PERFORMANCE OF NANOMETRE-LEVEL RESOLUTION CAVITY BEAM POSITION MONITORS AT ATF2

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IPAC'18
The 9th International Particle Accelerator Conference
Vancouver, British Columbia, Canada
1st May 2018

John Adams Institute for Accelerator Science

OUTLINE

Background

- The ATF2 and beam position stabilisation

Beam Position Monitor (BPM) Set-Up

- Low-Q cavity BPMs in the IP region
- Signal Processing
- Digitisation and FONT feedback
- Position calculations

Resolution results

- Resolution estimate methods
- Resolution results using a single sample
- Resolution results using waveform integration

Outlook & Summary

THE ATF2

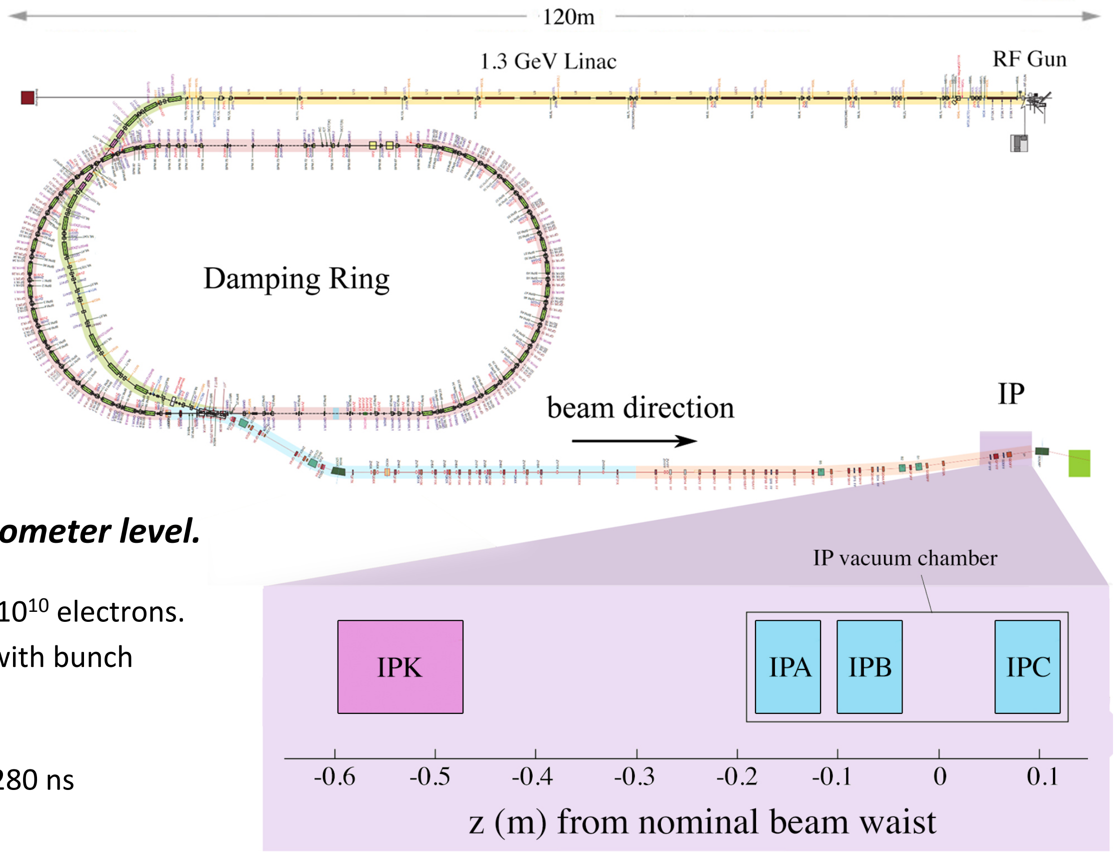
The Accelerator Test Facility (ATF2) is an electron accelerator at KEK in Japan designed to test technologies for the next generation of linear colliders.

