Halo Formation due to Beam-Beam Interaction

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Abstract

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TABLE 1. Energy, beam-beam tune shifts, and damping decrement for a few typical colliders

	beam energy [GeV]	tune shift per IP	total tune shift	damping decr. per IP
LEP	100	0.083	0.33	1.6×10^{-2}
KEKB	8, 3.5	0.097	0.097	2×10^{-4}
DAFNE	0.51	0.03	0.03	10^{-5}
LHC	7000	0.003	0.01	5×10^{-10}
Tevatron	980	0.01	0.02	5×10^{-12}

INTRODUCTION

In storage-ring colliders, the beam-beam interaction can generate beam halo. Different types of colliders may be distinguished according to the particles they bring into collision. Examples for lepton-lepton colliders are, in the order of increasing beam energy, AdA, DAFNE, BEPC, SPEAR, VEPP-4, CESR, KEKB, PEP-II, PEP, PETRA, TRISTAN, and LEP, all of which provide(d) electron-positron interactions. So far there have been only one lepton-hadron collider, HERA, and 4 hadron-hadron colliders, namely the CERN ISR, the SpS collider, the Tevatron, and RHIC. A fifth hadron collider, the LHC, is under construction at CERN. Table 1 lists beam energies, the beam-beam tune shift parameter ξ for a single interaction point (IP), the total tune shift parameter over all (n_{IP}) IPs, $\xi_{\text{tot}} = n_{\text{IP}}\xi$, and the damping decrement for a few representative colliders. The latter refers to the relative decrease in oscillation amplitude per turn. Beam energies range from a few GeV to several thousands of GeV. The beam-beam tune shifts per IP are of the order 0.003–0.01 for hadron colliders and about 10 times larger for lepton colliders.

In lepton colliders, radiation damping gives rise to a

‘steady-state’ equilibrium. Non-Gaussian beam tails may cause background and reduce the beam lifetime. They often limit the luminosity. In 1983, J. Seeman performed a comprehensive review [1] of experimental tails and performance limits in lepton colliders, comparing the experience at SPEAR, CESR, PETRA, and PEP. His observations were as follows. At low beam currents, the luminosity increases as the square of the bunch charge (equal for the two beams), and the beam-beam tune shift increases linearly. From a certain current value, known as the first beam-beam limit, the behavior changes, *i.e.*, now the vertical beam-beam tune shift stays constant, and the luminosity only increases linearly with further increasing beam current. The constant beam-beam tune shift is related to a blow up of the vertical beam size. The ultimate performance is reached at a higher current — the second beam-beam limit —, where the background becomes unbearable and/or the beam lifetime drops to unsustainable values. The background increase can be strongly nonlinear. As the beam current is increased, the tails expand, and the transverse scrapers, which usually ensure an adequate detector background, have to be further and further retracted from the beam, in order to maintain a reasonable lifetime. The second beam-beam limit is reached when the magnet openings near the interaction region cease to be in the shadow of the scrapers. J. Seeman noted that both the beam core and the tails grow in amplitude as a function of current. At the second beam-beam limit and for a 2-hour beam lifetime, the rms beam size of the blown up core corresponds to about 5% of the scraper opening, where the latter roughly equals the translated aperture of the low-beta quadrupoles. The factor of 20 between core size and aperture measures how far the tails extend to larger amplitudes. It was found to be a universal value for all machines, except for one notable exception: When, in a dedicated machine study at CESR, the verti-

cal IP beta function β_y^* was reduced from $\sigma_z/\beta_y^* \approx 0.4$ to $\sigma_z/\beta_y^* \approx 0.8$, the ratio of the scraper position to the rms core beam size increased from 20 to 30. Indeed, for this case the luminosity reduction due to the tail growth was three times larger than the purely geometric hourglass effect.

