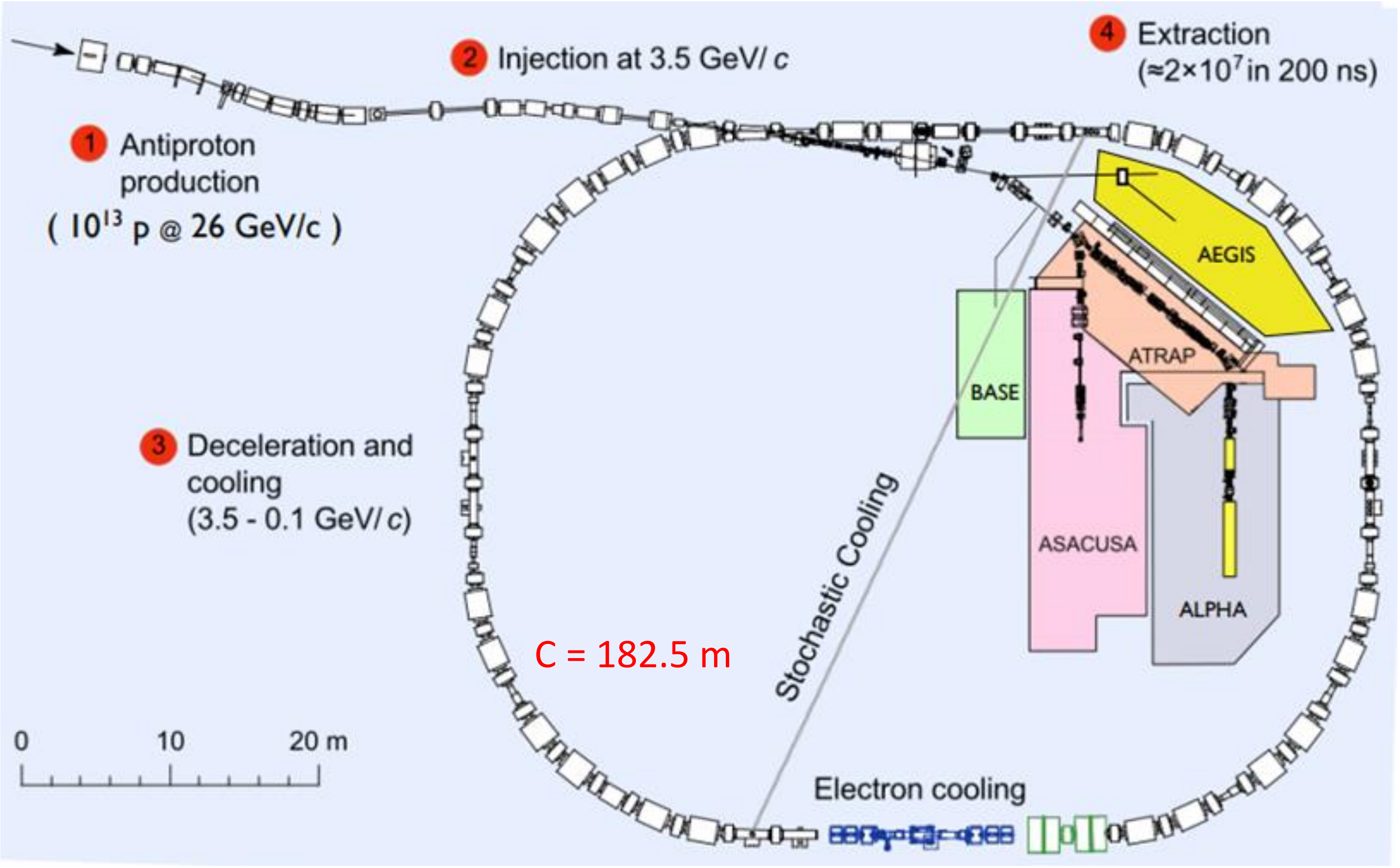
Operation of a Cryogenic Current Comparator for continuous beam intensity measurements in the AD

Miguel Fernandes

Beam Instrumentation Group Seminar

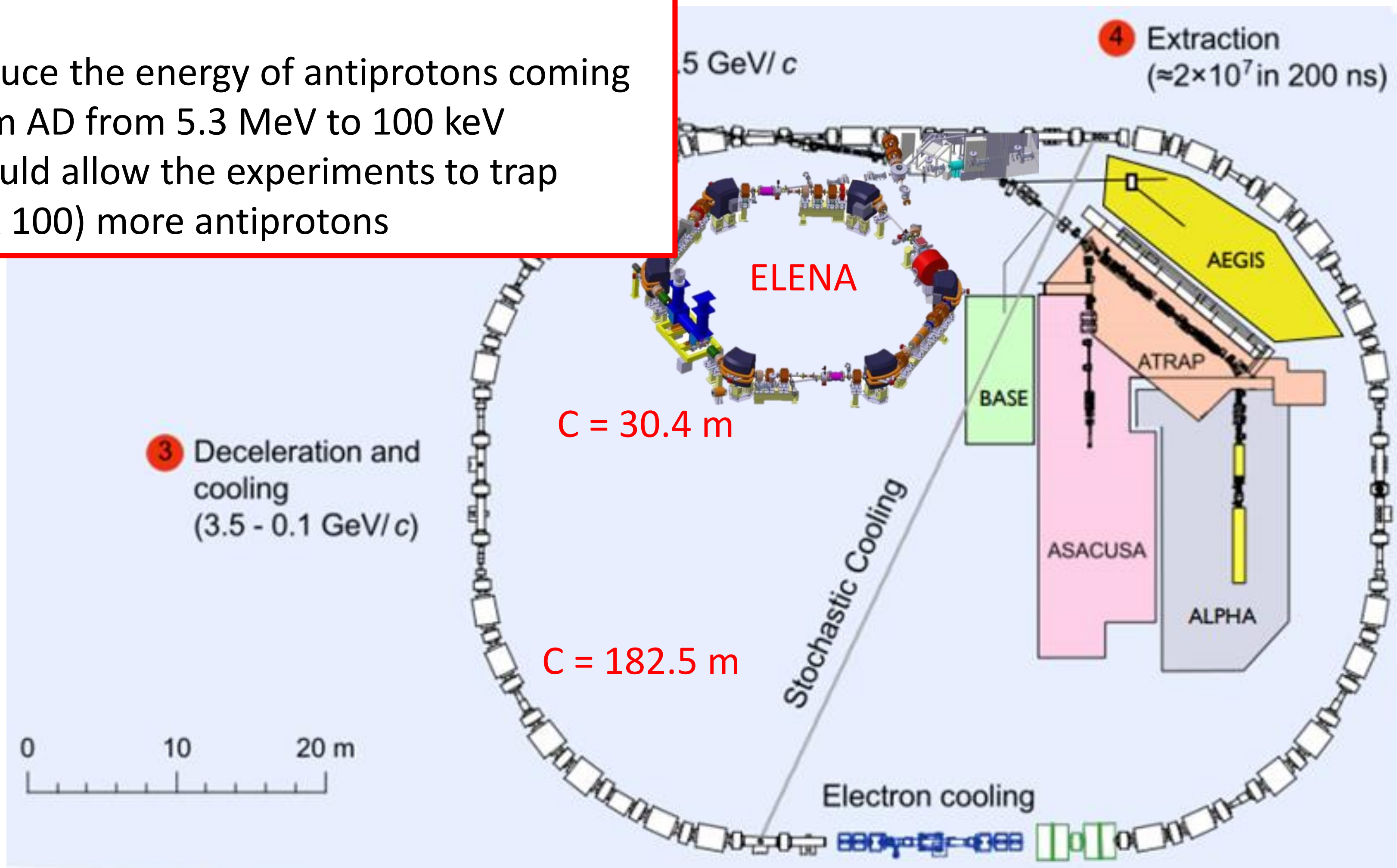
The Antiproton Decelerator (AD)

Antiproton Decelerator (AD)

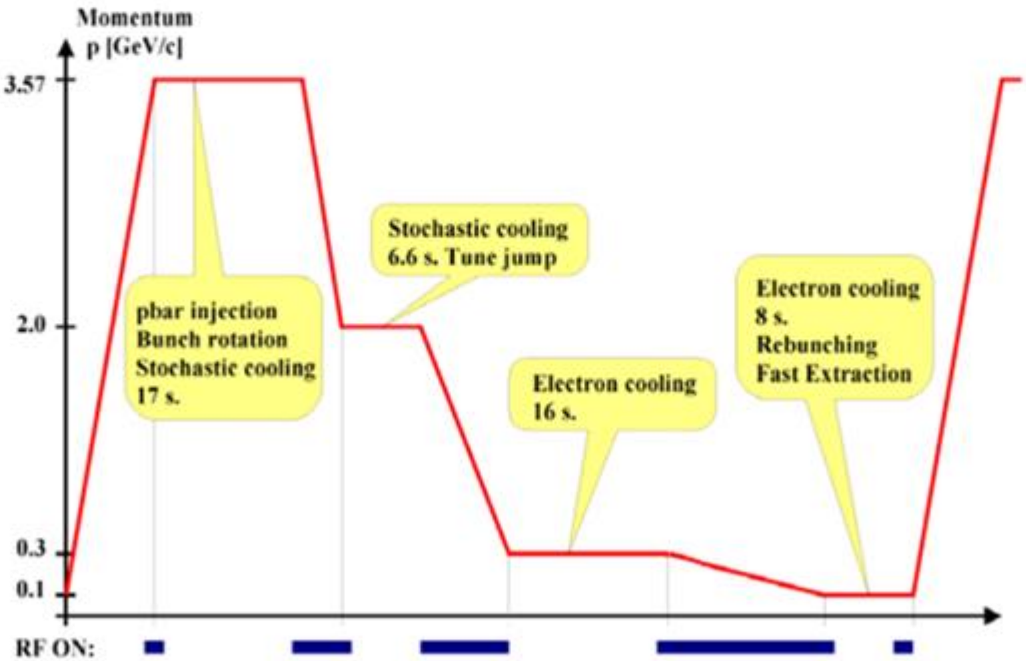


Antiproton Decelerator (AD)

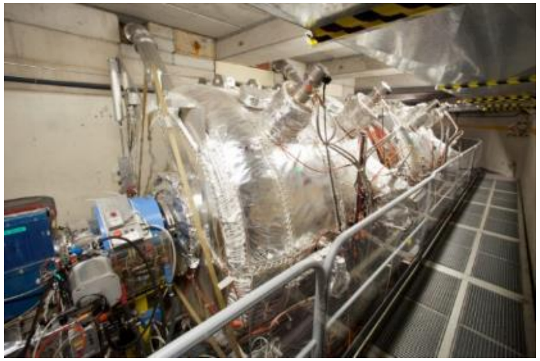
ELENA
- Reduce the energy of antiprotons coming from AD from 5.3 MeV to 100 keV
- Should allow the experiments to trap (~ x 100) more antiprotons

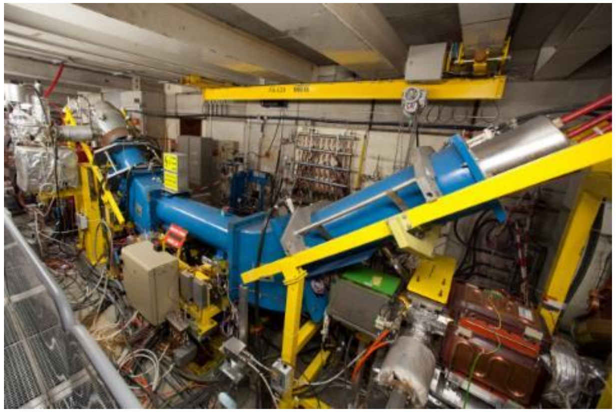


AD beam and cycle parameters



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

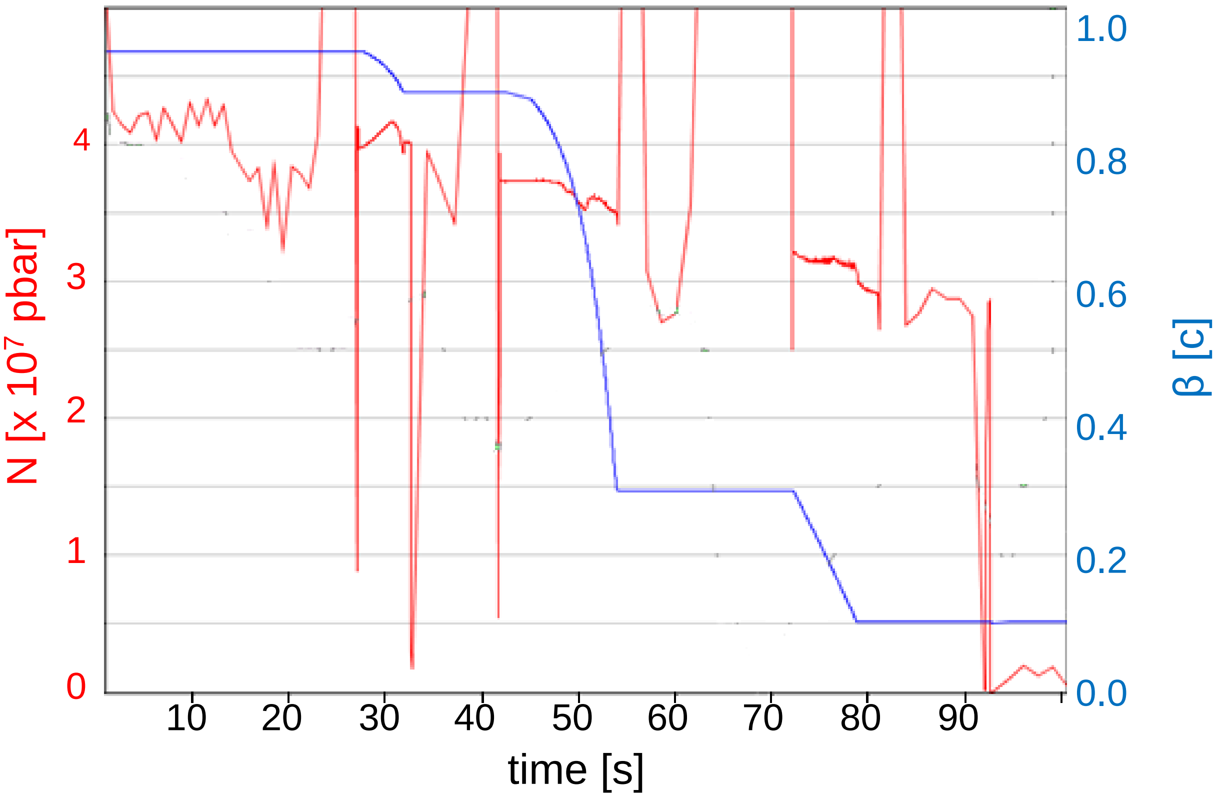
<u>DCCT</u>:

Insufficient resolution: > 1µA

<u>Fast BCTs</u>:

Limited to bunched phases

<u>Schottky monitor</u>:



Beam intensity monitoring

DCCT:

Insufficient resolution: > 1µA

Fast BCTs:

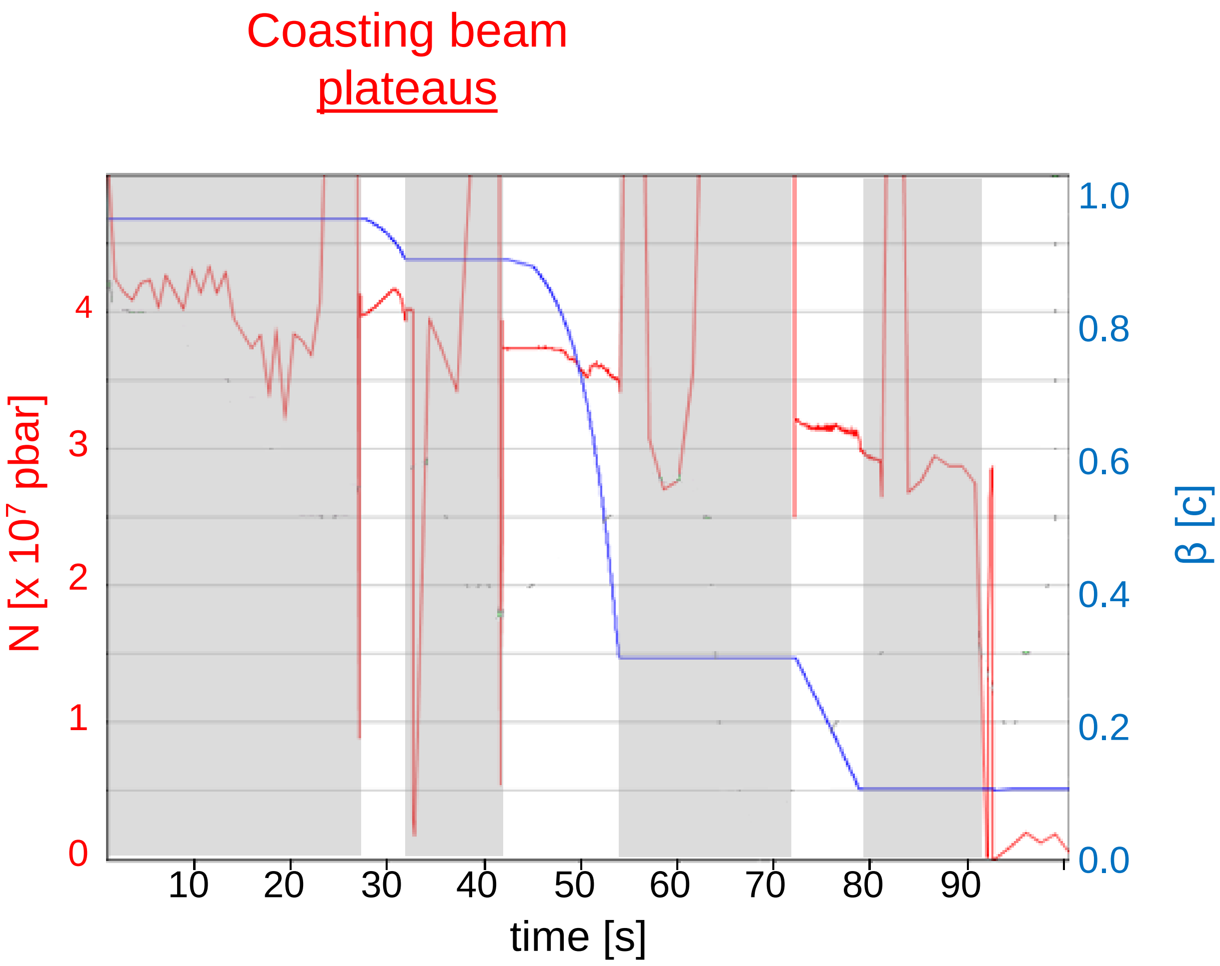
Limited to bunched phases

Schottky monitor:

