Field Quality Measurements at High Ramp Rates*

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Introduction

- In many instances, it is necessary to measure the field quality (harmonics) under dynamic conditions, e.g. to study:
  - Time decay and snap back of harmonics ("Fast" measurements; negligible field variation)
  - Eddy current effects during ramping or under AC operation. **(Rapid field variations)**

Other talks at IMMW-15

- An array of stationary coils has been used recently to measure field quality at high ramp rates (> 1 T/s).
- Some recent results with this system, and improvements made in the data acquisition and analysis, are presented here.

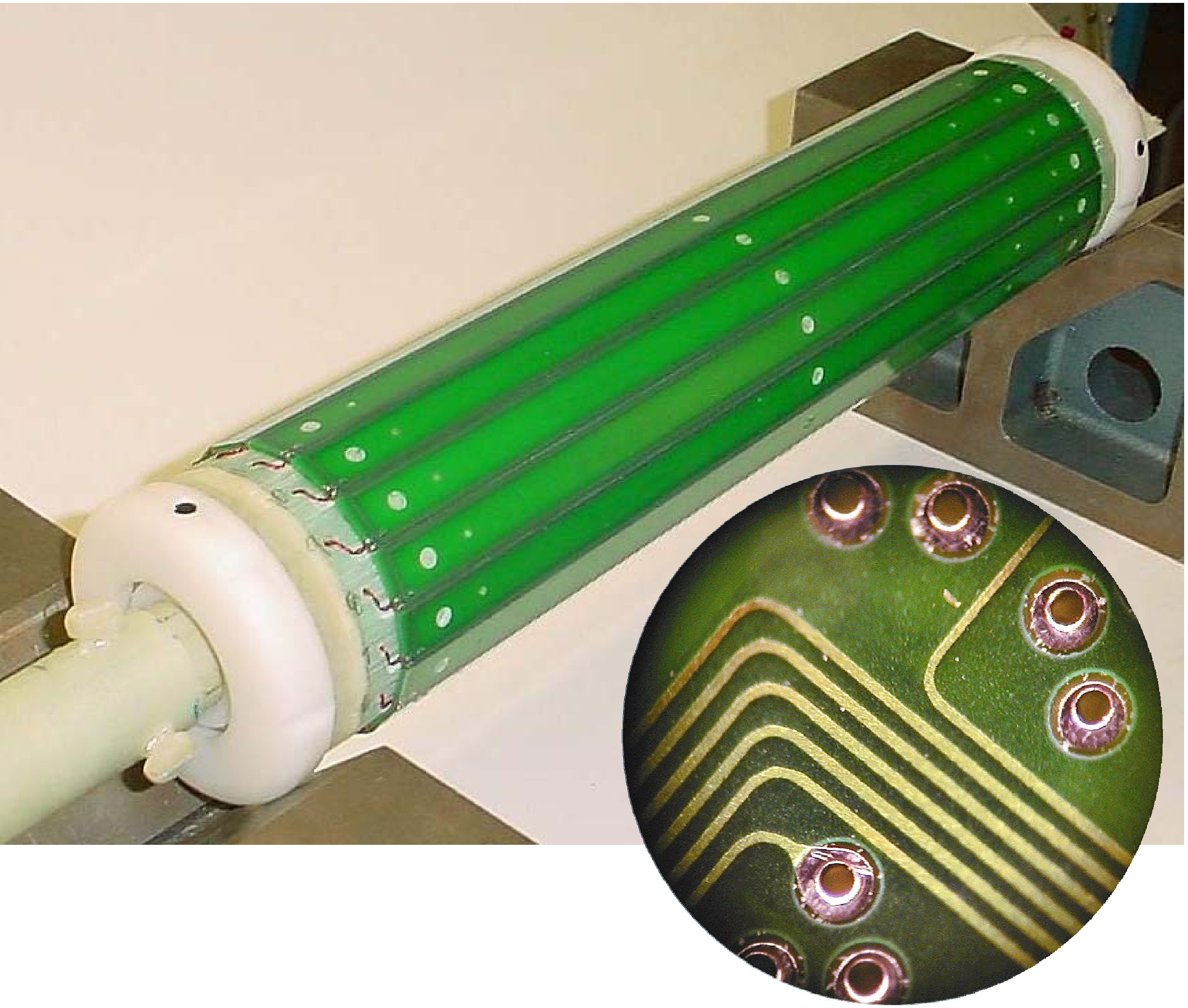
BNL Projects Needing High Ramp Rates

- Dipoles for a Biomedical Project:
  - Dipole field up to 0.4 T in a 4 T solenoid
  - Field to track motion of an unsedated rat's head (frequencies up to several Hz)
  - Effective ramp rate up to 25 T/s
  - A prototype was built and tested for field quality.
- Dipoles for the FAIR project at GSI:
  - 4 Tesla superconducting dipoles ramped at 1 T/s.
  - More than an order of magnitude faster than typical storage ring applications.
  - A prototype has been built and tested up to 4.3 T/s.
- Upcoming NSLS-II Corrector Measurements.

BNL System of Non-rotating coils

- Uses a set of 16 tangential pickup coils covering the full azimuthal range.
- Voltage signal is induced in each of the coils under ramping conditions, with the probe held stationary.
- Analysis of the angular distribution of the signals at any instant provides instantaneous harmonics.
- Time resolutions needed can be easily handled by modern data acquisition systems.
- Precise calibration is of utmost importance for accurate results.
- The probe can also be rotated to measure DC fields. This is used to calibrate the coils precisely, and also to measure the absolute values of initial flux at the start of a ramp.

BNL Harmonic Coil Array



16 Printed Circuit coils, 10 layers

6 turns/layer

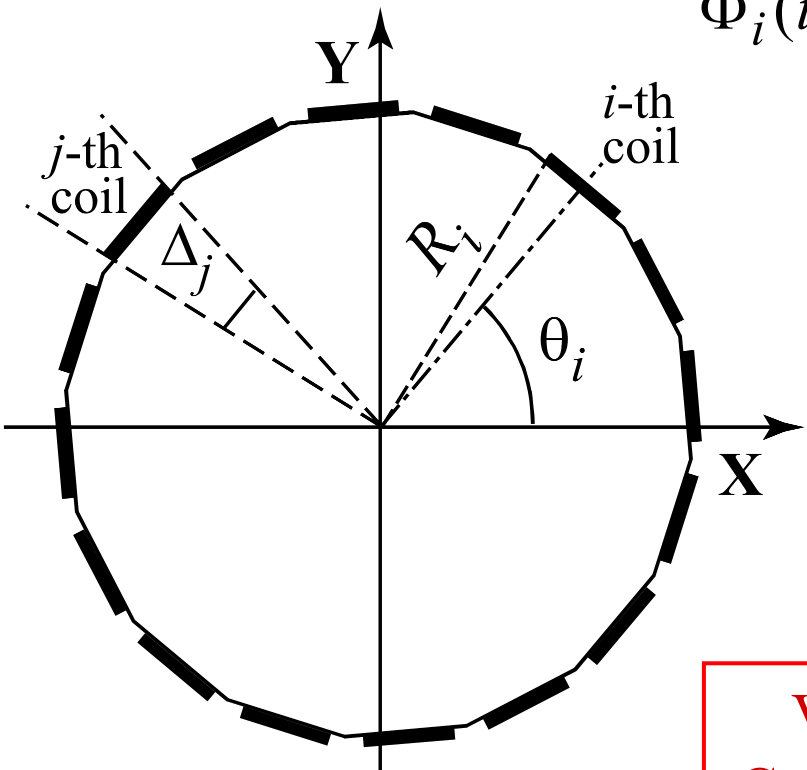
300 mm long

0.1 mm lines with 0.1 mm gaps

Matching coils selected from a production batch

Radius =
35.7 mm (BioMed)
26.8 mm (GSI)

