Special ColUSM: internal review of Tevatron hollow e-lens usage at CERN

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Present: S. Redaelli [chairperson], R. Bruce (RB) [scientific secretary], O. Aberle (OA), C. Adoriso (CA), T. Bear (TB), C. Bracco (CB), G. Bregliozzi (GB), H. Burkhardt (HB), R. Calaga (RC), F. Carra (FC), S. Claudet (SC), J. Coupard (JC), S. Fartoukh (SF), J. Ferreiri (JF), M. Giovannozzi (MG), JJ. Gras (JG), A. Grudiev (AG), W. Hofle (WH), E. Jensen (EJ), L. Lari (LL), Alick MacPherson (AM), N. Mariani (NM), T. Markiewicz (TM), A. Marsili (AMa), A. Mereghetti (AMe), O. Mete (OM), E. Quaranta (EQ), A. Rossi (AR), M. Schaumann (MS), H. Schmickler (HS), R. Schmidt (RS), G. Stancari (GS), E. Todesco (ET), R. Tomas (RT), G. Valentino (GV), A. Valishev (AV), J. Wenninger (JW), D. Wollmann (DW), M. Zerlauth (MZ)

1 Topics presented

1.1 S. Redaelli: Introduction and motivation

- SR recalled the basic principles of hollow electron lenses as well as the possible uses at CERN.

- The hollow electron beam, running in parallel with the main proton beam inside the lens, should enhance the diffusion speed of halo particles while not affecting the core. The e-lens should then work alongside with the existing collimation system. The resulting reduced halo population below the collimator cut decreases the loss rate during orbit movements, where beam is otherwise scraped off at the collimators. The e-lens thus serves as a robust and flexible halo scraper, which could possibly mitigate observed high losses in the LHC, especially during the squeeze. The use of crab-cavities requires furthermore halo scraping during stable beams, which cannot be done with conventional collimators. Furthermore, impedance might limit the present collimators go scrape closer to the core.

- SF asked about the contribution to the total impedance from the TCPs. SR replied that it is about 25% at 4 TeV. SF mentioned that this will decrease when scaled up to 7 TeV. RS raised the question whether some alternative low-impedance scraper could be invented. SR replied that this is certainly the case. He also commented that he brought up the impedance issue for discussion: maybe scraping with one jaw only could be no issue also with the present TCP.

- The hardware previously used in the Tevatron is now available and could be installed in the LHC (in IR4) or the SPS (close to the Coldex location).

- SR reviewed previous beam scrapings with collimators in the LHC and showed that scraping at injection did not alleviate the losses in squeeze as the beam tails are re-populated during the ramp. SR warned that this conclusion is based on one single scraping test done in 2012.

- HS asked whether the loss spikes observed during the scraping were caused by orbit movements. SR replied that they were mainly caused by the collimator cutting into the beam.

- HS questioned the statement that hollow e-lens is mandatory to operate the crab cavities. SR explained that there are single turn failures studies by TB for the MP team that indicate that orbit shifts up to 1.5 sigma could occur in one single turn. If the beam tails are overpopulated – as observed in beam measurements at 4 TeV – the total energy deposited on the collimators could be above safe limits. RS commented that it would be hard to improve the situation because this is the results of optimized interlocks for the crab cavities.

- WH asked whether the e-lens could cause a decrease in luminosity. SR replied that this should not be the case, as it is affecting only halo particles not contributing to luminosity. He pointed to the talk by GS were the Tevatron experience is reviewed.

- SF mentioned that if the scraping is limited by the amount of beam cut away in each step, and therefore by the collimator step size, one could consider scraping instead through a movement of the closed orbit. This could give a 1 µm precision instead of the present 5 µm. AV said that the different orbit for each bunch should be taken into account. JW commented that it might be tricky to control the orbit to this levels.

- WH asked whether the losses in the ramp could be better controlled by moving in the momentum collimators. SR replied that these losses are mainly betatronic, coming from the IR7 TCPs moving in to tighter settings. Therefore, the momentum collimators would not improve the situation significantly.

- The scope of the meeting was discussed:

    - Is scraping at the LHC needed?

    - Can the hollow e-lens work in principle at the LHC?

    - Can the Tevatron hollow e-lens hardware be used in the LHC or SPS?

    - What are viable alternatives to this method?

    - What beam tests and studies are needed?

    - Are there other possible functionalities for the electron lens at the LHC?

- SR discussed possible timelines for installation at CERN: It is too late to install the Tevatron hardware in the LHC during LS1, but it might still be possible in the SPS. Another alternative could be to do the LHC installation during a winter stop, e.g. in 2015. Otherwise the installation would have to be postponed to LS2.

