Royal Holloway contribution to CLIC

Stewart T. Boogert, Pavel Karataev, Konstantin Kruchinin , Alexey Lyapin, Laurie Nevay

John Adams Institute at Royal Holloway

John Adams Institute for Accelerator Science

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Talk outline

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- Cavity beam position monitors (S. Boogert, A. Lyapin)
  - CLIC specific BPMs
- Wake-fields (S. Boogert, A. Lyapin, J. Snuverink)
  - Simulation, comparison with BPMs
- ILC Multi-bunch operation at ATF2 (A. Lyapin)
- Optical transition and diffraction radiation (P. Karataev, K. Kruchinin)
- Backgrounds and IPBSM (S. Boogert, L. Nevay)
  - Beam delivery simulation
- Two beam tuning (J Snuverink, activity mainly transferred to JAI@Oxford Ryan Bodenstein)
- **Proposed future work**
- **Resources**
- Conclusions

CLIC Cavity Beam position Monitors

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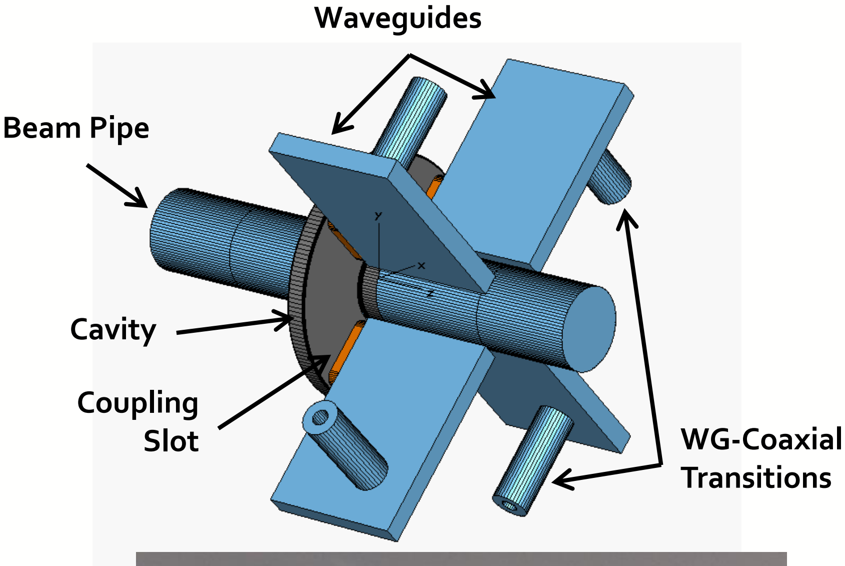
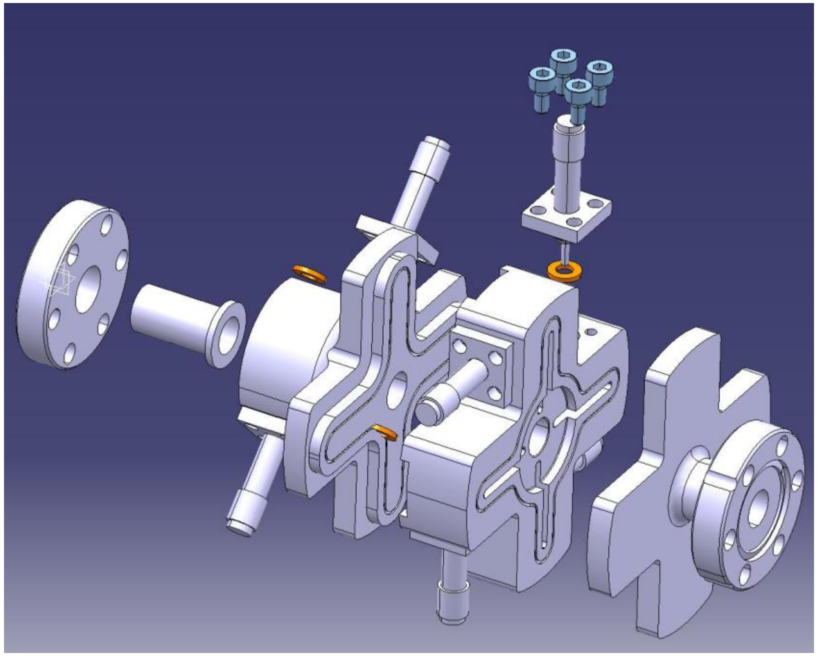
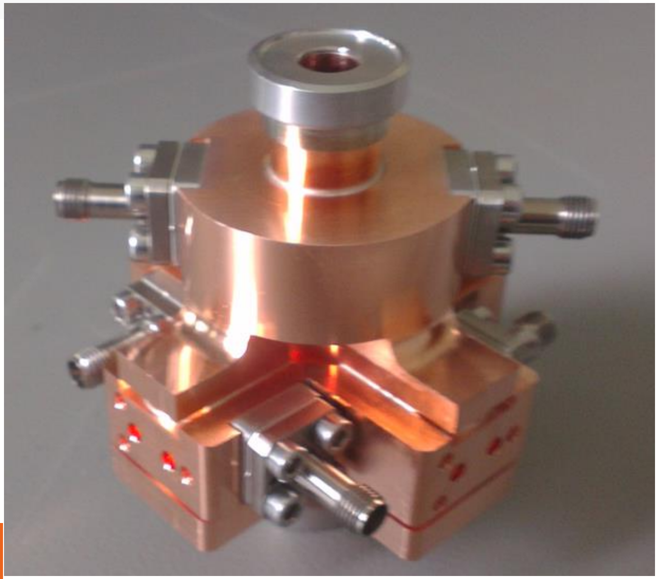
Stewart T. Boogert, Alexey Lyapin, Manfred Wendt, **Jack Towler**

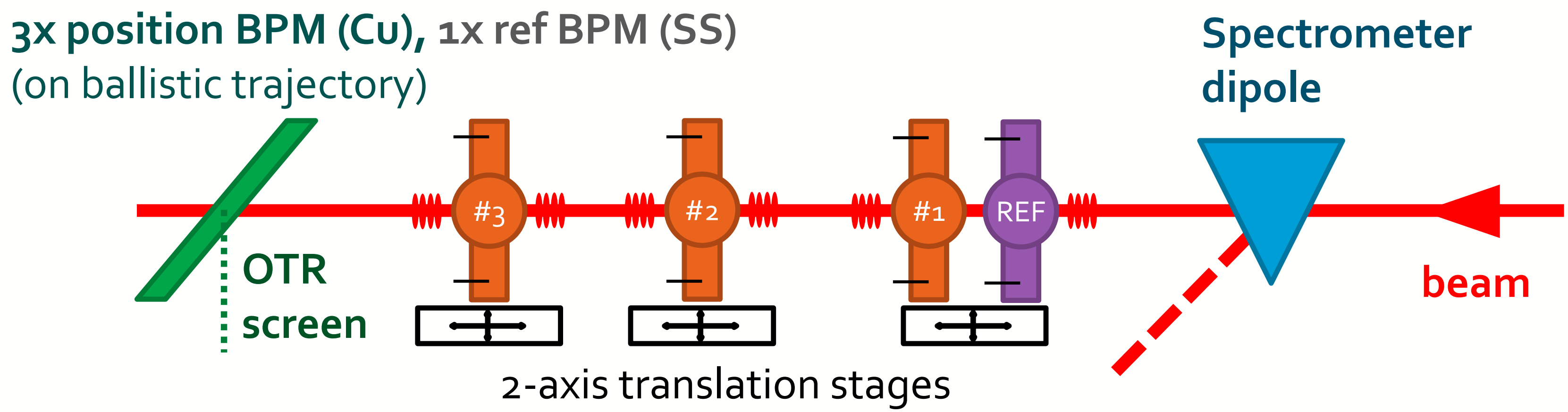
Position cavity



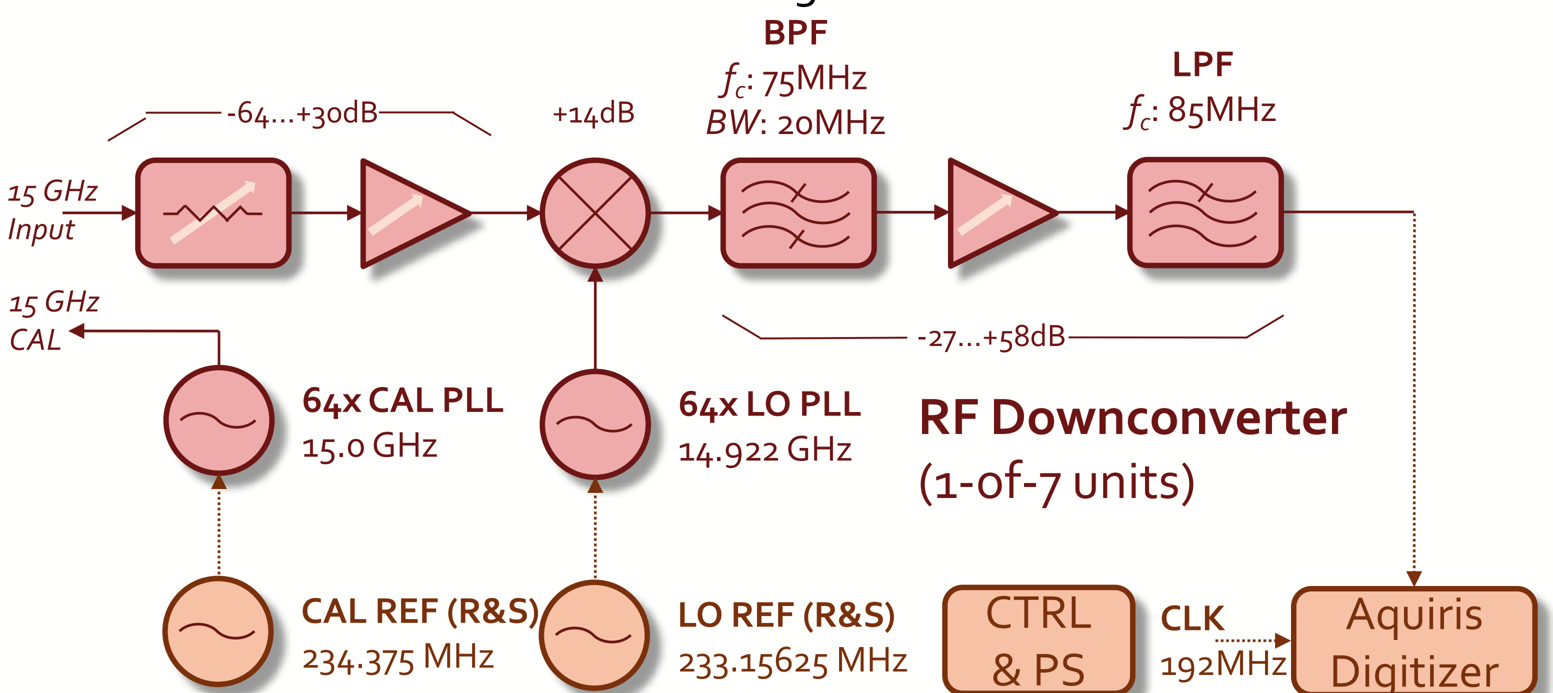




Cavity	Q_L	F_o /GHz
Reference	938	14.772
Predicted	500	15.0
Position	~830	14.996
Predicted	524	15.0

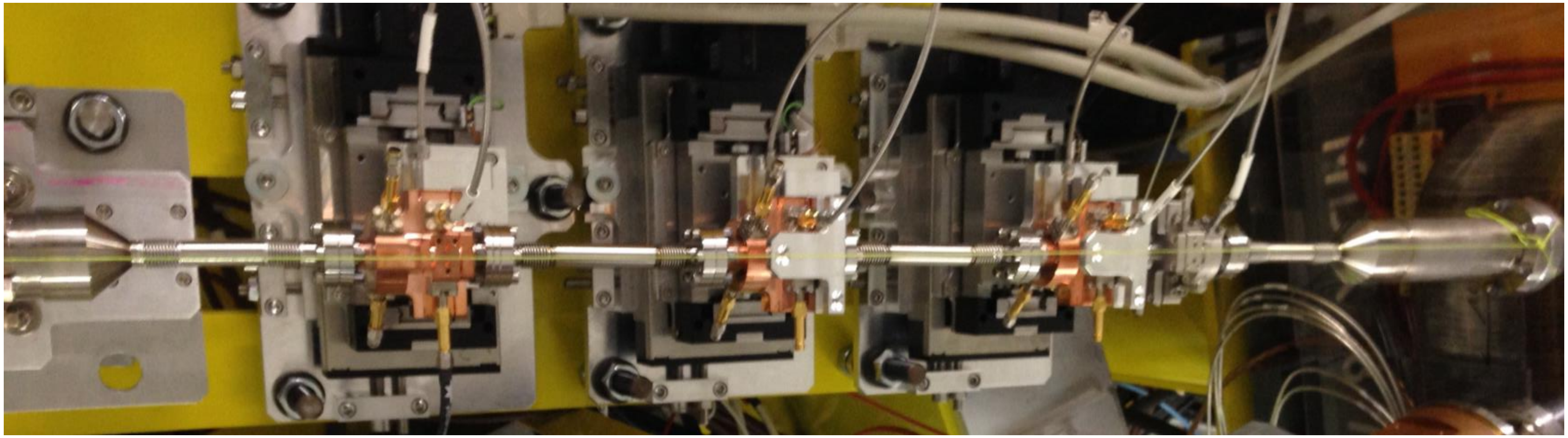


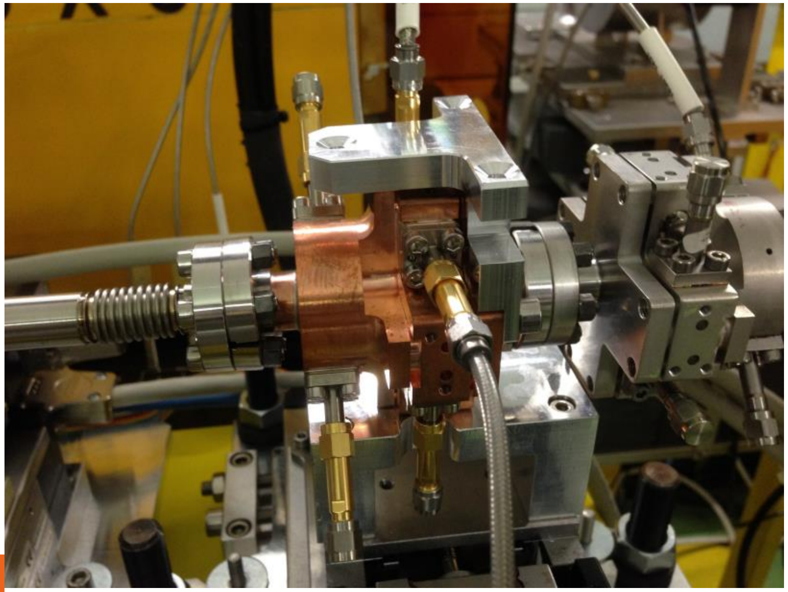
3x position BPM (Cu), 1x ref BPM (SS)
(on ballistic trajectory)
Spectrometer dipole
#3
#2
#1
REF
OTR screen
beam
2-axis translation stages



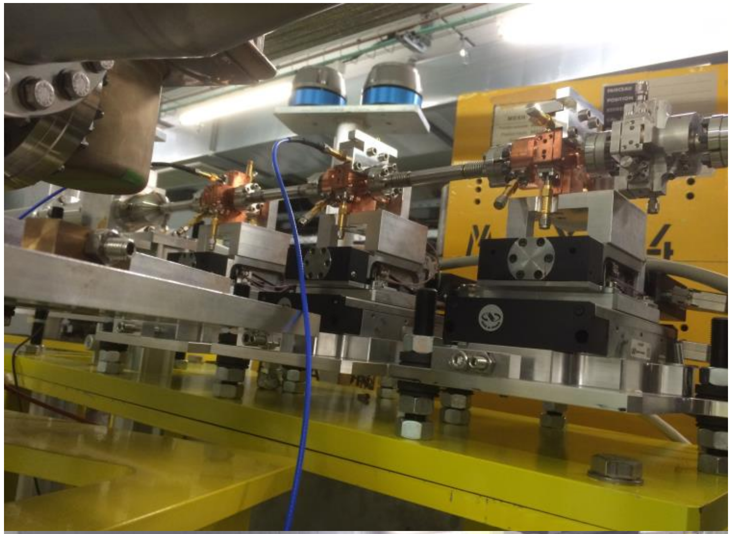
BPF
f_c: 75MHz
BW: 20MHz
LPF
f_c: 85MHz
-64...+30dB
+14dB
15 GHz Input
15 GHz CAL
-27...+58dB
64x CAL PLL
15.0 GHz
64x LO PLL
14.922 GHz
RF Downconverter
(1-of-7 units)
CAL REF (R&S)
234.375 MHz
LO REF (R&S)
233.15625 MHz
CTRL & PS
CLK
192MHz
Aquiris Digitizer

