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Modeling and Performance Evaluation of DCCTs in SSRF

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Outline

- Introduction to SSRF
- Overview of the DCCT system on the SR
- Noise Study
  - ➢ characterization
  - ➢ noise exploration
  - ➢ modeling
  - ➢ workaround
  - ➢ result
- Future tests
- Summary

Introduction to SSRF

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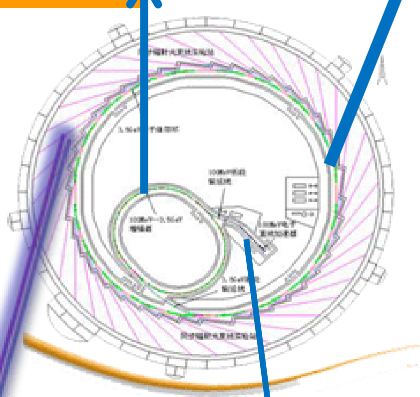
3.5GeV storage ring

full energy booster



7 beam lines for now

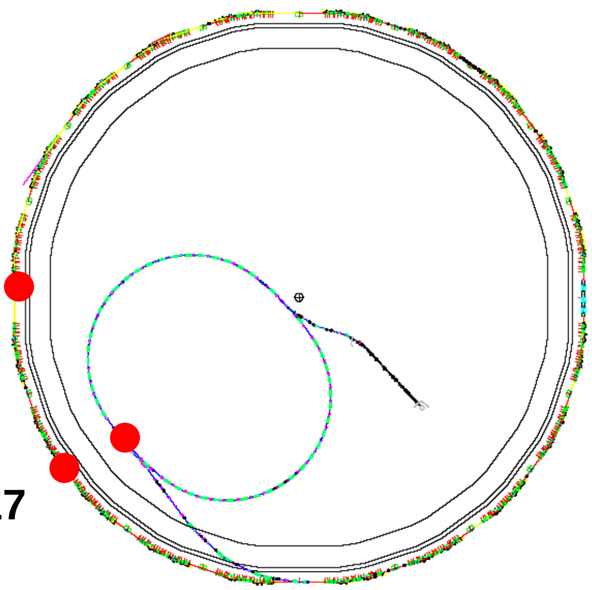
150MeV LINAC

DBA		Low Emittance mode	Normal mode
Energy	GeV	3.5	3.5
Circumference	m	432	432
Natural Emittance	nm*rad	3.9	11.2
Current	mA	200-300/5	200-300/5
Tune		22.22/11.32	22.22/11.32
Chromaticity		-56/-19	-56/-19
RF Voltage	MV	4.0~6.0	4.0~6.0
Energy Loss/Turn	MeV	1.448	1.448
Max beam power	kW	~600	~600

The only third generation light source in China
2465 proposals, 235 research teams, 3780 users since formal operation in 2009
Availability 97.6%, MTBF 55.3 hours, MDT 1.55 hours in 2011

Overview of the DCCT

The Primary Requirements



At least 2 DCCTs required:

Display current details during ramping cycle @ Booster
(whole ramping cycle 250ms, average current < 2mA)

Precise average current & lifetime measurement @ Ring
(typical current [140mA 210mA], lifetime 20~30hours)

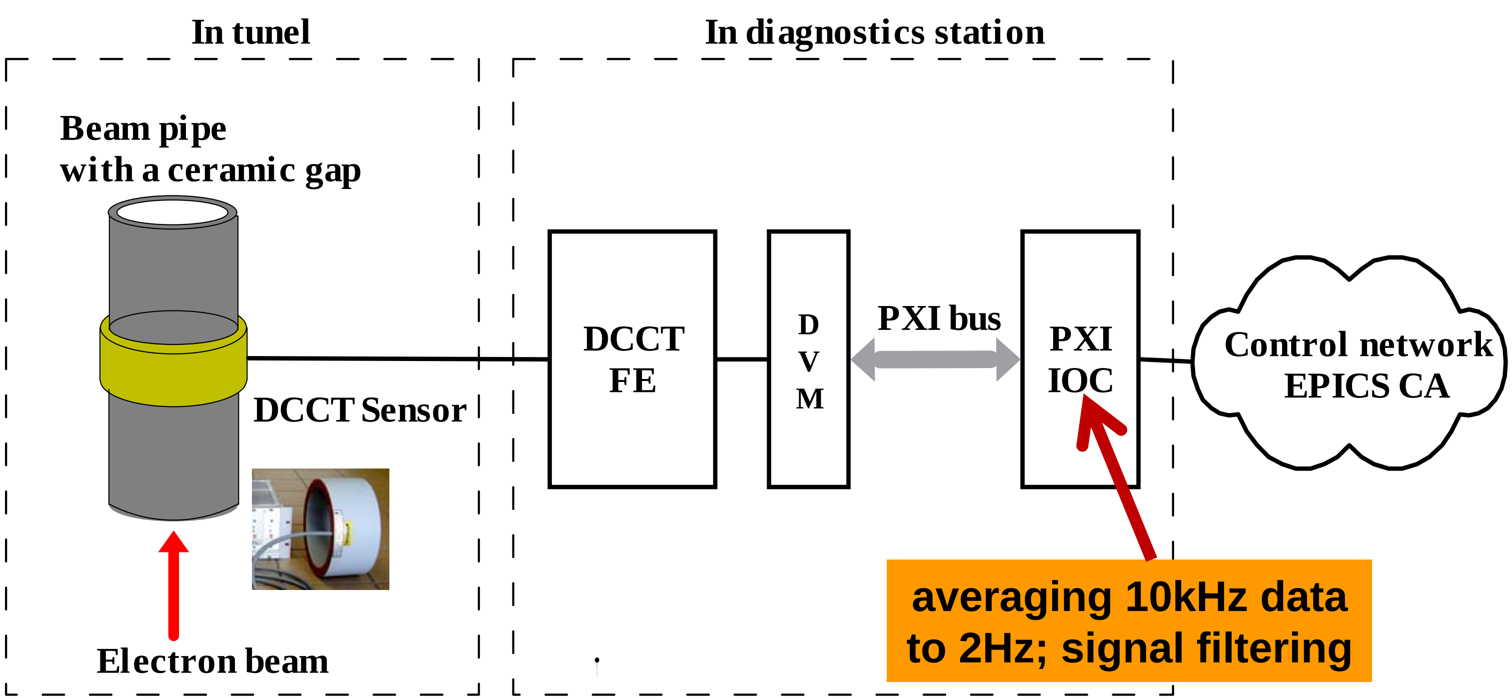
	Design goals
Ring DCCT	10 μA @ 1Hz
Booster DCCT	50 μA @ 10kHz

A general solution adopted to cover two applications:
- Raw sampling rate 10kHz, to capture booster current waveform
- The 2Hz high resolution data were produced by averaging the 10kHz data at the PC end
- Both 10kHz and 2Hz data available to users

