SUMMARY OF WORKING GROUP A ON "BEAM DYNAMICS IN HIGH-INTENSITY CIRCULAR MACHINES"

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Abstract

In this proceeding we summarize the presentations of the HB2012 Workshop session on "Beam Dynamics in High-Intensity Circular Machines" as well as the outcome of the discussion session.

INTRODUCTION

This working group hosted 29 presentations in dedicated sessions plus 5 presentations in a joint session with the working C. In this summary, only one talk from the joint session is included (the one from J. Holmes, see below), i.e. 30 talks are discussed. Many thanks to all the speakers who gave excellent and well-prepared talks! In addition to all the talks, a discussion session took place on Thursday afternoon, where the hot topics of the workshop were discussed.

Eight (i.e. ~ 27 %) speakers were from Asia-Russia (3 IHEP Beijing, 3 J-PARC, 1 KEK, 1 JNR), eleven (i.e. ~ 37 %) from Europe (7 CERN, 2 GSI, 2 RAL) and eleven (i.e. also ~ 37 %) from North America (1 BNL, 3 FNAL, 1 ORNL, 2 LBNL, 1 UMD, 1 JLAB, 1 SLAC, 1 TRIUMF). We summarize below the highlights of the working group. A brief summary (1 slide) per talk can be found in the Appendix of the slides of the summary given on Friday morning for those interested [1].

NEW INTERESTS / IDEAS: BEAM-BEAM AND CIRCULAR MODES

At HB2010, the issue of the interplay between space charge and beam-beam in colliders was raised [2]. This year, two talks were devoted to beam-beam, one from RHIC [3] and one from LHC [4]. The next goal for RHIC is to double the current luminosity by increasing the proton bunch intensity from 1.7×10^{11} p/b up to 3×10^{11} p/b with an upgraded polarized proton source, and to (partially) compensate the beam-beam head-on tune spread by two electron lenses, whose installation started this year. The maximum beam-beam parameter reached so far during p-p (polarized) runs is 0.017 with 1.7×10^{11} p/b and a transverse rms. norm. emittance of ~ 2.5 μm. Several observations still need to be fully understood: 1) fast beam losses during the first 1-2 hours of the fills; 2) no clear transverse emittance growth during the stores (due to dynamic aperture?); beam-beam coherent π-mode seen only in the vertical plane and not in the horizontal one (due to stabilization by coupling between the transverse planes?). In the LHC, the luminosity was considerably increased in 2011 and 2012, reaching a record peak luminosity of ~ 77% of the design luminosity of 10^{34} $cm^{-2}s^{-1}$. Many Machine Developments (MDs) took place and the one from Ref. [4] will be treated below. Furthermore, the interplay between beam-beam and impedance is under discussion at CERN to try and better understand observed instabilities (see below).

Circular modes (already proposed in the past) and their possible application (with flat beams) for the LHC [6] have been presented at HB2012. X / Y eigenmodes, in uncoupled case, may have clockwise / counter-clockwise optical modes, which is called a circular optics. To have a circular optics, the focusing has to be rotationally invariant in the transverse plane (which can be obtained with solenoids as focusing elements and bending magnets with special field index, or approximately with skew quads). A. Burov suggested using circular optics with flat beams to [6]:

1) Fight against space charge in the LHC complex at low energy. With circular modes, the space charge limit comes from the larger transverse emittance, whereas in the usual planar modes, it comes from the smaller one;

2) Increase the LHC luminosity using flat beams (instead of round ones as currently used) as in this case the luminosity is inversely proportional to the square root of the smaller emittance.

These concepts should be studied in detail to evaluate the real quantitative (maximum) gain for the LHC luminosity: this includes effects of dispersion and any other perturbation, as well as the Intra-Beam Scattering (IBS) with the small transverse emittance in one plane. Circular optics is also considered in the MEIC project to realize the matched electron cooling for diminishing the space charge impact [7].

