A Cryogenic Current Comparator for the AD

Miguel Fernandes (BI-PI)

CERN BI day

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Archamps, France
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Outline

1. Motivation for a Cryogenic Current Monitor
2. Cryogenic Current Comparator (CCC) principle
3. New CCC in the AD
   - Magnetic shielding
   - Expected current resolution
   - SQUID measurements and dynamic limitations
4. Summary & Outlook

Existing current monitors

<u>DCCT</u>:

Insufficient resolution for the low current (low β,N) regime.

<u>Fast BCTs</u>:

Limited to bunched phases

<u>L-Schottky</u>:

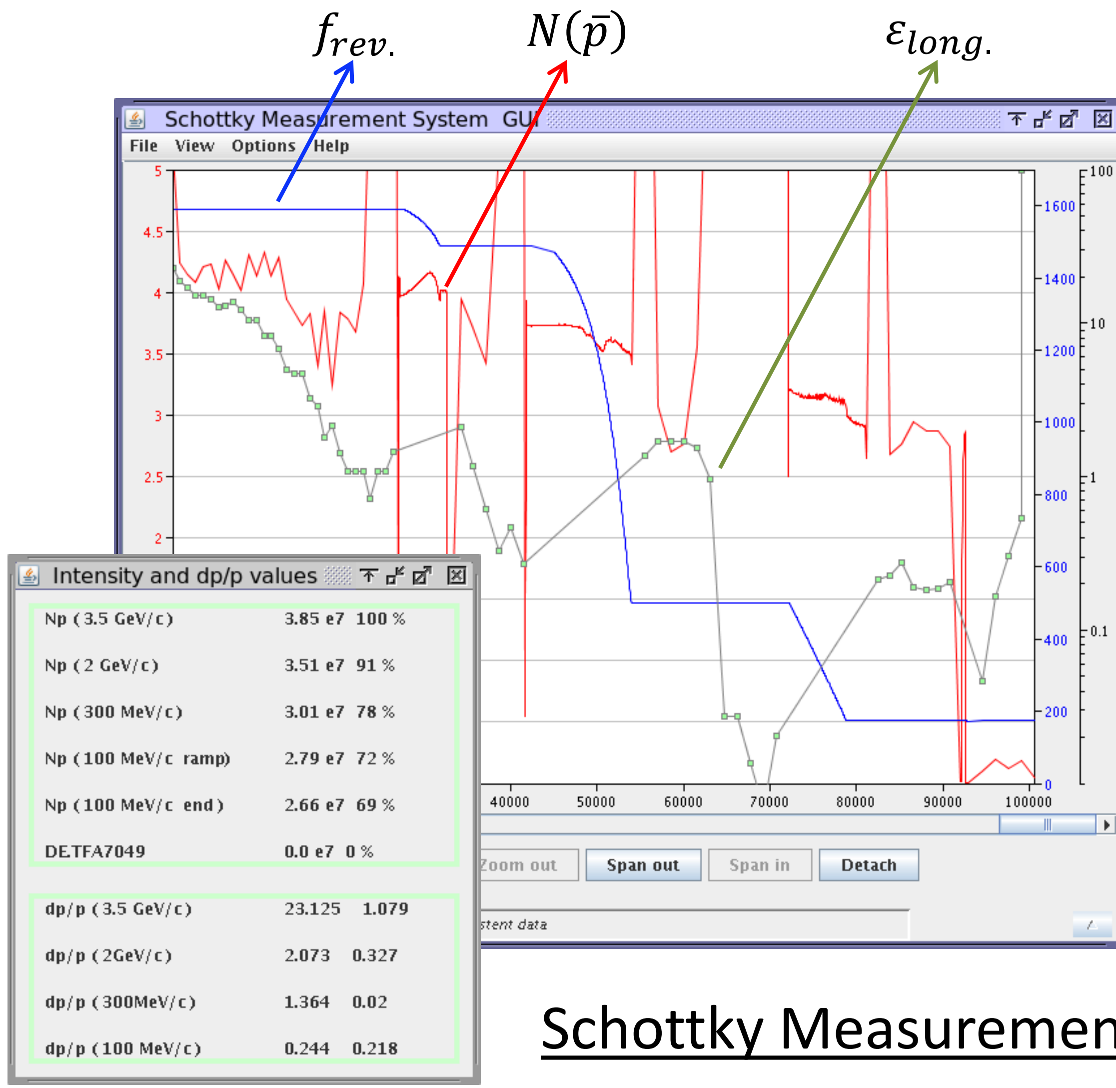
Bunched:

- time resolution of 20 ms
- accuracy error of <10%

Un-bunched:

- time resolution of 200 ms
- accuracy error > 10%

Complex calibration process



<u>Schottky Measurements</u>

Motivation for new monitor

Cryogenic Current Comparator

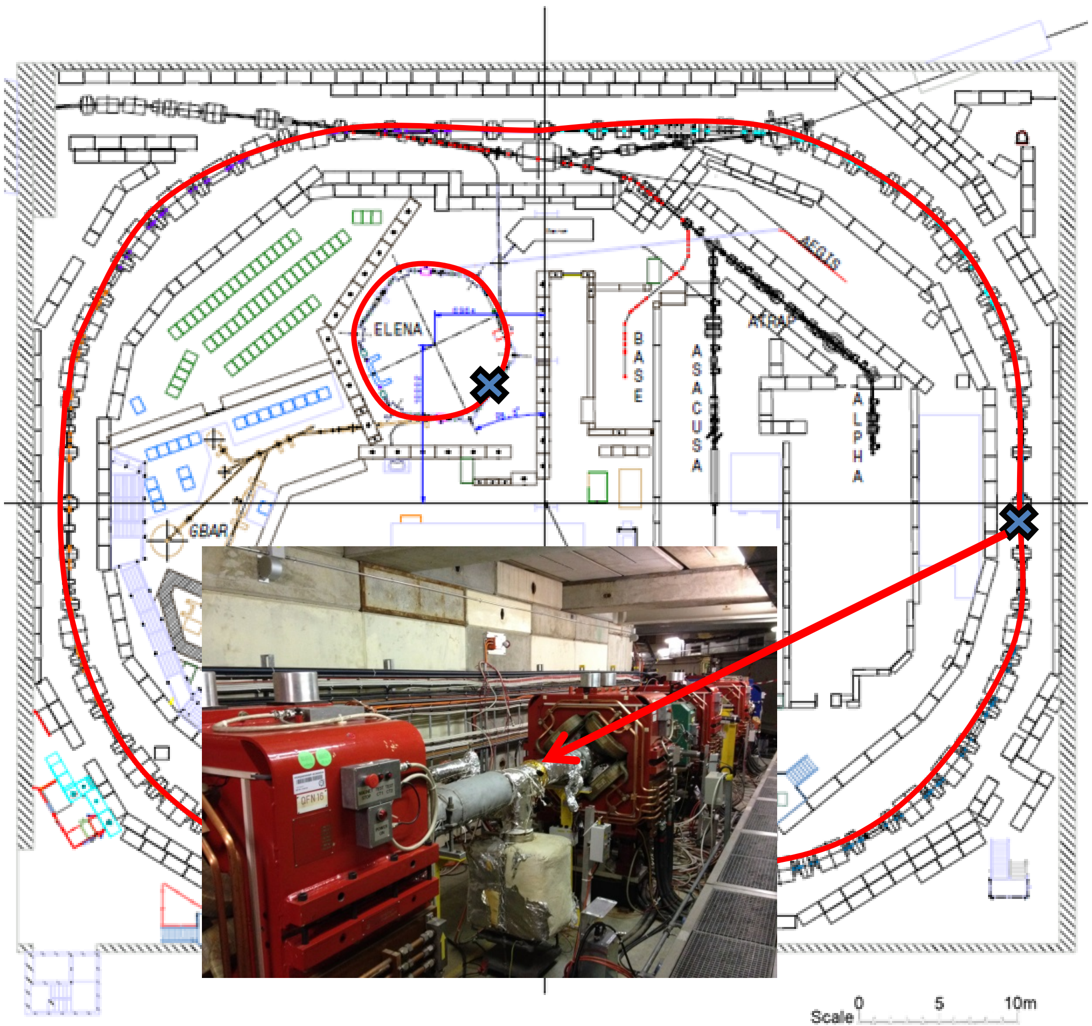
Why go cryogenic for a current monitor?

- Non-destructive measurements of charged beams current
- Current resolution of the order of **nA**
- In a frequency range from DC to several kHz
- Independency of beam shape, trajectory and energy
- Exact absolute calibration using an additional wire loop

First implementation as a particle current monitor done at GSI

- 6 new CCC monitors are planned to be installed in future FAIR complex
- Project developed in collaboration with GSI, Jena University and Helmholtz Institute Jena

