Beam Instrumentation at the Accelerator Test Facility 2

Stewart T. Boogert on behalf of ATF2 international collaboration instrumentation groups

Talk introduction

- Introduction to Accelerator Test Facility 2 (ATF2)
- Beam position diagnostics
  - Cavity beam position monitors (CBPMs)
    - Examples of measurements and usage at ATF2
  - Interaction Point BPMs (IPBPMs)
- Feedback systems (using stripline and CBPMs)
- Transverse beam size and emittance
  - Optical transition radiation monitors
  - High resolution optical transition radiation
  - Laserwire scanners
  - Interaction point laser interference fringe monitor (IPBSM)
- Conclusions and remarks

ATF2 goals

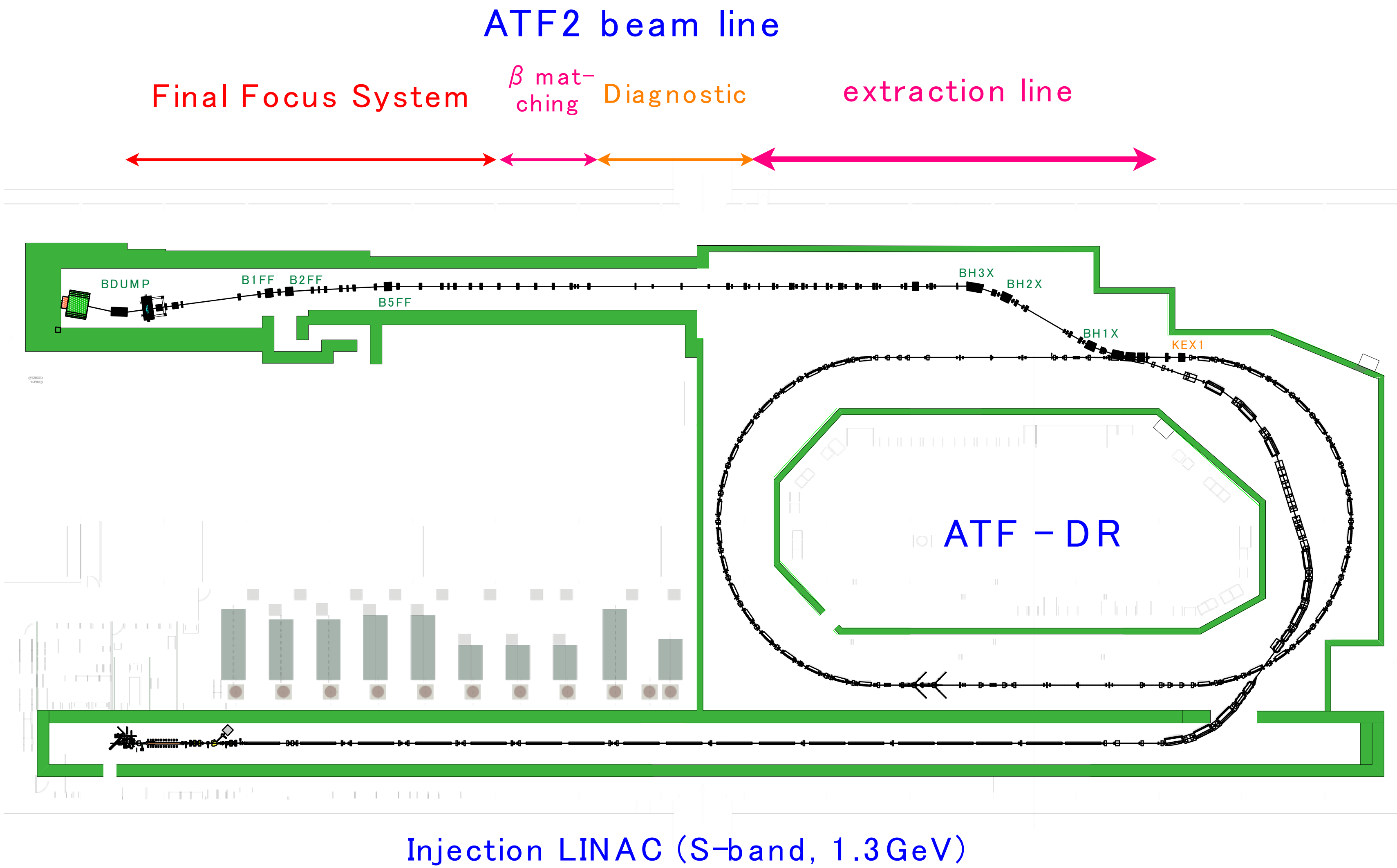
- Goal 1
  - Achievement of 37 nm vertical beam size
    - Demonstration of a new compact final focus proposed by P. Raimondi and A. Seryi in 2000
    - Maintaining of the small beam size (several hours at the FFTB/SLAC)
- Goal 2
  - Control of the beam position
    - Demonstration of beam orbit stabilisation with nano-metre precision at IP
    - Establishment of beam jitter controlling techniques at nano-metre level

ATF2 international collaboration

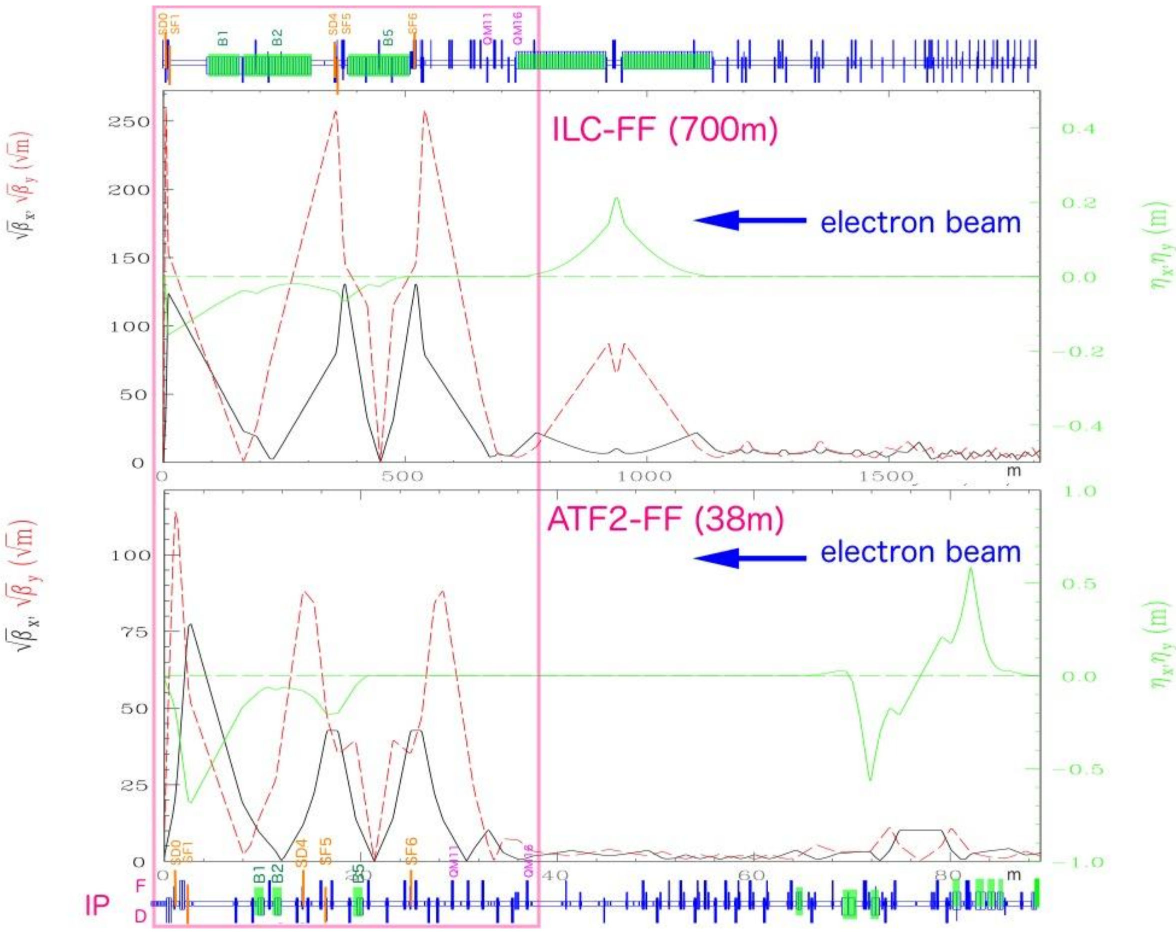
ATF Main Institutes

- CERN
- Germany
  - DESY
- France
  - IN2P3; LAL, LAPP, LLR
- UK
  - Univ. of Oxford
  - Royal Holloway Univ. of London
  - STFC, Daresbury
  - Univ. of Manchester
  - Univ. of Liverpool
  - Univ. College London
- Italy
  - INFN, Frascati
- Spain
  - IFIC-CSIC/UV
- Russia
  - Tomsk Polytechnic Univ.
- Japan
  - KEK
  - Tohoku Univ.
  - Univ. of Tokyo
  - Waseda Univ.
  - Nagoya Univ.
  - Kyoto Univ.
  - Hiroshima Univ.
- China
  - IHEP
- Korea
  - PAL
  - KNU
- India
  - RRCAT
- USA
  - SLAC
  - LBNL
  - FNAL
  - LLNL
  - BNL
  - Cornell Univ.
  - Notre Dome Univ.

ATF/ATF2 overview



ATF2 optics

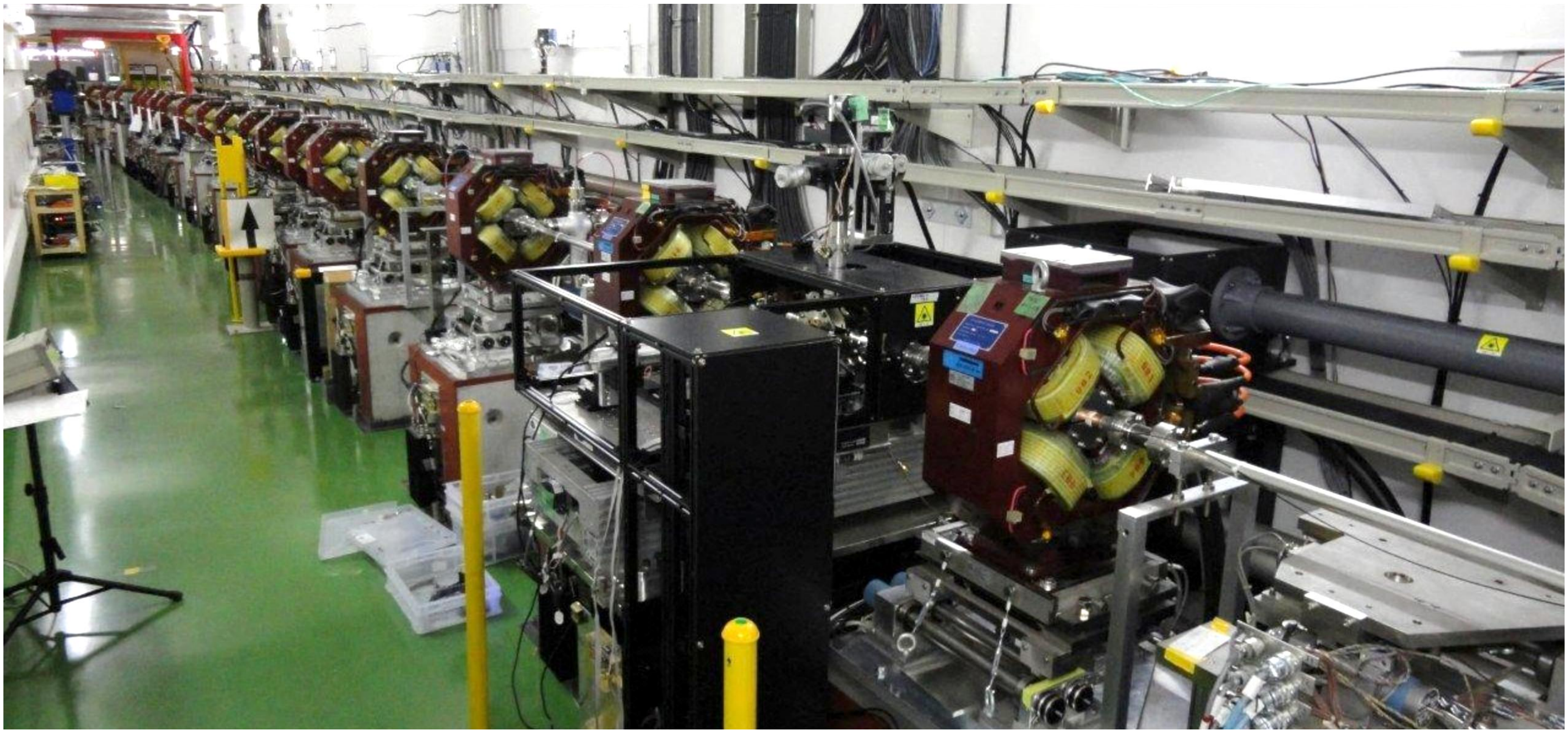


Energy scaled Raimondi-Seryi FFS optics

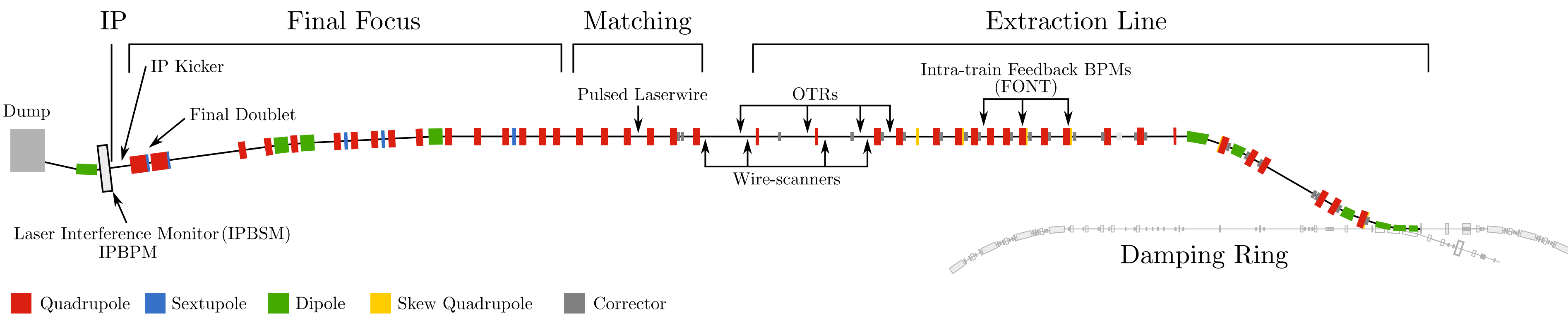
- Focus vertical size 37nm at *interaction point*
- Local chromaticity correction
- Relies on design dispersion in FF
- Preserve low emittance from ATF ring (12 pm.rad)
- Compact ~ 38 m

ATF2 view down towards focus

Interaction point | Final focus | Matching

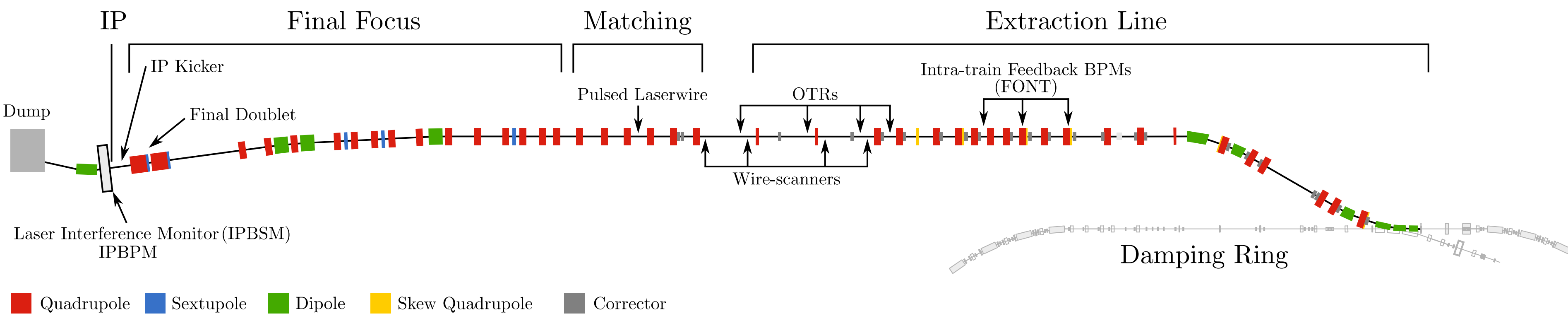


ATF2 beam instrumentation (goal 1)



- Cavity BPMs (KEK/KNU/PAL/JAI)
  - 35 C-band BPMs, 2 S-band, 2 IP C-band
- Multiple Optical transition radiation monitors (SLAC/IFIC)
  - 4 monitors
- Interaction point beam size monitor (Tokyo University, KEK)
  - Laser interference pattern Compton scattering

