2.6 Electron transport lines

Overview

The electron transport lines consist of all of the electron beamline segments that are neither part of the Linacs nor part of the injector. Ideally they transport the beam without increasing the emittance. They comprise systems of dipoles, quadrupoles and sextupoles that steer and focus the beams onto the design orbit passing through the insertion devices (IDs), which stimulate the beams to radiate in the x-ray region of the spectrum. Instrumentation is provided to measure the beam properties and position with respect to the design orbit. The electron beamline portions presented in this chapter are shown schematically in Fig. 2.6.1.

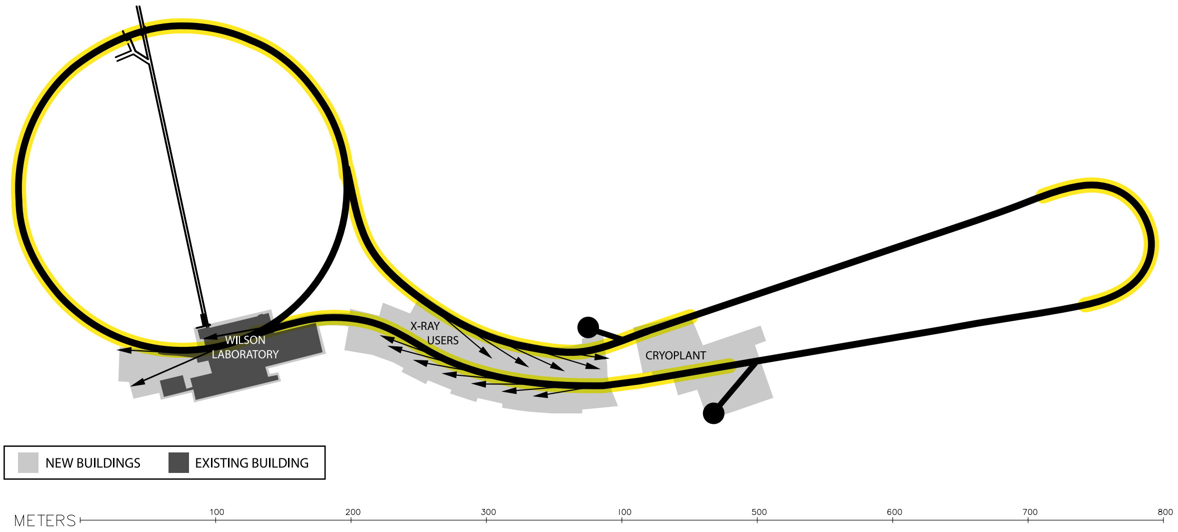

Figure 2.6.1: The yellow highlighting color indicates the portion of the electron trajectory discussed in this chapter

State of the art

Magnet quality apertures large enough for storage-ring service routinely reach one part in 10^4 compared to the ideal field at a radius large compared to the beam size. Residual gas pressures in the nanotorr regime are common at power depositions of several kW per meter. These qualities are adequate for the ERL. In component and beam-positional stability, the Swiss Light Source (SLS) currently holds the record for achieved vertical emittance in storage rings of < 3 pmrad in the vertical. The girders can be aligned to 50 to 100 μm. Using beam-based alignment, the rms orbit deviations from quadrupole centers can be held to about 10 μm [1]. At the LCLS, the orbit stability is measured at 3 μm rms with alignment of the undulator sections after beam-based alignment at under 10 μm [2].

ERL transport line parameters

The nomenclature used for the various transport line segments is shown below in Fig. 2.6.2 Numbers of components of various kinds needed in these segments are given in Tab. 2.6.1. A typical optical cell with component location is shown schematically in Fig. 2.6.3

