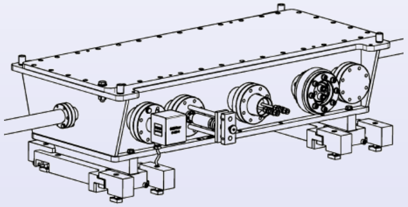
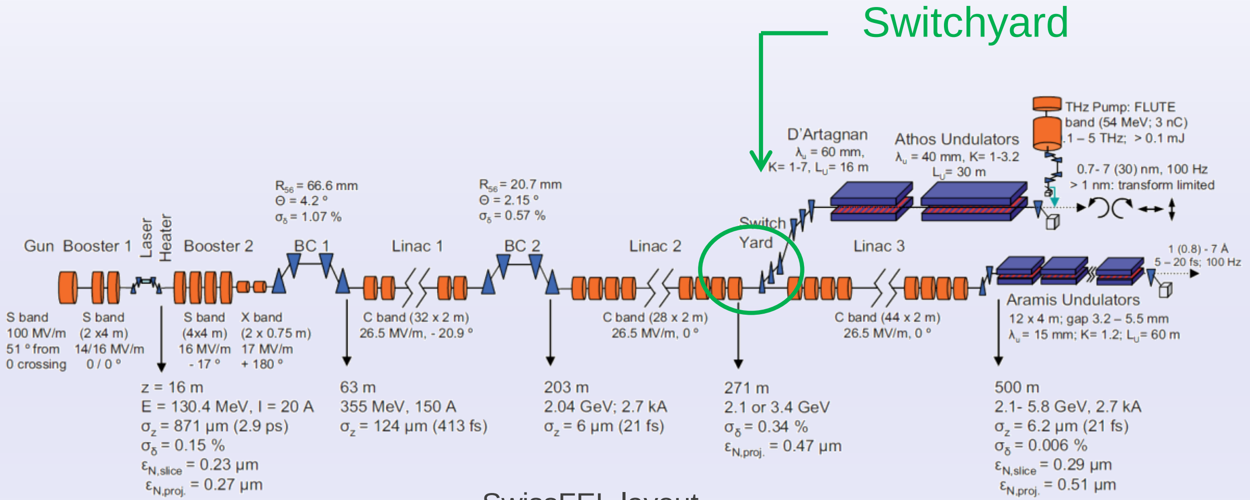
High stability resonant kicker system for SwissFEL at Paul Scherrer Institute

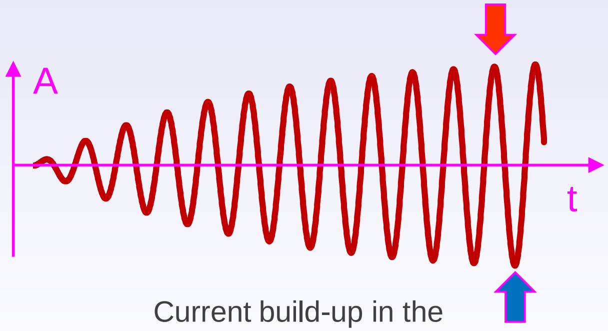
M. Paraliev, C. Gough, S. Dordevic



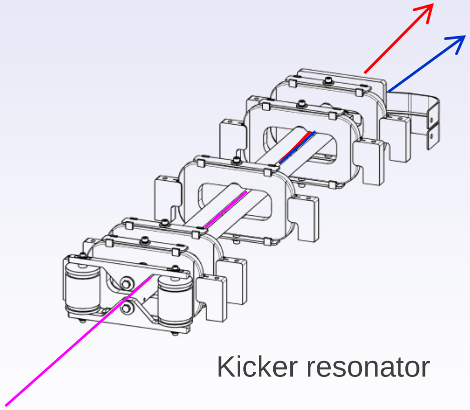
Kicker chamber
(in-vacuum magnet)