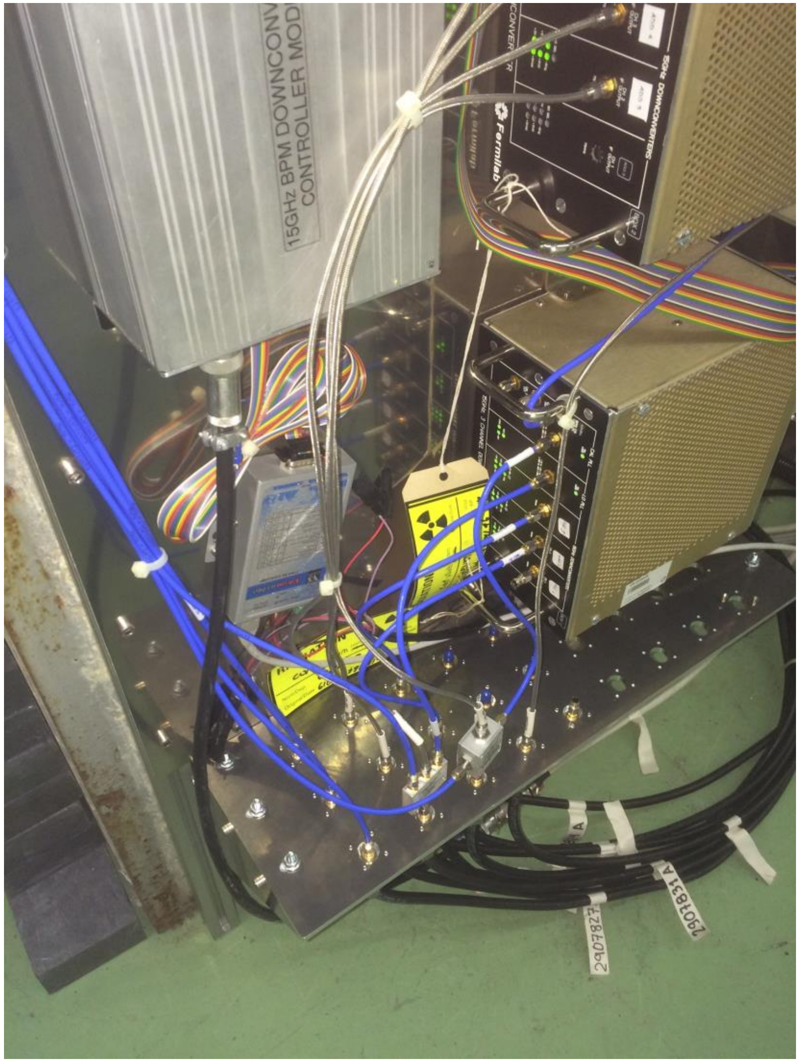
Photos of installed BPMs on beamline





Photos of installed movers and electronics

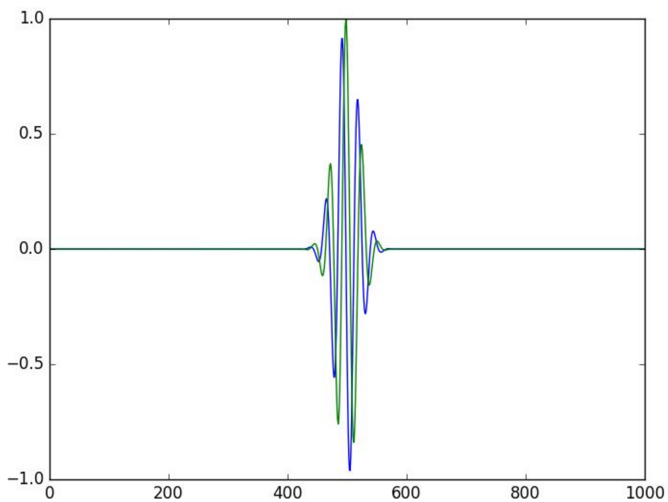




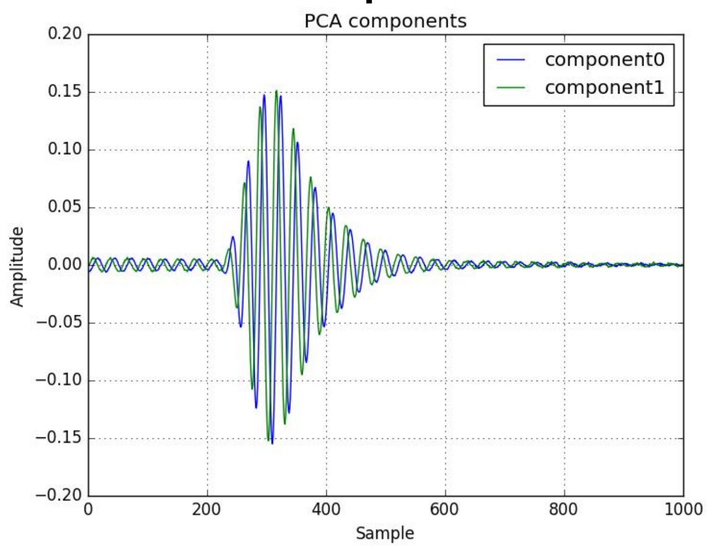
Signal processing

- 2 types of analysis used: Digital Down-Conversion (DDC) and Principal Component Analysis
- In both cases use a basis of windowed 2 orthogonal sin/cos-like signals
- DDC: Gaussian window, positioned arbitrarily
- PCA: Signal-derived window

DDC (sin/cos with Gaussian filter)



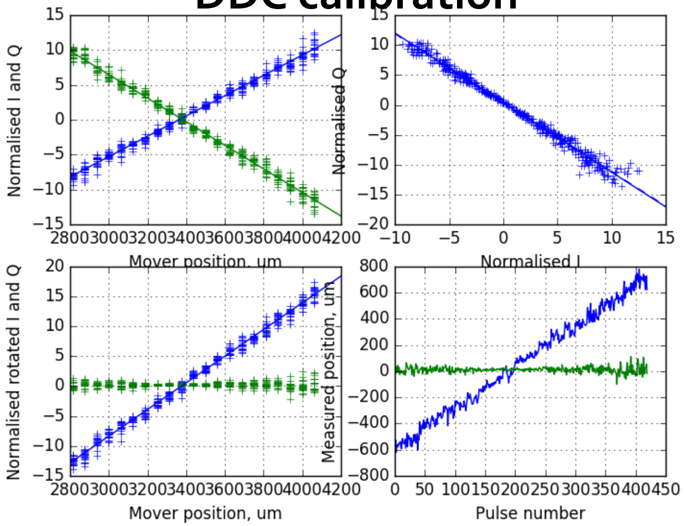
PCA components



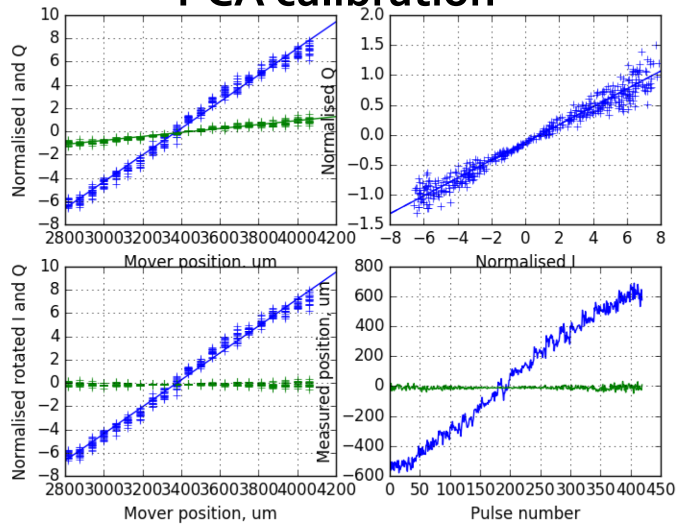
BPM Calibration

- Find the phase corresponding to the position
- Determine the position scale
- Use mover stages to ensure pure position offset (no angle) and high precision
- Currently 8-bit digitiser, so the dynamic range is reduced

DDC calibration



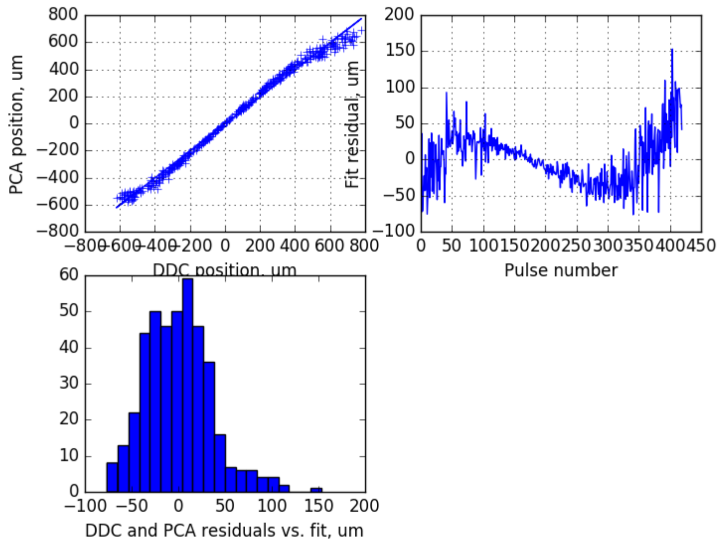
PCA calibration



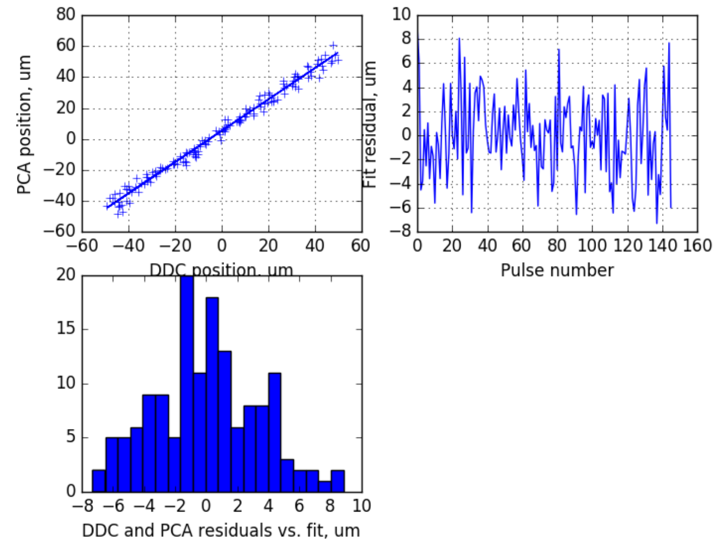
BPM Resolution

- Still commissioning BPM triplet (compare DDC and PCA to determine resolution for single BPM)
  - 6.2 um spread without a position cut
  - 3.3 um spread with a +/-50 um position cut

Wide range calibration(1 mm)



Narrow range calibration(100 um)



Wakefield simulations

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ATF2 – Ultra-small beam size diagnostic (BSM) (5)

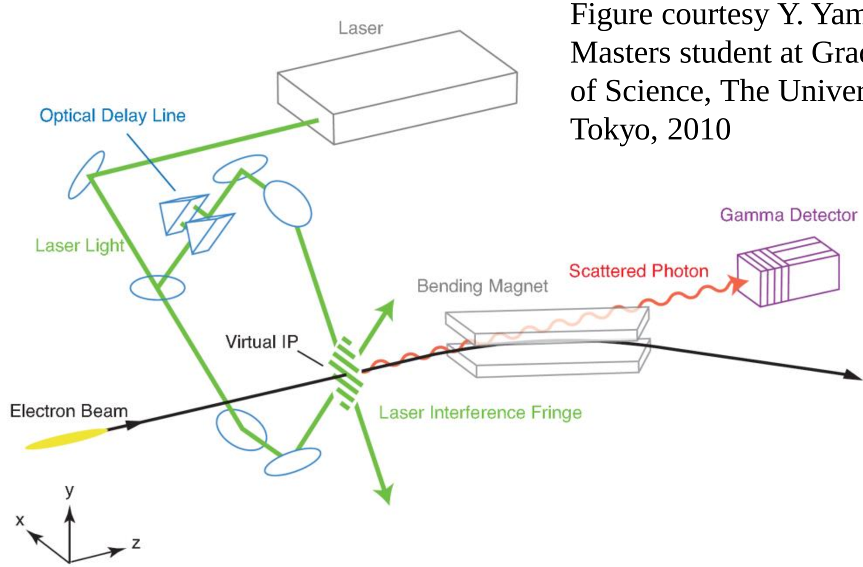
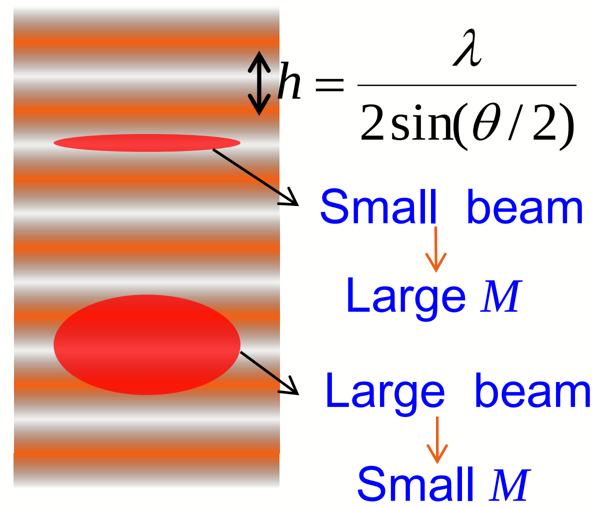
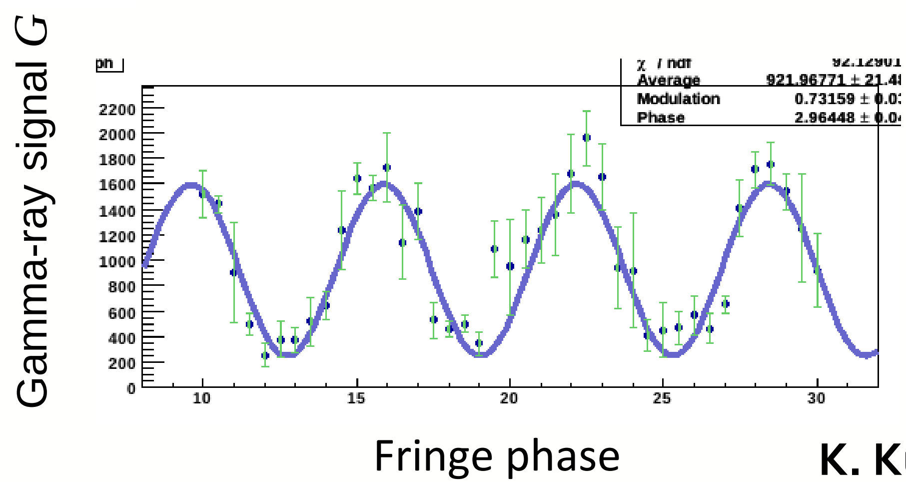


Figure courtesy Y. Yamaguchi, Masters student at Graduate School of Science, The University of Tokyo, 2010



Scan interference fringe phase,
Fit to measure modulation M:

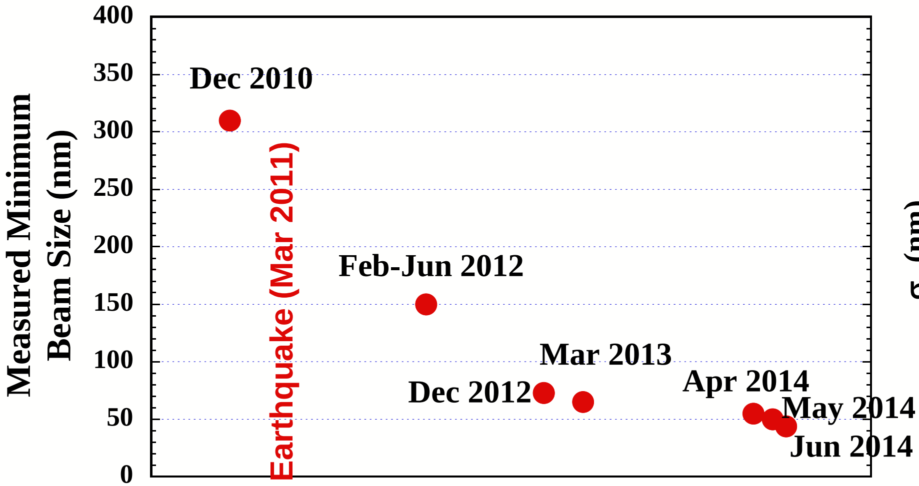
$$G(\phi) = G_0\left(1 + M\cos(\phi + \phi_0)\right)$$