1.2 G. Stancari: Beam experience at the Tevatron and status of hollow e-lens hardware

- GS reviewed the working principles of electron lenses and their different uses at Tevatron. The profile of cathode determines the electron beam profile for different purposes – long-range beam-beam compensation (Gaussian beam), abort gap cleaning and halo scraping (hollow beams) or tune shift compensation (square flat beam).

- GS mentioned the advantages of hollow electron beams over conventional scrapers, e.g. robustness, variable strength, low impedance, resonant excitation possible and no nuclear fragmentation of collimated ions.

- At the Tevatron, hollow beams were used in standard operation for abort gap cleaning. GS pointed out that the available hardware was used in every fill between 2003 and 2011. This proves the excellent reliability of this instrument.

- SR asked whether different guns are needed for the different beam shapes and GS confirmed that this is the case. On the other hand, the gun can be replaced within about 2 hours so one could envisage tests at the LHC with different type of electron beams.

- SR also asked about the achievable time structure with the present hardware. GS replied that the rise time is about 200 ns.

- Experimental studies on the hollow e-beam used as a halo scraper at Tevatron were presented, where the pulsed electron beam was synchronized with only one of the bunch trains of the anti-protons:

    - The increased loss rate was only visible at higher amplitudes, above about 4.5σ, i.e. the beam core was unaffected.

    - No emittance growth was observed for the affected bunch.

    - No detrimental effect on luminosity was observed.

    - Using collimator scans, where some beam was scraped and the collimator retracted again, it was shown that diffusion speed of the affected bunch train is enhanced.

    - A Fourier analysis of losses show clear spikes coming from beam jitter in the unaffected bunch trains. These spikes are suppressed in the affected bunch train.
    - When moving in collimators or changing the tune, the loss spikes in the affected bunch train were suppressed compared to the unaffected trains.

- At the LHC, beam jitter is less visible (sub-micron level) but some low-frequency vibrations were observed.

- GS continued to show the hardware design and dimensions of the present Tevatron hardware and of a new hollow 25mm cathode and gave the specifications for the needed interfaces (powering, cryogenics, cooling water, diagnostics). This hardware is available for installation at CERN.

- ET asked what design considerations are determining the longitudinal dimension of the electron lens. GS replied that the distance where the electron beam is parallel to the main beam must be significantly longer than the bends, where the main beam is passing through the electron beam. Furthermore, the required effect of the electron beam scales with the length of the lens and therefore constrains it. On the other hand, certainly a shorter total length could be achieved if a new device was designed for the LHC. This would require more detailed studies.

- EJ asked whether a non-perfect proton orbit in the electron lens would break the symmetry of the solenoidal field. GS replied that two small correctors ensure that the two beams are parallel. The steering of the hollow beam has to be done as part of the commissioning.

- HS asked about the total price for the electron lens. GS replied that the Tevatron project has cost about 5 million USD, out of which 2 million were for the hardware.

- JW raised the question whether a Gaussian electron lens could be used to create a tune spread in order to counteract instabilities and stabilize the LHC beams more easily beam-beam. This could also be used before going into collision. AV mentioned that a few 10^{-4} units of tune spread can be created at 1σ for LHC at 7 TeV with the Tevatron hardware. SF commented that this should be good enough for the LHC.

- SF asked how the diffusion rate would scale to 7 TeV. GS replied that the diffusion rate should scale as the square root of the kick.

- AG asked if the electron beam could be kept on continuously rather than in pulsed mode. GS replied that this is the case.