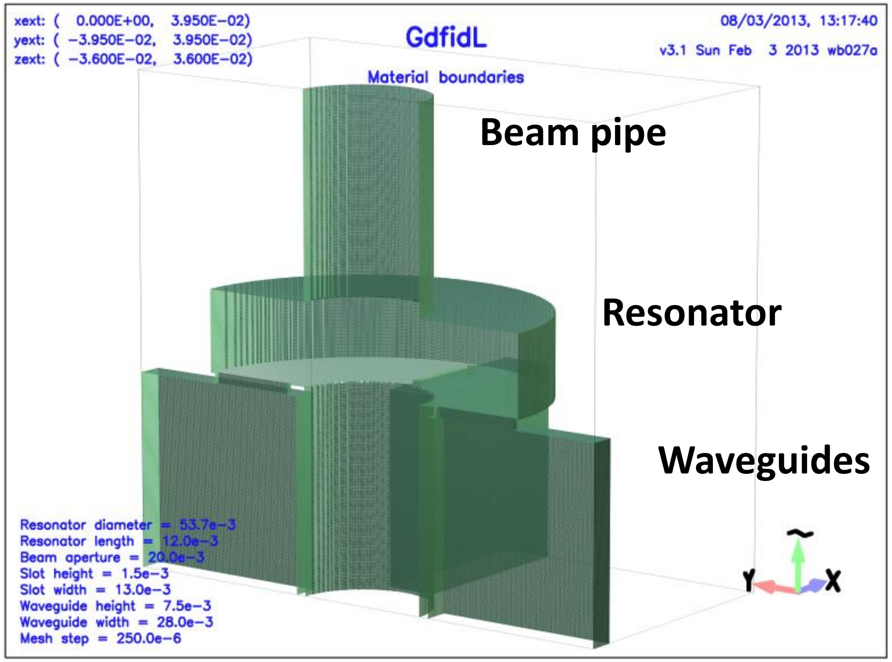
ATF2 beam instrumentation (goal 2)



- High resolution OTR (JAI/CERN/Tomsk PU/KEK)
  - Based on two lobe visibility of OTR point spread function
- Upstream (position and angle) and IP (position) feedback (JAI-Oxford)
  - High speed, low latency digital feedback
  - Interaction point BPMs (KEK/KNU/JAI-Oxford)
- Laserwire transverse beam size monitor (JAI)

CBPM : Design and principle of operation 1

- Most CBPMs are cylindrical cavities using dipole mode
  - Two orthogonal polarisations
  - Rectangular waveguides to suppress monopole mode
  - Symmetric couplers
  - Two beam apertures, C- and S-band.
  - IP C-band BPMs rectangular (see later)

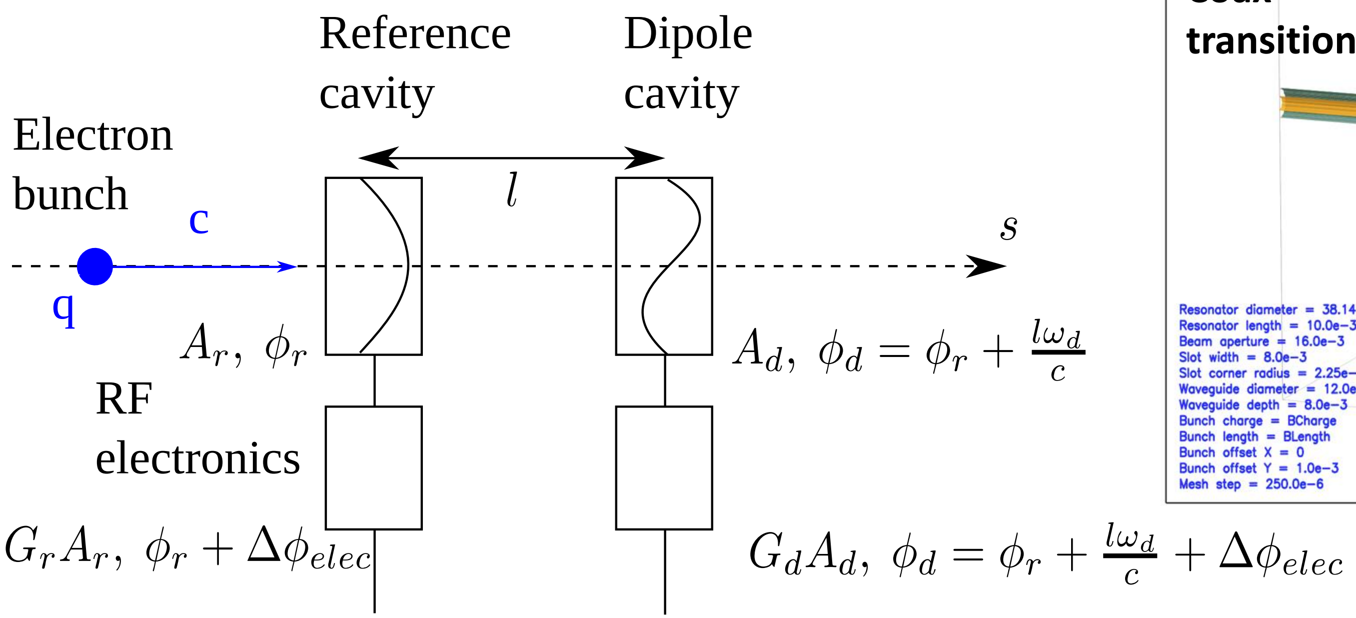


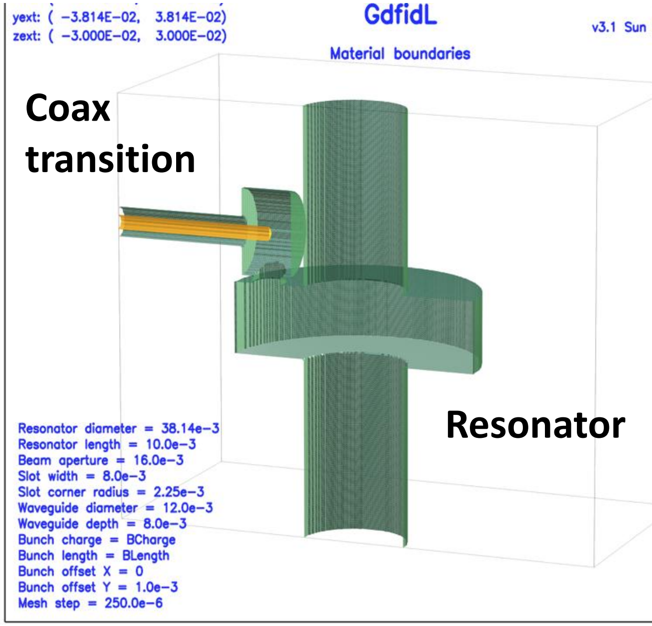
$$V(t) = q\, e^{-t/\tau - i\omega t}(S_d d + S_{d'} d' e^{\pi i/2} + S_\theta \theta e^{-\pi i/2})$$

Cavity voltage output | Charge | Dipole mode angular frequency | Displacement | Trajectory angle | Bunch tilt

CBPM : Design and principle of operation 2

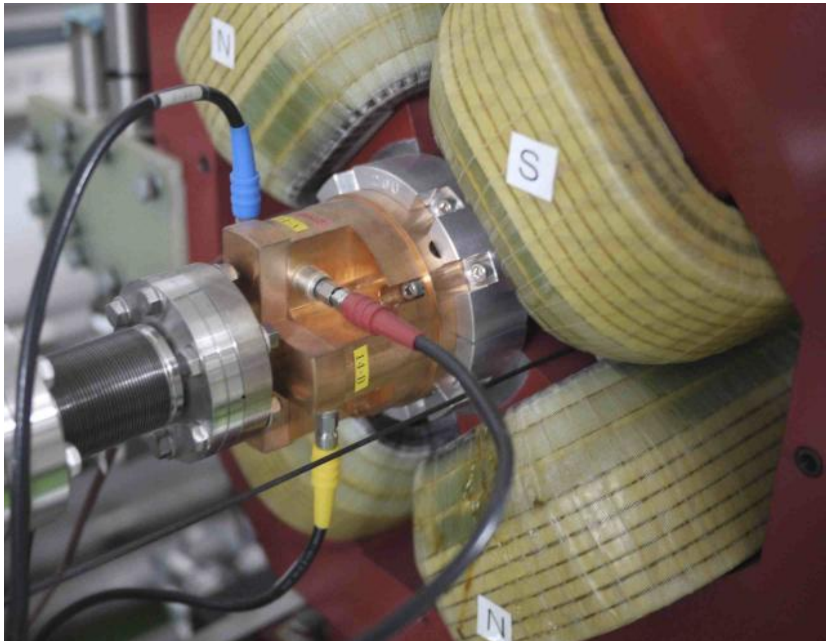
- Dipole signal proportional to q•y at some phase
- Need a *reference* cavity to monitor charge and phase
  - Use monopole mode of cavity at same frequency as dipole mode
  - Monitor beam charge and phase



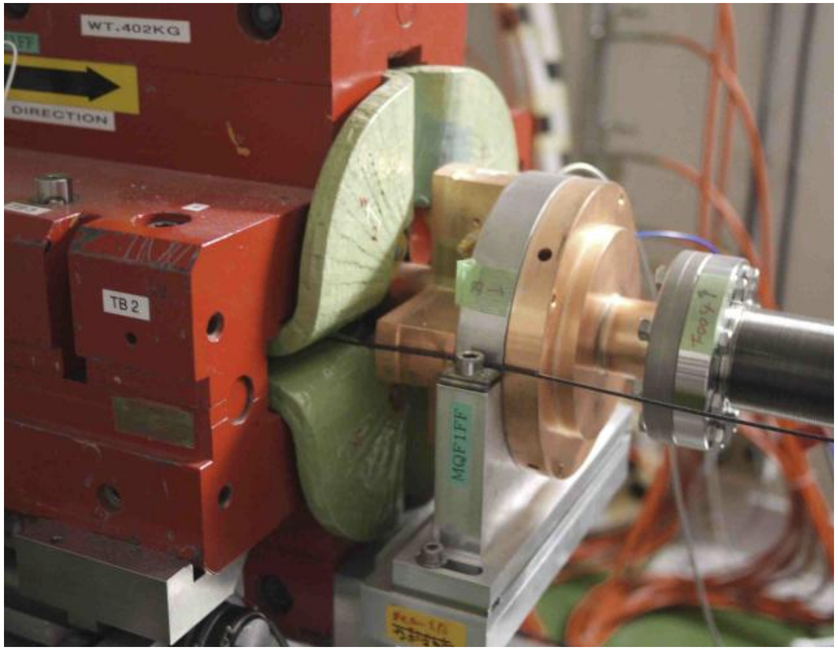


CBPM : Cavity pick-ups

- Most FF quadrupoles
- f_{dipole}= 6.426 GHz
- Design : KEK
- Manufactured : PAL
- Electronics : SLAC

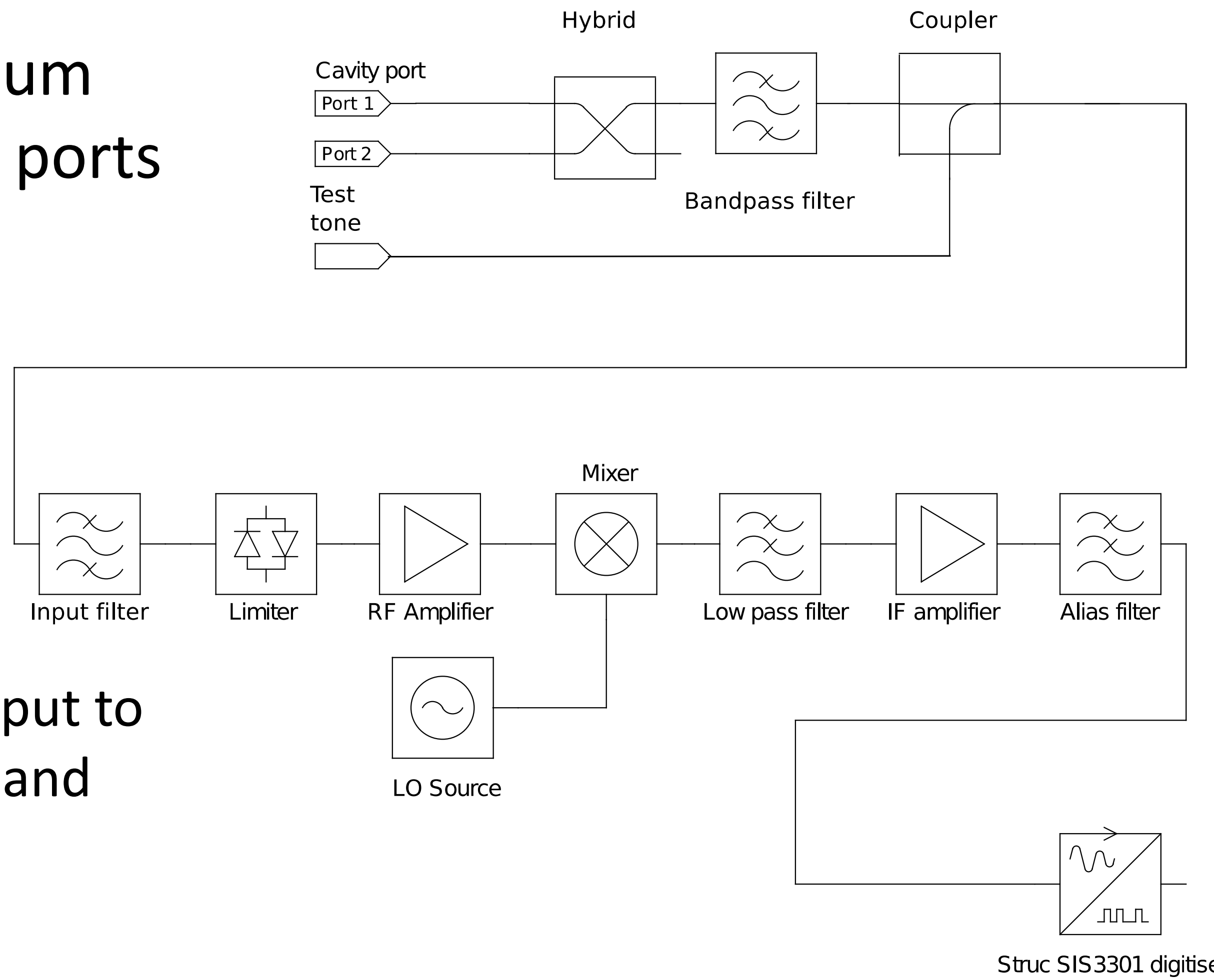


- Final doublet
- f_{dipole}= 2.888 GHz
- Design : KNU/RHUL
- Manufactured : KNU
- Electronics : RHUL

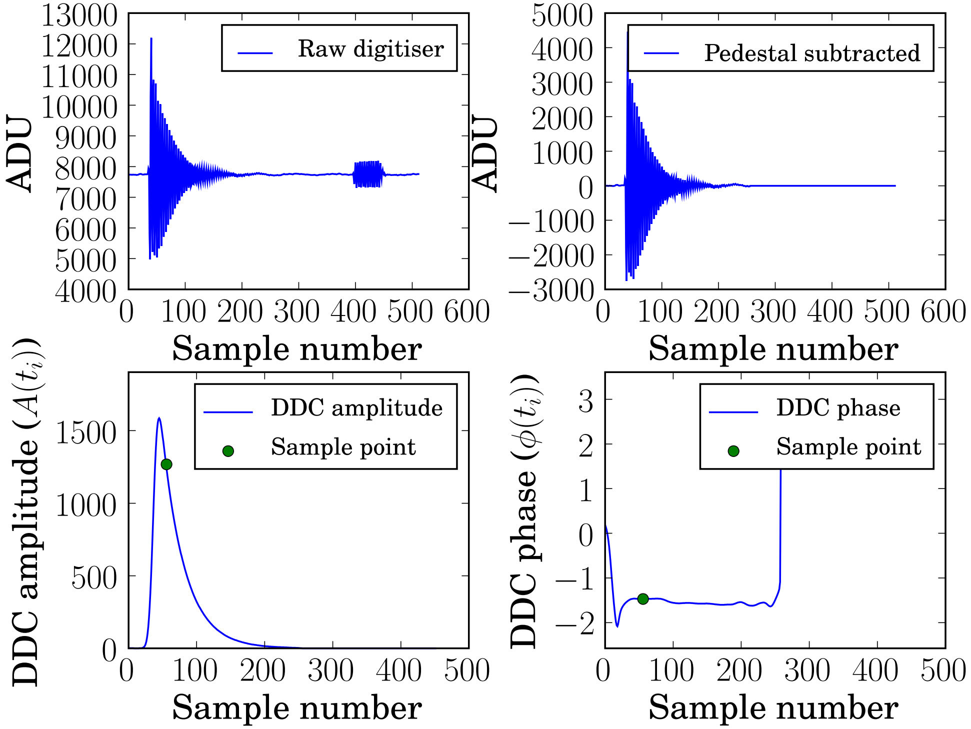


CBPM : Electronics

- Anti-phase hybrid to sum signals from opposing ports
  - Simple circuit
    - Limiter
    - Amplifier
    - Mixer
    - Low pass filter
  - IF frequency ~25 MHz
  - Integrated test tone input to check electronics gain and phase
  - 100 MHz digitisation