Basic Formalism



$$\Phi_i(t) = \int_0^t V_i(t)\cdot dt + \Phi_i(0)$$

Use rotating mode just prior to ramp

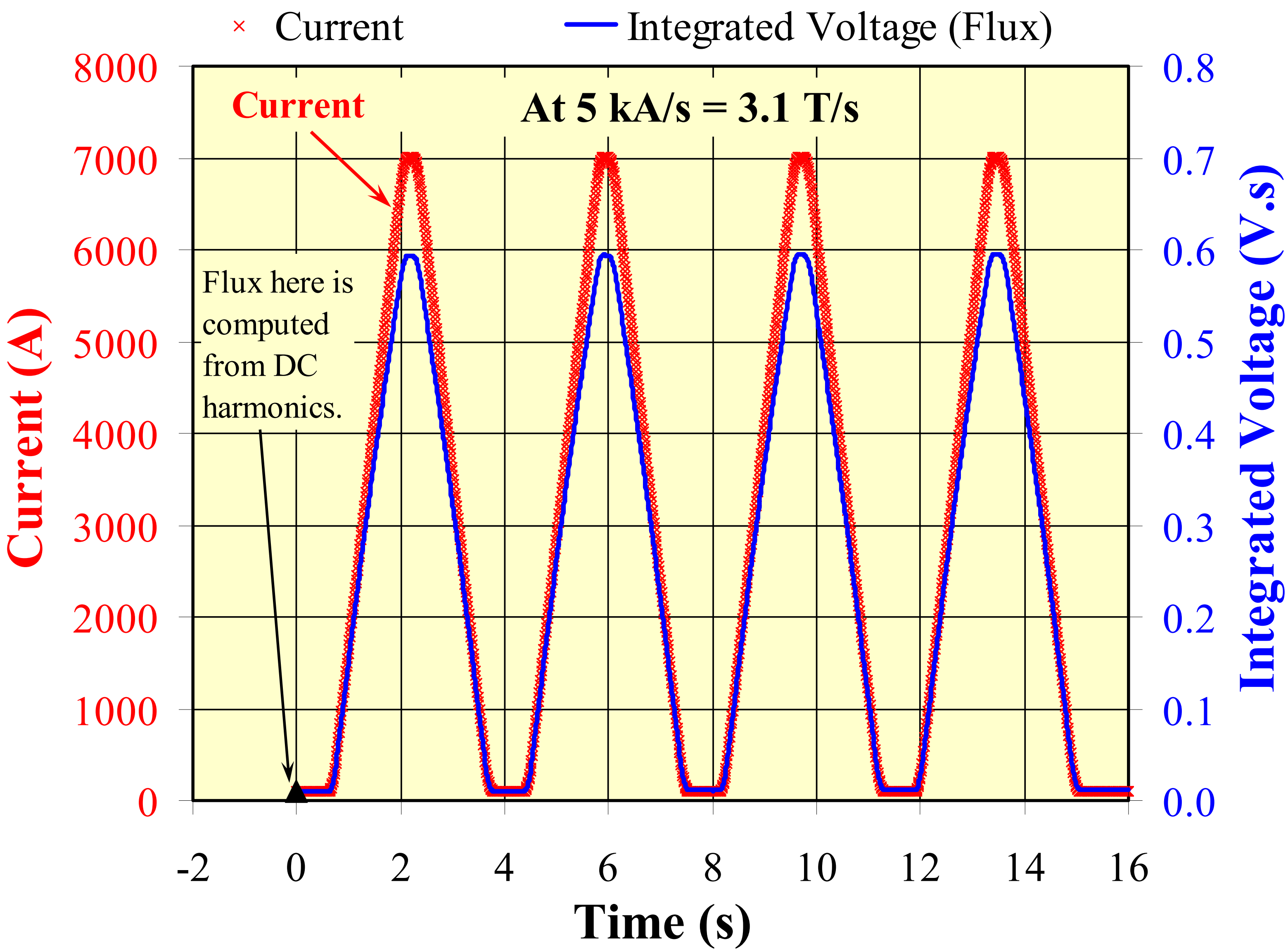
$$= \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left(\frac{R_i}{R_{ref}} \right)^n \sin\left(\frac{n\Delta_i}{2} \right) \times \left[B_n(t)\sin(n\theta_i) + A_n(t)\cos(n\theta_i) \right]$$