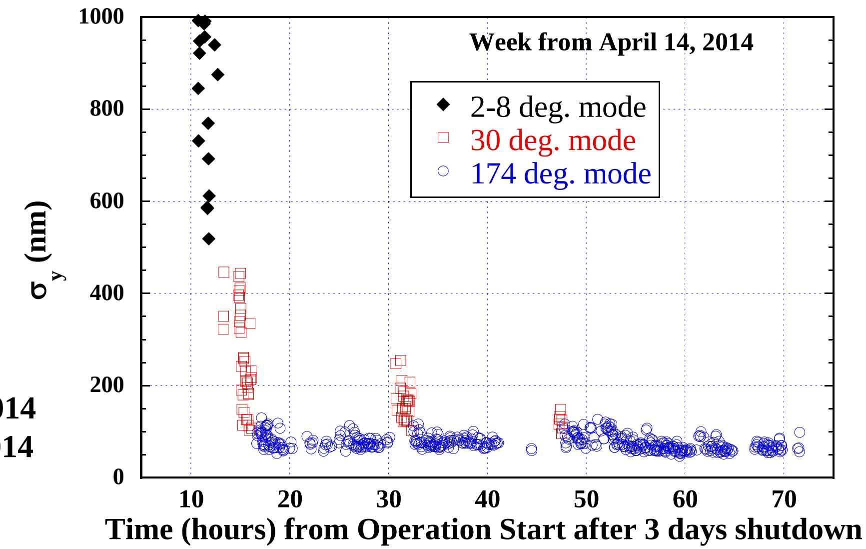


K. Kubo

ATF2 – Achieving small beam size (4)

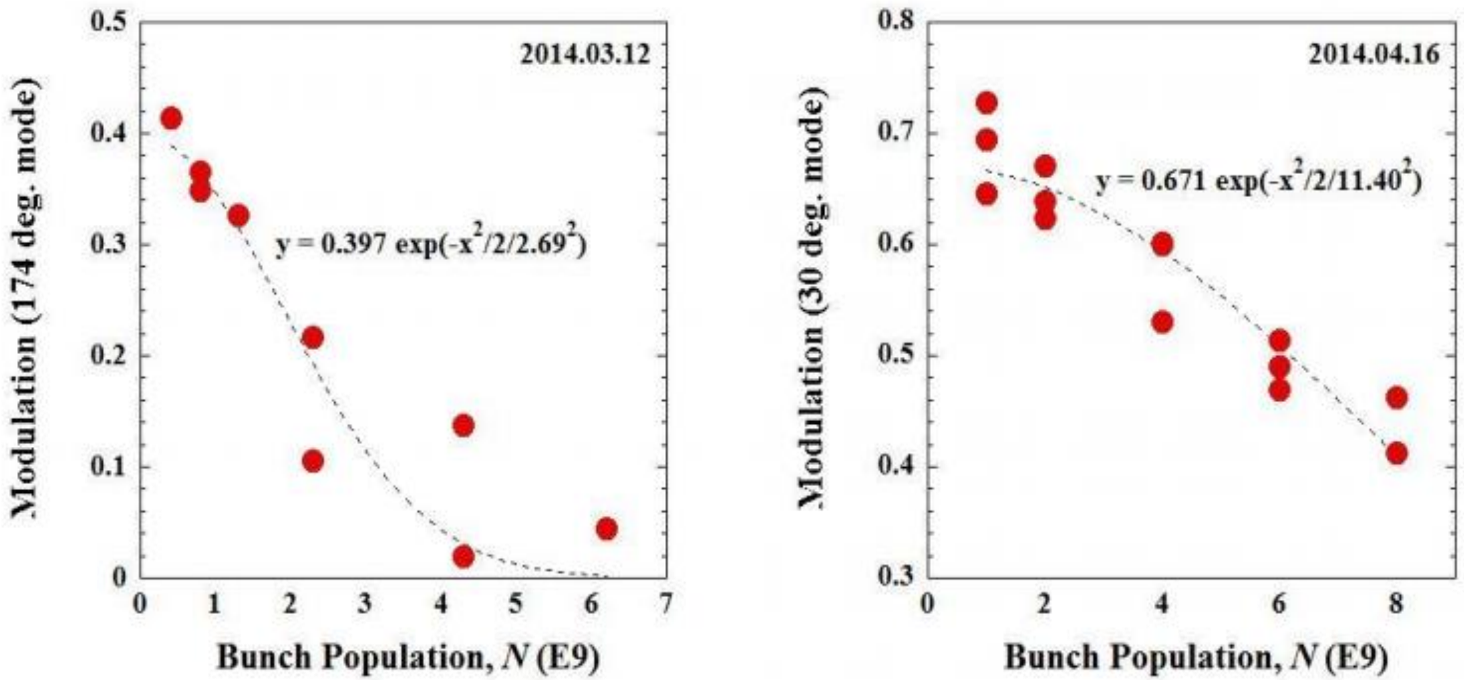
- ~44 nm beam size confirmed (design: 37 nm) at low intensity (June 2014)
- Small beam can be achieved repeatedly and quickly, even after machine shutdown
- Local Chromaticity correction was demonstrated
  - Without chromatic correction, beam size is ~450 nm
- Strong intensity dependence was observed. (It had not been expected.) → studies continued





K. Kubo

ATF2 – Motivation for wakefield studies at ATF2 (6)



- IPBSM modulation as function of bunch population. Measured with crossing angle 174 degrees (left) and 30 degrees (right).

Assuming $\sigma_y^2(q) = \sigma_y^2(0) + w^2 q^2$, w is fitted as 100 nm/nC.

ATF2 design bunch charge ~1.7 nC

K. Kubo

Wakefields (1)

- Wakefields are among the suspects to be causing the beam size growth in ATF2
- Intensity and orbit dependence
- Beam size improves with the optimisation of the position of strong wakefield sources
- Effect on the beam:
- Introduce a yz coupling (bunch tilt) perceived as apparent growth of the transverse beam size
- Can not be mitigated with optical elements of the beamline
- Important for ATF2 due to long bunches (~7 mm), less of an issue for linear colliders with shorter bunches

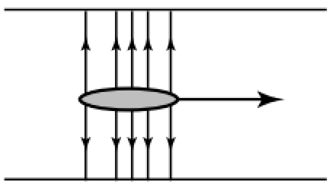
Wakefields (2)

- Created through interaction of the electromagnetic fields surrounding the beam with the walls of the beam chamber. Hence, two mechanisms:

K.L.F. Bane, A. Seryi, PAC07 , THPMS039

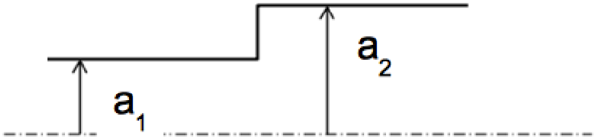
- Resistive wake – due to finite conductivity of the chamber walls

$$W(s) = \frac{Z_0 c}{2\pi^2 a^3}\sqrt{\frac{c}{\sigma s}}H(s)$$



- Geometric wake – due to geometric discontinuities in the chamber walls and resulting reflections

$$W(s) = \frac{Z_0 c}{\pi}\left(\frac{1}{a_1^2} - \frac{1}{a_2^2}\right)H(s)$$



- a aperture, H(s) beam distribution, σ conductivity

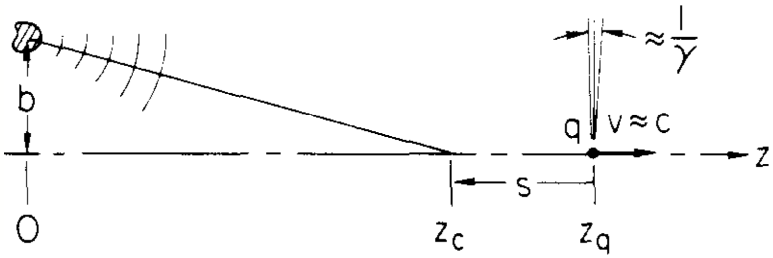
- Resistive wakes are important for short bunches in narrow apertures, so consider geometrical wakes for ATF2

Wakefields (3)

- Definitions of wake potentials:

$$W_z(\vec{r},\vec{r}',s) = -\frac{1}{q}\int_{z_1}^{z_2} dz\,[E_z(\vec{r},z,t)]_{t=(z+s)/c}$$

$$\vec{W}_\perp(\vec{r},\vec{r}',s) = \frac{1}{q}\int_{z_1}^{z_2} dz\left[\vec{E}_\perp + c(\hat{z}\times\vec{B})\right]_{t=(z+s)/c}$$



Catch-up effect

$$z_c \approx \frac{b^2 - s^2}{2s}$$

- Panofsky-Wenzel Theorem:

$$\frac{\partial \vec{W}_\perp}{\partial s} = \vec{\nabla}_\perp W_z$$

P.B. Wilson, Introduction to wakefields and potentials SLAC-PUB-4547

- For a pencil beam:

Dipole kick factor

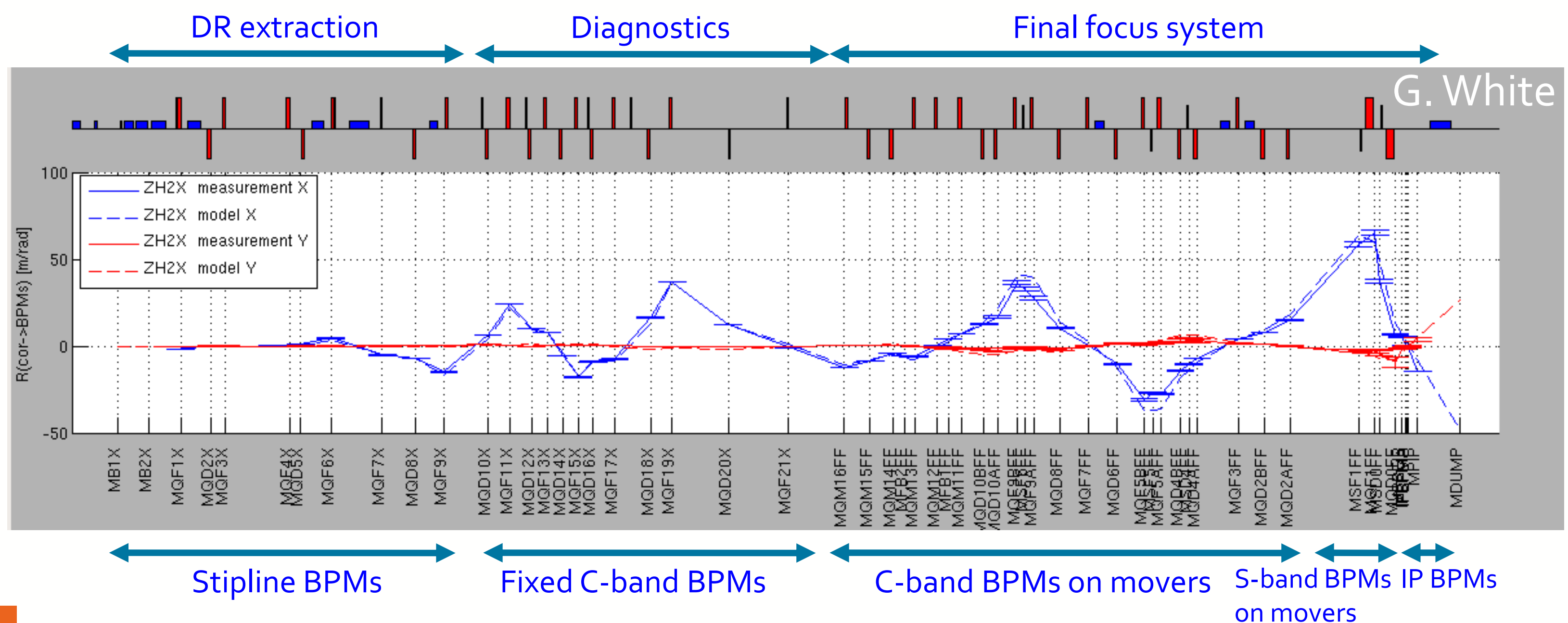
$$W_{\rm avg}(\bar{y}) = \frac{\int_{-\infty}^{\infty} W(z,\bar{y})\rho(z){\rm d}z}{\int_{-\infty}^{\infty}\rho(z){\rm d}z} \approx \frac{\bar{y}\int_{-\infty}^{\infty} W_n(z)\rho(z){\rm d}z}{\int_{-\infty}^{\infty}\rho(z){\rm d}z} = \kappa_\perp \bar{y}$$

Wakefields (4) – propagation of wakefield kicks

- The kick produced by wakefields propagates down the beamline according to the optics:

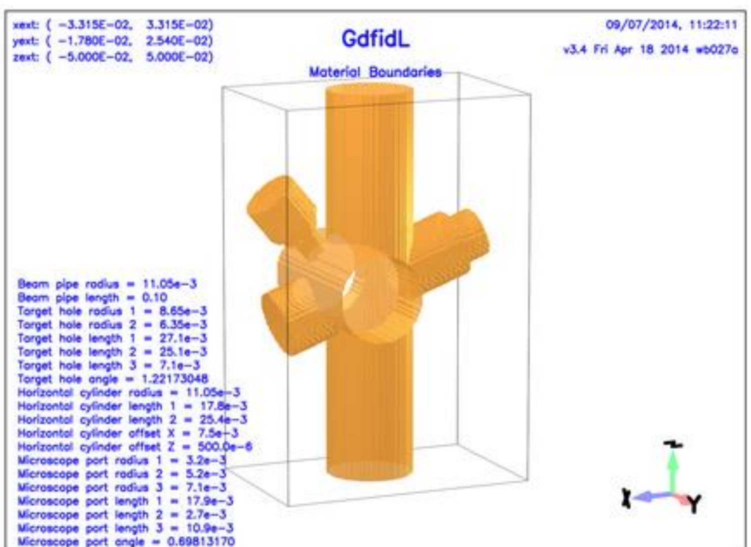
$$\Delta y \approx R_{34,a\to b}\frac{e\bar{y}}{E}\int_{-\infty}^{\infty} W_n(z)\rho(z)\mathrm{d}z\,, \quad R_{34,a\to b} = \sqrt{\beta_a\beta_b}\,\sin(\phi_b - \phi_a)\,.$$

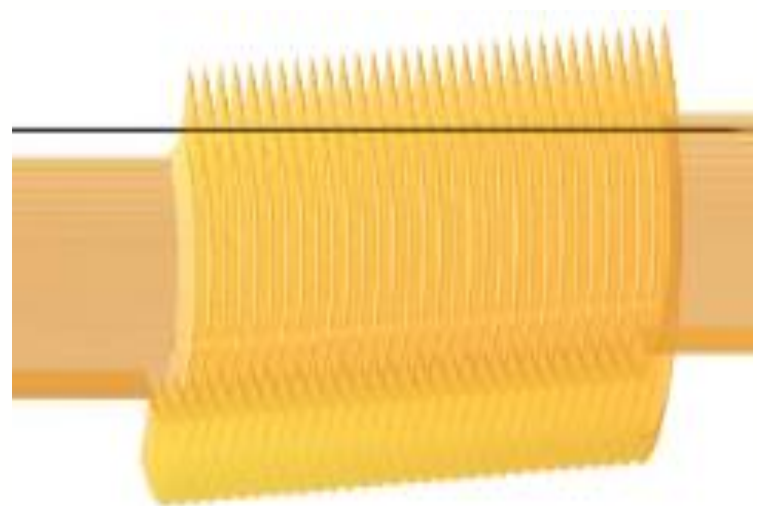
- This is similar to an excitation with a steering magnet for optics checks



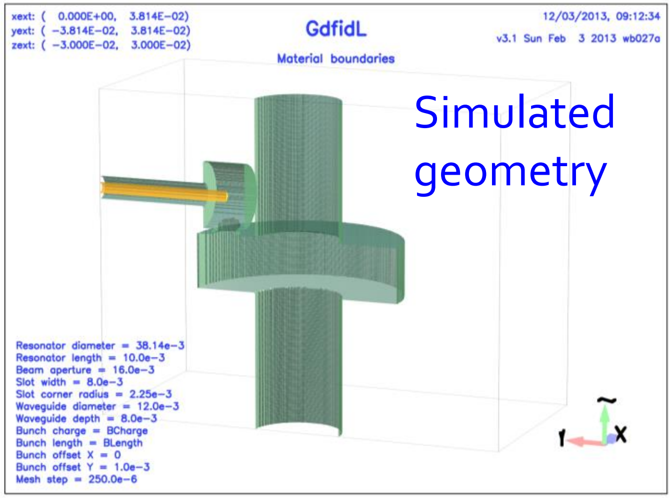
Wakefield simulations (1)

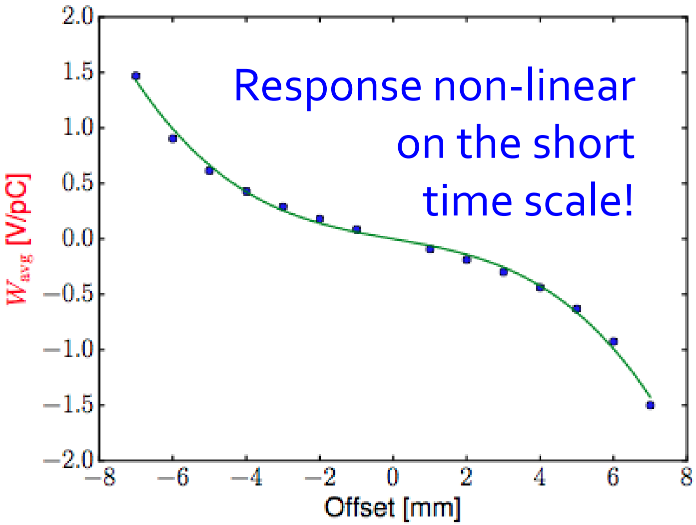
- Simulations done with a time domain FDTD solver (part of GdfidL software)
- gdfidl.de
- Geometries are meshed using a cubic mesh with diagonal fillings
- The beam is represented by a line charge travelling parallel to z-axis
- Most simulations are done for the nominal 7 mm bunch length (RMS)
- Typical mesh size 0.25 mm, 0.1 mm for more complex structures, such as bellows