CBPM :Digital signal processing



- Mix digitised signal

$$y_{\mathrm{DDC}} = \mathrm{Filt}\left[V_{\mathrm{cavity}} \times V_{\mathrm{LO}}\right]$$

- Calculate amplitude and phase of signal

$$A(t_i) = \sqrt{y_{\mathrm{DDC}}(t_i) \cdot y^*_{\mathrm{DDC}}(t_i)}$$

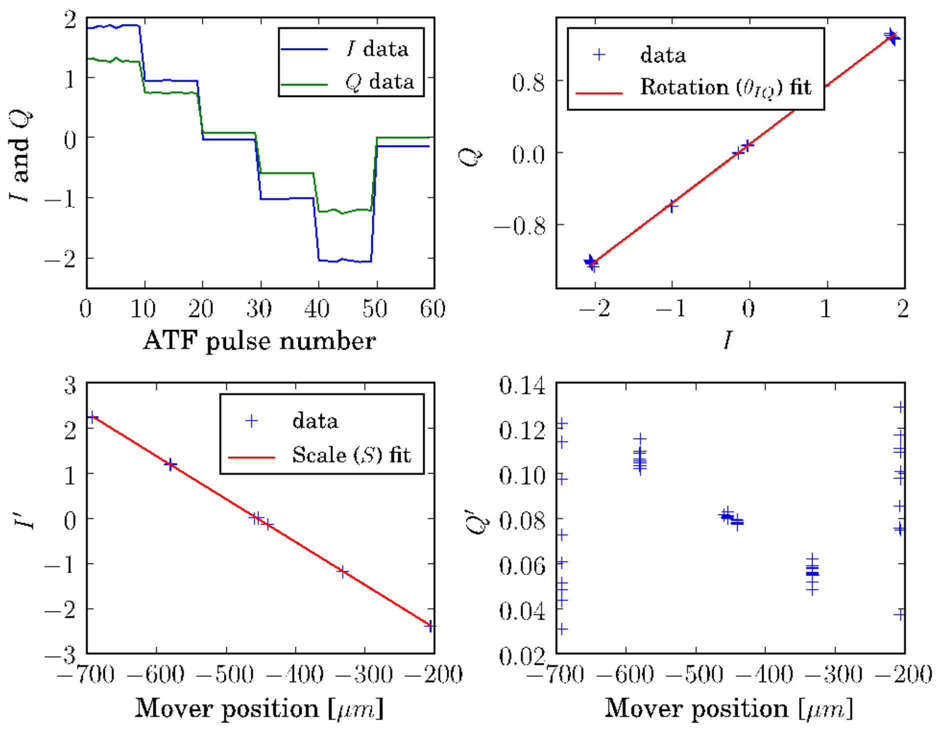
$$\phi(t_i) = \arctan\left[\frac{\mathrm{Im}[y_{\mathrm{DDC}}(t_i)]}{\mathrm{Re}[y_{\mathrm{DDC}}(t_i)]}\right]$$

- I and Q-phase components

$$I = \frac{A_d}{A_r}\cos(\phi_d - \phi_r)$$

$$Q = \frac{A_d}{A_r}\sin(\phi_d - \phi_r)$$

CBPM : Calibration



- Move BPM or beam and record I and Q
- Change in magnitude is proportional to displacement

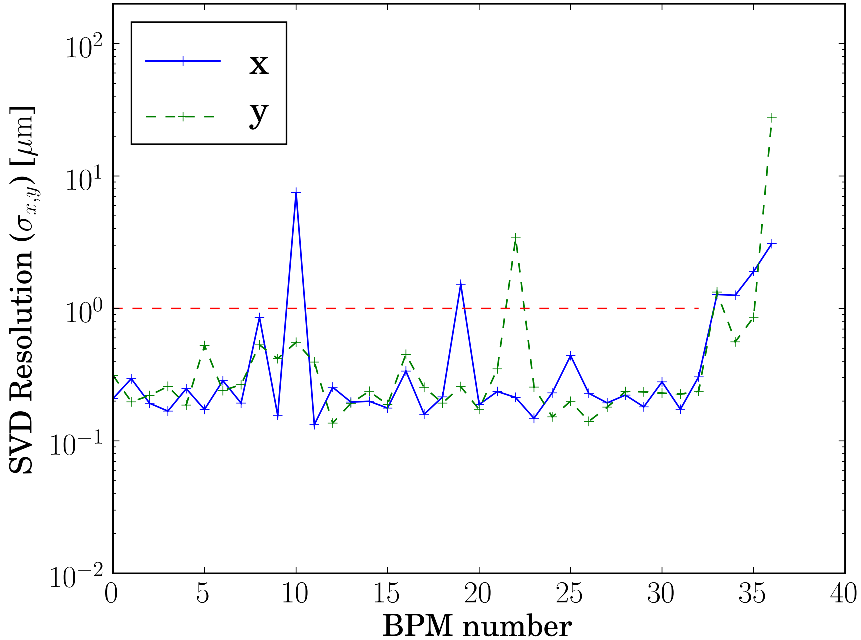
$$\theta_{IQ} = \tan^{-1}\left(\frac{dQ}{dI}\right)$$

- Rotate to position phase

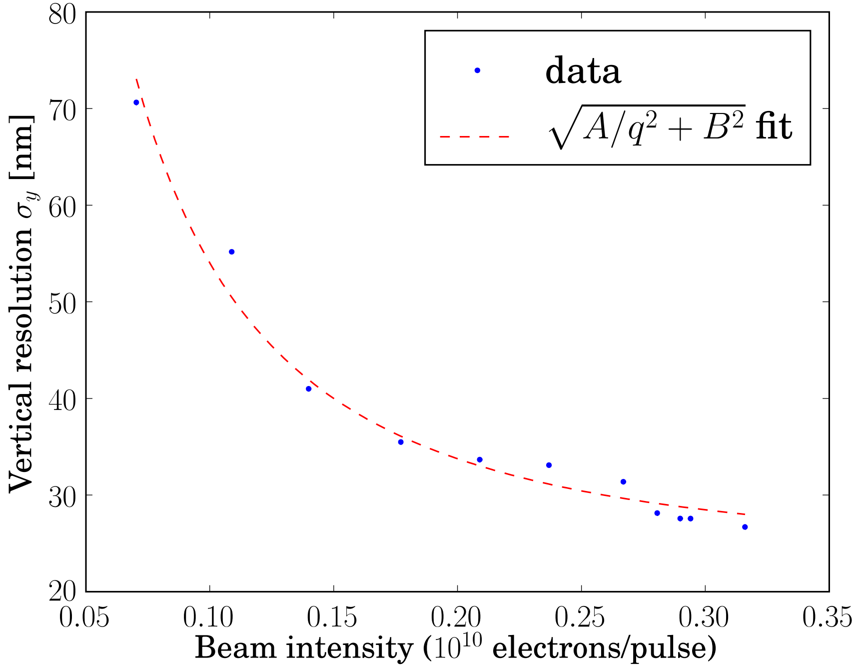
$$I' = I\cos(\theta_{IQ}) + Q\sin(\theta_{IQ})$$

CBPM : System performance

- Resolution measured using SVD model independent analysis

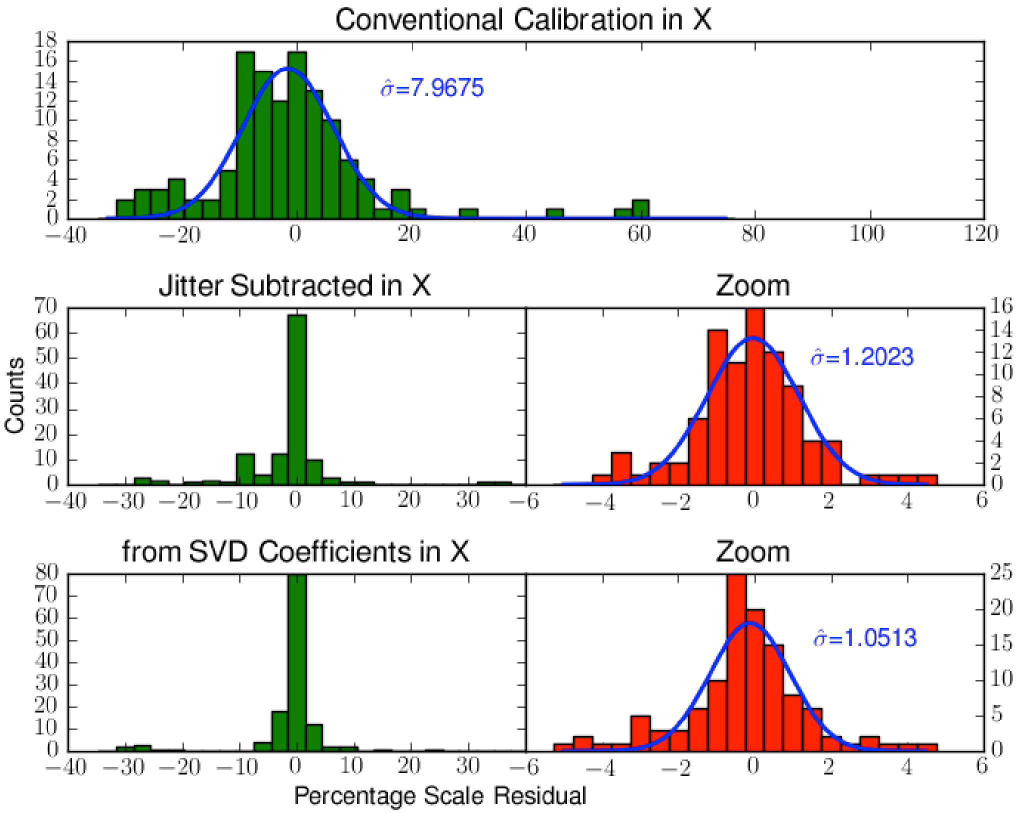


- Resolution as function of charge (no attenuation)



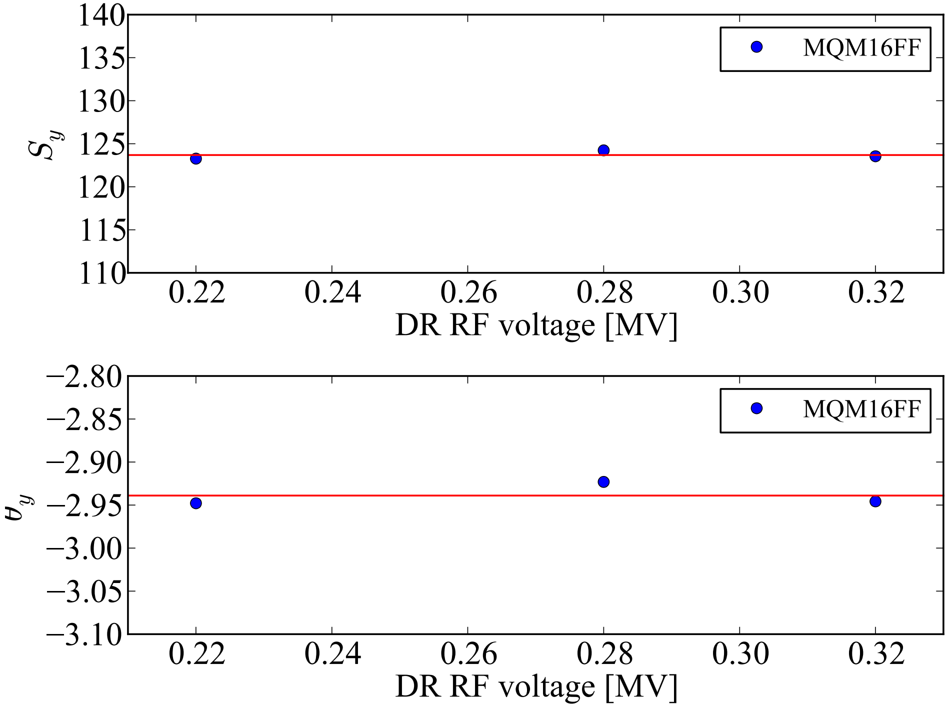
CBPM : Stability (MOPC27)

- Repeat calibration over three week period
  - Electronics indicate
    - Scale < 1%
    - IQ rotation ≈1° @ C-band
  - Verify scale and phase not changed
  - Beam orbit slow drift and jitter important in calibration
    - Subtract using MIA-SVD

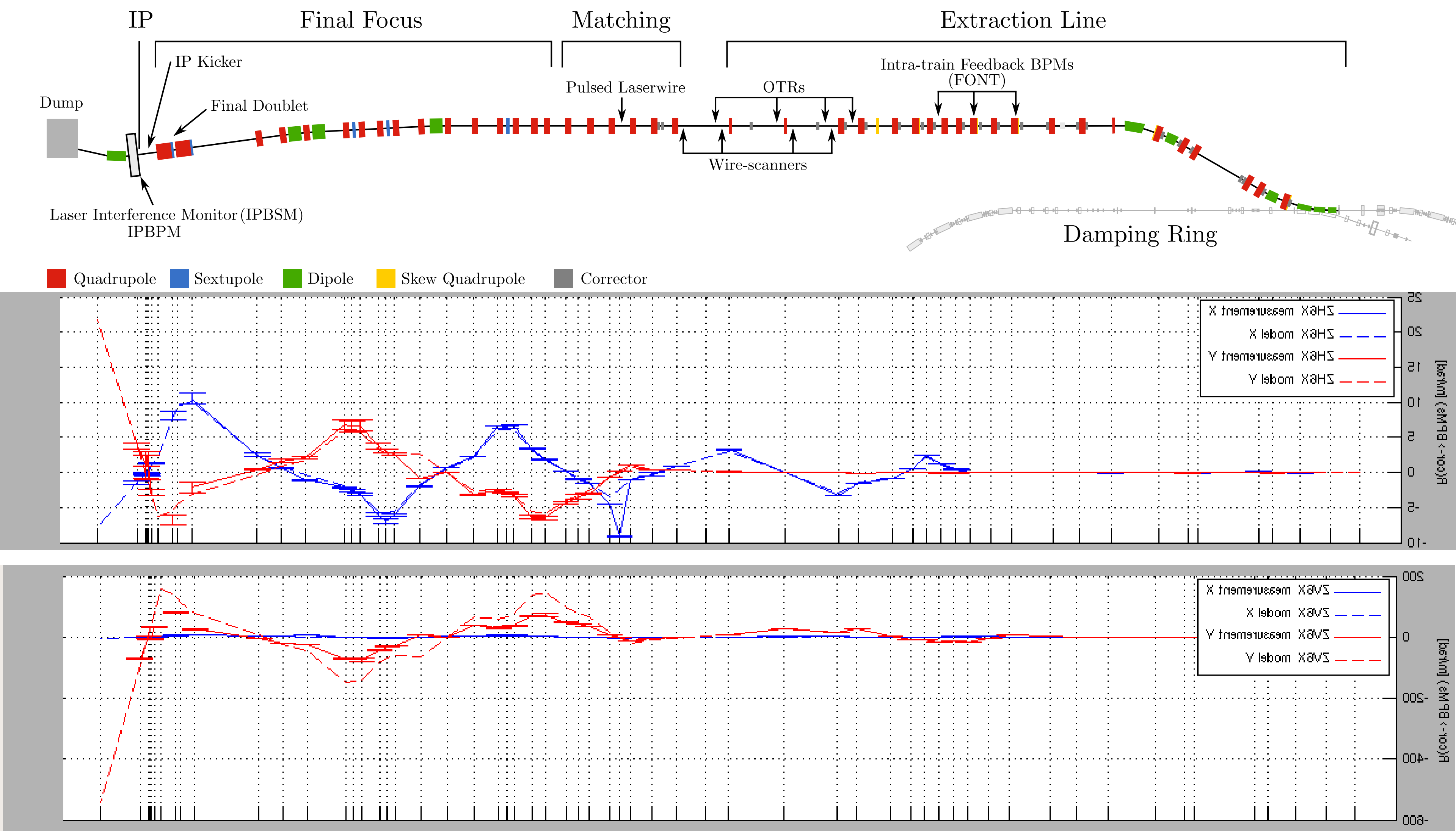


CBPM : Systematics (MOPC27)

- Interesting to check the effect on BPMS of
  - Bunch charge
  - Calibration movement range
  - Bunch length
  - Saturation of electronics and digitiser
  - Temperature
  - Optics

