# LHC TRANSFER LINES AND INJECTION SYSTEMS

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*Abstract*

The status and commissioning plans of the transfer line and injection hardware are presented with focus on the injection dump and kickers. Modifications of the beam loss monitoring in the injection region, its readiness for the start- up and commissioning strategy are shown. A new interlock strategy for the injection protection elements and the injection septum is introduced. The expected transfer line stability and possibilities to improve the turnaround with optimized SPS supercycles for LHC injection are discussed.

## TRAJECTORY STABILITY

The trajectory stability in the transfer lines TI 2 and TI 8 is dominated by the stability of the SPS extraction septum (MSE) power converters. The low MSE inductance of 80 μH is the cause of having almost no filtering effect from the load side on the current.

Three main frequency ranges of voltage instabilities can be distinguished for the MSE:

- Asymmetries in the power converter: 100 -200 Hz
- Measurements, stray fields: 50 Hz
- Regulation: few Hz

For the MSE power converter in BA6 the filter was further improved in LS1 which allowed to reduce the voltage ripple for the higher frequency ranges mentioned above. A reduction of the peak-to-peak ripple from 9 to 3.5 A is expected which has to be compared to the overall aim of having a ripple below 4 A.

The MSE power converter in BB4 has a better topology than the one in BA6 but an asymmetric 18 kV ac distribution network which is considered to partly cause the ripple. The other contribution came from a problem in the DC current transformer (DCCT) which showed a 5 A peak-to-peak oscillation when the power converter had been switched off, Fig 1. This caused the closed feedback loop to correct for this non-existing oscillation and therefore disturbing the power converter performance. The DCCTs in BB4 were repaired, Fig. 2, and the ones in BA6 tested without detecting this problem.

The filters in BB4 were improved, too. A total of 200 capacitors will be exchanged during LS1.

## FINAL TDI HARDWARE

The main upgrades of the TDI during LS1 concerned the beam screen. The old copper screen was replaced by a reinforced 6 mm stainless steel screen on a new supporting frame. The sliding system was upgraded, the central RF fingers were replaced by mechanical connections and the RF extremities bolted instead of electron beam welded. In total 8 temperature sensors were installed. The gearboxes were replaced by new greased ones. The cooling circuits were not in the initial TDI design but added later. Even though measurements of the cooling water temperature gradients had shown that the cooling circuits are not very efficient the same design will be kept for after LS1. The coating of the different TDI blocks was tested during bake-out. As a result NEG coating is not compatible with hexagonal boron nitrite (hBN) outgassing after baking at 300ºC, Figs. 3 and 4.

In Table 1 the original proposal of coatings is compared with the final solution. The adjacent chambers to the TDI will be NEG-coated and baked to improve the vacuum level and thus reduce the background for the experiments.

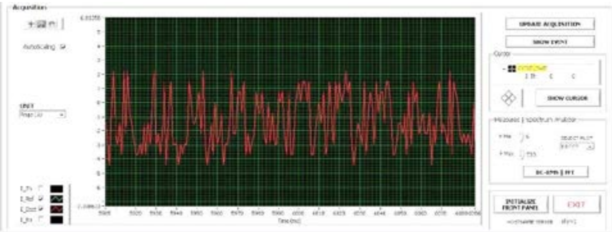

Figure 1: DCCT in BB4 before the repair. A 5 A peak-to- peak current oscillation is visible (PC switched off).

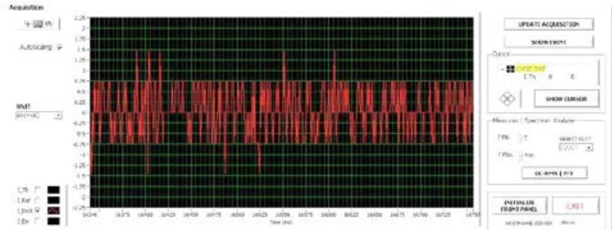

Figure 2: DCCT in BB4 after the repair. Note the scale. A ±0.75 A peak-to-peak current oscillation is visible which corresponds to the expected noise level.

