DRAFT **Report on slow resonant extraction in Main Injector for CKM**

The CKM experiment is asking for 120 GeV protons from the Main Injector, debunched with a residual ~ 10% 53 MHz modulation, and resonantly extracted over a slow spill of at least 1 s at a rate of 5e12 protons/s. At the desired rate of 6e15 protons/hour, the requested 6e19 120 GeV protons would be accumulated over 2 years, assuming 39 weeks/year and 120 hours/week.

The following document is addressing the following issues, which have been identified by S. Mishra :

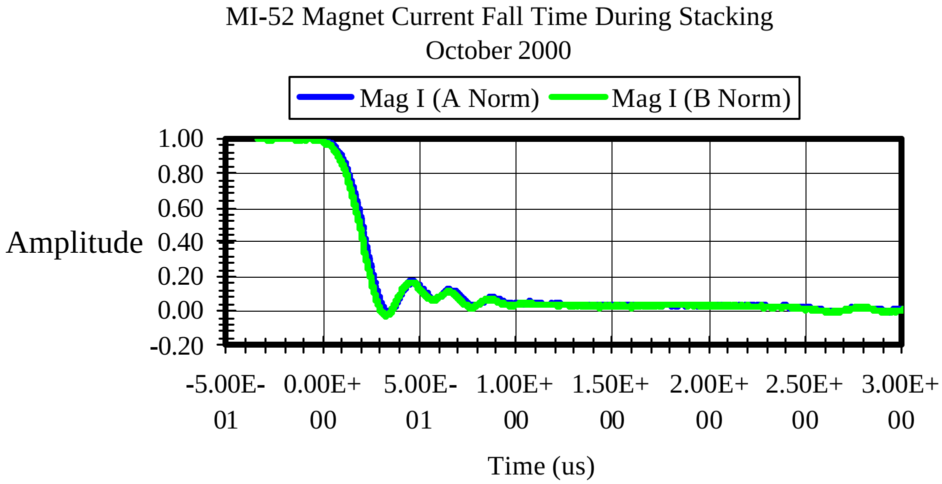
1) **Compatibility of single turn and slow resonant extraction in a same spill.** Alberto Marchionni
2) **6 seconds resonant extraction and its effect on magnet power supply and temperature issues, QXR, corrector ramp etc.** Dave Capista & Craig Moore
3) **Debunching of beam in the Main Injector.** Ioanis Kourbanis.
4) **MI30 Septa: do we need it for slow extraction, loss issues at 3e13 ?** Dave Johnson
5) **Radiological concerns.** Chandra Bhat

What follows are preliminary and partial answers to the previous technical questions. More time and in particular machine study time will be necessary to come to definite conclusions for some of the issues and to fully understand the implications of slow extraction at high intensity. Anyhow some preliminary conclusions are in order:

1) To be able to run single turn and slow resonant extraction in a same spill we would need to significantly improve the fall time of the NuMI kickers, but this mode of operation doesn't seem to be of any particular advantage.
2) Up to now no major technical impediment has been identified for a CKM dedicated cycle, with up to 6 s resonant extraction, if limited to a maximum rate of one every 20 s. Further investigations are necessary here.
3) The procedure of debunching the beam has to take into account beam loading and residual 53 MHz voltage on the cavities and the requirements imposed by the extraction line on the momentum spread of the beam. We need to better understand the requirements of CKM on the spill structure, other than the residual modulation at 53 MHz.
4) The present layout of the resonant extraction equipment in the Main Injector is probably not adequate. A new design needs to be developed including additional calculations to determine the level of losses and how to best control them.
5) Additional shielding material has to be added in the tunnel around the extraction region.

1) Compatibility of single turn and slow resonant extraction in a same spill, Alberto Marchionni

Both anti-proton stacking and NuMI use single turn kicker extracted batches from the Main Injector, while CKM needs slow resonant extraction, where beam is extracted over one or more seconds. In a spill with combined single turn and slow resonant extractions, the MI would be operated with a 3 s cycle including a 1 s flat top. One batch to the anti-proton target is followed by 4 batches for NUMI/MINOS, all single turn kicker extracted. The remaining batch in the machine is debunched and resonantly extracted in a 1 s spill to CKM. The main problem here is that the NuMI kicker, as currently specified, has a fall time of the order of 3 μs, with most of the fall time occurring in the first 1.5 μs. This makes it not compatible with an additional batch left over in the machine.
By comparison the following picture shows the fall time of the pbar kicker at MI52, as measured by Chris Jensen.