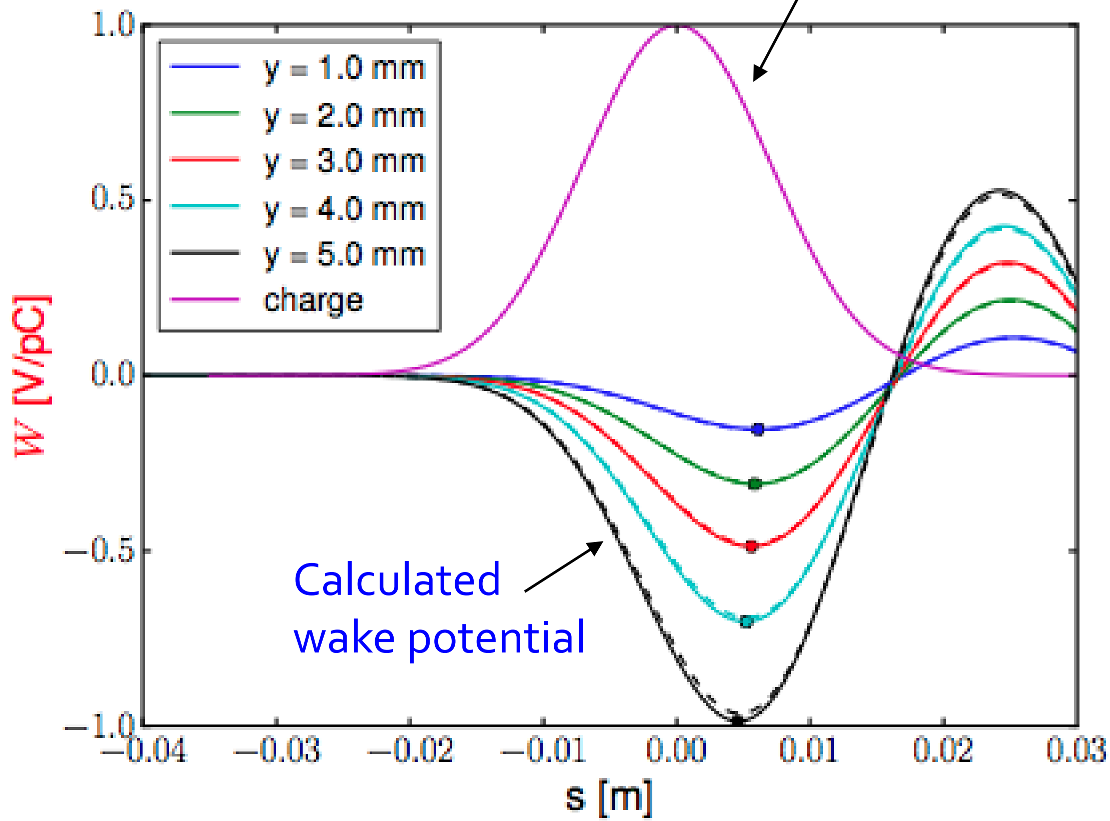


Wakefield simulations (2)





- Bunch length 7 mm, charge 1 pC
- GdfidL (solid) and ACE3P (dashed) results for a comparison



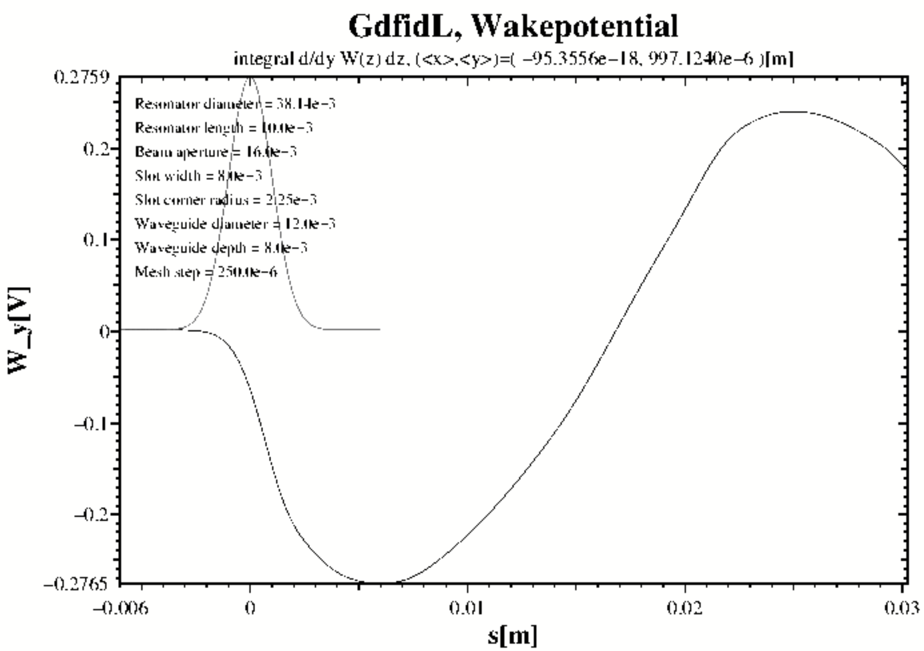
Wakefield simulations – component summary (3)

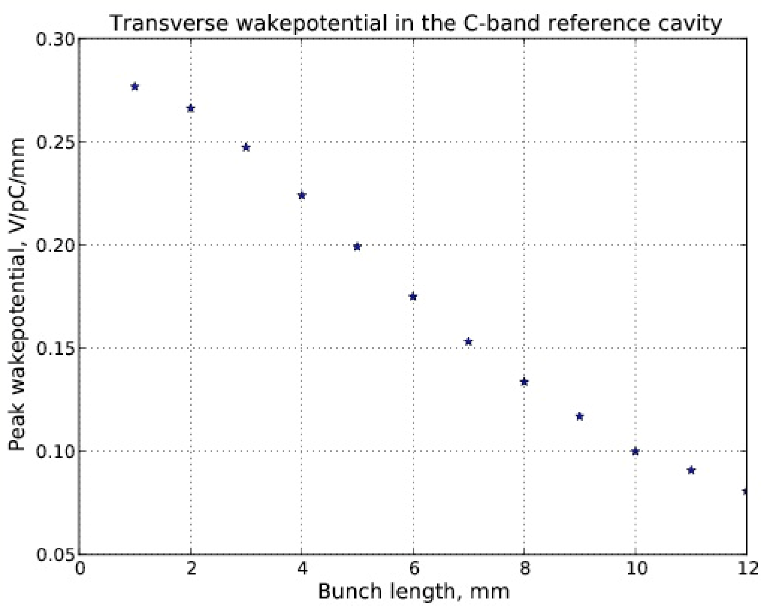
Element	Peak Wake (V/pC/mm)	Dipole kick factor (V/pC/mm)	Approximate quantity	Total
Bellows (unshielded)	0.10	0.06	100	6.00
Vacuum flange+step	0.06	0.04	100	4.00
C-band position	0.11	0.06	40	2.40
Vacuum flange	0.04	0.02	100	2.00
C-band reference	0.15	0.09	1	0.09
Vacuum ports(X)	0.07	0.05	6	0.30

- Offsets and beta function are important (not taken into account here)
- Most bellows and adjacent flanges are now shielded
- Position cavities are likely to be much better aligned compared to other elements
- Not all components have been analysed, exact geometries are rarely known!

Wakefield simulations – bunch length dependency (4)

- Typical dimension in the ATF2 beamline is ~25-50 mm dia, strongest resonances in C-band (not only cavities!) → strong dependency on the bunch length
- 2 effects related to the bunch length:
- Peak wake potential decreases with increasing bunch length
- Shorter bunch may not "see" the peak of the wake due to the catch-up effect





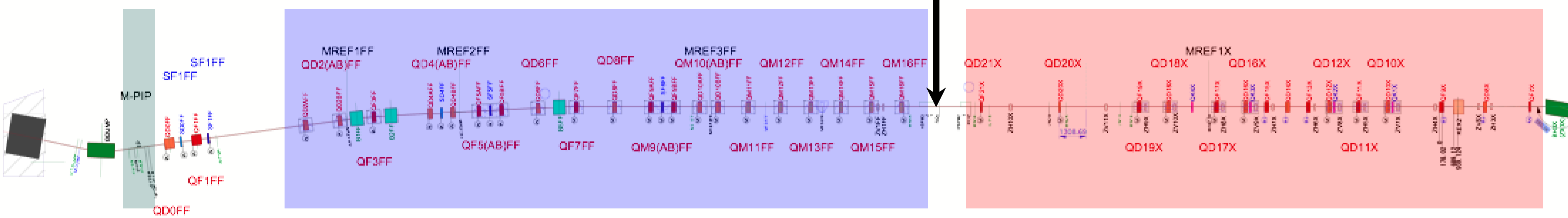
Cavity BPM system at ATF2 (1)

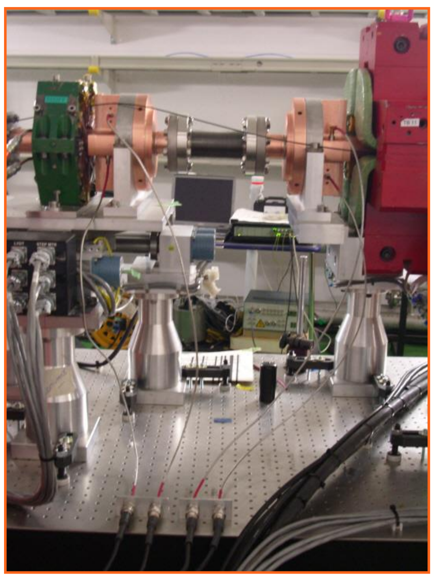
IP region
(4 BPMs)

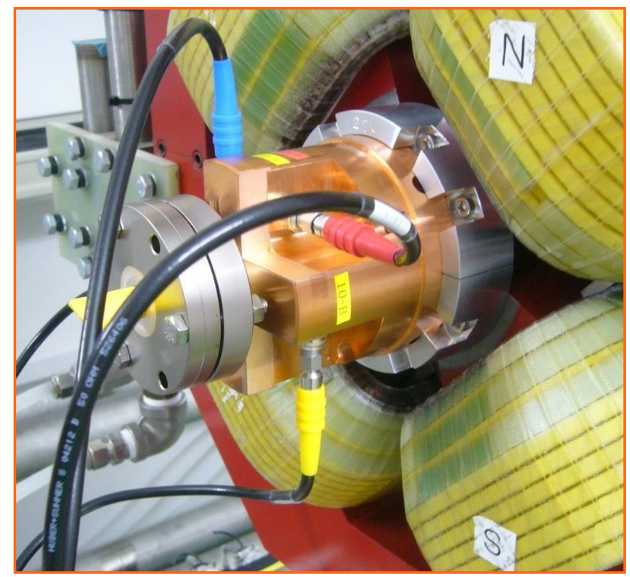
C-band BPMs
(on movers)

BPM test area

Strip line/Cavity BPMs
(mounted rigidly)



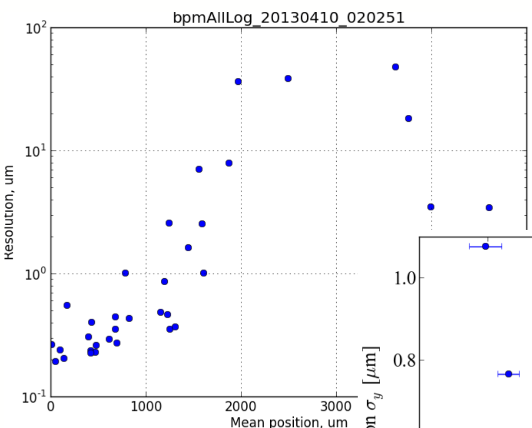


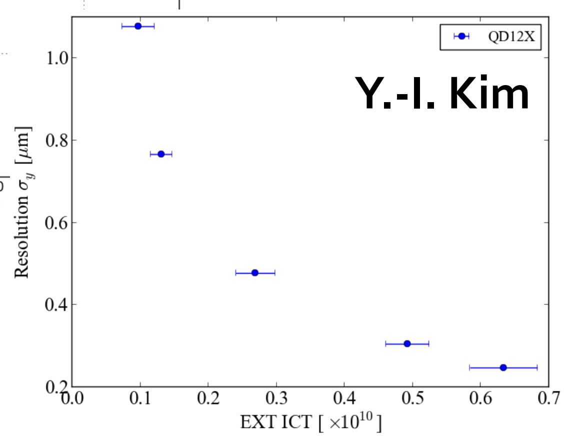


Cavity BPM system at ATF2 (2)

- Standard resolution around 200 nm
- Jitter-subtracted calibration – precision ~1 %
- Compensation for trigger timing variations
- Compensation for electronics drifts < 1% stability
- Large x or low q → degraded resolution

Try	With jitter		Jitter subtracted	
	Scale	IQ rotation	Scale	IQ rotation
1	-100.84	-0.0223	-101.14	-0.0201
2	-96.94	-0.0254	-100.42	-0.0197
3	-89.44	-0.0108	-100.15	-0.0130
4	-108.79	-0.0138	-99.44	-0.0151
5	-99.80	-0.0203	-100.83	-0.0189
6	-90.16	-0.0233	-101.09	-0.0249
7	-103.30	-0.0378	-101.26	-0.0243



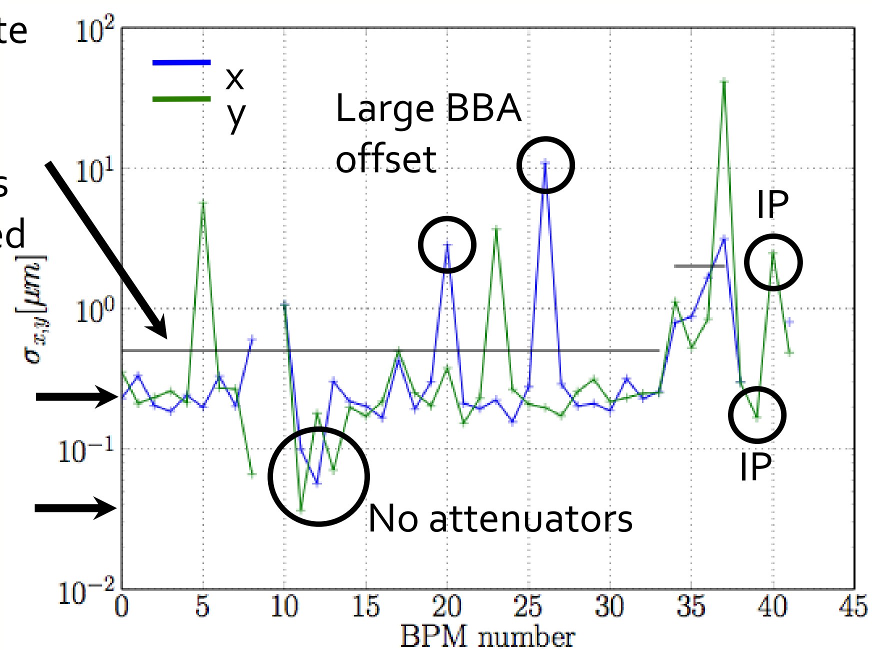


Y.-I. Kim et al. PRSTAB, 15, 042801, 2012

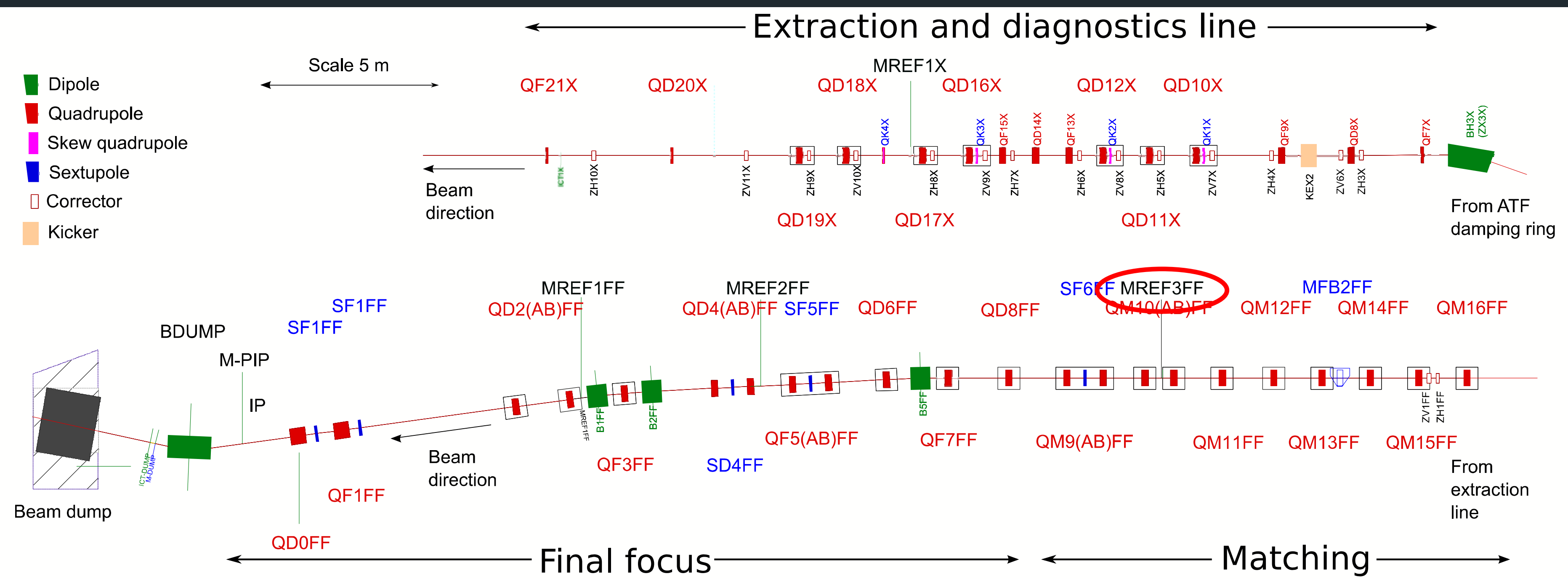
Lines indicate cut, at which BPM is labelled bad