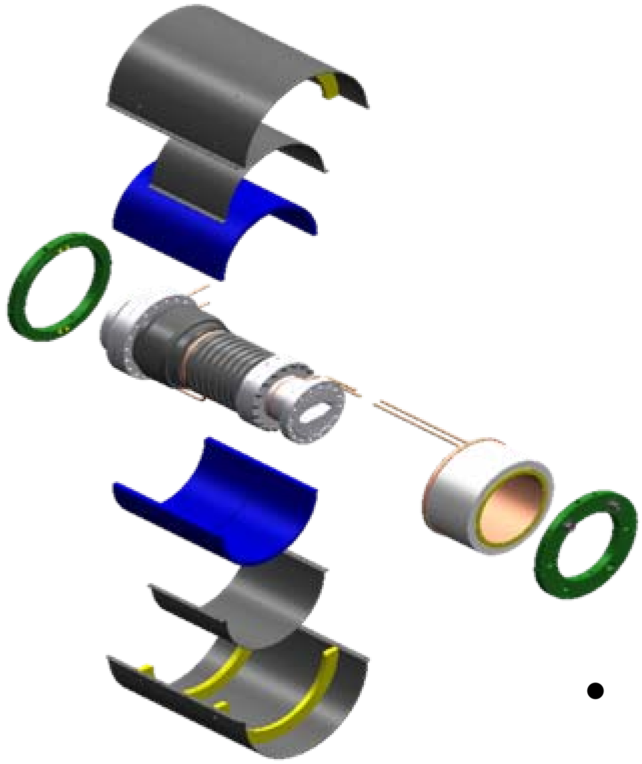
Total 2 DCCTs installed in the Ring
- DCCT15, primary average current monitor
- DCCT17, online backup

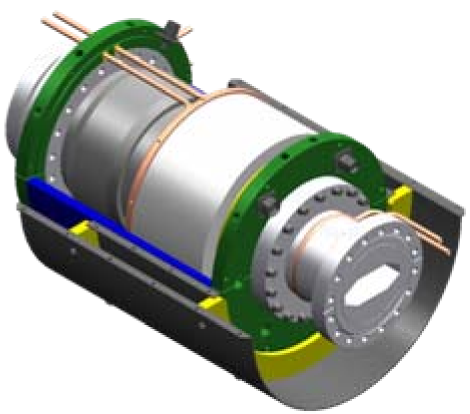
System Configuration

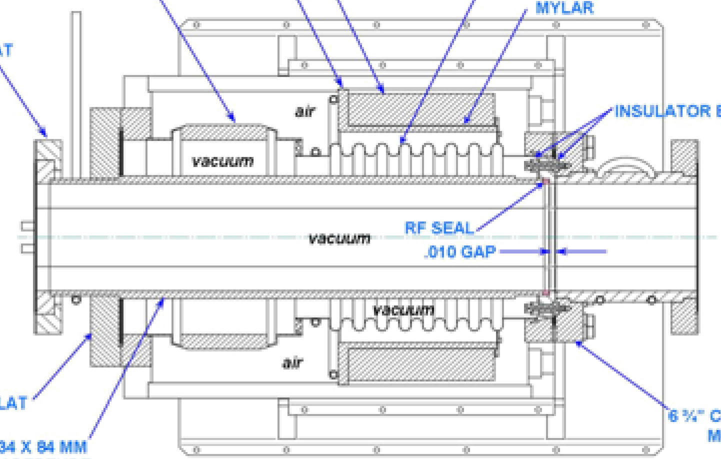
Component	Solution
Sensor	NPCT175 HR, 1 μA/√Hz
Shielding	Fabrication locally, design borrowed from SPEAR3
DAQ	PXI NI4070, 6.5bits DVM, 10kHz sampling rate
Data processing	digital filtering + averaging
Data server	10kHz and 2Hz data, EPICS IOCcore @ Linux



Shielding Design



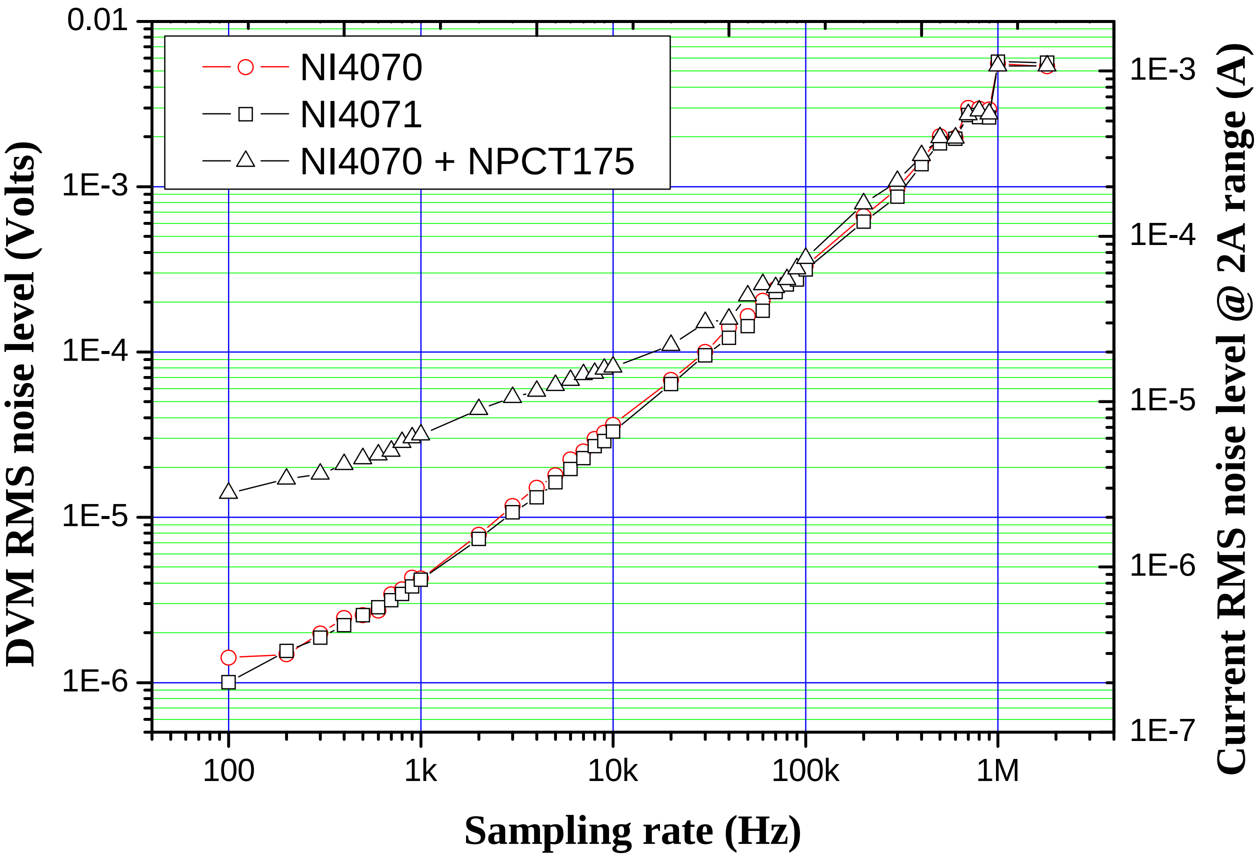




- Design **borrowed from SLAC**
- Well tested during SPEAR3 operation
- Easy for fabrication and installation
- Modular structure, can be used for both Booster and Ring with similar design