2) 6 seconds resonant extraction and its effect on magnets, Dave Capista

This addresses a mode of operation where a number "n" of MI cycles dedicated to anti-proton stacking and NuMI are followed by a "slow spill" cycle dedicated to CKM, with 6 batches resonantly extracted over a period of 6 s.
The main issue here is to understand the limitations imposed by the load currents of the magnets of MI and extraction lines.
Two scenarios have been considered:

1) one 6 s flattop slow spill cycle (total length=7.5 s) dedicated to CKM every 15 anti-proton stacking cycles of 1.5 s each, corresponding to a slow spill cycle every 30 s.
2) one 6 s flattop slow spill cycle (total length=7.5 s) dedicated to CKM every 6 anti-proton stacking+NuMI cycles of 2.0 s each, corresponding to a slow spill every 20 s.

Scenario # 2, with a CKM dedicated cycle of 6 batches each of 5e12 protons, resonantly extracted over a period of 6 s, would meet the desired rate of 5e12 protons/s at extraction, providing about 5.5e15 protons/hour. This scenario maximizes the rate of protons delivered to CKM, thus minimizing the number of cycles for anti-proton stacking and

NuMI, but still remaining within the load current limits of the magnets, as shown in the table below.
Scenario # 1 is just given for comparison. It does not include NuMI and a repetition rate of 1.5 s for anti-proton stacking is probably not compatible with the Debuncher operation.
The following table shows the rms load current (I_{rms}) values for these scenarios and the allowed maximum I_{rms} values for the Main Injector magnets and for some of the most relevant P1/P2 magnets.

Device	**I_{rms} or power scenario # 1**	**I_{rms} or power scenario # 2**	**Limit**
MI ramp	4832 A	4897 A	5000 A
Lam52	1133 A	1135 A	?
V701 (C magnet)	1669 A (17 kW)	1738 A (18.5 kW)	75 kW
Q703 (P1 line)	1499 A (10.2 kW)	1610 A (11.7 kW)	96.5 kW
HV703 (P1 line)	2643 A (50 kW)	2654 A (50 kW)	153 kW
HVF11 (P2 line)	2395 A (41 kW)	2375 A (40 kW)	153 kW

None of the power limits for the examined magnets are exceeded in these scenarios. Still the following questions need to be addressed:

1) limits for power supplies and feeder circuits
2) cooling limits over 6 s flattop
3) power limits for the remaining components

3) Beam debunching, Ioanis Kourbanis

1) We can try to paraphase the rf voltage till the beam fills the bucket. That can happen pretty fast (in about 100 msec) but there will be intensity variations through each bunch much bigger than 10% (almost 90-95%).
2) We can turn the rf off and let one Booster batch of 5E12 debunch till it fills the whole ring. That will take very long time (6-8 sec depending on the initial rf voltage and the bunch lon. emittance).We could of course use barrier buckets and limit the debunching to 1/7 of the ring which will happen in msec.
3) We can use a dedicated cycle with 6 Booster batches and let the beam debunch which will take less than a sec. Even here the use of barrier buckets would help to reduce the debunching time.
4) In both cases we debunch the beam, the final dp/p (a few times 10E-5) is so small that the requirements on beam loading and residual 53 MHz cavity voltage are extremely high (less than 500 V total 53 Mhz voltage). It would be useful to consider blowing up the longitudinal emittance before debunching or squeezing the debunched distribution with barrier buckets.
It would be good to know what the experiment's requirements on the dp/p are.

4) MI30 septa, Dave Johnson
There is a question of whether we can extract with just the two septa located at MI52 or do we need the septa located at MI30 (Q306). I will not perform any new calculations at

this time, but rather outline some of the issues with the septa at MI30 and results of previous calculations/studies.

