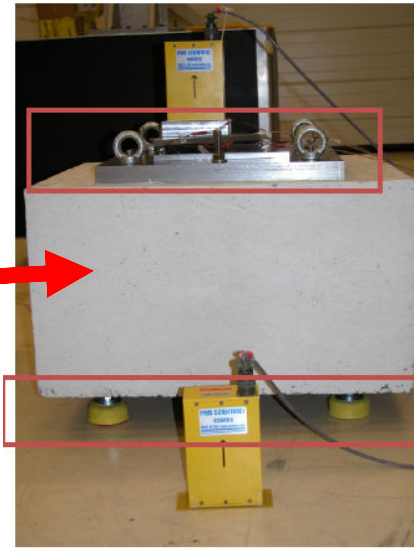
Tests with the large prototype

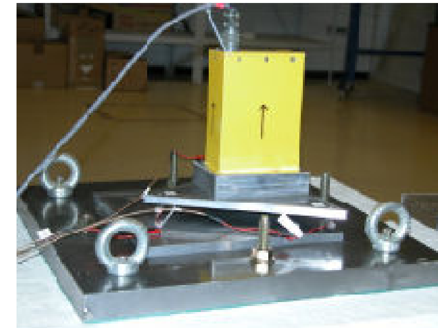
✓ **Results : integrated displacement RMS (with active table ON)**

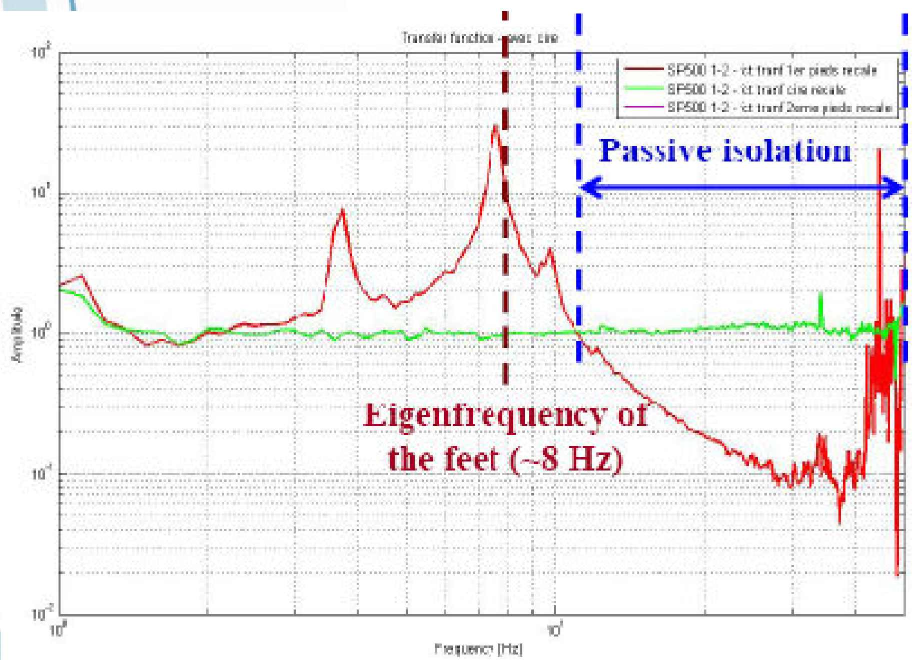


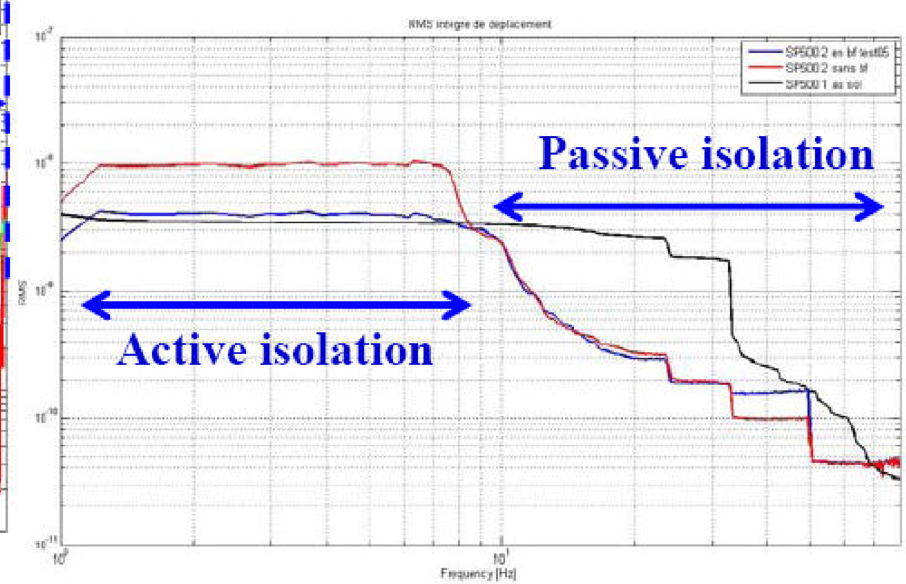
- No control
- With active isolation (TMC table)
- With active isolation (TMC table) and active compensation (PZT actuators)

Replace big TMC table by smaller device









There seems to be a consensus on:

- Mechanical stability in the nm-range can be improved by a factor 10 through active vibration control
- This means with typical ground motion levels of 3nm rms above 1 Hz the task is feasible for the MB quad, provided the additional technical noise is controlled.
- 10nm rms above 1 Hz was measured in the CMS cavern on the ground, close to 100 nm on top of the CMS detector.

  → the QD0 magnets can not be supported from the detector structure
- Interesting alternatives were proposed
  → see summary by A.Seryi
  For the CDR I (re)propose:

  plan A: L*= 3,5m with uttermost solid support structure for QD0
  plan B: L*~ 6m with shorter detector and QD0 in tunnel
  → Looking forward to the MDI review in January 2010

Idea of an adaptive controller for BBF

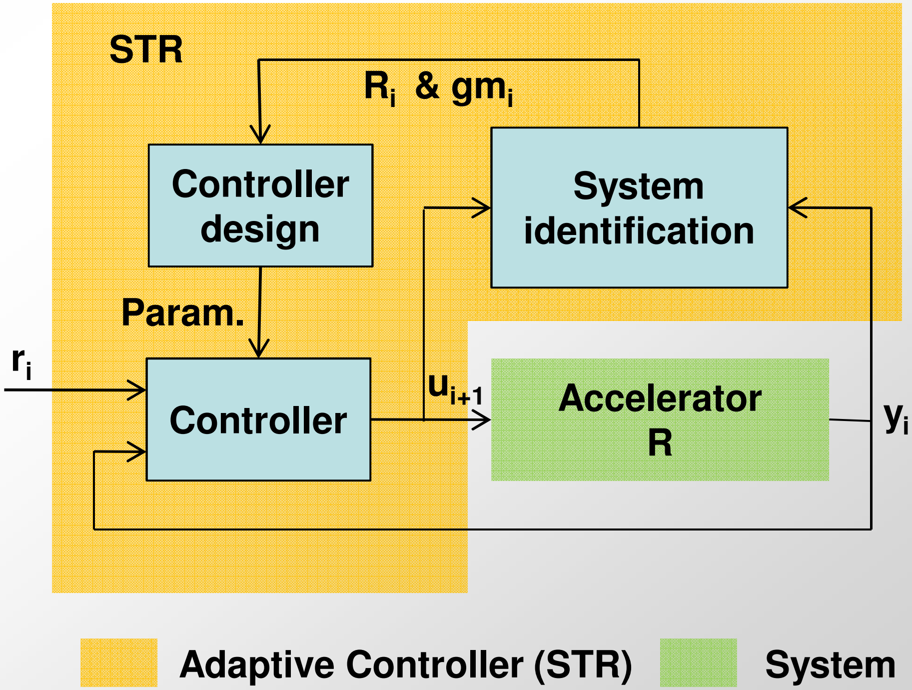
- Previous designs do not take into account system changes.

- **<u>Idea:</u>** Tackle problem of system changes by an online system identification