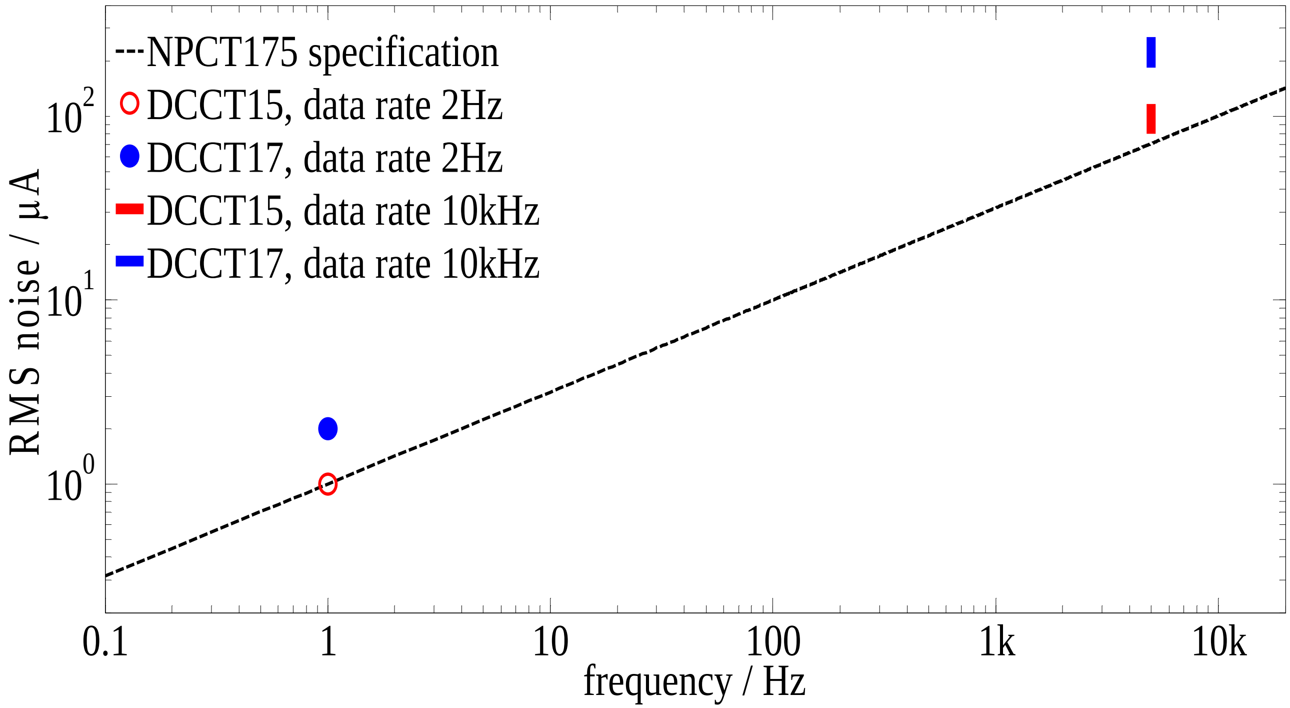
Noise test has performed for:

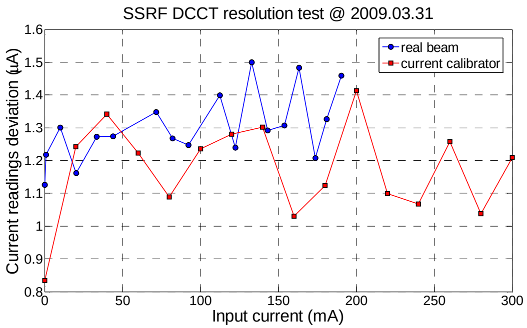
- NI PXI 4070 (6.5bit)
- NI PXI 4071 (7.5bit)
- NI PXI 4070 combined with NPCT175



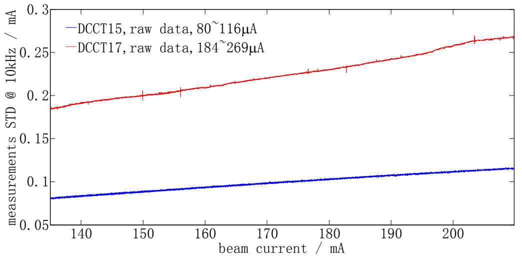
- 4071 do not have a significantly better performance
- The measurement noise mainly comes from NPCT sensor under the sampling rate of 40kHz and less
- The main source becomes the DVM electronics when the sampling rate is above 40kHz

System Performance





Resolution < 2uA @ 1Hz BW

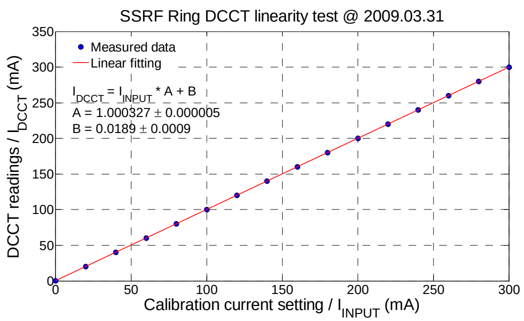


Resolution @ 5kHz BW

DCCT15 is better than DCCT17 (installation, ground loop, etc.)

Resolution of 2Hz data is close to the hardware limitation, hard to improve further

