Recent Magnetic Measurement Activities at BNL

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Introduction

- Magnetic measurement activities at BNL can be generally classified into three classes, based on the type of magnets measured:

  (a) Superconducting Magnets (RHIC, LHC, DESY)

  (b) Conventional Magnets (Spallation Neutron Source)

  (c) Insertion Devices (G. Rakowsky, National Synchrotron Light Source at BNL)

- This talk will focus primarily on the recent developments carried out in response to special measurement needs in some superconducting magnets.

Recent Measurements at BNL in Superconducting Magnets

- "Fast" Measurements for Dynamic Effects
(*500 μs to 2 sec time resolution; Time decay, snapback, eddy current effects.*)
- Helical Dipoles for the RHIC Spin Physics Program
(*Unusual 3-D field throughout.*)
Another talk at IMMW12.
- Post-RHIC "Routine" measurements
(HERA upgrade magnets, LHC twin aperture dipole prototypes.) **Not covered in this talk.**

“Fast” Measurements: Dynamic Effects

- Time decay of allowed harmonics at injection, and snapback on resuming the ramp, are well known problems in the use of superconducting magnets in accelerators.
- Typical time decay of harmonics is rather slow several minutes after reaching the injection current. However, the initial decay is much faster.
- Snapback occurs very rapidly, typically over a few seconds.
- Rotating coil systems in routine use at BNL for DC measurements have a period of ~3.5 sec. and can take approx. one reading every minute. A better time resolution is clearly needed to study the dynamic effects.

“Fast” Measurements: Hardware Issues

- Harmonics are measured during one rotation of the coil. Coil should spin as fast as possible to minimize “measurement time”.

  BNL uses voltmeters, with one power line cycle integration for noise rejection. This limits rotational speed.

  No. of angular points reduced from 128 to 64 (or 32) to gain a factor of 2 (or 4) in speed.

- Dead time between measurements should be eliminated, thus providing a nearly continuous time map of the harmonics.

  Modify software to keep acquiring data continuously and storing it in the voltmeters, rather than transfering it to the PC.

  Amount of data limited by 4K memory of timer card, which stores coil speed information. This memory could not be increased.

Coil Rotation Parameters

- **Two sets of parameters were used:**

(A) 32 angular positions, 16 time reads per revolution:
Allows T = 0.64 sec. to 1.0 sec.
Continuous data acquisition up to 256 revolutions.
Found unsatisfactory for higher order terms, but was OK for dodecapole in a quadrupole.

(B) 64 angular positions, 32 time reads per revolution:
Allows T = 1.28 sec. to 2.0 sec.
Continuous data acquisition up to 128 revolutions.
Satisfactory for harmonics measurements.

Dynamic Measurements: Analysis Issues

- Certain measurements, such as eddy current effects under ramping conditions, are required to be carried out while the current in the magnet is continuously changing.
- The conventional Fourier analysis, which is used for DC measurements, can not be used to calculate harmonics from the measured coil signals.
- In addition to the current, in general, the harmonics are also time dependent (due to time decay, snapback, superconductor magnetization, etc.)
- This makes a general treatment of the analysis quite difficult.

Approximate Analysis of Data

- A simplified scheme has been devised to analyze the data under the assumption that the *Normalized harmonics* are invariant during a single rotation of the coil. The absolute values of the harmonics (in Tesla, say) are thus proportional to the instantaneous current.

  The assumption is valid for moderate ramp rates and faster coil rotations.
- The scheme has the advantage of processing data on a rotation by rotation basis.
- The scheme uses Fourier analysis with some manipulations of the coil signal to account for the change in current during the measurements.

Tangential Coil Signal in a Varying Field

- **Field Expansion for the radial component:**

$$B_r(r,\theta,t) = \sum_{n=1}^{\infty} C(n,t)\left(\frac{r}{R_{ref}}\right)^{n-1} \sin[n\theta - n\alpha_n]$$

$C(n,t)$ = Instantaneous amplitude

α_n = phase angle, assumed constant over one rotation

R_{ref} = reference radius chosen for harmonics

- **Coil Parameters:**

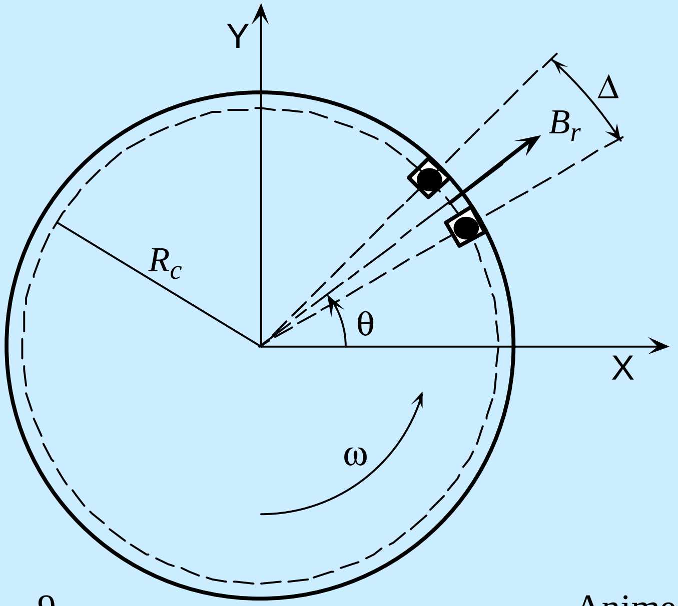
R_c = Radius of the coil

Δ = Opening angle

N = No. of Turns

L = Length

ω = Angular speed



Tangential Coil Signal in a Varying Field

- **Flux through a Tangential Coil:**

$$\Phi(t) = \sum_{n=1}^{\infty} \left(\frac{1}{n}\right) G_n\, C(n,t)\ \sin(n\omega t + n\delta - n\alpha_n)$$

$$G_n = 2NLR_{ref} \left(\frac{R_c}{R_{ref}}\right)^n \sin\left(\frac{n\Delta}{2}\right) = \text{ Geometric Factor}$$

δ = coil angular position at $t = 0$ and $\theta = \omega t + \delta$.

- **Coil Voltage :**

$$V(t) = \left(\frac{d\Phi}{dt}\right) = \sum_{n=1}^{\infty} G_n \omega \left[C(n,t)\cos(n\omega t + n\delta - n\alpha_n) + \left(\frac{1}{n\omega}\right)\left(\frac{\partial C(n,t)}{\partial t}\right)\sin(n\omega t + n\delta - n\alpha_n)\right]$$

Tangential Coil Signal in a Varying Field

- **Define:**

$$I_{avg} = \text{Average current during one rotation of the coil}$$

$$C_{avg}(n) = \text{Harmonic strength corresponding to } I_{avg}$$

$$R(t) = \left(\partial I/\partial t\right) = \text{ Ramp Rate at time } t$$

- **In terms of these quantities:**

$$V(t) = \sum_{n=1}^{\infty} G_n \,\omega\, C_{avg}(n) \left[\left\{ \frac{I(t)}{I_{avg}} \right\} \cos(n\omega t + n\delta - n\alpha_n) + \left\{ \frac{R(t)}{I_{avg}\, n\omega} \right\} \sin(n\omega t + n\delta - n\alpha_n) \right]$$

Tangential Coil Signal in a Varying Field

$$V(t) = \sum_{n=1}^{\infty} G_n \omega C_{avg}(n) \left[\left\{ \frac{I(t)}{I_{avg}} \right\} \cos(n\omega t + n\delta - n\alpha_n) + \left\{ \frac{R(t)}{I_{avg}\, n\omega} \right\} \sin(n\omega t + n\delta - n\alpha_n) \right]$$

- $V(t)$, in general, is NOT a periodic function of time.
- Coefficients of sine and cosine terms are not constants. Thus the above expansion is NOT a Fourier series.
- Goal is to obtain the quantities $C_{avg}(n)$ and α_n from $V(t)$, assuming that the current and ramp rate profiles, $I(t)$ and $R(t)$, are known.

Manipulating the Coil Signal

$$V(t)\left\{\frac{I_{avg}}{I(t)}\right\} - \sum_{n=1}^{\infty} G_n \omega C_{avg}(n) \left\{\frac{R(t)}{I_{avg}\, n\omega}\right\} \sin(n\omega t + n\delta - n\alpha_n)$$

$$= \sum_{n=1}^{\infty} G_n \omega C_{avg}(n) \cos(n\omega t + n\delta - n\alpha_n)$$

- The right hand side represents a Fourier series.
- If the coil signal, $V(t)$, is modified as expressed on the left hand side, a simple Fourier analysis can be used to obtain $C_{avg}(n)$ and α_n.
- Problem is that this manipulation itself requires the knowledge of $C_{avg}(n)$ and α_n. This problem is solved by using an iterative procedure.

