SPS CHALLENGES

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Abstract

In future the SPS should be able to transfer to the LHC the beam produced by a completely new pre-injector chain and required by the LHC for different upgrade scenarios. The issues related to this extremely challenging task are presented together with some possible ways of overcoming the problems that arise. Besides an increase in injection energy provided by PS2, these measures can include both an SPS vacuum chamber upgrade against the e-cloud and operation with larger longitudinal emittance for beam stability. As a result the power plant of the SPS RF system must be doubled. The SPS upgrade will also need the improvement or replacement of many other machine elements.

MOTIVATION

The SPS is challenged by two main LHC upgrade scenarios which are presently under consideration [1]. One of them is based on the ultimate LHC beam having bunches with intensity of 1.7×10^{11} spaced at 25 ns. Difficulties expected in producing this beam are discussed in [2]. Another scenario, which seems to be more acceptable for the LHC experiments, requires bunches spaced by 50 ns with 5×10^{11}/bunch.

At the same time, possibilities which could be offered by a completely new SPS injector chain (Linac4-SPL-PS2) are even more challenging for the SPS [3], [4]. Indeed, for the LHC beam 168 bunches spaced by 25 ns with 4×10^{11}/bunch could be injected at 50 GeV/c at 2.4 s intervals. For the FT/CNGS beam - a total intensity of 10^{14} per injection could also become available (full SPS ring).

At the moment the SPS is able to deliver at top energy the nominal LHC beam (1.2×10^{11} p/bunch) with the required transverse and longitudinal emittances. The maximum intensity in the SPS has been obtained for the CNGS type beam in 2004 [5]. A single bunch with 1.8×10^{11} (ultimate LHC intensity) was seen in the SPS at 26 GeV/c in 2006.

The present achievements and future needs in the SPS are summarised in Table 1. It is clear that the SPS upgrade is also required to provide the beam necessary for the LHC upgrade and as well as to make optimum use of the possibilities offered by the new injectors both for the LHC and for other users (FT, CNGS...). Initial studies, done in the framework of PAF [3], were continued in 2007 in the specially created inter-departmental Study Team, PAF-SPSU, [6].

In this paper the problems related to the LHC beam with 5.5×10^{11}/bunch and 50 ns spacing, the most demanding for the SPS, will be analysed, assuming that the way to produce this beam has been found in the PS2 [7].

	SPS record at 450 GeV	LHC request at 450 GeV	PS2 offer at 50 GeV/c
$N_b/10^{11}$	1.2	1.7/5.5	$3.6/7.2^{**}$
$N_{tot}/10^{13}$	3.5(5.3*)	9.2	12.0
I_{RF} [A]	1.5	3.5	4.6

Table 1: Maximum intensities achieved in the SPS up to now and future requests. 10% beam loss assumed for PS-SPS and SPS-LHC beam transfer. * CNGS beam at 400 GeV with 5 ns spacing and full ring. ** Intensity for 25/50 ns bunch spacing.

MAIN INTENSITY LIMITATIONS

The main intensity limitations for a single bunch are space charge and TMCI. The e-cloud, generated by the presence of many bunches in the ring, is at the origin of the single bunch vertical instability. Other multi-bunch limitations in the list are coupled bunch instabilities, beam losses, beam loading in the TW 200 MHz and 800 MHz RF systems as well as heating of different machine elements (e.g. MKE kickers). For future high intensity beams the measures to overcome these limitations include:

- Higher injection energy with PS2: 50 GeV/c instead of 26 GeV/c, see [8].
- New campaign for impedance reduction after its identification [9].
- Active damping of coupled bunch instabilities will need a beam control upgrade (transverse and longitudinal feedbacks) [10].
- Passive (Landau) damping from increased nonlinearity (synchrotron frequency spread) with
  - the 4th harmonic RF system (800 MHz) and
  - increased longitudinal emittance .

As we will see below, an increased longitudinal emittance is one of the most efficient and appropriate cures. It is already used now and can be more extensively applied in the future.

Single bunch

The tolerable limit for the space-charge tune spread in the SPS from past experience (ppbar) is believed to be $\Delta Q_{sc} < 0.07$. For the LHC bunch at 26 GeV/c ΔQ_{sc} is 0.05 for the nominal intensity and 0.07 for the ultimate intensity [11]. The bunch intensity for the upgrade scenario will increase this value to 0.23. One can expect the improvement ($\propto 1/\gamma^2$) from the higher injection energy, see Fig. 1, to be sufficient to counteract this. Indeed for the planned increase of injection energy to 50 GeV/s, $\Delta Q_{sc} = 0.06$, so that the tune shift is almost back to its present value.

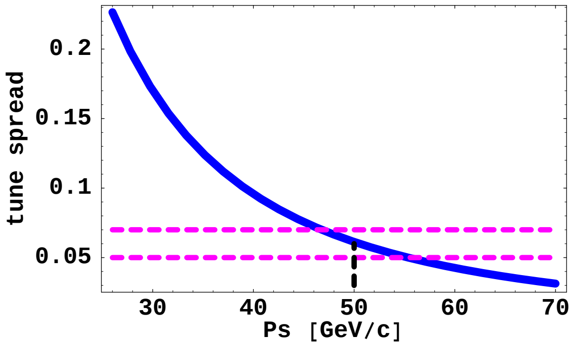

Figure 1: The value of ΔQ_{sc} for 5.5×10^{11}/bunch as a function of the SPS injection momentum.

Another possible bunch intensity limitation is the TMCI, transverse mode coupling instability, observed in the SPS with longitudinal emittance smaller than nominal [12], [13]. With an impedance model obtained from a best fit to measurements for the LHC bunch at 26 GeV/c (2006) the threshold intensity is $N_{th} \sim 1.4 \times 10^{11}$ [8]. For the matched voltage the threshold intensity scales as

$$N_{th} \propto |\eta|\varepsilon.$$

At 50 GeV/c the TMCI threshold will already be higher than at 26 GeV/c by a factor 2.5, see Fig. 2. Therefore the stability of a bunch with intensity of 5.5×10^{11} can be provided by an increase of emittance to 0.6 eVs. Other possible cures for this instability are increased vertical chromaticity and capture voltage (also needed for larger emittance).

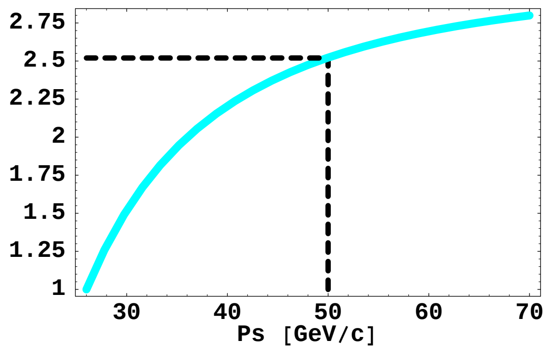

Figure 2: Relative change in the TMCI threshold as a function of the SPS injection momentum.

e-cloud

At the moment the effects connected with e-cloud give the main intensity limitation in the SPS for the nominal LHC beam. It leads to transverse emittance blow-up and instabilities - coupled bunch in the horizontal plane (seen at a few MHz) and single bunch in the vertical plane in the batch tail ($\sim$ 700 MHz). Present cures include an annual scrubbing run at the end of each SPS shutdown, operation with high chromaticity in the vertical plane and use of the transverse damper in the horizontal plane. Studies done with 1.1×10^{11} p/bunch for the coupled-bunch instability in H-plane at different energies [2] suggest that the instability growth rate scales as $\sim 1/\gamma$ and improvement can be expected at a higher injection energy.

On the other hand, in the vertical plane, simulations predict a threshold reduction with energy [14]. The results of the intensive MD studies in 2007 of the vertical e-cloud instability at different SPS energies are presented in [15].

Possible SPS chamber modifications as measures against e-cloud effects are now under extensive investigation by the SPSU Study Team [6]. They include

(1) TiN, graphite or other surface coatings [16],

(2) cleaning electrodes [17],

(3) grooves (in collaboration with SLAC, [18]).

The solution should satisfy the following main requirements: the possibility of application onto the existing vacuum pipe inside the magnets, stability over long-term, resistance to venting in the absence of baking, low beam-coupling impedance and no significant aperture reduction ($<$ 1 mm). It is planned to install three different samples in the SPS e-cloud measurement set-up (M. Jimenez, K. Cornelis et al.) during the 2007/2008 machine shutdown for beam tests in 2008.

Some improvement should be also expected for the 50 ns bunch spacing as is the expected case for the LHC itself [19]. This can be confirmed by HEADTAIL simulations.

Longitudinal coupled bunch instabilities

The longitudinal coupled-bunch instability of the LHC beam in the SPS is characterised by a very low intensity threshold [20]. A single LHC batch with 2×10^{10} per bunch becomes unstable during acceleration at $\sim$ 280 GeV/c. Possible impedance sources of this instability are the fundamental and HOMs (at 629, 912 MHz...) of the 200 MHz and 800 MHz RF systems. To stabilise the beam controlled emittance blow-up is performed twice during the cycle, in addition to the use of the 800 MHz RF system as a Landau cavity in bunch-shortening mode throughout the cycle. The first blow-up is with mismatched voltage at injection; due to filamentation the initial emittance of 0.35 eVs is increased to 0.42 eVs. The second takes place at around 200 GeV/c, with band-limited noise which blows up the emittance to 0.6 eVs.

At injection the coupled-bunch instability is observed at $\sim 1.1 \times 10^{11}$/bunch (with 800 MHz off). No significant change in threshold due to injection at 50 GeV/c is expected. Taking into account that the instability threshold scales as [21]

$$N_{th} \propto \varepsilon^2,$$

an emittance of 0.6 eVs will be required at injection for stability of a beam of 5.5×10^{11} per bunch and 50 ns bunch spacing.

Later in the cycle (above 250 GeV) controlled emittance blow-up to at least 0.9 eVs will be needed to stabilise the "50 ns scenario" beam. This in turn will require an upgrade of the SPS RF system as demonstrated in the next section.

SPS ACCELERATION CYCLE WITH PS2

To analyse the voltage and power requirements for high intensity beams injected at 50 GeV/c from future PS2 we need to have the corresponding magnetic cycle. An example of an acceleration cycle (synchronous momentum and its derivative) designed for this purpose is shown in Fig. 3. It is based on the present magnetic cycle for the LHC beam in the SPS and differs from it only below 150 GeV/c.

To avoid (or minimise) beam loss during acceleration the voltage programmes used in operation in the SPS usually provide a bucket area $A \simeq 1.4\,\varepsilon$. Therefore for $\varepsilon_{inj} = 0.6$ eVs at the beginning of the ramp we need $A = 0.85$ eVs (or 0.75 eVs with a filling factor in area of 0.9 and in momentum of 0.95). The voltage programmes for the 200 MHz RF system, corresponding to the magnetic cycle shown in Fig. 3, and found for longitudinal emittances of 1.0, 0.75 and 0.5 eVs are presented in Fig. 4 (top). The voltage for the smallest emittance value reflects the present situation with the LHC beam in the SPS and is shown for comparison. Due to the required controlled emittance increase to 1 eVs during acceleration, two voltage programmes are presented - for injected and extracted emittance values with transition between them (emittance blow-up) somewhere around 200 GeV/c. As one can see, for large emittances the maximum required voltage is close to the value at flat bottom and can only slightly be reduced by slowing down the acceleration ramp.

The matched voltage at injection as a function of injection momentum at constant longitudinal emittance is shown in Fig. 5. The required voltage is proportional to $|\eta|/\gamma$. As one can see the matched capture voltage is higher for injection above 26 GeV/c. For injection at 50 GeV/c with the available $V_{max} = 7.5$ MV at 200 MHz the injected emittance ε_{inj} should not exceed 0.8 eVs ($V_{inj} \propto \varepsilon_{inj}^2$). Even only lower ε_{inj} would be allowed for injection in the range (30-50) GeV/c. From this point of view the PS2 energy should not be much below 50 GeV.

If the voltage presently available is sufficient to accelerate high intensity beams with large longitudinal emittances, the RF power required for beam loading compensation is significantly higher than actually possible [22]. The power per 200 MHz TW cavity for $V = 7.5$ MV is shown in Fig. 6 together with the present limitations for pulsing

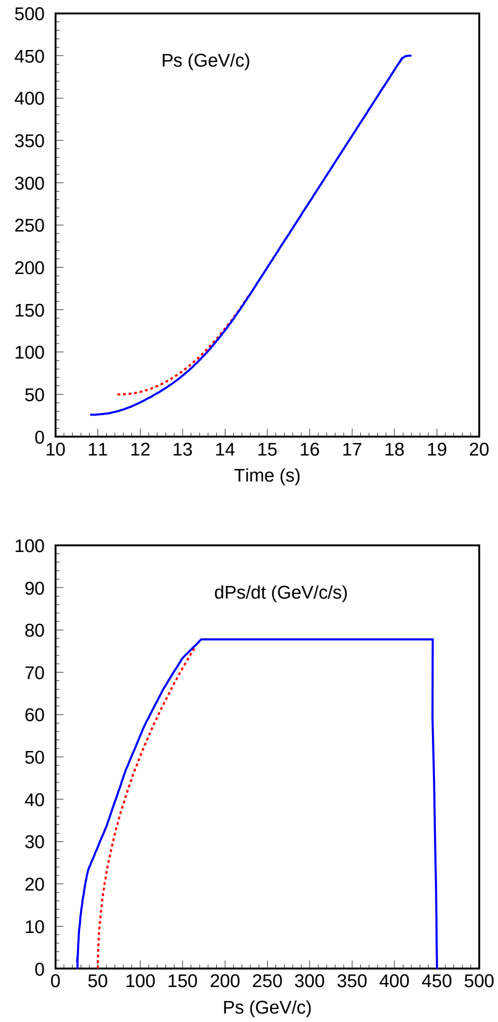

Figure 3: Synchronous momentum (top) and its derivative (bottom) for the LHC cycle now used operationally in the SPS (blue curve) and the cycle possible with the PS2 (red curve).

mode (LHC beam - half ring filled) and continuous operation (FT/CNGS beam - practically the whole ring is filled), for two values of beam current corresponding to the LHC upgrade scenario (top figure) and the maximum intensity available from PS2 (bottom figure). The effect of reducing the cavity length (number of sections) is also illustrated.

Following from this comparison of the power needed for future beams with the existing possibilities, it is clear that the 200 MHz and 800 MHz power plant should be doubled and R&D for the re-design of couplers and coaxial lines should start as soon as possible. Some reduction in required power can be achieved by optimisation of the cavity length ($5 \rightarrow 3$ sections) for high intensity operation [23], see Fig. 6.

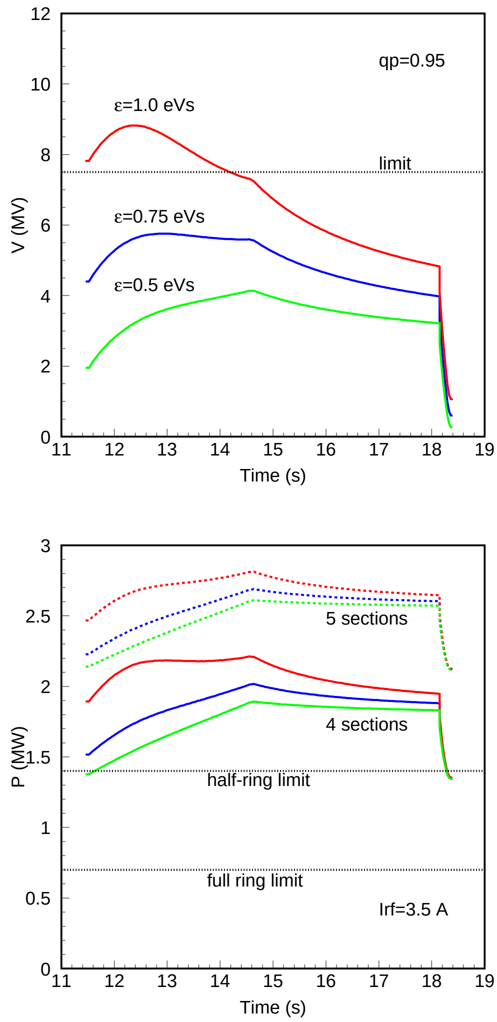

Figure 4: Top: voltage programme for the magnetic cycle from Fig. 3 for different values of longitudinal emittance together with present limit of 7.5 MV (dashed line). Bottom: corresponding power requirements for the SPS 200 MHz TW cavity with different number of sections for beam intensity for the LHC upgrade scenario with "50 ns spacing" together with actual power limitations.

Future CNGS/FT beam The voltage and power requirements for the LHC beam in the future can be compared with estimations [24] done for the future CNGS/FT beam and based on the possibilities offered by the new SPS injector - PS2 [4]. The maximum 200 MHz voltage required for accelerating a beam with an emittance of 0.7 eVs with acceleration times 3.0 s and 4.2 s (corresponding to an SPS cycle length of 4.8 s and 6.0 s) is shown in Table 2for filling the SPS from the existing PS injector and the future PS2.

The corresponding peak power per cavity needed for the total CNGS beam intensity of 4.8×10^{13} (nominal value), 7×10^{13} and 1×10^{14} (maximum available from PS2) is

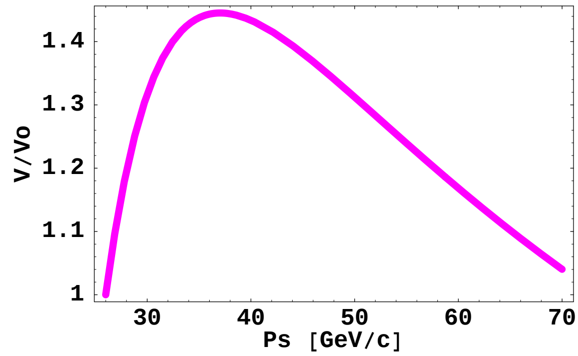

Figure 5: Matched capture voltage (normalised to the value at 26 GeV/c) required for $\varepsilon = const$ as a function of the injection momentum.

	SPS= 11 PS	SPS $\simeq$ 5 PS2	
t_{acc}	3.0 s	3.0 s	4.2 s
t_{cycle}	6.0 s	4.8 s	6.0 s
V_{max}	7.6 MV	10.5 MV	7.0 MV

Table 2: The 200 MHz voltage [MV] needed for accelerating the FT/CNGS beam in the SPS now and in the future with two different values of acceleration time - 3.0 and 4.2 s and an emittance of 0.7 eVs.

shown in Table 3 for two different SPS cycle lengths and different filling schemes.

RF power [MW]

N	SPS= 11 PS	SPS $\simeq$ 5 PS2	
$[10^{13}]$	$t_{acc} = 3.0$ s	3.0 s	4.2 s
4.8	0.65	0.75	0.5
7.0	0.85	1.0	0.7
10.0		1.4	1.1

Table 3: Peak RF power [MW] required per 200 MHz TW cavity to accelerate the nominal CNGS beam and the future FT/CNGS beam with different intensities and acceleration times.

As one can see, twice the RF power and 40% more voltage than available now are necessary for a short (t_{acc} = 3.0 s) acceleration cycle of 4.8 s. However in order to provide the same number of pot/year 25% more beam intensity should be accelerated in the SPS with the long cycle of 6 s ($t_{acc} = 4.2$ s). We can conclude that these RF requirements are also not very different from the needs for the LHC "50 ns spacing" upgrade scenario beam.

BEAM LOSS

In 2003 an LHC beam with nominal intensity and longitudinal parameters was accelerated in the SPS to top energy [20]. However this could be achieved only by inject-

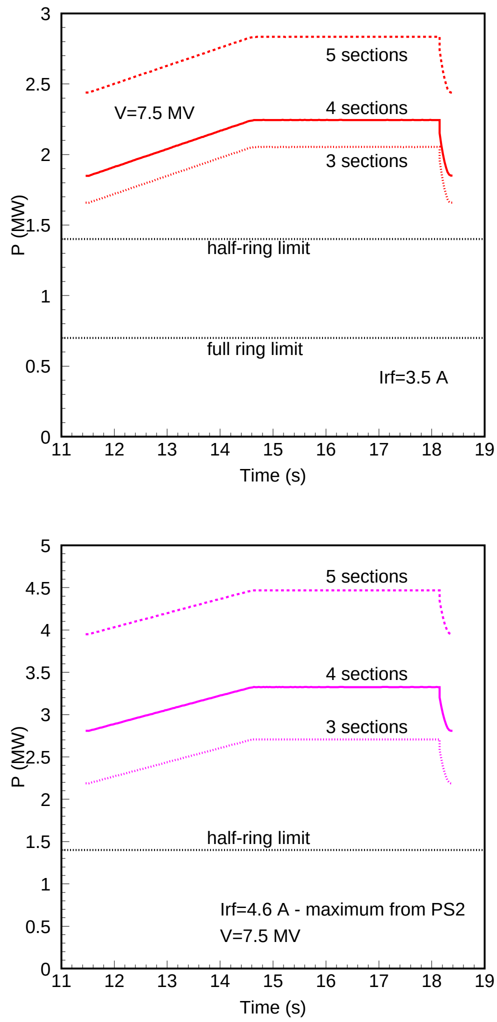

Figure 6: Power per SPS 200 MHz TW cavity having 3, 4 or 5 sections with $V = 7.5$ MV for LHC upgrade intensity from "50 ns spacing" scenario (top) and maximum PS2 intensity (bottom). The actual power limit in pulsing mode is believed to be 1.4 MW and for continuous operation 700 kW [22].

ing 15% more particles due to significant beam loss. After intensive MD studies, a reduction of losses to 7% was obtained at the end of 2004 with a new working point and additional RF gymnastics on the flat bottom [2], [26]. In general the injection and capture losses of the LHC beam in the SPS have a strong dependence on the batch intensity, Fig. 7. A reduction in relative loss to 3% was measured for a beam with 75 ns bunch spacing and nominal bunch intensity. Beam loss at high energies was also the main limitation for the intensity increase during the "record" CNGS run in 2004 [5].

Indeed, usually the relative beam loss increases with intensity due to different collective effects (space charge,

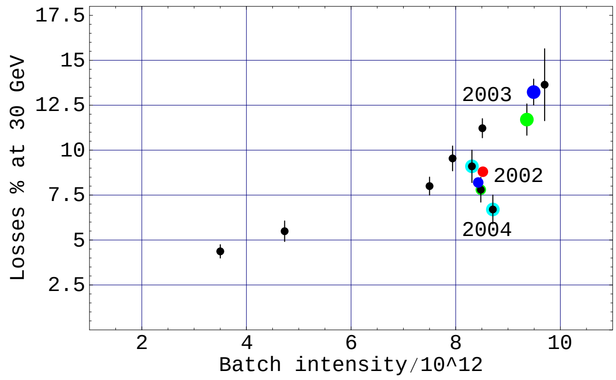

Figure 7: Relative capture loss for different batch intensities in the SPS.

beam loading, instabilities, increased beam size...):

$$\frac{\Delta N_{loss}}{N} \propto N.$$

However, to keep the same absolute loss ΔN_{loss}, responsible for the radiological impact, the relative loss should be reduced at higher intensity as

$$\frac{\Delta N_{loss}}{N} \propto 1/N.$$

As a result, for higher beam intensities, significantly improved machine performance and radioprotection will be required. The possible installation of beam collimation for beam loss control should also be considered.

SUMMARY AND DISCUSSION

The SPS must be significantly improved to match all other upgrades in the accelerator chain. Indeed, the present upgrade scenarios, both for the LHC itself and for its injector chain are very challenging for the SPS. Among them, the scenario with 50 ns bunch spacing and very high bunch intensity, is the most demanding in terms of required SPS upgrade. Nevertheless, the increased injection energy with PS2 ($\geq$ 50 GeV) should help to overcome certain single bunch limitations (such as space charge and transverse mode coupling instability - TMCI), and increased longitudinal emittance at injection (≥ 0.6 eVs) should cure multi-bunch effects (except e-cloud) and TMCI (completely). However in order to accelerate the "50 ns scenario" beam with large longitudinal emittance the RF system of the SPS must be upgraded: doubling the power plant with R&D for the most critical elements is indispensable.

The actual "bottle-neck" for the nominal LHC beam, the vertical e-cloud instability, will have even lower threshold at higher injection energy and studies of possible SPS vacuum chamber upgrade should be pursued now, taking into account the time which is necessary to find proper solutions in the laboratory and to test them with the beam in the SPS ring for long term effects. Resources are required so these studies can start now.

Control of the SPS impedance, and it's reduction when possible, is also essential for any future intensity increase.

Issues related to beam loss and radiation could become the most important limiting factors for future plans and should not be neglected.

There are other important components of the SPS upgrade for high intensity beams which were not discussed here:

- Injection kicker at 50 GeV/c
- Beam control:
  - longitudinal feedback, feed-forward and damper
  - transverse feedback/damper
- Beam dump
- Beam instrumentation
- Beam collimation

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