Various noise have been found at 10kHz data, lots of room for optimization

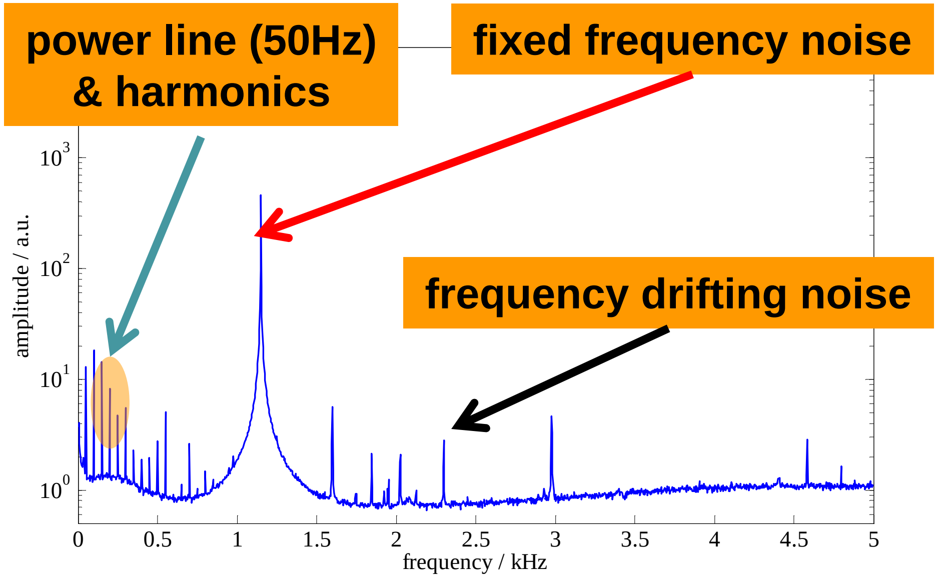


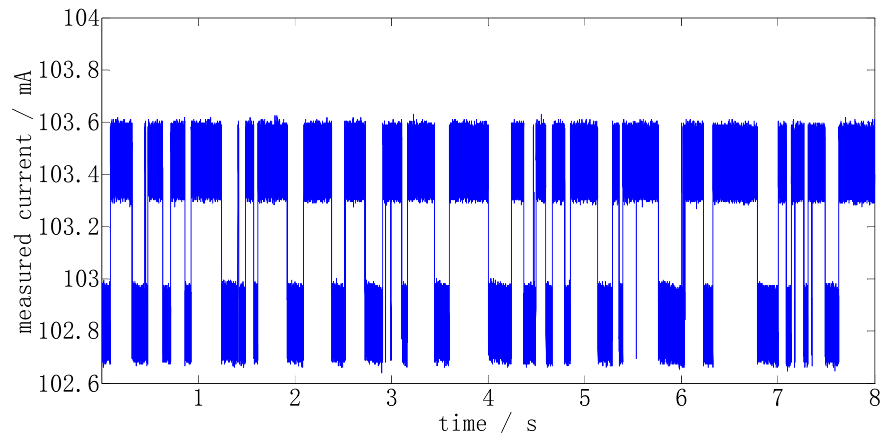
Nonlinearity < 0.03% @ 0 ~ 300mA

Noise Study

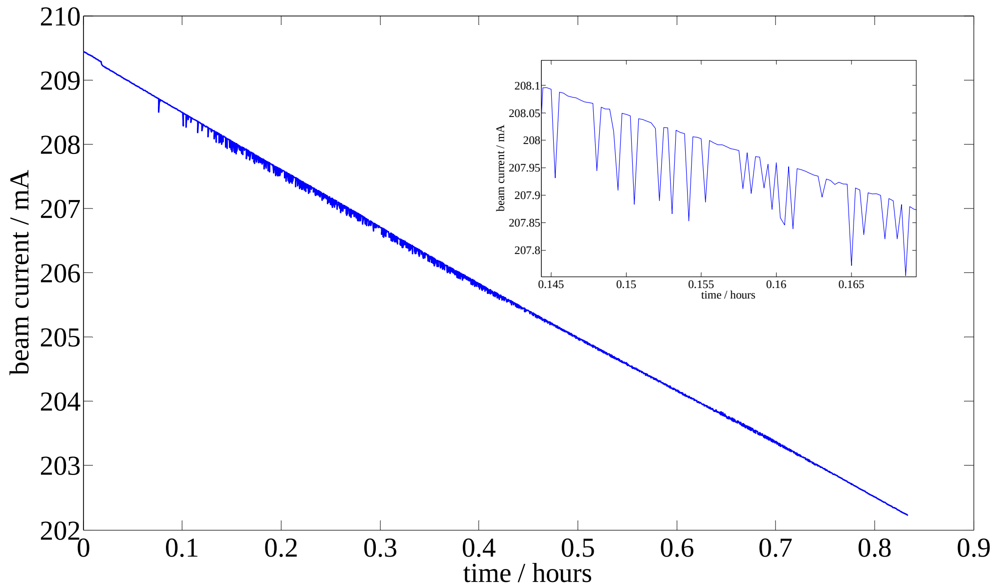
Noise Study: Characterization

Type of noise	frequency	amplitude	occurrence
power line noise	50Hz and its harmonics	<10 μ A for DCCT15	always
frequency specific noise	1.147kHz for DCCT15	~300 μ A	always
frequency drifting noise	few kHz	~100 μ A	always
square wave noise	/	-600 μ A	~once a week
zero drift	white	<1 μ A@1Hz	always



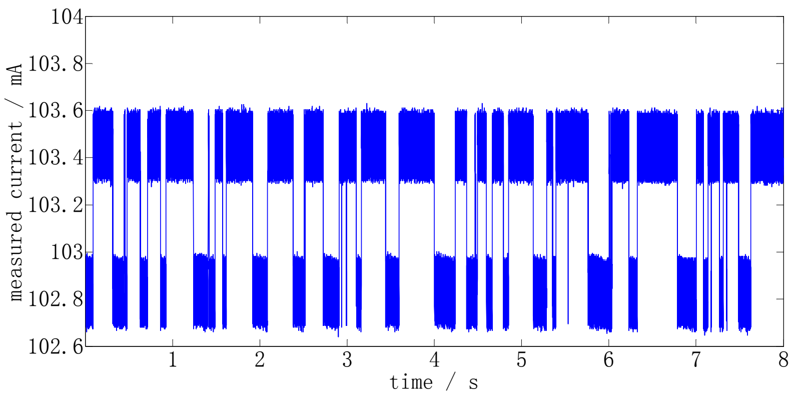


Square Wave Noise: Characteristic



It hurts the resolution badly, especial for lifetime measurement

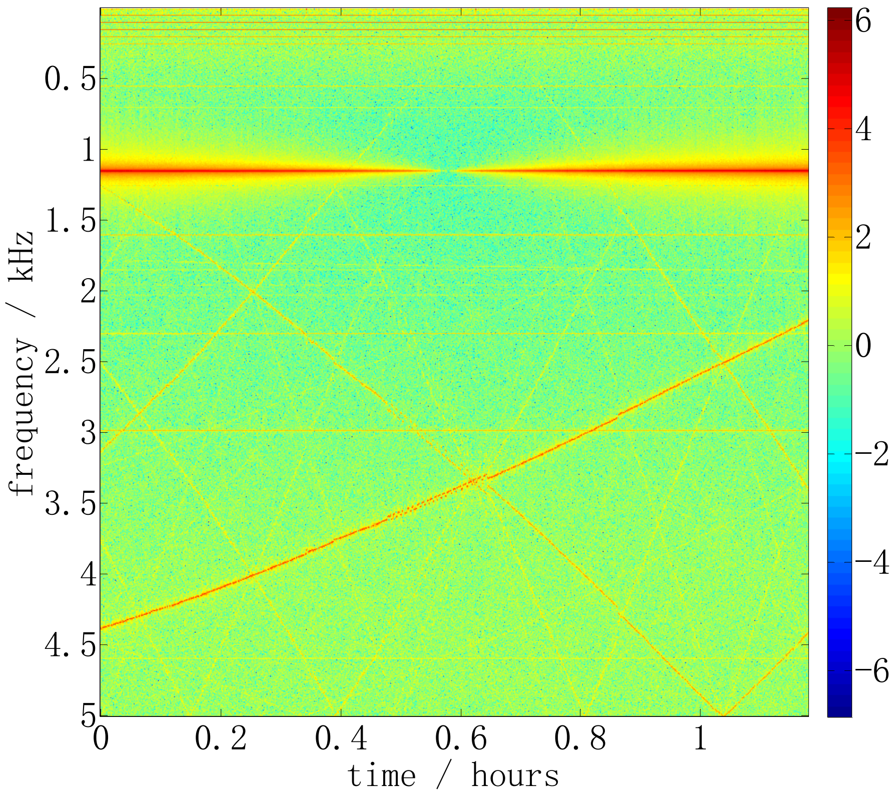
Hard to be removed with traditional time-domain or frequency-domain filtering means



appear randomly without any warning

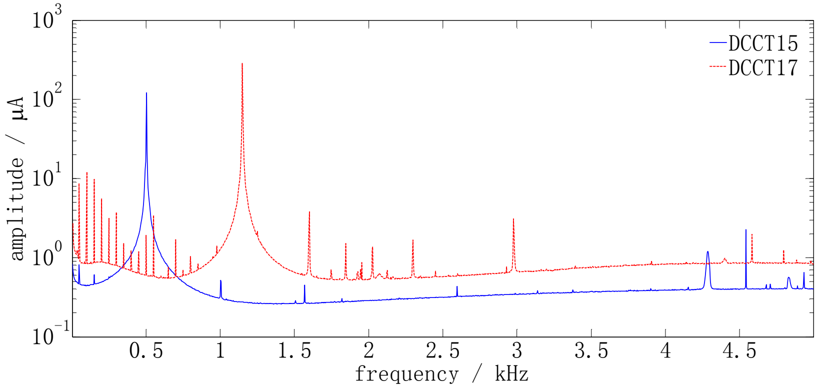
shaped as a square waveform with indefinite periods and fixed amplitudes