SwissFEL layout

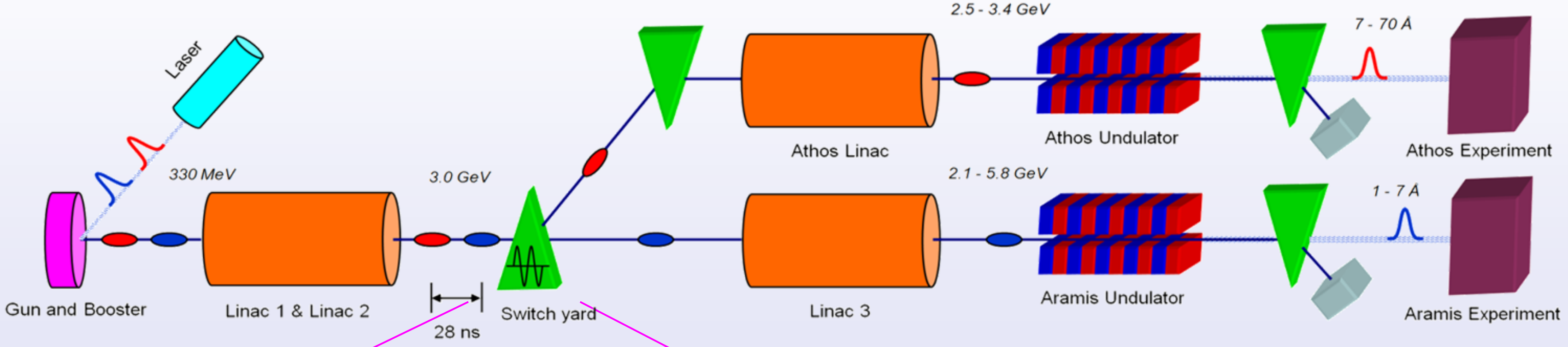


Current build-up in the kicker magnet and bunch extraction positions

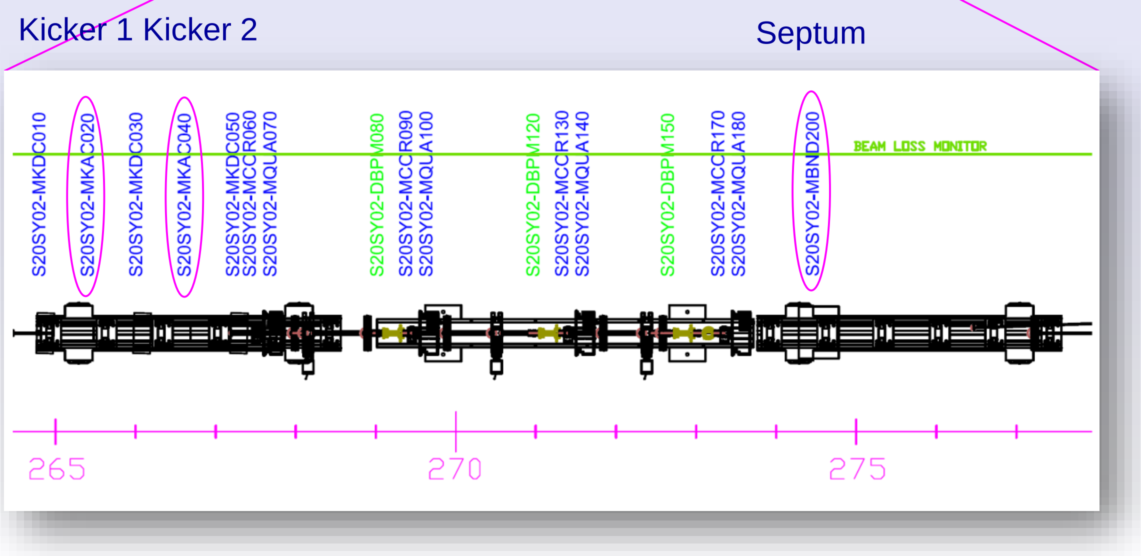


Kicker resonator

Overview



SwissFEL layout



Switchyard

Kicker system key parameters

Beam energy	– 3 GeV
Bunch separation	– 28 ns
Total deflection angle	– 1.8 mrad
Number of Kickers	– 2
Deflection angle error	– 80 ppm
Total magnets length	– 1.5 m
Line field integral	– 10 mT.m
Deflecting current	– 590 App

Resonant Kicker Concept

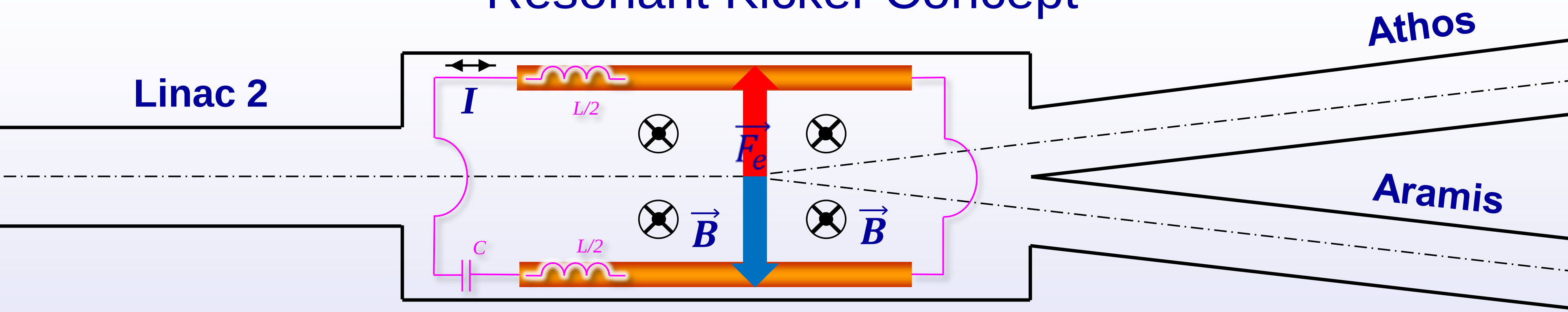
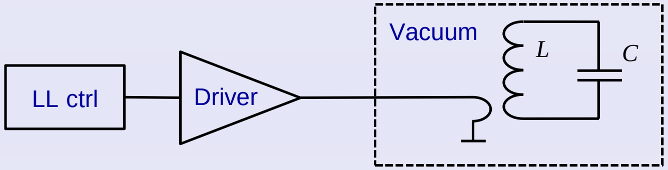
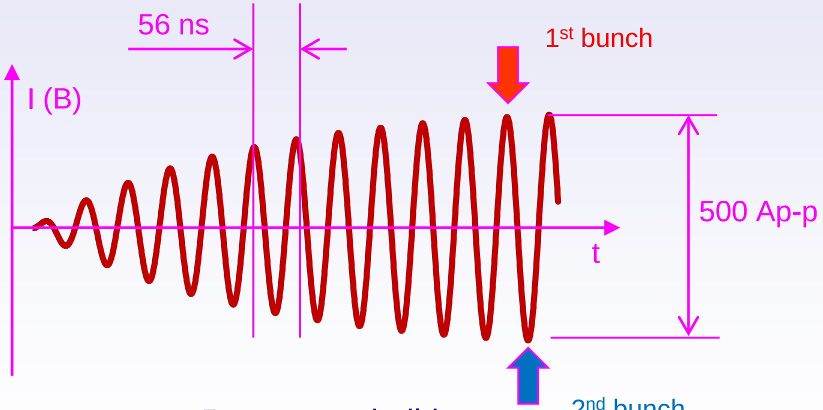


