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Synchrotron Facilities And Free Electron Lasers

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Introduction

Synchrotron radiation (SR) is electromagnetic radiation emitted when a charged particle travels along a curved trajectory. Initially encountered as a nuisance around orbits of high energy synchrotron accelerators, it gradually became an indispensable research tool in many applications: crystallography, X-ray lithography, micromechanics, structural biology, microprobe X-ray experiments, etc. So-called first generation SR sources were exploiting SR in parasitic mode at electron accelerators built to study particle collisions. The second generation of SR sources was the first facilities solely devoted to SR production. They were optimized to achieve stable high currents in the accelerator ring to achieve substantially higher photon flux and to provide a large number of SR beam lines for users. Third generation sources were further optimized for increased brilliance, i.e. with photons densely packed into a beam of very small cross-sectional area and minimal angular divergence (see the Appendix for more detailed definitions of flux, brightness and brilliance) and makes extensive use of the insertion devices such as wigglers and undulators. Free Electron Lasers (FELs), the fourth generation SR sources, open new research possibilities by offering extremely short pulses of extremely bright and coherent radiation.

The number of SR sources around the world now probably exceeds 100. These facilities vary greatly in size, energy of the electron (or positron) beams, range of photon energies and other characteristics of the photon beams produced. In what follows we will concentrate on describing some common aspects of SR facilities, their operation modes and specific radiation protection aspects.

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Synchrotron Radiation

Fundamentals of Dipole SR

SR facilities use exclusively electron or positron beams. The power radiated by SR emission is proportional to the mass m of the emitting particle as m^{-4}; therefore use of heavier charged particles would not be practical. A non-relativistic electron on a curved path will emit SR radiation in a non-directional "dipole" pattern (Winick 1994). At relativistic electron energies ($E >> mc^2$ = 0.511 MeV, electron rest mass energy) the amount of radiated energy increases dramatically and relativistic effects lead the emission pattern into a sharp forward cone with a characteristic angle $\theta_c = mc^2/E = \gamma^{-1}$. Curved electron trajectories are achieved in bending (dipole) magnets, where the curvature occurs in a plane perpendicular to the direction of the magnetic field. SR is emitted tangentially to the electron beam trajectory, leading to a "sweeping search light" pattern, illustrated in Fig. 1. This pattern forms a continuous "fan" in the horizontal plane and its vertical cross-section is extremely thin (γ^{-1}). In typical SR facilities electrons circulate in a closed orbit generated by a series of bending magnets. The energy ΔE lost by SR emission by one electron per complete circular turn is (Winick 1994):

$$\Delta E(\text{keV}) = 88.5\, E^4(\text{GeV})/R(\text{m}) \quad (1)$$

where E is electron energy in GeV and R is the radius in meters of the electron path curvature in the bending magnets. E (GeV) and the strength of magnetic filed B (Tesla) needed to maintain a path curvature R(m) are related as

$$B(\text{T}) = 3.333\, E(\text{GeV})/R(\text{m}) \quad (2)$$

so equation (1) can be rewritten as

$$\Delta E(\text{keV}) = 26.6\, E^3(\text{GeV})B(\text{T}) \quad (3)$$

Multiplying this result by the total circulating stored beam current in amperes yields the total SR power radiated in all bending magnets around the ring in kilowatts:

$$P(\text{kW}) = 26.6\, E^3(\text{GeV}) B(\text{T}) I(\text{A}) \quad (4)$$

To keep electrons circulating on the same orbit this power, as well as that of SR emitted from insertion devices discussed below, needs to be replenished by one or more accelerating RF cavities on the orbital path.

Dipole magnets were the first sources of SR and are still widely used in this role. The power spectrum of the emitted SR, i.e. radiated power per unit bandwidth, is continuous and depends on the energy of the electron beam and strength of the magnetic field. A characteristic feature of this spectrum is the so-called "critical energy" e_c, that can be calculated (Winick 1994) as

$$e_c\,(\text{keV}) = 0.665\, B(\text{T})\, E^2(\text{GeV}) \quad (5)$$

When plotted as function of normalized photon energy, k/e_c, dipole power spectra from different facilities will look fairly similar, hence a spectrum plotted in this fashion is called the universal SR power spectrum, illustrated in Fig. 2.

Insertion Devices

As discussed above, the electron path through a dipole magnet curves constantly in one direction, causing the SR to be distributed in a wide horizontal fan tangentially to the path curvature. Consequently, only a very small portion of the radiated dipole SR power can be used in an experimental station at some distance from the dipole, due to the small angular acceptance of the SR beamline geometry. However, an array of dipole magnets of alternating polarity will bend the electron path back and forth as illustrated in Fig. 3. The electron path undulates or wiggles along a straight line and a greater fraction of produced SR is emitted in the forward direction. Such arrays are collectively called "insertion devices" (IDs) and, because the net bending effect from an ID is zero, the IDs are located in straight sections of an accelerator ring. Besides producing much brighter SR beams than dipoles, thanks to the additive nature of the process, IDs allow tailoring spectral SR characteristics according to specific application needs. IDs are perhaps most commonly assembled of permanent magnets, but electromagnets or hybrid designs have been used as well. The strength of the magnetic field in IDs can be varied by either adjusting the gap between permanent magnet arrays or changing the current in electromagnets. Stronger fields are achieved by reducing the gap, but the beam aperture thus created must be large enough to avoid loss of injection beam or reduction of lifetime of a stored beam.

