COMPARATIVE SIMULATION STUDIES OF ELECTRON CLOUD BUILD-UP FOR ISIS AND FUTURE UPGRADES

G Bellodi*, ASTeC Intense Beams Group, RAL, Chilton, Didcot OX11 0QX, UK

Abstract

Electron cloud effects currently limit the performance of several proton accelerators operating with high beam current. Although ISIS, the 160 kW 70–800 MeV proton synchrotron at the Rutherford Appleton Laboratory (UK), has never appeared to be affected by the problem in its 20 years of operations, e-p instabilities could potentially be a cause of concern for future machine upgrades to higher beam powers. In this paper we review the present status of simulations for ISIS and compare it to preliminary results for the ongoing second harmonic upgrade and for two possible upgrade options in the future: a 0.5MW 180–800 MeV scheme and a 1MW 0.8–3 GeV scheme with an additional synchrotron using ISIS as a booster [1].

INTRODUCTION

The dynamics of electron cloud buildup and dissipation has been a recent subject of study at the Rutherford Appleton Laboratory (UK) in an attempt to address stability concerns regarding possible future upgrades of the ISIS synchrotron, while at the same time trying to understand why the problem has never risen during more than 20 years of operations. Preliminary results of ISIS simulations at injection energy (70 MeV) and in field-free sections of the ring have been presented elsewhere [2]: there we also discussed the limitations induced by the lack of experimental input on how the vacuum chamber geometry and material affect the electrons' production and dynamics. In this paper we compare ISIS results with preliminary simulations of three possible upgrade scenarios: a second harmonic upgrade, already under way, that should increase the circulating current by up to 50%, a 1 MW 0.8–3 GeV scheme and an alternative 1/2 MW 180–800 MeV scheme. Parameters for these machines are summarised in Table 1.

Physical model

The code ECLOUD [3, 4], originally developed at CERN, has been used in this study. The two main sources of electrons considered here are: lost protons and secondary emission from electrons hitting the walls. The longitudinal tracking code TRACK1D [5] has been run on the individual schemes to give quantitative predictions of total losses and the timing of their occurrence within the ramping cycle. The peak value of these (within 50 to 100 revolutions) has been considered as an input parameter for the EC simulations, and a constant yield efficiency of 100 electrons per lost proton, independent of the proton incident energy or impact angle, has been assumed. Proton losses are assumed to be proportional at any time to the instantaneous beam intensity. For the secondary emission model we use a fit to experimental measurements for chemically passivated Stainless Steel obtained at SLAC [6]: the fit has been scaled so that the maximum value of the secondary yield is δ_{max}=1.5 at E_{max}=300 eV and $\delta(0)\simeq$0.4. All simulations have been performed for a representative field-free section of the machine under study. The vacuum chamber is assumed to be a perfectly conducting pipe with rectangular cross section, while the beam is modelled with a Gaussian transverse distribution and a parabolic longitudinal profile.

ISIS UPGRADE SCHEMES

Dual harmonic upgrade

In its present configuration, ISIS consists of a rapid cycling synchrotron that accelerates protons from 70 to 800 MeV feeding them to a tungsten target for neutron production at 50 Hz. Intensity is limited by space charge at injection to about 2.5×10^{13} ppp. An upgrade in current is nonetheless being attempted via the simultaneous installation of a radio frequency quadrupole (RFQ) in the linac [7] and a dual harmonic h=2/h=4 RF system [8] in the ring: the resulting increased longitudinal phase space acceptance will make it theoretically possible for up to 3.8$\times 10^{13}$ protons to be stored in the ring without any additional losses, provided the phase and amplitude of the h =4 component are chosen within tight limits [9].
Longitudinal tracking simulations show that the ISIS current total losses can be reduced by a factor of 10 in the upgraded scheme, to below 0.8$\%$ of the circulating current: nearly half of them would occur in the first 1 ms after the end of injection, giving a peak loss rate of 231$\times 10^{-9}$ per proton per meter.
Assuming a bunching factor of $\sim$0.4 at this point in the cycle, the peak value of the electron-cloud line density is $\sim$0.1 nC/m, nearly 1/3 of the value obtained for the ISIS single harmonic case. If we arbitrarily increase the peak losses by a factor of 3, to make them comparable to the figure assumed for ISIS, the EC density also increases by the same factor, proving that the saturation levels vary linearly with the number of primaries produced, i.e. the beam loss rate. The effect of the increase in intensity is in this case smaller, and neutralised by the opposite effect induced by the different bunch spacing.