Un-bunched:

time resolution of $\sim 1s$

accuracy error > 10%



Beam intensity monitoring

DCCT:

Insufficient resolution: > 1μA

Fast BCTs:

Limited to bunched phases

Schottky monitor:

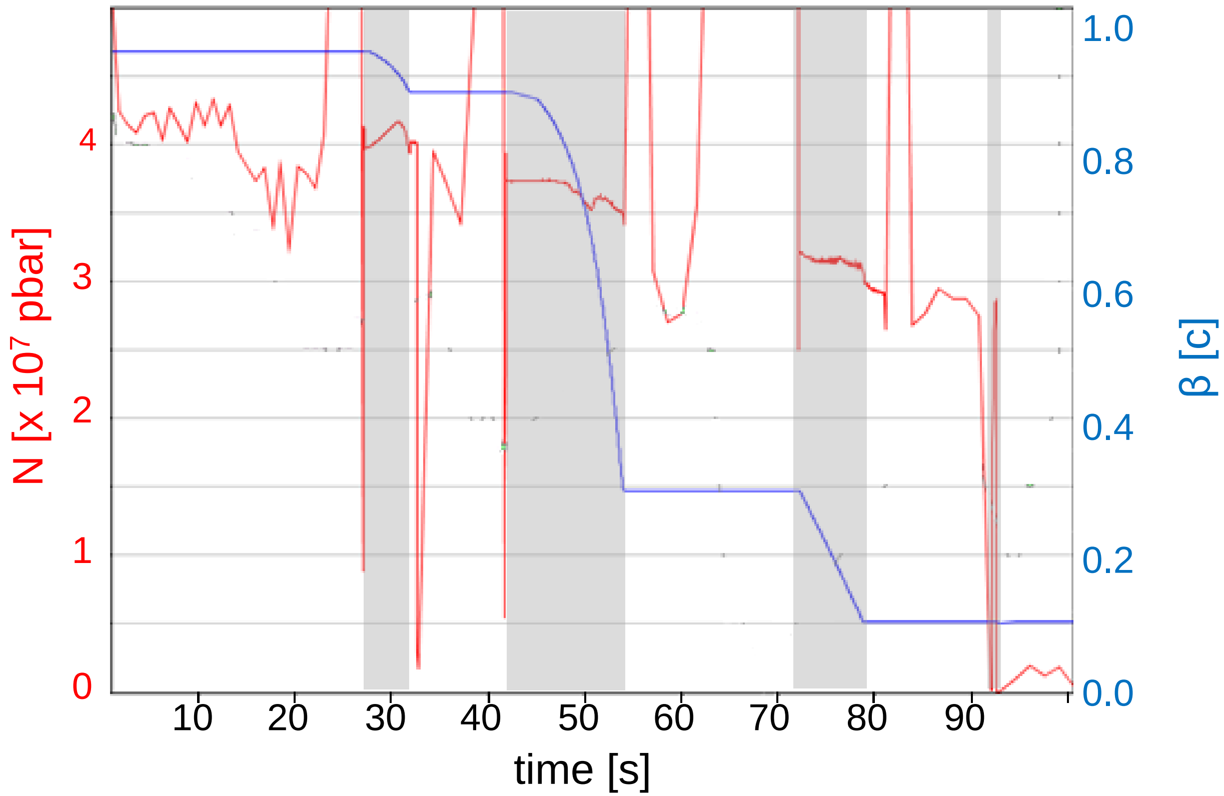
Bunched:

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: $< 5 \times 10^5$ charges
- Bandwidth: DC - 1 kHz

Operations ready:

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

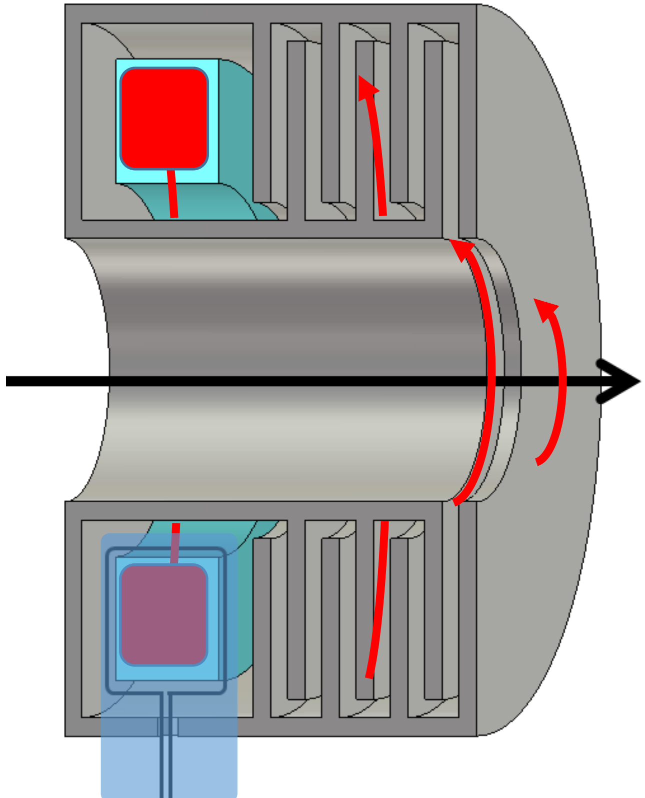
Requirements for the cryostat

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

Collaboration: GSI, Friedrich-Schiller-Universität Jena, CERN, University of Liverpool

Overview of the CCC

CCC functioning overview



Magnetic shield:

- Suppresses all field components except azimuthal beam component

Pickup coil:

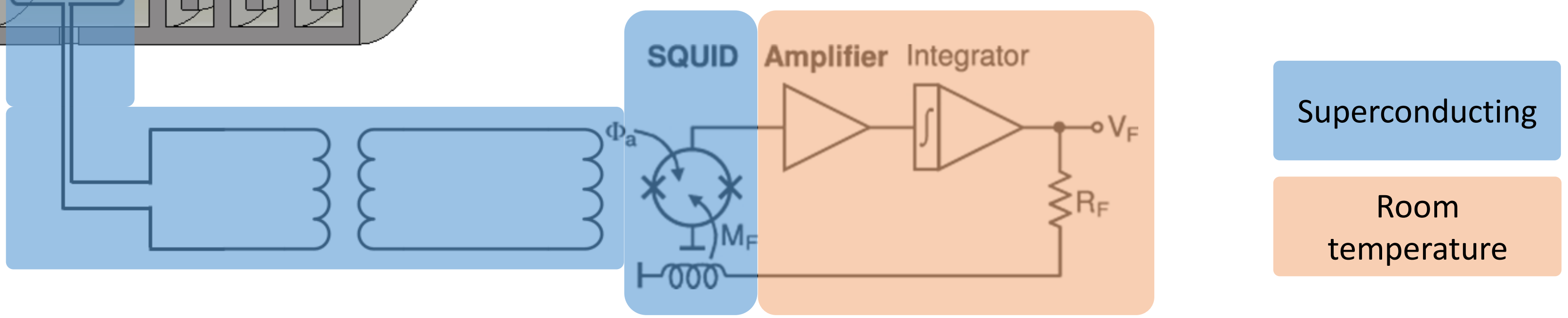
- Soft ferromagnetic material with high-permeability concentrates flux

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

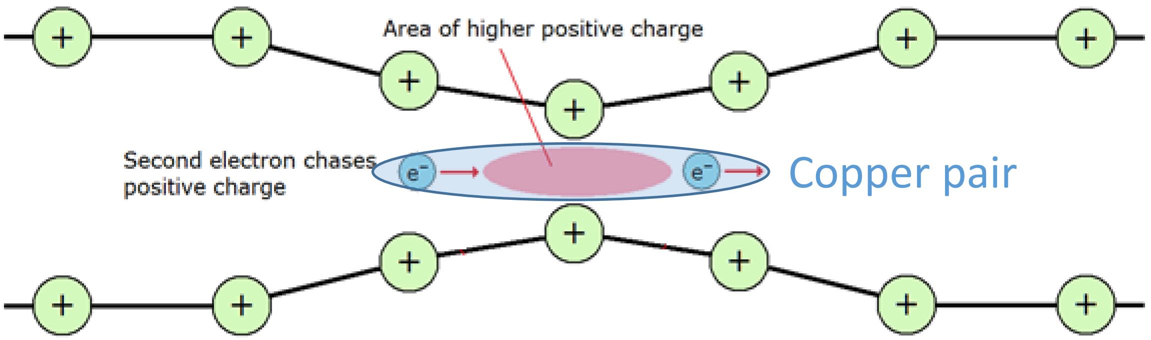


SQUID's in a nutshell

Superconductors:

- Zero resistance to electrical currents
- Magnetic field expulsion from bulk material
- Conservation of magnetic flux in closed loops

Current carriers are bounded states of two electrons (Cooper pairs)

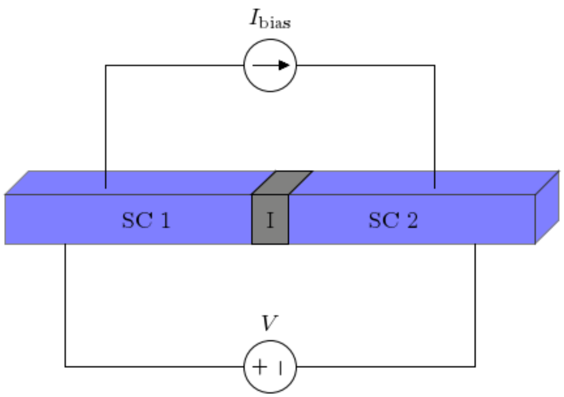


From: https://dc.edu.au/hsc-physics-ideas-to-implementation/

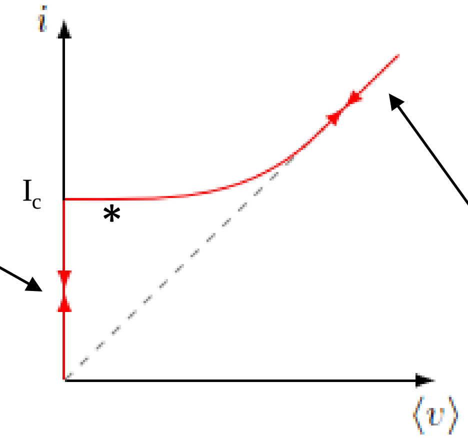
SQUID's in a nutshell

Josephson junction:

- Mixed superconducting and resistive current flow



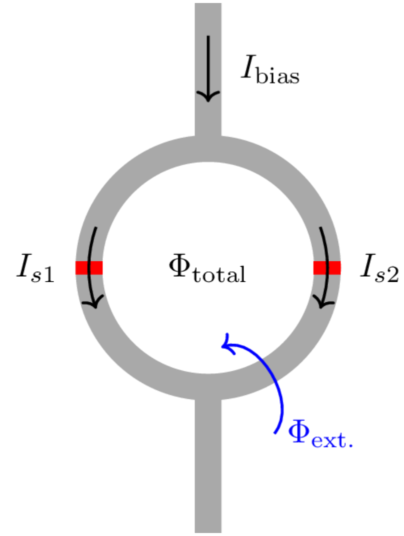
Tunneling of electron-pairs allows for a superconducitng current through a barrier



Tunneling of electrons resulting from pair break-up approximates an ohmic current **

* Only for certain parameters of Josephson junction. In general I-V curve is hysteretic.
** For small V

SQUID's in a nutshell



dc-SQUID

- Two Josephson junctions in parallel

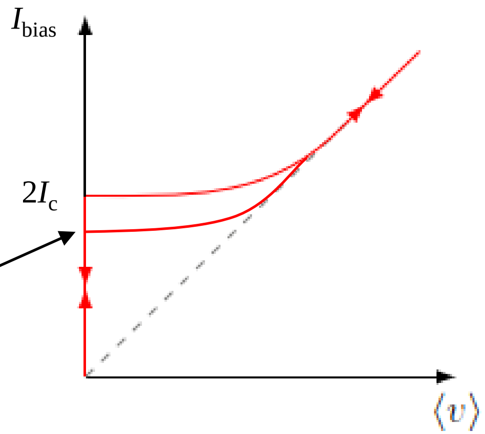
- No external flux applied: $I_{s1,2} = I_{\mathrm{bias}}/2$

- Constant magnetic flux threading closed loops:

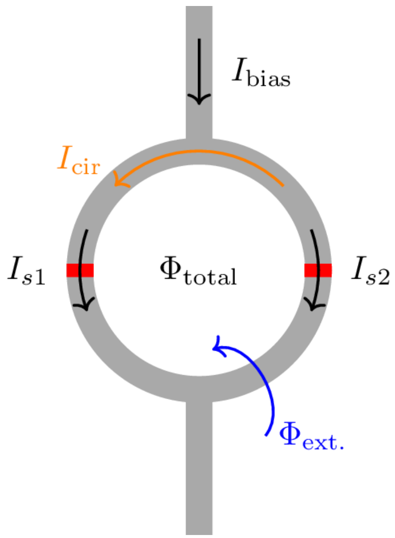
$$\Phi_{\mathrm{total}} = \Phi_{\mathrm{ext}} + \Phi_{\mathrm{cir}} = 0$$

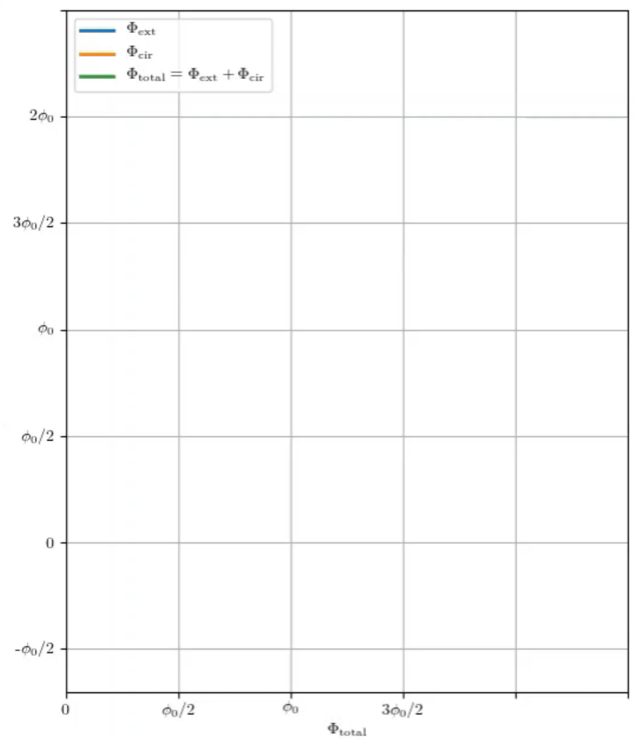
- Applying external flux:

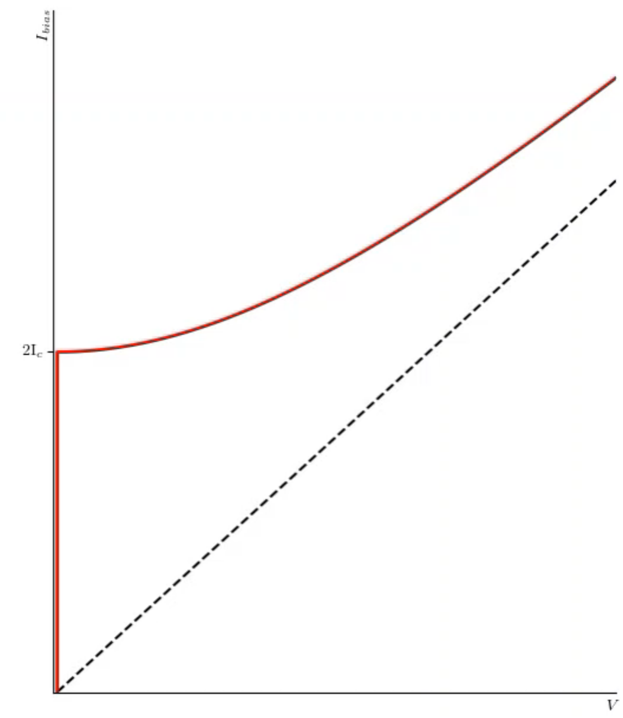
$$I_{s1} = I_{\mathrm{bias}}/2 + I_{\mathrm{cir}}$$
$$I_{s2} = I_{\mathrm{bias}}/2 - I_{\mathrm{cir}}$$



