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Multi-Batch P-bar Production via Snap Coalescing

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A plan to produce ~5x more Antiprotons/cycle using mostly existing equipment.

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3 October, 1994

ABSTRACT

A method is described to increase the yield of Anti-Protons/cycle by about a factor of five, without building new storage rings. In this method, the full circumference of the Main Injector is filled and accelerated. Existing RF cavities are then used to perform "snap coalescing" which clumps the charge in azimuth to produce 28 large RF bunches ~5ns long. These are then extracted and targeted in a single 11 μsec turn of the Main Injector. The resulting P-bars are injected into six turns of the Debuncher using a resonant kicker which injects every 21st RF bucket. The result is that every 3rd RF bucket in the Debuncher is occupied. After an h=30 rotation in the Debuncher, ESME simulations indicate a final momentum spread of ±0.25%. This is comparable to the current momentum spread after debunching. It is superior to the momentum spreads of ±1.2% and ±2% which would be produced by the Compressor Ring and Linear Debuncher.

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INTRODUCTION: MULTI-BATCH TARGETING

The Main Injector and Main Ring have the ability to accelerate 6 and 13 Booster batches/cycle respectively. In the current method of Antiproton production, however, only a single Booster batch is accelerated and targeted. This limitation is due to the 1.7 μ sec circumference of the Debuncher ring, which is essentially filled by the time spread of a single Booster batch. For this reason, a popular feature of antiproton upgrade scenarios has been a "Compressor Ring" [1], a sort of super-Debuncher with a circumference equal to the Main Injector (and located in the Main Injector tunnel). The full circumference of the MI would be targeted and the resulting P-bars injected into the full circumference of the Compressor ring. A normal 53-MHz bunch rotation would then be performed to reduce the momentum spread. This would be followed by a "compression" operation (an h=1 rotation of the unbunched beam) to squeeze the P-bars into a small fraction of the circumference prior to transfer to the existing Debuncher ring.

The Compressor Ring scenario provides a relatively straightforward factor of ~5 in the average rate of P-bar production. Several non-fatal technical problems remain. The momentum spread at the output of the Compressor Ring will be ~6x higher than the current momentum spread, due to conservation of phase space during the h=1 "compression" operation. It appears to be difficult to compensate for this by installing longitudinal stochastic cooling in the compressor ring, due to its large circumference and the fact that the compressor ring (an 8-GeV ring in the MI tunnel) will be operating far from transition. The large value of η also means that a large RF voltage will be required for debunching in the Compressor ring.

COMPRESSING THE CHARGE AT 120 GeV

An alternative method to perform multi-batch P-Bar production is to perform the azimuthal compression at high energy. This approach has the tremendous advantage of *not* requiring construction of the Compressor Ring. In the simplest scheme, the full 11 μ sec circumference of the MI would be filled and accelerated, then the charge would be herded into a single 1.6 μsec Debuncher-sized pulse before targeting. This could be done either by an "h=1/2" sawtooth rotation [J. Griffin showed me an ancient handwritten note on "How to Blow up the P-bar Target in a Single Pulse"], or by jumping the harmonic number by 1 unit [he and J. MacLachlan went so far as to perform some experiments along these lines a decade ago]. The difficulty with this approach is that it involves transporting buckets halfway around the circumference of the MI/MR, which requires a lot of time (a fraction of a second) and the full momentum aperture of the machine. The extra time taken is at 120 GeV, so that the power/cycle increases. This scenario is also probably the worst possible for P-bar targetry. Finally, this approach completely destroys the bunch structure in the machine, so that the Debuncher receives a debunched beam with the full ±2% momentum spread and 6x the normal intensity. Since there no opportunity to reduce this through bunch rotation, the burden on stochastic cooling is greatly increased. Difficulties with microwave instabilities of the intense, debunched 120 GeV beams are anticipated. For these reasons, this scenario was reconsidered and abandoned at the Bloomington meeting [2].

SNAP COALESCING

The major point of this note is to suggest a more effective alternative to compressing the charge at high energy, viz., Snap Coalescing [3]. This procedure is currently used in collider operation to combine the charge from 11 RF buckets into a single bucket. It involves a rapid phase-space rotation of the 11 bunches inside a single large h=28 (400ns) bucket. For P-bar production, a "sloppy" coalescing of ~15 RF buckets into a single bucket would be performed, in parallel over the entire circumference of the main injector. The result is to produce 28 "big bunches" evenly distributed at 21 bucket (400ns) intervals over the 11 μsec circumference of the Main Injector. For normal collider operation, these bunches are re-captured at 53 MHz. For P-bar production the coalesced bunches will be "squeezed" by snapping on the 53 MHz immediately prior to targeting, in a manner similar to the bunch compression currently performed for P-bar production. ESME [4] simulations (see figs 1-2) indicate a time spread of ±2.5ns on target should be achievable when starting with bunches of 0.15eV-sec.

FOUR EASY STEPS TO 5x MORE ANTIPROTONS

1) Fill the entire circumference of the Main Injector.

2) Snap coalesce at h=28 using the existing coalescing cavities. If a reasonable coalescing can be made for 15 out of 21 buckets, the number of usable buckets/cycle is 28*15=420 buckets. This is equivalent to 5 booster batches/cycle. The result is 28 Big Bunches approx. 5ns long and separated by 21 RF buckets.

3) Target one full turn of the MI, and fill the Debuncher using a kicker which lets in every 21st RF bucket. Since the harmonic number of the Debuncher is 90 and the Big Bunches are spaced every 21 buckets, the result is to have every 3rd bucket of the Debuncher occupied. This requires an 8-GeV kicker with rise and fall times less than 3 RF buckets (57ns), and a rep rate of 400ns.

4) Debunch the Big Bunches in the Debuncher at h=30 (=18 MHz). The time spread is increased from 5ns to 50ns, and the initial momentum spread of ±2% is reduced by a factor of ~8 to ±0.25%.

The final result is 5x more P-bars in the Debuncher, with a momentum spread of ±0.25%. This is comparable to the current debunched momentum spread of ±0.2%.