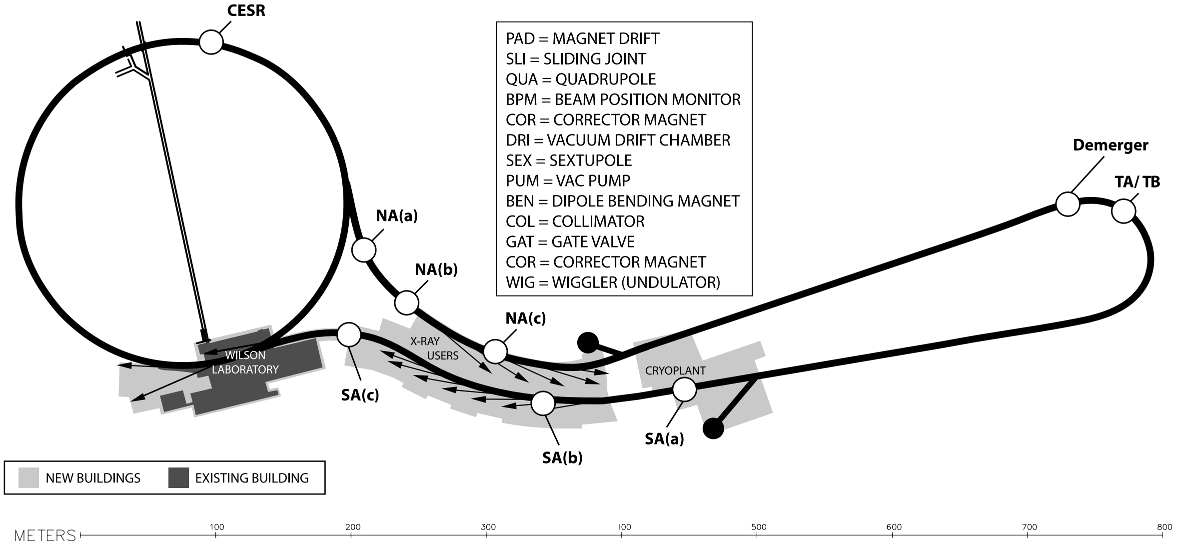

Figure 2.6.2: Segments of the electron-transport line

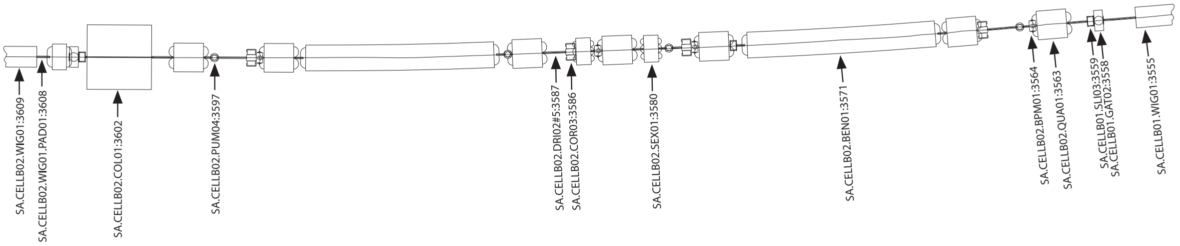

Figure 2.6.3: Typical cell schematic in south arc, undulator at right proceeding to next undulator at left. Note protective collimator and short bend immediately upstream of left hand undulator.

2.6.1 Magnet

Dipoles

The optics demands of an ERL are quite different from a storage ring since first- and second-order dispersion and time of flight terms must be carefully controlled at all points. These constraints combined with those of the terrain and existing infrastructure, plus other specialized needs, result in a large variety of dipole magnets in the design. The optics are arranged in achromatic cells comprising several dipoles and quadrupoles. In order to keep the beam orbit

Table 2.6.1: Some parameters of the transport line segments.

Quantity	TA	TB	SA	CESR	NA
Energy (GeV)	2.8	2.2	5.0	5.0	5.0
Length (m)	159.3	142.9	410.4	768	291.3
Dipoles (35 mm gap)	18	18	50	exist	29
Quadrupoles (bore 43 mm)	37	37	115	exist	63
Sextuples (bore 51 mm)	7	7	19	exist	16
10 m vacuum chambers	16	15	32	exist	24
Flanges	32	30	64	exist	48
Metal gate valves	3	3	20	exist	12
Tapers	1	1	20	exist	10
Beam Position Monitors	37	17	115	exist	63
Pump ports	47	41	58	exist	53
Lumped pumps	47	41	58	exist	53
Distributed pumps	$\approx$ 320m	$\approx$ 300m	$\approx$ 640m	exist	$\approx$ 480m
Vent ports	3	3	20	exist	12
Gauge ports	6	6	40	exist	24
RGA ports	3	3	20	exist	12
Sliding joints	19	17	51	exist	25
Ion clearing electrodes	16	16	41	42	28

Table 2.6.2: Dipole parameters by type.