SQUID's in a nutshell

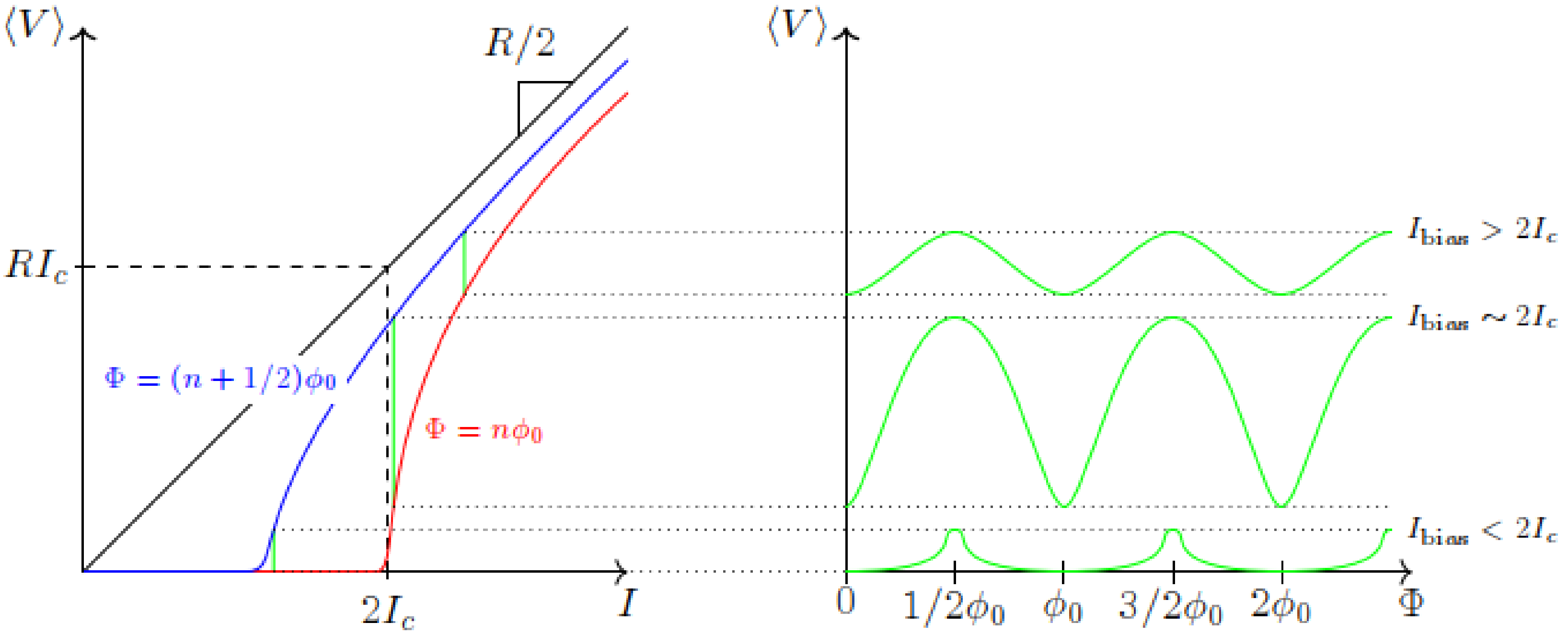






$$\phi_0 = \frac{h}{2e} = 2.067 \times 10^{-15}\,\text{Wb} \longrightarrow B \sim \text{nT} \quad \text{for A=1mm}^2$$

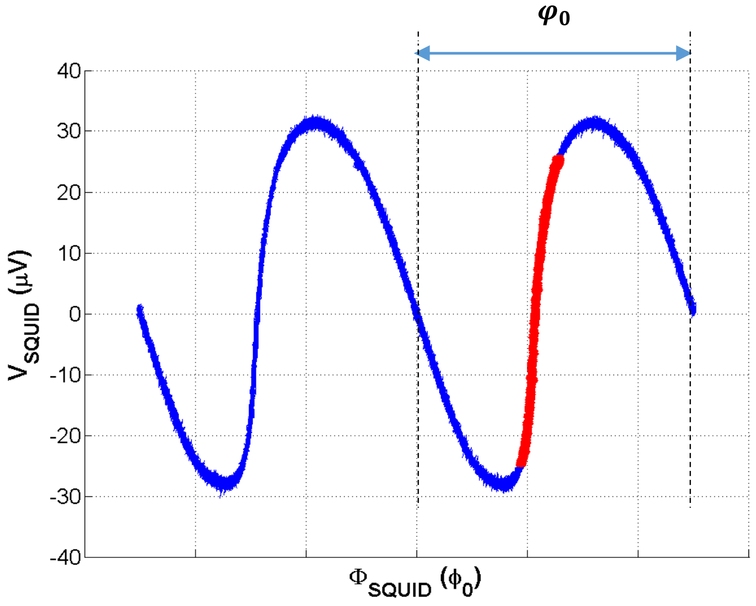
SQUID's in a nutshell

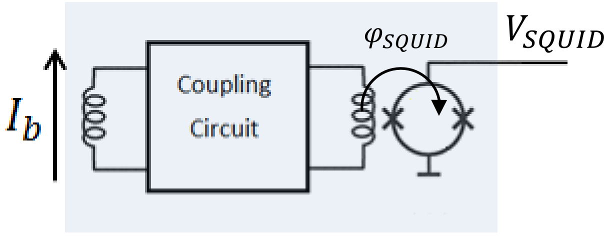


$$\Phi_{\rm SQUID}^{\rm noise} \approx 1 \times 10^{-6}\, \phi_0/\sqrt{\rm Hz}$$

SQUID devices

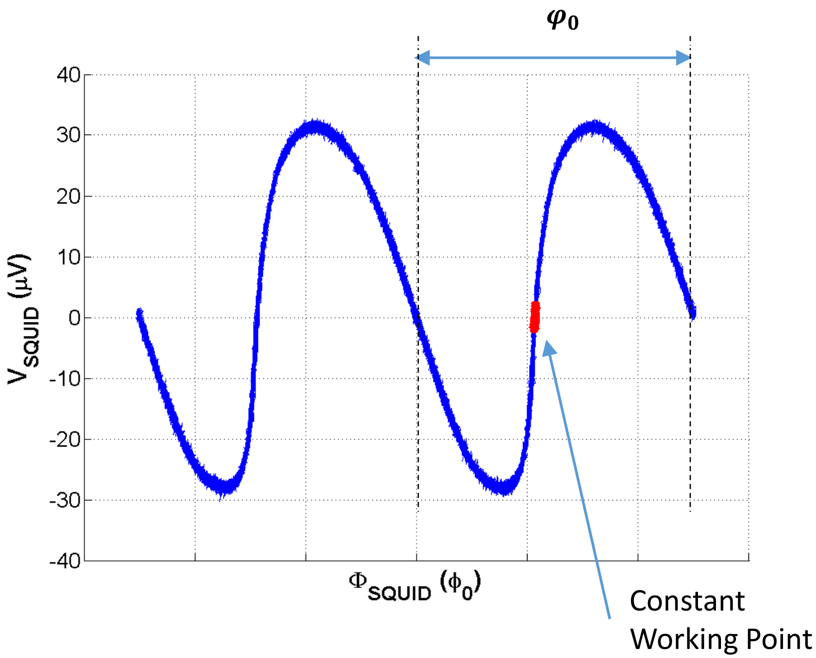
- SQUID’s are very sensitive magnetometers
- Periodic **voltage-flux** transfer function with period $\boldsymbol{\varphi}_0$ (flux-quanta)
- Voltage output of the order of $\sim 10\ \mu V$
- Periodic transfer function strongly limits its dynamic range

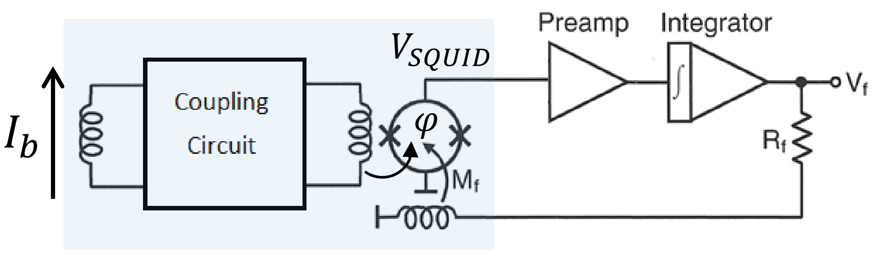




SQUID devices

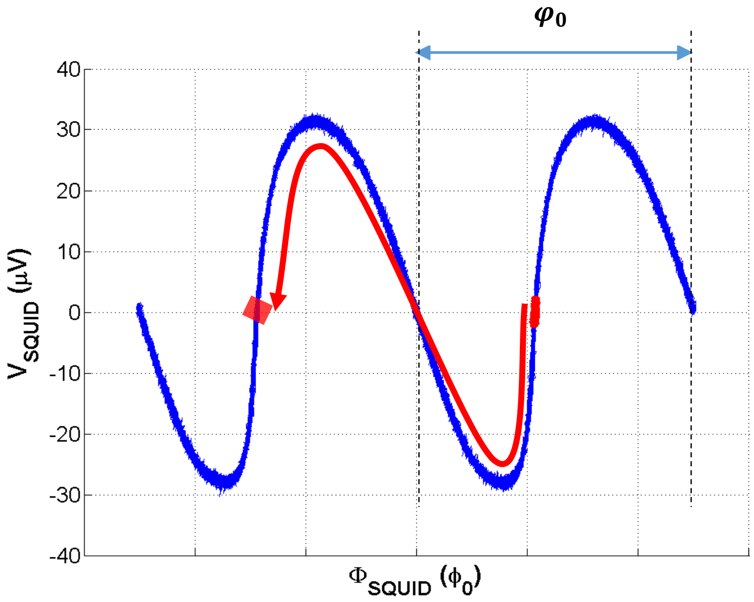
- Linearization of the transfer function using a feedback flux lock loop (FLL)
- Total flux in SQUID is kept constant at a fixed working point
- Possible to resolve variations of $10^{-6}\varphi_0$
- Dynamic range increased to up to 120 dB

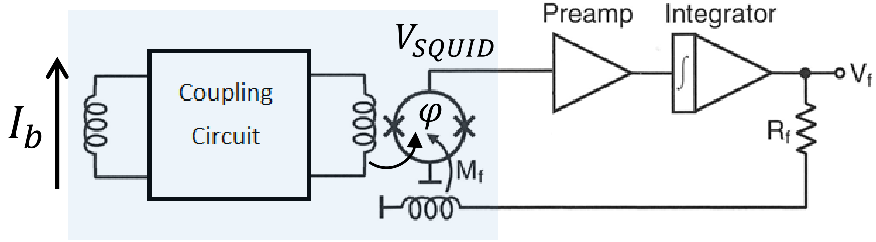




SQUID devices

- 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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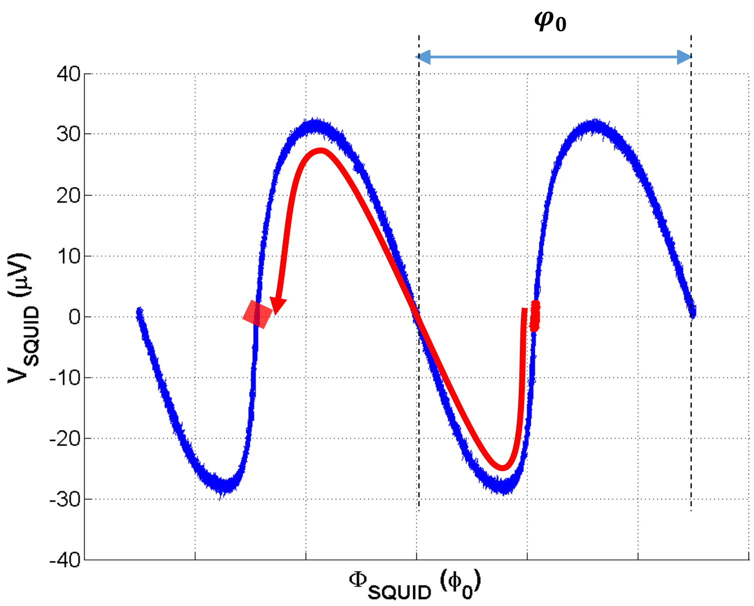
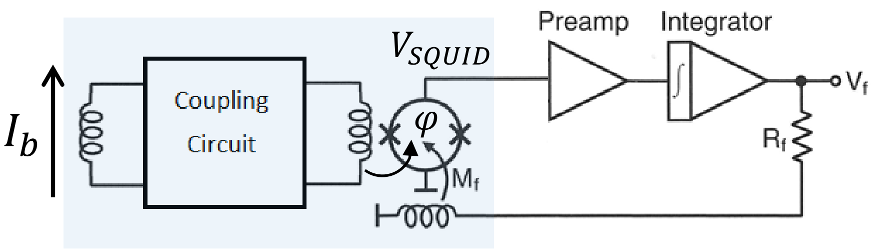
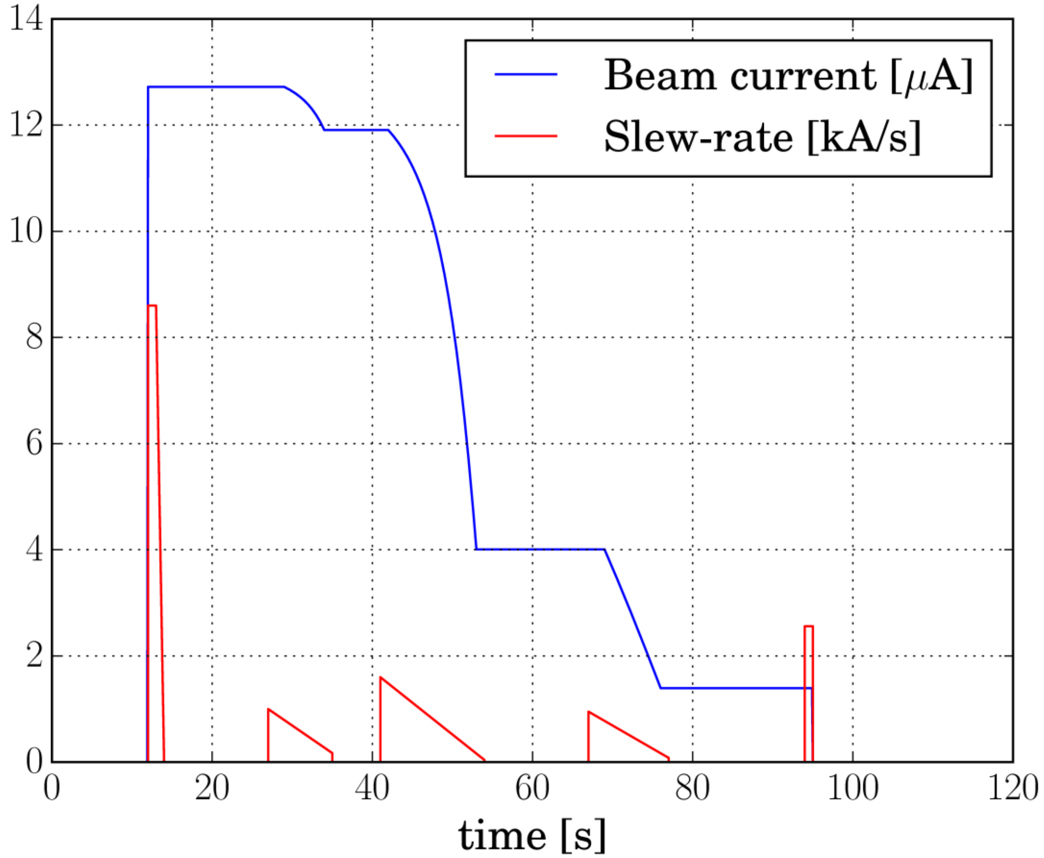