This result illustrates the effectiveness of snap coalescing as a means of trading time spread for momentum spread: the charge has been confined to 5ns in a 400ns bucket, or about 1.25% of azimuth. For comparison, the "bunch squeezing" in normal Pbar production confines the charge to 1ns in a 19ns bucket or ~5% of azimuth. It is this factor of ~4 which eventually provides the higher phase space density of P-bars in the Debuncher.

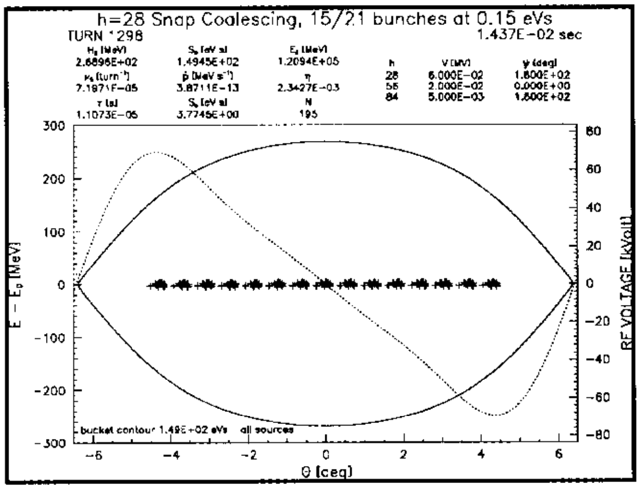

Fig. 1(a)

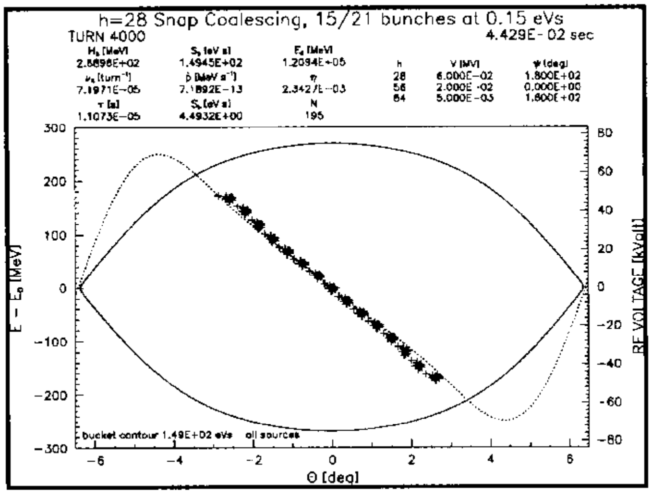

Fig. 1(b)

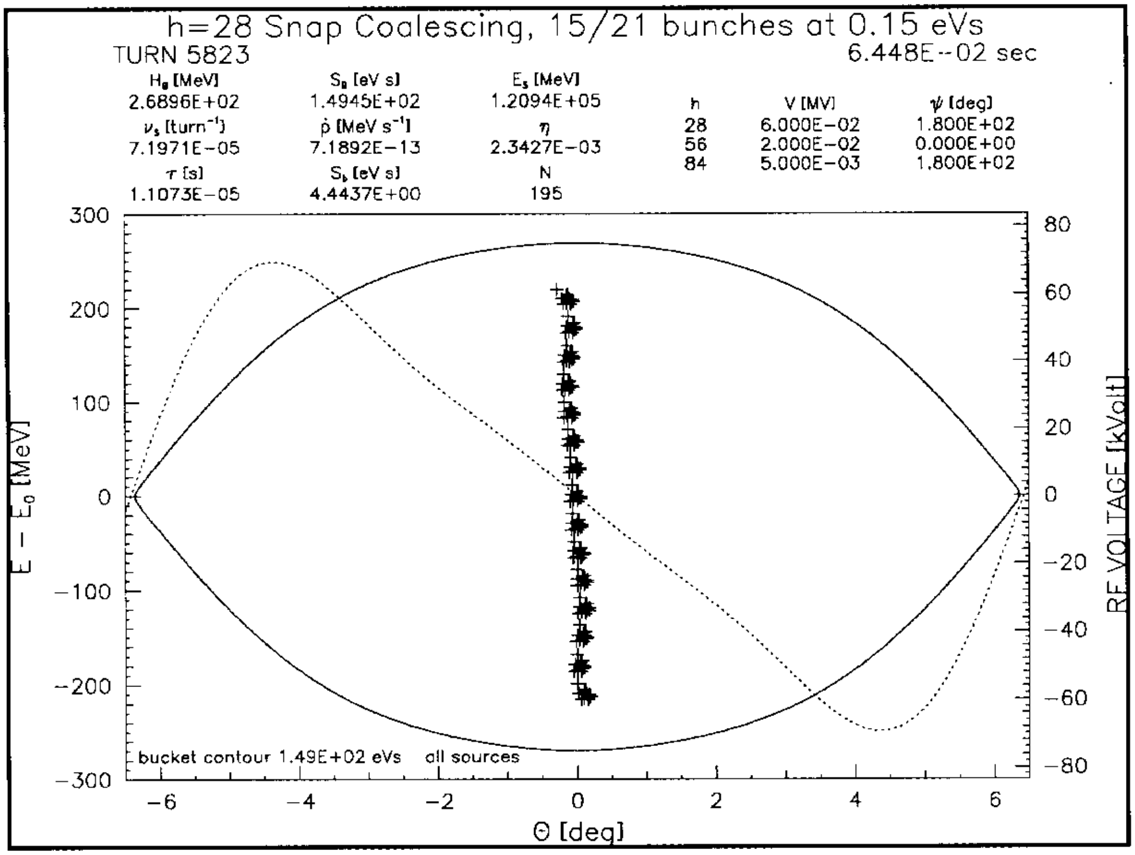

Fig 1.(c)

Fig. 1 - **ESME Simulation of Snap Coalescing.** Horizontal axis is azimuth in Main Injector, vertical axis is energy offset from 120 GeV. (a) Fifteen "normal" 53-MHz bunches are centered in a 2.5MHz bucket prior to coalescing. The 15 buckets have been partially debunched to reduce their momentum spread. The 2.5 MHz bucket includes two harmonics at the indicated strength to linearize the RF waveform. (b) Halfway through snap coalescing. The RF waveform has altered the energies of the individual bunches and the bunches begin to move together in time. (c) Snap Coalescing completed. The momentum spread has increased to +/-200 MeV and the bunches are on top of each other in time. The bunches are actually slightly under-rotated at this point; the rotation will be finished during the 53-MHz "squeeze" (see fig. 2). Time taken is 65 msec.

