# High resolution cavity BPMs: From prototype to production

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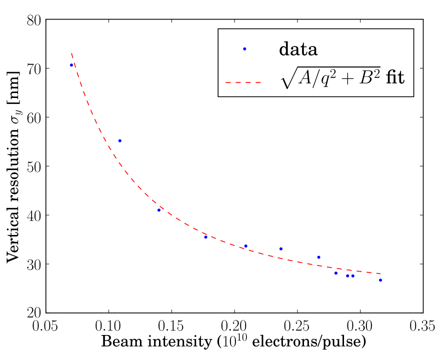
*with great thanks to Dirk Lipka (DESY) and Steve Smith (SLAC) and all contributors!*

# The plan

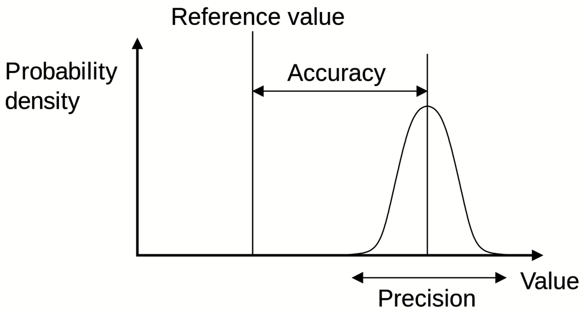
- Definitions and basics
- Test/R&D systems
- Production systems and practical requirements in large systems
- Industrialised CBPM

# Terminology applied to BPMs

- Resolution – sensor's ability to "see" a *change* in beam's position, defined by sensor and beam parameters and fundamentally limited by thermal noise
- Precision – *consistency* of measurements, defined by the resolution of the sensor, noise of the digital and analog electronics, and processing algorithms
- Accuracy – *how close* the measured values get to the true value, includes electric centre offset and calibration errors



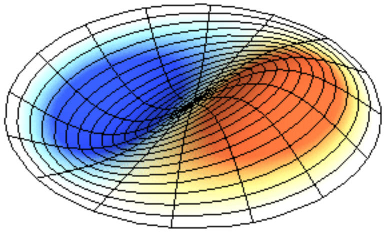

"Resolution" – precision measured at ATF2



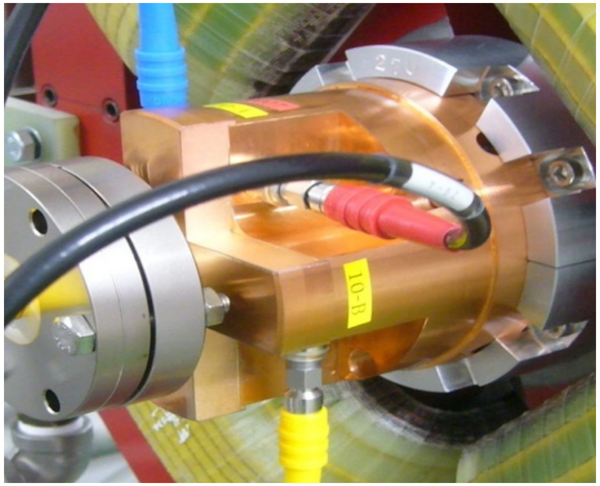

Source: Wikipedia

# Quick intro – cavity BPMs

- Use asymmetric TM110 mode to measure the beam's offset from the axis
- At least 2 (spatial and frequency) structure-based methods for symmetric mode rejection
- Resolution potential in single digit nm
- Require phase reference and charge measurements, need in-situ calibration



Asymmetric dipole mode used for position measurement and a real life cavity BPM in ATF2 Beamline (KEK)



# Test vs production systems

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- Test systems – predominantly built for "resolution" (precision) measurements
- Most test systems include 3 monitors (to enable predictions), so cost of both main (cavities, electronics) and secondary (movers for calibration) HW is important, but not critical
- Thorough bench testing or tuning part of process
- Test systems rarely mature to an online diagnostic, analysis is often done offline
- Stability is not an issue for test systems as measurements are taken over short periods (hours)

