FIREBALL HYPOTHESIS FOR THE TRIGGER OF SUDDEN BEAM LOSSES AT SuperKEKB

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Abstract

Although we need to increase stored beam currents to improve the luminosity, we have faced a serious obstacle of sudden beam losses (SBLs) in the main ring of SuperKEKB. This study examines whether SBL occurs by the same mechanism as observed in vacuum breakdown of accelerating cavities, that is triggered by a hot microparticle “fireball”.

INTRODUCTION

SuperKEKB is an asymmetric-energy electron (e^-) and positron (e^+) ring collider with a higher-energy (7 GeV) e^- beam and a lower-energy (4 GeV) e^+ beam stored in the low emittance double ring (main ring) with a circumference of 3 km and an rf frequency of 509 MHz. The design beam currents to be stored in the main ring are 2.6 A and 3.6 A for HER and LER, respectively.

We performed the phase 1 beam operation of SuperKEKB from February to June in 2016. In this phase, we had no Belle II detector component nor final focus magnets in the interaction region with no e^+e^- beam collision. The main purposes of this phase are vacuum scrubbing, low-emittance beam tuning, and beam background study for the Belle II detector to be installed before the next phase. We installed and used two horizontal beam collimators in the main ring tentatively during the phase 1 with a large physical aperture at the heads. Before starting the phase 2 beam operation in March, 2018, the Belle II detector components with a part of the beam-sensitive vertex detectors were installed at the interaction point. We installed the super-conducting final focus magnet system in the interaction region, and four more horizontal beam collimators and two vertical ones in the main ring. The major purpose and achievement in the phase 2 is that we have successfully demonstrated the nano-beam collision scheme [1] at SuperKEKB. The crux of the scheme is that the beta function at the interaction point (β_y^*), whose inverse is roughly proportional to the luminosity, can be squeezed down to values smaller than the bunch length for higher luminosities with suppressing the hourglass effect. So far, the smallest β_y^* and beam size have been achieved at SuperKEKB in the world among the colliders. After the phase 2 ended in July, 2018, we started the phase 3 beam operation in March, 2019, with seven (four) horizontal (vertical) beam collimators for LER and eleven (nine) horizontal (vertical) ones for HER, where the minimum physical aperture at the beam-collimator head was around ±1 mm depending on the beam operation status to suppress beam backgrounds at the Belle II detector. Those small physical apertures are inevitable in the nano-beam collision scheme because the smallest physical aperture at a beam-collimator head is roughly proportional to β_y^* in the scheme. The phase 3 is dedicated to taking physics data by the Belle II detector, where increasing the beam currents is another solid direction in the luminosity improvement. However, we have faced a serious obstacle in increasing the beam currents: sudden beam losses (SBLs), to be described in the next section. We observed no SBL in the phase 1 of SuperKEKB nor in the KEKB era.

In this paper, a hypothesis is proposed that SBL can occur by the same mechanism as observed in Ultra-High-Frequency (UHF) Continuous-Wave (CW) accelerating cavities, that is triggered by a hot microparticle (named “fireball” by the author). This hypothesis (fireball hypothesis) could give new directions and perspectives on overcoming the SBL obstacle, and on future high-intensity lepton accelerators.

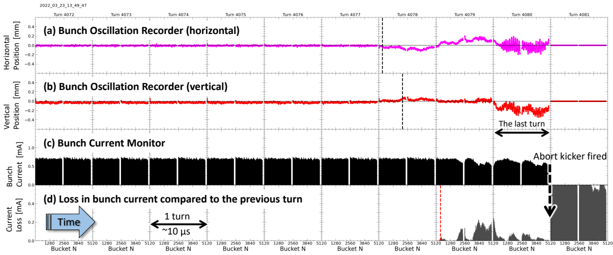

Figure 1: Example of SBL shown in Fig. 4 of [2]. Bunch-by-bunch (a) horizontal and (b) vertical positions, and (c) bunch current were measured in one of the straight sections of the SuperKEKB main ring. (d) Difference in the bunch current from that in the previous turn.

