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CHARGE AND CURRENT COMPENSATION OF INTENSE CHARGED BEAMS IN FUTURE ACCELERATORS

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Abstract

Proposals for future high-energy accelerators are characterized by demands for increasingly intense and energetic beams. The classical operation of high-current accelerators is severely constrained by collective electrodynamic phenomena, such as problems related to space-charge, to high-current flow, to beamstrahlung and pair production. These detrimental electrodynamic effects dominate the dynamics and the collision interactions of high-intensity beams. With the introduction of soft space-charge and current compensation techniques utilizing low- to medium-energy lepton beams with charge polarity opposite to that of the beams to be neutralized, all electromagnetic high-intensity limitations may be removed. The application of beam compensation is proposed for various sections of different types of classical accelerator systems, such as for ion sources and the low-energy beam transport sections of ion linacs, for the crossing points of circular and linear colliders and for the final focii of ion beam fusion drivers. The design and the operation of partially compensated accelerators becomes much more comfortable and design goals can be reached more easily without any significant electromagnetic perturbation. The ingredients of neutralization technology — low-energy electron and positron beams — are state-of-the-art and, as such, applicable today. Several methods of smooth beam compensation can be identified and must be studied and selected for each specific case. Practical experience has to be gained in dedicated pilot experiments.

1 INTRODUCTION

In conventional accelerator technology external electrical and magnetic forces are used for accelerating and focusing charged particle beams propagating inside evacuated tubes. The higher are the accelerated beam intensities the stronger become the electrodynamic forces which the beam exerts on itself and on its environment. The Lorentz transformations for electric and magnetic fields (e.g. Ref. [1], p. 657) show that, fortunately, the self-fields of relativistic beams cancel each other transversally in a classical environment. However, colliding high-intensity, high-energy beams of equal polarity suffer from uncompensated space-charge and are subject to severe limitations, which cannot be overcome even with stronger magnets and RF gradients. Colliding intense beams of opposite polarity experience strong uncompensated magnetic compression (pinch effect) with destructive results. A way out of the dilemma is, instead of reacting with external fields, the clever application of the strong intrinsic fields of high-intensity beams themselves. In nature it is a fact that free charges tend to neutralize and currents to cancel (Faraday’s induction law). A nice technical application of these self-neutralization tendencies are the ion thrusters developed in the space industry for satellite and spacecraft propulsion, where the ejected ion beams are charge and current neutralized with electrons from an electron cloud or from a plasma reservoir [2, 3]. Hence, nature is helping us with self-compensation, just as ferromagnetic materials help us spontaneously to generate magnetic fields or ferroelectrics to produce high surface charges and electric fields. Another practical example of current self-neutralization was the observation of the ‘inverse skin effect’ [4] in the high-current z-pinch plasma of the CERN antiproton-collector plasma lens [5]. The conventional generation of intense high-energy particle beams in an accelerator, on the other hand, is totally characterized by counteracting nature with external fields. Charges are separated, for example, at the exit of a particle source by an electric extraction field. With magnetic fields energetic beams are focused and their natural space-charge and emittance blow-up are confined. The acceleration of charged-particle beams is achieved with externally applied electric fields. With the application of beam compensation and neutralization techniques not only can conventional limits, such as the Langmuir–Child limitation, be beaten by orders of magnitude, but nature is taking over part of the work to achieve the control over high-intensity beams.

There have been very few attempts in the history of accelerator development to profit from the positive side-effects of the strong beam self-fields. At low intensities, the self-fields of classically generated charged-particle beams can normally be still controlled with conventional accelerator technology. By using intelligently the accelerated beams in interaction with other well-controlled charged-particle ensembles, such as clouds or low-energy beams of leptons, or a dense plasma, one may utilize the electromagnetic self-fields for focusing or neutralizing intense high-energy beams. In practice, it becomes possible to completely eliminate the self-fields and their negative consequences, even in the most critical regions of the most intense machines planned for the future.

Contrary to accelerator technology, neutralization techniques count as standard procedures in other technical fields: Neutral beam injection has for a long time been used for heating magnetically confined tokomac plasmas, and spacecraft and satellite propulsion function today with neutralized ion-beam thrusters in space [2, 3]. Plasma-neutralized ion sources are used for efficient ion implantation into large-volume, three-dimensional objects [6]. A few examples of using the self-fields of particle beams are known also in the high-energy particle accelerator environment. In 1974 D. Garbor [7] described an ‘electron space-charge lens’. Successful focusing of a 10-kA electron beam throughout the whole length of the induction accelerator ATA [8] was achieved one decade later with a positively charged plasma column. Less spectacular were the four-beam neutralization experiments carried through at DCI/Orsay between 1973 and 1983 [9,10]. The aim was to mutually neutralize charge and current of two uncompensated electron and two uncompensated positron bunches at a single crossing point during the time interval of crossing. Everywhere else in the DCI storage ring the four bunches were not neutralized. The attempts of this ‘hard’ neutralization procedure failed due to lack of precision in beam control and due to imperfections and differences of the individual bunch charges and currents, of the transverse and longitudinal charge and current distributions, and of the transverse and longitudinal bunch positions. Even with a more precise conventional technique the hard neutralization method appears impractical, if not impossible, especially at future linear colliders [11, 12]. In the widest sense the accelerator technology of electron-beam cooling can be also considered as a beam compensation method, since partially ‘internal’ self-fields serve for emittance reduction and beam current density enhancement. In contrast to the DCI compensation principle electron cooling can be considered as a ‘soft’ neutralization method. These practical experiences clearly prove the superiority of soft neutralization schemes, which are characterized by the implementation of charge and current self-neutralization in contrast to the ‘purely man-made’ hard compensation schemes.

Pilot experiments dealing with the strong self-fields of interacting beams are planned at FNAL and SLAC. In the FNAL experiment, which strongly resembles a Garbor lens system [7] low-energy electron beams are used as compressor lenses for the circulating antiproton bunches [13]. At the SLAC final focus test facility a plasma-beam interaction experiment is planned [14] with the goal to demonstrate charge compensation with the plasma constituents and self-focusing of the beam as well as beam current neutralization by compensating current induced in the plasma.

Much will be learned from these few experiments for a wide range of applications of beam compensation and neutralization, which may be envisaged in the critical sections of an otherwise conventional machine. Fully neutralized accelerators will remain an issue for the far future, since the open difficult technological problem of accelerating neutralized beams has to be solved. This paper is restricted to the cases of beam compensation at ion sources and in low-energy beam transport sections for ion beams, to neutralization in colliding-beam interaction-point regions and at final targets served by conventional accelerator systems. Contrary to the present belief in the accelerator community, it seems straightforward to develop various technical methods for beam compensation adapted to the specific features of the beams to be compensated. Owing to the natural tendency of ‘self-neutralization’ the most promising methods are based on the use of low-mass, low- to medium-energy, DC or pulsed electron and positron beams. The technologies to produce such low-energy lepton beams of defined intensity and time structure for beam compensation are well advanced today.

2 PRINCIPLES OF BEAM SELF-FIELD COMPENSATION

A charged axial particle beam is characterized by an electric field generated by its space-charge and by a magnetic field owing to its current I_b. Assuming constant current density j_b within the beam cross-section of radius r_b the radial space-charge field E_r is given by

$$E_\mathrm{r} = \frac{j_\mathrm{b} \cdot r}{2c\varepsilon_0} \quad \text{for} \quad r < r_\mathrm{b} \quad \text{and} \quad E_\mathrm{r} = \frac{I_\mathrm{b}}{2c\varepsilon_0} \cdot \frac{1}{r} \quad \text{for} \quad r > r_\mathrm{b} \ . \tag{1}$$

Similarly an azimuthal magnetic field B_φ is generated by the beam current I_b:

$$B_\varphi(r) = \frac{\mu_0 j_{\mathrm{b} \cdot r}}{2} \quad \text{for} \quad r < r_\mathrm{b} \quad \text{and} \quad B_\varphi(r) = \frac{\mu_0 I_\mathrm{b}}{2} \times \frac{1}{r} \quad \text{for} \quad r > r_\mathrm{b} \ . \tag{2}$$

In future accelerators these fields can reach enormous values. Already in the crossing points of LHC the electric space-charge fields (> 10^9 V/m) and the magnetic gradients (> 6×10^4 T/m) exceed by far externally feasible field values. In the final focus of future linear colliders, space-charge fields of 10^{13} V/m and magnetic gradients of more than 5×10^6 T/m are encountered. As long as such relativistic dense beams propagate without external fields through vacuum both radial self-fields are in equilibrium. If, however, the beam travels through matter at rest, for example through a stationary plasma, the plasma particles with the same polarity are expelled from the beam region, the plasma particles of opposite polarity are attracted and counter-current loops are induced according to Faraday's induction law. The denser the beam, the higher the self-fields, and the smaller the impedances (dimensions) involved, the faster these natural compensation processes take place.