In hadron colliders, halo particles ‘never’ come back to the core. As in lepton machines, they cause background in the physics experiments. In addition, large tails and losses can destroy the collimators, and they may also lead to quenches of superconducting magnets. Beautiful examples are available from the Tevatron, where at the start of a physics store the halo is carefully removed by transverse scraping. After this beam cleaning, sometimes it takes only 20–30 minutes, before the background signal from proton losses again reaches the original level. The Tevatron losses are sensitive to tune, coupling, and chromaticity, and they can be reduced by a careful control [2]. However, attempts to adjust these parameters may temporarily lead to excessive losses and occasional quenches. Another observation from the Tevatron is that the emittance growth in collision greatly varies from bunch to bunch within a 12-bunch train, as well as from store to store, by up to factors of 4 or 5. Frequently, the emittance blows up quickly, *e.g.*, by 20–30% in the first 30 minutes of a store, for all bunches but the first and last in a train [2]. Due to its appearance on the Tevatron emittance summary display, this is called the ‘scallop’ effect [2]. The first and last bunches behave differently, because they are missing the closest long-range beam-beam encounters on one or the other side of the head-on IPs, and, thus, their tunes are different.

GENERATION OF TAILS

In the past, a number of theoretical tail-generating mechanisms have been proposed and studied. These include incoherent scattering processes, *e.g.*, beam-beam bremsstrahlung in LEP [3], stochastic diffusion in the limit of zero memory between subsequent collisions [4], Arnold diffusion [5], resonance trapping [6], phase convection [7], resonance streaming [8, 9], and modulational diffusion [5, 10]. In the following we describe in more detail (1) incoherent scattering, which was the dominant mechanism in LEP and will be for LHC ion-ion collisions, (2) resonance streaming, for generic lepton colliders, and (3) modulational diffusion, for hadron colliders.

In LEP, tails were measured by moving single collimator jaws into the beam and detecting the loss rate downstream using pin diodes and scintillators [3, 11]. The loss rates could be translated into a beam lifetime, which varied with the collimator position. Halo levels corresponding to beam lifetimes of 1000 to 10000 hours could be

detected. The observed variation of the halo density with amplitude was reproduced in particle-tracking simulations including beam-beam bremsstrahlung [3, 11]. The main effect was the change in energy of individual particles due to the inelastic scattering at the collision point. The differential probability of incoherent bremsstrahlung for a single collision per particle is [12]

$$\frac{dN}{dE_\gamma} \approx 0.4 \frac{1}{E_\gamma} \alpha \left(\frac{r_0^2 N_2}{\sigma_x \sigma_y} \right) \left[\ln \left(\frac{4\gamma^3 m_e c^2}{E_\gamma} \right) - \frac{1}{2} \right],$$

where $E_\gamma > E_c \equiv 4\gamma^2 \hbar c / \sigma_z$, and N_2 denotes the bunch population of the opposing beam. The LEP halo was sensitive to the dispersion at the IP, which could be varied by symmetric dispersion bumps. Comparisons between simulations and measurements at 46.6 GeV for a beam-beam parameter $\xi \approx 0.025$ showed a reasonable agreement [3, 11]. The remaining small discrepancies are attributed to different physical apertures in the simulation and in the real machine. At higher beam-beam parameters, additional tails were observed, which appeared to be of a dynamic origin. A combination of rare large scattering events due to incoherent beam-beam bremsstrahlung and beam-beam dynamics was also found to be the major source of beam halo in simulations for KEKB [13]. Experimental studies confirming this prediction are not yet available. For the similar PEP-II factory, the background due to beam-beam bremsstrahlung was estimated as tolerable [14].

Coherent bremsstrahlung occurs for $E_\gamma < E_c \equiv 4\gamma^2 \hbar c / \sigma_z$ with a probability [15] $dN/dE_\gamma \approx 0.2(1/E_\gamma) \alpha (r_0 N_2 / (\sigma_x))^2$. This process is relevant only for $E_\gamma < 4\gamma^2 \hbar c / \sigma_z$. Thus, most likely, it does not much contribute to tail formation.

Two other incoherent collision processes, which are expected to limit the maximum luminosity in LHC ion-ion collisions, are pair production followed by electron capture and nuclear excitation with subsequent neutron emission. The approximate event probability for neutron emission is [16]

$$N \approx \left(\frac{N_2}{4\pi\sigma_x\sigma_y} \right) (3.42 \mu\text{barn}) \frac{(A-Z)Z^3}{A^{2/3}} \ln(2\gamma^2 - 1).$$

The corresponding probability for electron capture [17] does not reduce to a compact expression, but it scales similarly with energy and roughly as Z^7 with the atomic number. Total cross sections for various ion species in the LHC vary between 0.1 and 514 barn [18]. In the case of electron capture and lead-ion collisions, the charge of a lead ion changes by 1 unit, which corresponds to a change in its effective relative momentum error $\Delta\delta = 12 \times 10^{-3}$. This error is so large, that the particle will be lost in the dispersion suppressor behind the IP. In the case of neutron emission, the mass of the ion changes

by one atomic unit, which translates into a momentum error of $\Delta\delta = -5 \times 10^{-3}$. Such ions may remain within the momentum aperture, and could survive for a number of turns, forming a beam halo. For other ion species the cross sections and the induced effective momentum errors would be different.