PHYSICS OF COLLIDERS, STORAGE RINGS AND SYNCHROTRONS

IOTA (Integrable Optics Test Accelerator) is a future test ring in FNAL for Non-Linear Optics and OSC (Optical Stochastic Cooling) studies [8]. V. Lebedev already gave a talk at HB2010 on OSC in the Tevatron, where the OSC's concept was reviewed. The principle is similar to the normal stochastic cooling except with much larger bandwidth (~ 200 GHz): undulators replace the PU and Kicker. In this study, a new/better understanding is proposed and a possible application for the LHC is discussed. OSC seems a promising technique for the LHC, which would allow a well-controlled luminosity leveling and which could potentially double the average luminosity. However, the next step for the moment is to validate the cooling principles in IOTA.

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S. Paret discussed the possible LHC luminosity leveling with transverse offsets in Ref. [4]. Measurements were done in the LHC during an MD in 2011 with collisions in the 4 Interaction Points (IPs), varying the separation in IP8 from 0 to 2.5 σ_x in steps of 0.5 σ_x, and measuring the emittances and luminosities at all IPs. The simulations were performed with the BeamBeam3D code with a simplified collision scheme. The conclusions are that: i) a very good agreement has been obtained between theory, simulation and measurements for the luminosity vs. transverse offset (in IP8); ii) luminosity leveling with offset has been demonstrated; iii) no side effects have been observed. As discussed, this was measured during an MD in 2011 with a small number of bunches and since Spring 2012 many instabilities have observed with transverse offsets (in IP1 and 5) of ~1-2 σ. The instabilities have not been fully understood and this raises a question mark on the possibility to use this luminosity technique in the future.

The several transverse instabilities observed in 2012 at 4 TeV in the LHC remain to be fully understood. Depending on some parameters, these instabilities could be observed before the squeeze, during the squeeze, at the end of the squeeze, during the adjust process (beams separated by ~1-2 σ) and in collision. According to all the measurements performed so far, it seems that the instabilities could be pretty well understood with 1 beam only (with an impedance within a factor ~2, larger, compared to the model). However, with 2 beams the situation seems to be much worse. The interplay between octupoles and beam-beam, leading to a modified stability diagram was studied in detail, but this cannot explain all the observations [9]. The instability model was improved by taking into account the effect of the transverse damper [10], but something is still missing. Is it due to other nonlinearities (modifying the stability diagram from octupoles)? Is it due to 2-beam impedances? Is it due to coherent effects in the presence of impedance and beam-beam? Interesting simulation results have been obtained recently [11]. The next MDs should shed more light on these instabilities.

P. Baudrenghien presented at the discussion an anomalous phenomenon concerning the evolution of LHC bunch length (BL): in 2012 BL saturates and even decreases at some point, but in 2011 it only increased. Several things changed between 2011 and 2012: i) 4 TeV collision energy instead of 3.5 TeV, ii) tight collimators, iii) higher intensities, etc. More studies are needed in particular to see how the bunch shortening correlates with beam losses. It would be interesting to know what happens with and without beam-beam.

The CERN PS "Q20 optics" is a good example of "solving collective effects by the proper optics" [12]. This new optics is called Q20, as the integer part of the transverse tunes is 20 (instead of the nominal Q26 optics, where the integer part is 26). This optics was initially developed to fight against the TMCI (Transverse Mode-Coupling Instability), which required an increase of the chromaticity at about a certain intensity and whose threshold (without space charge) scales with the distance to transition (i.e. the absolute value of the slip factor). Lowering the tune decreases the gamma transition, which increases the absolute value of the slip factor (which is the important parameter in the beam dynamics). In fact several instabilities in the CERN SPS (e-cloud, longitudinal) have thresholds that can be raised by operating further away from transition. It was also found that due to the larger dispersion function the beam was bigger and therefore the incoherent space charge tune spread smaller. Therefore, this optics has really a lot of advantages (also for the IBS [13]) and it has been decided recently to switch to this new optics for the production of the LHC beam. Some drawbacks for the RF power were discussed in Ref. [14].