SUDDEN BEAM LOSS (SBL)

Figure 1 shows an example of SBL events. The most significant feature of SBL is a short time between the start of the beam-bunch position change or bunch-current loss and the beam abort timing, which is typically a few tens of microseconds, much shorter than those in common beam instabilities of the order of a millisecond or longer. The typical time of a few tens of microseconds is mostly the time from significant beam loss detection around a beam collimator or the Belle II detector to dumping beam bunches by the fast abort system. SBL can lead to serious damages on beam collimators (e.g. see Fig. 27 in [3]) and/or the Belle II detector, and can cause quench of the super-conducting final-focus magnet. At SBL, no significant beam-size change

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was observed with an X-ray monitor and an ultrahigh speed camera [2]. No change in the beam phase relative to the phase of the rf system was also observed, i.e., no energy loss observed in SBL. Therefore, the beam bunches were suddenly kicked in the transverse direction in microseconds. We have confirmed that no machine component is related to SBL by careful monitoring of the performance. SBL occurred at not only LER but also HER, not simultaneously but exclusively. The occurrence rate seems to depend on the bunch current with a threshold around 0.7 mA/bunch in the case of LER although that has not yet been confirmed due to the low statistics of SBL events.

There are several hypotheses to explain the trigger mechanism of SBL, including vacuum arcs at rf contacts, dust-beam interaction, and electron cloud. However, it is difficult for any hypothesis to explain the fast phenomena with a significant transverse kick in SBL except for the fireball hypothesis. This hypothesis is based on the vacuum breakdown mechanism observed in UHF CW accelerating cavities triggered by a fireball with a progression time shorter than a microsecond, to be explained in the next section.

FIREBALL BREAKDOWN IN UHF CAVITIES

Vacuum breakdown can be caused by a vacuum arc in an accelerating cavity, that could limit accelerator performance. It has been revealed by recent experimental studies that such vacuum arcs are mostly triggered by a hot microparticle[1] in UHF CW cavities [4, 5]. The physical process is:

1. A microparticle in a vacuum with a high sublimation point, e.g., carbon and molybdenum which are typical heater materials in high temperature furnaces for brazing, is heated by a high field of microwave in the cavity, turning into a fireball with a temperature reaching 1000 °C or higher, where the thermal conductivity between the microparticle and a metal surface of the cavity body is tiny if the fireball is attached on the cavity surface, or the microparticle is flying in a vacuum inside the cavity;
2. The fireball lands on a cavity surface with a relatively low sublimation point, e.g., copper;
3. Plasma is generated around the fireball landing point; and
4. The plasma eats the field energy in the cavity, leading to vacuum breakdown.

At any breakdown explained above (fireball breakdown), the microwave field level in the cavity drops rapidly in a time shorter than 1 µs, meaning that the generated plasma at the fireball landing point absorbs the field energy in a time scale of 100 ns. Because the typical stored field energy in a UHF CW cavity is 1 J, the absorbing power is several megawatts. Another feature is a current flash; significant X-ray is detected at the moment of any fireball breakdown during high-power operation with no beam injection into the cavity, where the X-ray is caused by impacts of electron currents on a cavity metal surface. The speed of the plasma evolution immediately after fireball landing can be estimated from the fast drop in microwave level in the cavity. The evolution time to become a macroscopic vacuum arc is of the order of 100 ns in the case of UHF cavities, that is much shorter than the revolution time of the SuperKEKB main ring (≈ 10 µs).

This phenomenon is not so frequent; the average breakdown rate of the thirty ARES cavities used for SuperKEKB LER and HER was 0.5/cavity/(four months) during beam operation in 2022 at an average cavity voltage (V_c) of 0.42 MV, which is approximately one breakdown of any ARES cavity per week[2]. On the other hand, the breakdown rate of the accelerating cavities for the SuperKEKB damping ring (DR cavities) is roughly 4.1/cavity/day at $V_c = 0.9$ MV estimated from the high-power tests at the test stand after rf conditioning at $V_c > 0.9$ MV. Assuming that the breakdown rates are the same between the ARES and DR cavities (at least, the mechanical structures are the same except for the coupling cavity of the ARES three-cavity system), the breakdown rate is roughly proportional to the ninth power of the cavity voltage. This strong field dependence can make a quasi threshold for the occurrence rate of fireball breakdown, that is reminiscent of the bunch-current dependence of the SBL occurrence rate.

Importantly, an essential situation for fireball breakdown is coexistence of different materials with largely different sublimation points in the same place.

