SQUID Based Cryogenic Current Comparator for measuring the AD beam

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AVA Topical Workshop
Detectors & Diagnostics for Low Energy Ion and Antiproton Beams

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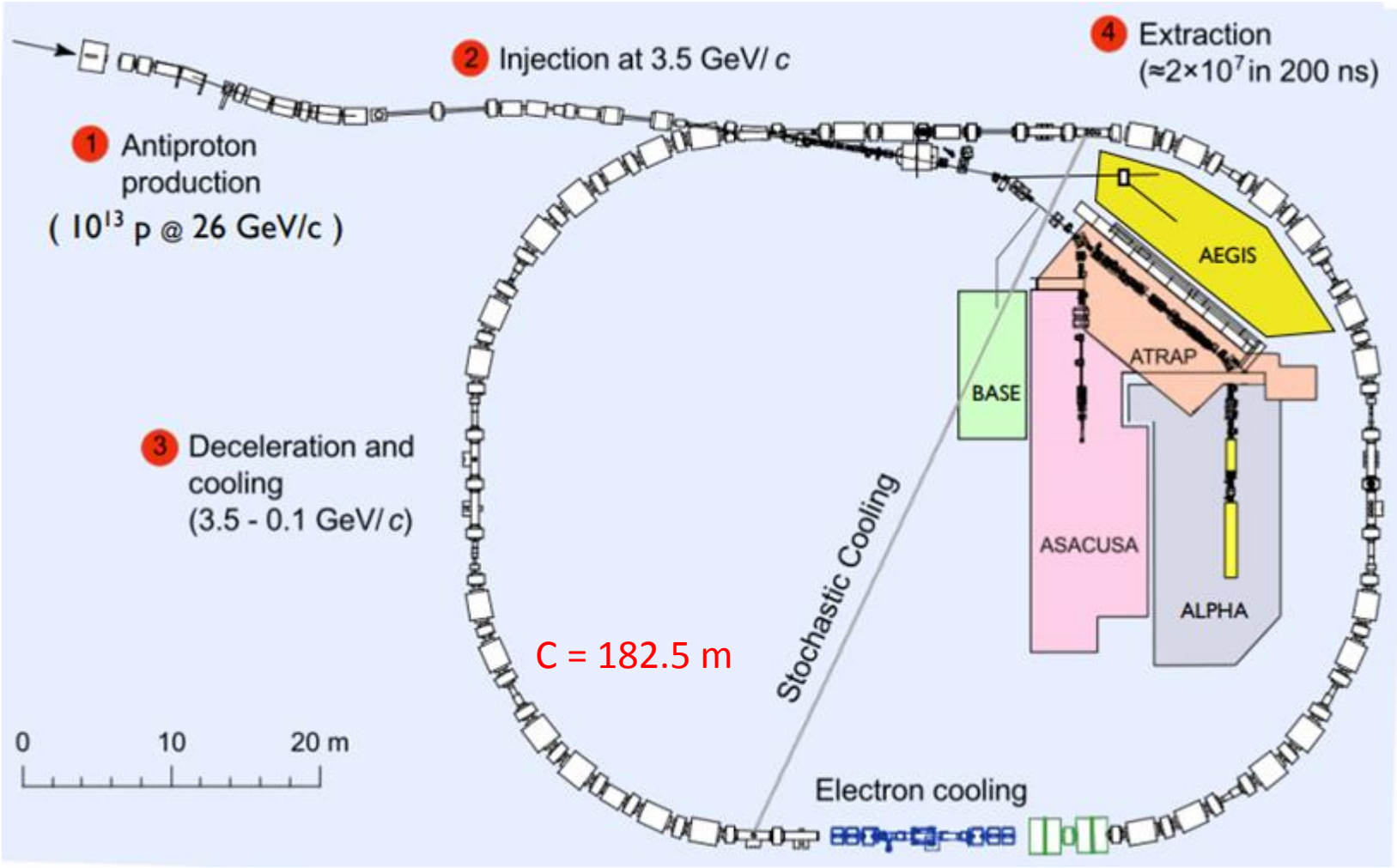
The Antiproton Decelerator (AD)

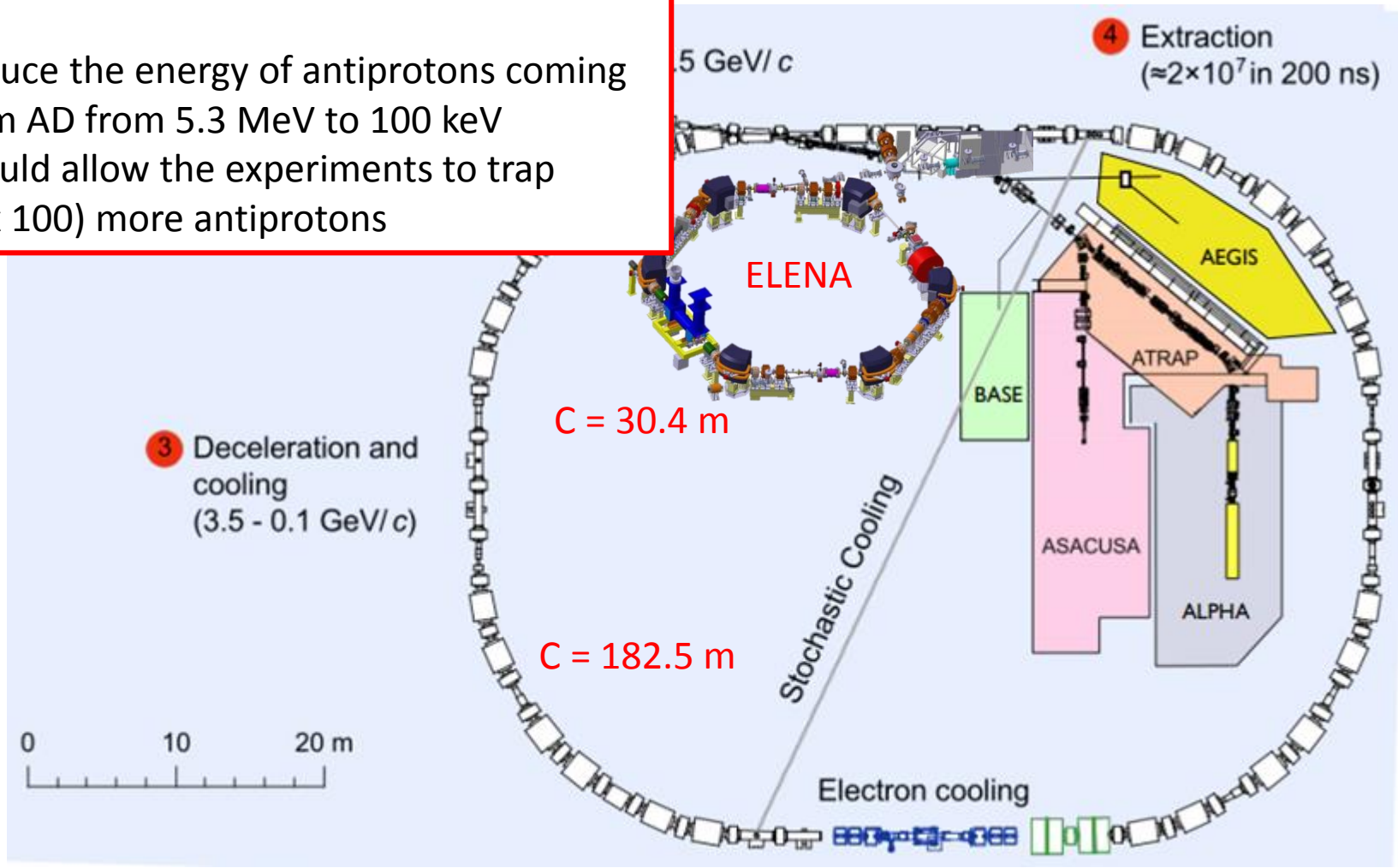
Antiproton Decelerator (AD)



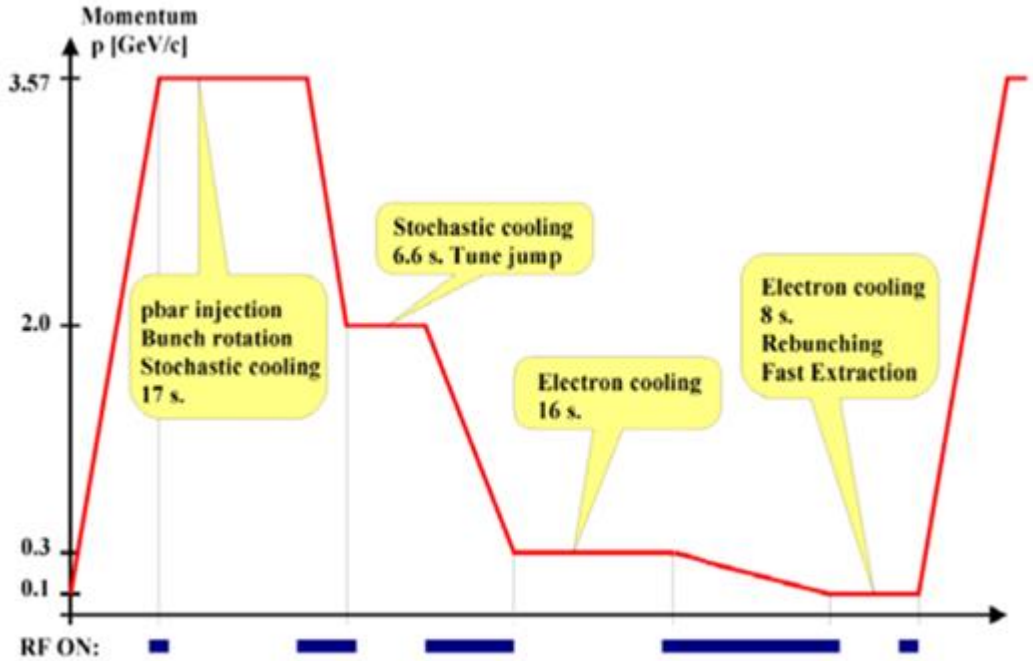
Antiproton Decelerator (AD)

ELENA

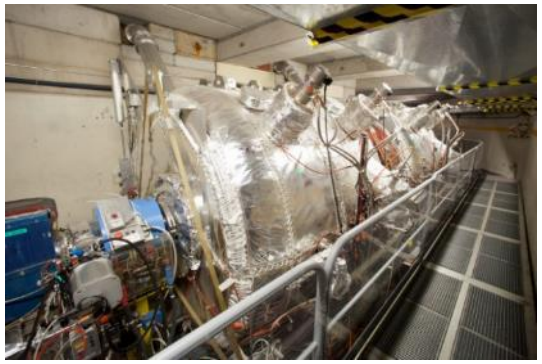
- Reduce the energy of antiprotons coming from AD from 5.3 MeV to 100 keV
- Should allow the experiments to trap (~ x 100) more antiprotons

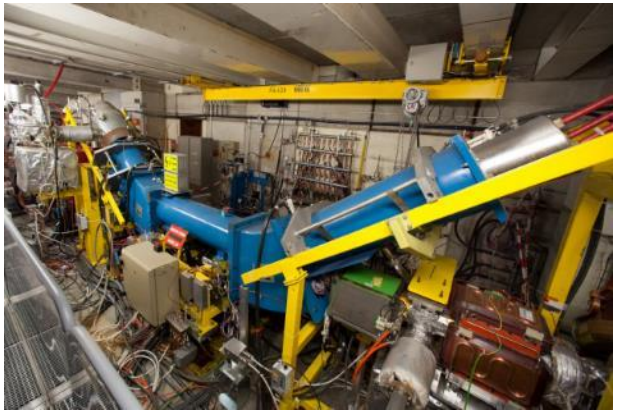


AD beam and cycle parameters



AD beam parameters	
Beta	(0.97 - 0.11) c
Cycle	~110 s
Frev	(1.59 - 0.17) MHz
N particles	(5 - 1) x 10^7
Current	**(12 - 0.1) µA**





Beam intensity monitoring

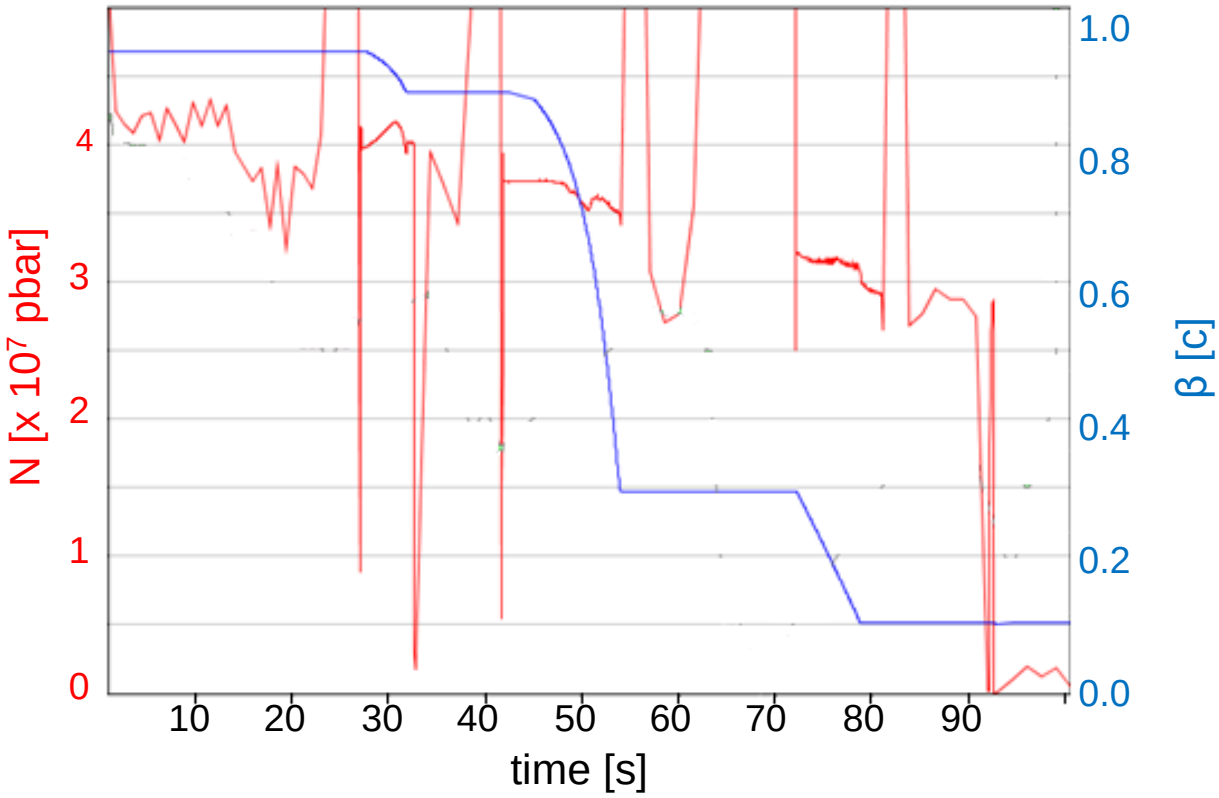
DCCT:

Insufficient resolution: > 1µA

Fast BCTs:

Limited to bunched phases

Schottky monitor:



Beam intensity monitoring

DCCT:

Insufficient resolution: > 1μA

Fast BCTs:

Limited to bunched phases

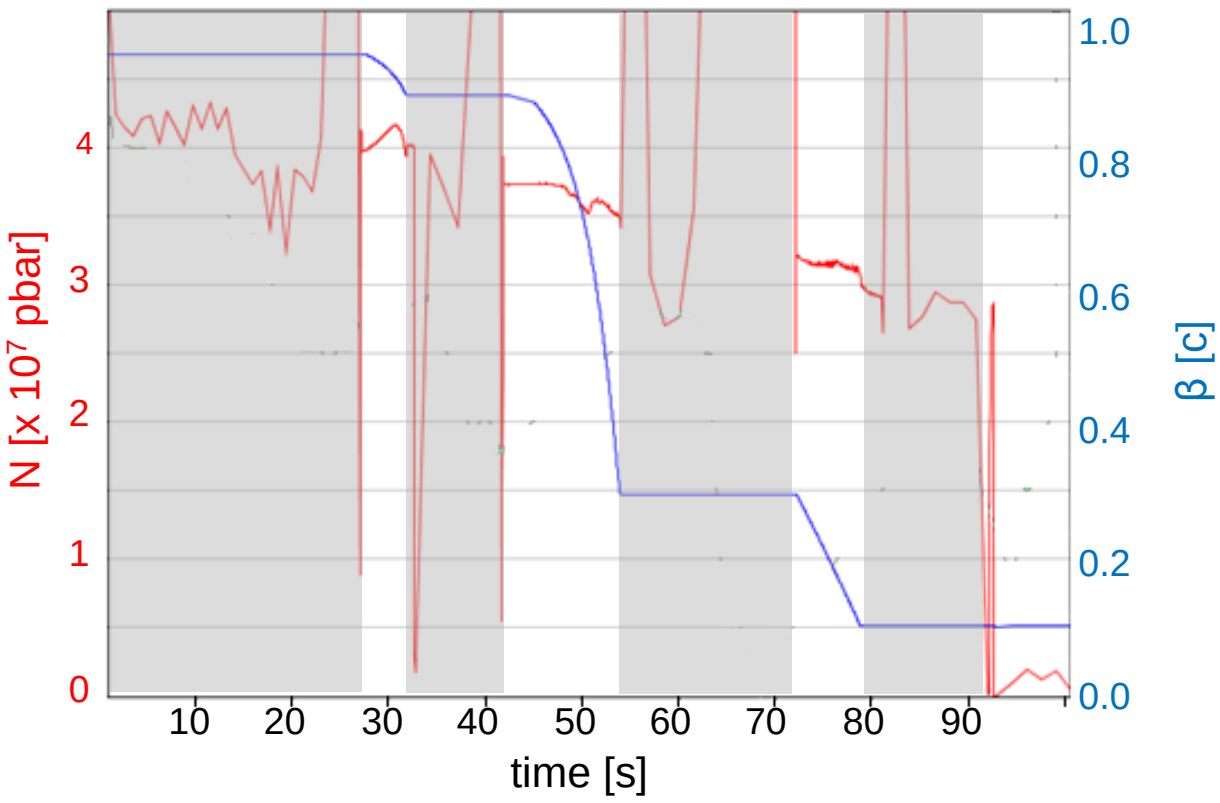
Schottky monitor:

Un-bunched:

time resolution of $\sim 1s$

accuracy error > 10%

Coasting beam plateaus



Beam intensity monitoring

DCCT:

Insufficient resolution: > 1µA

Fast BCTs:

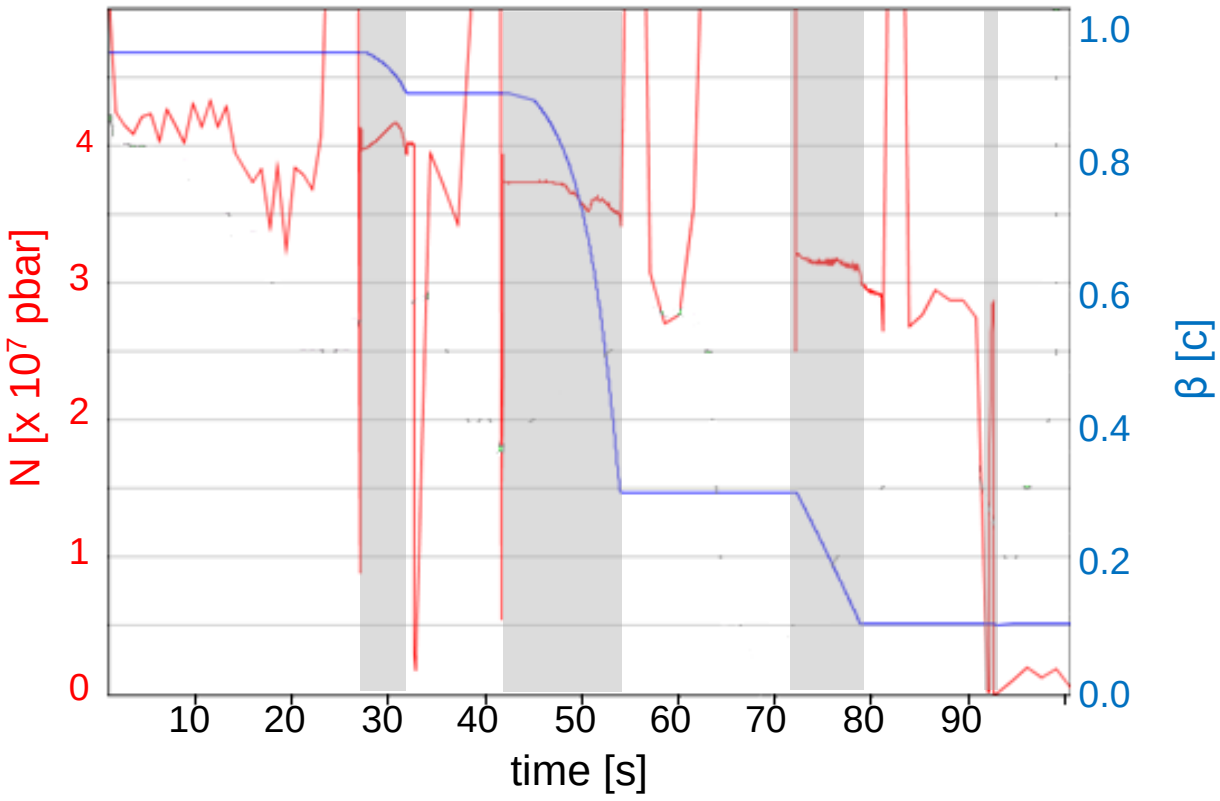
Limited to bunched phases

Schottky monitor:

Bunched:

- time resolution of 20 ms
- accuracy error of <10%
- Bunch shape dependent

Bunched beam ramps



Specifications for new monitor

Current/intensity measurement:

- Measure beam: Bunched and debunched
- Current resolution: < 10 nA
- Intensity resolution: < 5 x 10^5 charges
- Bandwidth: DC - 1 kHz

Operations ready:

- Integrated acquisition: FESA based
- Automatic operation: synchronized with AD cycle

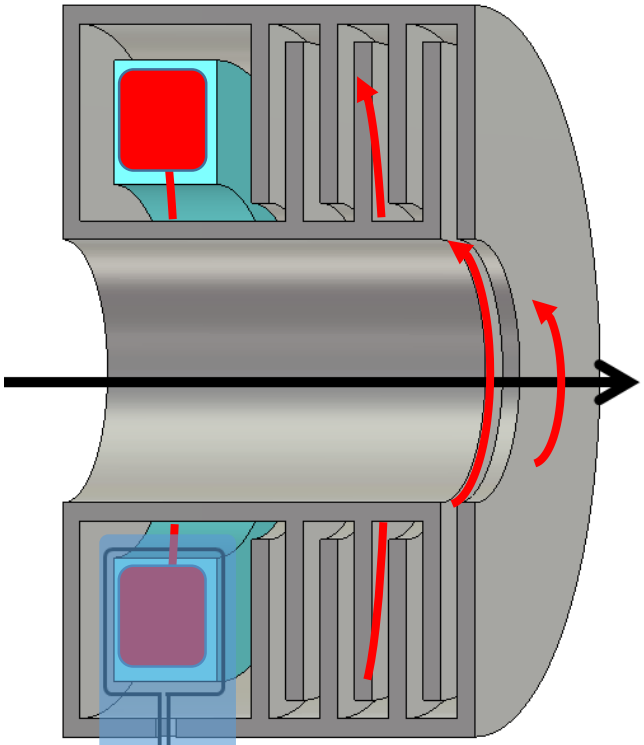
Requirements for the cryostat

- "Zero-boil off" using a pulse tube cryocooler as He reliquefier unit
- Stand-alone long term availability

Collaboration:

Overview of the CCC

CCC functioning overview



Magnetic shield:

- Suppresses all field components except azimuthal beam component

Pickup coil:

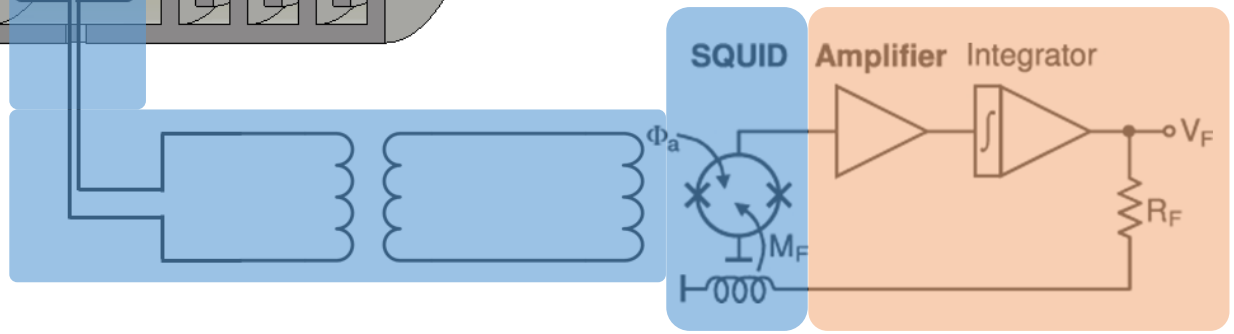
- Soft ferromagnetic material with high-permeability concentrates flux

Flux transformer:

- Couples magnetic flux (down to DC) to SQUID

SQUID + Electronic readout:

- Superconducting QUantum Interference Devices
- Measures the magnetic field induced in the SQUID's input coil

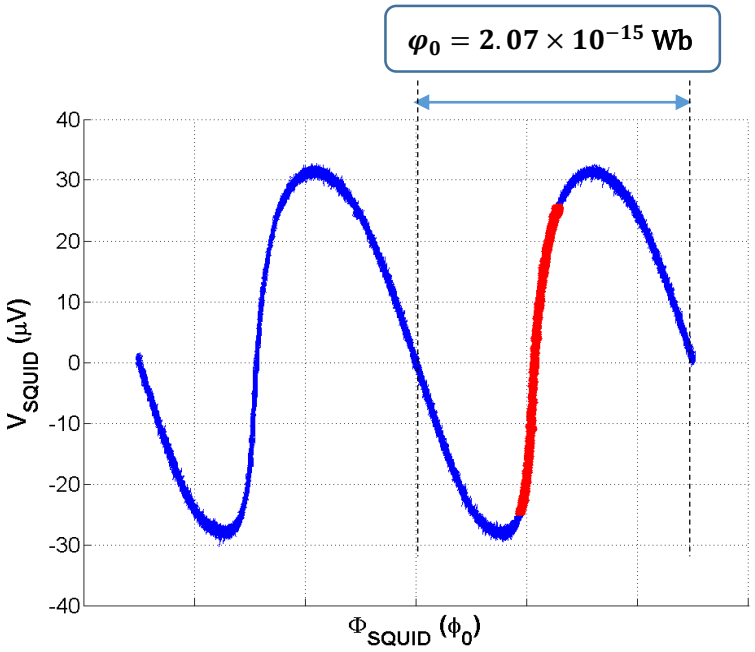


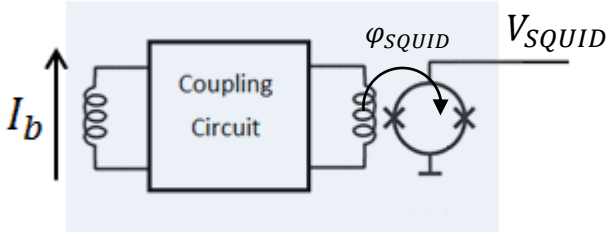
Superconducting

Room temperature

SQUID devices

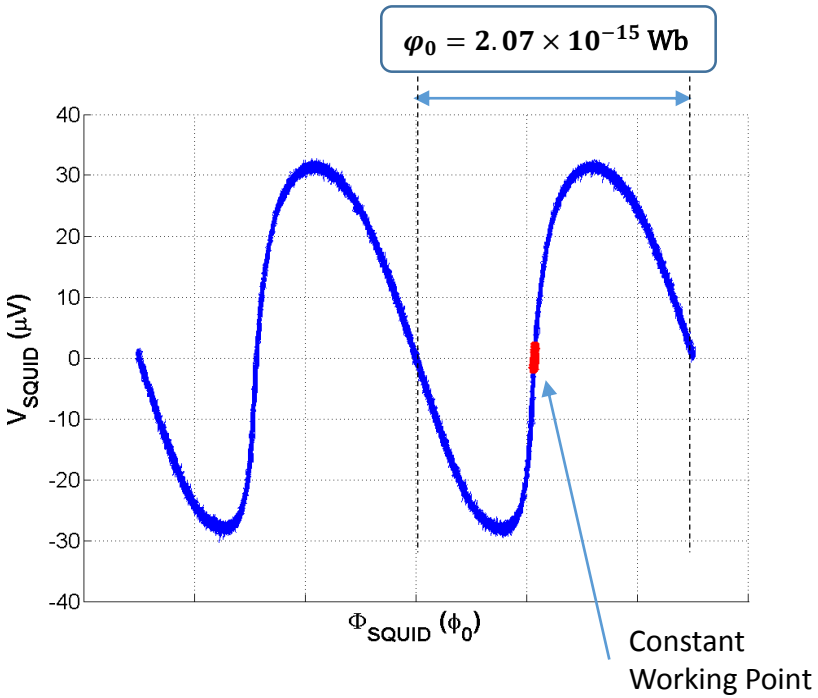
- SQUID's are very sensitive magnetometers
- Measure magnetic flux
- Periodic **voltage-flux** transfer function with period $\boldsymbol{\varphi_0}$ (flux-quanta)
- Noise as low as $\sim 1\,\mu\boldsymbol{\varphi_0}/\sqrt{Hz}$ or $\sim 1\,fT/\sqrt{Hz}$
- Voltage output of the order of $\sim 10\,\mu V$
- Periodic transfer function strongly limits its dynamic range

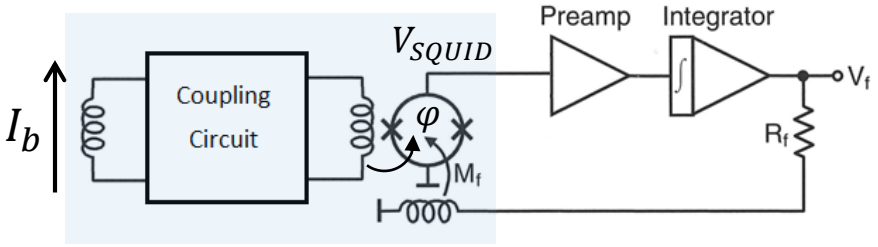




SQUID devices

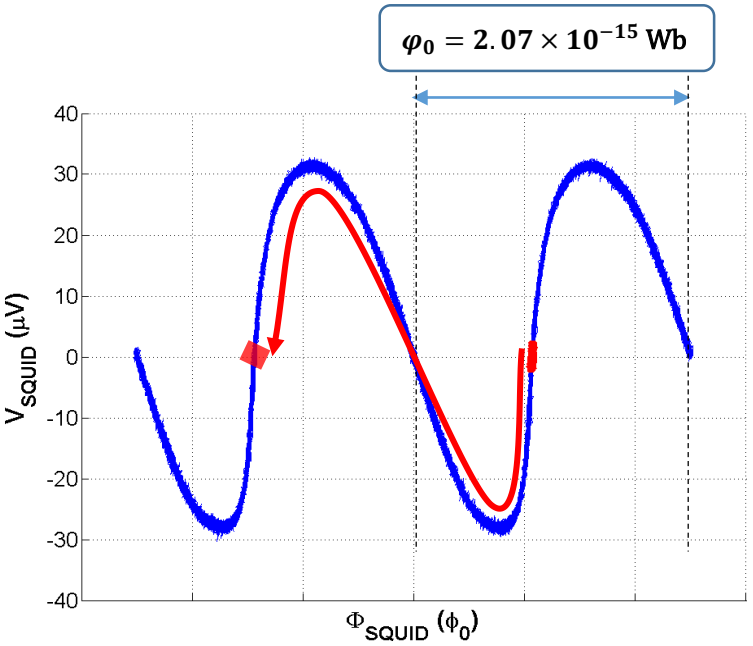
- Linearization of the transfer function using a feedback flux lock loop (FLL)
- Total flux in SQUID is kept constant at a fixed working point
- Possible to resolve variations of $10^{-6}\varphi_0$
- Dynamic range increased to up to 120 dB

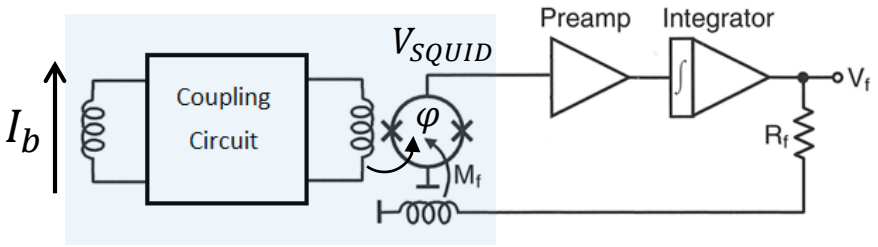




SQUID devices

- Flux jumps of working point may occur
- If feedback loop is too slow to track input signal
- If too much flux noise is coupled to the SQUID
- Increasing FLL bandwidth makes it faster, but also adds more flux noise
- Necessary to limit slew-rate of coupled signal to avoid flux-jumps





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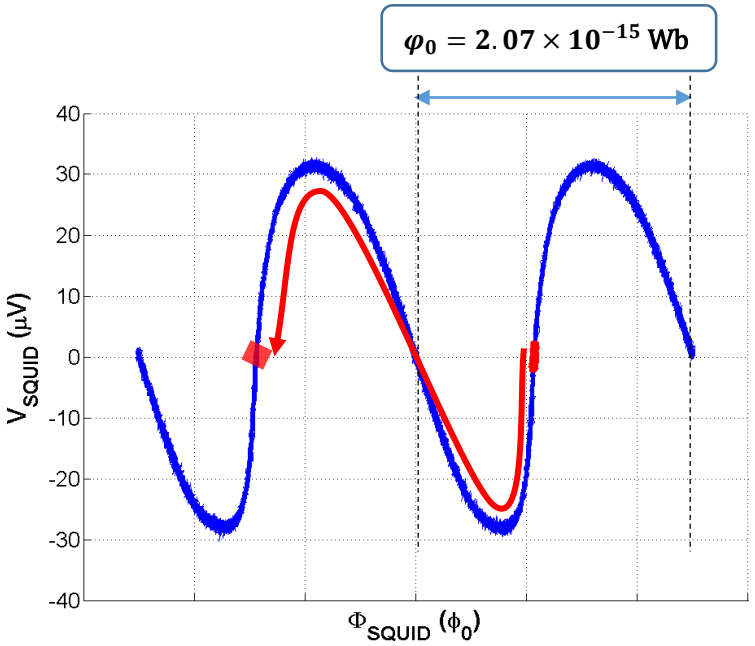
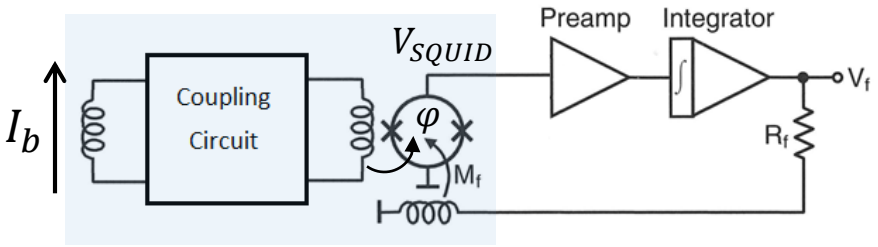
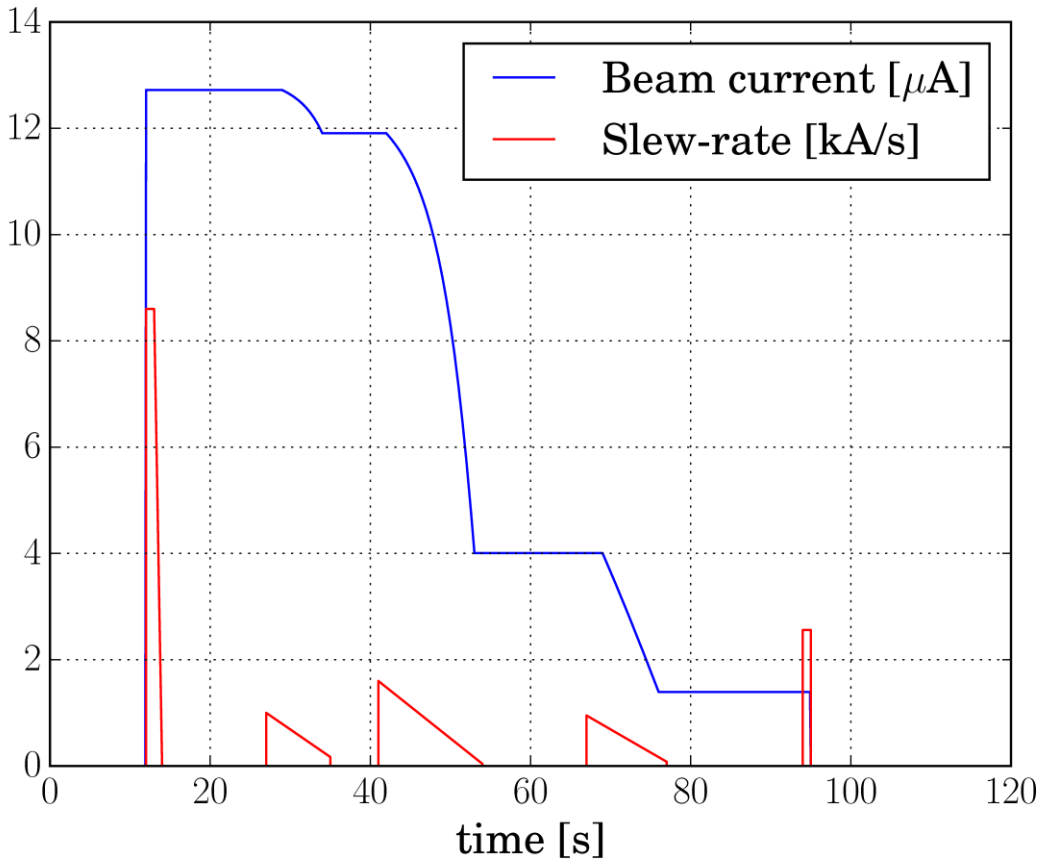