Table 1: TDI coating.

| | Original proposal | Final coating |
|---|---|---|
| BN blocks | Ti + NEG + Cu + NEG | Ti coating |
| Al blocks | NEG | Ti coating |
| CuBe blocks | NEG | No coating |
| Beam screens | Cu + NEG | No coating |

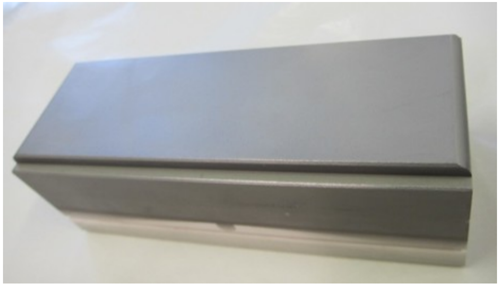

Figure 3: Boron nitrite blocks with coating of 5 μ*m* Ti, NEG, 2μ*m* Cu and NEG before the bake-out.

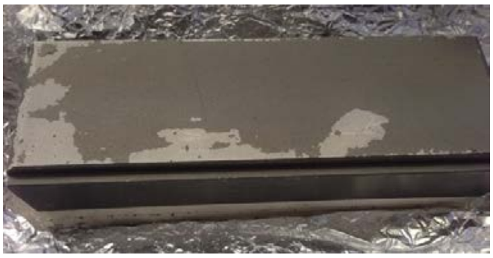

Figure 4: Coated boron nitrite blocks after bake-out at 300ºC.

The spare TDI units could be installed during the end of year stop 2015/16 if the time needed for bake-out is compatible with the planning. For these units it is foreseen to add Cu on top of Ti for the hBN blocks to reduce the beam impedance. This additional coating needs to be validated by tests.

## NEW INTERLOCKS

Two new interlocks for the injection septum current and the injection dump gap were put in place during LS1 and are described in the following paragraphs. The interlock on the gap of the transfer line collimators (TCDIs) is described in [1].

### *TDI Gap Interlock*

During the LHC Run 1 the TDI jaws suffered from elastic deformations due to beam induced heating. The jaw position measurement with linear variable differential transformers (LVDT) was compromised because of the flexible junction between jaw and its mount, Fig. 5. This caused reduced machine availability due to the interlocked tight TDI jaw position tolerances. The criticality of the TDI as injection protection element gave rise to add a redundant measure- ment of the gap between the jaws based on interferometry, Fig. 6. The angular acceptance of the interferometric sys- tem is increased by using reflecting tubes instead of mirrors. Also the position measurement shall be kept at all times, from beam position to parking with all possible jaw angles to avoid a re-initialisation of the position. All elements have undergone radiation tests up to 10 MGy. The feedthroughs will be tested for vacuum tightness on a spare for a duration

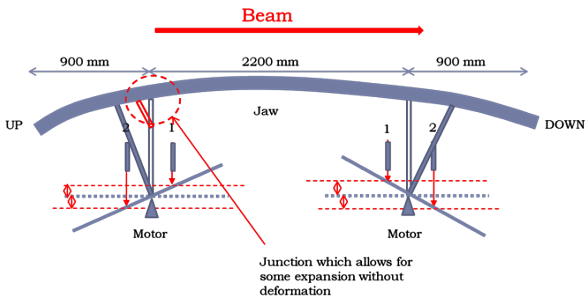


Figure 5: Deformation of the TDI jaw due to beam induced heating.

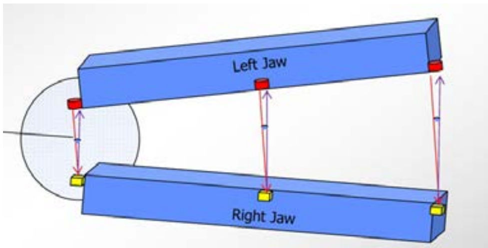


Figure 6: Position of interferometric sensors on the TDI jaw.

of 6 months. The spare TDI should be ready for installation in the end of year stop 2015/2016. As a difference compared to Run 1, this gap measurement will be connected to the Beam Energy Tracking System (BETS). The BETS will allow for 3 positions:

- *Injection:* 10 mm gap for normal injection operation; the interlock is triggered only if the gap is outside the tolerance or an BETS internal failure occurs.
- *Dump:* In case the TDI is positioned such that the injected beam is stopped, the BETS will be put on a maskable input to allow for the setup of injection system and the TDI itself.
- *Parking:* After injection the TDI is retracted to its parking position of ±50 mm to reduce the impedance, beam induced heating and the background for the experiments. In this case the BETS interlocks the SPS extraction.