Iterative Procedure

$$V(t)\left\{\frac{I_{avg}}{I(t)}\right\} - \sum_{n=1}^{\infty} G_n \omega C_{avg}(n)\left\{\frac{R(t)}{I_{avg}\, n\omega}\right\}\sin(n\omega t + n\delta - n\alpha_n)$$

$$= \sum_{n=1}^{\infty} G_n \omega C_{avg}(n)\cos(n\omega t + n\delta - n\alpha_n)$$

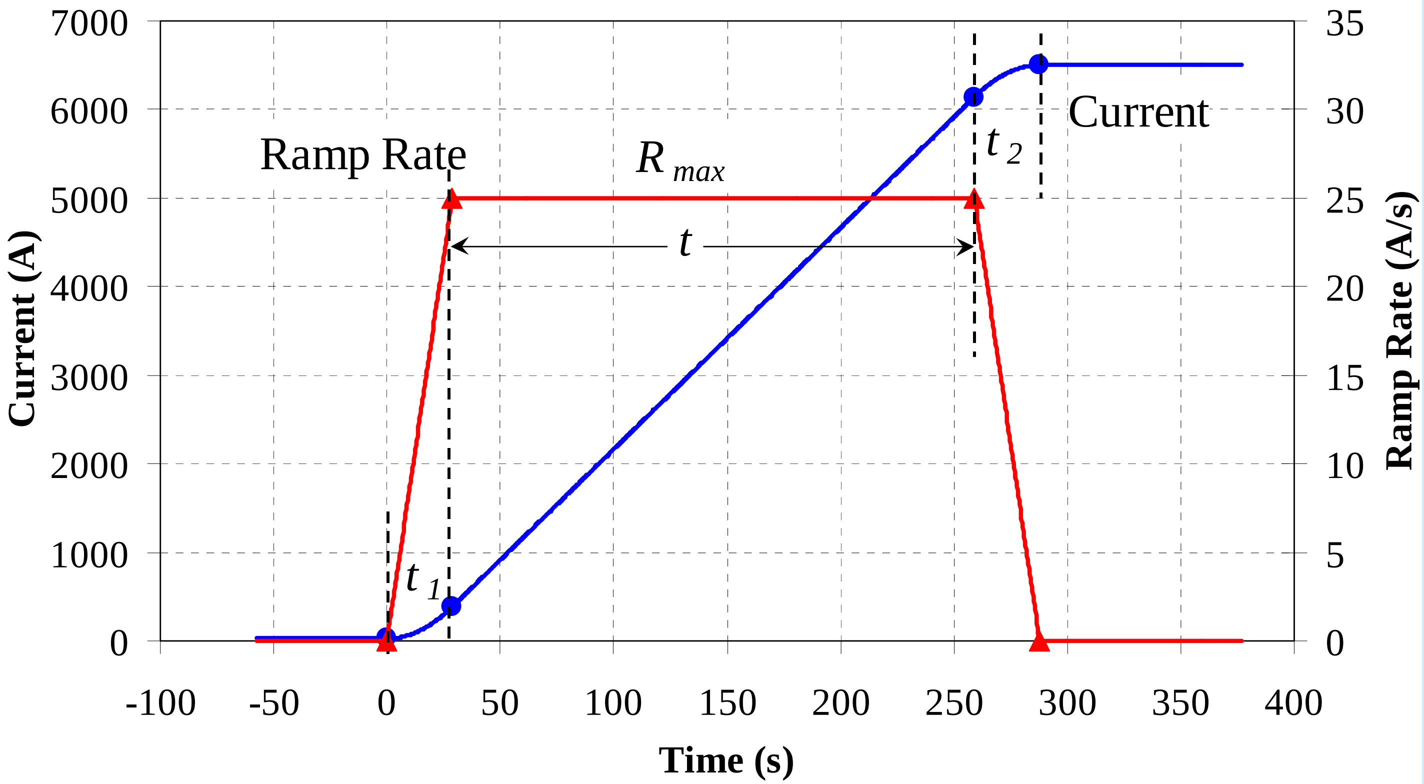
- Approximate values of $C_{avg}(n)$ and α_n are first obtained by neglecting the second term on the left hand side.
- The approximate $C_{avg}(n)$ and α_n are then used on the left hand side to obtain new values of $C_{avg}(n)$ and α_n.
- The process is continued until a convergence is reached. Typically, three or four iterations are sufficient.

Current Ramps

- Must avoid undershoots and overshoots.
- Two types: “Quadratic” and “Exponential”.
- “Quadratic”: Current Vs time has only linear and quadratic segments.
- “Exponential”: Current Vs time has linear, quadratic and exponential segments.
- Down ramps are always “Quadratic”.

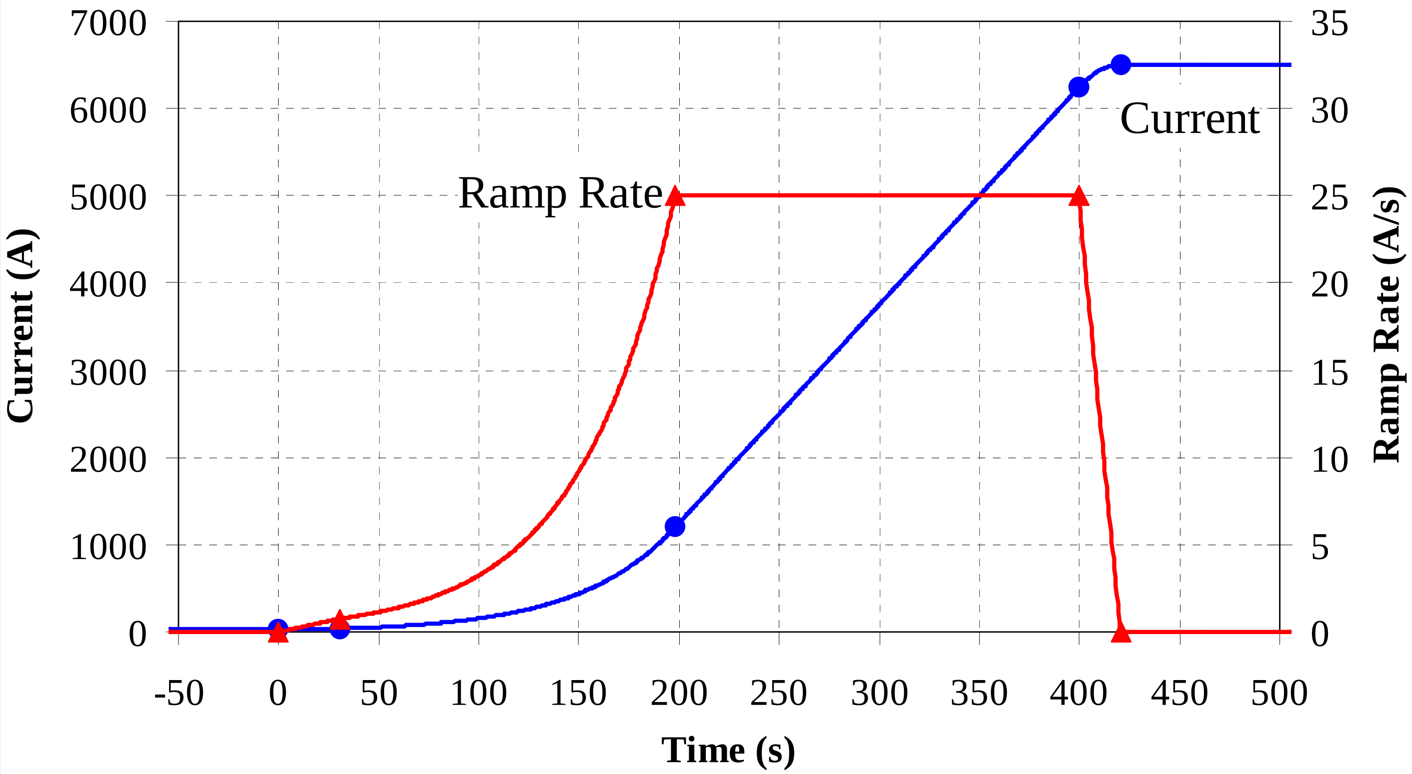
Quadratic Current Ramps

- Ramp rate varies linearly with time from zero to R_{max} in time t_1, stays constant at R_{max} for time t, then goes linearly to zero in time t_2.
- Characterized by I_{min}, I_{max}, R_{max}, $f_1 = t_1/(t_1+t+t_2)$ and $f_2 = t_2/(t_1+t+t_2)$
- Typically, $f_1 = f_2 = 0.05$ to 0.1