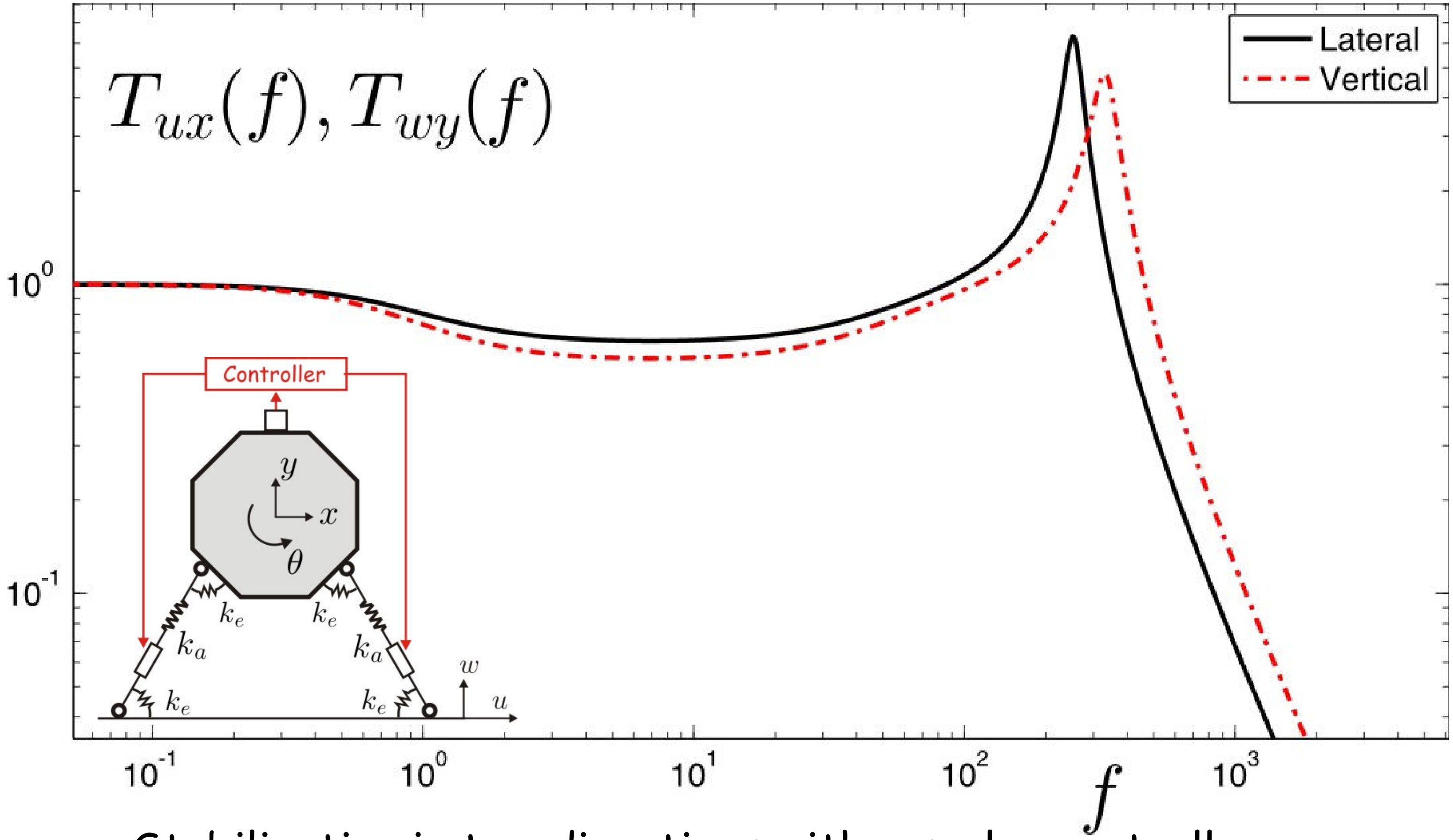
- Lear about the system by:
  - Input data
  - Output data
  - Guess about the system structure

- **<u>Usage:</u>**
  - For system diagnostics and input for different feedbacks (keep R as it was)
  - Input for an online controller design

- **<u>3 adaptive control schema [7]:</u>**
  - Model-Reference Adapt. Sys. (MRAS)
  - Self-tuning Regulators (STR)
  - Dual Control



Two legs



Stabilization in two directions with a scalar controller

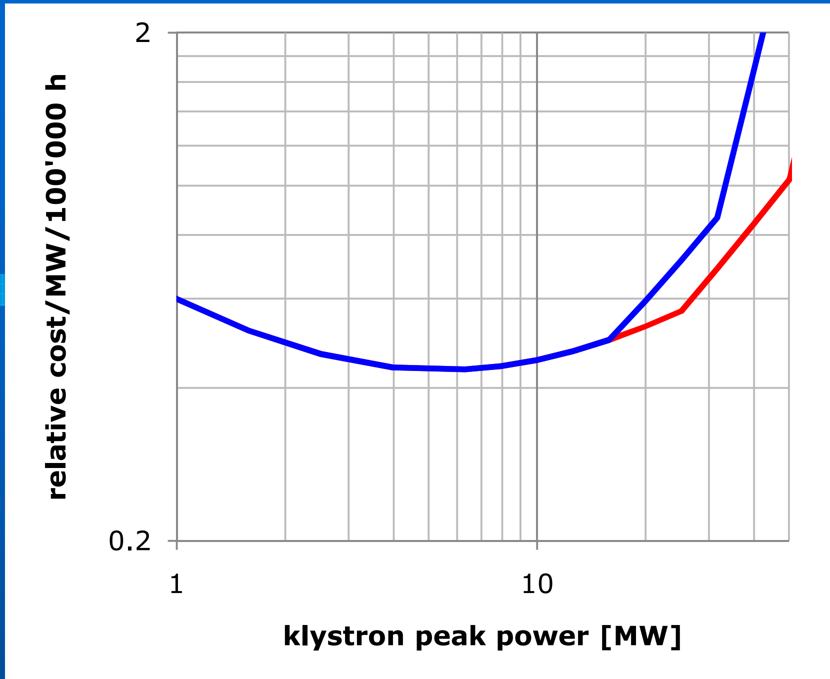
Summa Quads) Stability

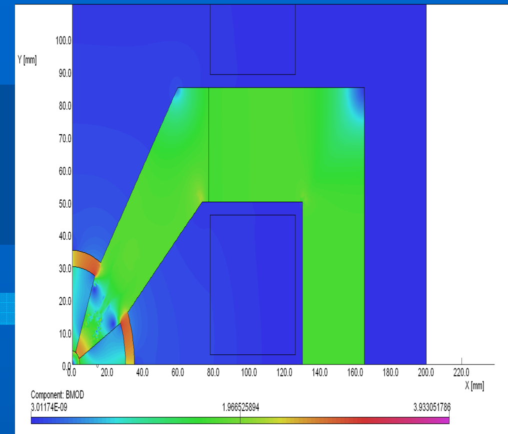
- MB quad tion has made good progress in 2009. The team is ts w asibility demonstration in 2010.
  on ed on CERN hexapod design: Why 6 inc en ers if only 2 degrees of freedom need to be co le ? → Stab. WG
- A ew for the options is proposed for late spring 2010:
  - entation details
  - es for the industrial noise
  - bility with BBF
- G gress in simulations of the controlers for BBF and MBQ s on.
  → ould now stop to separate the two processes by the arti al frequency of 1 Hz (4Hz) and make combined simulations.

  → CTC

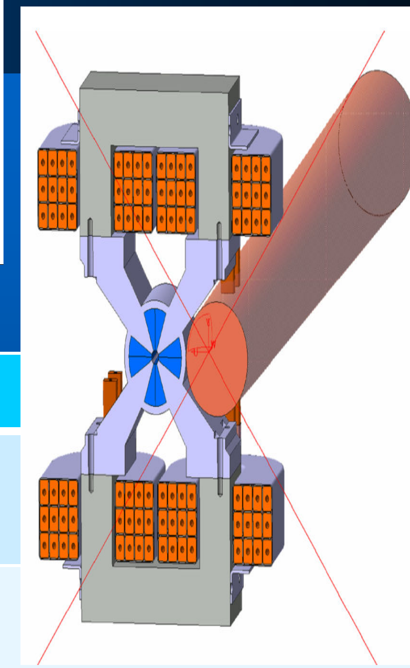
Individual contributions

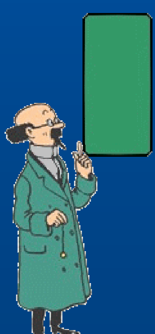
- **Drive beam Rf system : E.Jensen (CERN)**
- **Progress on QD0 magnet design: M.Modena (CERN)**
- **Solenoid compensation: B.Dalena (CERN)**
- **Crab Cavities: A.Dexter (Lancaster University)**
- **Tunnel Cross section: J.Osborne (CERN)**
- **Scheduling Issues: K.Foraz (CERN)**
- **Report from Cost WG: P.Lebrun (CERN)**
- **ILC rebalancing of general services: V.Kuchler (FNAL)**
- **IP Beam feedback: J.R.Lopez (JAI)**





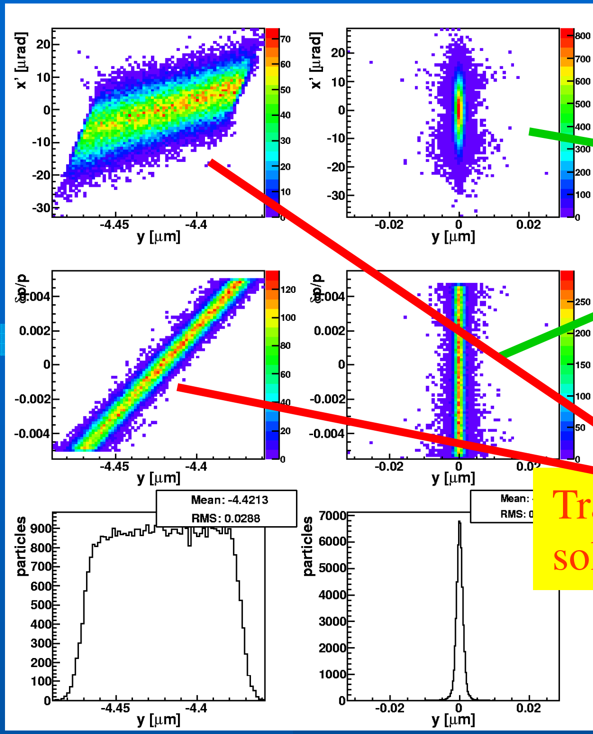
Grad [T/m] Sm_2Co_{17}	
Grad [T/m] $Nd_2Fe_{14}B$	





- For the CDR we will opt for an individual drive beam klystron power between 10…15 MW.

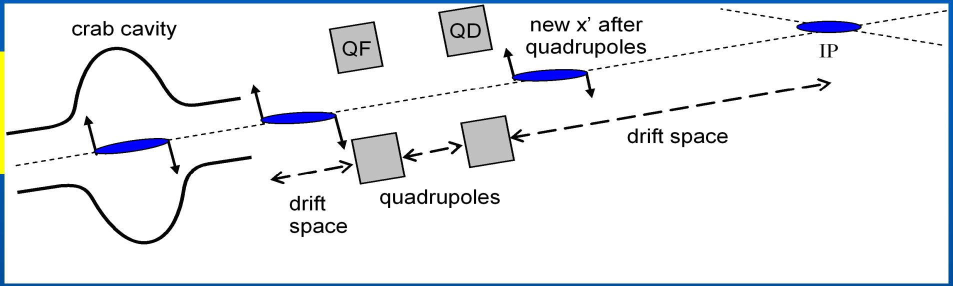
Good progress on PM design for QD0.



Tracking without solenoid

Tracking with solenoid

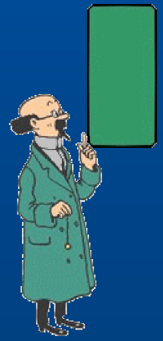
Crab Cavities



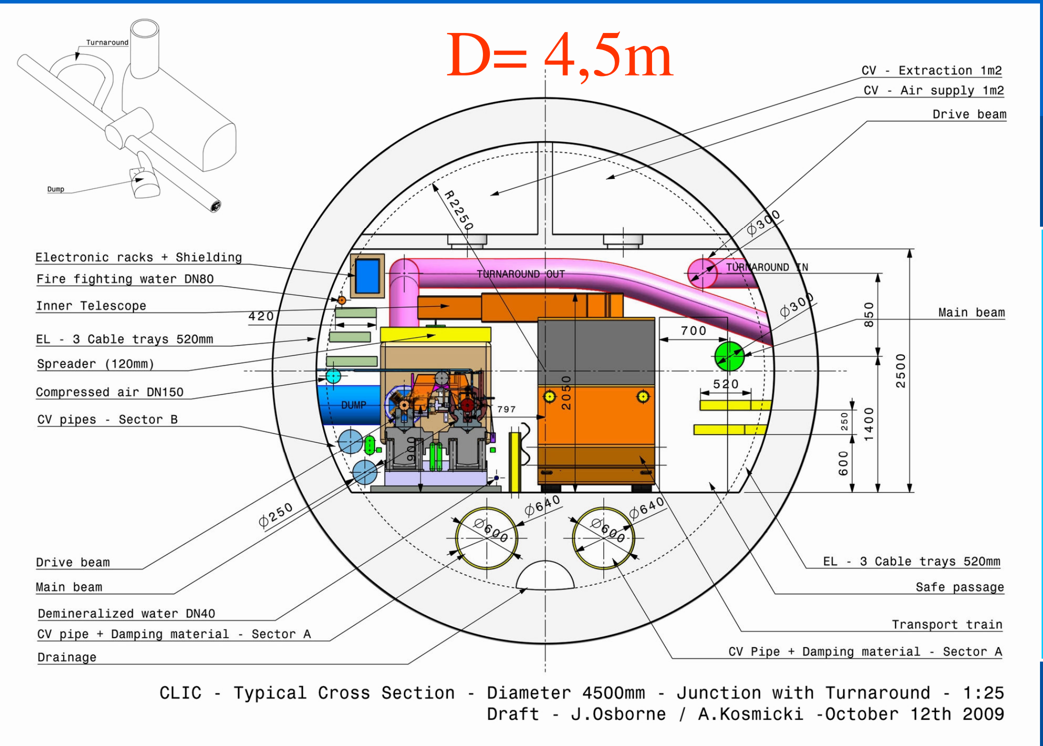
-Very challenging parameters for CLIC

-Impressive amount of work done

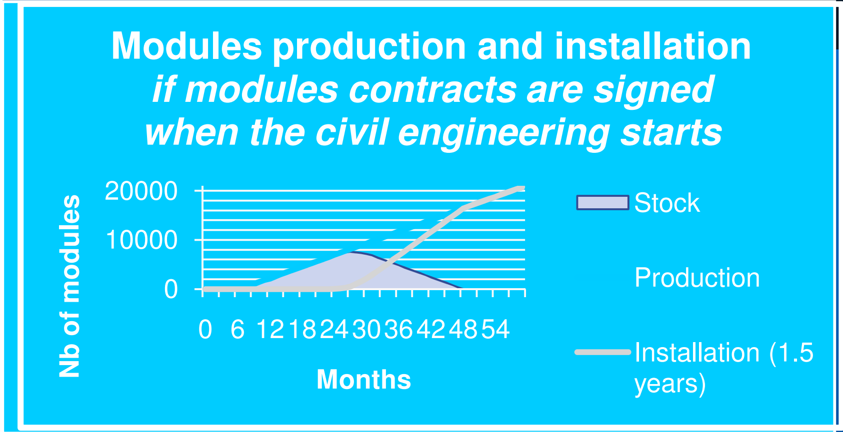
- Ready for CDR?

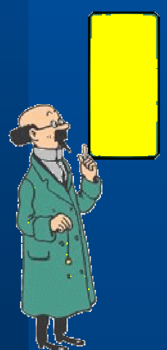


-Anti-Solenoid (bucking coils covering QD0) reduces (> 90%) the optical distortions at IP
- Interference with QD0 to be studied
- Radiation to be evaluated
- Main Solenoid field distortion in the tracker to be considered



Scheduling

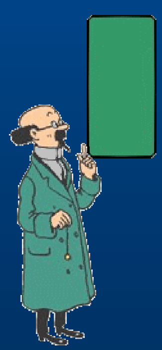




This is the tunnel cross section that we will use in the CDR

This is not yet the end of the story…

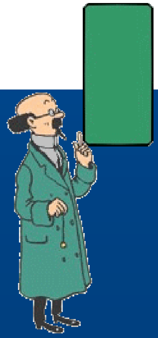
Very explicit worries about maintainability of equipment of the drive beam
Tunnel cross section is based on the assumption that the power dissipation to air can be limited to 150 W/m

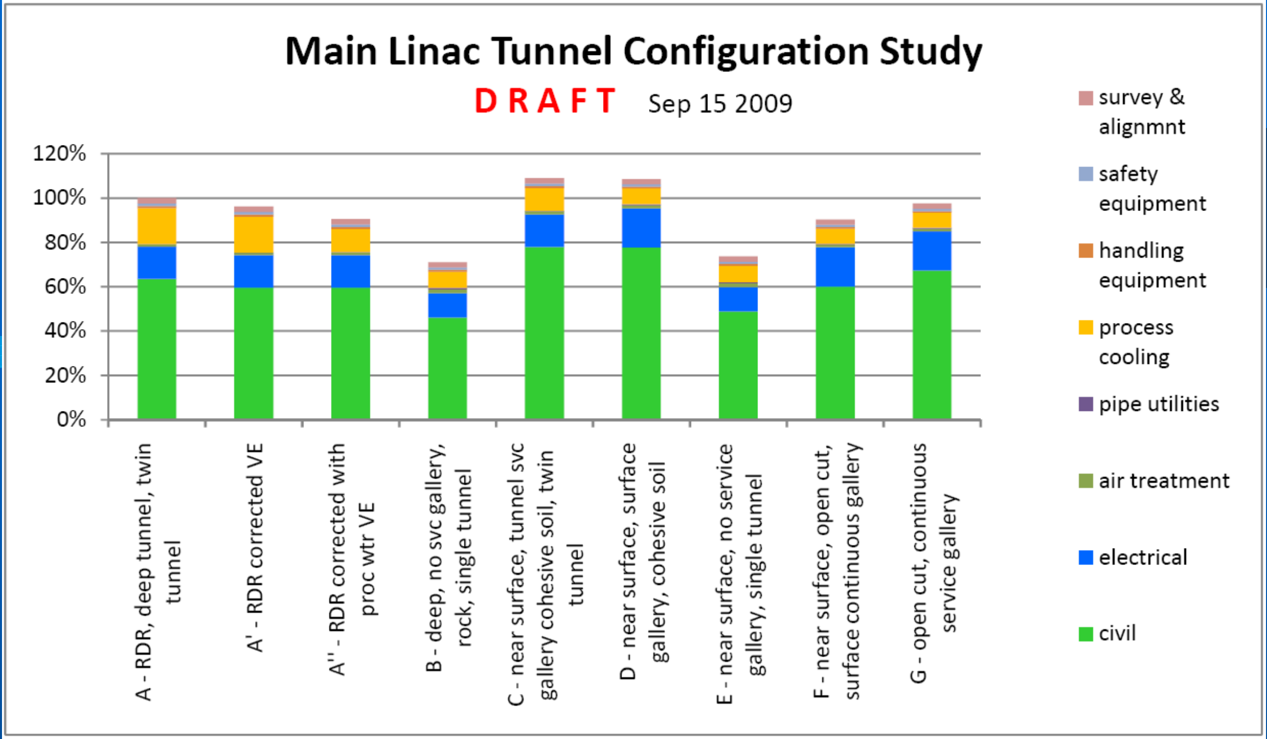


-Tools are ready to produce CLIC construction and commissioning schedule.

- Realistic data is needed for component production

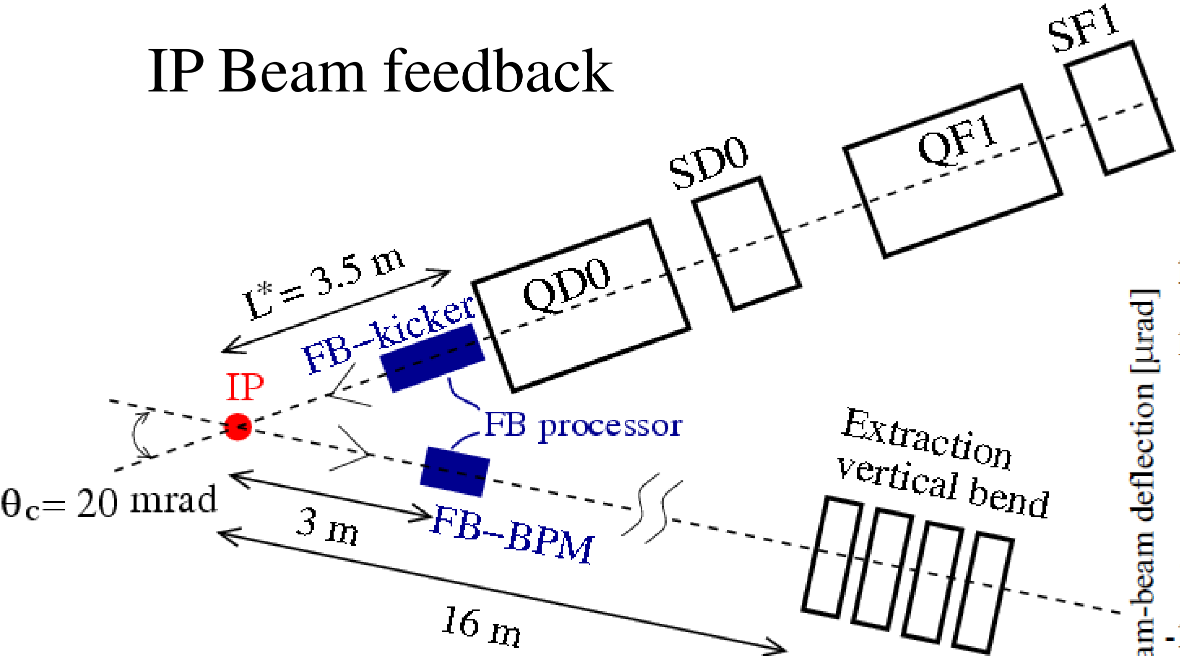
- CLIC Cost & Schedule (& Power/Energy) WG reorganized
- CLIC Study Costing Tool operational
- Methods for cost risk analysis and escalation established
- PBS of CLIC 3 TeV reorganized, PBS of CLIC 500 GeV established (CLIC TC)
- Analytical costing exercise of CLIC 3 TeV and 500 GeV started, based on updated PBS and expertise of PBS domain responsibles
  - Reporting September-November 2009
  - First iteration by end 2009
- Identification of cost drivers and cost reduction issuesFeedback to technical design on specific domains
- Good collaboration with ILC
  - Exchange of information: periodic meeting
  - Cooperation on specific topics, open information on others

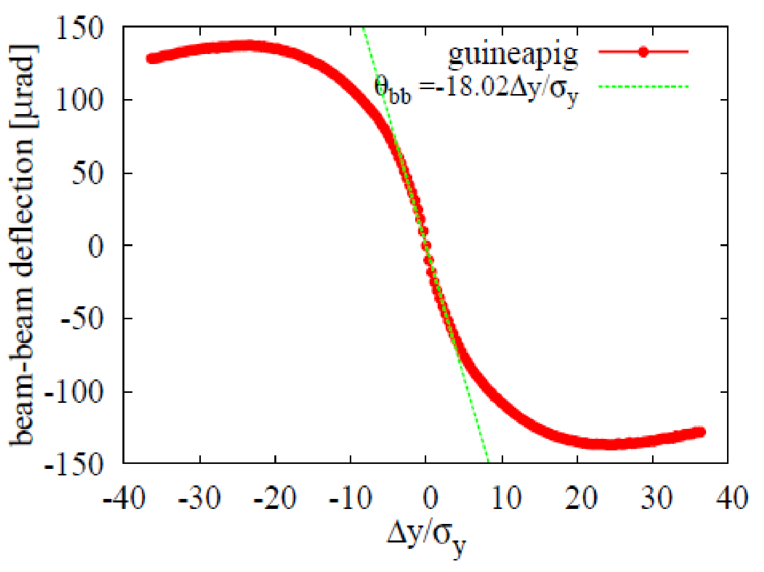


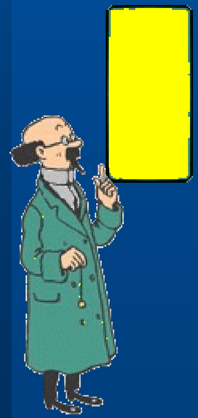


- Good collaboration between CLIC and ILC on general services
- Several studies on tunnel section and depth and klystron configurations for cost optimization.
- ILC seems to home in on a single 4.5 m diameter tunnel.
- Klystron configuration (power cluster vs distributed system) open

IP Beam feedback







- Potential gain for luminosity stabilization
- Almost straight forward for ILC, very challenging for CLIC
- Multi-input beam-beam deflection curve, only one observable, only one arithmetic operation possible (analog processor)
- Would be good to have a full simulation in the presence of BPM offsets and other processes driving luminosity jitter.
- Radiation hardness of equipment…occupancy of space within detector.

MB and DB phase alignment

- Phase alignment requirements
- Low DB and MB phase jitter
- Factor 10 gain out of real time feedback
- E.M. 12 GHZ phase monitor
- CLIC requirements for beam synchronous timing
- Results from Flash…preparations at DESY and PSI for their FEL projects

Presenters:

WG5: J.B.Jeanneret (CERN), A. Andersson (CERN), E.Jensen (CERN)

WG3: F.O.Ilday (Bilkent University), V.Arsov (PSI), M.Felber (DESY), F.Marcellini (Infn-int)

Tolerance on Phase and Gradient

- Luminosity and understanding/adjustment of the Beam Delivery and of the Final Focus

D.Schulte & R.Tomas, PAC09

$$\left\langle \frac{\Delta\mathcal{L}}{\mathcal{L}} \right\rangle = 0.01 \left[\left(\frac{\sigma_{\phi,coh}}{0.2^o} \right)^2 + \left(\frac{\sigma_{\phi,inc}}{0.8^o} \right)^2 + \left(\frac{\sigma_{G,coh}}{0.75 \cdot 10^{-3} G} \right)^2 + \left(\frac{\sigma_{G,inc}}{2.1 \cdot 10^{-3} G} \right)^2 \right]$$

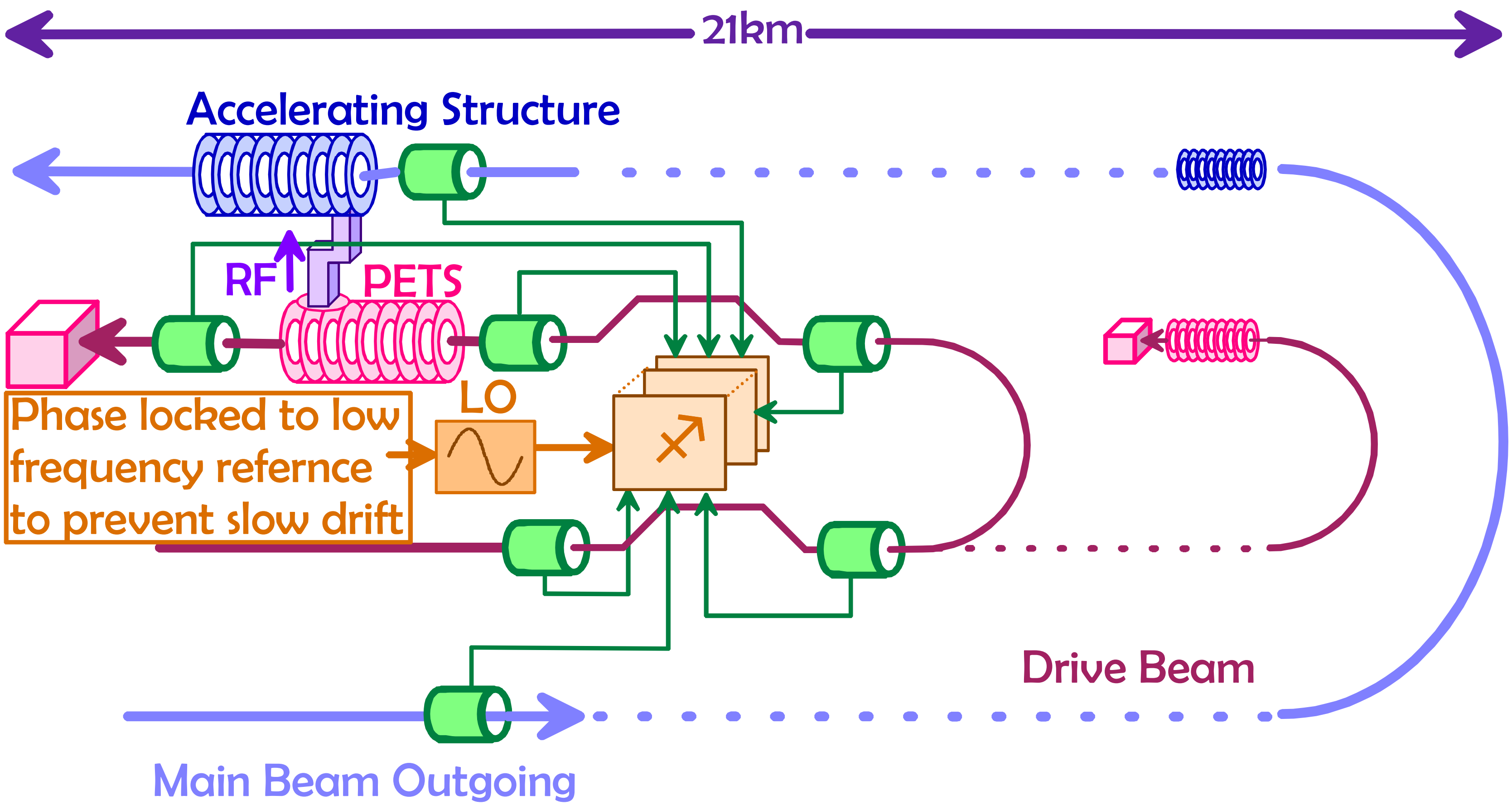
Overall cycle

DB intertrain (or sector to sector)

$$\delta\mathcal{L} \sim \delta_\phi^2 \text{ and } \delta_G^2$$

→ Not much margin on these

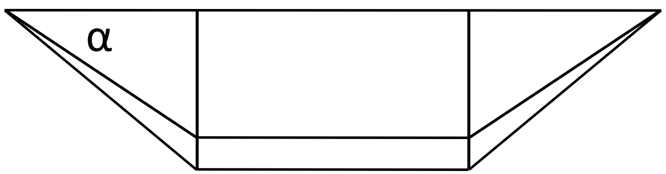
Phase measurements in CLIC



Phase control – II : data

$$\delta\phi = 0.2^o \ @f_0 = 12\mathrm{GHz} \ \equiv \ \delta z_{\mathrm{tol}} = 14 \ \mu \ \equiv \ \delta t_0 = 46 \ \mathrm{fs}$$

L_0 Chicane after TA



L_0 = 8m α = 0.1 rad

Tolerance on α :
- 1/10 δz_{tol}
- 4 magnets

$$\left\{ \begin{aligned} \Delta z_{\mathrm{chicane}} &= \alpha^2 L_0 \\ dz &= 2\alpha L_0 d\alpha \\ &\boxed{d\alpha = \frac{\delta z_{\mathrm{tol}}}{10\sqrt{4} \times 2\alpha L_0} = 4 \cdot 10^{-7}} \end{aligned} \right.$$

Use static magnets + variable deflectors for range $\delta\phi_r$=10°

$$\Delta\alpha_{\mathrm{defl}} = \frac{c}{2 f_0 \alpha L_0} \frac{\phi_r}{360} = 5 \cdot 10^{-4}$$

$$\Rightarrow \frac{\sigma_{\alpha,\mathrm{defl}}}{\Delta\alpha_{\mathrm{defl}}} = \frac{d\alpha}{3\Delta\alpha_{\mathrm{defl}}} = 3 \cdot 10^{-4} \ @ \ 1/\tau_{\mathrm{fill,MBAS}} = 30 \ \mathrm{MHz}$$

$$\Rightarrow \frac{\sigma_{\alpha,\mathrm{static}}}{\alpha_{\mathrm{static}}} = \frac{d\alpha}{3\alpha_{\mathrm{static}}} = 10^{-6}$$

All this being re-worked (less demanding)
F.Stulle, D. Schulte

Range inside which correction applies

relax for DB linac →

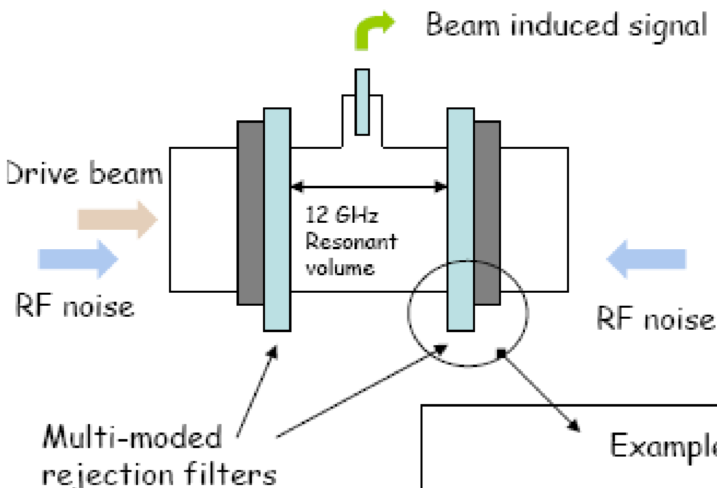
$$\delta z_{\mathrm{Linac}} \simeq 10\,\delta z_{\mathrm{decel}} \Rightarrow \delta\phi_{\mathrm{Linac}} = \frac{10}{12}\delta\phi_{\mathrm{decel}} \simeq 0.2^o \ @ \ 1\mathrm{GHz}$$

(Instead of 0.015°)

12 GHz low impedance noise-free pick-up concept

Igor Syratchev

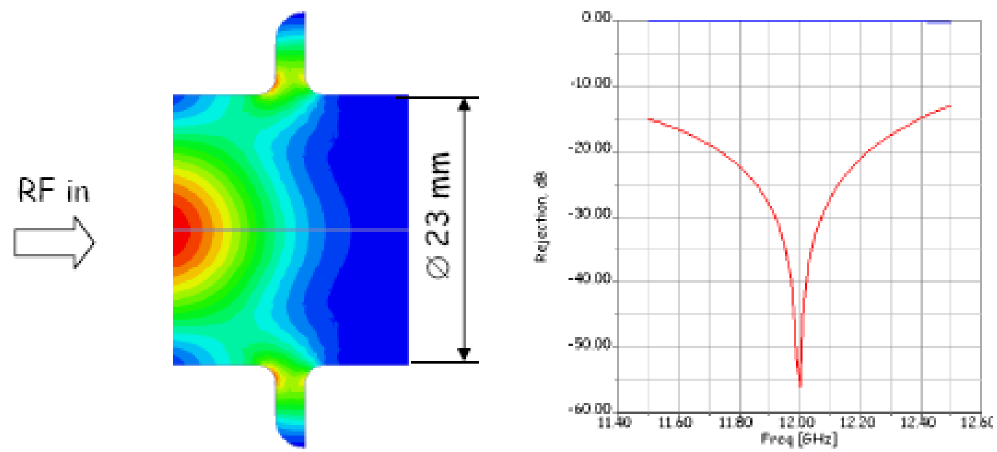
Schematic view of the 12 GHz pick-up concept



Considerations:

1. We have to keep big aperture of the pick up (I used 23 mm – similar to one in the PETS).
2. Low impedance!
3. The sensitivity of the device will depends on the RF nose rejection level
4. We need a resonant volume anyway (Q loaded to be defined)

Example: TM01 choke-type rejection filter



MB – DB phase feedback/feedforward

- Minimize phase jitter in both beams
- Gain factor 10 in phase jitter via RT feed-forward in DB turnaround
  Ingredients:
  E.M. Phase monitor → demonstration via Eucard 2012
  local oscillator with low phase noise: seems OK
  electronic phase detector
- stable turn-arounds
- precise and fast kickers for path lengthening

- In parallel correct slow drifts through feedback loop towards the beam sources

- DB-MB phase stability is a CLIC fe [illegible] !!

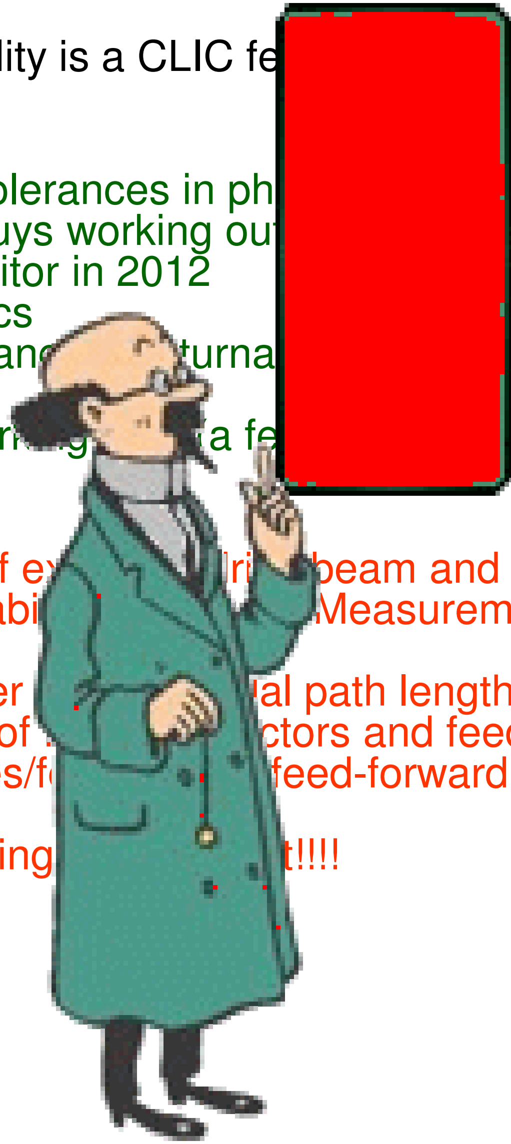
- What we have:
  - overall specs on tolerances in ph [illegible]
  - beam dynamics guys working ou [illegible] nized feedforward layout
  - an EM phase monitor in 2012
  - ideas for electronics
  - first guess of toleran [illegible] turna [illegible] ties

  - almost nobody wor [illegible] g [illegible] (a fe [illegible] rt time)

- What we need:
  - Full assessment of ex [illegible] ri [illegible] beam and mean beam phase stability and DB intensity stabi [illegible] Measurements on CTF3

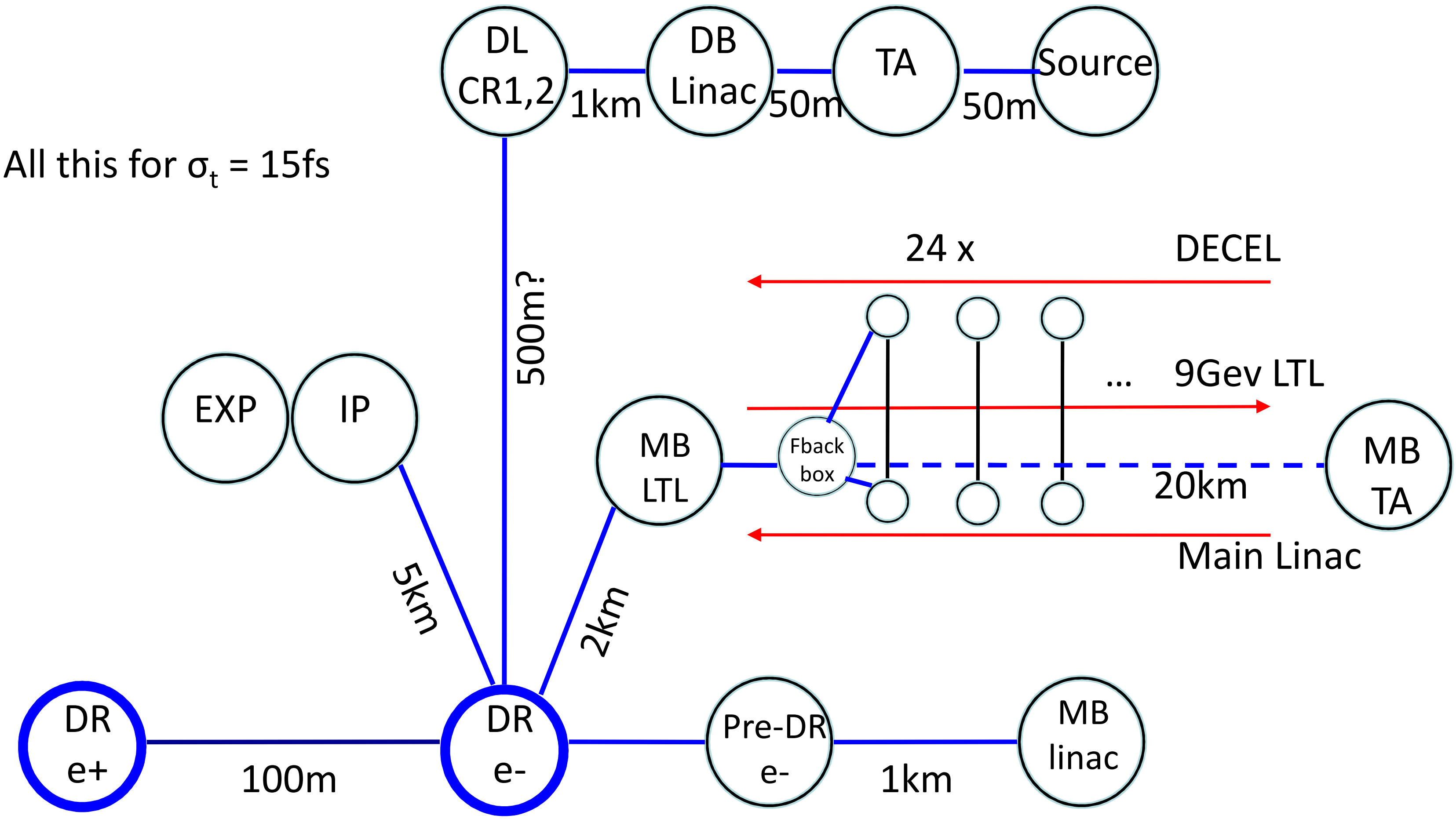
  - Evaluation of “other [illegible] al path length changes, temperature sensitivity….
  - electronics layout of [illegible] ctors and feed-forward chain
  - study on tolerances/f [illegible] feed-forward kickers

  - a small team working [illegible] t!!!!



CLIC will also need: Fast timing network

All this for σ_t = 15fs

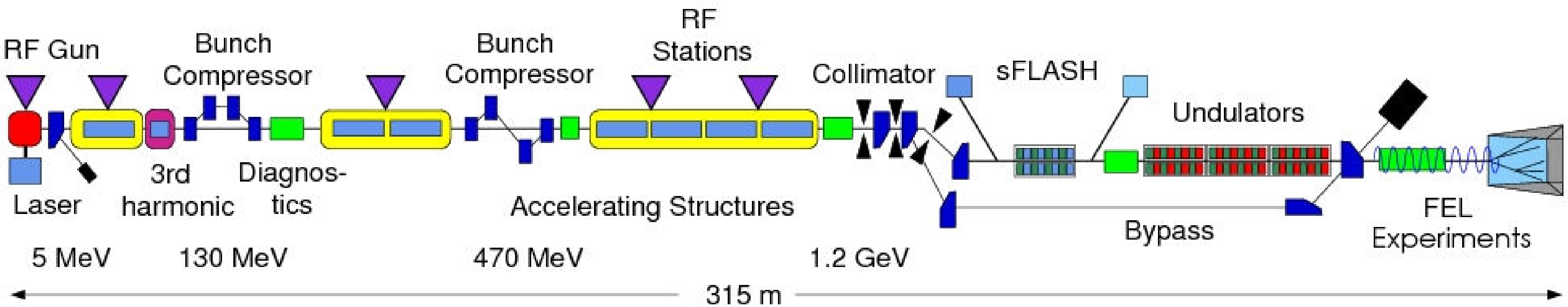


Here to synchronize the two complex
Tolrance : σ_t = 7.5fs

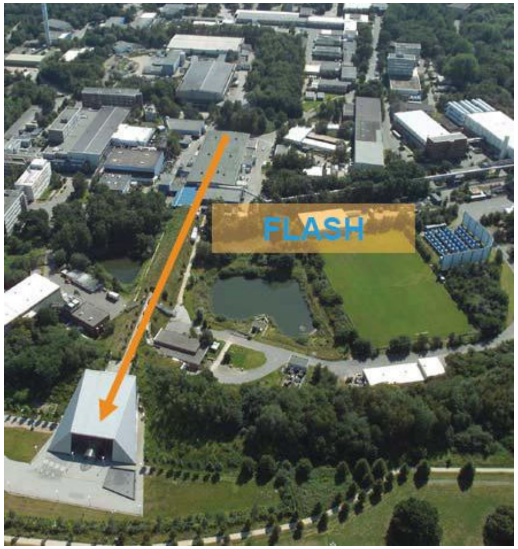
There is hope!

- Impressive preparation work at DESY and PSI for their FEL projects
- …but again, the reports from these preparations show how labor and R&D intensive this work is…
- CLIC can try to use several of these results and extrapolate to its needs:
  - reference clock distribution (1km → 30 km)
  - BAM = beam arrival monitor with 6 fs rms resolution based on optoelectrical elements (would probably work with the CLIC phase monitor)

FLASH – Free Electron LASer Hamburg

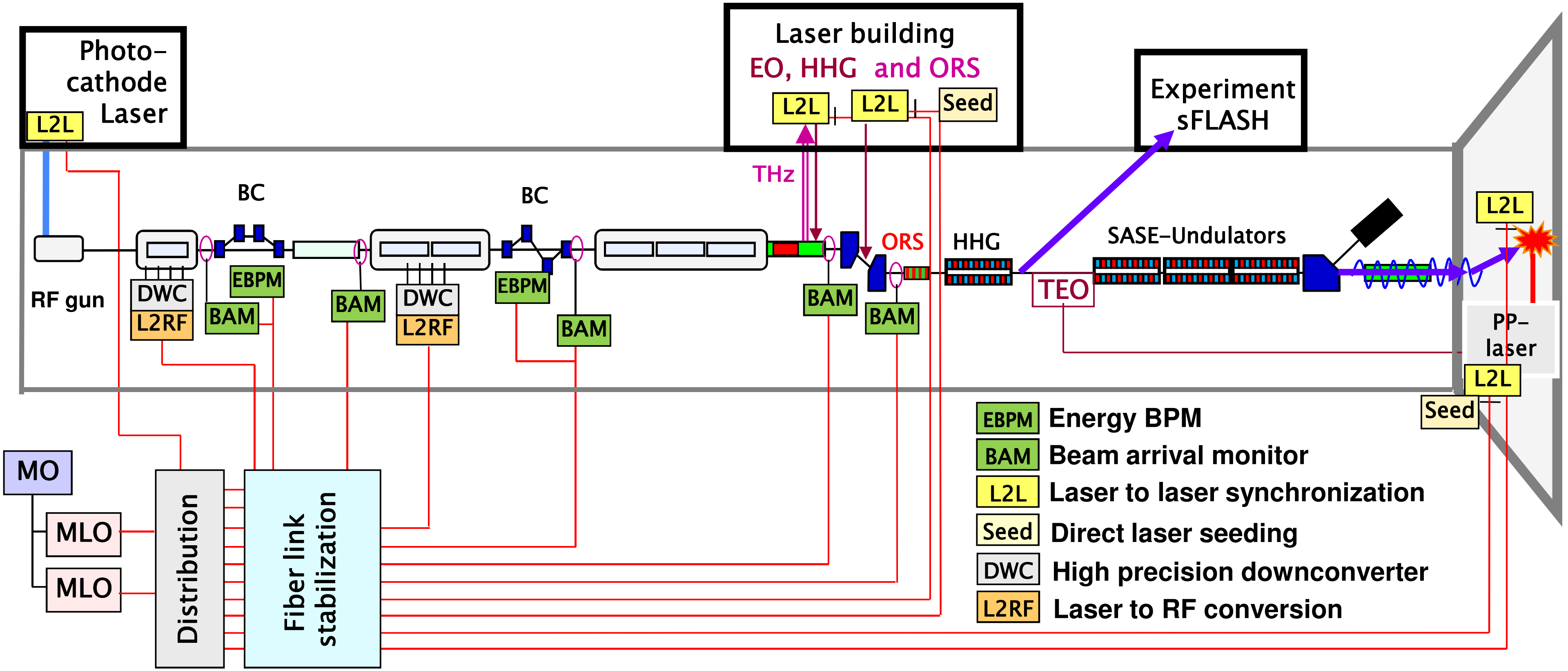


machine layout after shutdown: March 2010



- Started as test facility for the TESLA project
- Superconducting cavities at 1.3 GHz (~25 MV/m)
- 3rd Harmonic Module at 3.9 GHz
- Two dispersive sections for high peak currents
- First user facility for VUV and soft X-ray laser pulses
- Photon pulses have few 10 fs length
- Pump-Probe experiments require synchronization on a 10 fs scale

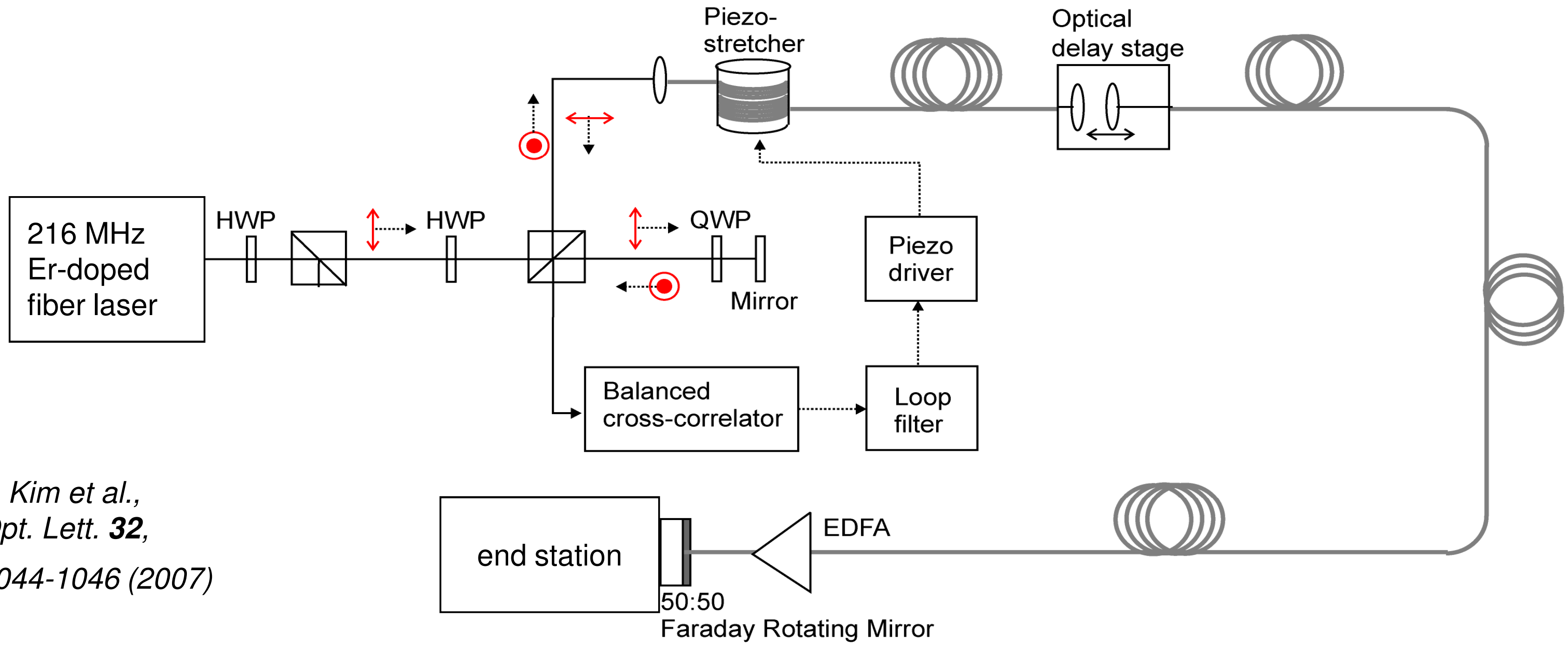
Schematic of the optical synchronization system at FLASH



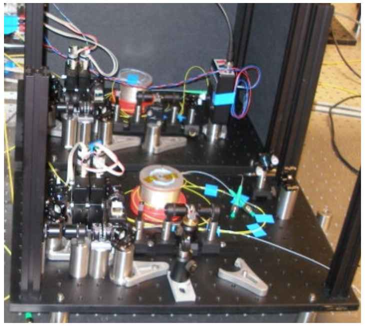
- beam based feedback stabilization of arrival-time
- high precision synchronization of lasers
- synchronization of all timing critical devices (up to 14)

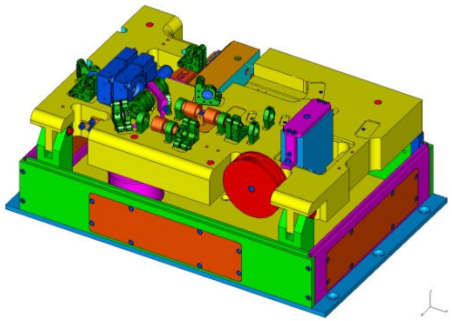
➔ Point-to-point synchronization ~ 10 fs rms (< 30 fs rms to beam)
➔ Permanent operation and long term stability / availability investigation

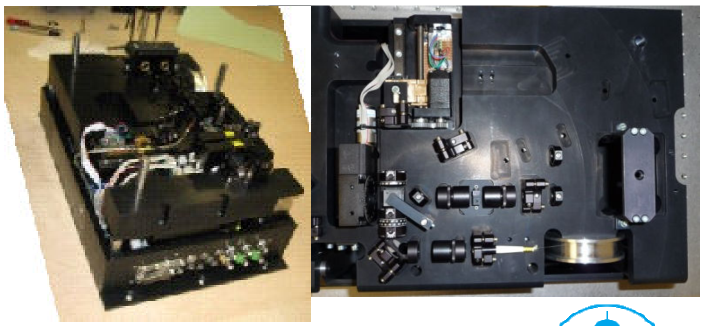
Fiber link stabilization



J. Kim et al.,
Opt. Lett. ***32****,*
1044-1046 (2007)



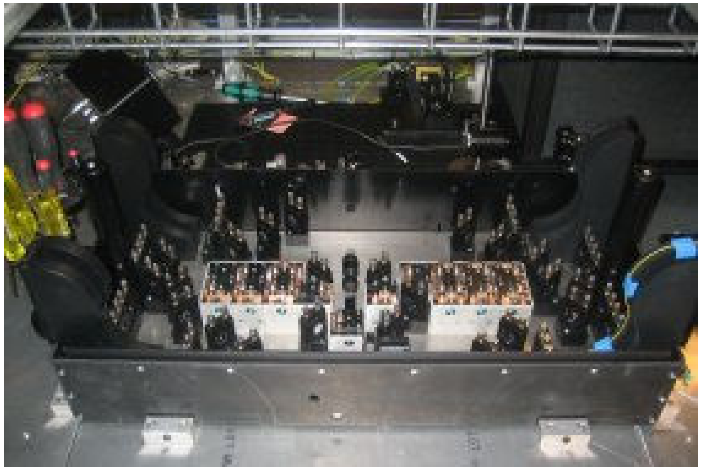


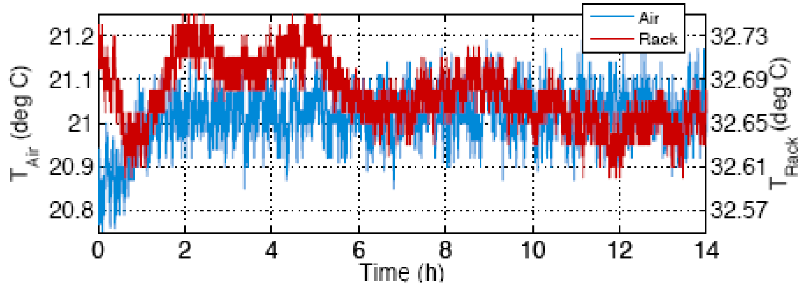


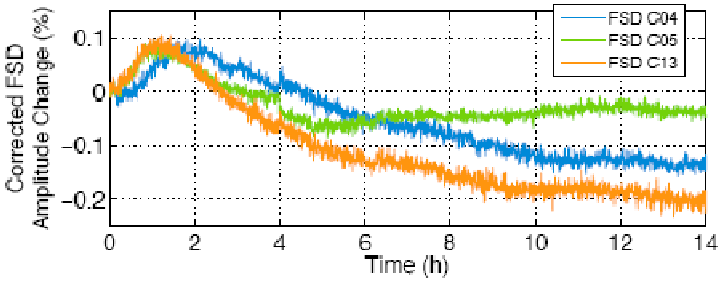
Courtesy F. Loehl

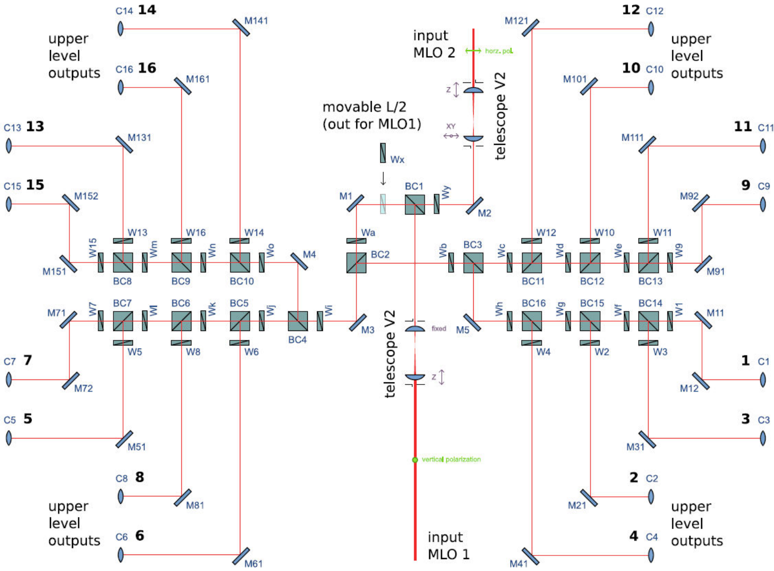
Distribution to up to 16 outputs

> Properties
  - baseplate made of Invar
  - two free space inputs, 16 collimator outputs
  - same pathlength for each output
  - 4-5 mW per output
  - ~ 85% incoupling efficiency at all collimators



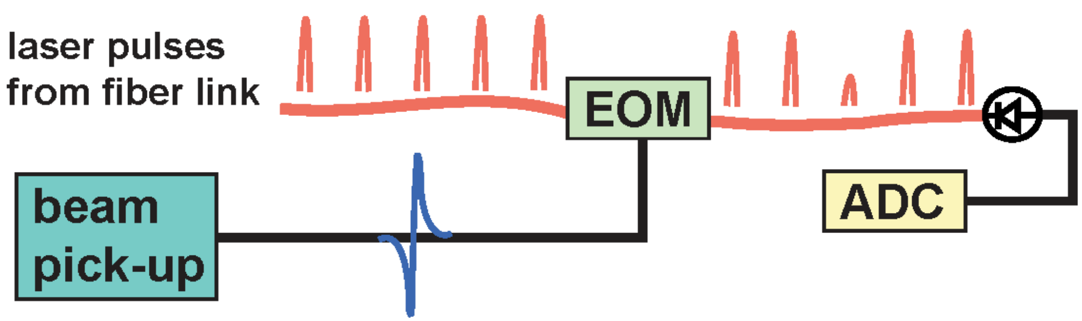


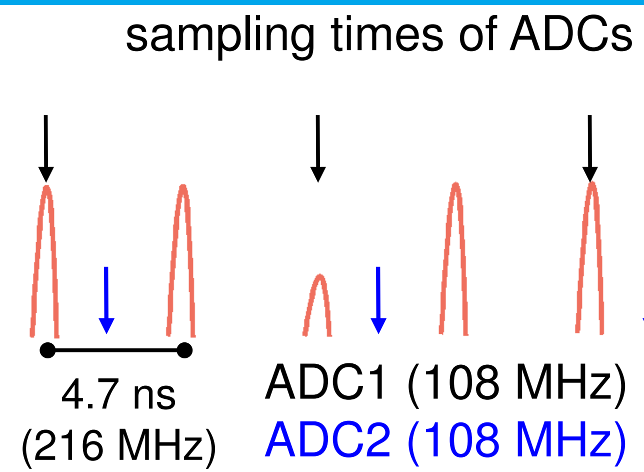


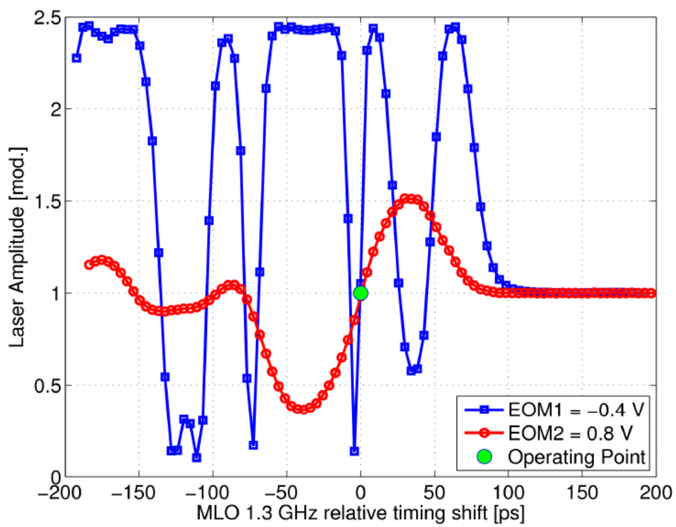


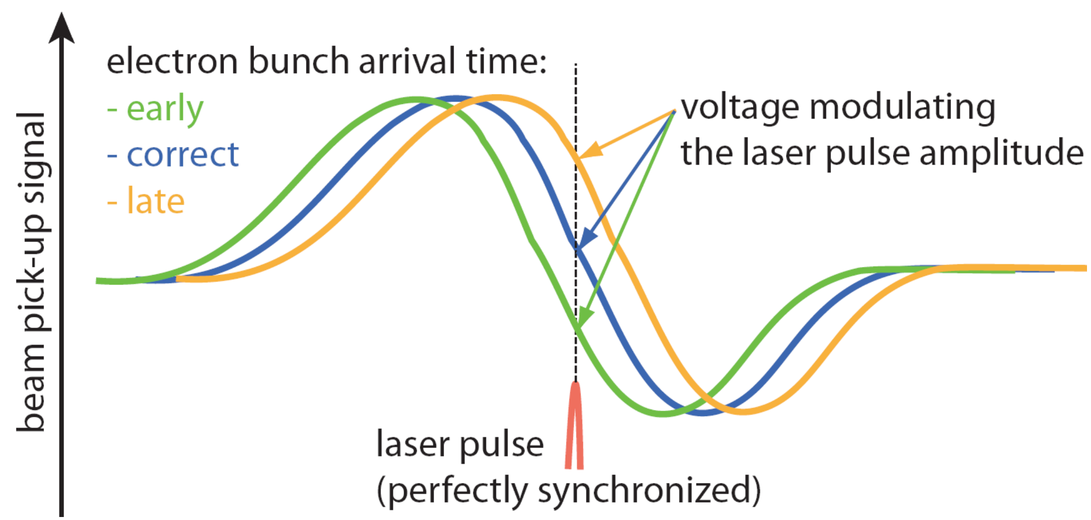
S. Schulz, FEL09, WEPC72

Beam arrival-time monitor (BAM)





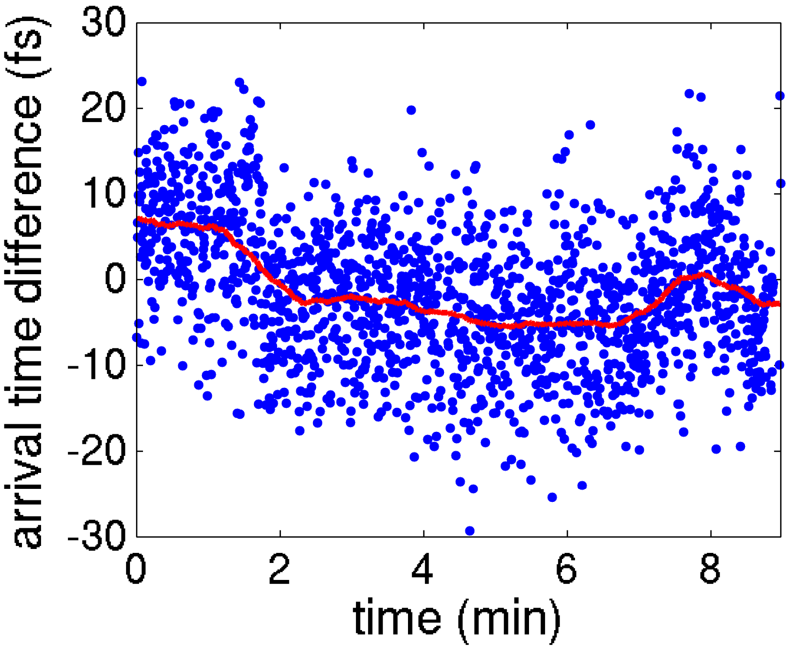


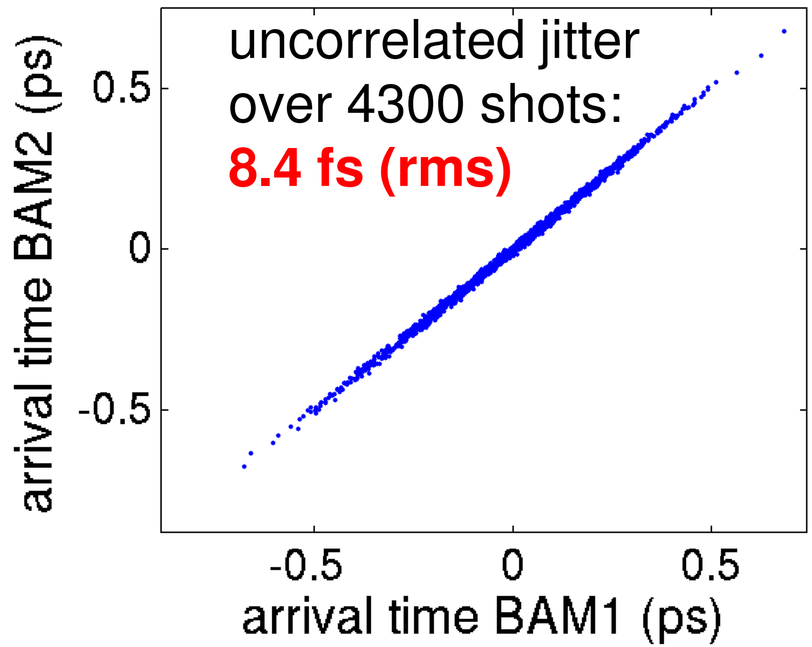


M. Bock, FEL09, WEPC66
F. Loehl, PhD thesis, DESY-THESIS-09-031, 2009

Patented 2006 by DESY

Arrival time correlation between two BAMs





Arrival time difference contains:

- high frequency laser noise (~3 MHz – 108 MHz)
- stability of two fiber links
- two BAMs

Single bunch resolution of entire measurement chain: **< 6 fs (rms)**

F. Loehl, PhD thesis, DESY-THESIS-09-031, 2009