As indicated above for LEP, the generation of tails can be simulated. In standard macroparticle simulations only few particles end up in the tails and the statistical error can accordingly be large. In 1989, J. Irwin proposed an elegant iterative scheme of ‘self-generated’ boundary conditions’ which improves the tail resolution by a factor of 10 in each iteration step [19]. In the first step, a number of macroparticles is tracked for a certain number of turns. A border is then drawn in phase space outside of which 10% of the macroparticles are found. In the next step, the full number of macroparticles are launched outside this boundary. Whenever a particle enters the inner region, it is replaced by another particle that has moved from the inside to the outside during the first step. In the following step again a boundary is determined outside of which 10% of the particles of the second step are found. These now correspond to 1% of the initial distribution. This process can be repeated an arbitrary number of times, until the desired resolution has been achieved. The two key requirements for this recipe to work are, first, randomness (*e.g.*, due to quantum fluctuation) and, second, reaching an equilibrium at each step. This computing scheme was implemented in two independent codes by D. Shatilov (‘lifetrac’ program) in 1992 [20], and by T. Chen and coworkers around 1993 [21]. These codes do not only include the beam-beam dynamics at the primary IP, but also model some additional effects such as frequent small-angle scattering, and parasitic collisions. They were applied to VEPP-2M, PEP-II, and DAFNE. In 1997, E.-S. Kim and K. Hirata developed a macroparticle algorithm incorporating rare large-angle scattering, which was employed in simulations for KEKB [13]. Rapid advance in computing power may soon render unnecessary the use of sophisticated simulation schemes. Examples for brute force macroparticle tracking are the TRS code by Tennyson [22] and K. Ohmi’s code [23]. Typical numbers of ‘particle $\times$ turns’ considered in the simulations range from a few 10^8 to several 10^9 . All the above codes were written for lepton colliders. Remarkable results were obtained by D. Shatilov [20] and by T. Chen [21], who superposed simulated beam density distributions and resonance lines, calculated in first order perturbation theory, on the transverse action space, and, thereby, revealed the role of individual resonances in the tail formation. Synchro-betatron resonances of typical order 5 to 8 were found to be important in PEP-II. The specific set of resonances strongly varied with the synchrotron tune [21]. Both Chen’s and Shatilov’s codes were also used to simulate the combined effect of

TABLE 2. Tune sensitivity of beam tails, beam lifetime and background, observed at various lepton and hadron colliders

accelerator	sensitive tune $ \Delta Q $	reference
ISR	0.002	Keil et al., 1975 [27]
SPS	0.001	Meddahi et al., 1991 [28, 29]
HERA	0.002	Willeke, 1997 [30]
VEPP-4	0.001	Temnykh et al., 1989 [31]
DAFNE	0.001	Boscolo et al., 1999 [32]
KEKB	0.001	Ohmi et al., 2003 [23]
LEP	0.001	Burkhardt, 2003 [33]
RHIC	0.001	Fischer, 2003 [34]
Tevatron	0.001	Zhang, 2003 [2]

beam-beam interaction and scattering off the residual gas for PEP-II. In T. Chen’s simulations the inverse lifetime was found to be the sum of the inverse lifetimes of the two processes computed separately [24], whereas in the earlier simulations by Shatilov and Zholents a large enhancement was seen [25]. Unfortunately, the PEP-II tail simulations have not been benchmarked against experiments [26]. K. Ohmi’s simulations of the present KEKB with 22 mrad crossing angle show tails extending to 30 rms beam sizes in the vertical plane [23]. Without crossing angle (or with crab crossing) the tails are reduced to about 20σ , consistent with Seeman’s rule of thumb [1]. For the Super-KEKB upgrade, they will again be similar to the present situation. DAFNE simulations with the lifetrac code show a strong sensitivity of the tails to the working point, easily changing by a factor 2 or 3 in amplitude for tune changes of 0.002 or less. An impressive agreement between simulated and measured optimum working point for maximum luminosity was achieved with a tune precision of about 0.001 [32].