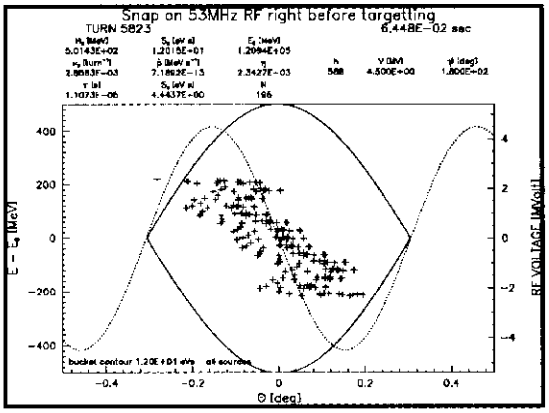

Fig 2. (a)

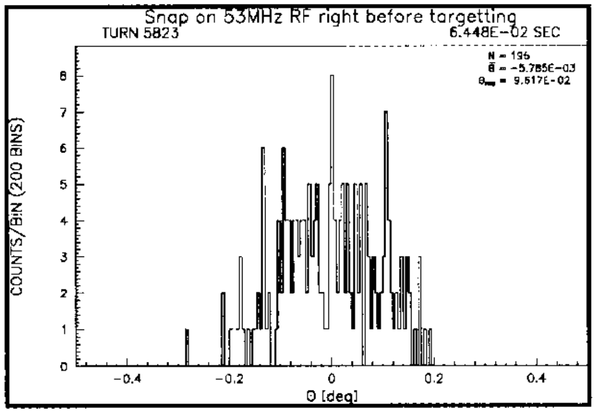

Fig 2.(b)

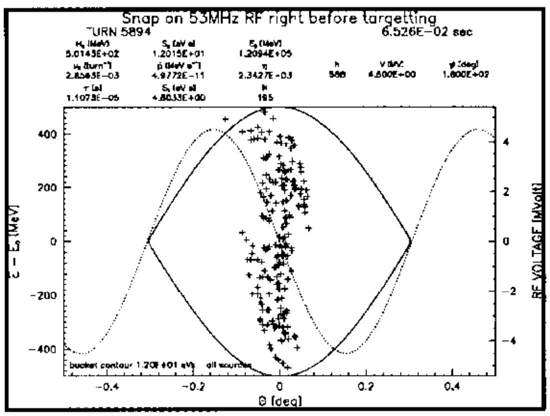

Fig 2. (c)

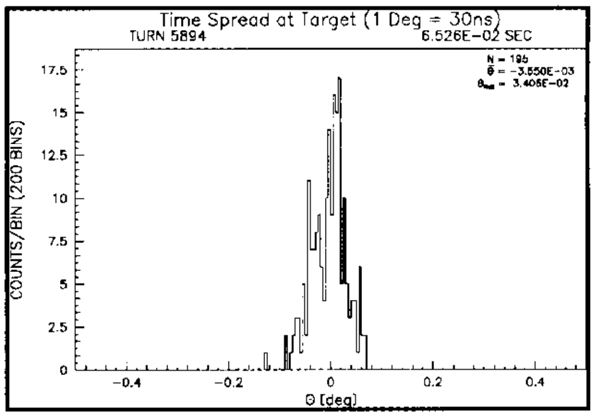

Fig 2.(d)

Fig. 2 - SQUEEZING THE COALESCED BUNCH AT 53 MHz PRIOR TO TARGETING. 2 (a) - The coalesced bunch in a 4.5MV 53MHz bucket at the moment the 53 MHz is snapped on. The momentum spread is +/-200 MeV and the bunch is somewhat under-rotated. (b) - Time spread at start of bunch squeezing. One degree is approximately 30ns. (c) - Bunch squeezing complete. The momentum spread is +/-450MeV, which is twice what could be achieved with the coalescing cavities alone. Total time for coalescing and squeezing is 65msec. (d) - The time spread on target is +/- 2.5ns.

The small time spread has been achieved via a large momentum spread (±500 MeV at 120GeV) which makes effective use of a large part of the momentum aperture of the Main Injector. It is also relatively fast (~60 msec for 60kV of 2.5MHz RF in the MI) since the charge only needs to be transported a small fraction of the circumference of the ring.

INJECTION INTO DEBUNCHER

Following coalescing, the 28 "Big Bunches" are then extracted and targeted in a single 11 μsec turn of the Main Injector. However, the circumference of the Debuncher is 1.7 μsec, so that the 28 bunches will arrive during ~6.5 turns of the Debuncher. This requires a kicker which will inject a single P-bar bunch every 400ns, without disturbing the other bunches already in the Debuncher. See fig. 3. The final result is that every 3rd RF bucket in the Debuncher is occupied (5ns bunches about 60ns apart). The flattop of the kicker waveform must be ~10ns, so that rise and fall times of 45-50ns are required. The characteristics of this kicker will be discussed in a subsequent section.