$$\frac{d\phi_s}{dt} \leq 1 \ldots 5\, M\varphi_0/s$$



Adaptation of the CCC to the AD beam

AD beam slew-rate

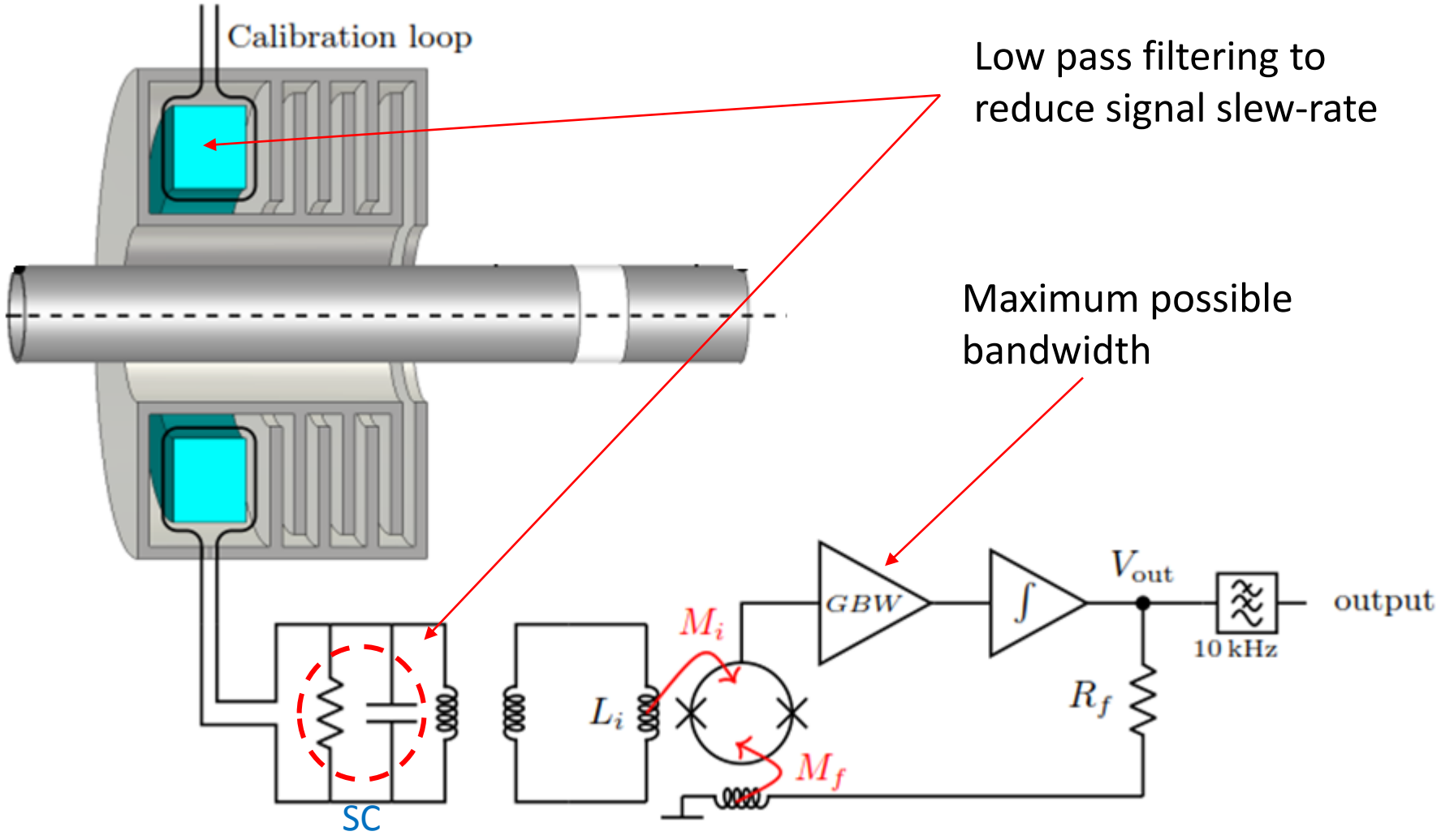


$$\frac{\phi}{I_{beam}} = 10\ \phi_0/\mu A$$

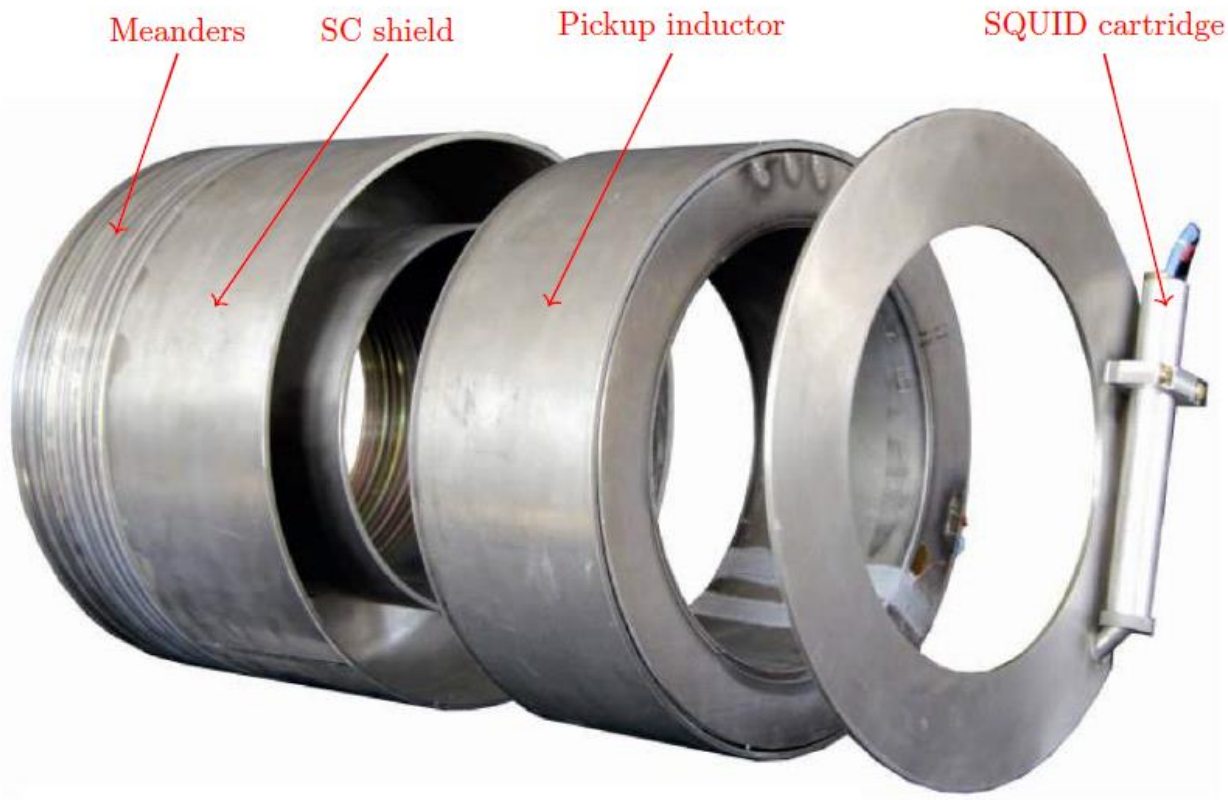
Flux slew-rate at SQUID

Filtering	Slew-rate
None	86 Gϕ_0/s
Core permeability	1.2 Gϕ_0/s

Filtering beam current signal

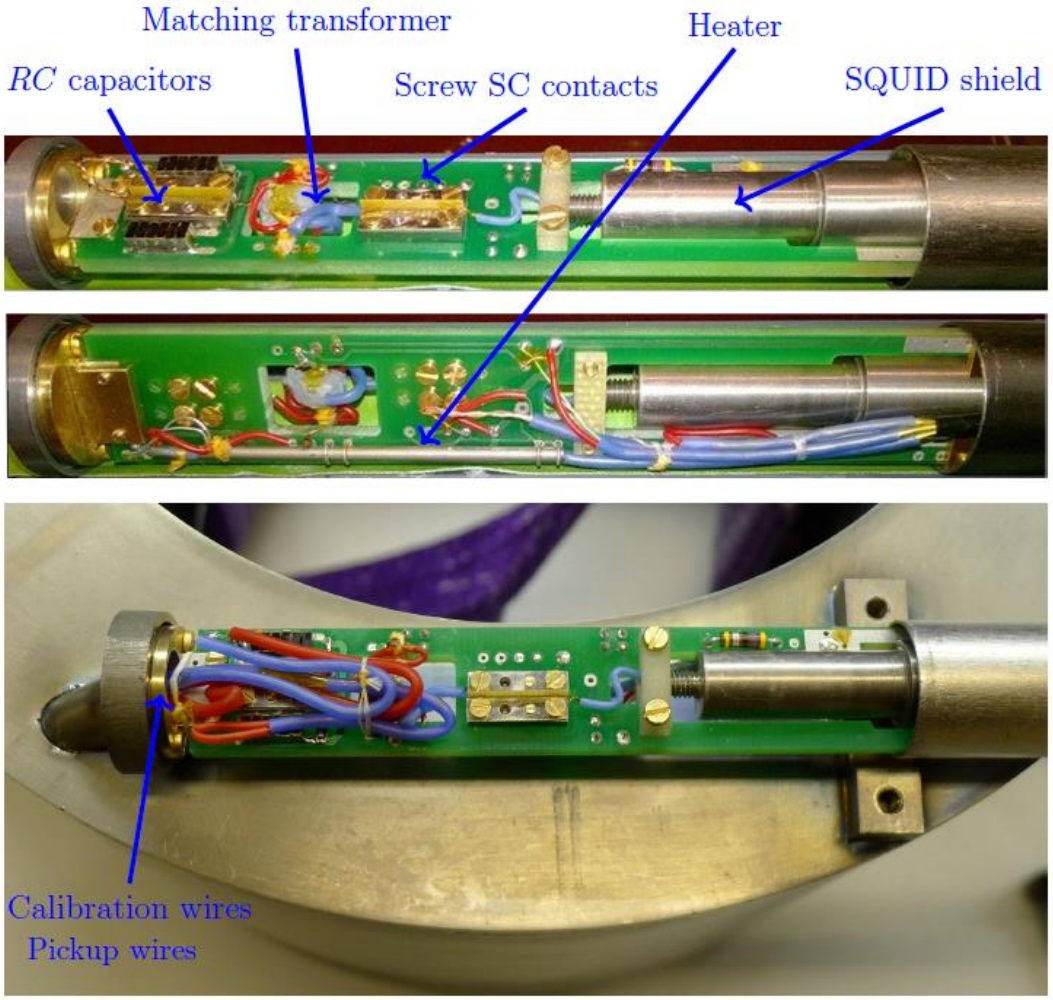


CCC components

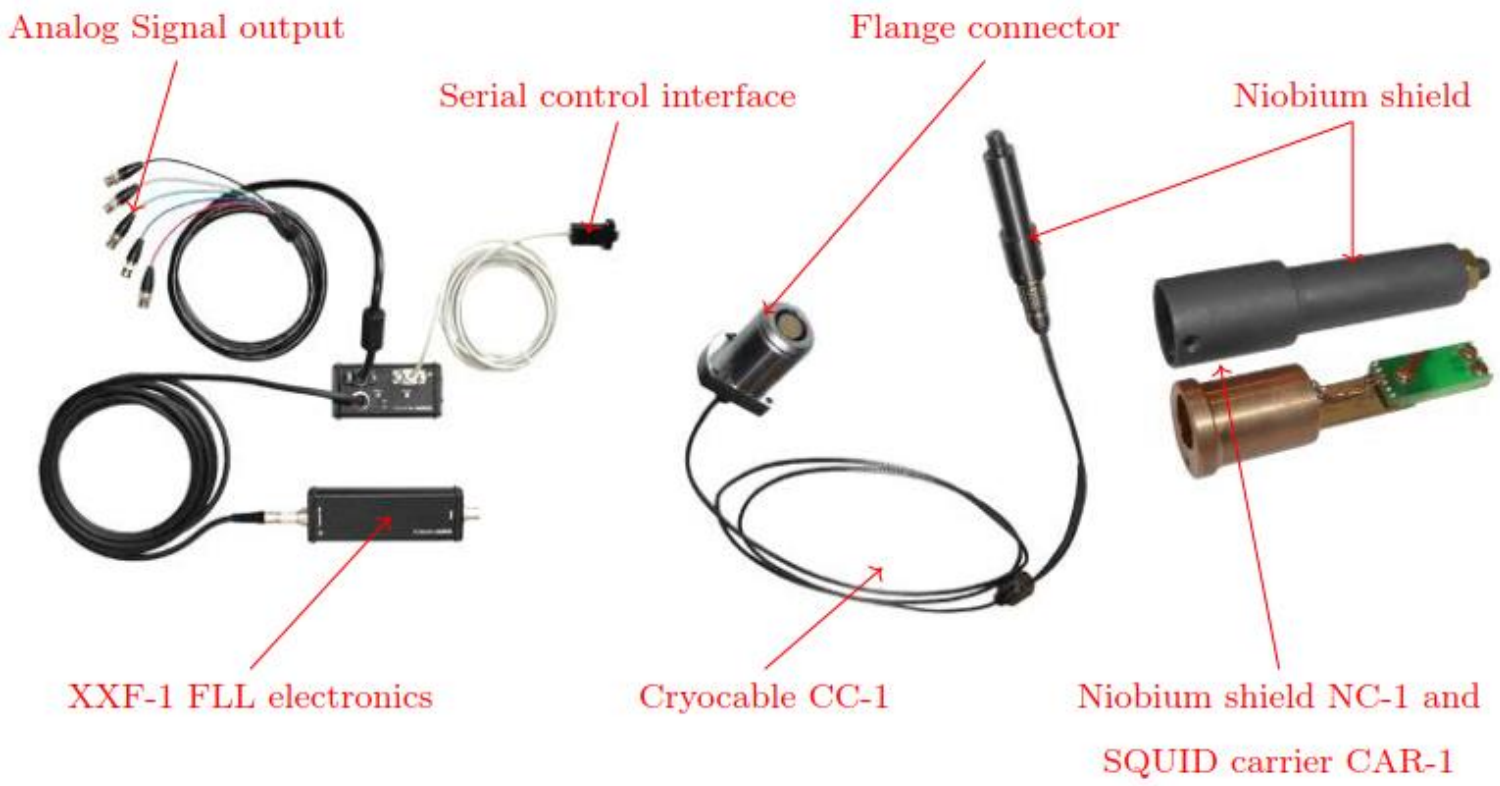


Magnetic shield had previously been fabricated by GSI and Univesity Jena as prototype for FAIR

CCC components



CCC components

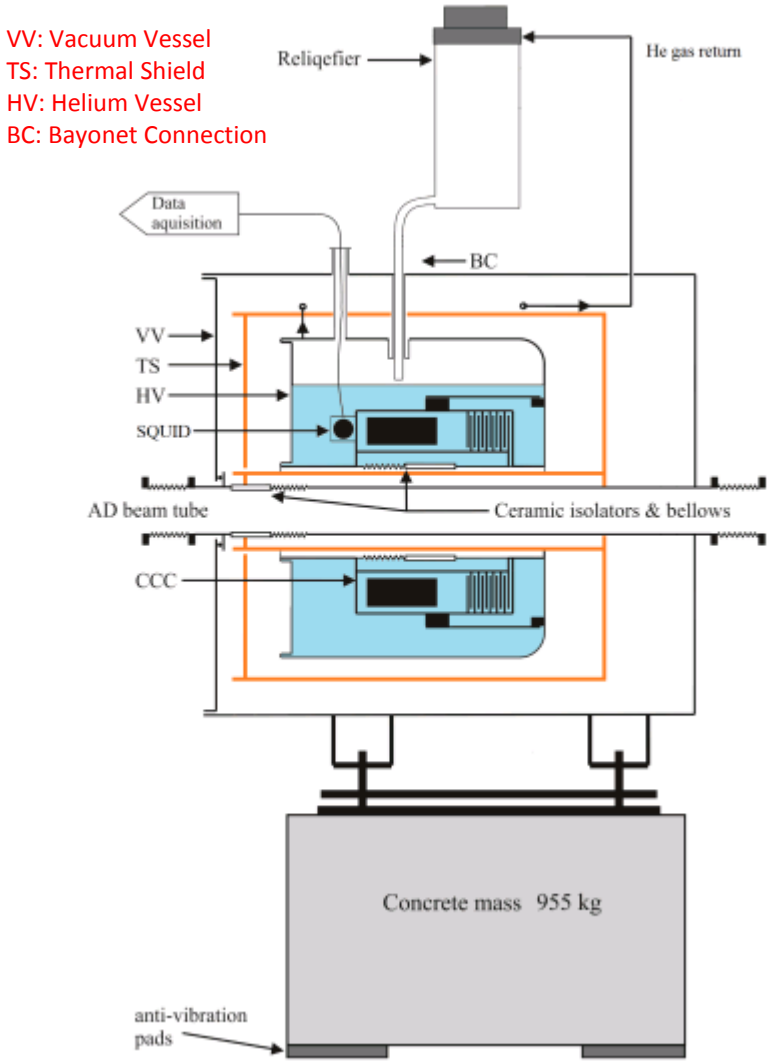


Magnicon SQUID and FLL electronics system

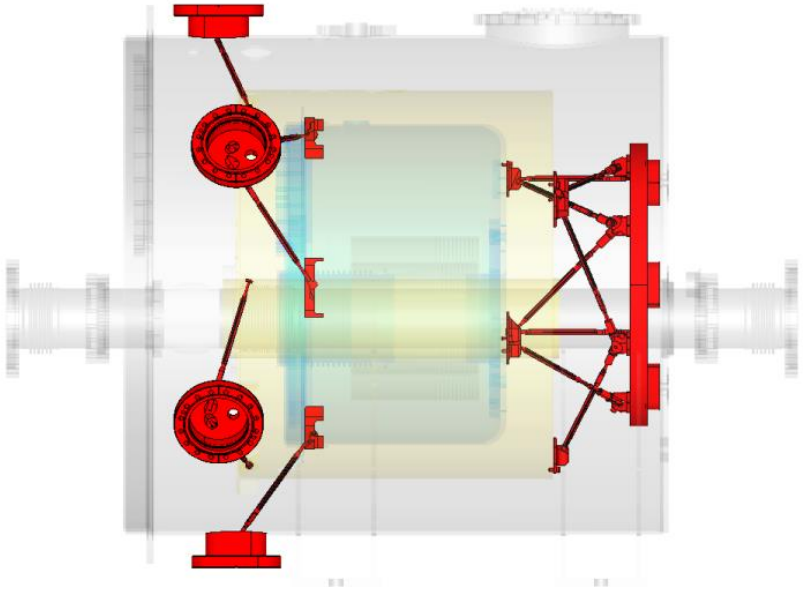
Cryostat design

Cryostat design

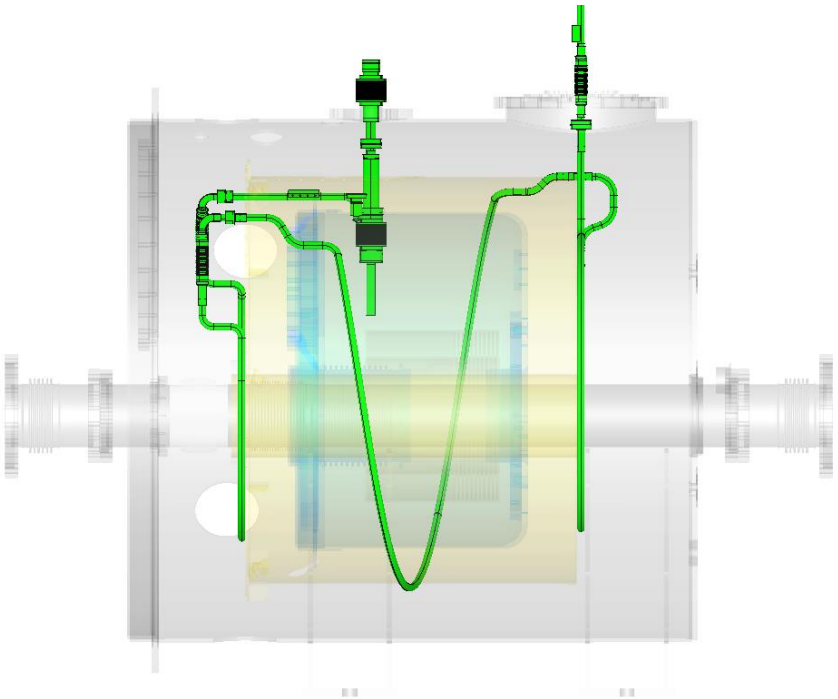
- New custom cryostat was designed and fabricated to host CCC monitor
- Insulating ceramic integrated to prevent mirror currents from shielding the beam signal
- Low heat-load to allow stand-alone operation
- Cooling power entirely provided by pulse-tube cryocooler
- HV Support designed to mitigate vibration transmission



