D R A F T 3 November 2017

The Quadrupole RF System: Design and Simulations

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I. INTRODUCTION

While the CERN and E821 scraping scheme of powering the electrostatic quadrupoles asymmetrically worked well for E821, the muon losses at late times were higher than desired for E989. The systematic error from muon losses in E821 was listed as 100 ppb, which was signifantly smaller than the dominant ones [1]. The coherent betatron oscillations (CBO) systematic error was listed as 70 ppb for the 2001 data set [1]. The goals for these errors stated in the E989 TDR are 20 ppb and < 30 ppb respectively. Another factor to remember is that the number of muons that were lost using this asymmetric scraping method was on the order of 15 to 20%, or perhaps even larger. The proposed RF system, which will scrape the beam and reduce the phase space, is calculated to lose around 5% of the beam, and to reduce or eliminate the systematic errors from both muon losses and the (CBO).

An RF voltage is applied to the quadrupole plates in the ring, rather than the asymmetric powereing of the quads has been proposed, which simulations show will significantly reduce both losses and the CBO. Already in 2003 it was suggested to add an RF dipole field to the ring to damp the CBO [2]. More recently it was realized that it would be possible to use an RF quadrupole field to cool the beam and reduce the losses. This system of simultaneously applying both types of RF fields has the potential to reduce both systematic errors significantly, to the projected levels in the TDR. The RF can be applied to all of the quads in the ring, or to a smaller number. The advantage applying it to all of the quadrupoles permits the RF voltage to be smaller to produce the same scraping effect.

Howard, who designed the quad pulsers, believes that the appliation of RF to the quads should be ok with the pulsers, as long as the capacitance of the system is not larger than that in the proposed design.

A. The proposed RF Scraping Scheme and Simulations

In the simulations the following conditions are assumed:

- A uniform magnetic field of 1.45 T
- The electrostatic quadrupoles go uniformly around the storage ring.
- The RF is applied to a single quadrupole. i.e. at one point in the ring located where a physical quadrupole is placed.
- The quadrupole and 20-pole components of the electrostatic quadrupole field is included in the simulation
- The distribution of 8,411 muons that come through the inflector and have been kicked by the kicker prototype pulse simulated by Seungcheon Kim [3] is used.

There are three ingredients in the simulation:

1. An RF quadrupole at the horizontal CBO frequency is applied to the quadrupole plates as shown in Fig. 1(a).
2. An RF dipole with the horizontal CBO frequency is applied to the same quad plates as shown in Fig. 1(b).

3. An RF quadrupole is also applied to the same plates with the vertical waist frequency as shown in Fig. 1(c).

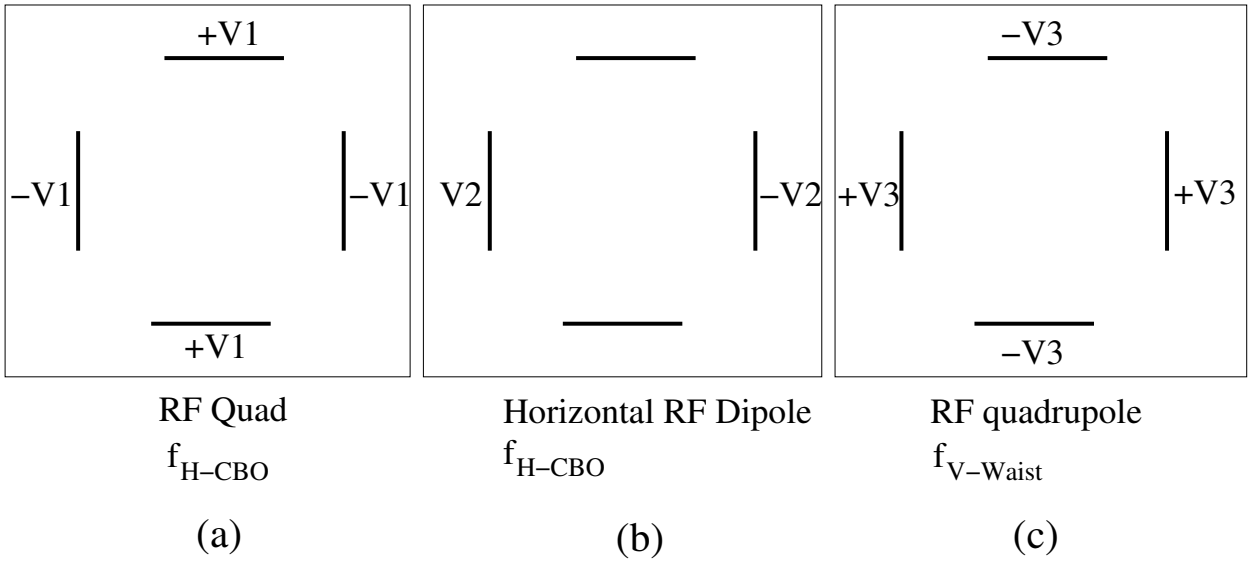


FIG. 1: The three contributions to the RF to be applied to the quadrupole plates. The sum of these three will be applied to a single plate. (a) The RF quadrupole field at $f_{\rm CBO}$. (b) The RF dipole field at $f_{\rm CBO}$. (c) The RF quadrupole at $f_{\rm VW}$

The RF quadrupole frequencies have the same voltage amplitude, although that could be changed to optimize the scraping. The horizontal RF dipole voltage has to be adjusted separately to optimize the elimination of the CBO.