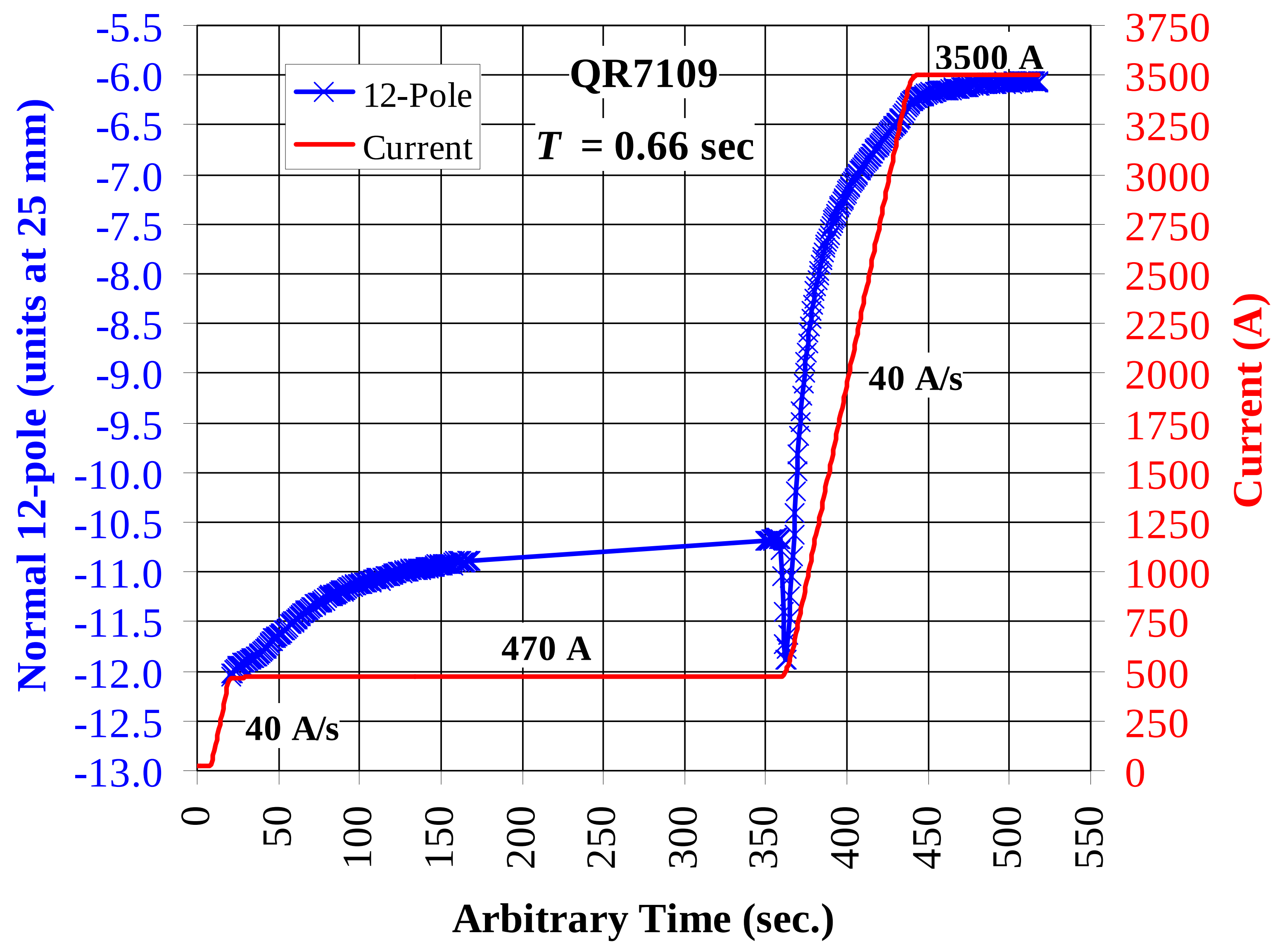


Exponential Current Ramps

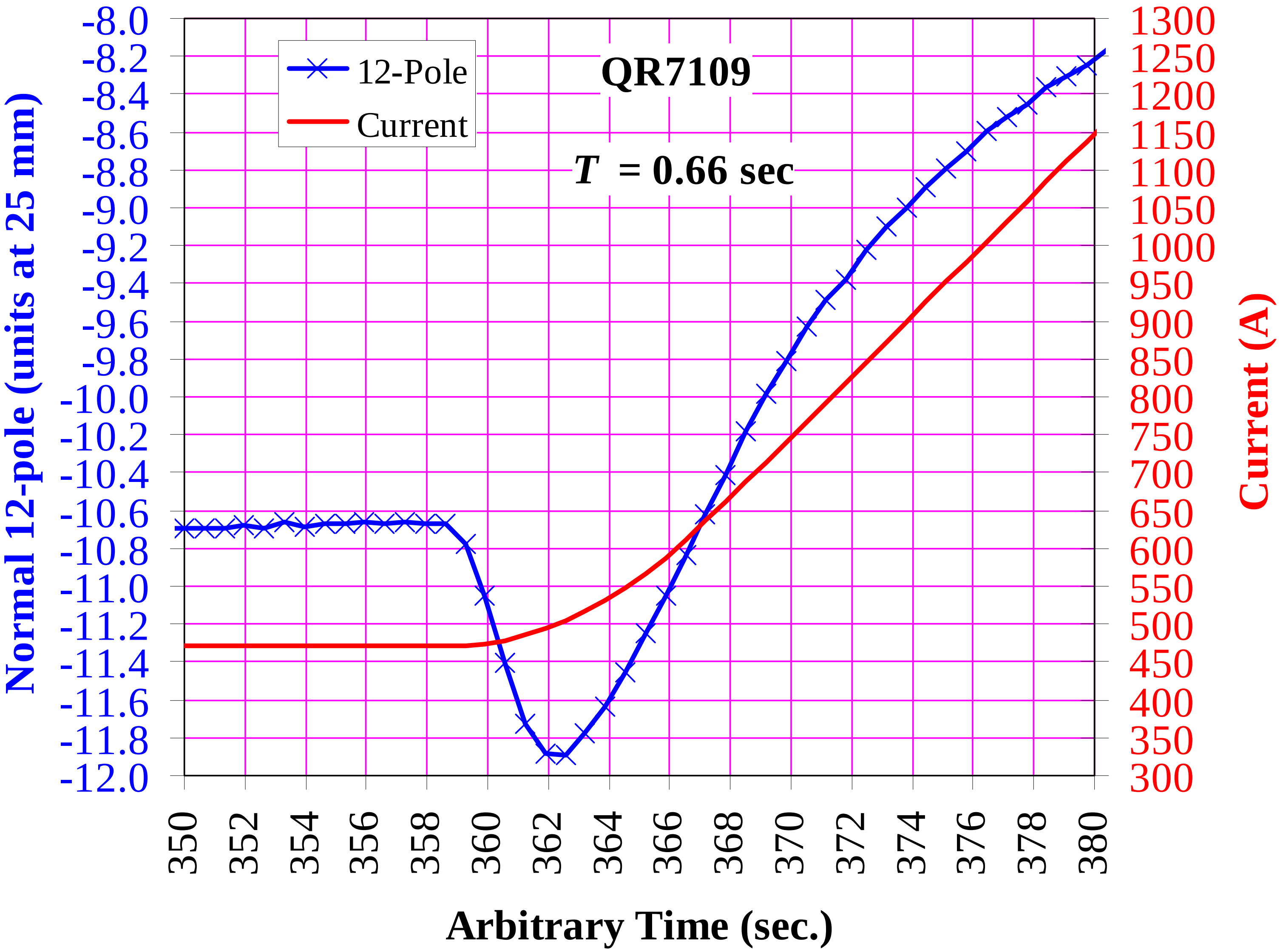
- Described in LHC Project Report 172, L. Bottura et al.
- Ramp rate varies linearly with time, then exponentially, then stays constant, then reduces linearly to zero.
- Characterized by I_{min}, I_{max}, $\Delta I_{sn\text{-}b}$, $R_{sn\text{-}b}$, R_{max}, $I_{exp\text{-}max}$ and f_4.
- Parameters need to be chosen carefully to generate meaningful profiles.