Obtained by fitting

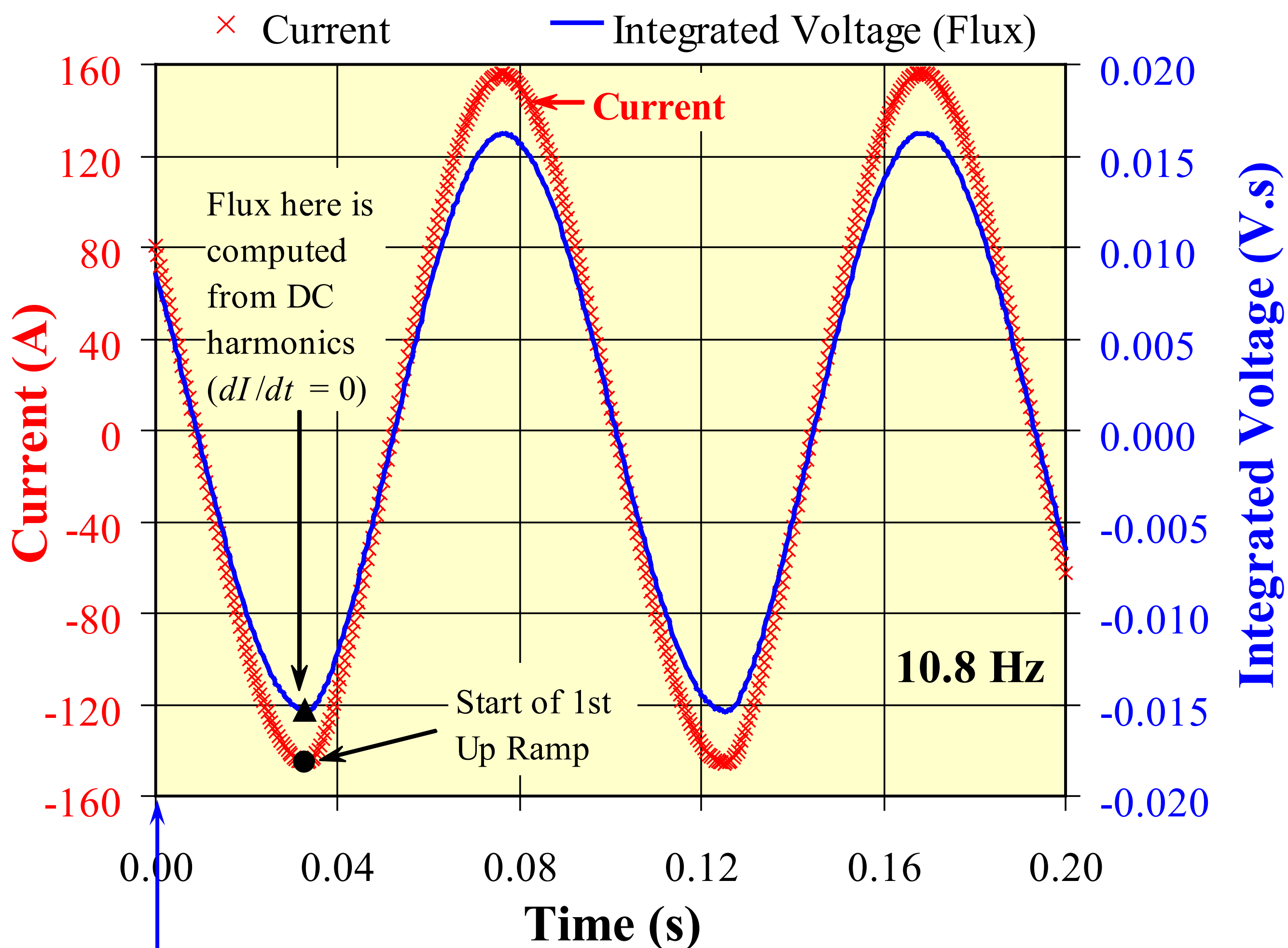
Voltage Offsets ⇒ Drift in harmonics
Corrected by checking cycle-to-cycle drift

Earlier measurements had used 16-bit ADCs for data acquisition. These have been replaced by an array of 17 HP3458A voltmeters for better resolution (*Many were borrowed for these measurements!*)

Typical Signal for Linear Ramps (GSI Dipole)



Typical Signal for Sinusoidal Ramps (BioMed)



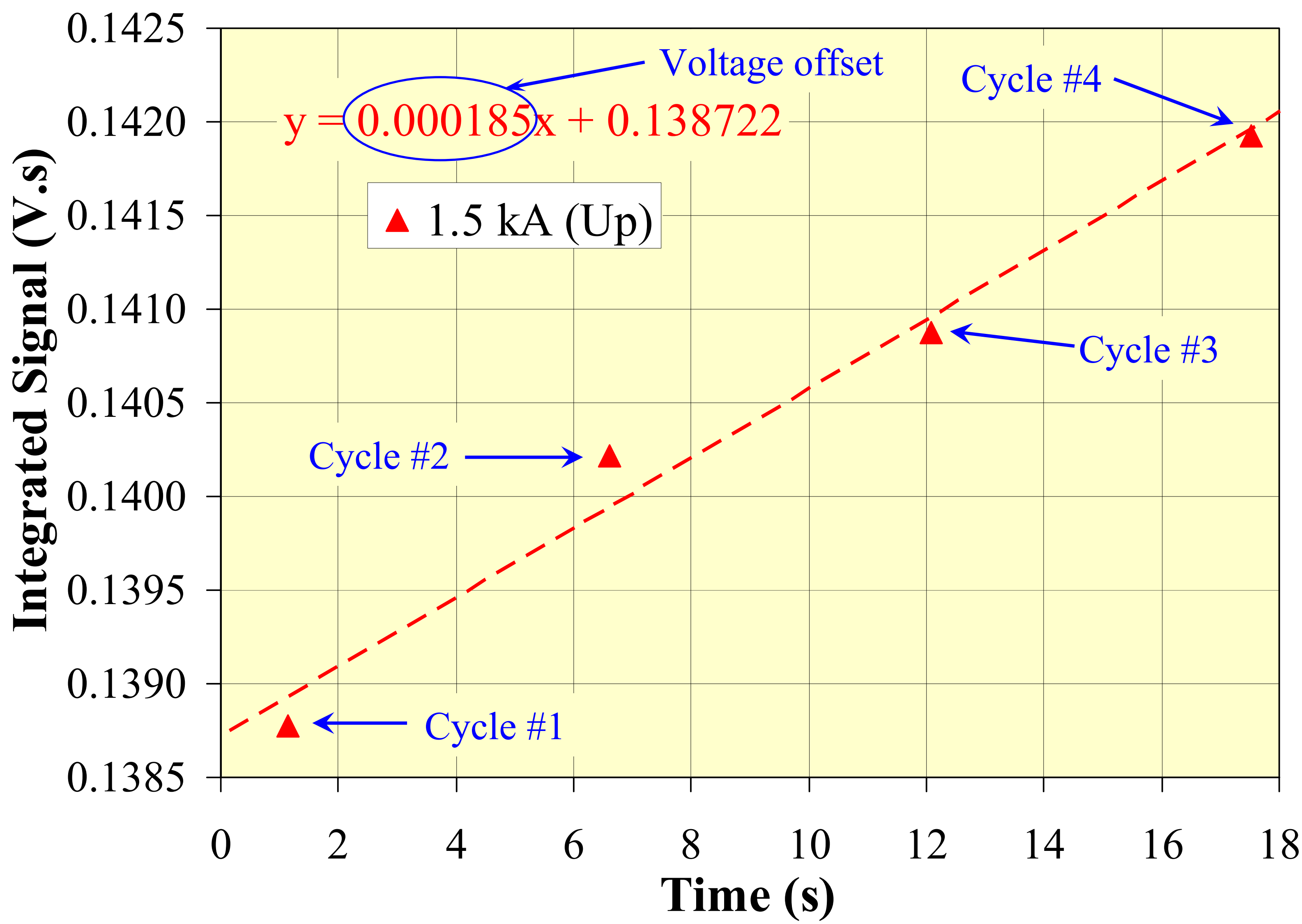
Typically, many cycles must elapse before the supply and the magnet are stabilized.

Can not use the DC harmonics at the start of ramps.

Use DC harmonics at the maximum negtive current, where dI/dt is zero.

Data acquisition starts at an arbitrary point after ~30 precycles and covers 10 cycles.