The horizontal CBO frequency is 490 kHz, and the vertical waist frequency is 1.7 MHz. In principle one could use a vertical oscillating dipole field, but the vertical CBO frequency is 2.5 MHz, which is too high for the bandwidth of the RF amplifiers which specify the guaranteed bandwidth to be 10 kHz - 3 MHz.

The principle of the RF at the vertical waist frequency is shown in Fig. 2. During the application of the RF, the vertical phase space is modified so that the beam is scraped on the collimators, and then relaxed back to its equilibrium phase space. The amplitude and phase of each of these RF components can be adjusted to optimize the final beam. In principle the horizontal scraping could be done with the RF quadrupole as well, where Fig. 2 would have $x, x\prime$ rather than $y, y\prime$.

This same principle could also be used to scrape horizontally, where in Fig. 2 $x, x\prime$ is substituted for $y, y\prime$

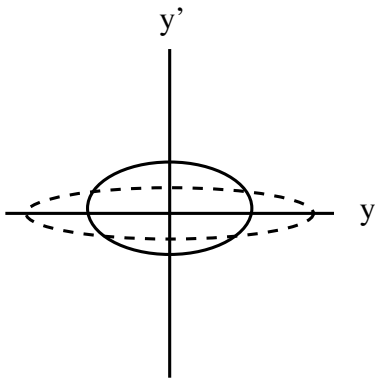


FIG. 2: The beam vertical phase space. The solid cuve shows the vertical acceptance of the ring, and the dashed ellipse shows the modification to the the RF quadrupole at the vertical waist frequency.

II. SIMULATIONS

A. KAIST Simulations

1. Introduction to KAIST Simulations

A homemade spin-tracking program has been used, written in `C++`. The lattice information is following.

- The ring has a radius 7.112 m.
- The collimator has a radius 45 mm, and is *continuous* along the ring circumference. Particles are *immediately* lost when they touch the collimator wall.
- A single detector is located at the fixed position.
- Neither inflector nor kicker is implemented.

The magnetic field is implemented homogeneous and uniform.

$$\mathbf{B} = B_0 \hat{y}, \tag{1}$$

where $\hat{y}$ points a direction perpendicular to the ring plane. B_0 is set to 1.451 T.

The electrostatic quadrupole is implemented to be *continuous* along the storage ring. Taking this account, the voltage is set to maintain the field index $n = 0.141$. The high voltage of the discrete quadrupoles of the realistic ring corresponding to this field index is 24 kV. The 20-pole correction to the quadrupole field is taken into account, adding 9th order term with respect to x and y into the linear field equation. The ratio between the 20-pole component and the quadrupole component of the electric potential used in the simulation is around 2%.

$$\mathbf{E} = E_0^{\text{4-pole}} \left(\frac{r}{r_0}\right) (\cos\theta, -\sin\theta, 0) + E_0^{\text{20-pole}} \left(\frac{r}{r_0}\right)^9 (\cos(9\theta), -\sin(9\theta), 0), \tag{2}$$

which is described in the accelerator coordinates again, where $r_0 = 45$ mm is the collimator radius and (r, θ) is the polar coordinates with respect to the (x, y) in the accelerator coordinates. The field strength at $(x, y) = (45$ mm, 0 mm) is given

$$E_0^{\text{4-pole}} = 0.38 \text{ MV/m}, \qquad E_0^{\text{20-pole}} = -0.038 \text{ MV/m}. \tag{3}$$

Those values were scaled with 156/360 to compensate the continuous quadrupoles from the discrete quadrupoles occupying 156° out of the ring circumference.

The RF electric field is applied to a localized region, in this case Q1S only, occupying 13° in azimuth. Basically we can come up with two different RF field, one is quadrupole field and the other is dipole field.

2. *Simulations without and with RF*

Figure 3 shows the beam horizontal mean(centroid) and RMS(width) as a function of time until 200 μs which approximately corresponds to 1341 turns for muons rotating around the design orbit. The amplitude of the mean oscillation, which also can be seen as the CBO amplitude, started around 10 mm and slowly being reduced with a lifetime $\sim$100 μs. The CBO amplitude is reducing because the 20-pole field shakes the Betatron oscillation frequency of the muons near the quadrupole plates.

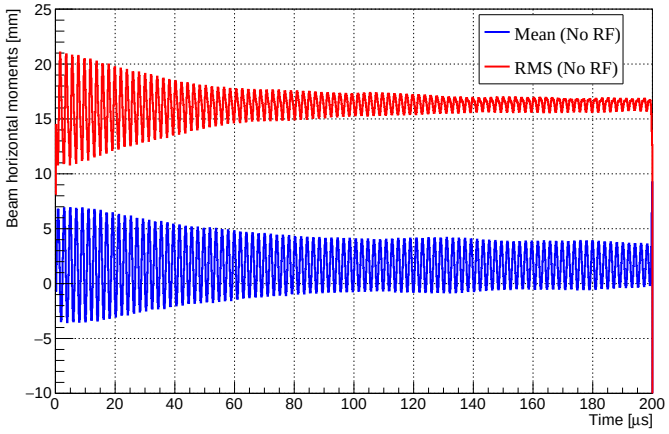


FIG. 3: Horizontal mean and RMS with no RF applied.