Cryostat design



LHe vessel support



Closed circuit cooling of termal shield

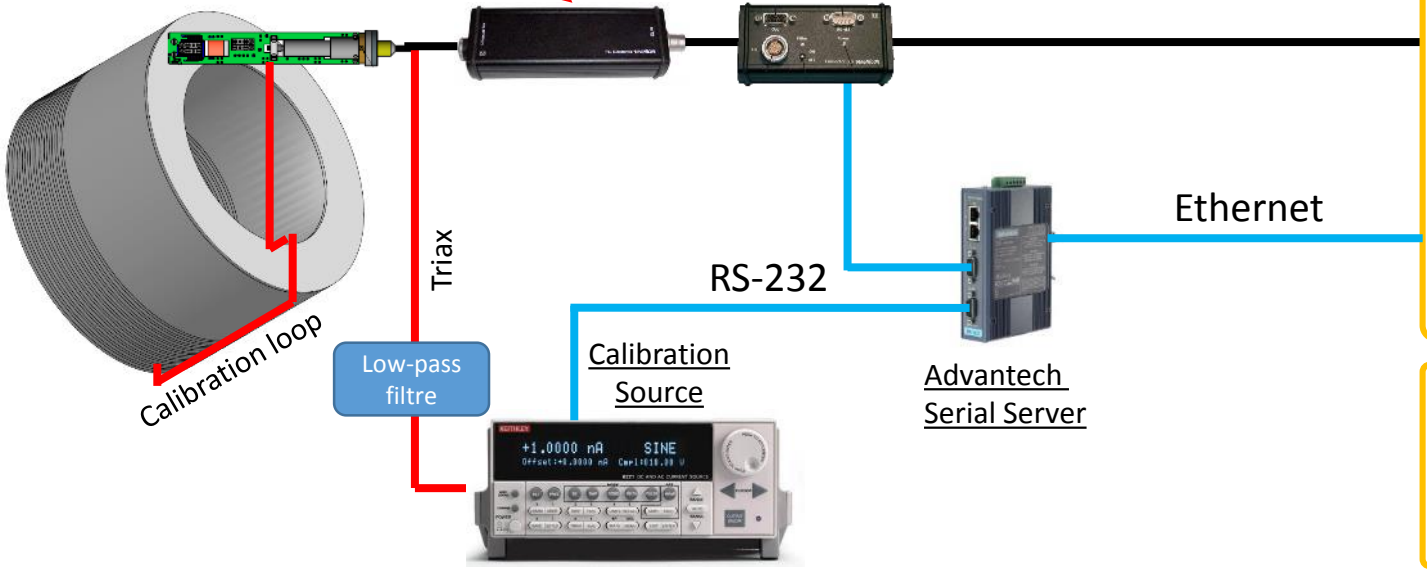
Cryostat installed in AD

CCC Acquisition and Control

Acquisition and controls

FLL Electronics
- Magnicon (20MHz)
- Settings:
  - R_{FLL} = 1 kOhm
  - GBW = 1.04 GHz

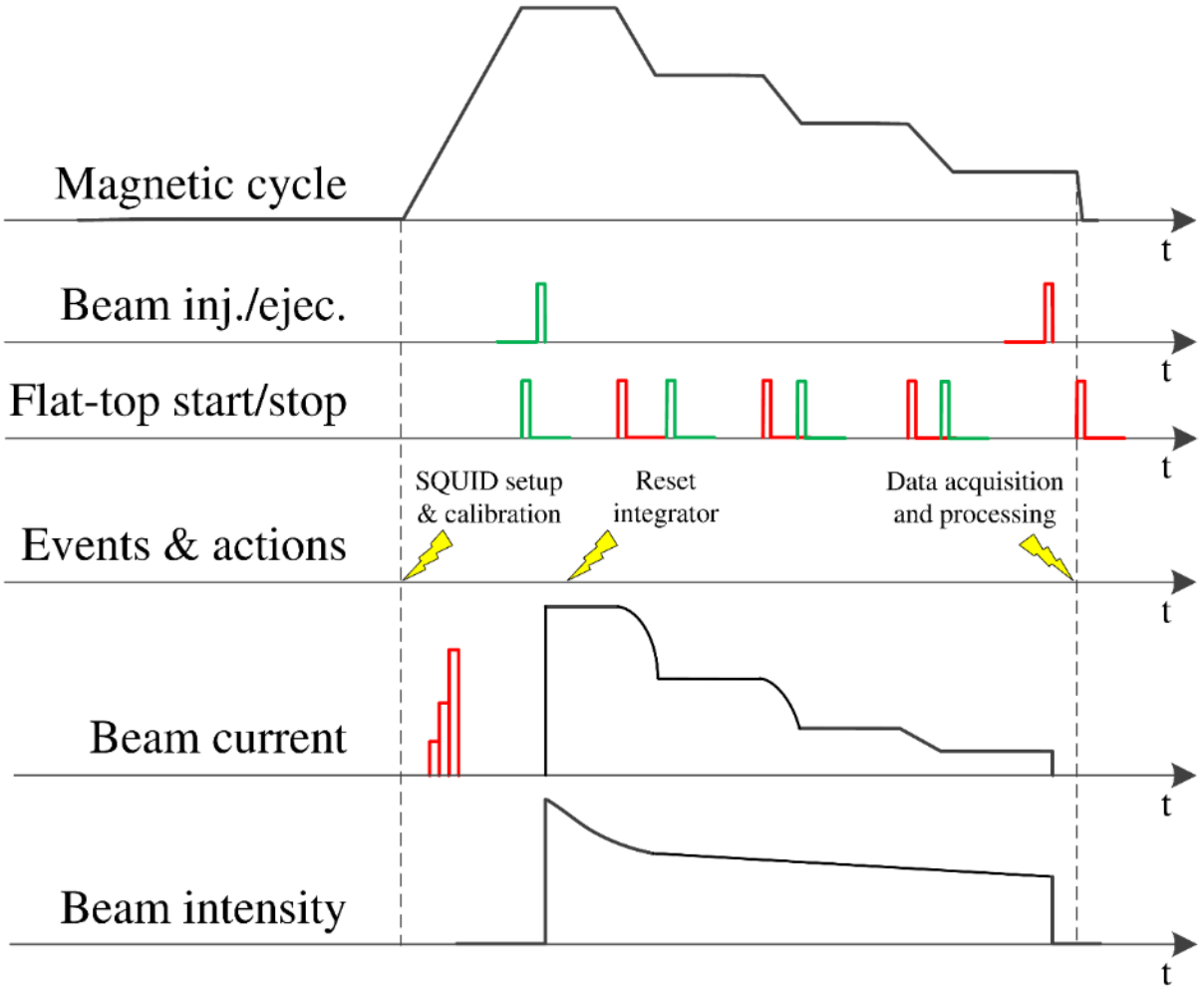
Acquisition / Controls
- VME architecture
- FESA SW + Expert GUI
- Signal acquisition at end of cycle and on-line
- Control of multiple SQUID/FLL parameters



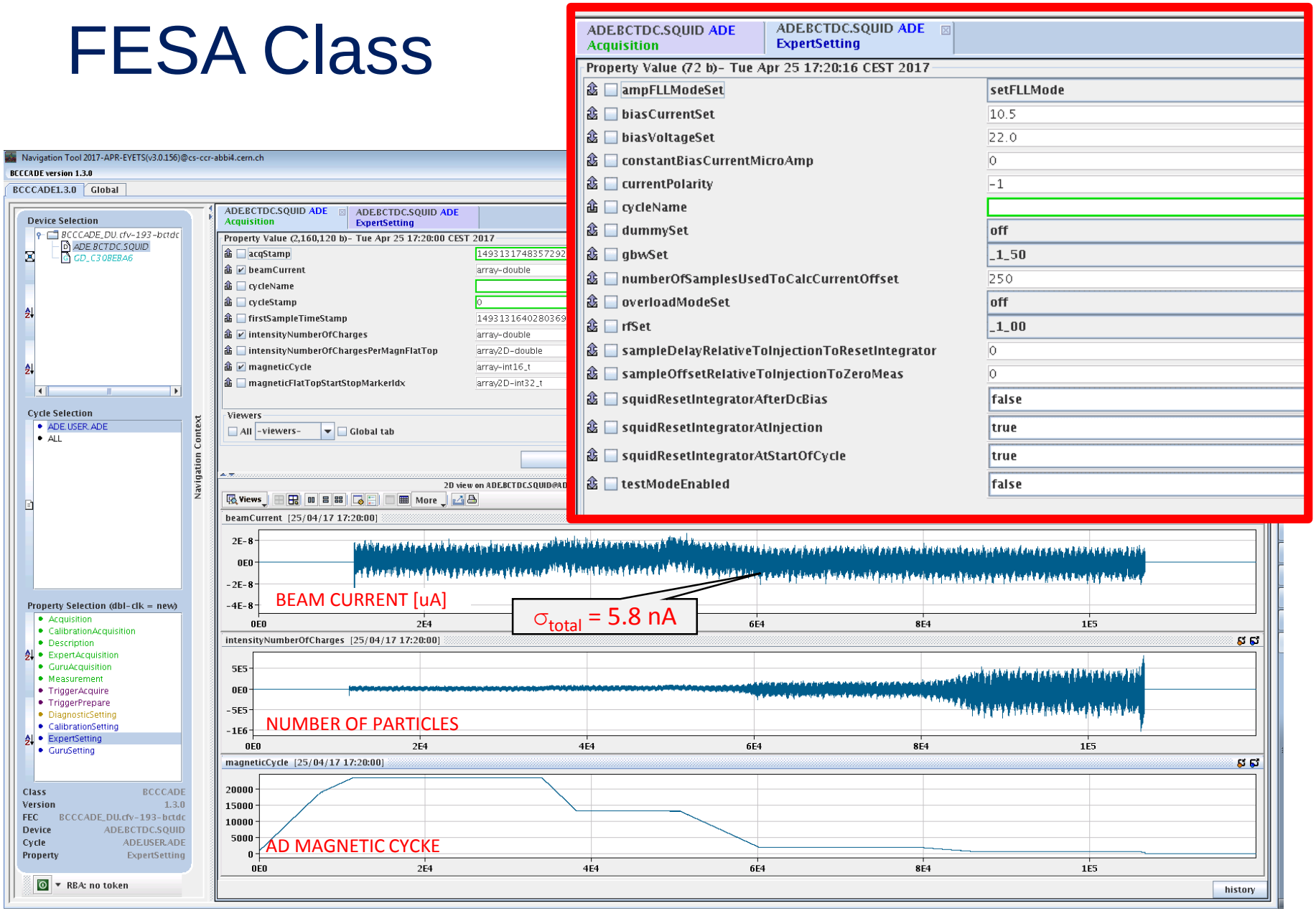
VME Crate
1. CPU L866
2. CTRV timing
3. VD80 ADC
   - 16 channels
   - 16 bit
   - +/- 10V
   - 800kOhm
   - Isolated diff. inputs

NIM Crate
1. AD B-field cycle
2. Current/Nparticlenormalization

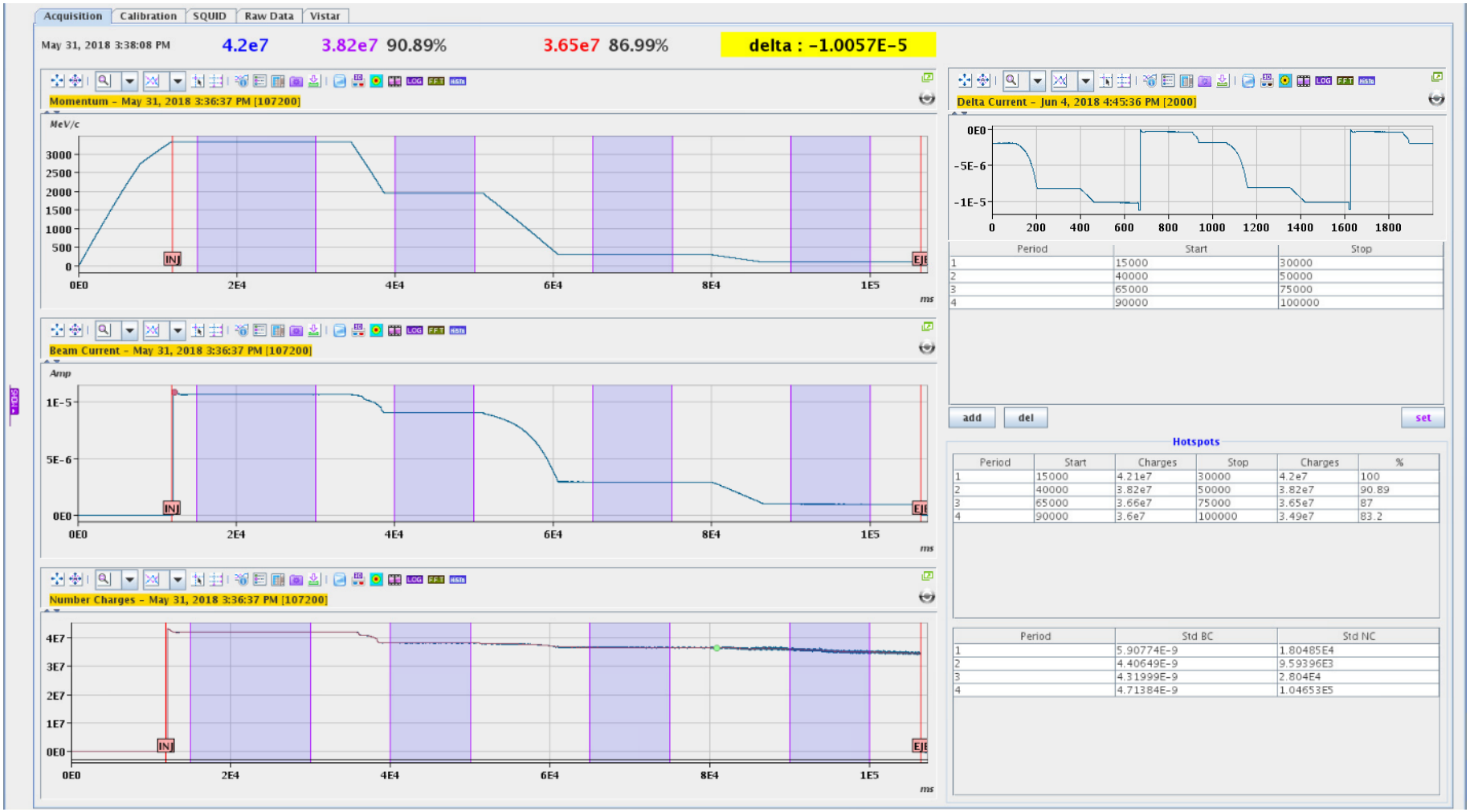
AD cycle synchronization



FESA Class

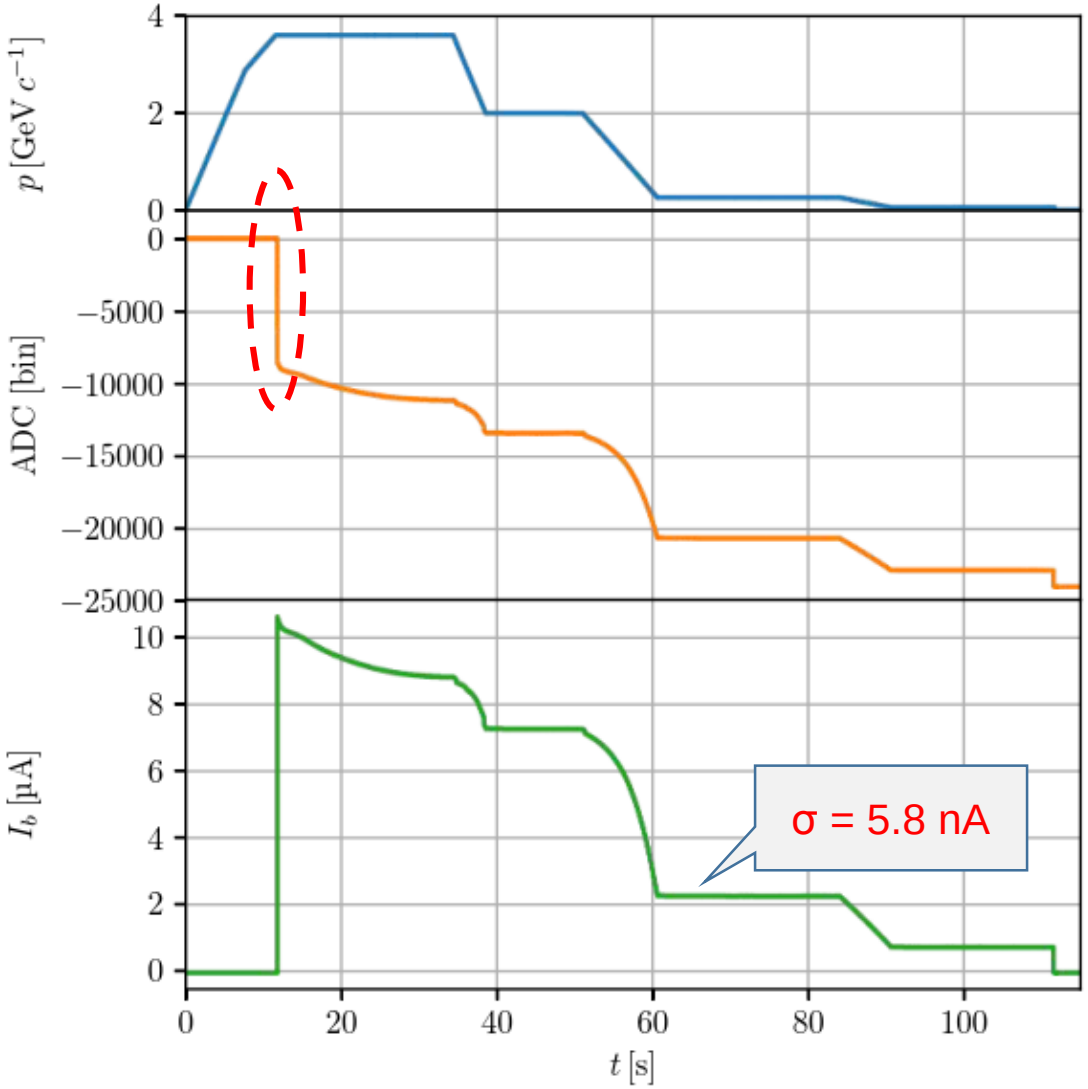

ADE.BCTDC.SQUID ADE Acquisition
ADE.BCTDC.SQUID ADE ExpertSetting
Property Value (72 b)- Tue Apr 25 17:20:16 CEST 2017
ampFLLModeSet
setFLLMode
biasCurrentSet
10.5
biasVoltageSet
22.0
constantBiasCurrentMicroAmp
0
currentPolarity
-1
cycleName
dummySet
off
gbwSet
_1_50
numberOfSamplesUsedToCalcCurrentOffset
250
overloadModeSet
off
rfSet
_1_00
sampleDelayRelativeToInjectionToResetIntegrator
0
sampleOffsetRelativeToInjectionToZeroMeas
0
squidResetIntegratorAfterDcBias
false
squidResetIntegratorAtInjection
true
squidResetIntegratorAtStartOfCycle
true
testModeEnabled
false
BEAM CURRENT [uA]
σtotal = 5.8 nA
NUMBER OF PARTICLES
AD MAGNETIC CYCKE