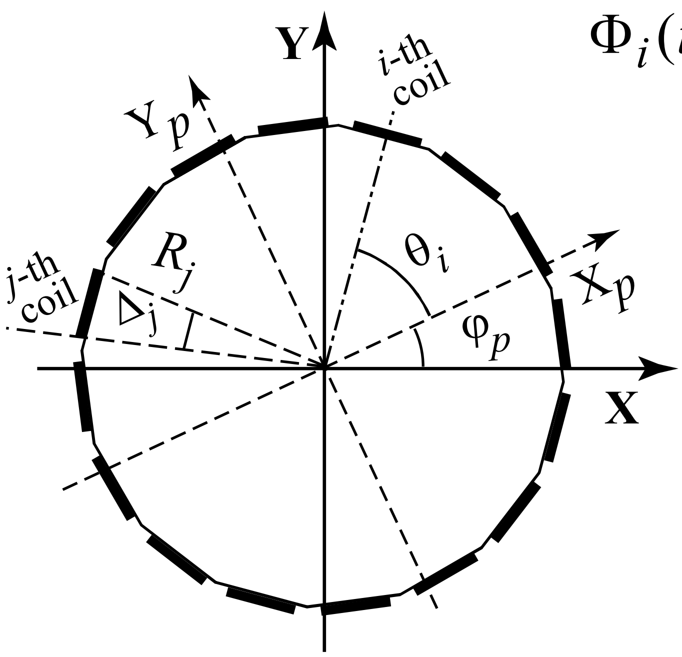
Offset Correction (GSI Dipole at 2 T/s)



Higher Harmonics and Aliasing

- With 16 signals, only a few lower order harmonics can be measured.
- Higher order harmonics are required, for example, to center the data in a dipole.
- The lower order terms may have errors also due to aliasing from higher order harmonics.
- Real solution is to have more coils, but it may be impractical due to physical size limitations and data acquisition cost.
- We have used a scheme to effectively double the number of angular positions by doing measurements with two angular positions of the probe.
- Interpolation at fixed currents is used to combine data from different runs, which may not have identical ramps.

Signals With Probe Rotated by an Angle



$$\Phi_i(t) = \int_0^t V_i(t)\cdot dt + \Phi_i(0)$$

$$= \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left(\frac{R_i}{R_{ref}} \right)^n \sin\left(\frac{n\Delta_i}{2} \right)$$

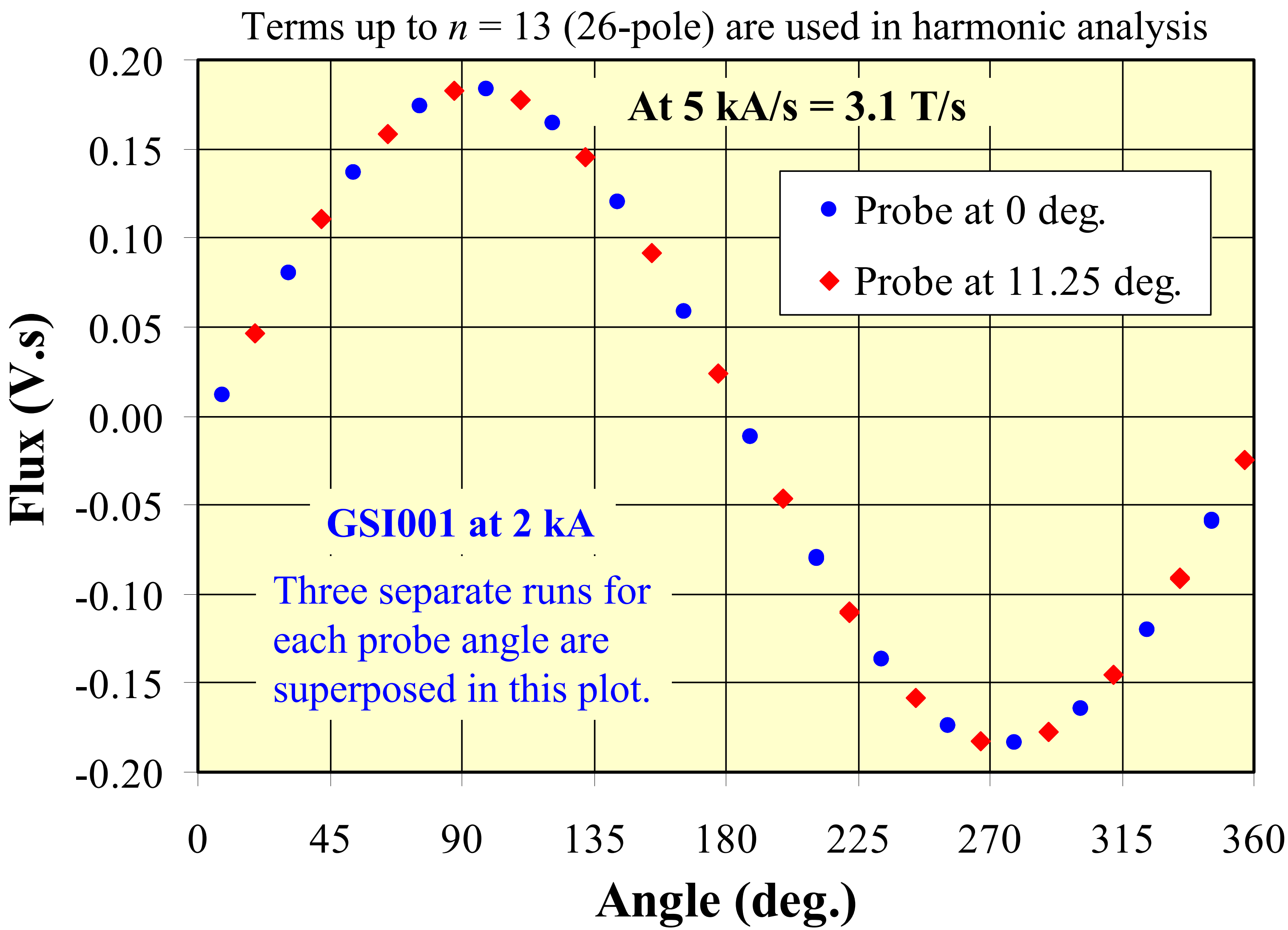
$$\times \left[B_n(t)\sin(n\theta_i + n\varphi_p) + A_n(t)\cos(n\theta_i + n\varphi_p) \right]$$

We have used $\varphi_p = 0$ and $\varphi_p = 11.25$ deg. (nom.)