This example shows that, whereas we have no chance to act upon such dense beams over a short distance with conventional external electric and magnetic fields, the clever utilization of the beam self-fields interacting with a controlled environment of charged particles offers the opportunity to either exert strong fields — equivalent to the self-fields — on the beam or to cancel all self-fields. In the latter case the high-energy particle bunch behaves like a neutral object. Whatever is the goal of a space-charge compensation action, the desired effect is determined by the ratio of beam density n_b and external charge density n_ex. Complete space-charge neutralization of a beam with particles of charge state Z is realized by singly charged external charges, if at any time and location

$$n_\mathrm{ex} = Z n_\mathrm{b} \ . \tag{3}$$

If the external charges are elements of an auxiliary beam propagating with velocity v_ex , and forming a current density v_ex, the neutralization condition is written as

$$j_\mathrm{ex} = j_\mathrm{b} \cdot \left| v_\mathrm{ex} / v_\mathrm{b} \right| , \tag{4}$$

where the main beam velocity v_b equals approximately the speed of light c. Hence, it is favourable to accomplish full space-charge neutralization of relativistic beams with slow (low-energy) auxiliary particle beams (or clouds). The directions of v_ex with respect to v_b do not matter for pure space-charge compensation.

In the presence of a high-conductivity medium composed of external charges, full current neutralization may occur, which however, requires current densities flowing in adverse directions

$$j_\mathrm{ex} + j_\mathrm{b} = 0 \ . \tag{5}$$

Complete current compensation is achieved with beams of different polarity propagating with the same charge density and velocity ($v_\mathrm{ex} = v_\mathrm{b}$) and in the same direction, or with overlapping beams of same polarity, but opposite velocities. Current self-neutralization is enforced by the induction law, according to which an electric field

$$E_{\mathrm{in}} = -\left(\frac{\mathrm{d}(l \cdot I_{\mathrm{b}})}{\mathrm{d}t} + r \cdot I_{\mathrm{b}} \right) \tag{6}$$

is generated in the compensating medium, when a high-energy particle bunch is passing through and where l, r are inductance and resistivity, respectively, per unit length of beam, medium and surroundings. Equation (6) is valid, when the induced wall current is much smaller than the induced current through the cloud. Since the cloud is 'in contact' with the beam, capacitive contributions of the cloud to the loop impedance can be neglected in Eq. (6).

The particles of the conducting medium are accelerated by E_{in} in the direction of the main beam. A high-energy electron beam entering a conductive medium, for example a plasma, immediately excites a return current carried by the plasma electrons moving in the opposite direction. If a positron beam passes a reservoir of low-energy electrons, the electrons are driven into the same direction as the positron beam propagates, in this way compensating for the positron current. In a conventional vacuum chamber current compensation ($I_{\mathrm{ex}} + I_{\mathrm{w}} + I_{\mathrm{b}} = 0$) takes places partially with the wall current I_{w} in the vacuum tube. Any conducting medium (auxiliary beams, electron clouds, etc.) between the beam orbit and vacuum chamber will take over part or all of the compensating current according to the (dynamic) impedance distribution in the system. Consequently, complete and simultaneous space-charge and current compensation can only be obtained with equal densities ($n_{\mathrm{ex}} = n_{\mathrm{b}}$), equal particle velocities ($v_{\mathrm{ex}} = v_{\mathrm{b}}$) and overlapping current densities ($j_{\mathrm{ex}} = j_{\mathrm{b}}$). This state should be defined as 'full beam neutralization' or 'beam neutralization'.

If only space-charge compensation could be achieved without local current neutralization, then the charge-neutralized beam would experience a strong self-focusing owing to the uncompensated azimuthal magnetic self-field [Eq. (2)]. This ('passive lens') effect can be used, for example, to change the luminosity at the interaction points of circular or linear colliders within certain limits. However, the crossing of uncompensated particle bunches of different polarity, such as in an $\mathrm{e}^{+}\,\mathrm{e}^{-}$ collider, leads to an unacceptable compression due to the combined magnetic self-fields (pinch effect) rising with more than 10^{15} A/s (e.g. at TESLA 500 GeV/ 500 GeV [15]) and inducing an electric field E_{in} of the order of 10^{9} V/m against the collider's overall current direction. The opposite effect occurs when two particle bunches with the same polarity are colliding: Both magnetic self-fields cancel each other and no longitudinal electric potential is induced (overall $\mathrm{d}I_{\mathrm{b}} / \mathrm{d}t = 0$ at IP), while the combined space-charge field blows up the emittance of both bunches.

At low kinetic energies the space-charge forces of a beam are no longer transversally cancelled by the forces of the magnetic self-field. Longitudinally there is not even space-charge compensation at high kinetic energy. The Langmuir–Child (L–C) law limits the maximum current density j_{b} in a plane gap of width a as a function of the accelerating voltage U_{ac} to approximately

$$j_{\mathrm{b}} = C_{\mathrm{LC}} \times U_{\mathrm{ac}}^{3/2} / a^{2} \,, \quad \text{where the L – C constant } C_{\mathrm{LC}} = \left(\frac{4\varepsilon_0}{9} \right) \sqrt{\frac{2eZ}{m_{\mathrm{i}}}} \quad , \tag{7}$$

ε_0 is the dielectric constant and m_{i} and Z are the mass and charge number of the beam particles, respectively. A similar law is valid for the beam current density in a conventional accelerator at low kinetic energies. In the cylinder-symmetrical case the azimuthal magnetic field of the beam and the inhomogeneity of the current density at the edge of the beam have to be taken into account. The $U_{\mathrm{ac}}^{3/2}$ L–C law remains, however, qualitatively valid. For γ (= total energy divided by the rest energy of the particle) slightly greater than one, Forrester [16] derived a relativistic, plane-gap L–C current-density ratio [relativistic current density j_{re} divided by normal L–C density $j_{\mathrm{LC}} = j_{\mathrm{b}}$ given by Eq. (5)]:

$$\frac{j_{\mathrm{re}}}{j_{\mathrm{LC}}} = \frac{9}{16}\left(\frac{\gamma-1}{2}\right)^{-3/2}\left\{\int_{0}^{1/2(\gamma-1)}[t(1+t)]^{-1/4}\mathrm{d}t\right\}^{2} \tag{8}$$

which progressively decreases with rising γ. Also the maximum current density of an annular, ultra-relativistic beam ($\gamma >> 1$) in a cylindrical, conducting vacuum tube, approximately increases with γ instead of $\gamma^{3/2}$ [17]. Hence, in this sense, slightly relativistic and ultra-relativistic beams are even stronger intensity-limited than low-energy beams. Still the space-charge limit increases with γ, and also in conventional accelerator systems, which are severely space-charge squeezed at low β and γ, higher densities can by obtained at higher particle energy by expensive accumulation techniques.

Contrary to beams of neutral particles, charged-particle beams suffer from strong emittance blow-up near the L–C limit due to the space-charge fields. The degradation of normalized emittance on the way through an accelerator is irrevocable with standard technology. Only with accumulation and beam-cooling techniques may a degraded emittance be restored up to an intensity limit determined by the γ-value at which the cooling system is operating. The nearer the beam intensity approaches the L–C current density the stronger is the blow-up. The ratio of the beam current density j_{b}, which is flowing in the axial direction, to the L–C density j_{LC} is defined as the poissance π [18]:

$$\pi = j_{\mathrm{b}} / j_{\mathrm{LC}} \ , \tag{9}$$

which can be considered as the normalized perveance of the beam. The radial dimension of the beam envelope expands under space-charge from an initial beam radius r_{b} after a distance z to an output radius r_{bo} according to

$$\int_{0}^{\sqrt{\ln(r_{\mathrm{bo}}/r_{\mathrm{b}})}} \exp(u^{2})\mathrm{d}u = \sqrt{\frac{\pi}{18\pi}} \times \frac{z}{r_{\mathrm{b}}} \tag{10}$$

and not including the natural emittance contribution to the beam divergence. A beam with poissance $\pi = 1$ doubles its radius and increases its normalized emittance, also due to the additional angle spread, by more than one order of magnitude after a distance of approximately ten initial beam radii. Hence, strong compression of low-energy ion beams (exiting from an ion source) with external magnets has disastrous and irrevocable effects on the beam quality. Full neutralization of such low-energy beams can, on the other hand, totally remove the tendency of beam blow-up and even yield perfect emittance preservation of beams with poissances π far above 1.