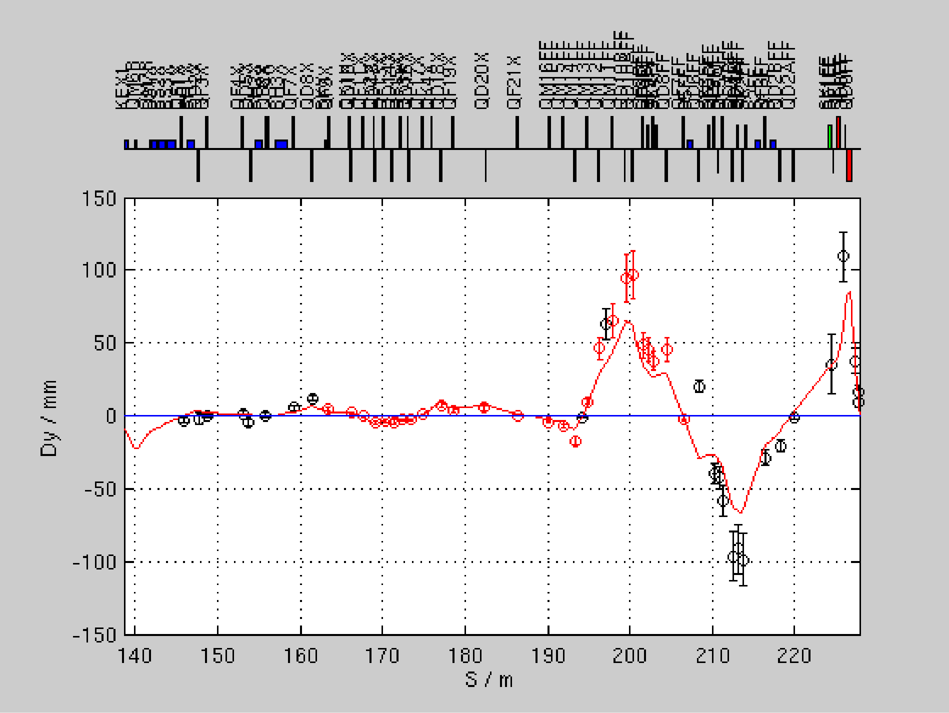


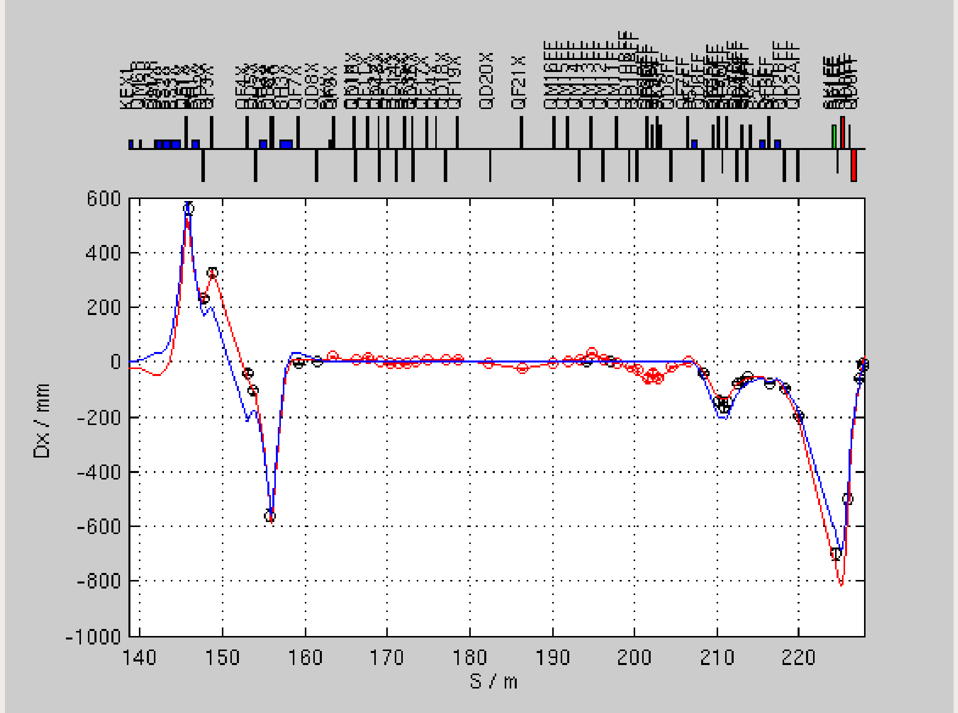
CBPM : Orbit kick response



CBPM : Dispersion measurement

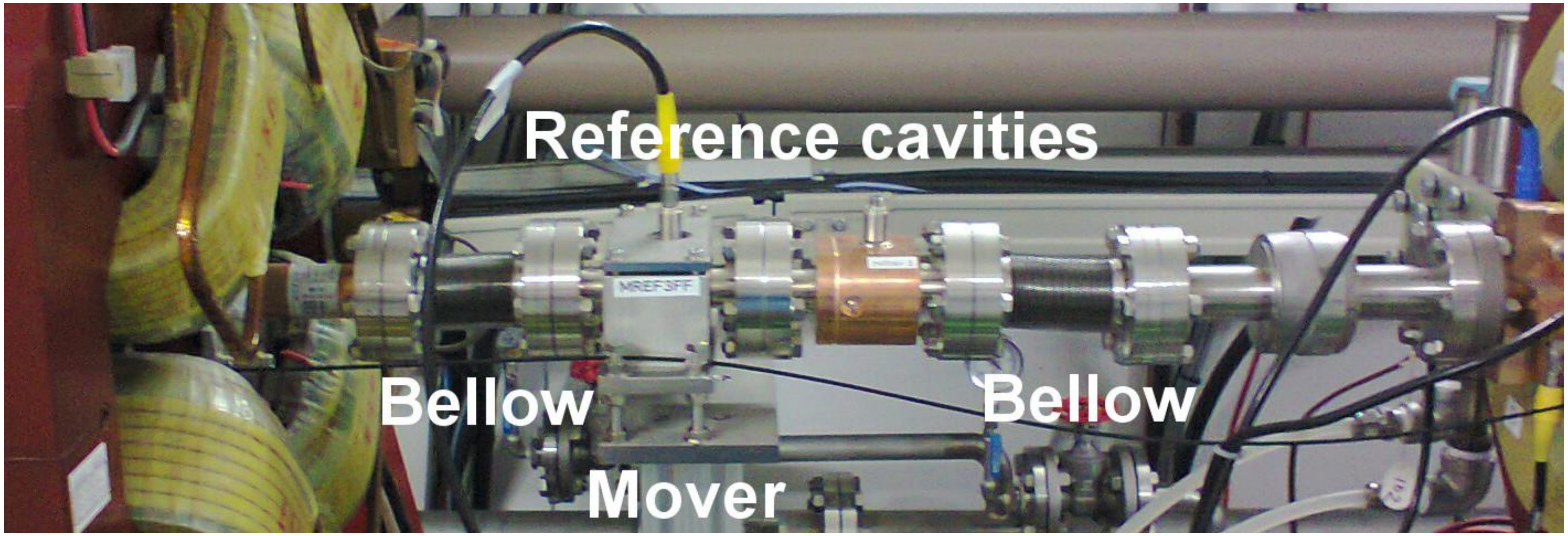
- Vary beam energy in ATF damping ring by a small shift in the RF frequency
  - Record response in stripline and CBPM systems
  - Online comparison with optics model (FFS based on dispersion)





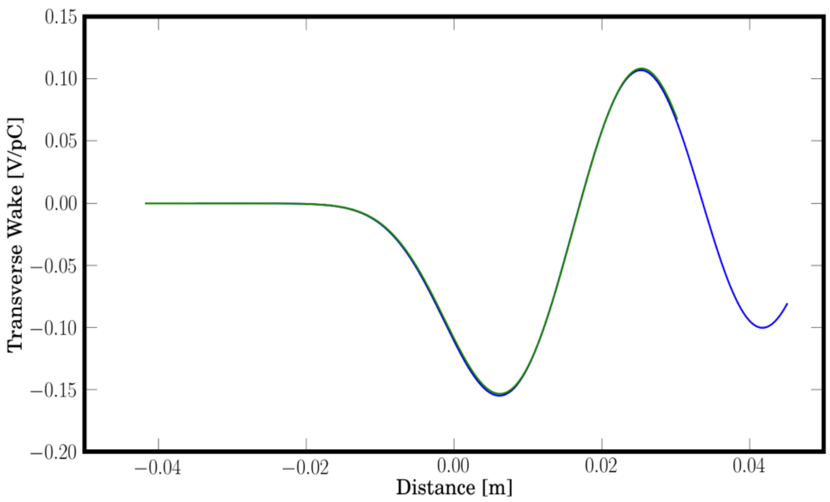
CBPM : Wakefield measurement

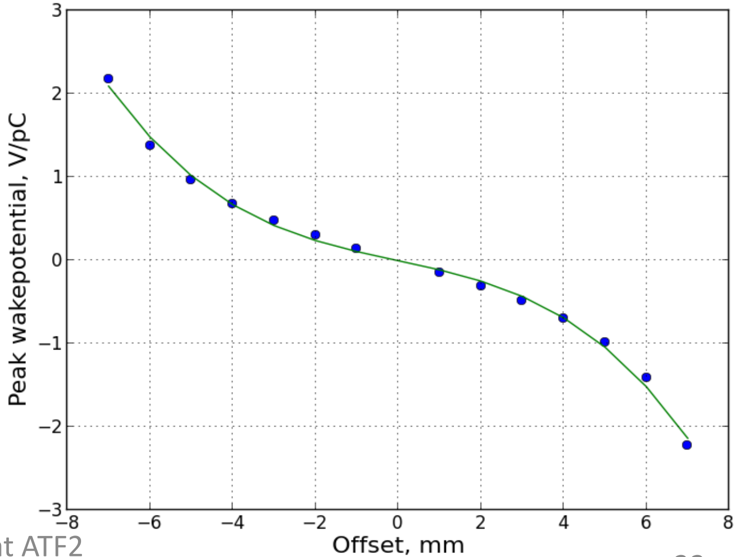
- Goal: measure wakefield from cavity BPM
- Using movable setup with 1 or 2 reference cavities
- Looking at downstream orbit change
- Setup was used to compensate wakes from other locations
- Crucial for reaching small beam size

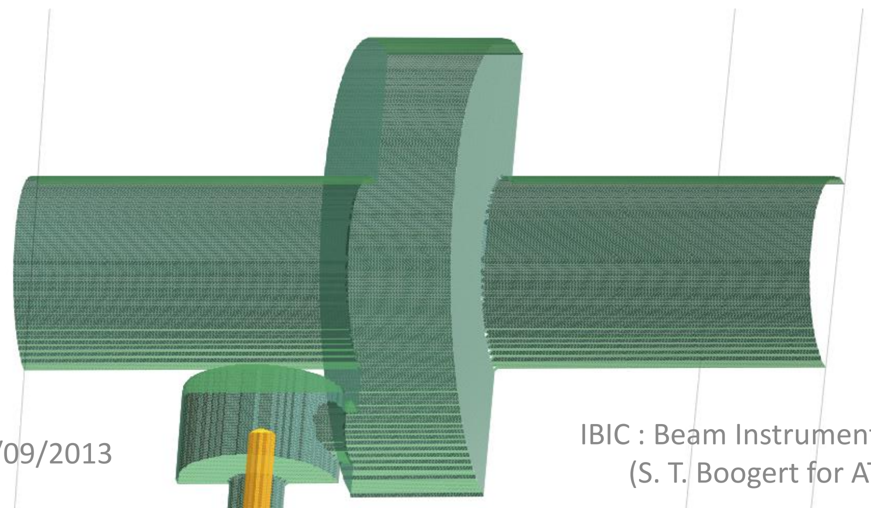


CBPM : Wakefield simulation

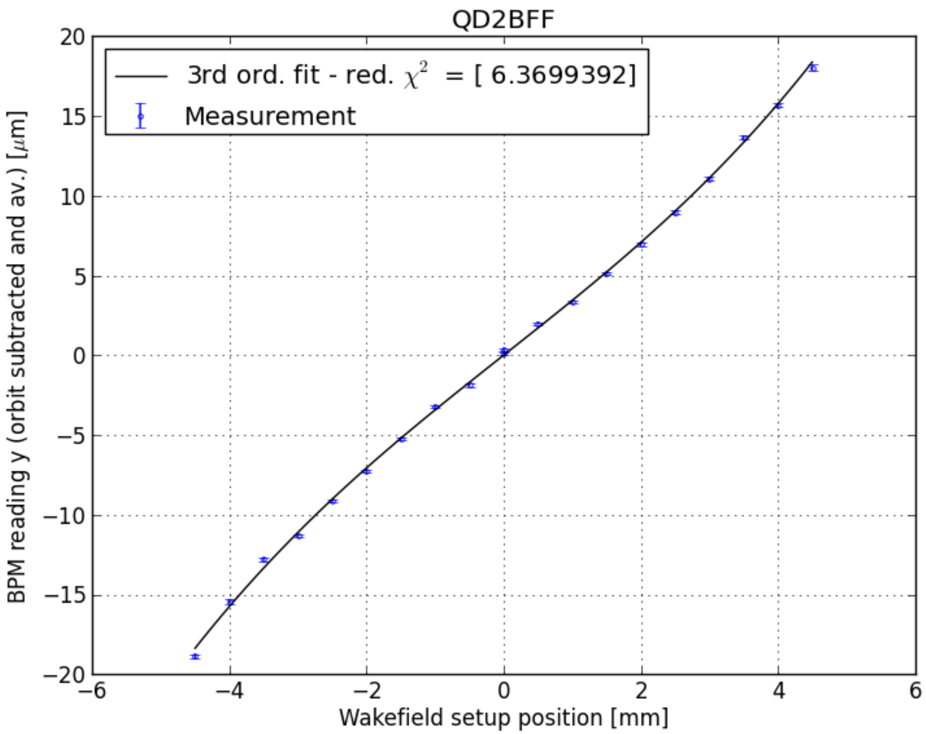
- Geometrical wake fields computed numerically with GdfidL (http://www.gdfidl.de) and ACE3P
- Electromagnetic fields calculator in any 3D-structure
- Finite element method
- All higher modes included (up to cut-off frequency)
- The beam is represented as a line charge traveling along the z-axis with optional offsets in x and y, Gaussian distribution in z
- Good agreement with different methods
- Non-linear for large offsets







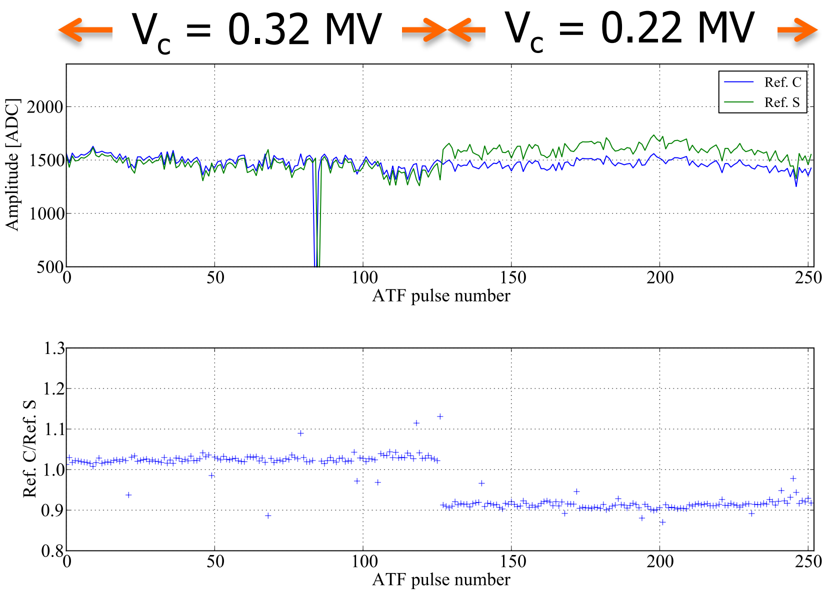
CBPM : Wakefield measurement example



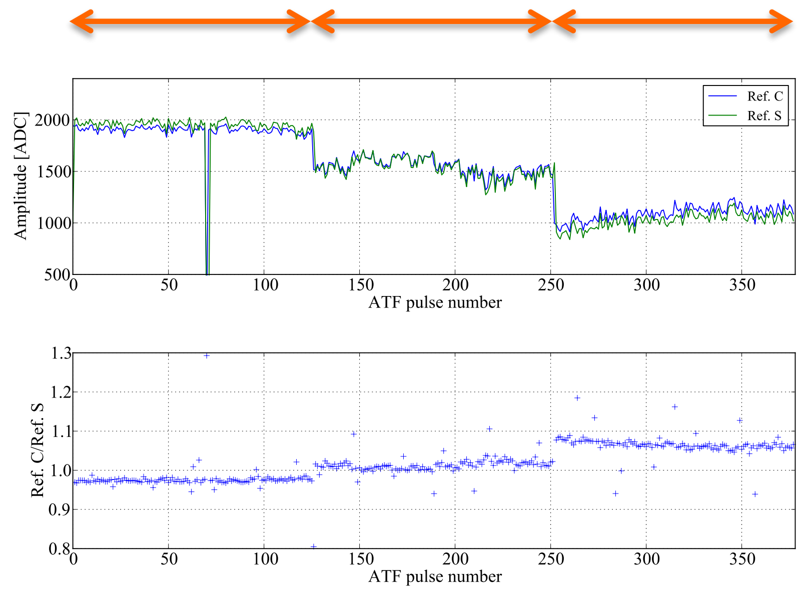
- Wakefield kick will change the beam orbit slightly
- Experiment is ideally placed as many high resolution cavity BPMs both upstream and downstream of the setup
- Procedure:
  - Take all upstream cavity BPM readings
  - All BPM readings averaged subtracted
  - Find contribution between those BPM readings and downstream cavity BPM readings
  - Subtract orbit per pulse (by SVD matrix inversion)
  - Remaining correlation with setup movement will give wakefield kick
- Orbit and shape follows simulation well
- Some discrepancy in absolute size compared to simulation (calculation + tracking).

