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ASYNCHRONOUS TRANSFER OF BEAM BETWEEN ACCELERATORS

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Longitudinal matching of the beams in two accelerators requires the momentum and phase of the beam bunches in the first machine be matched to the empty rf buckets in the second. It does not require frequency matching. With asynchronous transfer, momentum and phase are monitored, but not controlled. Transfer takes place at the instant they are adequately matched. This system does not attempt to perfectly match either phase or momentum, and a diminutive residual error is expected. The required precision of the low level rf devices is less than for synchronous transfer, and the system is basically simpler. For Booster-to-AGS transfer, at full Bdot using this scheme, the Booster radius would have to be changed about four inches. This arrangement would work with the Booster at its design radius by moving the beam within the Booster aperture. Lower Bdot or some crude pre-alignment of the phase would be required. Either boxcar or "one-bunch-at-a-time compacting" AGS transfer to RHIC could be done asynchronously on an AGS flattop. A small change in beam radius within the present AGS aperture would suffice.

Introduction

The frequency of a beam in a circular accelerator and, in particular, the very high accuracy to which it can be measured is primarily an effect of the ring on the beam, averaged over many turns. Once a single bunch leaves the ring and heads down a transfer line, it has no associated "frequency". For a train of bunches, the frequency is only defined to the accuracy the spacing between bunch centers can be measured and is only relevant to the extent that changes in that spacing affect later performance. In particular, changes that are small compared to the bunch width will not cause dilution in beam emittance later. For the three 0.25 μsec spaced Booster bunches going to the AGS, having a timing uncertainty of ~2 nsec in the center of the 130 nsec wide bunches, frequency is only defined to ~0.5% in the transfer line; and for the 12 bunches out of the AGS going to RHIC, with a 0.5 nsec error in the location of these 20 nsec bunches, the frequency is defined to ~0.05%. Thus "meshing" the accelerators, or having a phase match for a finite number of sequential bunches transferred between them, does not require precisely matching frequencies in the two accelerators.

Asynchronous meshing accepts some error in phase and momentum matching between the accelerators in exchange for a simple system requiring lower precision devices. The precision of match depends on the time available and thus Bdot. The two accelerators are built and operate without a fractional ratio of radii, and thus they run [asynchronously] at slightly different frequencies when protons in them have the same momentum. The frequencies must be close enough that the small resultant timing errors in the leading and trailing bunches does not cause significant phase errors in the destination accelerator. They must also be close enough in frequency so that the phase between the two machines does not shift more than the allowed error of match for each turn of the receiving ring. Conversely, The frequencies must be enough different so that a full 360° of shift occurs during the time that the momenta are adequately matched. Thus, the rate of change of momentum (Bdot) in the first accelerator must be low enough so that, while the momenta are matched, there are enough turns in the second ring for a full 360° of phase slip with a small enough phase shift per turn to give an adequate phase match. The achievable precision is Bdot dependent.

The sequence of events is simple. The momentum of the injector is monitored. (This can be relative to the second ring's momentum, if the second ring's momentum is not adequately stable.) When the momentum match is within tolerance, a signal is sent to an AND gate. The phase of the bunches in the injector are continuously compared with the buckets to be filled (gated rf) in the receiving ring. This eliminates any errors caused by phase shifts between the injector rf and its bunches due to changes in the stable acceleration phase angle of the bunches in the injector or synchrotron oscillations that could develop without the rf phase loop. As the frequencies are different, the phase signal will be a smoothly varying beat. When the phases match to within tolerance, a signal is also sent to the AND gate. Transfer must be initiated when there is both momentum AND phase match. As both signals are smoothly changing, the references can be slightly offset to provide anticipation time for ejection equipment to turn on. Variations in

Bdot will only effect the accuracy of transfer if excessive anticipation is needed or if Bdot increases to the point that a phase match is not achieved within the period when there is a momentum match. For Booster-to-AGS transfer, the time to transfer will strongly affect the repetition rate of the Booster. The ability to transfer at high acceleration rates (Bdot) will reduce transfer time, and thus increase repetition rate. Only when both accelerators are at a constant, unchanging, momentum (Bdot = 0), does a true frequency lock between the two accelerator rf systems remove the constraint that transfer must take place at a precise time. The beams remain aligned only as long as momenta remain equal. If the time that the momenta are equal is short as with high Bdot, extraction timing must be precise even for frequency-locked transfer.