ATF2 goals:

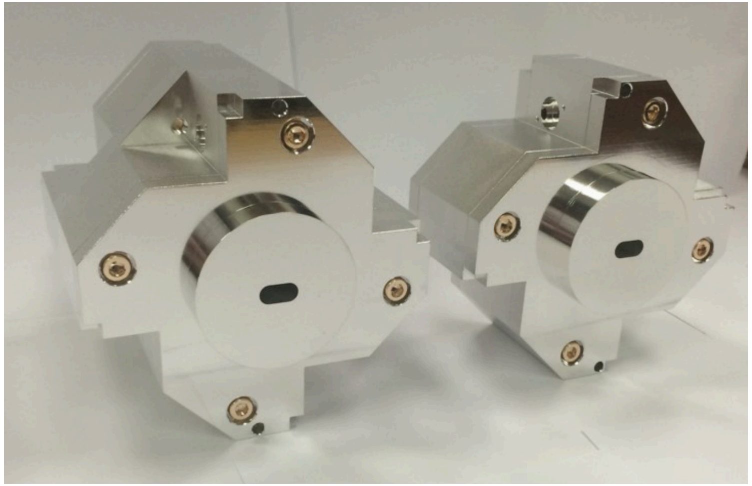
- Achieve 37 nm vertical beam size.
- ***Stabilise the beam position to the nanometer level.***

The ATF2 generates bunches of between 10^9 and 10^{10} electrons. 2 or 3 bunches per train are extracted at 3.12 Hz with bunch separations of between c. 140 and 300 ns.

Results shown here are for 2-bunch trains with a 280 ns bunch separation.



LOW-Q CAVITY BPMS

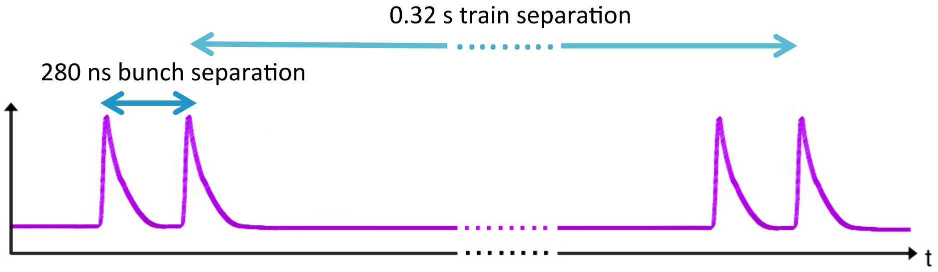


Cavity BPMs. S. Jang et al., in *Proc. IPAC'16*, paper THOAA02, pp. 3149-3151.

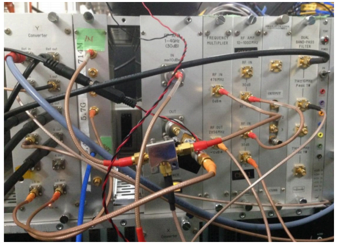
BPM	Q_L	f (GHz)	τ (ns)
IPA	1041	6.428	26
IPB	902	6.427	22
IPC	698	6.428	21

Vertical position y-port BPM measurements.

- High resolution cavity BPMs utilise electromagnetic field modes (at GHz frequencies) that couple to the transverse position of the bunch in the cavity (and the bunch charge).
- Waveguides spatially filter x and y position-dependent modes. The y-ports are of interest for vertical position stabilisation.
- Low Q cavities mean fast decay times to avoid signal contamination between bunches, vital for intra-train feedback.
- The BPMs are mounted on an *x-y* mover system, enabling the vertical and lateral position and pitch to be adjusted.

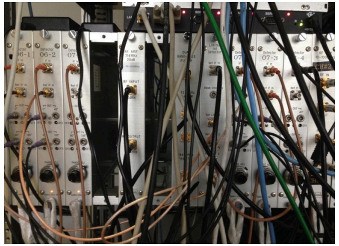


SIGNAL PROCESSING



First stage mixer

Takes the 6.4 GHz IP cavity BPM signals (*position and charge-dependent*) and reference cavity signal (*charge-dependent*) and mixes each with an external common 5.7 GHz local oscillator (LO) to produce outputs at 714 MHz.