$$\frac{d\phi_s}{dt} \leq 1 \ldots 5\ M\varphi_0/s$$



Adaptation of the CCC to the AD beam

AD beam slew-rate

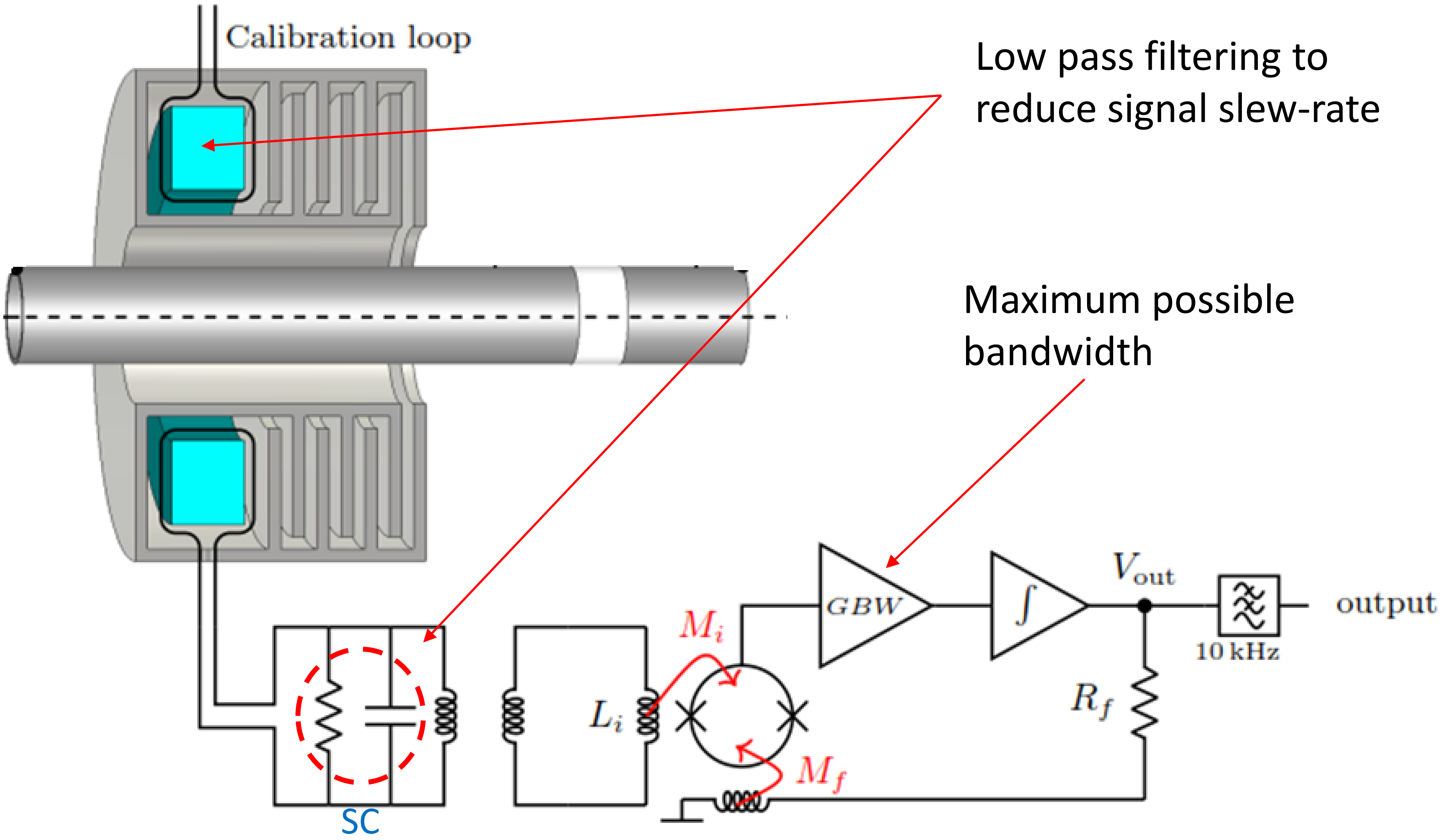


$$\frac{\phi}{I_{beam}} = 10\ \phi_0/\mu A$$

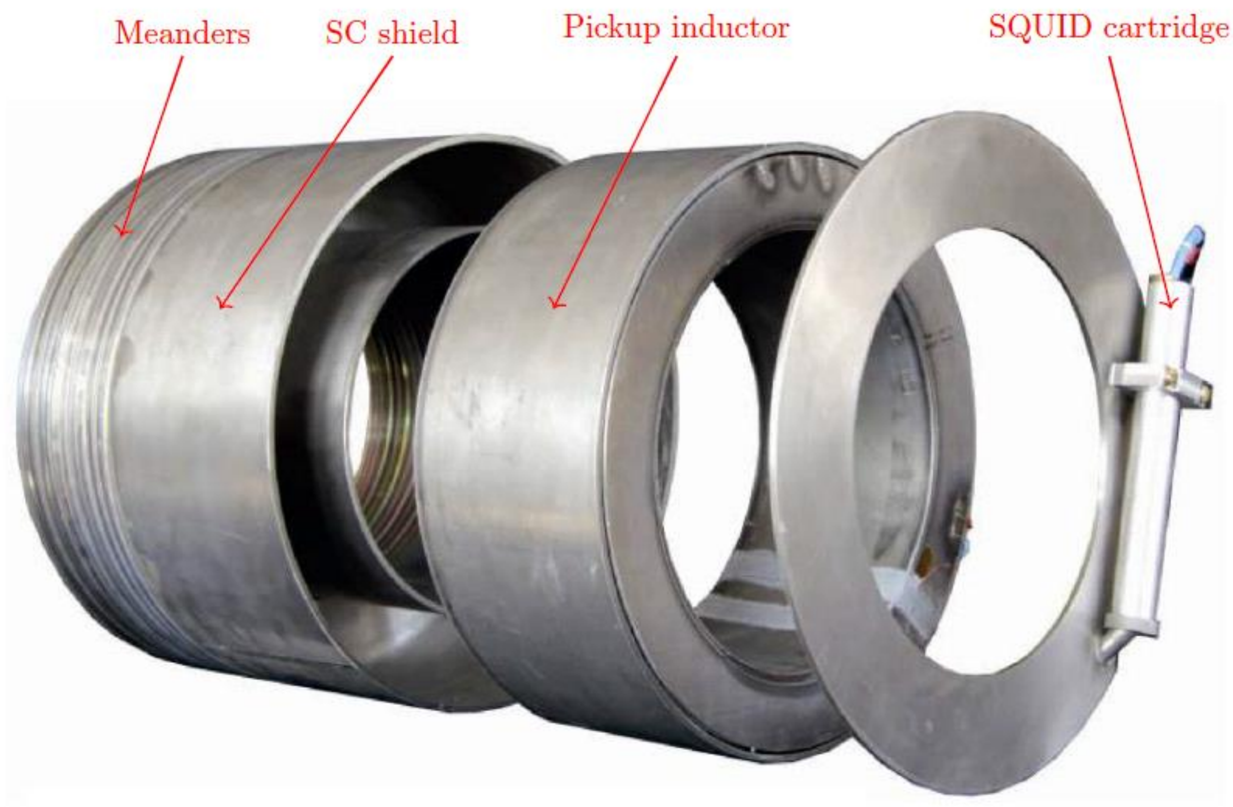
Flux slew-rate at SQUID

Filtering	Slew-rate
None	86 $G\phi_0/s$
Core permeability	1.2 $G\phi_0/s$

Filtering beam current signal

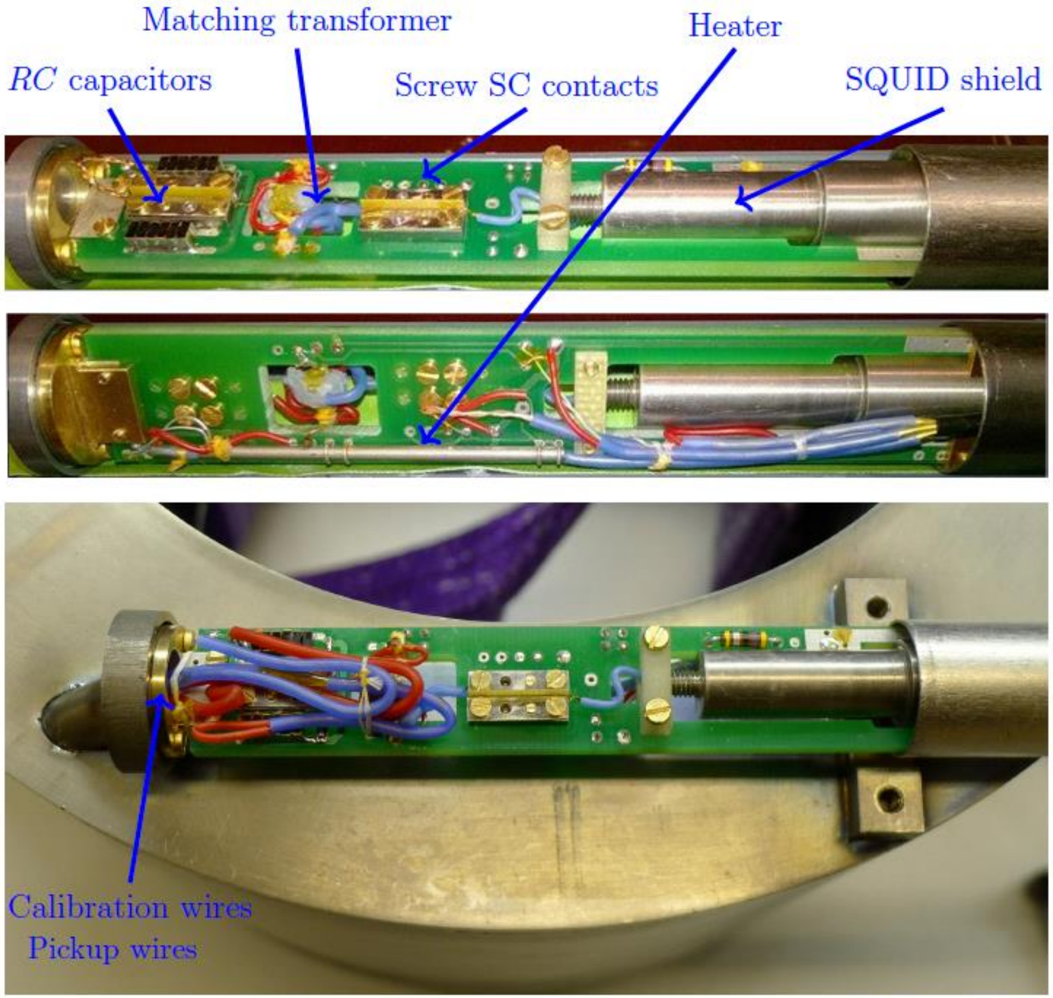


CCC components

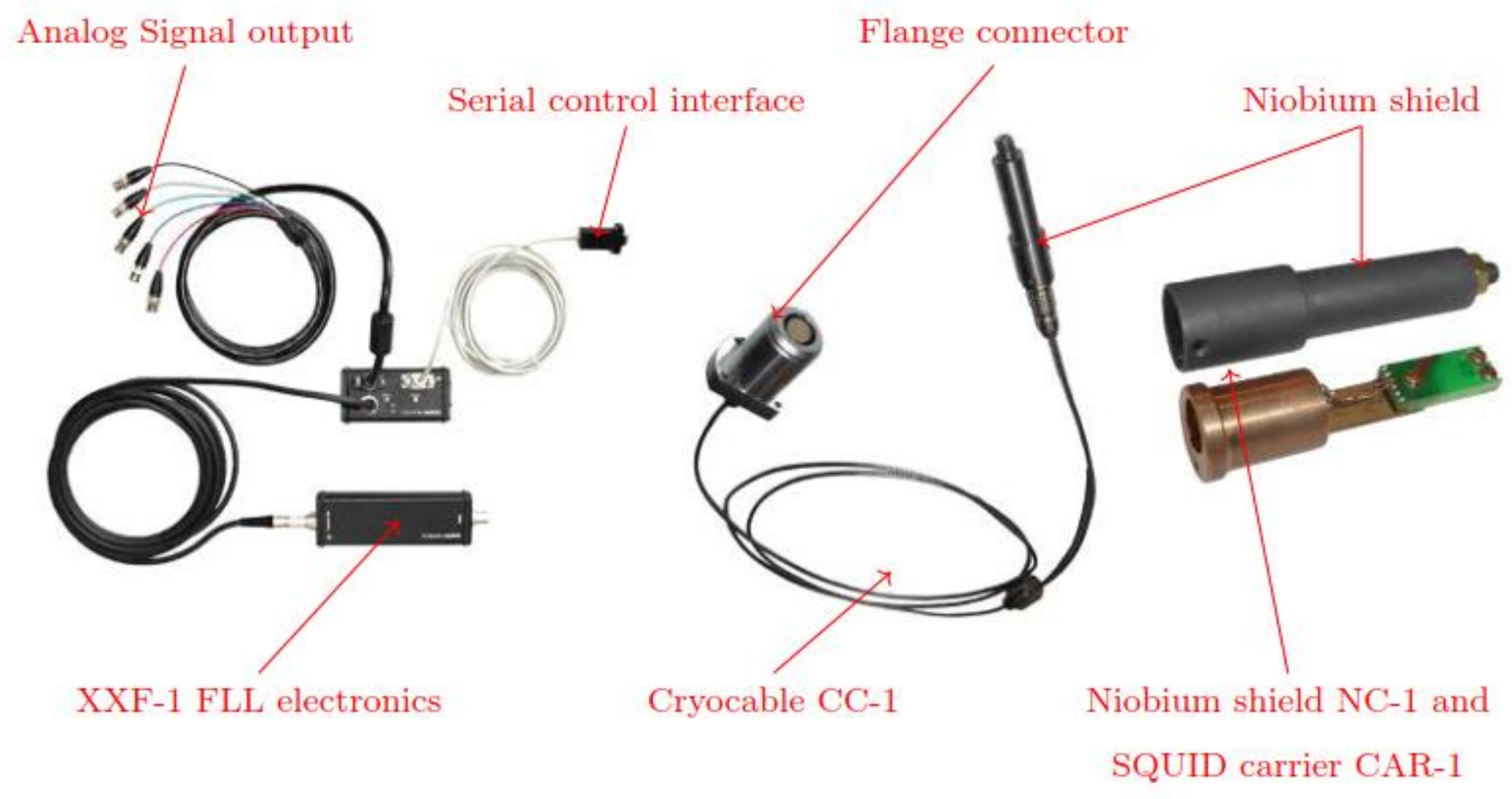


Magnetic shield had previously been fabricated by GSI and Univesity Jena as prototype for FAIR

CCC components



CCC components



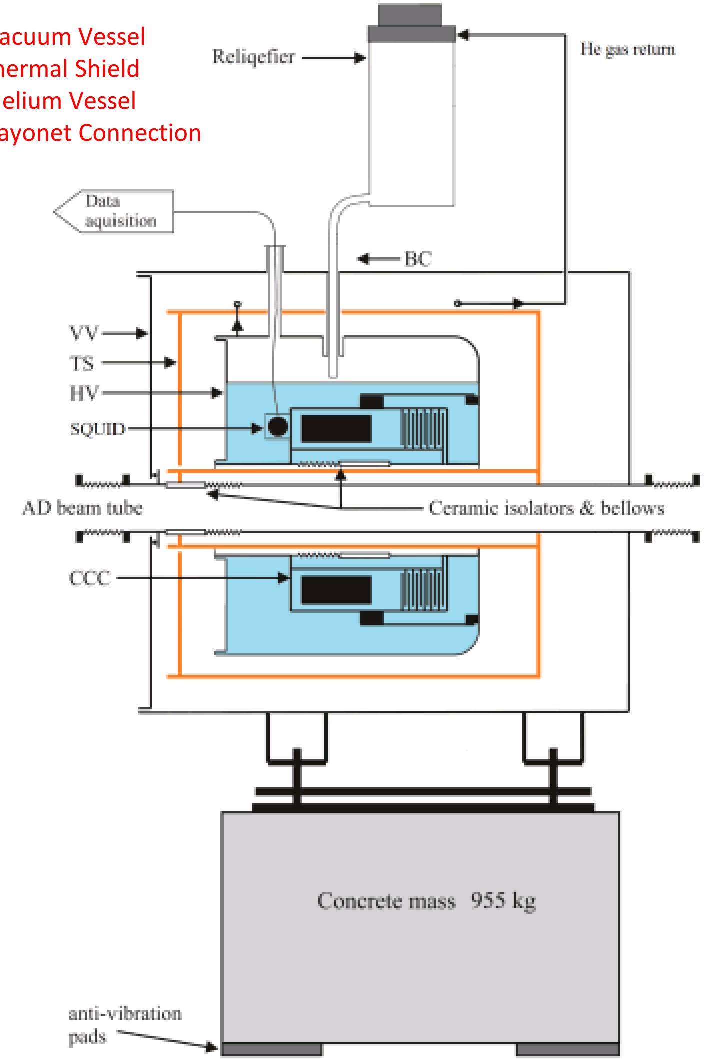
Magnicon SQUID and FLL electronics system

Cryostat design

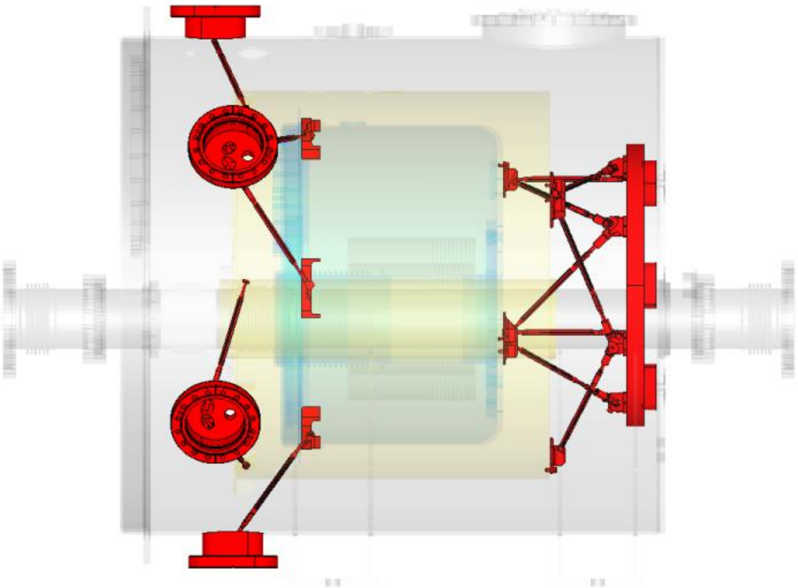
Cryostat design

- 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

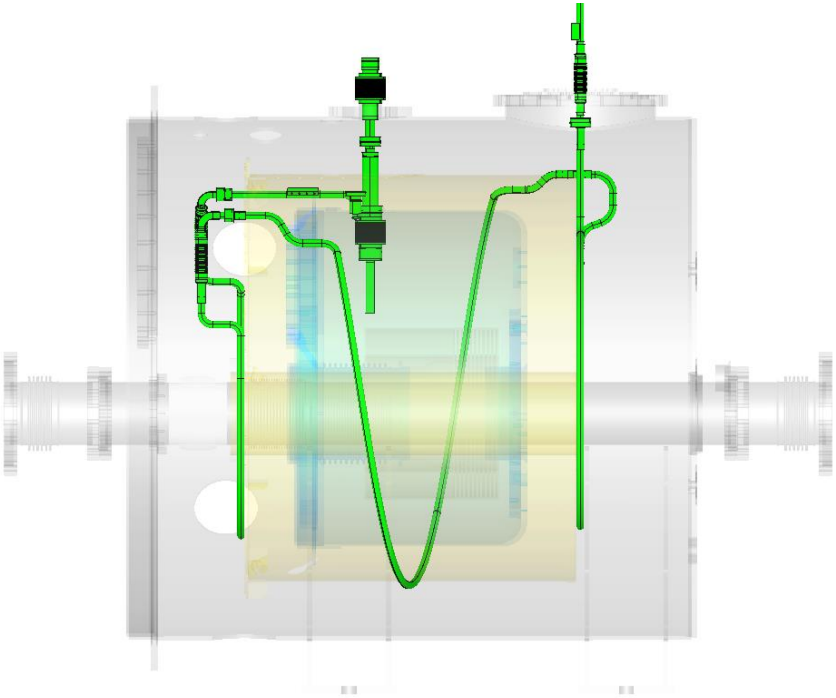
VV: Vacuum Vessel
TS: Thermal Shield
HV: Helium Vessel
BC: Bayonet Connection