Type	Quantity	Field (T)	Arc Length (m)	Radius (m)
1	4	0.467	4.000	35.7
2	6	0.443	3.870	37.6
3	6	0.351	3.802	47.5
4	16	0.578	3.000	15.8
5	14	0.479	3.000	15.8
6	4	0.292	2.955	57.1
7	12	0.312	2.937	53.5
8	8	0.425	2.925	39.3
9	2	0.312	2.923	53.5
10	2	0.319	2.920	23.7
11	4	0.331	2.822	50.4
12	12	0.253	2.807	65.9
13	2	0.602	1.995	15.2
14	2	0.300	1.000	25.3
15	4	0.443	0.500	37.6
16	1	0.136	0.489	122.4
17	14	0.028	0.300	600.0
18	1	0.057	0.249	294.1
19	1	0.136	0.245	122.4
20	2	0.070	0.250	238.1

within 10% of its transverse size, the dipole field strength within each achromat must track one another within 10^{-7}, whereas if all of the dipole fields in each achromat vary together the tolerance is a more reasonable 10^{-4}. In order to achieve this, and minimize the number of high-precision power supplies needed, the lengths of the dipoles have been adjusted to allow powering of all strong dipoles in each section of the ERL from a single power source. The fields and lengths of the individual dipoles are given in Tab. 2.6.2. In view of the need to avoid unnecessary halo, the field quality of the dipoles is stated as departure from the ideal dipole field by no more than ±1 part in 10^4 within the 12.7 mm radius of the beam pipe. Subsequent simulations may ease this requirement. In considering the coil cross section, the cost of power over five years must be balanced with the cost of materials for construction. For that reason, we lean toward copper coils. The stated power supply requirements reflect a relatively low-current density in the coils. A concept cross section is shown in Fig. 2.6.4. The 14–600 m bend-radius magnets are provided to keep upstream-generated radiation from propagating down the x-ray beam lines into the hutches.

Quadrupole magnets

The field quality of the quadrupoles is specified for the ERL optics to be such that the field at 12.7 mm off-center is to be within 2 parts in 10^4 of the field of an ideal quadrupole at that radius. It is expected that the cores of these magnets will be manufactured using lamination

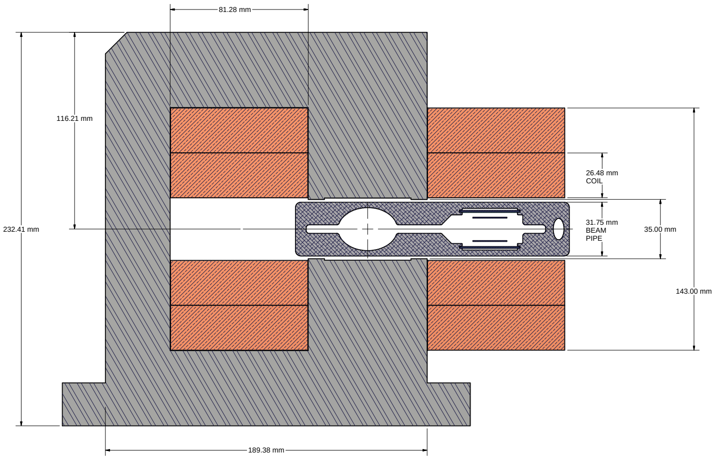

Figure 2.6.4: Concept design of a dipole using lamination technology

technology and that copper will be used for the coils to minimize the power usage. Figure 2.6.5 shows a cross-section. Table 2.6.3 gives the distribution of quadrupole strengths used in the optics design. The bore of the quadrupoles are 43 mm with an effective length of 0.5 m.

Sextupole magnets

Sextupole magnets are used to adjust the lattice parameters as described in §2.1. Figure 2.6.6 shows a cross-section of the 51 mm bore sextupoles having an effective length of 250 mm. Table 2.6.4 displays the strength distribution.

H and V steering magnets will be capable of +/- 0.4 mrad and will be installed in pairs occupying the same longitudinal space, in emulation of the current design contemplated for NSLSII [3]. The scheme is depicted in Fig. 2.6.7. There will be 150 of these in the warm parts of the machine, and 64 superferric pairs in the Linacs.

Magnet supports

In order to provide solid, low-thermal, low-vibration expansion mountings for the magnet strings comprising the ERL confinement system, a plinth wall is proposed. Figure 2.6.8 and Fig. 2.6.9 show the concept for the quadruple − sextupole pairs and dipoles separately.

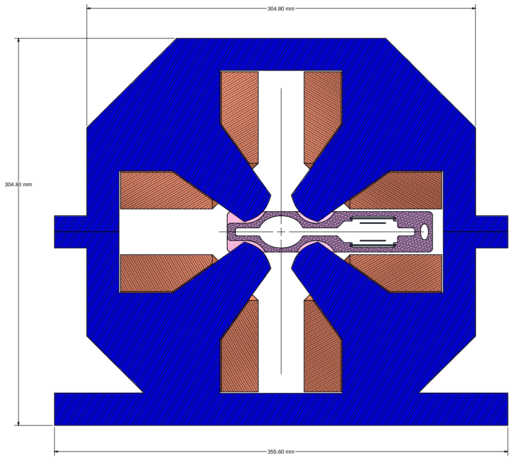

Figure 2.6.5: Quadrupole lamination cross section showing cut-outs for poles in vacuum chamber.

Table 2.6.3: Quad strengths – All quadrupoles are normal conducting with the exception of the Linac lenses which are superferric.

Strength (T/m)	Linac A&B	TA	SA	CESR	NA	TB
0.0 – 5.0	70	3	19	exist	8	5
5.0 –10.0	0	34	10	exist	10	28
10.0 –15.0	0	0	39	exist	22	4
15.0–20.0	0	0	7	exist	18	0
20.0 –25.0	0	0	22	exist	4	0
25.0–30.0	0	0	11	exist	1	0
30.0–35.0	0	0	7	exist	0	0
> 35	0	0	0	0	0	0

Table 2.6.4: Sextupole strength distribution.

Strength (T/m^2)	TA	SA	CESR	NA	TB
0–100	7	0	exist	16	7
100– 200	0	4	exist	0	0
200 – 300	0	1	exist	0	0
300 – 400	0	14	exist	0	0

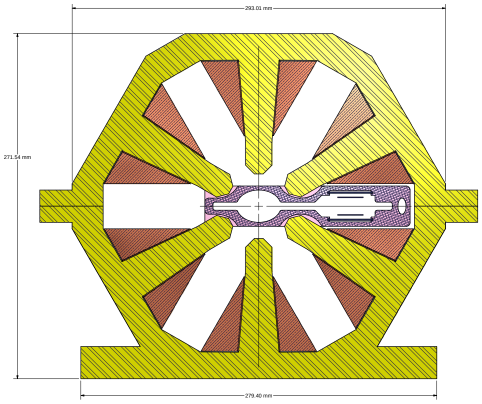

Figure 2.6.6: Sextupole lamination cross section showing pole cutout in vacuum chamber at sextupole location.

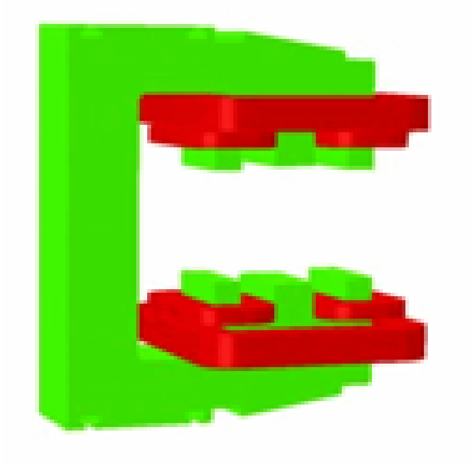

Figure 2.6.7: 3D depiction of the NSLS2 156 mm combined correction magnet that can be emulated in the ERL.

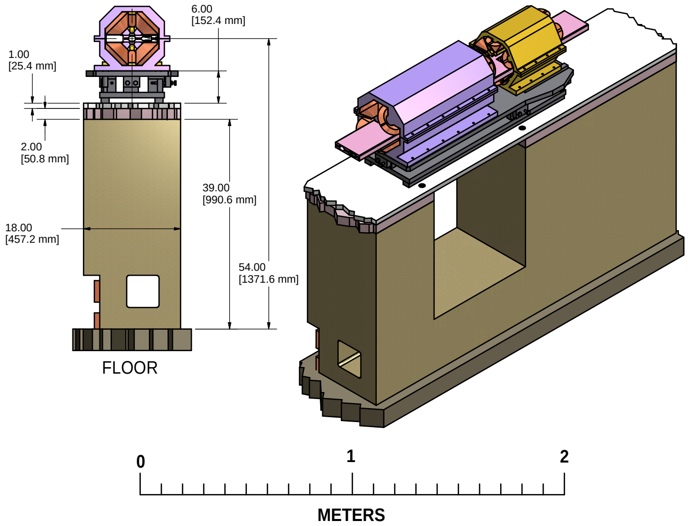

Figure 2.6.8: Quadrupole-sextupole combination mounted on the plinth wall with fine-position adjusting mount.

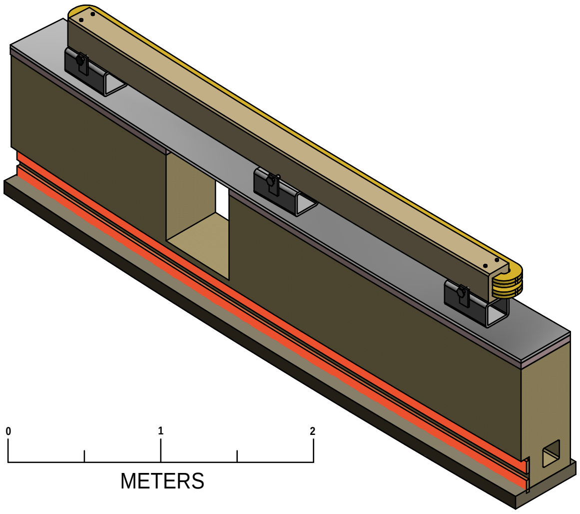

Figure 2.6.9: : Dipole mounted on the plinth wall.

Magnet power supplies

General requirements for all power supplies are listed in Tab. 2.6.5. The stability requirements shall be met for any combination of ±5% line-voltage change (both long and short term) and $\pm 5^o C$ change in ambient air temperature or $\pm 2^o C$ change in cooling water input temperature (long term). All power supplies dissipating more than 200 W must be water cooled. The control interface shall be capable of updating set point and readback of current at greater than 5 Hz rate. Power supplies and other electronics will be located in racks outside the shielding wall but as close to the magnets, vacuum equipment, and instrumentation as possible.

Table 2.6.5: Magnet power supply general parameters

Parameter	Conditions	Tolerance
Input Voltage	See tables below 60 Hz	±10 %
Power factor at load	At or above 50% rated power	> 90%
Control resolution	See individual descriptions	18 or 16 bit
Output voltage ripple & noise		< 0.2% rms
Transient recovery	±5% line voltage transient	0.2% within 100 ms
Output current stability (see above)	1s− 24 hr referred to full scale	Dipole $\pm 2.5 \times 10^{-5}$; Quad $\pm 5 \times 10^{-5}$ 6-pole $\pm 1.0 \times 10^{-4}$; Corr. $\pm 2.5 \times 10^{-5}$
Cooling water	Operating	30 ± 5°C. 100 psi max

Dipole power supplies

Five large dipole-power supplies will be required − one for each section of the ERL. Two smaller supplies will be used for strings of short (30 cm) dipoles in each of the arc sections. All require high quality regulation with 18-bit control and provision for monitoring at a similar resolution. Output voltage and currents are shown in Tab. 2.6.6

Table 2.6.6: Dipole power supply parameters

Quantity	Output Voltage (V)	Output Current (A)	Input Voltage (V)
2	300	750	480 −3 phase
3	200	750	480 −3 phase
2	80	20	208−1 or −3 phase

Quadrupole power supplies

Each quadruple requires an independently adjustable current. Most quadrupoles' requirements are satisfied by 1.5 kW power supplies with a smaller number between 1.5 and 5 kW as shown in Tab. 2.6.7 High quality regulation with 18 bit resolution for control and monitoring is needed.

Table 2.6.7: Quadrupole power supply parameters

Quantity	Output Voltage (V)	Output Current (A)	Input Voltage (V)
211	15	100	208 −1 phase
45	25	200	208 −3 phase

Sextupole power supplies

Each sextupole requires an independently adjustable current with power supply parameters in Tab. 2.6.8.

Table 2.6.8: Sextupole power supply parameters

Quantity	Output Voltage (V)	Output Current (A)	Input Voltage (V)
49	30	50	208−1 phase

Dipole corrector power supplies

Each dipole corrector (steerer) requires independently adjustable bipolar current. These supplies are designed to regulate well around zero current and cross-over sign without significant transients. Requirements are given in Tab. 2.6.9

Table 2.6.9: Corrector power supply parameters

Quantity	Output Voltage (V)	Output Current (A)	Input Voltage (V)
290	±30	±50	208 −1 phase

2.6.2 Insertion devices

Currently the Delta undulator is the primary candidate for the insertion devices (see Tab. 2.6.10 for a list of parameters), which include 3 of 25 m length and 11 of 5 m length in the plan as shown in layout diagram Fig. 2.6.10.

2.6.3 Vacuum chambers, pumps and instrumentation

The vacuum chamber, pumping and vacuum instrumentation as well as BPM and ion clearing electrode concepts are dealt with in §2.2. A rough shape of the chamber is indicated by figures of magnet cross sections in the previous paragraphs.

2.6.4 Collimators

Intra-beam scattering (IBS) results in a halo of electrons about the core of the electron beam which, if neglected would result in unacceptable radiation in the insertion devices of small

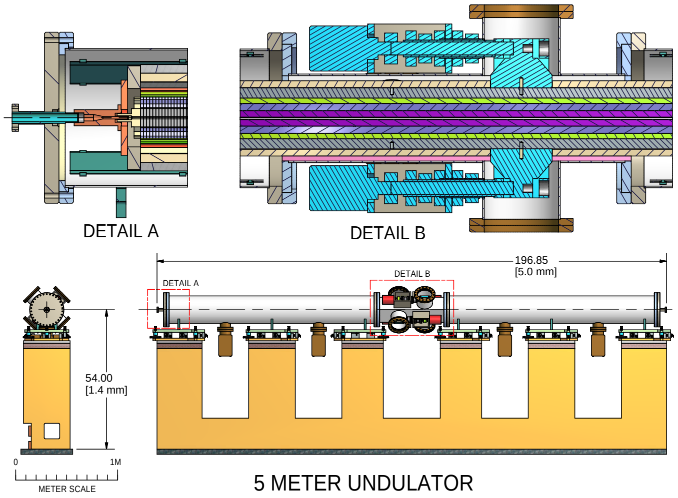

Figure 2.6.10: Delta undulator 5 m length supported by the plinth wall.

Table 2.6.10: Undulator parameters

Unit Length	5 m
Period	20 mm
Material	NdFeB
Gap/Bore	5 mm
Peak Field	0.91 T helical
	1.296 T planar

(5 mm) aperture. Protective collimators are thus necessary to assure that the consequent radiation can be dealt with by the personnel shielding. In the x-ray halls, the Touschek and Intra Beam Scattering (IBS) losses at the collimators are typically one to a few pA. In other areas, the IBS losses are more substantial and need a different collimator type. Concepts for the two types of collimators are discussed in the vacuum chapter, §2.2.4.

2.6.5 Extraction beamline (EX)

Purpose

It will be advantageous to have a low repetition rate, low emittance beam of variable current for studying matters relevant to the physics of the ERL and various FEL schemes. Seeding schemes, XFEL-O, and other studies will arise as accelerator science advances.

Injection

The bunches for the extracted beamline could come from the dedicated operation of the primary injector up to a bunch charge of ≈ 200 pC or somewhat higher. If higher charges or simultaneous operation with x-ray running are required, then a second injector will be needed. Space for such an injector is available. A repetition rate of up to 10 kHz with 1 nC per bunch is envisioned.

Layout

Figure 2.6.11 shows the layout of the EX section beginning just downstream of the beam stop. The fast kicker discussed in §2.1.12 produces a 1 mrad bend, initiating the extraction process. A bunch compressor and transport optics deliver the extracted beam to the shielded area shown in the figure, terminating in a beam stop capable of 5 kW dissipation. The part of the EX section downstream of the bunch compressor is shielded by a special heavy concrete enclosure.

2.6.6 CESR

As discussed in §2.1.8, the baseline design is to use a portion of the existing CESR lattice with all its ancillary hardware as part of the return arc. While the IBS generated in CESR is relatively large and the emittance growth per unit length greater than in other parts of the transport, both are acceptable. The emittance of the beam in the north arc after the CESR portion of the transport is degraded by only a factor of two. As a later upgrade, the CESR arc can be modified for reduced IBS losses and smaller emittance growth.

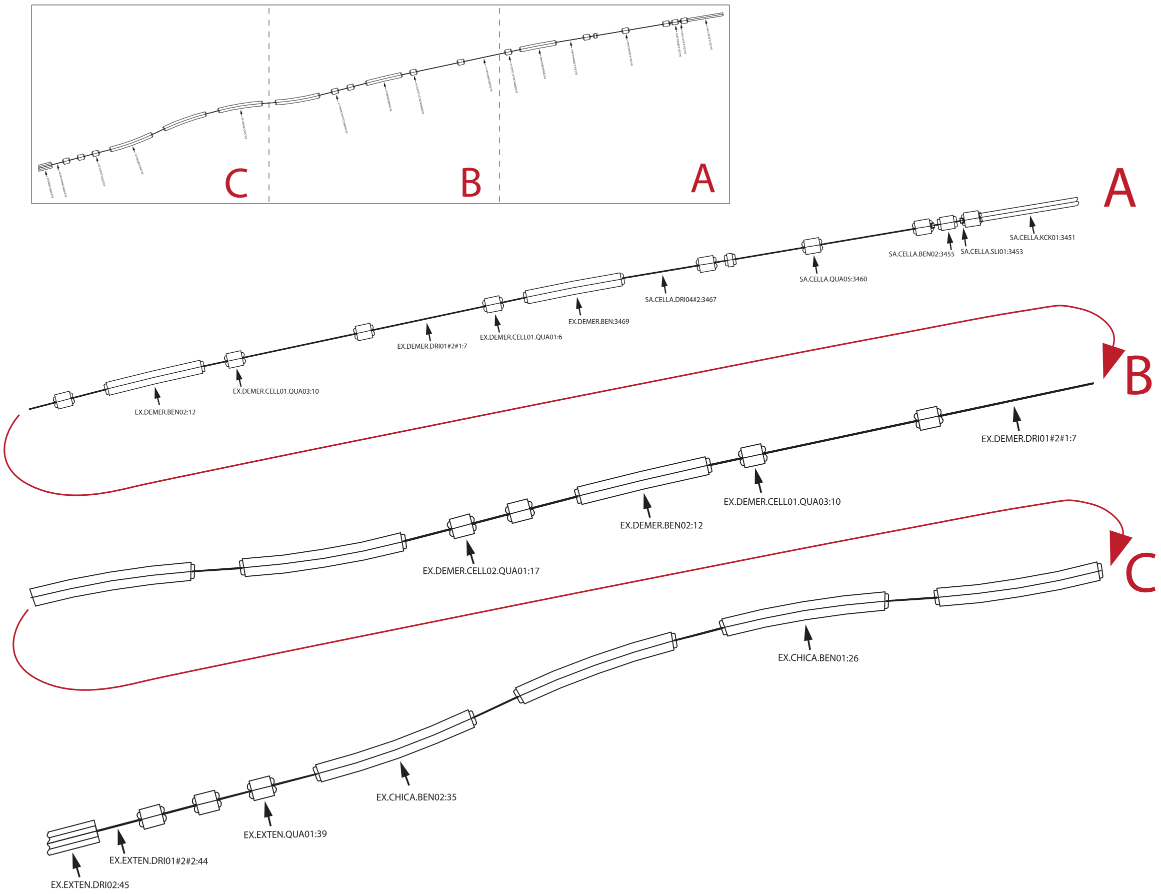

Figure 2.6.11: Layout of the EX beamline beginning just downstream of the stop for the decelerated beam.

References

[1] Boege, M. *et al. Ultra-low vertical emittance at the SLS.* In *The 23rd Particle Accelerator Conference*, pages 2279–2281. Vancouver, British Columbia, Canada (2009).

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[3] Danby, G. *et al. Design and measurement of the NSLS II correctors.* In *The 23rd Particle Accelerator Conference*, pages 148–150. Vancouver, British Columbia, Canada (2009).