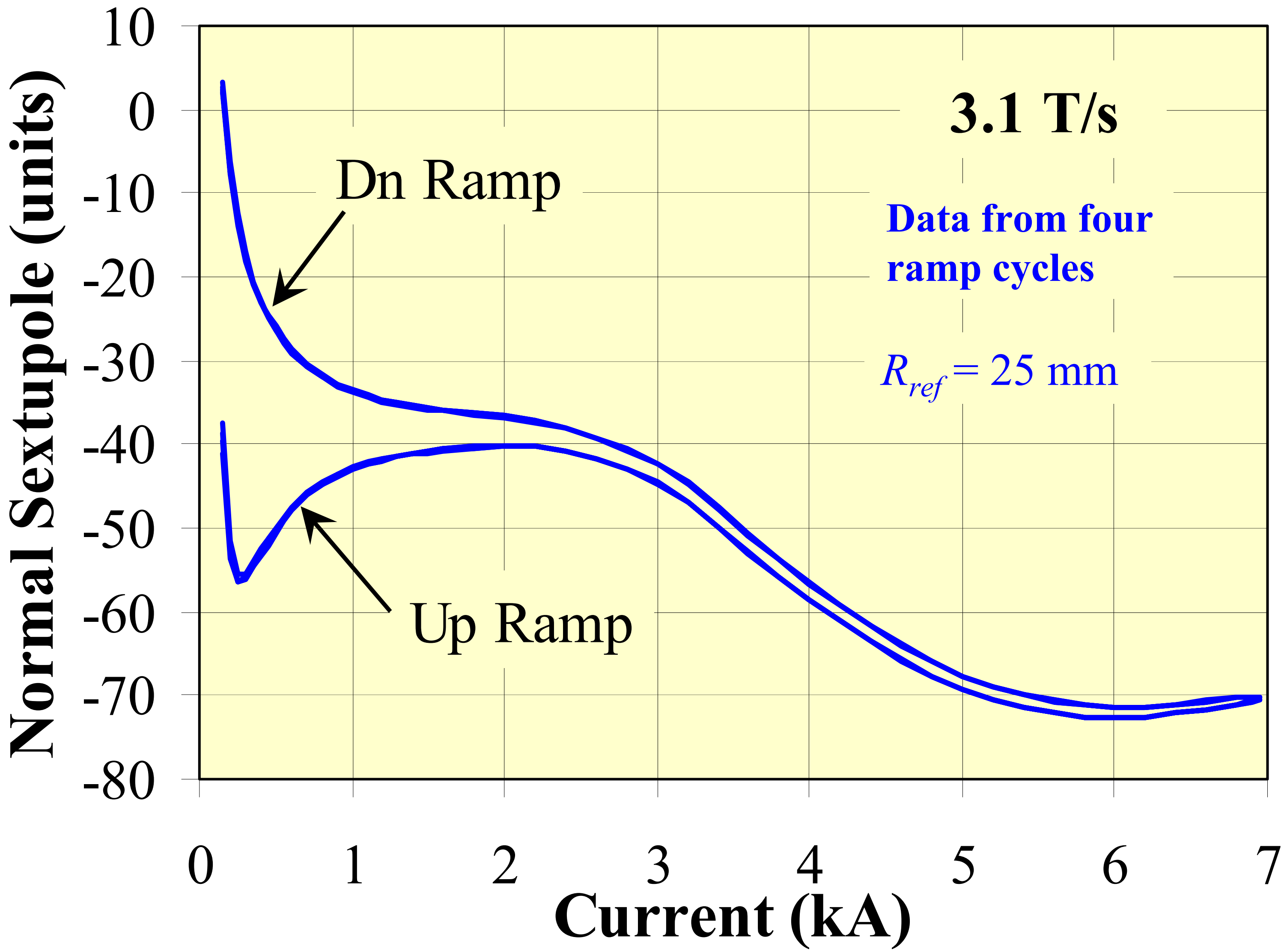
Exact angles were measured using angle encoder.

- X-Y is the "measurement" frame, and is fixed in space.
- X_p-Y_p is the "probe" frame and coincides with the measurement frame when the probe is positioned using an index pulse from the angle encoder.
- The geometric parameters of the coils are known in the probe frame.

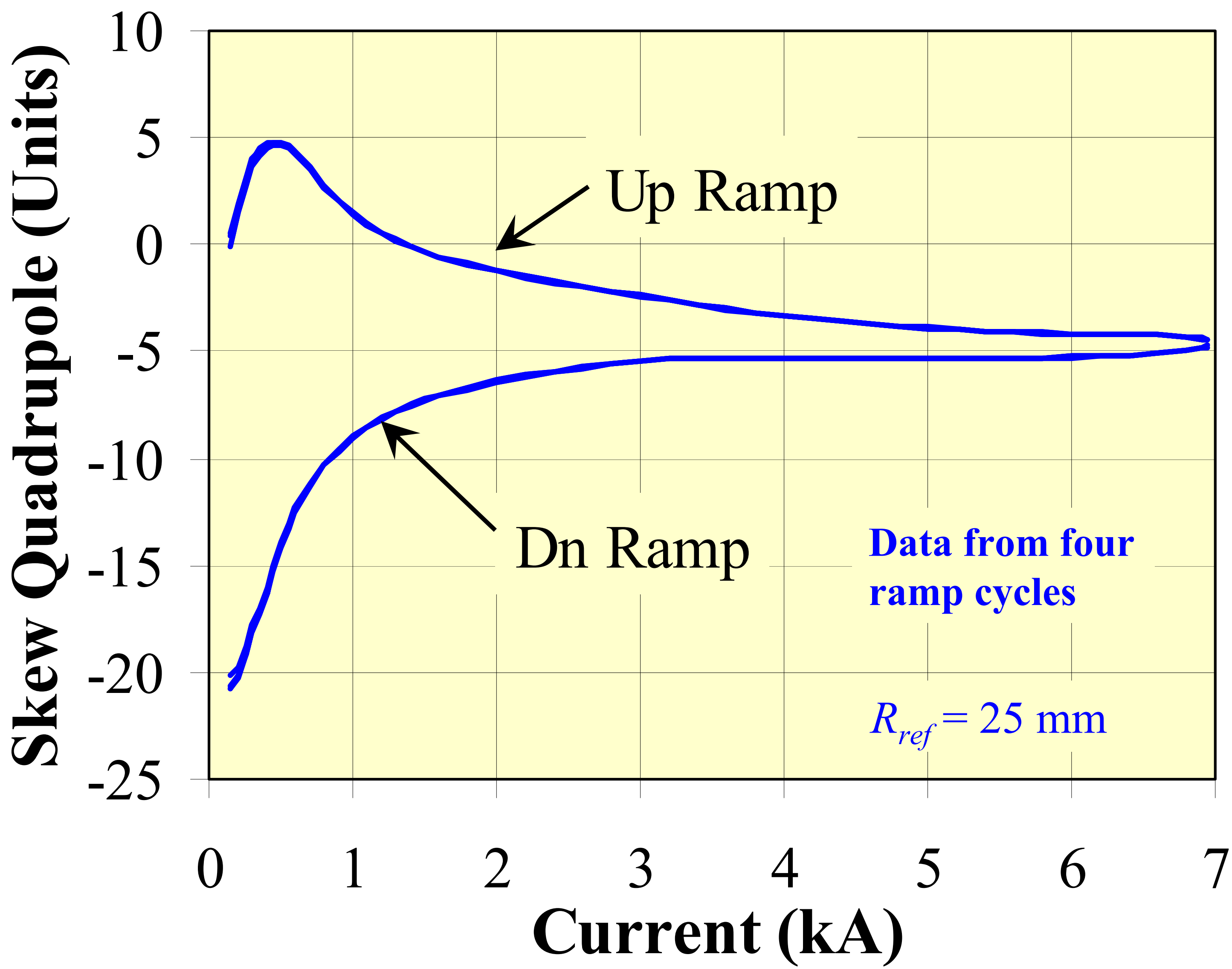
Typical Angular Profile (2×16 points)