# Test systems: NanoBPM (BINP/SLAC/KEK/UK)

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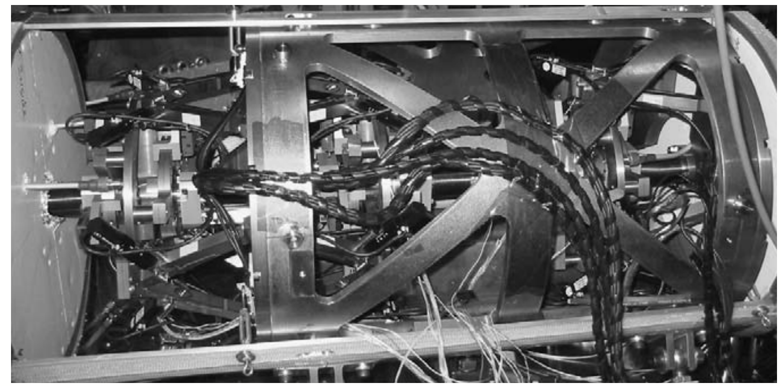
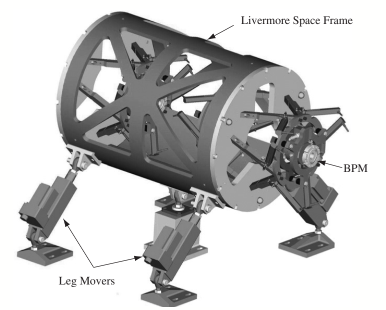
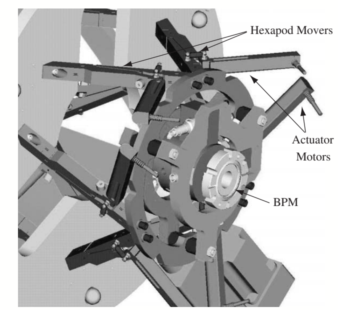
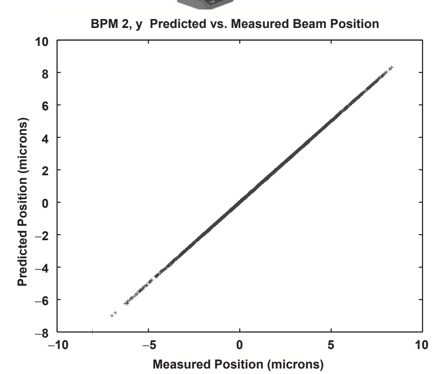
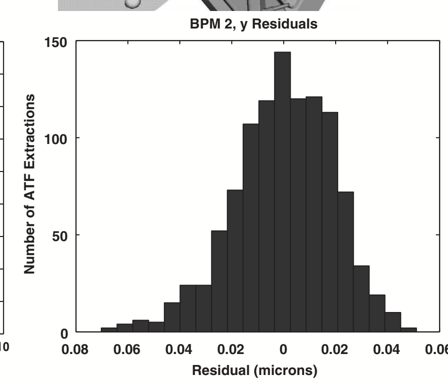
- Used space technology to rigidly suspend 3 BPMs and control their position and pitch + position, pitch and roll of the supporting frame
- Range ~100 um
- Consistently demonstrated precision below 20 nm: 16 nm best, with a distance tracking system 12 nm
- Probably the first example of extensive use of digital processing and ML





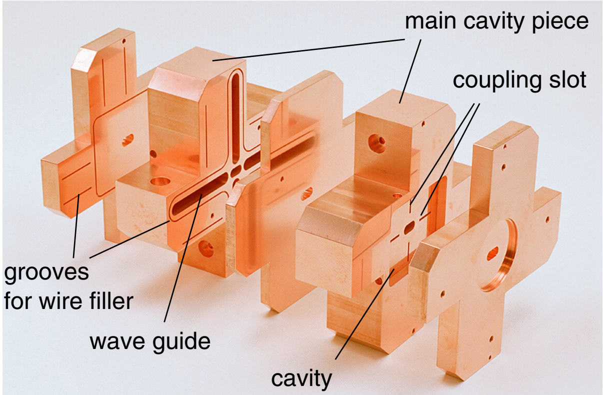



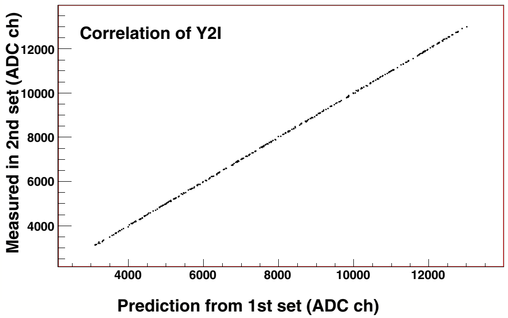



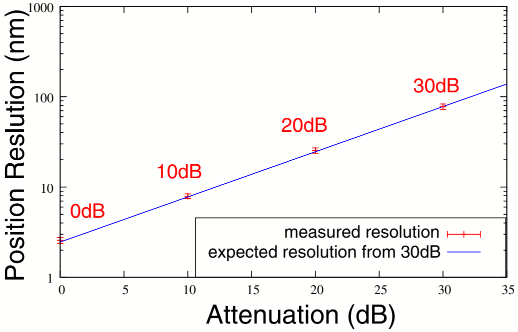



# Test systems: IPBPM (Y. Honda et al, KEK)

- Special system for IP region of ATF2, requirement: 2nm precision
- x/y decoupled – polarisations become separate modes
- Was unable to operate at full gain due to saturation, at max gain achieved 8.7 nm