CBPM : Bunch length measurement

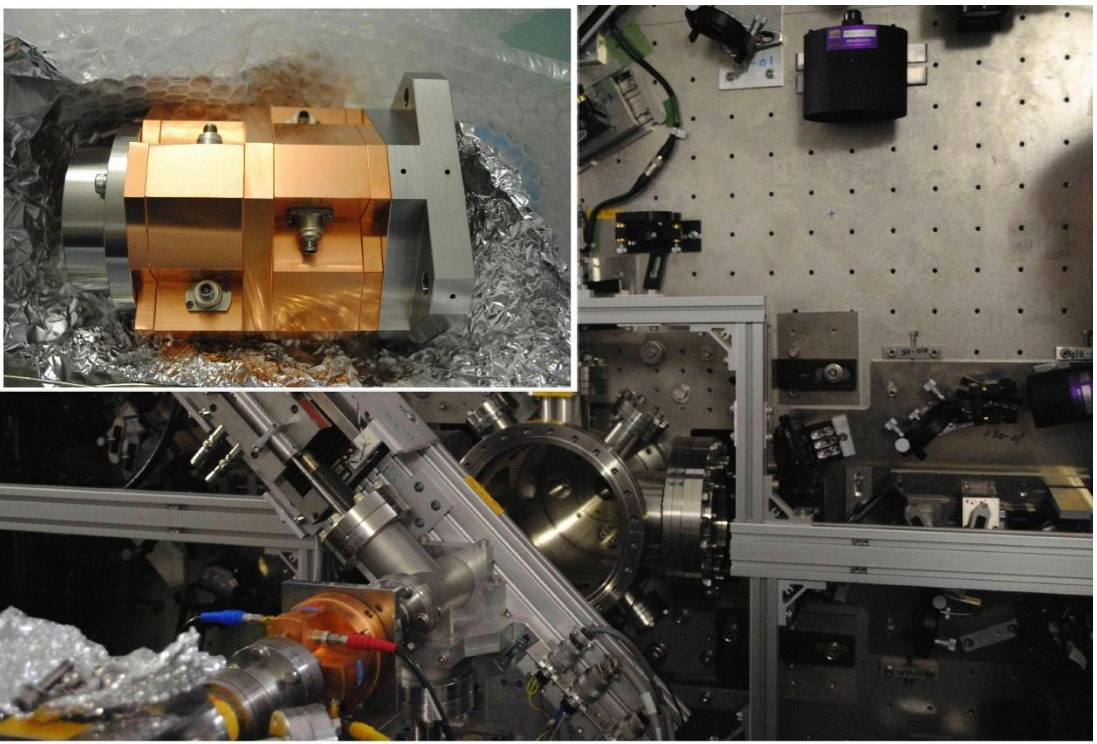
- Monitor signal from two different frequency reference cavities (C- and S-band)
  - Clearly see dependence on damping RF gap voltage
  - Bunch intensity (IBS induced bunch length change)



Different charge settings



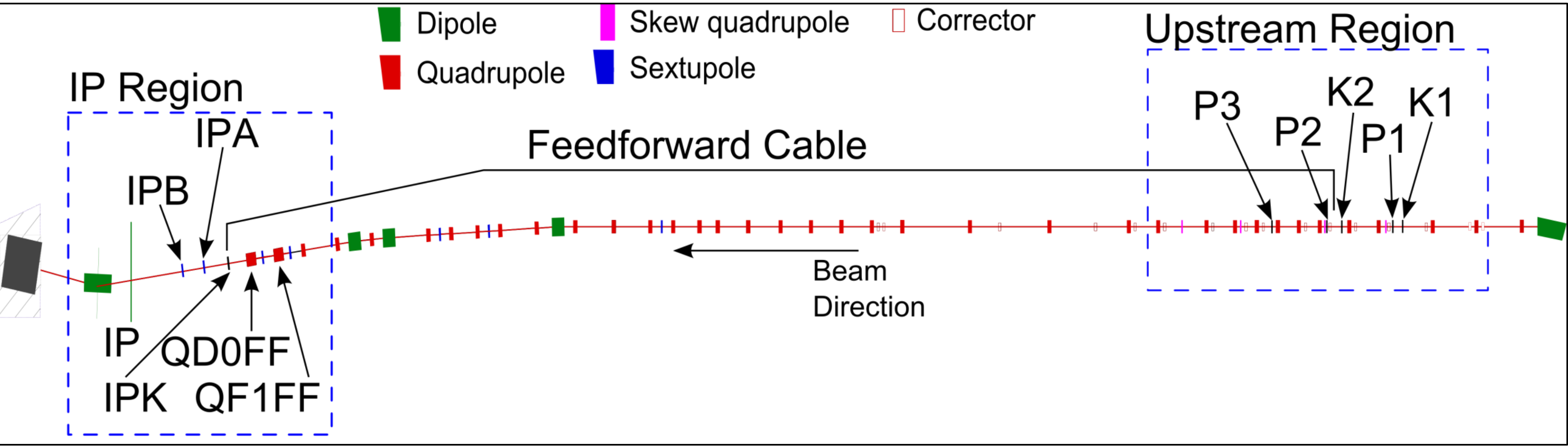
Interaction point BPMs (TUPC22)



- Rectangular cavities
- 2 per mechanical unit
- f_{dipole}(vert) = 6.421 GHz
- f_{dipole}(horiz) = 5.707 GHz
- Low-Q for bunch signal separation
- Mounted in IPBSM system
- 2 stage down conversion
  - 1st to common 714 MHz
  - 2nd to baseband or ~25 MHz (like other cavities)

Sub-micron beam stabilisation (WEBL2)

Feedback On Nanosecond Timescales (FONT): talk by M. Davis Wed. 11.40



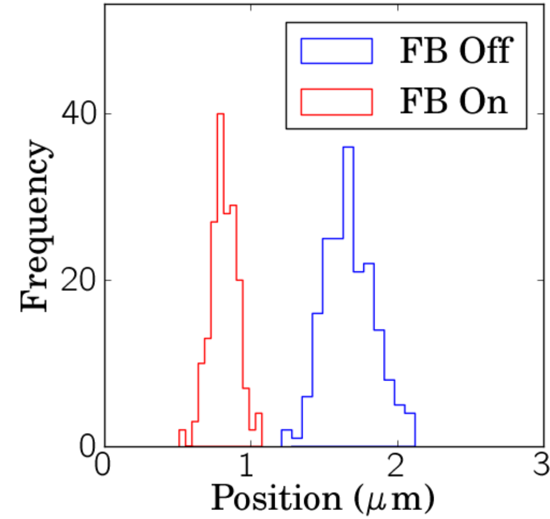
Beam stabilised at ATF2 interaction point using 3 techniques:

1) Upstream feedback: correction derived using stripline BPMs, applied upstream

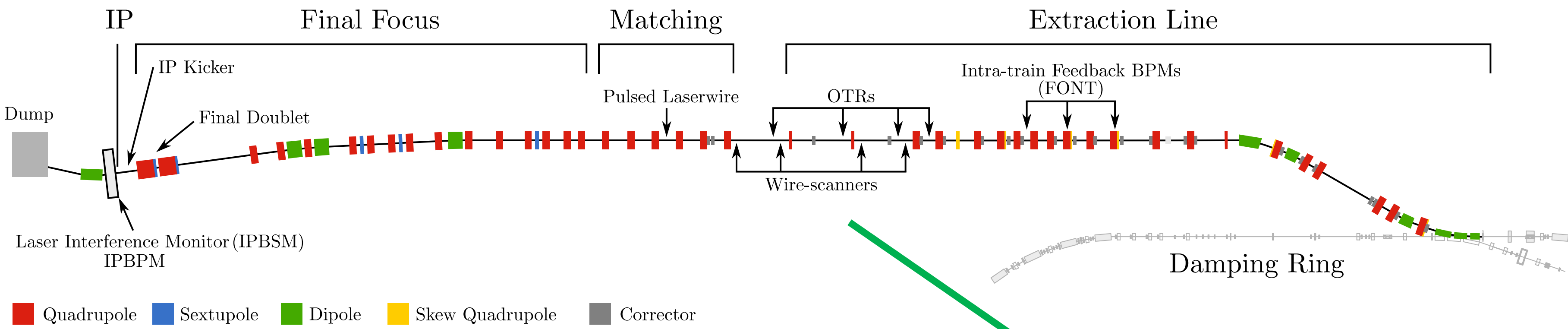
2) Feedforward: correction derived upstream, applied locally at IP

3) IP feedback: correction derived using cavity BPMs, + applied locally, at IP

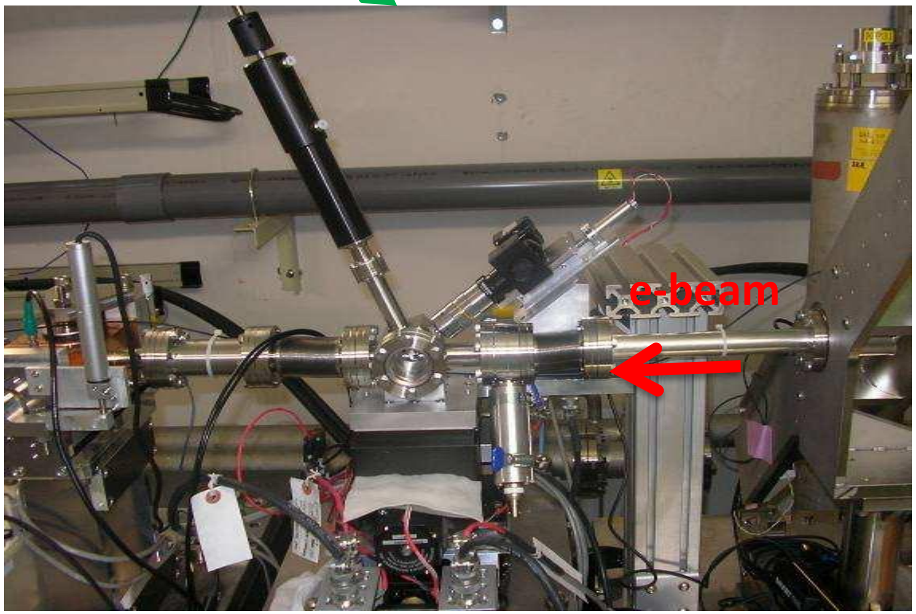
→ beam successfully stabilised to ~ 100 nm



Multi-OTR system



- The multi-OTR system is made of **4 OTRs** installed in the zero-dispersion part of ATF2 EXT line, **near WS** for comparison
- The objective of this project is the **fast measurement of the emittance** (single shot for beam size, 1 min for emittance) with:
  - High statistics
  - **2 µm** resolution
  - **$2x10^{10}$ single bunch** and **$2x10^{11}$** for **20 multi-bunched** beam (2.8 ns spacing)