Finally, Oliver Boine-Frankenheim reminded us that in FAIR SIS-18 and SIS-100 (but in many other machines it is the same case) different incoherent and coherent effects occur simultaneously and it is of utmost importance to properly study and be able to simulate the interplay of these incoherent and coherent collective effects. The tune spectra for high intensities, i.e. including Space Charge (SC) have been studied and the theory (with the simplified airbag model) extended to include the effect of the image currents (which are important for thick beams). A good agreement between the new theory, PATRIC simulations, and measurements has been obtained in SIS18 for thin beams. For thick beams, a broadening of the lines is observed, leading to more Landau damping and in this case a self-consistent space charge model is required (i.e. PATRIC simulations are needed) to fully explain the physics. It was noted also that in a dual RF bucket, simulations show pronounced (low-order) head-tail modes in the presence of SC. Similar indications have been observed during in CERN PSB experiment. This will be followed up.

"TABLE-TOP" EXPERIMENTS

UMER

UMER (University of Maryland Electron Ring) is a research machine of 3.7 m diameter, using low energy e-, to study all kinds of space charge effects, which could help to increase the brightness of existing and future accelerators. Since the beginning of 2012 a better transmission has been obtained (i.e. the past initial fast losses were removed) thanks to a careful re-alignment. Two recent longitudinal studies have been performed: i) SC induced multi-stream instability and ii) solitons in SC-dominated beams. The SC induced multi-stream instability was predicted in 1990 [15], it has been recently experimentally confirmed for short bunches [16] and it has been recently observed in UMER for long bunches [17]. As concerns the solitons (solitary large-amplitude waves that persist and retain their shape over long distances) in SC-dominated beams, recent observations have been made in UMER, with a very good agreement with simulation. Any new proposals are

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welcome (discussions started about the possibility to study the beneficial effect of circular modes on space charge).

S-POD

S-POD (Simulator for Particle Orbit Dynamics, at Hiroshima University) is a tabletop experimental tool for the various SC effects in high-intensity and high-brightness hadron beams. It uses non-neutral plasmas physically equivalent (as governed by a similar Hamiltonian) to charged-particle beams in periodic AG channels, in traps. The advantage of traps is that they are very compact (as short as ~20 cm in axial length), very cheap (few k$), they have an extremely wide parameter range, a high resolution and precision measurement and there is no radio-activation. There is also 1 Penning electron trap (operational: S-POD IV), using an axial magnetic field for transverse confinement, while the longitudinal confinement is done by electrostatic potential (and a magnetic mirror). Recent experiments have been performed to study the collective resonance excitation, lattice dependence of stop bands, resonance crossing, halo formation and ultra low-emittance beam stability. New experiment proposals and suggestions are welcome!

UPGRADES / NEW MACHINES

There are many upgrades and new machines, with a trend to inject at higher energies to reduce the incoherent space charge tune spread.

CSNS

The CSNS (China Spallation Neutron Source), whose construction was launched in 2011, uses a pulsed accelerator with an H^- linac and a proton RCS (Rapid Cycling Synchrotron) [18]. In the linac design an equipartitioning focusing scheme is adopted to avoid coupling instability. The CSNS is designed to accelerate proton beam pulses to 1.6 GeV kinetic energy at 25 Hz repetition rate, striking a solid metal target to produce spallation neutrons. The accelerator provides a beam power of 100 kW on the target in the first phase and then 500 kW in the second phase by increasing the average beam intensity 5 times while raising the linac output energy. In the phase one, an H^- ion source produces a peak current of 25 mA H^- beam. A RFQ linac bunches and accelerates the beam to 3 MeV. A DTL linac raises the beam energy to 80 MeV. The project is expected to be ready for user operations in the first half of 2018.

ISIS

ISIS (whose name is not an acronym, but refers to the ancient Egyptian goddess, and was selected for the official opening of the facility in 1985; prior to this it was known as the SNS, or Spallation Neutron Source) at RAL uses a LINAC, accelerating H^- ions up to 70 MeV followed by an RCS that increases the beam energy up to 800 MeV at a rate of 50 Hz, delivering ~0.2 MW beam power [19]. The limiting factors are space charge, instabilities, injection, etc. and the half integer is an important factor for all of them, which explains the many studies dedicated to it. Three upgrades are foreseen to increase the beam power. Upgrade 1: New 180 MeV Linac to reach ~ 0.5 MW. Upgrade 2: New 3.5 GeV RCS to reach ~1+ MW. Finally, upgrade 3: New 800 MeV Linac to reach 2-5 MW.