Monitor specifications

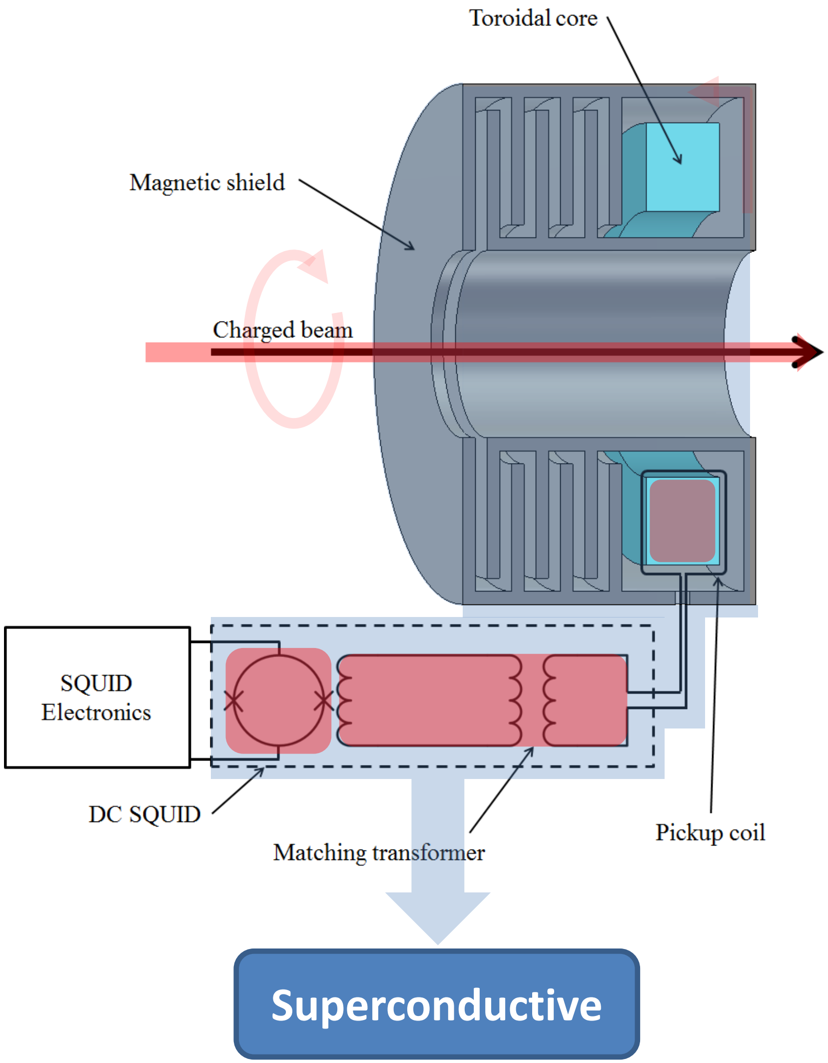


AD	
Beta	0.97 … 0.11
Machine cycle	85 s (**DC and bunched**)
N particles	(5 … 1) x 10^7
DC current range	**(12 … 0.3) µA**
Aperture	160 mm (→ 100mm)

Resolution: < 10 nA
Accuracy: < 5%
Bandwidth: dc … ~1kHz

Working principle

Components



Magnetic shielding:
- Suppress all field components except the azimuthal component

Pickup core
- Soft ferromagnetic material with high-permeability
- Single turn pickup coil

DC Flux transformer
- Couples magnetic flux to SQUID
- Works from DC – high frequencies

SQUID* + Electronics
- Measures current in pickup coil

Field from AD beam current:

Distance: 100 mm
Current: 12 … 0.3 µA
B_θ field: 18.5 … 0.6 pT

B_{Earth} = 50 µT

*SQUID: Superconductive QUantum Interference Device

Working principle

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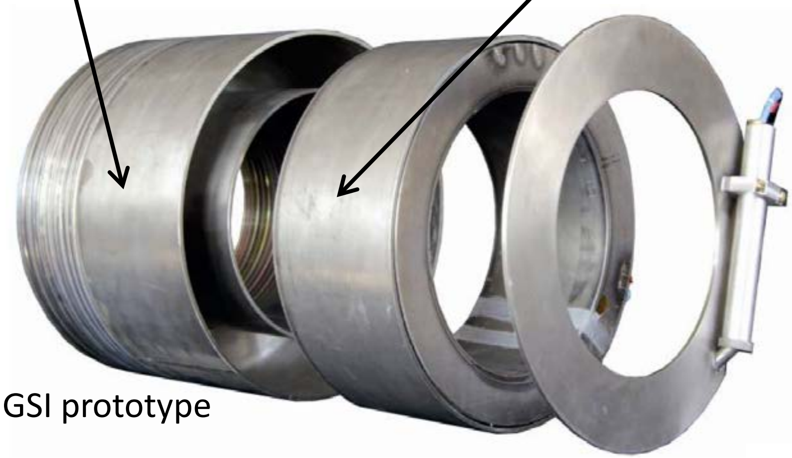
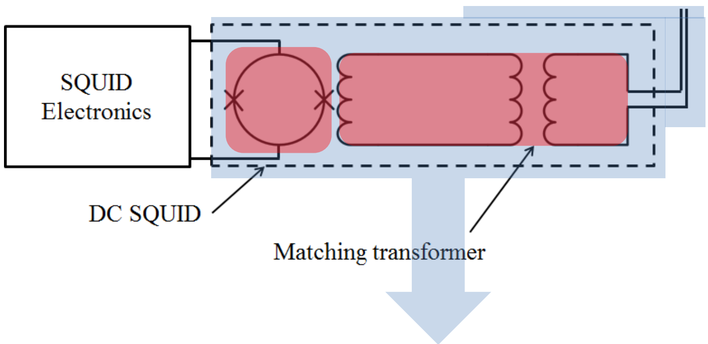


* GSI prototype



Superconductive

Field from AD beam current:

Distance: 100 mm

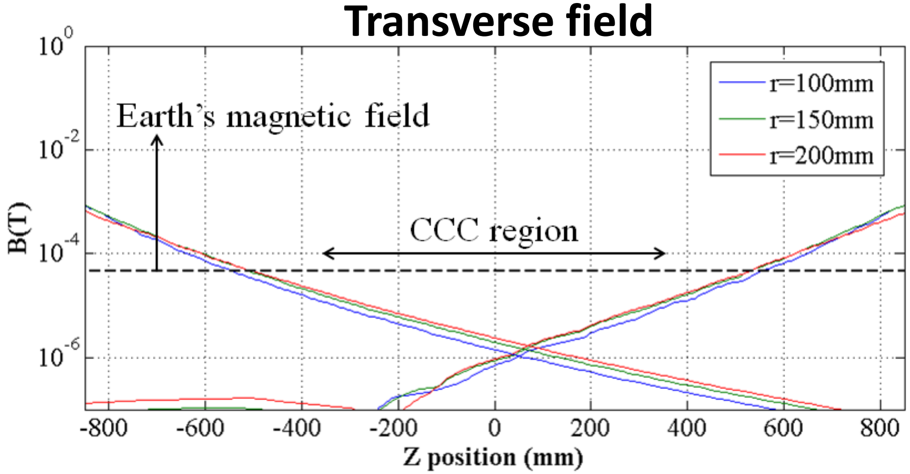
Current: 12 … 0.3 µA

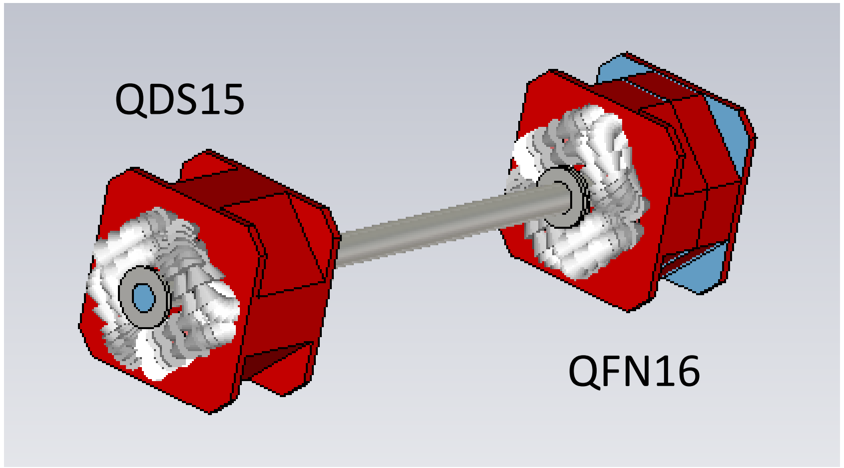
B_θ field: 18.5 … 0.6 pT

B_{earth} = 50 µT

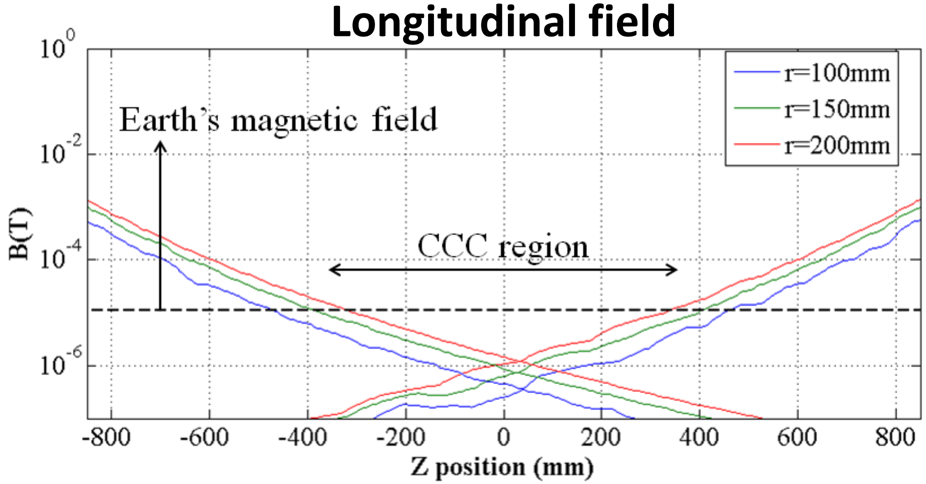
AD: magnetic environment

Transverse field





Longitudinal field

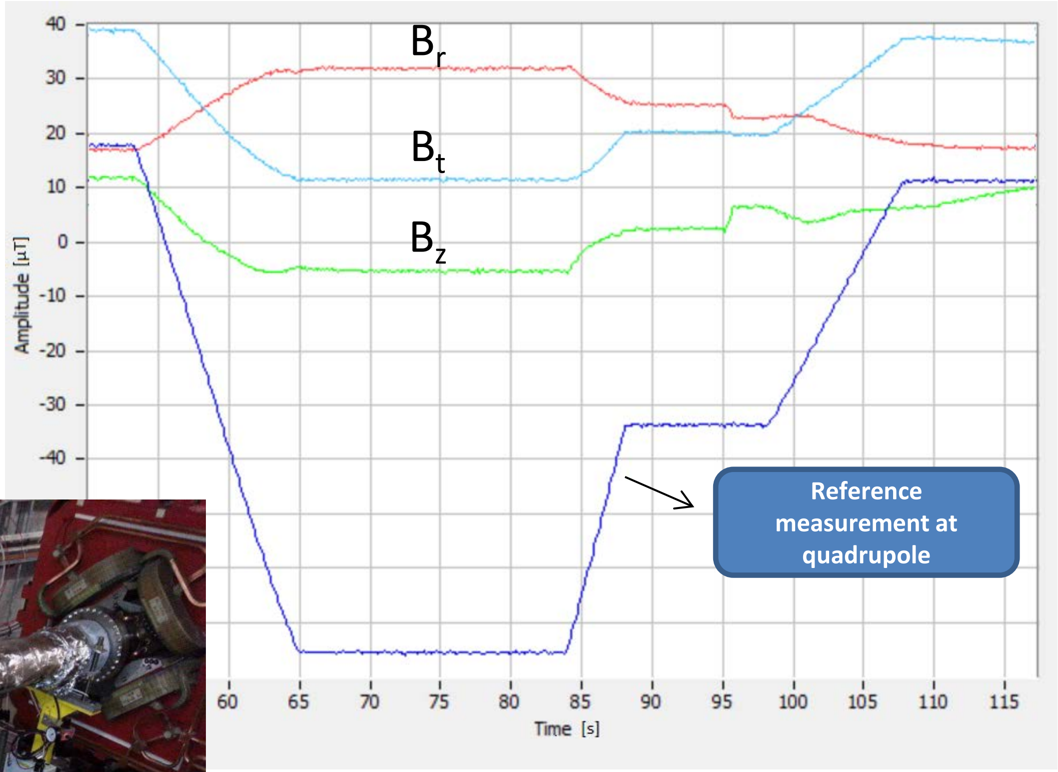


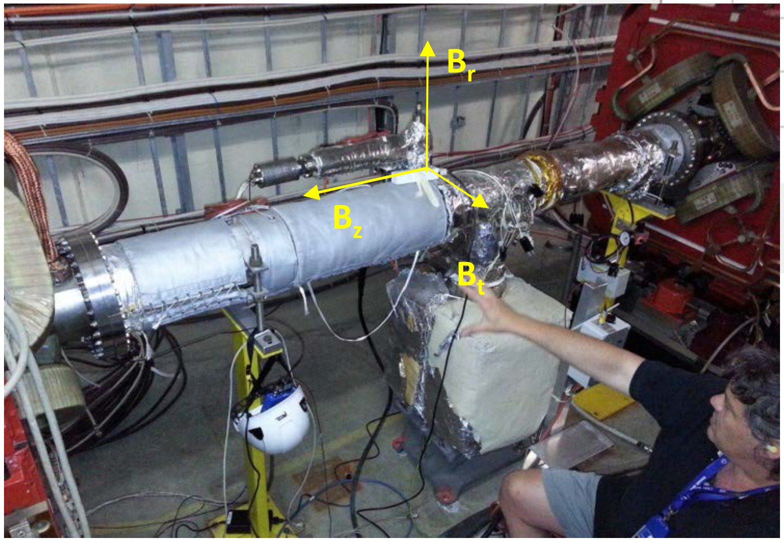
- Only 2 closest quadrupoles were considered
- Maximum magnet current was considered
- Field obtained in longitudinal plane of maximum field

$|z|<300$ mm → $|B_{stray}| < |B_{Earth}|$

AD: magnetic environment

- Measurement of magnetic field in location previewed for CCC
- Magnets following AD cycle
- Measured fields are not significant



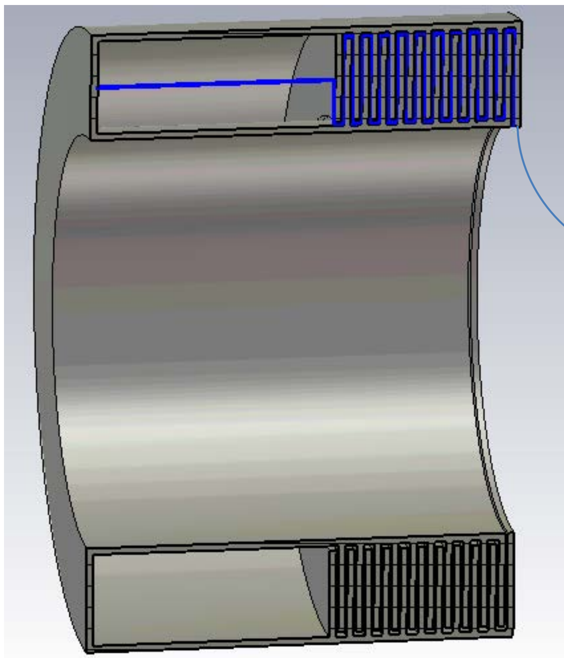


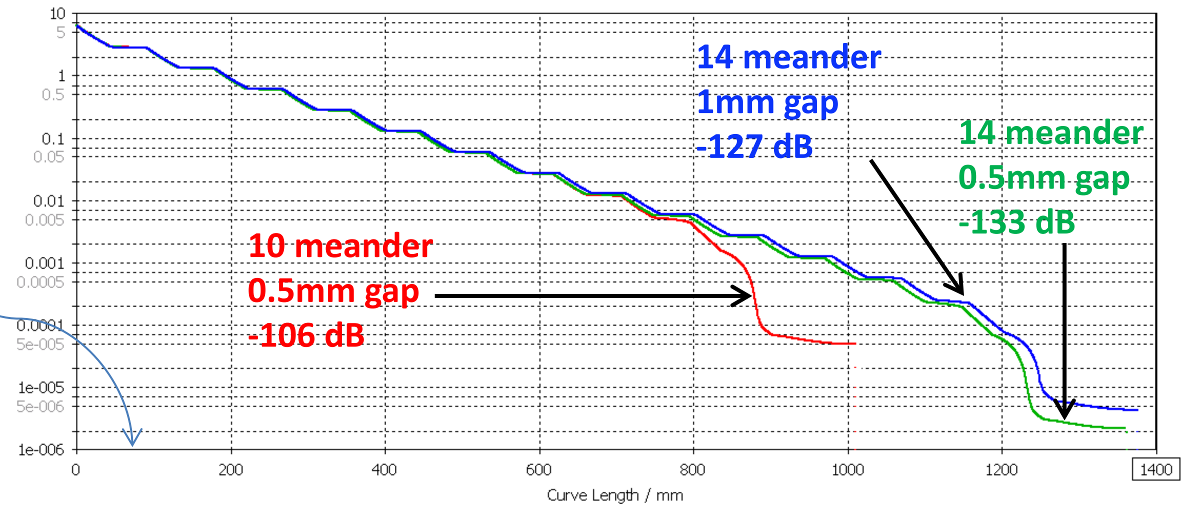
*Courtesy of Marco Buzio

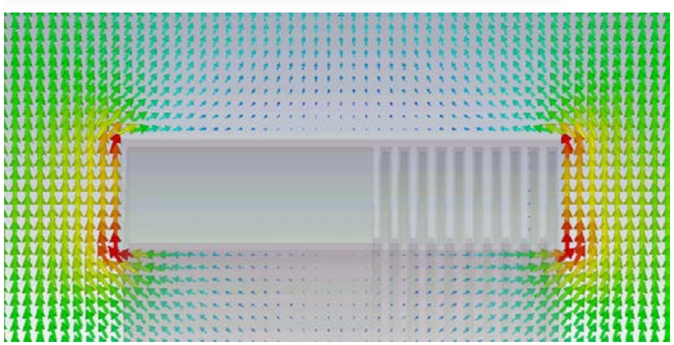
Probe:

Bartington MAG 03S-1000 fluxgate

Magnetic shielding







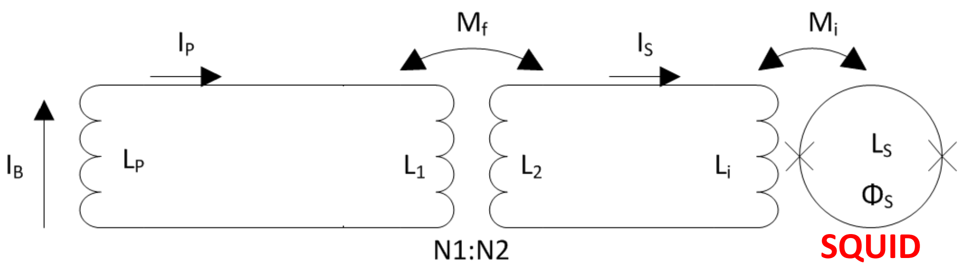
- Number of meanders is the dominant factor to total attenuation
- Magnetic field:
  - Earth: 50 μT;
  - Signal: $\sim pT$

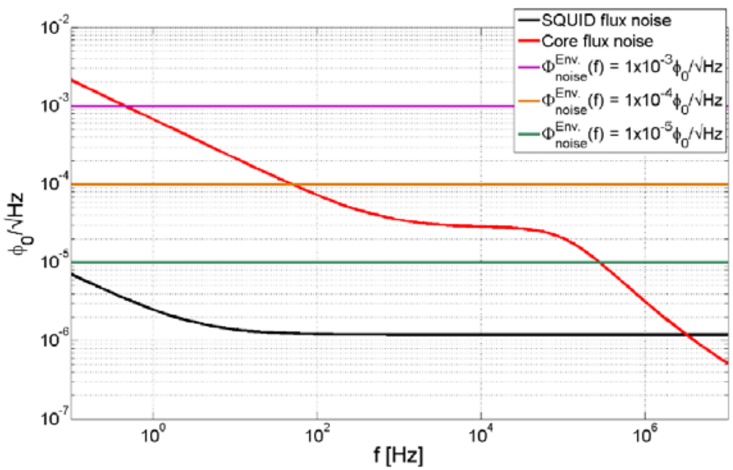
$$A_{tt} \geq \sim 120\ dB$$

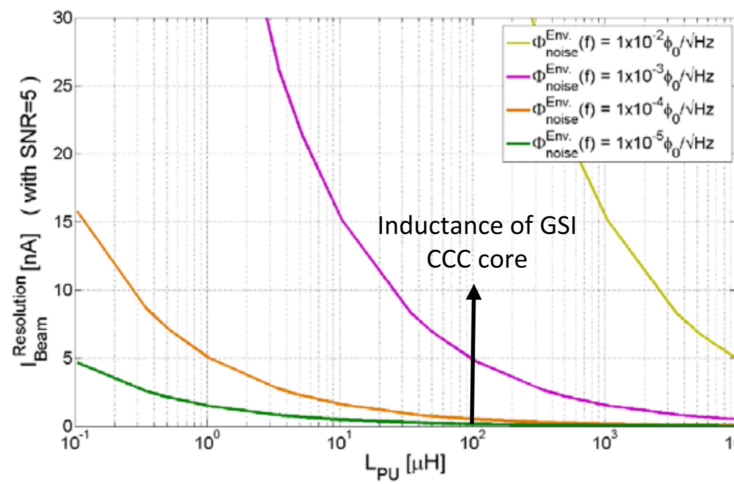
- Coupling strength to magnetic core of magnetic field from beam is much higher than for other modes