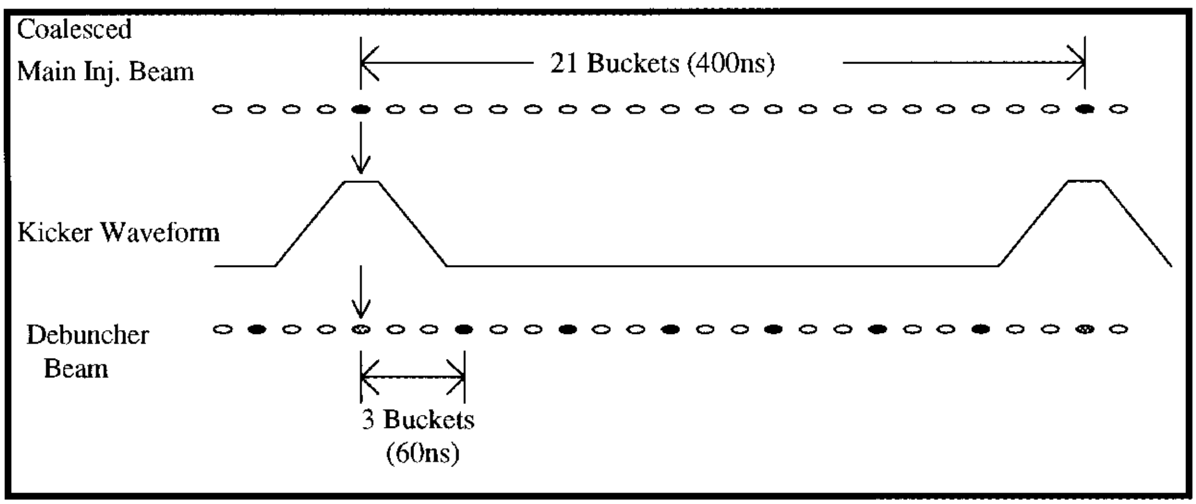

Fig. 3. BUNCH STRUCTURE AND KICKER WAVE FORMS FOR DEBUNCHER INJECTION. In the Main Injector, every 21st RF bucket contains a coalesced bunch. The coalesced bunches are extracted and targeted in a single turn of the Main Injector, and the P-bars are injected into six turns of the Debuncher. At the end of injection, the Debuncher has every 3rd bucket occupied. Kicker rise times of 45-50ns and a repetition rate of 400ns are required.

GEAR RATIOS FOR DEBUNCHER RING INJECTION

Multi-turn injection into the Debuncher requires that the "gear ratios" work out such that one bunch does not arrive on top of another bunch which is already circulating. Fortunately, with the Big Bunches spaced in time by 21 RF buckets, and a Debuncher harmonic number of h=90, the result is that every 3rd RF bucket in the Debuncher is occupied. The corresponding bucket numbers in the MI and Debuncher are listed in the table below.

Main Injector Bucket #	Debuncher Bucket #
0	0
21	21
42	42
63	63
84	84
105	15
126	36
147	57
168	78
189	9
210	30
231	51
252	72
273	3
294	24
315	45
336	66
357	87
378	18
399	39
420	60
441	81
462	12
483	33
504	54
525	75
546	6
567	27

TABLE 1 - BUCKET NUMBERS IN THE MAIN INJECTOR AND DEBUNCHER. This is where things land when every 21st bucket in the MI (h=588) is kicked into the Debuncher (h=90). The result is that every 3rd bucket in the Debuncher is occupied, which conveniently allows the beam to be debunched with an h=30 RF system in the Debuncher. (Actually, there are two unoccupied h=30 buckets in the Debuncher since there are only 28 Big Bunches from the MI. Can you find them?).

ADIABATIC DEBUNCHING AT h=30 IN THE DEBUNCHER RING

The result of the kicker operation is that every 3rd RF bucket in the Debuncher occupied. This is an ideal situation for debunching at 1/3 of the normal RF frequency (53MHz / 3 = 18 MHz). This is possible since the Debuncher harmonic number is h=90 which is divisible by 3.

Each bunch occupies a 5ns time spread in a 19ns*3=57ns bucket, or about 8% of azimuth. Thus one expects that the initial ±2% momentum spread (from the P-bars surviving in the momentum aperture of the Debuncher) may be reduced by about an order of magnitude by debunching. This is verified by ESME simulations (fig. 4) which indicate a final momentum spread of ~±0.25% (0.115% RMS). This is to be compared to the current momentum spread of ~±0.2% after debunching.

In this simulation, the individual times of the 120GeV coalesced protons on target were taken for the initial time spread in the Debuncher. The initial momentum distribution of the P-bars was taken as a ±2% square-box distribution. The bunch was then rotated down with 900kV of 18MHz RF. For the debunching simulation, I also treated myself to 250kV of second harmonic (36 MHz). This has not been optimized, and I have not investigated how the results depend on the presence of the 2nd harmonic cavities.

There is a possibly lower-cost alternative to 900kV of 18MHz RF, which is to partially debunch the beam using the existing 53MHz, then completing the debunching using a smaller amount (~300kV) of 18 MHz. This has not yet been looked at.

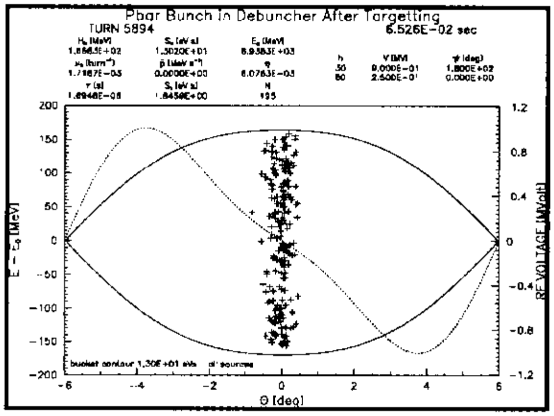

Fig 4. (a)

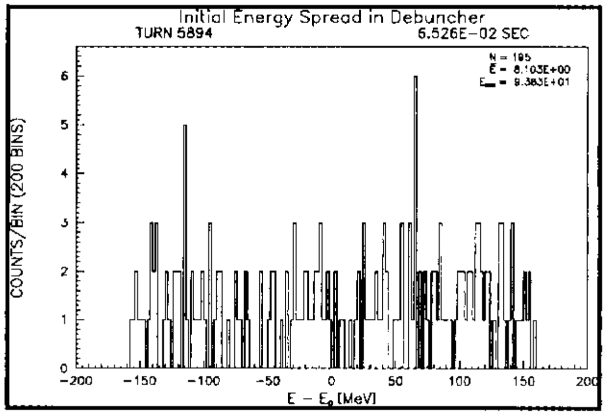

Fig 4.(b)