That the tails are sensitive to tune changes of 10^{-3} , *i.e.*, much smaller than the incoherent tune spread, was observed at many colliders, both with lepton and hadron beams, as is illustrated in Table 2. Tune scans at RHIC parallel to the main diagonal unveiled the different influences of 9th, 13th, 14th, and 17th order resonances [34], causing changes in the background level by a factor of 2 or 3. Surprisingly, the background on the 13th order resonances was better than that on resonances of 17th order [34]. In the Tevatron, two-dimensional scans were conducted, for both protons and antiprotons. Loss rates here vary by a factor 100 depending on the working point [2]. Among the lepton colliders an outstanding example is KEKB, whose automatic tune feedback system continually controls the working point with a precision of a few 10^{-4} [23]. At KEKB, the tune-feedback set point depends on the beam current (thus taking care of coherent tune shifts due to impedance and electron-cloud effects) and the target values are different in collision and

at injection. The tune feedback uses the signal from non-colliding pilot bunches in either ring, so as to avoid complications from the beam-beam interaction (*e.g.*, strong Landau damping and beam-beam induced tune spread). That it is not always easy to detect the tunes with the necessary accuracy, especially with beams in collision is illustrated by typical Schottky spectra from the Tevatron, which exhibit a multitude of synchrotron sidebands, signals from the other plane or from the opposing beam and a superposition from different bunches, as well as noise ‘ghostlines’ wandering about in frequency.

The strong sensitivity to the working point hints at the importance of resonances. In general, resonances are of the form $mQ_x + nQ_y + oQ_s = q$, where m , n , o and q denote integers, and the Q_i ’s are the betatron and synchrotron tunes. The sum $|m| + |n| + |o|$ is the resonance order p . Conversion from transverse phase-space coordinates x and x' to the action-angle variables I_x and ϕ_x proceeds, *e.g.*, in the horizontal plane, via $x = \sqrt{2I_x/\beta_x} \sin \phi_x$, and $x' = \sqrt{2I_x/\beta_x} (\cos \phi_x - \alpha_x \sin \phi_x)$. Two important parameters characterize the resonance islands: the total island width in the action space ΔI_{tot} and the island tune Q_i ; the latter is the rotation frequency around the island center in units of the revolution frequency. The island tune induced by head-on beam-beam collisions assumes a maximum value at a certain amplitude, that increases with the resonance order. For PEP-II this maximum is reached at about 2σ for a 4th order resonance and at about 8σ for a resonance of 16th order [21]. The resonance width increases monotonically with amplitude.

In 1981, J. Tennyson proposed the mechanism of resonance streaming to explain the vertical tails and the beam-beam limit observed in SPEAR [8, 9]. Here an external diffusion or dissipation, *e.g.*, radiation damping or quantum excitation, is enhanced in the vicinity of a resonance. The enhancement is particularly pronounced, if the contour of constant energy intersects the resonance line at a shallow angle ψ in the 2-dimensional action space (I_x, I_y) . A small change in energy due to the external diffusion can then translate into a change of the resonance oscillation center that is larger by a factor $1/\sin \psi$. Further denoting the angle between the direction of external diffusion and the energy surface by χ and the external diffusion coefficient far from the resonance by D_{ext} , the enhanced diffusion coefficient close to the resonance becomes $D = D_{\text{ext}} \sin^2 \chi / \sin^2 \psi$. This mechanism appears to be the dominant transport process in lepton machines, and has surfaced in many tail simulations.