mOTR : Beam size measurement

Single OTR panel

Working mode & Reference system

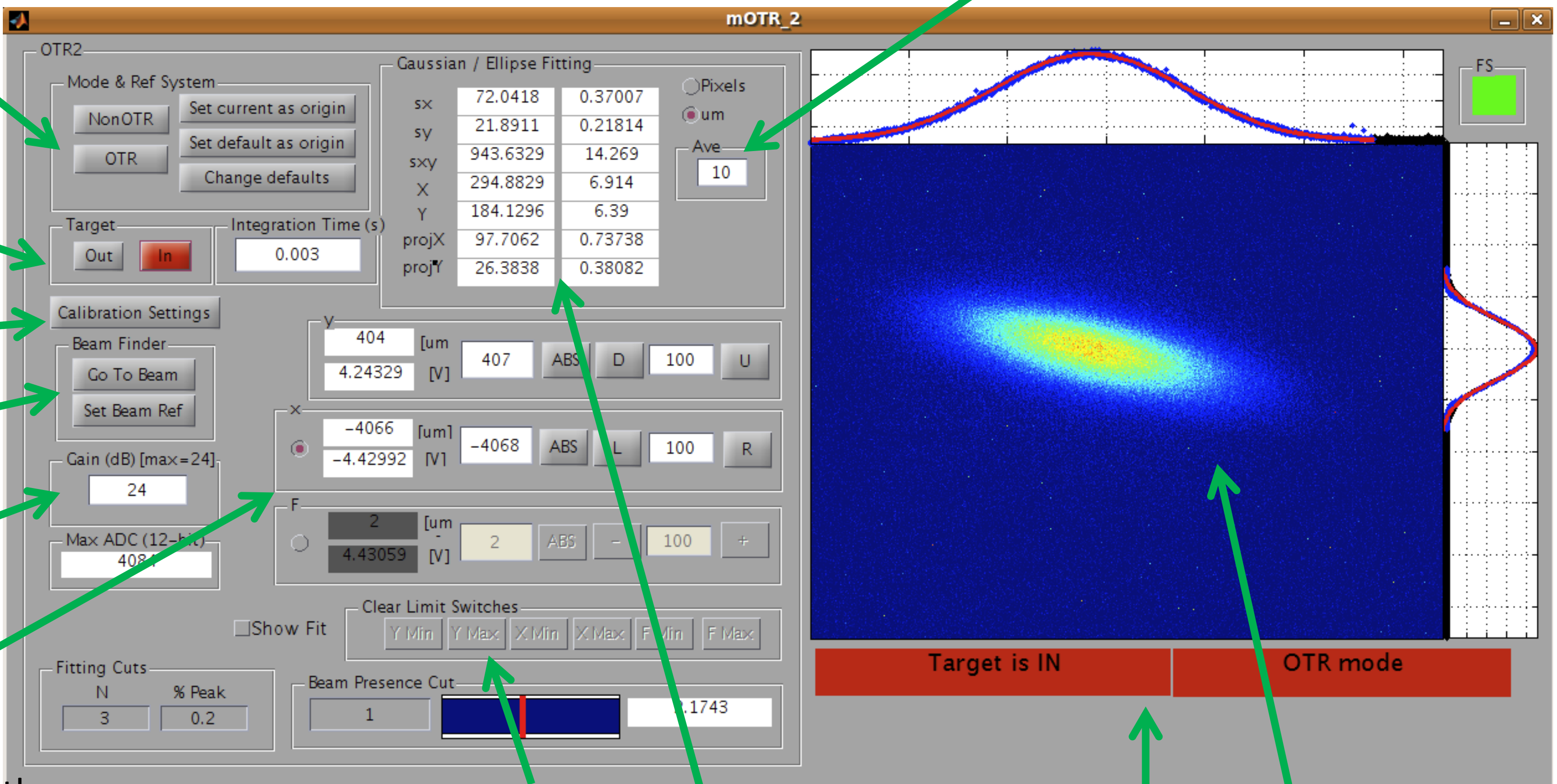
Number of measurements

Target control

Calibrations

Beam finder

CCD Gain



Position & movement of the movers

Limit switches status

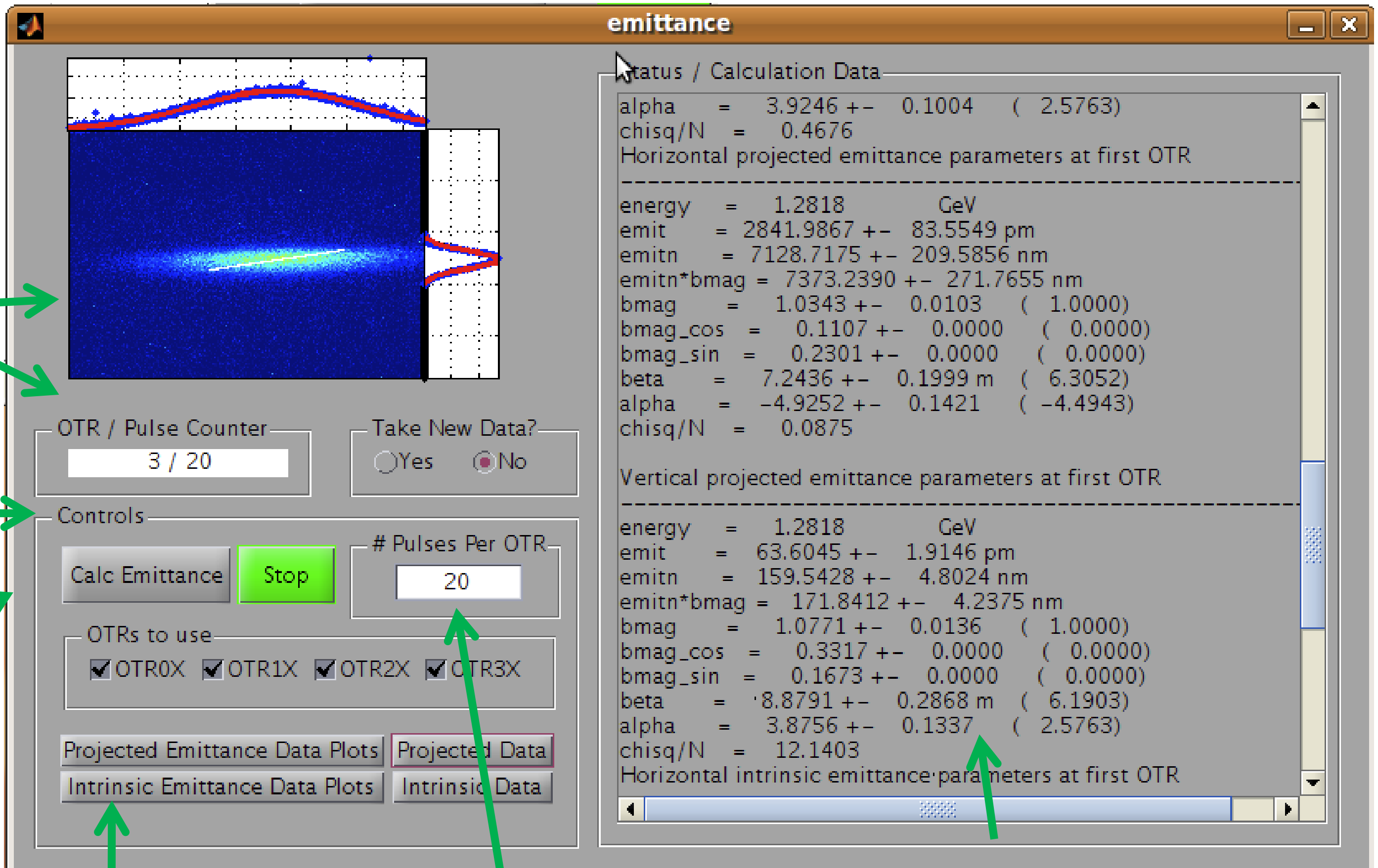
Machine status

Ellipse fitting and analysis

CCD image and beam fitting

mOTR : emittance measurement

Emittance panel



Current OTR info

Start/stop emittance procedure

Number of OTR to be used

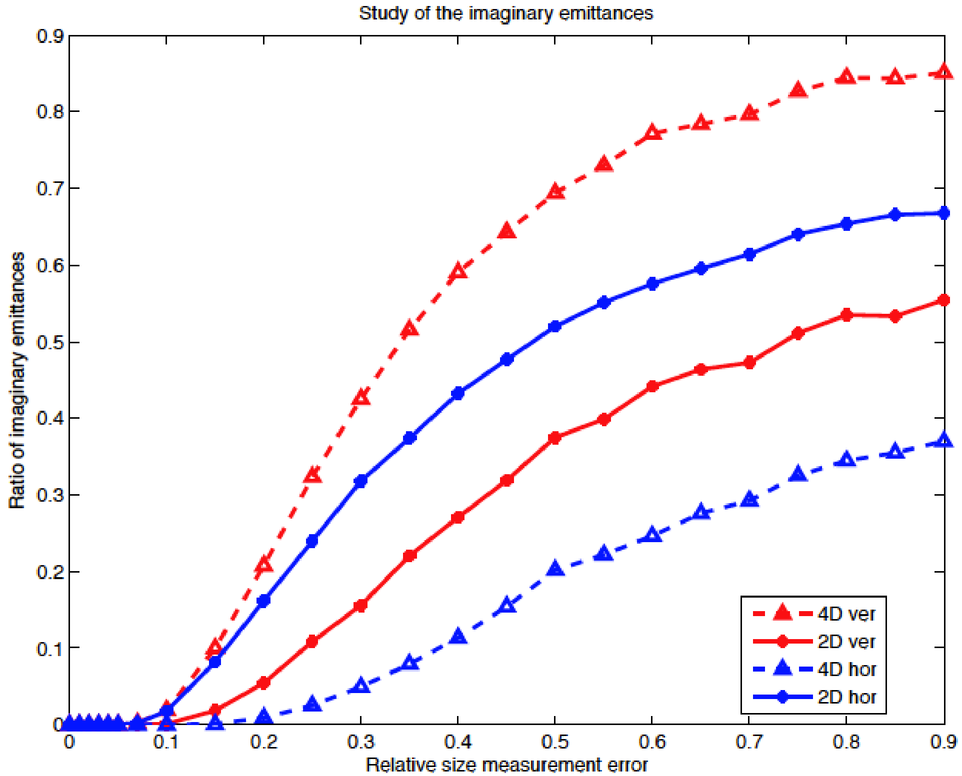
Data analysis and plots

Number of measurements per OTR

Calculation data

mOTR : emittance reconstruction

- Analytical study of the conditions of solvability of the systems of equations for emittance reconstruction
  - Projected
  - Full
- Possible uses at ILC/CLIC
  - RTML
  - Tune up diagnostic

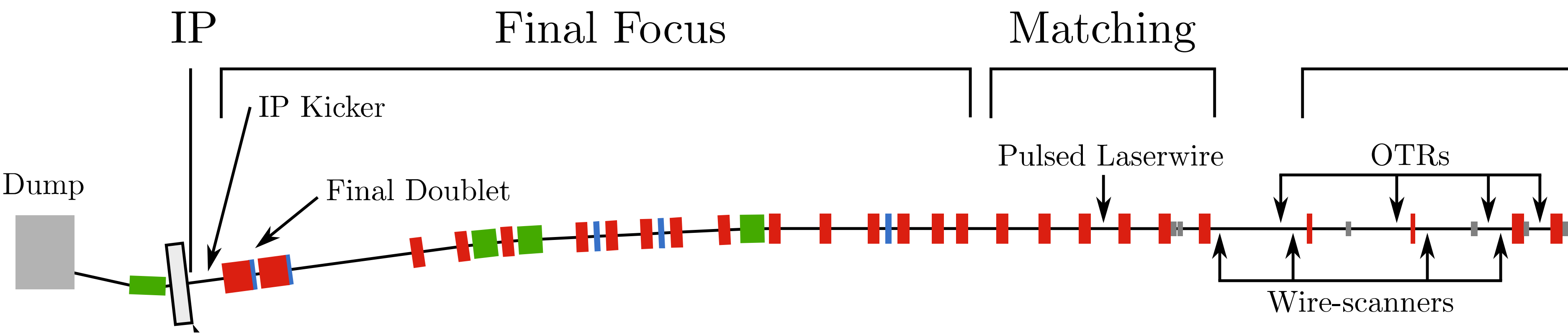


mOTR : Summary

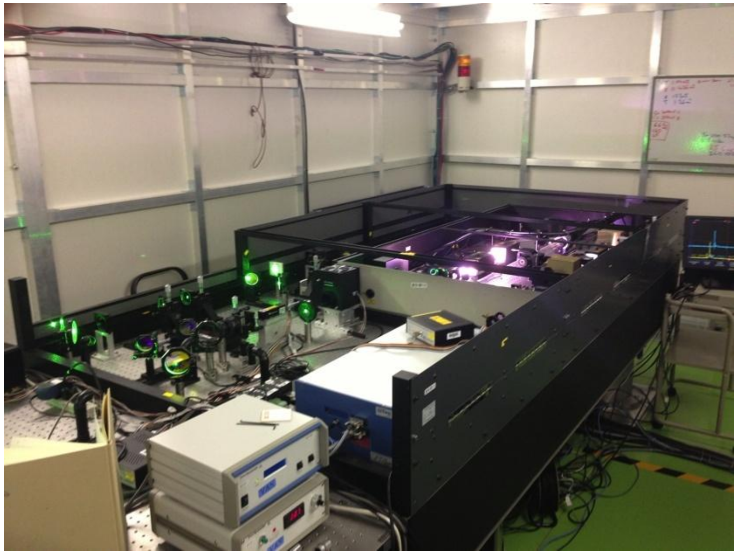
- The **m-OTR system** of the ATF2 EXT has demonstrated its performance as a **fast** (1min) and **reliable** system for measuring the beam size and the emittance. The system is **totally integrated** in the **online model** and it is **crucial** for **tuning procedures** of the beamline as: coupling correction, beta matching, energy spread measurements… Studies to ameliorate these procedures are under study
- A **systematic measurement campaign** to determine if the new target configuration is able to avoid the **wakefield effect** of the **simultaneous measurement** of the 4 OTRs has to be made
- We have **studied analytically** the **conditions of solvability** of the systems of equations involved in the process of emittance reconstruction and we have obtained some rules about the **locations** of the **measurement stations** to avoid unphysical results. **Simulations** have been made to test the robustness with high coupling scenarios and measurement errors. The results of these studies will be very **useful** to better determine the location of the emittance measurement stations in the **diagnostic sections** of **FLC**s.
- OTR monitors are **mature** and **reliable** diagnostic tools that could be **very suitable** for the setup and tuning of the machine in single-bunch mode. It can be very useful during **start up** and **commissioning** phases of the **RTML**. The **feasibility** of using a m-OTR system in **transfer lines** of the **ILC RTML** as well as a study of the different **materials** for the OTR **target** and possible limitations of operation is ongoing.

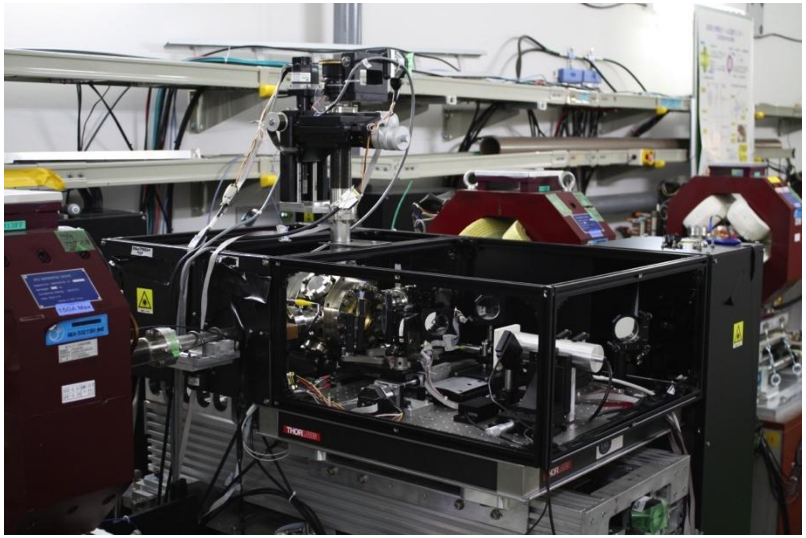
Laserwire (MOPF16)

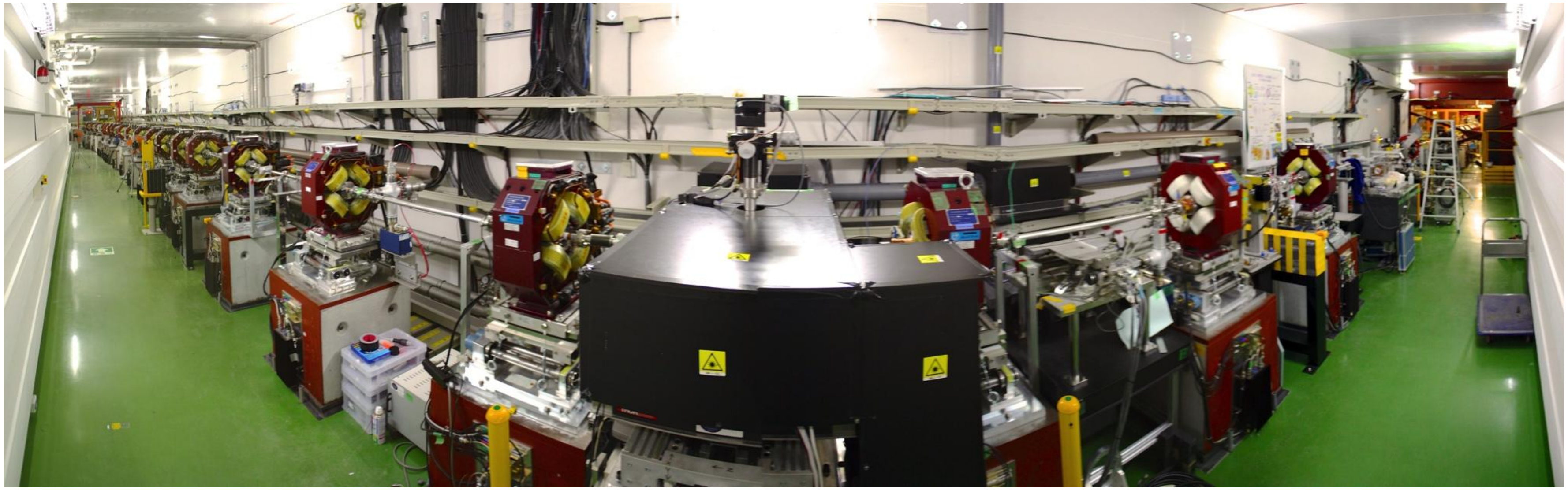
- Aim to make high precision measurements of 1 µm vertical beam sizes
  - Screens and wires cannot withstand the energy density
  - Focused laser which Compton scatters with electron beam
  - Electron beam focused to <1µm at virtual IP point (MFB2FF)
  - Downstream Cherenkov (lead-aerogel) based γ–ray detector



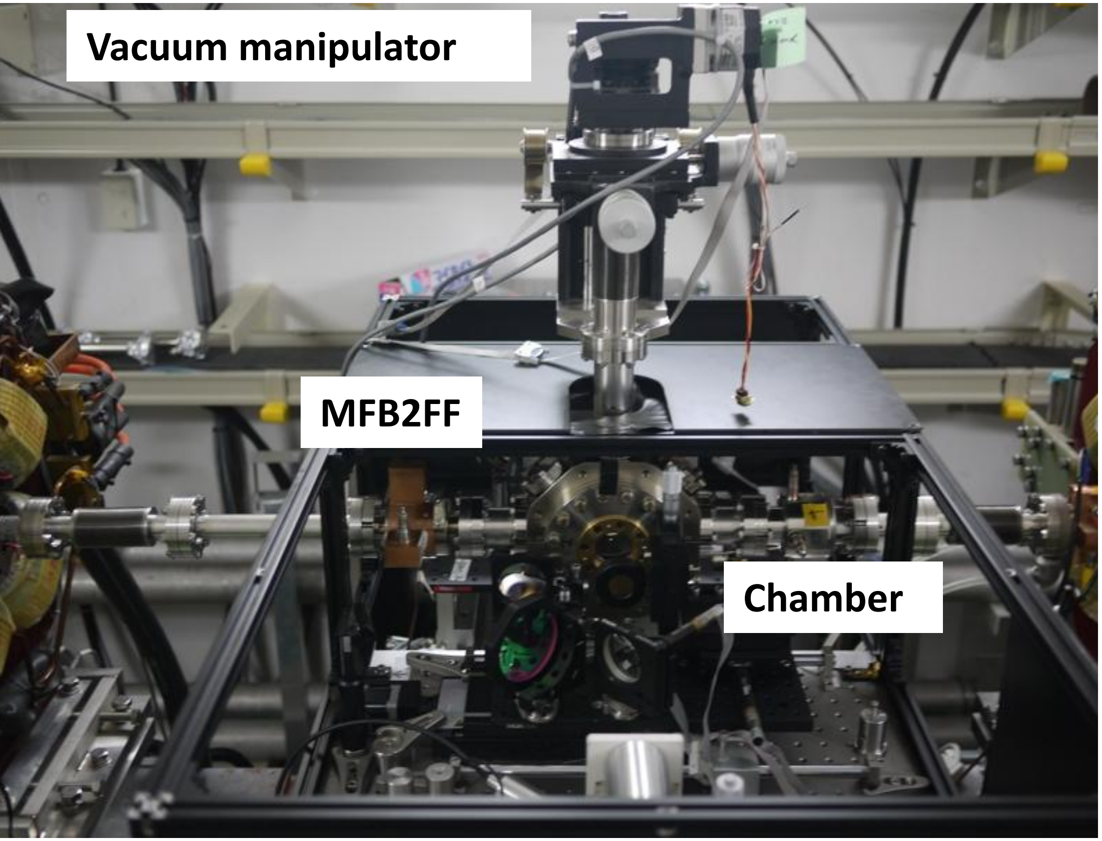
LW : Installation (1)







LW : Installation (2)