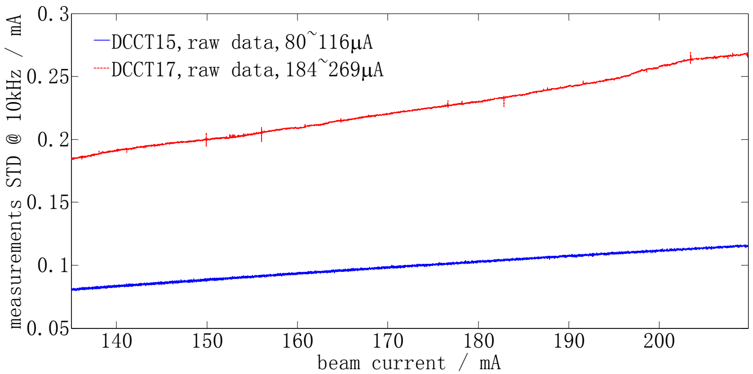
Narrowband Noise : Characteristic



- power line noise (50Hz) and its harmonics
- frequency specific noise (1.147kHz)
- frequency drifting noise(4.4kHz—2.2kHz during this period)

- The total intensity of the narrowband noise is approximately proportional to the beam current





Noise Study: Influence

Type of noise	influence
power line noise	the resolution of the 10kHz data
frequency specific noise	
frequency drifting noise	
square wave noise	resolution of both the 10kHz data and the 2Hz data; system measurement error; lifetime measurement error
zero drift	resolution of both the 10kHz data and the 2Hz data

Noise Study: Exploration

Type of noise	exploration
power line noise	feed reverse current to cancel out the DC component of the beam current, to see whether it comes from: sensor, nonlinear ADC, etc.
frequency specific noise	
frequency drifting noise	
square wave noise	try to find the correlation between the noise and other machine parameters: RF voltages, beam current, etc.
zero drift	/

Narrowband Noise Exploration

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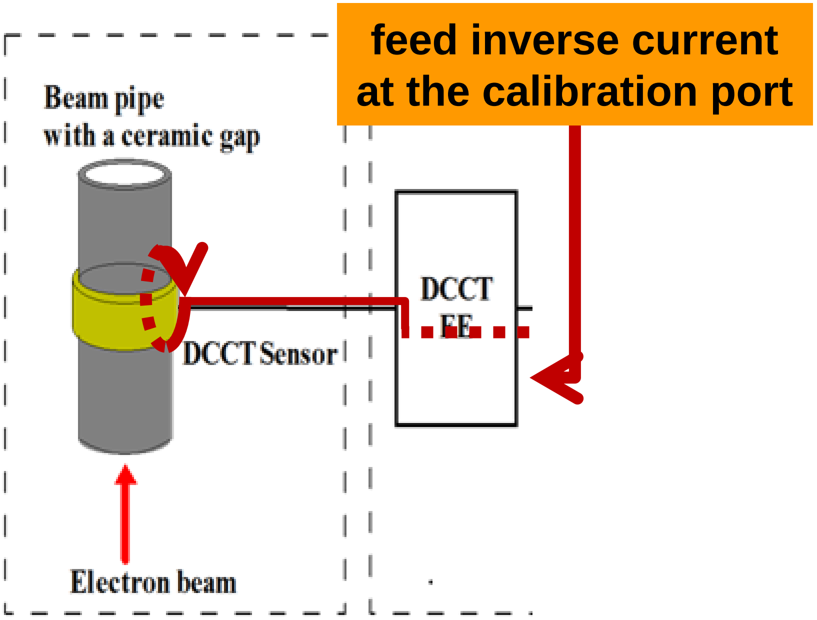
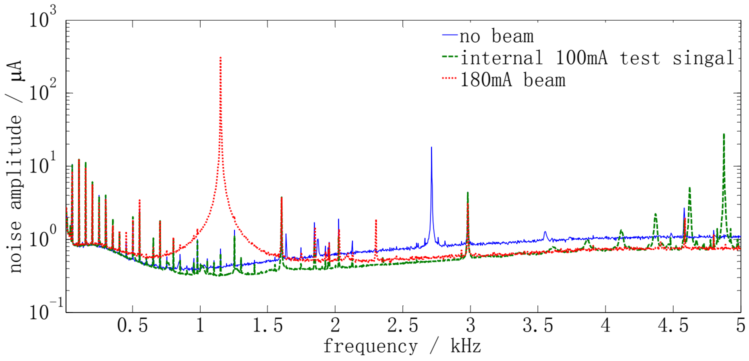
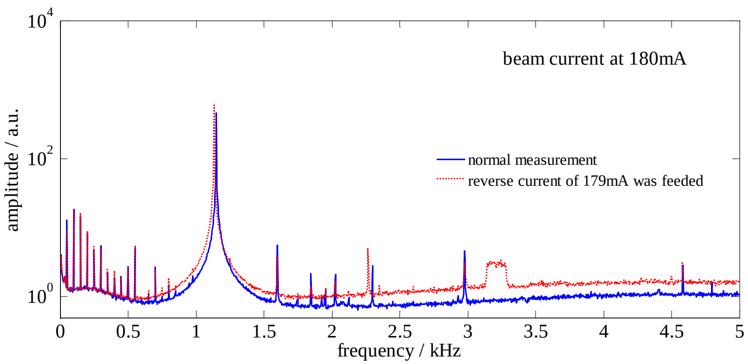