LIU and HL-LHC

The goal of the LIU (LHC Injectors Upgrade) project is to deliver reliably to the LHC the beams required to reach the goals of the HL-LHC (High-Luminosity LHC) project [20]. The CERN LHC injectors are quite old: PS is 53, PSB is 40 and SPS is 36 years old. LHC currently produces ~1 fb^{-1} / week and ~1-2 fb^{-1} / day will be needed for HL-LHC, meaning that much more beam brightness will be needed in the future from the injectors. There is a relatively good understanding of the many collective effects and possible cures and a detailed upgrade plan for the injectors has been clearly defined. LINAC4 (160 MeV H^-) will replace LINAC2 (50 MeV H^+) to gain a factor of 2 in the incoherent space charge tune spread. To profit from this in the PS, the PSB extraction kinetic energy will be increased from 1.4 to 2 GeV, to gain a factor 1.6 in the incoherent space charge tune spread. Detailed studies of SC effects in PSB, PS and SPS have been started in collaboration with KEK, GSI, LBNL, etc. Several longitudinal and transverse instabilities have to be cured in all the machines and some RF limitations have to be overcome, etc. The current goal is to perform the main LIU interventions during 2018 and to start commissioning for HL-LHC in 2019 of basically 4 new machines.

FAIR

The core of FAIR (Facility for Antiproton and Ion Research at GSI) is a double-ring accelerator (SIS-100 Tm heavy ion synchrotron) with a circumference of ~ 1100 meters, which will be associated with a complex system of cooler and storage rings and experimental setups. The synchrotron will deliver ion beams of unprecedented intensities and energies. Thus also intensive secondary beams can be produced, providing antiprotons and exotic nuclei for groundbreaking experiments. SIS-100 should deliver protons (238U28+ ions) at an energy of 30 GeV (2.7 GeV/u) with 4×10^{13} p (4×10^{11} ions). This means that a factor 100 should be gained compared to the present short single bunches. The existing facility UNILAC/SIS-18 provides the ion-beam source and injector for FAIR.

NICA

The NICA (Nuclotron based Ion Collider Facility at JINR, Dubna) collider rings will provide: i) collisions of heavy ion beams 197Au79+ from 1 to 4.5 GeV per nucleon kinetic energy; ii) light-heavy ion colliding beams of the same energy range and luminosity; iii)

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polarized beams of protons and deuterons in collider mode; iv) beams of light ions and polarized protons and deuterons for fixed target experiments. In addition to the sources and linacs, there is a Booster (25 Tm), a nuclotron (45 Tm) and the two superconducting rings with a circumference of ~503 m where 23 bunches per ring collide. Two regimes are anticipated: 1) SC-dominated (1-3 GeV/u, where the cooling time is faster than the IBS growth time) and 2) IBS-dominated (3-4.5 GeV/u, where the cooling time is equal to the IBS growth time). Several cooling techniques are used: stochastic cooling is sufficient for IBS suppression and beam stacking, while electron cooling can be used for cooling in the total energy range and can provide effective stacking at small energy only.

CEBAF and MEIC

JLab operates a recirculating SRF linac, CEBAF (Continuous Electron Beam Accelerator Facility), in upgrade to 12 GeV, for a fixed target program. The conceptual design of a Medium Energy Electron Ion collider (MEIC) since year 2000 has been completed. Ion beams with ultra high bunch repetition rate, low intensity but high brightness must be produced and stored to support the high luminosity of the collider (up to 1.4×10^{34} $cm^{-2}s^{-1}$). Such beams have never been produced. The design concept of a new ion complex has been developed to specifically address these challenging issues, including suppressing SC and IBS. Circular optics has been considered to realize the matched electron cooling for diminishing the space charge impact. A test facility based on JLab ERL FEL was proposed for a proof-of-principle experiment for the ERL-circulator electron cooler design concept. It is expected to complete this experiment in 3 years. The design optimization (cost reduction/staging option) and other R&D are also in progress.