# Test vs production systems

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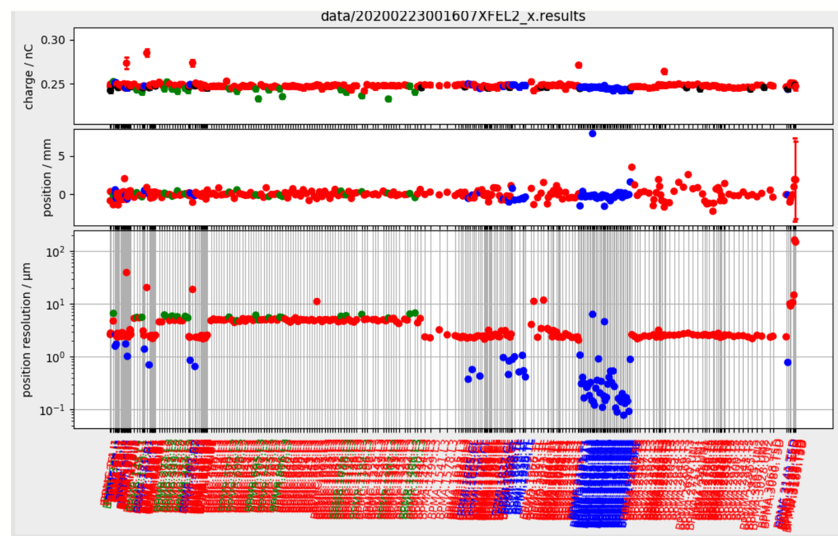
- Issues with much larger production systems are related to cost, stability and operation
- Large numbers -> costs multiplied by 100's or 1000's, so use of additional sub-systems must be limited
- Bench testing/tuning must be minimal (acceptance)
- 24/7 operation, as little intervention as possible
- Stability or non-invasive calibration a must, operation with no re-calibration over months
- *Stability is more important than accuracy* (machine re-start, golden orbit, etc.)