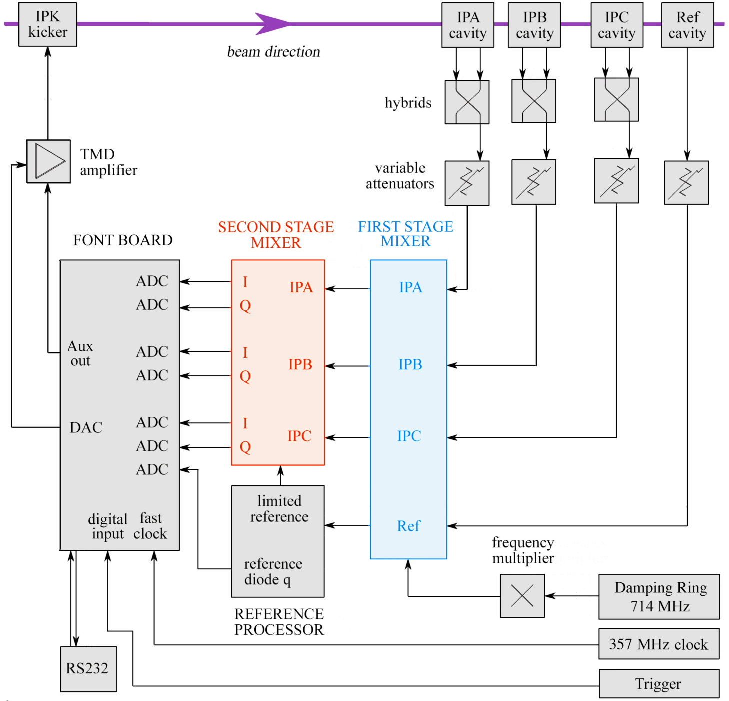


Second stage mixer

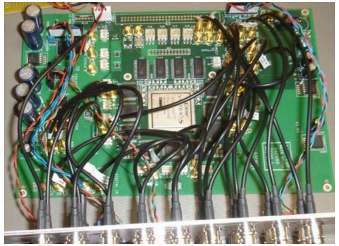
Mixes the 714 MHz dipole cavity signal using the limited 714 MHz reference as the LO, giving 2 signals at baseband:

I signal (dipole and reference mixed **in phase**).

Q signal (dipole and reference mixed **in quadrature**).

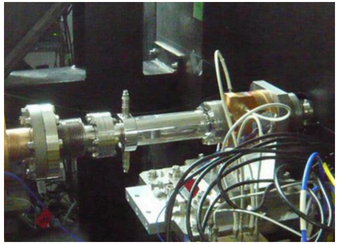


DIGITISATION & FEEDBACK



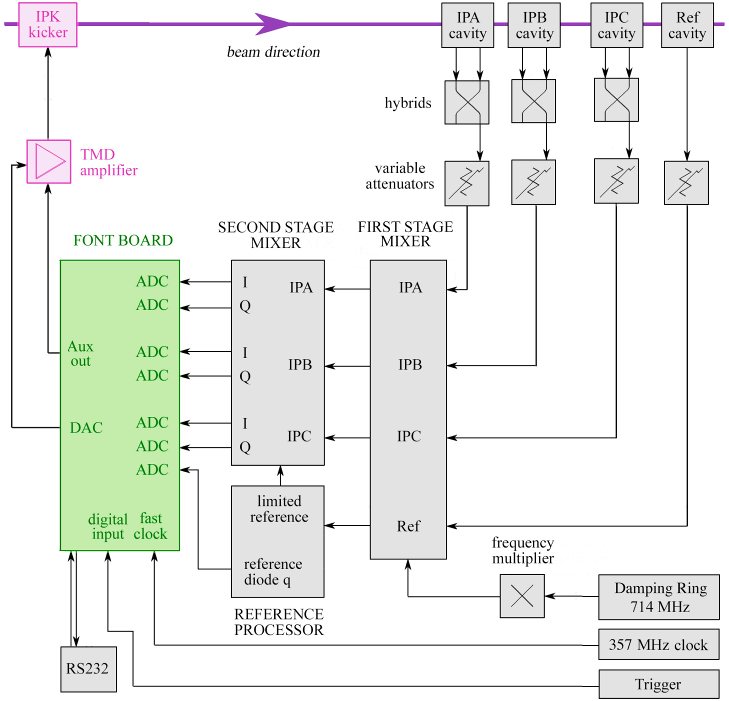
FONT BOARD

The I, Q and charge (q) signals are digitised on the FPGA-based FONT board at 357 MHz and used to compute beam positions. In feedback the on-board firmware calculates the position of the first bunch and generates a kick signal to correct the next bunch in the train with a latency shorter than the 280 ns bunch separation.