The simple physical rules and relationships, based on elementary electrodynamics, reported in this chapter, allow approximate estimations and extrapolations to be performed in different cases of beam compensation. Detailed calculations and simulations, in order to theoretically study the various possible processes of beam compensation and neutralization, are not the subject of this paper. They should be, in the first instance, performed with emphasis on phenomenological electrodynamics combined with (relativistic) fluid and magneto-hydrodynamics. Simulations based purely on particle tracking methods are not suited to deal with beam compensation at high intensities. The most important aim should be, however, to gain practical experience with various beam compensation schemes from a number of dedicated pilot experiments and to build up physically relevant and theoretically reliable methods for modelling the technical applications of beam compensation.

3 FUTURE APPLICATIONS IN ACCELERATOR TECHNOLOGY

3.1 Neutralization of ion sources

Conventionally ion beams for accelerators are extracted by means of an electric potential from the plasma of an ion source into vacuum. The extraction gap of an ion source is the most critical location in the low-energy beam transport chain, since the ion space-charge is high and not accompanied by a confining magnetic self-field. During extraction the L–C law [Eq. (7)] limits the output current to an extremely small value compared with the abundancy of ions available in the source plasma. A tiny plasma layer of 1 μm × 30 μm × 30 μm generated, for example, by a short-pulse laser from a solid target surface contains 10^{14} ions, whereas the ion bunches of the future LHC collider are populated by 10^{7} (Pb) or 10^{11} (protons) at most. Another severe degradation caused by classical ion extraction near the L–C limit is the strong blow-up of the original source emittance ε_s by the ion space-charge forces, as described by Eq. (10) and by the action of external magnetic compression elements, e.g. solenoids, in the extraction chain. In a classical accelerator system these order-of-magnitude losses of particle number density and the degrading of beam quality may be partially offset by applying, after subsequent acceleration, complex and expensive accumulation and beam cooling techniques, which were invented several decades ago with the aim of accumulating very rare particles such as antiprotons.

The difficulties in obtaining with classical means high beam intensity while maintaining good beam quality can be circumvented by utilizing ion-beam space-charge compensation [19–25] in the extraction gap of the source and by eventually stretching the compensation out into the first few low-energy beam transport sections of the ion linac. The focusing of the electron beam onto the exit of the ion source and the acceleration by the extraction potential reduce the beam diameter and increase the electron density, which should be matched to the ion-beam density at this point according to Eq. (4), in order to avoid strong ion-beam compression. The ion beam leaving the neutralization region of the extraction gap has to be properly matched to the subsequent classical accelerator sections profiting from the higher L–C limit valid at higher ion energy. Strong compression must be imperatively avoided also in the compensated stage, before the ion beam enters a non-neutralized section. Otherwise the beam degradation at the transition to vacuum environment can be worse than without beam neutralization.

The most convenient media for (positively charged) ion-beam space-charge neutralization are co- or counter-moving low-energy DC or pulsed electron beams [19–25]. With counter-moving electron beams additional magnetic compression of the ion space-charge is achieved, whereas co-moving electron beams lead also to ion current neutralization. The latter is more suitable for ion beams, which have been already accelerated to a higher kinetic energy. At the extraction gap of an ion source a current determined by Eq. (4) can be extracted in addition to the L–C current (Eq. 7), as experimentally demonstrated in Ref. [24]. Since the ions move very slowly, a high electron current density is required for charge density neutralization. The total beam power of a DC electron beam would be too high, even in the case of low kinetic electron energy; hence, pulsed electron beams are preferable for external injection into the extraction gap of an ion source. During the mutual overlap ion and electron beam diameters are both shrinking (self-neutralization of space-charge and pinch effect owing to the counter-moving electron beam's magnetic field) instead of blowing up, when not neutralized. The self-neutralization of the space-charge of the free carriers is a very fast process, which proceeds until the ion and electron-beam space-charge fields have fully cancelled each other. A further contribution to the shrinking of the beam radii is the normal emittance contraction of the electron and ion beams when accelerated by the ion-source extraction potential in opposite directions. The beam compensation in the extraction gap of an ion source as described in Ref. [25] is an example of the acceleration of a charge-neutralized beam. A current-neutralized ion beam can not be accelerated in this way. Simultaneous space-charge and current self-neutralization is nicely demonstrated in an experiment described in Ref. [20], where thermionically generated electrons are drawn by the space-charge field into an ion beam at the exit of a laser ion source.

The beam compensation at the exit of an ion source would be superfluous, if an ion beam of required intensity could be classically extracted with a normalized emittance ε_n lower than the one needed in the target accelerator after having passed the most critical low-energy beam transport elements. In LHC, for example, a normalized emittance $\varepsilon_\mathrm{n} = 1.5 \times 10^{-6}$ mrad is specified for Pb ions. If the absolute emittance ε can be well kept at a value below $\varepsilon_\mathrm{n} / \beta\gamma$ for the specified output current amplitude, neutralization or expensive accumulation and cooling techniques are not needed to fullfil the LHC design specifications. If, however, the normalized source emittance ε_s is already larger than the required normalized target emittance ε_n, then, even with beam neutralization, such an ion source is not suited for feeding the accelerator without accumulation and cooling.

The application of ion-beam neutralization is based on the availability of a source, which has the potential to produce a sufficient number of ions at low enough source emittance ε_s:

$$\varepsilon_\mathrm{s} = \varepsilon_\mathrm{n} = \sqrt{\frac{4\pi}{m_\mathrm{p} c^2 A}} \sqrt{\frac{kT \cdot I_\mathrm{i}}{j_\mathrm{i}}} \qquad (11)$$

where m_p is the proton rest mass, k the Boltzmann factor, c the velocity of light, A the atomic weight of the ion, T the surface temperature, I_i the ion current and j_i the ion current density. A convenient type of ion source for pulsed ion-beam compensation is a laser-driven plasma source as long as the source emittance is smaller than the required normalized emittance of the target accelerator. For low output emittance a low surface temperature T (least heating) and high current density j_i (hence, a small laser spot) are required. For higher charge states a high power density of the order of TW/cm^2 is essential, in order to establish a strong electromagnetic ionization field in the laser spot on the target. Therefore the laser must feature short pulse length (ps or fs) and short wavelength to be focused to a minimum spot size. The laser pulse energy determines the amount of material evaporated from the target and must be minimized. Excess energy, e.g. if the laser pulse is too long, degrades again the emittance [Eq. (9)]. After the ions are generated in a complicated way, they move on, fully neutralized, inside the source chamber toward the extraction gap, where the beam compensation with electrons has to start. In the neutralization experiments performed at CERN [21–25], ferroelectrically generated electron-beam pulses of about 50 ns length, 1 to 5 A current amplitude and 10 to 30 A/cm^2 current density have been sent in the opposite direction: through the extraction gap into the source equipped with an Al target. When just neutralizing the L–C current density of Al^{1+} or

Al^{2+} ions the totally extracted current density measured immediately after the neutralization section was equal to $2 \times j_{LC}$, as it must be according to the L–C law. Strong enhancement of ion-source output current has also been reported in Refs. [19] and [20].

The danger of emittance blow-up at the exit of a neutralization section must be counteracted with adiabatic ion-beam expansion in the neutralization region up to a beam radius, where space-charge becomes insignificant. If the resulting beam cross-section is too large to fit into the next conventional accelerator element, additional accelerating gaps must be passed by the ion-beam before it can be released into a non-neutralized section.

Figure 1 shows the principle of a possible compensation scheme in the case of a laser ion source, which is able to preserve the source emittance until the end of the neutralization section. It can, however, be adapted to other ion sources (including DC sources), which fulfil the output parameter specifications. Two electron guns (EG1 and EG2) provide bursts of counter-moving, intense, short electron pulses at high repetition rate, charge-neutralizing the interior and the adjacent exterior region of the extraction gap. EG3 is an electron gun generating electron pulses with slightly higher charge, current, and pulse length compared with the extracted ion-beam pulse. The charge neutralization of the ion pulse is taken over by the electron beam from EG3, which also current-neutralizes the ion pulse. By natural divergence the ion-beam diameter would grow until the space-charge forces became small, if it were not neutralized. In order to match the ion beam to the subsequent classical accelerator section, e.g. an RFQ, the neutralizing electrons must be removed and the ion-beam diameter decreased by a second pulsed accelerating gap in front of the RFQ. The injected ion current amplitude controlled by the ion source should match the RFQ acceptance.