200 nm

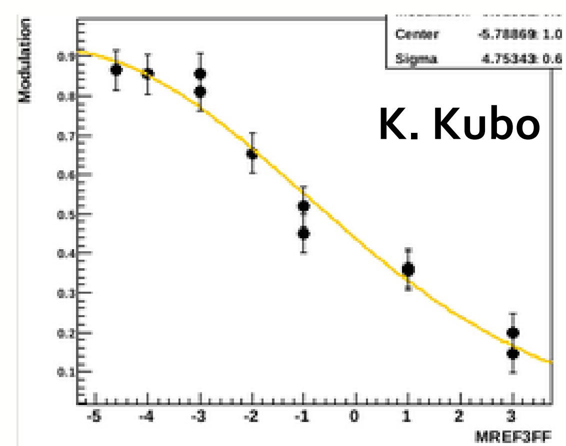
40 nm



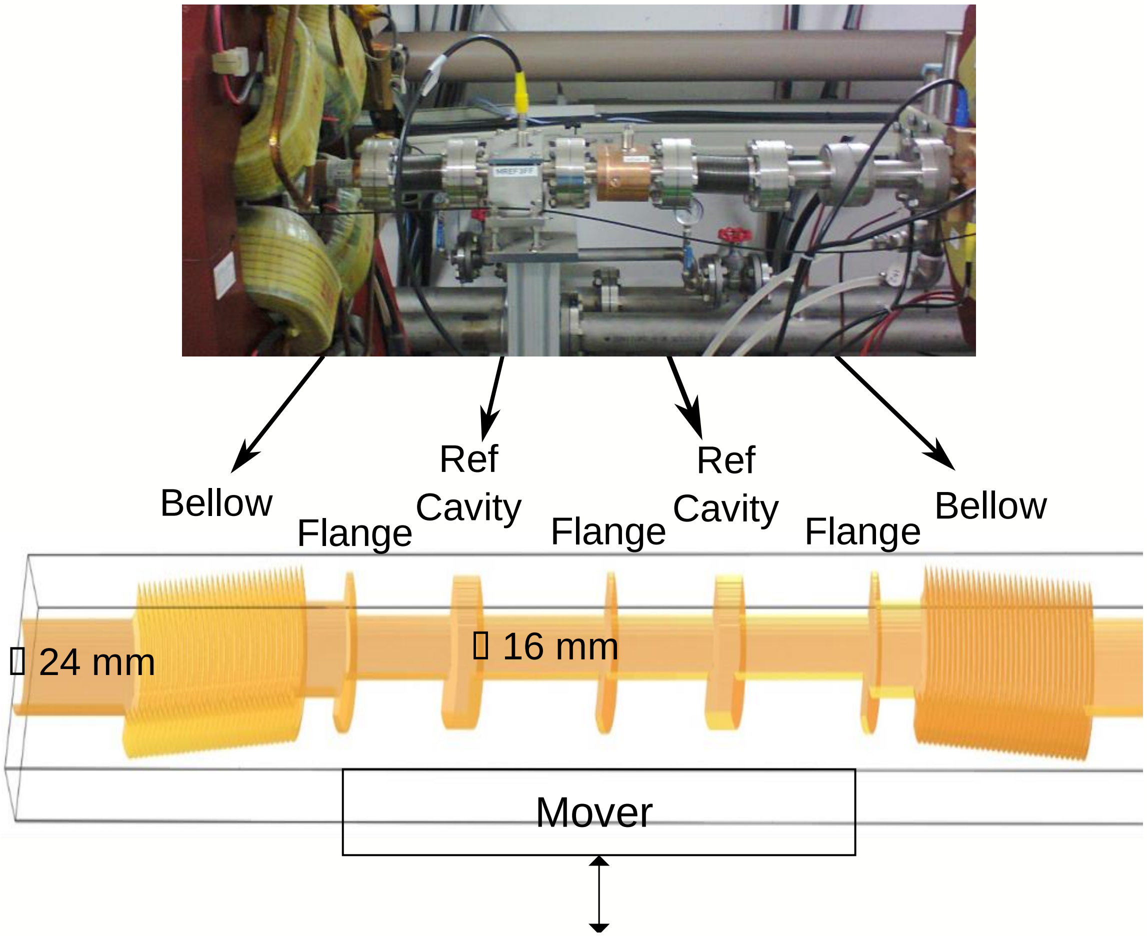
Wakefield source setup (1)

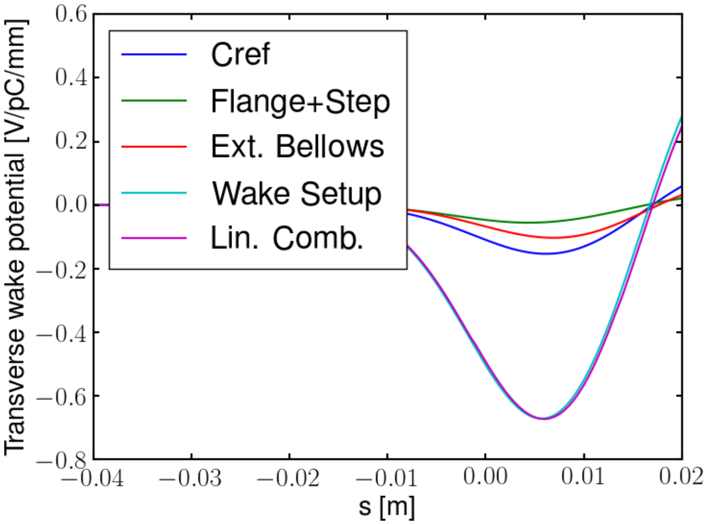


- 2 reference cavities on mover at high beta location ("MREF3FF"), later replaced by a collimator and unshielded bellows on independent movers
- Study and measure wakefield effects
- Partially compensate wakefields from other sources



Wakefield source setup (2)

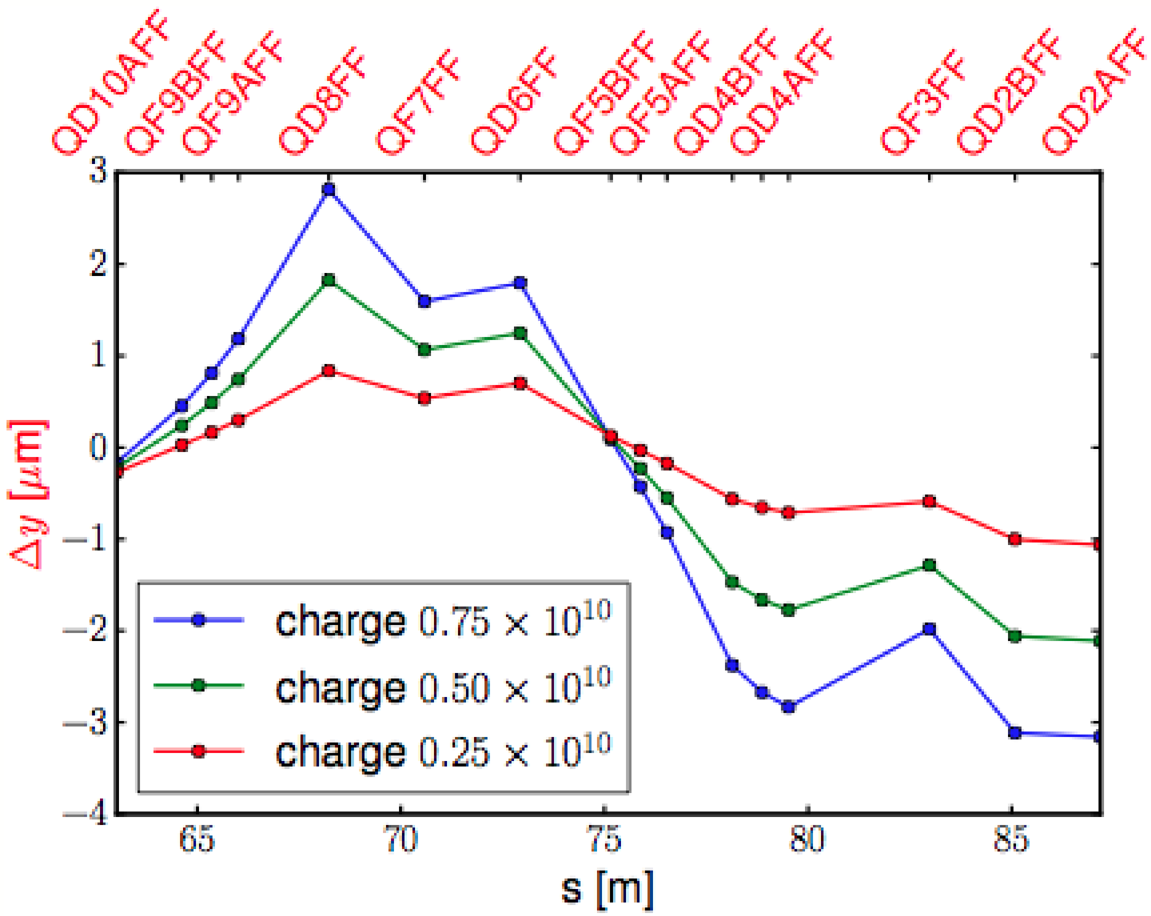




- Analysed every component separately and the whole setup
- Linear combination in agreement as expected
- Considerable contribution from ancillary components, geometries to the best of our knowledge

Tracking simulations

- Wake potentials imported in PLACET (tracking code), implemented by J. Snuverink
- Realistic simulation of the wakefield effects
- Observing the orbit change
- Also longitudinal wakefields added (only ~1% effect on orbit change)
- Offsets follow beta-functions



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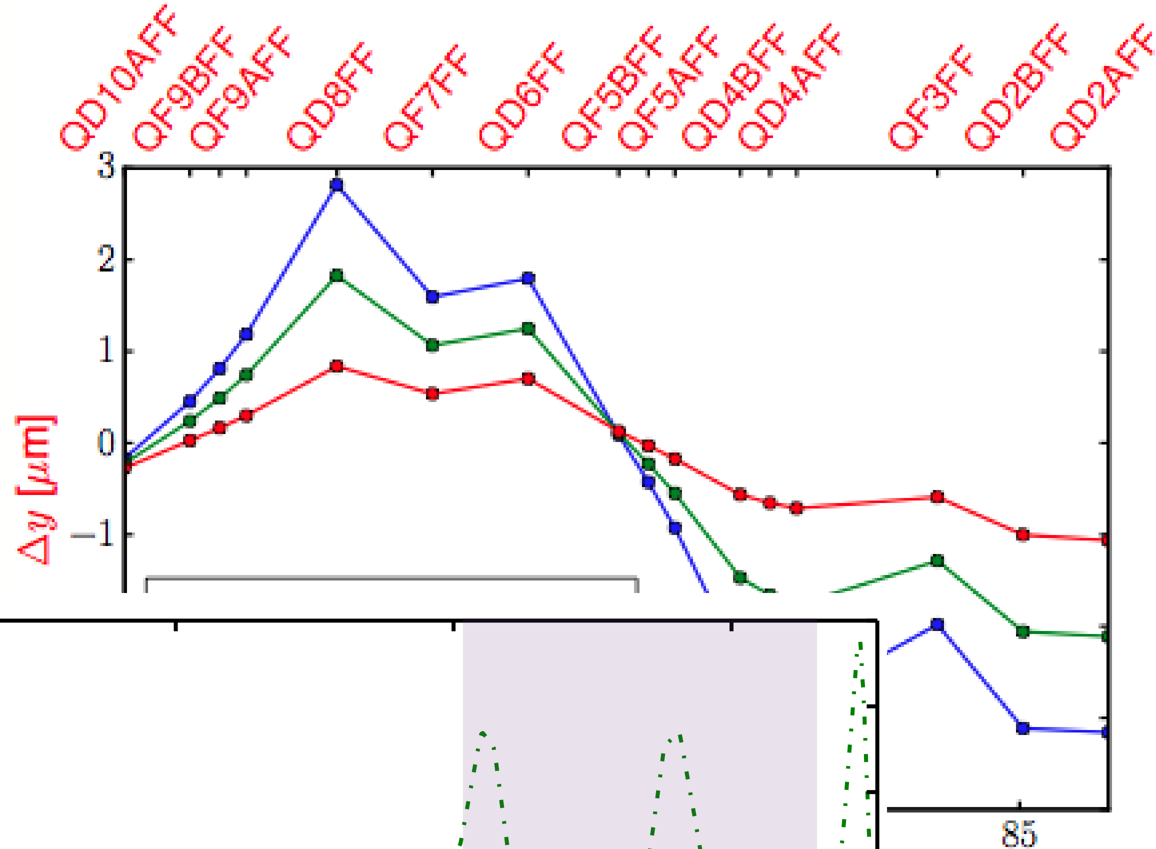
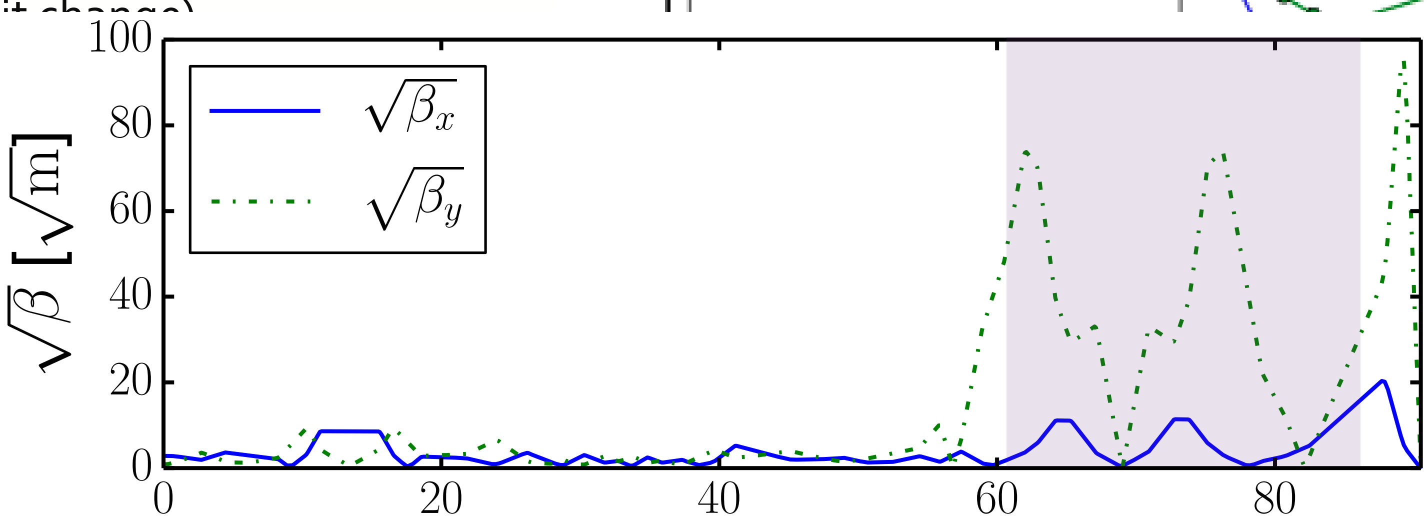