Noise spectrum without beam, with test signal and with beam

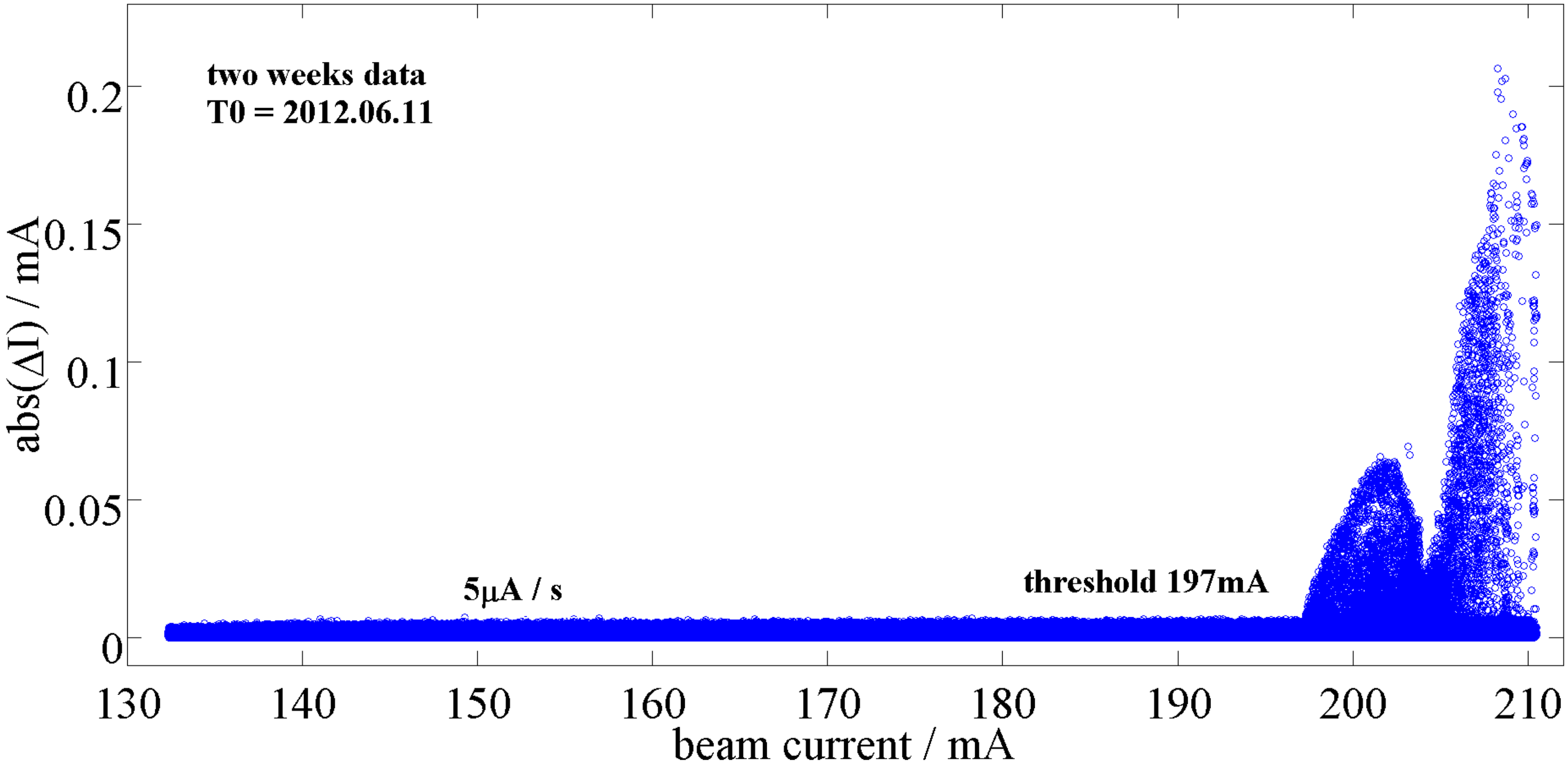


Noise spectrum with & without inverse current

- Most of the NB noise is excited by the beam
- The spectrum scarcely changed after the reverse current was fed. Hence, the noise is DC unrelated.

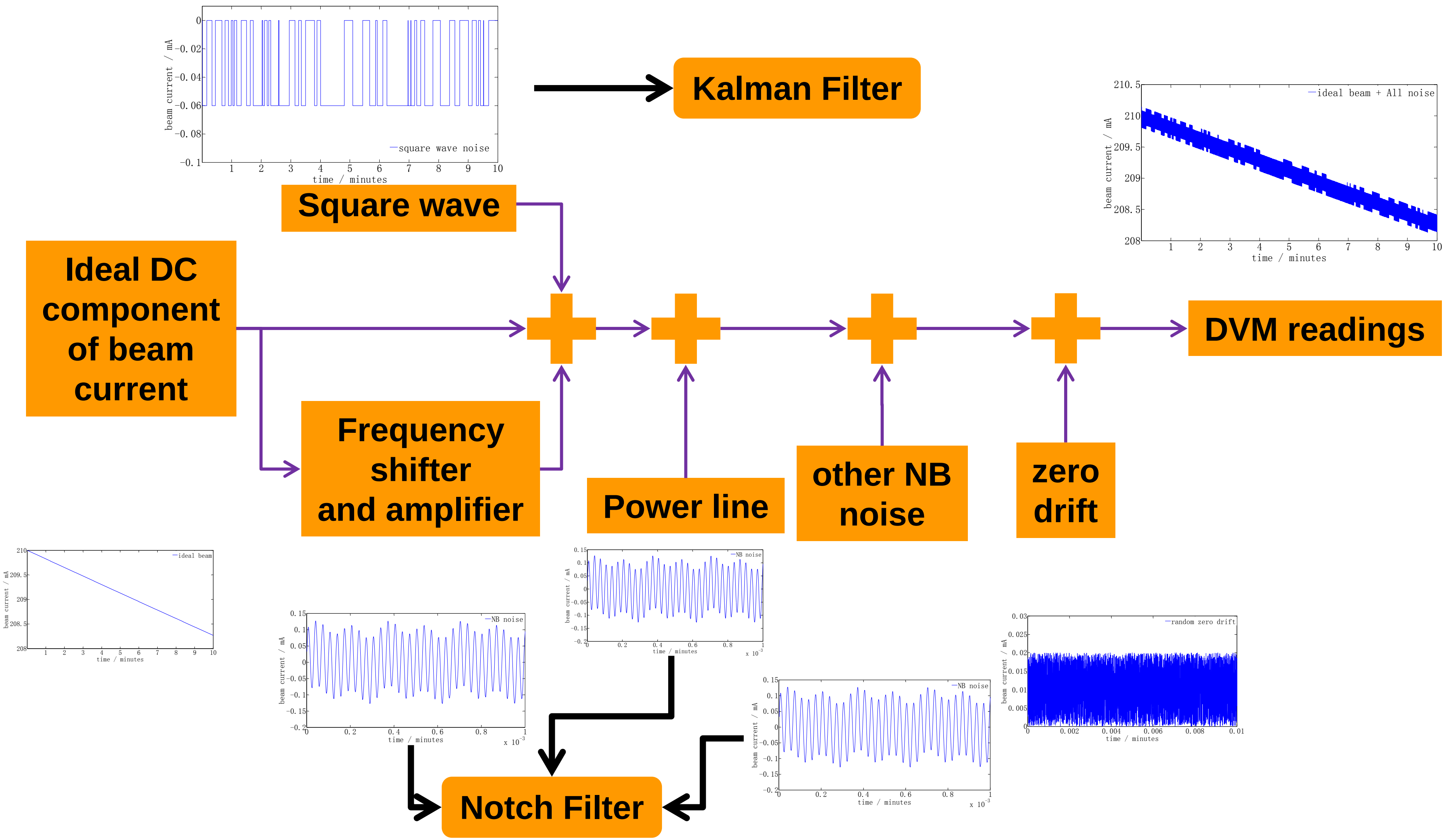
Square Wave Noise: Exploration

Type of noise	exploration
square wave noise	try to find the correlation between the noise and other machine parameters: RF voltages, beam current, etc.



No other relations have been found between the noise and machine parameters except that this type of noise does not appear when the beam current is below 197mA, and has an interesting distribution around the high current area

DCCT Modeling



Noise Study: Workaround

Type of noise	workaround
power line noise	narrowband, multiple frequencies, unstable frequencies: adaptive notch filter
frequency specific noise	
frequency drifting noise	
square wave noise	unpredictable occurrences, wideband, hard to remove in time-domain as well as in frequency-domain: Kalman filter
zero drift	installation optimization

frequency drifting noise

power line & harmonics

$$f(t) = f_0(t) + \mathfrak{F}^{-1}\left(g\left(\mathfrak{F}(t)\right)\right) + h(t) + \sum p_i(t) + \sum n_i(t) + z(t)$$