Illustration of bunches separation using a resonant deflecting system



Simplified electrical circuit



Resonance build-up

Resonant technology

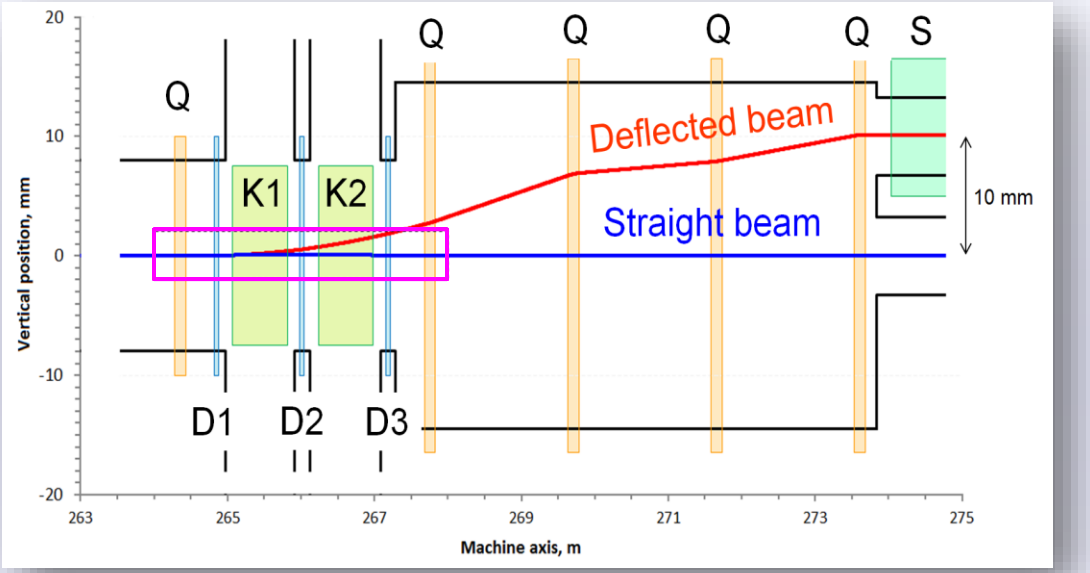
- ✓ No RL transient slope
- ✓ No skin effect slope
- ✓ Lower voltages (HV is enclosed in vacuum)
- ✓ Solid state technology
- ✓ Compact design

- ➢ New driver technology
- ➢ Complex amplitude measurement (ppm)
- ➢ Demanding synchronization
- ➢ Resonance frequency control

Ref.: M. Paraliev, C. Gough, “*Development of High Performance Electron Beam Switching System for Swiss Free Electron Laser at PSI*”, Proc. IPMHVC 2012, p. 691, San Diego, CA, USA, 2012

Beam trajectory

Switch Yard



Field regions and beam trajectory in SwissFEL switch yard

Color rectangles represent the corresponding field regions

Q – Quadrupole magnet

Kx – Kicker magnet

Dx – Dipole magnet

S – Septum magnet

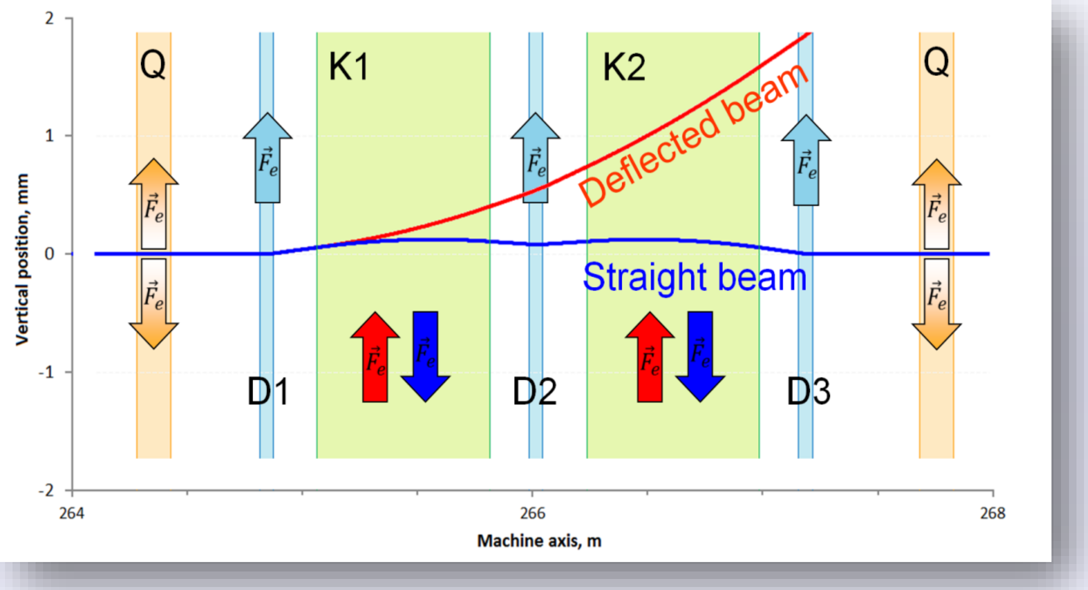
The two kickers K1 and K2 (together with the accompanying dipoles D1, D2 and D3) provide about 1.8 mrad deflection.

Adding the quads contribution the effective deflection is reduced to about 1 mrad.

Beam separation at the entrance of the septum magnet is nominal 10 mm.

Beam trajectory

Kickers' region



Beam trajectory in the kickers' region

Color rectangles represent the corresponding field regions

Q – Quadrupole magnet

Kx – Kicker magnet

Dx – Dipole magnet

The kickers K1 and K2 deflect both bunches ("straight" and "deflected") vertically but in the opposite direction.

Deflecting both beams results in 50% reduction of the required magnetic field strength (respectively the current in the magnets)

The three dipole magnets get the "straight" beam back to its original trajectory and increase deflection angle of the deflected beam.

Resonant Kicker (RK)