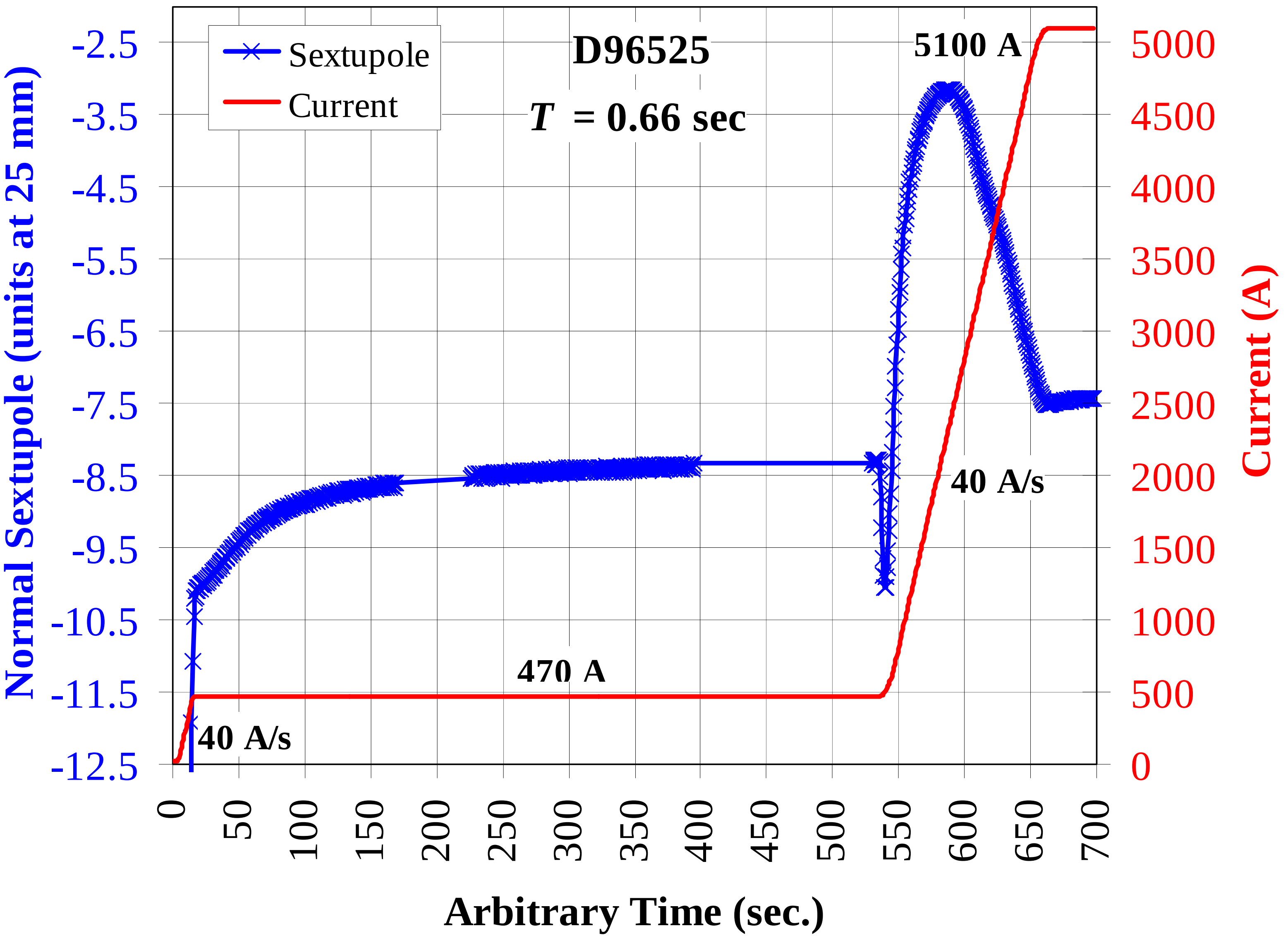
RHIC Quadrupole



RHIC Quadrupole

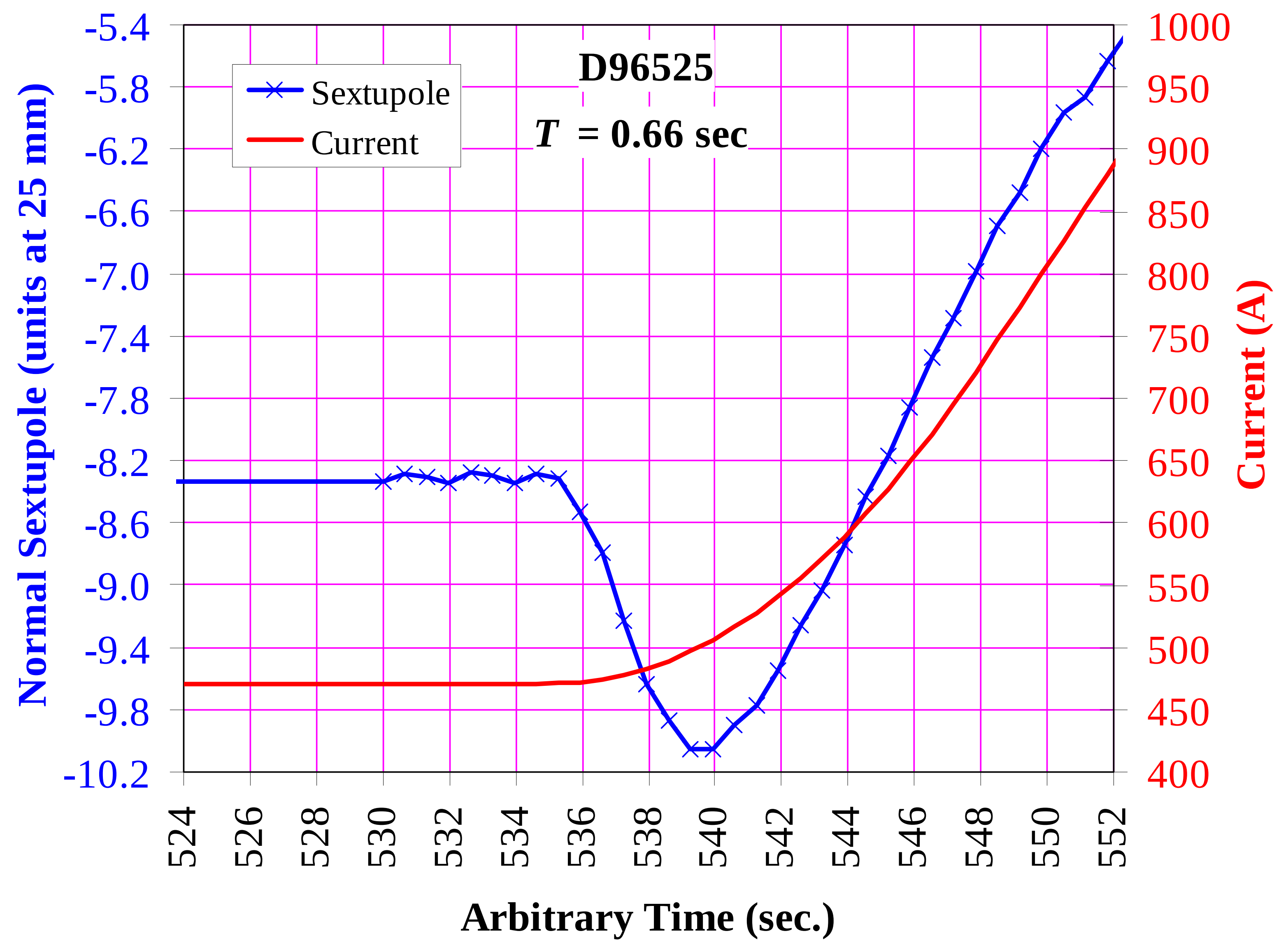


RHIC Dipole



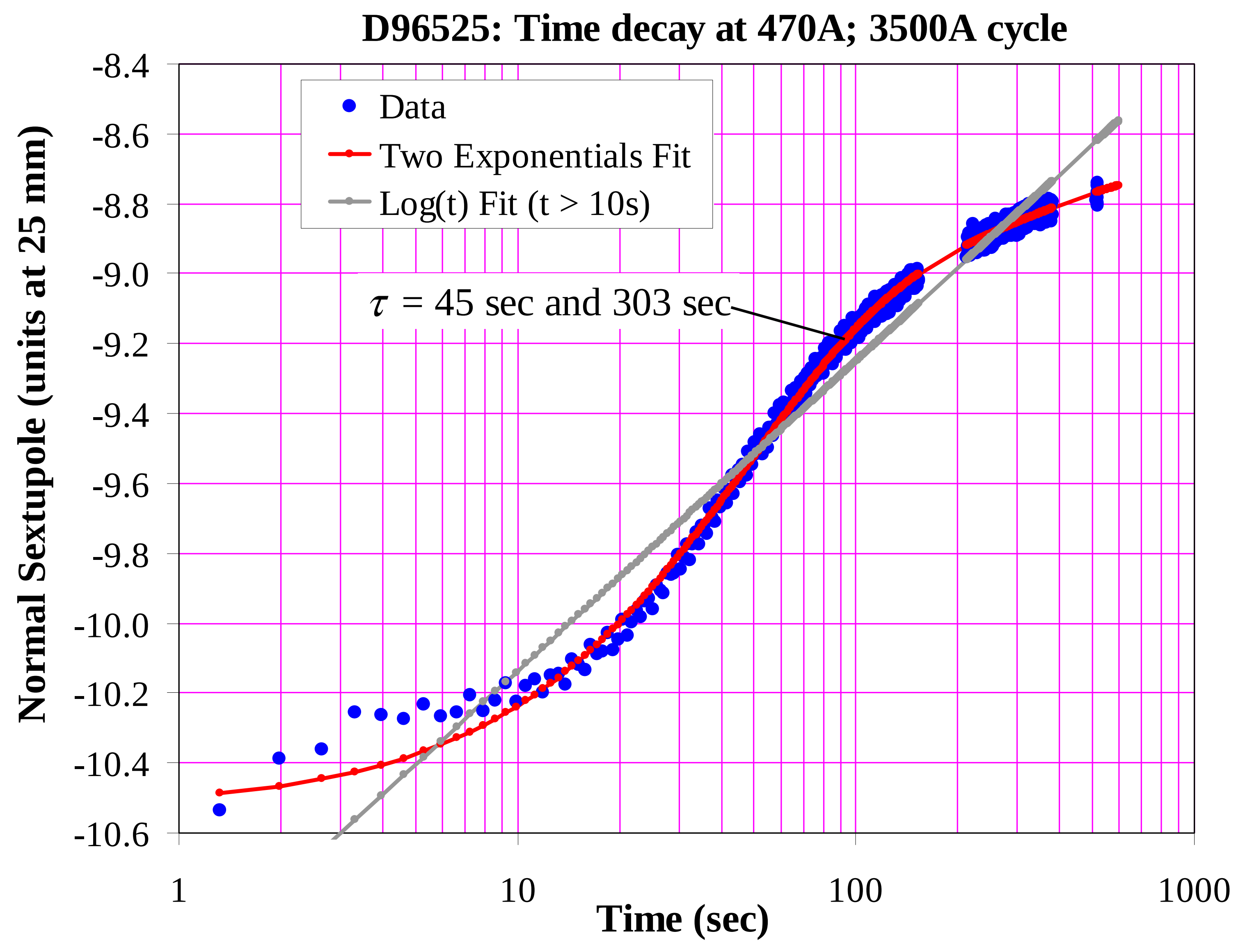
Sextupole
Current
D96525
T = 0.66 sec
5100 A
470 A
40 A/s
40 A/s
Normal Sextupole (units at 25 mm)
-2.5
-3.5
-4.5
-5.5
-6.5
-7.5
-8.5
-9.5
-10.5
-11.5
-12.5
Current (A)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Arbitrary Time (sec.)