TMD amplifier & IPK kicker

The kick signal from the FONT board is amplified (using an amplifier designed for up to ±30 A of drive current to meet ILC and CLIC requirements, taking 35 ns to reach 90 % of peak). The kicker IPK applies the corrective electromagnetic pulse.



POSITION CALCULATION

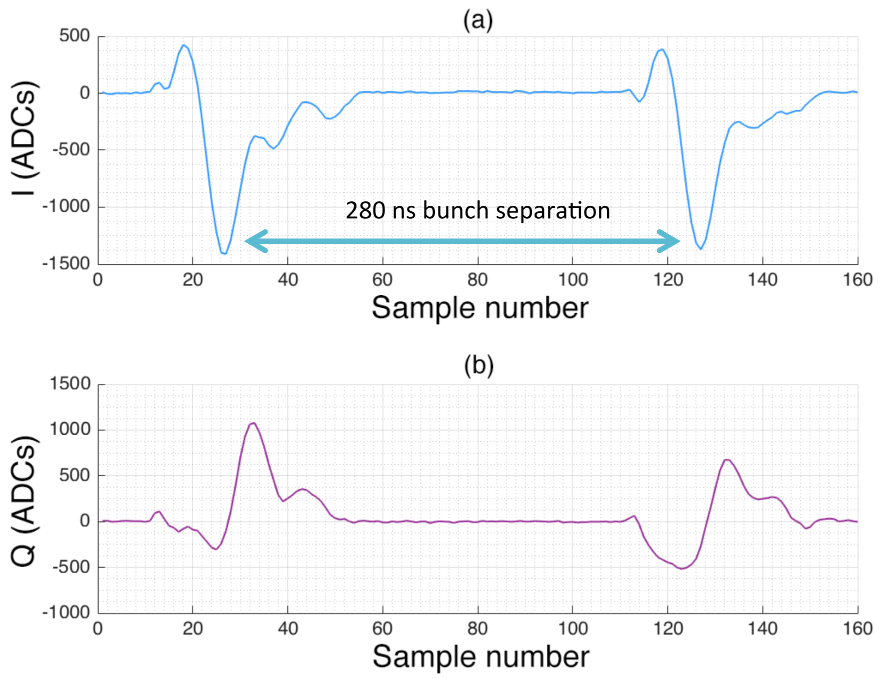
I and *Q* pulses are sampled and a linear combination is used to determine vertical bunch position, *y*.

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

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

$$y = \frac{I'}{qk}$$

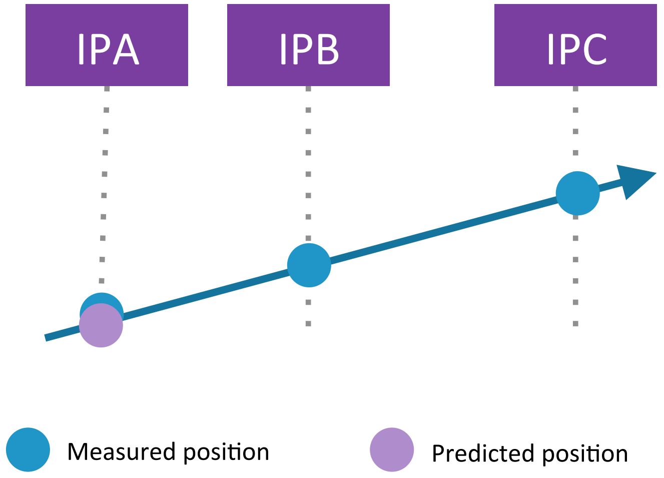
q is the bunch charge measured using a monopole cavity BPM. θ_{IQ} and *k* are determined from a calibration where the beam is moved a known amount within the cavity.



ADC counts versus sample number for a two-bunch train (a) I signal, (b) Q signal. Two-bunch train measured using IPB. The sample separation is 2.8 ns.

RESOLUTION CALCULATION (GEOMETRIC)

The measured positions at two BPMs are used to predict the position at the third using a linear transport model. The residual difference between the predicted and measured results is used to estimate the resolution.



Schematic of the resolution experimental set-up using all three BPMs.

e.g. predicting positions at IPA:

Geometric method: $y_{\mathrm{IPA}} = a_1 y_{\mathrm{IPB}} + a_2 y_{\mathrm{IPC}}$

Constants a_1 and a_2 are obtained from trigonometry using known BPM separations.