The reason why there's such a large oscillation for the first 100 μs can be explained by the fact that the high momentum muons and the low momentum muons are not lying on the exactly opposite phase in the horizontal phase space as shown in Figure 4. This is more clearly shown in Figure 5. The mean oscillation for the high momentum muons ($p > p_{\text{magic}}$) and the low momentum muons ($p < p_{\text{magic}}$) have a different phase to each other, not being cancelled as a total. This is dealt with by introducing the RF electric field oscillating with the CBO frequency as in Figure 6. Two different RF modes were applied, namely the dipole field and the quadrupole field. Both of them can resonate the beam and manipulate their phase space. With the dipole field oscillating with the CBO frequency, all muons are resonant with the field so it's capable of scraping the muon beam and also of modulating

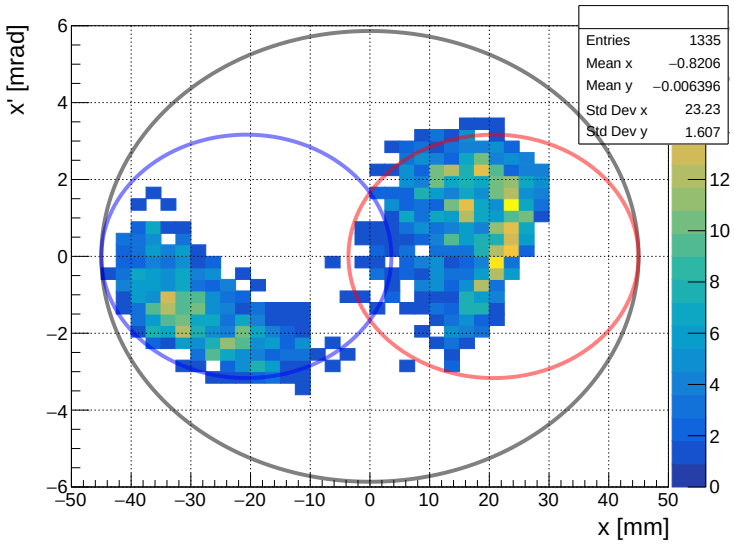


FIG. 4: Horizontal phase space only for the muons whose momentum difference with the magic momentum is higher than 0.2% ($|dp/p| > 0.2\%$). The black, red and blue ellipses are the acceptance of the magic momentum muon, the high momentum muon (+0.25%) and the low momentum muon (−0.25%), respectively.

TABLE I: RF parameters.

Q1S RF	Dipole	Quadrupole
Amplitude [kV]	5	5
Freqeuncy [kHz]	520	490
Phase [deg]	0	90
Duration [μs]	0-5	5-15

the Betatron oscillation frequency. This can be seen by comparing the blue curve (with RF) and the green curve (without RF) or the red curve (with RF) and the yellow curve (without RF) in Figure 7. Indeed during the first 5 μs when the dipole field is being applied, the CBO frequencies of the high momentum muons and the low momentum muons were shifted. This dipole field was applied until their phase becomes exactly opposite to each other, and then the RF quadrupole field was applied for another 10 μs to reduce their amplitude altogether. Even thought there are several small growths and cool downs in CBO oscillation with RF in Figure 6, the all RF field was turned off at 15 μs, not to have a possibility of disturbing other electronic systems or the stable muon storage especially during the data taking period. Only 5% of muons were lost due to the RF field. In Figure 8, one can check the RF field reduced both the mean and RMS of the horizontal distribution. Those are horizontal phase spaces at 80 μs, where one is without RF and the other is with RF.

The RF parameters I have used in this simulation are in Table I. 5 kV amplitude of RF electric potential is not small, and in the real experiment we are restricted to apply under 1 kV to avoid undesirable sparks and interferences, also because of the hardware limitations. However, we can expect the same effect using the parameters in Table I with expanding the RF region.

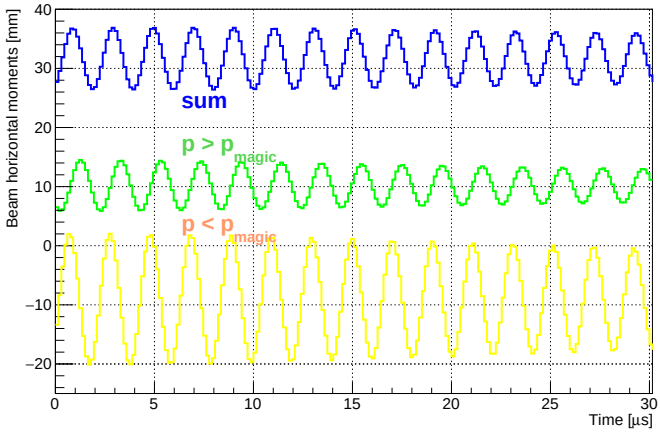


FIG. 5: Horizontal mean of the muons with upper magic momentum and those with lower magic momentum. The total mean is represented as "sum" and it has a 30 mm vertical offset in this plot.