# Production systems: XFEL

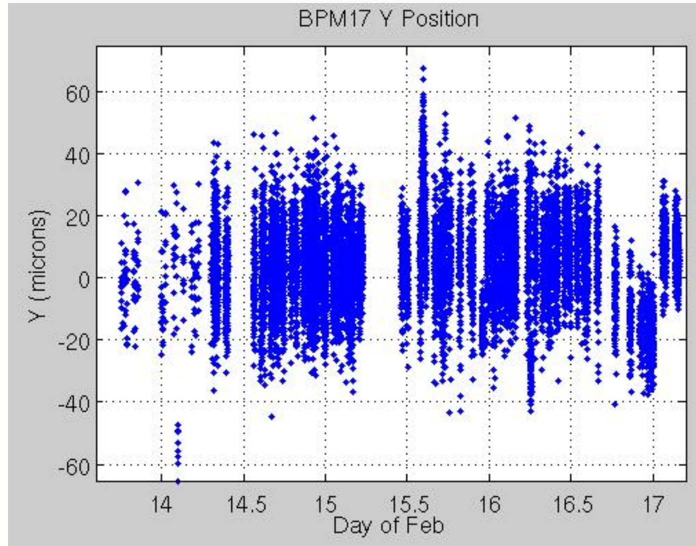


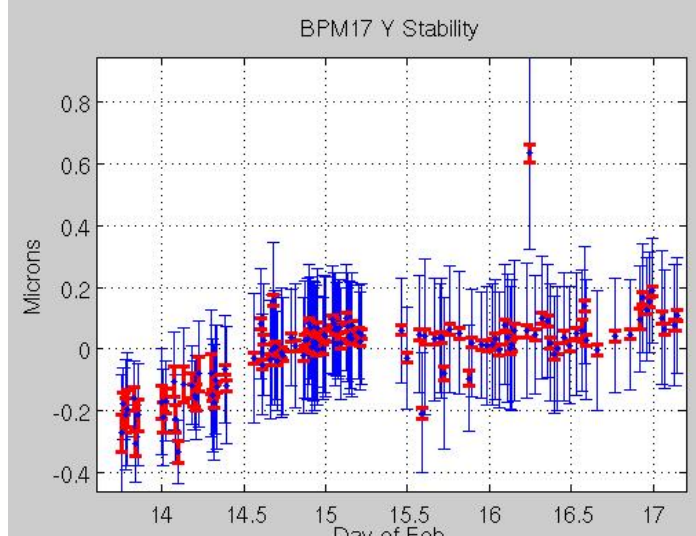
- 130 cavity BPMs
- Bunch 1 operation: each BPM system pre-calibrated in another linac! ~1-2% corrections in-situ, ~5% long-term (many months)
- Modular electronics, automated gain control, active temp stabilisation
- Ext clock distributed
- Remote FW&SW updates
- Precision ~300 nm

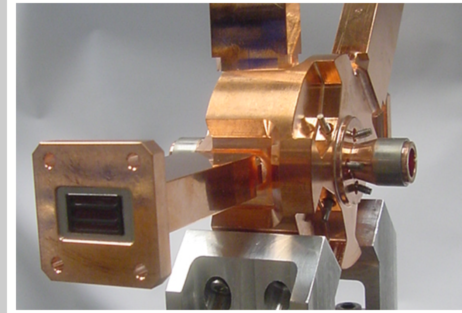


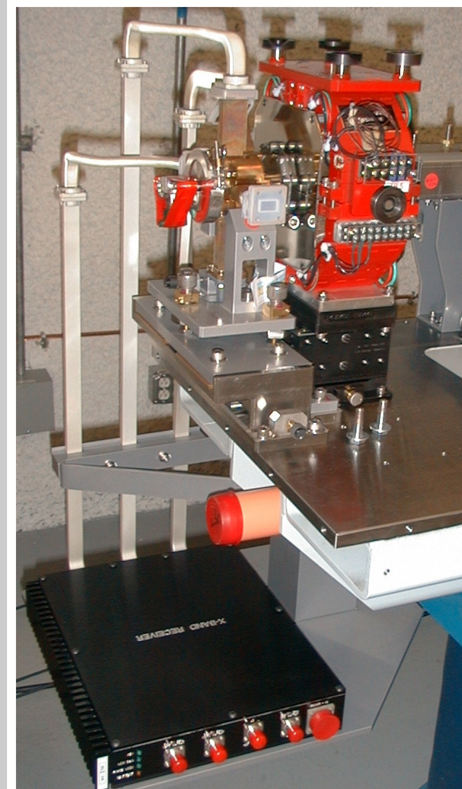
# Production systems: LCLS-1

- X-band, 36 cavities
- Typical precision ~200 nm
- Measured BPM stability ~200 nm over 3.5 days
- Better not to calibrate BPMs! -> golden orbit lost if measured with a "bad" calibration
- Ideas on continuous sub-beam jitter beam motion to correct calibrations



