

Achieve Long G10 Kicker Pulse Tops for Au Run at Low Energies (BES-II)

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I. Introduction:

The G10 magnets are a set of four ferrite kickers in the AGS used to extract beam into the AtR (and typically on to RHIC). A single G10 module current pulse is about 400 ns long with little pulse flattop. Each module has an individual delay trigger, which can be manipulated to change the time spacing between these 4 pulses to form different sum pulses. We will describe several configurations for extraction at different energies below the nominal AGS to RHIC transfer energy (~ 9.8 GeV/n).

II. Device

G10 (Fig. 1) has 4 modules, which are inside the tunnel and are close to each other. Each single module has a fixed current pulse, determined by the circuit characteristics. The Thyatron needs a minimum of about 1-2 kV to fire but needs at least 2.5 kV (~ 205 counts in pet) to fire stably. A diode tree was designed to prevent PFNs from possible crosstalk. But it is jumped out right now and it is not required for operation.

G10 uses an ALE power supply (max 50 kV). It was originally designed based on the ratings of cables and magnets. The regulation is 0.2% (100 V) pulse-to-pulse. Its nominal voltage is about 30 kV (about 1 kA, and about 2500 counts in pet).



Fig. 1

III. BES-I related history overview

The long pulse top design is for RHIC. BES-II (starting Run-19) [Phys. Rev. Accel. Beams [25](#), 051001]. BES-II required longer bunches in RHIC. At that time, we were looking at the data from BES-I. The tables (Table 1 and Table 2) below show the Low Energy run history for Au and PP.

Species: $^{197}\text{Au}^{79+}$			
	Total particle energy [GeV/nucleon]	Calendar time in physics	Total delivered luminosity
Run-8 Run Coordinator: Todd Satogata	2.5	3/10/2008 - 3/12/2008 15 h test	no physics
Run-10 Run Coordinator: Todd Satogata	3.85 (Tandem)	04/22/2010 - 05/27/2010 4.6 weeks	4.23 μb^{-1}
	2.5 (Tandem)	06/07/2010 - 06/09/2010 29 h test	no physics
Run-12 Run Coordinator: Christoph Montag	2.5 (Ebis)	06/25/2012 - 06/27/2012 2 days test	no physics But got 1 event
Run-18 Run Coordinator: Greg Marr & Chuyu Liu	3.85 fxt (Ebis)	05/30/2018 - 06/04/2018 4.3 d	54 μb^{-1}

Table 1

Species: PP			
Run-13 Coordinator for this test: Christoph Montag	5.86 GeV PP beam in RHIC with rigidity of 2.5 GeV/nucleon Au beam with acceptable lifetime for collider operation	06/05/2013 APEX	Yellow only, no collisions

Table 2

IV. BES-I related injector parameters

Since we did Au in BES-II, let's focus on the Au data from BES-I. Table 3 below will show related injector parameters in our interest.

$^{197}\text{Au}^{79+} + ^{197}\text{Au}^{79+}$			
	Injector Merge Pattern	Bunch Spacing at AGS extraction (ns)	Estimated full width Bunch length (ns)
Run-10, Tandem 3.85 GeV	Booster: h=6, 4 loads AGS: 24, 12, 4 (h=24, 12, 4, 12)	694.2 4 bunches equally spacing	32
Run-12, Ebis 2.5 GeV	Booster: 421, 8 loads AGS: 8, 4, 2 (h=16, 8, 4, 12) Initial merge setup	1450.5 2 bunches equally spacing	93 (Cut down to 50)
Run-18, Ebis 3.85 GeV	Booster: 421, 4 loads. AGS: 4, 2 (h=24, 12)	1388.3 2 bunches equally spacing,	55 (With One 9 Mhz installed)

Table 3

V. BES-I related extraction Rigidity relationship

Since G10 is used for AGS extraction, Table 4 below will show AGS extraction energy, AGS extraction rigidity, RHIC injection rigidity relationship. We use 9.7960062 GeV as our nominal AGS extraction energy.

AGS Extraction Energy E (GeV/N)	AGS Extraction Rigidity $B\rho$ (Tm)	RHIC Injection Rigidity $B\rho$ (Tm)	Scale factor
9.7960062	83.2210136	81.1137824	1
3.8500176	31.880809	31.073558	0.383086
2.5000114	19.800154	19.298797	0.2379

Table 4

VI. BES-I related G10 operating data history

Table 5 lists the estimated operating voltages and the archived operating voltages for G10 for the BES-I runs. The estimations were derived from the 9.796 GeV Archived Data.

	G10	
	Estimation Using Gpm scope	Archived Data using Gpm scope
Run-10, Tandem 3.85 GeV AU2	5.36 V/Module Sum=5.36*4=21.44 V Scale factor=0.383086	3.8 V/Module Sum=3.8*4=15.2 V
Run-12, Ebis 2.5 GeV AU3	4.44 V/module Sum=4.44*3=13.32 V Scale factor=0.2379	3.8 V/Module Sum=3.8*3=11.4 V
	Run with 3 modules	Run with 3 modules (2, 3 and 4)
Run-17, Ebis 9.796 GeV	14 V/module Sum= 14*4=56 V	14 V/module Sum= 14*4=56 V
Run-18, Ebis 3.85 GeV	5.36 V/Module Sum=5.36*4=21.44 V Scale factor=0.383086	5.3 V/Module Sum=5.3*4=21.2 V

Table 5

VII. G10 kicker signal layout

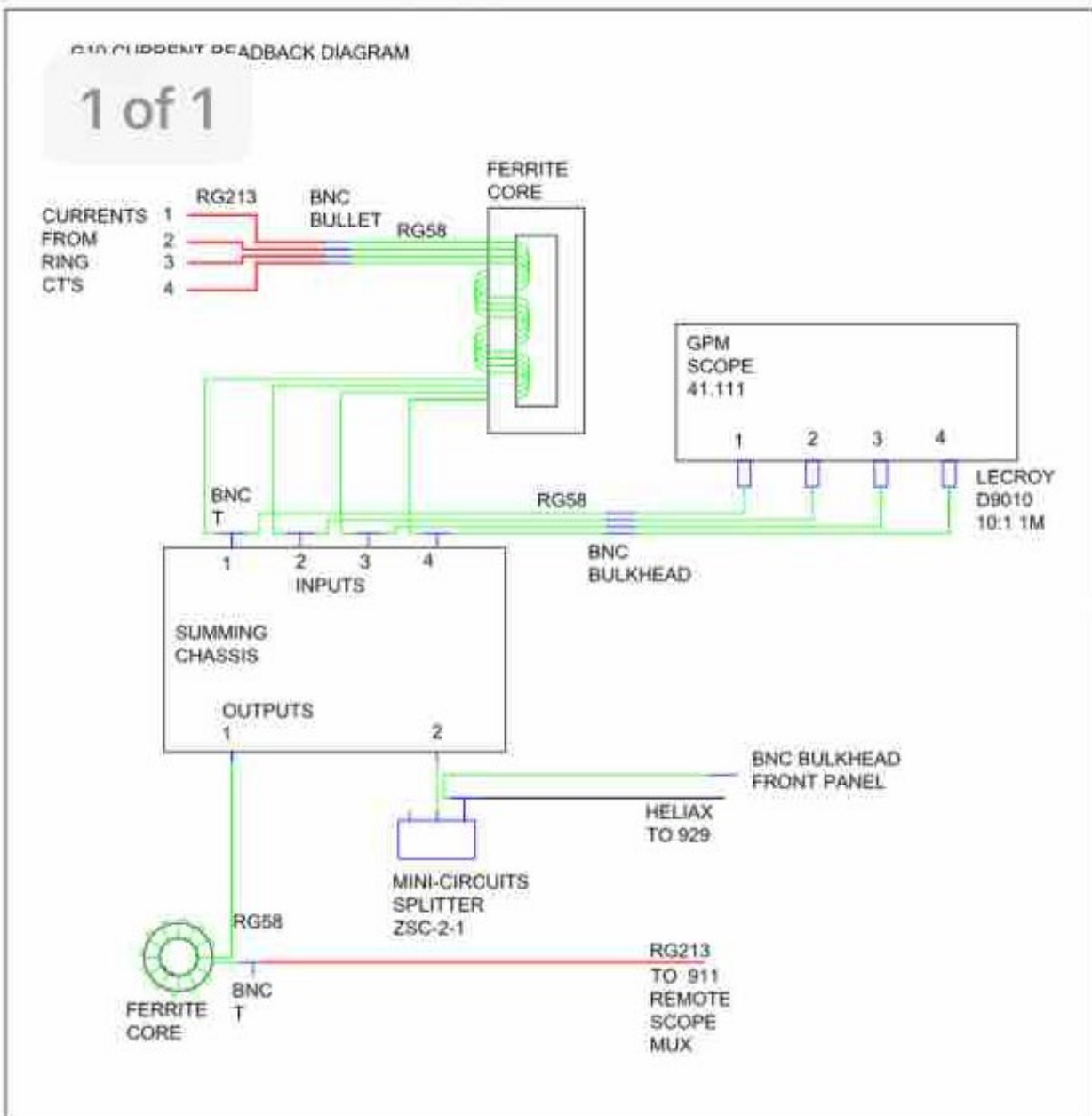


Fig. 2

Fig. 2 is the G10 current readback diagram provided by Yugang Tan [1]. As the diagram shows, the local scope is upstream of the summing chassis. The input to the 911 mux system is downstream of the summing chassis. The local scope shows individual module current. The 911 mux system shows the sum signals of the 4 individual modules current. The summing is done by the summing chassis.

During this research, we did 2 upgrades to get a better signal. First, we upgraded the signal to noise ratio by connecting the unused output channel (OUTPUT 1) of the summing box to the 911 mux system [2]. Before this change, 911 mux and 929 mux were sharing the same output channel (OUTPUT 2).

Second, we found that the 911 G10 current mux signal was flat without any noise when turned off the discharge trigger. So, the noise is from the discharge trigger. [3] When G10 is set to be on with higher than 0 counts, the GPM scope signals look much cleaner than the mux [4]. There was no signal attenuation between the gpm and mux. However, the noise patterns were different between the gpm and the mux due to different signals path. The gpm doesn't see much noise. The mux saw some noise patterns due to the long signal path. Then, Yugang installed a choke downstream of the OUTPUT 1 of the summing box and upstream of the 911 mux system input to reduce the noise on the mux signal.

With the choke for the mux signal path, both gpm and the mux see the same signal now at 0 count. The signal is at the pulsing time shaped like the kicker current demonstrating that the choke got rid of the noise for the mux and left only the real current at 0 count. If not, the gpm and the mux should still see difference in the noise pattern due to different signal paths. [5] As a result, we don't need to subtract the baseline when looking at the G10 mux signal anymore [6]. Note that the relative position from bunch to kicker was changed slightly when measured on the scope after these upgrades. The shift was measured to be roughly 50 ns. [7]

VIII. Old data for G10 long pulse top

Below are some old data (5/1/2002) provided by the Pulse Power Group regarding G10. I added some marginal notes after talking to the Pulse Power engineers in these pictures using pencil. Next, I will explain more about my marginal notes, which are best to my understanding.

In Fig. 3, Remote Reference is in counts in pet. The convention between these values is: Max counts is $2^{12}=4096$, which corresponds to 10 V as max for Remote Vref and 50 kV as max for the real V output. The nominal setting for G10 is 2800 counts at that time. I marked it with a star.

AGS G10 MCR REMOTE REFERENCE SET POINT 5/1/2002

Remote Reference	Remote Vref	readbac k	V output	I pulse
1600	3.924	3.83	19,150	
1800	4.400	4.23	21,150	
2000	4.904	4.64	23,200	
2400	5.870	5.44	27,200	
2600	6.360	5.85	29,250	
★2800	6.870	6.16	30,800	← This one should be the nominal setting.
3000	7.347	6.17	30,850	

X5

$2^{12} = 4096 \Rightarrow 10V \Rightarrow 50kV$

Fig. 3

Fig. 4 is measured on the local scope. It shows the case when the 4 pulses are spaced in 150 ns interval. One division of the scope is 100 ns. Note that there were grounding changes in the building that make the signals less clean now compared to when these old data were taken in 2002.

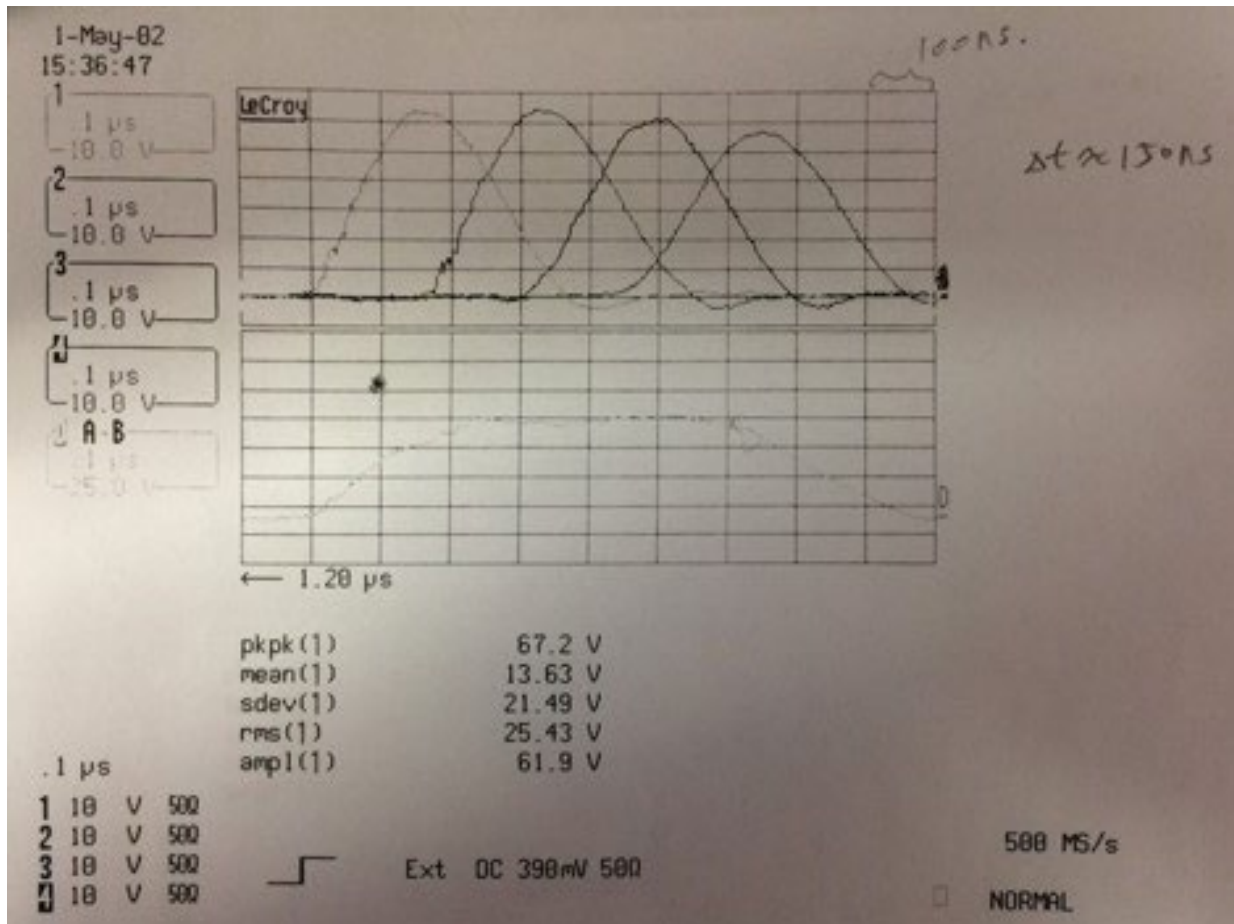


Fig. 4

Fig. 5 is measured on the local scope. It shows the case when the 4 pulses are spaced in 100 ns intervals. One division of the scope is 100 ns. Note that there were grounding changes in the building that make the signals less clean now compared to when these old data were taken in 2002.

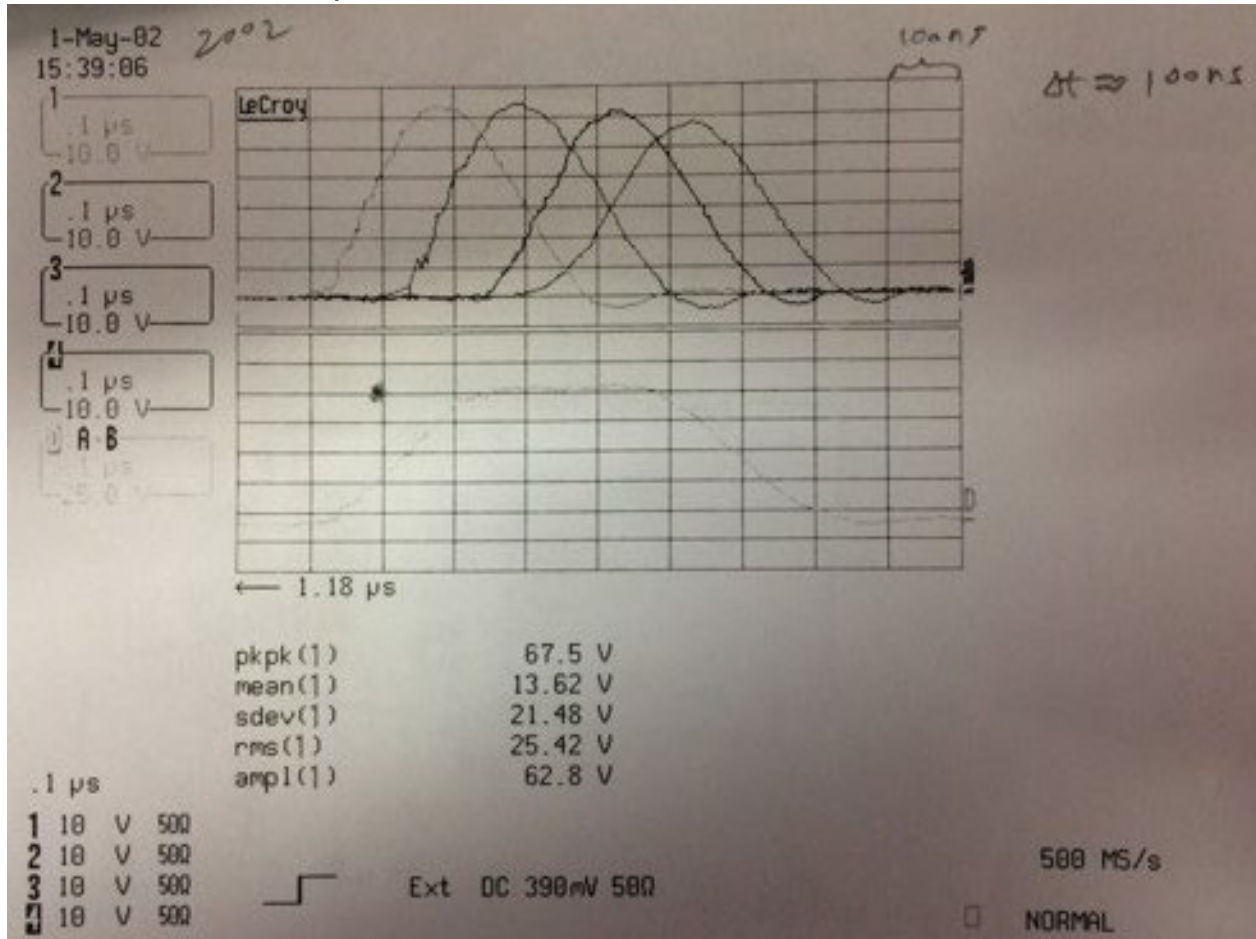


Fig. 5

IX. Gpm scope data from previous runs

In this section we will go through the Gpm data from the previous Low energy runs and several nominal runs (9.796 GeV) close to our research period. This is to get an idea of how G10 and its related instrumentation and controls system behaved experimentally before exploring different long pulse top options using these systems in the next session.

The Gpm data is sourced from the local scope signals and is translated through the controls system. We trust the mux signals more than the gpm signal when there is any discrepancy because we believe the mux signals went through less digitization.

Fig.6 shows the G10 gpm scope data during a 9.796 GeV run from Run-16, 5/2/2016, Fill 19850. The resolution on this gpm data is 1ns/point. We can see this is around 14 V/Module. $\text{Sum}=14*4=56 \text{ V}$.

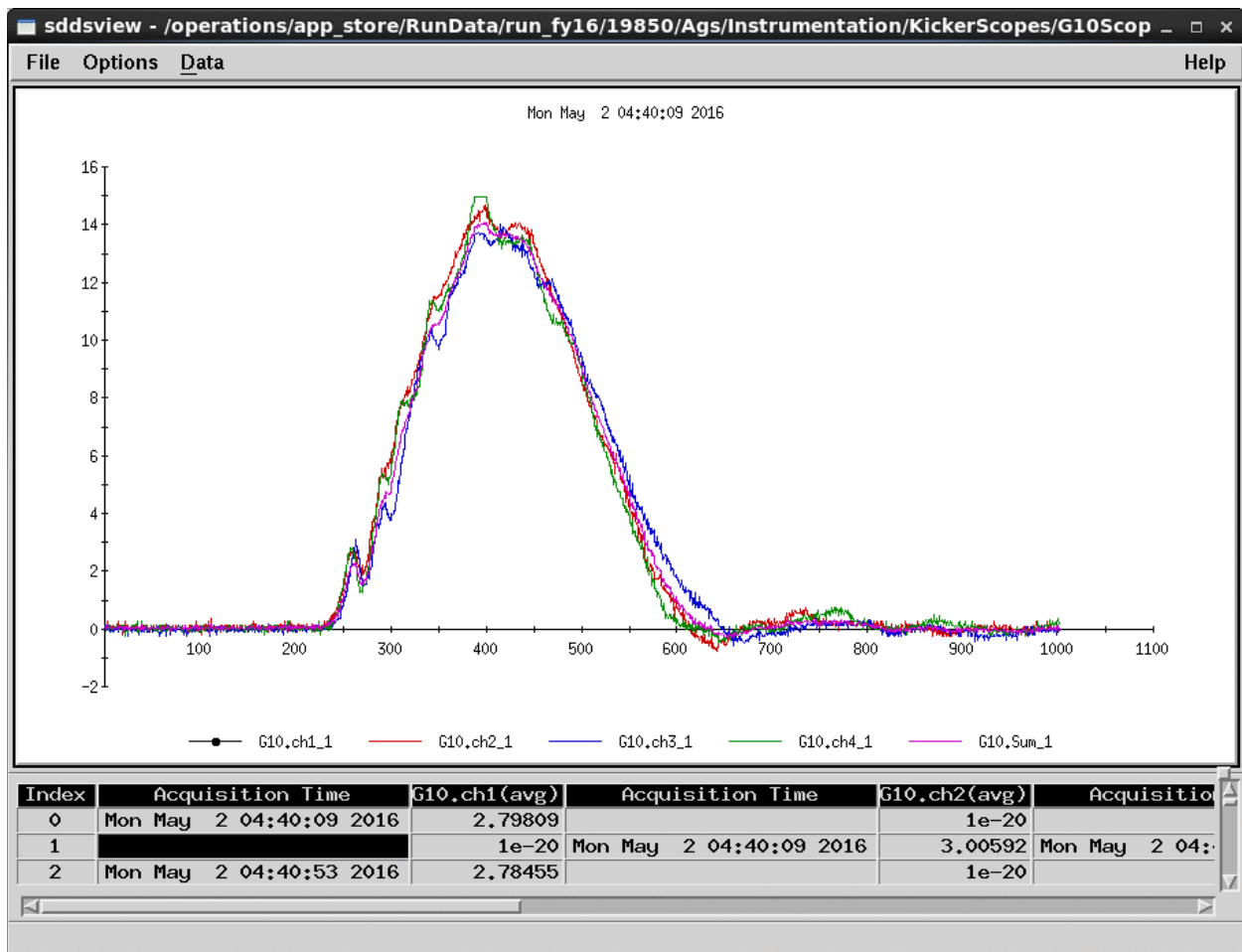
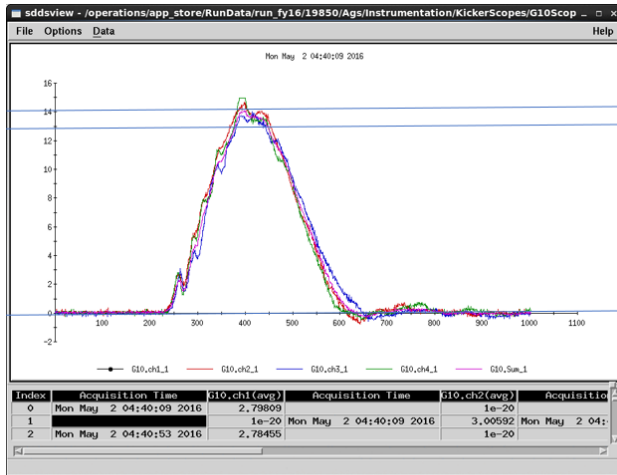
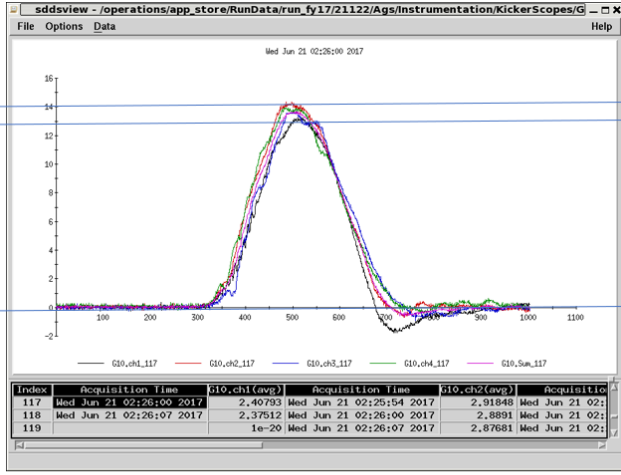


Fig. 6

Fig. 7 compares how things behaved between two 9.796 GeV runs from different years. We can see the shape and the height of some modules changed slightly from run to run with the same voltage settings in pet.



G10 Scope, 9.796 GeV
Resolution: 1 ns/point
Run-16, 5/2/2016, Fill 19850
14 V/Module
Sum=14*4=56 V
counts/readback=2500/2487



G10 Scope, 9.796 GeV
Resolution: 1 ns/point
Run-17, 6/21/2017, Fill 21122
14 V/Module
Sum=14*4=56 V
counts/readback=2500/2488

Fig. 7

Fig. 8 shows the G10 gpm scope data during a 2.5 GeV run from Run-12, 06/26/2012, Fill 17031. The resolution on this gpm data is 1 ns/point. We can see this is around 3.8 V/Module. $\text{Sum}=3.8*3=11.4 \text{ V}$.

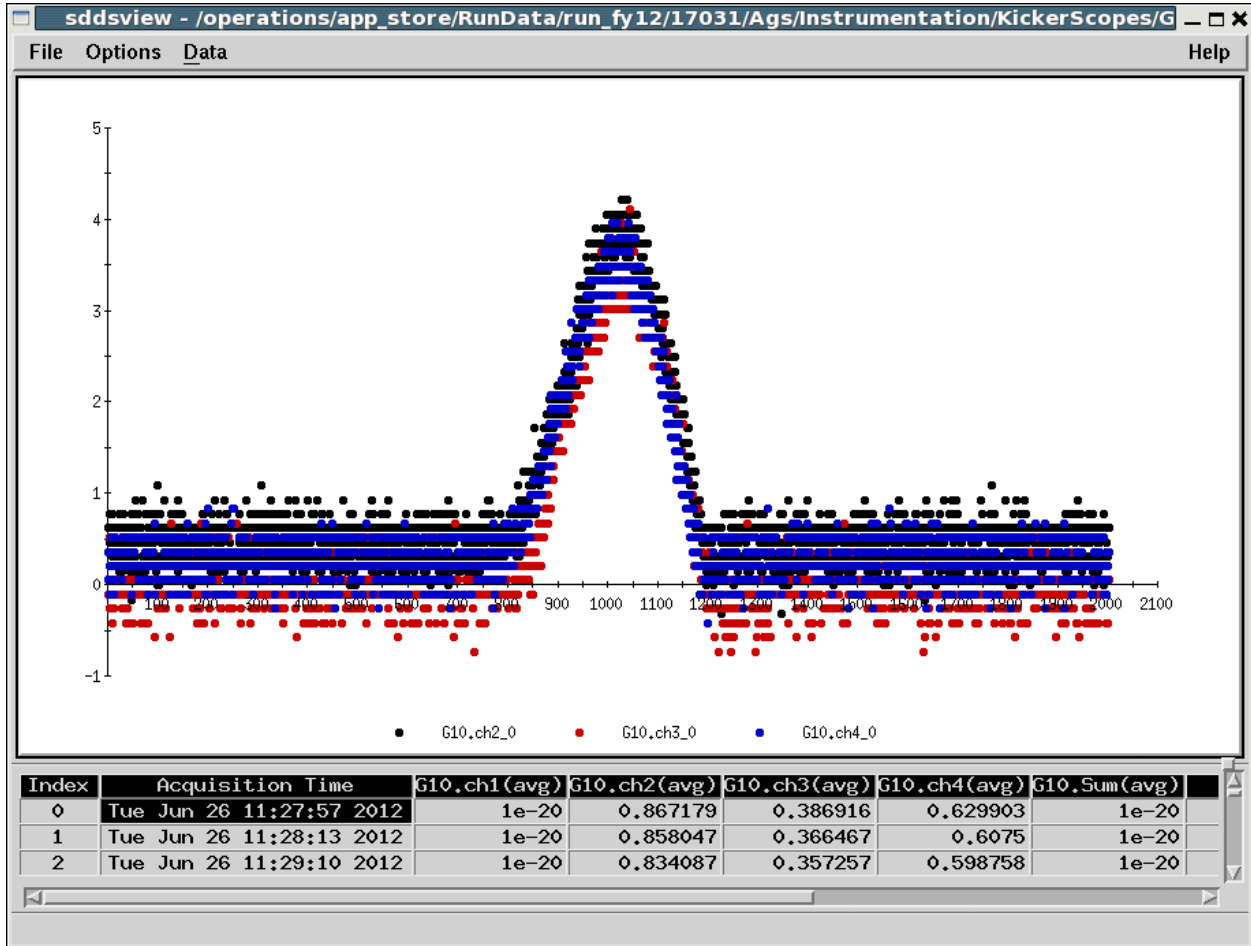


Fig. 8

Fig. 9 shows the G10 gpm scope data during a 3.85 GeV run from Run-10, 05/24/2010, Fill 14019. The resolution on this gpm data is 1 ns/point. We can see this is around 3.8 V/Module. $\text{Sum}=3.8 \times 4=15.2 \text{ V}$.

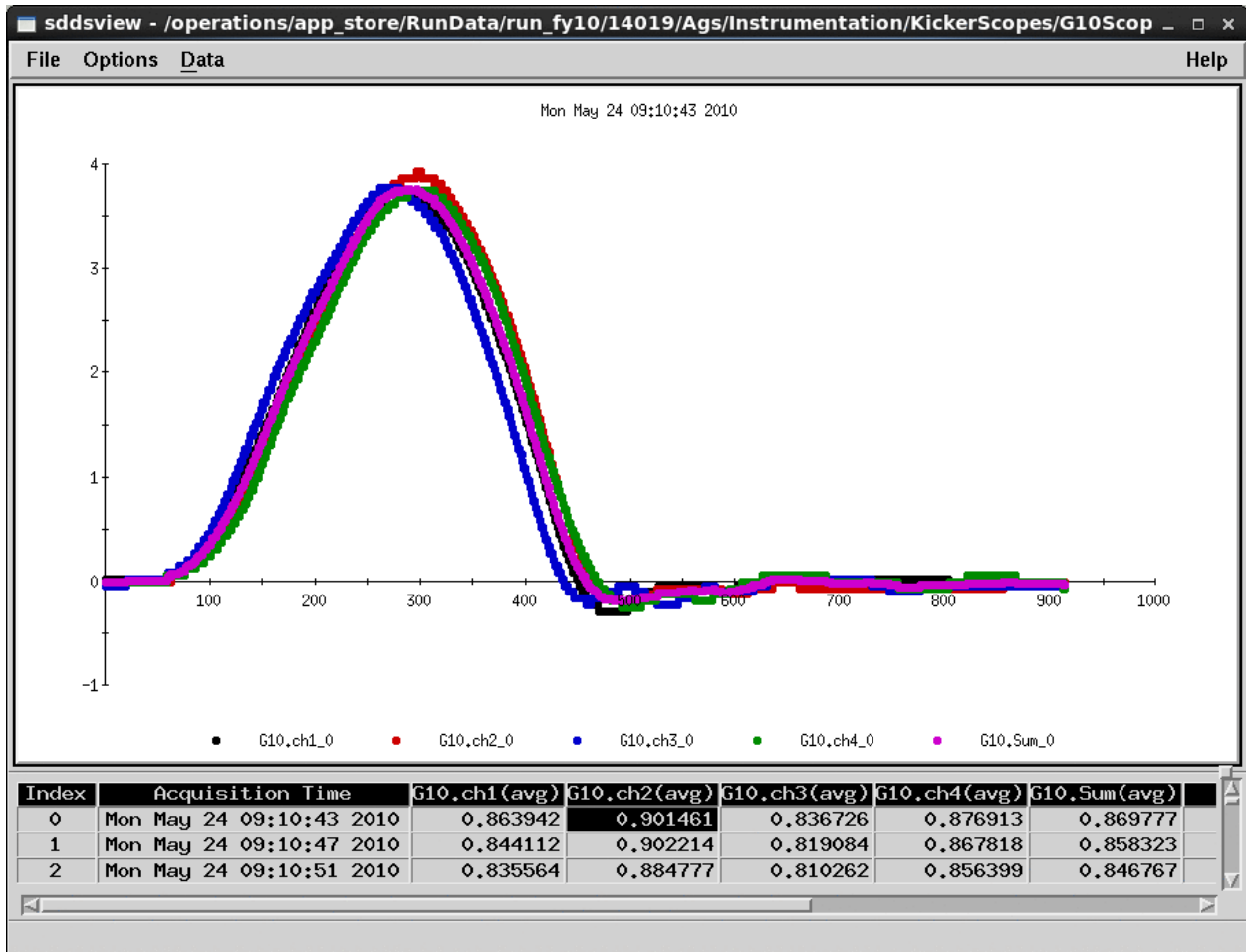


Fig. 9

Fig. 10 shows the G10 gpm scope data during a 3.85 GeV run from Run-18, 06/03/2018, Fill 22011. The resolution on this gpm data is 0.1 ns/point. We can see this is around 5.3 V/Module. $\text{Sum}=5.3 \times 4=21.2 \text{ V}$.

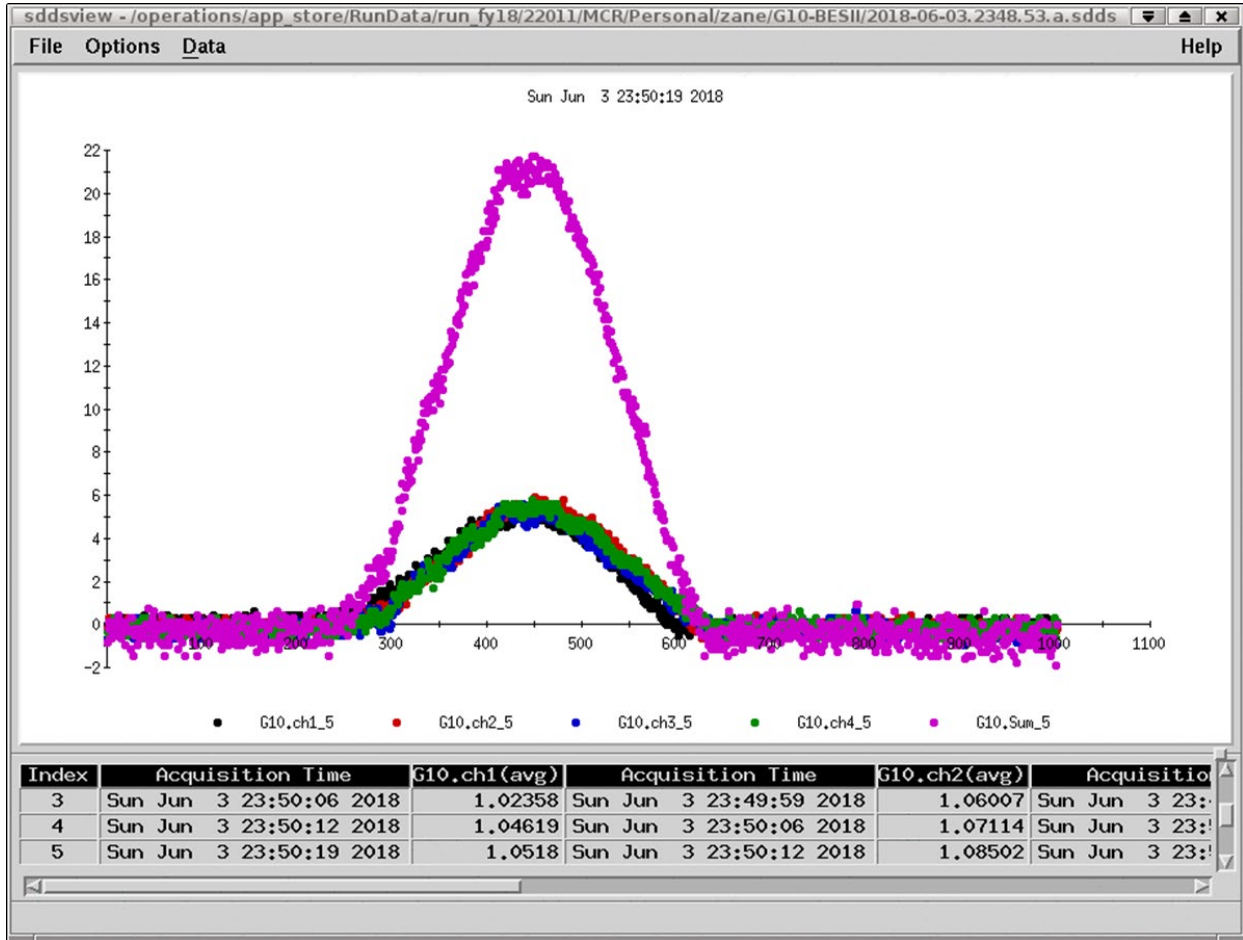


Fig. 10

X. Featured Long pulse top options found in the study

Table 6 summarizes the G10 settings from BES-I. The settings can be controlled through pet application. The archived data are in blue color while the calculated values are in orange. We can see that the calculated values weren't always compatible with the archived settings.

Table 6 also listed several featured long pulse top configuration options found in the study. Note that the delays may be slightly drifted from these values to recreate the desired configuration.

Historical & Featured Settings for G10 (Blues are archived data. Oranges are the calculated values.)								
Shifts (ns)	Target Settings			Pulse top (ns)	Fine Delays (ns)			
	Remote Vref (counts/readback)	Per Module (V)	Sum (V)		M1	M2	M3	M4
0(Run10)	695/689 [?]	3.8 vs. 5.36	15.2 vs. 21.44		56901 [56113 (G)]	35 [?]	65 [?]	50 [?]
0(Run12)	660/31	3.8 vs. 4.44	11.4 vs. 13.32		57295 (G)off	?	?	?
0(Run16)	2500/2487	14	56		56935 (Y)	35	65	50
0(Run17)	2500/2488	14	56		56901 (Y)	35	65	50
0	935/928	5.36	21.44		56901	35	65	50
★ 150	2500/2489	14	19.66 vs. 19	335	56901	184	361	500
155	2500/2489	14	19.4	345	56901	185	364	515
160	2500/2489	14	18.5	350	56901	186	367	530
★ 125	1500/1492	8.8	15.2	225	56901	160	300	425
★ mixed	2500/2485	14	32.5	100	56901	45	265	265
0(Run18)	950/940				56992	65	75	70

Table 6

Now let's go through the data of the featured long pulse top options in more detail. I labeled these options with stars in Table 6, so they are easily identifiable.

The red star labels the longest pulse top configuration found using 2500 counts for the remote Vref (Fig. 11) [8]. The modules are about 150 ns apart. The pulse top is 335 ns long. The sum pulse was measured 702 mV on the scope. The sum pulse without any shifts was measured to be 2000 mV on the scope. On the gpm scope, the peak of the sum pulse without any shifts was about 56 V. So, we expect the sum pulse for the long pulse to be $56 \cdot (702/2000) = 19.66$ V on the gpm scope. The gpm scope data (Fig. 12) agrees with the calculation.

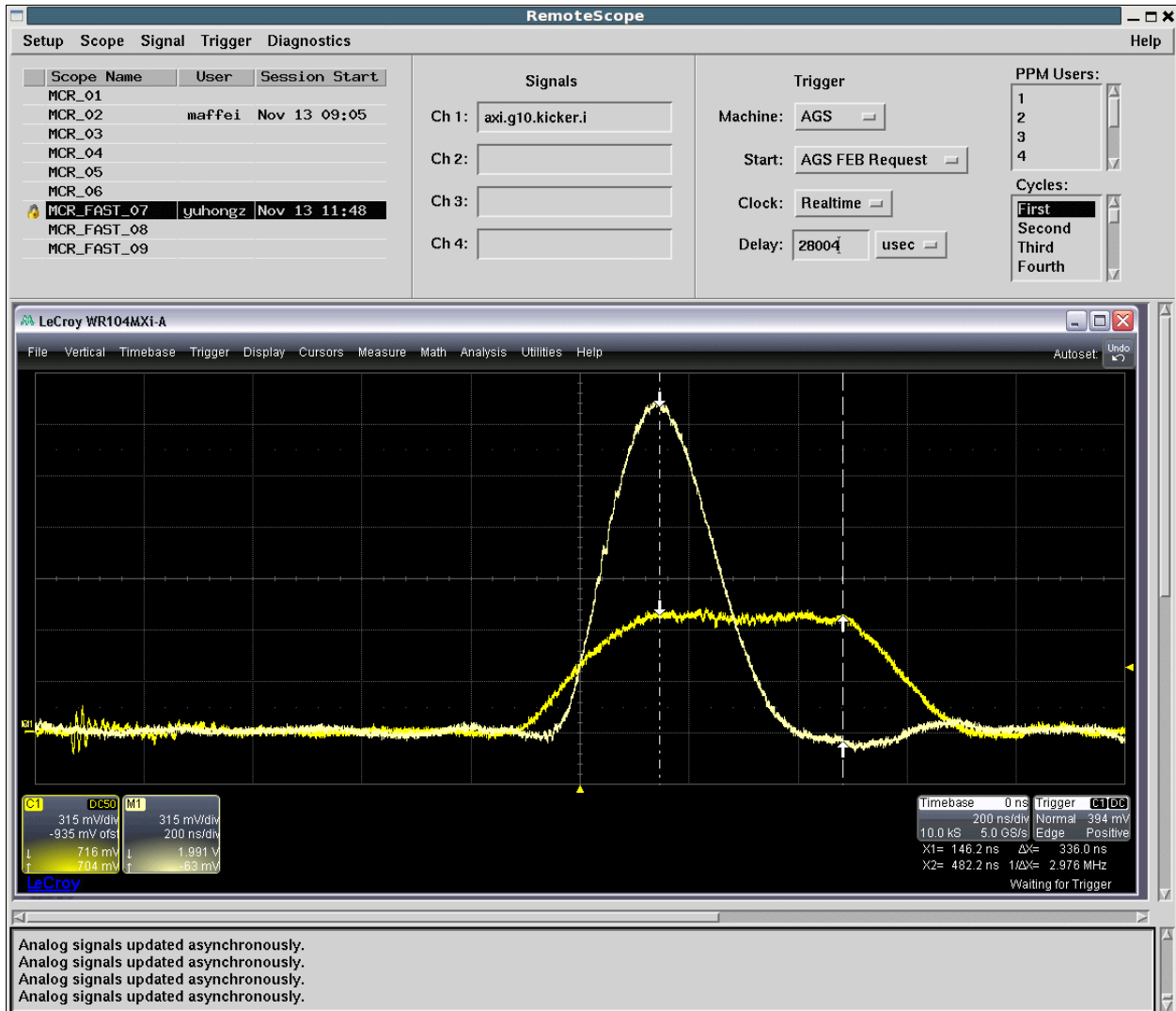


Fig. 11

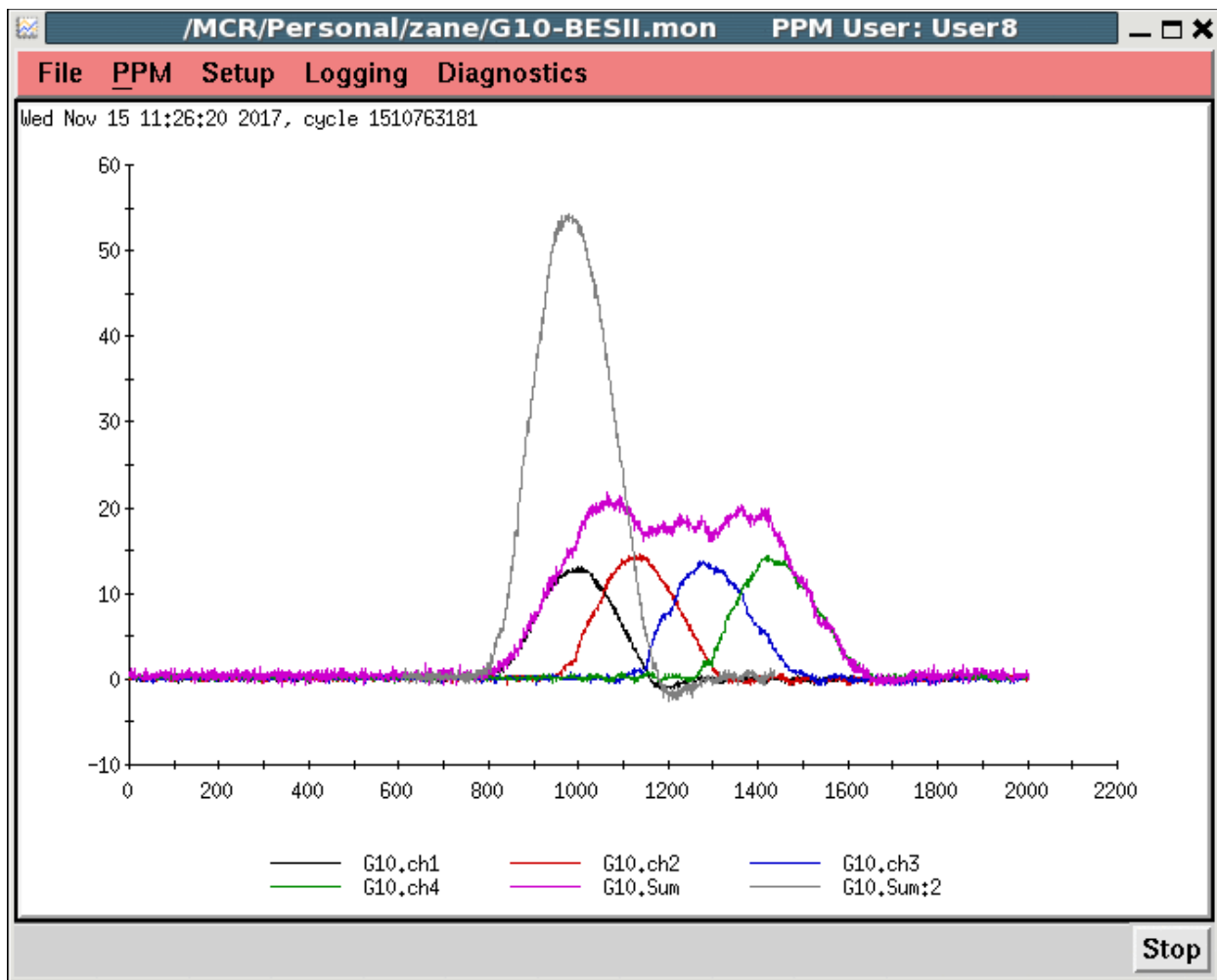


Fig. 12

The green star labels the longest pulse top configuration found using Run-10's sum (Fig. 13) (Fig. 14) [9][10]. The modules are about 125 ns apart. The Pulse top is 225 ns long.

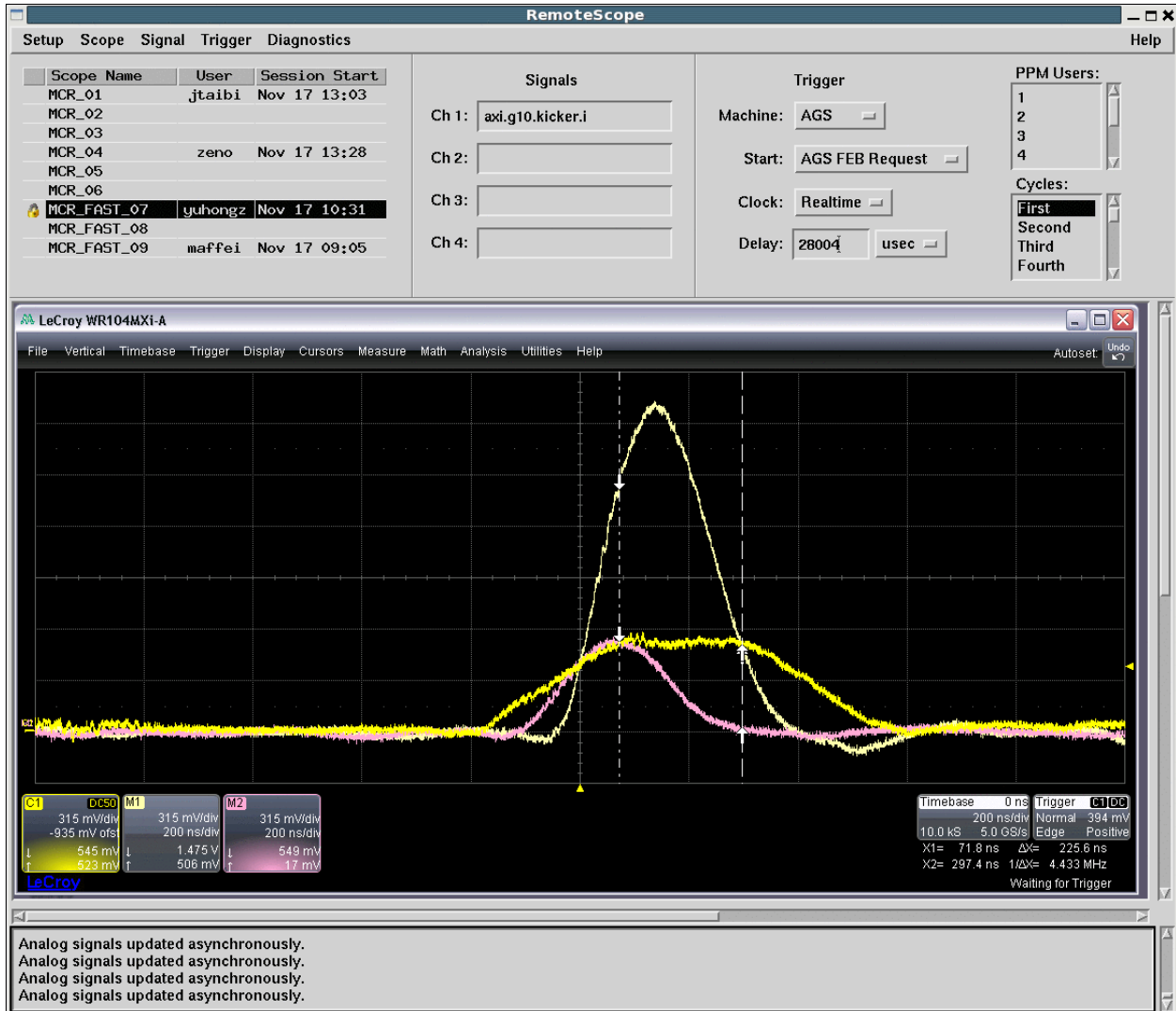


Fig. 13

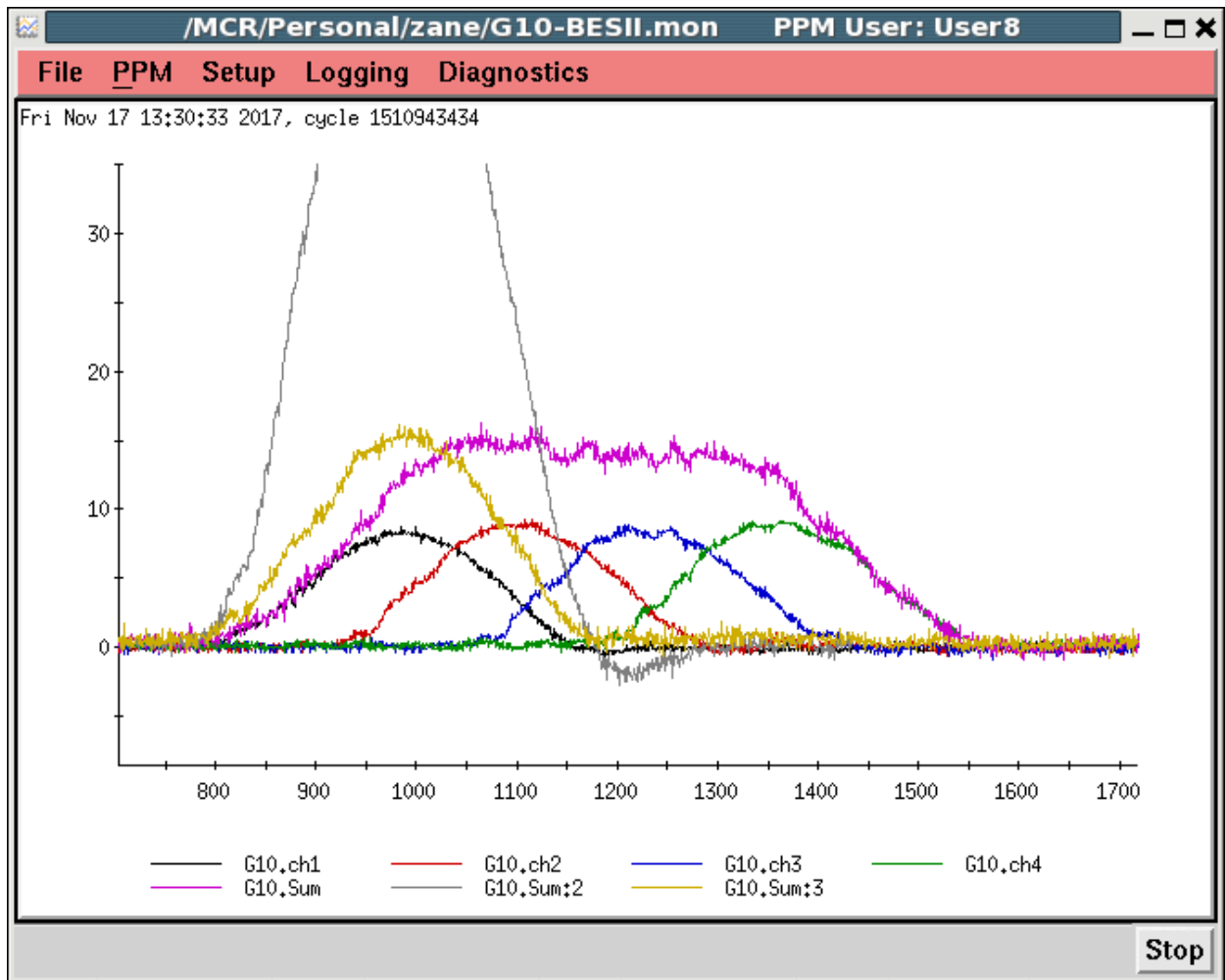


Fig. 14

The black star labels the highest sum pulse top voltage configuration found using 100 ns pulse top (Fig. 15) (Fig. 16) (Fig. 17) [11]. The pulse top is 100 ns long. The sum pulse was measured 1.133 V on the scope. The sum pulse without any shifts was measured to be 1.968 V on the scope. So, the shifted sum top is $1.133/1.968=0.576$ of the unshifted sum peak amplitude.

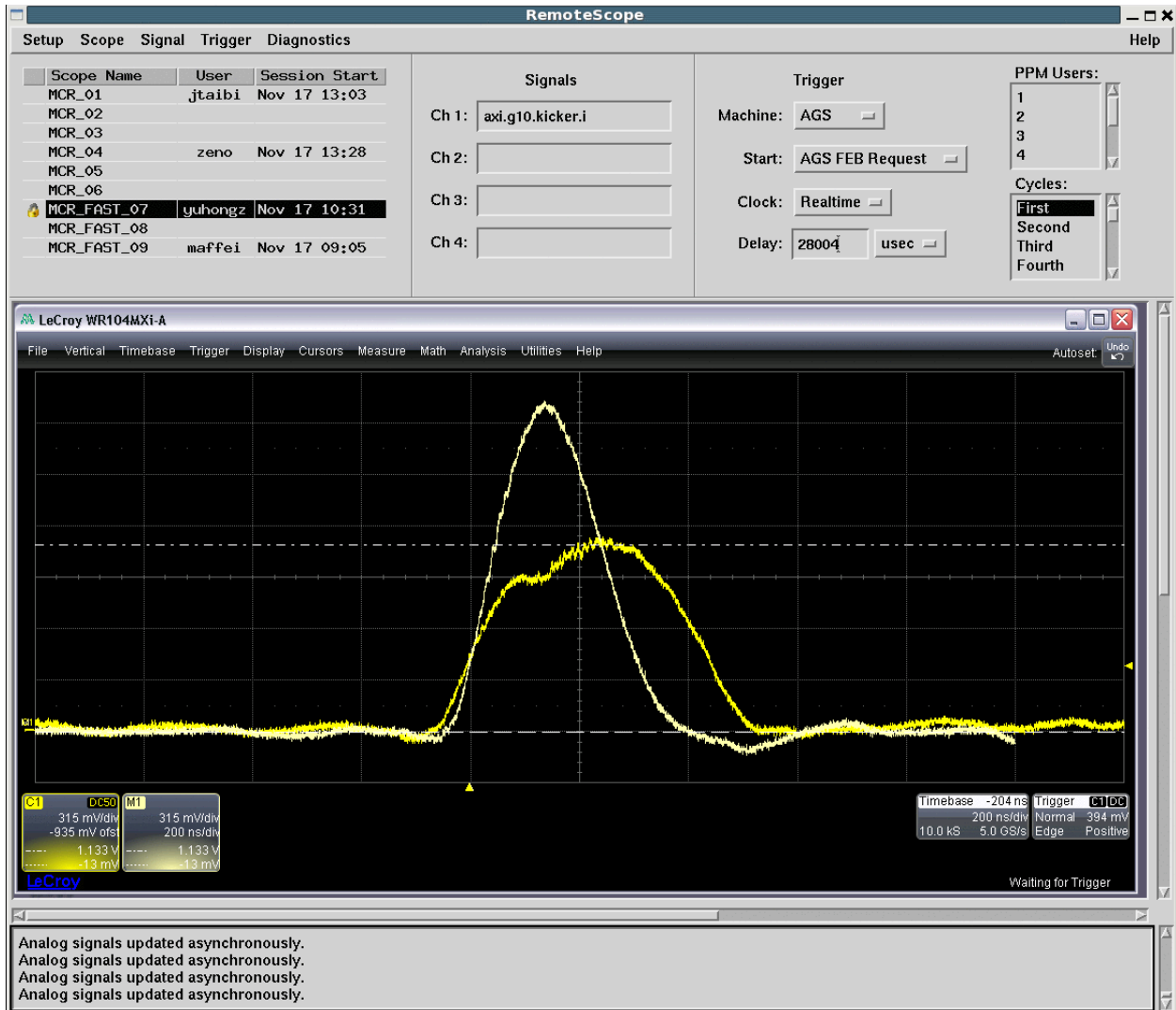


Fig. 15

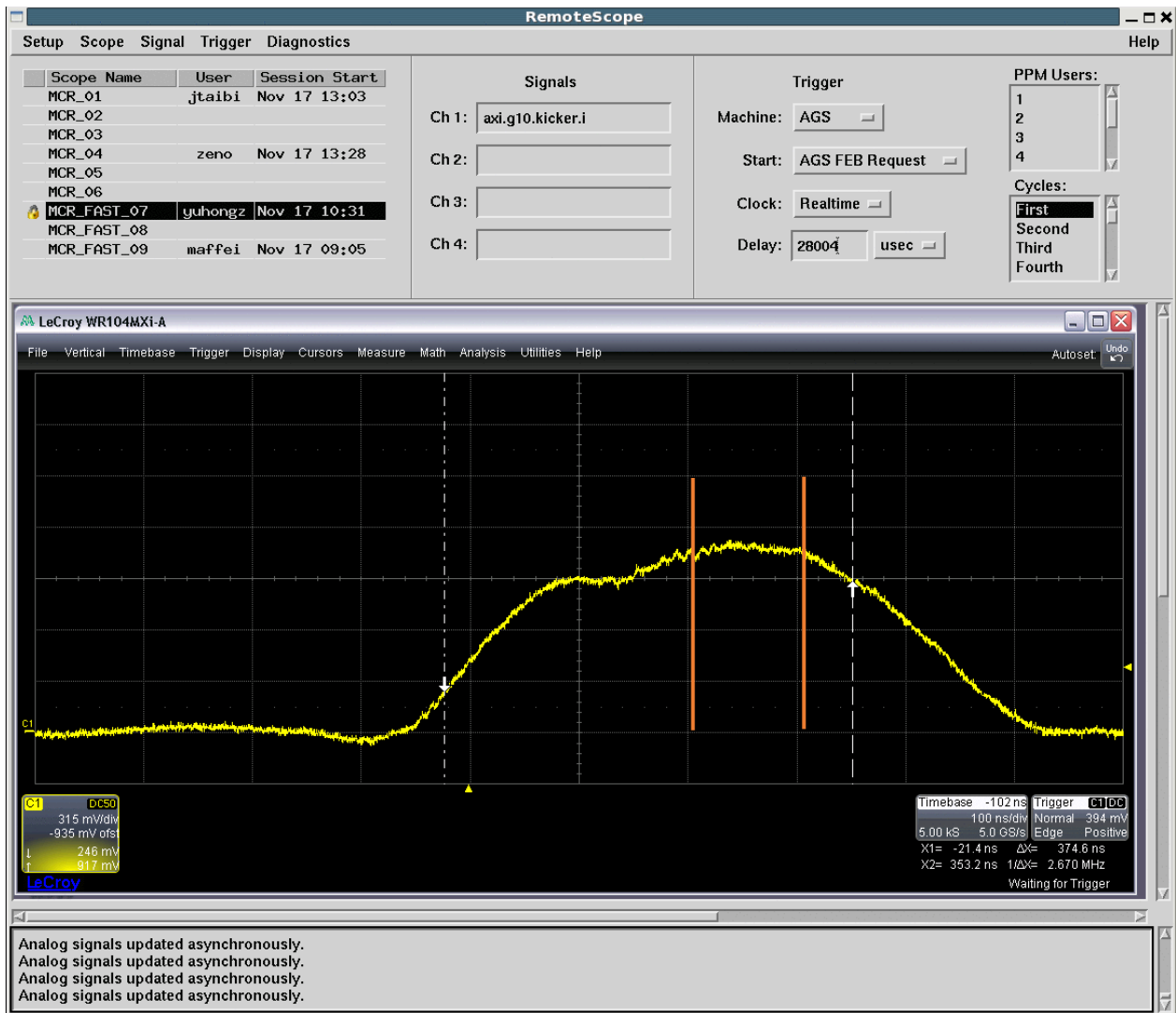


Fig. 16

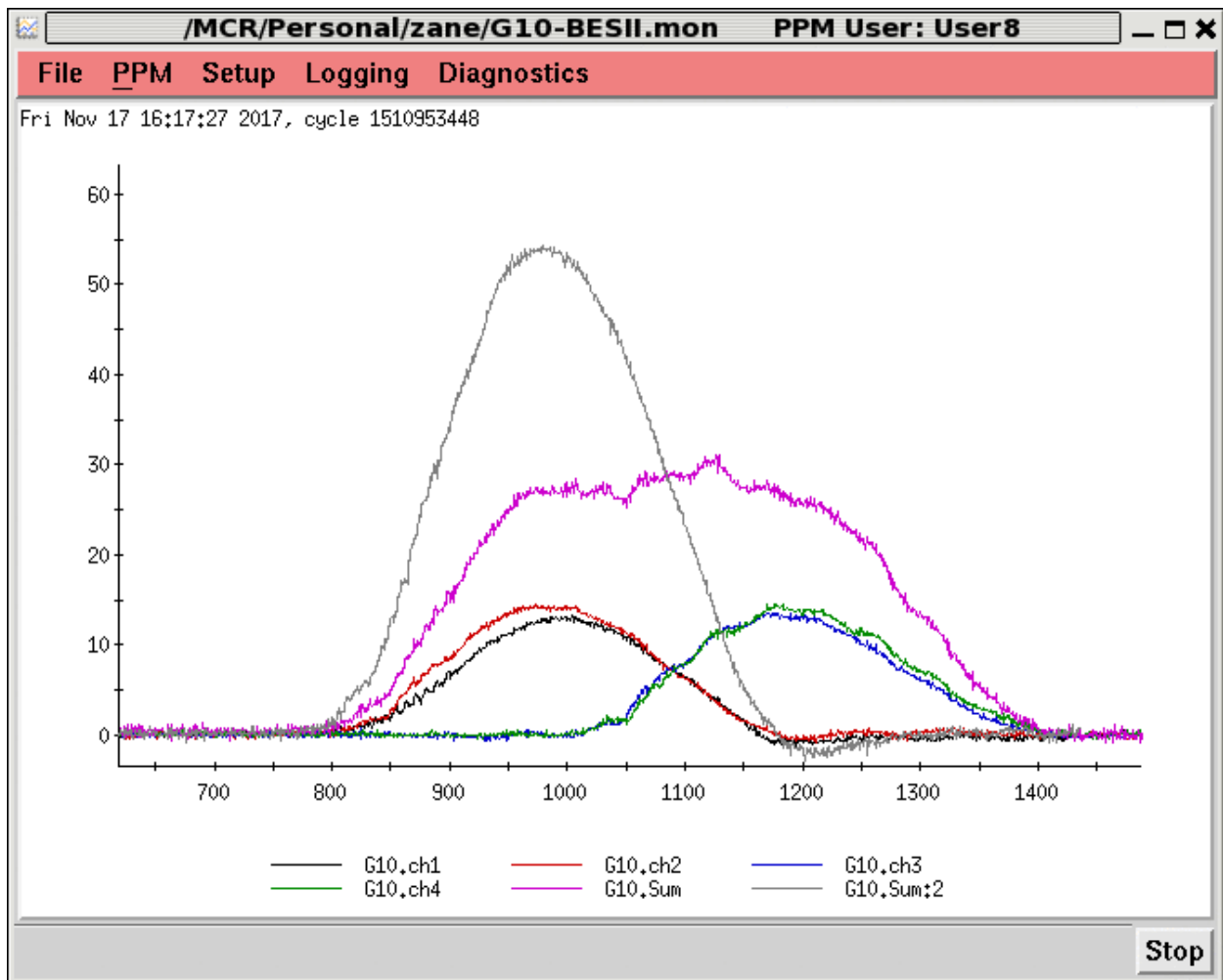


Fig. 17

XI. Dial in long pulse top settings for BES-II

This session we will go through the timeline that relates to our topic.

1) The machine development period for BES-II.

FY18 was the last year that had BES-I. The machine development period for BES-II interleaved with Mode: 3B [12]. (Beam operation 05/30/18 - 06/04/18. Mode: 3B: $^{197}\text{Au}^{79+}$ at 3.85 GeV/nucleon particle energy on fixed target $^{197}\text{Au}^{79+}$ foil inside STAR. See Table 1, 3, 5 and 6.)

a) G10 data during FY18 3.85 GeV run can be found in Fig. 10 and Table 6 [13]. We found 950 counts as the G10 setpoint for the aligned mode. Several long pulse top settings were explored without beam to match the 950 counts aligned mode. They were 136 ns flattop [14], 160 ns flattop [15], 170 ns flattop [16] and 200 ns flattop [17].

b) The accuracy of the GPM signal and the mux signal for G10 kicker current was studied and tested. Found and implemented 2 changes (added a choke and changed the input to the mux system) to improve the signal to noise ratio of the mux signal. Details are explained in section VII.

c) Calculated constraints for the long pulse setting for different extraction patterns [18].

i) For the 4-bunch extraction pattern:

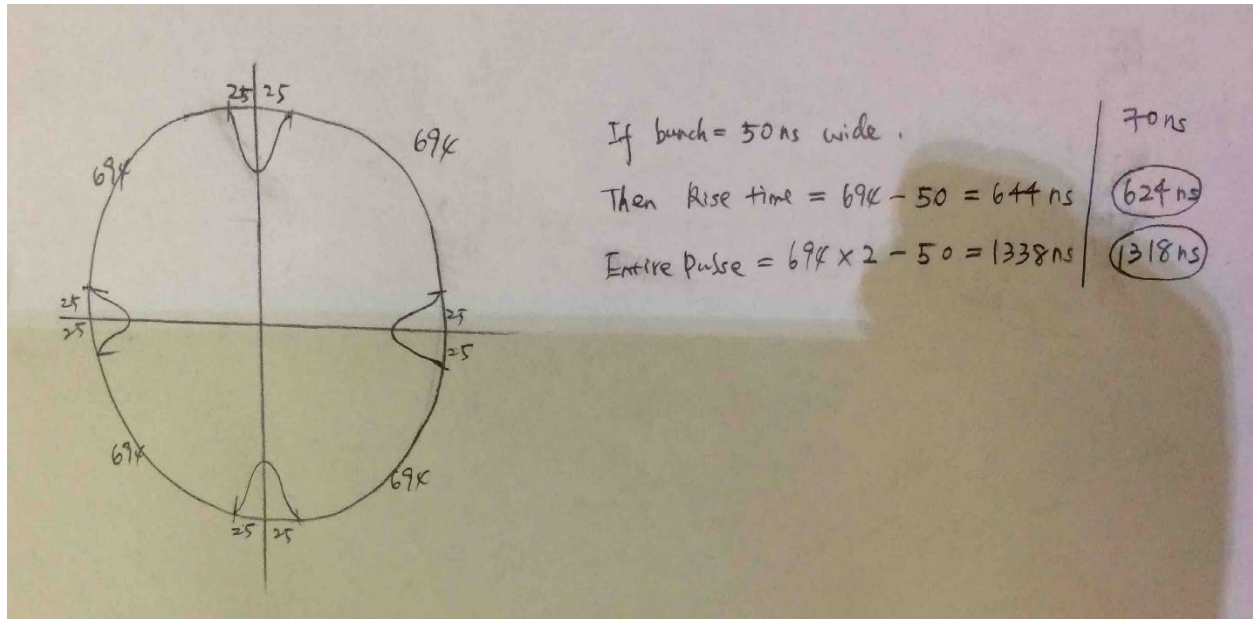


Fig. 18

Bunch spacing is about 693 ns (See table 3 and Fig. 18).

If the bunch is about 90 ns long, the limit for the rising time is $693 - 90 = 603$ ns; the limit for the entire pulse is $693 \times 2 - 90 = 1296$ ns.

If the bunch is about 100 ns long, the limit for the rising time is $693 - 100 = 593$ ns; the limit for the entire pulse is $693 \times 2 - 100 = 1286$ ns.

Fig. 18 also covers the 50 ns and 70 ns bunch length cases.

ii) For the 6-bunch extraction pattern:

Bunch spacing is about 462 ns.

If the bunch is about 50 ns long, the limit for the rising time is $462-50=412$ ns; the limit for the entire pulse is $462*2-50=874$ ns.

If the bunch is about 59 ns long, the limit for the rising time is $462-59=403$ ns; the limit for the entire pulse is $462*2-59=865$ ns.

If the bunch is about 64 ns long, the limit for the rising time is $462-64=398$ ns; the limit for the entire pulse is $462*2-64=860$ ns.

If the bunch is about 70 ns long, the limit for the rising time is $462-70=392$ ns; the limit for the entire pulse is $462*2-70=854$ ns.

iii) If we make the bunch at AGS extraction ($h=12$) next to each other, the bunch spacing will be 231 ns.

If the bunch is about 59 ns long, the limit for the rising time is $231-59=172$ ns. A single module of G10 gives 200 ns rising time. So, we cannot do it this way.

If the bunch is about 30 ns long, the limit for the rising time is $231-30=201$ ns, the limit for the entire pulse is $231*2-30=432$ ns. Although quite tight, we can put the bunch next to each other at AGS extraction with regular G10 pulse top (400 ns pulse).

2) BES-II started in Run19

Note that the IndependentPPM mode can be enabled to allow different G10 module fine delay settings for different PPM users. The b/y fine delay placeholders (non-PPM) were added to the mode switch tape to support the IndependentPPM mode [20].

a) Dialed in setting for 3.85 GeV

G10 current setpoint for the aligned mode was 1150 counts for FY19 instead of 950 counts during FY18 [19].

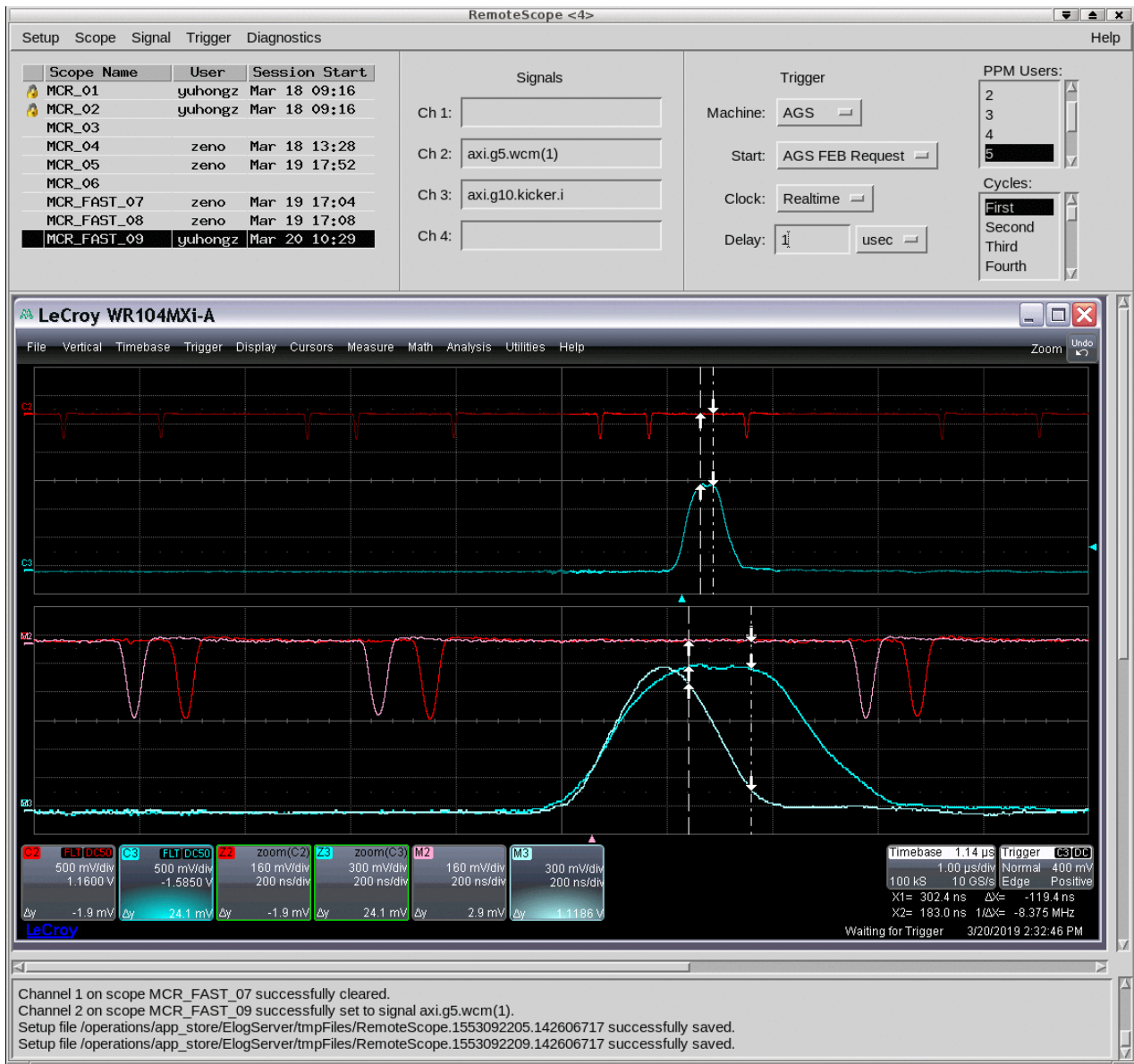


Fig. 19

Fig. 19 shows the long pulse top settings dialed in for 3.85 GeV. M3 in Fig. 19 was the narrow pulse setting that the long pulse top setting matched to. For the long pulse top setting, the pulse top was about 119 ns, the rising time was about 292 ns, the entire pulse was about 672 ns. The bunch length was about 64 ns. These are within the limitations for the 6-bunch extraction pattern resulting from a 2 to 1 merge setup in the AGS at that time. They also of course within the limitations for the 4-bunch extraction pattern for a 64 ns bunch. See details in [20]. The narrow pulse setting can be found in [21].

A 100 ns pulse top setting was also explored but didn't use for the beam can be found in [22].

b) Dialed in setting for 4.85 GeV



Fig. 20

Fig. 20 shows the long pulse top settings dialed in for 4.59 GeV. For the long pulse top setting, the pulse top was about 60 ns, the rising time was about 310 ns, the entire pulse was about 685 ns. The bunch length was about 50 ns. These are within limitations for both the 6-bunch extraction pattern and the 4-bunch extraction pattern for a 50 ns bunch. See details in [23]. The narrow pulse setting can be found in [24].

XII. SUMMARY

A number of timing configurations for the G10 extraction kicker were discussed. The delay settings allow for longer, flatter current pulses. The pulses are suitable for extracting long bunches, but the length comes at the expense of a lower peak current.

XIII. ACKNOWLEDGEMENT

Y. Tan, W.Zhang, G.Marr

XIV. REFERENCES

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[3]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=B ooster-AGS-EBIS_2018&DATE=05/23/2018&DIR=none#822010

[4]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=B ooster-AGS-EBIS_2018&DATE=05/22/2018&DIR=none#820755

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[6][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=B
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[9][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=rh
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ic-AuAu_2017&DATE=11/13/2017&DIR=none#724187)

[10][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=r
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[11][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=r
hic-AuAu_2017&DATE=11/17/2017&DIR=none#725161](http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=r
hic-AuAu_2017&DATE=11/17/2017&DIR=none#725161)

[12][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
Booster-AGS-EBIS_2018&DATE=06/29/2018&DIR=none#849657](http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
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[13][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
Booster-AGS-EBIS_2018&DATE=12/18/2018&DIR=none#896984](http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
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[14][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
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[15][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
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[16][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
Booster-AGS-EBIS_2018&DATE=05/25/2018&DIR=none#824205](http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
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[17][http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=
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[18]<http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS&DATE=06/04/2019&DIR=none#1017902>

[19]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS_2019&DATE=02/28/2019&DIR=none#930527

[20]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS_2019&DATE=03/20/2019&DIR=none#949139

[21]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS_2019&DATE=03/20/2019&DIR=none#949131

[22]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS_2019&DATE=02/28/2019&DIR=none#930725

[23]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS_2019&DATE=06/27/2019&DIR=none#1045114

[24]http://www.cadops2.bnl.gov/elogs/entryList.jsp?DATABY=day&ELOG=Booster-AGS-EBIS_2019&DATE=06/27/2019&DIR=none#1044946