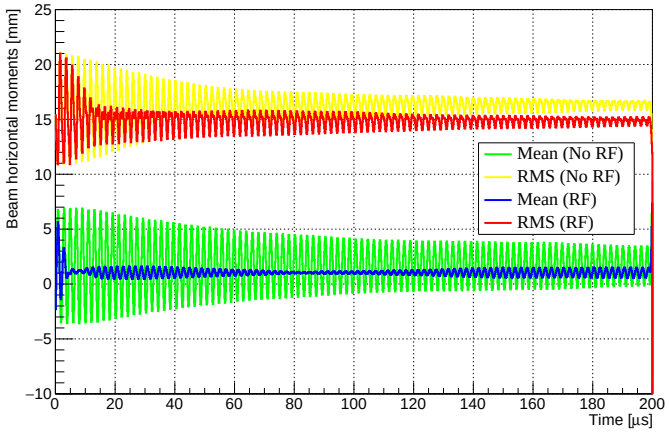


FIG. 6: Horizontal mean and RMS.

3. Summary of KAIST Simulations

In this simulation study, it is proved that the RF electric field oscillating with the CBO frequency can reduce the CBO amplitude significantly, without losing more than 5% of muons.

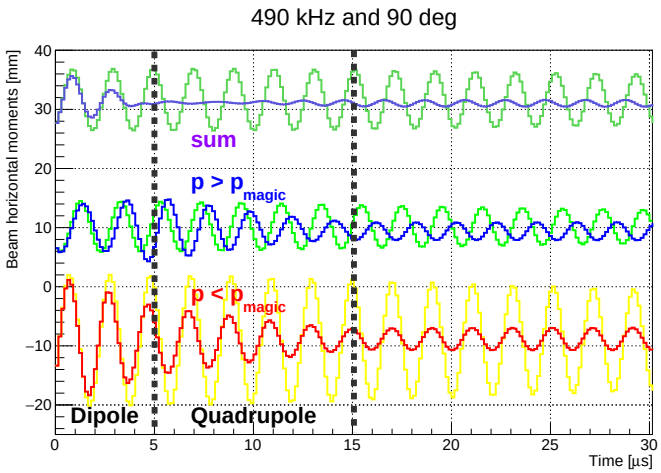
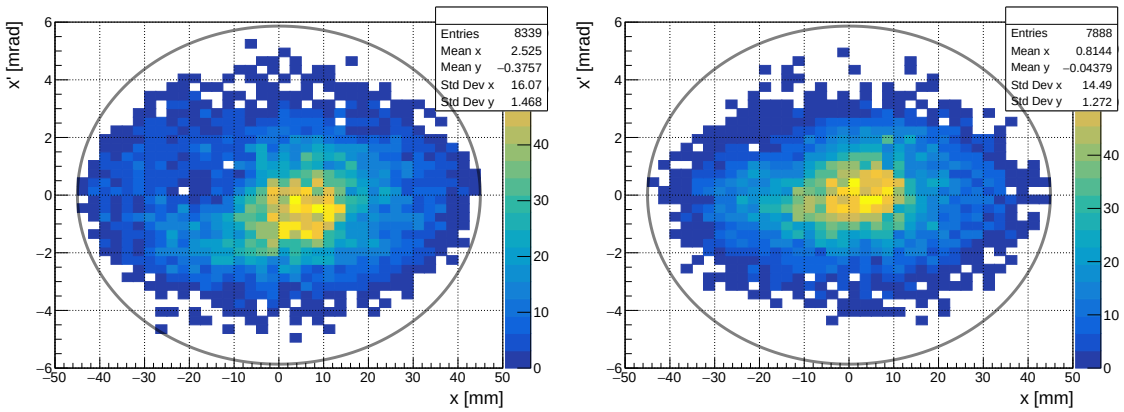


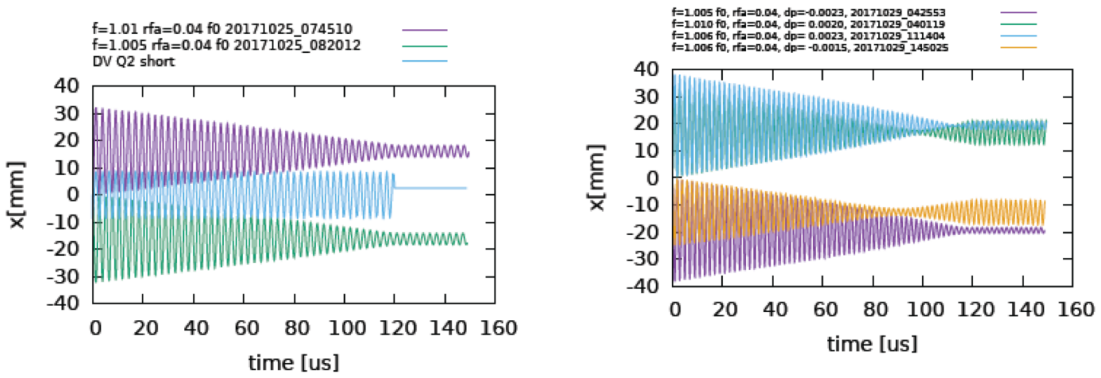
FIG. 7: Horizontal mean of the muons with upper magic momentum and those with lower magic momentum when the RF field is applied. The total mean is represented as "sum" and it has a 30 mm vertical offset in this plot. The blue, red and purple curves are the results with RF.