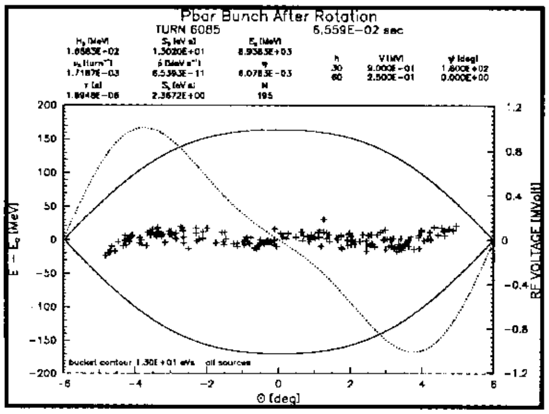

Fig 4. (c)

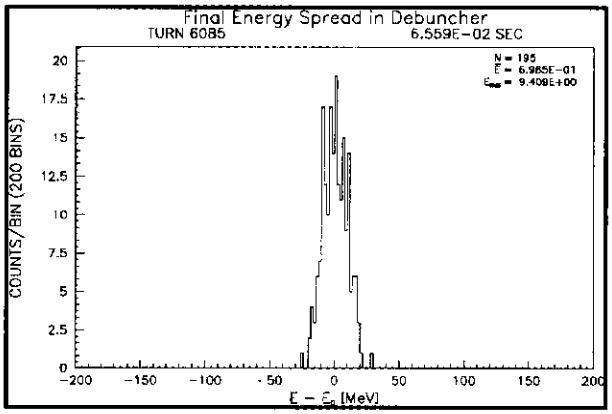

Fig 4.(d)

Fig. 4 - DEBUNCHING AT h=30 IN THE DEBUNCHER. (a) The 5ns bunch in an h=30 (18MHz) bucket in the Debuncher immediately after targeting. The time spread of individual particles was taken from their time spread on the target (fig. 2c,d). (b) Initial energy spread of the Pbars was taken to be an 8-GeV +/-2% square box representing the momentum aperture of the Debuncher. (c) Phase space distribution after rotating down in the Debuncher. (d) Final energy spread in the Debuncher is approximately +/-0.25%.

SO, WHAT'S THE KICKER?

Injection into the Debuncher requires an 8-GeV kicker which lets in every 21st RF bucket (400ns repetition rate). The flattop must be the length of the bunches at the P-bar Target, or about 5ns full width. The bunch spacing in the Debuncher is 3 RF buckets or about 60ns. Thus, rise and fall times of 45-50ns are required.

The parameters of this kicker magnet are compared to the D-48 kicker [5] in Table 2. In this table, I have assumed the new Debuncher kicker based on the D48 design but segmented into 3 sections along its length. This was necessary in order to meet the constraints of a 45ns filling time, 25kV maximum voltage on the drive cables and magnet, and a reasonable 12.5 Ohm impedance. The magnet is an "H" magnet with 4 drive cables on each side, so a total of 24 RG-220 (50-Ohm) drive cables are required. The D-48 kicker has 16 drive cables each running at 30kV.

Also indicated on this table are the parameters for two more speculative alternate designs: a single 3m long, 75-Ohm, 150kV RF kicker magnet suitable for driving with a ferrite-loaded resonator, and an 83-ohm, 330kV air-core RF kicker suitable for driving with an air-core coaxial resonator.

If the kicker magnet turns out to be a major problem, there is a scenario for which coalescing takes place at h=14 instead of h=28 in the MI. This results in bunches separated by 6 RF buckets in the Debuncher, so that the kicker rise time and cycle time could be 120ns and 800ns respectively. This scenario requires new 1.25 MHz coalescing cavities in the MI.

KICKER MAGNET	D48 Kicker	New Debuncher	3m Resonant	Air-Core	
B (gauss)	1053	500	500	250	gauss
Length total (m)	5.84	3.00	3.00	3.00	meter
Stored Energy (j)	157.47	13.43	13.93	10.44	joules
# of Segments (length x w)	2x2	3x2	1	1	
#drive cables (total)	16	24	1	1	
Segment Length (m)	2.400	0.900	2.800	2.800	meter
Gap Height (m)	0.057	0.050	0.050	0.150	meter
Gap Half-Width (m)	0.033	0.025	0.050	0.050	meter
Inductance (uH)	1.71	0.57	3.52	1.17	uH
Current (peak) (A)	4,793	1,989	1,989	2,984	Amp
Voltage (magnet) (V)	30,000	25,000	150,000	330,000	Volt
Zo (Ohms)	6.3	12.6	75.4	110.6	Ohms
Capacitance (total) (nF)	43.7	3.6	0.6	0.1	nF
Filling Time (ns)	273.8	45.0	46.7	10.6	ns
Kicker Ferrite Epsilon	11.000	11.0	11.0	1.0	
Flux-Return thickness(m)	0.025	0.020	0.022	0.100	meter
Flux-Return B-field(g)	1,369	625	1,142	125	gauss
RESONATOR		RG-220 (x24)	Ferrite Cavity	Air Cavity	
Resonator Length(m)		70.000	3.000	110.000	meter
Resonator mu		1.000	100.000	1.000	
Resonator Epsilon		2.250	13.000	1.000	
Resonator Delay (ns)		350.000	360.555	366.667	ns
Total Delay(ns)		395.000	407.222	377.273	ns
Resonator I.D.(cm)		0.500	40.000	2.000	cm
Resonator O.D.(cm)		0.685	62.926	12.632	cm
Resonator Bmax(gauss)		1,591.551	1,989.438	596.832	gauss

TABLE 2 - PARAMETERS FOR DEBUNCHER KICKER OPTIONS. The column for the D48 kicker is taken as representative of the current state of the art. The "New Debuncher" column is a design scaled conservatively from the D48 parameters, and requires segmenting into 3 sections along its length in order to meet the rise-time requirements. The "3m Resonant" column is a full-length, 75-Ohm, 150kV RF kicker suitable for driving with a ferrite-loaded coaxial resonator. The "Air Core" column is an 110-Ohm, air-core, 330kV RF stripline kicker suitable for driving with a coaxial air-core resonator. The air-core design needs 1/2 the magnetic field strength of the other designs because it gets equal kicks from the electrostatic and magnetic fields.