In hadron colliders, tune modulation, *e.g.*, due to power-supply ripple or ground motion, is thought to be responsible for much of the diffusion observed. The tune modulation introduces sideband resonances around the primary resonances. The size of the sidebands depends on the modulation frequency, the modulation amplitude,

the size of the primary resonance and the detuning with amplitude. If the modulation frequency is near the island tune, adjacent sidebands overlap and the motion becomes chaotic already for extremely small modulation amplitudes. In the parameter plane spanned by the modulation depth q and the modulation tune Q_m , the chaotic region is roughly bordered by the three lines [35] $(q/Q_I)(Q_m/Q_I) = 1/p$, $(q/Q_I)^{1/4}(Q_m/Q_I)^{3/4} = 4/(p\pi)^{1/4}$, and $(q/Q_I)(Q_I/Q_m) = 1/p$, where p is the resonance order. The destruction of resonance islands by tune modulation was verified in the E778 experiment at Fermilab [36]. Studying a simple simulation model of the beam-beam interaction with tune modulation, in particular the chaotic motion near a primary 1-dimensional resonance with weak coupling to a second resonance [37, 38], T. Satogata found an exponential growth in amplitude instead of the diffusive growth predicted by the conventional theory of modulational diffusion [10]. Moreover, normalizing the distance to the coupling resonance as $\alpha \equiv \Delta Q/q$, the simulated growth rate shows steep downward jumps at every integer of α , whereas steps are predicted at every second integer only (however, the theoretically predicted integer differs by one unit depending on whether or not the driving resonance is also modulated [10]). More theoretical studies of modulational diffusion are clearly needed.

DIFFUSION

One of the most important results of the Sp̄pS collider is the necessity of matching the beam sizes of the two colliding beams. If the emittance and intensity of one beam was reduced by scraping, the loss rates of the other beam increased by a factor of 2 [28, 29]. When colliding beams with 20% different beam sizes, the emittance of the larger beam decreased and the emittance of the smaller slightly increased, until the sizes became equal after about 3 hours [28, 29]. These observations indicate fast particle losses at large amplitudes. It is controversial how well the proton tail growth and particle losses in hadron colliders can be parametrized by a diffusion process. While good local fits to a diffusion model have been obtained for collimator experiments at HERA [39], diffusion was found to be inconsistent with various tracking simulations (*e.g.*, survival plot vs. no. of turns [7], or the beam-beam model of S. Peggs & T. Satogata [38]), and also with SPS scraper measurements [7]. A. Gerasimov suggested to employ a generalized ‘jump and diffusion’ model [7]. The transverse speed of the beam halo was measured at the Sp̄pS collider using collimator retraction by B. Jeanneret and colleagues [40]. At HERA, M. Seidel fitted local loss rates recorded after moving a collimator both into and away from the beam to a diffusion

TABLE 3. Transverse diffusion speed at different amplitudes measured in three hadron colliders

acc.	ampl.	growth [$\mu\text{m}/\text{turn}$]	growth [$10^{-4} \sigma/\text{turn}$]
SpS [40]	6, 9 σ	0.13, 0.9	1, 7
HERA [39]	5, 6.5 σ	0.05, 0.25	0.6, 3
RHIC [41]	6, 9 σ	0.25, 20	2, 200

model [39]. Measurements for the inward and outward movements of the HERA collimator resulted in the same fitted diffusion coefficient. R. Fliller III has performed similar studies at RHIC [41]. The measurements in both HERA and RHIC can be described by a diffusion coefficient which steeply increases with transverse action as $B \equiv \langle \Delta I^2 \rangle / \Delta t \approx a J_x^n$ with $a \approx 0.1 \mu\text{m}^{2-n}\text{s}^{-1}$ and $n \approx 5$. M. Seidel could reproduce the observed diffusion in a simple beam-beam simulation with a random tune drift of amplitude 5×10^{-5} (0.1 s correlation time) and a harmonic tune modulation of amplitude 2×10^{-4} at 1200 Hz [39]. A few measured data points are compared in Table 3. The transverse speed of escaping particles is nearly the same for all three machines. In the case of HERA and RHIC we estimated the transverse motion per turn as $\Delta x \approx \sqrt{\beta D T_0 / I}$, where T_0 is the revolution period, D the diffusion coefficient at action I , and $\beta \approx 100$ m.