RHIC

In RHIC (Relativistic Heavy Ion Collider at BNL) the maximum Beam-Beam (BB) parameters obtained are: i) 0.003 with Au-Au (heavy ions) runs and $N_{Au} = 1.3\times10^{9}$ and ii) 0.017 with p-p (polarized) runs and $N_p = 1.7\times10^{11}$ (and transverse emittances of ~2.5 microm). The current nominal working point (28.695, 29.685) is between the 2/3 and 7/10 resonances. Some more information was already mentioned in Section 2. The next luminosity goal for RHIC is to double the current luminosity by increasing the proton bunch intensity from 1.7×10^{11} p/b up to 3×10^{11} p/b with an upgraded polarized proton source, and to (partially) compensate the beam-beam head-on tune spread by two electron lenses, whose installation started this year.

CODES AND SIMULATIONS

During his talk on Monday, I. Hofmann [21] discussed the issues on code benchmarking. In our working group the same issues had attention. Although a lot of progress has been made in simulations over the past decade, it seems we are not yet at the point where we can predict beam losses and emittance growths with sufficient precision. In this respect, of particular interest is the CERN PSB and PS machines' intensive campaign to study space charge effects [20]. This effort promises higher quality experimental data for further code benchmarking.

In the past decade, one of the big challenges for space charge simulations was to simulate long-term behaviour, i.e. more than ~1/2 or 1 million turns. PIC (Particle-In-Cell) codes are affected by noise, which may compete with the physical mechanisms one tries to simulate. Increasing the number of macro-particles mitigates this problem, but this is un-practical for long-term simulations. Frozen SC models (i.e. where the source of the detuning with amplitude remains unaffected by beam loss) are adopted, as they are noise free, but they are valid for small beam loss [22]. The neglected self-consistency may lead to "the close to resonance collapse" (avalanche beam loss due to periodic crossing of a resonance near the working point). Hence the frozen model might not be correct, as the beam is almost completely lost. To study this effect, a Markovian ansatz (updating only the beam intensity) was proposed in Ref. [22] to approach the condition of self-consistency, and in this case the "close to the resonance collapse" does not seem to take place anymore. In this approach, self-consistency seems to mitigate the impact on beam losses on SIS-100. This has to be continued with maybe new benchmarking data in the CERN PS in the future.

In Ref. [23], it has been proposed to perform simulations with measured Extended-Twiss (E-Twiss) parameters. This was done in J-PARC MR using a turn-by-turn monitor. A linear envelope theory using the measured E-Twiss parameters was developed and simulations of SC effects using the measured E-Twiss parameters were performed, revealing in particular that the x-y coupling at sextupoles seems dominant for the beam loss.

Finally, the community expressed some concerns about the status of the ESME code, which is not supported anymore (the latest versions seem to have some issues), while the community thinks that this is really an important tool.

MONTAGUE RESONANCE

The (4^{th} order SC) Montague resonance can lead to particle loss in the plane of smaller emittance / aperture. Two MDs performed in the past in the CERN PS have been used since as benchmarking experiments: i) a static one, where the beam is injected in the machine with a fixed working point and the working point is changed for each injection; ii) a dynamic one, where the beam is injected in the machine with tunes far from each other, which are programmed to cross. In fact several studies were performed, crossing from below the diagonal or

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from above, and with different speeds. Many simulations were also performed in the past and good results were already obtained. Using the IMPACT code, which had many improvements over the last years (with a parallel PIC code, using z as independent variable, split-operator, etc.) and a more involved description of the lattice of the PS machine, simulations were performed for all the measurements done in the past. These 3D self-consistent SC simulations reproduce all the experiment data reasonably well [24], which might signify the end of a nice study…

WIDE-BAND FEEDBACKS

The talk on wide-band feedbacks [25] generated a lot of interest and comments. The motivation for such a feedback is to control the Electron-Cloud Instability (ECI) and TMCI in the SPS and/or LHC. The full bunch length can be as low as 1 ns, and therefore a high bandwidth is required if one wants to detect and damp intra-bunch motion. There were also some discussions about the effect of the usual bunch-by-bunch feedbacks, which are known to be able to raise the TMCI intensity threshold. Important progress in the different R & D areas of the project has been made during the last year. As concerns the development of kickers, there is a collaboration between LNF-INFN, LBL and SLAC and excellent progress was made in 2012. The goal is to evaluate 3 proposals: i) stripline (arrays? tapered? staggered in frequency?); ii) overdamped cavity (transverse mode); iii) slot and meander line (similar to stochastic cooling kickers). Furthermore, nice SPS MD results driving a single bunch have been performed. It seems in particular that it was only possible to excite the positive head-tail modes, which is maybe explained by the effect of SC on the negative modes. This experiment could be redone with a much lower intensity where SC would be much smaller. Macro-particle simulation codes are being performed with a realistic feedback system (with the CMAD, HEADTAIL and WARP codes). Finally, a proof-of-principle channel for closed loop tests in SPS before the 2013 shutdown is foreseen, using existing kicker and pick-up.

