Beam Collimation in the Low and High Energy Accelerators.

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A high beam power of (0.2-4) MW in the existing and planned high intensity machines like Rutherford Appleton Laboratory ISIS, Los Alamos PSR, SNS, JHF, ESS, and FNAL and BNL Proton Drivers implies serious constraints on beam losses in the machine. The main concerns are the hands-on maintenance and ground-water activation. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses to an allowable level. There are several specific issues in the collimation system design for accelerators of this energy range compared to the high energy machines like Tevatron, LHC and VLHC.

	low energy accelerators	high energy colliders
Max. E_{kin}	(1-24) GeV	(1-100) TeV
beam power	(0.2-4) MW	(0.0001-0.02) MW
cycle duration	$2-60\,Hz$ bump is difficult to keep the beam close to collimators	10 hours different primary collimators can be used at injection and at the top energy
beam loss at injection	$0.1-30\%$	1%
beam loss at the top energy	$1-3\%$ high efficiency of collimation is necessary during the total cycle	$10-20\%$ high efficiency of collimation is necessary at collisions
beam loss concerns	irradiation and heating during total cycle	detector background and SC magnets quench
(aperture)/(beam size) at injection	$\sim 1.5-2$	~ 5 large space for the secondary halo at collimation
closed orbit deviation during the cycle	$\pm(2-5)$ mm secondary collimators are far from the beam	± 0.2 mm
utility section length	$\sim 10\%$ of accelerator length relatively expensive	$\sim 1\%$ of accelerator length can be designed to fit the collimation system requirements

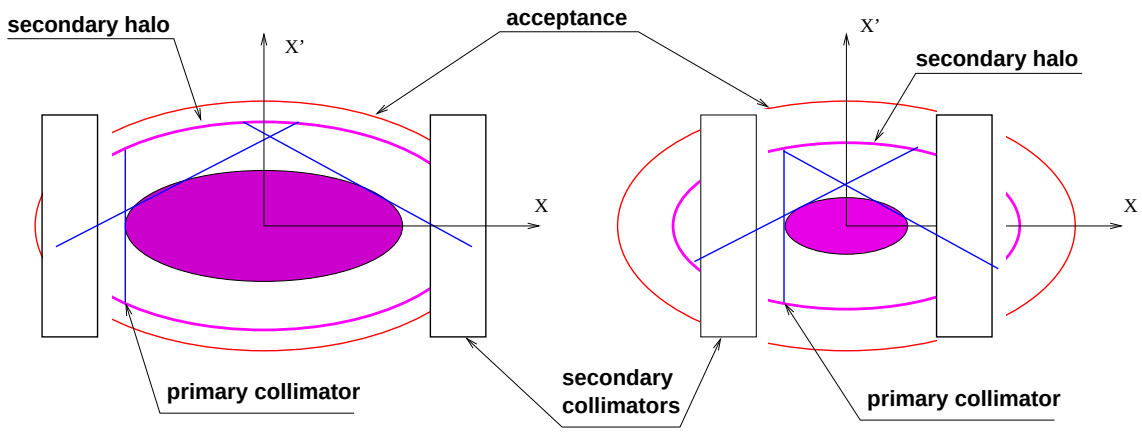

Figure 1: Beam collimation in a small and large aperture machines.

In a high intensity low energy machine a painting injection is used to increase the size of the circulating beam in order to avoid space-charge effects for emittance preservation. Because of this the aperture of accelerator is only about 50-100% higher compared to the beam size. While in a high energy accelerators the aperture is usually a factor of 3-5 bigger compared to the circulating beam at injection. The secondary halo produced by the primary collimators should not exceed the aperture limit. This imposes additional constrains on the choice of primary collimator length and material in a low energy machines. The large amplitude particles from a secondary halo oscillate here in a very nonlinear fields produced by the chromaticity correction sextupoles and nonlinear part of the main magnet field. Because of these a realistic simulations of collimation process is very important for the low energy accelerators.

The main issues are:

Primary collimators length
Two-stage approach
Off-momentum collimation
Collimation during accelerator cycle

1 Primary collimators length

There is large difference in the optimal length of the primary collimators for the top energy and injection. This is not important for the high energy accelerators because the main concern is background in the detector at the top energy, but in the low-energy accelerators losses at injection are comparable to them at the top energy on power.

The σ of multiple Coulomb scattering angle in a collimator is defined by the following equation:

$$\Theta_o = \frac{0.0136\ [GeV]}{\beta \cdot P \cdot c\ [GeV]} \cdot z\sqrt{\frac{x}{X_o}} \cdot \left[1 + 0.038 \cdot ln\frac{x}{X_o}\right] \qquad (1)$$

Here P, $\beta \cdot c$ and z are momentum (GeV/c), velocity, and charge number of the particle, and x/X_o is thickness of the collimator in radiation lengths.

The thickness and material of primary collimators effect the outscattered proton angular distribution and nuclear interaction rate in it. Such a thin scatterer should give a considerable angular kick to the halo particles, but their amplitude should remain smaller than the machine aperture on their way to the secondary collimators. Horizontal and vertical phase planes at injection for the Fermilab Booster in the primary and secondary collimators are shown in Fig. 2 for 0.15 mm thick graphite primary collimators. This thickness is optimal for injection energy, but unfortunately it is not enough for the top energy. An optimal primary collimator at the top energy would be 0.2 mm tungsten collimator.

Horizontal and vertical phase planes at injection and at the top energy in the primary and secondary collimators are shown in Fig. 3 and 4 for 0.1 mm thick tungsten primary collimators. 0.2 mm thick collimator is optimal for the top energy but too long for injection. It produces very large tail of outscattered particles which will be lost on

the aperture during the first half of a betatron oscillation. Most of this particles are intercepted by the first secondary collimators located at 20° and 37° behind the primary collimators. A supplementary collimator located immediately after this collimators, but from the other side of the beam, permits to intercept the second part of high amplitude particles.