Cryostat design

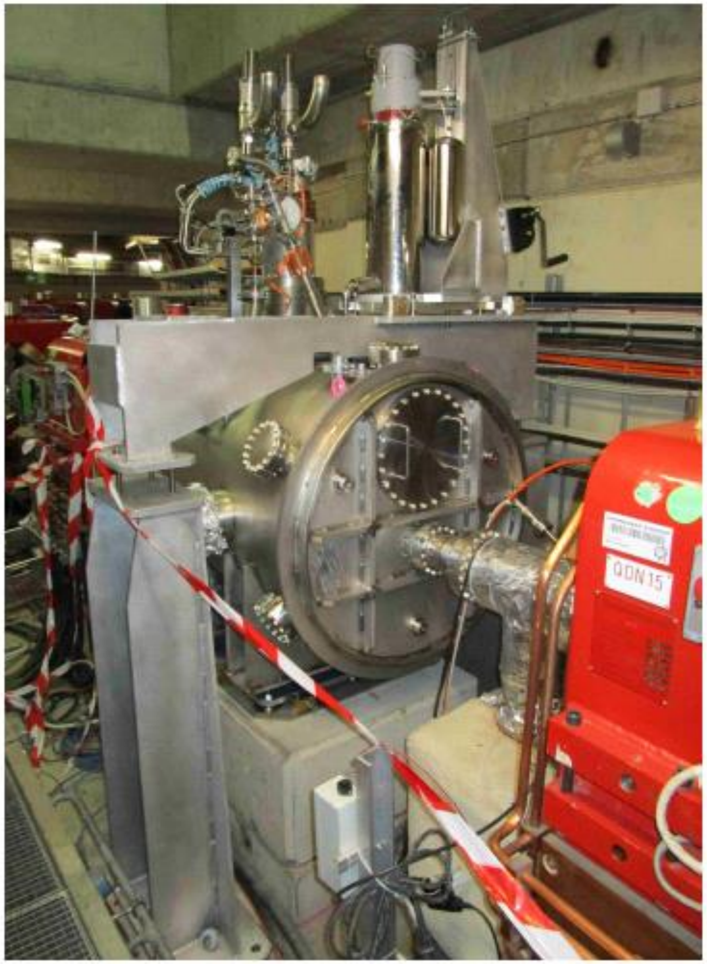


LHe vessel support



Closed circuit cooling of termal shield

Cryostat installed in AD

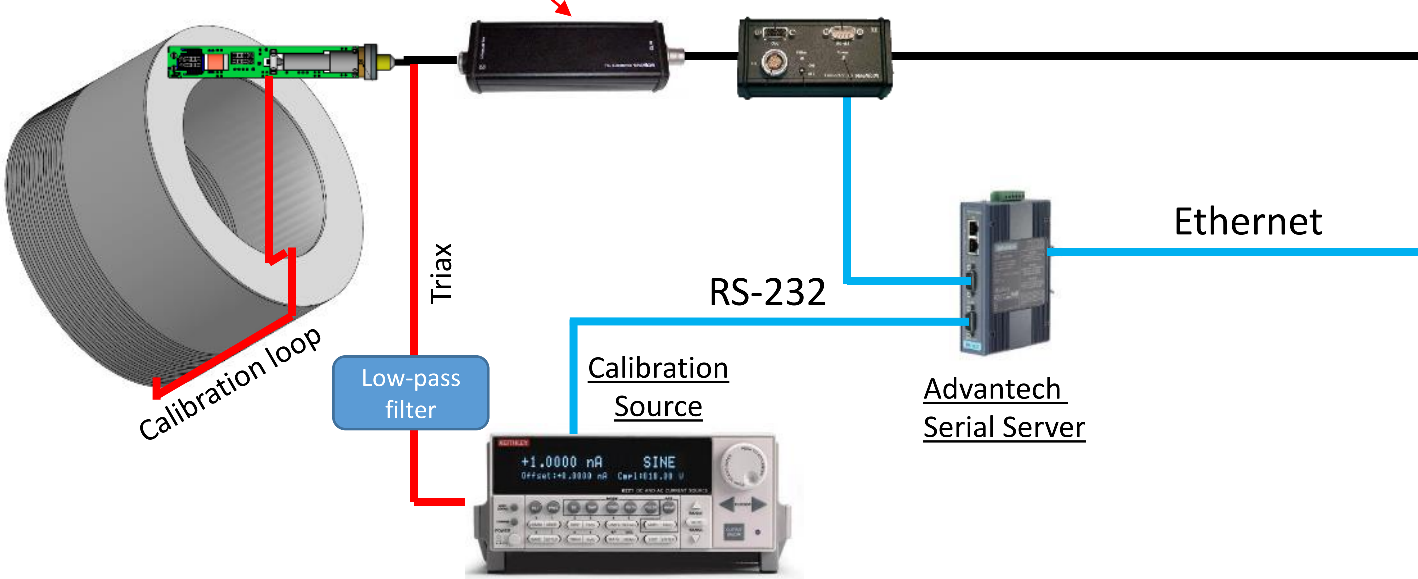


CCC Acquisition and Control

Acquisition and controls

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

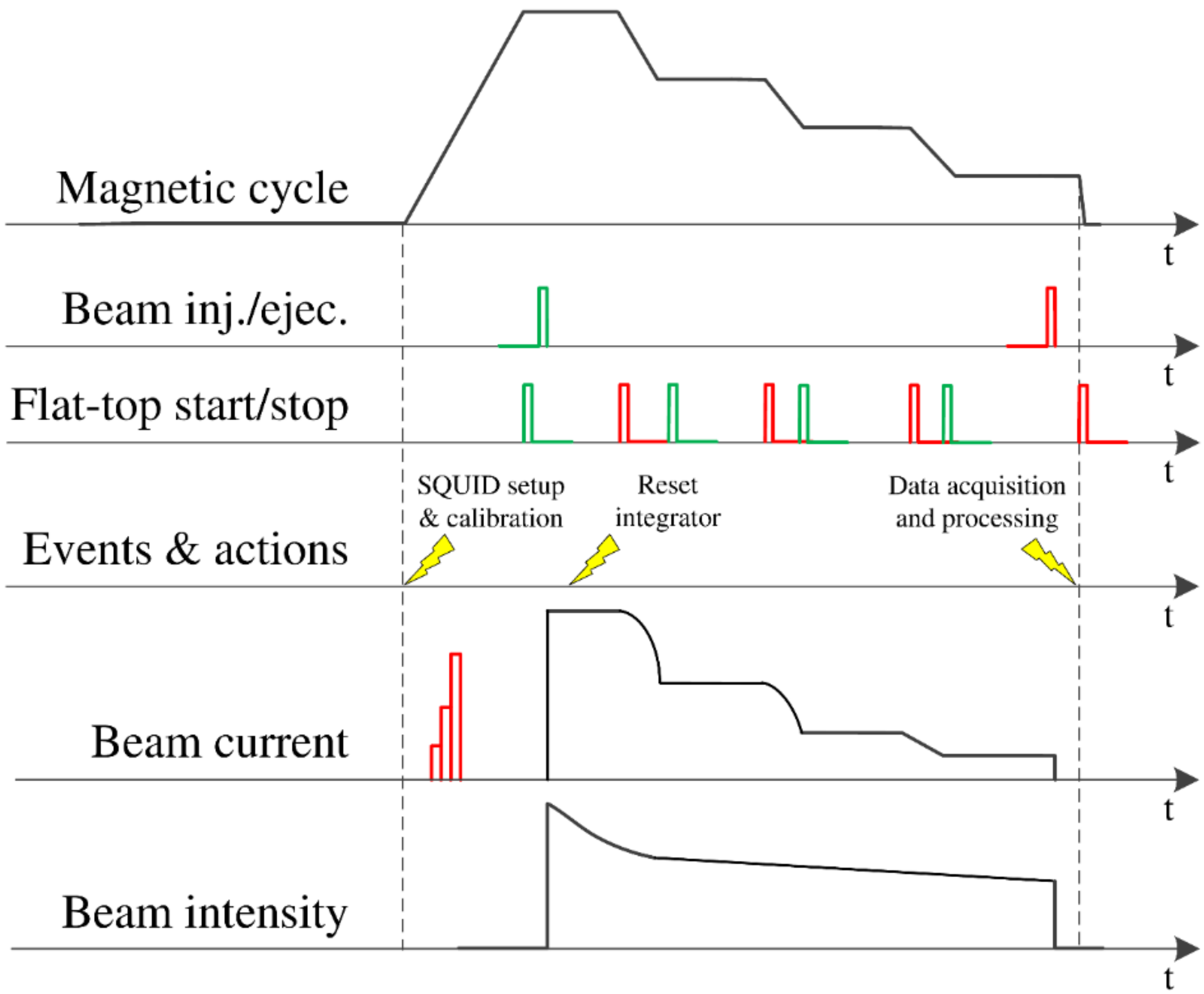
Acquisition / Controls
- VME architecture
- FESA SW + Expert GUI
- Signal acquisition at end of cycle and on-line
- Control of multiple SQUID/FLL parameters



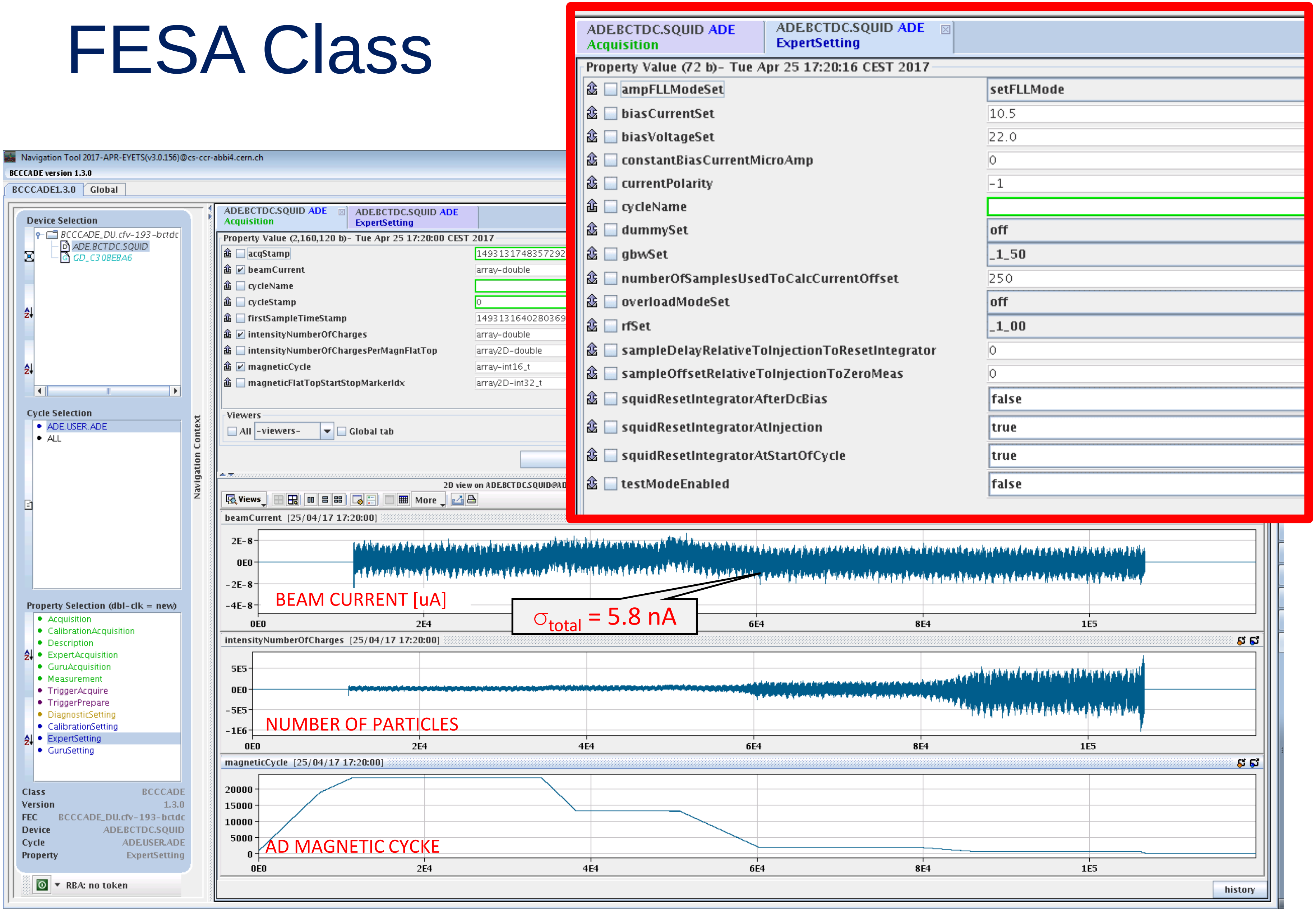
VME Crate
1. CPU L866
2. CTRV timing
3. VD80 ADC
   - 16 channels
   - 16 bit
   - +/- 10V
   - 800kOhm
   - Isolated diff. inputs

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

AD cycle synchronization



FESA Class



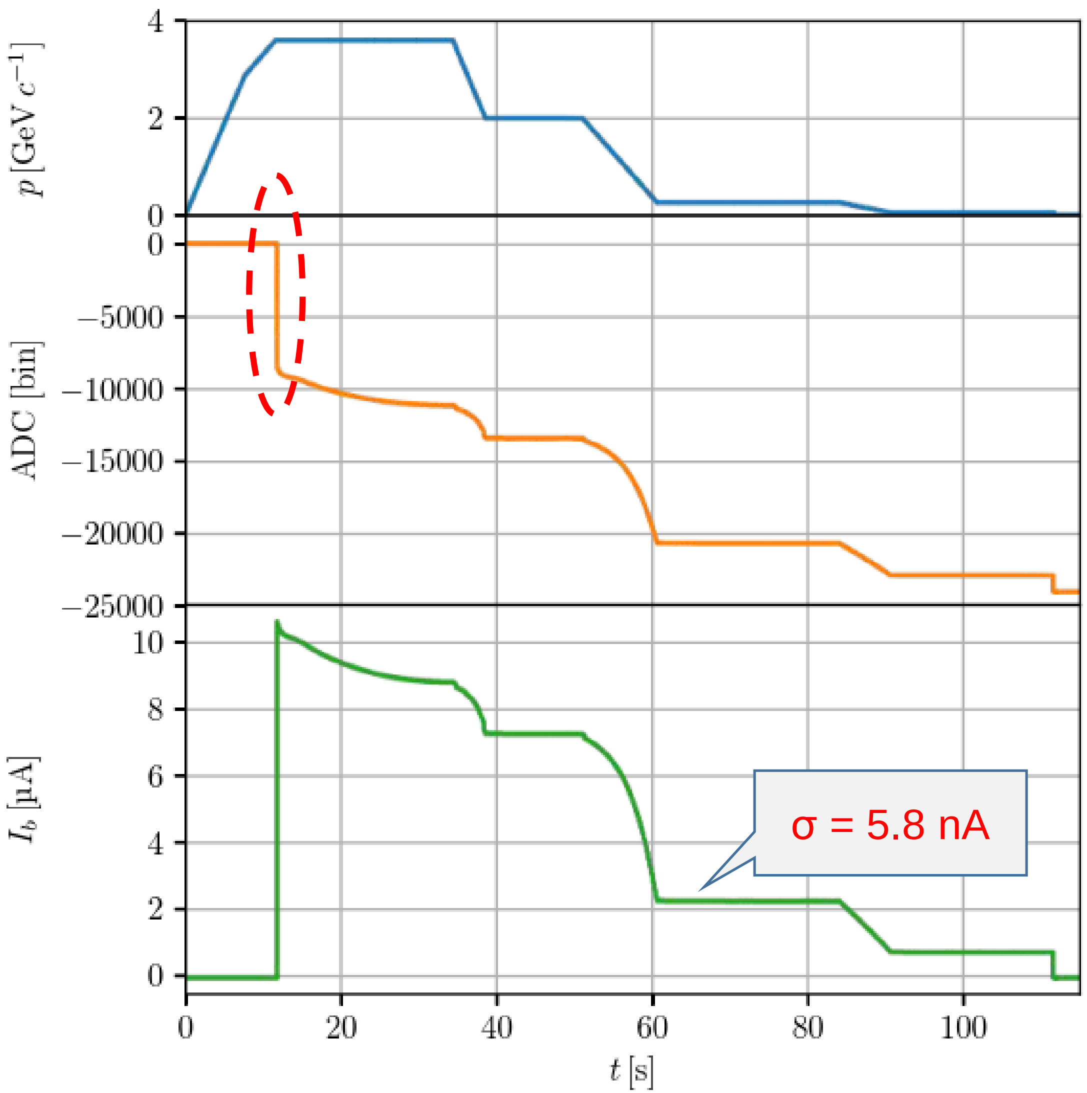
Navigation Tool 2017-APR-EYETS(v3.0.156)@cs-ccr-abbi4.cern.ch
BCCCADE version 1.3.0
BCCCADE1.3.0
Global
Device Selection
BCCCADE_DU.cfv-193-bctdc
ADE.BCTDC.SQUID
GD_C30BEBA6
Cycle Selection
ADE.USER.ADE
ALL
Property Selection (dbl-clk = new)
Acquisition
CalibrationAcquisition
Description
ExpertAcquisition
GuruAcquisition
Measurement
TriggerAcquire
TriggerPrepare
DiagnosticSetting
CalibrationSetting
ExpertSetting
GuruSetting
Class BCCCADE
Version 1.3.0
FEC BCCCADE_DU.cfv-193-bctdc
Device ADE.BCTDC.SQUID
Cycle ADE.USER.ADE
Property ExpertSetting
RBA: no token
Navigation Context
ADE.BCTDC.SQUID ADE Acquisition
ADE.BCTDC.SQUID ADE ExpertSetting
Property Value (2,160,120 b)- Tue Apr 25 17:20:00 CEST 2017
acqStamp 1493131748357292
beamCurrent array-double
cycleName
cycleStamp 0
firstSampleTimeStamp 1493131640280369
intensityNumberOfCharges array-double
intensityNumberOfChargesPerMagnFlatTop array2D-double
magneticCycle array-int16_t
magneticFlatTopStartStopMarkerIdx array2D-int32_t
Viewers
All -viewers- Global tab
Views More
beamCurrent [25/04/17 17:20:00]
BEAM CURRENT [uA]
σ_{total} = 5.8 nA
intensityNumberOfCharges [25/04/17 17:20:00]
NUMBER OF PARTICLES
magneticCycle [25/04/17 17:20:00]
AD MAGNETIC CYCKE
history
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