Phase and momentum mismatches are seen as coherent oscillations in the receiving ring. In the absence of an active damping system, these oscillations filament the bunches in longitudinal phase space, resulting in growth of the bunch area in that space. Damping the coherent oscillations before filamentation occurs would prevent emittance growth, even with a finite mismatch. This damping system requires observing and modifying the phase of individual bunches relative to the rf in this ring. The period of synchrotron oscillations is typically many turns, so looking at only the injected bunches will not reduce this signal's bandwidth significantly. This signal is then phase shifted for loop stability and sent to the high level rf system to shift the phase of the appropriate cavities, as the bunches pass through, to damp the phase oscillations.

Only those cavities that have the injected bunches passing through should have the rf phase shifted to damp the oscillations. To prevent this damper from affecting other bunches, the other cavities with older bunches in them should not have their rf shifted. Thus these correction signals must be routed to different cavities each rf cycle, following the bunches around the ring each turn. This feature of the system would be difficult to execute, and will require significant engineering. If there is a beam loading compensation system in the second ring's rf system, it will have to deal with each bunch independently, and thus the above needed feature will be available. The phase error could be added to the beam loading compensation system signals sent to the appropriate rf cavities for those bunches whose synchrotron oscillations need damping.

A Numerical Example for Booster-to-AGS Transfer

Take the following parameters as fixed:

Pt is the beam transfer momentum (2.251 Gev/c)
Bt is the beam transfer main magnet field (0.546 Tesla)
fo is the AGS RF frequency (4.114 Mhz or Mbunches/sec)
Rob is the "nominal" Booster average radius (1264 inches) (1/4 of the AGS)
Phw is the full width of Booster bunches (187 deg.)
Pw is the fractional full width momentum spread (1%)
Emt is the longitudinal emittance (1.5 eV-sec.)

Then as one varies these parameters:

Bdot is the rate of change of main field (Tesla/sec)
delP is the allowable error in momentum (Gev/c)
(which is twice the maximum momentum error of the transferred bunches in the AGS as a result of this delP and Bdot.)

The following can be calculated:

Gate time: Tg = delP*Bt/Bdot (Sec)

No. of AGS revolutions: Na = fo * Tg / 12(bunches/AGS turn)

Phase shift per AGS turn: delPh = 400deg / Na (deg/turn)
(which is twice the maximum phase error of the transferred bunches in the AGS as a result this delP and Bdot)

Frequency difference Booster to AGS:
delf = delPh * fo / 360*12 (deg/turn) (Hz)

Required change in Booster radius:
delR = delf * Rob / fo (inches)
(from 1/4 of the AGS's radius)

Diluted emittance:
Emd = (Phw+0.8*delPh) * (Pw+0.8*delP) * Pi / 4

Emittance Growth:
Emg = Emd / Emt (%)

The expected Booster bunch will nearly fill a ~190° wide bucket and have a 1% momentum spread. To minimize emittance growth, the allowable errors in phase and momentum matching should have the same aspect ratio. This system will randomly mismatch the bunch with the AGS bucket with a rectangular, evenly filled, probability distribution whose dimensions are the errors. On average, the additional area of the beam emittance from these errors add only as 80% of maximum error in each dimension as half of the bunches are transferred within an 80% circle in phase space.