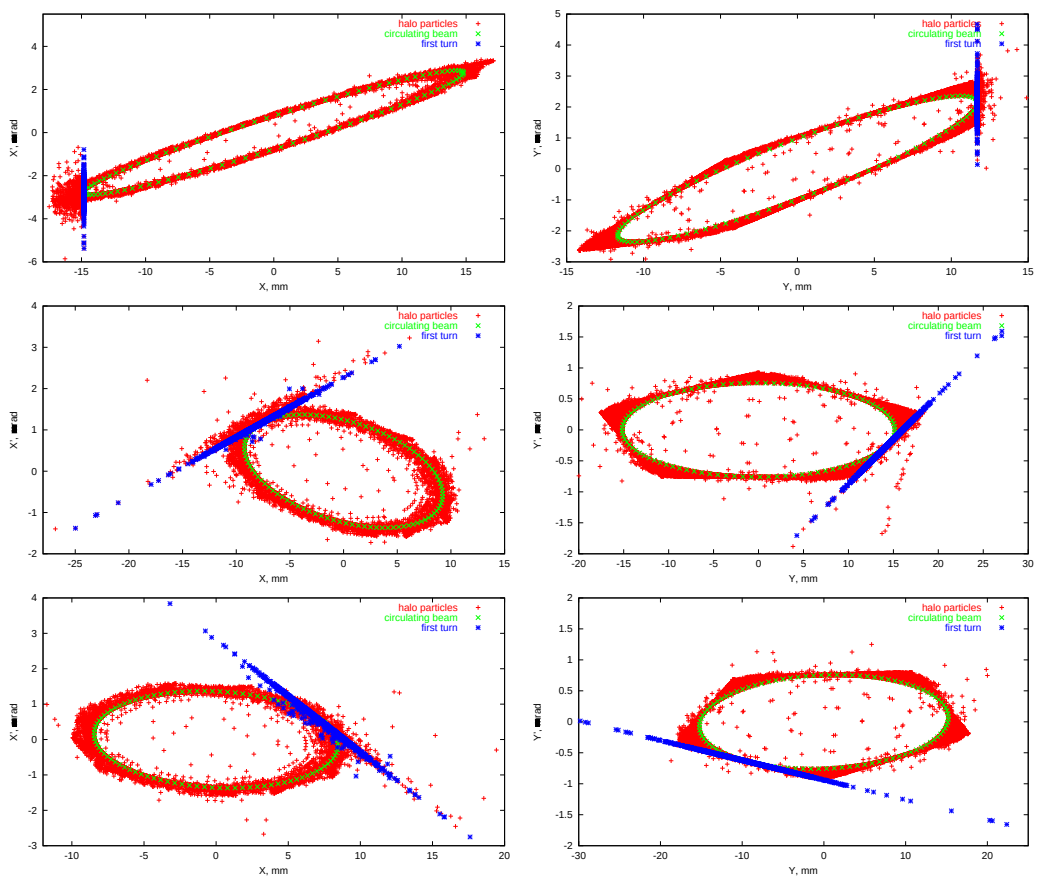

Figure 2: Horizontal (left) and vertical (right) phase space at injection in the primary collimators (top), secondary collimators SH1 and SV1 (middle), and collimators SH2 and SV2 (bottom). Graphite primary collimator thickness is 0.15 mm. Fermilab 8 GeV Booster.

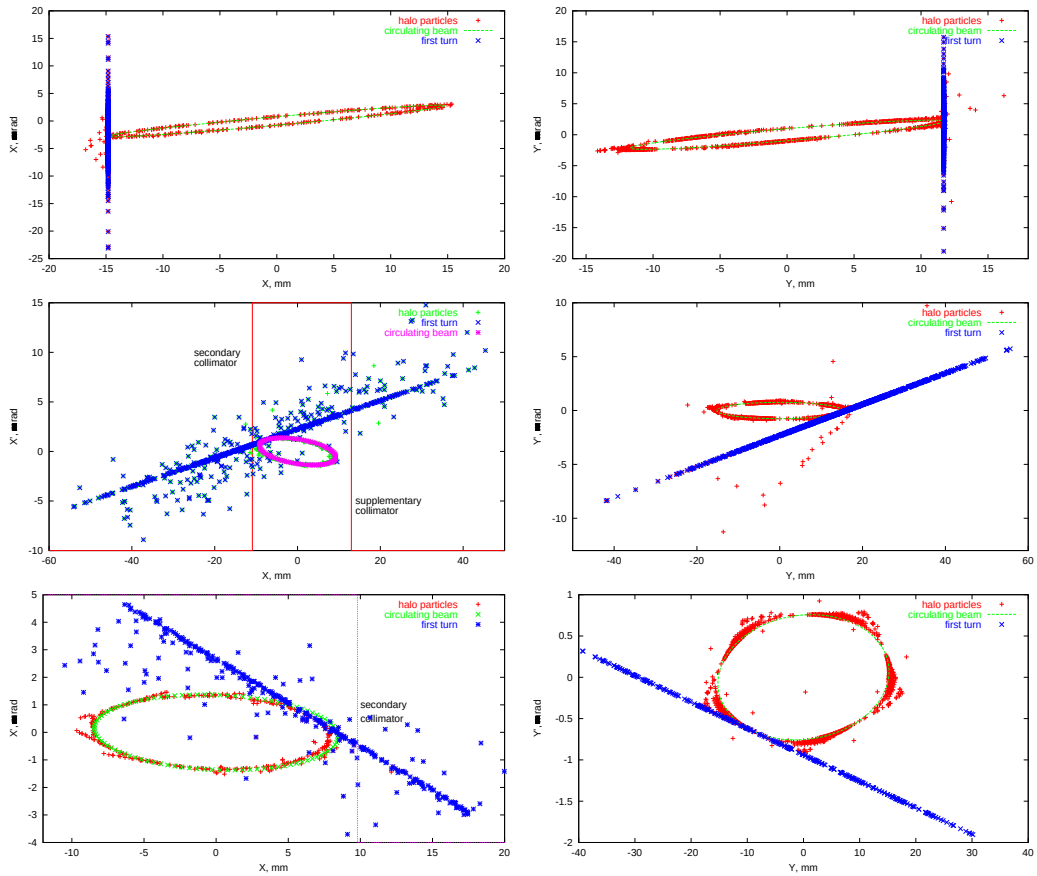

Figure 3: Horizontal (left) and vertical (right) phase space at injection in the primary collimators (top), secondary collimators SH1 and SV1 (middle), and collimators SH2 and SV2 (bottom). Tungsten primary collimator thickness is 0.1 mm. Fermilab 8 GeV Booster.