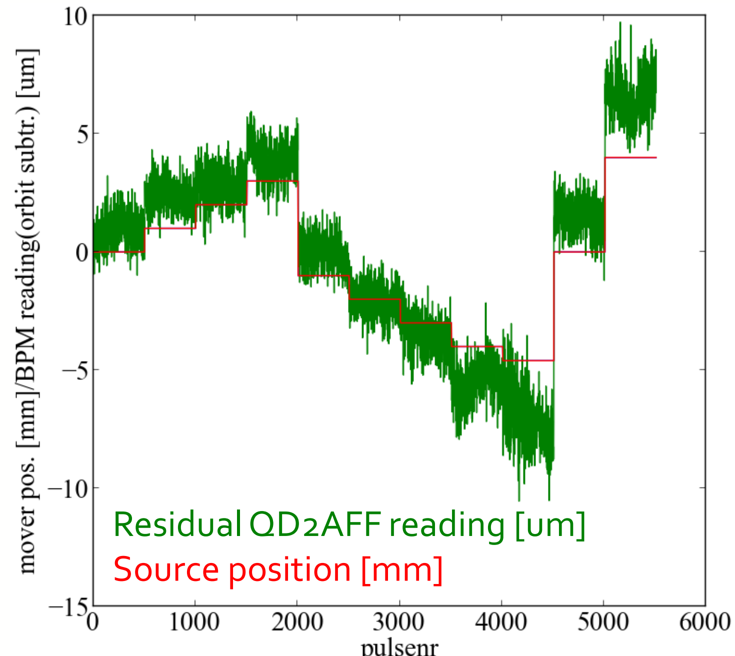


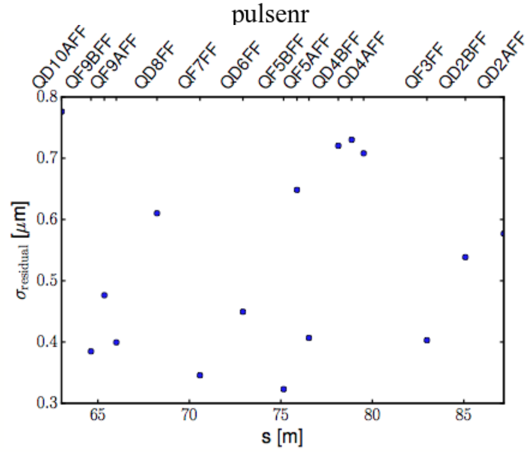
Measurements (1)

- Take all BPM readings when setup is in initial position and find correlation between upstream (before the wakefield source) and downstream BPMs by matrix inversion
- Pseudo-inverse using SVD (as we have noisy over-constrained data) for correlation matrix **X**: **A** (n_1 x *m*) – upstream BPMs; **B** (n_2 x *m*) – downstream BPMs; **R** (n_2 x *m*) – matrix of residuals:

$$\mathbf{A}\,\mathbf{X} = \mathbf{B} \qquad \mathbf{R} = \mathbf{A}\,\mathbf{X} - \mathbf{B}$$

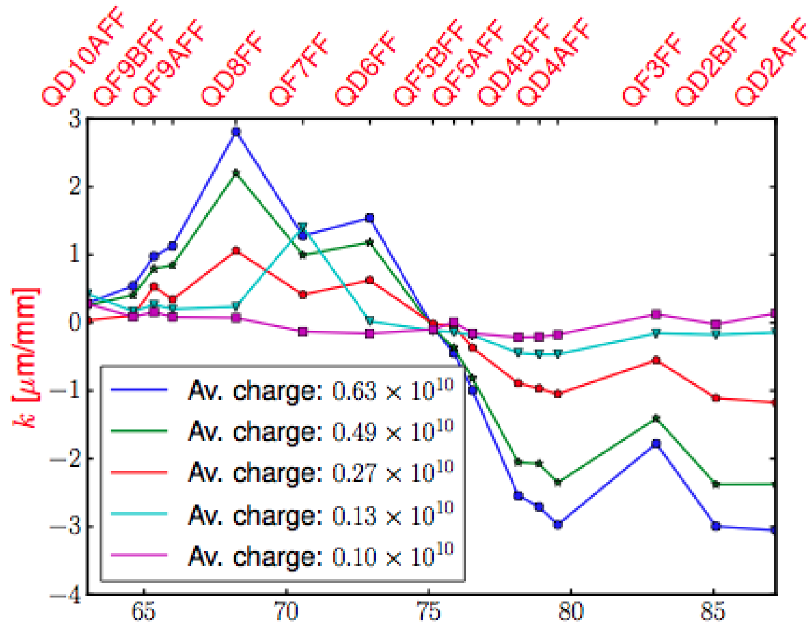
- Residual indicates the precision of the orbit reconstruction (but here error on the mean!)
- Subtract the projected orbit pulse by pulse in *wakefield* data using the *same* correlation matrix
- Wakefield kick remains in the residual

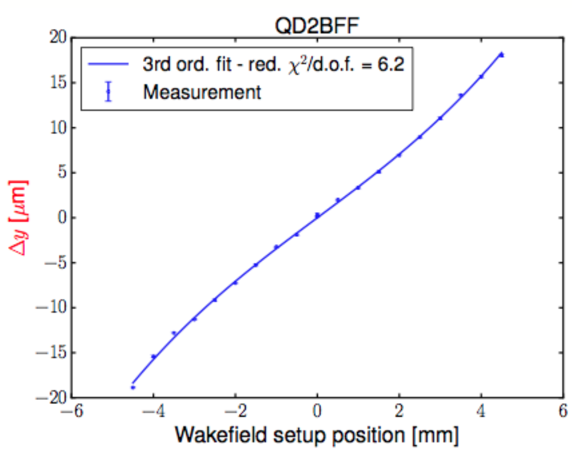


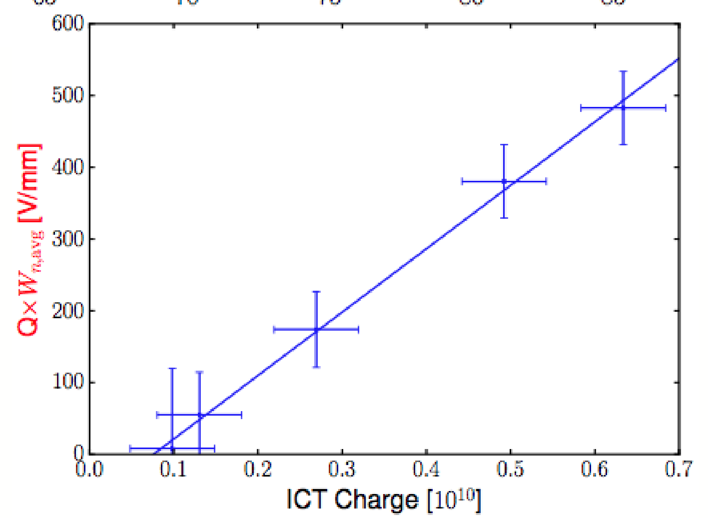


Measurements (2)

- Clear correlation seen for all downstream BPMs with expected orbit pattern
- Charge dependence as expected
- Orbit reconstruction is degraded at low charge due to reduced BPM resolution
- ICT pedestal and charge calibration may be a little off
- Non-linearity observed

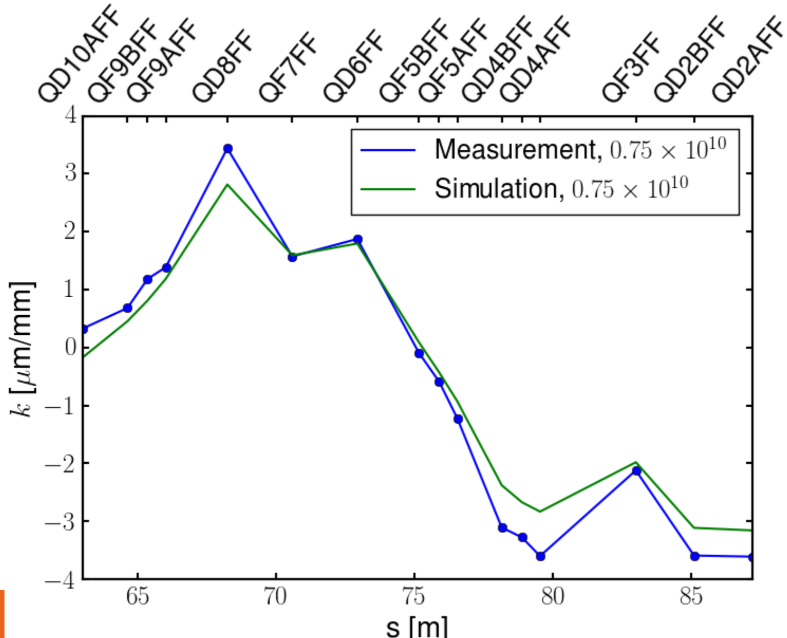


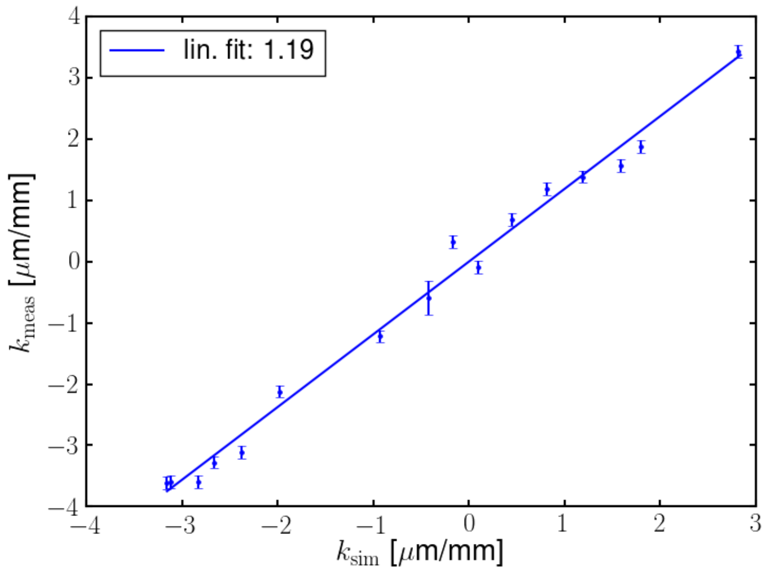




Measurements (3)

- Measured orbit shape agrees well, about a factor 1.2 between measurement and simulation
- Other uncertainties (apart from the exact geometry of the source)
  - Bunch length: about half a mm in DR (not measured in EXT), effect on wakefield 5-10%
  - Bunch charge: ICT calibration error 5-10%
- PRSTAB paper published





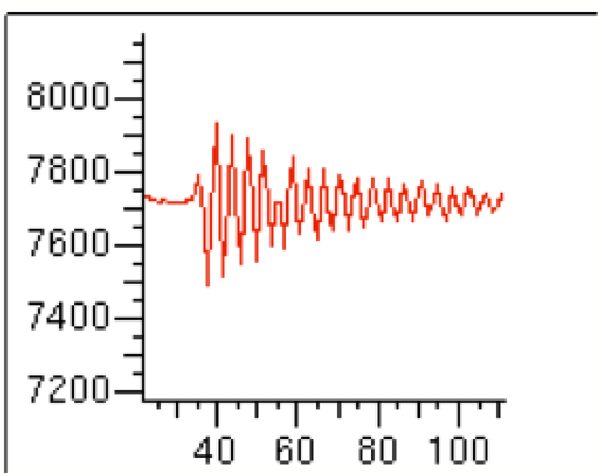
ILC Cavity Beam position Monitors (multi-bunch operation)

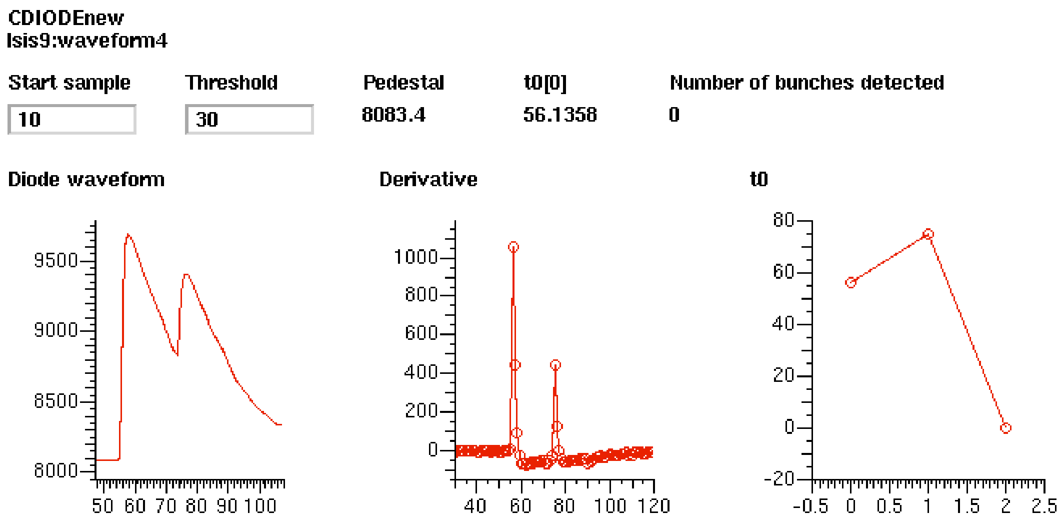
ROYAL HOLLOWAY UNIVERSITY OF LONDON

Stewart T. Boogert, Konstantin Kruchinin, Alexey Lyapin, Emi Yamakawa

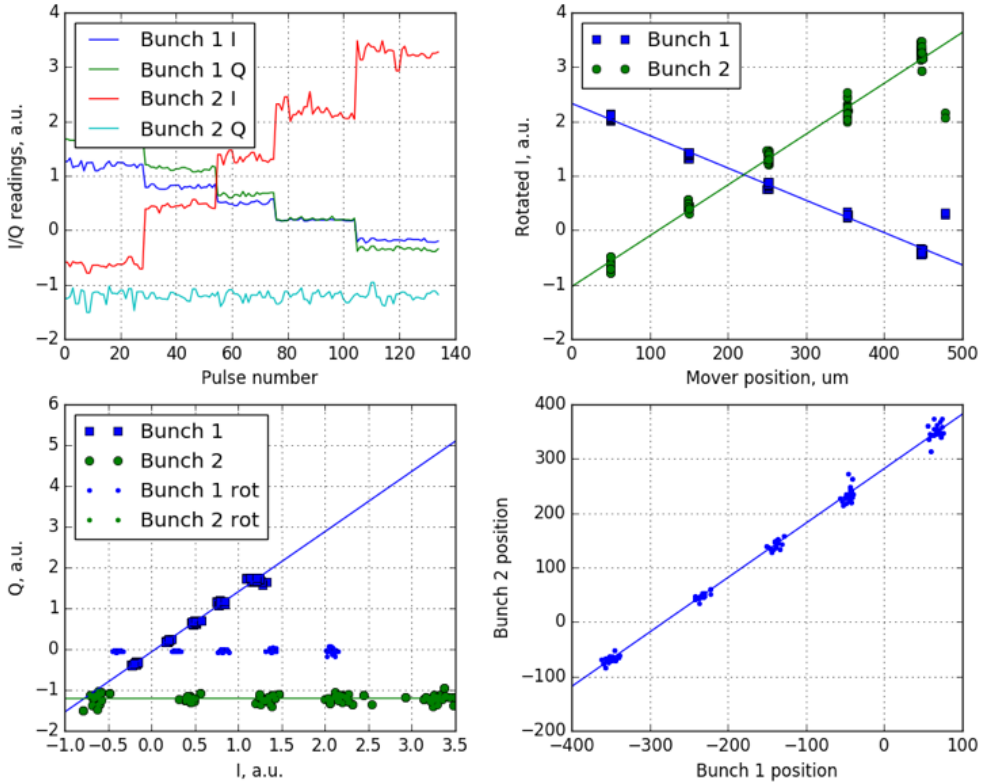
Two bunch operation

- Position jitter could systematic in the goal 1 beam size measurement
- 2 bunch operation
- Measure first bunch
- Stabilize second bunch





Two bunch calibration (subtraction off)



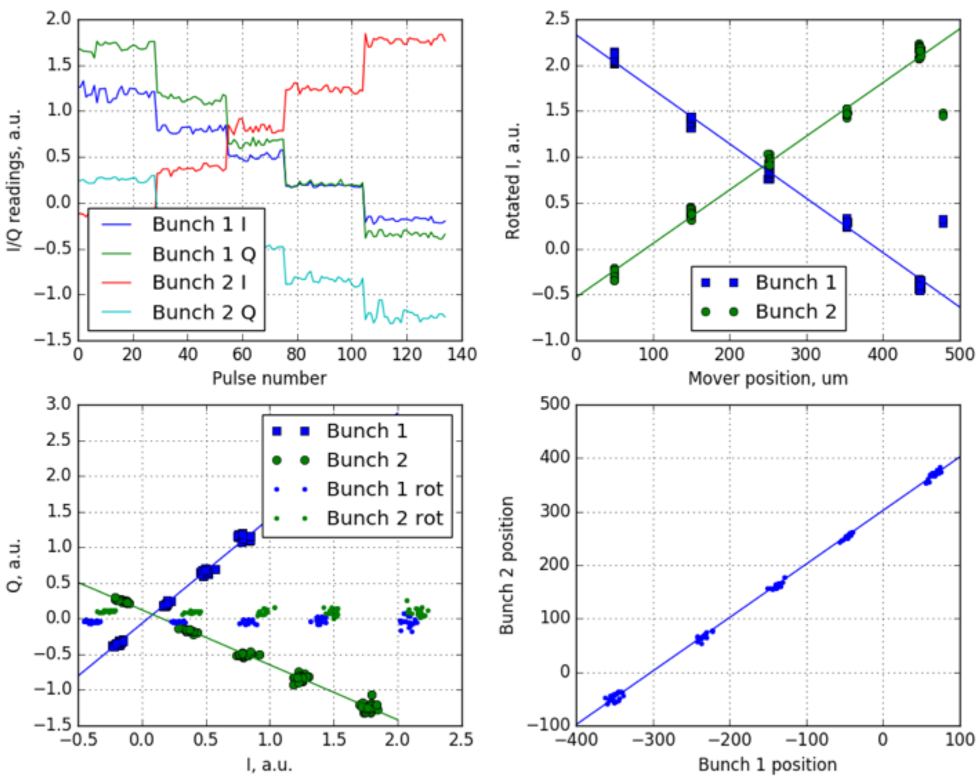
Scales:

168 um/a.u. and 107 um/a.u.