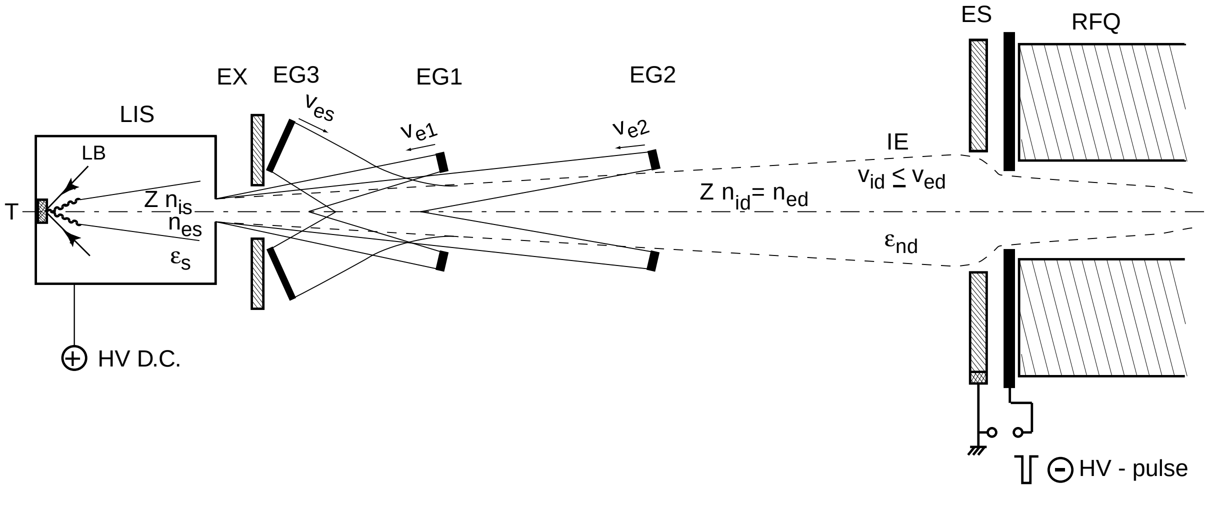

Fig. 1: Principle of an ion-beam compensation scheme for ion-beam enhancement and emittance preservation. LIS = laser ion source; LB = laser beam; T = target; EX = extraction gap; EG1,2,3 = electron guns; IE = ion beam envelope; ES = electrical separation gap; RFQ = radio-frequency quadrupole; Z = charge state; ε_s = source emittance; n_{is} , n_{es} = ion and electron in the source, $v_{e1,2,3}$ = electron velocities from EG1,2,3; ε_{nd} = emittance in drift space; n_{id} , n_{ed} = ion and electron densities in drift space; v_{id} ,v_{ed} = ion and electron velocities in drift space.

The ion-source compensation experiments reported in Refs. [20–25] have demonstrated the basic principles of ion-beam neutralization with low-energy electrons. Before applying, however, any compensation scheme in a real injector line, as for example for the heavy-ion injection into LHC, pilot experiments must be envisaged at an operational full-size ion source with a low-energy beam transport system including the first classical acceleration unit(s) of the ion linac. The pilot experiment could be planned at any low-emittance ion source available at CERN or elsewhere (e.g. GSI). More details on the layout of such a pilot experiment are given in Ref. [26].

3.2 Beam compensation in the crossing regions of circular colliders

The accelerated beam intensities of circular accelerators have steadily grown during the past decades and will further increase in future machines. Whereas in the early accelerators the electric and magnetic self-fields of the beams could be neglected, engineers building future accelerators will be confronted with serious problems, which are caused by the electromagnetic interactions between the beams and their environment. When running, for example, LHC at maximum beam intensity, a problem has been identified, which has to be traced back to the interaction of the space-charge and the current of the LHC beams with electron clouds generated in the vacuum tube by synchrotron radiation. The electron-cloud-induced energy dissipation is a typical high-intensity problem for the operation of the LHC collider. Other problems, which concern as well the high-energy physics experiments, appear, for example, at the LHC intersection points, where both LHC beams collide. The focusing of the LHC beams in the low-β insertions leads to a beam diameter of about 15 μm at the crossing points and to electric and magnetic self-field gradients of 10^9 V/m and 6×10^4 T/m, respectively. These gradients exceed already by far the gradients which can be achieved with conventional technology. During the crossing of two LHC bunches their magnetic self-fields cancel, whereas the amplified space-charge fields cause local blow-up kicks with the final results of a tune spread growth and of a reduced beam lifetime. The increase of tune spread will be the greater, the less perfect is the mutual overlap of the crossing bunches. LHC operation seems still possible as such, but will be much more difficult at the highest intensity levels. The same is true for the LHC high-energy physics experiments. The beam is naturally degraded by the high rate of desired particle interactions, but it should not be eaten up by the parasitic collective electromagnetic effects. At top intensity the flexibility of luminosity control is strongly constrained. An operation scheme with constant luminosity, which may be requested by some of the experiments, is practically very difficult to control. Certain experiments (CMS) even lose a substantial part of their triggers for data-taking just after a new LHC fill, since the initial luminosity is too high for full digestion by the detector equipment.

The LHC beams cannot be neutralized over large sections of the machine, but global understanding of the interactions between electron clouds and the LHC beam self-fields is essential to properly solve the energy-loss problems in superconducting magnets and in the straight sections of the machine. The electron-cloud phenomena are dealt with in Refs. [27–30], however longitudinal effects seem to be not included in these considerations. Axial currents are, for example, induced in the electron clouds by the rapidly varying bunch currents, which lead to an inhomogenous density distribution of cloud and energy dissipation along each accelerator section. Electron-cloud problems are not further treated in this article.

A controlled localized LHC-beam compensation scheme [31], however, with the aim of neutralizing the bunches of both LHC beams in the neighbourhood of the interaction points (IP) before crossing takes place and in the most critical sections — where long-range beam–beam interactions occur — could end up in the elimination of the most perturbing collective electromagnetic beam–beam effects (Fig. 2). The results would be a simpler machine operation and a gain in beam lifetime. It can be shown [31] that with a neutralization scheme at the IP, which is closely matched to the experimental environment and which is in tight feedback with the rest of the LHC machine, the luminosity could be either slightly increased with respect to the design specifications or adjusted in limits of less than one order of magnitude. Then experimental runs at constant or much-less-varying luminosity conditions can be envisaged for certain experiments.

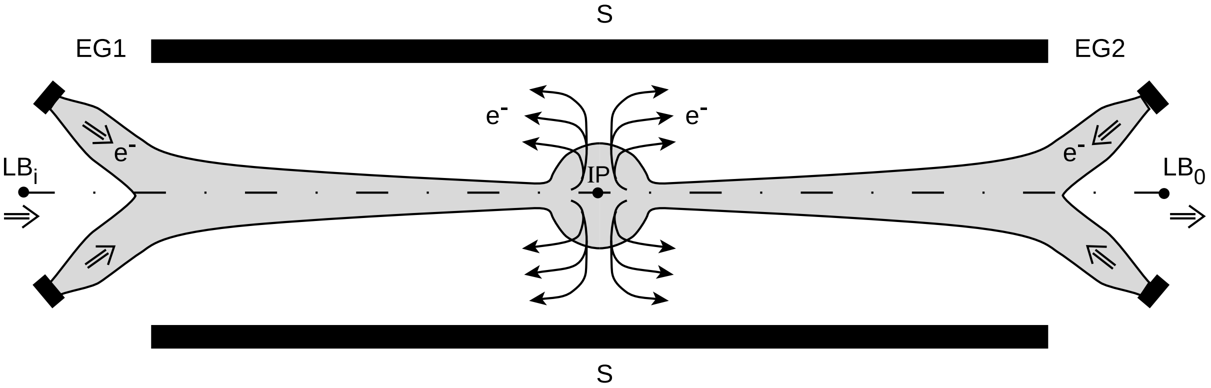

Fig. 2: The principle of a neutralization system for the LHC IPs. EG1,2 = electron guns; S = solenoid; $LB_{i,o}$ = in- and outgoing LHC bunches.

The technical realization of an IP neutralization scheme for protons (p) and ions (A) in LHC could be achieved with low-energy (1 to 20 keV) DC electron beams of the order of a few amperes of total current. Equation (4) shows that less electron density than LHC beam density is sufficient for full space-charge neutralization. The principle of a realistic LHC IP neutralization system is shown in Fig. 2. The in- and outgoing LHC bunches LB_i and LB_o pass through a channel with decreasing diameter filled with low-energy electrons. Two low-mass electron guns EG1 and EG2 are positioned symmetrically with respect to IP outside the solenoidal magnet S a few metres away from IP and inject continuously hollow, low-energy DC electron beams with a current I_e towards IP. The cathodes may be positioned on a radius corresponding to the beam screen. If a smaller angle for electron-beam injection into the central solenoid S is required, the gun can be split into two halves, which can be moved towards the bunch orbit after completion of the LHC acceleration cycle, as is foreseen in the design of certain Roman Pot detectors. In order to introduce a minimum of massive equipment into the vacuum chamber, guns with cold cathodes and with high efficiency are needed. In Ref. [31] a layout for such an electron gun is proposed.

Neither strong magnetic dipole nor quadrupole fields can be tolerated between EG and IP. The axial B-fields of central magnetic solenoid magnets are, on the other hand, very favourable for focusing and guiding the incoming electron beams to the IP and smoothing the local contraction of the electron-beam envelope diameter occurring behind each LHC bunch. Figure 2 shows how the end fields of the central solenoid compress the annular electron stream. The elongation of the electron trajectory length inside the solenoid leads to a higher density, and in the case of constant I_e, to a decrease of electron-beam radius. Another contribution to the shrinking electron-beam envelope is given by the average increase of electron velocity induced by the repeated longitudinal kicking of the incoming LHC bunches until they are fully neutralized. The slow-down by the outgoing LHC bunches is on the other hand negligible, since these are largely neutralized. The LHC bunch attraction in the vicinity of IP is so strong that all electrons in a cylinder of at least 10 r_b around the bunch are captured and carried along with the bunch (self-neutralization), when traversing a neutralization length L of a few metres. Therefore, the compression of the electron beams inside S to a radius of 1 to 3 mm shall lead to almost full neutralization of the LHC bunches. Near the IP the space-charge forces of the counter-moving electron beams slow down the electron velocity and both electron beams expand. The fraction of energetic electrons captured in the space-charge fields of the LHC bunches continues to traverse IP in the original direction. The major part of the slow electrons (a few kW total) is lost inside or just outside the central solenoid on a very large surface area of the order of m^2. The electrons captured in the LHC bunches are more energetic and have to be deflected onto small dumps before they hit the next superconducting magnets. To reduce interference with sensitive detector elements screening could be necessary in certain places.

With the proposed system the LHC-beam IP neutralization can be achieved in either of two extreme compensation modes. Practically, a regime of a mixture of both modes will result:

- The electron charge density is reduced below the LHC-beam charge density and the electron beam diameter is made larger than the LHC beam diameter at the position where the LHC bunches enter the neutralization section. In this case the LHC beam will be mainly charge neutralized, but weakly current neutralized by the low-density electrons. Hence, the azimuthal magnetic self-field is uncompensated and a progressive self-focusing (Fig. 3a) of the beam with shrinking r_b changes the optics in the interaction region and must be compensated by different settings of the low-beta insertion modules. This type of beam compensation acts like a plasma lens with an ‘underdense’ plasma density [32] and may be called an electron-beam-plasma lens. Attention has to be paid to avoid nonlinear self-focusing. If the beam density distribution profile is rectangular and if the electron density is also constant across r_b, the resulting focusing is linear, but unrealistic. If the LHC beam is Gaussian, then the distribution of the neutralizing electron cloud around and inside the beam induced by the beam space-charge potential is not linear either, but just cancels the nonlinearity introduced by the Gaussian density profile and the focusing is linear. Imperfections in the distributions of both beams finally cause unavoidable nonlinear focusing, the result of which on the steady LHC operation has to be investigated more deeply in this compensation scheme. However, the negative contributions by these imperfections can be estimated as less important than the full beam–beam effects caused by the normal crossings of non-neutralized LHC bunches. For the IP environment it is important that this neutralization mode does not lead to a substantial current neutralization equivalent to an increase of the total electron beam energy, so that special electron beam deflection and dumping elements may not be required.
- The second extreme of bunch neutralization occurs when the electron beam density is equal to or higher than the beam density (‘overdense’ electron beam plasma). Then the LHC bunch currents induce a bunch-internal compensating electron current of the same amplitude and density as the LHC bunch. Hence, the neutralizing electrons are accelerated to a substantial fraction of the speed of light. The process is equivalent to the self-neutralization of an ion beam ejected through a dense electron cloud from an ion thruster

into space [2]. Depending on electron density and on travelling length through the neutralization region, the LHC bunch will be fully charge and current neutralized before crossing the equally neutralized counter-bunch at IP (Fig. 3b). This mode of total neutralization results in negligible self-focusing. As in the case of no neutralization at all, the bunch propagation toward IP is characterized by a linearly shrinking bunch diameter, but also by the absence of any electromagnetic perturbation in IP. Any imperfections of charge, charge distribution, current amplitude and position of the LHC bunches, which are disastrous in non-compensated mode become totally insignificant in the case of full charge and current neutralization. For the operation of the experiments and of the machine this mode would be ideal, if there was not the high kinetic-energy gain of those electrons which are 'picked up' by the LHC bunches. Total electron-beam powers of 50 kW and more per beam have to be digested in the interaction regions. It is difficult to see how to cope with this amount of energy without deflecting and dumping the electron beams before the LHC bunches hit the superconducting magnets. In reality, both neutralization modes will be mixed and via the electron beam density the repartition of neutralization modes can be controlled. Therefore the electron guns must allow full control over the electron beam parameters. Details of the neutralization process and of the accompanying self-focusing with the consequences for the operation of machine and experiments is considered in Ref. [31].

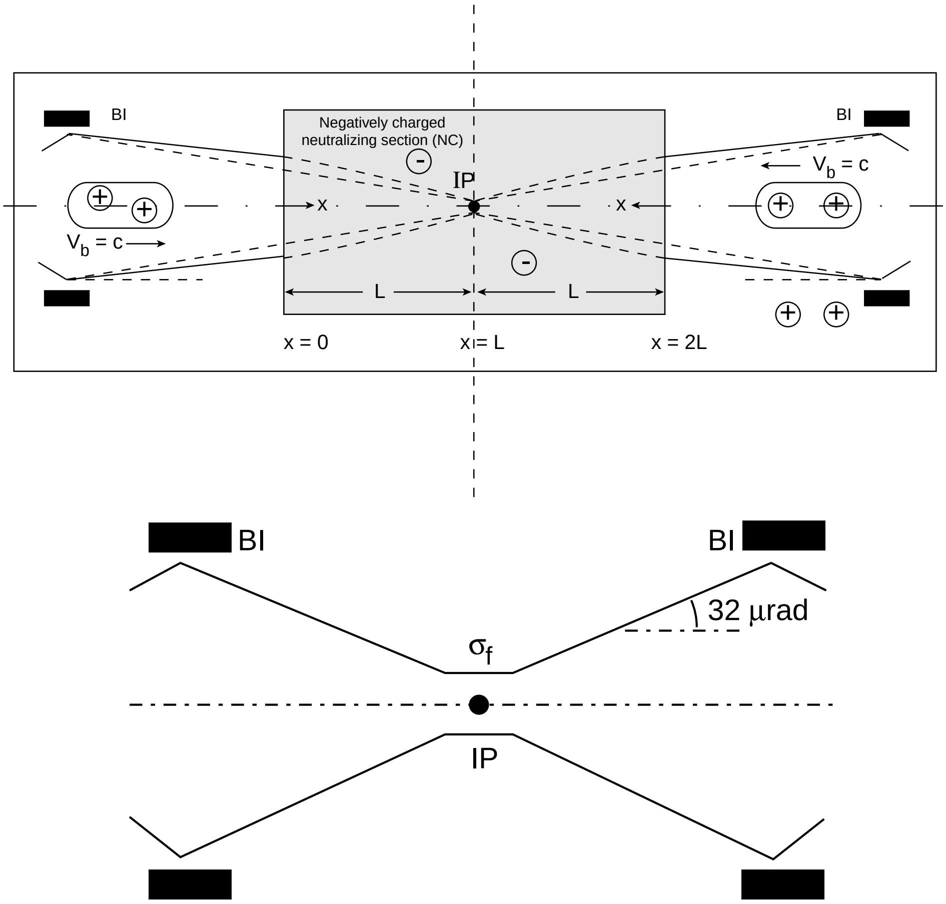

Fig. 3: a) Envelopes of fully space-charge-neutralized, but not current-neutralized proton bunches near the IP of LHC: σ_f = bunch diameter at IP; σ'_0 = angle at entrance into neutralizing section NC; L = distance between entrance of NC and point of smallest spot size (IP); BI = low-beta insertion. b) Beam envelopes of fully charge- and current-neutralized bunches or of non-neutralized bunches with conventional IP crossing.

The long-range beam–beam interactions in dipole- and quadrupole-free LHC sections, where both colliding beams share the same vacuum chamber (e.g. in the low-beta insertions), could be also reduced by beam compensation. Full LHC-beam neutralization is not required in these sections, screening by beam compensation is sufficient. Beam compensation schemes for such sections are considered in more detail in Ref. [31]. The described partial beam neutralization model can be also considered for other high-intensity circular colliders. LHC is a very convenient candidate, since the neutralization system involves only one high-energy particle species (p or A) and one neutralizing medium particle (electron) and can be made fully symmetric around the IP region. Colliders operating with p–pbar or μ^+–μ^- beams not only involve more high- and low-energy particle species, but the neutralization scheme cannot be built symmetrically. Provided there are not strong physics reasons to collide x^+ with x^- beams, it is technically easier to build x^+–x^+ colliders neutralized with electron beams or x^-–x^-colliders neutralized with positron beams. This is, with a few restrictions, also true for hadron–lepton colliders (for example, a p–e^+ scheme, which can be neutralized with electron beams).

The design and installation of a beam compensation system for a specific circular accelerator such as LHC has to be preceeded by pilot experiments at any convenient beam line of operational machines, in order to test the different elements of such a scheme and to gain experience with its operation. Such pilot experiments can also give more insight into the problem of the energy losses via electron clouds. Currently, two pilot experiments are in preparation at FNAL and at SLAC, in which the interaction of high-energy beams with slow electrons or with a stationary plasma are studied. The aim of the FNAL experiment in the frame of the Tevatron’33 upgrade project [13] is not beam neutralization, but compression of the antiproton bunches with the low-energy electron beam space-charge forces, in order to compensate for the pinch effects of the p–pbar interactions and to reduce the beam–beam tune spread. This test will offer excellent opportunities to study the practical operation of an ‘electron beam compressor lens’ and the role of imperfections and nonlinearities for beam compensation in a circular collider environment. At the SLAC Final Focus Test Facility [14] a ‘passive plasma lens’ experiment [32] is planned. In the first phase a high-energy electron beam from the SLAC linac is sent through a plasma of 3 mm thickness. The plasma electrons are instantaneously ejected out of the beam region such that the positive ion charge compensates partially or fully for the electron-beam space-charge. The result is a self-focusing of the electron beam comparable to the electron-beam-plasma focusing described above. The focusing effects on the beam can be investigated in the SLAC experiment as a function of plasma density. At high plasma density also current neutralization can be studied. In a later stage plasma interaction with energetic positron beams can be tested. Then also the ‘self-neutralization’ of a high-energy positron beam may be studied.

The FNAL and SLAC beam-interaction experiments will contribute significantly to the experience of handling beam-compensation devices in general. It is, however, imperative to study also the beam neutralization schemes with electron beams at the crossing points of circular colliders in dedicated pilot experiments.

3.3 Beam compensation at the final focus of linear colliders

The beam intensity in the arcs and in the interaction regions of LHC is already high enough to produce several inconvenient perturbations. It may be well worth eliminating these perturbations, but, accepting some limitations for the flexibility of operation for the experiments and the machine, LHC may still be operated without beam compensation devices in a rather ‘clean’ way. The beam confinement in LHC is so good that the experimental physicists can place detectors very near to the beam and can study particle interactions at very small angles. Much less particle losses will occur from the beams circulating in LHC than in any previous high-energy accelerator for particle physics.

All studies of linear colliders currently pursued in Europe, US and Japan envisage schemes based on ‘conventional’ electron–positron collisions, which unfortunately reverse this positive trend and lead to crossing conditions much worse than in LHC. The high current densities of the e^+ and e^- beams of a collider of 0.5 TeV generate near the final focus locally electric- and magnetic-field gradients of the order of 10^{13} V/m and 10^{6} T/m, far in excess of the gradients at the IPs of LHC. During crossing the space-charge of both beams cancels. Self-pinching takes place under the influence of the azimuthal magnetic self-fields, so strongly that during the time of overlap several betatron oscillations may occur. Electrons and positrons are electromagnetically deflected and bending angles of the order of 10^{-3} rad not only spoil the beam after crossing, but significantly reduce the solid angle available for experimental observations of high-energy physics reactions (e.g. compared to LHC). Moreover the strong ‘beamstrahlung’, the pair production and the generation of ‘mini-jets’ [33–34] induced by the collective electromagnetic interactions perturb strongly the operation of the detectors at the (single) final-focus experiment. The critical design parameters, such as the luminosity, are no longer fully determined by the final purpose of the collider, as they should be, but imposed by the destructive electromagnetic effects characterized for luminosity by the beamstrahlung parameter δ and the disruption parameter D. The introduction of these parameters imposes further artificial constraints, for example, on the shape, on the cross-section and the crossing angles of the beams in the final focus. It is evident that the influence of the destructive electromagnetic phenomena grows with increasing collider energy.

Although the former two-beam and four-beam experiments at DCI/Orsay [9, 10] have already demonstrated clearly the difficulties in properly colliding dense, non-neutralized, high-energy e^+ and e^- bunches, this scheme has been pushed to the extreme in the linear collider proposals. Ideas have even been forwarded, which suggest colliding two energetic e^+ and e^- beam pairs in the final focus of a linear collider as was tried at DCI. This type of neutralization has to be discarded for practical reasons and for the imperfections inherent also in future linear collider machines. Such linear collider schemes are not only asymmetric, but suffer from the interaction of strong electrical and magnetic moments in the final focus raised by differences of charge, current amplitude, charge distribution and position of the colliding bunches.

By introducing a ‘smooth and redundant’ (with respect to compensating particle density) charge and current neutralization BEFORE bunch crossing virtually all electromagnetic perturbations in the final focus can be eliminated. Such a neutralization system (Fig. 4) resembles the previously described LHC IP compensation scheme, but requires much less precision, since the colliding bunches are not continuously recirculated. The necessary precision for final-focus colliding is also very modest compared to the requirements of the DCI-four-beam neutralization scheme, where no redundancy could be tolerated. The compensating beams can be injected with a comparably higher energy than in the LHC-beam compensation scheme, in order to ease the low-energy beam formation, the transition from the non-compensated to the neutralized state and to minimize the additional self-focusing of the collider beams during the transition phase. With the elimination of the collective electrodynamic perturbations in the final focus of a linear collider the set of basic design parameters is freed, for example, from the beamstrahlung and disruption parameters. The design limits for a particular linear collider scheme are significantly relaxed. This can be fruitfully used for redesigning the different linear colliders currently under study and to improve on the remaining deficiencies of each of these schemes. The luminosity of a linear e^+–e^- collider with neutralized beams will be then uniquely determined by the e^+ and e^- beam intensities and emittances and by the focal lengths of the lenses of the final-focusing system. Round beam cross-sections can be chosen for the collider beams in the final focus, which are best suited for maintaining an efficient luminosity control to obtain high integrated luminosity over long operation times [35]. Since, after crossing, the outgoing bunches are well confined, very small crossing angles can be chosen giving more solid angle for low-angle physics observations.

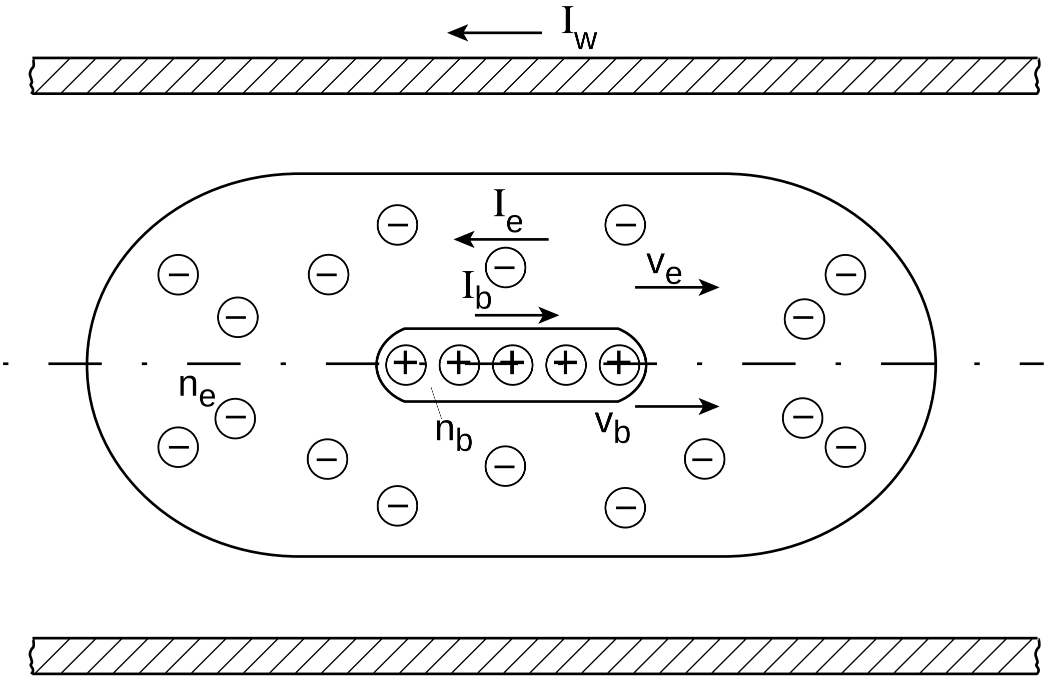

Fig. 4: Compensation of a high-energy bunch of positively charged particles with a pulsed low-energy lepton beam of opposite charge and current direction. I_b = bunch current; I_e =electron current; I_w = wall current; n_b , n_e = bunch and electron charge densities; v_b , v_e = bunch particle and electron velocities.

For reasons of symmetry and of practical simplicity e^+–e^+ and e^-–e^- (or p–p) colliders are preferable to e^+–e^- linear colliders, as in the case of circular colliders. But, if high-energy physics is opting for an e^+–e^- machine with strong arguments, this scheme can also be dealt with by neutralizing the electron beam with positrons and the positron branch with electrons. In the case of linear colliders the low-energy beams need not to be DC. Pulsed beams with bunch length and particle number per bunch greater than those of the high-energy bunches are more economic and can be more easily dumped than DC beams. Enough space, much more comfortable than in LHC, can be provided between the last classical collider elements and the final focus to generate and direct the low-energy (< 1 MeV) e^+ or e^- beams, which gradually assist in the self-neutralization of the main beam on its way toward collision. The focusing resulting from the classical final-focus quadrupoles can be increased with passive plasma lenses

[14, 31–32], which may be combined with and precede the neutralization sections on either side of the final focus. The need for colliders with multi-bunched beams may be removed in the case of neutralized colliding bunches, but multi-bunched beams can equally well be served with beam compensation, if necessary. The neutralized bunches cross each other like neutral objects without the appearance of any electric or magnetic moment. Hence, in the absence of ‘positive’ or ‘negative’ pinching, only reactions determined by the cross-sections of possible elementary particle interactions change the original bunch configurations. After crossing both neutralized bunches propagate in a perfectly confined way and according to the simple geometrical optics of neutral beams until the charge density has lowered so much that the neutralizing positrons and electrons can be separated from the main beams with external magnetic fields, if desired. The low-energy beams can be deflected and dumped and also the main beams can be directed in a controlled way to a dedicated beam dump. The beam neutralization at linear colliders also opens the way for designing more than one interaction point in the same collider; hence, a more economic use of such an expensive machine becomes possible. Imperfections and nonlinearities are much less important for a single-pass crossing than for the repeated crossings in a circular collider.

As in the case of circular colliders the technology of neutralization systems with low or medium-energy lepton beams exists and can be considered as already being well mastered today. Pilot experiments, such as the ‘passive plasma lens’ experiment at the SLAC FFTB [14], where the plasma takes over the role of the neutralizing lepton beams, shall be very beneficial also for gaining practical experience with the handling of such beam compensation systems. The plasma length of 3 mm (!) applied in this experiment is sufficient to deliver already well measurable data on beam compensation. It also gives an impression of how short is the length within which self-neutralization of a high-energy charged-particle bunch occurs with slow leptons.

The cost of a linear-collider beam compensation device can be considered as negligible compared to the main linac costs. In order to get the necessary funding for constructing a future linear collider, it is therefore recommended to the accelerator community, not to drop the chance to build a ‘clean’ collider designed for doing a high-energy physics job and to get rid of the disastrous collective electromagnetic phenomena.

3.4 Compensation at the target of an ion-beam fusion driver

In the past several proposals have been made for charged-particle accelerators to drive inertial confinement fusion ICF [36–39]. Except for a scheme proposed at LBL, which was characterized by two parallel high-current induction linacs [38], all other proposals deal with ‘conventional’ accelerator structures composed of many parallel ion sources, linacs, accumulation and cooling rings including exotic ideas such as non-Liouville stacking, and a high multiplicity of beams arriving at the final fusion target. Depending on ion pulse length, target mass and method of target heating (direct or indirect), beam line numbers from 50 to 2000 are cited. An overall ion-beam current density of the order of 10^7 A/cm^2 has to be transferred onto a target to produce the necessary compression and heating to fusion temperature. The enormous complexity and multiplicity of the fusion driver proposals is artificial and witnesses the poor capabilities of conventional accelerator technology to extract sufficient current from an ion source and to accelerate high-current beams in a single or in a few beam tubes. If the classical point of view is consequently pursued, that is, to transport and focus the multiple non-neutralized beams in vacuum just down to the final target, the whole scheme of energy deposition fails, because the ion beams cannot be stopped onto the target. There are two reasons for the failure imposed by the basic rules of electricity:

- the ion space-charge stopped on a pellet repels the drive beams;
- currents always close in loops and cannot cease to flow in one point.

Both rules impose the following consequences: if the drive beams are not neutralized, return currents must be established, and, if there is no reservoir of surplus electrons available at the target, the ions of the drive beams themselves must return while carrying a large part of their energy back from the target in an uncontrolled manner. A driver system without beam neutralization would fail in the same way as a non-neutralized ion-beam injector for an MCF tokomacs or a non-neutralized ion thruster for spacecraft propulsion independent of the kinetic energy to which the ions are accelerated in these devices.

The energy deposition problems, which the conventional fusion driver technology inevitably runs into, can be fully avoided by neutralizing each incoming ion beam in or in front of the reaction chamber before it hits the target. Then total energy transfer to the target and absence of electromagnetic fields and forces at the pellet are guaranteed. The incoming ion beams have anyway to be focused to the final target, the fusion pellet, in order to generate the necessary power density. The final spot size will be unperturbed by electromagnetic fields and uniquely determined by the ion beam emittances and the focal lengths of the final focusing lenses. Efficient focusing has been demonstrated with high-current-carrying plasma lenses [5, 40]. Such lenses could be easily combined with the electron beam sources for the heavy ion beam neutralization. The electron guns must be very intense and robust, but do not have to fulfil stringent conditions neither of precision nor of high beam quality. It seems amazing that the two reasons cited above as responsible for the failure of classical final-focusing schemes — space-charge and current flow — can be just employed to initiate the self-neutralization process without disturbing the final focusing and energy deposition. The total electron-beam energy necessary to neutralize heavy ion beams of the order of 100 kA total current, 10 GeV kinetic ion energy and a few nanoseconds pulse length is partially drawn from the ion beams, but amounts to less than 10^{-4} of the total ion-beam pulse energy, e.g. less than 10 kJ for an 80 MJ driver.

Though with local beam compensation at the levels of driver sources and driver target the ion beam multiplicity can be reduced, we may still have to count with a limited number of beam lines. Remembering the partially neutralized ATA induction linac example characterized by an (‘ion-column-focused’) electron beam of 10 kA [8], the number of beams for a fusion driver of about 100 kA ion current may be hopefully less than 10 instead of several thousands [36]. If accumulation and cooling techniques are used in the driver accelerator system, it operates more effectively with the accumulation of ion beams at higher kinetic energy, but since the costs for storage and cooling rings rise steeply with accumulation energy a compromise has to be found. A fully neutralized fusion-driver range working with two or four ion beams only in the 100 kA range is not within the reach of today’s technology, mainly owing to the lack of an efficient acceleration method for neutralized ion beams. Nevertheless, with beam compensation heavy-ion fusion drivers will remain serious competitors for laser-driven, inertial-confinement fusion devices.

4. TECHNOLOGICAL CONSIDERATIONS FOR BEAM COMPENSATION

In the previous chapters several examples and proposals of beam compensation have been dealt with. Numerous different techniques can be imagined employing quasi-stationary, low- or medium-energy electron, positron, ion, or plasma beams as neutralizing agents. As long as charged-particle beams are involved, the technology to generate the compensating beams is practically equivalent to classical accelerator technology. The example of DCI is the classical application of a neutralization scheme restricted to the instant of mutual bunch penetration: The aim of reaching complete charge and current neutralization by tailoring each of the two energetic electron and the two energetic positron bunches in terms of identical charge and current distributions could not be achieved due to lack of precision and owing to machine imperfections. Such a compensation scheme is fully ‘man-made’ and does not include any self-neutralization prior to the mutual penetration of the four bunches.

Self-neutralization can be easily demonstrated when sending charged-particle beams through a plasma. It is however, rather difficult to generate large, stable volumes of plasma and often the plasma ions disturb the beam propagation and the purpose for which the beam is produced. The generation and propagation of low- and medium-energy lepton beams, on the other hand, can be considered as standard technique today. It is therefore straightforward to replace high-energy lepton beams (DCI) and plasma channels by low-energy lepton beams when beam compensation including self-neutralization is envisaged. Today electron guns constructed along classical lines allow not only the control of electron beam current and current density, but also of the kinetic energy, the temporal and the spatial distributions of the electrons separately. Impressive examples are the electron guns built for electron cooling purposes [41]. More advanced and compact guns may incorporate cold cathodes, such as ferroelectric cathodes [42] and field emitter arrays (FEA) for DC and pulsed applications [43].

For ion source neutralization (Fig. 1) classical pulsed sources [20] as well as ferroelectric guns [25] have been tested. Co- and counter-moving electron beams can be applied to very low-energy ion beams. At the extraction gap of an ion source counter-moving electrons are more practical, otherwise the electron beams have to be generated inside the ion source. When intense low-energy ion beams have to be transported over a large distance, several high-repetition rate pulsed electron guns are needed for ion beam neutralization and for matching the ion beam at the transition from the neutralized region to a non-compensated classical accelerator section.

The local beam compensation in a circular machine, as at the LHC IPs, must be designed with DC electron beams generated by very compact, low-mass and reliable guns with cold field-emission cathodes. Best candidates for this application are ring-shaped, FEA-based DC electron guns [42] producing annular beams around the main proton beams. The guns must be flexible with respect to electron-beam current amplitude and kinetic energy, and reliably guarantee a stable operation. The electron guns have to be placed outside the central detector solenoids, but well away from superconducting magnets and dipole fields. The solenoidal magnets, which are incorporated into the interaction region of each LHC experiment, govern the electron beam transport toward the IP and form an essential part of the compensation scheme. The main technical problems of LHC beam compensation are less on the electron gun side, but rather linked to the dissipation of the energy, which the compensating electrons attain by current compensation during the neutralization process. It will be a serious problem to incorporate the rather massive and also expensive deflector elements into the already frozen design of the LHC intersection regions, such that the cold components of the LHC cryosystem are efficiently protected, but also the data-taking of the detector equipment of the experiments is not perturbed. Another technical problem is the integration of the electron guns for beam compensation, the low-beta insertion quadrupoles and an online luminosity-measurement facility into a closed control loop, which has to follow any changes of the LHC and the electron beam intensities starting from LHC injection to beam dumping during the whole filling cycle of LHC. The feedback system eventually has to compensate for the self-focusing and luminosity changes resulting from beam compensation in the relevant IPs.

The technological requirements to be fulfilled by the compensating lepton sources for linear colliders are less stringent than the IP compensation requirements in a circular collider. The number of charges per bunch is not so different, but linear colliders feature shorter bunch lengths and the current amplitudes can be one or two orders of magnitude higher than in circular colliders. Hence, pulsed operation of the compensating lepton guns is more suitable. In all linear collider schemes there is sufficient distance between the last element of the final focusing system and the focus, which gives a sufficiently large overlap for smooth charge and current self-neutralization of the high-energy bunches with the low-energy compensating lepton beams. Lepton beams with some charge, current and pulse length redundancy can be injected with initial energies of less than 1 MeV. The lower the injection energy the more redundancy in charge and space has to be provided for the correct completion of the self-neutralization process.

The most critical section of an accelerator driver for ICF is the target area, which is predestined for beam compensation. Near a fusion target very severe environmental conditions govern the performance of all elements in its vicinity. The pulsed electron sources for heavy ion beam compensation have to deliver not only sufficient charge for the (self-)neutralization of the ions, but have to withstand the severe radiation and contamination conditions induced by the fusion processes. Ceramic ferroelectrics can be considered as candidates for this application, since they have proven very reliable as trigger elements in high-power plasma switches [44]. Such electron sources could be placed rather near to the fusion target, e.g. at the entrance holes of the ion beams.

At present, there is an apparent lack of computational means to model and predict precisely beam compensation processes. The present particle-tracking methods used in conventional accelerator environments are not sufficient to describe properly the electrodynamic phenomena occurring during beam compensation interactions between different charged-particle species. A considerable effort is needed to provide well-matched models on the basis of fluid theory and magneto-hydrodynamics. Since, during self-neutralization the compensating leptons are rapidly accelerated, it is necessary to develop simulation methods which combine even relativistic fluid dynamics with classical accelerator methods. The development of appropriate models makes sense only if it can proceed in parallel with the preparation and operation of indispensable pilot experiments dedicated to the different applications of beam compensation.

5 CONCLUSIONS

If in future the high-energy physics community envisages the construction of accelerators with steadily increasing power density, beam compensation techniques have to be inevitably adopted to overcome the severe limitations caused by the high beam charge and current concentrations. In spite of the successful ATA experiment [8], a completely neutralized accelerator system remains a challenge for the far future. But already today beam compensation and neutralization can be applied in the critical sections of conventional high-intensity accelerators. Amongst the numerous possible neutralization schemes, the so-called ‘smooth’ and ‘redundant’ beam compensation can be economically realized with low-energy lepton beams. The ‘smooth’ compensation principle includes natural self-neutralization interactions between the different beam species, which are beneficial in comparison with the ‘hard’ compensation reactions between mutually penetrating, but non-neutralized high-energy particle bunches, as attempted with the DCI experiments [9, 10]. While some beam compensation devices can be designed and built in a straightforward way, the implementation in some other specific systems may involve non-negligible problems and a need for R&D to be carried through in pilot experiments with the aim to develop the adequate compensation techniques. In this article the aspects of beam compensation in a few specific parts of various types of accelerators have been investigated.

At the low-energy end of a hadron accelerator the ion source is a major bottleneck owing to ion beam space-charge (for example, in the lead ion beam injector for the LHC). Ion beam neutralization in the extraction gap of an ion source can remove the most severe natural intensity limitations of classical extraction, while full emittance preservation can be achieved. The higher the desired ion output current density, the stronger is the required compensating electron beam intensity. Pulsed electron beams injected from outside into the source are best suited to fulfil the space-charge neutralization conditions. Such a compensation scheme is very economic in comparison with the much more expensive and less efficient schemes for ion beam intensity enhancement based on ion accumulation and on electron cooling.

Another example for the application of neutralization techniques in the LHC is the neutralization of the high-intensity LHC bunches on each side of the interaction points in the solenoidal fields of the central detector magnets with low-energy DC electron beams. LHC beam compensation removes the increase of beam–beam tune spread occurring during bunch crossings at high LHC intensity. The beam compensation results in a simpler machine operation including easier luminosity control by the low-beta insertions and in a longer beam lifetime. Moreover some additional (self-)focusing and consequently higher luminosity could be reached, if desired, though attention has to be paid to the nonlinearities and asymmetries of self-focusing. Since luminosity can be adjusted within certain limits (in the range of one order of magnitude) experimental runs could be envisaged at constant luminosity, thus providing the most economic use of the expensive high-energy particles. As disadvantages one has to take into account the non-negligible energy to which the neutralizing electrons are accelerated by the LHC beam in the case of current neutralization. The surplus energy has to be dumped out of the IP region by electron beam deflection after bunch crossing. The (conventional) beam dumping hardware is not only the most massive material of the whole beam-compensation apparatus including the electron guns, but also the most expensive part. The operation with beam compensation, and especially with variable beam cross-section in the IPs, is only possible under the control of a non-trivial feedback loop including the electron guns, the low-beta insertion elements, and a continuous online luminosity-measurement set-up.

Future linear colliders are predestined for beam compensation. The reactions, which high-energy physicists want to study and for which the colliders are built, are (especially in TeV colliders) completely submerged in a variety of disastrous collective electromagnetic effects occurring in the final focus. With a smooth beam compensation system based on low-energy lepton beams the electromagnetic phenomena of pinching, beamstrahlung, pair and mini-jet production and beam spoiling after crossing can be fully eliminated. Since there is no beam blow-up, small angle observations are re-established for the high-energy physics experiments, which are also favoured by the choice of a very small crossing angle under neutralization conditions. With beam compensation the luminosity of the collider is given by beam currents and emittances and by the focusing characteristics of final-focusing lenses only, just like in a low-intensity machine. The linear collider beam compensation leads not only to striking improvements in design and performance, but can be, compared with other applications of beam compensation, rather simply and economically (in relation to total collider cost) realized with existing technology. The single-pass beam mode, the short beam neutralization lengths and the large space available in the final-focus region greatly facilitate the installation of the beam compensation equipment. A machine, like NLC at SLAC, could probably still be operated without beam compensation. It would be, however, very desirable to incorporate a beam compensation scheme for pilot-testing the method in a large collider. TESLA would certainly profit from beam compensation in terms of high-energy physics productivity, beam quality, higher compactness and probably reduced total cost. If TeV colliders are not just considered as expensive toys, but planned for efficient high-energy physics experiments, then the application of beam compensation at these energy levels is imperative.

The full deposition of total ion beam energy on a target for inertial-confinement fusion can be guaranteed by focusing the ion beamlets from a fusion-driver accelerator onto the target in the reactor chamber and by compensating for their charge and current out of reservoirs of low-energy electrons. The minimum spot size which can be achieved with the neutralized beams on the target is given by ion beam emittance and the characteristics of the final-focusing devices, which may be easily combined with the electron generators in the case of plasma lenses as focusing elements. The scheme widely benefits from the natural self-neutralization of the ion beamlets, when passing the electron reservoirs. Also the ICF driver beam compensation is cheap compared to the overall cost of the fusion plant.

Applications at other critical points of high-intensity accelerators, for example, at spallation source, at the exit of cooling and damping rings, where beam densities might have been brought up to the space-charge limit valid at the energy level of the accumulator rings, have not been considered in this paper and should be treated elsewhere.

The generation of compensating particle beams is well within the reach of today’s standard accelerator technology; hence, the application of such techniques is not only a matter for the future, but also a concern for the present. The best way to proceed now is to set up dedicated pilot experiments and to gain practical experience.

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