As an example, if the transfer is with a Bdot of 8 Tesla per second and a Booster radius five inches larger than one-quarter of the AGS radius, these events would occur. A gate would open when the momentum is 0.05% low and remain open until the momentum is 0.05% high. During this time, the AGS would make ~22 revolutions. As the Booster's beam radius is 5 inches larger than 1/4 the AGS's, the Booster rf frequency would be ~16kc low causing ~18° of phase slip between the machines for each AGS revolution. When the phase difference is less than +/- 9°, transfer would be triggered. This maximum momentum error of +/- 0.05% matches, in the Booster bucket, the maximum phase error of +/- 9°. Half of the transfers take place with less than 80% of this error. Thus the bucket grows, on average, from 1.49 to 1.72 ev-sec--a 16% increase. Device tolerances:

A - Gauss clock (B) and momentum gate: 1 parts per 10^4
B - Phase detector: 3° in 180°.
C - Bdot: <10% (if triggering of septa and AGS RF compensation require triggers more than ~100 μsec before extraction, this must be proportionally better).
D - Booster RF Amplitude: no requirements here, as transfer is bunch synchronized, an error in the stable phase angle is not part of error budget.
E - Booster Radius: <10 mils, for $\leq 2/10^4$ delp/p.

Keeping the radius constant to this tolerance every cycle will be tough with pulse-to-pulse rf amplitude and Bdot variation. Feeding this information forward to the radial loop will help.

Other Options

The precision of longitudinal match, or amount of residual error, is determined by the planned Bdot of the Booster at extraction. Table I gives the relevant parameters for various Bdots. As before delR is chosen to share the transfer error equally between momentum and phase errors (delP and delPh). The faster the Bdot, the poorer the match. As the phase shift per AGS revolution is dependent only on the relative radii of the accelerators, it is "built in". It must be large enough so that a full 360° of phase shift between the Booster and the AGS will take place during the limited number of turns that the momentum is matched acceptably, even at the maximum error in Bdot. A 400° phase slip is used to allow for a 10% increase in Bdot without destroying synchronization. There is latitude in fine tuning the radius by changing the location of the beam in the Booster. This may be as great as +/- 1 inch. Changes of beam location in the AGS are only one-quarter as effective due to its four-fold larger radius.

Table I

Bdot	delP/Pt	Na	delPh	Bunch Area	Emittance Growth	delR
9.0	0.1013	21.1	18.99	1.74E+00	16.9%	5.63
8.0	0.0955	22.3	17.90	1.72E+00	15.9%	5.00
6.0	0.0827	25.8	15.50	1.69E+00	13.7%	3.75
5.0	0.0756	28.3	14.13	1.67E+00	12.5%	3.13
3.0	0.0454	36.5	10.96	1.63E+00	9.6%	1.88
2.0	0.0302	44.7	8.94	1.60E+00	7.8%	1.25
1.0	0.0151	63.3	6.32	1.57E+00	5.5%	0.63
0.5	0.0239	89.5	4.47	1.55E+00	3.9%	0.31
0.25	0.0169	126.5	3.16	1.53E+00	2.7%	0.16
0.1	0.0107	200.3	2.00	1.51E+00	1.7%	0.06

If construction was not under way and the Booster radius "frozen", the conservative course of radius choice for asynchronous matching to AGS would be to add four inches to the Booster radius. This will allow full Bdot (8 T/sec) transfer of beam to the AGS with the beam 1 inch to the outside in the Booster for a delR of 5 inches. Dilution would be ~15%. If needed, the option of lower Bdot operation for better matching would be available. With the beam 1 inch to the inside in the Booster for an effective radial difference of 3 inches and Bdot less than ~3.3 T/sec, dilution could be decreased to ~10%.

Booster-to-AGS Transfer with Standard Booster Radius

With the Booster radius fixed, the available change in radius is the one inch of available aperture. Table I shows that at ~1.6 T/sec transfer could be done with very small dilution. This low Bdot will cut into the Booster repetition rate, but would allow for this simple method of matching.