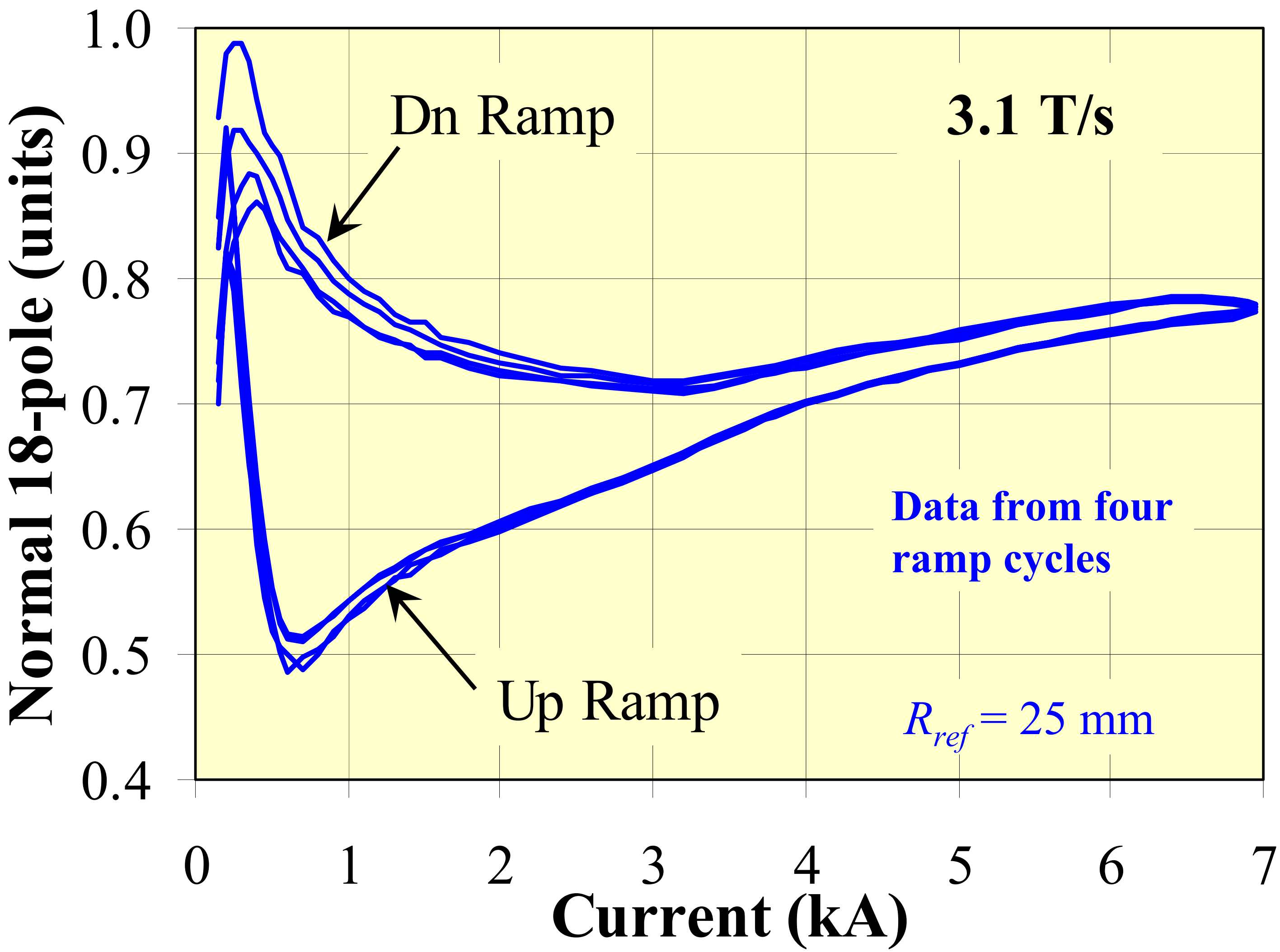
Cycle-to-Cycle Reproducibility (Sextupole)



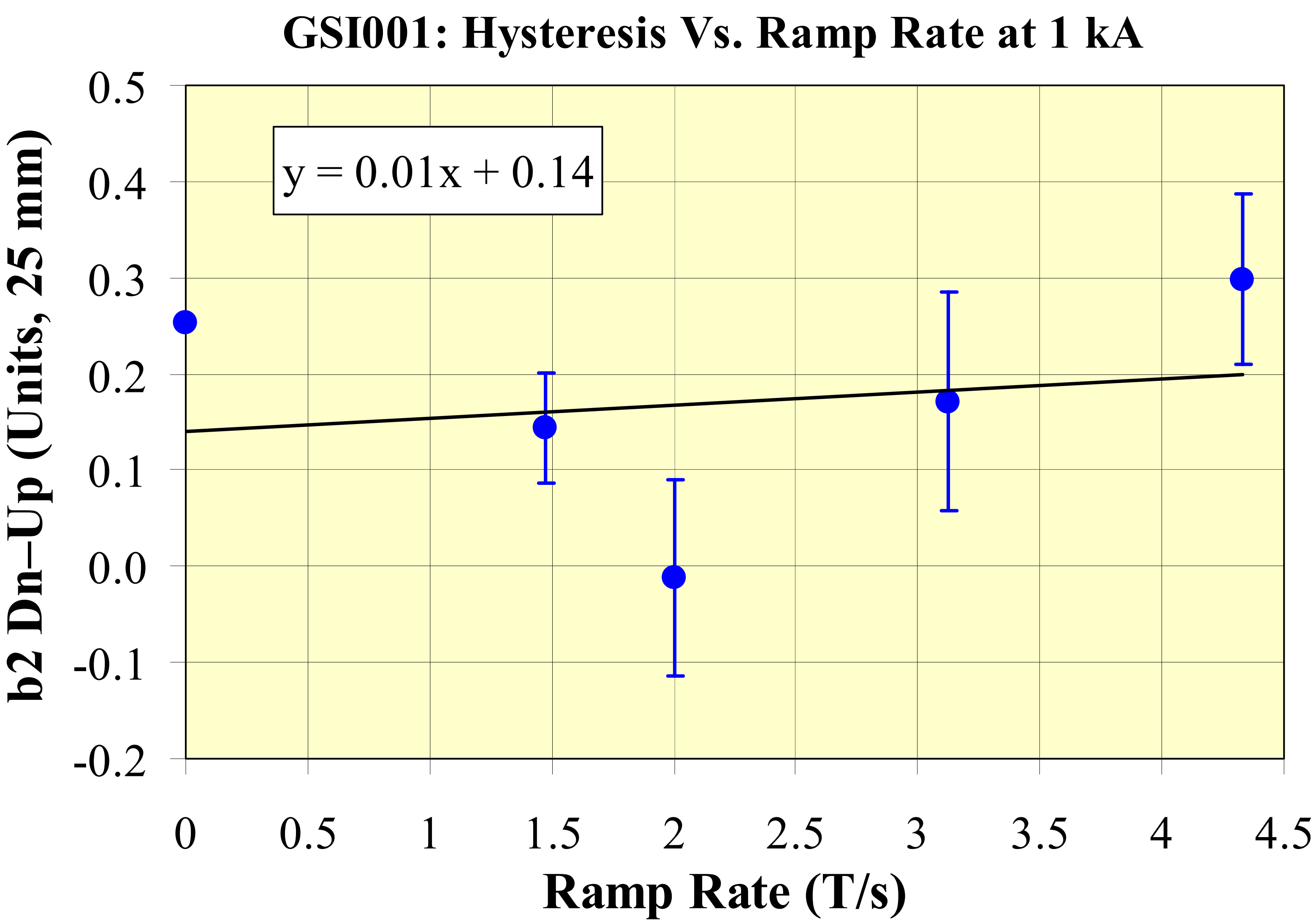
Cycle-to-Cycle Reproducibility (Skew Quadrupole)