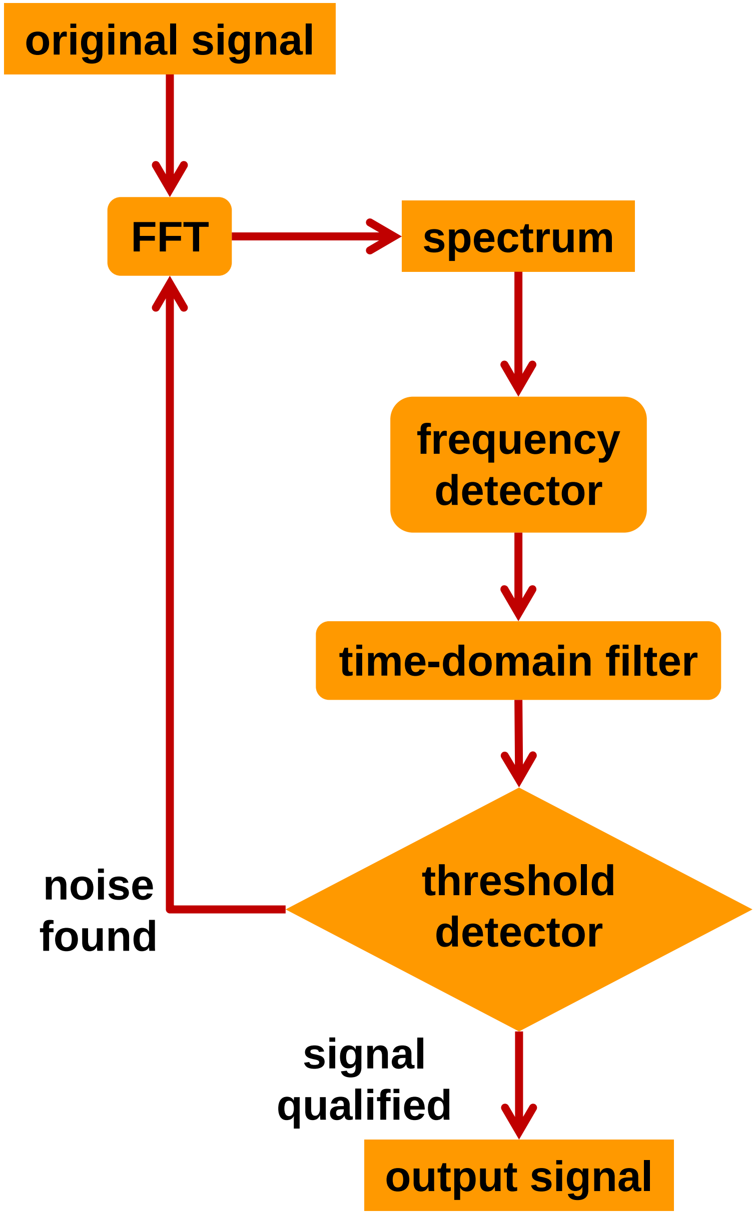
original beam signal

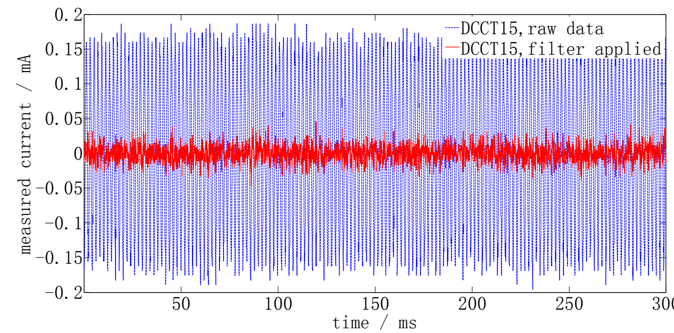
square wave

other NB noise

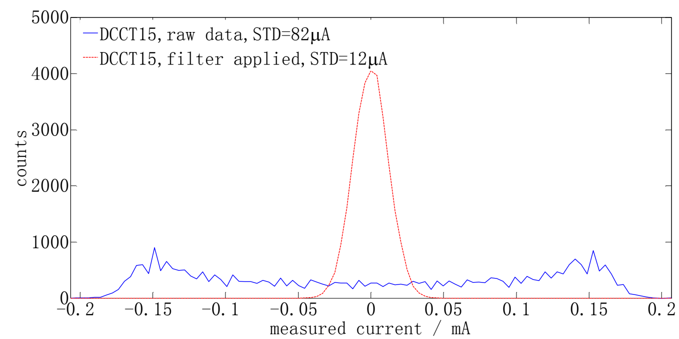
zero drift

Workaround: Adaptive Notch Filter

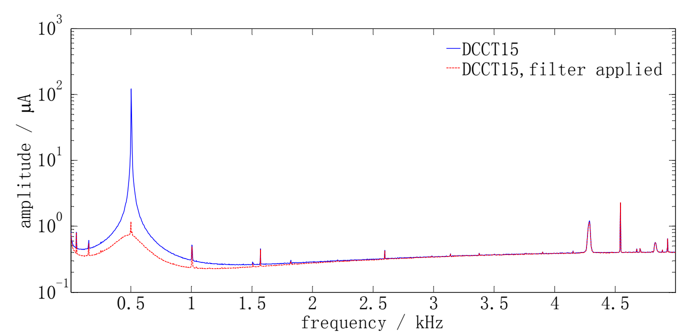




current waveform before and after filtering



histogram before and after filtering



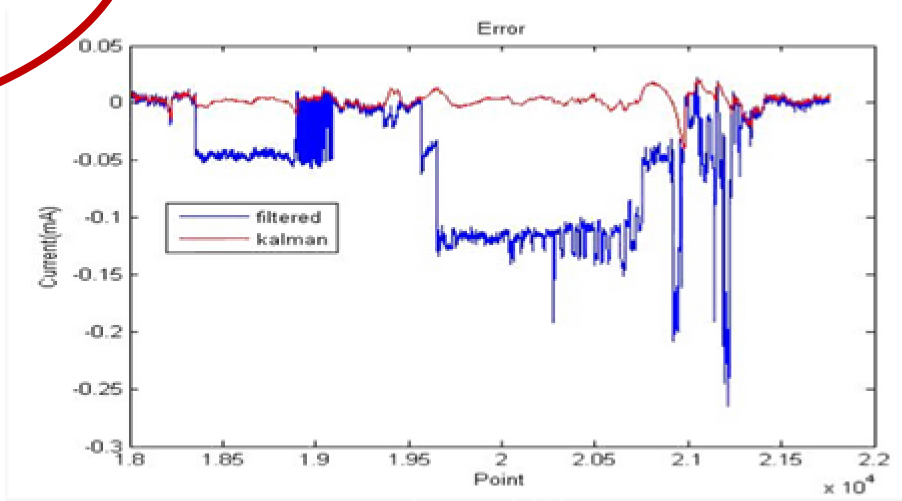
spectrum before and after filtering

Workaround: Kalman Filter

Measurement Update ("Correct")
Compute the Kalman gain
$K_k = P^-_k H^T (H P^-_k H^T + R)^{-1}$
Update estimate with measurement z_k
$\hat{x}_k = \hat{x}^-_k + K_k (z_k - H \hat{x}^-_k)$
Update the error covariance
$P_k = (I - K_k H) P^-_k$

Time Update ("Predict")
(1)Project the state ahead
$\hat{X}^-_k = A \hat{x}_{k-1} + B u_{k-1}$
(2)Project the error covariance ahead
$P^-_k = A P_{k-1} A^T + Q$