Until the interferometric measurement is ready, the value for the gap calculated from the LVDTs will be used as BETS input. The change from the LVDT gap calculation to the interferometric gap measurement as input is transparent for the BETS.

### *MSI Current Interlock*

The current in the injection septa (MSI) are presently protected against fast changes by the Fast Magnet Current Change Monitors (FMCM) interlock. The current value itself is protected by the SPS power converter hardware interlock (FEI) which is based on the measured current and calibration tables. Due to the lack of passive protection elements downstream the MSI it was deemed important to monitor and interlock the MSI current by the BETS. To keep modifications on the BETS side to a minimum, the present MSI power converter electronics will be replaced by an FGC LHC power converter electronics. This also allows to easily synchronise foreseen de-gaussing cycles of the MSI with the LHC ramp. The MSI power converter will be linked via fiber optics to the BETS. The BETS transfer function translates the current into an energy value; on the BETS side it is checked if the current stays within its limits corresponding to a 1-σ trajectory oscillation and the energy within 450±1 GeV.

The same argument of missing horizontal passive protection elements holds for the strong bending magnets at the end of the transfer lines downstream of the TCDI collimators. Extending the BETS interlock on these magnets shall be envisaged.

## MKI UPGRADES

Prior to LS1 only 15 out of 24 screen conductors were installed, in the LHC injection kicker magnets (MKIs), to avoid flashovers. The 15 conductors were arranged such that the ferrite is screened and - in order to reduce the flashover probability - the lower part of the chamber close to the high voltage bus bar was left without screen conductors. In this configuration most of the MKI magnets had a power deposition of 70 W/m; a value which - known from operation in 2012 - does not limit injection. However, the MKI8D magnet had a power deposition of 160 W/m which limited injection between high-luminosity fills due to extended waiting times to let the ferrite yoke cool down. The increased heating in the MKI8D originated from twisted conductors. The beam screens of all 8 MKIs have been upgraded during LS1. The outside metallization has been removed from the ceramic tube starting about 20 mm before the open-circuit end of the screen conductors. A conducting metal cylinder with a vacuum gap of 1 – 3 mm to the ceramic tube has been added. These modifications allow all 24 screen conductors to be installed: in addition the predicted maximum electrical field, on the surface of the ceramic tube, with 24 screen conductors installed is 40% less than was the situation for the 15 screen conductors pre-LS1.

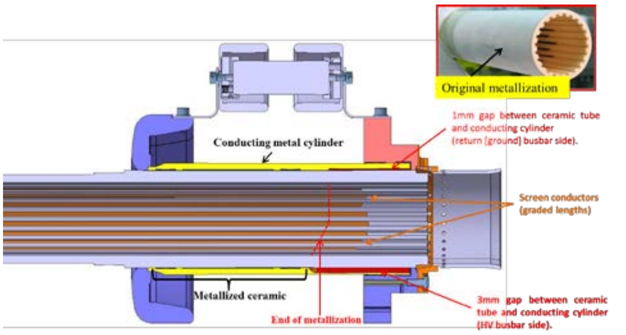


Figure 7: Improved MKI beam screen with 24 graded length conductors and a conducting metal cylinder with a vacuum gap of between 1 to 3 mm to the ceramic tube.

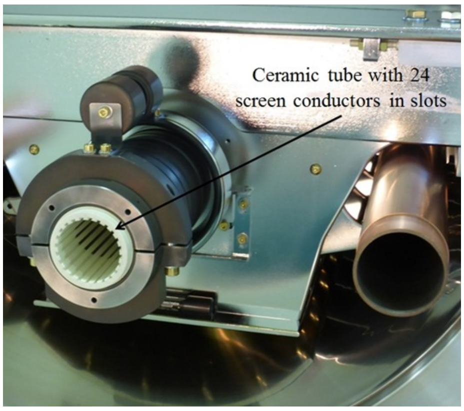


Figure 8: Ceramic tube with 24 screen conductors in slots.