THE KICKER POWER SUPPLY

The 400ns repetition rate of the kicker power supply is a major concern. A peak power of 300MW is required given the stored energy of ~14 Joules and a 45ns filling time. Thyratrons and spark gaps cannot be used since they will not turn off and re-fire in 400ns. The 300MW is outside the peak-power capability of a single power switch vacuum tube. A straightforward though expensive solution is an array of switch tubes (e.g. 24 tubes of 12.4MW each, one for each of the 24 RG-220 drive cables). Each tube puts out a peak current of 500A to generate a 25kV pulse into 50Ω.

An example of a tube which exceeds these requirements is the Varian/EIMAC X-2159 [6] which can hold off 60kV and is rated for 760A in a pulsed mode. It is a power tetrode which is as big as a garbage can. The tube apparently can put out the required repetitive waveform on a CW basis without exceeding its plate power dissipation specification. Since the actual duty cycle of the kicker waveform is $\sim 10^{-6}$, it is likely that a smaller tube would also work. An array of 24 of these represents a worst-case solution to the kicker power-supply problem.

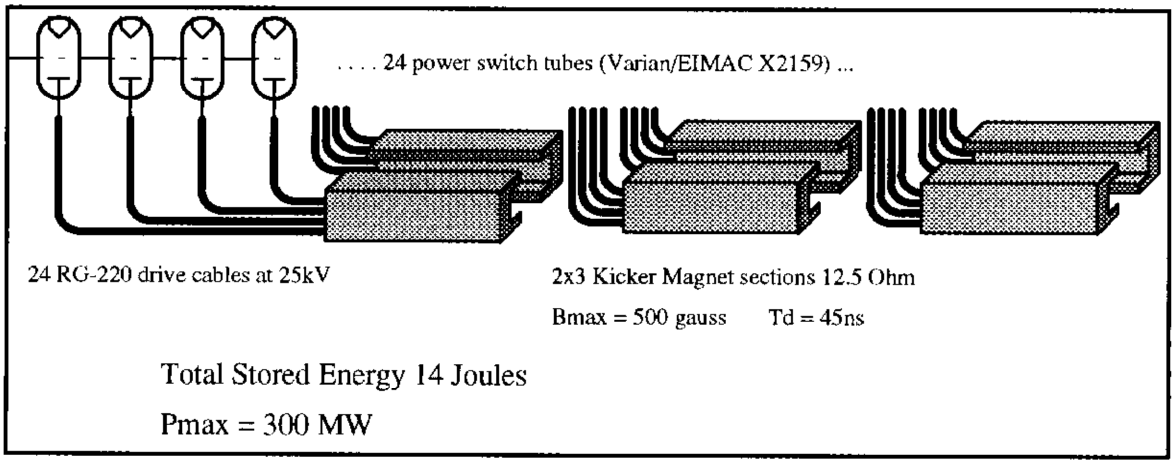

Fig. 5. Direct-drive (non-resonant) Debuncher injection kicker power supply. Supply is DC coupled and direct drive to provide fewest constraints on kicker rep rate and pulse width, etc. Switch tubes must be used instead of thyratrons, etc. because of the 400ns cycle time. This represents the straightforward but most expensive injection kicker design.

RESONANT KICKER OPTIONS

Given the 400ns repetitive wave form and the high peak power, a resonant design is a promising alternative. The simplest implementation of this is to connect the kicker output cables back to its inputs via a ~400ns loop of cable, so that the energy in one pulse could be largely recycled to form the next pulse. A directional coupler [7] and drive circuit would be inserted into this cable loop in order to pump up the resonator and "square up" the circulating pulse. If a Q of 10-20 could be achieved with this type of resonator, the power requirements might be reduced to the point where a single tube (or possibly a solid-state) drive circuit would suffice. The resonant-kicker solution would also require a spark-gap or thyratron to rapidly extinguish the resonating pulse at the end of the injection cycle.

Three types of resonators have been considered. These are indicated schematically in figs. 6-8. The bottom section of Table 2 gives the parameters for resonators appropriate for each of the 3 magnet designs.

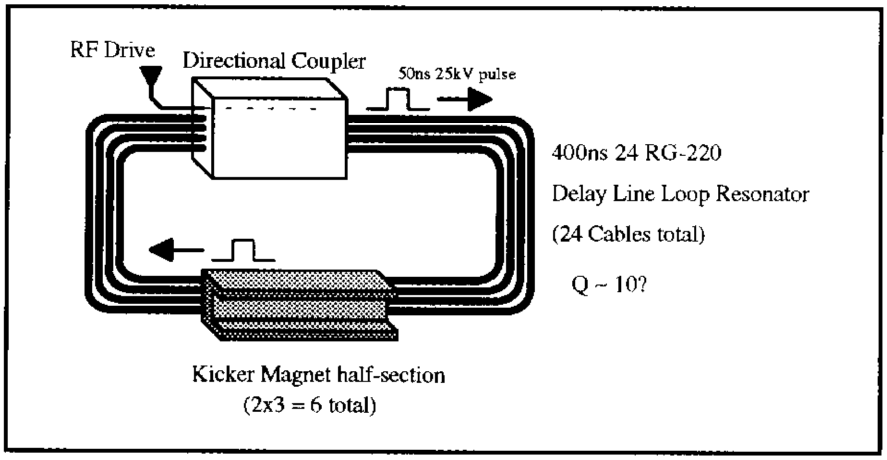

Fig 6. The first "RG-220 x24" resonator is based on RG-220 cables normally used to drive kickers. The attenuation figures at 10MHz for RG-220 indicate ~5% attenuation in 350ns for the cable alone, so that an overall Q of ~10 seems plausible. This system requires a specially-built directional coupler (a stripline type device which can be located upstairs) to drive the oscillator loop.