The intent of the septa at MI30 was to provide an initial separation at the entrance of the septa at MI52, thus minimizing the losses at MI52 and concentrating them in MI30, where they could potentially be shielded. The septa at MI30 have 2 mil wires while the septa at MI52 have 4 mil wires. At about 80 kV the septa were to provide a 68 ur kick. The placement of this septa is critical on the phase advance between the septa (and beta function at the septa). If the phase advance is too great you lose circulating beam on the MI52 septa, if it is too small you hit the MI52 wires with the extracted beam. I believe the initial thoughts for the separation at MI52 was on the order of 10 mils which implies that you need (for an average beta of 40 meters) something like 4.85 degrees of phase advance between the two locations at the extraction tune of 25.485. There were several simulations by different people (M. Martens and J. Johnstone) using the design lattice to locate the septa. Using the same model, different answers for the location were obtained. To date, I don't believe the discrepancy has been resolved.

If we demand that there are no (or minimal) losses on the MI52 septa, *that is the 10 mil notch between the circulating and extracted beam hits the MI52 septa entrance,* then the stability of the flattop orbit must be on the order of 0.125 mm on a pulse to pulse. Although the MI is a very stable machine, I don't believe we have reached this level of stability on a routine day-to-day basis. To get an idea of how stable the phase advance between the septa, assume the notch could move +/-5 mils (0.125mm) before either beam hits the septa calculate $dQ = (11/25/360) \sin^{-1}(dx/\beta\theta)$ where β is average beta and θ is kick angle. This implies that the extraction tune needs to be stable on the order of 0.003, but taken with orbit stability it should be much better. **The bottom line is that although this might work on paper , I think it will be very challenging to make this work operationally, if possible at all.**

The current location is just upstream on Q306 by about 4 meters in the middle of the Recycler electron cooling region. The electron return beam pipe is over the MI centerline about 6 inches. Simulations for NUMI indicate that the major loss will be in the first half-cell after the septa. **The sensitivity of the electron cooling equipment to beam loss and residual activity needs to be addressed with the electron cooling group**.

The Recycler extraction/injection kicker in the MI is located at Q304, which is 90 degrees upstream of the septa. During extraction of protons from MI or injection of pbar into MI, a closed orbit distortion between the kicker and Lambertson at 321 used to reduce the amplitude of the oscillation from the kicker, called a counterwave, is utilized. The amplitude of these orbit distortions is about 25 mm at the septa location. Since the septa wires were supposed to be at ~14 to 16 mm, this is clearly a problem. **Therefore, the present kicker system at 304 cannot coexist with the septa.** Either the septa moves to another location (and I don't know of another suitable location) or we have to add another kicker at the end of the MI30 straight section.

The design separation at the entrance of the MI52 extraction Lambertson between the largest amplitude particles in the circulating beam and the smallest amplitude particle of the extracted beam was to be 12 mm. The design high voltage for the septa was 80 kV/septa. During the last slow spill attempt in Feb of 2000, we only used the two MI52 septa at an increased voltage of 100 kV/septa. This should have given about 83% of design separation. The separation at the entrance of the MI Lambertson should have been ~ 10 mm. We obtained multiwire profiles of the resonant extracted beam to the F17 location. No attempt to optimize efficiency or minimize loss was made… i.e. this was a proof of principal.

Since the MI52 septa have 4 mil wires the losses on the septa will be twice that of the MI30 septa with 2 mil wires. **If the septa at MI30 is removed, we should exchange it with the upstream septa at MI52 to reduce losses**.

5) Radiological concerns for Main Injector in slow spill mode, Chandra Bhat

We have closely examined the radiological concerns arising from the operation of the MI in slow spill mode. We assume

- 6E15/hr with a yearly beam delivered to the switchyard area of 3E19 protons at 120 GeV.
- Beam loss at the extraction septum = 2% of the total beam.
- MI tunnel floor slab thickness = 2.0 ft at MI52 location and 2.5 ft at MI30 location

The ground water and surface water contamination do not pose any problems. However, the residual activation of the components in the vicinity of the extraction septum is found to be of concern. According to A.I.Drozhdin et.al., the residual dose at contact is about 20 R/hr for 30 days of operation at 1.6E13p/s. When these are linearly scaled to the beam intensity mentioned above we find a dose rate of about 2R/hr for 30 days of operation. These issues should be addressed in detail. Additional shielding material must be added to protect the personnel working in the vicinity of the septum and down-stream of the Lambertson.