With a 1 inch radius difference, the phase change per AGS revolution would be ~3.4° per turn or 105 turns would be required for a full 360° of phase slip. Table II shows what momentum error would have to be allowed for various Bdots to allow a full 360° of phase slip. The maximum phase error would only be +/- 1.7°. Also shown are the resultant bunch areas after the mismatched beam filamented in the AGS. For a 20% increase in bunch area, Bdot could be ~2.2 T/sec; if more dilution is acceptable, a faster Bdot could be achieved. Higher rf voltage and the above mentioned injected bunch synchrotron oscillation damper would reduce this dilution, but extraction losses may increase with larger momentum errors.

Table II

Bdot T/sec	delP for 360 deg	Phase Growth deg	Area ev-sec	Growth
9.0000	0.5066%	94.83	2.94E+00	97.48%
8.0000	0.4503%	84.30	2.75E+00	85.02%
7.0000	0.3940%	73.76	2.57E+00	72.98%
6.0000	0.3377%	63.22	2.40E+00	61.33%
5.0000	0.2814%	52.69	2.23E+00	50.10%
4.0000	0.2251%	42.15	2.07E+00	39.27%
3.0000	0.1689%	31.61	1.92E+00	28.84%
2.0000	0.1126%	21.07	1.77E+00	18.82%
1.0000	0.0563%	10.54	1.63E+00	9.21%
0.5000	0.0281%	5.27	1.56E+00	4.55%
0.2500	0.0141%	2.63	1.52E+00	2.26%

Another method to permit increasing Bdot would be to do a crude phase match to the AGS. This would reduce the amount of phase slip required during the momentum "window". The allowed Bdot would increase with the reduction in possible phase error. If the phase was matched to +/- 90°, Bdot could be over 4 T/sec and if the beam was placed in the correct quadrant, full Bdot transfer could be obtained. The maximum phase error includes motion of the Booster bunches within their buckets, as well as rf mismatches. The asynchronous transfer eliminates these errors.

Heavy Ion Transfer - Booster-to-AGS

For heavy ion transfer, the process is somewhat reversed. There will only be one load per AGS cycle, thus the three Booster bunches can go into any adjacent AGS buckets. As the extraction momentum is approached, the AGS rf is phase shifted to match the Booster bunches at the precise momentum of transfer. The only emittance growth will be due to errors in instruments and the errors in the leading and trailing bunches due to the small frequency difference (~0.15° for a 1 inch radial difference).

AGS-to-RHIC Transfer

The transfer of beam from AGS to RHIC requires high enough precision that it must be done on as AGS flattop, at essentially zero Bdot.

Momentum match	+/- 0.005%
Phase match	+/- 1°
Time for 360 rev of RHIC	~5 msec
Max. Bdot/B	~1%/sec
Freq. difference	200 Hz
Radius diff. in AGS	0.23 in.

Thus, there will be a phase match every 5 msec and when the momentum is correct, transfer will be made.

Increasing Longitudinal Brightness in RHIC

Another proposed method for filling RHIC involves longitudinal packing by placing AGS bunches closer than the 225 nsec spacing in the AGS. This would be done by extracting the AGS beam, one bunch at a time, into RHIC buckets. These buckets would be closer together as the RHIC rf would at two to four times the nominal AGS rf frequency. Table III shows the AGS frequency shift and radius change as a function of the desired packing factor. It is assumed that a bunch will be extracted every 100 msec.

Table III

Packing Factor	Phase Shift per Turn deg	Freq. Change Hz	Radius Change in
2.0	0.62	125.0	0.1419
3.0	0.63	126.7	0.1438
4.0	0.63	127.5	0.1447

Conclusion

Initial Booster-to-AGS matching can be done asynchronously at a low Bdot. In the future, as the needs and capabilities of the various systems are better known, a low precision phase matching system could be built to allow high Bdot transfer. RHIC injection matching could be done asynchronously for both modes of transfer.

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