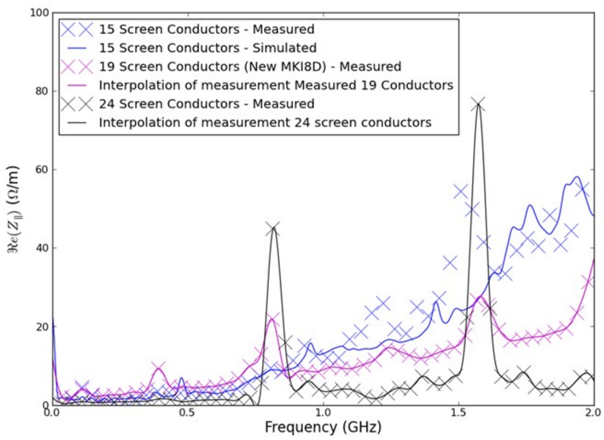


Figure 9: Longitudinal beam coupling impedance for different numbers of screen conductors in the MKI. Courtesy H. Day.

The 90º twist of the conductor slots, in the old MKI8D, along the length of the ceramic chamber, orientated the 9 screen conductor gap, at the downstream end of the MKI8D, from the high voltage bus bar to the ferrites, and therefore caused increased heating of the magnet yoke, especially at the downstream end. The newly manufactured ceramic tubes are carefully inspected to ensure that they do not have a twist: however a twist of the conductor slots, with the now installed full complement of 24 screen conductors, would not have a significant effect upon yoke heating. The expected power deposition after LS1 is approximately 50 W/m, thus, heating of the MKI ferrite yoke is not expected to limit injection.

In order to increase the emissivity of each MKI vacuum tank ion bombardment of the tank, in an atmosphere of argon and oxygen, has been performed, Fig 10. However the initially very promising results of samples could not be repeated for the actual tank due to limitations on the treatment temperature. Hence the emissivity in the range of wavelengths of interest was not improved. However, even without increased emissivity of the MKI vacuum tanks, the power deposition after LS1 (approximately 50 W/m), is not expected to limit injection. For the future, indirect cooling of the ferrite yoke by adding cooling channels is very difficult due to the brittleness of the ferrite: in addition water cooling is not compatible with the high voltage and vacuum demands.

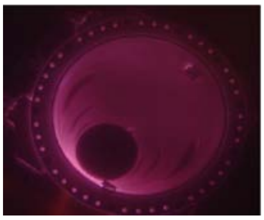


Figure 10: MKI tank during ion bombardement in Argon and Oxygen atmosphere (left) and after the bombardment (right).

Another option under investigation is to significantly reduce the surface area of a plate below the ferrite yoke to improve radiative heat transfer between the ferrite yoke and tank.

In order to validate the high voltage performance of the MKI magnet with the full complement of screen conductors the magnets have been tested up to 56.4 kV pulse forming network (PFN) voltage (nominal at Point 8 is 51.3 kV): as expected from predictions the flashover performance is even better than for the originally installed screen with 15 conductors. Tests of the beam screen have also been carried out outside the magnet, with background pressure of neutral hydrogen in the range of $1 \cdot 10^{-9}$ to $1 \cdot 10^{-7}$ mbar. The test setup will be modified such that the injected hydrogen gas can be ionized during the tests, to better represent the effect of the beam in the LHC.

Other upgrades to the MKIs during LS1 include increased emissivity of clamps and corona shields for the damping resistor of toroidal ferrites. V2b RF fingers were installed and the by-pass tubes NEG coated. In view of dust particles creating beam loss (UFOs), improved cleaning of the ceramic tube has given a substantial reduction of dust particles relative to the MKI8D installed during the technical stop 3 (TS) –, 2012 – which itself was a lot better than the pre-TS3 MKI8D; During the LS1 upgrades, the ceramic chambers have been flushed with high pressure nitrogen and the dust particles captured in a filter: subsequently the number of dust particles in the filter has been estimated by the CERN material and metrology section (EN-MME-MM). The MKI8D installed during TS3 in 2012 resulted in $390 \pm 47 \cdot 10^6$ particles after flushing and this unit showed low UFO occurrence in beam based measurements; with the new cleaning procedure the number of particles is reduced by another factor of 20 – 40, thus, the occurrence of UFOs in the MKI magnets should be significantly reduced after LS1.

Further upgrades nearby the MKIs during LS1 include NEG coating of beam position screens and timing modules (BTVSI and BPTX) and installation of NEG cartridges on the cold-warm transitions and MKI interconnects.