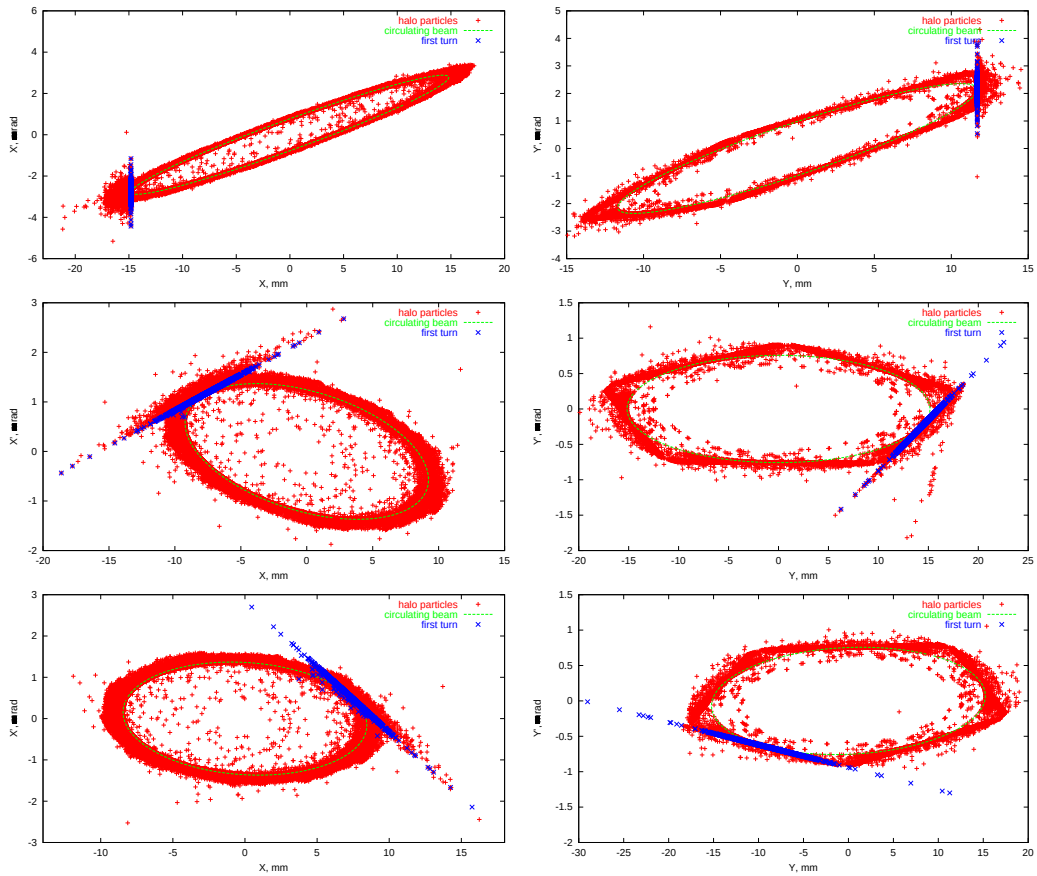

Figure 4: Horizontal (left) and vertical (right) phase space at the top energy in the primary collimators (top), secondary collimators SH1 and SV1 (middle), and collimators SH2 and SV2 (bottom). Tungsten primary collimator thickness is 0.1 mm. Fermilab 8 GeV Booster.

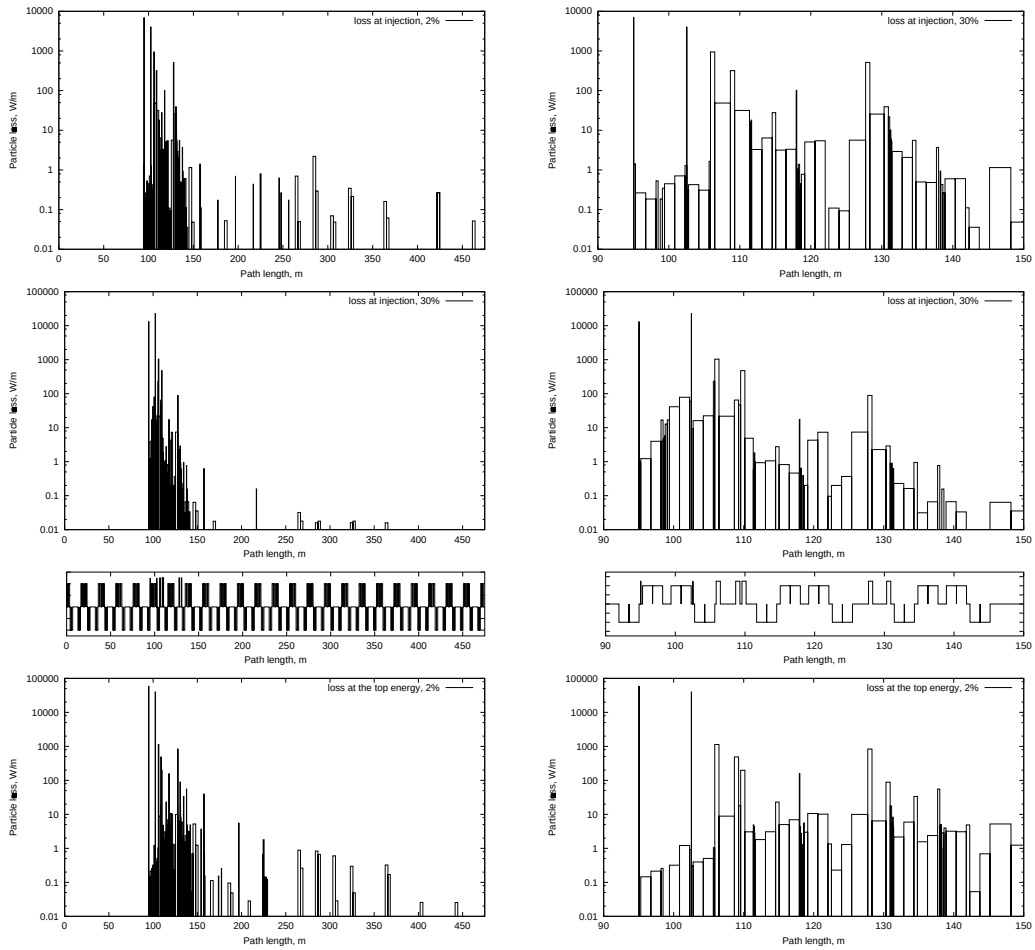

Figure 5: Beam loss distribution along the accelerator for 30% beam loss at injection with graphite 0.15 mm thick primary collimators (top), with tungsten 0.1 mm thick primary collimators (middle) and with tungsten 0.1 mm thick primary collimators for 2% beam loss at the top energy (bottom). Intensity is $5 \cdot 10^{12}$ ppp. Repetition rate is 15 Hz. Fermilab 8 GeV Booster.

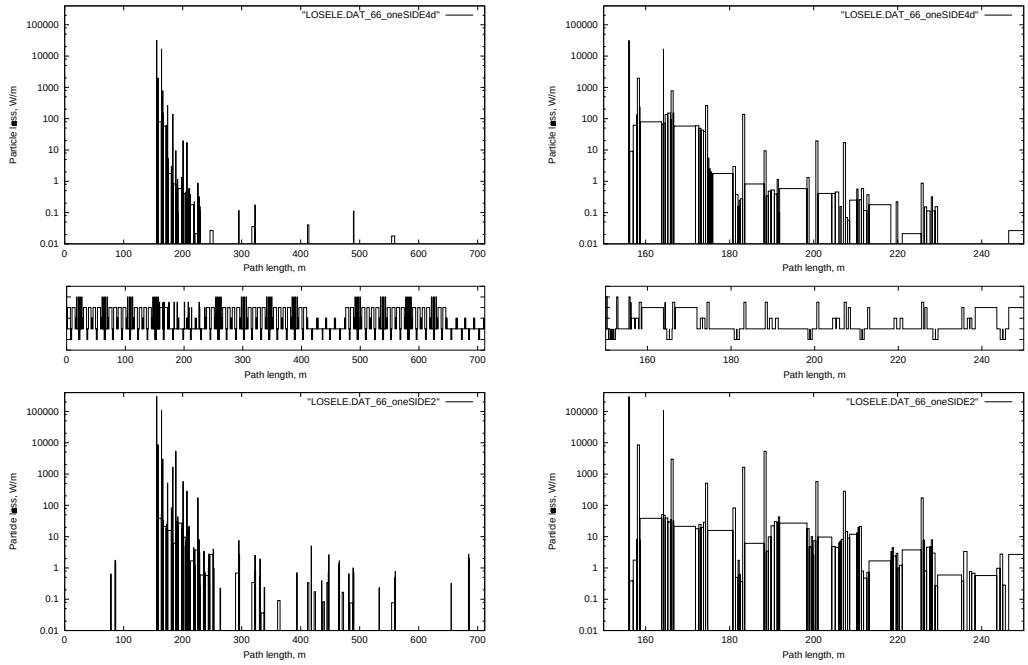

Figure 6: Beam loss at injection (top) and at 16 GeV (bottom). It is assumed that 10% of intensity is lost at injection and 1% at the top energy. Fermilab 16 GeV Proton Driver.

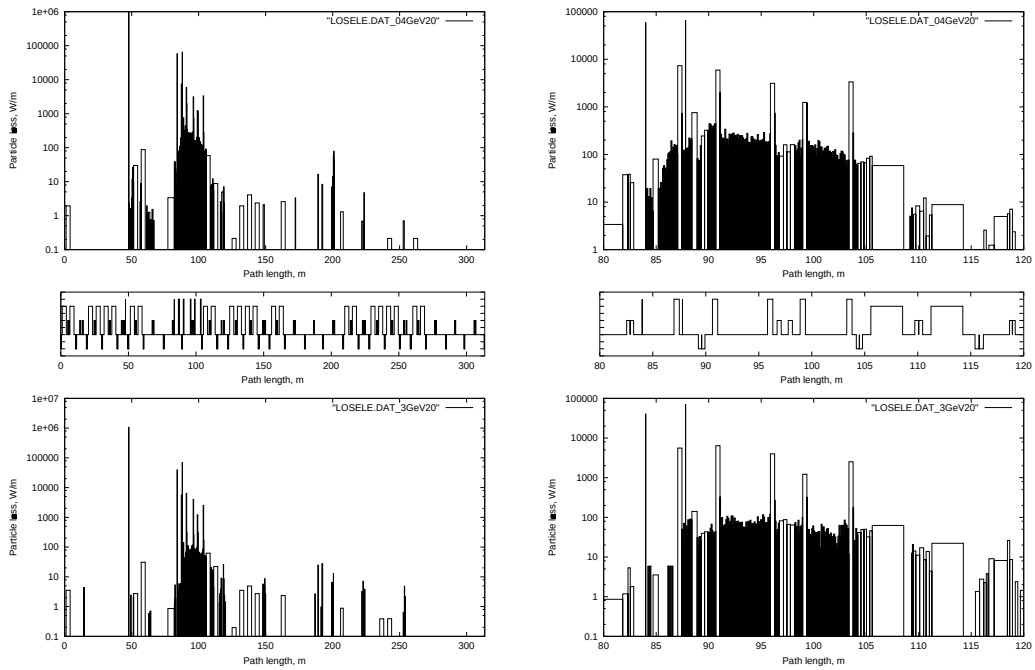

Figure 7: Beam loss distributions at 10% particle loss at injection (top) and 1% loss at the top energy (bottom) for the system with 1 mm thick primary collimators and 0.4 m long secondary and supplementary ones. Dipole aperture is R93.5mm. JHF 3 GeV Proton Driver.

2 Two-stage approach

The mean rate of ionization loss is given by Bethe-Bloch equation:

$$-\frac{dE}{dx} = K \cdot z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} ln \frac{2m_e \cdot c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 \right] \qquad (2)$$

Here K is a constant, T_{max} is the maximum kinetic energy which can be imparted to a free electron in a single collision, Z/A is a ratio of atomic number to atomic mass of collimator material, and I is a mean excitation energy.

For materials usually used for the secondary collimators this rate is from 1.4 to 2.4 $MeV \cdot g^{-1} \cdot cm^2$ in a range of proton momentum of 1-10000 GeV/c. Because of large angle of multiple Coulomb scattering for low energy particles, particles outscattered from the collimator pass through a short length of the collimaror, but loose sufficiently higher relative energy for ionization. This produces a tail of low energy particles lost shortly behind the secondary collimator in a low energy machines. A two-stage approach does not work in this case. A set of supplementary collimators is necessary to deal with particles outscattered from the main secondary collimators.

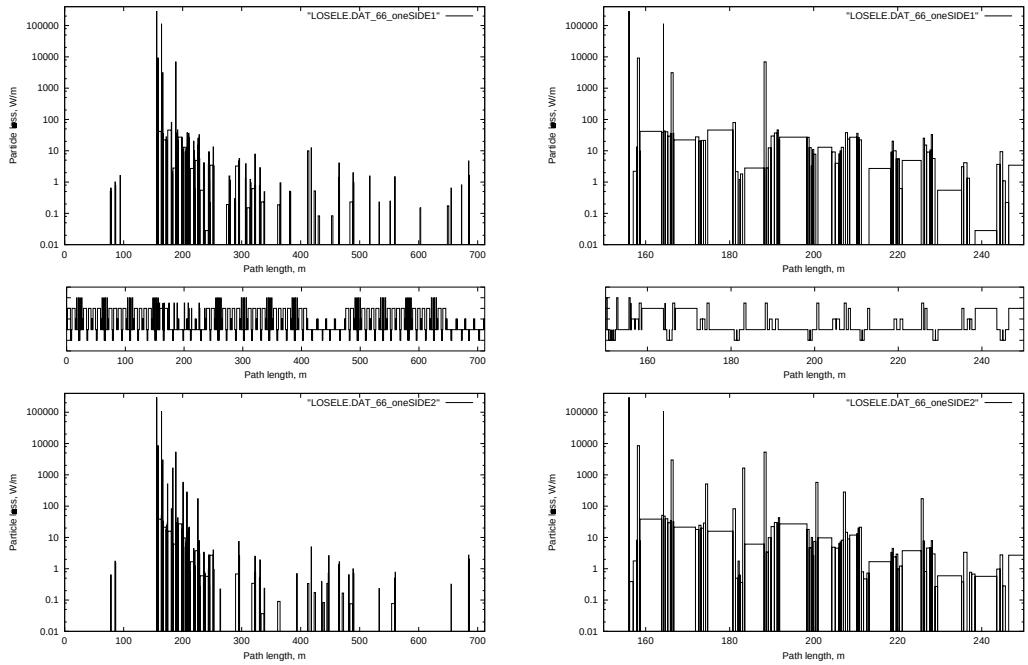

Figure 8: Beam loss at 16 GeV with 3 secondary collimators at 1 mm offset with respect to the primary ones (top) and with additional 5 supplementary collimators at 3 mm offset (bottom). It is assumed that 1% of intensity is lost at 16 GeV. Fermilab 16 GeV Proton Driver.

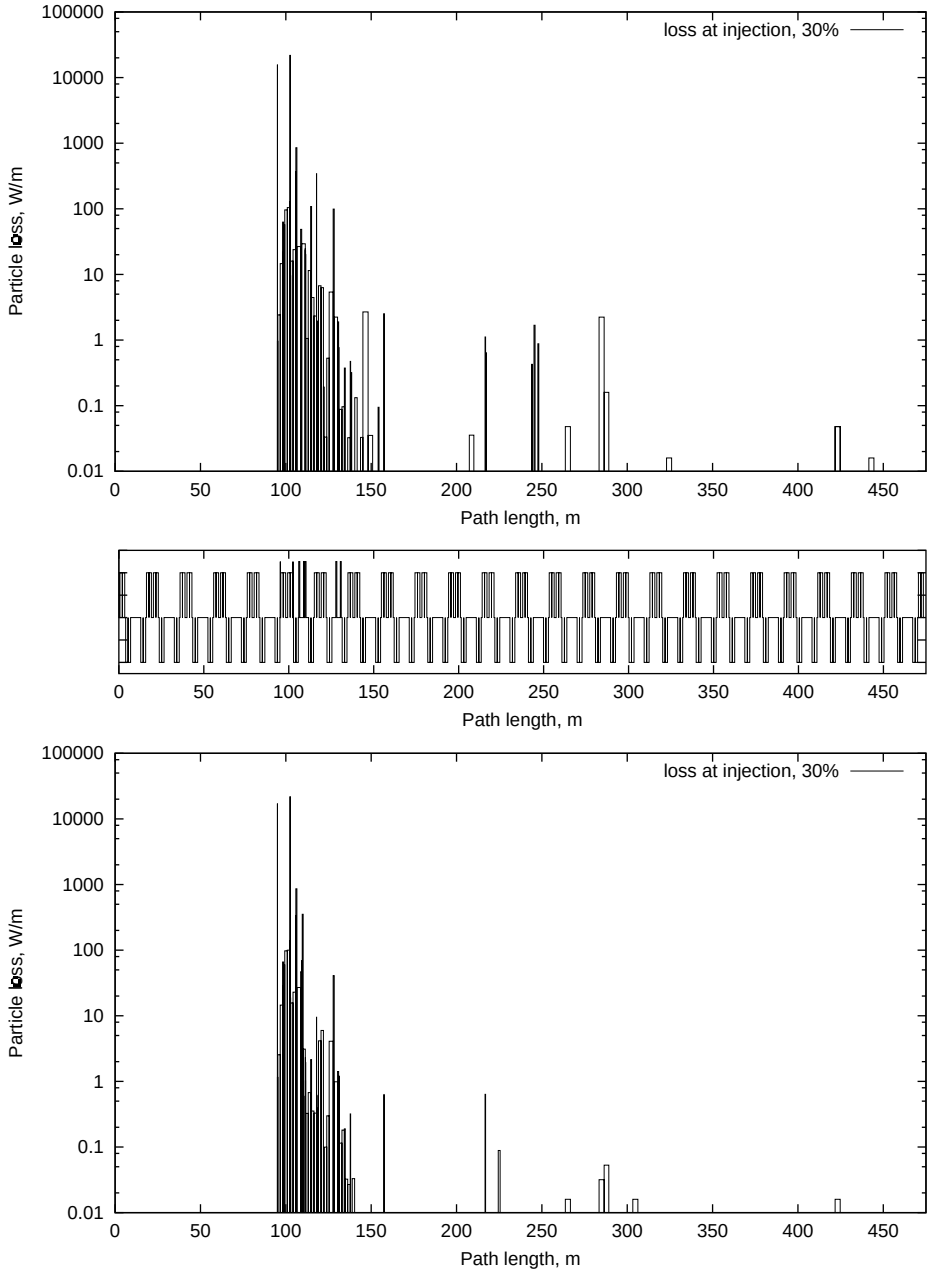

Figure 9: Beam loss distribution along the accelerator for 30% beam loss at injection without additional collimator (top) and with additional collimator behind the first secondary collimators. Tungsten primary collimator thickness is 0.2 mm. Fermilab 8 GeV Booster.

3 Off-momentum collimation

In a high energy accelerators the length of collimation section amounts of about few percent of the total length. It is allowed to design this section to fit the collimation section requirements because the total cost of accelerator does not increase much. Two primary and a set of secondary collimators at optimal phase advances and dispersion can be used for momentum collimation of particles with different sign of momentum deviations. Momentum collimation is done here during the first turn after particle interaction with the primary collimator. In a low energy accelerators the length of collimation section amounts up to 10-15% of the total length. The cost of this region is relatively high with respect to the total price of the machine. And the attempt to preserve a higher periodicity of accelerator dictates the choice of equivalent lattice design for all long straight sections in the machine. As most of the technological system (injection, RF, extraction) require a dispersion free straights, the collimation system is mostly concentrated in a dispersion free region, with only primary and first secondary collimators located in the last part of the arc section upstream of the collimation straight. This is necessary for the momentum collimation. In this case usually there is no space for the second secondary collimator and for collimation of particles with different sign of momentum deviations. These particles will be intercepted at the later turns by the same off-momentum collimators in a half of synchrotron oscillation, than the sign of momentum deviation is changed.

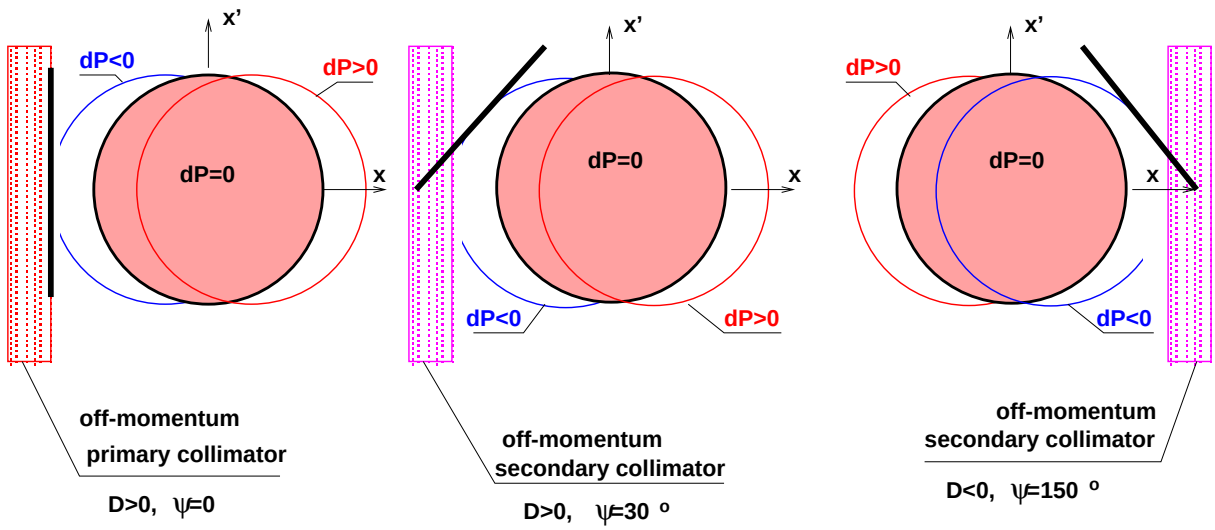

Figure 10: Off-momentum collimation.

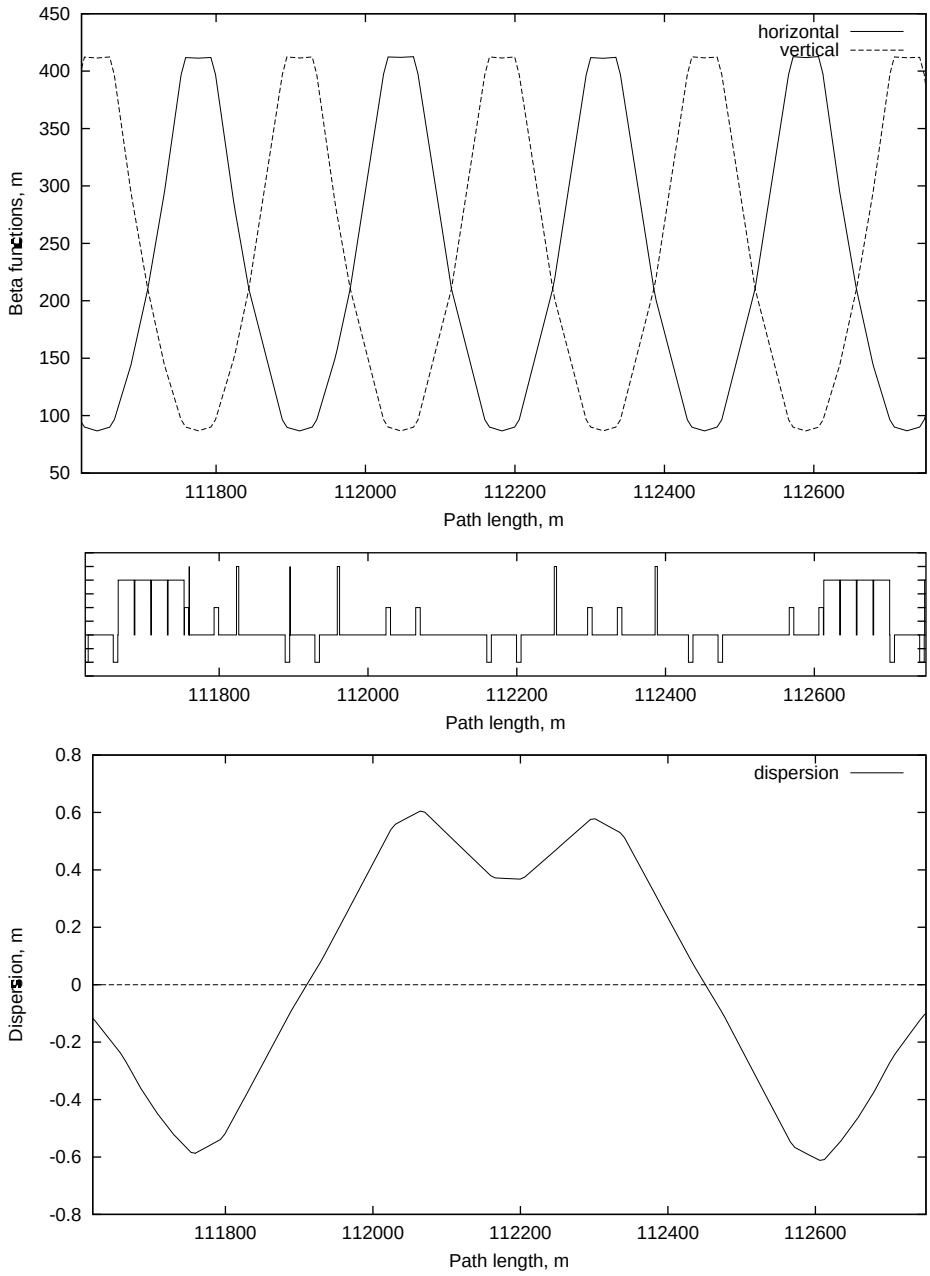

Figure 11: Beta functions and dispersion in the collimation region. VLHC

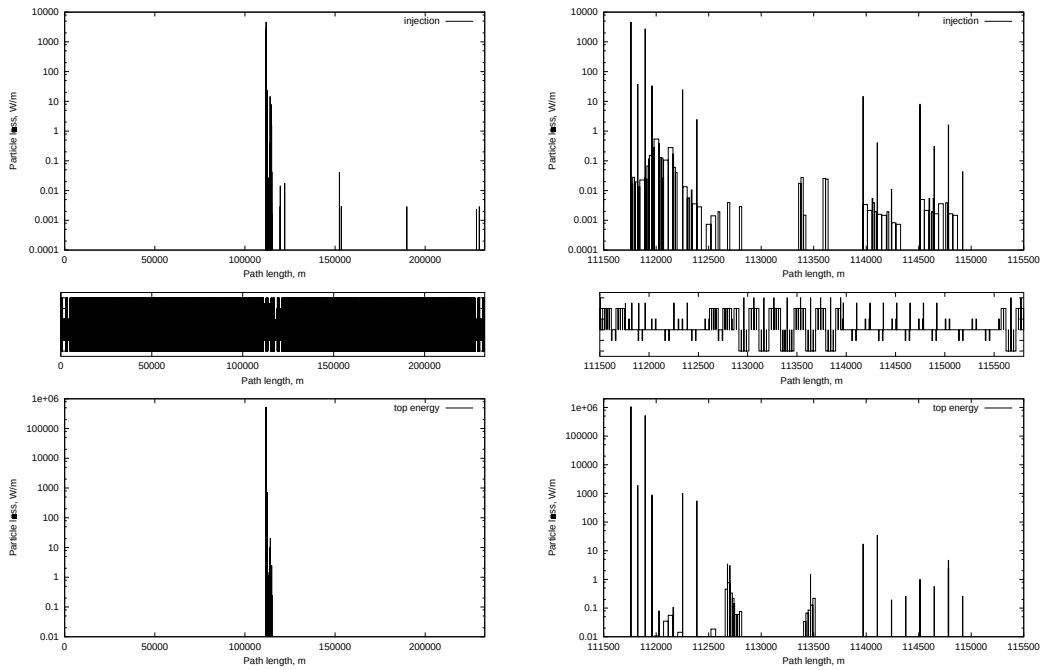

Figure 12: Beam loss distribution along the accelerator at injection (top) and at collisions (bottom). VLHC

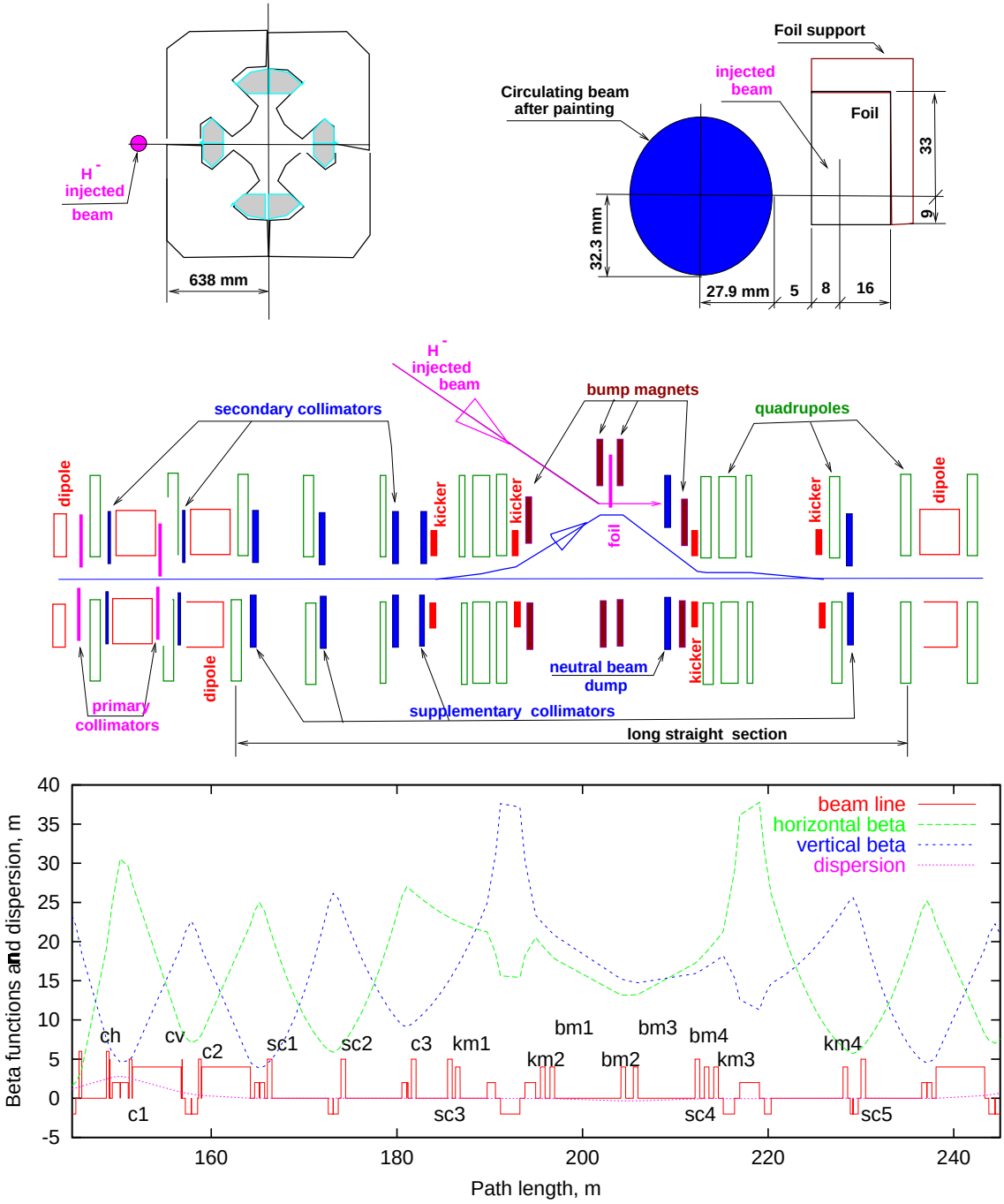

Figure 13: Beam collimation and beam painting systems (top) and beta functions and dispersion (bottom) in the Fermilab Proton Driver.

4 Collimation during accelerator cycle

Low energy accelerators are fast cycling machines. Because of that it is difficult to use different primary collimators at injection and at the top energy. The simulations shows that the loss rate at injection in the Fermilab Booster at the magnets behind the primary collimators is ~100 W/m. It can be reduced to 1 W/m if the primary collimator thickness is changed during the cycle from 0.003 mm to 0.1 mm for tungsten or from 0.15 mm to 5.4 mm for graphite. In principal this can be done by rotation of primary collimator constructed as a disk of different thickness.

Closed orbit instability in the fast accelerators is much larger compared to the high energy colliders. This does not permit to place secondary collimators close to the beam. Usually this instability is about 2-5 mm. This reduces a collimation efficiency.

The collimators are placed at the beam edge after injection, and stay their during the accelerator cycle in spite of beam size reduction at acceleration. With collimators in a fixed position with respect to the beam orbit in the Fermilab Proton Driver, ~99% of the beam halo energy is intercepted in the 60-m long collimation section. About 1% is lost in the rest of the machine with the mean rate of 0.12 W/m. At several locations the beam loss is noticeably higher (~7 W/m), exceeding the tolerable rates. These 'hot' locations should be taken care of via local shielding. Using a local bump which keeps the beam at the edge of the primary collimators and close to the first secondary collimators during the cycle one can localize a majority of the beam loss in a 35-m long region and to reduce the average loss in the ring to 0.05 W/m. But unfortunately, the orbit bump is seems to be pretty complicated.

Table 1: Beam loss in the Proton Driver.

	Beam loss		
Collimation system	Collimation region	Rest of the ring	Peak loss rate in the ring
	kW	kW	W/m
AT THE TOP ENERGY ($E_{kin} = 16\ GeV$)			
No collimators	0.470	11.050	2700
three secondary at 2 mm	11.375	0.146	13.2
three secondary at 2 and 3 mm five supplementary at 5 mm	11.449	0.071	6.7
with bump three secondary at 2 and 3 mm five supplementary at 5 mm	11.487	0.033	4.7
AT INJECTION ($E_{kin} = 0.4\ GeV$)			
three secondary at 2 and 3 mm five supplementary at 5 mm	2.879	0.001	0.2
at RF capture loss three secondary at 2 and 3 mm five supplementary at 5 mm	2.877	0.003	1.0

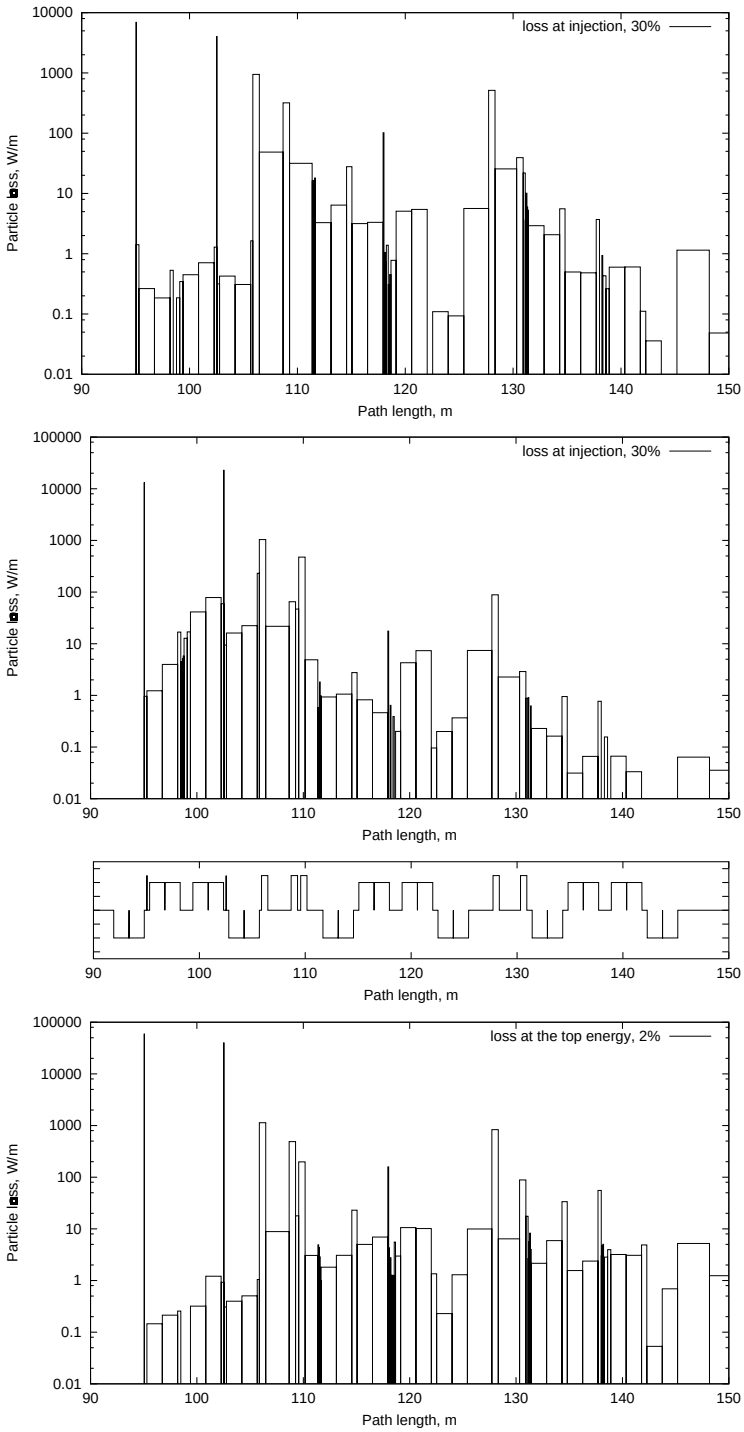

Figure 14: Beam loss distribution along the accelerator for 30% beam loss at injection with graphite 0.15 mm thick primary collimators (top), with tungsten 0.1 mm thick primary collimators (middle) and with tungsten 0.1 mm thick primary collimators for 2% beam loss at the top energy (bottom). Intensity is $5 \cdot 10^{12}$ ppp. Repetition rate is 15 Hz. Fermilab 8 GeV Booster.

The mechanical design of the Fermilab Proton Driver collimator is shown in Fig. 15. The collimators consist of 2 pieces of stainless steel, 0.5 m long, welded together in an ”L” configuration. The collimator assembly is welded inside a stainless steel box of outside dimensions approximately 230 mm x 130 mm and with bellows on each end. A total of 11.5 KW of DC power is expected to be dissipated in the collimators. 11.5 KW of power can be removed from a single collimator by circulating standard low conductivity water through cooling channels on the outside of the collimator box. A flow of 2.2 GPM will remove 11.5 KW of power with a temperature rise of 20C.

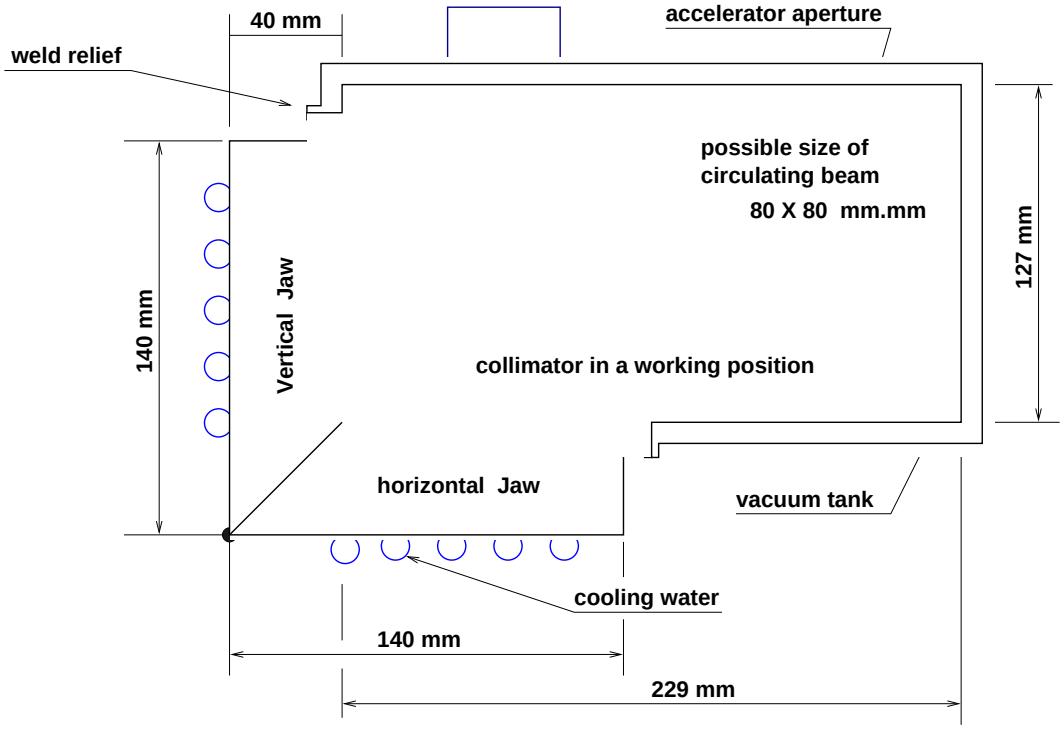

Figure 15: Secondary collimator cross section.