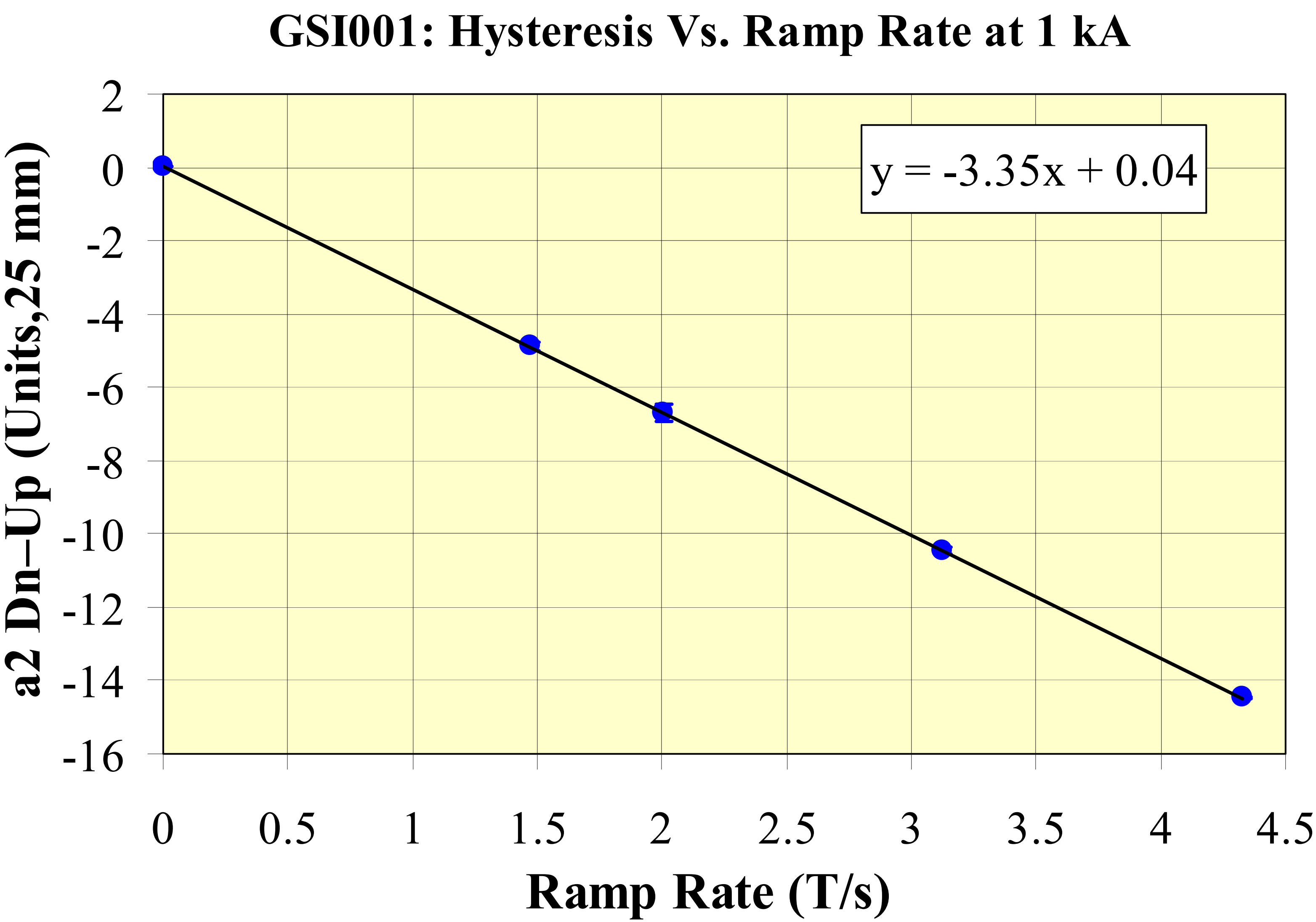
Cycle-to-Cycle Reproducibility (18-pole)