There are ongoing studies of chromium (III) oxide ($Cr_2O_3$) and amorphous carbon coating of the ceramic tubes. $Cr_2O_3$ coated samples from industry were obtained and some of these were measured to have a peak secondary electron yield (SEY) of less than 1.4, after some conditioning, which is the critical value for the electron cloud build-up for the MKI geometry, Fig 11. For comparison the naked ceramic of the tube has a peak SEY of 6-10. A contract has recently been placed in industry to develop the application procedure of the $Cr_2O_3$ coating for a 3 m long ceramic tube.

A 50 cm long ceramic tube has been coated with a thin layer (200 nm) of amorphous carbon and resulted in an SEY of 1.25 – 1.5; this increased value compared to the expected SEY of 1 originated from uncoated parts in the measurement area, e.g. the sample holder. The tube will be high voltage tested in the near future.

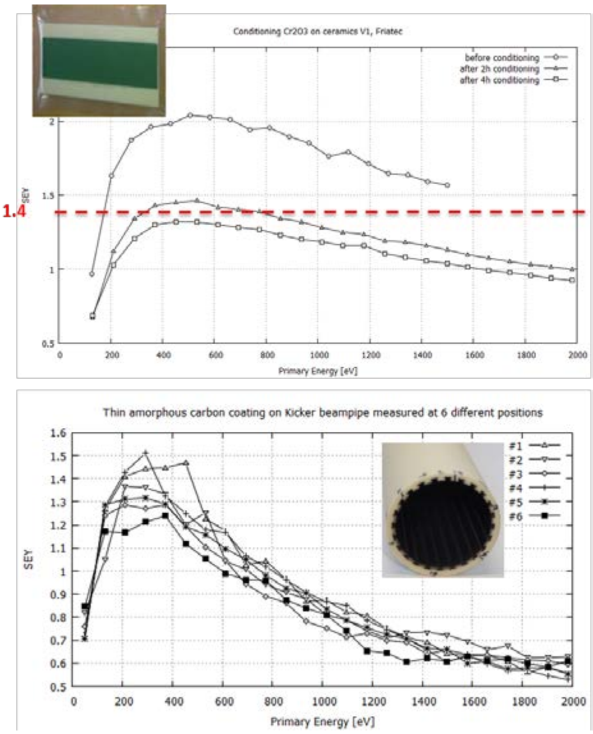


Figure 11: Secondary electron yield of $Cr_2O_3$ coating (top) and amorphous carbon coating (bottom). Courtesy M. Mensi.

## MODIFICATIONS OF THE BLM SYSTEM

The motivation to modify the beam loss monitoring (BLM) system in the injection region originates from avoid- able beam dumps at injection. Loss showers from the transfer line collimators (TCDI) hit from the outside of the cryostat the sensitive LHC loss monitors where the tunnels of the transfer lines TI 2 and TI 8 merge with the ring tunnel. Even if higher dump thresholds were acceptable in this region at injection energy, the saturation level of the ionization chambers presents a limit. To overcome this dynamic range limitation, little ionization chambers (LIC) were tested and after validation installed. They allow to move the upper dynamic range limit by a factor 10 compared to the standard ionization chambers (IC). For the new monitors the threshold limit can be overcome if the higher thresholds are accepted during the time the machine is at 450 GeV injection energy. The new monitors are installed such that redundancy between the well tested ICs and the new LICs is kept. The ICs where higher thresholds would be required to keep machine availability at injection, are connected to blindable crates. These crates will have the possibility to receive a timing signal and accordingly blind out the interlock input at the moment of injection. The criterion to select monitors which shall have the blind out possibility is a factor 5 margin between the operational loss level and the dump thresholds. Also, the expected loss levels should be within a reasonable signal to noise ratio. The loss levels which entered the analysis considered operation with TCDI half gap openings of 4.5 σ. Since the measured LHC aperture was larger than expected, the TCDIs were opened by 0.5 σ to reduce the number of unnecessary dumps at injection. The future TCDI opening depends on the available aperture after LS1. During LS1 two new processing crates were installed, one per injection point, and the cabling was modified to route all blindable monitors to those crates. The next steps are the FPGA development, the setting up of a test bench, the verificaton of the system in the laboratory, and eventually machine protection tests with beam in the machine when the new firmware will be deployed. The machine protection commissioning of the new firmware requires several pilot beam injections per beam validation two functionalities:

- Interlock inhibit:
  - Close injection protection collimator
  - Inject pilot
  - Check that the interlock of dedicated crates is inhibited and only that
- Energy check:
  - Disconnect timing cable from CISV on BLM crates of P2 and P8 surface (i.e. energy level fall to 7 TeV)
  - Inject again pilot
  - Check that dedicated crates' interlock request is not inhibited

If the new firmware will be ready for tests in the machine right at the startup or after a technical stop will be addressed in the LHC machine protection panel (MPP).