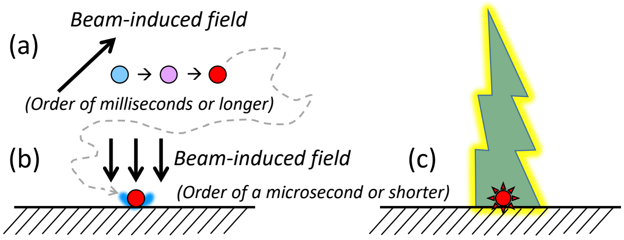

Figure 2: Physical process proposed in the fireball hypothesis. (a) A microparticle with a higher sublimation point is heated by a beam-induced electromagnetic field into a fireball. (b) The fireball landing on a metal surface with a lower sublimation point, plasma (shown with blue in this figure) is generated around the landing point with high electromagnetic fields applied. Then the plasma eats the field energy for evolution. (c) Large currents from the evolved plasma interacting with beam particles significantly.

FIREBALL HYPOTHESIS FOR SBL

Beam collimators at SuperKEKB have two different materials with largely different sublimation points: the beam-collimator head made from tantalum, tungsten, or carbon, and vacuum chamber made from copper. Therefore, fireball breakdown can occur around the beam collimators in principle. In this section, detailed physical process leading to

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[1] also called a dust or a particulate

[2] There has been no significant change in the average breakdown rate since the KEKB era.

Table 1: Simulated equilibrium temperatures in Celsius of spherical microparticles made from tungsten. The time in second to reach 1000 °C from 30 °C is also shown in parentheses. ϵ_e and ϕ indicate emissivity and diameter of the microparticle, respectively. d indicates the transverse distance between the beam bunch and the center of the microparticle.

	$\epsilon_e = 0.1$		$\epsilon_e = 0.2$		$\epsilon_e = 0.3$	
ϕ [mm]	d = 2 mm	5 mm	2 mm	5 mm	2 mm	5 mm
0.01	1019 (0.4)	595	842	467	748	400
0.05	1600 (0.7)	802	1253 (0.7)	597	1079 (0.9)	495
0.10	1542 (1.6)	767	1194 (1.9)	567	1022 (2.6)	469
0.50	1670 (6.6)	819	1293 (7.3)	607	1107 (8.5)	503
1.00	1704 (12)	763	1322 (13)	558	1133 (15)	458

Table 2: The same as in Table 1 for tantalum.

	$\epsilon_e = 0.1$		$\epsilon_e = 0.2$		$\epsilon_e = 0.3$	
ϕ [mm]	d = 2 mm	5 mm	2 mm	5 mm	2 mm	5 mm
0.01	923	534	759	421	673	362
0.05	1687 (0.4)	904	1347 (0.4)	695	1175 (0.5)	589
0.10	1625 (1.0)	877	1284 (1.1)	668	1113 (1.3)	564
0.50	1799 (3.7)	940	1423 (4.0)	718	1235 (4.3)	607
1.00	1830 (7.0)	896	1449 (7.4)	679	1258 (7.9)	570

SBL based on the fireball breakdown mechanism shown in Fig. 2 is investigated, and then the possibility of occurrence of each step of the process is discussed.

Physical process

The process is divided into three elementary steps:

1. A microparticle with a higher sublimation point is heated by a beam-induced electromagnetic field into a fireball (step 1) shown in Fig. 2(a);
2. The fireball lands on a metal surface with a lower sublimation point, leading to plasma generation and evolution (step 2) shown in Fig. 2(b); and
3. There is a significant interaction between currents from the evolved plasma and beam particles circulating in the SuperKEKB main ring (step 3) shown in Fig. 2(c).

Step 1: Heating of a microparticle into a fireball This step is examined based on a first-principles simulation using `CST Particle Studio` to calculate temperatures of microparticles located and fixed near a beam bunch. The equilibration temperature is determined by the heat value and thermal radiation power, where the microparticle is located inside a vacuum duct with no contact with any solid. The results for microparticles made of tungsten or tantalum (materials of the SuperKEKB beam-collimator heads) are shown in Table 1 and Table 2, respectively, for a bunch length of 6 mm, total current of 900 mA, and 1272 bunches per ring, which is a typical set of operational parameters for SBL at LER. The results show that fireballs can be generated realistically if a submillimeter or smaller microparticle gets to a few millimeters from a beam bunch for a second with a low emissivity of the fireball material. It is also revealed that fireballs can be generated more probably around tantalum than tungsten.