Residual: $\delta = \mathrm{std}\left(y_{\mathrm{pred}} - y_{\mathrm{meas}}\right)$

Resolution: $\sigma = \frac{\delta}{\sqrt{1+a_1^2+a_2^2}}$

RESOLUTION CALCULATION (FITTING)

An alternative "fitting" resolution estimate method applies a linear regression to predict the I' signal at the third BPM based on the I' signals at the other two BPMs.

Fitting method:

Apply fit to find I', then convert into positions and find the resolution as for the geometric method.

Additional fit parameters, such as Q', q, or horizontal I' and Q' values derived using x-port dipole cavity information, can be included.

Resolution calculation method	**Fit parameters**
Fitting *I'*	$I'_{\mathrm{IPA}} = c_1 I'_{\mathrm{IPB}} + c_2 I'_{\mathrm{IPC}} + c_3$
Fitting *I'*, *Q'*	$I'_{\mathrm{IPA}} = c_1 I'_{\mathrm{IPB}} + c_2 I'_{\mathrm{IPC}} + c_3 Q'_{\mathrm{IPB}} + c_4 Q'_{\mathrm{IPC}} + c_5$
Fitting *I'*, *Q'*, *q*	$I'_{\mathrm{IPA}} = c_1 I'_{\mathrm{IPB}} + c_2 I'_{\mathrm{IPC}} + c_3 Q'_{\mathrm{IPB}} + c_4 Q'_{\mathrm{IPC}} + c_5 + q c_6$
Fitting *I'*, *Q'*, q and *x*	$I'_{\mathrm{IPA}} = c_1 I'_{\mathrm{IPBy}} + c_2 I'_{\mathrm{IPCy}} + c_3 Q'_{\mathrm{IPBy}} + c_4 Q'_{\mathrm{IPCy}} + c_5 + q c_6$ $c_7 I'_{\mathrm{IPBx}} + c_8 I'_{\mathrm{IPCx}} + c_9 Q'_{\mathrm{IPBx}} + c_{10} Q'_{\mathrm{IPCx}}$

Constants c_1, c_2 … obtained from a linear regression.

RESOLUTION RESULTS - SINGLE SAMPLE

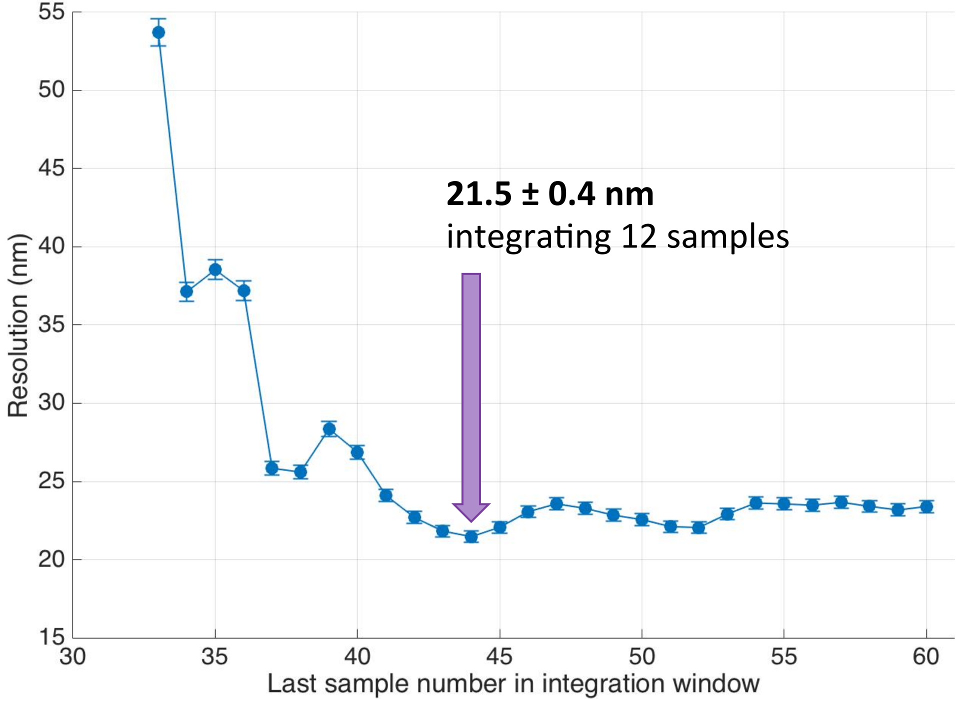
Resolution estimates with 10 dB attenuation on the dipole cavity outputs and at a charge of ~0.5 x 10^{10} electrons per bunch using predictions at IPA and a **single sample** of the digitised waveforms.