Current resolution

- Expected noise limited current resolution:
  - SQUID intrinsic noise (Magnicon)
  - Ferromagnetic core noise (Nanoperm)
  - Environmental noise





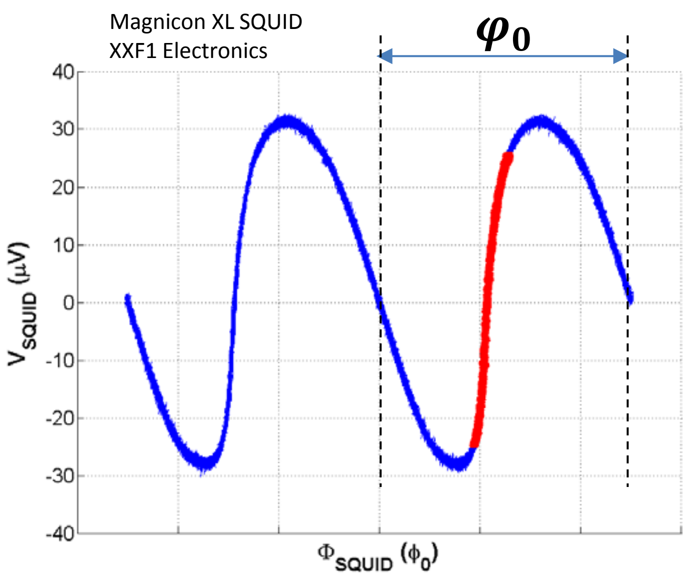


- A high beam current signal coupling is desirable to increase resolution (SNR):
  - High pickup inductance
  - Optimal inductance matching
  - Low-noise ferromagnetic core materials

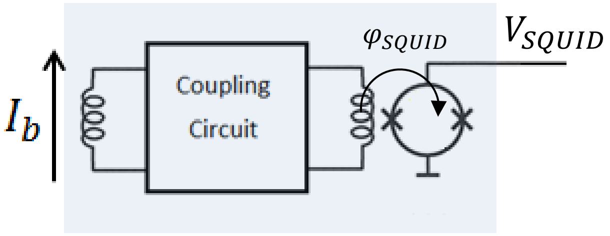
SQUID measurements

- SQUID's are very sensitive magnetometers:
  - Noise figures as low as $\sim 1\, \mu\boldsymbol{\varphi}_0/\sqrt{Hz}$
  - Sensitivity $\frac{\partial V}{\partial \varphi} \sim 700\ \mu V/\boldsymbol{\varphi}_0$

$$\boldsymbol{\varphi_0 = 2.07 \times 10^{-15}\ [T.m^2]}$$



- Periodic transfer function limits its dynamic range



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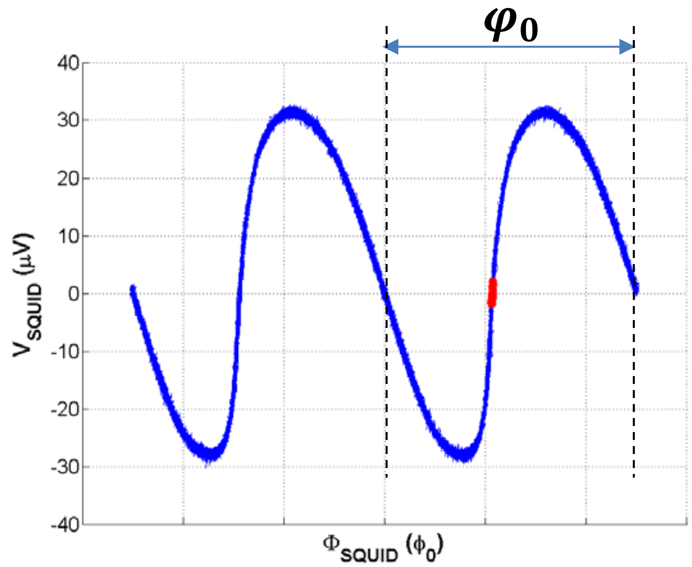
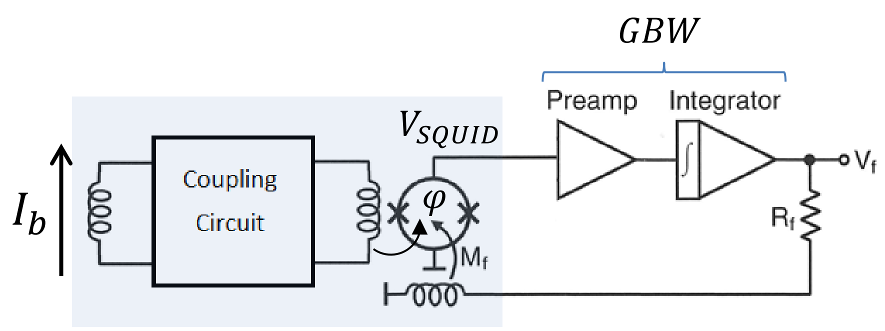
- Periodic transfer function limits its dynamic range
- Feedback loop is used to linearize response – **Flux Lock Mode (FLL)**
- Gain and bandwidth of FLL loop depend on V_{SQUID}, GBW and R_f





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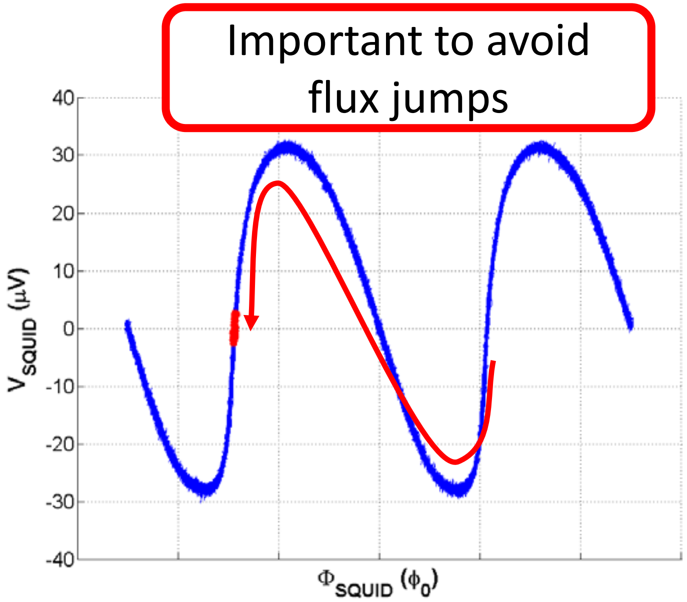

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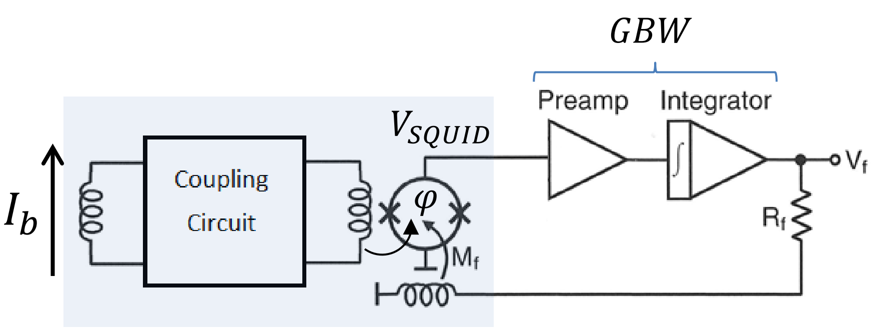


- Gain and bandwidth of FLL loop depend on V_{SQUID}, GBW and R_f

SQUID dynamic limits

Flux-jumps may occur due to:

- High slew-rate of input signal → Increase bandwidth
- Excessive noise → decrease bandwidth

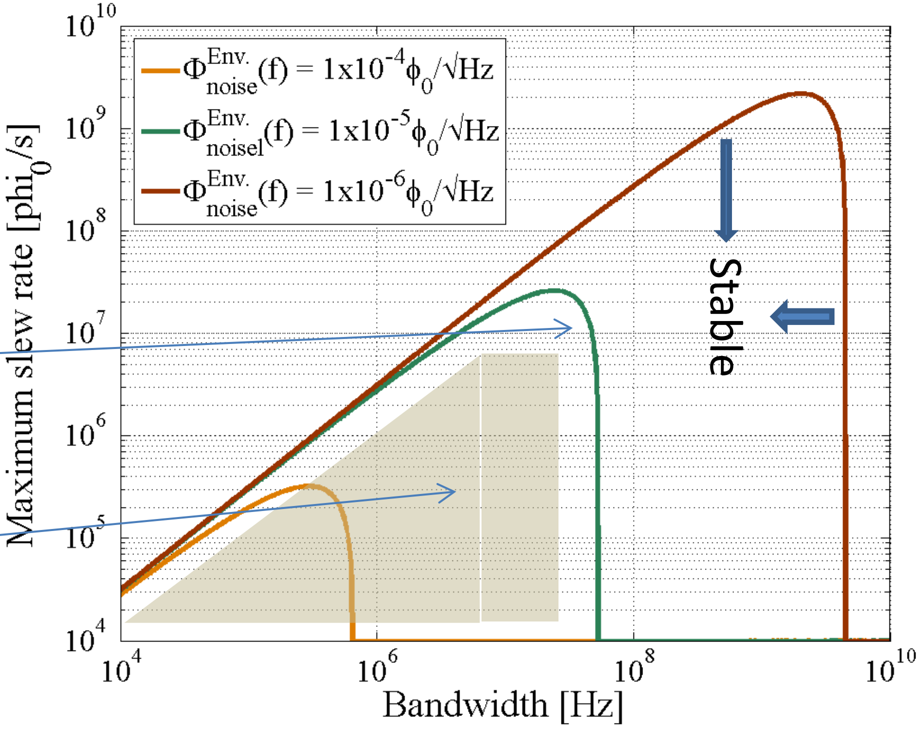
Noise level of recent GSI installation:

- With older CCC shield and core material

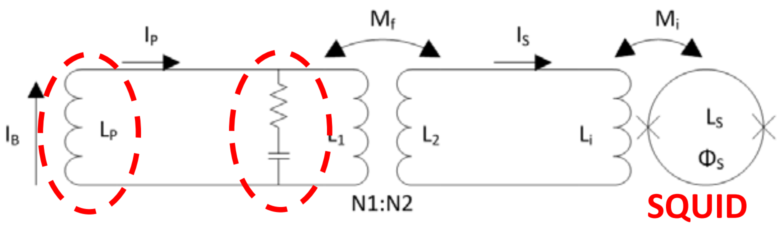
SQUID dynamic limits:

- Bandwidth of FLL system: $< \mathbf{20\ MHz}$
- Slew-rate of input signal flux: $< \mathbf{5\ \varphi_0/\mu s}$

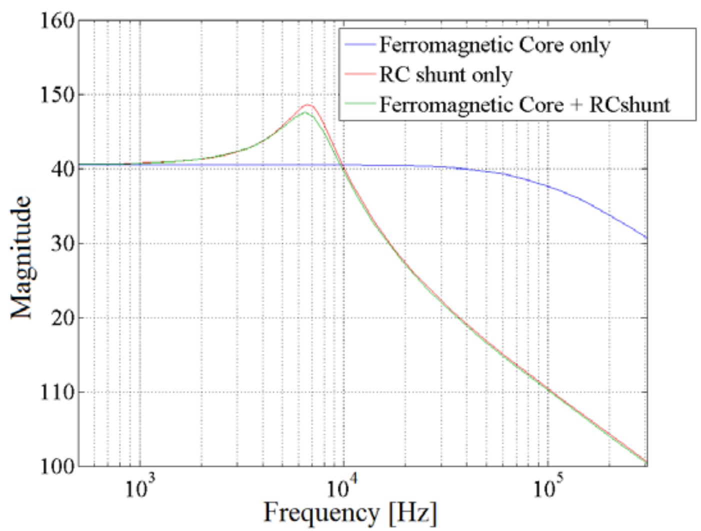
Flux-jump rate: 1/hour



AD injection

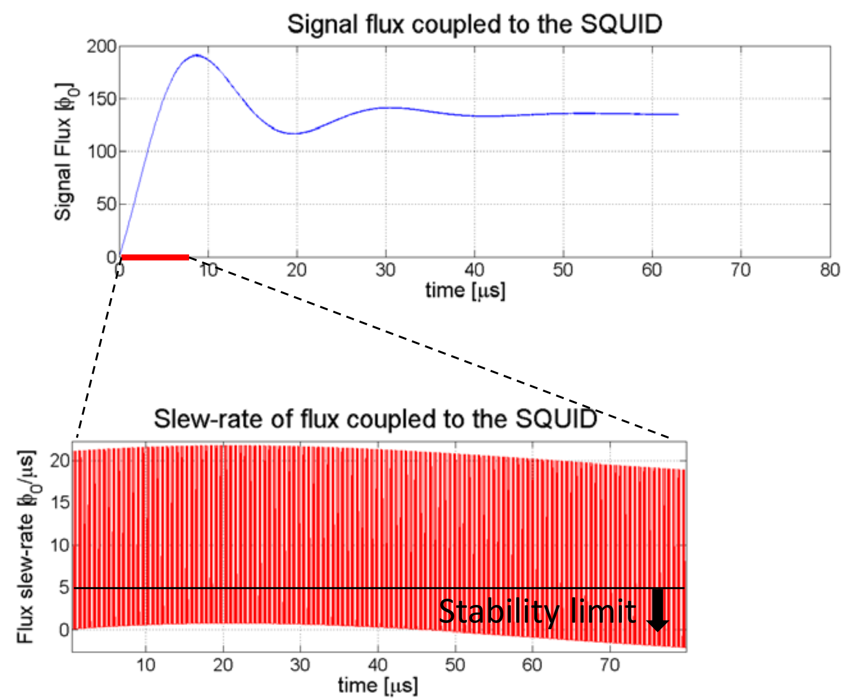


RC-shunt
(R = 1Ω, C = 10μF)

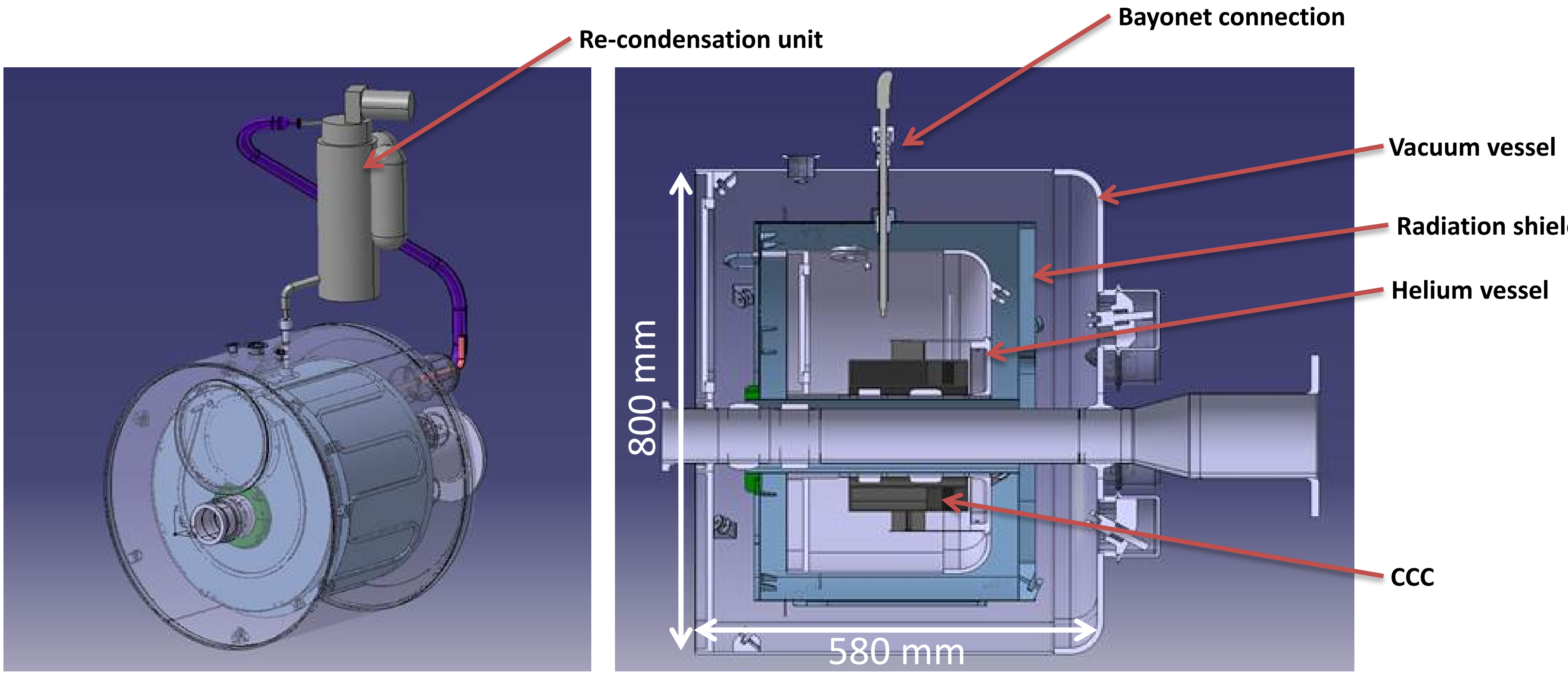


Beam parameters (highest slew-rate):

- I_{av} = 12 μA
- $4\sigma_l$ = 30 ns
- T_{sep} = 105 ns
- h = 6 (4 bunches)



Cryostat design



- Close cycle operation using LHe re-condensing unit Cryomech PT415:
  - Liquification rate: ≥ 27 l/day (from cold gas) equivalent to > 0.81 W
  - First maintenance after 20.000 hours of operation cycle; three years of warranty
- LHe vessel support was optimized for reduced heat in-leak and higher frequency of first vibrational mode

Summary

- AD and future ELENA would both profit from an improved beam intensity measurement diagnostic
- Low-temperature Superconductor Cryogenic Current Monitors are currently the only devices able to measure DC currents with **nA** resolution
- AD beam dynamic characteristics need to be taken into account to ensure proper operation of the CCC
- Cryostat design takes into requirement to have a autonomous operation, reduced mechanical vibrations, and temperature stability

Outlook

2014

- Start construction of cryostat that will take place at CERN
- Components with longer lead-times have been order: ceramic gaps; He re-condensing unit
- Measurement of frequency response of CCC (outside cryostat) at Jena University

2015

- Finish cryostat manufacturing
- Test of cryostat and CCC monitor in lab conditions
- Dead-line for installation in AD is June 2015
- CCC beam commissioning

Acknowledgements

- GSI: Febin Kurian, HansJoerg Reeg
- FSU / HI Jena: René Geithner, Ralf Neubert
- CERN: Jocelyn Tan, Lars Soby, Andrew John Lees, Torsten Koettig, Marco Buzio, Romain Ruffieux, Michal Krupa, Silvia Aguilera
- University of Liverpool: Carsten Welsch

Thank you for your attention!