In the fireball hypothesis, a microparticle is assumed to come from a surface of or close to a beam-collimator head, where the microparticle should be charged up, negatively in LER or positively in HER to get close to a beam bunch for a certain time. Some experiments and theories indicate that microparticles can be charged up by irradiation negatively or positively depending on the situation [6]. The heads of the SuperKEKB beam collimators are subject to strong synchrotron radiations during beam operation, so that microparticles around beam-collimator heads have a chance to be charged up positively or negatively. Similar phenomena were observed in the photon-factory ring accelerator PF-AR at KEK [7].

Step 2: Fireball landing and plasma generation Even though we do not know the details in this step, we can parameterize the physics with two parameters: the current of electrons and metal ions from and the initial temperature of the plasma because only the two quantities are related to the interaction with beam particles to be described in the next step.

During this step, the fireball material is assumed to break up into infinitesimally small pieces, and will not be taken into account in the next step; only the currents from the evolved plasma will interact with beam particles.

Step 3: Significant interaction with beam The interaction between the currents from the evolved plasma and beam particles is calculated using first-principles Particle-In-Cell (PIC) simulation of `CST Particle Studio` (CST PIC solver) for a vertical beam collimator of SuperKEKB LER with a ±2 mm physical aperture at the head. A fireball is assumed to land 17 mm away from the center of the head in the beam direction ($z = -17$ mm at $y < 0$), indicated by the vertical red cone in Fig.3. Equinumerous e^- and copper ions (Cu^+) are generated at the fireball landing point, emitted in the normal direction to the copper surface plane with an angular spread of ±45°. The emission time is modeled as a gaussian function with one-sigma width of 1 µs, where this simulation covers the time period of five-sigma, i.e., the simulated time (t) reaches $t = 10$ µs with a peak emission current ($I_{\rm peak}^{(emi)}$) at $t = 5$ µs. The initial velocities of emitted particles at the fireball landing point are determined by the initial temperature ($T_{\rm ini}^{(emi)}$) according to the Maxwell distribution. The two parameters of $I_{\rm peak}^{(emi)}$ and $T_{\rm ini}^{(emi)}$ determine the parameterization of this simulation model. Positron bunches with a bunch length of 6 mm and a bunch charge of 7 nC come with a two-bucket spacing, i.e., approximately at a 4 ns interval, which is a typical parameter set for SBL at LER. In this condition, the peak electric and magnetic field strengths at the fireball landing point due to the beam bunch are approximately 2.8 MV/m and 7.4 kA/m, respectively, which are roughly the same as those on the inner surface of UHF cavities during high-power operation (e.g. see [5]). In the early stage of this simulation, emitted e^- moves from the side of the fireball landing point ($y < 0$) to the other side ($y > 0$) at every passage of beam bunches in a time scale of 10 ns. On the other hand, Cu^+ can not significantly move in this time scale due to the heavy mass; they significantly move in a time scale of 1 µs. In any case, no current can be emitted from the fireball landing point if the charge density reach the space charge limit at the kinematic energy of emitted particles.

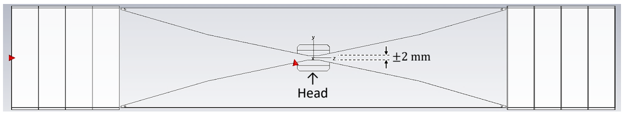

Figure 3: PIC simulation for the SuperKEKB beam collimator. The red cones indicate particle sources. The horizontal cone in the left-hand side is for e^+ beam bunches with 7 nC/bunch, 6 mm bunch length, and 4 ns bunch spacing. The vertical cone is for plasma particles consisting of electrons and copper ions emitted at the same point.

What to calculate is a transverse kick angle (k_y) during the beam bunch passage. Setting up zero transverse momentum in the initial state, the transverse kick angle is calculated as:

$$k_y = P_y/P_z \tag{1}$$

where P_y (P_z) indicates the y-directional transverse (z-directional longitudinal) momentum of the beam bunch after it passed. The momentum and its standard deviation of the beam bunch is calculated as:

$$P_y = \frac{1}{Q_b}\sum_{i=1}^{N_{\rm mp}} p_y^{(i)} q^{(i)} \tag{2}$$

$$\Delta P_y = \sqrt{\frac{1}{Q_b}\sum_{i=1}^{N_{\rm mp}} \left(p_y^{(i)} - P_y\right)^2 q^{(i)}} \tag{3}$$