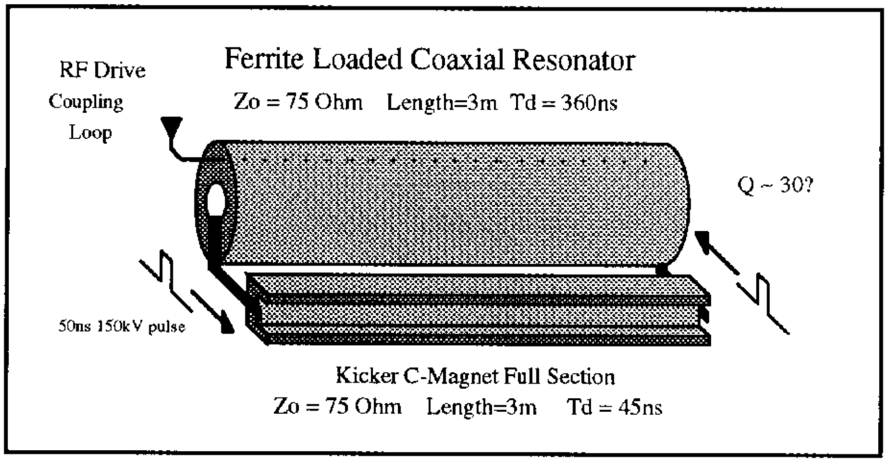

Fig. 7. A ferrite-loaded coaxial cavity could provide a very compact 350ns delay. A first-pass set of parameters ("Ferrite Cavity" table 2) indicate that an overall length of 3m may be practical, which is convenient since this is the length of the kicker magnet itself. Thus a very compact resonator loop structure is possible, with the pulse spending ~45ns propagating the 3m length of the kicker, then spending ~350ns returning in the ferrite-loaded coaxial cylinder. Various design considerations lead to ~75 Ohm impedance and ~150kV P-P operating voltage on the resonator. The directional coupler could be incorporated into such a structure by the addition of an off-axis conductor whose impedance and "transformer ratio" could be adjusted via geometry.

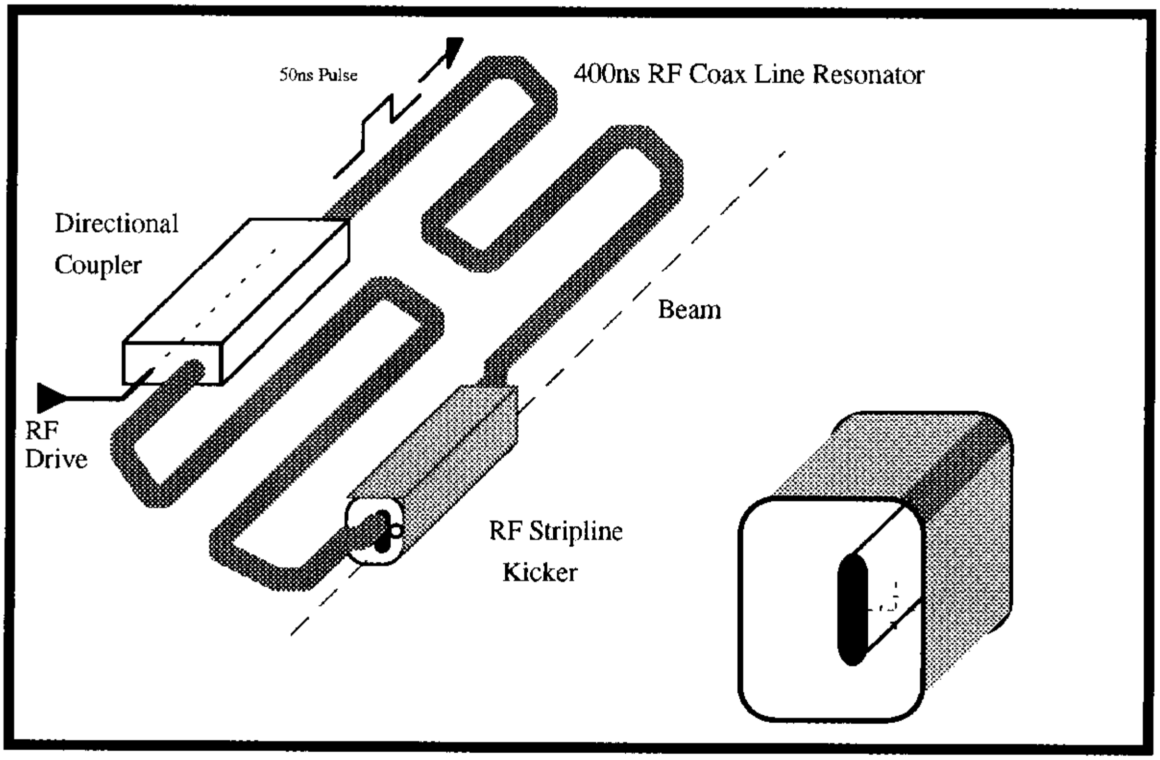

Fig. 8. An "Air Core" magnet and resonator design is also possible. This would essentially be a continuous 400ns loop of coaxial pipe, with a peculiar cross section (to obtain good field uniformity) in the 3m section through which the beam passes. The beam and kicker pulse must pass in opposite directions through the stripline in order that the kicks from the E field and B field add to each other. The coupling loop would be incorporated into a section of the coaxial line. In this design one is led to rather high impedances ~100Ω and high voltages ~330kV. A high Q seems fairly certain in such a design.

An important question for any resonant design is whether it would be adequate for all modes of operation of the Debuncher. It is probably impossible to put both a resonant and a normal injection kicker into the space available in the Debuncher. It might be possible to use a standard kicker magnet with both a resonant and one-shot (thyratron/PFN) supply.

P-BAR PRODUCTION TARGET ISSUES

Survival and safety issues for the P-bar production target are non-trivial in any multi-batch targeting scheme (including the compressor ring scenarios). I will essentially ignore this, except to point out that:

- a beam-sweeping system [8] more aggressive than that planned for the Main Injector will be essential,
- it is somewhat easier to sweep the beam at 11 μsec than 1.6 μsec,
- the beam can be defocused without losing all of the benefits of the additional protons on target, and
- the cost of the sweeping system is small WRT the Compressor Ring or Linear Debuncher.

The design of the beam-sweeping system should also anticipate that the MI may have enough transverse aperture to inject two booster buckets side-by-side (betatron stacking) so that the eventual increase in P-bars/cycle will be not 5x but 10x.