Ground water and surface water contamination

We have revisited the issue of ground water (GW) and surface water (SW) radioactive contamination due to the slow spill operation of the MI.
The maximum and the average star densities in the uncontrolled soil are calculated using Monte Carlo code CASIM. The estimation of the contamination is done using geological sample data.

Limit on yearly GW and SW radioactive Contamination:
GW : 20 pCi/ml (^{3}H), 0.4pCi/ml (^{22}Na)
SW : 2000 pCi/ml (^{3}H), 10pCi/ml (^{22}Na)

We find that the ground water contamination arising from this mode of operation of the MI will be many orders of magnitude smaller than the allowed limit if the reduction factor estimated in EP note 18 is used. For surface water we calculated for two cases viz., continuous flushing and no flushing for about 10 years of operation. We find that the surface water contamination does not pose any problem. However, at-most caution should be taken and we strongly suggest to monitor the contamination level of the water in accordance with FRCM.

I would like to thank Kamran Vaziri for many useful discussions.

References

1) A.I. Drozhdin, P.W. Lucas, N.V. Mokhov, C.D. Moore, S.I. Striganov, “Radiation environment resulting from Main Injector beam extraction to the NuMI beam line”
2) C.M. Bhat and N.V. Mokhov, “Radiation levels around the Fermilab Main Injecor extraction septa”
3) K. Vaziri and P. Kesich, “Tritium concentration factors for MI30, MI52 and MI62 locations”, E.P. note # 18

Estimation of Radioactive Contamination in GW and SW due to Slow Spill Operation of MI

(MI52 amd MI30 Locations) Chandra Bhat (03/17/2003)

Expected Total Beam Intensity to Switch Yard:		**6.00E+15**	**per hr or**	**3.00E+19**	**per year**
Allowed Beam loss/year:	**6.00E+17**	**(We assume 2% of MI full batch for every 1.9 sec)**			
			H3	**Na22**	
		Buildup	**5.47E-02**	**2.34E-01**	
The Highest Star Density In the Uncontrolled Soil :			**1.00E-06**	**Star/cc**	
Reduction Factors (10years of Operation):					
	From Geological Map of MI52 Area (EPNote18)		**2.26E-10**		
	From Geological Map of MI30 Area (EPNote18)		**6.30E-09**		

GROUND WATER ESTIMATIONS:

Radioactive Nuclei	**Initial Maximum Concentration (pCi/ml-yr)**	MI52 Location Using EP Note18 **Final Concentration (pCi/ml-yr)**	MI30 Location Using EP Note18 **Final Concentration (pCi/ml-yr)**	**% of Total Limit MI52**	**% of Total Limit MI30**
^{3}H	**59.18**	**1.34E-08**	**3.73E-07**		
				0.00	**0.00**
^{22}Na	**5.26**	**1.19E-09**	**3.31E-08**		

SURFACE WATER PROJECTIONS:						
Average Star in the Uncontrolled soil :				1.00E-09		
(5m radius, 20m long column)						
	Water Concentration (With Annual Flushing) (pCi/ml-yr)			Water Concentration (No Flushing) (pCi/ml-yr)		
YEAR	Beam Intenisty	^{3}H	^{22}Na	^{3}H	^{22}Na	% of Allowed Limit
2004	6.00E+17	3.130	0.277	3.130	0.277	2.927
2005	6.00E+17	3.130	0.277	6.088	0.489	5.196
2006	6.00E+17	3.130	0.277	8.884	0.652	6.961
2007	6.00E+17	3.130	0.277	11.526	0.776	8.338
2008	6.00E+17	3.130	0.277	14.022	0.871	9.416
2009	6.00E+17	3.130	0.277	16.382	0.945	10.264
2010	6.00E+17	3.130	0.277	18.612	1.000	10.935
2011	6.00E+17	3.130	0.277	20.720	1.043	11.469
2012	6.00E+17	3.130	0.277	22.712	1.076	11.896
2013	6.00E+17	3.130	0.277	24.594	1.101	12.242
2014	6.00E+17	3.130	0.277	26.373	1.120	12.523