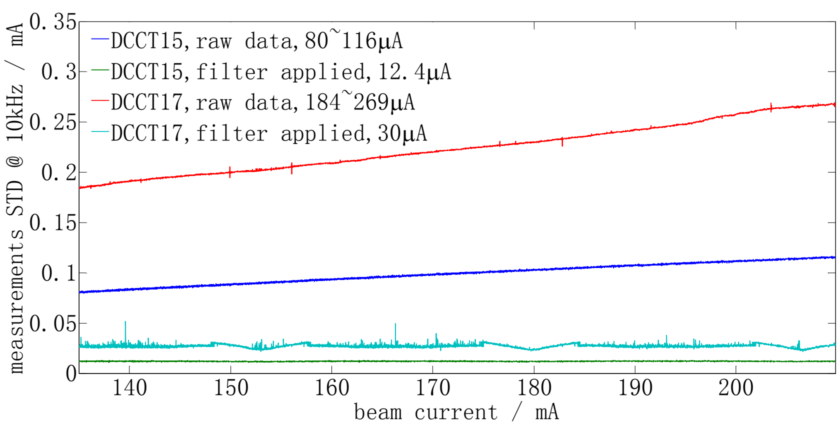
Initial estimates for $\hat{x}_{k-1}$ and P_{k-1}



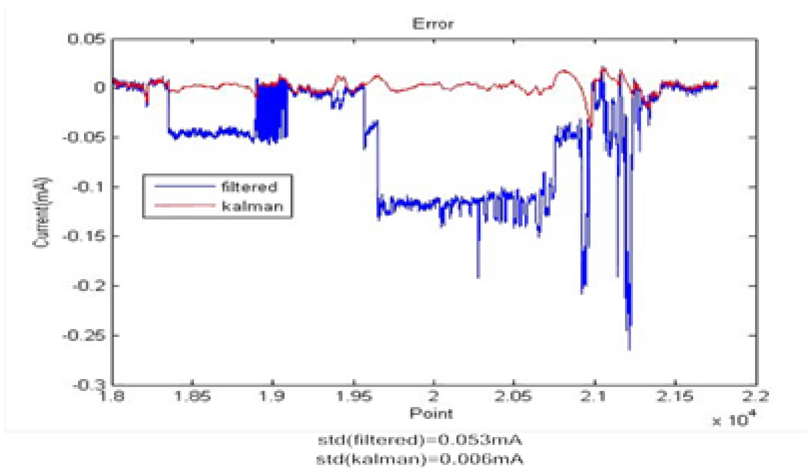
std(filtered)=0.053mA
std(kalman)=0.006mA

Noise Study: Result

Type of noise	result
power line noise frequency specific noise frequency drifting noise	resolution reduces from (DCCT15/DCCT17 @10kHz) 80 μ A~116 μ A/184 μ A~269 μ A to 12.4 μ A/30 μ A
square wave noise	resolution reduces from 53 μ A to 6 μ A for 2Hz data
zero drift	/

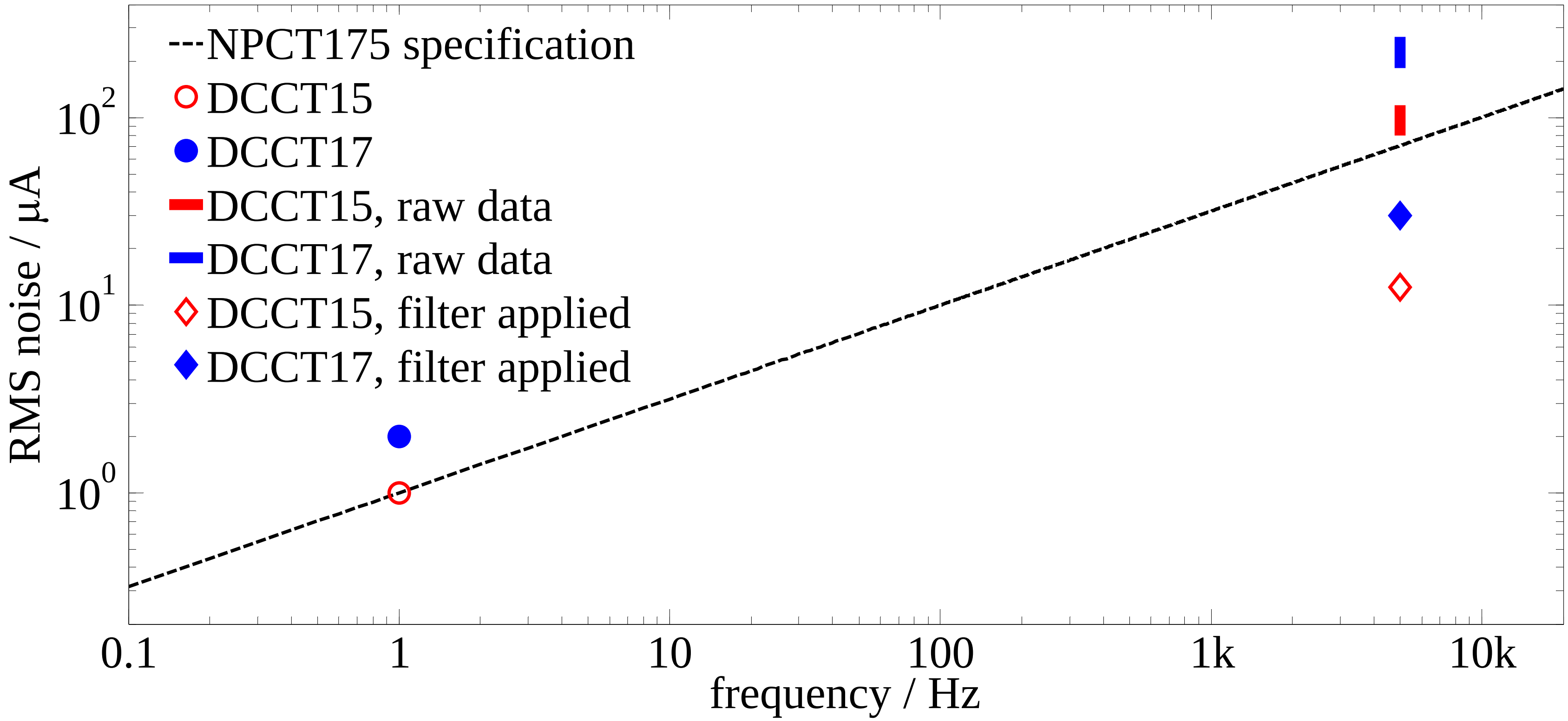


Resolution before and after adaptive notch filtering @ 5kHz BW



Resolution before and after Kalman filtering @ 1Hz BW

Comprehensive Evaluation



- **No significant improvement for 2Hz data**
- **Much better than the specification for 10kHz sampling rate after the filtering**
- **Improved 10kHz data could be useful for machine study (such as energy calibration)**

Future Tests

What We Will Do Next

- Make more correlation analysis to locate the source of the square wave noise
- Optimize the installation to minimize the zero drift
  - ➢ The 10kHz data (on the storage ring) is filtered in order to increase the 2Hz data performance, which turns out it’s limited by the zero drift
- Use BPM sum signals as a replacement for some special situations
  - ➢ Some algorithms have already been tested to pick up the “good” BPMs as talked in another article of these proceedings.
- And more . . .

Summary

Conclusions

- The combination of NPCT175+NI 4070 DVM with sampling rate of 10kHz was picked up to meets the basic needs in SSRF
- Various kinds of noise exist and affect the system despite the shielding, including NB noise, random square wave from nowhere and zero drift problem
- After using the adaptive notch filter and the Kalman filter, the performance of the DCCT has a significant improvement
  - ➢ Adaptive notch filter (DCCT15/DCCT17 @10kHz):
    - 80 μ A~116 μ A/184 μ A~269 μ A to 12.4 μ A/30 μ A
  - ➢ Kalman filter (@2Hz):
    - 53 μ A to 6 μ A
- Anyway, the methods are intended only as a stopgap. We will keep looking for where the noise comes from and try to get rid of it from the first place