Expert GUI


Acquisition
Calibration
SQUID
Raw Data
Vistar
May 31, 2018 3:38:08 PM
4.2e7
3.82e7 90.89%
3.65e7 86.99%
delta : -1.0057E-5
Momentum - May 31, 2018 3:36:37 PM [107200]
MeV/c
Beam Current - May 31, 2018 3:36:37 PM [107200]
Amp
Number Charges - May 31, 2018 3:36:37 PM [107200]
ms
Delta Current - Jun 4, 2018 4:45:36 PM [2000]
Period Start Stop
1 15000 30000
2 40000 50000
3 65000 75000
4 90000 100000
add
del
set
Hotspots
Period Start Charges Stop Charges %
1 15000 4.21e7 30000 4.2e7 100
2 40000 3.82e7 50000 3.82e7 90.89
3 65000 3.66e7 75000 3.65e7 87
4 90000 3.6e7 100000 3.49e7 83.2
Period Std BC Std NC
1 5.90774E-9 1.80485E4
2 4.40649E-9 9.59396E3
3 4.31999E-9 2.804E4
4 4.71384E-9 1.04653E5

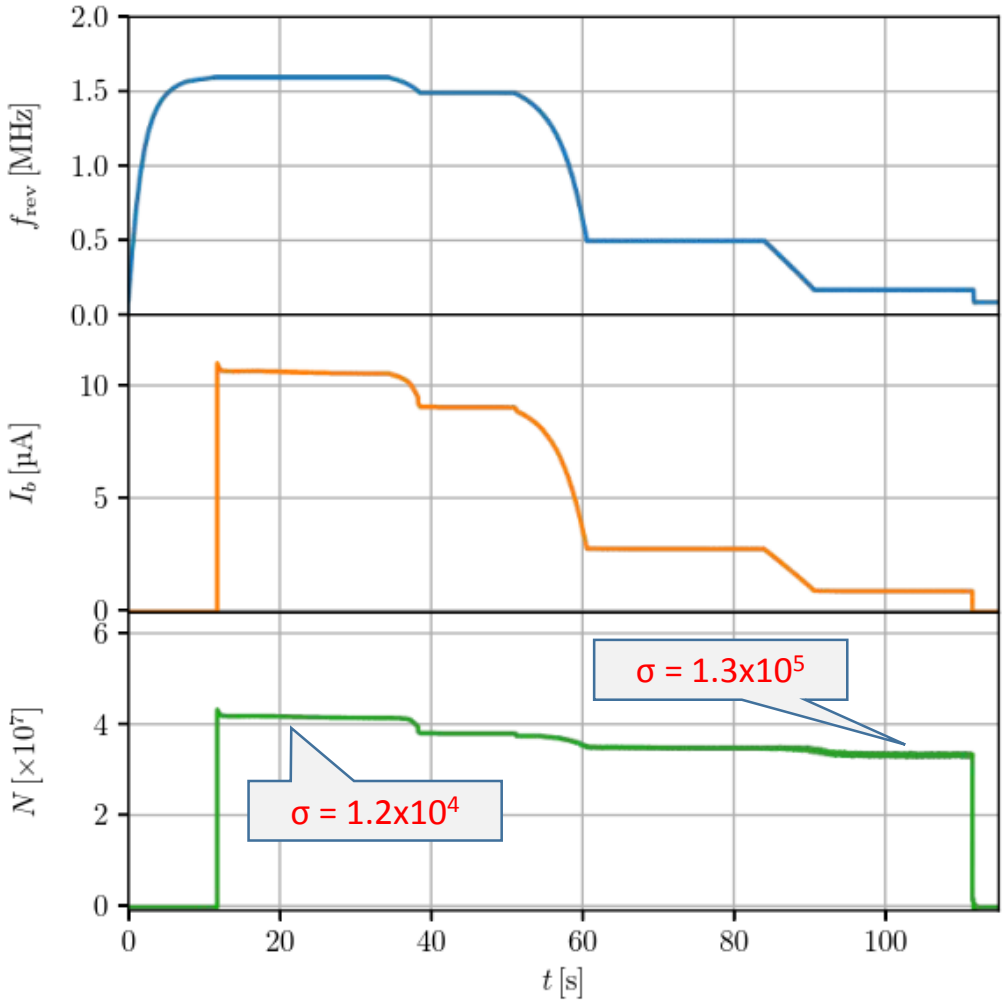
Beam measurements and performance

Beam current measurement



- Flux jump at injection causes loss of baseline
- SQUID/FLL stable throughout the rest of the cycle
- Resolution within < 10 nA (with cryocooler and vacuum pumps running)

Beam intensity measurement



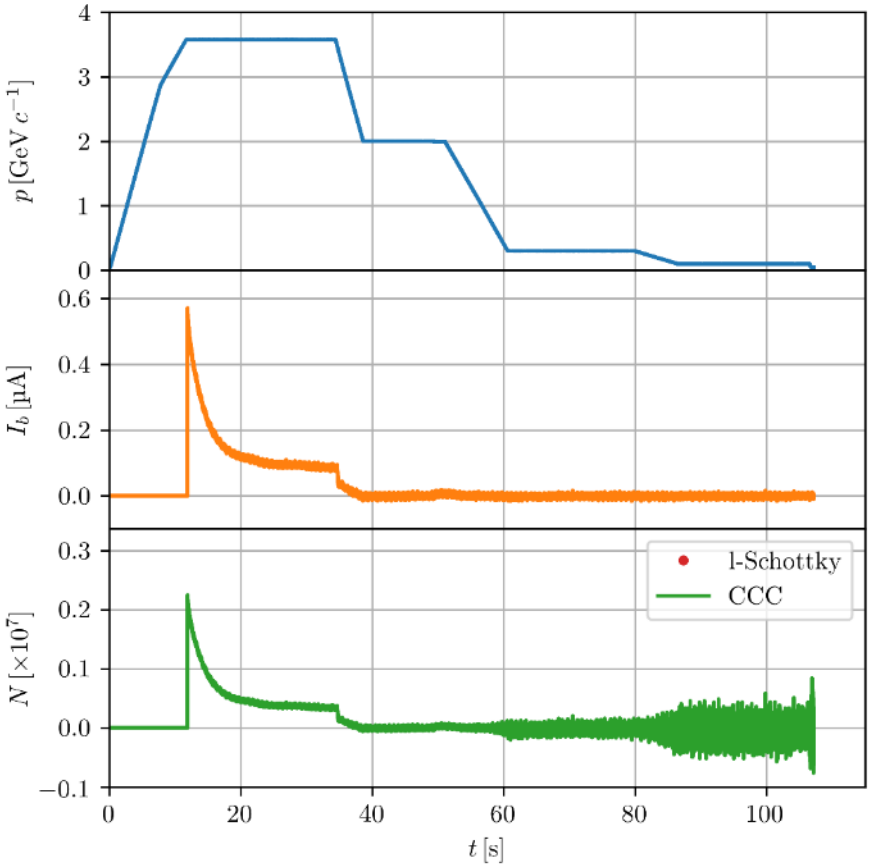
$$N = \frac{I_{\mathrm{beam}}}{Q \cdot e \cdot f_{\mathrm{rev}}}$$

- Baseline corrected at the end of the cycle
- Beam intensity calculated by normalizing against f_{Rev}
- Intensity resolutions at low-energy ~10^5 charges

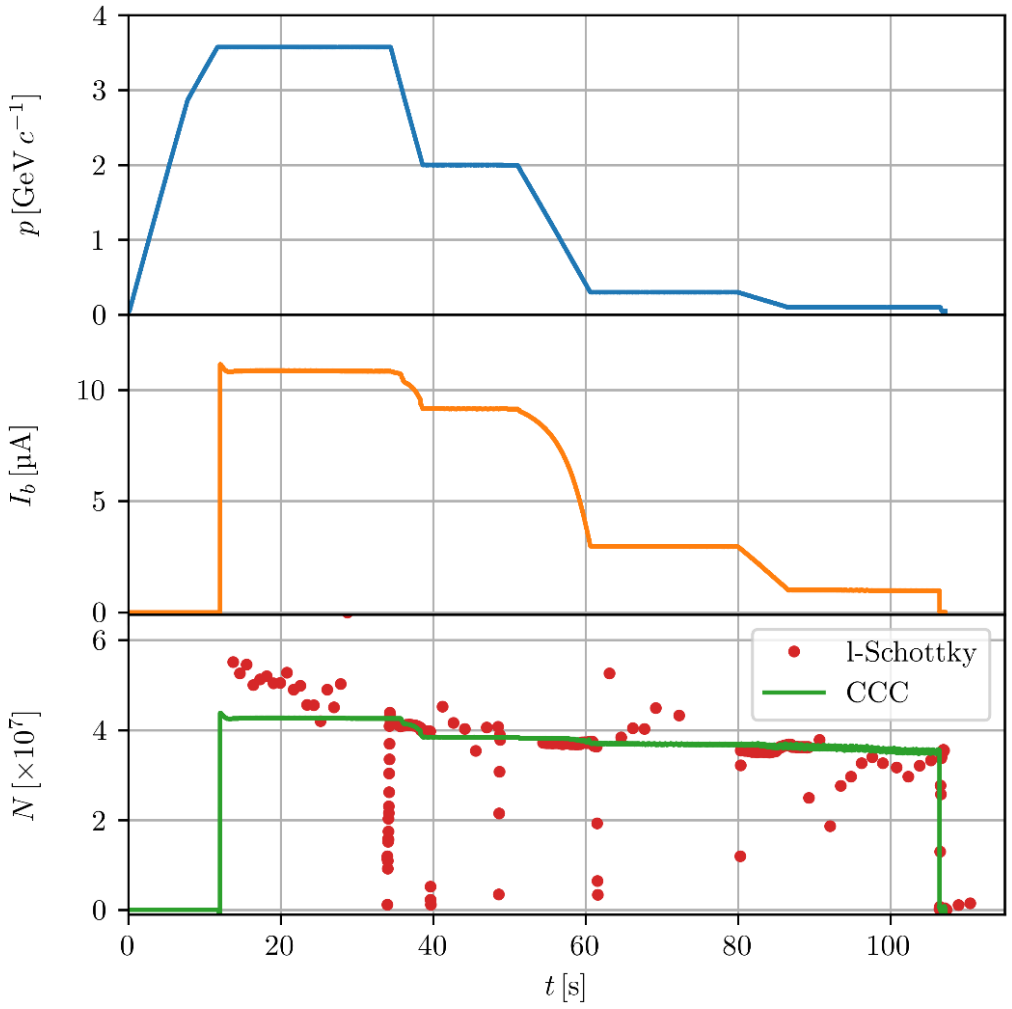
Operations usage of the monitor

- Number of delivered particles is primary figure of merit for operations
- Accurate beam intensity measurement is fundamental to assess operational efficiency
- Good time-resolution enables more accurate troubleshooting of beam losses
- Very useful during beam setup enabling faster identification of problems

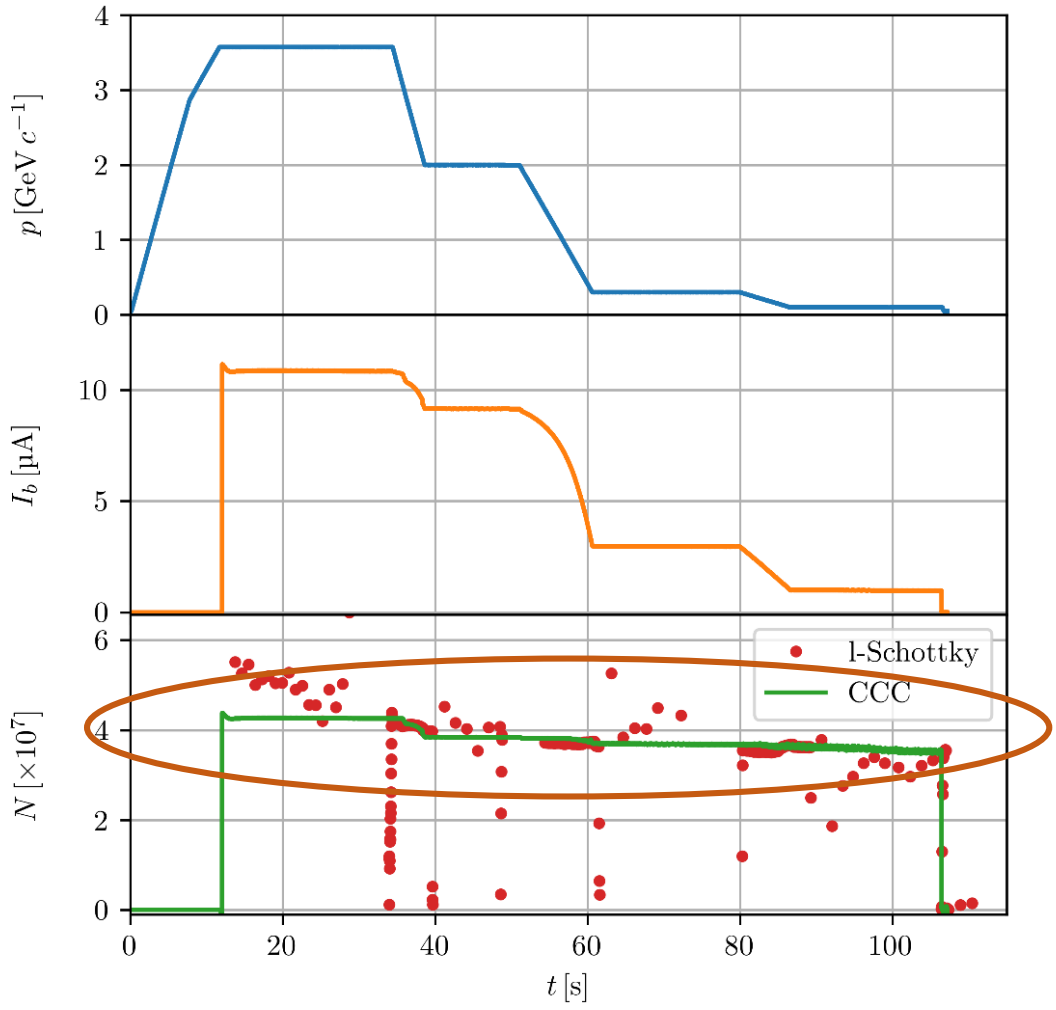
First beams injected 2018



Comparison with Schottky monitor



Comparison with Schottky monitor



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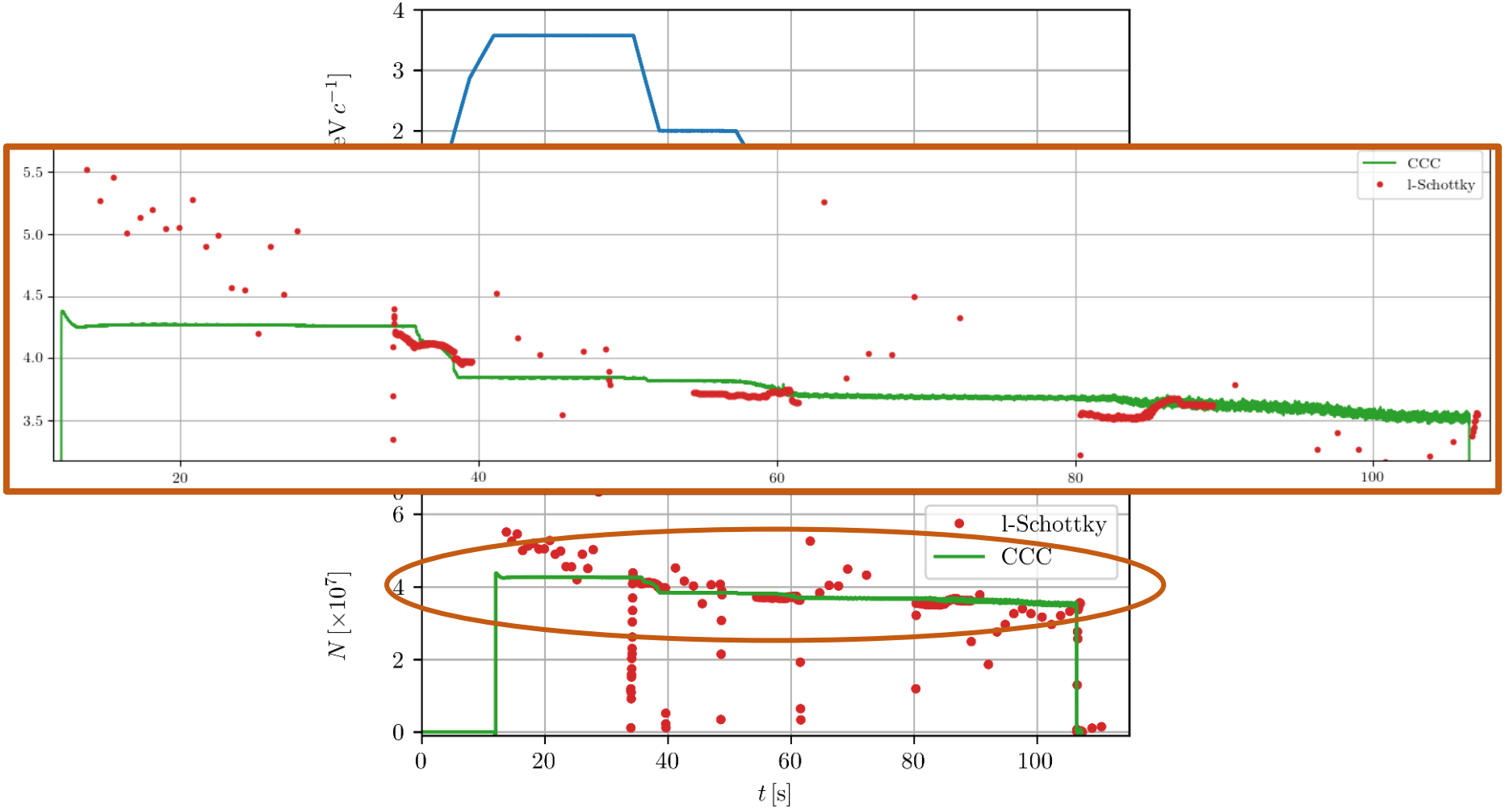
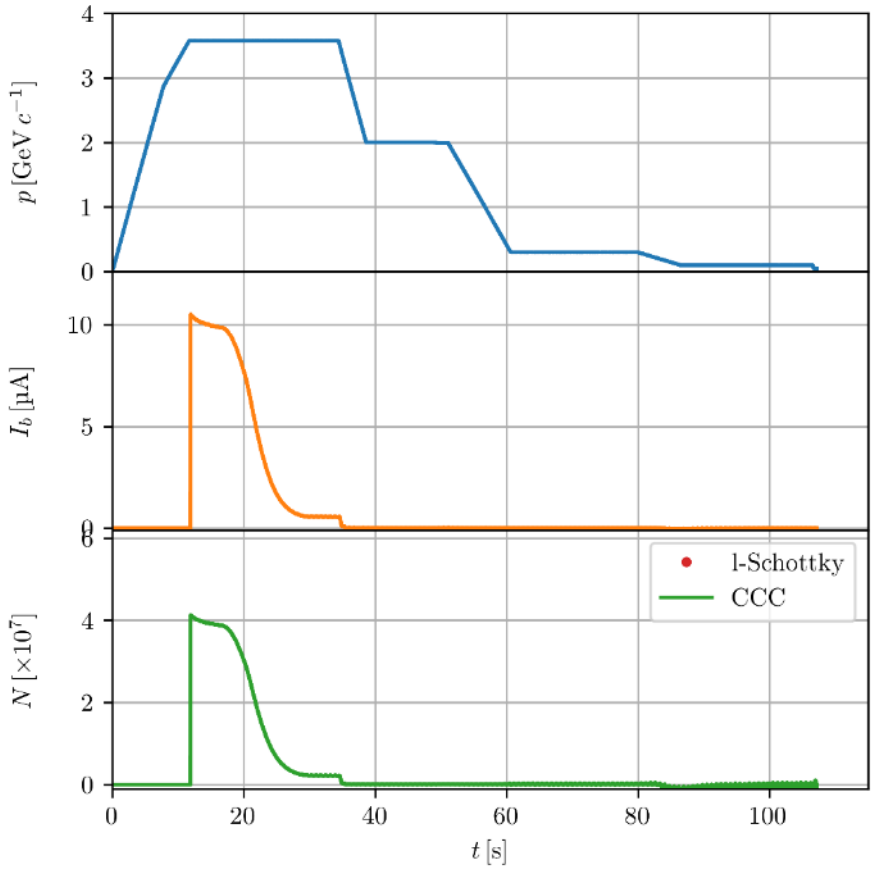
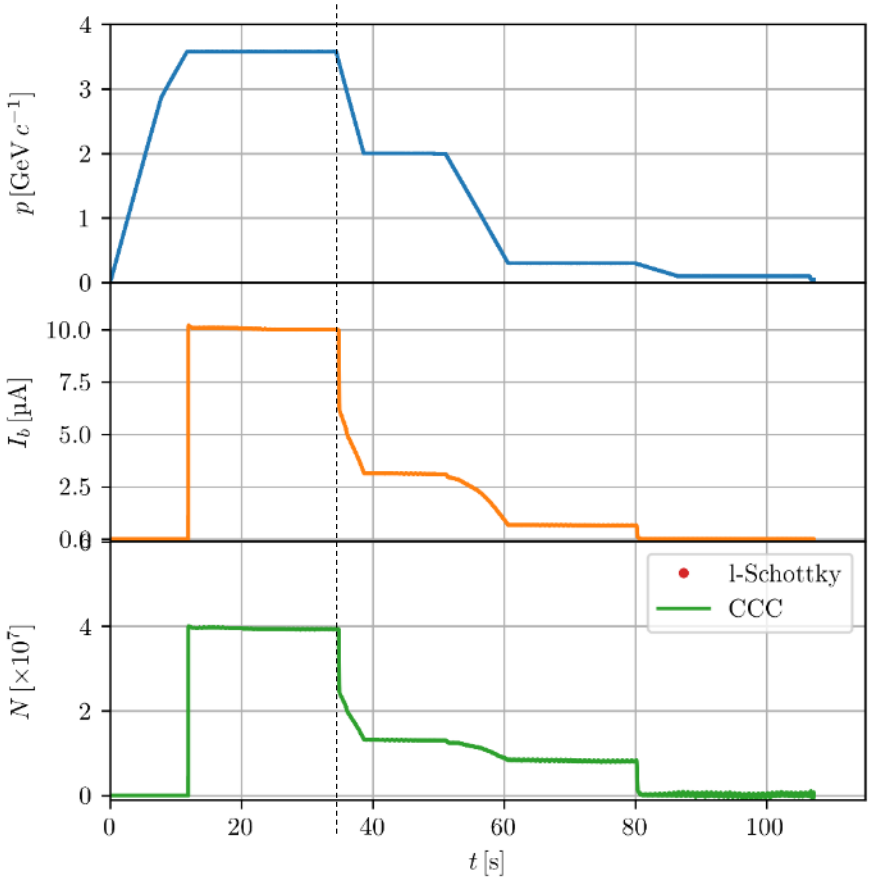