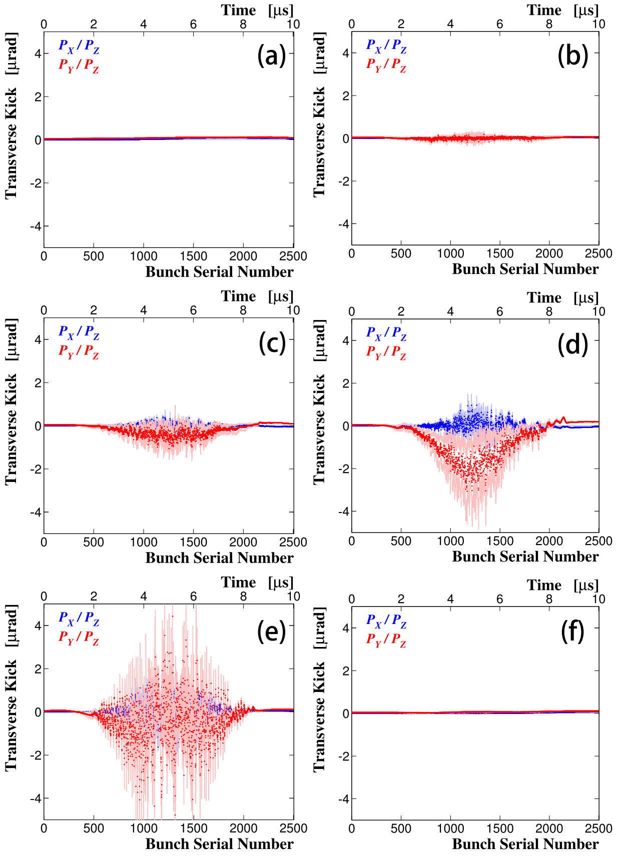

Figure 4: Kick angles of e^+ beam bunches simulated with the CST PIC solver up to $t = 10$ µs of one revolution time of the SuperKEKB main ring. (a) No particle emission from the fireball landing points. (b) to (e) for $I_{\rm peak}^{(emi)} = 70$ A and $T_{\rm ini}^{(emi)} = 1000, 10\,000, 300\,000, 1\,000\,000$ °C, respectively. (f) in the same conditions as in (d) except that no Cu^+ is emitted, i.e., only e^- emitted.

and the same for P_x and P_Z, where $p_y^{(i)}$ ($q^{(i)}$) indicates the y-directional transverse momentum of particles (electric charge) of the i-th macroparticle in the PIC simulation for the beam bunch, Q_b is the bunch charge (7 nC), and $N_{\rm mp}$ is the number of macroparticles in the beam bunch (= 266). The kick angle should be non-zero if there are particle emissions from the fireball landing point, leading to interactions between the e^+ beam bunches and emitted particles of e^- and Cu^+. However, the kick angle can be non-zero even with no particle emission at the fireball landing point, i.e., $I_{\rm peak}^{(emi)} = 0$, due to some numerical noise. Figure 4(a) shows kick angles of the 2500 e^+ beam bunches (up to $t = 10$ µs) with no emission at the fireball landing point. There are non-zero kick angles of the order of 100 nrad, but they are negligibly small because significant kick angles for SBL should be around 1 µrad or larger. On the other hand, Fig. 4(b) shows kick angles with particle emissions at the fireball landing point with $I_{\rm peak}^{(emi)} = 70$ A and $T_{\rm ini}^{(emi)} = 1000$ °C, where 70 A is the same as the peak current of the e^+ beam bunch in this simulation, and 1000 °C is the typical temperature of fireballs. There is no significant kick even in Fig. 4(c) for $T_{\text{ini}}^{(emi)} = 10\,000$ °C. Significant kicks appear for $T_{\text{ini}}^{(emi)} > 100\,000$ °C as shown in Fig. 4(d) where the e^+ beam bunches are attracted by the emitted e^- at the fireball landing point at $y < 0$. However, too high temperature does not lead to large kick angles as shown in Fig. 4(e). For $I_{\text{peak}}^{(emi)} = 70$ A, several hundreds of thousands degrees Celsius leads to significant kick angles around 2 µrad for the beam bunch center of charge.