1.3 V. Previtali: Simulations of hollow e-lens in the LHC and SPS

- VP presented simulation results of the effect of the hollow electron lens with the goal of assessing its effect in the LHC and SPS.
- Initial simulations with Lifetrack of the Tevatron experiments show an agreement within a factor 2-5 of the halo removal rate. The fact that the core is unaffected is well reproduced.
- For the CERN machines, a new routine describing the electron lens has been implemented in SixTrack. First a perfect e-lens and a linear machine plus sextupoles were considered, and later octupoles and imperfections, such as the real distribution of the electron beam, were added. Some imperfections still remain to be added. Three different modes of operation of the e-lens were considered for the LHC simulations:
  - DC (always on): a very weak effect was observed on the proton beam and is not suitable as a halo scraper in a linear machine. With octupoles, about 5% of the beam is scraped in 20s.
  - AC (e-lens pulsed in resonance with betatron motion): can be used to quickly drive halo particles onto the collimators. Depletes 90% of the halo in 20s in a linear machine but only 40% with octupoles added.
  - Random (randomly pulsed turn-by-turn): Depletes 40% of the halo in 20s both in a linear machine and with octupoles.
  - A fourth mode, harmonic, has not yet been simulated for the LHC.
- The main conclusions of VP studies is that the present hardware could be successfully used at the LHC to control the halo diffusion speed in a useful range, also before bringing the beams in collision (note that at the Tevatron it was only used with colliding beams to enhance the resonances caused by beam-beam effects).
- The cleaning performance is improved by a higher electron current. By increasing the current, 70% of the halo between 4 σ and 6 σ can be cleaned in 20s in the LHC.
- It was also found that the e-lens increases the impact parameters on the TCPs by about a factor 10. This should have little effect for standard LHC operation but could enhance the cleaning efficiency of crystals were to be used.
- VP went on to discuss the advantages of an installation in the SPS instead: The SPS is more similar to the LHC than the Tevatron (proton machine, weakly coupled, same working point), it would allow CERN to acquire experience with the e-lens (interfaces, controls, operation) and would be another possibility to validate simulation results. Therefore, meaningful beam studies could be done also in the SPS.
- The disadvantages of the SPS are instead the lower energy and less instrumentation. Furthermore, the elliptical beam size at the proposed location makes the scarper act mainly in the vertical plane, while the installed LHC collimator is horizontal. A shift of 5m could solve this.
- The halo cleaning in the SPS has so far only been simulated with a perfect machine. In this case the cleaning times are similar to the LHC.
- JW and RS asked whether if installed in the SPS, what would happen in case of a failure, for example of the cryo, and whether the SPS would still work if the e-lens fails. SR and GS replied that the vacuum in the e-lens does not rely on cryogenics and can operate warm. Therefore the e-lens should have no effect on regular SPS running if turned off. Clearly, prior to

the installation the design must be validated from the impedance point of view.

- HS asked if similar experiments could be performed at BNL. AV and GS answered that a Gaussian e-lens is in use there and that it might not be easy to negotiate extra time for experiments. The necessary change of the cathode would take some 2 hours, but hardware for generation hollow beams are not presently foreseen.
- RS raised the question of the influence of the bends of the e-lens, where the electron beam crosses the core of the proton beam. Could this, especially in random mode, induce emittance growth in the core? GS replied that it has been shown experimentally that the DC mode has no effect on the main beam, but that no such have been done with random mode. RS said that testing this could be a good motivation for installing the e-lens in the SPS.

1.4 A. Rossi: Feasibility of installation in the LHC and SPS

- AR gave an overview of different integration aspects that have to be considered for a possible installation of the e-lens in the LHC or the SPS.

- In LHC, the RB44 location in IR4 is considered. In order to fit in the physical space available between the beam pipes, the e-gun and collector have to be rotated by 90 deg, which is possible from the point of view of functionality. A preliminary integration study by Y. Muttoni proved the feasibility of the installation of the Tevatron hardware in the LHC. The integration of auxiliary devices such as power supplies and current leads has not yet been studied.

- SC asked whether the cooling would still work if the device is tilted. GS replied that this is not an issue since only the gun and collector are rotated, not the solenoid.

- WH commented that it should be checked whether there is a conflict with a space in IR4 reserved for the ADT and whether this was on the other side of IP4 or not. AR said that this should be checked, especially in view of that both sides might be required if an e-lens should be installed to operate also on the other beam.

- In the SPS, the integration study is less advanced than in the LHC, but indicates that the e-lens can fit in the Coldex location. If crab cavities are installed in the same location, there might be no space to install an additional Y-chamber to make it possible for the beam to bypass the e-lens (however, the strict necessity of the extra Y-chamber is still to be assessed). Also, cryogenics cannot be supplied to both crab cavities and the e-lens at the same time.

- EJ asked whether the e-lens could be shifted longitudinally in the SPS. AM commented that there should be a 6.6m empty space on the right if it, while there is a magnet on the left.

- HS asked whether it would be possible to generate the solenoidal field with a normal-conducting magnet instead of the present superconducting device, which requires cryogenics. GS answered that the strong 6.5 T field cannot be generated with existing technology for warm magnets. Possibly a weaker field could be used, but then the whole device would have to be re-constructed which is not easily done.

- AR gave an overview of the different interfaces that have to be considered for integration (mechanical, thermal, electrical and instrumentation).

- For cryo, the e-lens is to be considered as a stand-alone-magnet with a need of supply and return connections for cryogenics. The need of additional cryo installation in the LHC depends on whether the RF will have a dedicated cooling system. In that case, a simple prolongation system can be made. If not, the QRL has to be modified with new valves, inlet and outlet.

- For vacuum, the e-lens should be enclosed between two valves with pumps. The detailed integration work here is still to be done. Possible beam instabilities from e-cloud and pressure should be investigated. Also, the possible baking temperature should be checked. Tests on the e-lens on the surface are required for these aspects before installation.

- Preliminary studies have been done on impedance but more a more detailed follow-up should be done. The first results indicate high longitudinal impedance, meaning that some design modifications might be necessary.

- For the powering, studies are still to be done of whether existing power supplies can be used.

- SR raised the question to whom the integration issues in the SPS should be addressed.

