PRELIMINARY DESIGN OF THE DUMPING KICKER SYSTEM FOR THE 3000MJ BEAM OF A 20 TeV ACCELERATOR

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ABSTRACT

The energy stored in the high energy, high intensity beams considered so far for the 20 TeV accelerator is to great (3000 MJ) that a detailed investigation should be undertaken in order to establish the feasibility of such machines. A preliminary thinking is given here about the most important part of a fast dumping system, i.e. the kicker magnet system. A special attention is devoted to the reliability of the system. The specifications of the insertion where should be put the magnets and the longitudinal gap the beam has to present in order to extract the beam without losses of particles are discussed. The influence on the response time of the system and the resulting losses of particles in the ring, of the large unavoidable distance between any beam loss monitor and the dumping system is considered. A new matched kicker circuit is proposed which could particularly well fit the very long kicker magnets required for this application.

1. INTRODUCTION

The total energy in the beam of protons accelerated up to 20 TeV is so high that any fault of the machine presents a serious risk of destruction of important parts of the equipment. It is therefore necessary to carefully investigate whether the means to get rid of the beam can be found in order to establish the feasibility of such machines. The 20 TeV kinetic energy of each particle and their maximum number considered so far (10^{15}) yield a total amount of energy stored in the beam of the order of 3200 MJ!

Preliminary thinking is given here about the most important part of a fast dumping system i.e. the kicker magnet system needed to safely extract the beam and send it to an external absorber. This system would be in fact an improved and enlarged version of the internal dumping systems of the ISR or SPS machines where the problem of dumping first occurred but at a considerably lower level (2 x 4 MJ in the ISR beams is nowadays the highest energy stored in proton beams (cf ref (1)), and without superconducting magnets which are known to be sensitive to eventual particles loss). A special attention is therefore given to the reliability of the system and a comparison with other possible designs is made which shows that a fast extraction system is, if designed in the right way, the most reliable solution. A special insertion is needed in the optical lattice of the accelerator in order to allow the extraction, and the general features of this insertion are discussed. The influence of the longitudinal structure of the beam itself on the loss rate is also considered and it is advised to only contemplate beams which always present sufficient longitudinal holes (equivalent to 20 μs total) in order to reduce the particles losses to a level acceptable by the superconducting magnets. The response time of the system is shown to be a critical problem, this being mainly due to the large unavoidable distance between any beam loss monitor and the dumping system itself. The 20 TeV energy and the relatively short "lever arms" which could likely be obtained lead to very long kicker magnets for which the commonly used delay-line kicker principle can hardly be applied, this yielding a too great number of small modules which could impair the reliability of the system. A "matched" but "lumped" kicker magnet is suggested which could particularly well fit the very powerful kick needed for this application and the basic ideas for a further eventual development work are outlined.

2. DISCUSSION ABOUT POSSIBLE DESIGN PRINCIPLES

It is worth while to begin any discussion about the dumping of beams of so high stored energy by looking briefly into other methods which could, at first sight, be considered :

i) a heavy absorber block quickly pushed in the beam :
if the beam and an obstacle are going closer with a relatively small velocity (depending of the weight of the absorber) a particle of the beam can just miss the obstacle and hit it after a certain number of revolutions giving the so-called "penetration depth". It turns out that this "penetration depth" is, even for the long revolution time considered here (250 μs), still very small e.g. about 0,3 mm for a beam diameter of 3 mm and a velocity of 0,1 m/s. This would result in scattering of all the particles onto the edge of the absorber.

ii) Fast scraping : the scraping method is commonly used (e.g. in the ISR) in order to circumvent the problem of scattering in a thick absorber and uses mainly the scattering onto a thin target followed by a thick absorber and then get high absorption efficiency. The time-constant of this process (about 1 ms for the ISR) being proportional to the 2/3 power of the revolution time would become here of the order of 20 ms: this is considered much too long for reason of safety (see later).

iii) Internal fast dumping : in this method used in the ISR and SPS a kicker magnet deflects (vertically) the beam in one turn duration, onto an absorber block placed around the vacuum chamber. Blow-up of the beam is commonly used, by different means, to decrease the thermal stress in the material of the absorber block (cf ref (2)). Here the needed spreading of the beam would be so large that this solution is impractical as it would lead to a special vacuum chamber aperture of about one metre diameter. Furthermore the radioactivity created by this process would be accumulated in the ring, a feature which is undesirable.

iv) Fast external dumping : the beam must be extracted from the ring as fast as possible and as safely as possible and a fast kicker system followed by a septum magnet steering the beam in a purposely designed channel ending with an absorber must be the general features of the chosen principle. In the following we suggest to look into difficulties this principle could bring, particularly the problems of reliability and particles loss.