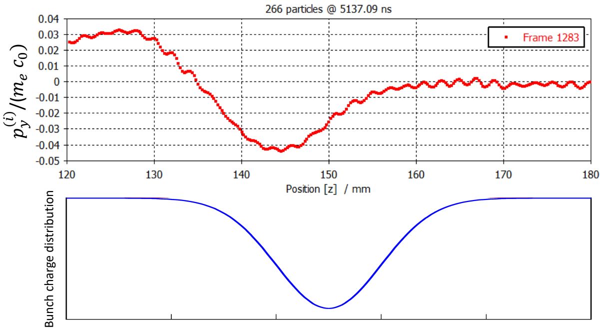

Figure 5: Transverse normed momenta (upper) and electric charges (lower) of the macroparticles of the beam bunch as a function of the z position in the beam direction for Fig. 4(d) at $t = 5137.09$ ns. m_e and c_0 are the electron mass and speed of light in vacuum, respectively. Normed momentum of 0.01 roughly corresponds to a kick angle of 1 µrad for LER.

The kick angles in Fig. 4(d) reach around 4 µrad at the largest including the standard deviation, which means that kick angles of each macroparticle are different inside a beam bunch. Figure 5 shows an example of transverse momenta of the macroparticles inside a beam bunch after it passes as a function of the z position, showing a significant gradient. The first half of the beam bunch is lightly kicked, on the other hand, the second half is largely kicked, which is consistent with the observation that not all but a part of a beam bunch is lost in most of the SBL events. According to this simulation, the first half of a significantly kicked beam bunch can survive in SBL in this case.

Figure 4(f) shows kick angles in the same conditions as in Fig. 4(d) except for copper ions: no Cu^+ emitted in Fig. 4(f), i.e., only e^- emitted at the fireball landing point. This means that Cu^+ ions can push up the space charge limit of emitted e^-. Figure 4(e) indicates that too high initial temperature does not make the average kick angle larger.

Figure 6 shows kick angles for HER with the same beam bunch parameters as in Fig. 4 except for the sign of charge. The kick angles in Fig. 6(a) are roughly half of that in Fig. 4(d) even with the same emission parameters of $I_{\text{peak}}^{(emi)}$ and $T_{\text{ini}}^{(emi)}$. The kick angles shown in Fig. 6(b) are comparable with those in Fig. 4(d).

SUMMARY AND FUTURE PROSPECTS

The fireball hypothesis for SBL at SuperKEKB has been proposed based on the vacuum breakdown mechanism observed in UHF accelerating cavities. As results of the first-principles numerical simulations performed in this study, fireballs can be generated by the beam-induced electromagnetic field, and not only LER but also HER beam particles can be kicked by a few to several µrad although the investigated parameter space is still limited. This simulation is to be performed for other landing points, i.e., not close to the beam-collimator head. It also should be verified if such kick angles are enough to lead to SBL.

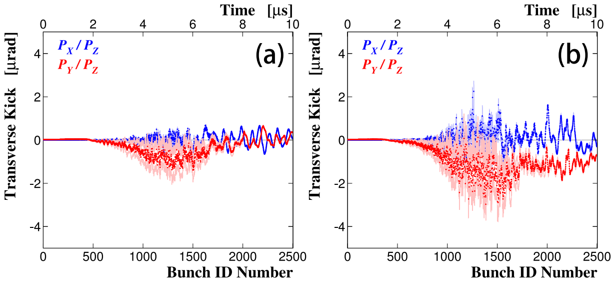

Figure 6: Kick angles of e^- beam bunches simulated with the CST PIC solver up to $t = 10$ µs of one revolution time of the SuperKEKB main ring for emission parameters of (a) $I_{\text{peak}}^{(emi)} = 70$ A and $T_{\text{ini}}^{(emi)} = 300\,000$ °C, (b) $I_{\text{peak}}^{(emi)} = 280$ A and $T_{\text{ini}}^{(emi)} = 100\,000$ °C.

How to demonstrate the fireball hypothesis is to observe:

- Acoustic wave generated from the fireball landing point, and
- SBL with a single beam (LER or HER only) with the same beam operation parameters as in physics run.

The final goal is to understand what is essential in the fireball hypothesis, and to find out the way to prevent significant transverse kicks of beam bunches in SBL because removing all dusts, candidates of fireballs, in an accelerator is not realistic.

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