Residual within +/- 100 um:

12.8 um

Two bunch calibration (subtraction on)



Scales:

168 um/a.u. and 171 um/a.u.

Residual within +/- 100 um:

2.9 um

Optical Transition Radiation

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Optical Transition Radiation (OTR)
Optical Diffraction Radiation (ODR)

Robert Kieffer, Thibaut Lefevre, Stefano Mazzoni

CERN: European Organization for Nuclear Research

Michele Bergamaschi, Pavel Karataev, Konstantin Kruchinin,

John Adams Institute at Royal Holloway, University of London

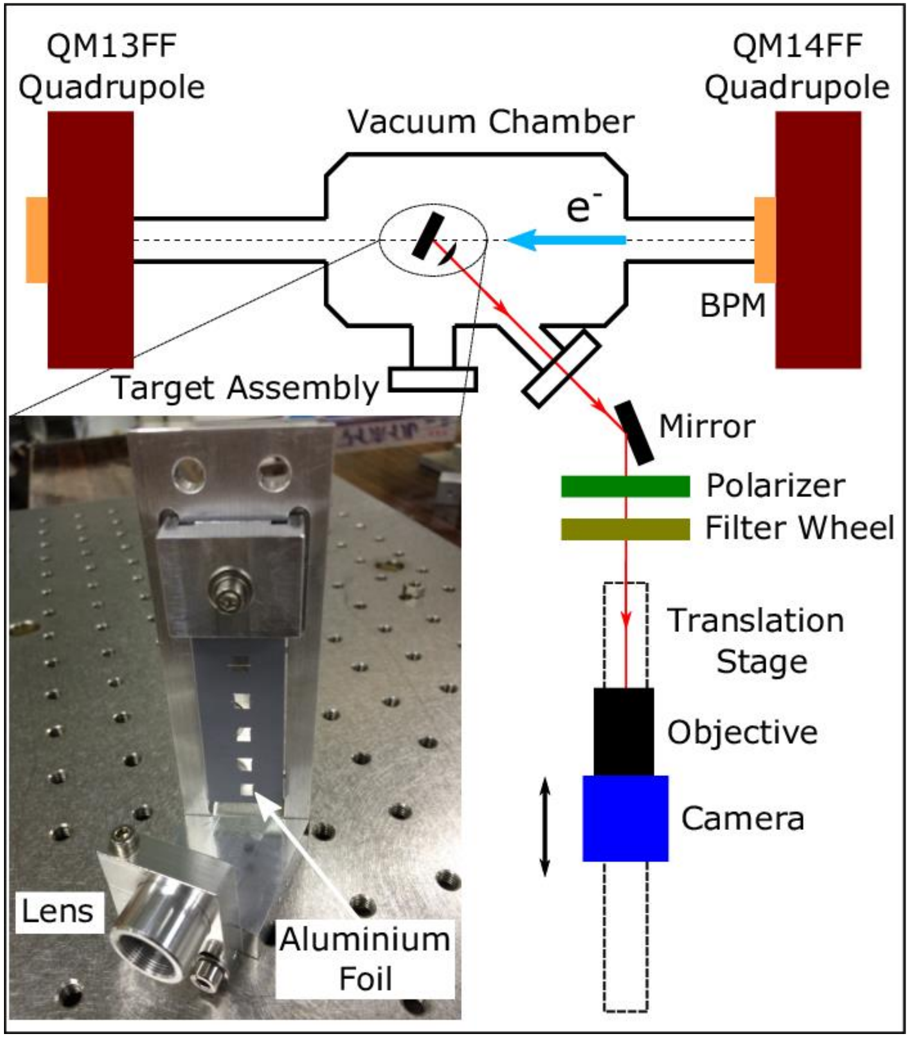
Alexander Aryshev, Nobuhiro Terunuma, Junji Urakawa

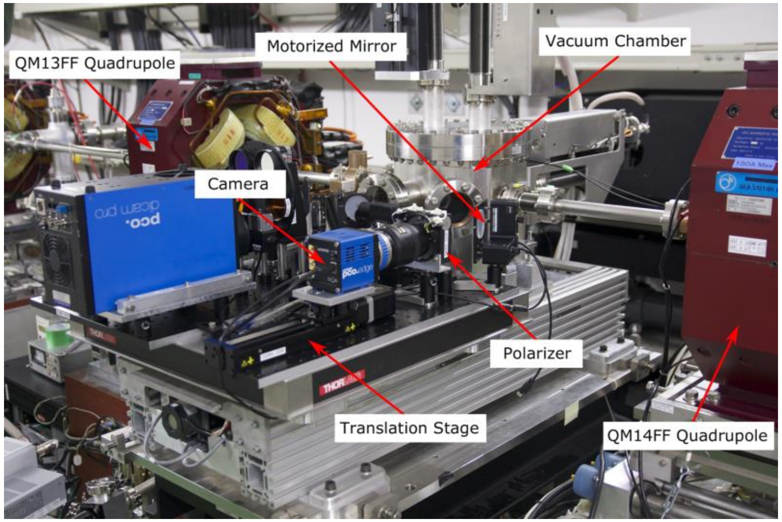
KEK: High-Energy Accelerator Research Organization

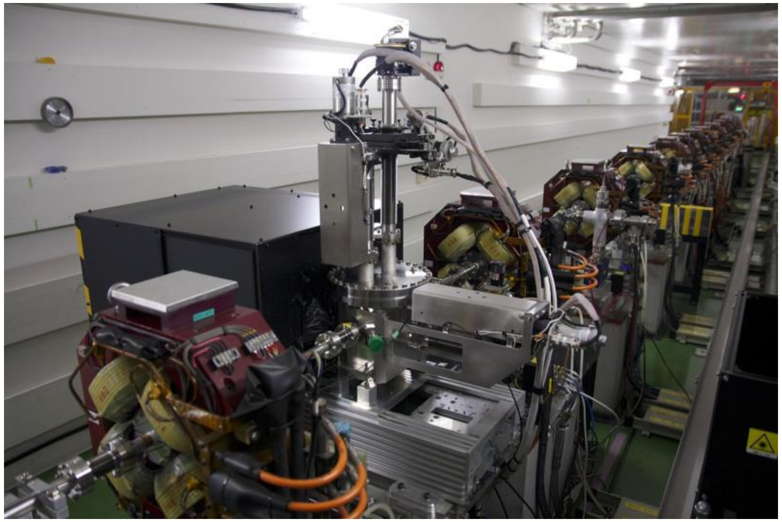
Aim:

- Develop a high resolution single shot beam size and emittance diagnostics station:
  - Non-invasive beam size measurement using Optical Diffraction Radiation;
  - Sub-micrometer beam size diagnostics using Optical Transition Radiation;
- Simple in use, robust technique for CLIC and ILC

OTR/ODR Experimental layout

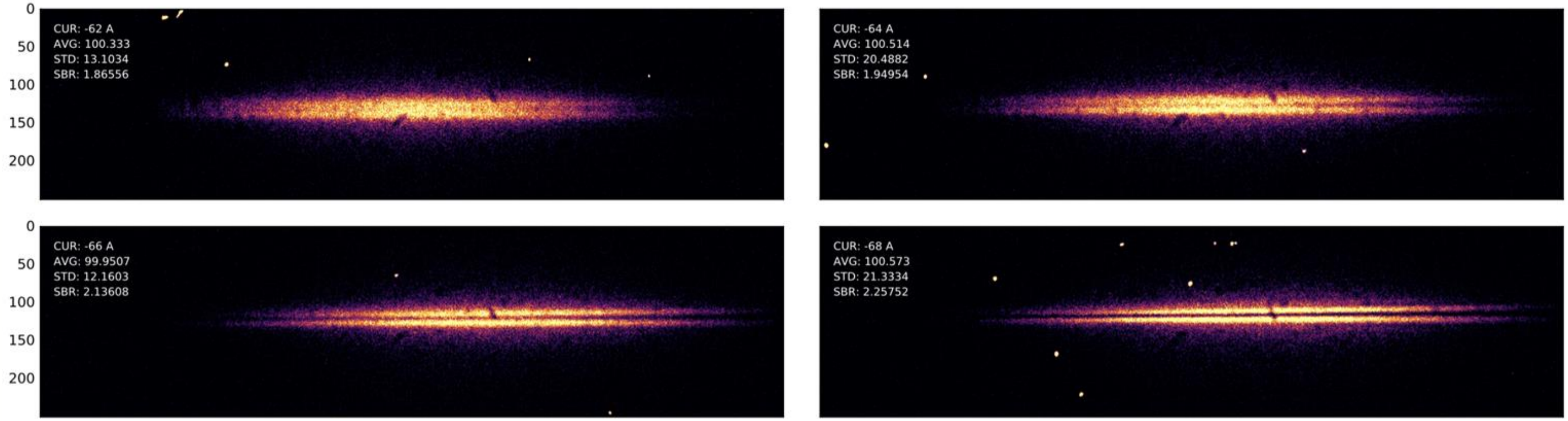




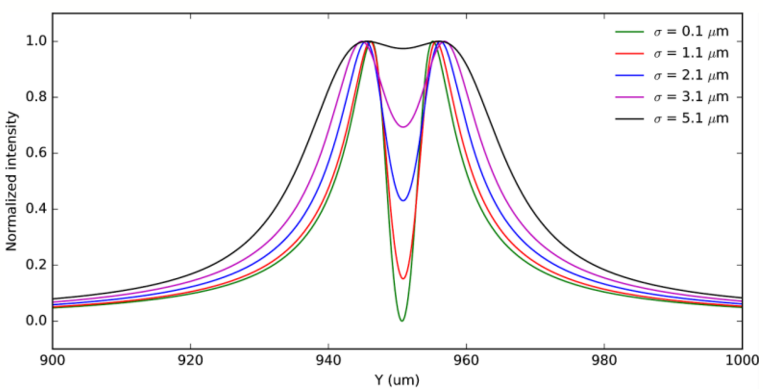


OTR Measurements

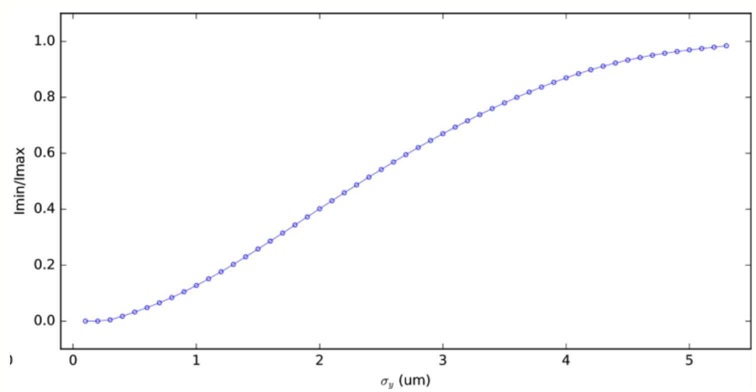
OTR images



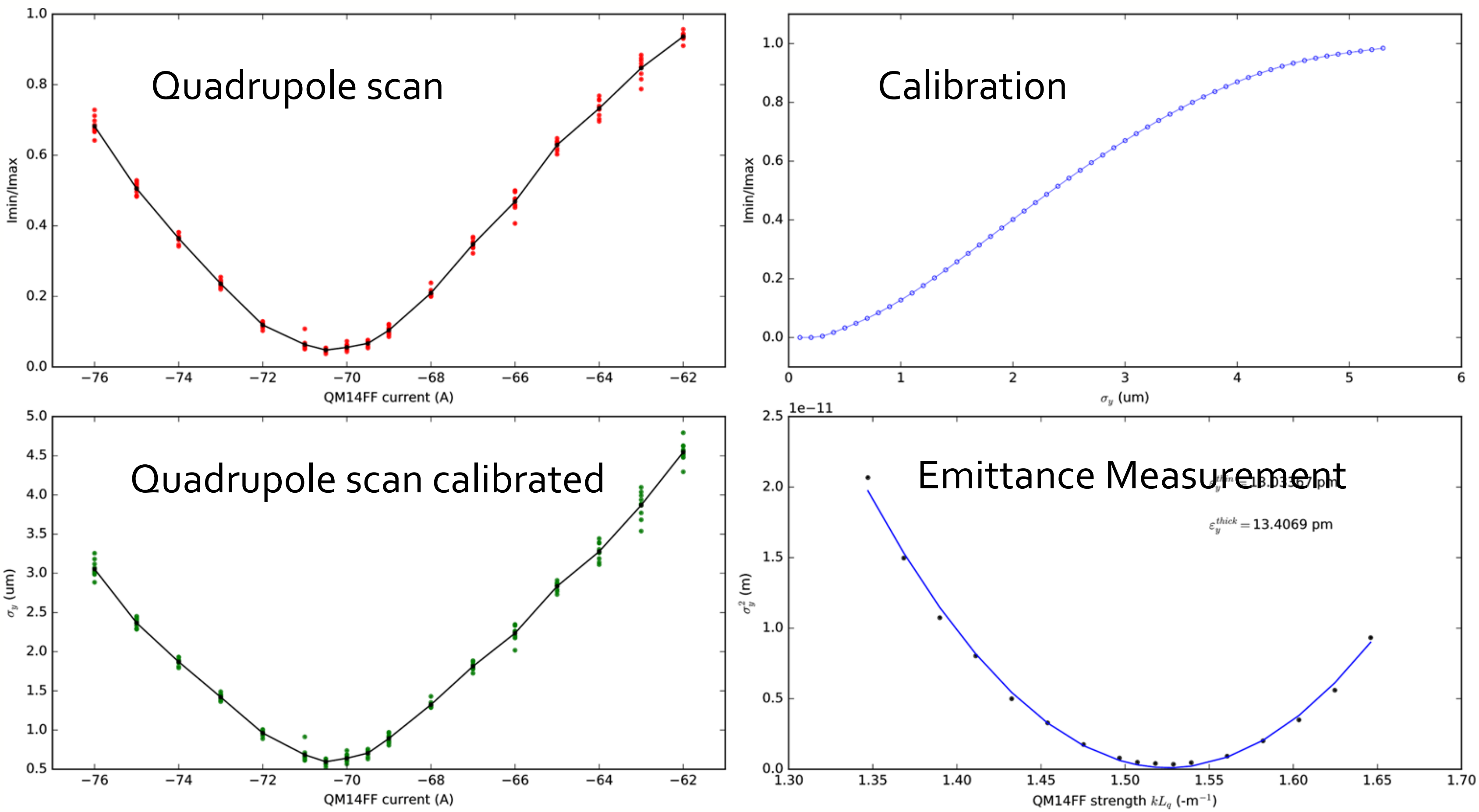
Beam size effect



Calibration



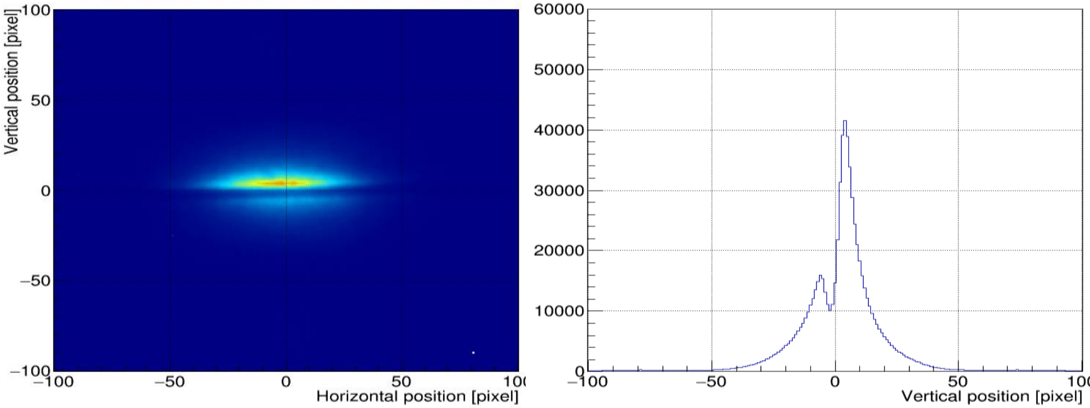
OTR Results



Quadrupole scan
Imin/Imax
QM14FF current (A)
Calibration
Imin/Imax
σ_y (um)
Quadrupole scan calibrated
σ_y (um)
QM14FF current (A)
Emittance Measurement
$\varepsilon_y^{thick} = 13.4069$ pm
σ_y^2 (m)
1e−11
QM14FF strength kL_q (-m^{-1})