References:

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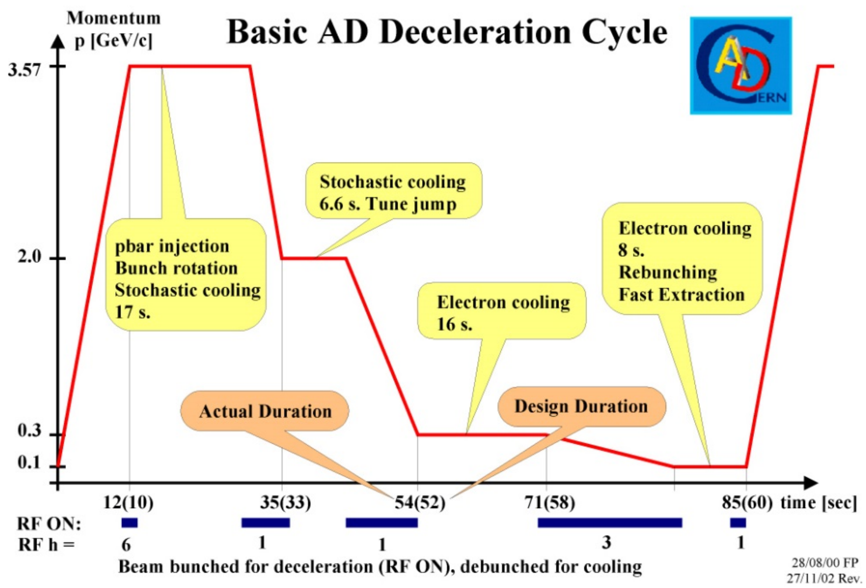
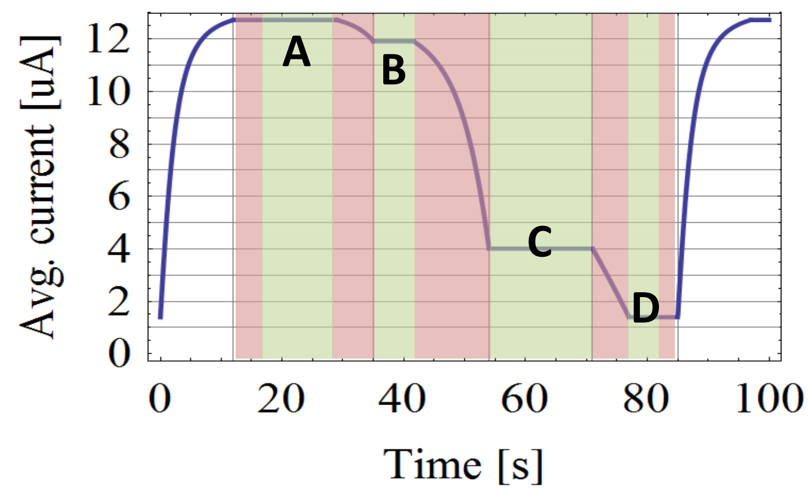
BACKUP

AD beam parameters

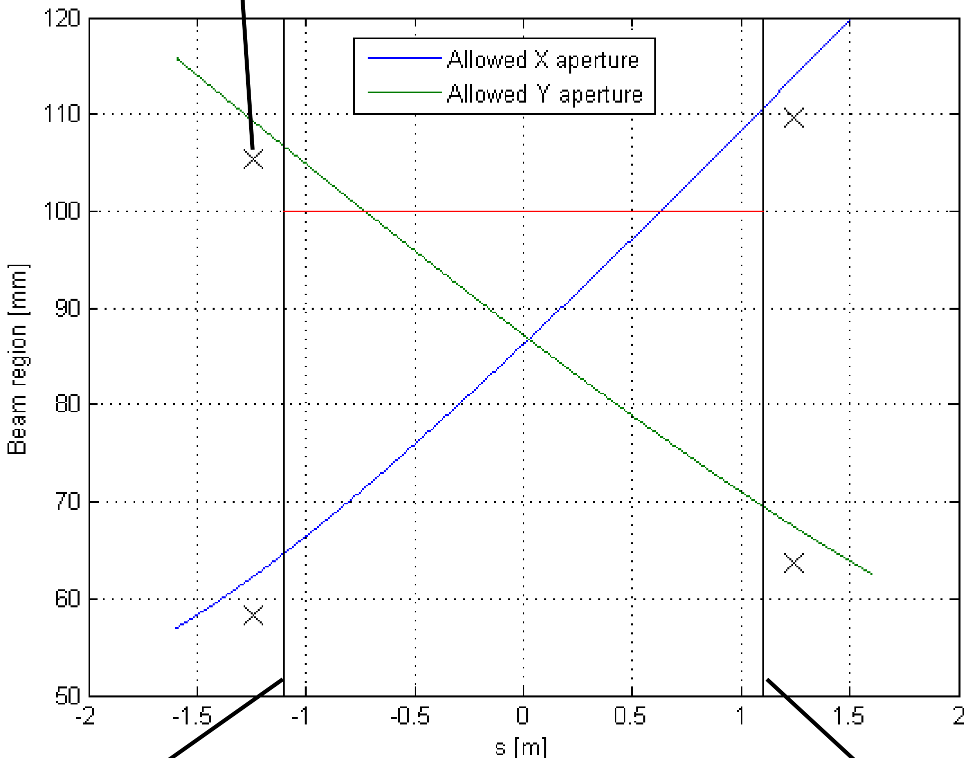




	A			B			C			D		
Momentum [GeV/c]	3.57			2.0			0.3			0.1		
Revolution freq. [MHz]	1.6			1.5			0.5			0.2		
Total intensity [pbar]	5.0E+07			5.0E+07			5.0E+07			5.0E+07 **(1.0E+07)**		
Phase	inj.	d.c.	cap.	deb.	d.c.	cap.	deb.	d.c.	cap.	deb.	d.c.	cap.
Bunch length 4σ [ns]	30	d.c.	172	420	d.c.	136	859	d.c.	104	370	d.c.	110
Harmonic (= N bunches)	6 (4)	-	1 (1)	1 (1)	-	1 (1)	1 (1)	-	3 (3)	3 (3)	-	1/6 (1)
Average current [uA]	12			11			4			1.3 **(0.3)**		
Bunch peak current [uA]	426		74.2	45.6	-	140.8	22.3	-	40.9	17.3	-	174.1

AD Section 15 – Beam pipe aperture

Magnetic edge points



Flange near QDS15

Flange near QFN16

Allowed inner diameters for beam pipe in Section 15 of AD:

Beam region < 100 mm:

– 0.725 < s < 0.632 [m]

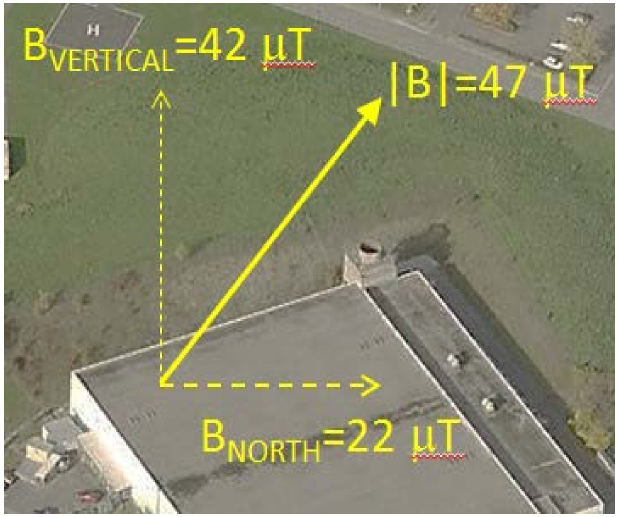
Beam region < 95 mm:

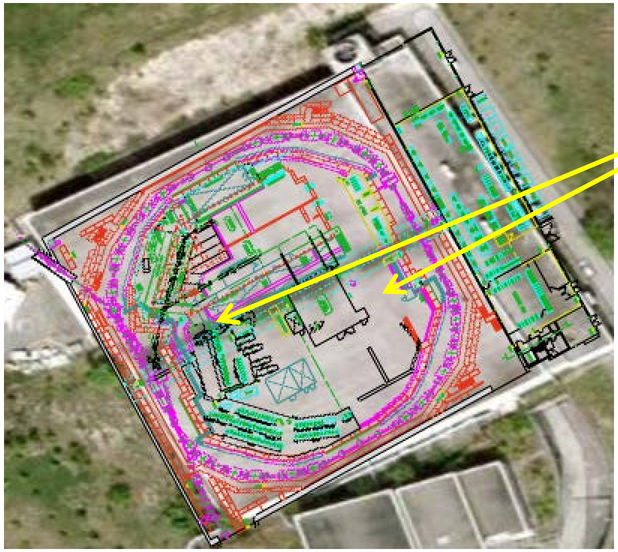
– 0.443 < s < 0.406 [m]

Emmitance equal do AD aperture.
Orbit errors: $X_{c.o.}$= 7 mm; $Y_{c.o.}$ = 5 mm

Magnetic survey of AD-hall

* Courtesy of Marco Buzio (CERN)





Earth's magnetic field:

- Daily and yearly change < 1%

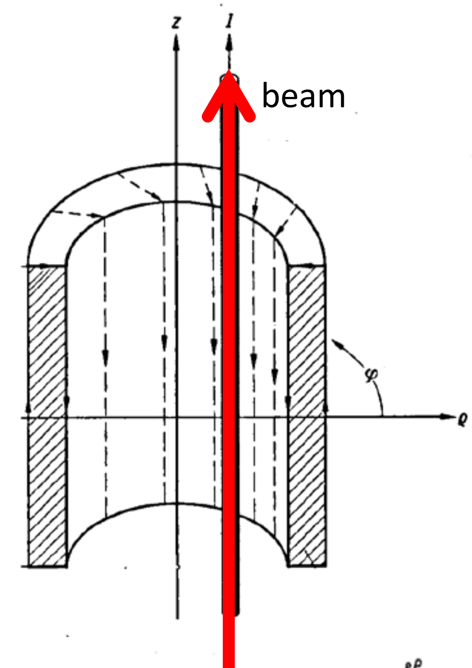
Measurements inside AD hall:

- General field levels:
  $B_{VERTICAL} \lesssim 35\ \mu T$ $B_{HORIZONTAL} \lesssim 30\ \mu T$
- Field at concrete shielding blocks:
  $|B| \lesssim 10\ \mu T$
- Scaffolding structure behind kicker spools:
  150 µT (70 µT @ 0.2 m)

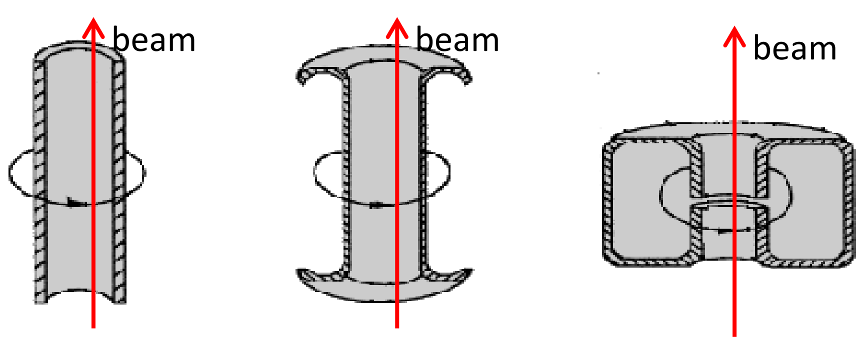
Magnetic Shield

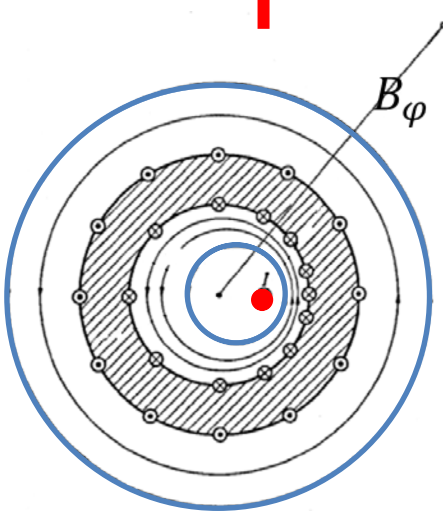
Superconducting cavities attenuate non-azimuthal magnetic field components:

- Symmetrize field from offset beams
- Attenuate external background fields



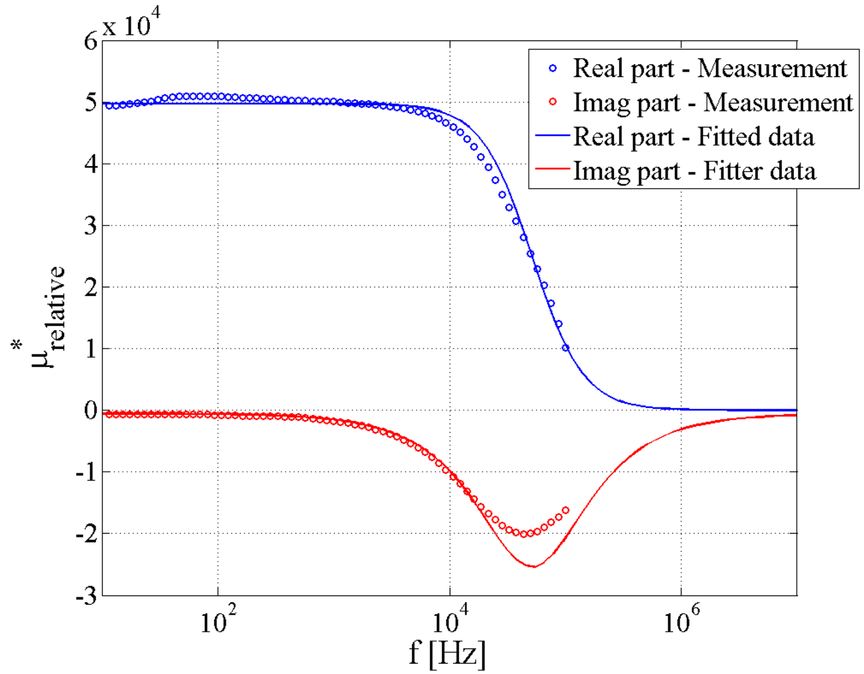
The same effect can be obtained by reversing the shielding design



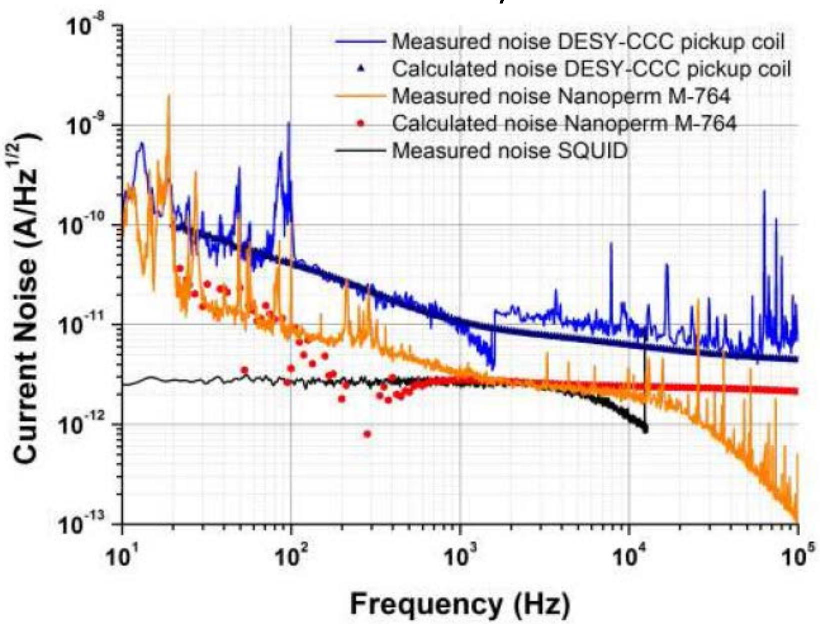


$$B_\varphi = \frac{\mu I}{2\pi\rho}$$

Magnetic core thermal noise

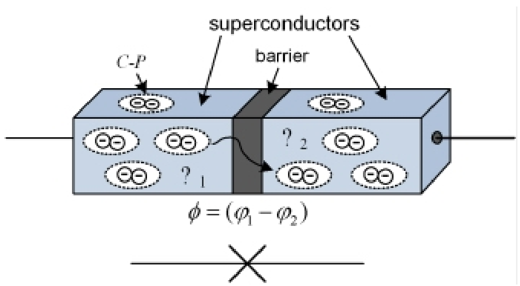


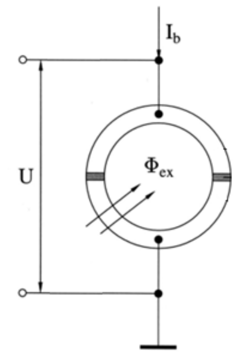
* Courtesy of René Geithner

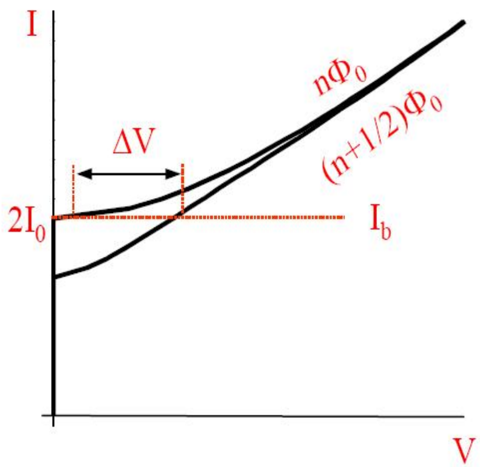


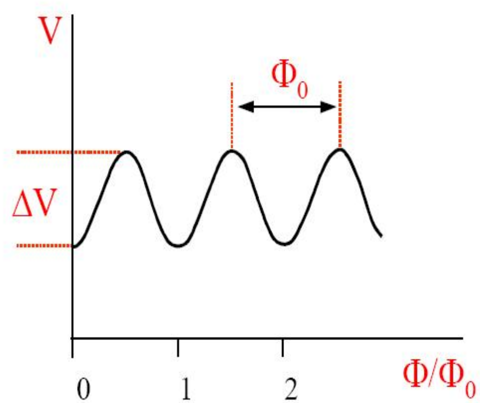
$$< I_C^2 >_{PSD} = \frac{4k_B T}{\omega L_0}\left(\frac{\mu''(\omega)}{[L_i/L_0 + \mu'(\omega)]^2 + \mu''(\omega)^2}\right)$$