The periodically alternating magnet array subjects electrons traveling along the ID axis *z* to an approximately sinusoidal magnetic field, $B_y = B_0 \cos k_p z$ and period length $\lambda_p = 2\pi/ k_p$ related to spacing of the magnet poles. An important quantity, deflection parameter *K*, is then defined as (Schlueter 1994)

$$K = eB_0/ k_p mc = 0.934\, B_0(\mathrm{T})\lambda_p(\mathrm{cm}) \quad (6)$$

The peak angular deflection of electron trajectory (with respect to axis z) is K/γ and $K/\gamma k_p$ is the peak amplitude. The value of *K* is useful in distinguishing two types of IDs, wigglers and undulators. The SR power radiated by an ID can be calculated (Chao 1999) as

$$\mathrm{P(kW)} = 7.257\times10^{-5}\, E^2(\mathrm{GeV})\, K^2 N I(\mathrm{A})/ \lambda_p(\mathrm{m}) \quad (7)$$

where *N* is the number of periods in the array (i.e. there will be 2*N* poles and path deflections). Unlike with the dipole SR field, most of this power will be directed towards the SR beamline and experimental station.

Undulator. If the angular deflection K/γ remains equal or smaller than γ, i.e. $K\leq 1$, the opening angle of SR from the device will be similar to a “point” source as pictured in Fig. 4. This class of type of ID is called “undulator”. SR emitted by an individual electron at different magnetic poles of this device interfere coherently and result in a narrow photon beam with a spectrum containing peaks at the harmonics of the fundamental energy. The fundamental energy can be “tuned” to a degree by adjusting the strength of the magnetic field and the period of the pole array for a given electron energy. The opening angle of the beam at any given wavelength, due to constructive interference, is decreased by $\sqrt{N}$ and therefore brightness increases as N^2.

Wiggler. In this device $K>>1$, i.e. the electron beam undergoes large deviations from along the ID axis. In an undulator an observer on axis downstream would see continuous SR as the electron beam undulates. In a wiggler (see Fig. 4), he would see only periodic flashes when electrons are pointing in his direction. The wiggler SR spectrum is similar to that of the dipole, characterized by critical energy following eq. (5) above, but 2*N* times as intense due to the presence of 2*N* magnetic poles.

Insertion devices can be better adjusted to specific experimental needs than dipoles and came to much greater prominence in the 3rd generation of synchrotron facilities. Further details on ID design and characteristics can be found in (Schlueter 1994) and (Chao 199)..

Synchrotron Facilities

Conventional SR facilities of 2nd and 3rd generation consist of an injector, storage ring and SR beamlines with experimental stations. The injector and storage ring have much in common with other electron accelerators and use the same type of components, with their configuration and operation optimized for SR production. On the other hand, SR beamlines are very unique and present very specific radiation safety aspects not encountered anywhere else.

Injector

The injector consists of one or more accelerators producing and accelerating electrons (or positrons) to be injected into a storage ring. At the initial stage of an injector resides the electron source called “electron gun”. A gun may produce electrons by thermionic emission (using heated cathode), by photo-electric emission when the photocathode is irradiated by laser light pulses, or by combination of both. Electrons are extracted either by DC high voltage (DC HV guns) or by RF power (RF guns). The latter allow much higher field gradients and resulting electron energies. Acceleration stages following the gun have specific requirement on electron bunch structure and frequency. Consequently, a large portion of the current generated by the gun may not be accepted and will be lost at the gun exit or in the first portion of the accelerator. The gun area may therefore be an intense source of radiation, albeit of low energy. In general, this problem is more acute in thermionic guns. For example, in a thermionic RF gun the pulse structure is determined by the frequency of the RF structure and the beam has a large energy spread. An alpha magnet is typically required to reduce the energy spread of the beam and a chopper may be used to select bunches with acceptable timing. Both these devices will be sources of radiation. Photocathode RF guns generate much shorter pulses and pulse structure is determined by the laser pulse structure, which can be better matched to the acceptance of following accelerator stages.