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
INJ
EJE
ms
Beam Current - May 31, 2018 3:36:37 PM [107200]
Amp
Number Charges - May 31, 2018 3:36:37 PM [107200]
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

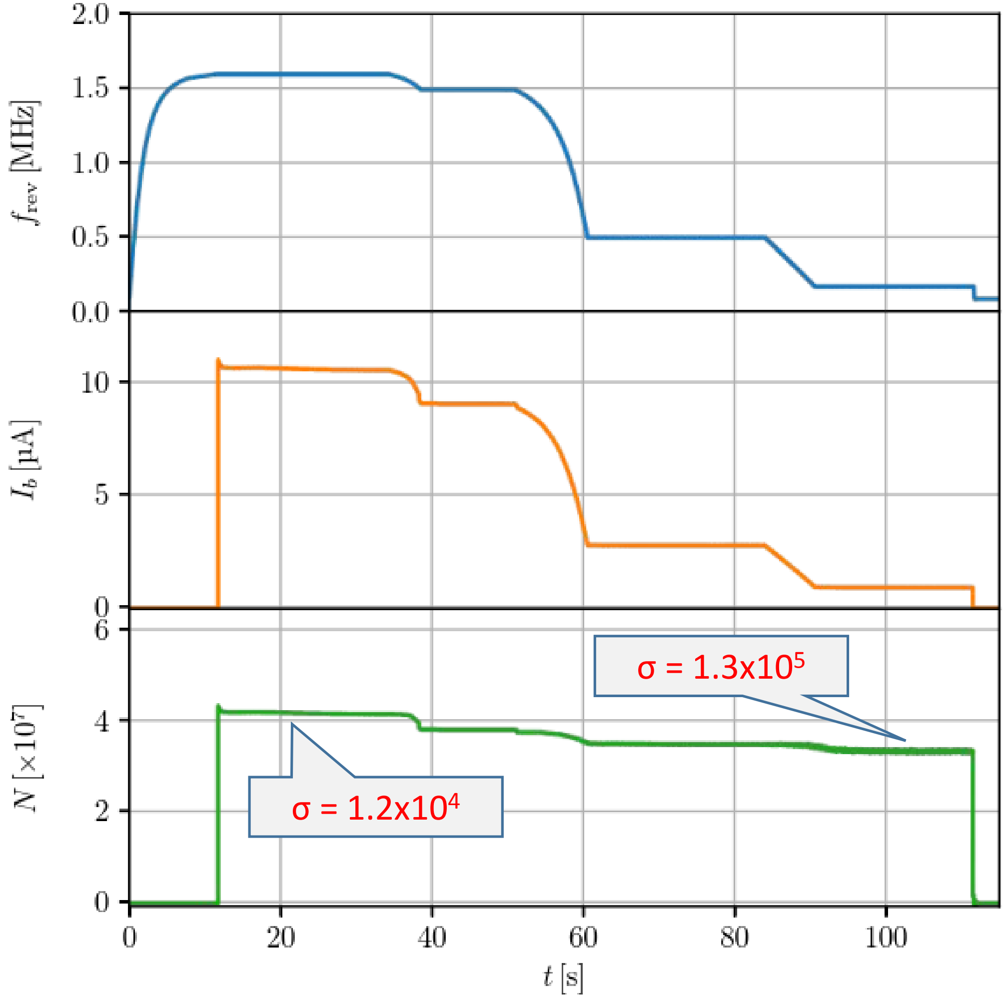
Beam measurements and performance

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)

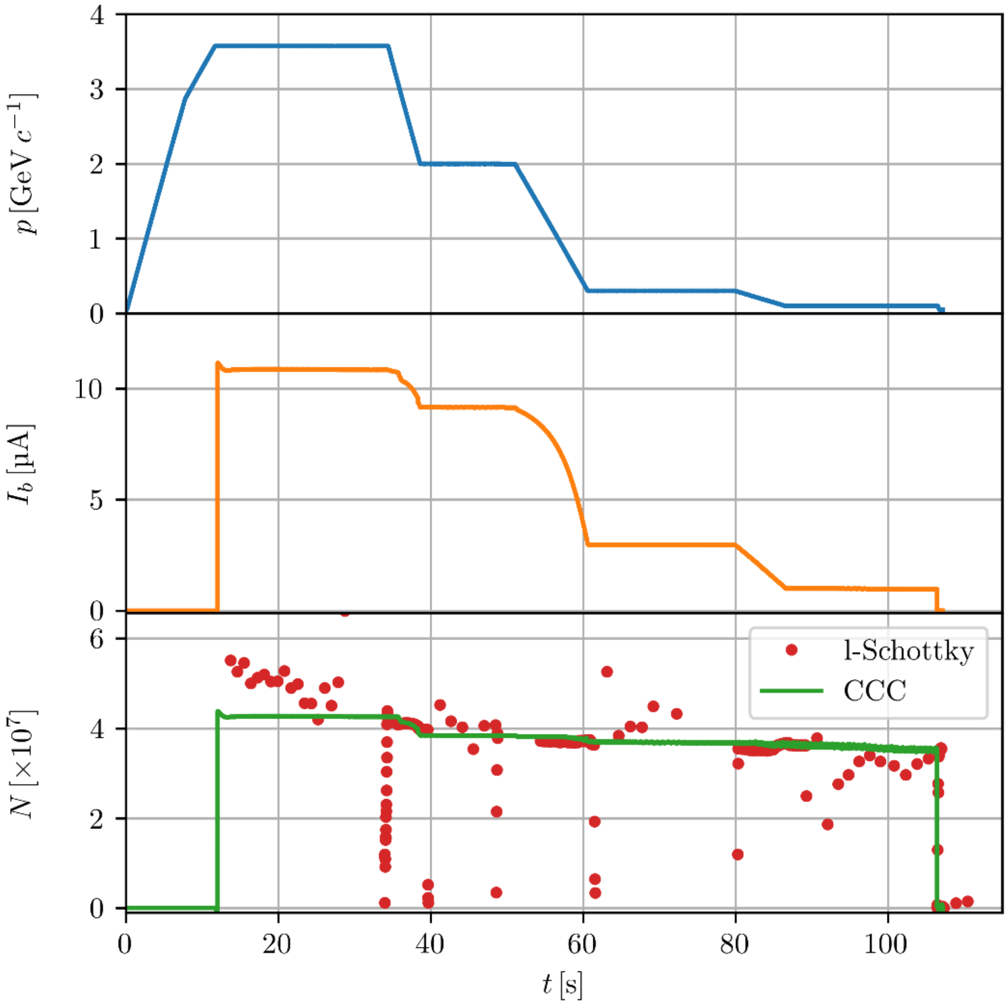
Beam intensity measurement



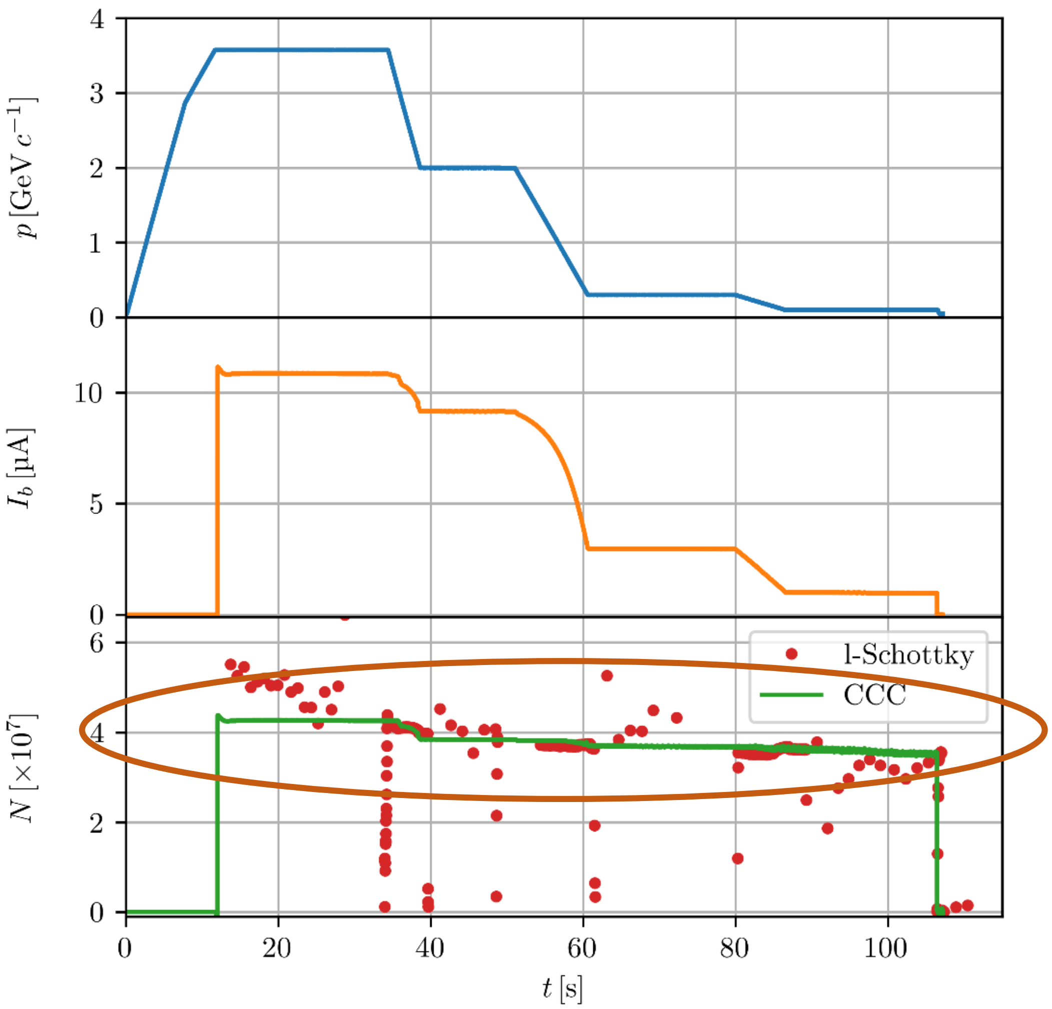
$$N = \frac{I_{\text{beam}}}{Q \cdot e \cdot f_{\text{rev}}}$$

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

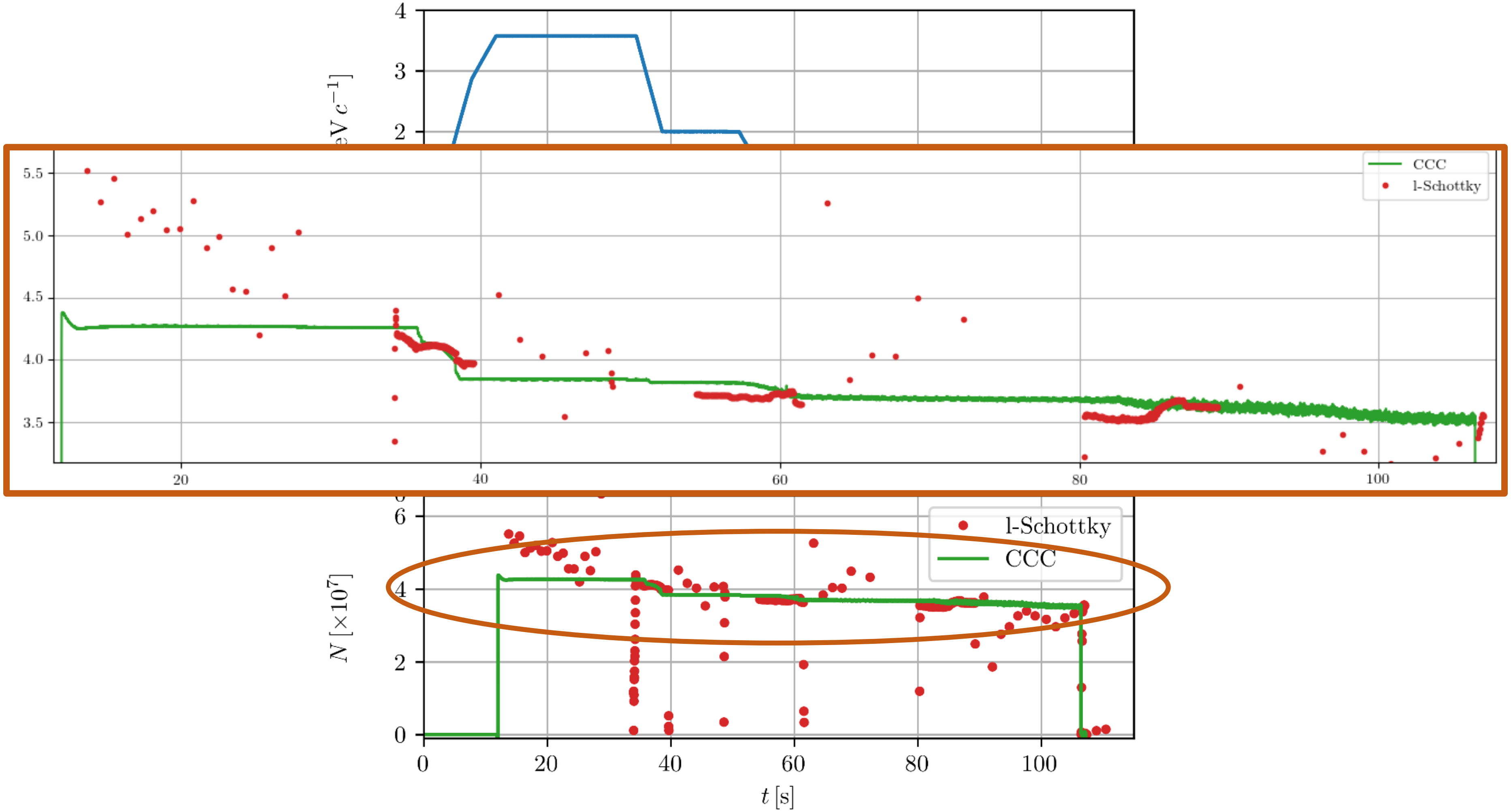
Comparison with Schottky monitor

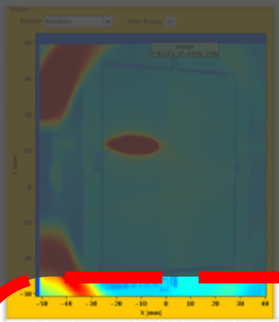


Comparison with Schottky monitor



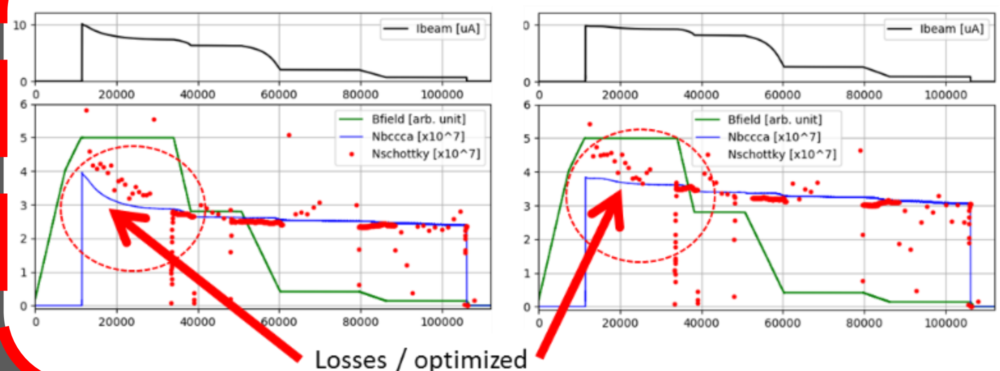
Comparison with Schottky monitor





BTVs

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

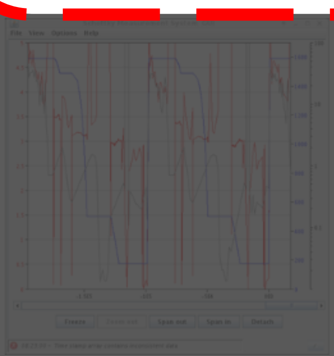


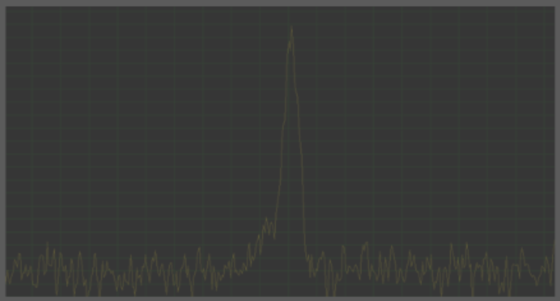
BCCCA

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!