SQUID's basics

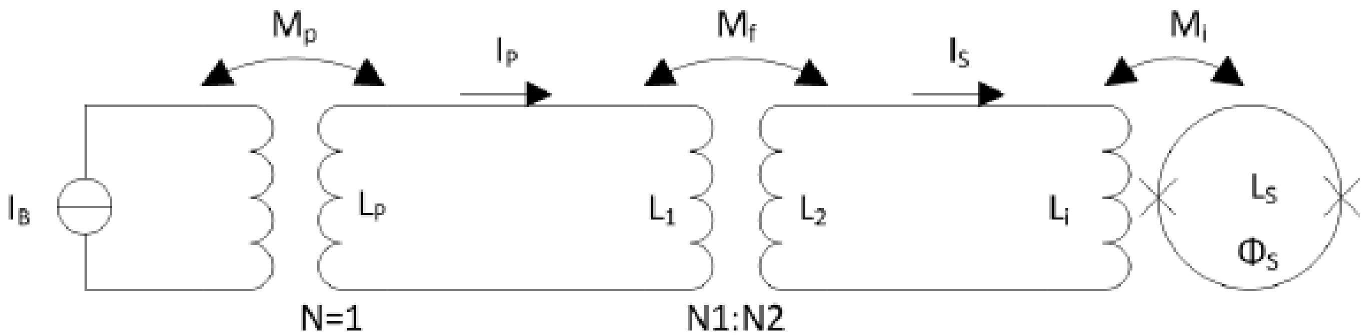






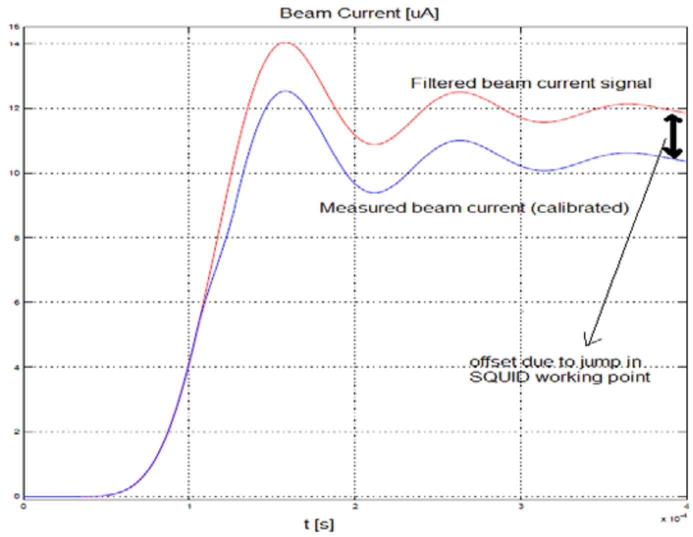


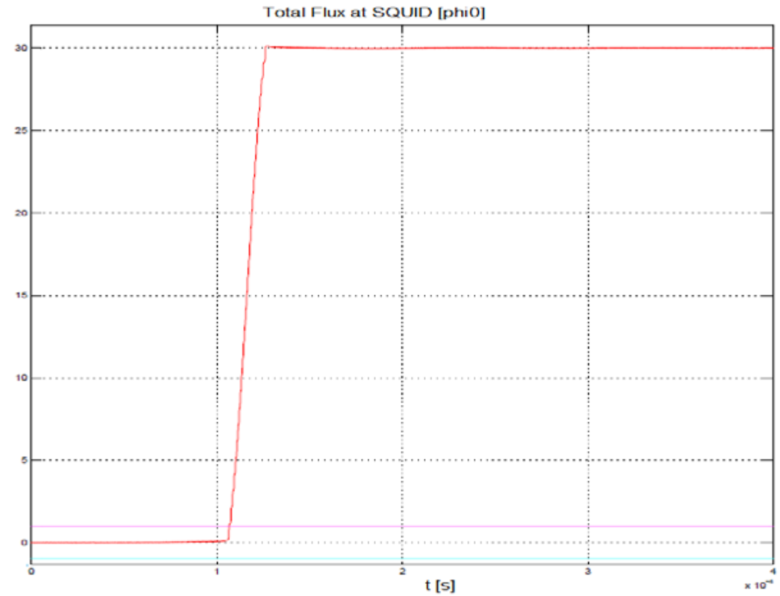
Coupling circuit

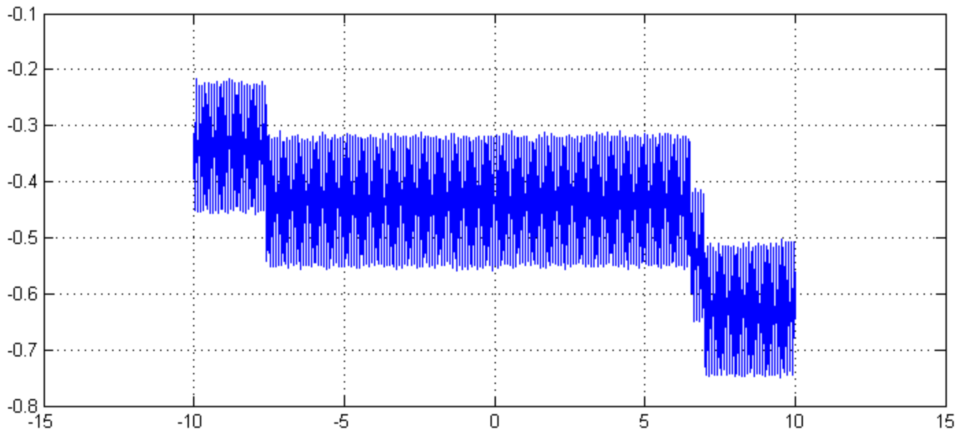


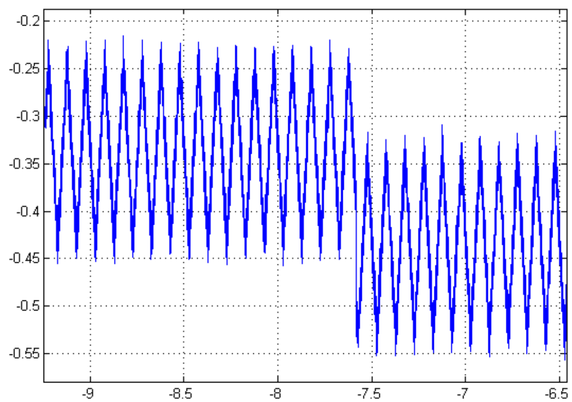
$$S_{I_B} = \frac{\Phi_S(t)}{I_B(t)} = \left[\frac{M_i M_P M_f}{(L_P + L_W + L_1)(L_2 + L_i) - M_f^2}\right]$$

FLL flux-jump examples

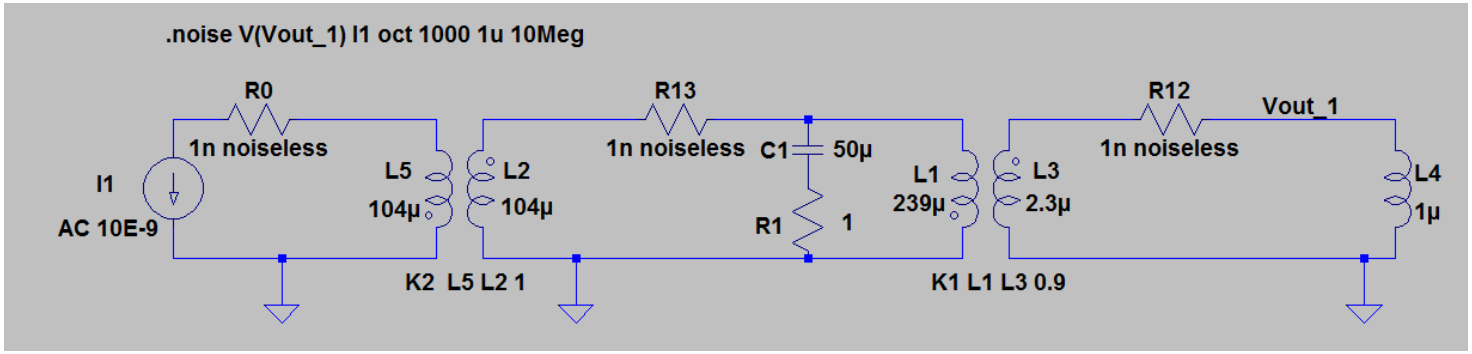








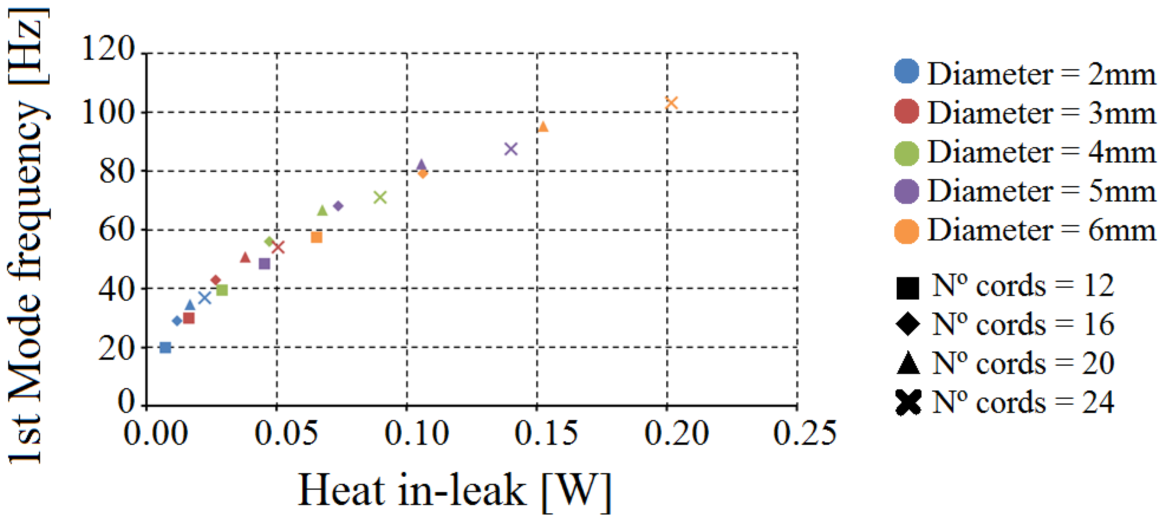
Thermal noise from RC-shunt



- Noise level (referred to beam current) at T=4.2K:

	C=10uF	C=50uF
BW=1kHz	0.017 nA	0.085 nA
BW=10kHz	0.5 nA	1.2 nA

Cryostat support optimization



	50 K [W]	**4.2 K [W]**
Kevlar supports (16×)	0.5864	0.0473
Bayonet + Safety Valve	3.6065	0.1832
Cryostat instrumentation	0.8185	0.0527
Heater wires	0.0195	0.0004
SQUID cabling	0.0162	0.1798
Total	5.0471	0.4219