(a) (b)

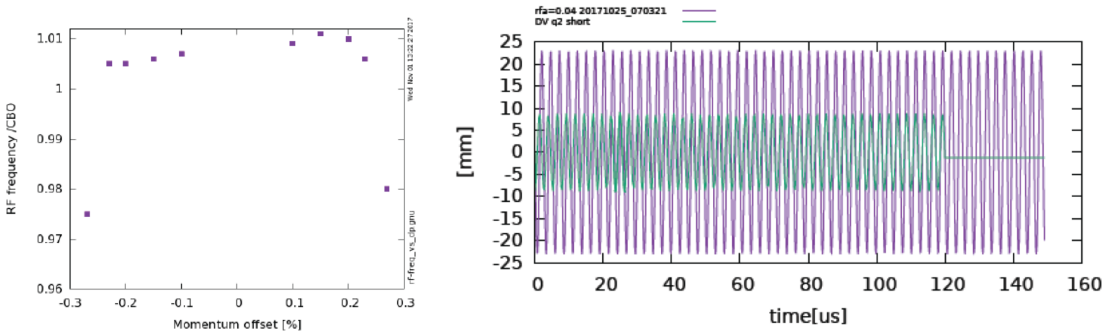
FIG. 8: (a) The horizontal phase at 80 μs when there was no RF field, (b) when the RF field was applied with the parameters in Table I.

B. Cornell Simulations



(a) (b)

FIG. 9: (a)A single particle with zero position offset, but ±0.2% momentum offset. Q2 short voltage modulated with f_{RF}. The CBO frequency depends on momentum. The effectiveness of voltage modulation depends on $f_{CBO} - f_{RF}$. (b)The most effective RF Frequency depends on particle momentum.



(a) (b)

FIG. 10: (a)Most effective RF frequency vs. muon momentum. Note that near the quadrupole plates the gradient is small and the focussing is weak. The $f_{RF} = 0.985$ for some damping at all momenta with a 20 μs RF pulse. (b) The RF has no effect on the on-momentum particles, i.e. the magic momentum particles.

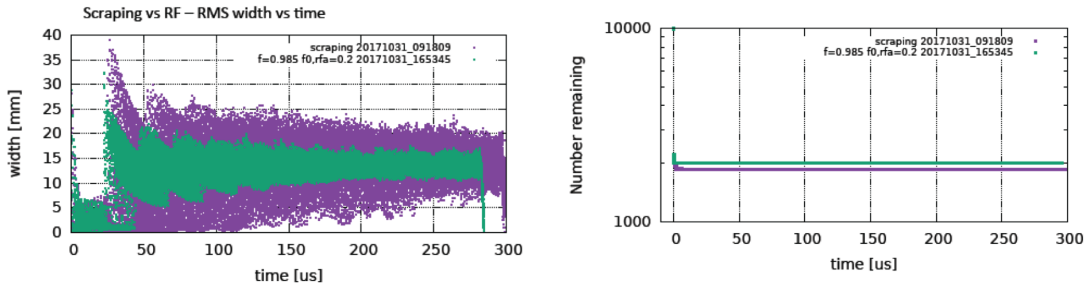
The E821 style scraping parameters used in the simulation are given in Table II. The following assumptions are made:

- Quadrupole final voltage is ±25 kV
- Quadrupole scraping ramp is 18 → 25 kV

For the RF manipulation, the voltage on Q2 short is modulated at αf_{CBO}, where $\alpha \sim 1$, with an amplitude of 5 kV.

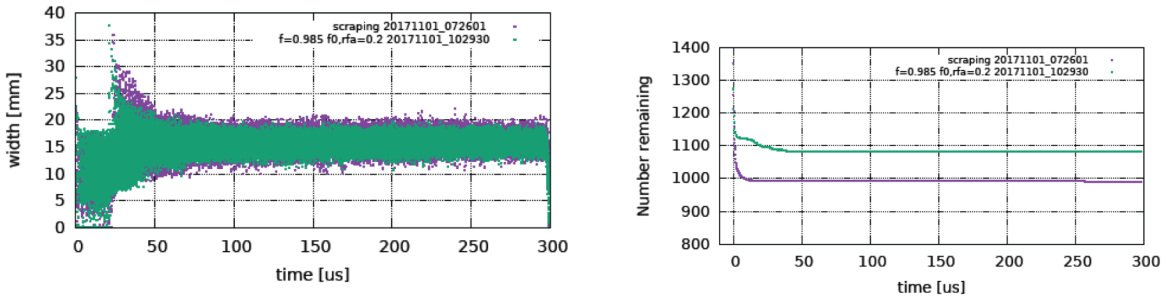
Quad	Top	Bottom	Inner	Outer
Q1	+25	+18	25	25
Q2	+25	+18	-18	25
Q3	+25	+18	-18	25
Q4	+25	+18	25	-18

TABLE II: The E821 Scraping Parameters.



