Spill ripple compensation with direct field ripple measurements

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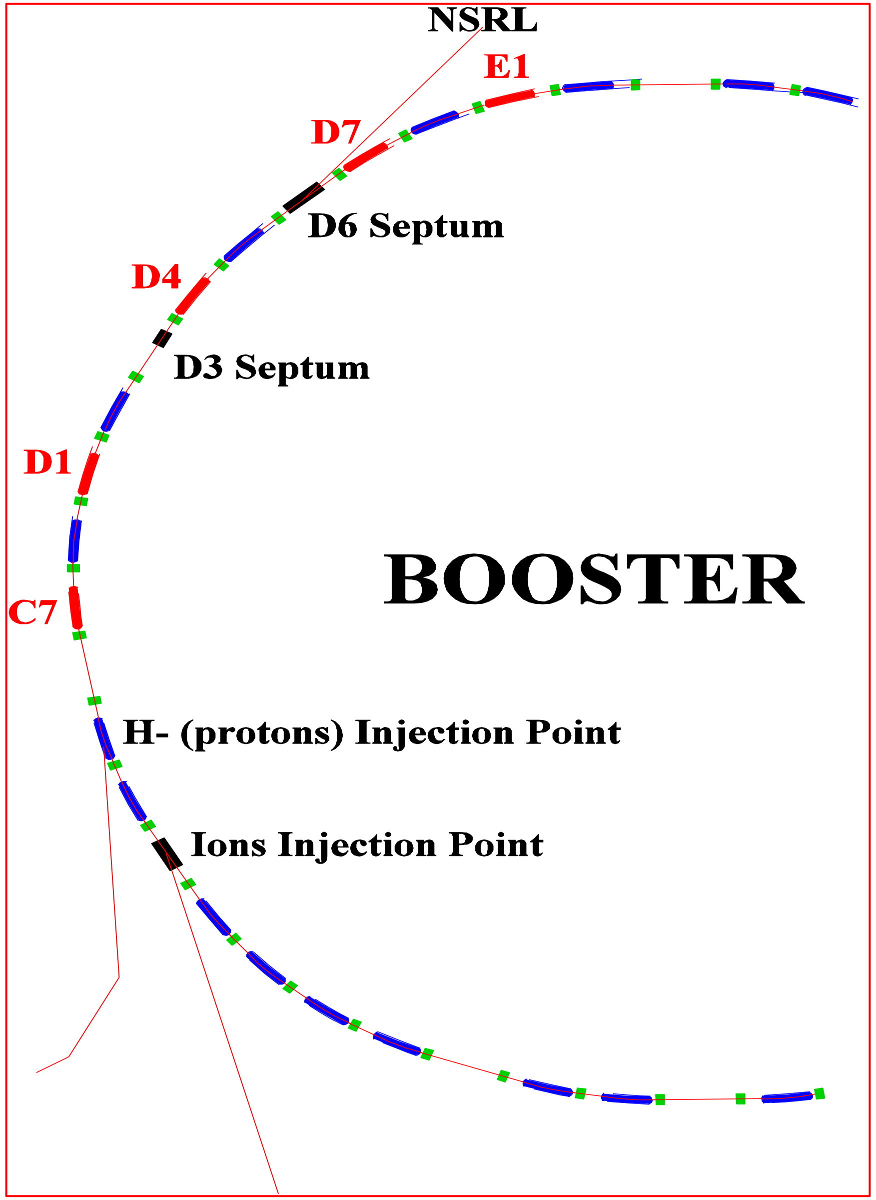
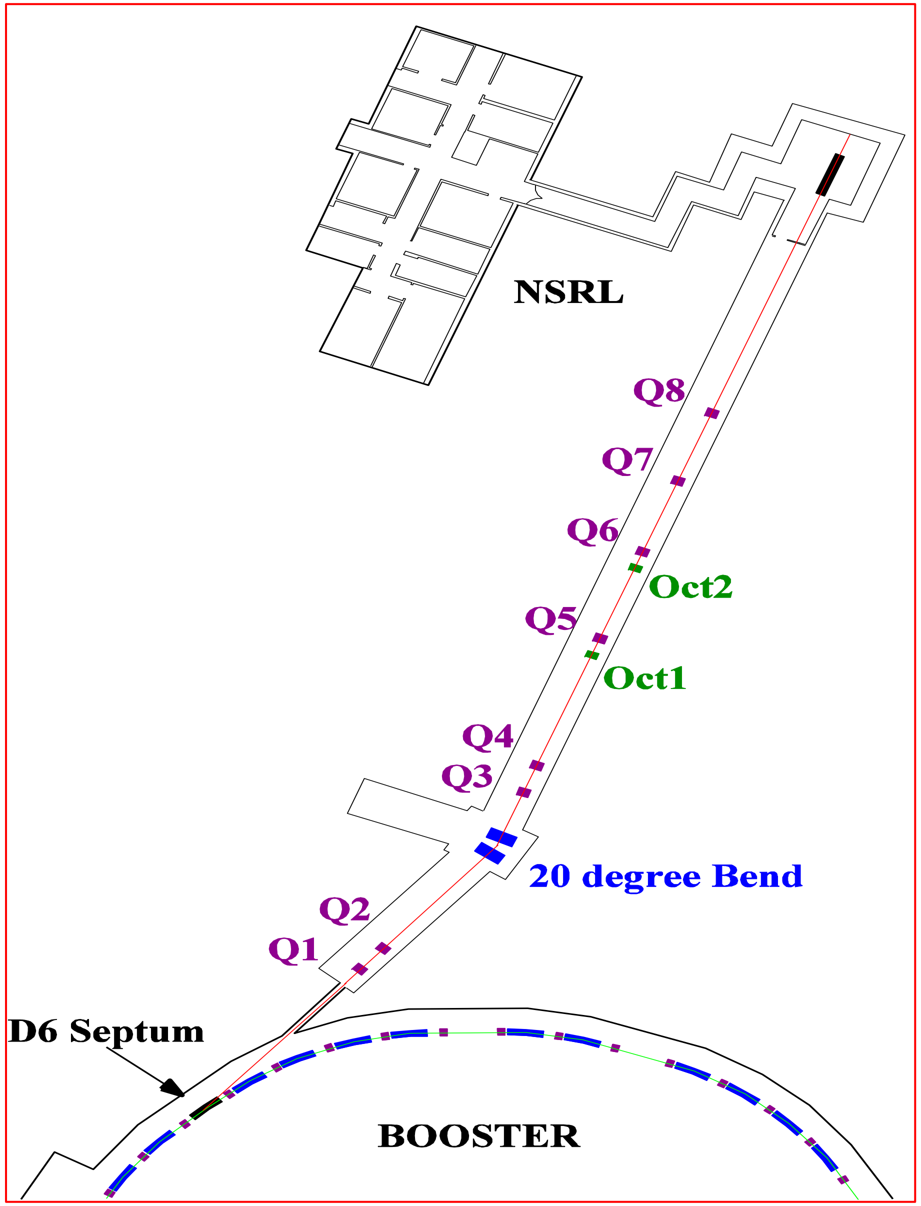
Topics:

- AGS Booster Slow Extraction
- Some thoughts on spill structure
- Eddy currents in quadrupole vacuum chambers
- Direct field ripple compensation

AGS Booster Slow Extraction

Booster to NSRL Slow Extraction





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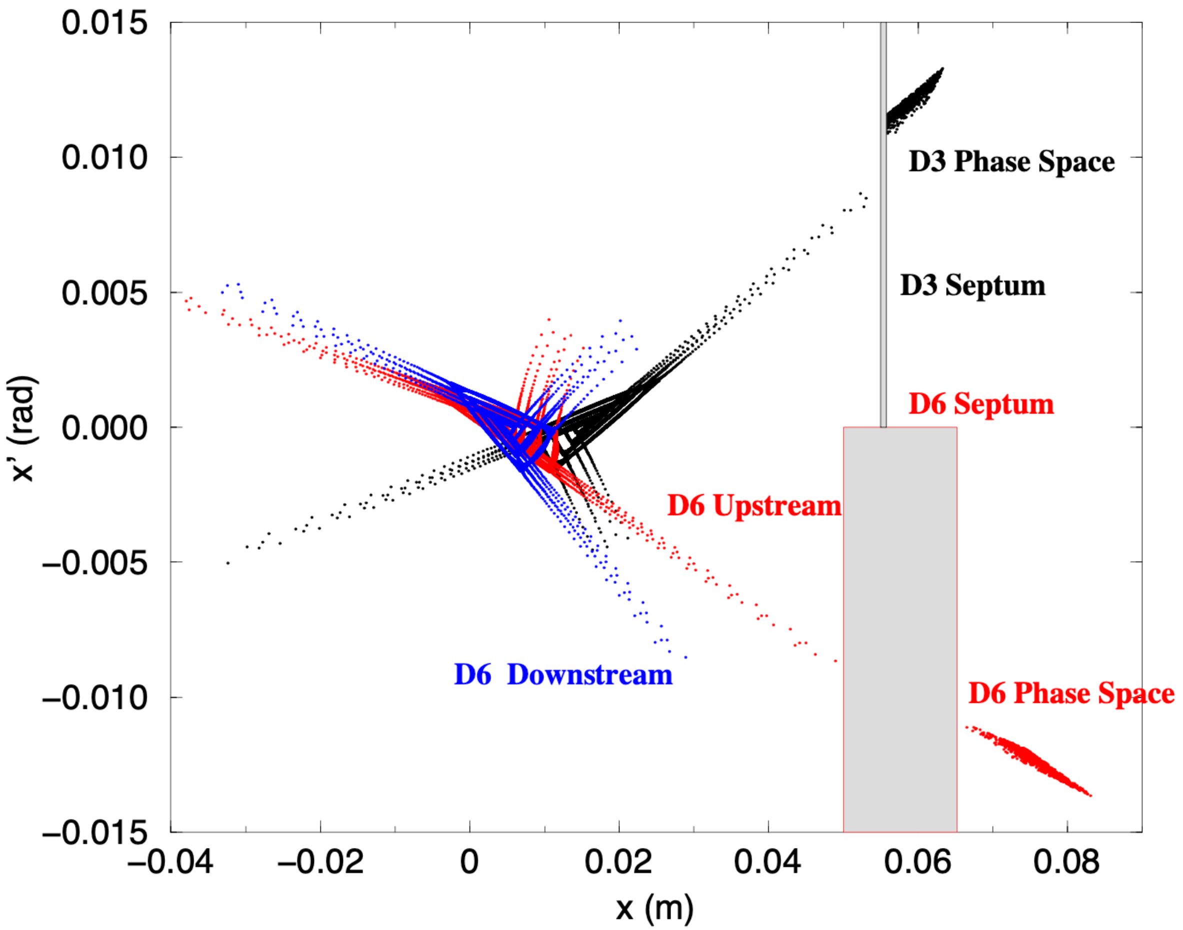
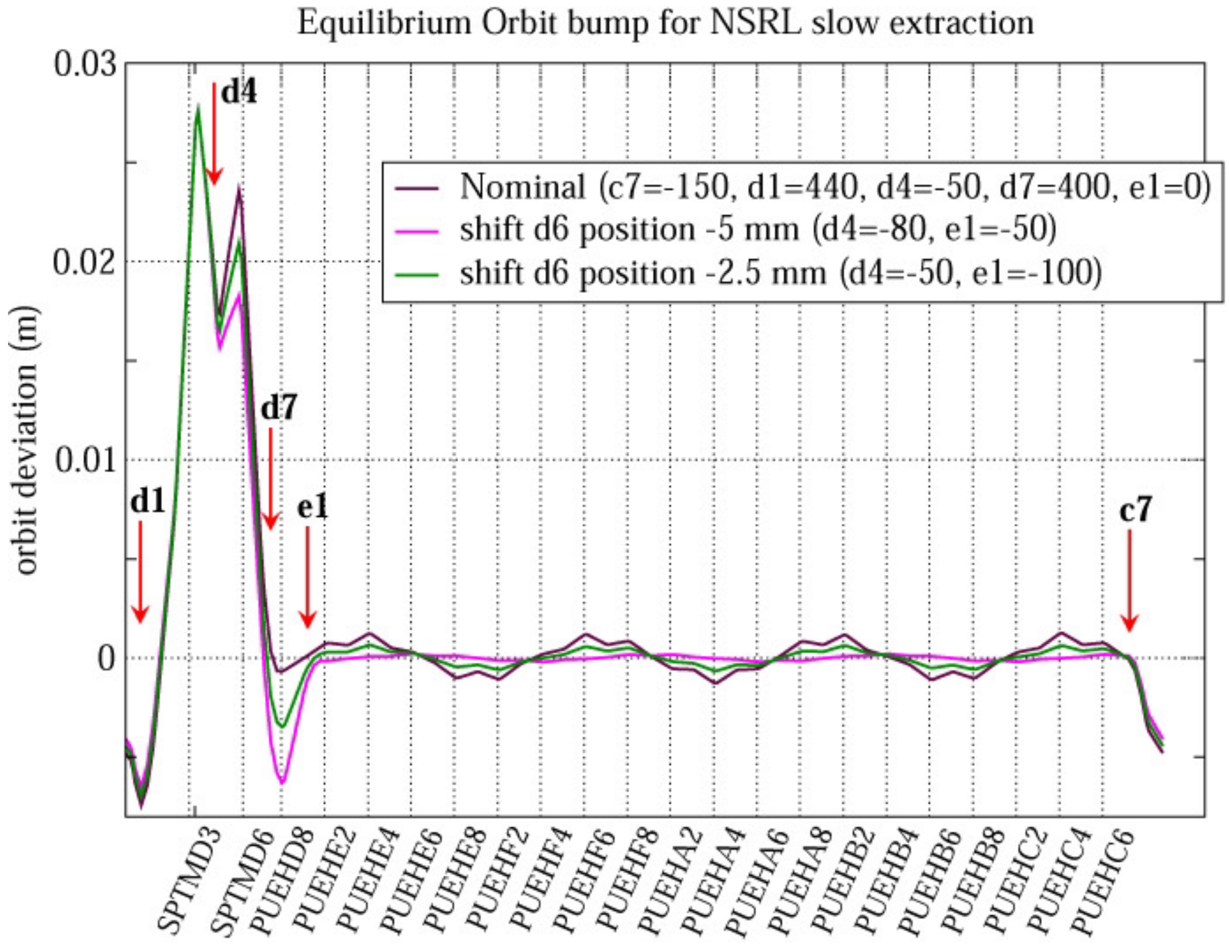
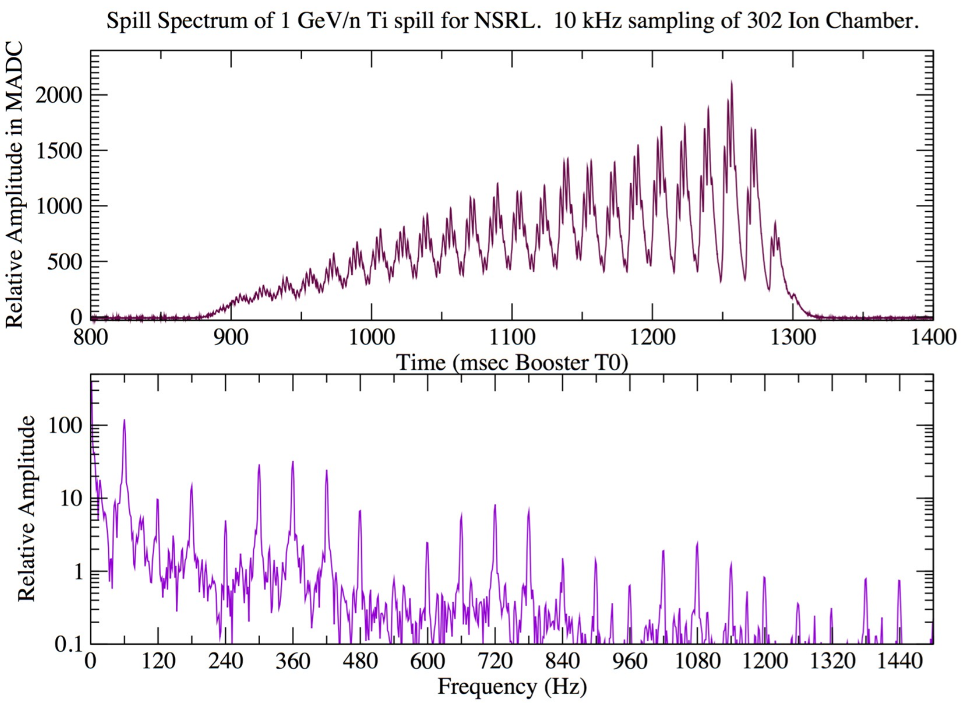


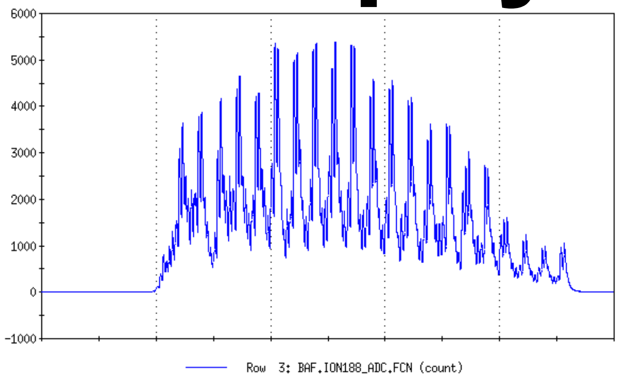
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.04
−0.02
0
0.02
0.04
0.06
0.08
x (m)
x' (rad)
D3 Phase Space
D3 Septum
D6 Septum
D6 Upstream
D6 Downstream
D6 Phase Space



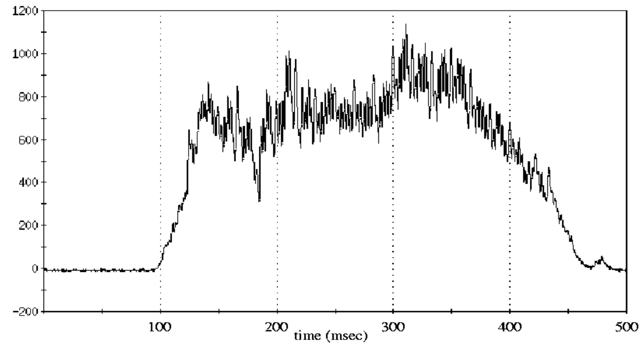
Equilibrium Orbit bump for NSRL slow extraction
orbit deviation (m)
0.03
0.02
0.01
0
Nominal (c7=-150, d1=440, d4=-50, d7=400, e1=0)
shift d6 position -5 mm (d4=-80, e1=-50)
shift d6 position -2.5 mm (d4=-50, e1=-100)
d1
d4
d7
e1
c7
SPTMD3
SPTMD6
PUEHD8
PUEHE2
PUEHE4
PUEHE6
PUEHE8
PUEHF2
PUEHF4
PUEHF6
PUEHF8
PUEHA2
PUEHA4
PUEHA6
PUEHA8
PUEHB2
PUEHB4
PUEHB6
PUEHB8
PUEHC2
PUEHC4
PUEHC6

NSRL Biology users don't care about Spill – electronics and physics user do!

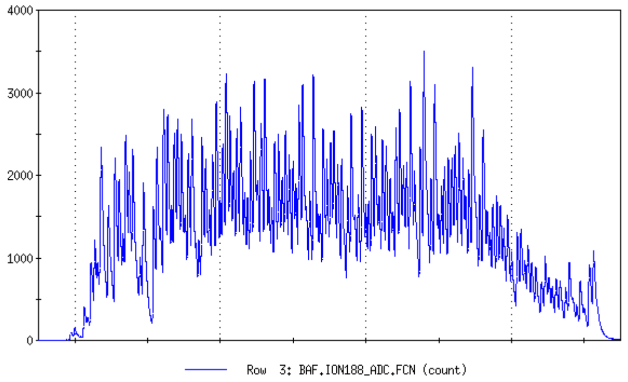




Normal Spill, active filter on.



RF Empty bucket filtering



Tune Modulation using tune trim quads; 60 Hz correction only, using spill signal for feedback.

Thoughts on Spill Structure

Spill Structure Theory: Harmonics analysis

Spill is created by transforming the particle distribution in tune space into a continuous constant stream of particles.

$$S(t) = \frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt} = \Lambda_0\left(\frac{dQ_0(t)}{dt} + \frac{dQ_R}{dt}\right)$$

Where,

$$\frac{dQ_R}{dt} = \sum_n (n\omega_0)\left(\delta Q_{R,n}\cos(n\omega_0 t + \phi_0)\right)$$

Variations in tune can be expressed in terms of variations in *K(s)*

$$\Delta Q_K(t) = \frac{1}{4\pi}\sum_{i=1}^{N_K}\beta_i \cdot \Delta K_i(t)$$

Variations in dipole fields, orbit variations in sextupoles, modulate tune

$$\Delta Q_B(t) = \frac{1}{8\pi\sin(\pi Q)}\sum_{i=1}^{N_B}\sum_{j=1}^{N_S}\Delta\theta_{B,i}(t)\cdot S_j\beta_j^{3/2}\beta_i^{1/2}\cdot\cos\left(-\pi Q + \left|\phi_i - \phi_j\right|\right)$$

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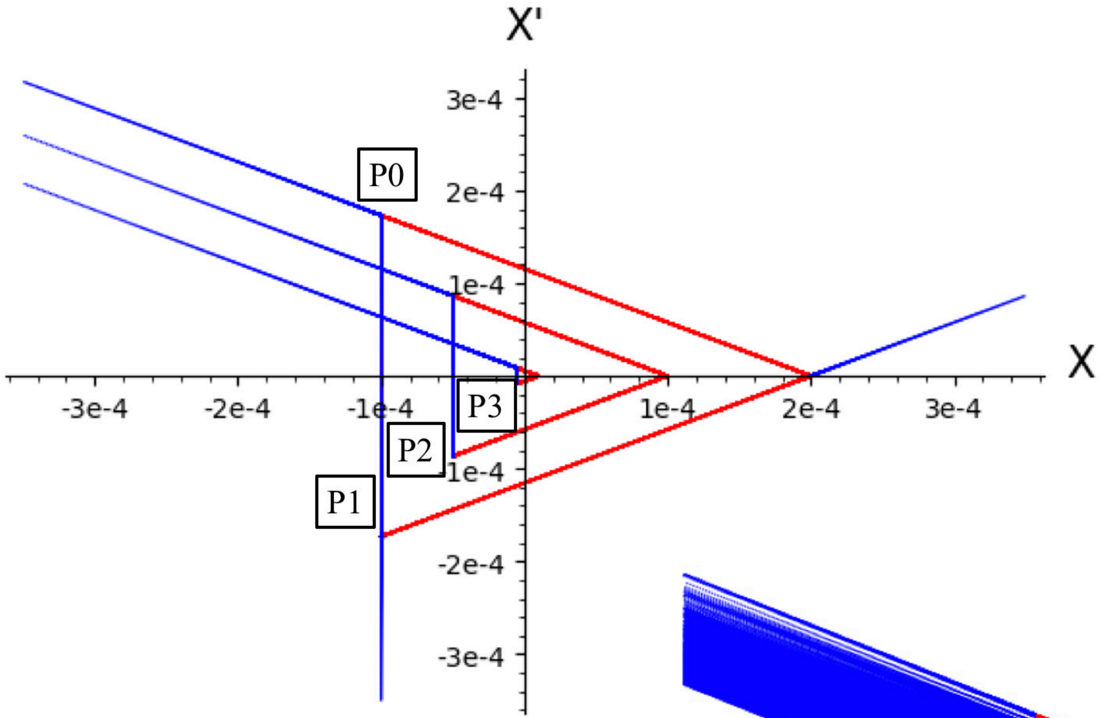
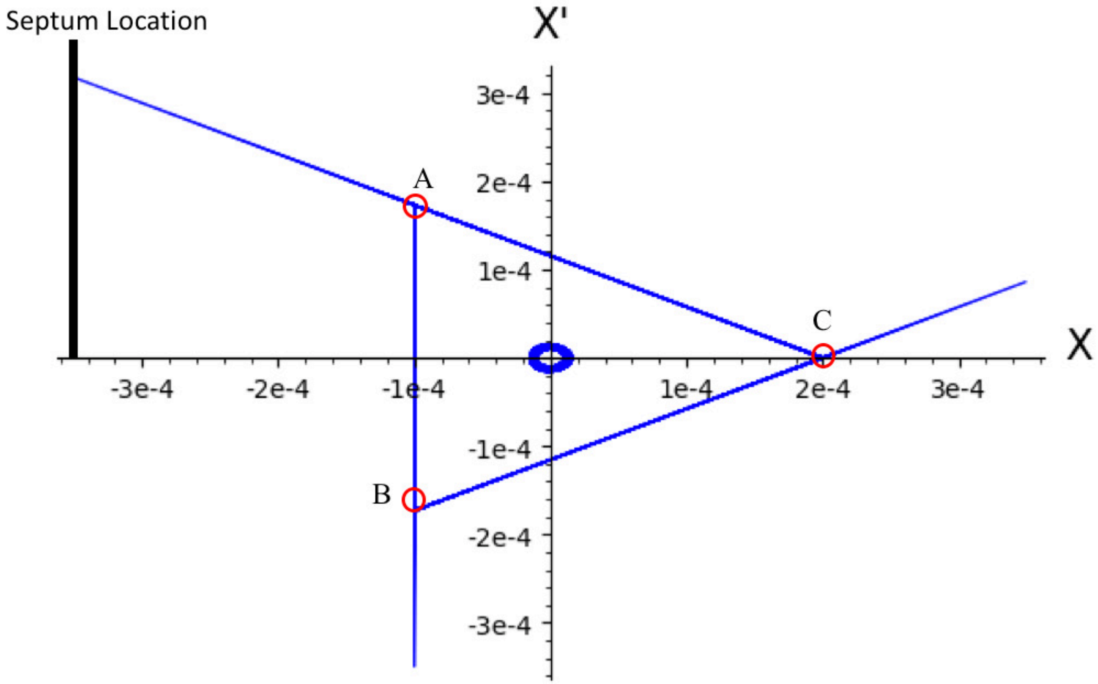
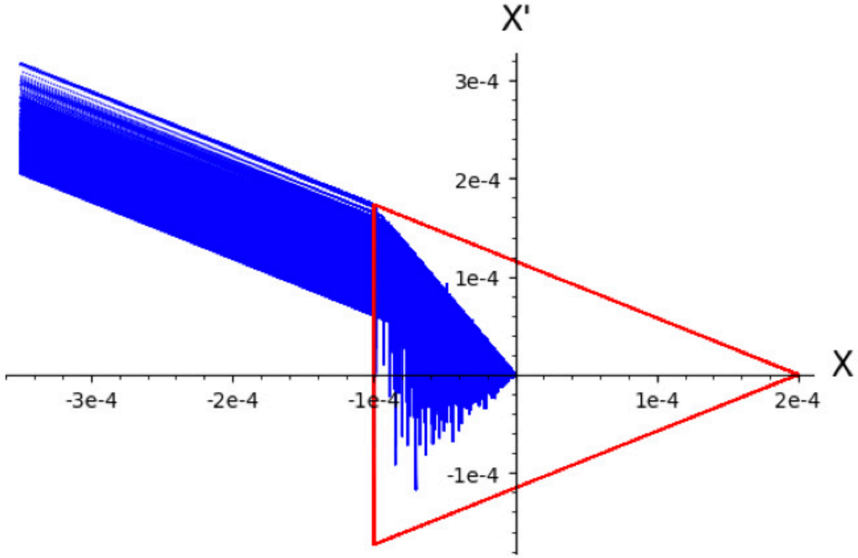
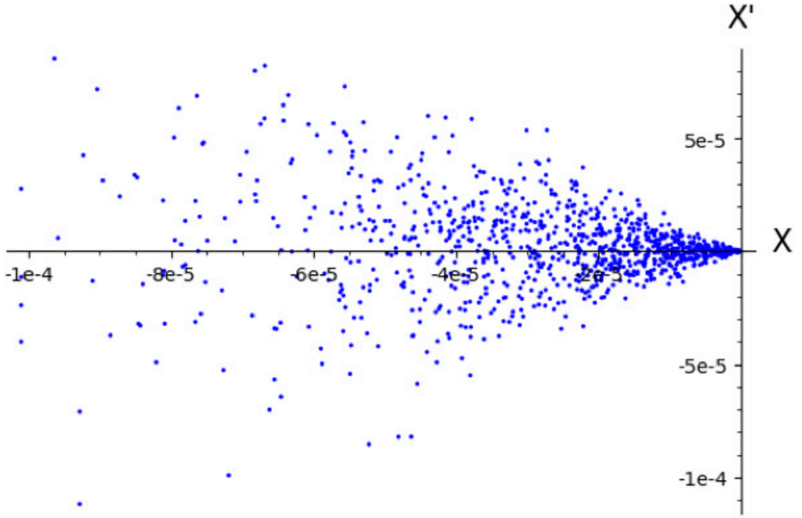
Transit Time Theory

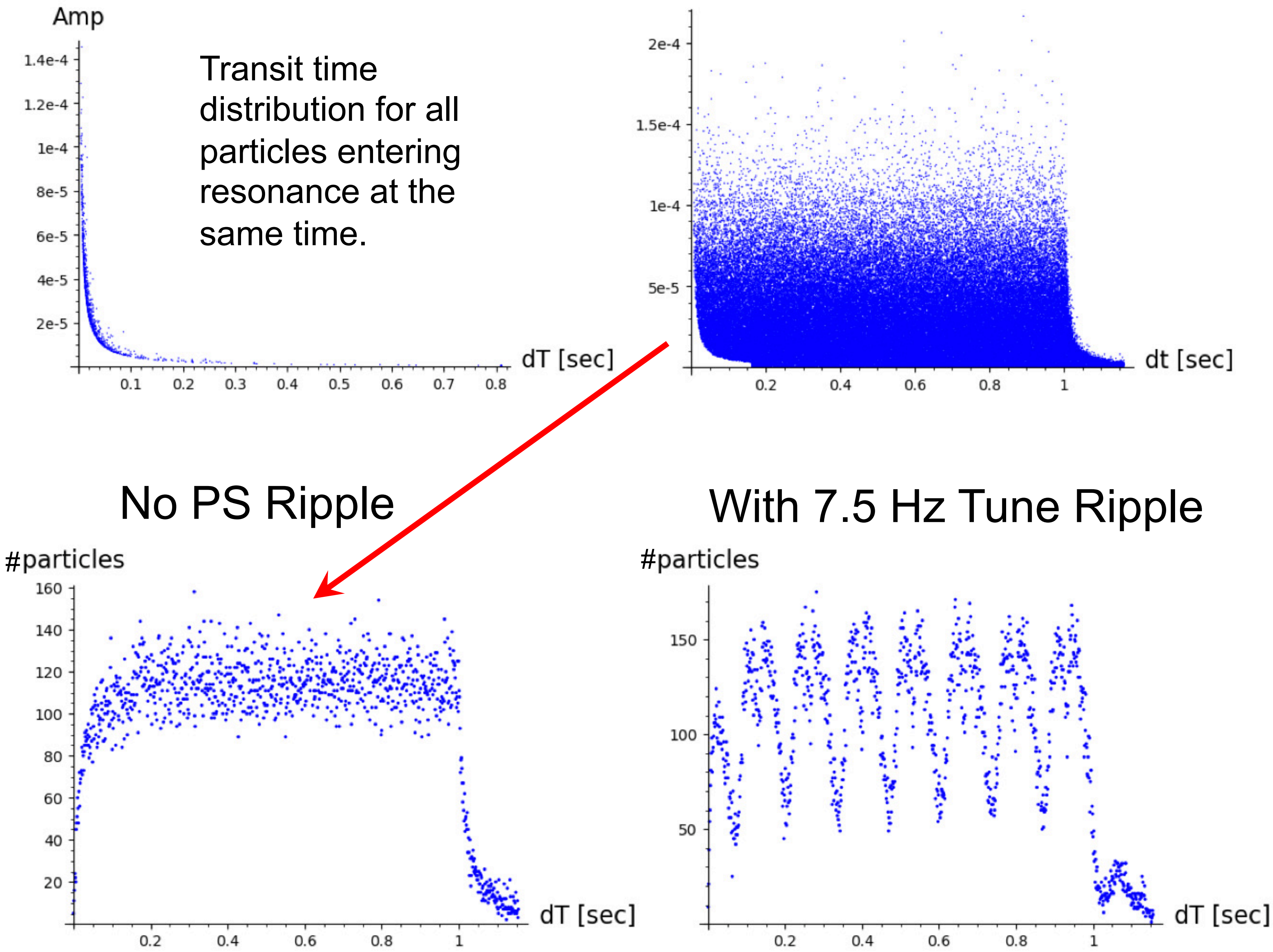








Spill Simulations Using Transit Time Monte-Carlo Model



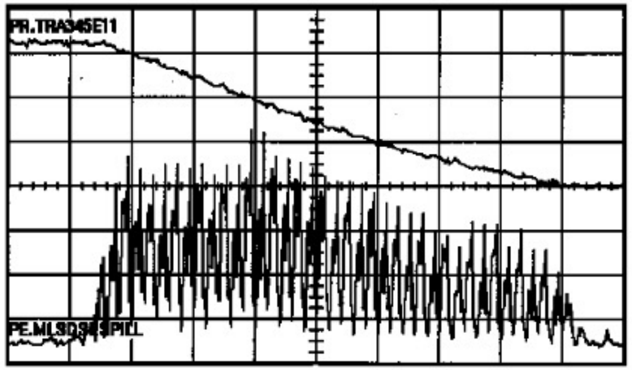
How do people compensate?

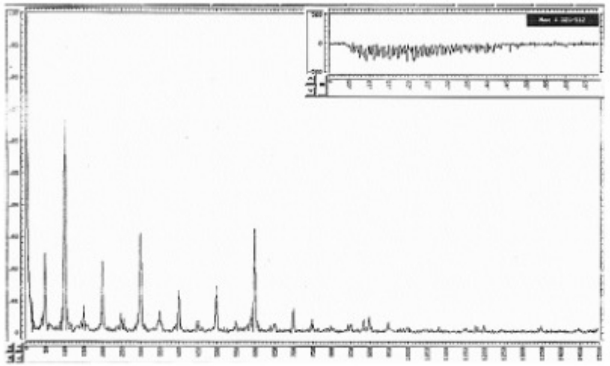
Many methods can improve the spill structure.

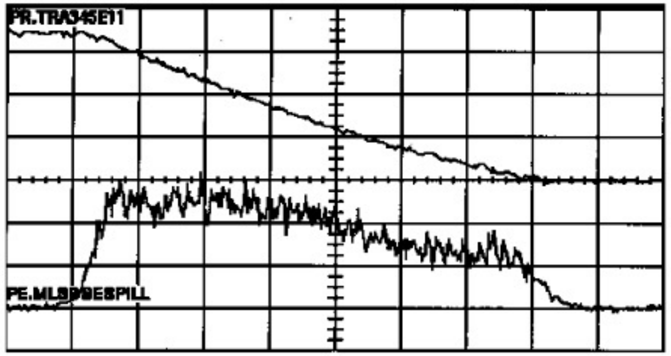
- RF empty bucket filtering
  - Works extremely well, especially for non-line harmonic source terms
  - Intrinsically imposes RF on the spill
- Ripple compensation using a high frequency quadrupole
- Ripple compensation using active filters
- Measuring transfer functions - who contributes the most?
- **New idea: ripple compensation using direct measured field variations inside the beam pipe in a reference magnet**

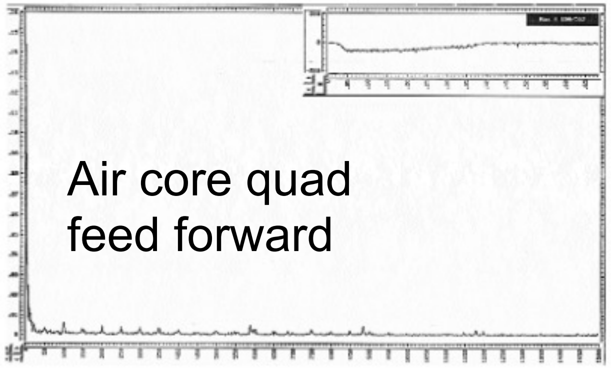
Quadrupole Compensation

CNAO, MedAustron, Italy









Air core quad feed forward

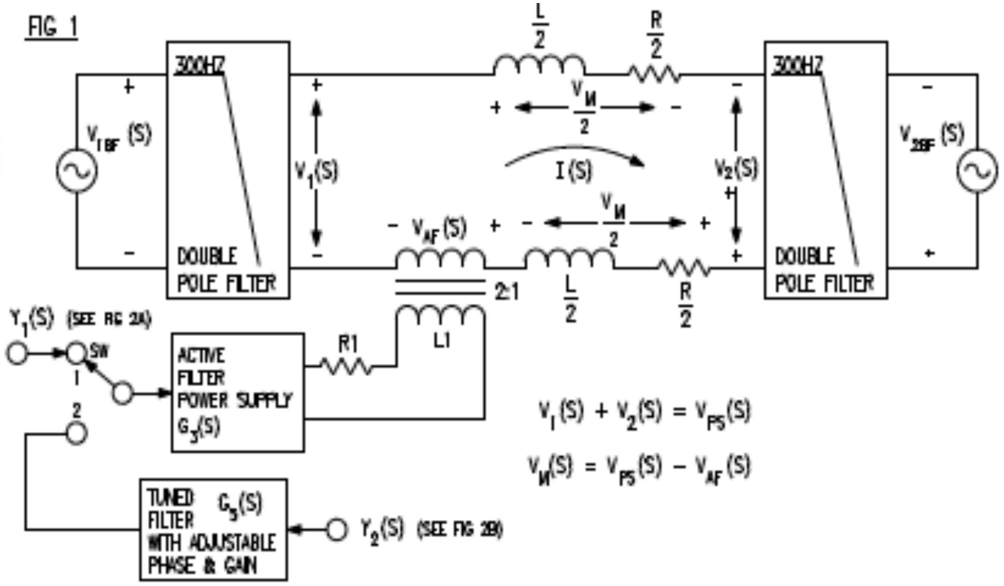
A horizontal focusing quadrupole inserted into the accelerator lattice can be modulated on frequencies seen in the measured spill.

The sources of the harmonics are from multiphase power supplies that have inherent ripple at harmonics of the AC line frequency.

By measuring the ripple harmonics and then feedforwarding corrections to the air core quadrupole, the spill harmonics can be removed.

Active Ripple Filter

FIG 1



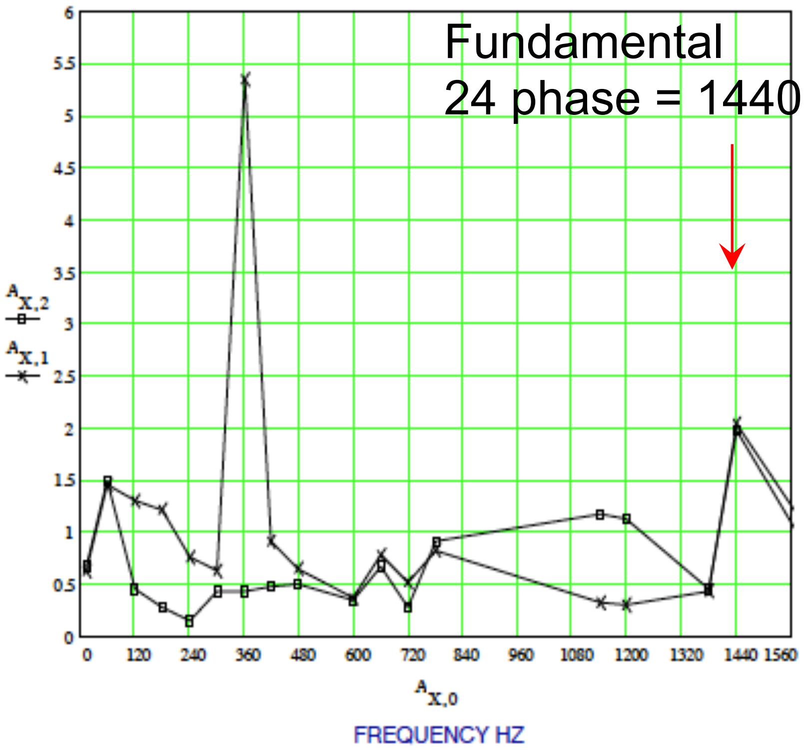
The tuned filter is basically performing an analog FFT, via bandpass (Butterworth) filters.

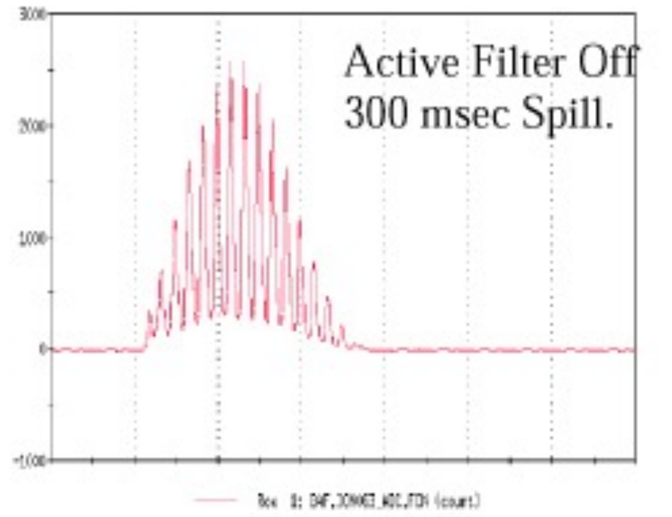
Each filter stage passes a narrow band around a 60 Hz harmonic. A gain and phase are applied to the output of the filter.

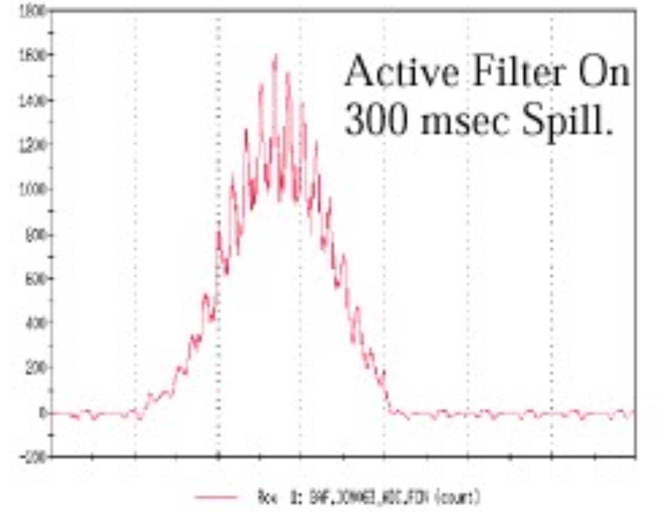
All filter outputs are added together to form a single reference to the Power Supply.

For NSRL we have an active filter on the Booster, but it only compensates what is detected in the Booster main magnet power supply. It can do a good job reducing the ripple but doesn't see all the components the beam sees.

1. Ax,1 IS THE RIPPLE WITHOUT THE ACTIVE FILTER CORRECTION
2. Ax,2 IS THE RIPPLE USING THE ACTIVE FILTER CORRECTION, WITH SWITCH (SW) IN POSITION 2 (SEE FIG. 2). TUNED FILTER WAS TUNED TO CORRECT 120 HZ, 180 HZ, 240 HZ, 360 HZ, 720 HZ.







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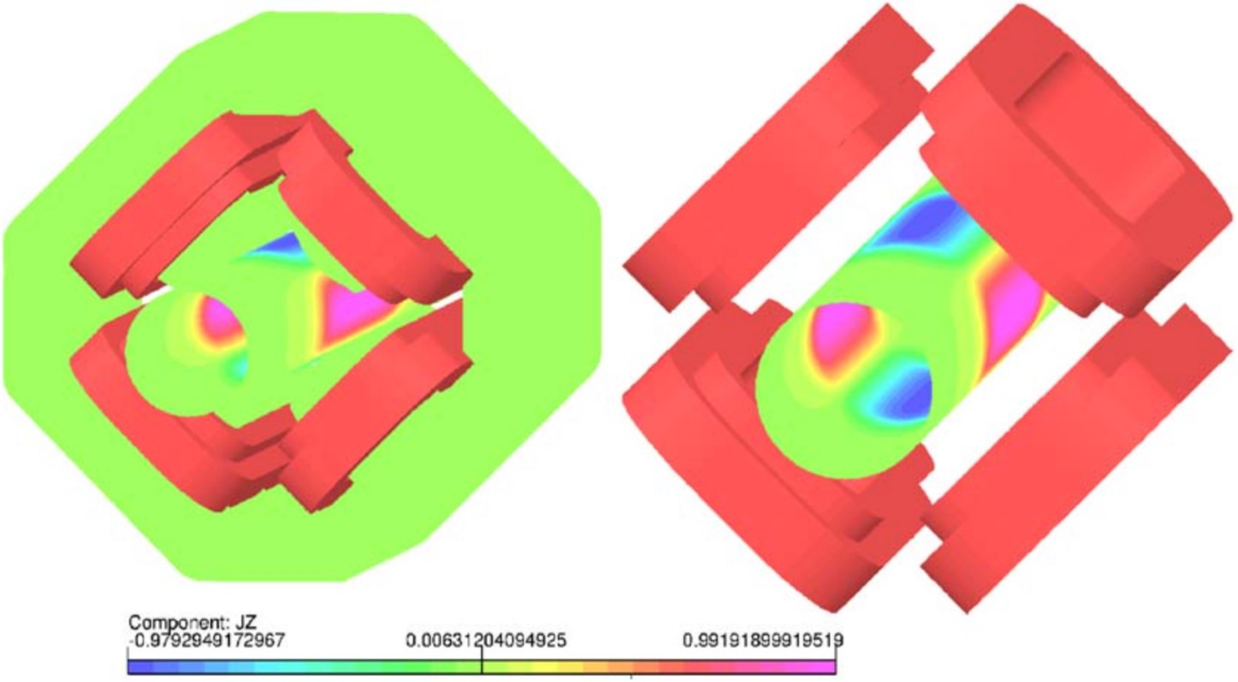
Eddy currents in quadrupole vacuum chambers

Vacuum chamber eddy current effects

Consider an electrically thin chamber with circular cross-section.



Booster Main Quadrupole: eddy currents in vacuum chambers
5 turns main coils
1 turn trim coil

A sinusoidal excitation of the form:

$$B_{ext}(t) = B_0 \sin(\omega t)$$

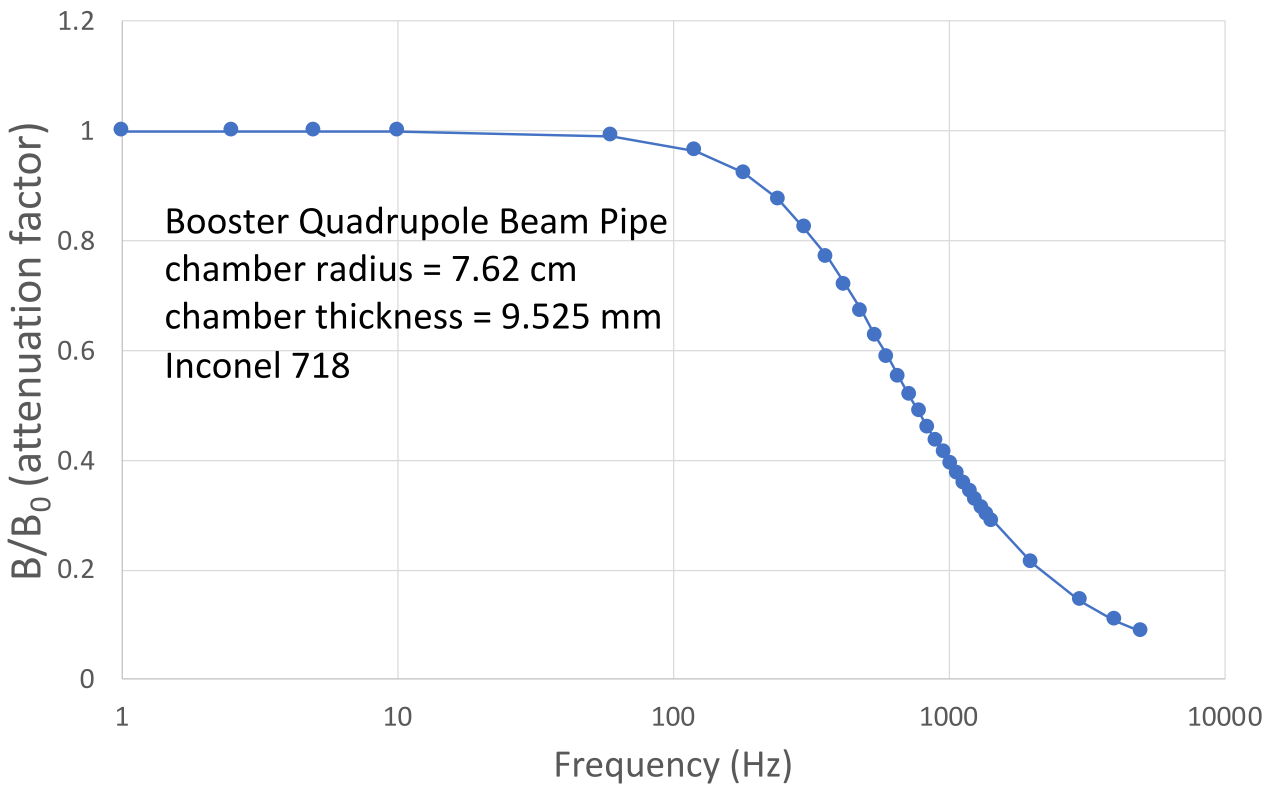
Applied transversely to the beam pipe of radius b and wall thickness d, the steady-state time dependence for the magnetic field penetrating the chamber is

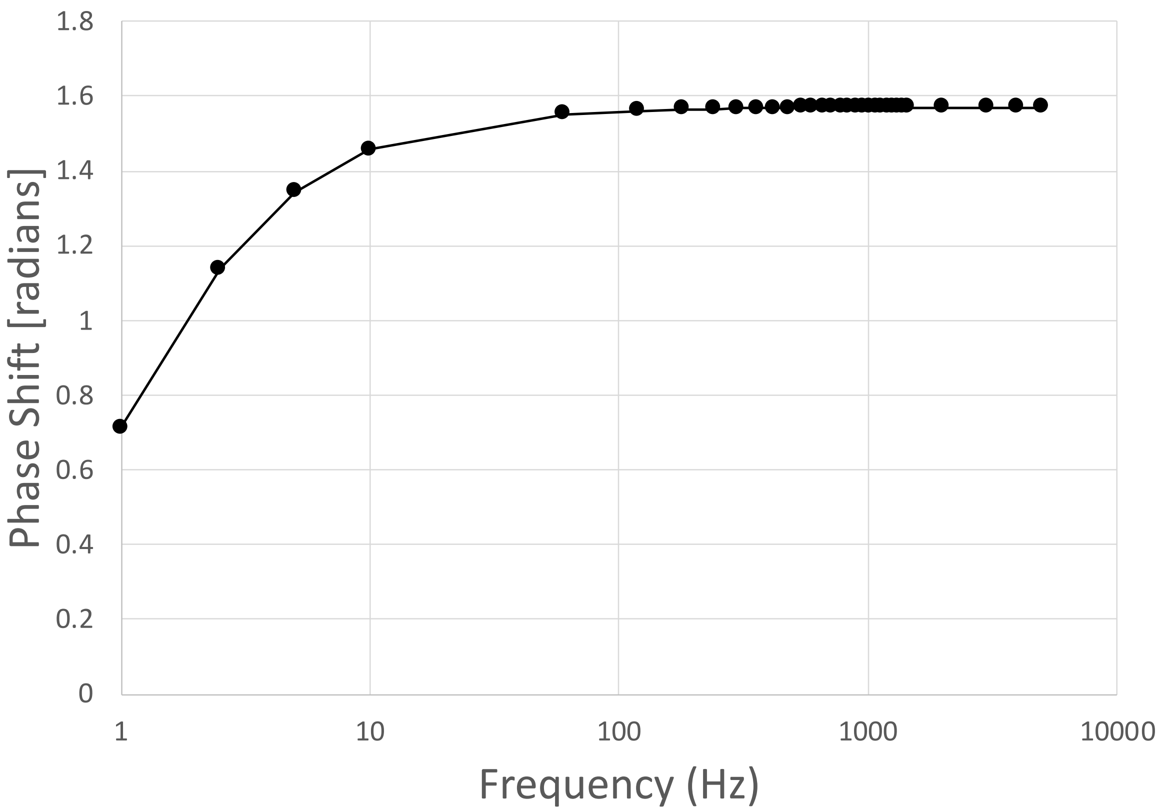
$$B_{int}(t) = \frac{B_0}{\sqrt{1+(\omega\tau)^2}} \sin(\omega t - \tan^{-1}(\omega\tau))$$

where,

$$\tau = \frac{1}{2}\mu_0 \sigma_c b d$$

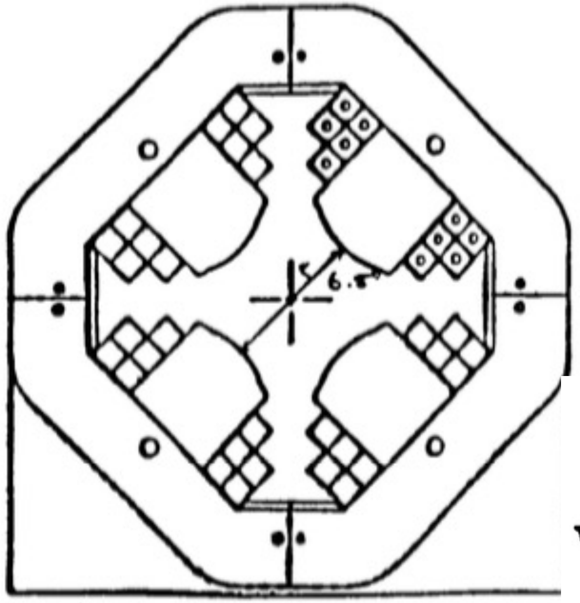
Vacuum chamber eddy current effects



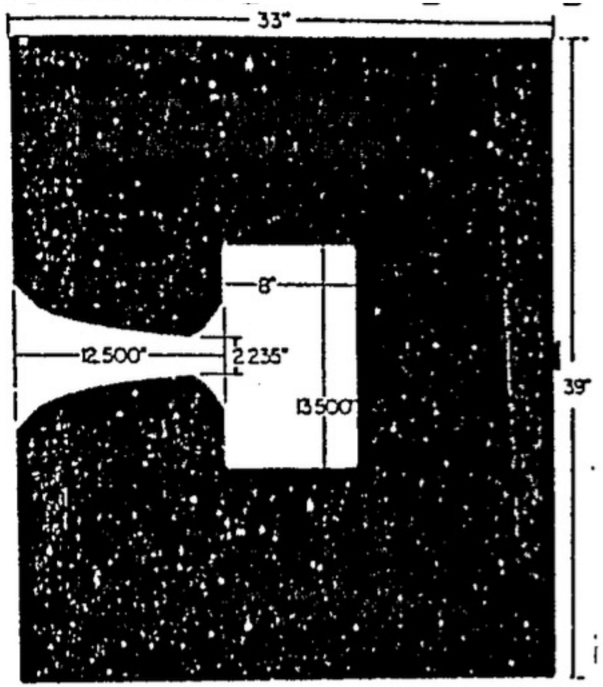


Direct Field Ripple Compensation

Direct ripple compensation



Quadrupole magnet.



$$4\pi \times NI = \int_0^{r_q} B_1 r \, dr = \frac{B_1 r_q^2}{2}$$

$$V_q = \frac{dB_1}{dt} \bullet W_q N_q \bullet L_q \times 2coils$$

where:

W_q=coil width (cm)
N_q=#of turns
L_q=Length of coil (cm)

$$\frac{dB_1}{dt} = \dot{B}_1 (T/sec)$$

$$A_{eff} = \text{Effective Area} = W_q \times N_q \times L_q$$

AGS Combined function Magnet

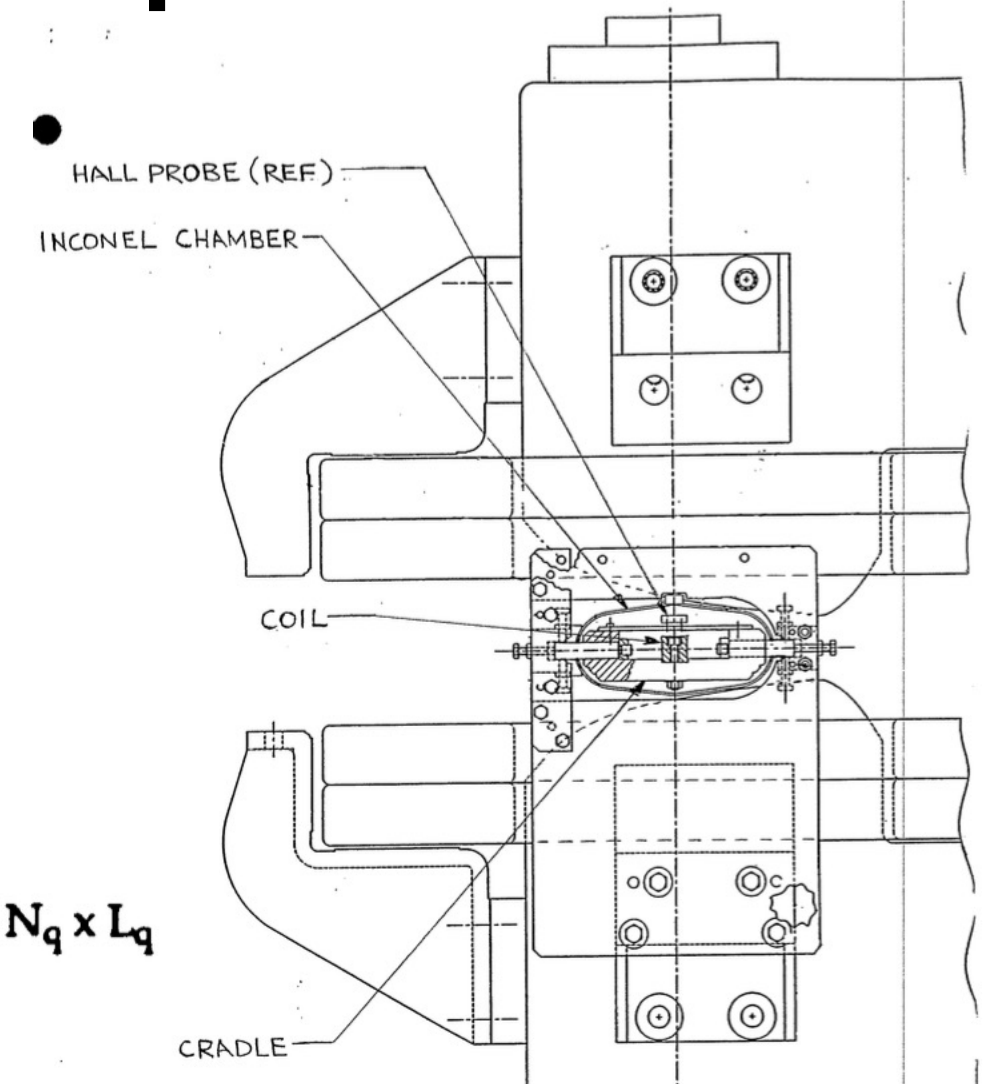
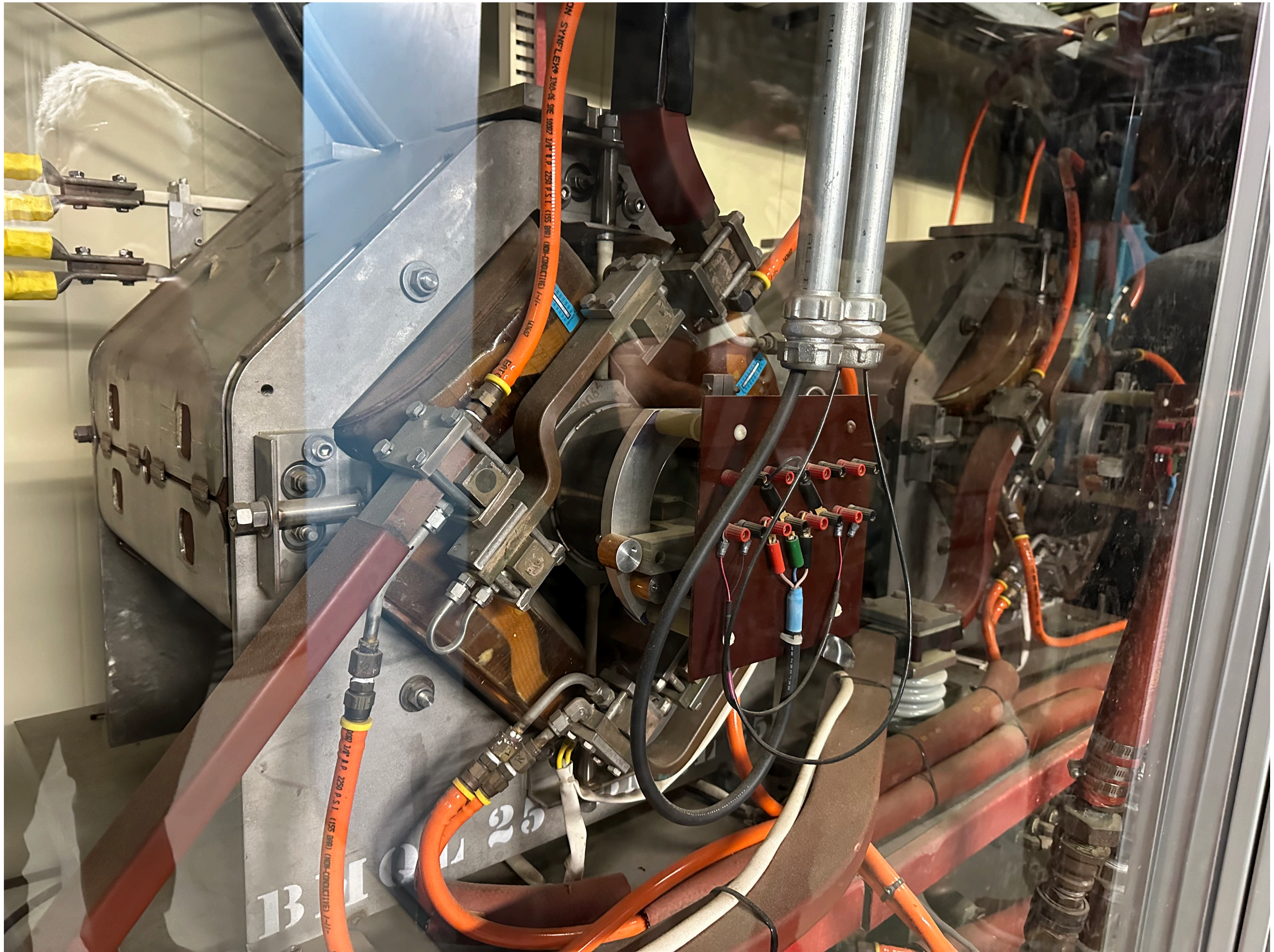


FIGURE 3 (SCALE: 1/4)
CRADLE/COIL SUPPORT
END VIEW A-A OF FIG. 2
(TYPICAL - BOTH ENDS)

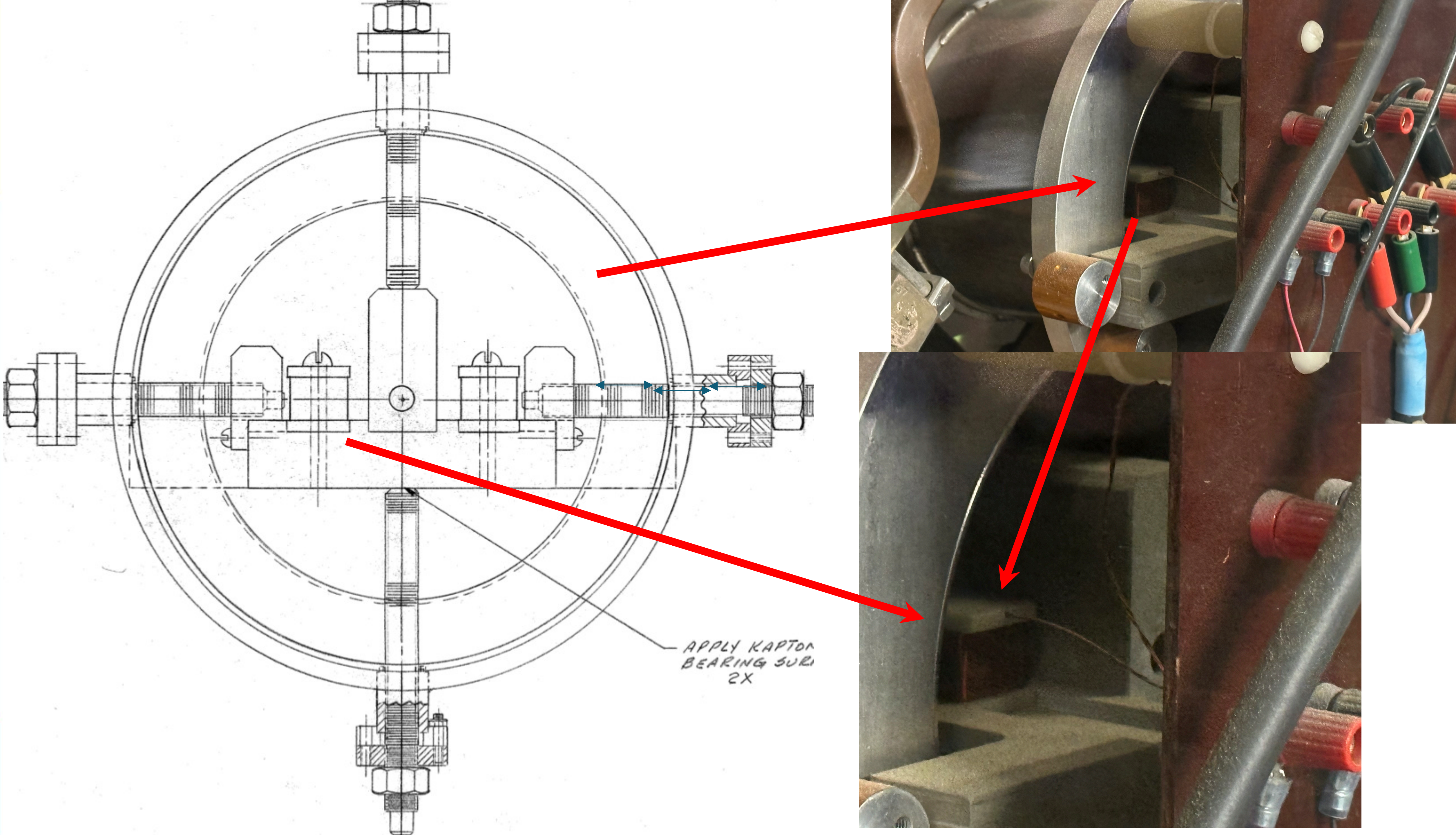
Booster Reference Quadrupole



Magnet sits in a cage next to the MM Power Supply. Magnet is wired in series with all Dipoles and Quad in the main bus in the Booster (all dipoles and quads are wired in series).

Reference quad includes vacuum chamber and cooling water.

Inside is a static reference coil to measure the back-emf from the ramping of the magnet.


APPLY KAPTO
BEARING SUR
2X

What makes this (possibly) better?

Pro's

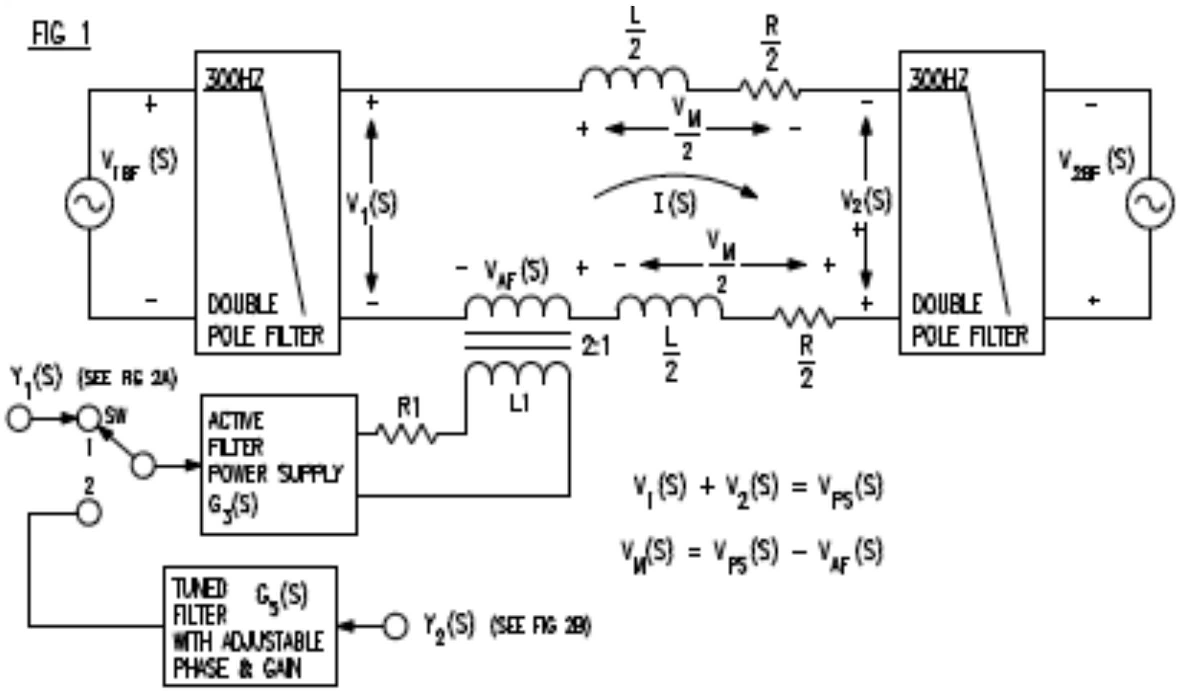
1. Measures a signal that is in the same reference frame as the beam
2. Includes attenuation and phase shifts from induced eddy currents
3. Measures the actual gradient variations causing the dQ/dt
4. Does not need a beam signal for feedback/feedforward