Megawatt upgrade - I phase

Preliminary design studies have also commenced for a more ambitious, longer term ISIS upgrade to 1 MW

* g.bellodi@rl.ac.uk

Table 1: *Machine parameters used in these simulations for the different ISIS upgrade schemes.*

Parameter	ISIS	DHRF	1/2 MW	1 MW
Ring circumference (m)	163.3	163.3	163.3	490.
Injection energy (MeV)	70	70	180	800
Extraction energy (GeV)	0.8	0.8	0.8	3.
Energy at peak loss (MeV)	76.	71.3	192.4	1100.
Bunch population (10^{13})	1.25	1.875	3.9	1.875
Harmonic number	2	2	2	6
Bunch length (*at peak loss*) (ns)	236	541.6	330.9	60.1
Interbunch gap (*at peak loss*)(ns)	480	189.6	152.9	244.1
Pipe semi-axes (cm)	(6.3,8.)	(6.3,8.)	(6.3,8.)	(2.,2.4)
Transv. RMS bunch sizes (cm)	(2.3,3.4)	(2.3,3.4)	(1.5,2.2)	(1.,1.2)
Peak proton loss rate (10^{-9}/p/m)	763	231	101	0.34
Peak EC line density (nC/m)	0.31	0.085	0.95	0.0011

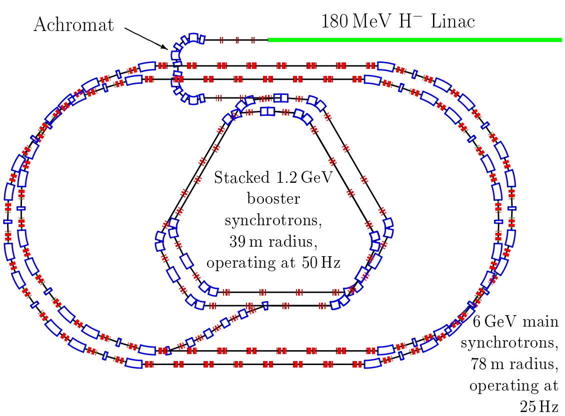

Figure 1: *Layout of the multi-MW ISIS upgrade in its final phase (courtesy of C. R. Prior).*

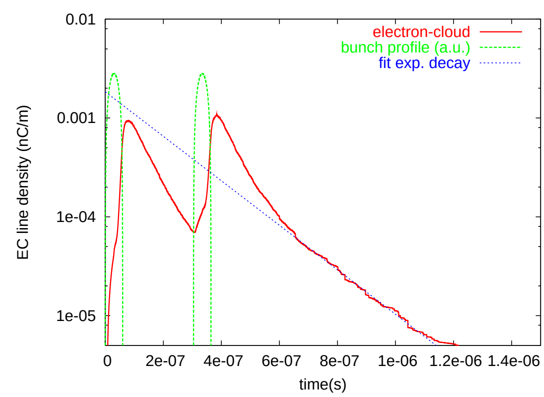

Figure 2: *Line density for a field-free region of the ISIS-MW racetrack lattice.*

beam power or possibly 4–5 MW through a multi-staged approach, as described in more detail in [1]. The first phase would involve the construction of a new proton synchrotron, with injection directly from the 800 MeV beam from ISIS and acceleration to 3 GeV for a 1 MW spallation neutron source, or 8 GeV at reduced frequency for bunch compression tests for a neutrino factory. The new ring would have a racetrack lattice design (see Fig. 1), with h=6 or h=12 and mean radius 78 m (three times that of ISIS). In Phase 1 a bucket to bucket transfer is proposed from ISIS to the new synchrotron, which would only be filled for 1/3 of its total circumference. Successive phases would involve the substitution of ISIS with two booster rings stacked upon each other and finally the addition of a second racetrack ring.

Longitudinal simulations have been carried out using as input beam the distribution obtained from the ISIS modelling with the dual RF system: an optimised choice of RF voltages to be applied through the 20 ms cycle seems to be able to reduce all theoretical losses to virtually negligible levels ($< 0.01\%$). This, together with the specific bunch filling pattern for this stage of the machine, should significantly reduce any risk of EC-related instability. Any electron-cloud formed during the passage of 2 bunches will dissipate in the long gap before the next injection, with a nearly exponential decay rate as shown in Fig. 2. A decay time $\tau \simeq$180 ns can been derived from a fit to the line density after ∼200 ns delay from the passage of the last bunch, and can be related under certain approximations to the value assumed for $\delta(E_0)$ for $E_0 \simeq 0$ in the way described by [10].