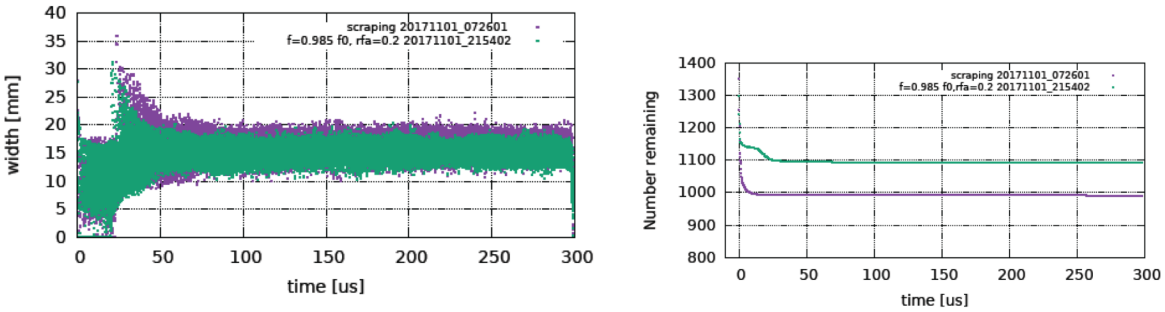
(a) (b)

FIG. 11: (a) Scraping vs. RF width vs. time. Gaussian momentum distribution with width = 2%; emmittance $\epsilon = 0$, bunch length = 0. The green band is with RF, purple with E821 scraping (b) Number of muons surviving after beam manipulation. Green is with RF, purple with E821 scraping.



(a) (b)

FIG. 12: Scraping vs. RF width vs. time. Gaussian momentum distribution with width = 2%; emmittance $\epsilon = 40$ mm-mrad, bunch length = 0. The green band is with RF, purple with E821 scraping (b) Number of muons surviving after beam manipulation. Green is with RF, purple with E821 scraping.



(a) (b)

FIG. 13: Scraping vs. RF width vs. time. $dp/p = 2\%$; emmittance nominal, bunch length = 0. The green band is with RF, purple with E821 scraping Dave R, please fix this, I'm confused. (b) Number of muons surviving after beam manipulation. Green is with RF, purple with E821 scraping.

III. DETAILS OF THE RF SYSTEM

A. The basic layout

The RF system is applied to the quadrupole system by capacitively coupling them to the quadrupole plates. The RF is added on top of the high voltage that produces the electrostatic quadrupole field. The quad system will need to be modified so it can be operated in the E821 scraping method, or with the RF. It will be modified so that the "input" for the RF is terminated when the RF is not connected as shown in Fig. 14. This option was studied to demonstrate that the current on the 1 MΩ resistor and other currents to see if there might be issues that are not there before the terminating resistor R2 is added.

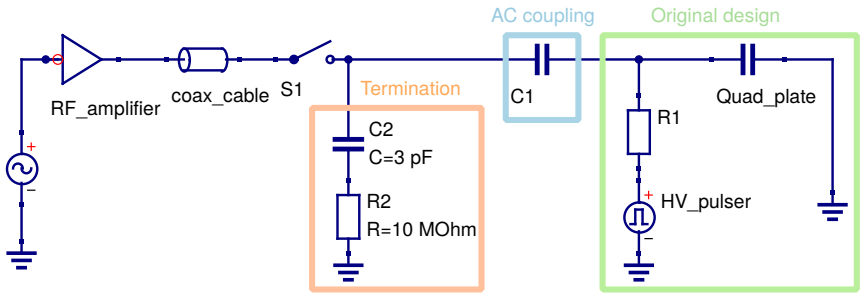


FIG. 14: The quadrupole circuit showing the addition of the RF system. The RF system isl capacitively coupled to the quadrupole plates through C1. When the RF system is not connected, the line to the plates is terminated through C2 and the 10 MΩ resistor R2.

A schematic of how the RF signal is sent to the quadrupole plates is shown in Fig. 15. The cartoon of how these signals are used on the quad plates is shown in Fig. 1 in the introduction.