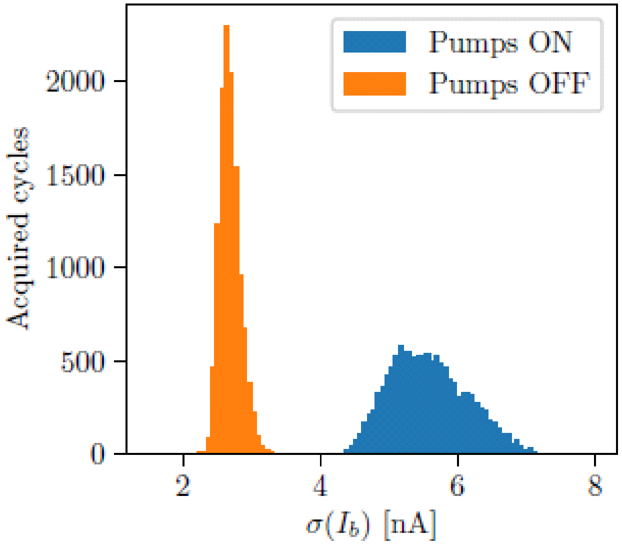
Shottky

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

Performance analysis

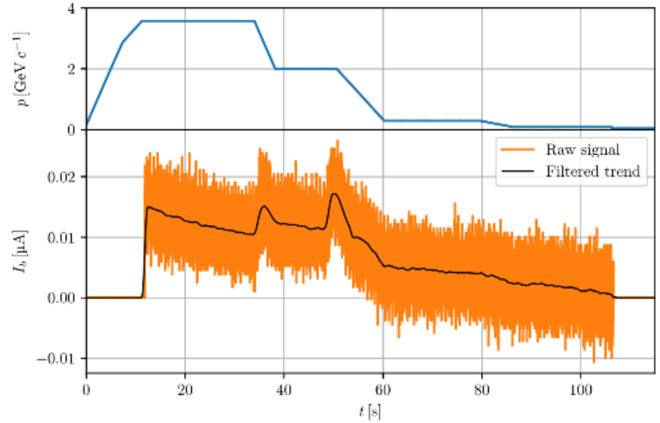
- Measurement resolution
- Computed as the signal standard deviation in 1s interval
- Analysis of ~25000 cycles
- With cryostat insulation vacuum pumps on/off
- Corresponds to resolution in terms of number of particles of:
  - N = (1-3) x 10^4 at <u>injection energy</u>
  - N = (1-3) x 10^5 at <u>ejection energy</u>

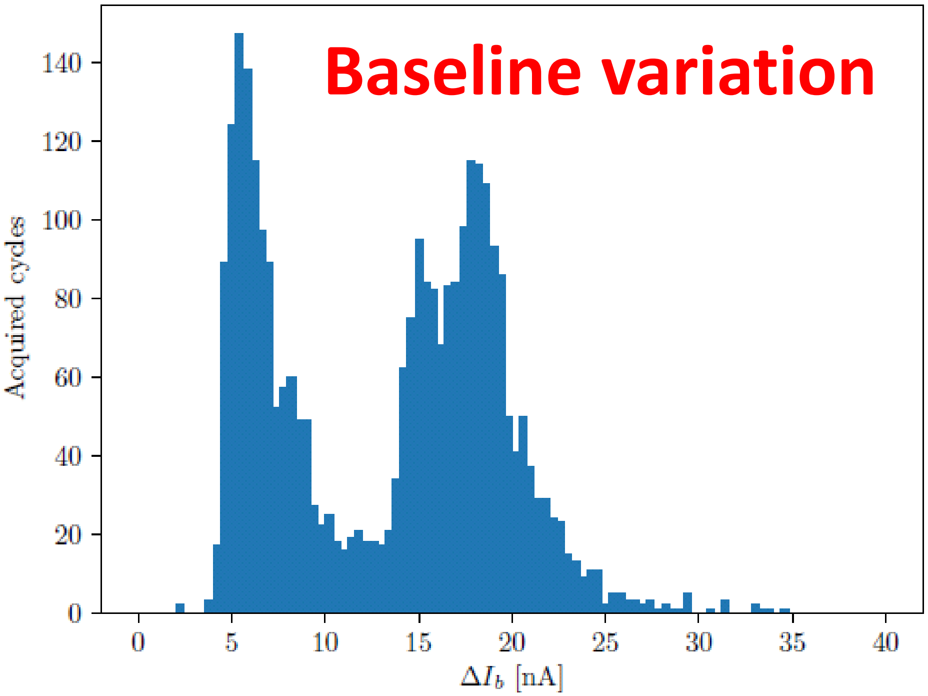
Current resolution



Performance analysis

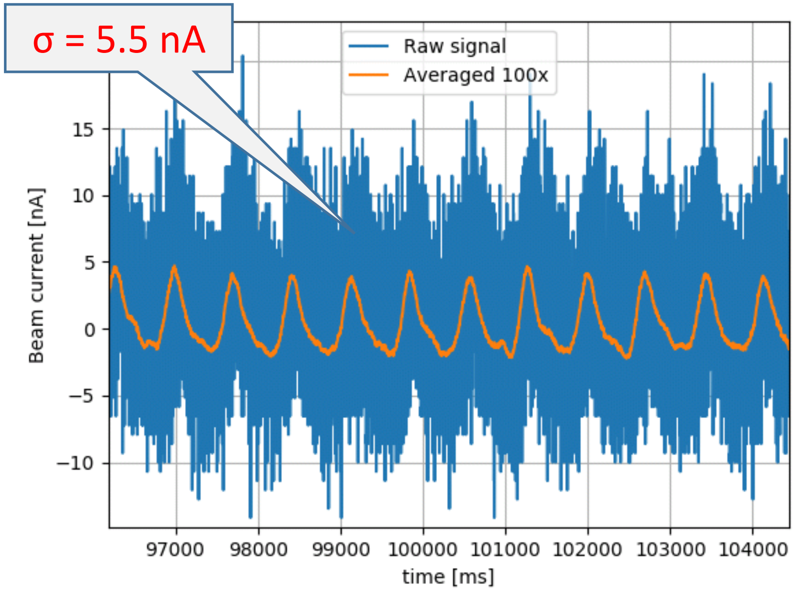
- Slower baseline drifts are dominant measurement error
- These are mainly caused by helium gas pressure variations
- Additionally perturbation induced by cycling the acccelerator
- Baseline drift obtained from cycles with no injected beam



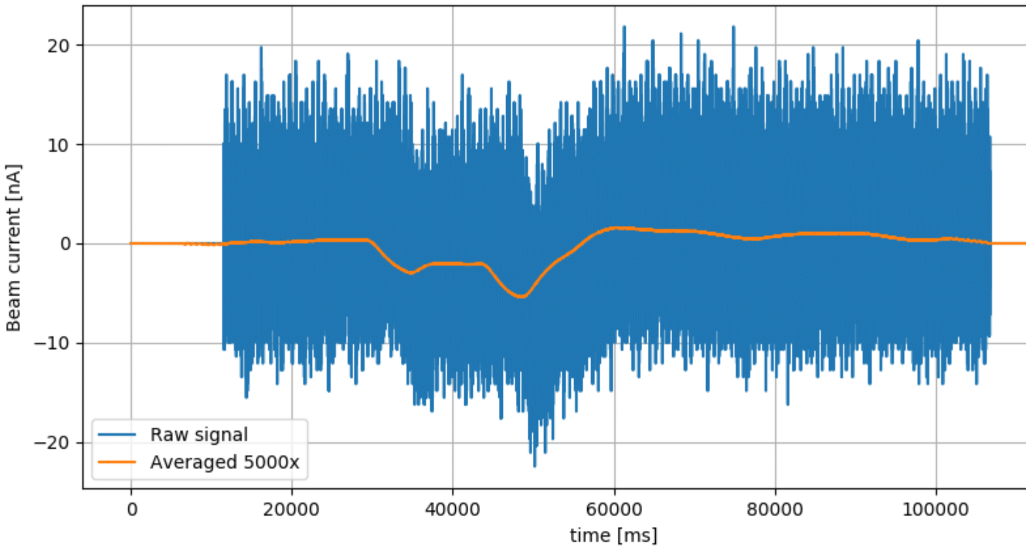


Extra: Noise performance improvements

Perturbation from cryocooler



Perturbation from magnetic cycle



Conclusions

- Measurement noise performance under initial specification
- Able to stably cope with AD bunched beams (except at 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 with FESA class and 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**

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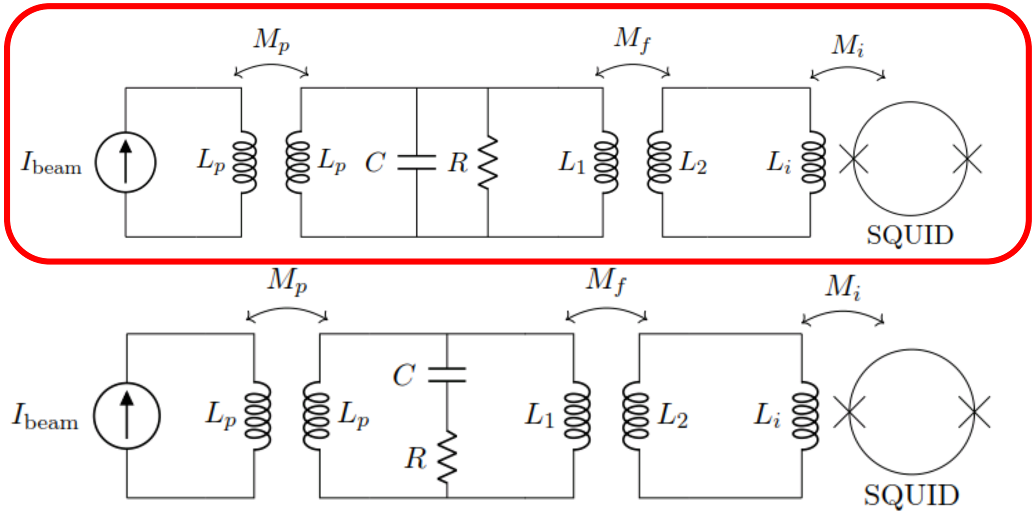
R. Geithner; R. Neubert , J. Golm

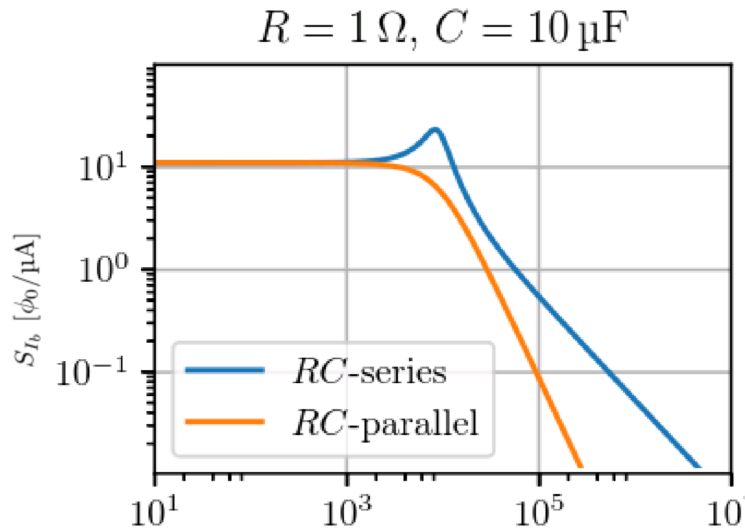
C. Welsch

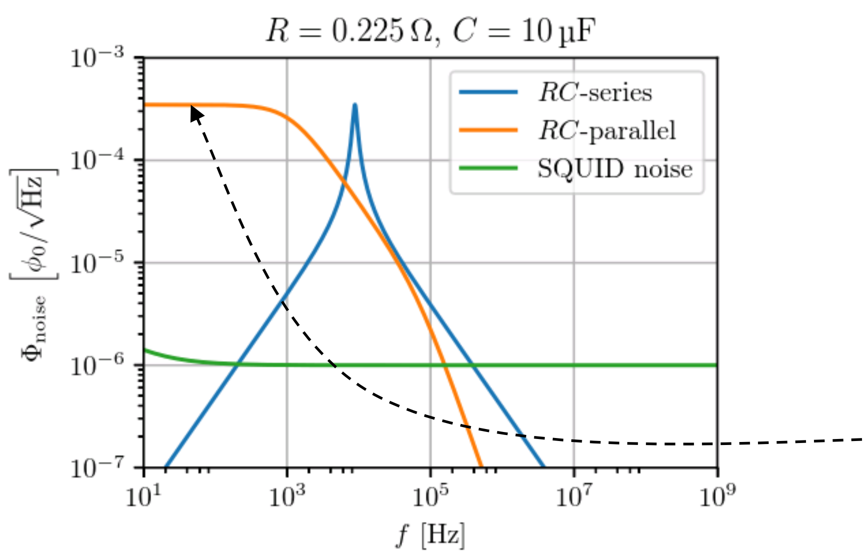
Thank you for your attention!