Tail simulations for the PEP-II B factory revealed a strong effect of a single parasitic collision on either side of the primary collision point [24]. Large tails develop, if the separation is less than 8σ . Long-range collisions are an even greater concern for the hadron colliders. They perturb the motion at large betatron amplitudes, where particles come close to the opposing beam, thereby causing a ‘diffusive’ aperture [42], *i.e.*, a sudden steep rise in chaotic diffusion, high background, and poor beam lifetime. This problem increases in importance from the SpS, over the Tevatron, to the LHC. At the SPS a pretzel scheme separated the two beams over most of the ring, except at three head-on collision points [29]. Most of the 9 long-range encounters had a separation of 6σ , but the closest was only 3σ . When the pretzel orbit was reduced by a factor of 2, the background rates increased almost 4 times [28, 29]. At the Tevatron, the number of parasitic encounters is 70. The beams are separated on a helical orbit, created by electrostatic dipoles. The experience is similar to the SPS. The beam lifetime drops and the loss rates increases, if the helix size is decreased from the nominal value [2]. In the LHC, there will be 30 long-range collisions around each of the 4 primary collision points, before the beams are separated into two separate pipes. The total number of long-range encounters is 120. Weak-strong simulations predict the ‘diffusive aperture’ at about 6σ [43]. The diffusion coefficient outside this diffusive aperture can be estimated analytically [44]. A

simplified model which combines the diffusion due to intrabeam scattering, gas scattering, and long-range collisions predicts the time evolution of loss rates and the beam profile during a physics store in the LHC [46]. The long-range collisions act as ‘dynamic collimators’ and deplete the beam halo above 6σ . An ongoing experiment at the CERN SPS models the combined effect of all LHC long-range beam-beam collisions by a 1 m long longitudinal wire fed with 267 A current [45]. At amplitudes above 8 mm ($\beta \approx 50$ m), the wire should induce a diffusive aperture with a typical transverse diffusion speed well above 1 mm per second. In first experimental tests during the 2002 SPS run, varying the distance between the center of the wire and the beam resulted in a large increase of particle loss and a steep reduction in beam lifetime when the separation decreased below 9σ [45]. This is consistent with the simulated effect of changing the crossing angle in the LHC [43].

COUNTERMEASURES

There are a few basic rules for reducing beam tails, namely the beam sizes should be matched, the collisions should be centered, and the tunes should be optimized. Also the tails are smallest for zero crossing angle. Nonlinear magnetic elements can modify the resonance parameters at large amplitudes [31, 47]. Octupoles were used at VEPP-4/VEPP-2N and at DAΦNE. The octupoles have two converse effects: they either reduce the tune footprint or they decrease the width of resonances and ‘unfold’ the detuning with amplitude. Which of these two effects prevails has so far been decided experimentally. Wherever possible, a self-compensation should be introduced, such as a cancellation of long-range beam-beam forces by alternating horizontal and vertical crossing at two interaction points [48, 49], or by an additional cancellation between long-range and near collision effects for superbunches [50]. Lepton tails may be suppressed using quadrupole wigglers [51]. In the future, tails of hadron beams could be cooled by means of optical stochastic cooling or electron cooling.

Tune modulation due to power-supply ripple can be suppressed either by active filters or by a tune modulation feedback on the beam. The second option was demonstrated at HERA in 1996 [52]. A tune monitor detected tune modulation of amplitude 10^{-5} in the few 100 Hz frequency range. Additional tune modulations locked to the power supply frequency were introduced, whose phases and amplitudes were adjusted, so as to cancel individual lines in the beam tune spectrum. Cancelling two 300-Hz lines and one 600-Hz line, the proton loss rate in HERA was reduced by 40% [52]. Finally, wires, like the SPS wire mentioned above, can compensate for the

effect of long-range collisions [53], or an electron lens may counteract both head-on and long-range beam-beam effects [54]. The wire-based compensation under study for the LHC employs a local correction on either side of each IP, where the beams are already separated. Simulations promise an increase in diffusive aperture by 1 or 2σ [55]. Understandably, the correction ceases to work close to the opposing beam.

CONCLUSIONS AND THANKS

Impressive simulations with a high predictive power are available for modern lepton colliders, though a few unsettled discrepancies remain between codes and machines (*e.g.*, concerning the combined effect of gas scattering or coherent bremsstrahlung and beam-beam). For hadrons, the transverse amplitude-dependent diffusion rates in the SpS, HERA, and RHIC are extremely similar. The Tevatron Run-II and the LHC enter a novel regime where long-range collisions are the dominant perturbation. The latter cause fast losses and deplete the beam halo. Examples from LEP and the LHC ion operation have demonstrated the possibility of new and surprising incoherent effects, that in some cases may dominate the halo production. Various methods to manipulate the beam tails are available or under study, for example octupoles, Tevatron electron lens, and the long-range beam-beam compensation using current-carrying wires.

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