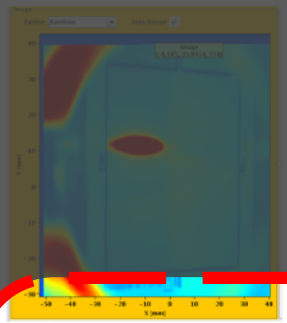
Beam setup 2018

Problem with Stochastic cooling



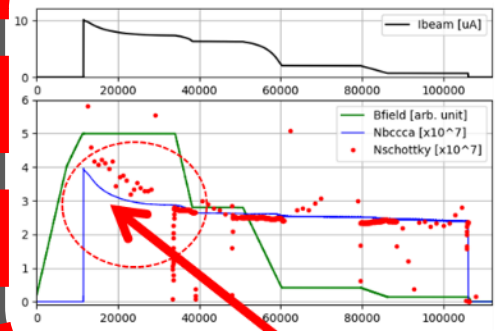
Beam loss in 1st ramp

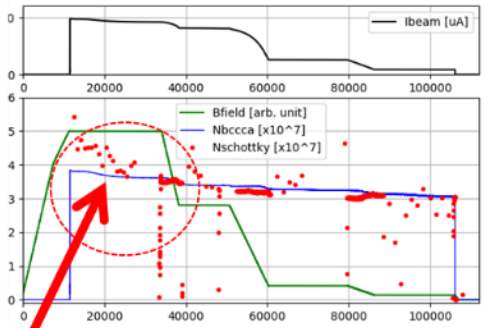




BTVs

- 11 BTV systems on injection and ejection lines at the AD – as well as one at septum in ring.
- Working well.





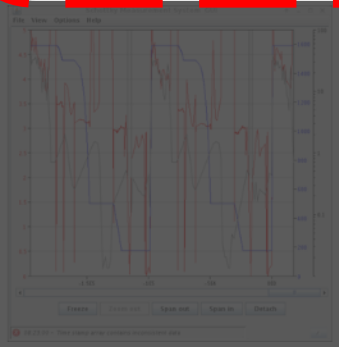
Losses / optimized

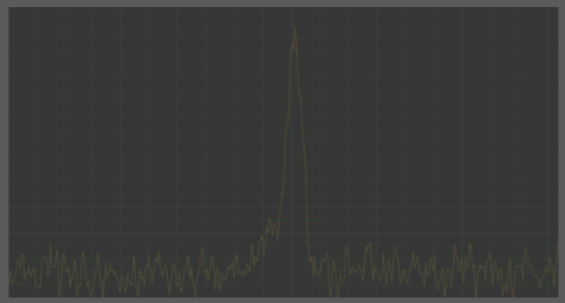
BCCCA

After a few hick-ups this system is now working very well and is being used as a major diagnostic tool.

→ VERY USEFULL, especially during startup !

Will be incorporated into VISTAR later!





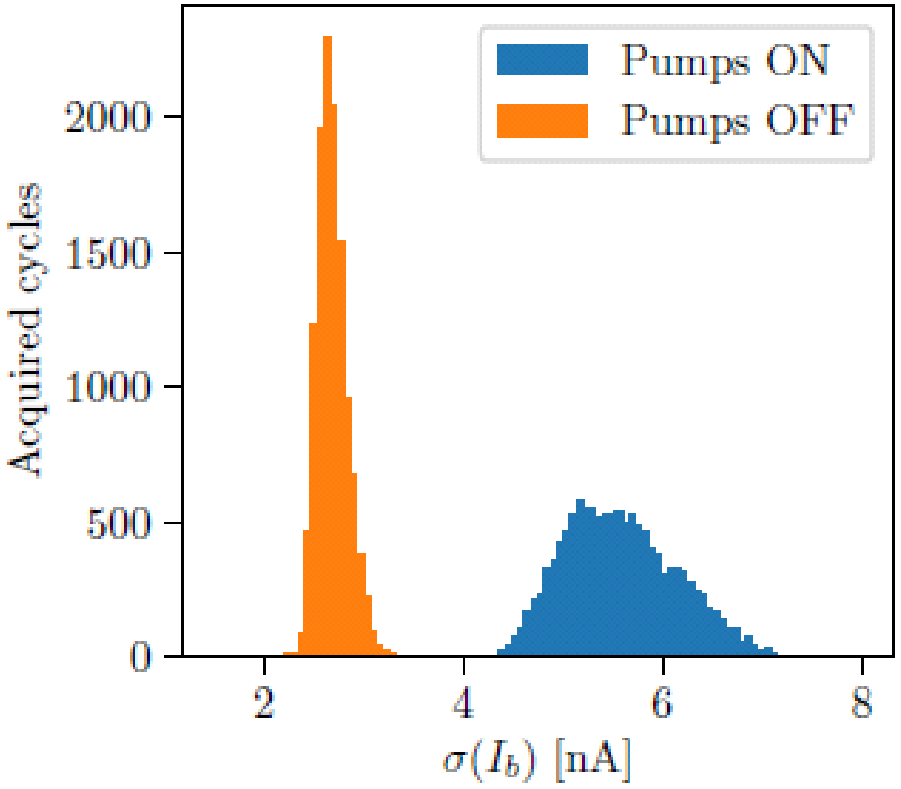
Shottky

- Working pretty well, but also in need of acquisition system upgrade.
- Planned for LS2

Performance analysis

- Measurement resolution
- Computed as the signal standard deviation in 1s interval
- Analysis of ~25000 cycles during 2017
- With cryostat insulation vacuum pumps on/off

Current resolution



Performance analysis

- Measurement resolution
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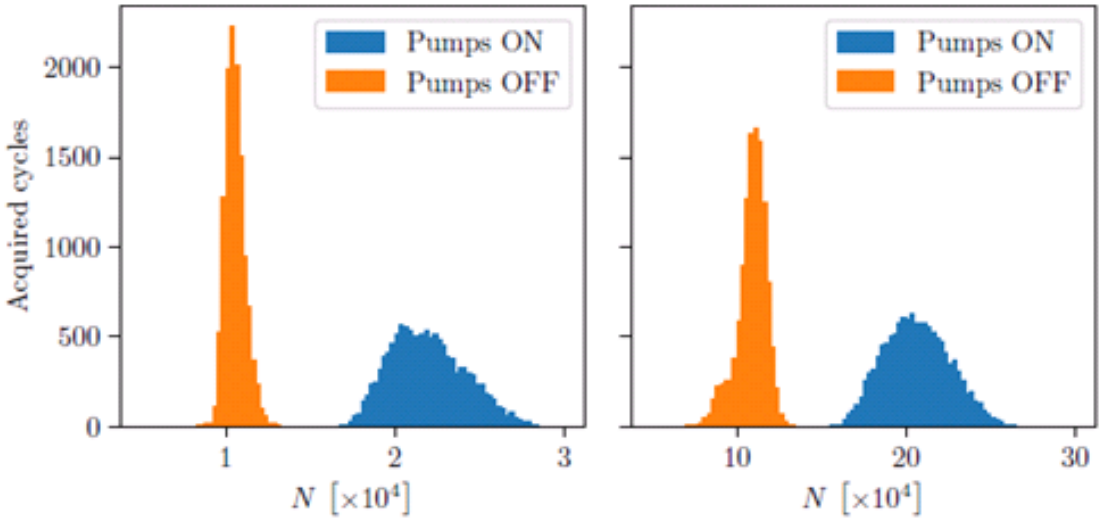
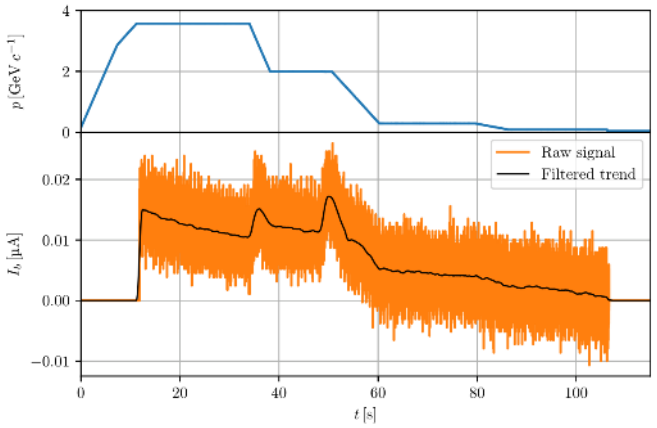
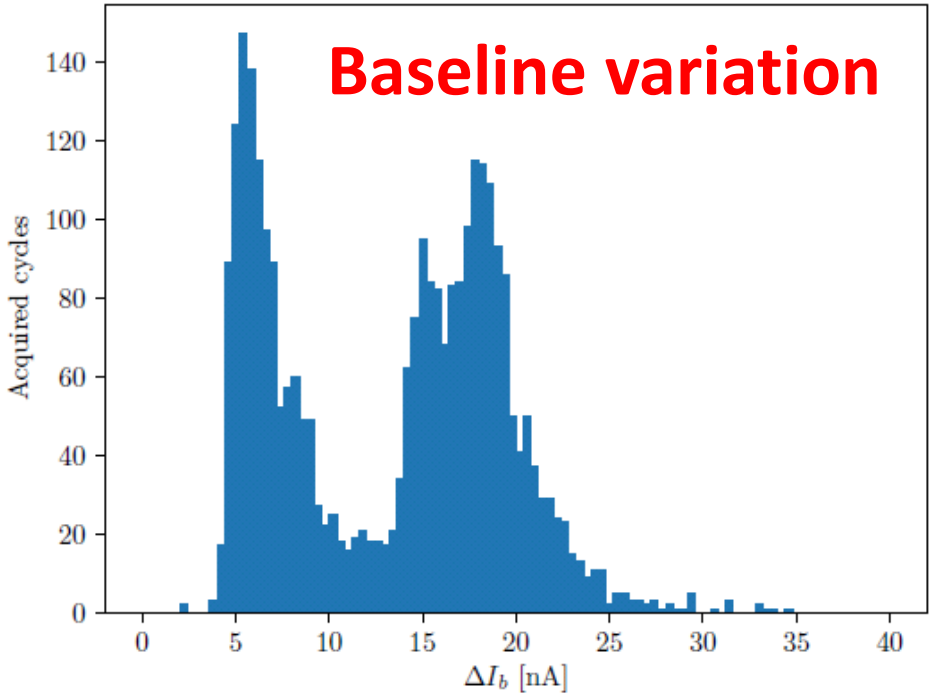
Intensity resolution



Performance analysis

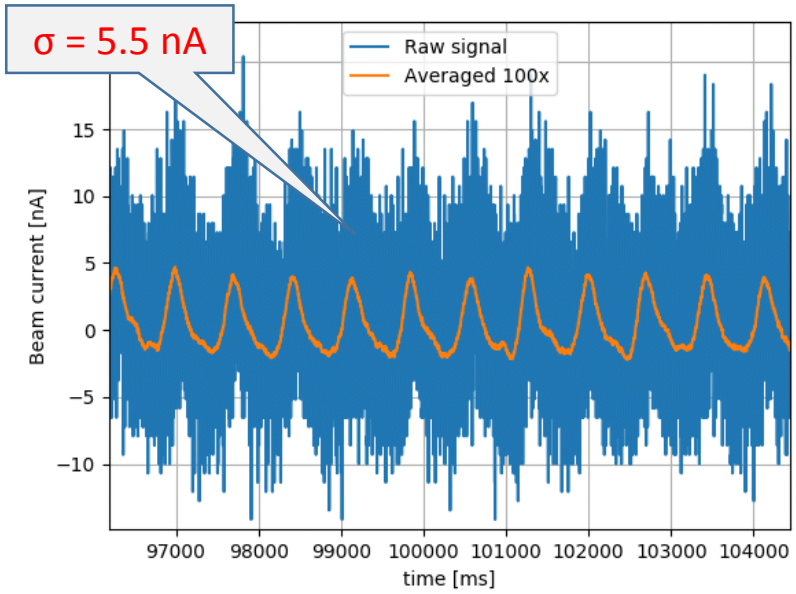
- Slower baseline drifts are dominant measurement error
- These are mainly caused by helium gas pressure variations
- Additionally perturbation induced by cycling the acccelerator
- Baseline drift obtained from cycles with no injected beam



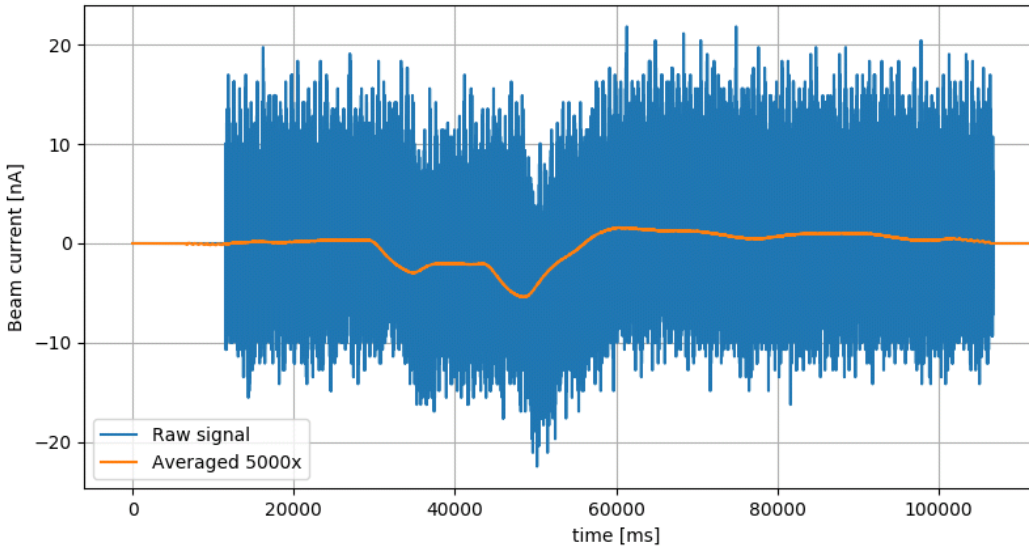


Extra: Noise performance improvements

Perturbation from cryocooler

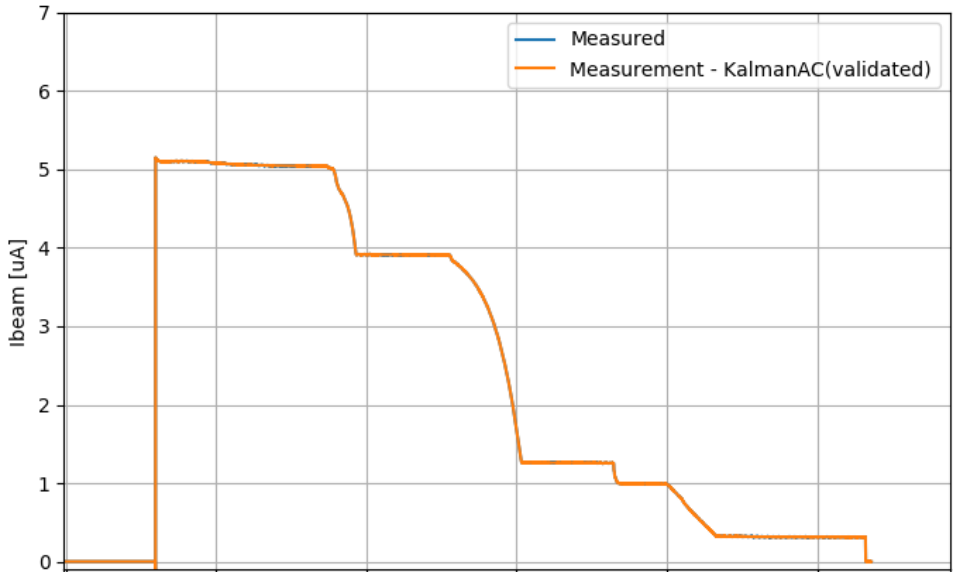


Perturbation from magnetic cycle



Filter cryocooler perturbation

- Composed of frequencies: 1.4Hz + 2x harmonics
- With varying phases and amplitudes
- Estimate perturbation using adaptative **Kalman filter**
  - Model for Kalman filter: DC + AC(1.4Hz + 2x h)