RHIC Dipole

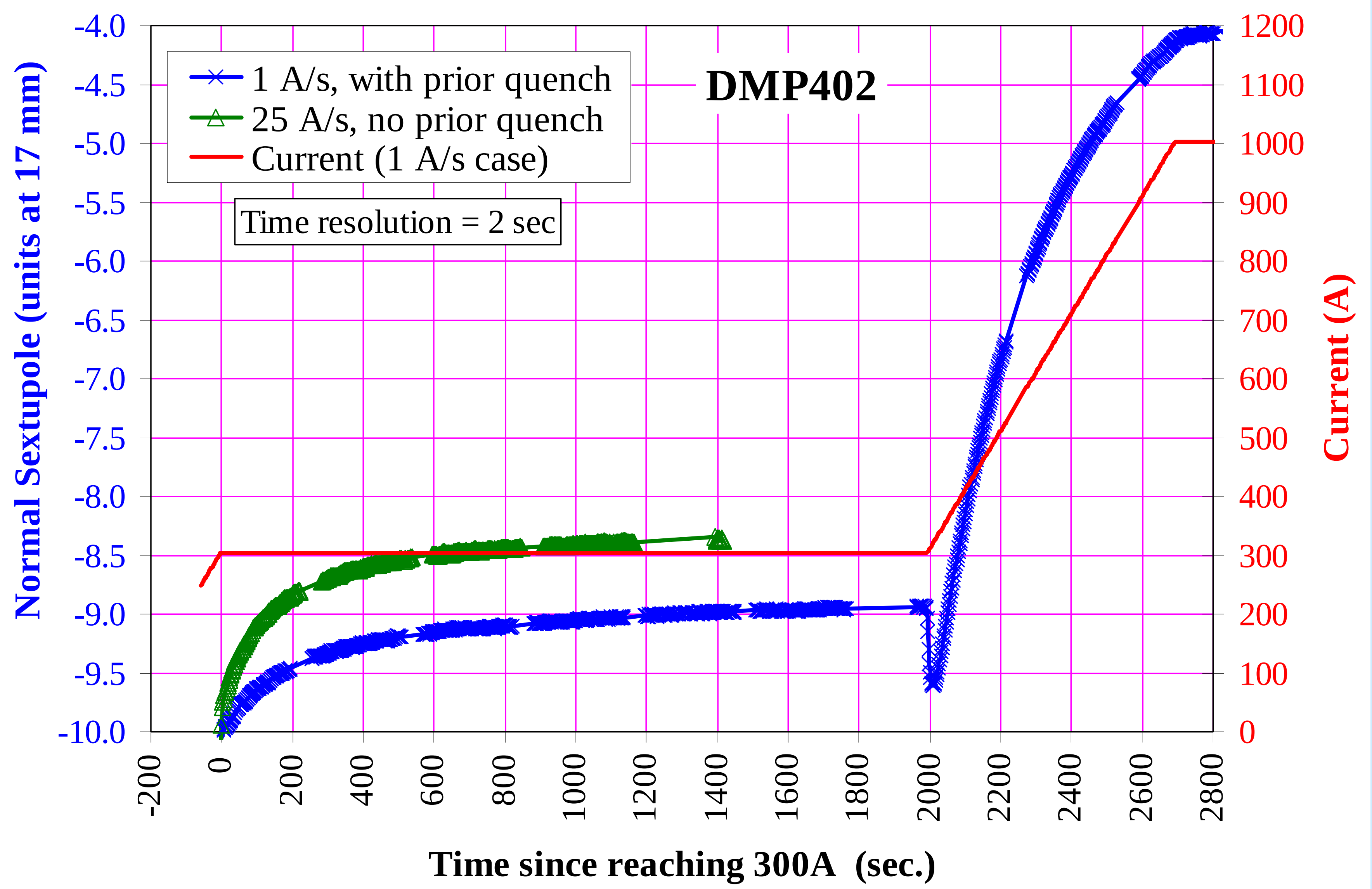


D96525
T = 0.66 sec
Sextupole
Current
Normal Sextupole (units at 25 mm)
-5.4
-5.8
-6.2
-6.6
-7.0
-7.4
-7.8
-8.2
-8.6
-9.0
-9.4
-9.8
-10.2
Current (A)
1000
950
900
850
800
750
700
650
600
550
500
450
400
524
526
528
530
532
534
536
538
540
542
544
546
548
550
552
Arbitrary Time (sec.)

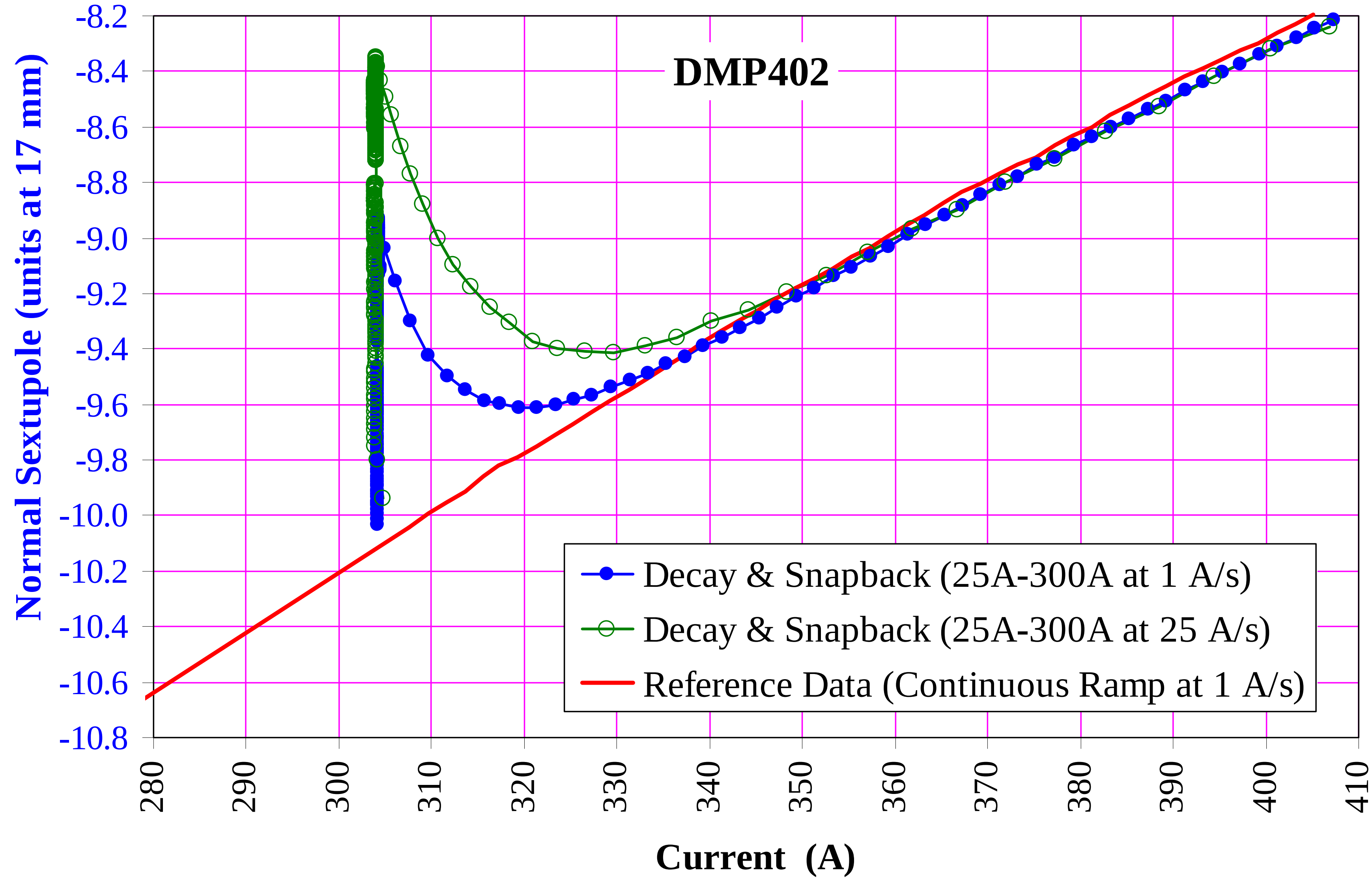
RHIC Dipole


D96525: Time decay at 470A; 3500A cycle
● Data
Two Exponentials Fit
Log(t) Fit (t > 10s)
τ = 45 sec and 303 sec
Normal Sextupole (units at 25 mm)
-8.4
-8.6
-8.8
-9.0
-9.2
-9.4
-9.6
-9.8
-10.0
-10.2
-10.4
-10.6
1
10
100
1000
Time (sec)

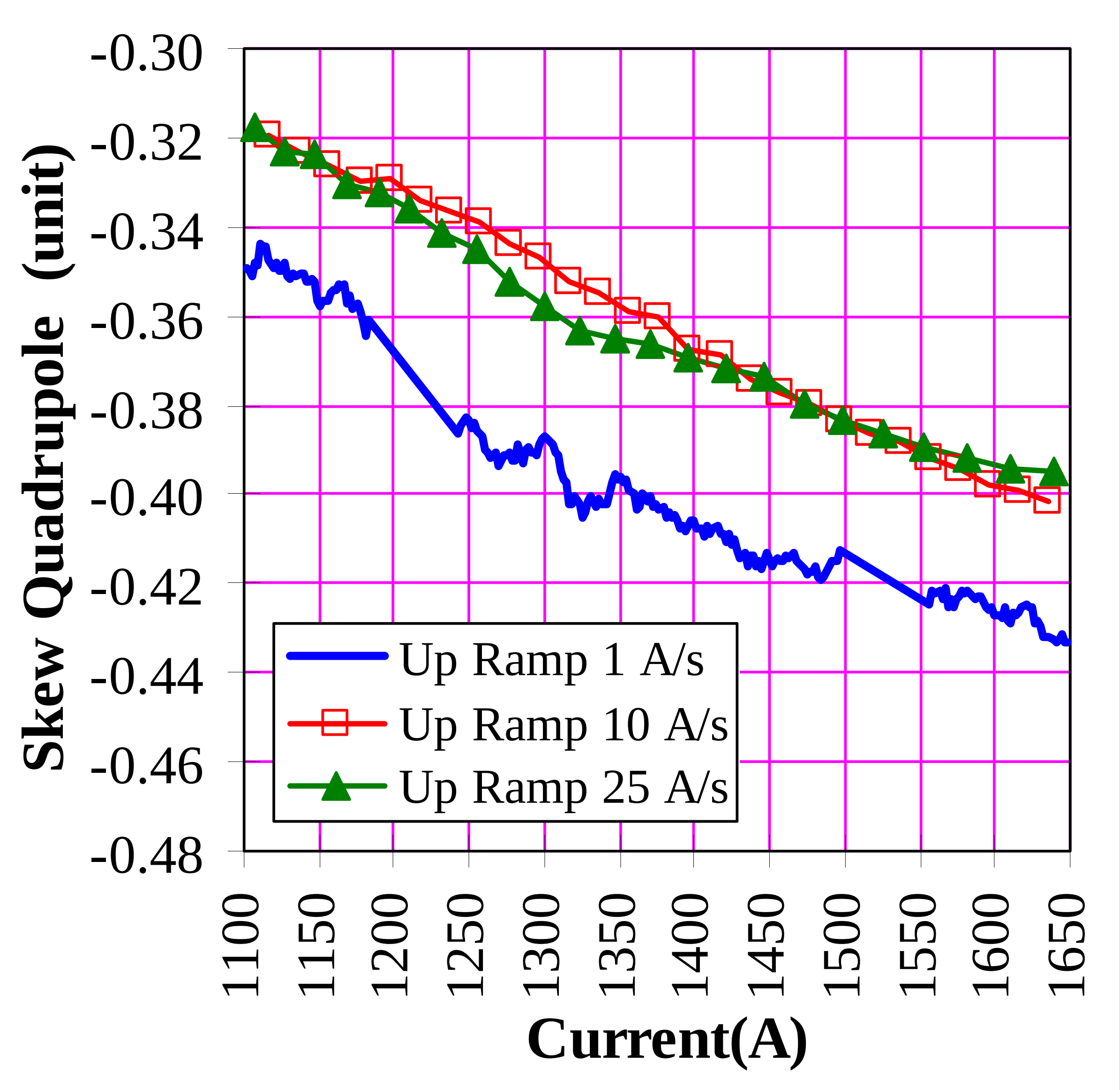
Prototype Twin Aperture Dipole for LHC



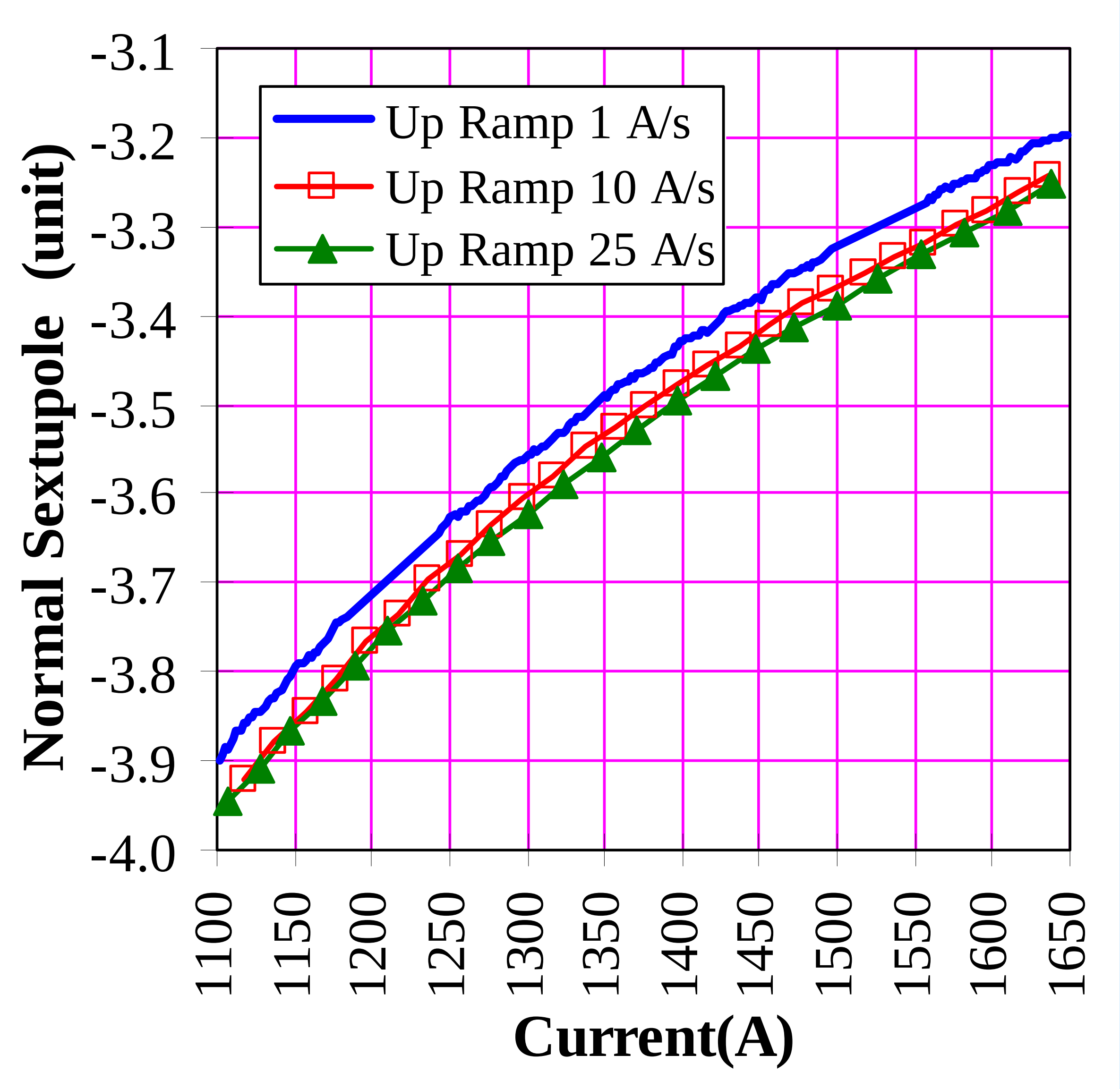
Prototype Twin Aperture Dipole for LHC



Eddy Current Effects in DMP402



Eddy Current Effects in DMP402



Eddy Current Effects at Very High Ramp Rates

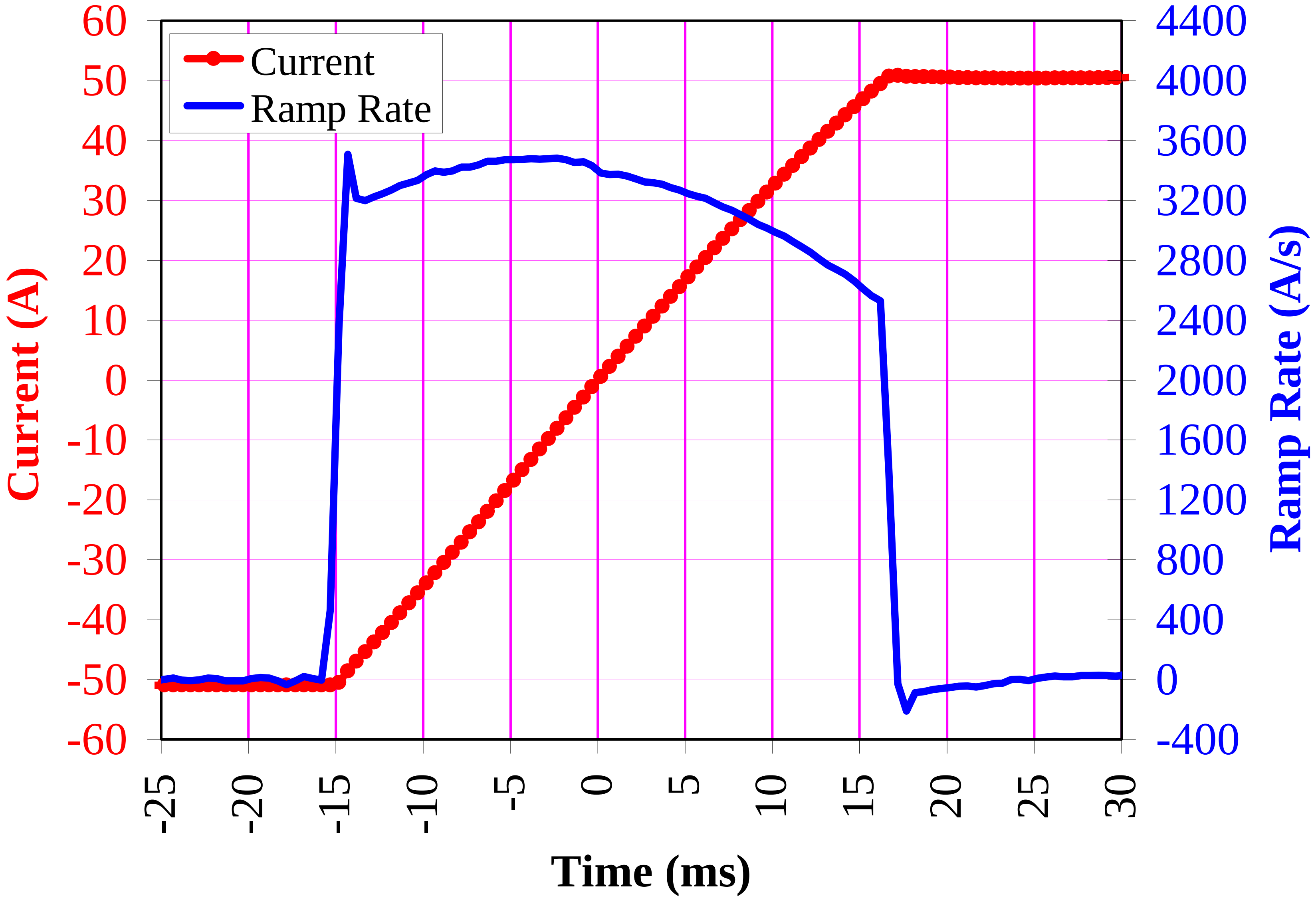
- Focus on Transfer Function, rather than harmonics.
- Measured using non-rotating coil.