- RS asked about why an installation in the LHC in LS1 is not possible. SR replied that the time required cryogenics is the main bottleneck.

- SR asked further whether an installation could be possible in a Christmas stop, for example in 2015. SC replied that at least 4-5 months are necessary for warm-up, welding, cool-down and recommissioning, meaning that a Christmas break is not sufficient. SR concluded that in that case the installation is probably not possible before LS2. On the other hand, the options should be kept under consideration in case of extended Christmas stop in 2015. We should consider which preparatory works could be done in LS1 to speed up a later installation.

- WH asked whether the installation of the e-lens in IR4 in the LHC is compatible with installation of CAN cavities. AR replied that this is probably not the case, although it still has to be studied.

- AV commented that if an installation in the SPS is to be considered, beam dynamics studies should be carried out, in particular on the effect of the solenoid on the coupling. Possibly corrections might be needed at injection energy. SR and RS discussed that the solenoidal field could instead be ramped, keeping it off at injection.

- SR concluded that more resources and studies are needed to conclude whether the SPS installation is feasible.

1.5 H. Schmickler: Possible alternatives for halo scraping at the LHC

- HS presented several alternatives to the e-lens for use as halo scraper.

- A beam-beam wire compensator could possibly be used with different parameters to extract halo particles. Such compensators could be integrated in future TCT collimators, according to preliminary studies. On the other hand, this project is not approved and requires more studies. It also not clear if the wire could provide the required scraping functionality.

- Cooling, if possible to implement, could be a better alternative than scraping the halo away, but the talk by HS will not focus on this

- A tune modulation at a fixed frequency of 10-500 Hz could be used. This introduces new resonance lines. Provided that the halo is at a different tune than the core (amplitude detuning), the halo particles could cross these new resonances and be extracted while the core is unaffected.

- HS reviewed some tune modulation experiments that have been performed at HERA in order to counteract emittance growth, on behalf of O. Bruning who performed these studies.

- WH and SF commented that this experiment would give the opposite: an emittance growth due to a power supply ripple was cancelled by the tune modulation. Thus, the tune modulation alone should be detrimental for the beam. HS responded that the halo could be affected by a tune ripple that is small enough not to induce emittance growth.

- For the LHC, it would be enough to modulate one warm magnet in IR7 with a Δk of 0.02% at 300 Hz according to calculations by Oliver Bruning.

- Also other means such as the ADT or AC dipole could be used in the LHC to extract halo particles at a tune different from the core. In principle the AC dipole should work for this purpose without modifications, but in case the frequency would anyway have to be changed, HS presented the necessary upgrades.

- WH commented that if only a 2μrad kick is sufficient, it could be possible to use the ADT. The dynamic range would have to be measured, and if the existing hardware is not performing well enough, improvements could be implemented, possibly in LS1.

- WH commented also that one could envisage to make some MDs on resonant extraction with the ADT with the presently installed hardware. SR remarked that it should be investigated if this could be fit into the next MD block.

- JW commented that it would be very challenging to tune the modulation during the squeeze when the tune of the main beam is anyway varying. There is a thus a risk that the core would be hit by a resonance. HS confirmed that this method is not suitable for use during the squeeze. AV raised the question about whether how well the working point is known. Presently, there are no tune measurements working reliably during the high intensity operation.

- SR commented that it must be made sure that the halo particles are far enough from the core in the tune diagram. The main advantage of the hollow beams is that the scraping is done by transverse particle amplitude. The proposed method relies on a correlation between transverse amplitude and tune shift. Can we ensure this condition at the LHC? RS mentioned that these questions could be addressed to Xavier Buffat, who is working on the tune diagrams. It should also be considered that different bunches can have different tune.

- HS continued to talk about different means of halo diagnostics and pointed out that the halo is not well known in the LHC. Such diagnostics would need to measure the beam density with a 10^{-6} dynamic range.

- Synchrotron light monitors have the suitable dynamic range but are affected by stray light from the beam pipe, which might make the technique unsuitable for the LHC.

- Photon counting techniques, such as luminescence monitors, could be a better alternative but have the drawback that a second monitor is needed. A pressure bump can be used to increase the dynamic range.

- BD commented that the needed pressure bump might be too high in order to have good statistics in the beam tails. HS remarked that one could also extend the integration time.

- RS agreed that a halo monitor for the LHC should have high priority, especially in view of the future installation of crab cavities.

- TM remarked that Alan Fischer is already developing a halo monitor. HS replied that this is an active mask which is more relevant for electron machine – for the LHC there might be too much stray light for this to work.

- SR commented that the alternative methods to halo scraping could be easier to implement, in case limitations would arise early on. Therefore they should also be thoroughly investigated.
- SR concluded that some well-defined criteria should be established, with which one could quantitatively assess the effectiveness of the different methods for halo cleaning.