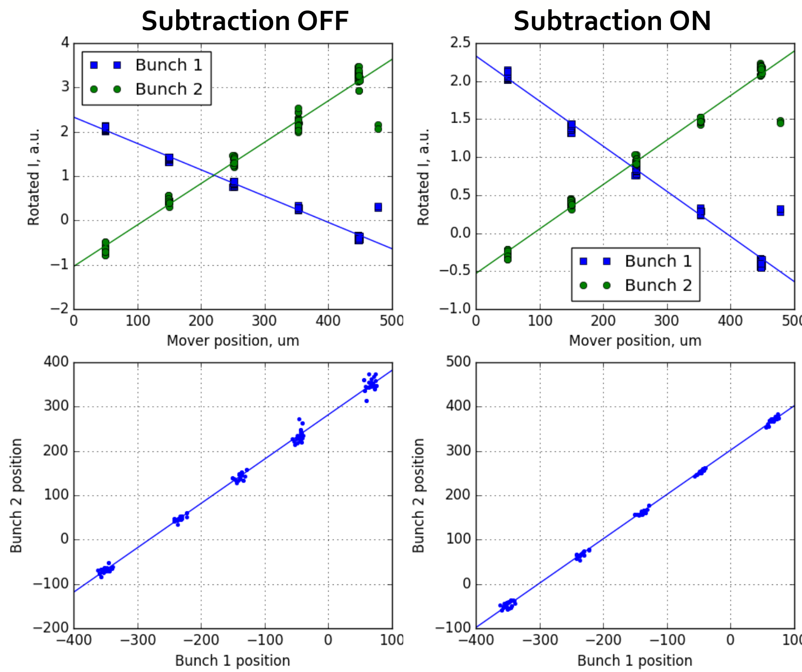



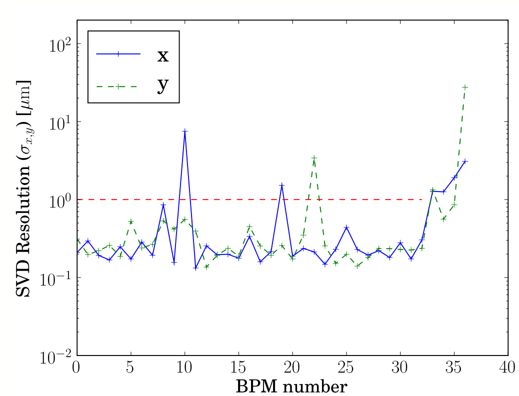



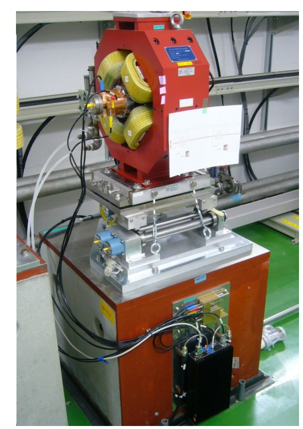


# (Almost) Production systems: ATF2

- Maxed at ~40 cavities mounted on 4- and 6-poles, typical precision 250 nm (without 20 dB att 20-30 nm)
- In-situ mover or orbit bump calibrations, with jitter subtraction, 1% precision
- Signal injection into electronics, measured electronics stability ~0.1% over 4 days
- High-Q cavities decay time longer than typical bunch separation (300 ns vs 150-200ns), signal subtraction demonstrated
- Raised the question of wakefield effects (feature of long bunches at ATF2), although in theory the easiest part to align!
- International effort: cavities – KEK, UK, PAL; electronics and quad movers – SLAC; digital processing, EPICS integration – UK

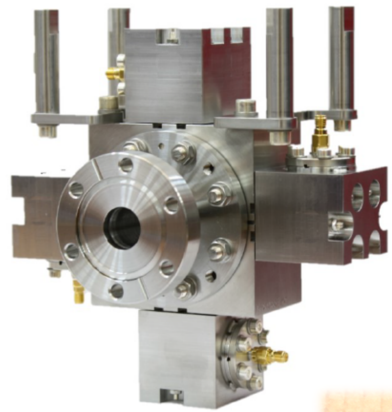


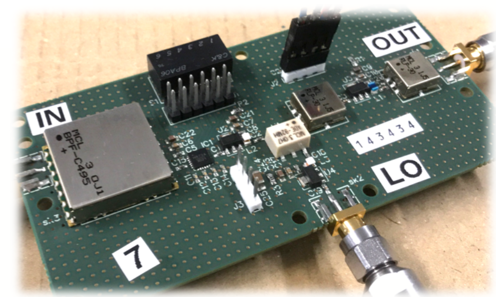



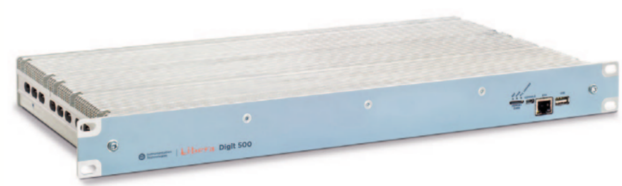



# Industrialised CBPMs (RHUL-FMB Oxford-Instrumentation Technologies)

- RHUL partnered with Industry to try and improve accessibility of CBPM technology, mainly with small installations in mind
- With FMB-Oxford, developed C-band cavities that are sealed (not brazed), so can be repaired if needed, easy to manufacture, have a high yield and require minimum bench testing
- Developed analog electronics, but realised that integrated Cavity BPM electronics (including analog+digital+FPGA+CPU+EPICS/Tango) are a perfect fit
- Test system currently unavailable, tests TBC
- Have our first client, starting deliveries





# Conclusions and final remarks

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- Large CBPM systems exist and perform well
- Large distributed system -> issues are mainly related to stability and operation
- Solutions exist, they either increase complexity or rely on digital processing and active calibration
- Examples of both lab and industry led industrialisation