	Resolution (nm)
Resolution calculation method	**Single sampling**
Geometric	49 ± 1
Fitting I'	49 ± 1
Fitting I', Q'	43 ± 1
Fitting I', Q', q	43 ± 1
Fitting I', Q', q and x	42 ± 1

Geometric and a simple fit to I' are in agreement.

Improvement on fitting Q'. Suggests residual position information in *Q'* after the phase rotation and/or that beam conditions have changed to make the calibration constants no longer accurate.

RESOLUTION RESULTS - INTEGRATION



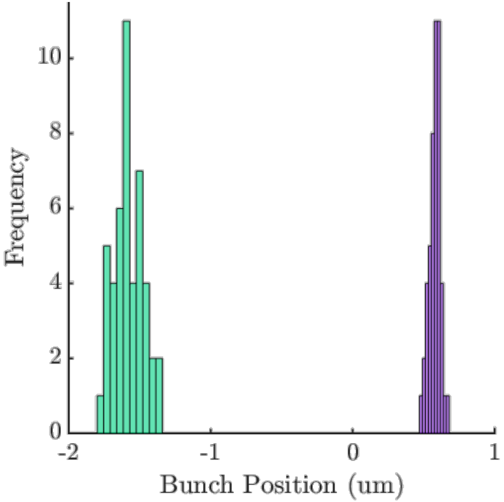
- Plot shows how geometric resolution varies using a cumulatively increasing integration of the pulse.
- Integrating improves resolution to ~20 nm by increasing signal information used to improve position sensitivity.
- Results are now consistent for all resolution methods: suggests calibrations using integrations are less likely to leave residual position-dependent information in Q'.

Resolution calculation method	Resolution (nm) Single sampling	Integration
Geometric	49 ± 1	21.5 ± 0.4
Fitting I'	49 ± 1	19.9 ± 0.4
Fitting I', Q'	43 ± 1	19.5 ± 0.4
Fitting I', Q', q	43 ± 1	19.5 ± 0.4
Fitting I', Q', q and x	42 ± 1	19.2 ± 0.4

FURTHER WORK & OUTLOOK

- Multi-sample integration has been shown to improve resolution from 50 nm to 20 nm in offline analysis.
- Integration has now been incorporated in feedback firmware giving the possibility of 20 nm resolution for real-time operation.
- First feedback test results demonstrate position stabilisation to **41 ± 4 nm**.
  (See poster by Rebecca Ramjiawan: WEPAL025)

Feedback	Position jitter (nm)	
	Bunch-1	Bunch-2
Off	106 ± 11	96 ± 10
On	106 ± 11	41 ± 4



Distribution of bunch 2 positions measured at IPB, with feedback off (green) and feedback on (purple).

- Investigate sensitivity to bunch phase and other sources of background in the IP electronics.
- Study waveform features to enable operation at 0 dB and a charge of 1 x 10^{10} electrons per bunch without saturating.

SUMMARY

- A resolution of ~**20 nm** has been obtained for real-time operation using three low-Q cavity BPMs in the IP region at the ATF2 at KEK in Japan.
- First results using this improved resolution show beam position feedback stabilisation to ~40 nm.
- Such high-resolution BPMs will be vital for beam delivery system tuning at future high-energy e+e- linear colliders: CLIC and ILC.

THANK YOU

Many thanks to KEK for providing beam time for these experiments, and the ATF2 staff and our collaborators for their outstanding support and help.

Supported by the UK Science and Technology Facilities Council, CERN, and the European Commission's Horizon 2020 Programme through the Marie S.-Curie RISE project E-Jade, Contract No. 645479.

- ATF2 IP BPM RESOLUTION RESULTS - T. Bromwich et al., in Proceedings IPAC'18, paper TUZGBD5
- ATF2 IP FEEDBACK RESULTS - R. Ramjiawan et al., in Proceedings IPAC'18, paper WEPAL025