3) TYPICAL CHARACTERISTICS OF A KICKER SYSTEM

The insertion in the ring where the beam dumping hardware will be put has to be designed to ease the solution of the problem. It is clear indeed that the lattice cell, even in the most favourable case considered (i.e. the normal focusing of group II of this workshop) has no free space long enough to fit any kicker system : for a minimum deflection of 30 mm, and supposing the kicker and the septum magnets are separated by a betatron phase advance of $\pi/2$, one obtains a kick angle of about 0,075 mrad which means, with a magnetic field of

0,1 T, a kicker length of 50 m! Even by using a higher field magnet (which means to abandon the ferrite material common in kicker magnets), the length needed for a kicker magnet cannot be found in the lattice cell. Then a special insertion "matched" to the regular lattice has to be designed: obviously the betatron functions have to be high at kicker and septum locations, and the phase advance near to $\pi/2$ yielding a large deflection lever arm. The slow extraction being supposed horizontal and needing a large free aperture, the kick of the beam dumping is preferably vertical, then the specifications of the insertion are for the vertical dimension. Furthermore the dispersion function α_p is preferably low in that insertion to get small apertures and good control of the beam. Taking as an example the insertion proposed for the slow extraction of UNK (cf ref. (3)) and scaling it by a factor taking into account the higher energy one gets a lever arm of 350 m and this means a maximum betatron function of the order of 1800 m in the insertion. For a 30 mm septum offset distance and taking into account several effects which increase the needed kick e.g. the beam height ≃ 10 mm, the closed orbit error ≃ 10 mm, the sine of the phase advance ≃ 0.7 one gets a total length of 140 m (with a field of 0,1 T), corresponding to a physical length of about 180 m. This kicker length being not negligible compared to the lever arm it still increases the needed space to almost 200 m. Before going ahead with this exercise, it is necessary to consider other solutions to avoid the field limitation commonly encountered with ferrite material (even with 0,2 T the kicker length is still prohibitive). Fortunately for a 20 TeV machine with a revolution duration of 250 μs it is probably acceptable to consider field rise-times of the order of few μs (i.e. beams with a longitudinal hole of the same order of magnitude, see later the problem of loss) and the use of laminated iron is then possible for the yokes of the kicker magnets and the field can be increased up to 1 T. In table 1 typical figures of the important parameters of a kicker system are given for three field values (0,1 T corresponding to the previously considered case of ferrite for comparison with the two other fields corresponding to laminated iron), for a septum offset distance of 30 mm and a HV of 60 kV.

Table 1

Typical figures for a beam dumping kicker system

Field	0,1	0,5	1	(T)
Effective length	180	28,5	14	(m)
Total length	200	33	16	(m)
Pulse current	6,36	31,8	63,6	(kA)
Characteristic impedance	4,72	0,94	0,47	(Ω)
Magnet inductance	0,94	0,94	0,94	(μH/m)
Number of modules	18/36	5/10	5/10	
Module length	10/5	5,7/2,85	2,8/1,4	(m)
Rise time	2,2/1,1	6,28/3,14	6,17/3,09	(μs)
Total capacitance	476/953	664/1330	1330/2660	(μF)

Since the solution with 0,5 T magnetic field tends to lead to a moderate number of modules with realistic features and good performances, it seems a logical choice for any further development work, particularly the technology of iron laminated HV fast kicker in ultra-high-vacuum.

4. PROBLEM OF LOSS OF PARTICLES

During the rise of the magnetic field in the kicker magnet the particles are not deflected enough and some of them are sent in the septum, other undergo a strong coherent oscillation in the ring and if there is no aperture restriction they are extracted at their second passage in the kicker magnet (whose pulsed magnetic field has to last slightly more than one turn duration). The fraction of lost particles is roughly given by:

$$\frac{n}{N} = \frac{t}{t+d}\,\frac{T_R}{T_{Rev}} \qquad \text{(for a coasting beam)} \qquad (1)$$

with : t = septum thickness
d = beam diameter
T_R = rise-time
T_{Rev} = revolution duration

It can easily be shown that even with a very thin septum (≃0,1 mm) and a very short rise-time of 0,3 μs this loss can be as high as 4.10^9 particles, a value which could bring the protecting absorber (in beryllium) of the septum to 200°C. For more realistic rise-times (cf. table 1) of 3 μs this loss grows to $4 \cdot 10^{10}$ and the temperature builds up to 2000°C. It is clear that the only way to avoid this problem is to profit from the time structure of the beam (if bunched) or to manage a beam longitudinal hole (if coasting) and to carefully ensure this time structure is kept over all operations at high intensity. As it has been seen a rise-time of the order of few μs is also to be considered for hardware limitation reason.