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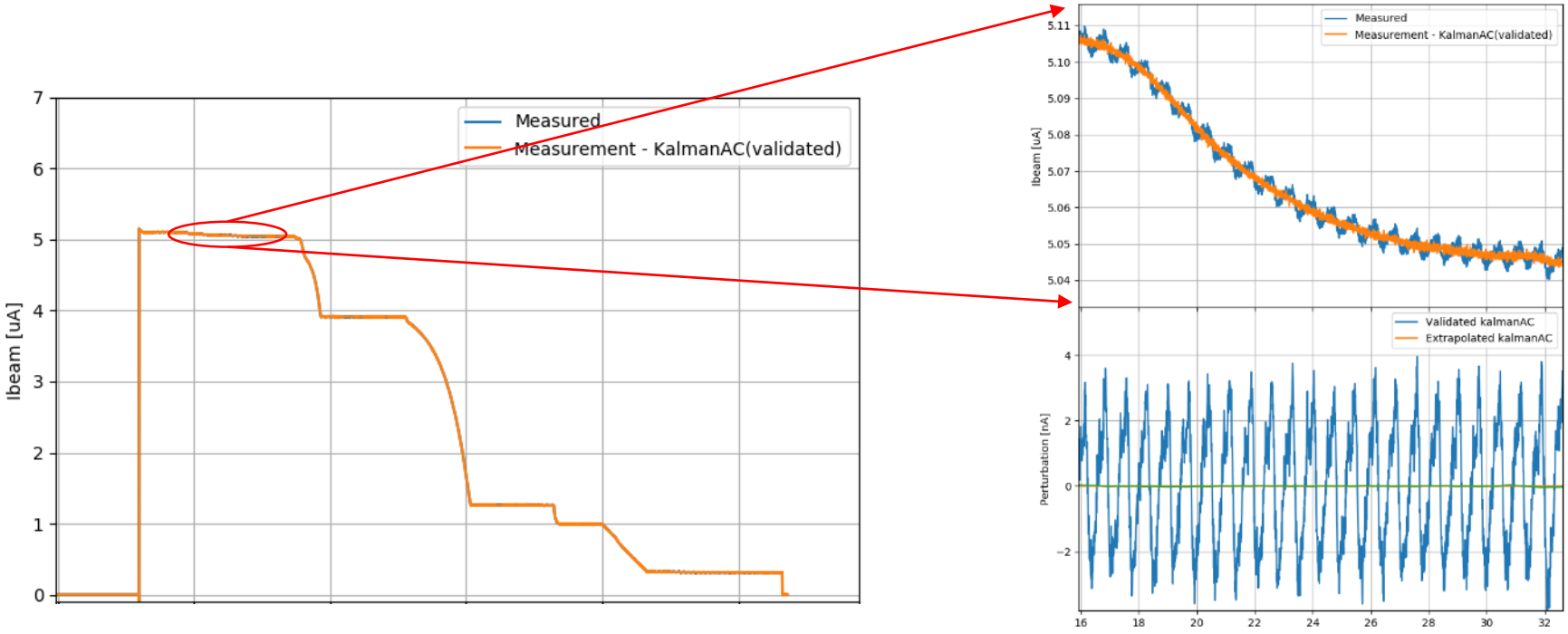

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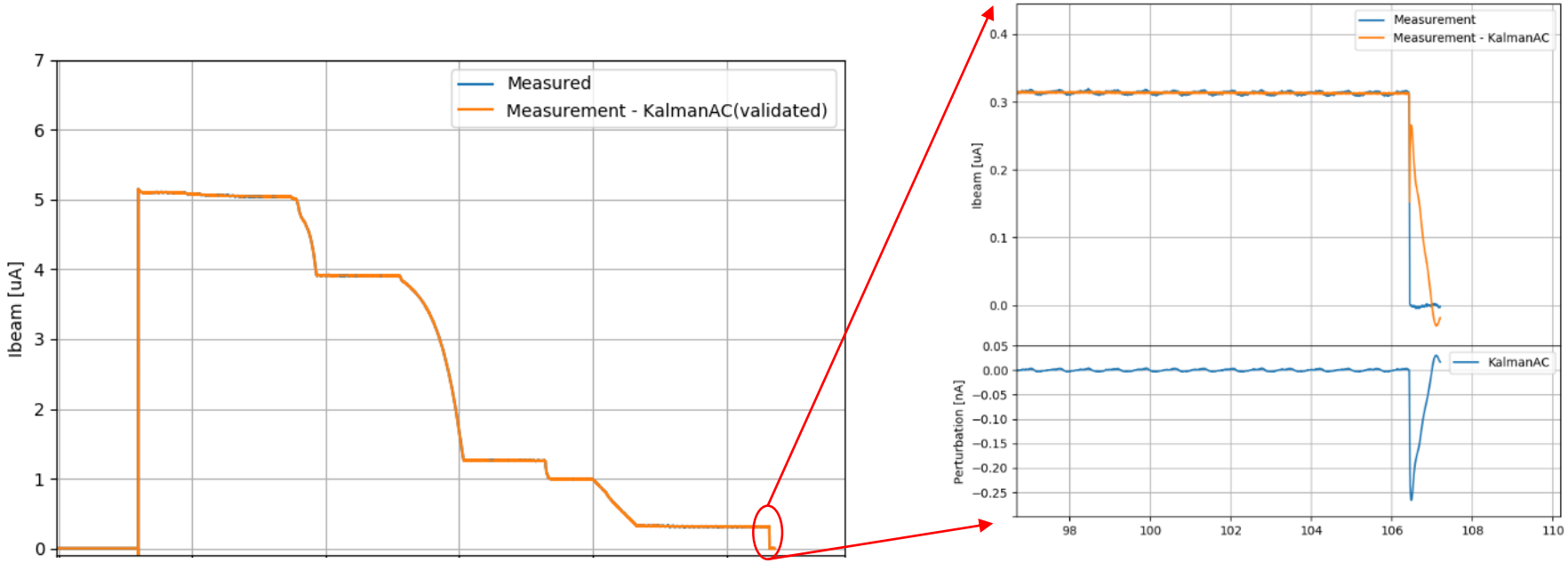

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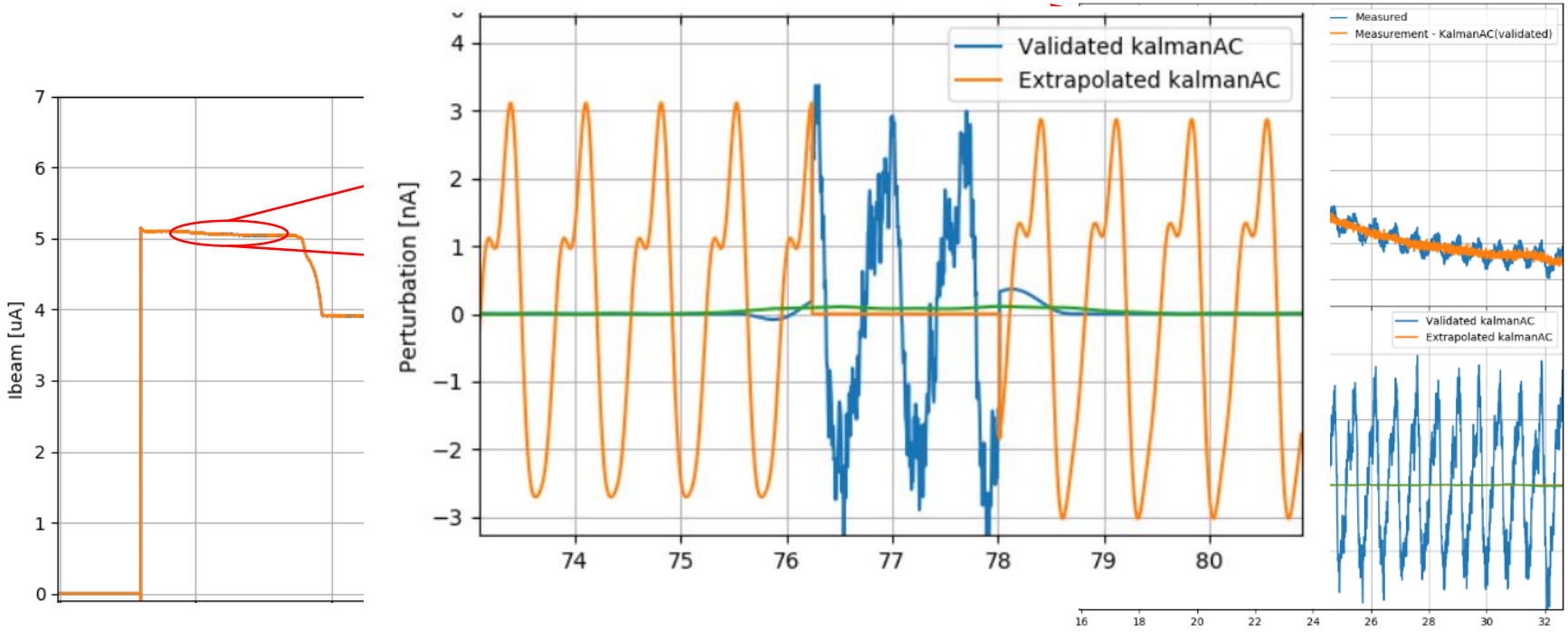

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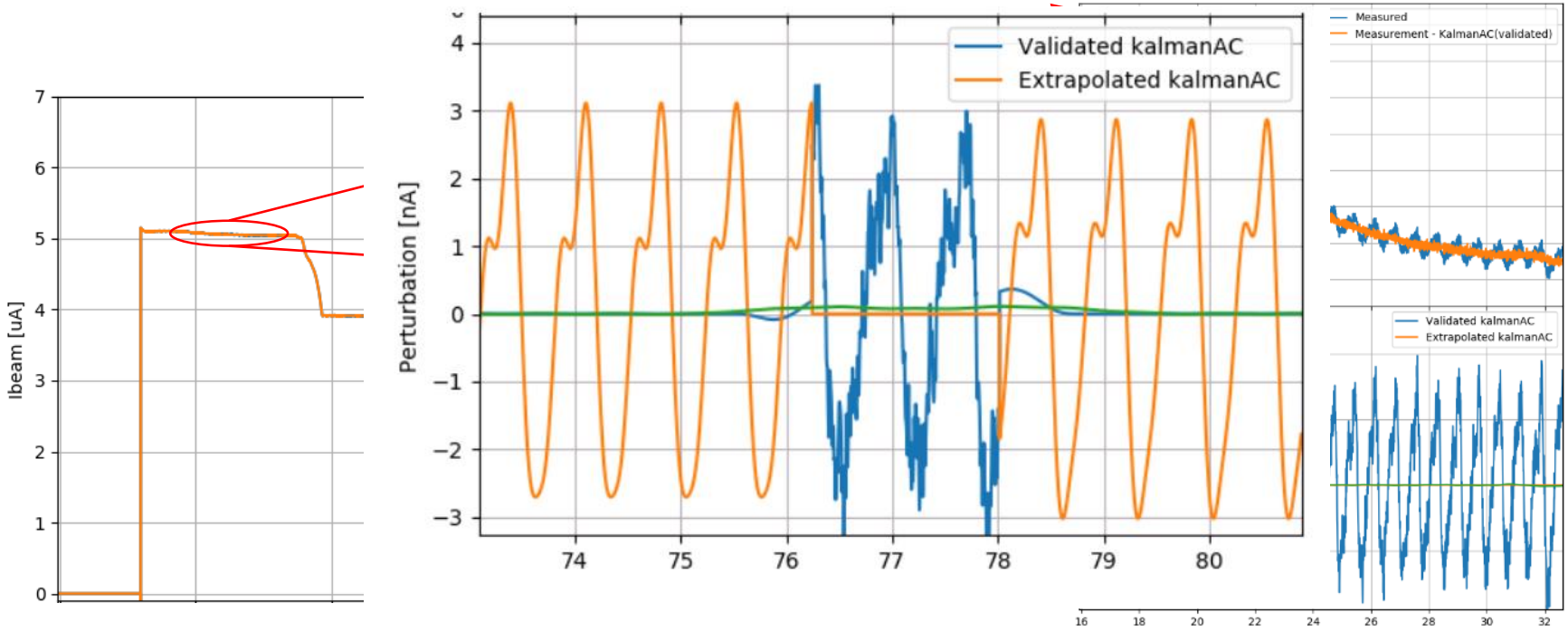


Conclusions

- Measurement noise performance under initial specification
- Able to stably cope with AD bunched beams (except injection)
- Very good immunity to mechanical vibrations
- Cryogenic system enables “long” term operations (~3/4 month)
- Assessed long term stability over entire year run
- Automatic system control and in FESA class expert GUI

On-going work

- Investigate source of flux jump at injection
- Improve availability of cryogenic system
- Mitigate perturbations by controlling and stabilizing cryostat pressure
- **Proposal of a new CCC monitor for the ELENA**

Acknowledgements

J. Tan, W. Devauchelle, S. Pederson, D. Alves, E. Oponowicz, M. Ludwig, T. Koettig, A. Lees, A. Vacca, F. Carrasco, J.P. Brachet, D. Lombard, G. Foffano, R. Speroni

T. Schiwckert; T. Sieber; F. Kurian;

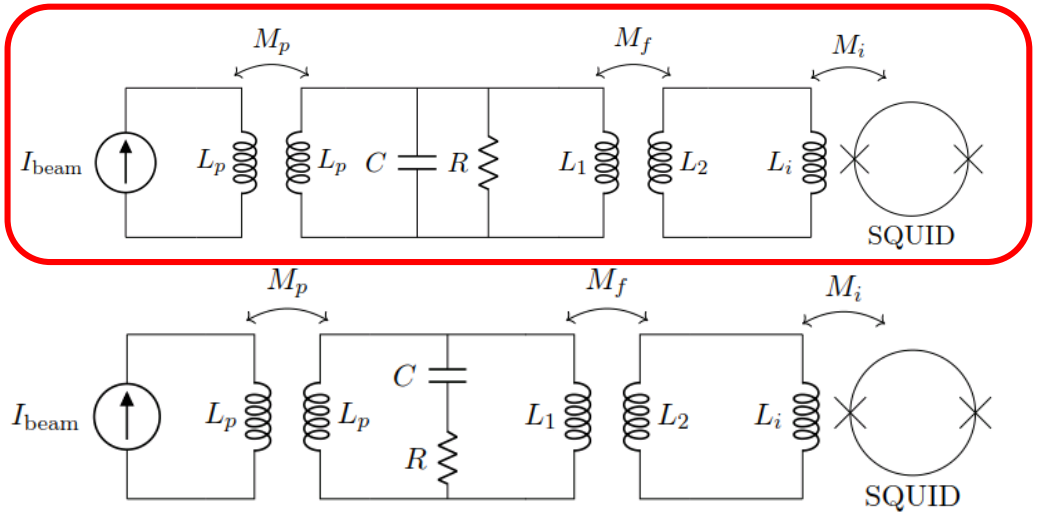
R. Geithner; R. Neubert , J. Golm

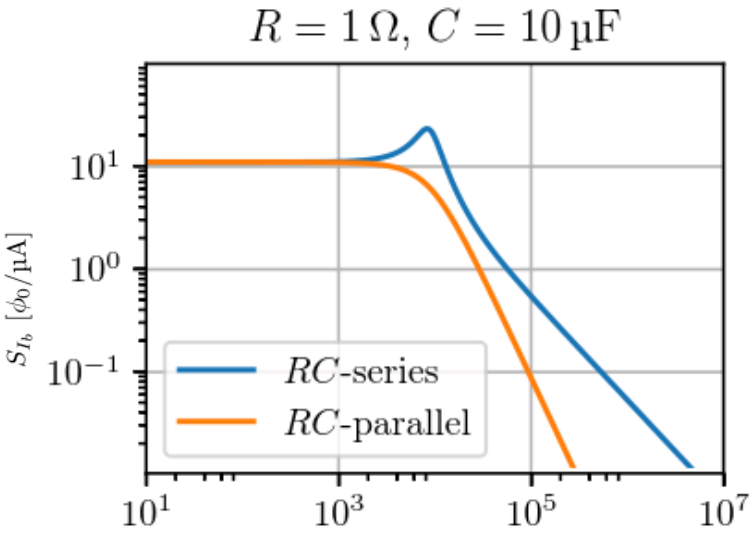
C. Welsch

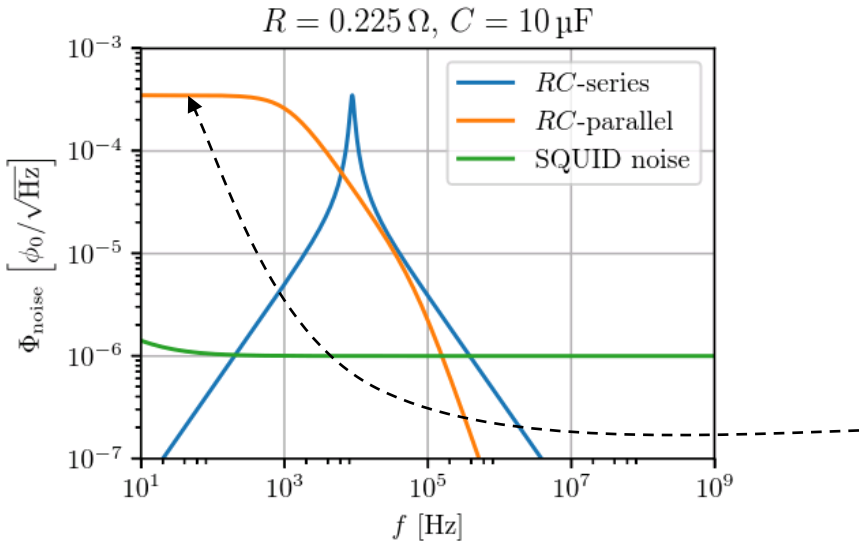
Thank you for your attention!