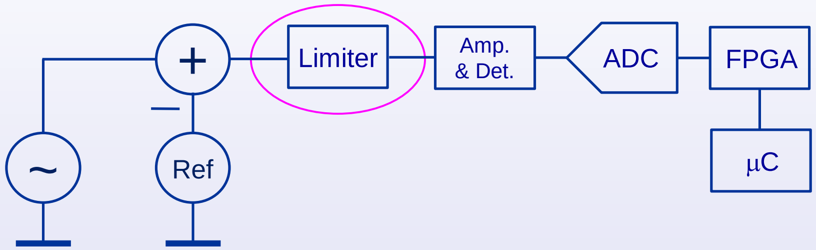
Construction

Prototype kicker in vacuum chamber

Two kickers installed in SwissFEL tunnel

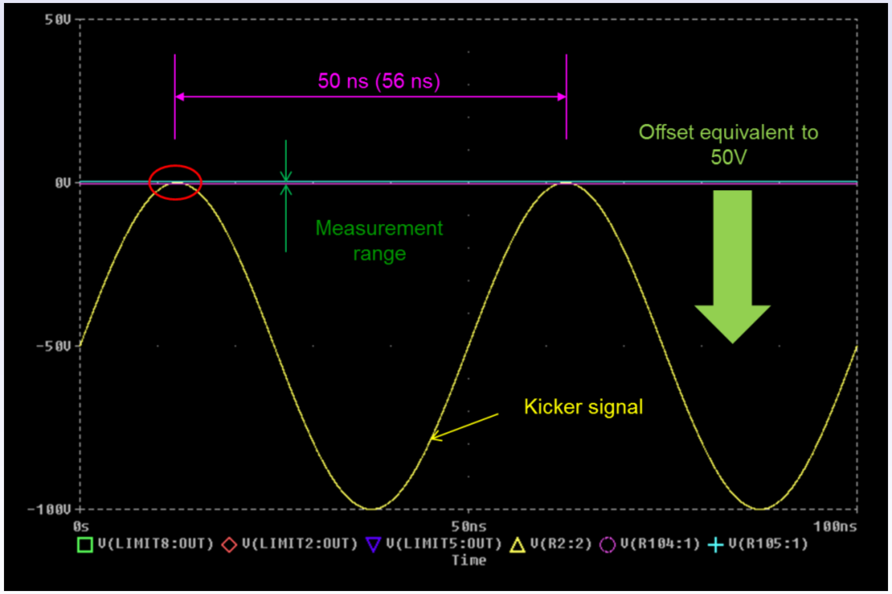
Precision amplitude measurement system for RK

Balanced measurement

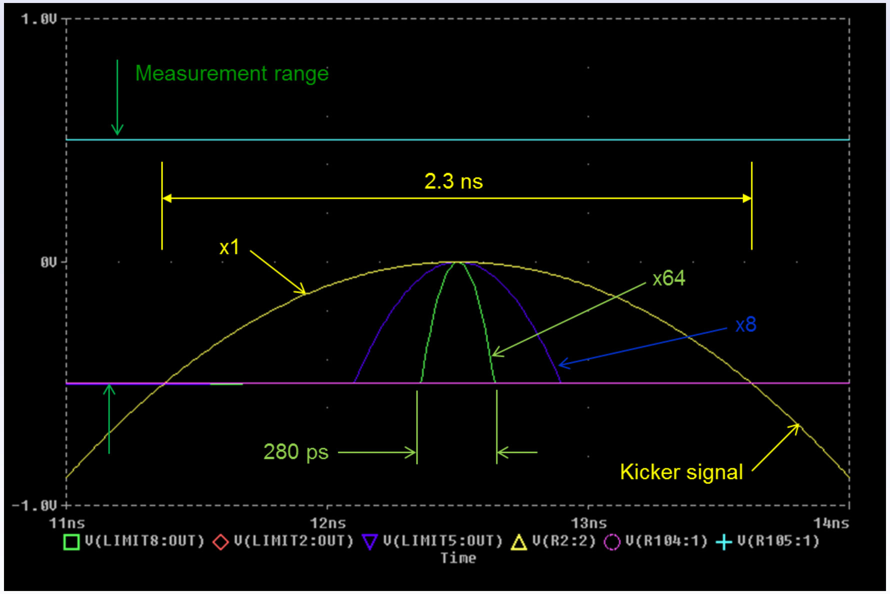


Prototype kicker in vacuum chamber

- Heavy overload (10000%)
- Fast recovery x1 ns
- 6 stages matrix amplifier-detectors
- 10 bit, 40 Ms/s ADC
- FPGA peak detector



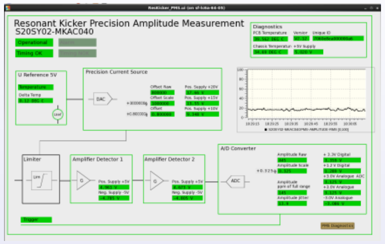
Waveform offset (pSpice)



Signal before and after amplification (x8 and x64, pSpice)

Precision amplitude measurement system for RK

Expert panel



Resonant Kicker Precision Amplitude Measurement
S20SY02-MKAC040

Operational
Timing OK

Diagnostics
PCB Temperature
Version
Unique ID
Chassis Temperature
+5V Supply

U Reference 5V
Temperature
Delta Temp

Precision Current Source
Offset Raw
Offset Scale
Offset
Pos. Supply +20V
Pos. Supply +15V
Pos. Supply +10V

Limiter

Amplifier Detector 1
Pos. Supply +5V
Neg. Supply -5V

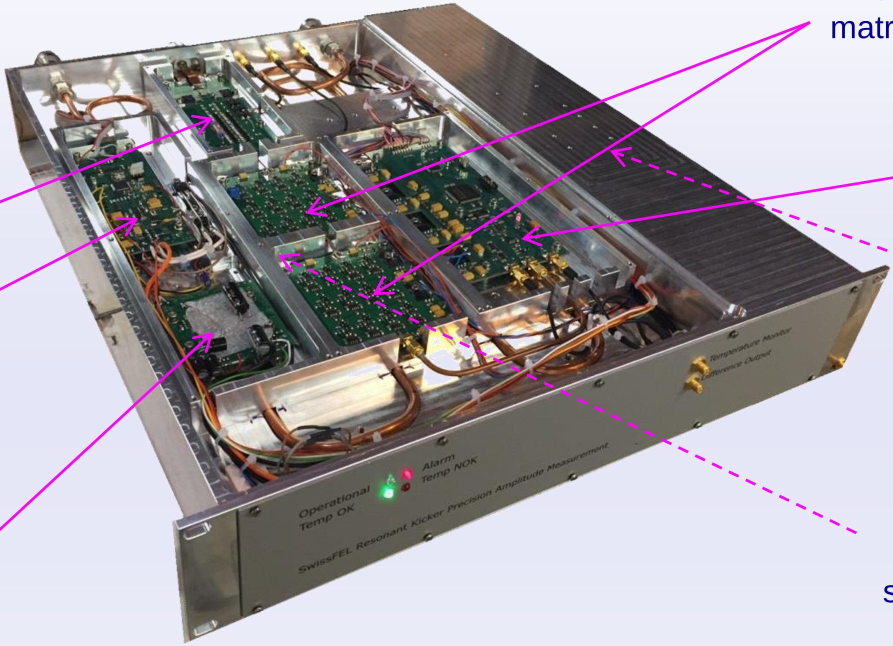
Amplifier Detector 2
Pos. Supply +5V
Neg. Supply -5V

A/D Converter
Amplitude Raw
Amplitude Scale
Amplitude ppm of full range
Amplitude jitter
+ 3.3V Digital
+1.2 V Digital
+3.0V Analogue ADC
+3.0V Analogue
-3.0V Analogue

Trigger

PMS Diagnostics

Hardware



Low noise difference matrix amplifier/detector

10 bit 40 Ms/s ADC and FPGA module

Power supply (Bottom side)

DC/DC converters, regulators, filters and self diagnostics module (Bottom side)

Balancing unit and input limiter

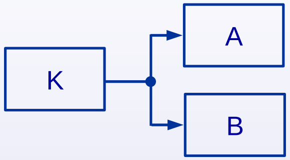
Precision 20 bit programmable current source

Temperature controlled reference voltage source

- Resolution ~0.3 ppm, noise floor ~0.6 ppm, range ± 150 ppm
- Fast recovery (<10 ns) analogue input limiter – withstanding 10000% overload
- Actively thermo-stabilized voltage reference source (0.35 ppm rms)
- High stability programmable (20 bit resolution) current source - 2 A (for balancing)
- Self diagnostics module – device status (internal temperatures, supply voltages and etc.)
- 2U rack mount water cooled chassis

Precision amplitude measurement system for RK

Calibration and measurements

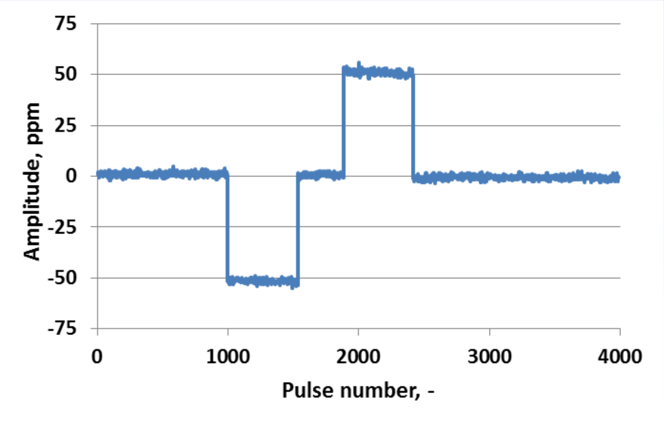


Measurement configuration – two simultaneous amplitude measurement systems (A and B)

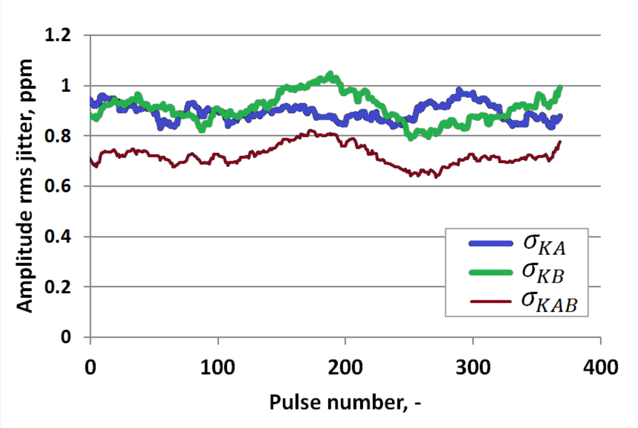
$$\sigma_{MC}^2 = Var\left(\frac{MA+MB}{2}\right) = \frac{Var(A)}{4} + \frac{Var(B)}{4} + Var(K)$$

$$\sigma_K = \sqrt{2\sigma_{MC}^2 - \frac{\sigma_{MA}^2}{2} - \frac{\sigma_{MB}^2}{2}}$$

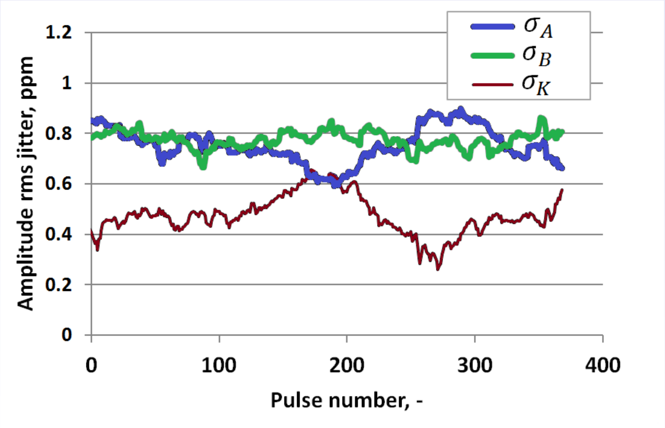
$$\sigma_A = \sqrt{\sigma_{MA}^2 - \sigma_K^2}; \qquad \sigma_B = \sqrt{\sigma_{MB}^2 - \sigma_K^2}$$



Calibration



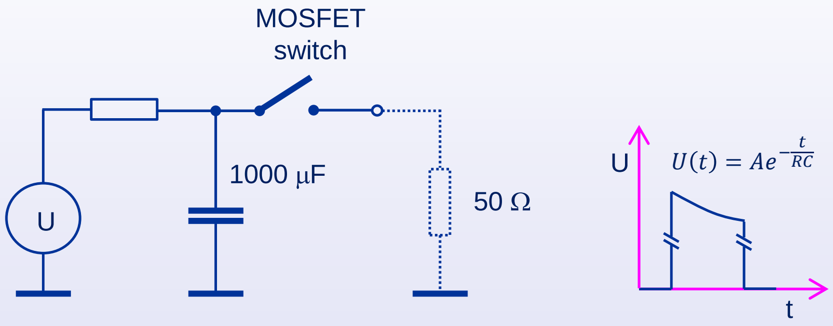
Jitter of measured amplitude by meas. system A, B and average of A and B



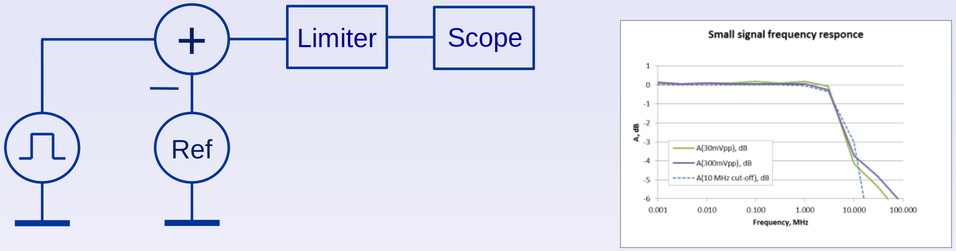
Calculated jitter of meas. system A, B and the kicker

Pulse amplitude measurement

Different methods comparison



MOSFET based pseudo-rectangular pulse generator with exponentially decaying plateau



Precision offset measurement and its frequency responce

*The following variables are adjusted to overlap at the end of the pulse where the influence of limited bandwidth and skin effect should be least pronounced: offset of 2., gain of 3., gain (2.05 used instead 2.19 calculated) and offset of 4

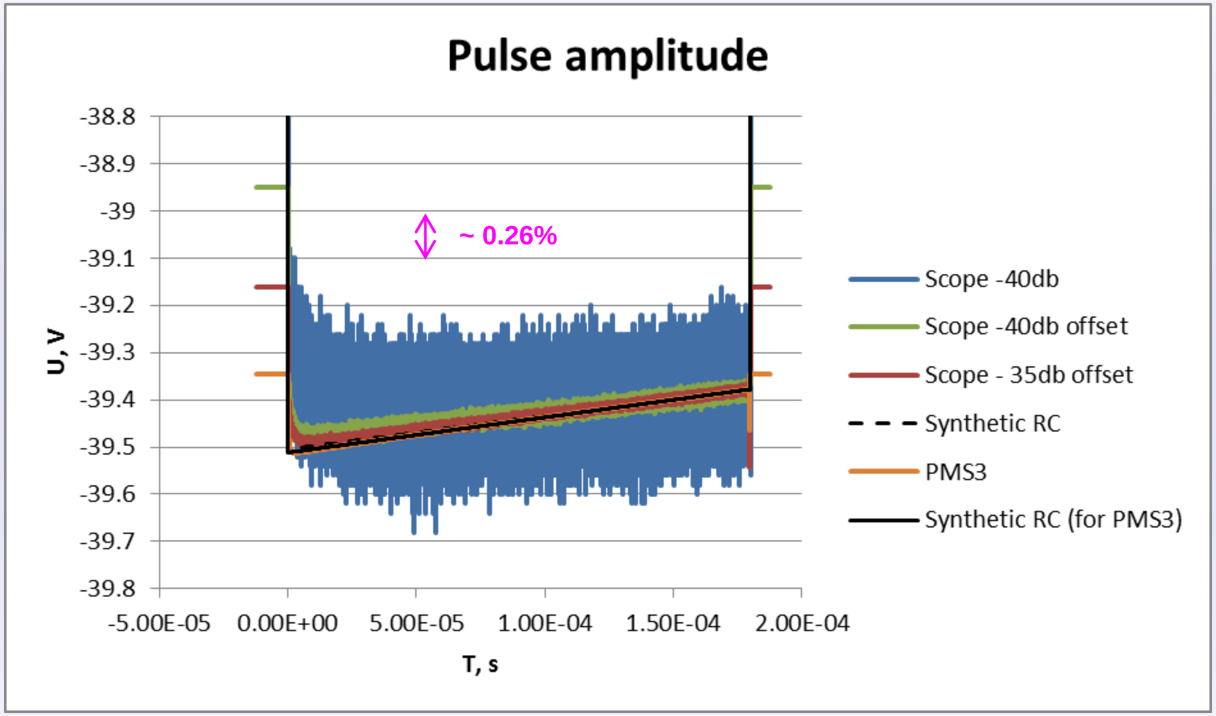
Low inductance MOSFET based pseudo-rectangular pulse generator with exponentially decaying plateau was used to compare* different pulse measurements with exponentially decaying synthetic pulse.

<u>Measurement configurations:</u>

1. Direct scope measurement (signal is attenuated 40 dB and measured directly with the scope)
2. Offset scope measurement (signal is attenuated 40 dB and scope offset function is used to increase precision)
3. Offset scope measurement (signal is attenuated 35 dB and scope offset function is used to increase precision.) This is to produce maximum signal using ~scope offset limits.
4. Balanced measurement (with PMS3)
5. Mathematical exponentially decaying pulse.

Pulse amplitude measurement

Different methods comparison

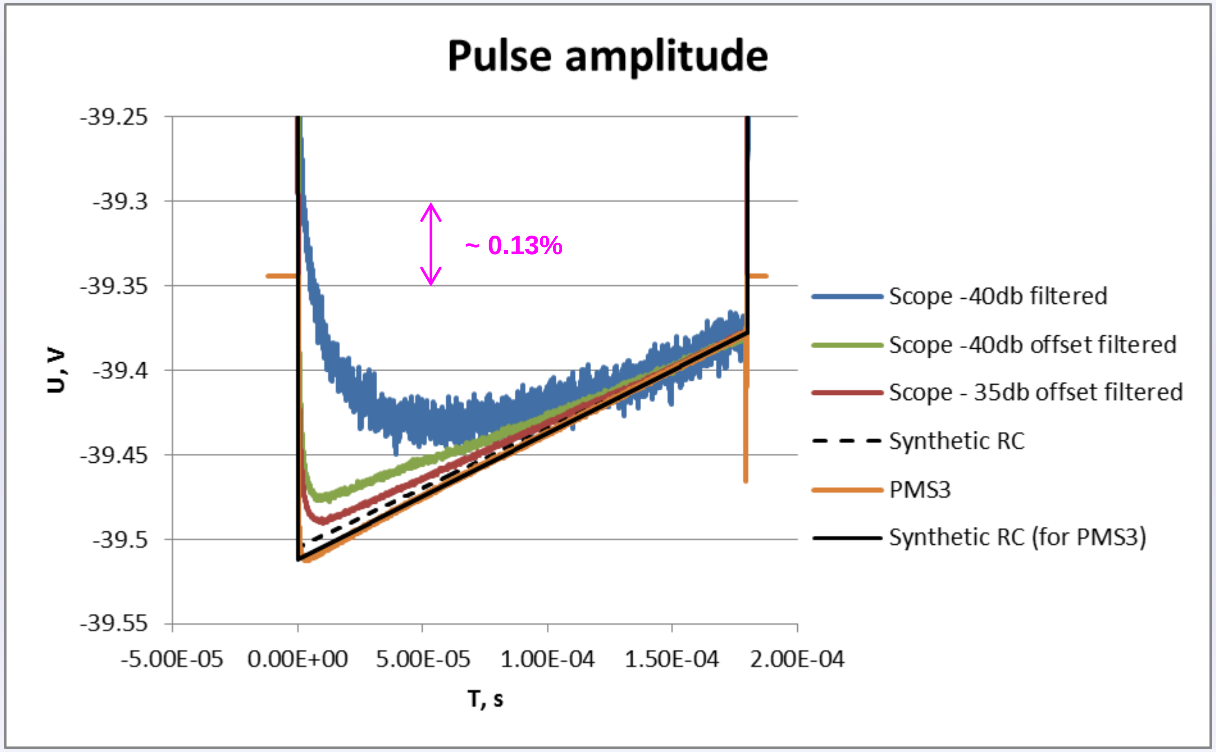


Pulse waveform measured with the different methods compared with synthetic 180 us exponentially decaying pulse

Due to small difference in the load impedance two different synthetic pulses are shown – with time constant 56.1 ms (“attenuated”) and 52.9 ms (“PMS3”)

Pulse amplitude measurement

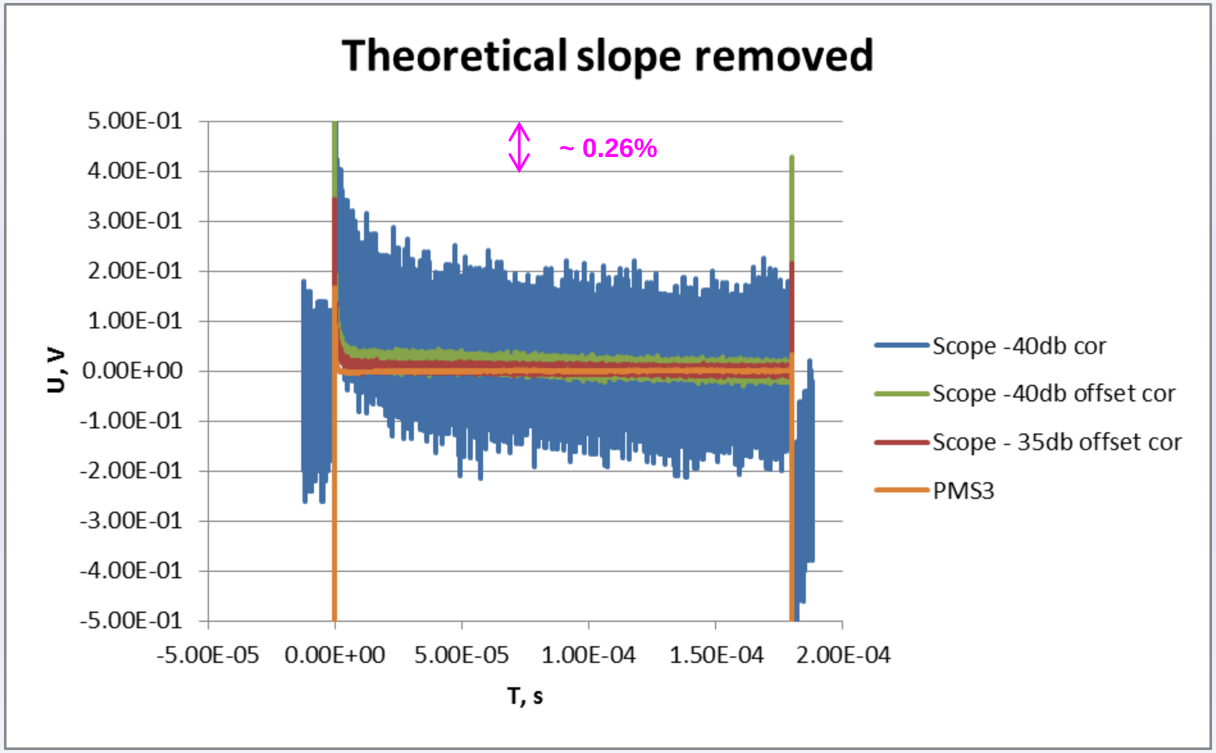
Different methods comparison



Pulse waveform measured with the different methods (smaller vertical scale) – for better comparison measurements 1., 2. and 3. are filtered to reduce noise (running average of 100 samples)

Pulse amplitude measurement

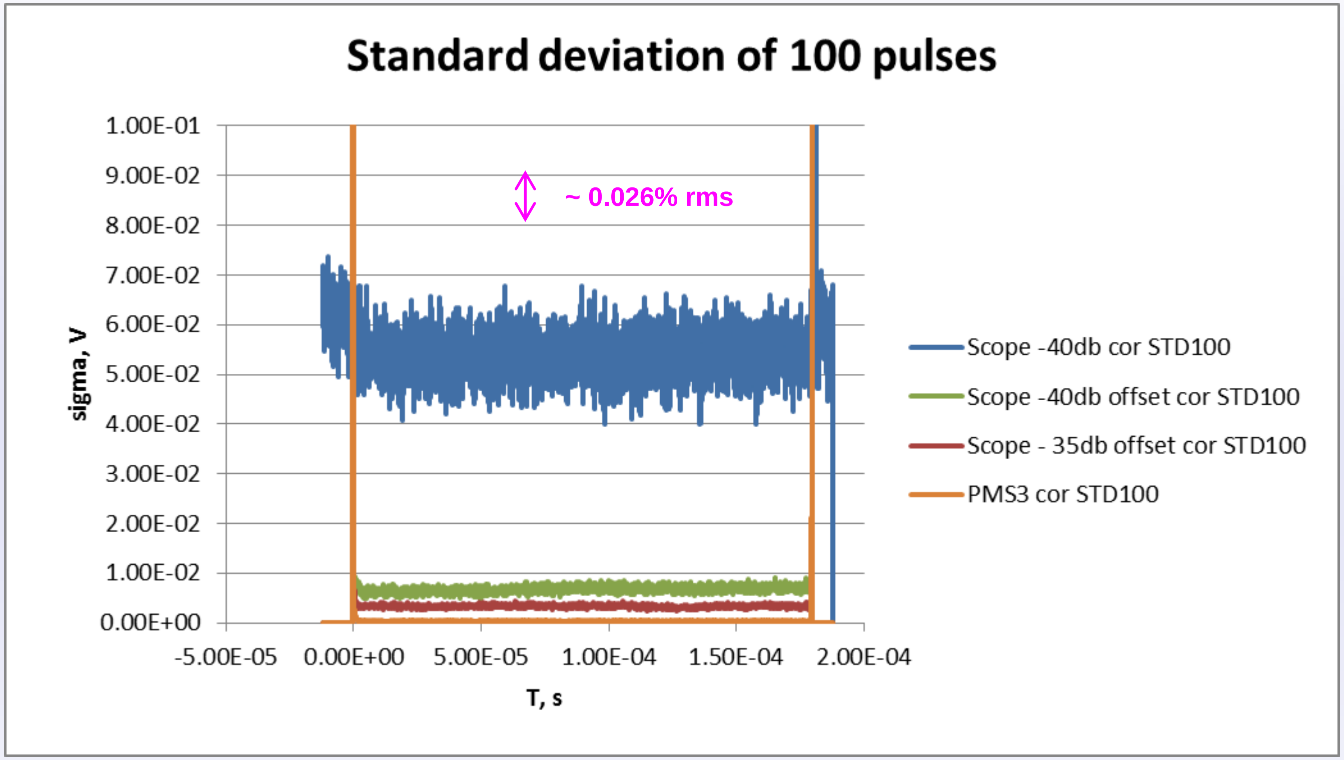
Different methods comparison



Theoretical pulse slope is removed for noise evaluation
(difference from ideal pulse)

Pulse amplitude measurement

Different methods comparison



Noise floor evaluation - running standard deviation of 100 samples

The averaged relative rms noise floor of the different measurements is as following:

1. Scope direct (-40db) – 1400 ppm
2. Scope offset (-40db) – 173 ppm
3. Scope offset (-35db) – 85 ppm
4. PMS3 – 9 ppm

Conclusion

A novel concept for bunches separation using a resonant kicker magnet was developed and evaluated. A prototype of the resonant kicker was designed and built together with dedicated driver and precision amplitude measurement system.

Since the shot-to-shot stability is crucial for this novel concept to work, the stability of the prototype system was extensively evaluated:

- ✓ Shot-to-shot amplitude stability (feedback ON): ~1.5 ppm rms
- ✓ Shot-to-shot amplitude stability (feedback OFF): ~0.8 ppm rms
- ✓ Shot-to-shot phase stability: RF pulse average ~5 mdeg (instantaneous <24 mdeg)

The precision amplitude measurement system (based on “balanced method”) is useful not only for sin waves but for pulses as well.

- ✓ Several different pulse measurement methods were comparted
- ✓ Balance method gave ~9 ppm noise floor

THANK YOU FOR YOUR ATTENTION!

Additional material

Evaluation of standard deviation, based on two noisy measurements

Assumptions:

Noise is additive and uncorrelated (Cov(A,B) = 0, Cov(A,K) = 0 and Cov(B,K) = 0)

Notation:

System under test K with st. deviation σ_K

Noise of Measurement system A with st. deviation σ_A

Noise of Measurement system B with st. deviation σ_B

Measured series MA (from meas. system A) with st. deviation σ_{MA}

Measured series MB (from meas. system B) with st. deviation σ_{MB}

Averaged series MC ($MC = \frac{MA+MB}{2}$) with st. deviation σ_{MC}

$$MA = A + K;\ MB = B + K;\ MC = \frac{MA + MB}{2}$$

$$\sigma_{MA}^2 = Var(MA) = Var(A) + Var(K)$$

$$\sigma_{MB}^2 = Var(MB) = Var(B) + Var(K)$$

$$\sigma_{MC}^2 = Var\left(\frac{MA + MB}{2}\right) = \frac{Var(A)}{4} + \frac{Var(B)}{4} + Var(K)$$

$$\sigma_K = \sqrt{2\sigma_{MC}^2 - \frac{\sigma_{MA}^2}{2} - \frac{\sigma_{MB}^2}{2}}$$

$$\sigma_A = \sqrt{\sigma_{MA}^2 - \sigma_K^2};\qquad \sigma_B = \sqrt{\sigma_{MB}^2 - \sigma_K^2}$$

Additional material

Derivation

$$\sigma_{MC}^2 = Var\left(\frac{MA+MB}{2}\right) = \frac{1}{4}Var(MA+MB)$$

$$\sigma_{MC}^2 = \frac{1}{4}[Var(MA)+Var(MB)+2Cov(MA,MB)]$$

$$Cov(MA,MB) = Cov(A+K,B+K)$$

$$Cov(MA,MB) = Cov(A,B)+Cov(A,K)+Cov(B,K)+Cov(K,K)$$

$$Cov(MA,MB) = Cov(K,K) = Var(K)$$

$$\sigma_{MC}^2 = \frac{1}{4}[Var(MA)+Var(MB)+2Var(K)]$$

$$\sigma_{MC}^2 = \frac{\sigma_{MA}^2}{4}+\frac{\sigma_{MB}^2}{4}+\frac{\sigma_K^2}{2}$$

$$\sigma_K^2 = 2\sigma_{MC}^2-\frac{\sigma_{MA}^2}{2}-\frac{\sigma_{MB}^2}{2}$$

$$\boxed{\sigma_K = \sqrt{2\sigma_{MC}^2-\frac{\sigma_{MA}^2}{2}-\frac{\sigma_{MB}^2}{2}}}$$