NEW POSSIBILITIES FOR BEAM-BEAM AND SPACE-CHARGE COMPENSATION: MCP GUN AND ELECTRON COLUMNS

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Abstract

We propose to use microchannel plate (MCP) as a gigantic quantum efficiency photo-cathode in electron guns. Another proposal is to use electron columns formed by ionization electrons in a longitudinal magnetic field for compensation of space charge effects in high intensity proton synchrotrons. Strong magnetic field is to assure that transverse distribution of electron space charge in the column is the same as in proton beam. Electrostatic electrodes are to control the accumulation and release of the electrons. Ions are not magnetized and drift away without affecting the compensation.

MCP ELECTRON GUN

The essence of the idea is a suggestion to use MCP as a cathode of electron gun. Figure 1 below shows possible arrangement of the MCP for a DC and RF gun: MCP is mounted either in between usual Pierce electrodes (DC gun) or in the center of the wall of an RF gun. The cathode is illuminated from behind. Each photon hitting the MCP plate generates an avalanche of electrons resulting in about 1000 of them leaving the other surface of the cathode. Those electrons are accelerated by either DC electric field between cathode and anode and by RF electric field exited by RF generator inside 1 and a half cell RF cavity (a standard RF gun arrangement).
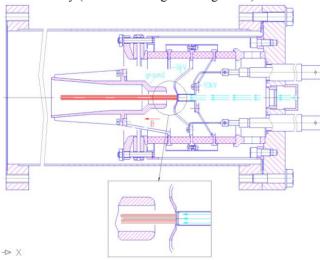

Figure 1: Layout of a DC gun with MCP cathode.

There are a number of advantages the MCR cathode guns offers compared to commonly used ones :

a)   there is no need in heating filament and corresponding power supply (in DC guns)
b)   because of no heating, mechanical gun stability (e.g. distance from cathode to other electrodes) can be achieved much easier than in ordinary guns

c)   because of no heating, much better vacuum conditions should be expected in the MCP gun
d)   due to much lower cathode temperature, emittance of MCP gun e-beam is expected to be 4-5 times smaller than in ordinary electron guns
e)   quantum efficiency of MCP cathode is 10^5-10^7 times of those common type photocathodes used in RF guns (they have QE in the range from few e-4 to few %)
f)   because of that, a ultra low (wrt to standard photocathode scheme) laser power is required
g)   that opens possibilities to reduce laser pulse power amplitude stability (lower power pulse are thought to be much easier to stabilize than high power ones)
h)   the feature of the MCP when the plate is illuminated from behind is extremely attractive as it greatly simplifies optical system delivering light to the cathode (in ordinary schemes, the laser beam should inconveniently go through the RF cell openings)
i)   it is believed that MCP guns may allow higher degree of polarization than ordinary ones (of coarse, the MCP should be made of GaAs or like material, and advantage is multiple interaction of electrons with microchannel plate surface).

Prototyping and experimental study of the MCP cathode DC gun should answer following questions:
a) maximum charge and current MCP is capable to deliver (thought to be in the range from few nC to m.b. microC and more)
b) dilution of the laser pulse or front due to traveling of electrons thru the microchannels
c) MCP lifetime vs current/charge emitted
d) technological issues (mounting, laser windows, etc)

ELECTRON COLUMNS

It is known that compensation of space charge forces in high current proton beams is possible is the amount of electrons stored in the beam is equal to [1] $<\eta>=1/\gamma^2$ where η is relative fraction of the electron charge wrt to proton charge, or degree of charge compensation ; and γ is relativistic factor of protons. The conditions for effective compensation are that electron distribution is the same as proton one (preferably in all three dimensions) and that the system of electrons and protons is dynamically stable. Using electron lenses is one possibility to achieving that, but the method is not very simple and has certain limits [2]. Partial neutralization by ionization electrons – those which are born by ionization of residual vacuum by charged beam – was tried before with some success but

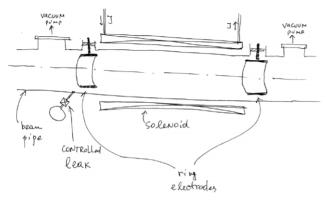the stability criteria was not easily assured [3].

Figure 2: Layout of the electron column. .

Modification of the latter method of passive neutralization could be more attractive if both protons and electrons are immersed in the longitudinal magnetic field which is a) strong enough to keep electron from escaping from the transverse position they are born at; b) strong enough to keep the system of e-p stable; d) weak enough to allow ions escape and not affect the process of charge compensation.

The easiest possibility is to have toroidal accelerator, modified betatron [4], where solenoids provide beam focusing all along the beam orbit. In the existing accelerators where high energy protons are guided and focused by transverse magnetic fields of dipoles and quadrupoles, there is a possibility to satisfy condition (1) in average having many space charge (SC) compensating elements around the ring – ideally, one per every superperiod of the lattice.

The fraction of the ring circumference occupied by electron columns should be equal to $R=\eta/\eta_0$ where η_0 is the degree of local SC compensation, e.g. if $\eta_0=1$ – full charge compensation inside solenoids – then, $R=\eta$.

Schematically, the compensation section may look as shown in Fig.2 and consist of solenoid magnet, a pair of ring- or cylinder-shape electrodes to control the accumulation of electrons, controlled leak to vary vacuum pressure at the location of electron columns (EC) and vacuum ports for possible differential pumping. The system of electrodes may be more complex than just two rings and, for example provide desired distribution of potential along the z-axis. Voltages can be made time-dependent to track changes of proton beam parameters (energy, size, etc). The solenoid field distribution can be varied too in order to reduce x-y coupling it introduces .

For the 8 GeV ring (Recycler or FNAL Main Injector), one needs only $R=1/\gamma^2 =1/80=1.2\%$ of the ring occupied by electron columns with full degree of compensation $\eta_0=1$. For 1.4 GeV ring (CERN PS) $\gamma=2.4$, required space is $R=16\%$ for $\eta_0=1$ or 8% for $\eta_0 =2$.

The time needed to generate enough electrons to compensate proton space charge – so call "neutralization time - is equal to [5] $\tau=0.05$[ns]/P[Torr].

For a purpose of SC compensation in average (no tracking current profile) τ should be of the order of 100 us (characteristic time scale of beam, parameter variation due to acceleration) or longer – that calls for vacuum pressure of $P=$5e-7 Torr or better. There is also a possibility to attain neutralization time which will allow to have variable electron density for the head/tail and center of the bunch $\tau=100$ ns if $P=$5e-4Torr. (All for H2 dominated vacuum. Injection of other gases via a controlled leaks can be considered for this purpose).

It is important that Larmor radius of ionization electrons $r_L=pc/eB$ is smaller than proton beam radius (so electron distribution is not smeared off the proton distribution). Characteristic energy of electron is about $E\sim min(I, U\_sc)$, where $I\sim10$ eV is ionization energy, and $U\_sc=30J/\beta(1-\eta_0)$ is about 120V for uncompensated 4A beams. Larmor radius for 10 eV electrons in B=1kG is about 0.1 mm that is much less than beamn radii in the accelerators of interest.

Coupling (in the units of tune-split) introduced by one solenoid is about $\kappa=(B\ L)/(4\ \pi\ B\ \rho)$ that is about 0.005 for 1kG 1m long solenoid in 1 GeV machine – it is not negligible, but can be either compensated by skew correctors or – even easier – by proper choice of B-field directions in different ECs (or by local compensation in one CS).

Formulae from [5] which estimate possible electron distortions by elliptical proton beams and stability of the e-p system indicate that B=1 kG should be sufficient for the electron columns.

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