It is also interesting to estimate the influence of the large unavoidable distance between any beam loss monitor and the dumping system even if this system is perfectly safe. Indeed in the case a sudden beam loss is detected, the loss signal has to go from the beam loss monitor to the control room (supposed to be at the centre of the ring) and then to the beam dumping system and it is only when the tail of the beam has hit the loss place that the danger disappears (cf fig. 1). Supposing the distance between every two beam loss monitors in the ring is negligible, the loss duration (i.e. signal delays plus the time for a beam hole going in the dumping system and neglecting the response-time of this system) is:

$$\Delta T = \frac{T_{Rev}}{n_H} + F\,T_{Rev} + \frac{T_{Rev}}{\pi}$$

n_H being the number of beam holes, and F the fraction of the circumference between the incident and the dumping system. In the worst case this delay goes up to $\Delta T = (\frac{1}{n_H} + 1 + \frac{1}{\pi})T_{Rev}$, for instance ΔT = 580 μs for $n_H = 1$ and ΔT = 370 μs for $n_H = 6$. The admissible instantaneous loss to avoid superconducting quenching being estimated as $10^6\ m^{-1}$ at 20 TeV, this sets up the loss rate $\Delta n/\Delta T$ a beam loss monitor has to detect to trigger the beam dumping system:

$$\frac{\Delta n}{\Delta T} = \frac{10^6}{T_{Rev}\,(\frac{1}{n_H} + 1 + \frac{1}{\pi})} \qquad (m^{-1}s^{-1}) \qquad (2)$$