1/2 -Megawatt upgrade

An alternative, less expensive option of beam current upgrade involves increasing the ring injection energy to 180 MeV with a new linac [11], thus reducing the space charge constraints on the beam intensity at injection. Preliminary tracking simulations suggest acceleration to 800 MeV and total beam powers of up to 0.5 MW could be achieved. By carefully tuning the dual harmonic RF voltages to minimise the losses, these can be confined to the first 1.5 ms after injection and can be limited to below 0.8% of the circulating beam current (at a peak rate of 10^{-7}

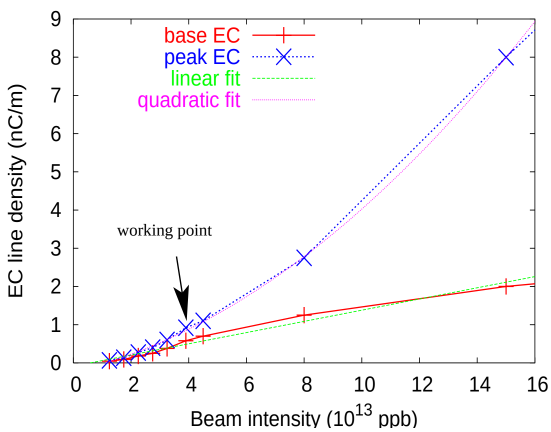

Figure 3: *Variation of the base and peak EC line density levels as function of beam intensity (ppb) for the ISIS 1/2 MW upgrade scheme.*

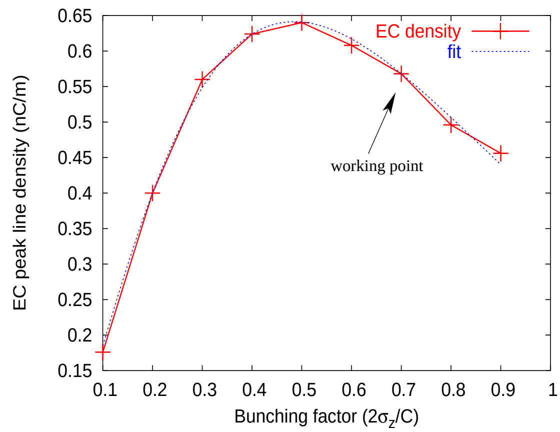

Figure 4: *Variation of the peak EC line density as function of the bunching factor for the ISIS 1/2 MW upgrade scheme.*

per proton per meter).
Assuming an emittance of $\epsilon_{n,rms} = 20\pi\mu m \cdot rad$, the electron cloud buildup reaches saturation after the passage of 5–6 bunches, with a peak line density of ∼0.9 nC/m, nearly 3 times the value found for the current ISIS and comparable to results obtained for PSR [12] when assuming a parabolic longitudinal bunch profile. The effect on the EC buildup of the factor of 8 decrease in peak loss rate is soon neutralised by the effect of the threefold increase in beam intensity (Table 1). Fig. 3 shows how the base value of the EC line density varies quasi-linearly with the beam intensity, while the peak value (at the height of the trailing-edge multipacting) has a quadratic-like dependence.
In a different study we analysed how the EC peak line density varies as a function of the bunching factor (here taken to be the ratio between the full bunch length and the sum of the bunch and interbunch lengths). Fig. 4 shows a functional dependence of the form $x^n e^{-qx}$, with the value currently used in these simulations being around $x \simeq$0.7.

CONCLUSIONS

We have presented results of EC buildup simulations for three possible upgrade scenarios of the ISIS proton synchrotron. In all cases EC formation is due to electrons initially generated from proton losses (quantitatively estimated by longitudinal tracking simulations) and subsequently amplified through a mechanism of trailing edge multipacting. In the short term, the second harmonic upgrade case should not be too dissimilar from the ISIS single harmonic case. In a longer term, any serious EC buildup in the 1 MW racetrack ring should be prevented by the large bunch spacing that allows for cloud dissipation, whereas the 1/2 MW scheme could be a cause for concern due to the very high beam intensity and thus should be further investigated, possibly with instability studies.
Given the uncertainty about the actual level of losses in these scenarios, and the amount of charge that it will be feasible to inject, we also examined how the EC buildup varies when changing some fundamental input parameters and found a linear dependence on the rate of proton losses, a non-linear dependence on the bunch intensity and δ_{max} and a pseudo-Poissonnian dependence on the bunching factor.

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