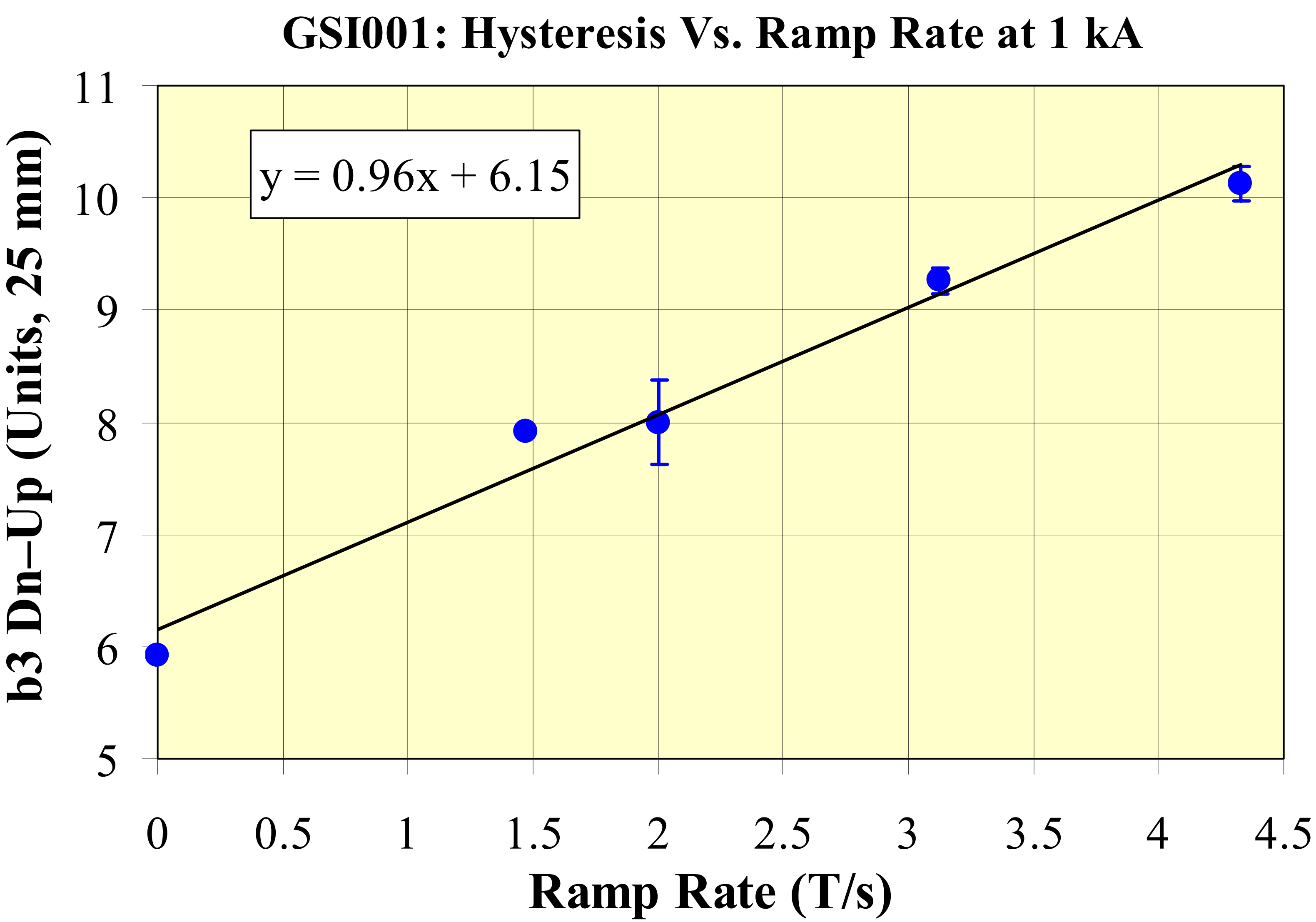
Ramp Rate Dependence: Normal Quadrupole



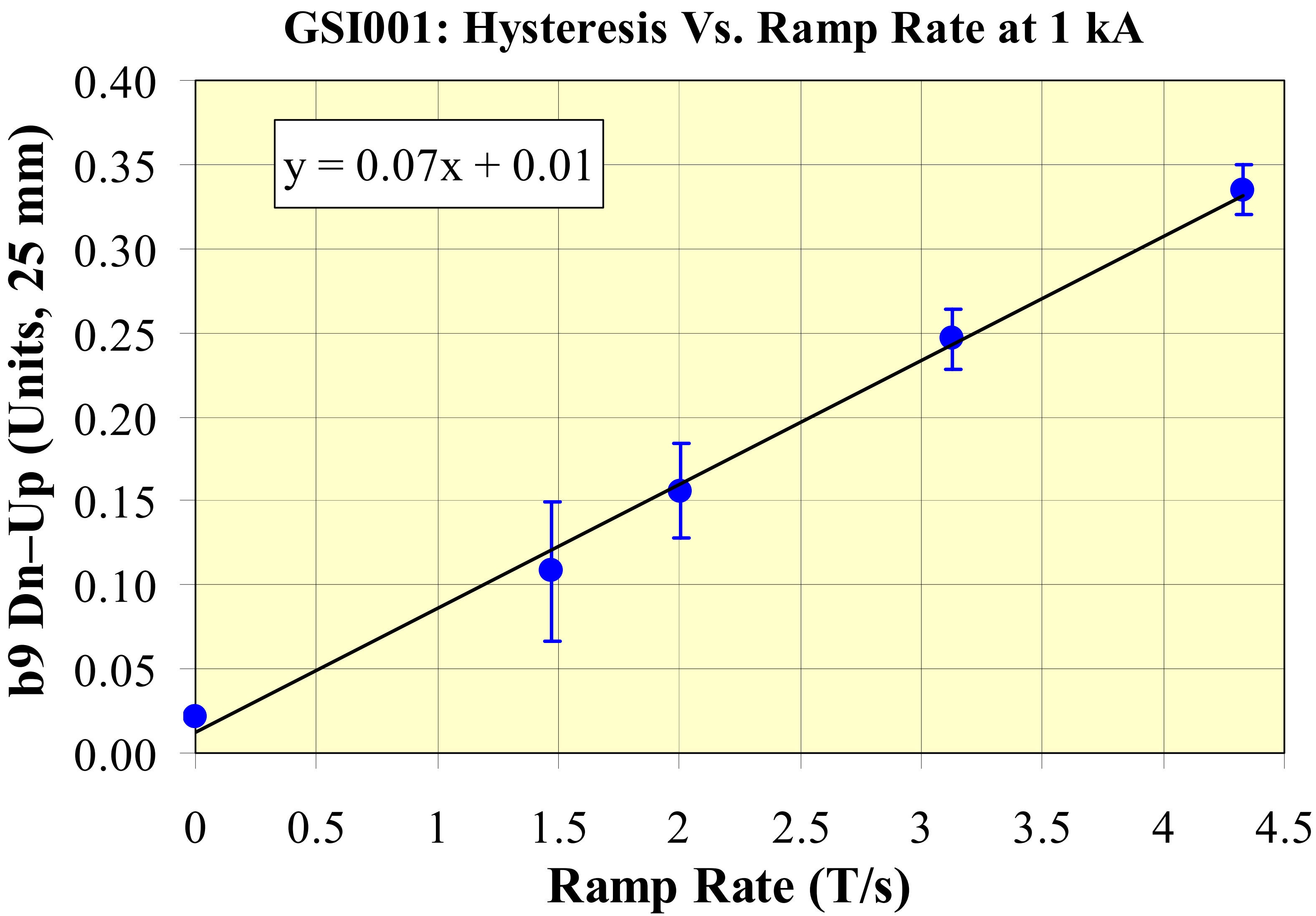
Ramp Rate Dependence: Skew Quadrupole



Ramp Rate Dependence: Normal Sextupole



Ramp Rate Dependence: Normal 18-pole



Ramp Rate Dependence in GSI001 at 1 kA

n	Slope (units/Ts^{-1})		Intercept (units)	
	Normal	Skew	Normal	Skew
2	0.01	-3.35	0.14	0.04
3	**0.96**	0.51	**6.15**	0.14
4	-0.19	-2.07	-0.01	0.11
5	**1.60**	-0.01	**0.71**	0.02
6	-0.07	-0.31	0.03	0.09
7	**0.42**	-0.02	**0.42**	-0.04
8	-0.04	0.00	0.00	-0.02
9	**0.07**	0.00	**0.01**	-0.03
10	-0.02	0.00	-0.02	0.02
11	**0.07**	-0.02	**0.07**	0.04
12	-0.02	0.00	0.05	0.00
13	**-0.03**	0.00	**0.06**	-0.08

Bold = Allowed Terms

Summary

- Field quality measurements at high ramp rates (> 1 T/s) can be made using an array of stationary coils.
- Data analysis schemes were presented for both linear ramps as well as sinusoidal ramps.
- It may be difficult and expensive to incorporate the number of coils required for accurate, reliable measurements of harmonics.
- Multiple orientations of a probe with fewer coils can be used to overcome aliasing, and to achieve the desired accuracy.
- Interpolation of data at fixed currents considerably simplifies the requirement of having identical ramps in different runs.
- Measurement of higher harmonics allows centering of data.
- Results in a prototype GSI dipole show that the noise in the measurement of harmonics is ~0.1 unit at 25 mm.