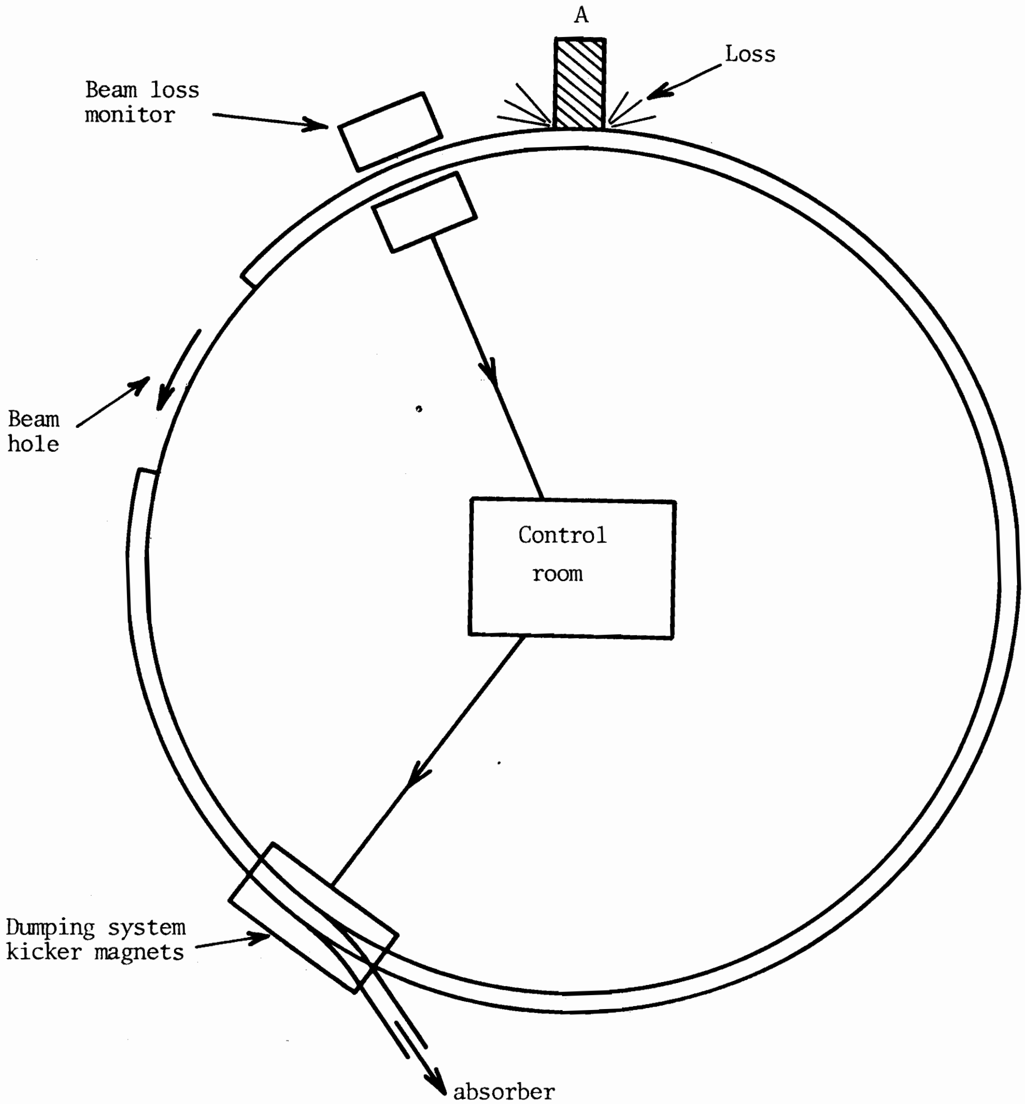

Figure 1

A beam loss occurs in A, the beam loss monitor delivers a trigger signal which goes to the dumping system via the control room. The beam hole must be at the kicker magnets before they are triggered.

for instance : $\frac{\Delta n}{\Delta T} = 2{,}7\ 10^9/m^{-1}s^{-1}$

According to the detected level of loss, a fast logics has to decide whether it is interesting to wait for a "hole" in the beam or to dump it as soon as possible (the corresponding loss, given by equation (1) will go in the absorber protecting the septum and not in the superconducting magnets).

5. RELIABILITY OF A BEAM DUMPING FAST KICKER SYSTEM

The system must be ready to dump the beam completely and at any time with the previously quoted performance, even in the case of internal fault. It would be impossible to operate the machine with a beam dumping system which would need to be energized in case of emergency or should not be able to fulfill its function before going "off". The system has to be DC charged and thus the capacitors and the switches have to withstand high voltages over long runs without any breakdown. Furthermore the response-time i.e. the delay between the instant a trigger signal comes in and the time the magnet is energized has to be shorter than all its time-constants in order to dump the beam a last time, in case of internal fault, before being automatically switched off.

The experience gained with the operation of the ISR beam dumping system (where the fault rate is as low as one per two years) permits to settle the general principles to design reliable pulse generators :

i) the kicker magnets should be fed by a minimum number of pulse generators. The reliability of a system (i.e. the probability to work without fault in a given time), this system being made of n modules which can break down independently, is $R = r^n$ if r if the reliability of one module. For instance with r = 0,9 (one fault per year for 10% of the trials or for 10% of a great number of identical modules). The reliability of the system is for n = 10, $R = 0,9^{10} = 0,35$ which is very low compared with the reliability of one module. This means that the mean number of trials before the first breakdown occurs would be 1,5 instead of 10 for one module. The number of pulse generators is limited by the maximum current a pulse generator can safely deliver for a long duty time. A spark-gap has been designed, built and tested for high current capability of the order of 100 kA, ref (4). This type of switch, providing further development work is made about it (for energy tracking), could be used to feed two modules in parallel. To avoid the catastrophic consequence of having an incomplete kick due to faulty firing of only one pulse generator, all pulse generators must be interconnected in order to trigger all of them in this case.

ii) Redundancy and derating

If n' modules are added to the needed modules the reliability of the system becomes:

$$R = \sum_{i=0}^{n'} C_n^i \, p^i \, r^{n-i} \quad \text{with } p = 1-r$$

For example : N = 12 n' = 2, r = 0,9 gives R = 0,89, almost equal to the reliability of one module. Two additional modules would give R = 0,9907. It could now be discussed whether the redundancy has to be "active" (the redundant modules are added to the strict minimum number of modules, and are in use) or has to be a "waiting" redundancy (redundant modules are ready to be used) or has to be a spare redundancy. The first solution has the advantage to allow a derating of each individual module and therefore gives a better module reliability which drastically improves the reliability of the system. The two other solutions need a certain delay due to connexion time or installation time. A good compromise seems to be a mixing of the first and last solutions (i.e. active redundancy, derating of each module, spares). As an example, the two ISR beam dumping systems previously made with 2 x 4 independent modules and magnets were then fed by two spark-gaps (one per ring) for reasons explained above, and after that 2 x 2 pulse-forming-networks were added allowing a 50% derating. As expected the reliability is now very close to unity.

iii) Lumped but matched kicker magnets

The kicker magnets with very short rise-times are commonly made at CERN as delay-lines, vacuum capacitors being integrated in the ferrite yoke to get a good matching to the pulse generator impedance, at least for low frequencies. As already seen laminated iron will be preferred to get higher field of the order of 0,5 T. The experience in this field shows that 0,1 mm laminations could give rise-times of less than 10 μs. To avoid a complicated capacitor structure in vacuum a new lumped kicker circuit (see appendix 1) is suggested which can be studied for this purpose: this circuit can in principle offer a perfect matching over all frequencies and nevertheless give a rise-time delivered by a delay line, by using an additional "overshoot" capacitor.