Backup

Coupling circuit low-pass filter





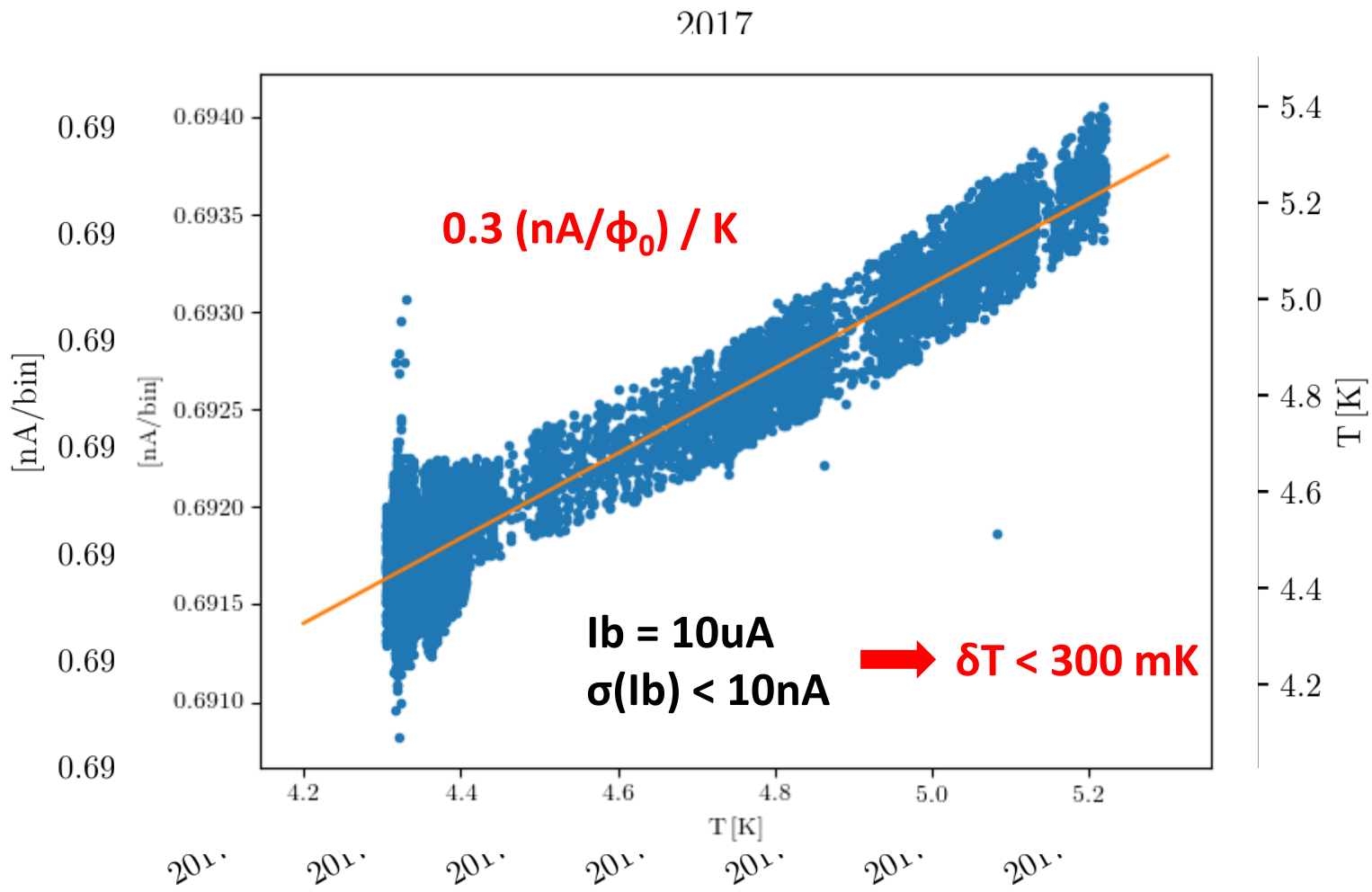


Filtering	Slew-rate
Core permeability + RC-parallel	**0.97 Mϕ_0/s**

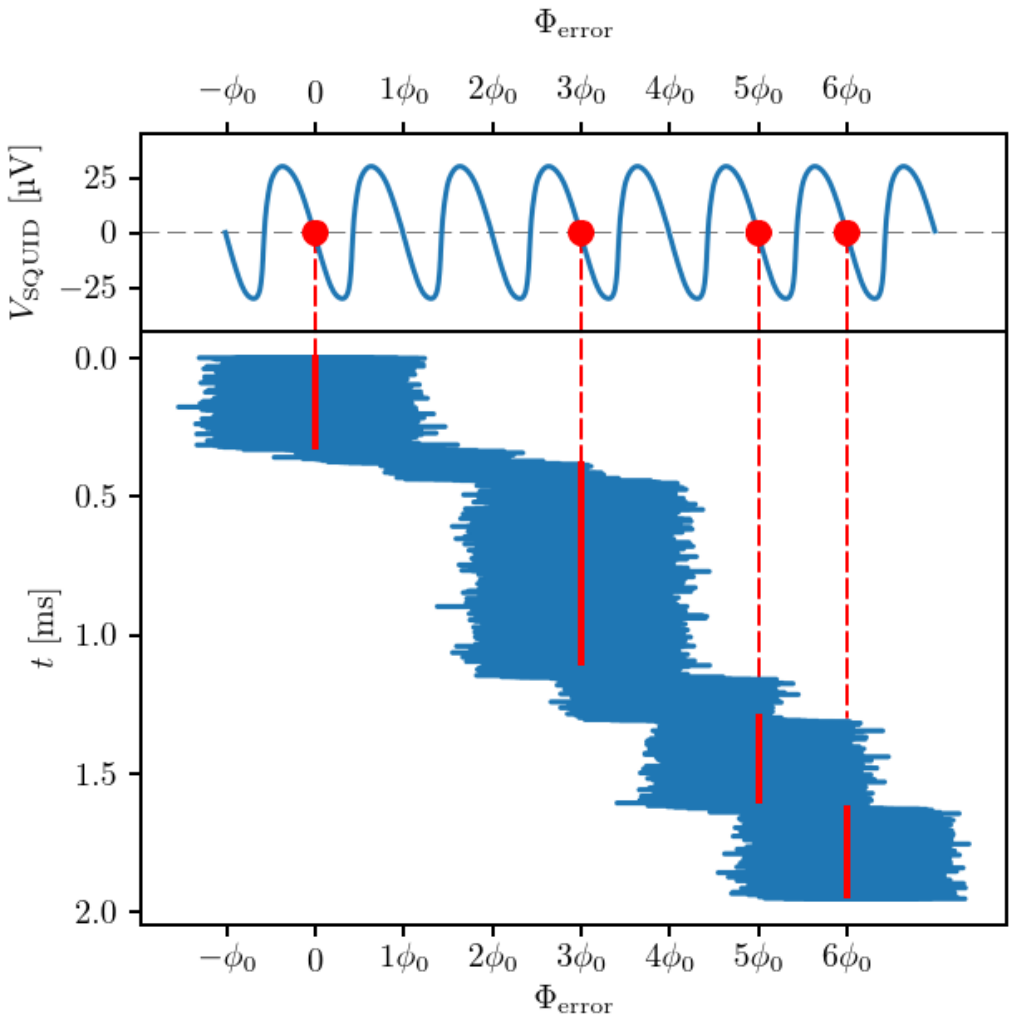
Additional flux noise at low freq:

$$\sigma(I_{\text{b}}) = 0.92\,\text{nA}$$

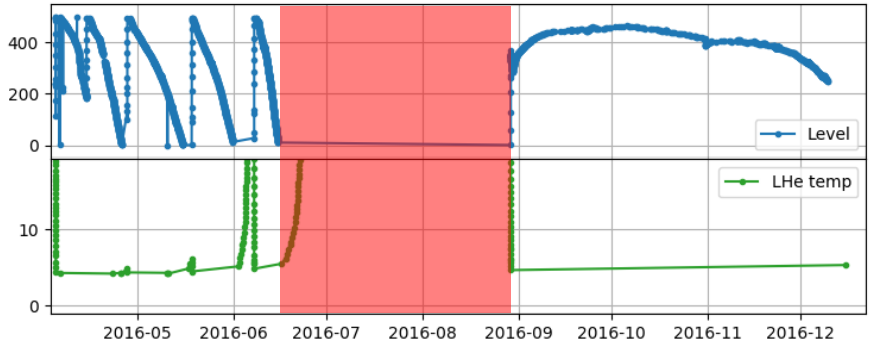
Calibration vs. Temperature



Flux jumps

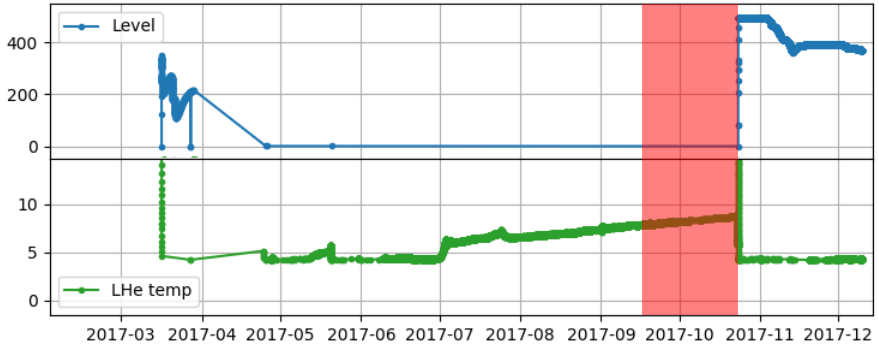

Φ_{error}
$-\phi_0$ 0 $1\phi_0$ $2\phi_0$ $3\phi_0$ $4\phi_0$ $5\phi_0$ $6\phi_0$
V_{SQUID} [μV]
25
0
−25
t [ms]
0.0
0.5
1.0
1.5
2.0
$-\phi_0$ 0 $1\phi_0$ $2\phi_0$ $3\phi_0$ $4\phi_0$ $5\phi_0$ $6\phi_0$
Φ_{error}

Cryogenic availability



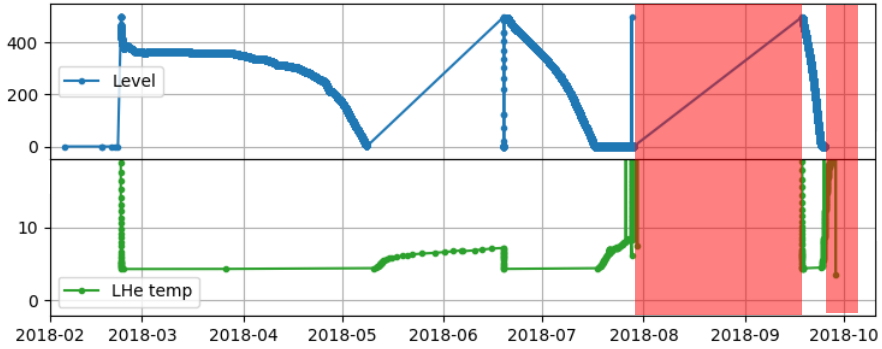
2016

- Started actively pumping the insulation vacuum
- Air contamination at end of year



2017

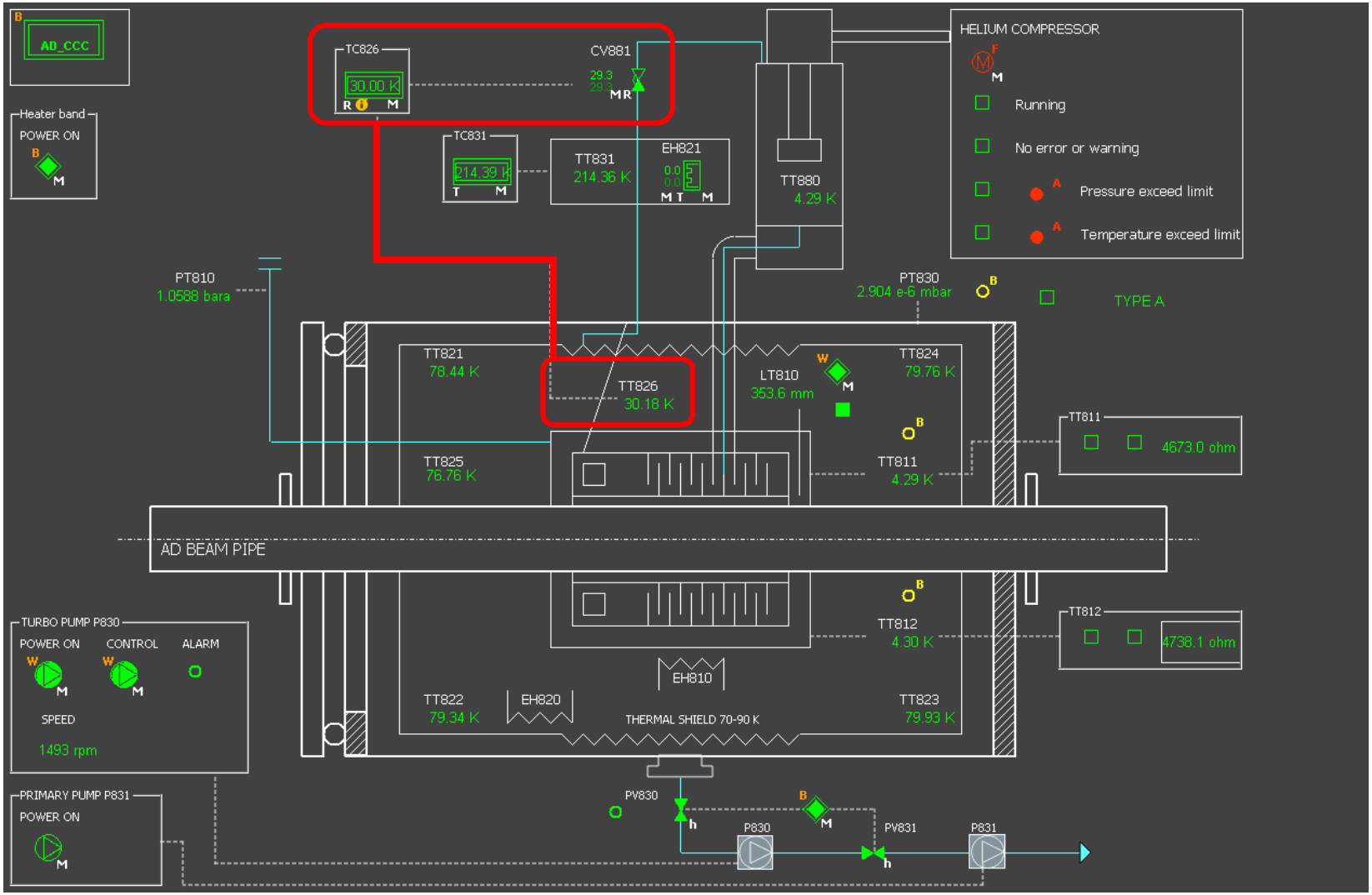
- Power glitch stopped turbo pump that compromised vacum
- Still possible to work with gas
- ~1 month unavailable



2018

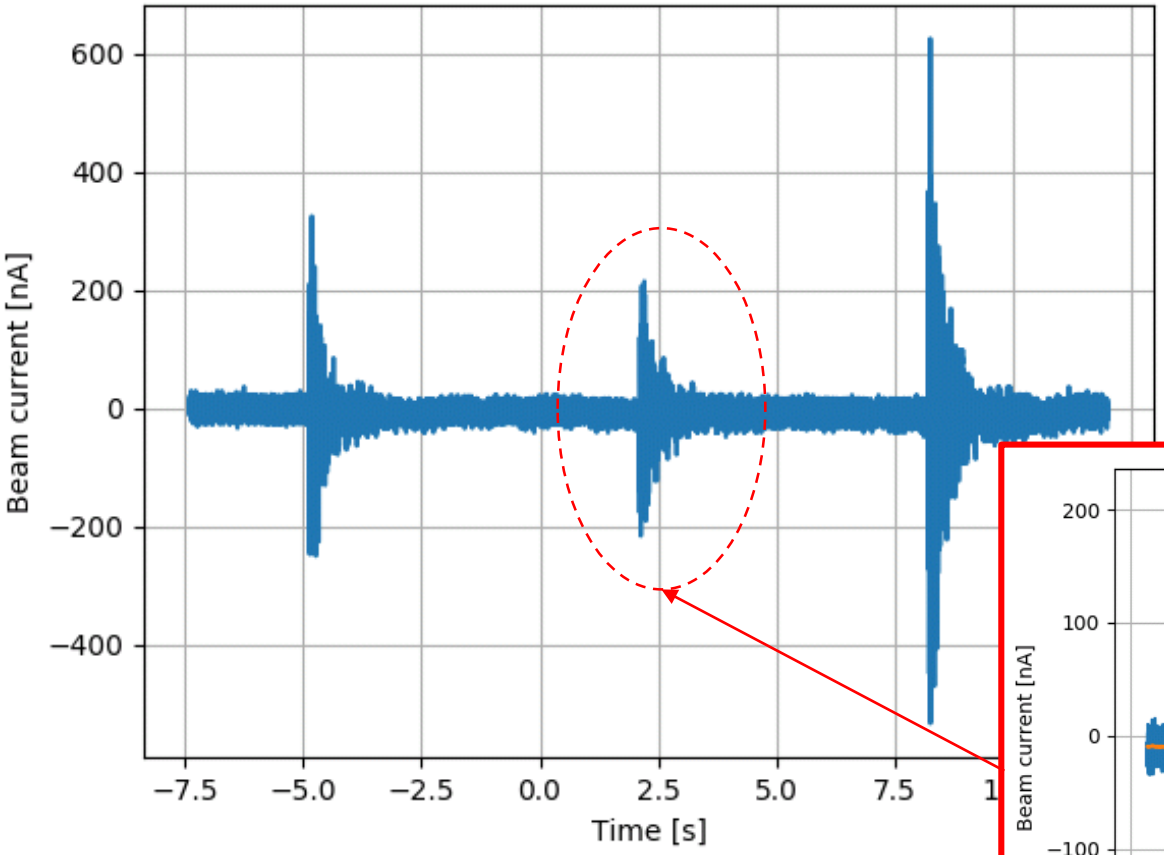
- New controls for vacuum pumps and vacuum valves
- New remotely controlled gas flow-valve was installed
- ~2 month unavailable

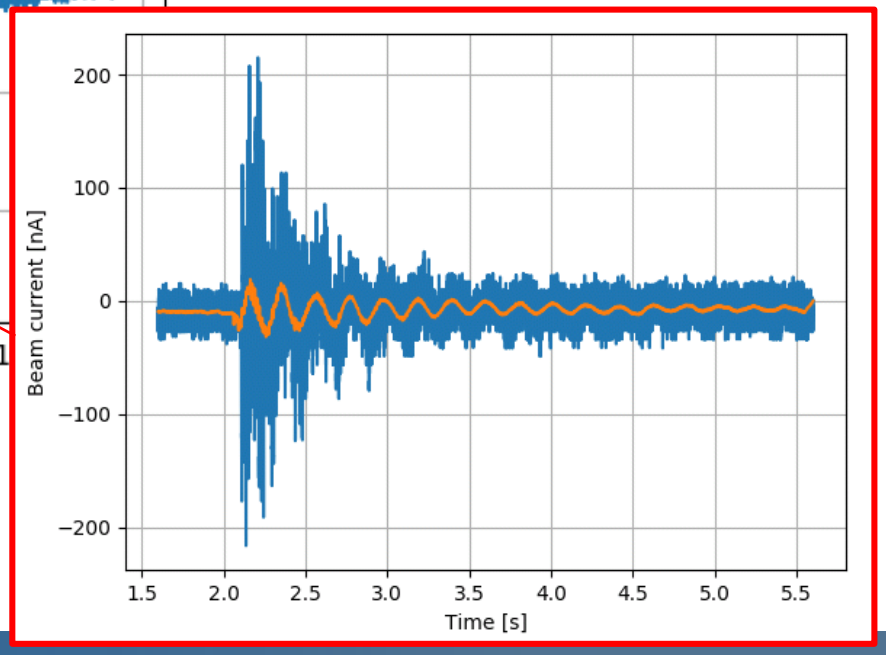
Stabilize cryostat operation



Stabilize cryostat pressure

Immunity to mechanical vibrations



Main vibration modes as captured by SQUID:

- 65 Hz
- 115 Hz
- 78 Hz
- 5 Hz