INJECTION FOIL

As most of the (current and future) linacs are H^- linacs, an injection foil is needed, and even if this foil is very thin and used for only few turns per proton, a lot of care should be devoted to this equipment (and surrounding ones) as most of the beam losses will be located there. The case of SNS, which is now operating at ~1 MW with more than 10^{14} p/p @ 60 Hz and more than 900 MeV, was discussed in Ref. [26]. The overall beam loss is small and most of it is downstream of the ring injection stripper foil (within 20 m). ORBIT simulations (with the full SNS ring lattice and apertures) were performed with 3 different foil scattering models. The linear dependence of the beam losses on foil thickness was confirmed. A more quantitative analysis of foil scattering and BLM (Beam Loss Monitors) results has been started but there are several unknowns: BLM calibration, exact number of foil hits per proton, etc.

IMPEDANCE WITH FINITE LENGTH

The longitudinal impedance of 2D azimuthally symmetric devices of finite length has been studied in Ref. [27]. The model is a cylindrical cavity loaded with a toroidal material connected to circular infinite beam pipes. The method consists of finding 4 vectors by using the field matching method for the magnetic field (to have 3) and to use the mode matching method for the electric field (to have the 4th). In the field matching approach, the continuity of the EM (Electro-Magnetic) field components on separating surfaces is used, whereas in the mode matching method, one uses a decomposition of the fields in summation of modes and matches each mode coefficient by proper field projection on the correspondent mode. The results are valid for any finite length, any non-relativistic beam velocity, and any material. Several successful tests have been performed with the thick-wall formula, CST simulations, Shobuda-Chin-Takata's model and Mounet's model. It was also applied to some equipment in the SPS. The next step is to compute the transverse impedance, which could be important for short collimators and/or kickers.

SCALING LAWS FOR THE 3RD ORDER RESONANCE

During the ramping of an FFAG, betatron tunes cross many nonlinear resonances. The emittance growth and beam loss when crossing the 3rd-order resonance was reviewed in Ref. [28]. Some experimental results could not be fully understood and explained by past works from Chao et al. and Aiba et al. Setting 20% as the tolerable emittance increase or 2.5% as tolerable trap-fraction in resonance crossing, scaling laws for the critical allowable resonance strength were derived (by solving Hamilton's equations of motion by perturbation). A pretty good agreement with experimental measurements is now obtained. This new scaling law can be useful in the design of high power accelerators, to estimate the emittance growth in cyclotron, and the requirements of the slow beam extraction using 3rd-order resonance. A non-scaling FFAG has recently been commissioned and an experiment test was suggested.

FOLLOW-UP FROM LAST HB2010

One of the highlights of HB2010 was the Van Kampen modes [5] and the more exact treatment of the longitudinal instabilities. A much lower intensity threshold is found with this more involved method (compared to the rigid-bunch approximation usually used from Sacharer's formalism [29]). Recent simulations from M. Migliorati seem to confirm these new results [30]. Furthermore, these new results could explain observations in the CERN SPS during the ppbar period (loss of Landau damping in bunch-lengthening mode for an inductive

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impedance above transition), which were not yet understood [31].

During HB2010, the importance of studying instabilities with associated electronic feedbacks was also raised as this could completely change the picture. There was a need to discuss more closely with the feedback experts (gain vs. frequency, noise issues etc.). Furthermore, including a realistic model for the different feedbacks in simulation codes was considered as an interesting and challenging subject. Both aspects were tackled. The first seems to be particularly important for instance in the LHC and a lot of work is ongoing in this direction with the damper experts [32]. The second point is of particular importance also for the electron cloud and/or transverse mode-coupling instabilities and it is an ongoing activity [25].

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