Backup

Coupling circuit low-pass filter





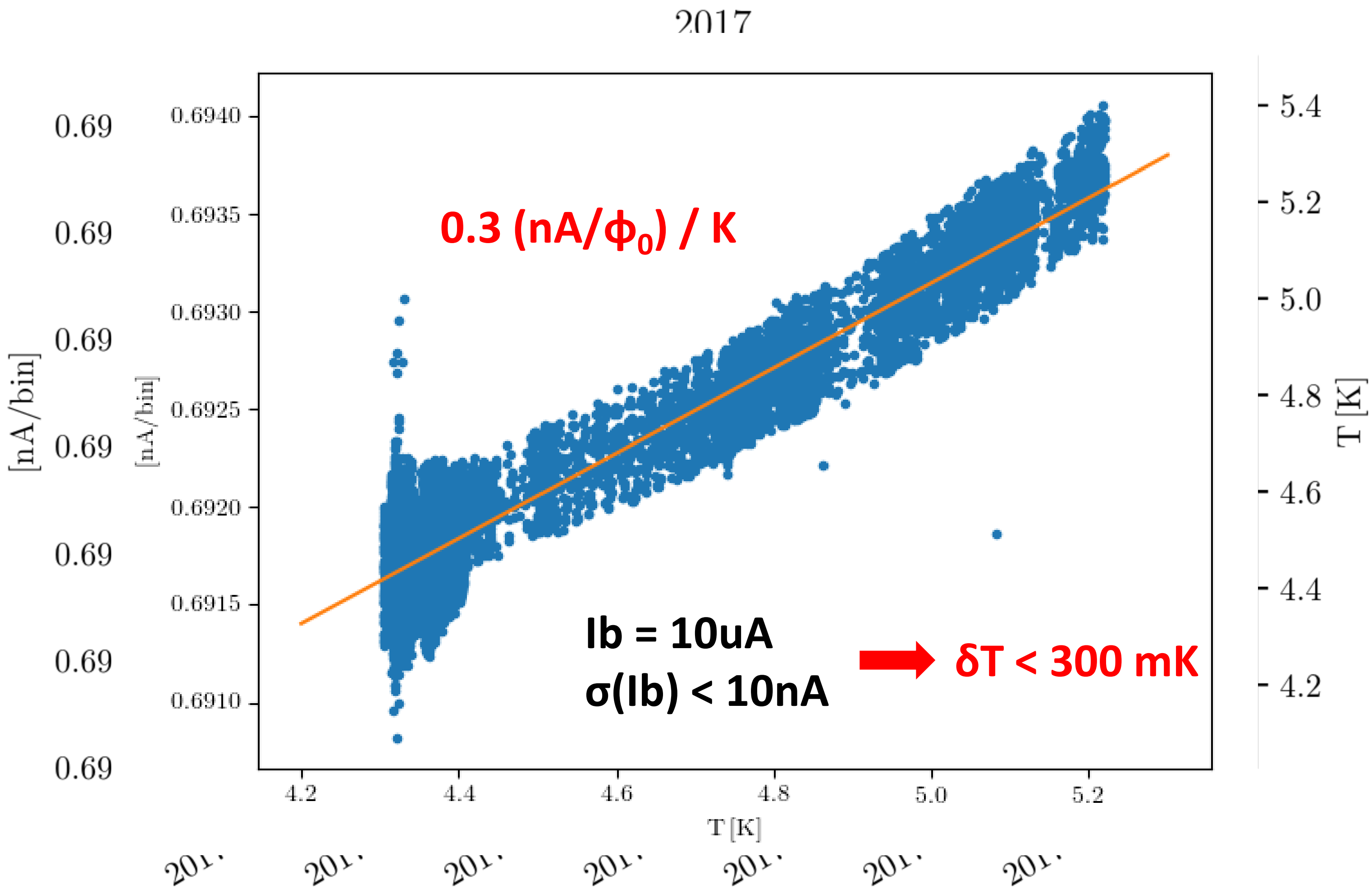


Filtering	Slew-rate
Core permeability + RC-parallel	0.97 $M\phi_0/s$

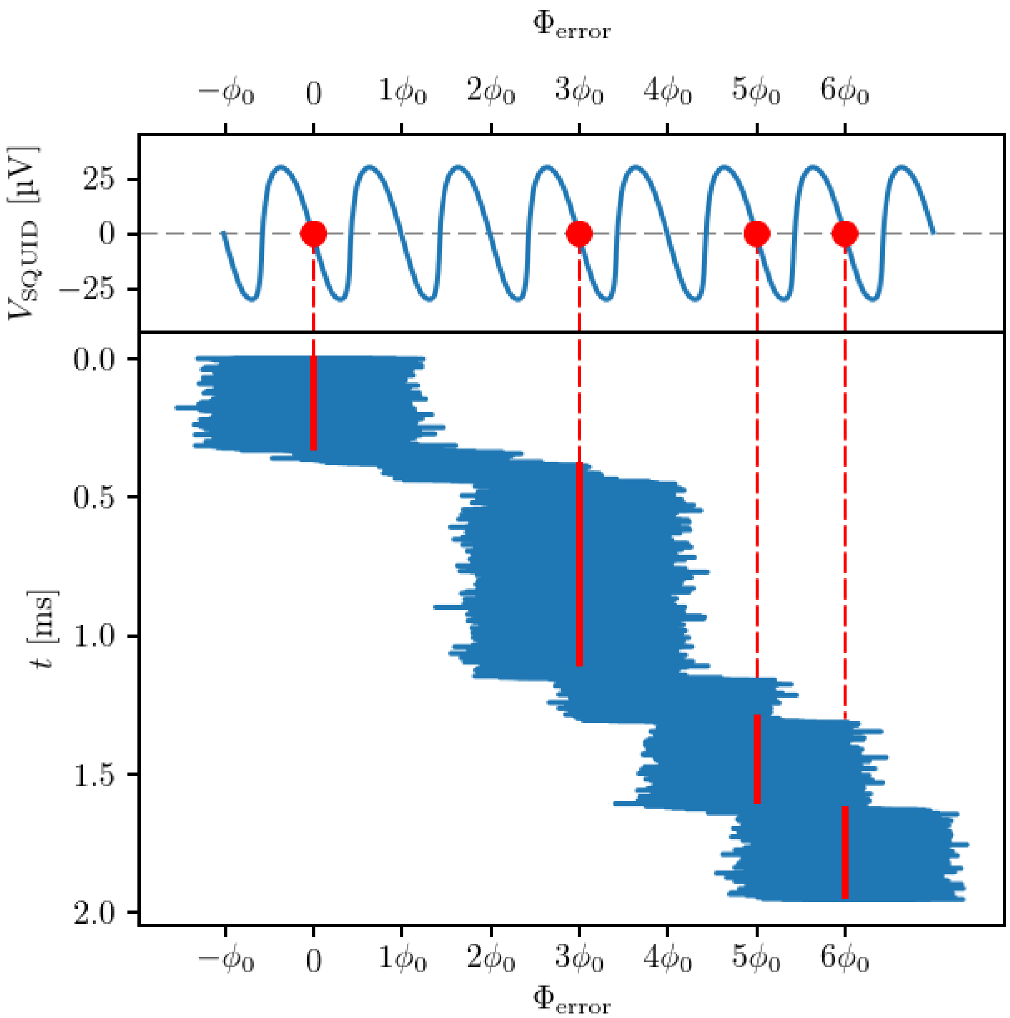
Additional flux noise at low freq:

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

Calibration vs. Temperature

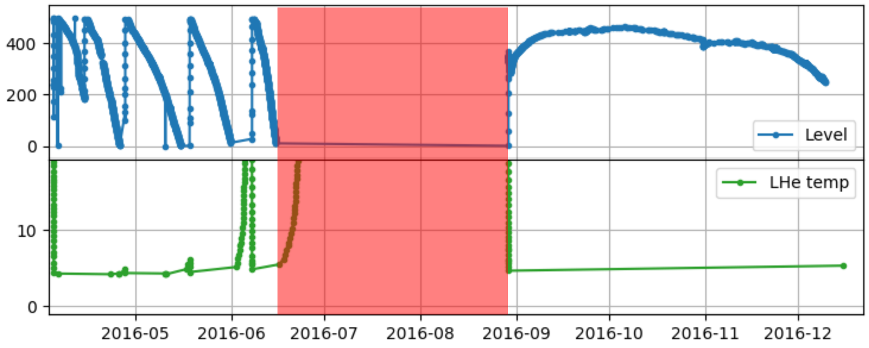


Flux jumps



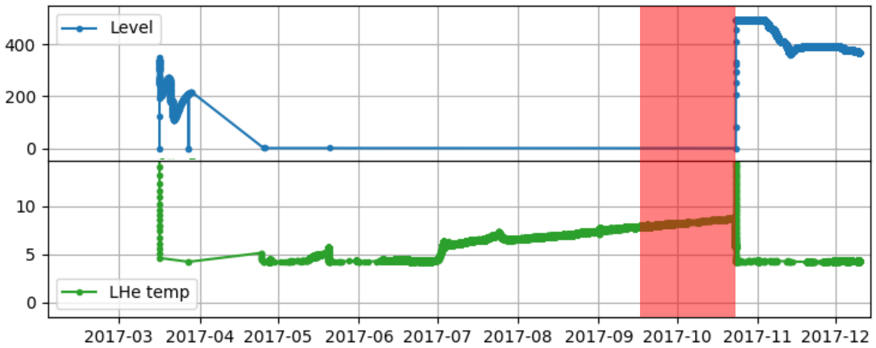
Φ_{error}
$-\phi_0$ 0 $1\phi_0$ $2\phi_0$ $3\phi_0$ $4\phi_0$ $5\phi_0$ $6\phi_0$
V_{SQUID} [µV]
25
0
−25
t [ms]
0.0
0.5
1.0
1.5
2.0
$-\phi_0$ 0 $1\phi_0$ $2\phi_0$ $3\phi_0$ $4\phi_0$ $5\phi_0$ $6\phi_0$
Φ_{error}

Cryogenic availability



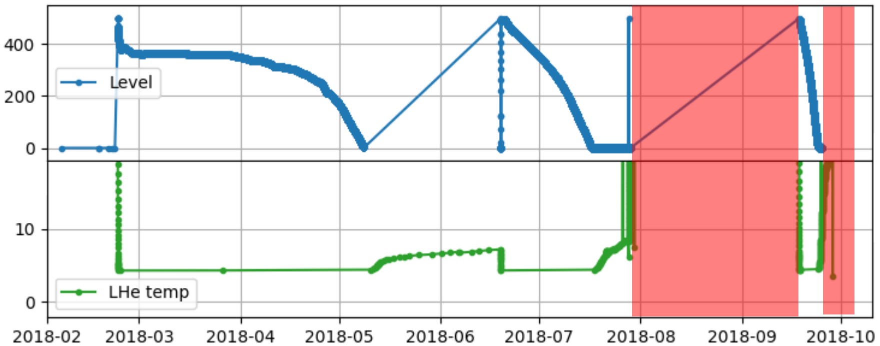
2016

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



2017

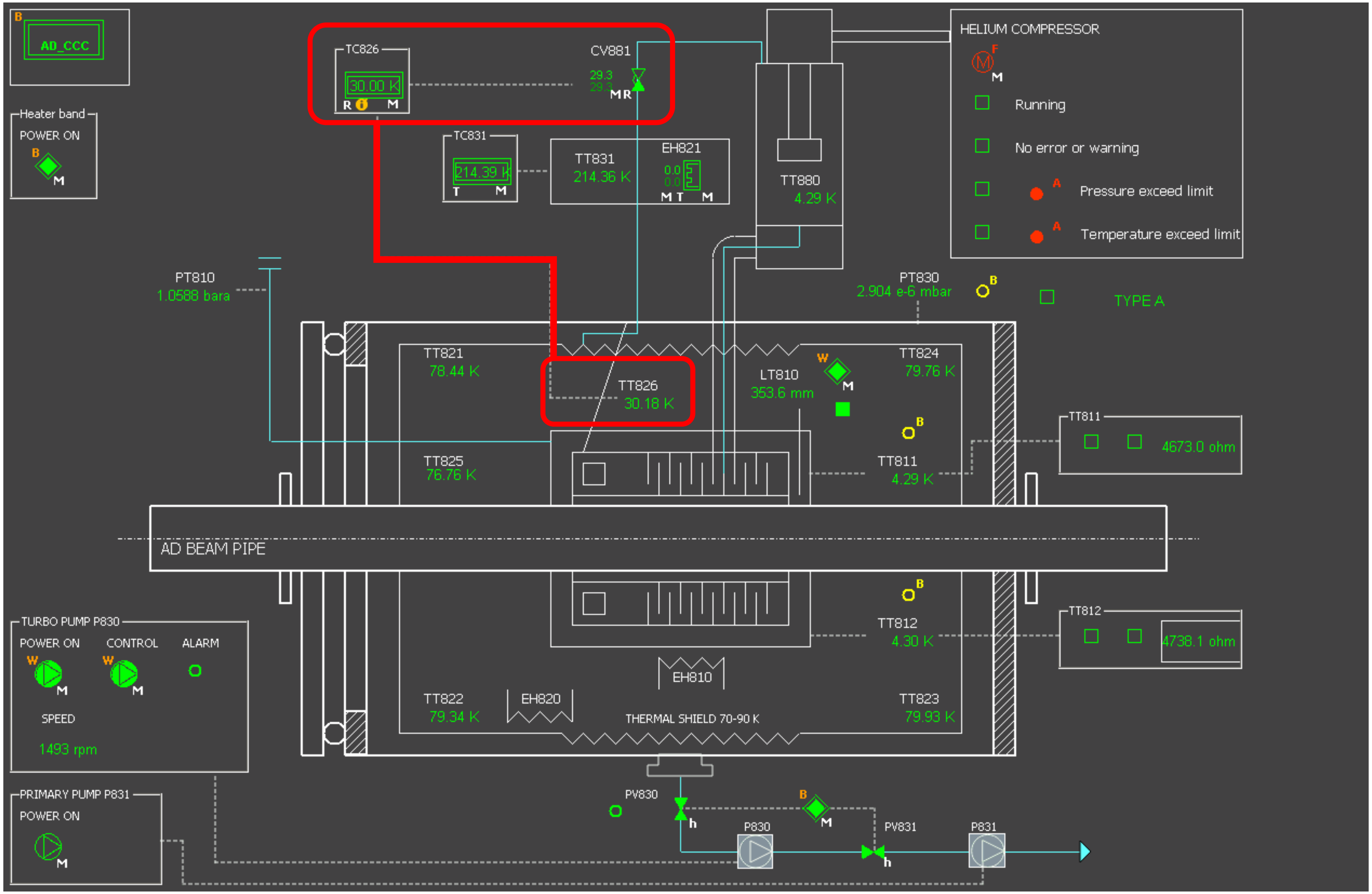
- Power glitch stopped turbo pump that compromised vacum
- Still possible to work with gas
- ~1 month unavailable



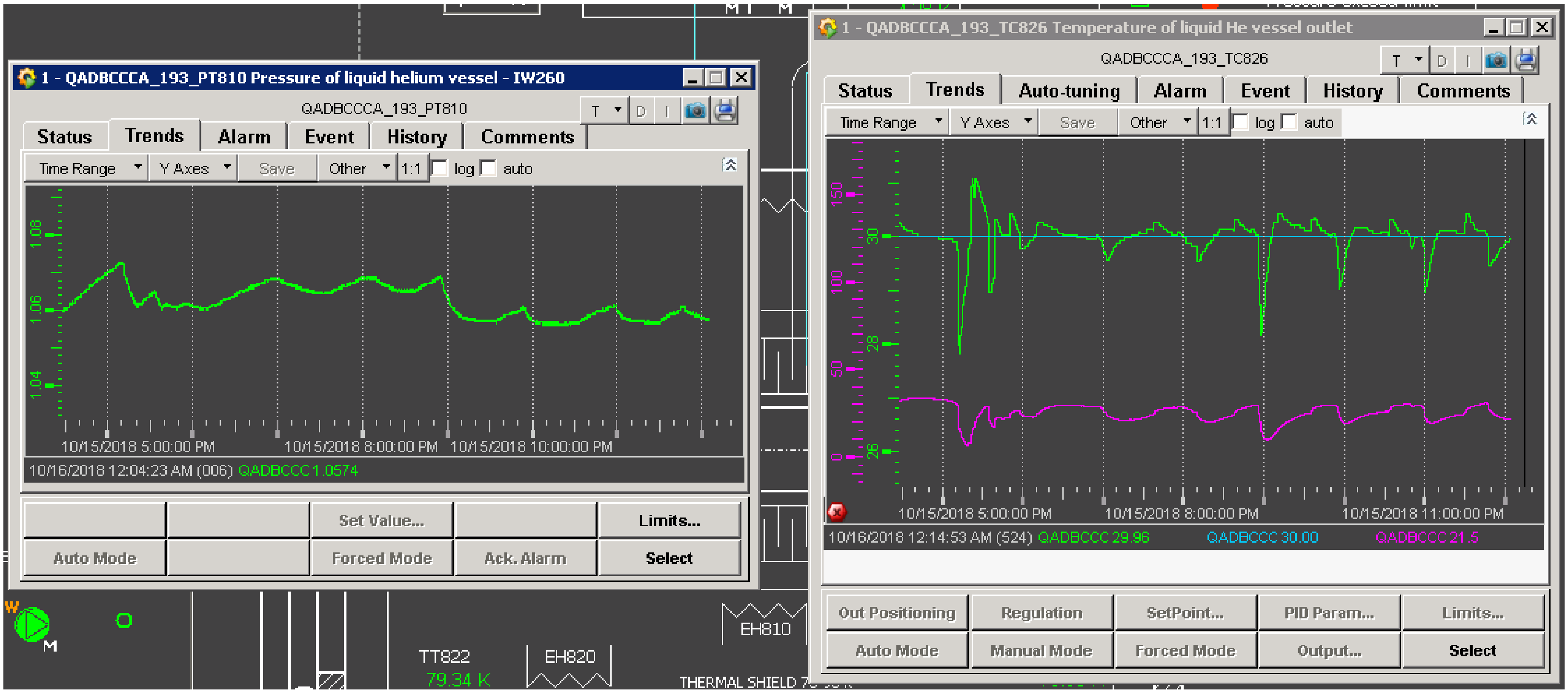
2018

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

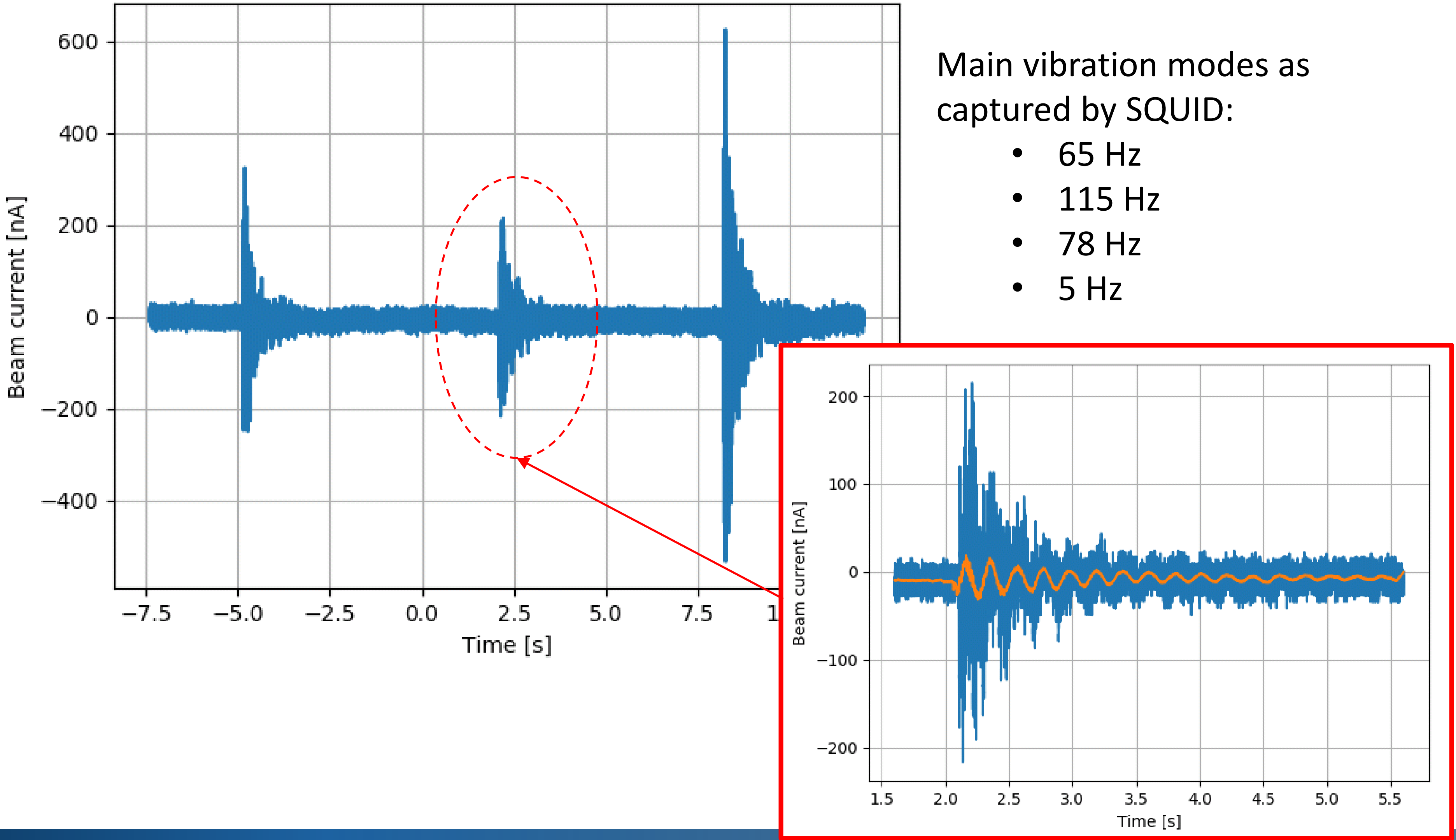
Stabilize cryostat operation



Stabilize cryostat pressure



Immunity to mechanical vibrations



Main vibration modes as captured by SQUID:

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