A simulation of the current

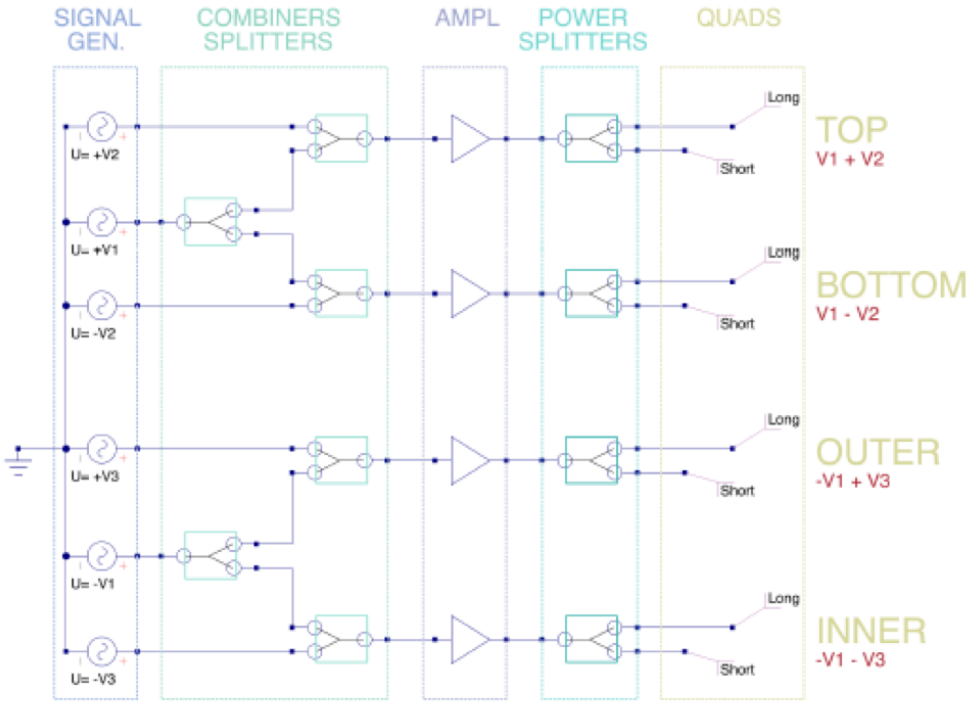


FIG. 15: The RF signal generators, splitters and the connections to the quadrupoles. This figure gives the details of the left-hand side of Fig. 14

B. RF Tests at Fermilab

The RF system prototype was tested at Fermilab in August 2017. It is documented in docdb note 4301 by Young-Im Kim. A schematic of the setup is shown in Fig. 16

IV. DISCUSSION AND CONCLUSIONS

V. REFERENCES

[1] G. Bennett, et al., (Muon $(g-2)$ Collaboration), Phys. Rev. **D73**, 072003 (2006).
[2] Y. Orlov and Y. Semertzidis, E821 Note #431, (2003).
[3] Seungcheon Kim, GM2-doc-7607-v1, 28 Jul 2017. See also Diktys Stratakis, GM2-doc-4461-v1, 18 Oct 2016, and Seungcheon Kim GM2-doc-4886-v2, 03 Feb 2017.

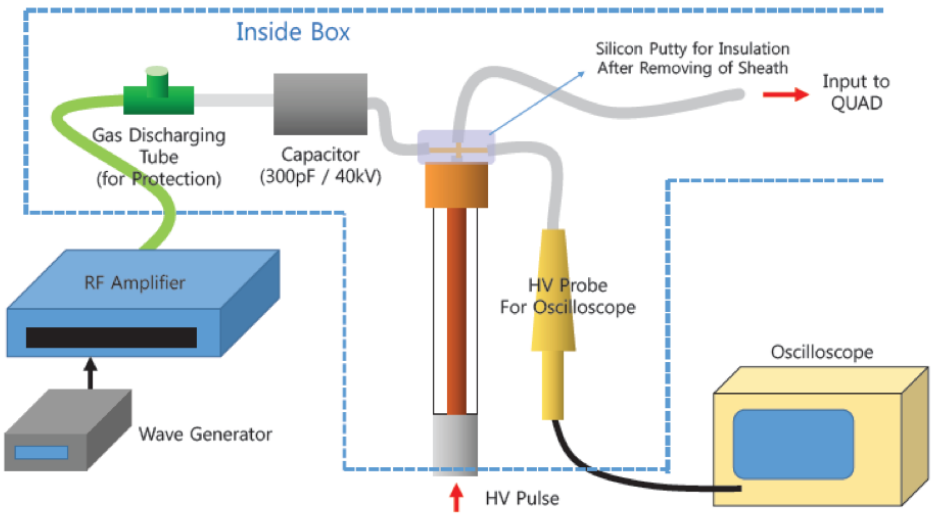


FIG. 16: A schematic of the experimental setup used to test if the RF system would be compatable with the existing pulser system.

RF Amplifier Data Sheet

TOMCO

BT-AlphaA Series
10kHz-3MHz
250W, 500W

- NMR, MRI, EPR
- Radar
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The BT-AlphaA series is a range of class AB RF power amplifiers covering the 10kHz to 3MHz frequency range.

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- Extremely high phase and amplitude stability
- Very fast pulse rise/fall times
- High linearity
- Very low interpulse noise
- Competitively priced

Suitable for NMR, MRI, NQR, EPR, pulsed radar, ultrasonics and other scientific applications.