BOOSTER FILLING SEQUENCE

In snap coalescing, only ~15 out of each group of 21 RF buckets can be successfully rotated. Thus, the ideal filling pattern of the MI is 28 groups of 15 filled buckets, each separated by 6 empty buckets. There are several approaches to this:

1) Ignore the problem and fill whole ring. The 6 extra buckets will be accelerated, improperly rotated, and extracted onto the target at the wrong time. The P-bar target will see ~20% more radiation due to the extra buckets, and the out-of-time P-bars which come through when the kicker is off will be lost somewhere in the Debuncher. This effect should be small considering the fact that ~99% of the particles which survive 8 GeV collimation to get into the Debuncher are not P-bars and fall out anyway. However, these losses may be more localized than the more diffuse losses from pion and kaon decay.

2) Knock out the unused buckets in the Booster. Fill all 84 booster buckets, then find some way to abort out four groups of 6. This would leave 4 groups of 15 buckets in each booster cycle, and 7 total booster cycles would be needed to provide the 28 bunch trains for coalescing.

3) Add a sophisticated extraction sequence for the booster which allows groups of 15 bunches to be extracted, then cogs the MI around, then injects the next 15, etc. This is the most efficient use of Booster cycles, and a 5 or 6-cycle filling might be possible.

CYCLE TIME AND P-BARS/SECOND

Loading 6 batches will add 0.33 sec to the cycle time. The coalescing takes about 60msec for 60kV of 5 MHz RF. Thus the overall cycle time will increase from 1.5sec to 1.89 sec. Most of the time added will be at low energy, so the average power will go down by ~20%.

The number of P-bars/time will go up by a factor of:

(5 batches/cycle)(1.5 sec/1.86 sec) = 3.97

This number can be slightly increased in several ways:

- If more than 15/21 buckets can be successfully coalesced, this goes straight into protons-on-target. This may require additional harmonics in the coalescing wave form. For example, if 18/21 buckets could be coalesced then there will be effectively 6 booster batches/cycle.

- The P-bar production cycle in my (archaic) copy of the MI design report shows ~0.2 seconds resting at zero current in the magnets. If this is indeed the plan, then the first 3 booster batches are free if one is willing to "rest" the magnets at 8 GeV.

With 18/21 bunches rotated and a cycle time of 1.7 sec, the improvement factor would be 5.2x.

CAN THIS BE DEMONSTRATED WITH THE MAIN RING?

The "Snap Coalescing" of the entire circumference of the Main Ring can be demonstrated with existing (& planned 1994 upgrade) cavities. Probably no more than 13/21 buckets can be coalesced without adding more, higher harmonic cavities. (Adding these cavities would be good for collider luminosity in any case). The bucket height for the final 53-MHz "squeeze" before targeting will not be as high in the MR as for the MI, so the time spread on target will be somewhat worse, but still adequate.

The kicker issue can be partially finessed (for the purposes of a demonstration) if one is willing to pull out the 28 bunches one-by-one, and spaced by ~2 sec to allow the lithium lens to recover. The Debuncher would be cogged around to the correct phase to accept each new P-bar bunch during this time. This would require that the coalesced bunches be stored & captured at 53 MHz rather than simply squeezed before targeting. Similarly, the P-bars would not be immediately debunched in the Debuncher, but captured in the 53 MHz until all bunches were injected. The rise time of the existing Debuncher kicker might not allow 3-bunch spacing of the injected beam. It should, however, be possible to significantly exceed 1 booster-batch worth of P-bars into the Debuncher.

The final debunching in the Debuncher will unavoidably require new 18MHz cavities. I am told that it will be damned hard to find a place to add a new cavity without removing some of the 53MHz cavities. One could still debunch at 53 MHz and obtain some (factor 2~3) reduction in momentum spread.

CONCLUSIONS

This plan should raise the production rate of P-bars from the ~10mA/hr planned for the Main Injector to ~50mA/hr, which is sufficient to support $L > 10^{33}$ $cm^{-2}sec^{-1}$ at least one detector. It produces P-bars with 5x the intensity, and with a debunched momentum spread comparable to the current system.

The required parts list includes:

- A new Debuncher injection kicker with a high rep rate or resonant power supply.
- 900kV of 18MHz RF for the Debuncher (possibly less using 2-step debunching).

The optional-but-desirable parts list includes:

- A target sweeping system which avoids the need to de-focus the beam on target.
- Third harmonic cavities for coalescing as many bunches as possible in the MI.
- 2nd harmonic cavities (36 MHz) for the Debuncher.
- Improvements (or cleverness) in the filling sequence from the Booster.

This system is compatible with further P-bar source upgrade scenarios involving the "Pbar Depository Ring" but incompatible with a Linear Debuncher or Compressor Ring. Betatron stacking (injecting multiple batches side-by-side in the Main Injector) could provide an additional factor of 2x-4x in P-bar intensity in the Debuncher at low cost and with no additional momentum spread. This would yield an overall factor of 10x-20x in P-bars in the Debuncher, sufficient for luminosities well above 10^{33}.

References

1. - "Tevatron Energy and Luminosity Upgrades Beyond the Main Injector," Presented at the 8th Meeting of the DPF, Albuquerque, August 2-6, 1994, J.Strait, et al. (Also available as FERMILAB-Conf-94/249). "Pre-Conceptual Pre-Design for a Tevatron Upgrade to 2 Tev Beams and $L>10^{33}$ cm^{-2} sec^{-1}", G. P. Jackson et al, March 1993.
2. Report from the Bloomington DPF Workshop on Future Hadron Facilities, July 6-10, 1994, J. Maclachlan and S. Holmes, editors.
3. "Performance Comparisons of the Different Coalescing Schemes Used in the Fermilab Main Ring", I. Kourbanis, G.P. Jackson, X. Lu, Proc. IEEE 1993 PAC Washington DC.
4. ESME-v8 User's manual (J. MacLachlan). The starting point for my work was a simulation of Snap Coalescing in the Main Injector which JM gave me.
5. D-48 Kicker design review materials.
6. The EIMAC/Varian Quick Reference catalog (dated 1975) lists the X-2159 in pulsed regulator service as having a 60kV holdoff voltage and a 780A peak output current. The detailed X-2159 data sheet (dated 1973) has curves up to 800A plate current and a continuous anode dissipation spec of 1250kW.
7. Coaxial directional couplers are available from Microwave Techniques Inc. Raymond, Maine.
8. F. Bioniosek, "A Target Sweeping System for the Main Injector", April 1994.