CONCLUSION

There is no fundamental limitation which could prevent to design and build a reliable system able to dump the high energy, high intensity beam considered in the 20 TeV storage ring, provided the beam time structure has a sufficiently long "hole" (or better several holes distributed along its circumference) for all operations. It has been seen that the distance any signal triggering the dumping system has to do is so large that this sets up the admissible level of loss the superconducting magnets can accept without quenching. The guide-lines for an eventual further work are quite obvious: design of an optimal insertion, development of lumped-matched kicker circuit and fast iron laminated magnets. A good reliability of this system can then be achieved if:

- the systen is "fail-safe"
- the number of modules is minimum
- the rise-times and response-times are as short as possible
- the internal and the machine faults are interlocked via fast logics
- derating and redundancy are sufficient.

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APPENDIX

A matched circuit for lumped kicker magnets

The delay-line kicker magnet brings difficulties due to its complicated structure in vacuum which limits its use to relatively high impedance (≈ 10 Ω) and short length (≈ 1 m) and shows pulse reflections and flat top small oscillations because of its low-pass filter properties. Theoretically a frequency dependent impedance can be matched for all frequencies (which is needed for a pulse which has a wide frequency spectrum) if an "inverse" impedance is put in parallel (inverse meaning that their product is not reactive). A new very simple circuit is considered in which an additional resistor-capacitor branch is put in parallel to the lumped (inductive) kicker magnet (see fig. 2). One can show that the load impedance is (in Laplace transform notation) :

$$Z_L = \frac{(R + Lp)\ (R + 1/pC)}{R + Lp + R + 1/pC}$$

and reduces simply to R if L/R = RC and then if R = Zc the load is perfectly matched for all pulse shapes (for all frequencies) which is never achieved for all used circuits (lumped or delay-line circuits). This circuit will not show any pulse reflections impairing the pulse shape (particularly the flat top) and can be used with pulse generators with rise-times as short as possible. The advantages over other kicker circuits are no complicated vacuum capacitor structure, perfect matching, lower cost, better HV reliability, one feed-through instead of two. The overshoot capacitor added to the pulse-forming-network allows to achieve a very short rise-time of the field of the magnet: if its time-constant is equal to L/R the magnet time-constant is L/2Zc. A small scale low voltage model has been built according to this circuit and has shown the expected performances.

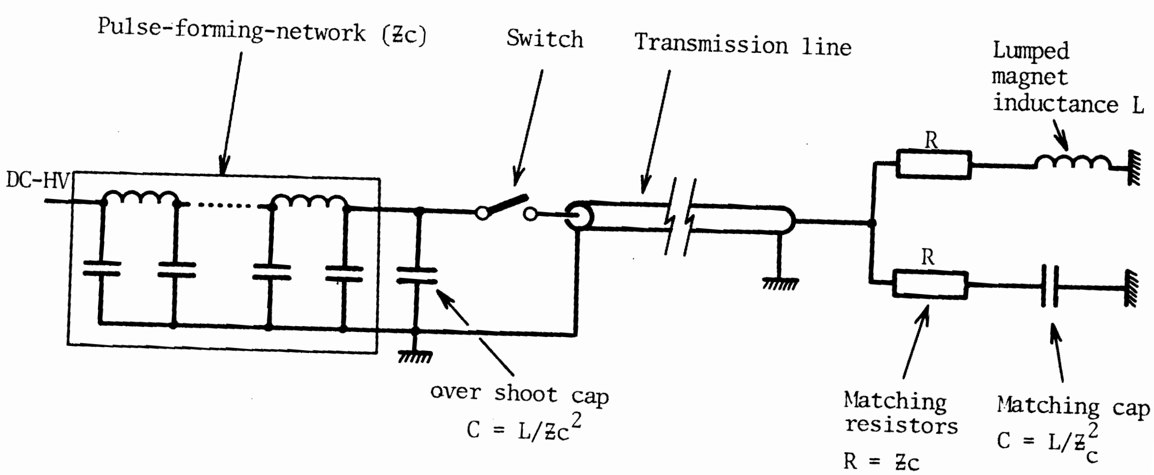

Figure 2

The lumped but matched kicker magnet circuit which can deliver a pulsed field with a rise-time of the order of L/Zc