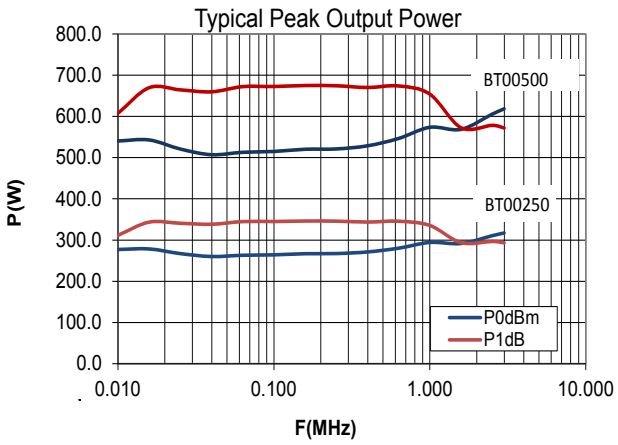
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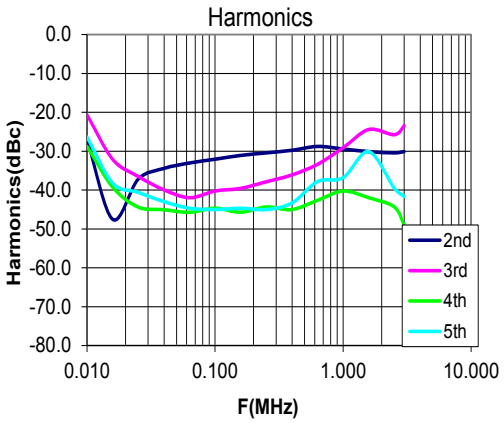
BT-AlphaA Series	
Model numbers	BT00250-AlphaA / BT00500-AlphaA
Rated power	250W / 500W minimum[1]
P1dB	200W / 400W minimum[2]
Gain	54dB / **57dB** minimum
Type	Class AB MOSFET
Frequency	10kHz-3MHz[3]
Gain flatness	±1.5dB maximum (measured at 1/10th rated output power)
Max. duty cycle	20%[4]
Max. pulse width	100ms[5]
Rated power in CW mode	25W / 50W[6]
Pulse droop	0.5dB maximum across 100ms pulse[7]
Pulse rise and fall times	100ns typical using a pre-gate RF input signal
Gate delay	Rising edge: 2µs typical Falling edge: 1µs typical[8]
Harmonics	Odd: -20dBc typical, -12dBc maximum Even:-30dBc typical, -20dBc maximum
Spurious	<-70dBc maximum
Output noise (blanked)	<10dB above thermal (100kHz bandwidth)
Phase change/power	<5° from -40dB to full power
Phase stability	<1° across 100ms pulse
Output sample	-50dB into 50 Ω (forward voltage sample)
Input/output impedance	50 Ω nominal[8]
Load VSWR	Tolerates at least 3:1 @ full rated power without shut down[9]
Remote interface	Parallel status monitoring via 25 pin D connector[10]
Connectors	RF output: N type RF input, gate, sample:BNC[11]
Cooling	Forced air
Indicators	DC Power, RF Power, Enable, Selected, Mismatch, Over-temp, Over-duty, Shutdown
Protection	Load VSWR, duty-cycle, pulse width, over-temperature
Gain control range	10dB minimum for 0-5V control voltage
RF drive RF gate (blanking)	0dBm nominal, 10dBm for no damage 0-5V CMOS
Physical	19" Wx 500mmD x 180mmH (3RU x 19" rack mounting), 13kg / 17kg
Mains power	110-240V, 50-60Hz, single phase, 1kVA / 2kVA max.[12]
Compliance	CE

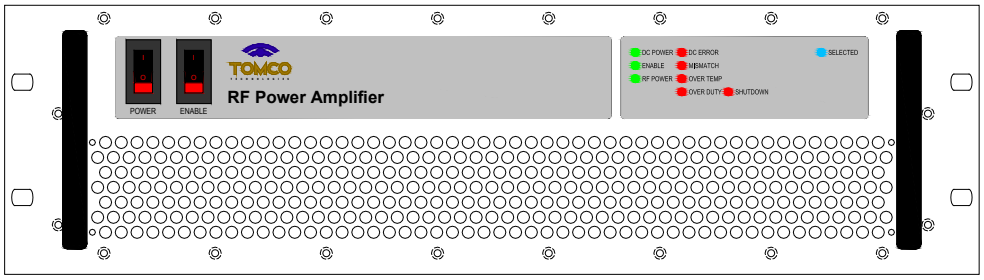
1. PEP for input power of 1mW
2. Minimum output power at 1dB gain compression
3. The amp provides useful power outside this range, but performance is not guaranteed
4. Duty cycle is internally limited in pulsed mode
5. Maximum gate pulse width in pulsed mode (internally limited)
6. CW mode automatically enabled at output power level less than approx.10% of full rated power
7. Measured at max. pulse width at nominal P1dB level
8. Rising edge measured from rising edge of GATE pulse to 90% RF output voltage.
   Falling edge measured from falling edge of GATE pulse to 10% RF output voltage
9. Self resetting protection shuts the amplifier off if the load SWR is excessive
10. Pin out at www.tomcorf.com/pdf/interface.pdf
11. Other connector types available on request
12. 3-pin IEC. mains supply must include an earth

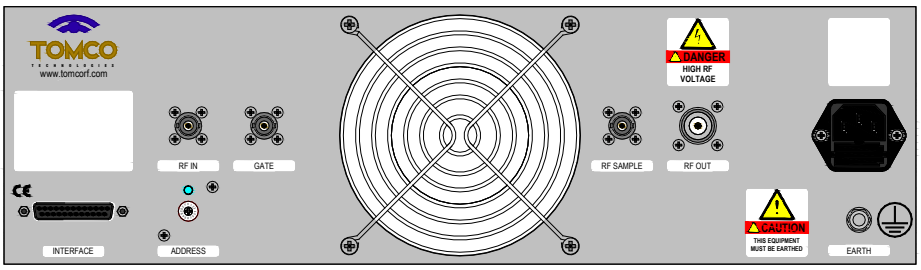
FIG. 17:

BT-AlphaA Series
10kHz-3MHz
250W/500W









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Hong Kong: +852 8121 4277

FIG. 18: