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A Test of the Refurbished Jump Targets in the AGS

L. Ahrens

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Collider Accelerator Department
Brookhaven National Laboratory

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L. Ahrens, D. Gassner

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

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Introduction and summary:

The AGS ring is equipped with two sets of beam-scraping blades or edges and also referred to as "targets". The target position can be shifted rapidly toward or away from the circulating beam - hence the adjective "jump" gets associated with "target" for this system. The vertical edge of the beam, either top or bottom, can be scraped using a single vertically-moving "window frame" shaped set of edges located in the E15 straight section. (The beam always passes through this window frame). The beam horizontal edge can be cut into by either of two independent blades located in the C5 straight section, one outside and one inside of the circulating beam. Though the "in the ring" pieces of this system - the edges and the drive mechanisms - have remained functional over the ~ 15 years since they were installed [1], the controls for using the targets were never incorporated into the accelerator Controls System and had rather predictably become unusable. The C-AD Instrumentation and Beam Components group and Controls group mounted a substantial and successful effort this spring to recover jump target capability. On 13 June 2006 the system was used to scrape the polarized beam at flattop - at extraction energy for RHIC injection. Measurements both of the effect on the beam and of the resulting radiation and radiation pattern were taken. Those measurements are reported here. The system as used was not yet in a configuration to be handed over to Operations. The "raw" data associated with this study can be found in the Booster-AGS fy06-pp Elog, 13Jun06, 13:30 - 16:00.

The main motivation for recovering the system and doing the study is associated with the program to accelerate polarized beam for RHIC. Transverse emittances are important beam parameters strongly affecting the extent to which polarization can be maintained during acceleration. Of course transverse emittances are also very important in determining the luminosity ultimately produced by the RHIC collisions. Having an additional tool to affect these emittances is useful. There is even a significant possibility that the scrapers could improve the quality of the delivered beam enough that using these targets would need to be incorporated into an operational role.

The study reported here was a first commissioning of the new controls and a "with-beam" demonstration that the old hardware was functional. This was successfully accomplished. Given this, the next "accelerator physics" objective was to measure how the transverse emittance was changed due to scraping. The instrumentation used for this was the AGS IPM.

In planning for the beam work, an additional issue of high priority became obvious, namely that the targets were new sources of radiation with the usual associated ground water activation issues. This subject had to be respected in a conservative way. As will be described below, the results from the study demonstrate that ground water activation is not easily handled for the present location of the targets. There is a need to immediately consider other ring locations for the targets.

System description - the jump targets:

The scraper blades are made of Aluminum. (Some relevant information about target survival in proton beams is given in reference 2). We use standard coordinates: z along the beam, y up-down, x radially in-out. The targets are 1/8 inch (3.175mm) thick - normal to the beam (i.e. in "z"). Each blade moves perpendicular to the beam (z) axis - for vertical scraping in the "y" direction, and in this case the other scraper dimension ("x") is large compared with the beam transverse dimensions. The width of the blade in "y" is much larger that the region of the target where the beam is interacting.

Beam - target interaction: When a proton passes through the target blade it will interact electromagnetically with the electrons in the aluminum, multiply scattering and losing energy, and may also interact strongly with the aluminum nuclei. A proton that goes through the blade will be deflected through an angle, will lose some energy through dE/dx, and may scatter strongly. The relative importance of each process is quantified by the aluminum absorption length (~400mm), the radiation length (90mm), and dE/dx (0.44 MeV/mm). A single pass through the target blade then corresponds to 0.8% of an absorption length, 3.5% of a radiation length, and a loss of 1.4 MeV. At AGS extraction energy (25 GeV) this dE/dx corresponds to a loss of momentum dp/p of about .06e-3 while the beam half width dp/p is about 1e-3. Multiple scattering from a single pass will on average give an additional angle of about 0.12 mradian where the 10pi normalized beam at a beta max has a half width of about 0.14mradians.

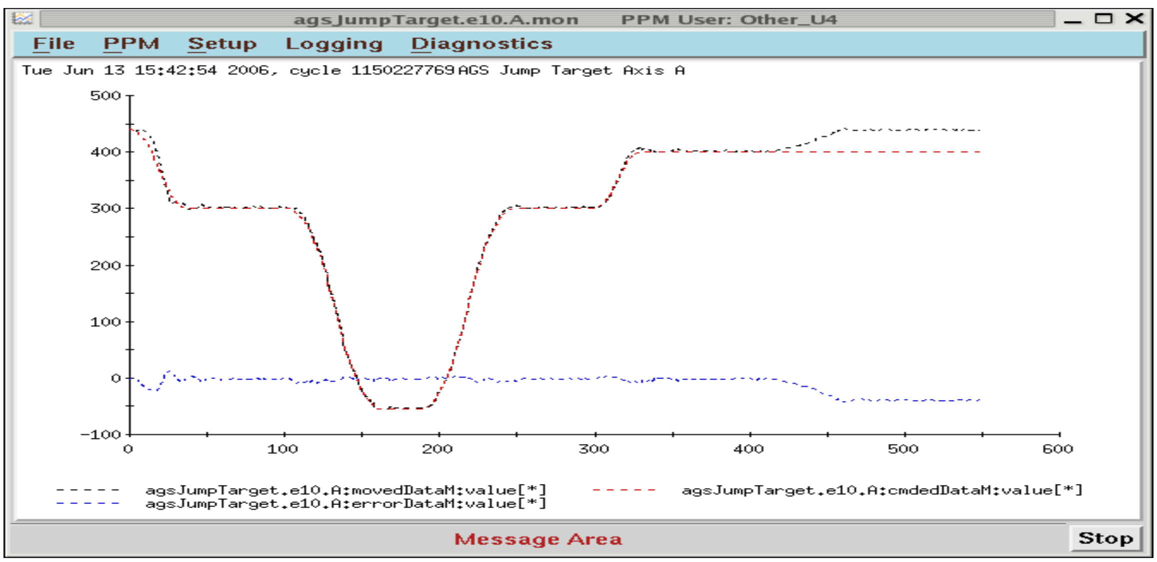
The upshot of this is that a single pass through the target gives the proton a large angle kick - of the same order as the beam size- while the associated momentum loss is relatively small - less than 10% of the beam momentum spread. And the single pass probability for a nuclear interaction is too small to be important. The expectation then is that the transverse emittance of particles in the portion of the beam that can hit the target will quickly grow over successive turns until these particles hit some more substantial aperture and leave the machine. Prior to the beam work, we did not know where the particles would get lost around the ring - at apertures quite near the target, due to large single-pass changes in the trajectories, more uniformly spread around the ring given the statistical nature of some aspects of the scattering, or localized but away from the target at one of the standard machine limiting apertures for slowly growing beam processes. What was found (see below) was that a majority of losses were within a few magnets of the target.

System description - additional instrumentation:

The primary diagnostics to judge the effect of a jump target on the beam were the circulating beam current transformer, the distributed AGS ring loss monitor system and the ionization profile monitor (IPM). The current transformer output tells how much beam is lost. The loss monitor system tells where the beam is lost. The loss monitor system also measures the amount of beam lost, though in a less quantitative way than the current transformer. This is useful to check for consistency. The IPM measures projections of the beam in the vertical and horizontal planes. From these with a Gaussian fitting it reports beam emittances. This machinery is not necessarily optimized for understanding the beam shape produced by the scraping. The change in responses of individual wires can also be seen but was not explicitly saved. The IPM output given here is not ideal for this study.

Machine / jump target setup:

The study used the standard AGS U4 RHIC production magnet cycle and general setup. The scraping was done at AGS extraction energy on the long flattop portion of the main magnet cycle. This flat begins 600 ms after AGS T0 and continues till 2000ms. RHIC transfer and the associated orbit bumping are completed by 950ms. The target insertion began after this time at 1200ms and started to remove beam at about 1350ms. We worked at extraction because it was a simple situation. In particular there was no time dependence of the beam for many hundreds of milliseconds around the target insertion time so measurements were in this sense clean. The requirements from the target positioning machinery were also relaxed. A similar exercise with the scraping applied at AGS injection is surely desired and is within the capabilities of the system, but was not attempted here.



Here are shown some of the available readbacks from one of the target drives (horizontal, inner) - requested position, measured position and error (.155mm/count) - vs time (ms). The target position moves from "home" to "ready" to "plunge" and then retracts again.

One major challenge to using jump targets in general is to move them into the beam quickly, smoothly, and without overshoot. The new system is designed to do this. That work is not covered here. Indeed the first author is not competent in these control knobs yet. We took a "canned" setup for the adjustment of the many motor parameters which was very adequate for our needs. (In a more general application, beam scraping during acceleration or during a very short interval in the acceleration cycle is generally necessary and so the system would be more seriously tested. We have a long flat period in the acceleration cycle for the scraping described here). Starting at 1200ms the target is first moved from a **home** position to a **ready** position closer to the beam but not yet interacting measurably. Then at a second time the target is moved further in to the desired beam-intercepting **plunge** position. Shortly after this the target is retracted back to ready and then back to home position. For the vertical target sequence the home position in counts was 0, ready was -75, and plunge was -150. The counts-to-mm calibration for the vertical is 0.124mm/count, so this sequence corresponds to two steps, each of 9.3mm.

Some results from the study:

The figures referred to in the following are in Appendix A at the end of this report. The machine was accelerating 1.1e11 protons to the usual ~25 GeV energy (Ggamma = 45.5). The beam was kept bunched (accelerating rf on) across the flattop. Appendix A, figure 1 is the loss pattern for this AGS cycle (with the targets not jumping). The horizontal axis gives the location of the loss monitors around the ring. The detectors are long thick coaxial cables with the gaps between the inner and outer conductors acting as an ion chambers. Each cable extends along two AGS main magnets. The beam is "dumped" into the J10 absorber region at about 2000ms into the cycle. The loss peak shows up in the monitor located beside the J11 - J12 magnets. Hereafter the loss monitors will be identified by the more downstream magnet that they cover, i.e. the dump loss peaks in the J12 loss monitor. The loss monitor printout shows the loss patterns measured for five contiguous time "windows" during the acceleration cycle, marching from early to late up the page. The table at the top of the application display gives (in the "SUM" row) the total ion chamber losses around the ring for each time window. The table reports the drop in circulating current (from the current transformer) in the XF DIFF row. For the data in Figure 1 then, the loss monitors reported 237 +/-10 counts of loss and a drop of current of 1805 counts in the 2300ms window (integrating from 1800ms to 2300ms). The circulating current intensity reported in the application is not calibrated. A check against the carefully calibrated intensity reported on the MCR scalars imply that the application's 1805 count current actually corresponds to 1.12e11 protons and we will apply this calibration factor in discussions from here on.

With the E15 vertical target jumping into the beam at 1350ms and taking out 20% of the beam (see figure 3), the loss pattern of figure 2 results. The closest monitors, E16 and E18, together see about 55% of the 105 counts total loss during the jump window. Adding the loss visible at F02 , F12 and H12 accounts for 80% of the total loss seen around the ring. Jumping the E15 target further into the beam resulted in the data given in Figures 4 and 5. About 70% of the beam is scraped away. Now E16 and E18 together see 50% of the total loss and the five monitors listed above account for 73% of the total. We conclude that the losses scale up reasonably linearly with the amount of beam removed. The secondary peaks at F12 and H12 are now more pronounced, perhaps more believable. The AGS lattice has vertical beta function maxima at the #11 straight sections, and these specific #11 locations, H11 and F11 are the usual limiting vertical apertures. These peaks would be consistent with the expected loss locations for a vertically slowly growing beam. The beam loss seen at F02 would be consistent with particles hitting near the peak of a betatron oscillation initiated at E15 - about a quarter wavelength upstream.

Figure 6 and 7 gives the loss pattern with the horizontal target at C5 taking away 15% of the beam. At least qualitatively the conclusion as far as the radiation pattern is unchanged. The majority of the losses are close to the scraping target. The loss monitor just upstream of C5 happens to be a noisy channel, which results in a somewhat messy picture.

One further detail concerning these loss patterns is here mentioned, lest someone is closely paying attention to the size of the losses in the later "dump" window. The sensitivity of the AGS loss monitors under normal conditions is about {500 counts/(1Tp)} * (K.E./1.5GeV) from our old high intensity days. This agrees reasonably with the losses seen here associated with the target insertions. On the other hand, the losses associated with the dump are only a third this big. We take this as an indication that the J10 Dump steel is indeed containing a significant fraction of the energy of the beam when the beam is pushed into the dump, keeping the energy from getting to the loss monitors. This indeed is the point of the Dump and so is not too surprising.

The observed jump target loss patterns have a major piece that corresponded to large scatters and local losses. This observation means that the ring area near the target must be able to cope with local beam losses of the same order as the total beam being removed by the target. In order for the polarized emittance reduction by scraping to be useful a substantial fraction of the total beam has to be removed. The ring region near the target then has to be appropriate for the situation where most of the beam is lost there. Given the present state of our understanding and concerns about creating activation outside the tunnel in the soil, the high losses seen near the jump targets require that the targets' locations be in regions of the ring where we are protected, which means sections which has waterproof covers. The only such sections are from E20 on through the target building, i.e. through the F and G superperiods.

Emittance measurements other results and some conclusions from the jump target study:

Appendix B contains pictures of the IPM response to the various target scraping setups. This information is taken from the Booster-AGS Elog of 13 Jun 06. Emittances given below are always in units of "þ mmmr". Error estimates are generally not made. The IPM reports quite different profiles depending on whether the beam is bunched or unbunched. This is qualitatively understood as resulting from the different transverse electric fields from the beam (bunched vs unbunched) distorting the trajectories of the ions being collected. Since we work at a fixed ring magnetic field, the rf can be turned off during the measurements and so the beam becomes debunched. Some of the IPM data is taken with rf on (hence bunched) and some with rf off. The tabulated numbers reported by the IPM on the figures in appendix B are frequently confusing (at best). Not much care was taken during the study to get to a well understood digital data presentation format. The profile pictures rather than the tabulated numbers are used in this discussion.

The first IPM picture (Appendix B, figure 1) shows the response with no scraping active. The measured profiles do not change across the porch. Reported emittances (H,V) are (18 and 19). The rf is on. To remind what this summary means: the reported transverse emittances with no scraping, measured from 1000ms to1800 ms were about (h; v) (18+/-0.5; 19+/-0.5); units p-mmmr and normalized emittances, 95% calculated from the sigma of a Gaussian fit, rf on.

Figure 2 gives the effect of a 20% scrape in the vertical. The reported vertical emittance is reduced by 3, the horizontal by 1.5. One can see in the vertical (magnified) profiles that the edges of the profiles become and remain steeper after the scrape i.e. the first three profiles in the mountain range have wider skirts than the last three.

The same scraping situation is presented in figure 3, only now the beam is debunched. Here the vertical emittance is reported shaved from 14 to 12, and the horizontal from 14.25 down to 13.5.

Figure 4 reports the effect of a severe vertical scrape - 70% of the beam removed. The IPM measurement is taken with the rf off. The vertical is reduced from 14 to 8, and the horizontal from 14.5 to 12.5.

Finally, figure 5 gives the result (bunched beam) for a rather slight horizontal scrape (12%). The reported horizontal emittance decreases from 18 to 15 and the vertical from 19 to 18. A magnified version of the profiles was not taken and the rf had to be left on for the measurement. Turning the rf off resulted in the scrape going away - presumably indicating that the radial position of the beam was slightly different at scrape time on the porch with the rf not holding it to a fixed frequency or radius.

At this point no further analysis has been carried out on this data. The situation is encouraging in that the profiles change qualitatively as expected. But the method for extracting relevant information from the IPM data is not optimized. Here even the (somewhat unique) procedure in the application for the saving of the complete profile as digital information had not yet been understood by the studiers.

The machinery for scraping worked. To use it during acceleration or at injection would be more challenging, but should be quite possible. Some details of the setup need to be optimized, and a friendly interface is required.

No measurements of polarization were attempted. This takes us back to the radiation safety - ground water activation issues. An exploration of the effects of scraping on polarization either requires taking a lot of scraped AGS cycles or making the measurement in RHIC. The latter is too expensive if we need to explore the space - i.e. how much scraping is optimal from the point of view of the RHIC bottom line. So for this work we need to have a location for the targets where the beam loss is not a radiation issue.

On a slightly different aspect of the study, the amount of beam shaving was a parameter varied during the study. The vertical shaving was initially set to be about 2.7% (current transformer measurement) of the circulating beam. Over many AGS cycles this configuration was judged to be stable. This is an encouraging albeit qualitative indication of system reproducibility.

References

(1) E.R. Beadle, E.S. Roger, R.E.Thern, A Beam Scraper using a Linear Motor, PAC 1989 p. 1476 (also BNL - 41825).

(2) R. Thern, Destruction Limits of Aluminum and Boron Carbide Targets, AGS Studies Report #203, 25Mar86.

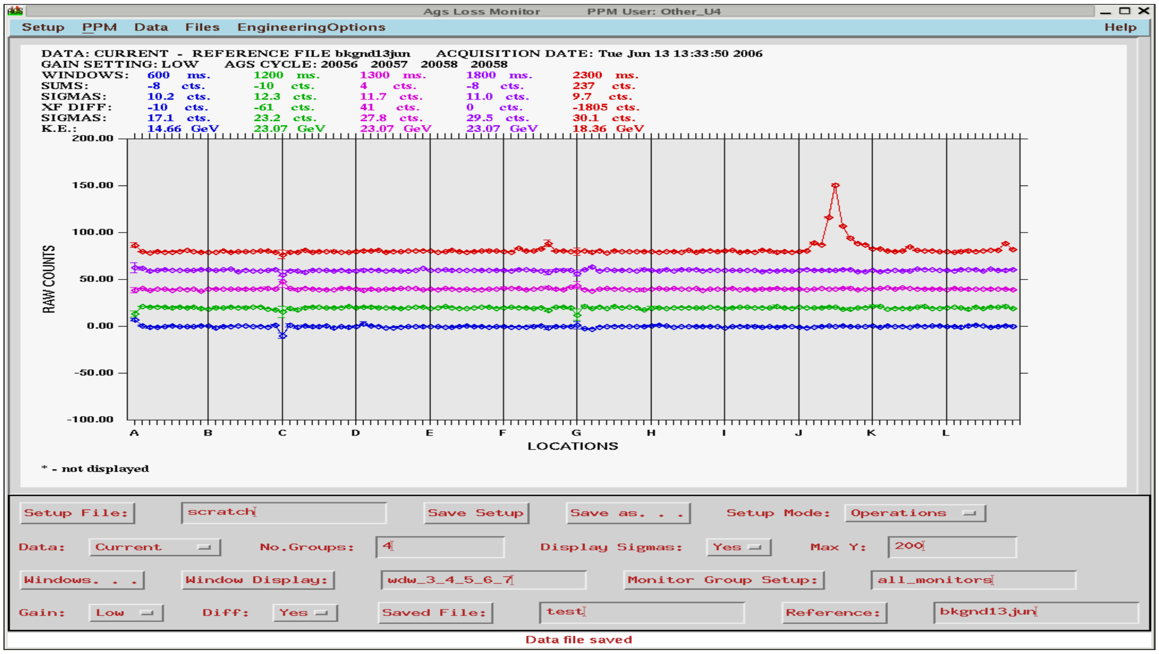


Figure 1: AGS loss pattern and numbers: "no scraping" losses around the J10 Dump. The five lines give integrated losses over five contiguous time windows. The last (highest) includes the beam dumping at the end of the cycle. The second down from the top covers the period when a jump target would be inserted.

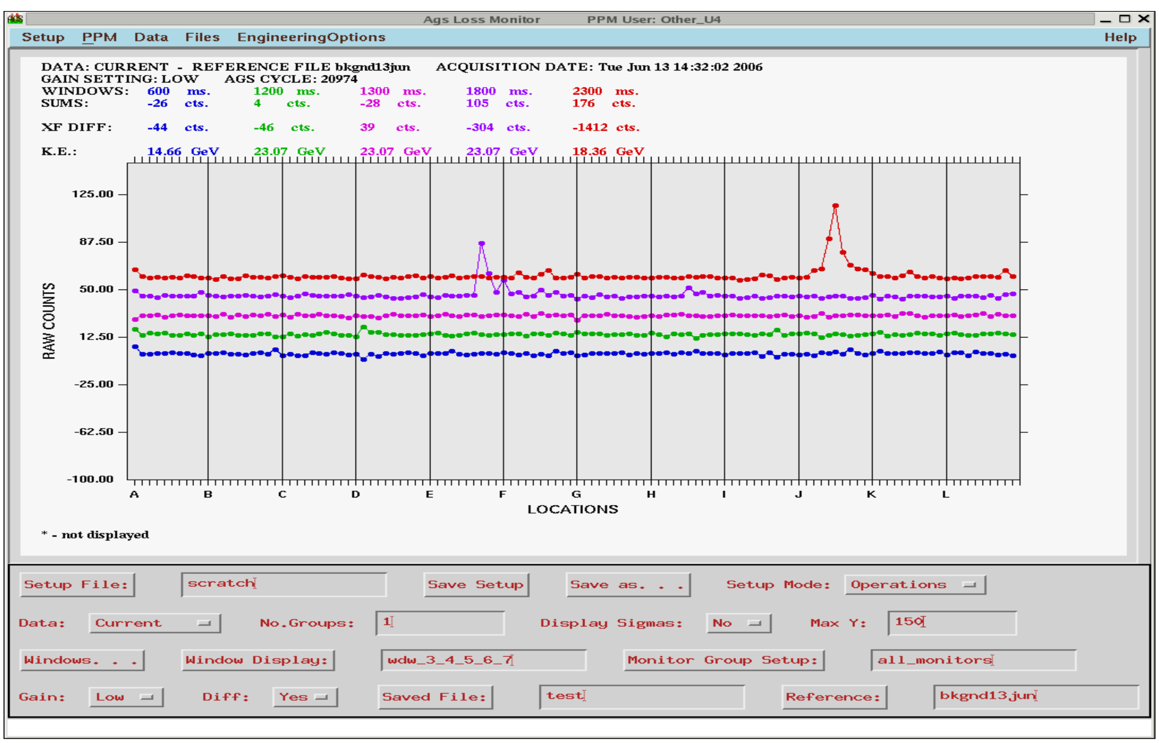


Figure 2: AGS loss pattern, 20% loss via vertical scrape. The loss pattern associated with the E15 target insertion show up starting at the loss monitor located at E15-E16.

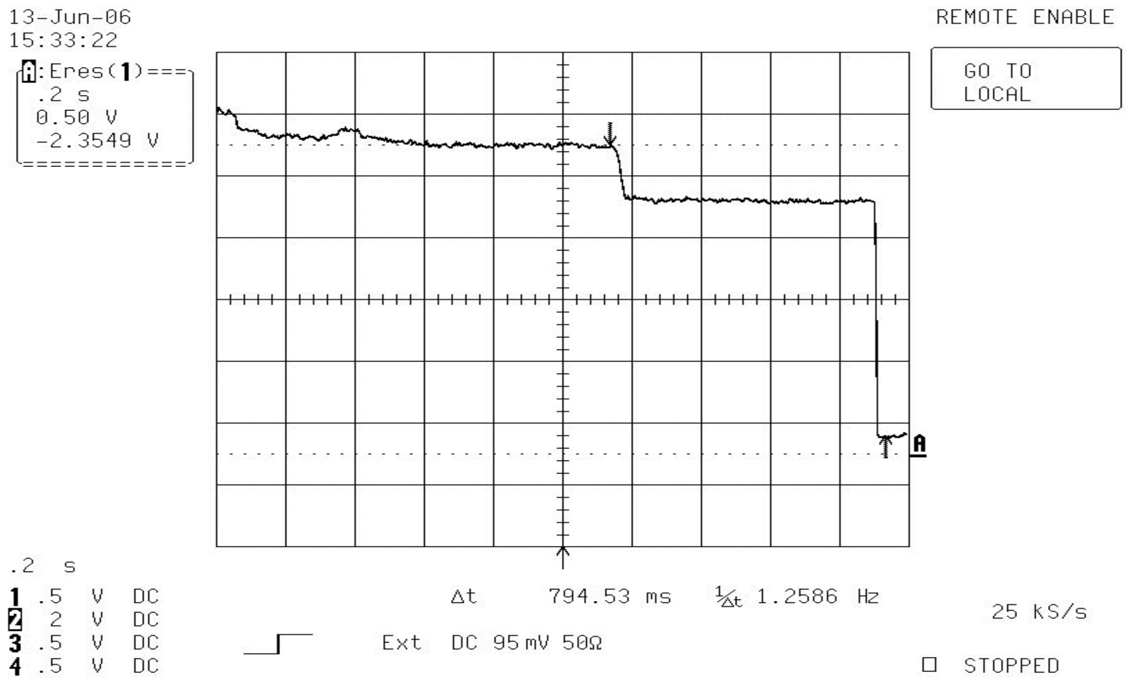


Figure 3: AGS Current transformer trace associated with the 20% vertical scrape. Scope trigger 1200ms (start of the "plunge"). The step down occurring less than one box (200ms) after the center line (the trigger point) is the result of the jump target interaction.

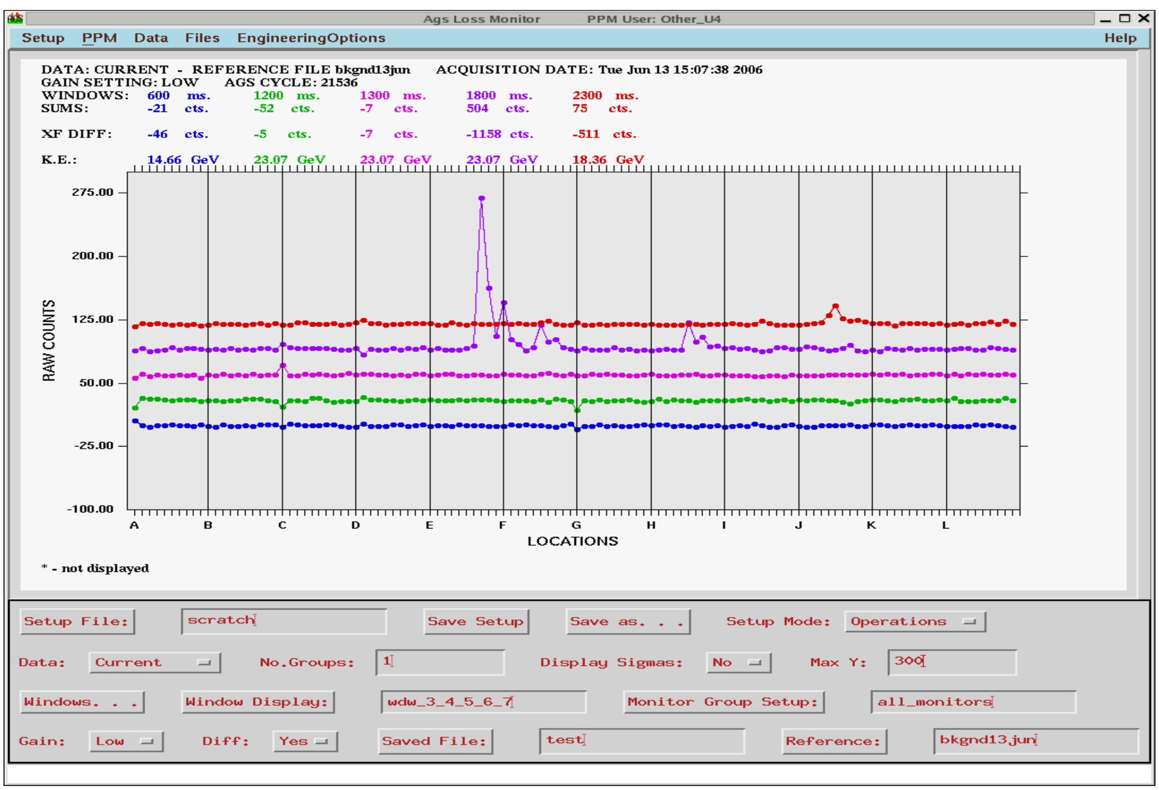


Figure 4: AGS loss pattern, 70% vertical scrape. The loss patterns remain very much unchanged relative to a gentler scrape except for their magnitudes.

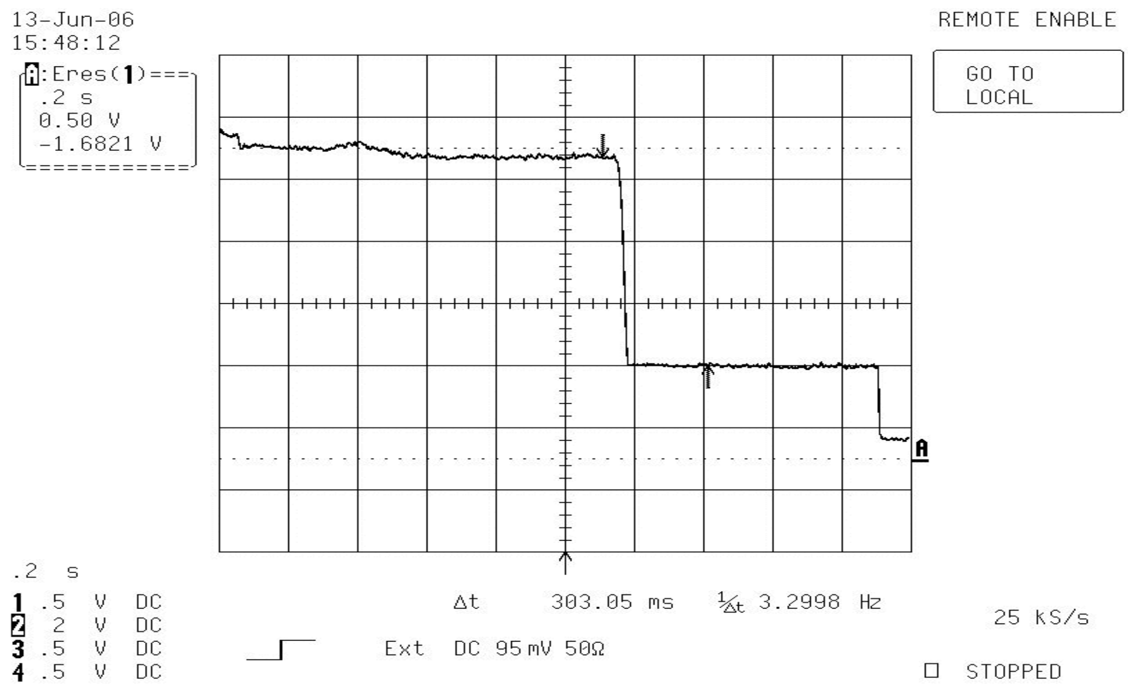


Figure 5: Current transformer corresponding to the 70% vertical scrape

Figure 6: Horizontal scrape (at C5). The loss pattern is not so pretty, but the location is once again significantly local.

Appendix B: IPM response to scrapings.

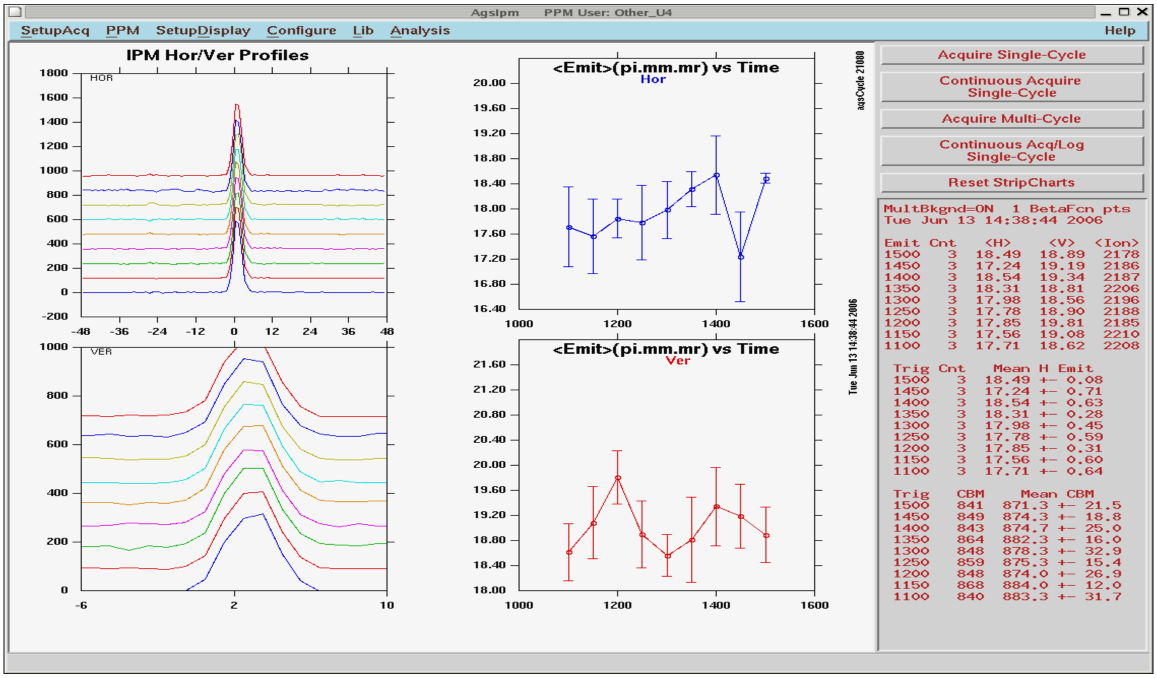


Figure 1 No scraping, rf on. Note the lower left "blowup" of the vertical profiles taken starting at 1100ms every 50 ms till 1500ms. The beam affects seven of the IPM rods (1.25mm spacing). The amplitudes on these rods are nearly constant with time.

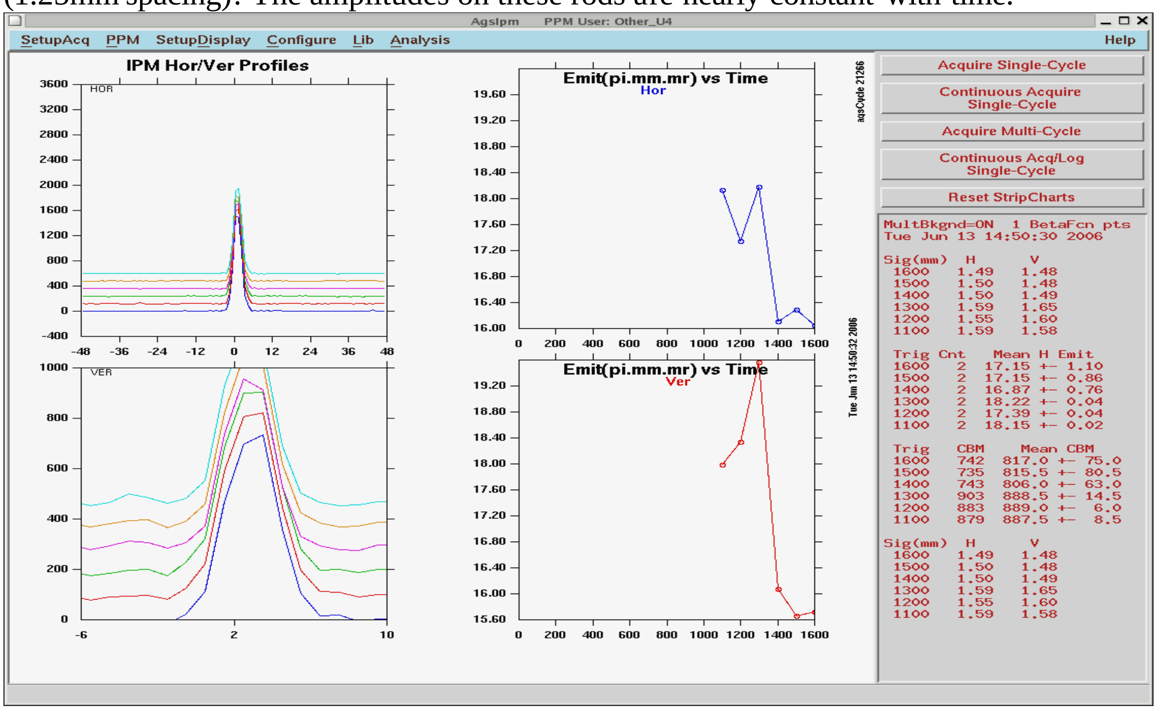


Figure 2: 20% vertical scrape. IPM has rf on across flat top. Counting from bottom, scrap occurs between profile 3 and 4. Edges get sharper. Fit emittance shows step (in both planes).

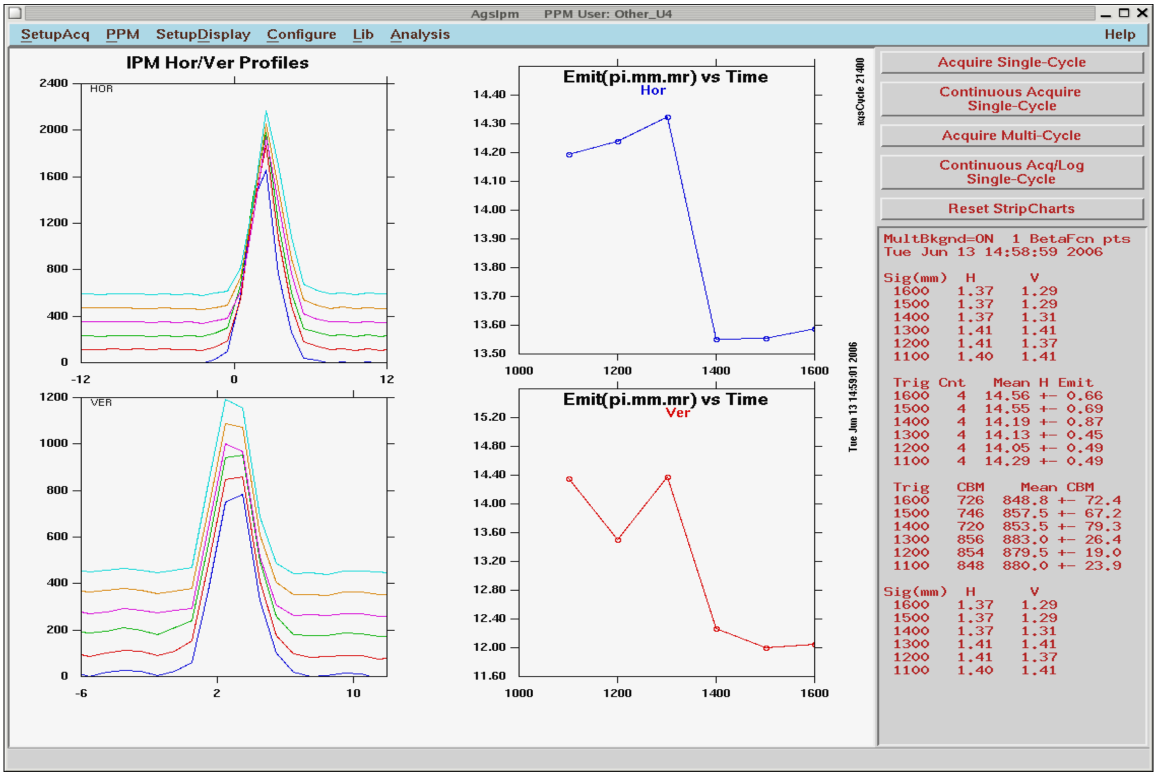


Figure 3: 20% scrape, now the rf is turned off, i.e. the beam is debunched. These smaller profiles again show sharper edges with scraping (i.e. after trace 3 from bottom).

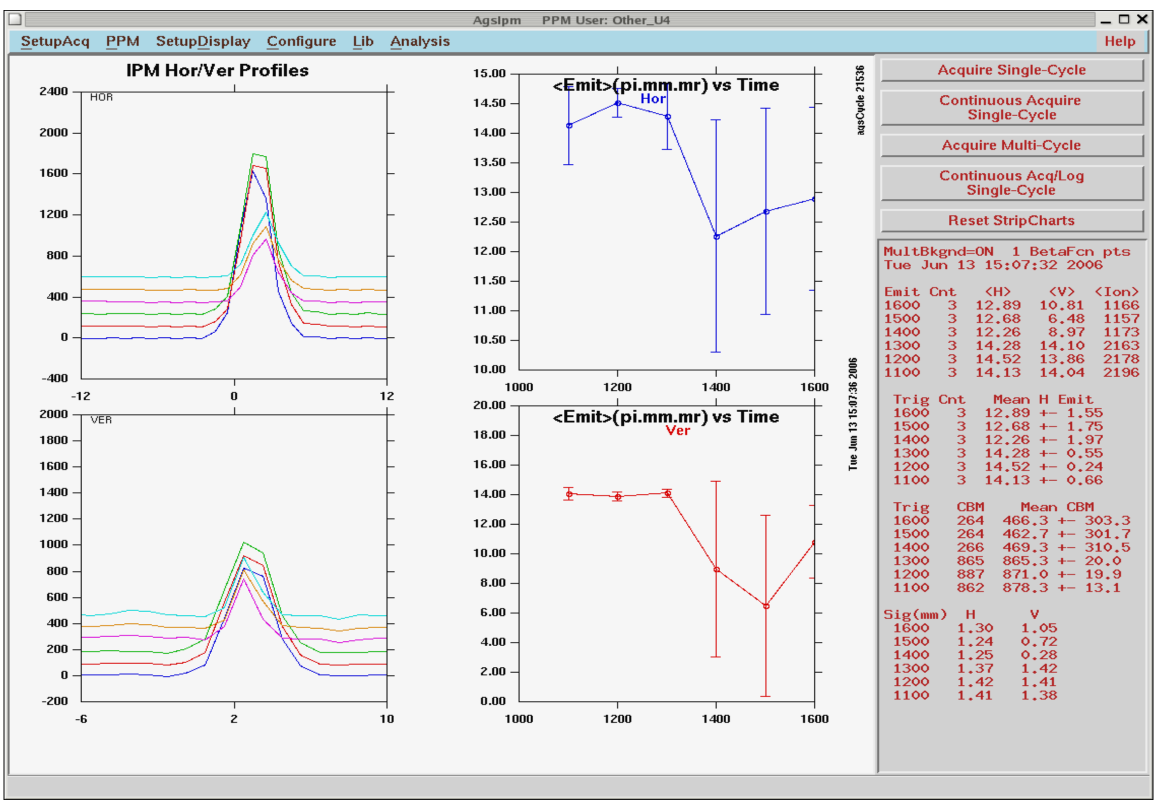


Figure 4: Large (70%) vertical scrape. rf off.

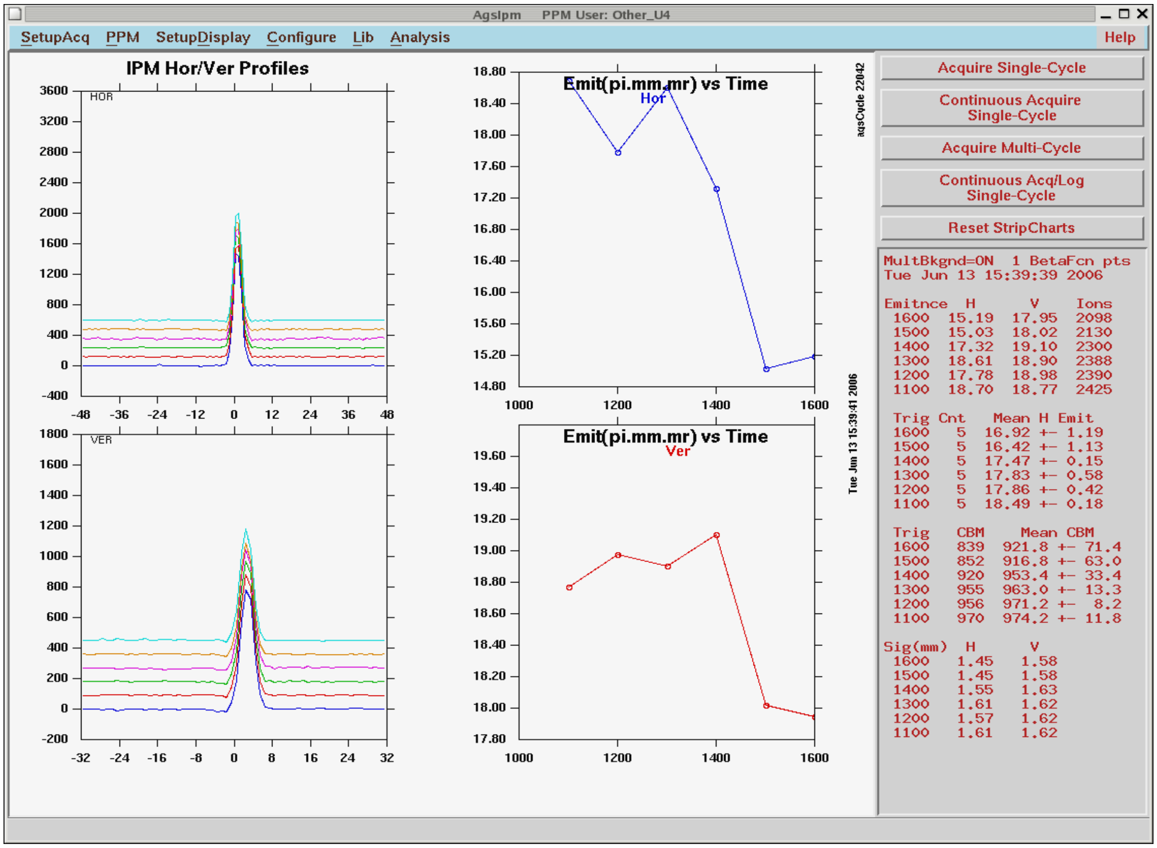


Figure 5: Horizontal 15% scrape, rf on.