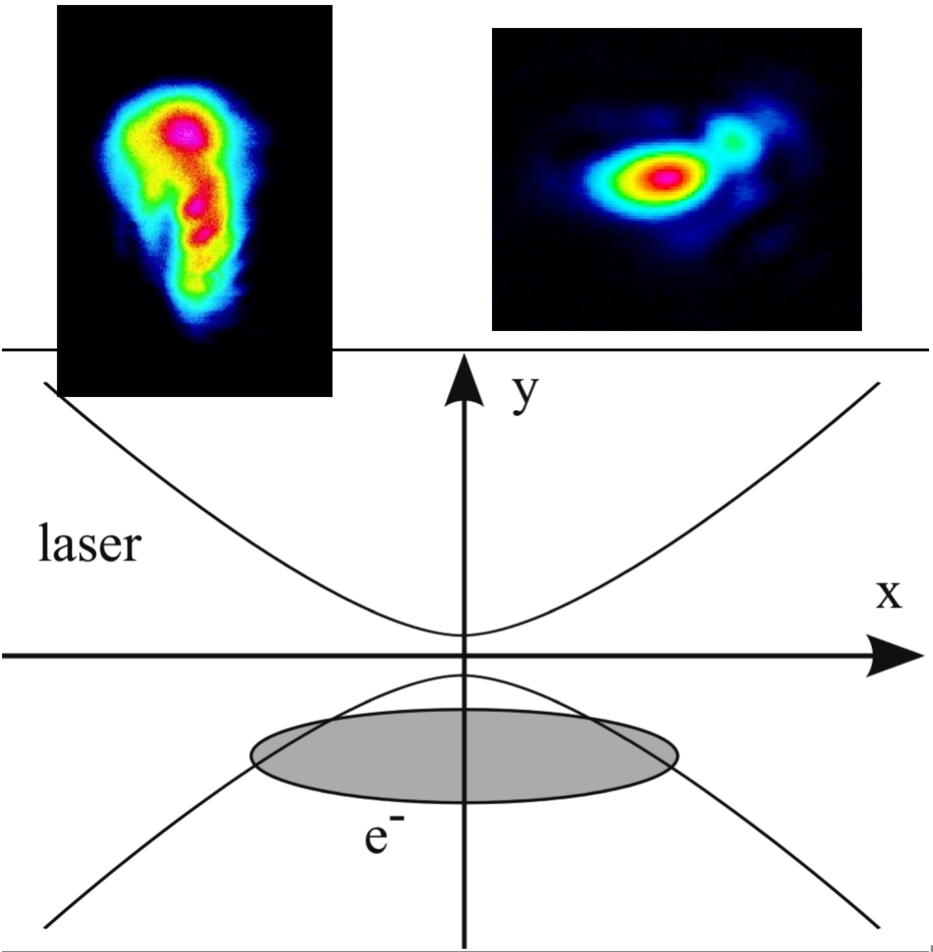
- GW class locked and seeded Nd:YAG laser
- Short focal length corrected lens
  - Mounted directly to interaction chamber
- Chamber has motion control in two axis
- Vacuum manipulator
  - OTR screen to align collisions

LW : Laser measurement

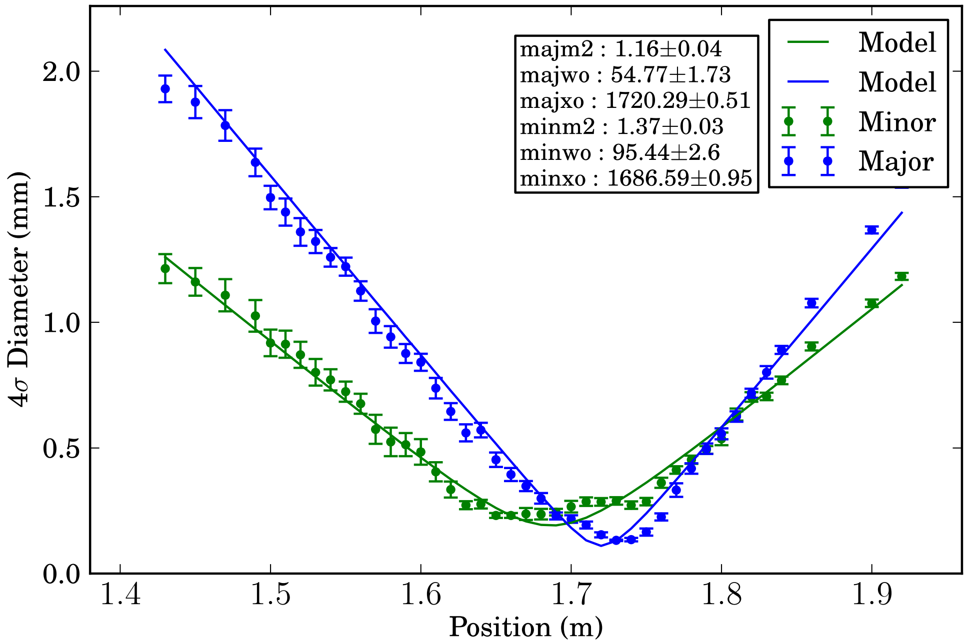
Average Compton rate

Electron density **Laser power density**

$$\langle N_\gamma \rangle = N_b P_L \frac{\sigma_C \lambda}{ch} \int_x \int_y \int_z \rho_e(x,y,z)\rho_L(x,y,z)\,dxdydz,$$

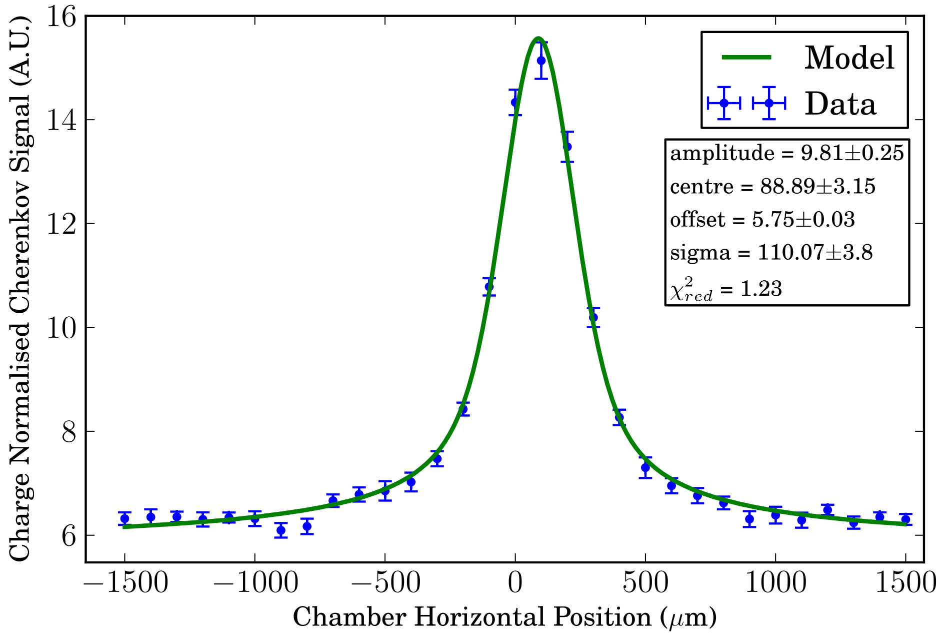


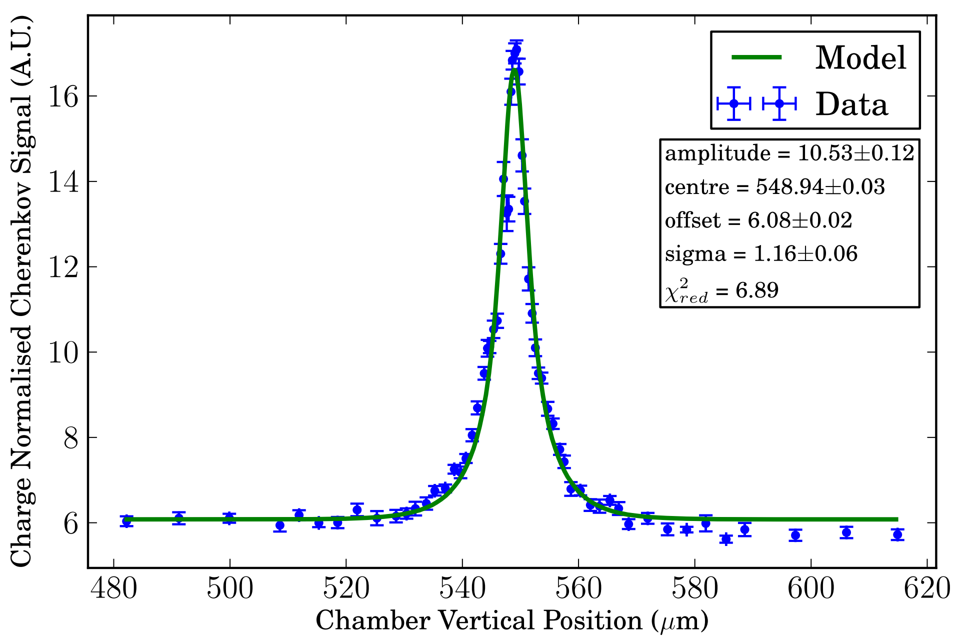
- Laser measurements using CCD camera
  - Laser is astigmatic
  - Parametrise laser focus



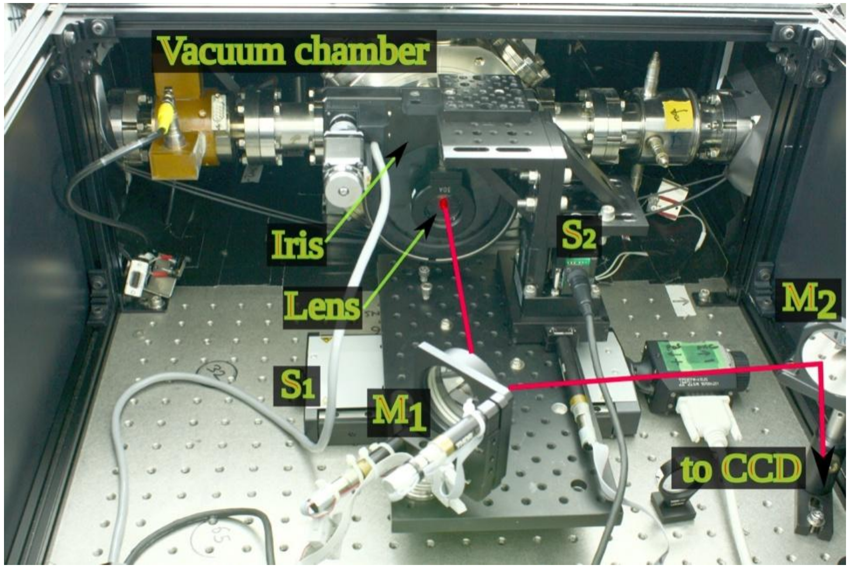
LW : Recent measurements

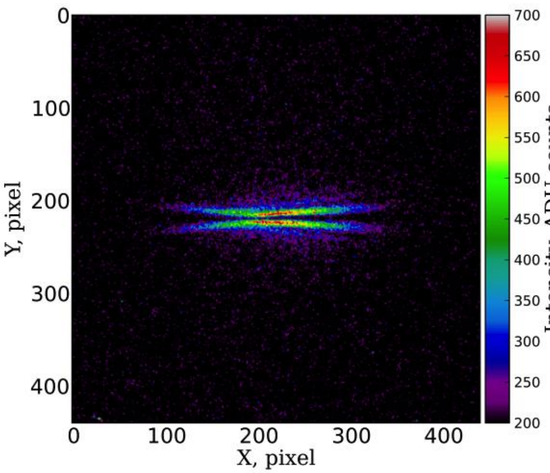
- First measure horizontal beam size
  - Shift focus position
  - Fit to overlap integral
- Vertical scan (at horizontal maximum)
  - Again fit using horizontal electron beam size
  - 5-10% uncertainty on 1 μm

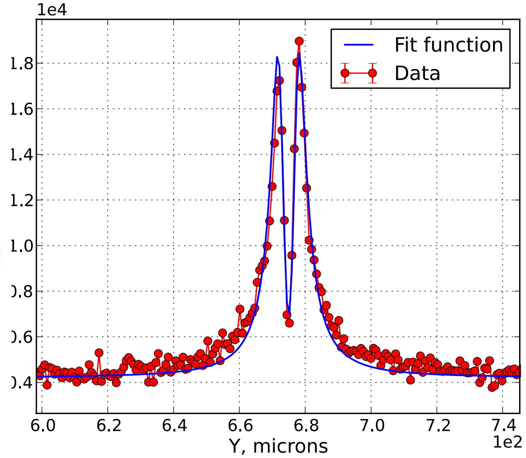




High resolution OTR (WEAL2)







- OTR screen in LW used for temporal and spatial alignment
  - Post LW-IP OTR optical system installed
  - Two lobe OTR using vertical polarisation
  - Visibility is measure of beam size
  - See talk by K. Kruchinin WEAL2
  - Sub micrometre sizes measured

Interaction point beam size monitor (IPBSM)

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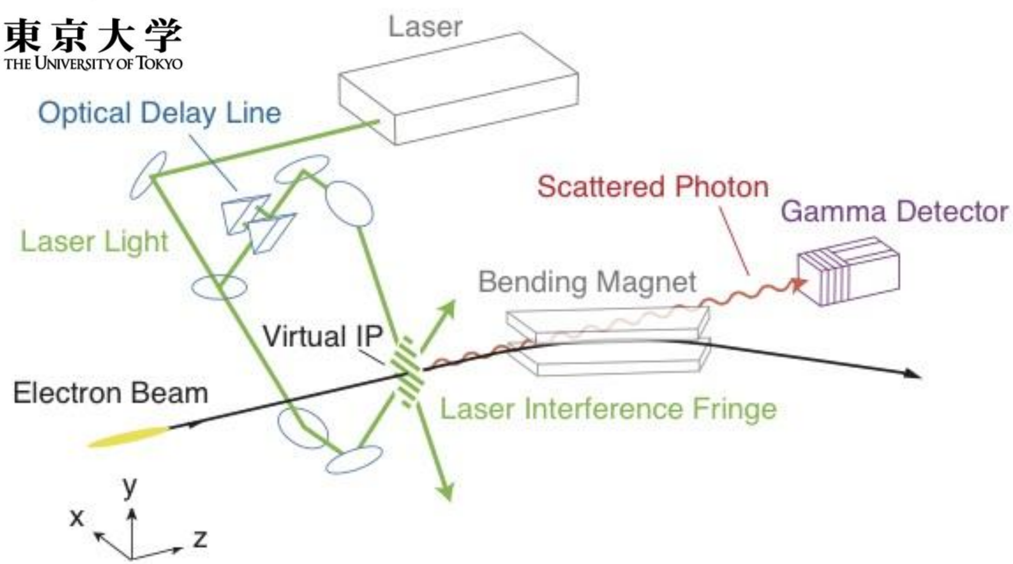
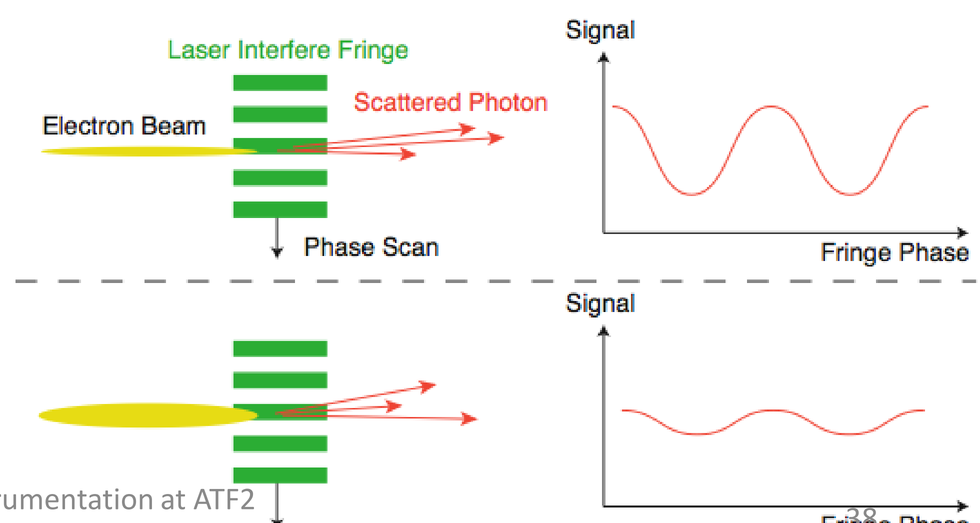
THE UNIVERSITY OF TOKYO



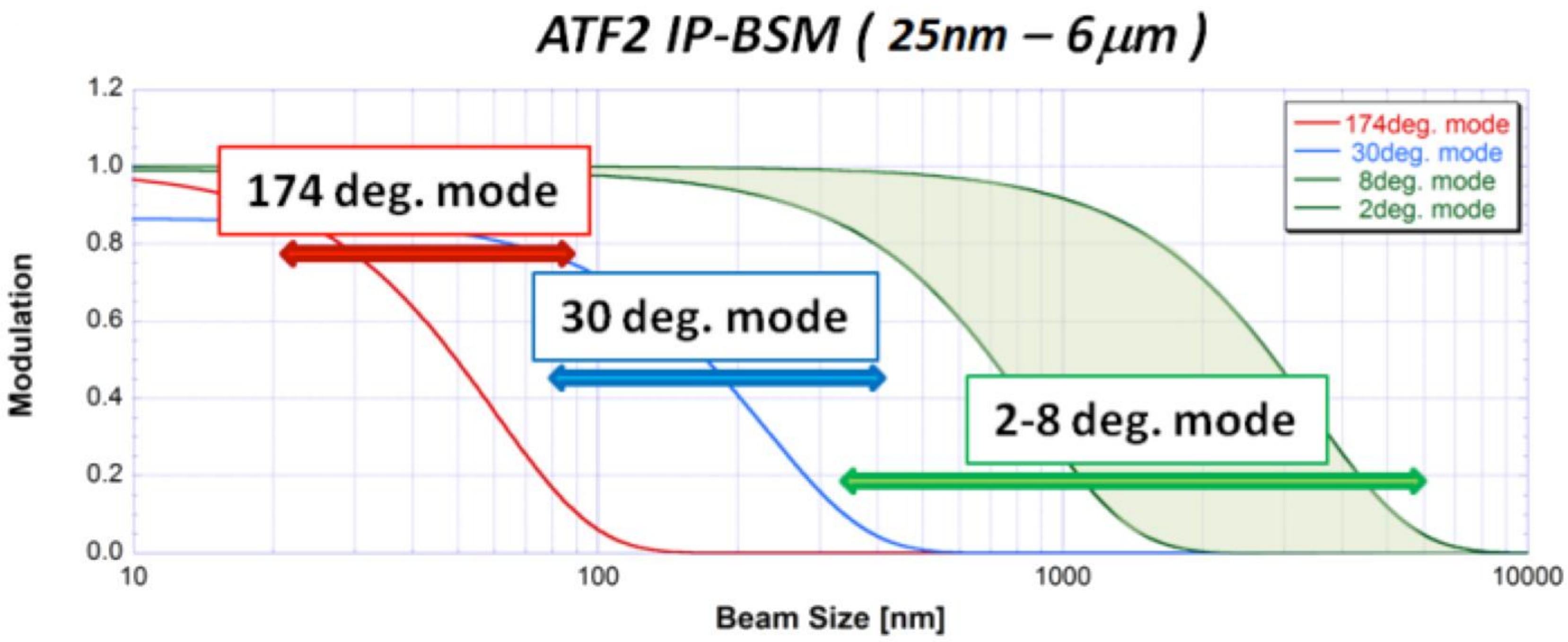
- Beam size measurements at ATF2-IP
  - Solid (W,C) wire scanners (>2 µm or more)
  - Laser interference fringe monitor

- Collide electron beam with laser interference pattern
  - Fringe pitch gives range of beam size measurement

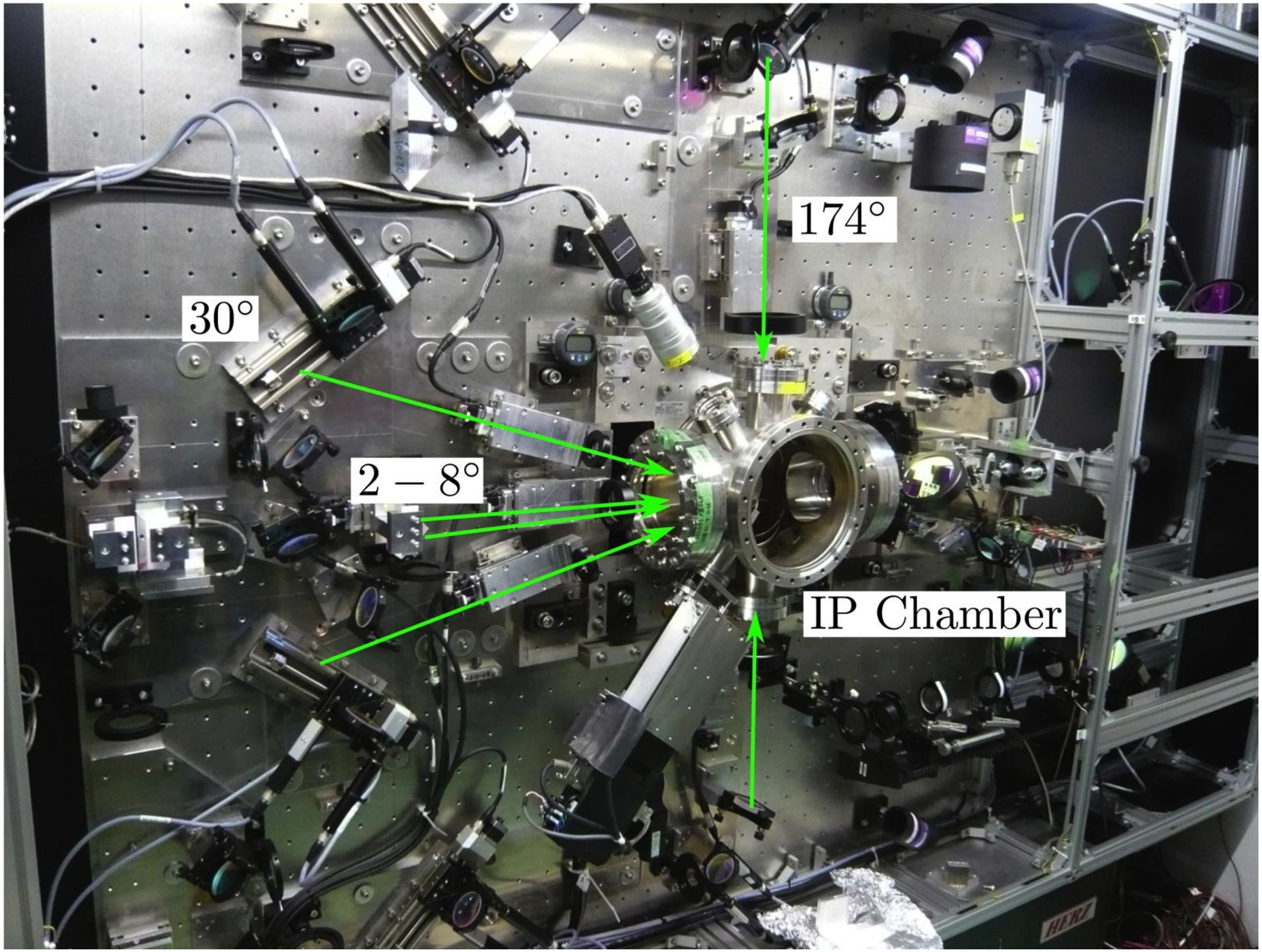


IPBSM : Modulation

- Three laser crossing angles, 2-8°, 30° and 174°
  - Access to beam sizes from 6 μm down to 25 nm
  - Overlapping ranges for different modes

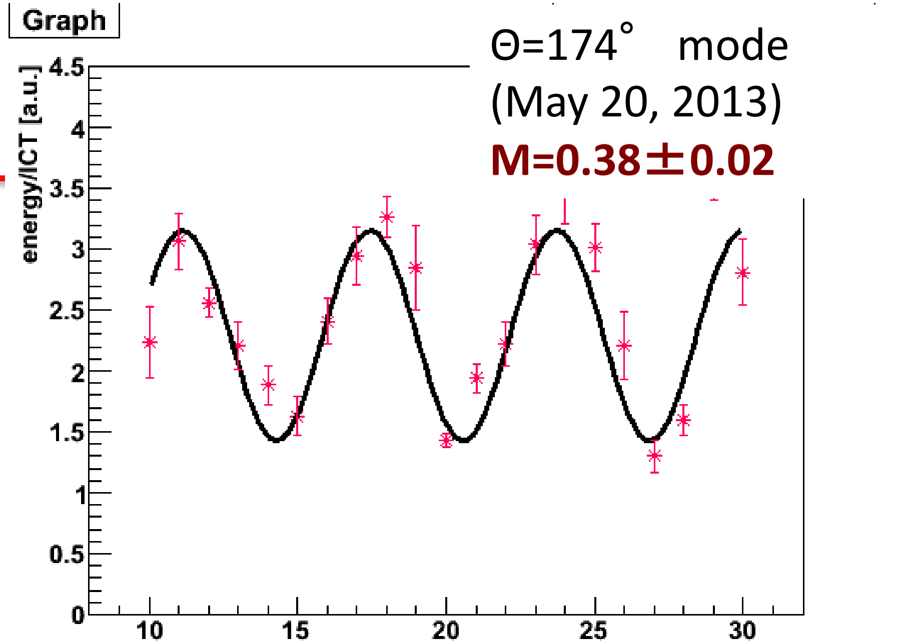


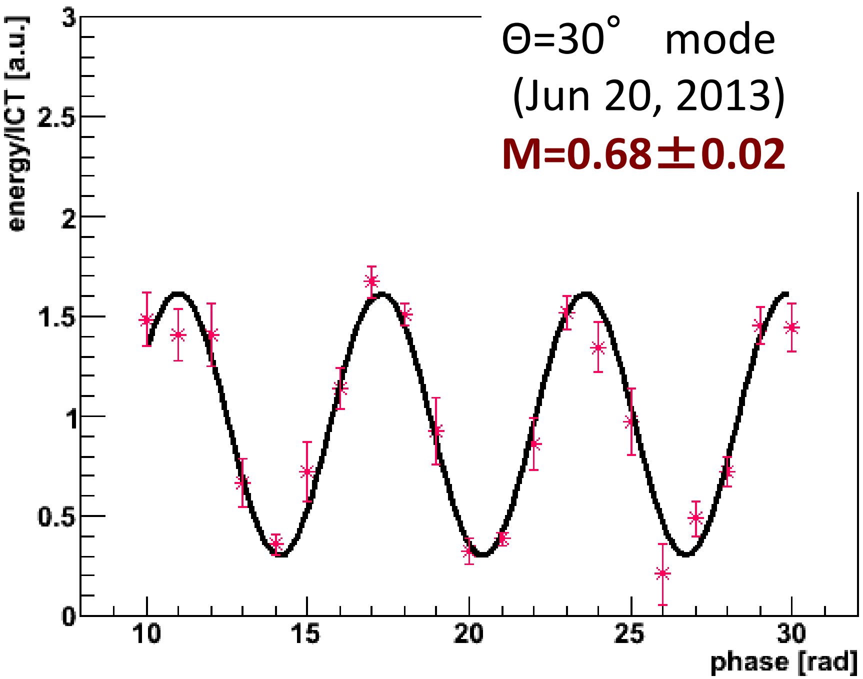
IPBSM : Installation at IP

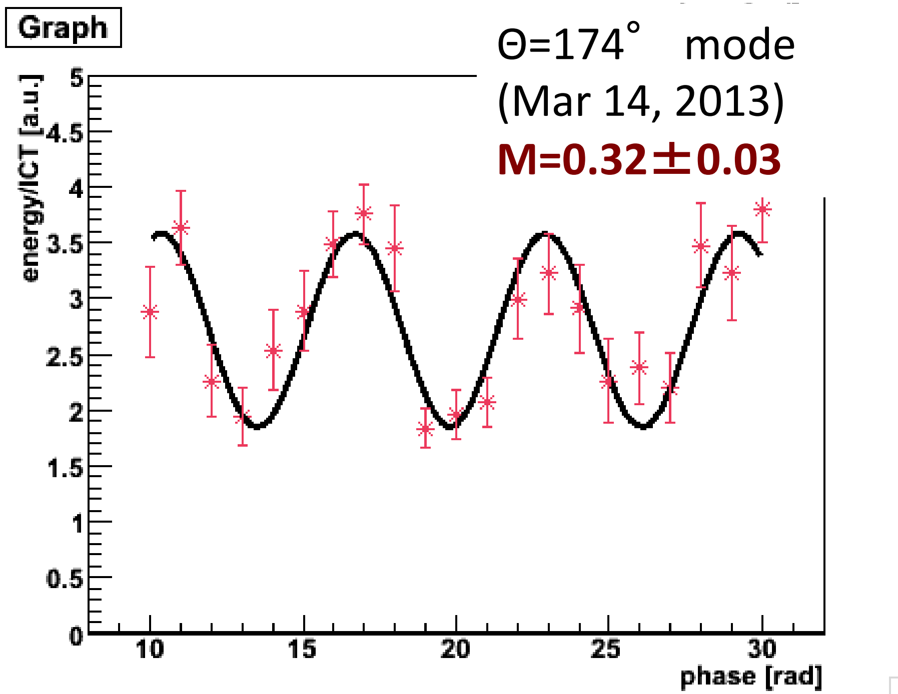


IPBSM : Example of beam size measurements

- *Study of M reduction factors are ongoing*



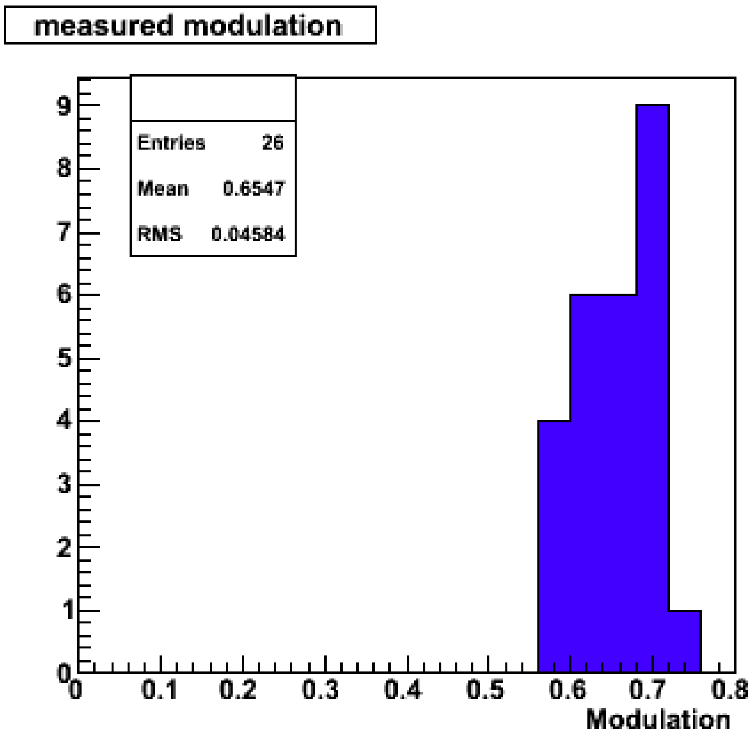




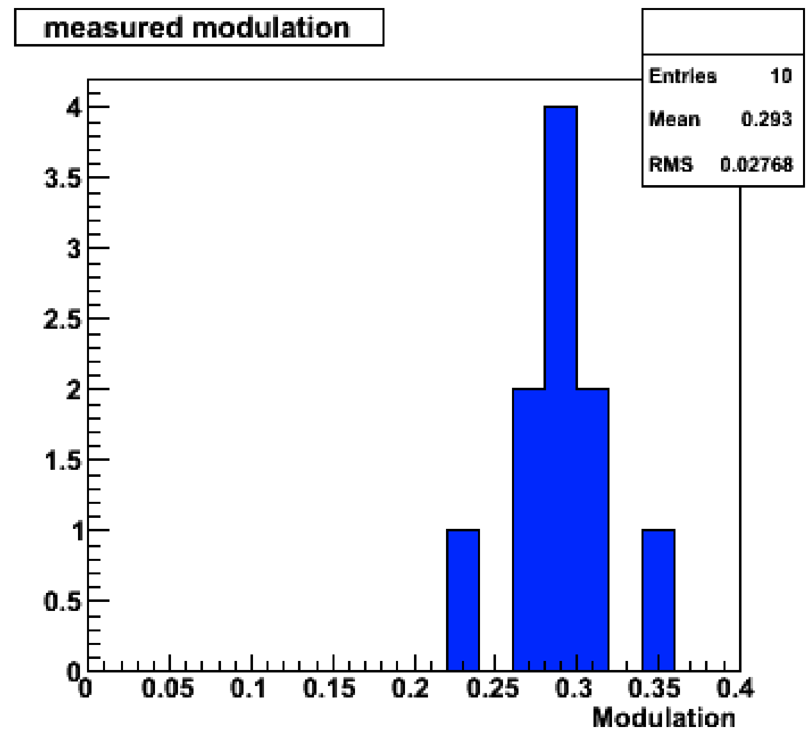
IPBSM : Demonstration of performance

- **5 ～ 10% stability** in consecutive fringe scans

Θ=30° mode
N=26 scans
(Jun 20, 2013
M=0.65±0.05



Θ=174° mode
N=10 scans
Mar 14, 2013
M=0.29±0.03



Conclusions (1)

- Successful program of beam instrumentation at ATF2
  - CBPM system operating well for 3 years
    - High resolution 250 nm (27 nm)
    - Calibration scale stable, low systematic effects
    - Measurements of small wakefields, important effect for optimisation of ATF2
  - OTR essential for ATF2 goals
    - Emittance measurement and coupling correction streamlined at ATF2
  - Novel Compton scattering systems : Laserwire and IPBSM
    - Laser setup and maintenance always a problem

Conclusions (2)

- IPBSM routinely measuring beams < 100 nm in vertical size
  - Shift towards study and reduction of systematic uncertainties
- Laserwire tests for ILC complete
  - Aspect ratio a problem, but can measure 1 micrometre beams
- Novel use of OTR could replace problematic LW but not for ILC/CLIC bunch trains
  - Achieved sub micrometre resolution
- Feedback systems work ongoing
- Beam instrumentation is in a good state of readiness for a linear collider, but more work is still needed

Other LC instrumentation at IBIC2013

- BPMs
  - CLIC low-Q BPMs (TUPC19, TUPC20)
- UV diffraction radiation beam size monitor
  - CESR-TA (WEAL3, WEPF18)
- Gas jet profile monitor (CLIC)
  - MOPF09
- Beam loss monitoring (CTF3)
  - WEPC43