## DEDICATED LHC FILLING

The LHC filling time could be reduced by optimising the supercycle composition [2]. Presently the supercycle has a length of 43200 ms of which 21600 ms are used by the LHC cycle. To the time of the LHC cycle one has to add 5 basic periods for beam production in the injectors and the LHC Injection Quality Check (IQC) wich corresponds to 6000 ms. This results in a minimum dedicated LHC filling supercycle length of 27600 ms and a potential reduction of 15600 ms. This difference will be smaller in 2015 due to the stop of CNGS. A shorter supercycle of about 36000 ms is expected, so the possible supercycle length reduction is 8400 ms. A drawback of a dedicated LHC filling is the uncertainty in the effective filling time which can vary between one to several hours. This could be a problem for injector experiments with a rigidly scheduled beam time.

## SPECIFIC COMMISSIONING TESTS

During the long shutdown several machine components were exchanged or adjusted and require specific testing. The SPS and parts of the transfer lines were realigned and therefore the SPS extraction channel aperture will be scanned to check for obvious aperture limitations already during the sector test. A proper scan of the extraction bump and available apertures for the extracted and circulating beam will be done as soon as the same cycle is available as for operation during beam commissioning. The SPS extraction kicker (MKE) waveforms will be scanned carefully to find a representative position to place the intermediate intensity bunch trains which are used for steering the transfer line trajectories. A kick response measurement is foreseen for both transfer lines and their adjacent LHC sectors to identify wrong polarities of correctors and beam position monitors and to verify the dispersion matching from the transfer lines into the ring. Similarly to the SPS the injection apertures will be scanned coarsely during the sector test together with orthogonal steering tests in the injection region. The above mentioned modifications of the MKI magnets together with adjustments of the damping resistor require to re-measure the MKI waveforms. Also the two new BETS interlocks for the MSI current and the TDI gap interlock will be tested in addition to the standard commissioning procedures. All tests mentioned in this section can be largely covered during the sector tests depending on beam availability. The commissioning of the blindable crates for BLMs can be done the earliest during beam commissioning.

## CONCLUSION

The trajectory stability of TI 2 and TI 8 was dominated during run 1 by the voltage ripple of the SPS extraction septum power converter. After LS1 gentle improvements can be expected for the TI 2 stability due to an optimised filter gain and in TI 8 due to a repaired DCCT.

Major changes to the beam screen of the TDI shall mitigate the experienced issue due to beam induced heating. Foreseen coatings need further investigation, the presently installed jaws have either Ti or no coating. Installation of a TDI spare in the 2015/16 end of the year stop could be envisaged if the bake-out time is compatible with the planning.

A redundant TDI gap interlock based on interferometry which is connected to the BETS is being developed and should be ready after a six month testing period on the spare TDI. Presently the existing LVDT measurement will be used as input for the BETS.

Also the MSI current measurement will be connected to the BETS since no passive protection is in place in the horizontal plane. Extending this interlock upgrade shall be envisaged also for the strong bending magnets at the end of the transfer lines right downstream the transfer line collimation.

The MKI8D heating problem is solved; many upgrades concern better heat transfer, reduction of dust particles and improved vacuum levels. Studies on improved tank emissivity, indirect ferrite cooling and coating of the ceramic chamber are ongoing.

The necessary hardware to route selected BLMs to blind- able crates is installed. Tests in the lab and with beam are defined while the deployment strategy remains to be clarified.

Dedicated LHC filling would allow to reduce the super-cycle length from 36 to 28 s. It could have a negative effect on injector physics scheduling.

Realignments of big parts of the machines and many upgrades of the hardware require several additional measurements for the startup. A big part of these measurements can be done during the sector tests.

## REFERENCES


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