Eddy Current Effects: γ_T Quads in RHIC

- RHIC has normal quadrupole correctors which are pulsed from +50A to –50A in approx. 30 ms as the beam crosses the transition energy.
- This amounts to a ramp rate of ~ 3300 A/s.
- It is important to know whether the quadrupole field lags the current due to eddy current effects.
- Difficult to measure harmonics with adequate time resolution using rotating coils.
- We have measured the quadrupole field strength using stationary quadrupole coils with a time resolution of 0.5 ms (500 μs).

Gamma-T Jump in CRF132; Run 41; March 28, 2001

Gamma-T Jump from –50A to +50A; Other Supplies at 0 A.



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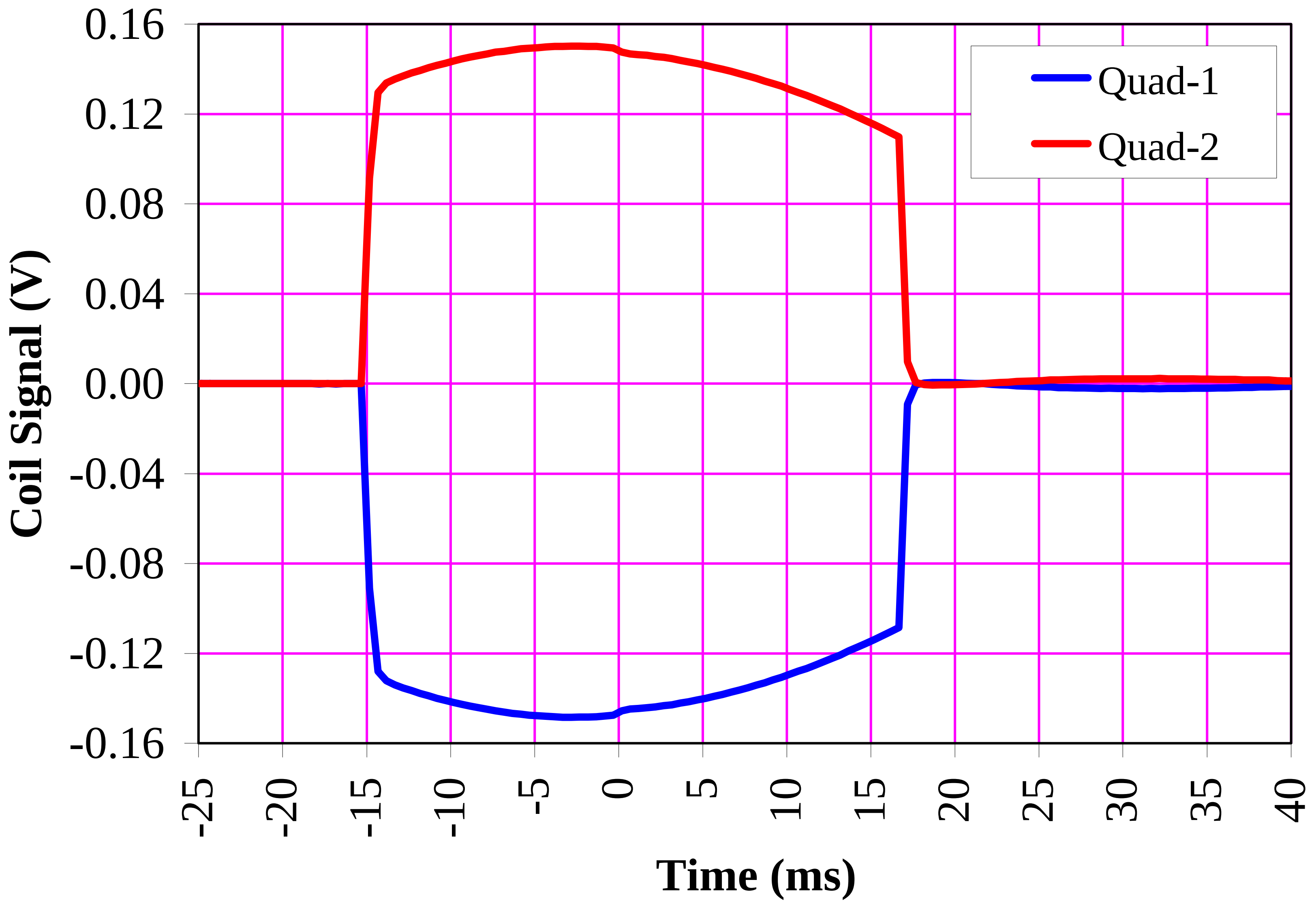

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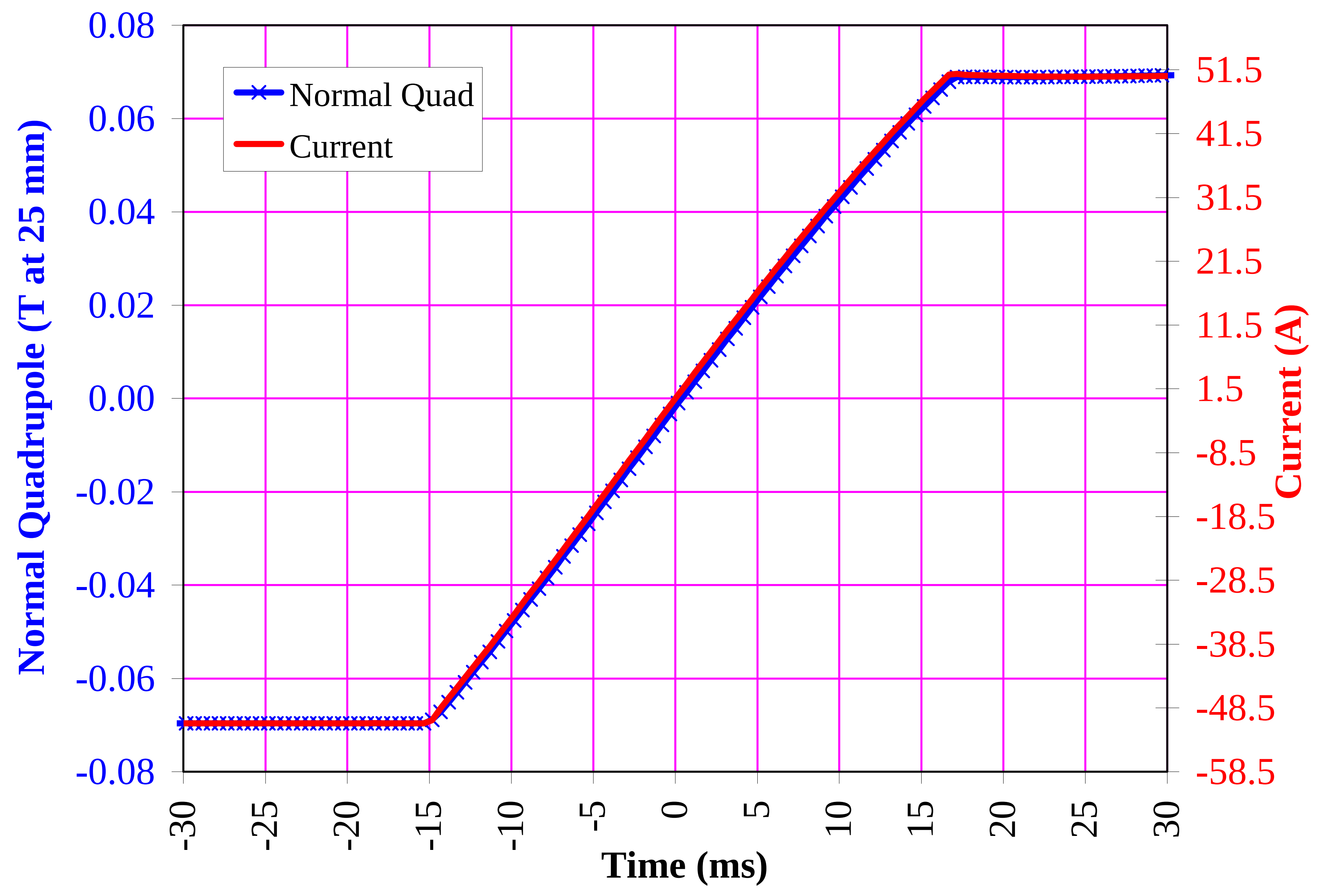

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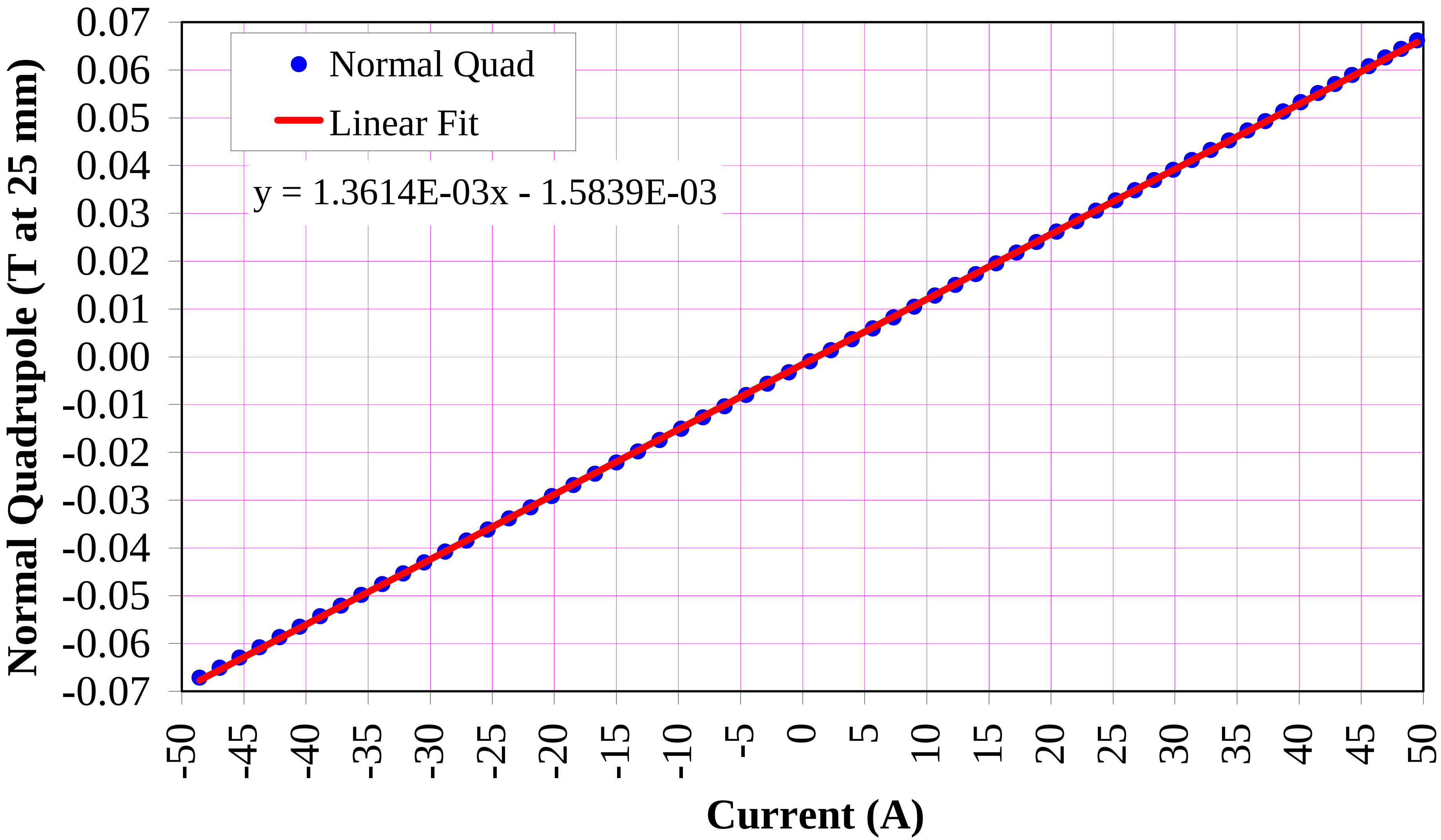


Magnetic Measurements in Helical Dipoles

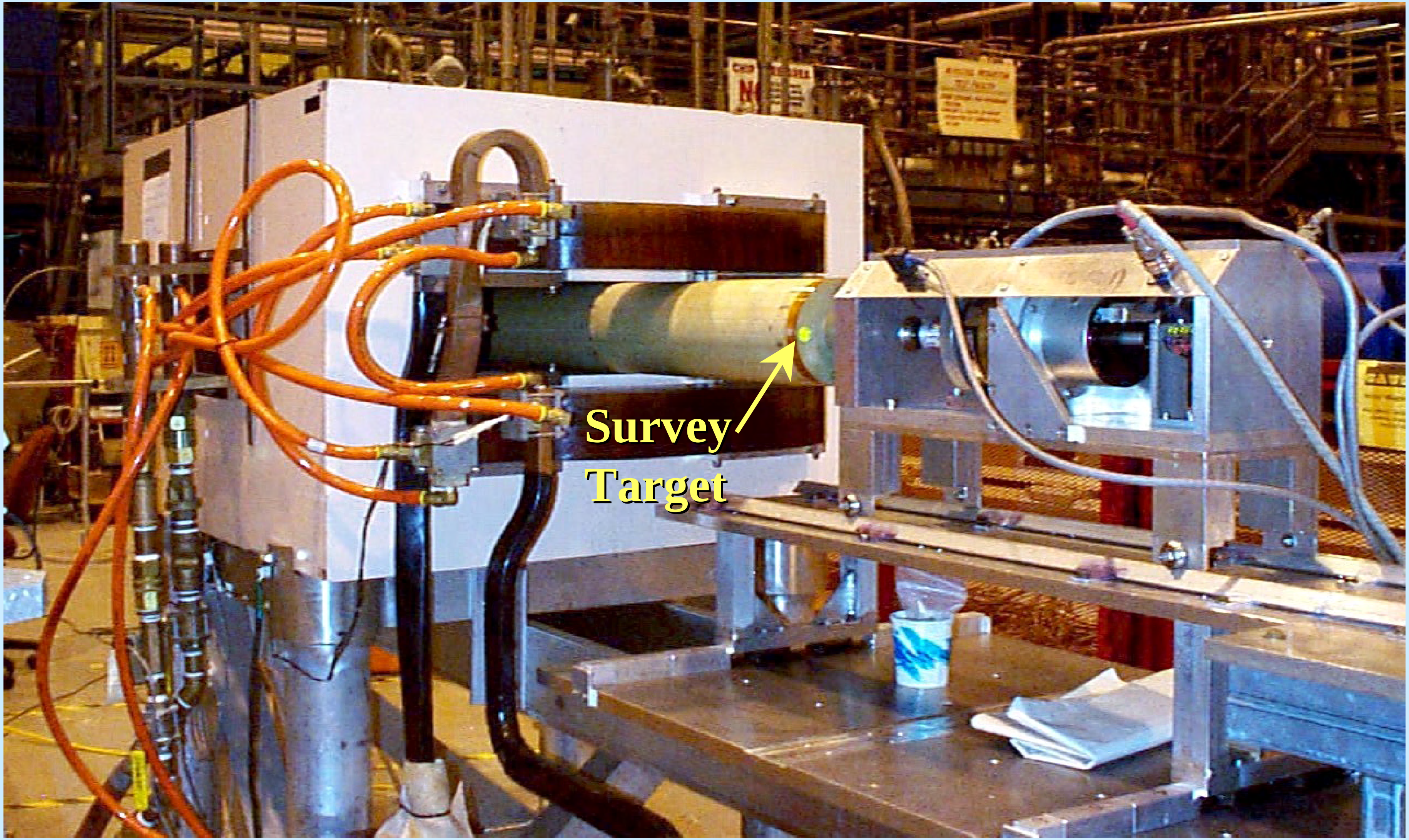
- BNL is producing 48 helical dipoles for Siberian Snakes and Spin Rotators to be installed in RHIC under a joint BNL-RIKEN spin physics program.
- The dipole field in these magnets rotates by 360 degrees over a length of 2.4 meters, giving a 3-D field throughout.
- A 51 mm long rotating coil was built for these measurements and the analysis was modified for the 3-D field.
- **A separate talk at this workshop will give more details.**

Picture of a helical dipole magnet coil

Conventional Magnets for the SNS

- Sector dipole magnets for the Spallation Neutron Source are being assembled at BNL.
- Production measurements will be made using a 2.49 m long, 164 mm diameter rotating coil.
- A rectangular aperture requires measurements to be made at several horizontal positions of the coil.
- A built-in horizontal gradient in the integral field implies that the coil position in the magnet be accurately determined.
- The magnet and the rotating coil have survey targets to determine the coil position with respect to the magnet.
- In addition to the dipoles, other magnet types (quadrupoles and correctors) of various apertures will also be measured for the SNS. (~ 150 magnets total).

Dipole Magnet for the SNS



Survey Target

Magnetic Measurement Facilities at the National Synchrotron Light Source

- 2.5 m Hall Probe Bench
- Moving-Wire Integrated Multipole Bench
- 2 m Pulsed-Wire Bench

Dedicated to measurement of Insertion Devices and (warm) beam transport and special-purpose magnets

(More information in a talk by G. Rakowsky)

Summary

- After the completion of RHIC, recent activities at BNL have primarily focussed on the study of dynamic effects and on production measurements of helical magnets.
- New hardware and analysis techniques were developed to carry out these measurements.
- Standard measurements were carried out on magnets built at BNL for the HERA luminosity upgrade project.
- Production measurements on conventional magnets for the SNS and superconducting magnets for the LHC have just begun.