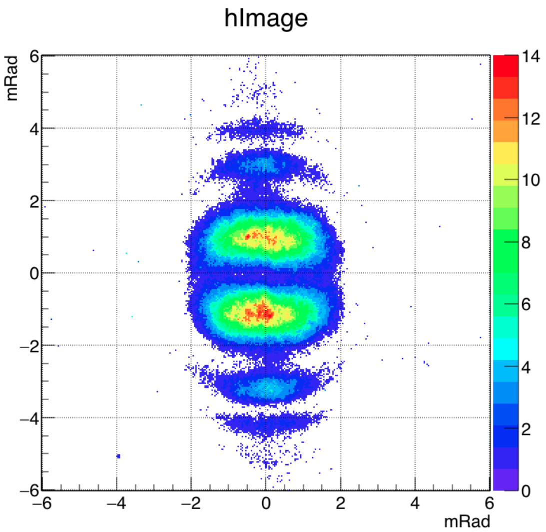
ODR Measurements

ODR is generated when a charged particle moves through a slit in a metal screen in vacuum



ODR imaging: gives an opportunity to diagnose the beam position wrt to the slit center with micron-scale accuracy

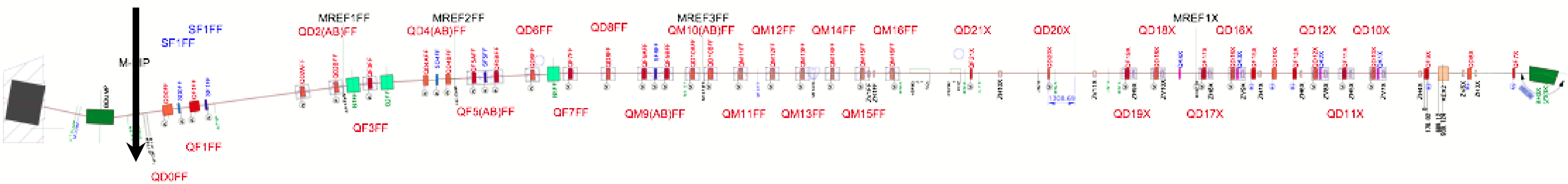
ODR angular distribution: gives an opportunity to diagnose the beam size.
These measurements were done for 30 micron predicted beam size



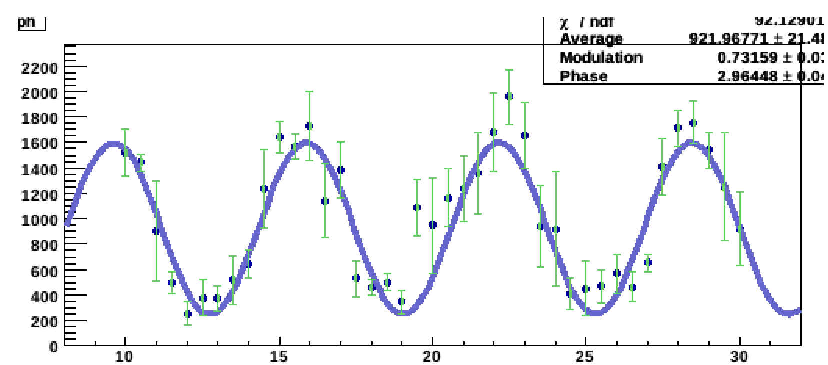
Background simulation

Motivation for background simulation

IP BSM

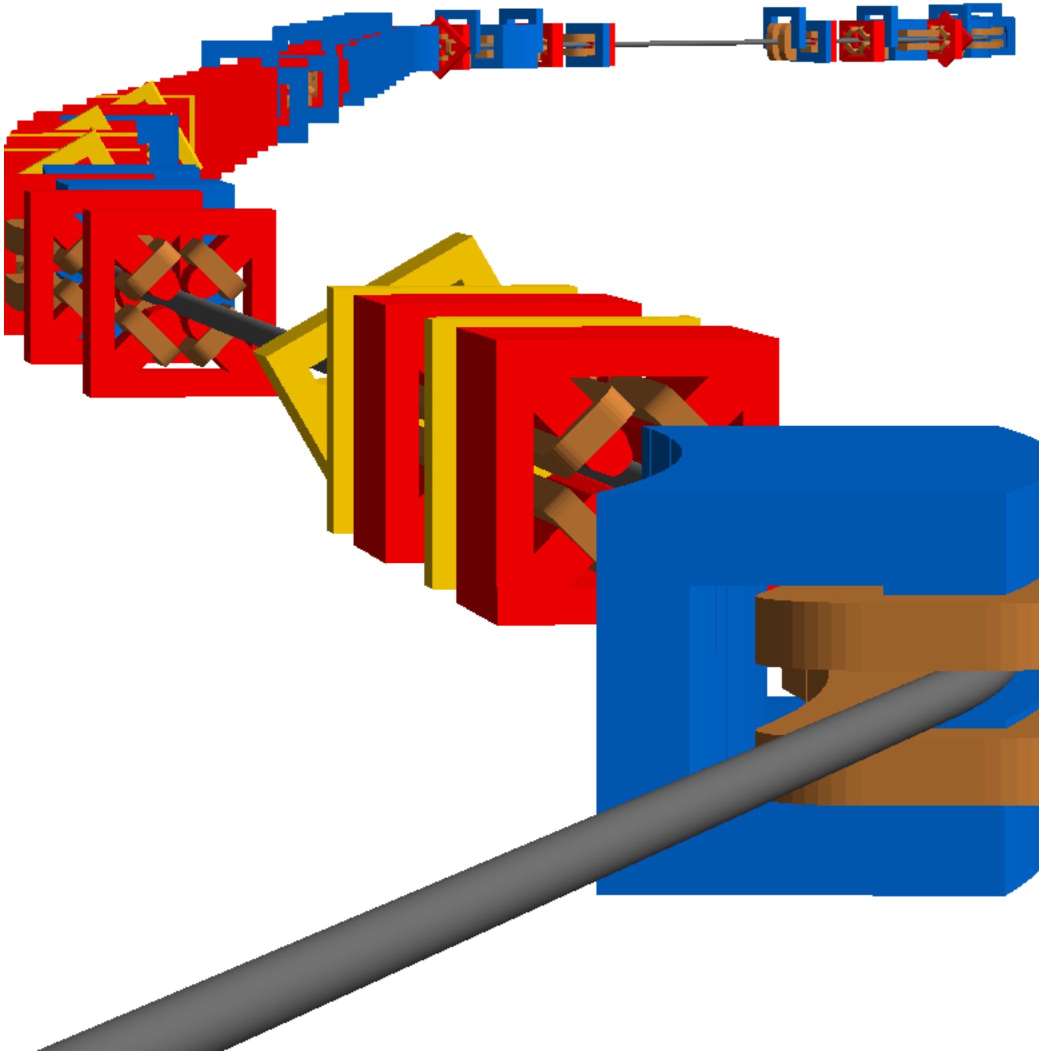


- Backgrounds in IPBSM region
  - Important potential systematic to IPBSM measurement
  - Final performance limit?
    - Laser related (optics, geometry, stability)
    - Beam related (wakes, backgrounds)
    - Beam stability



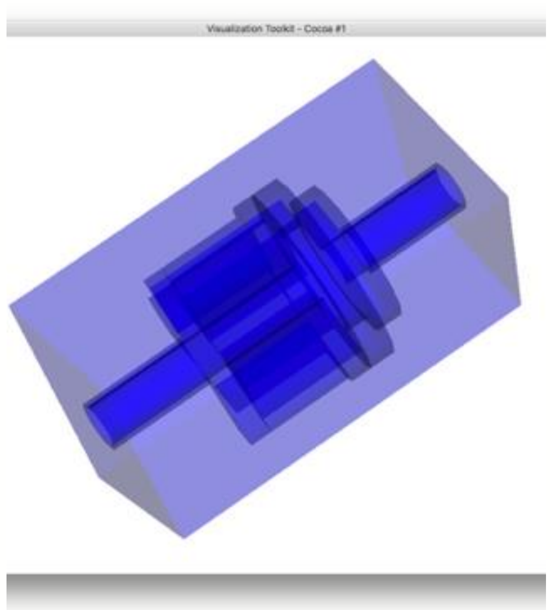
Recent developments in BDSIM

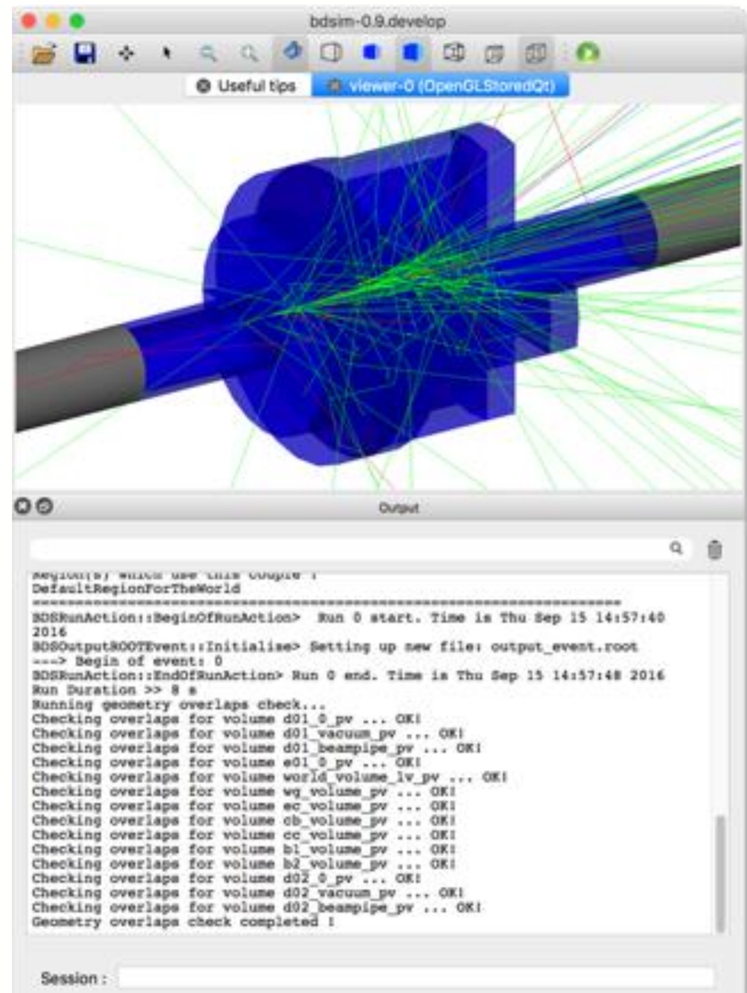
- BDSIM Geant4 based code
  - Predicting background rates
- Rapid and simple geometry description
  - Beam line elements
  - Tunnel geometry and supports
  - Magnet geometry and fields
    - External fields



BDSIM applied to ATF2 (Beamline geometry)

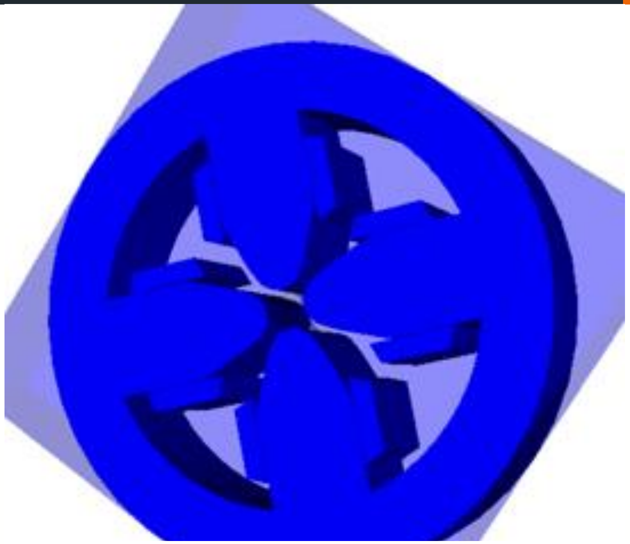
- Cavity BPM geometry
- Complex geometry with exclusions
- Simple script language (python)

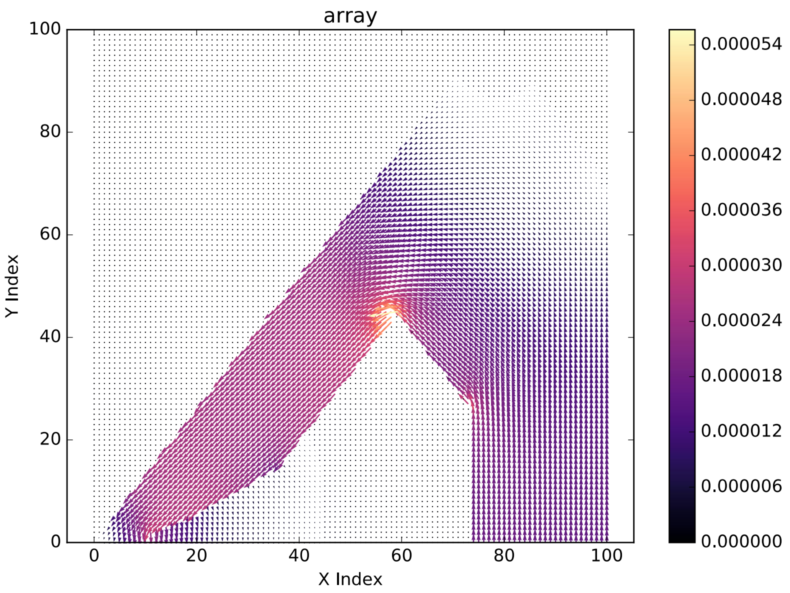




BDSIM applied to ATF2 (magnet geometry)

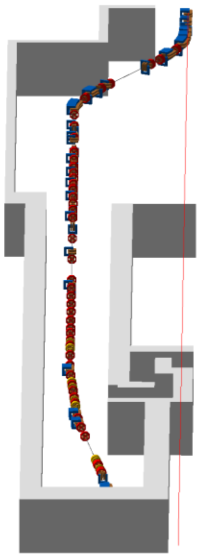
- Use Poisson for external field computation
- Load field map into BDSIM
- Track lost particles using RK4,6 through external fields
- Potentially large effect backgrounds at IP

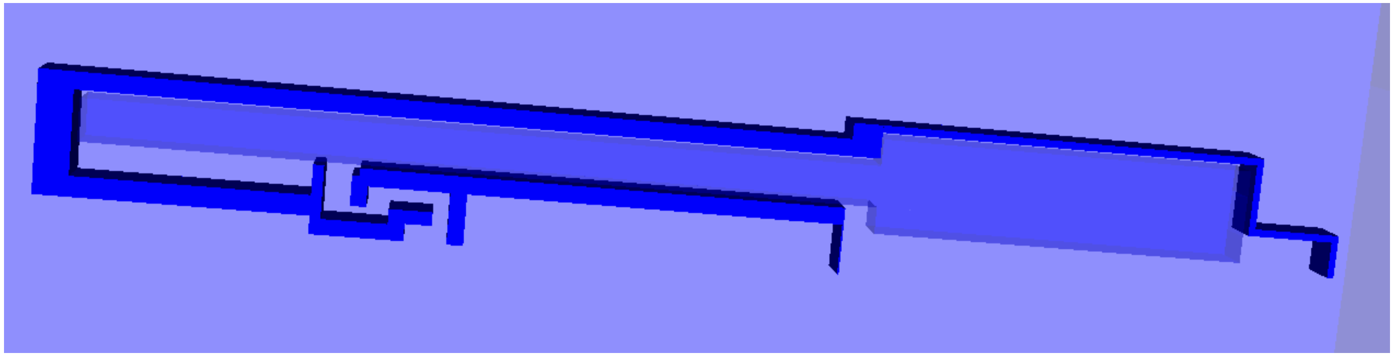




BDSIM applied to ATF2 (tunnel geometry)

- Tunnel geometry also implemented
- Secondary effect
- Supports and girders measured, but need to be implemented (simple task)





Proposed 2 year work plan

- Kruchinin (PDRA)
  - Focus on systematic effects limiting ATF2 beam size measurement, based as much as possible at KEK (eJADE)
- Nevay (PDRA)
  - Complete ATF2 background model and compare with IPBSIM
- Lyapin (Senior scientist)
  - EM simulations applied to ATF2, wakefields etc, cavity design
- Boogert (Academic)
  - Background simulation, comparison with IPBSIM

Proposed deliverables

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- Multi-bunch operation of high-Q cavity BPMs
- Support of EM simulations for low-Q cavity beam position monitors
- KEK based support for ODR/OTR experimental program
- Complete ATF2 background simulation and comparison with IPBSM
- Complete wake-field simulations of all ATF2 components and tracking studies
- Complete measurements and publication on CLIC BPM @ CLEAR, working towards 20 nm resolution.

Resources

	RHUL	CERN
• Staff effort (months):	RHUL	CERN
• S Boogert (10%)	2.5	0
• P. Karataev (10%)	2.5	0
• A. Lyapin (10%)	5	0
• L. Nevay (10%)	5	0
• Kruchinin (100%)	2	22
• **Total**	**17**	**22**
• **Consumables, travel (k£):**	**15**	**15**

Summary

- CLIC BPM
  - Resolution at few um
- ATF2 High-Q BPMs
  - 20-30 nm resolution, few um multi-bunch resolution
- OTR/ODR
  - Sub-micron ~0.5 um resolution achieved
- Wakefield simulation and tracking
  - Developed for ATF2, confirmed sources to be removed (see PB talk)
- Background simulations
  - Geant4 model almost complete and model being developed by masters students