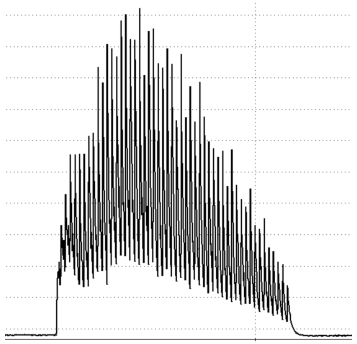
Con's

1. Signal is very small
2. Environment is noisy

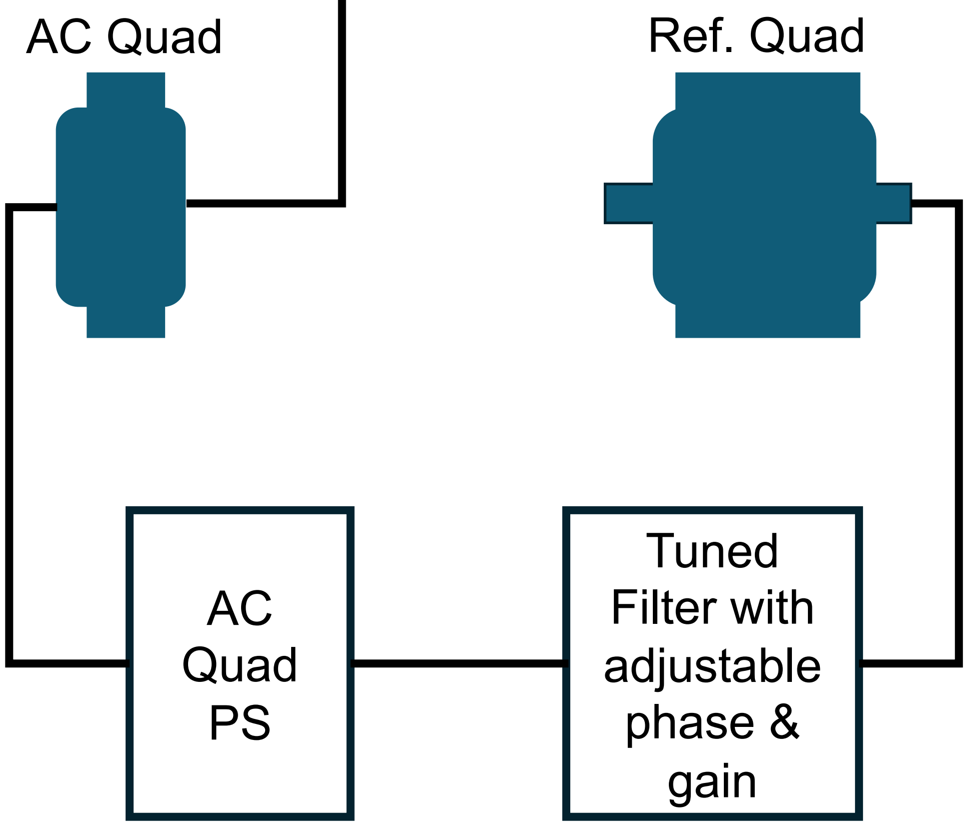
Preliminary implementation

The correction system is very similar to the active filter





Spill is used as figure of merit. Not for direct feedback or feedforward

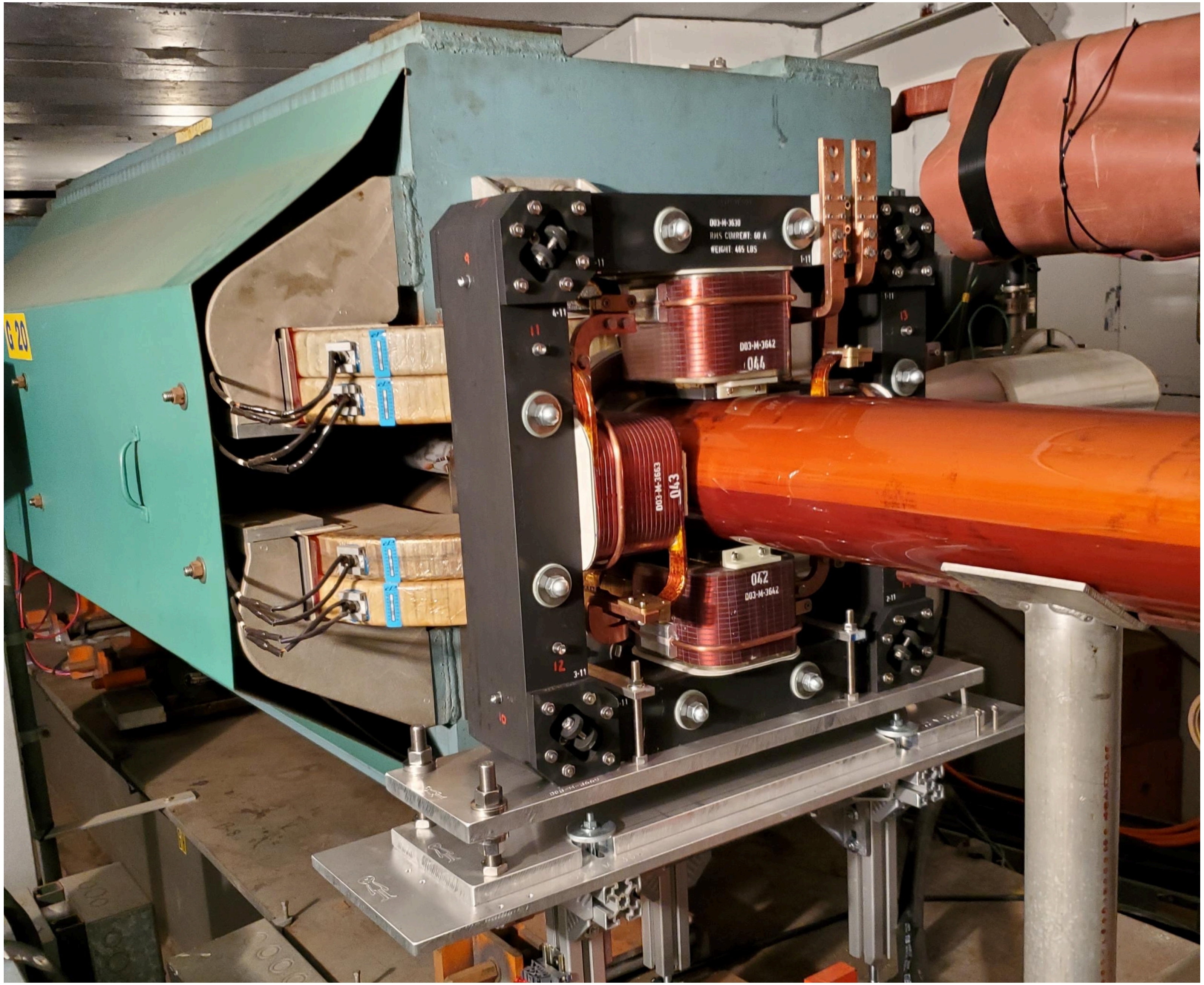


AGS AC Skew Quadrupoles

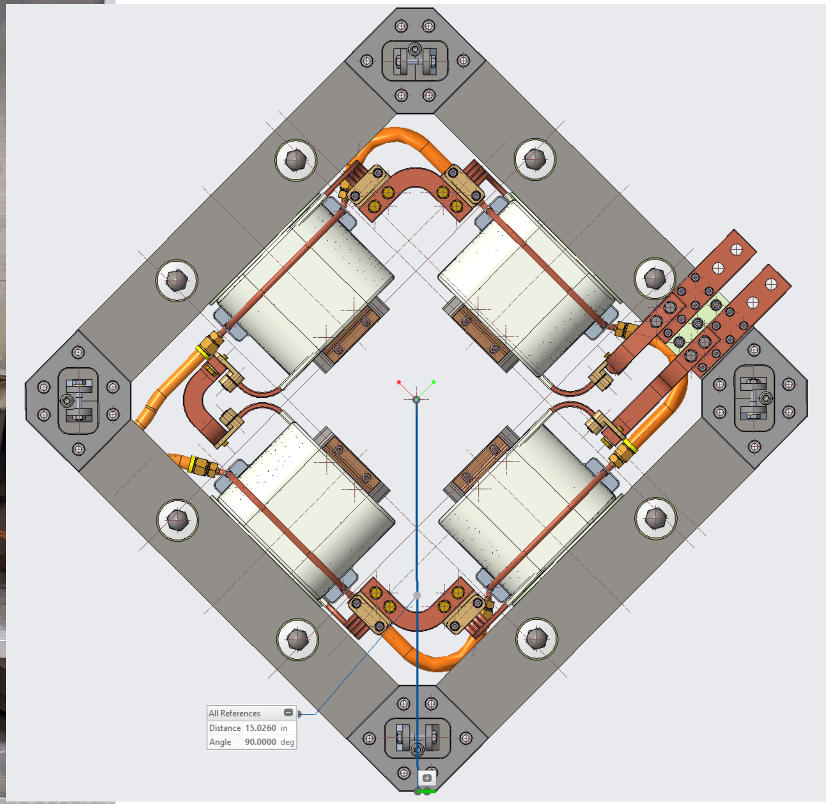
As built the parameters are:

$L = 0.17$ meters
$K1 = (1/Brho) * 6.7e\text{-}3 * I$

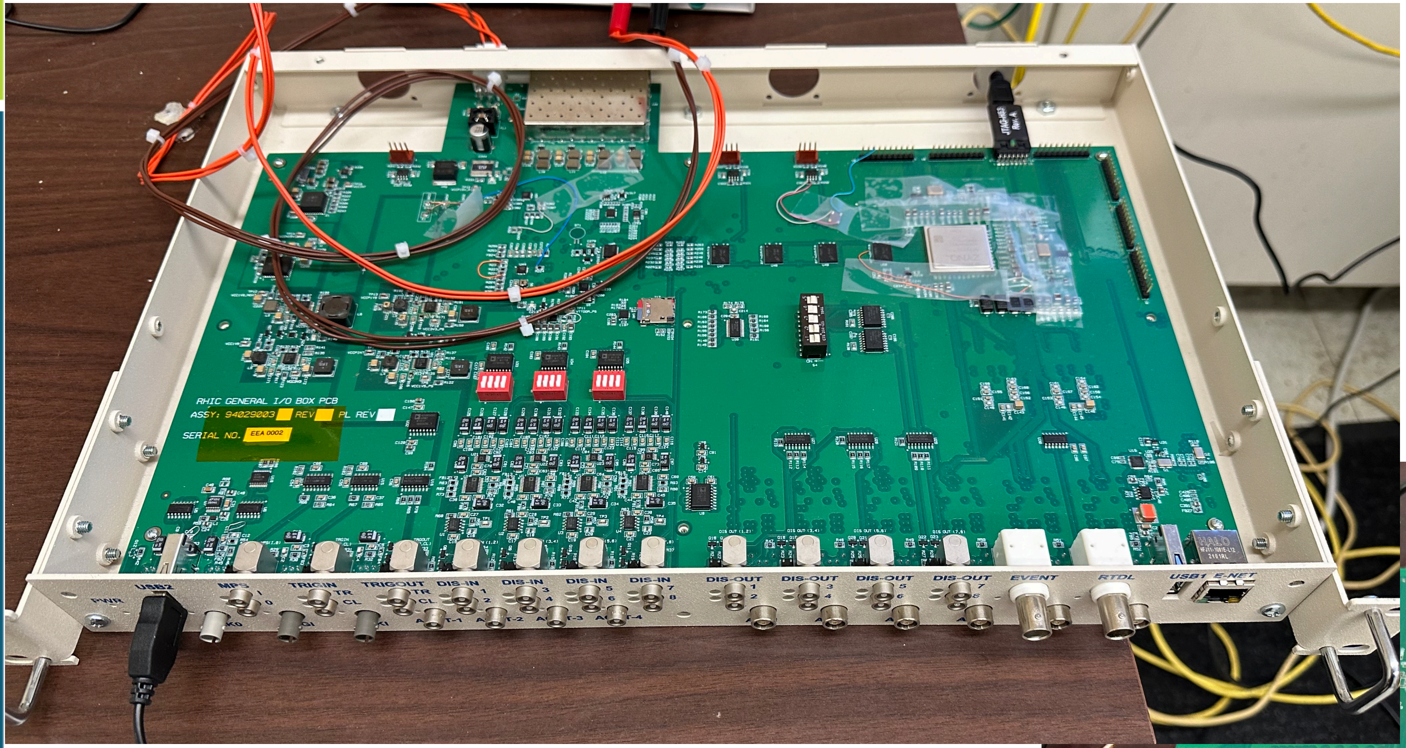
"I" is the current,
6.7e-3 is the calibration factor in Tesla/meter/Amp

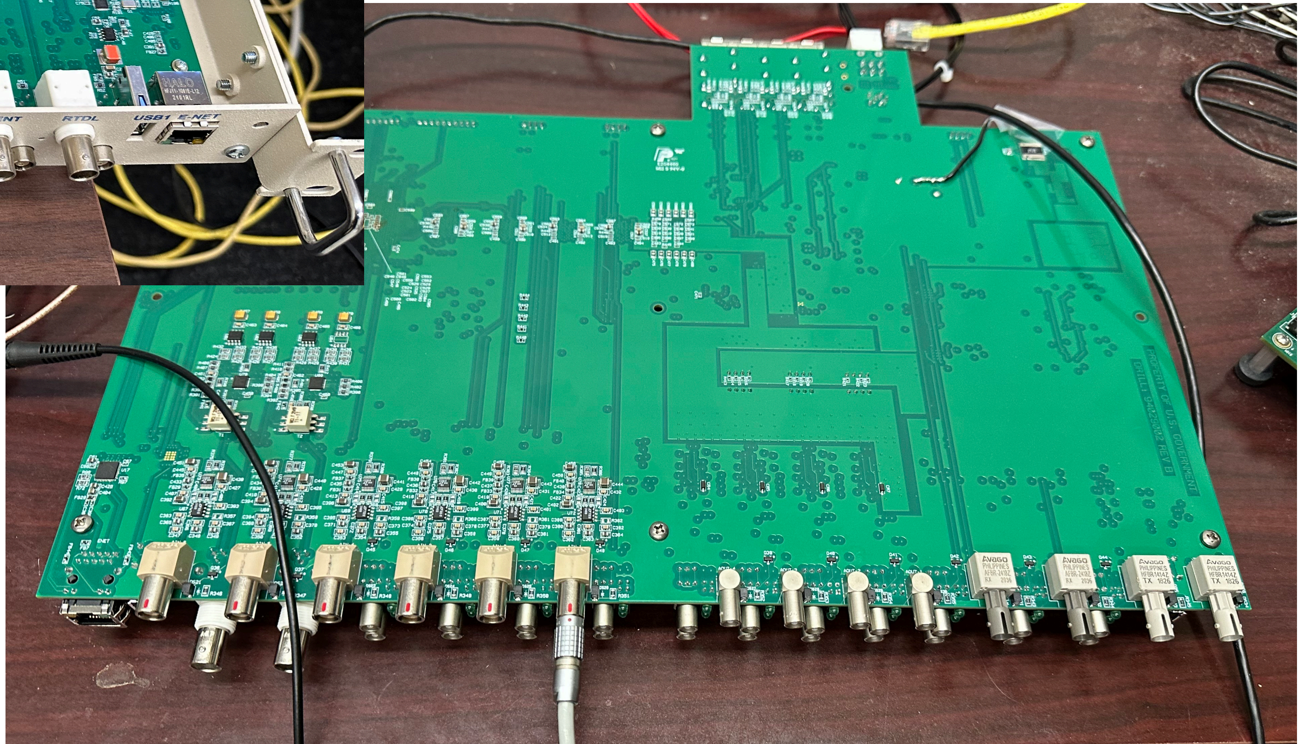


Location for new AC Quad



Controls Interface – under development





Status of project

We have in place

1. Reference magnets with fix coil measurements
2. An A/C quadrupole (still needs to be installed)

We are working on

1. how to better process the signals from the reference magnets
2. Replicating analog signal processing using digital controls
3. Getting a power supply (funding coming this year)

Plan is to get things in place and begin studies this fall.