The first acceleration stage after the gun is usually a linac. For low energy facilities it may be the only accelerator needed. Linacs are typically used in one-pass-through mode and are therefore not the cost-efficient method to reach energies approaching 1 GeV and beyond. Intermediate and high-energy (several GeV) facilities usually also include a booster synchrotron following a linac. Ultimately, the injector supplies accelerated electrons to the storage ring where, in some cases, additional acceleration of the stored beam may take place. Electron beam is transferred between injector components and from injector to storage ring using devices such as fast kicker magnets and electrostatic septa. Large portions of the electron beam may be lost at these points of beam transfer and these locations typically require stronger shielding and additional radiation safety measures. In addition, some profile monitors or beam scrapers are generally used along the transport line for diagnosis or beam tuning and, when they are inserted into the beam, they become radiation sources that may need local shielding.

Storage Ring

Electrons produced in the injector are ultimately transferred to the storage or accumulation ring where they circulate for an extended period of time. The storage ring consists of a closed-loop evacuated beam pipe in which stored electrons, kept in orbit by a series of bending magnets, recirculate for several hours or days. High values of stored current are desirable since, as indicated in eqs. (4) and (7), the SR power is proportional to the current. Electric current is defined as charge per second, e.g. 1 A = 1 C/s. In a typical storage ring, electrons may execute millions of revolutions per second at speed of light, so the stored current results from a relatively small recirculating charge. For example the NSLS ring has a circumference of 170 m and uses stored current of 280 mA. Highly relativistic electrons (2.8 GeV in this case) circulate at speed of light and complete a turn in t_r = 170 (m) / 3×10^8 (m/s) = 5.66×10^{-7} s, which is equivalent to a recirculating frequency of $f_r = t_r^{-1}$ = 1.76 MHz. The stored current of 0.280 A is the result of a charge q_r = 0.280 (C/s)/1.76×10^6 (s^{-1}) $\approx 1.6\times10^{-7}$ C, or only 10^{12} electrons circulating over million times (1.76×10^6) per second. From 280 mA of 2.8 GeV electrons we compute a stored beam power P_s = 0.28 (A) × 2.8×10^9 (eV) = 784 MW! This is a very impressive number, but we realize from the discussion above that if we were to deliver the beam to a target, this amount of beam power could be sustained only for $t_r = 5.66\times10^{-7}$ s after which time all stored electrons would be lost. Such total beam loss would deliver an energy of $10^{12} \times 2.8 \times10^{12}$ (eV) $\times$ 1.602×10^{-19} (J/eV) = 448 J. This “stored energy” has a direct relationship to radiation dose resulting from a total loss of stored beam. In spite of the caveat expressed above, the stored beam power is not a useless concept, because for a given configuration the power carried by SR will be some constant fraction of the stored beam power. The limiting factor here is that this fraction cannot exceed the power that can be supplied by the RF cavity, which, incidentally, is a source of X-rays on its own. Similarly to SR, gas bremsstrahlung production is also proportional to beam current and therefore to beam power.

Modern storage rings are typically “filled” to the maximum desired current in times on the order of 5 – 10 minutes. Because electrons need constant acceleration through an RF cavity to replenish power lost by SR emission, electrons must be delivered to the storage ring with a time structure that matches that of the RF field. The RF frequency is usually much higher compared to the recirculating frequency f_r of the ring. This creates stable areas around the ring circumference, called “buckets”, where electrons can be stored. Electrons are injected in “bunches” into these buckets, where buckets may contain multiple bunches. In some specific applications (e.g. storage ring –based FELs, discussed later) may require a special time structure of the stored beam where only certain buckets are filled. Characteristic parameters of four storage rings are presented in table 1.

The storage ring beam line is a very dense assembly of massive insertion devices and dipole magnets, complemented by quadrupole magnets, weak corrector magnets, diagnostic devices, etc. This dense packing is usually beneficial in that it may provide substantial amounts of local shielding for bremsstrahlung exiting at shallow forward angles. This feature is compromised to a degree when C-shaped dipoles are used, as illustrated in Fig. 5.

When observed from the outside, many storage rings display the distinctive feature of a “ratchet” outside ring shielding wall, designed to allow easier penetrations for the SR beamlines, as illustrated in Fig. 6. This structure is also apparent in the examples of two SR facilities, NSRRC and NSLS-II, illustrated in Figs. 7 and 8, respectively.

Modes of Operation

In modern storage rings the lifetime of the stored current extending over many hours are typical, as shown in table 1. The traditional mode of operation consists of a short period of injection until the ring is filled, followed by a long period with circulating stored beam only. The stored beam undergoes a slow exponential decay until it reaches a predetermined limit, e.g. 50% of the maximum stored current. At that point the remainder of the stored beam may be discarded and a new injection occurs, or an injection is made to refill the ring to its top current. During the short injection periods relatively large beam losses and associated levels of prompt radiation may be generated, particularly if the injection efficiency is poor. In stored beam operation, the slow decay of stored beam occurring as a distributed loss is of little consequence to dose rates in occupied areas behind shielding, but its cumulative contribution to integrated doses outside ring, and its contribution to skyshine and boundary dose needs to be considered. A sudden loss of stored beam at one point may result in measurable instantaneous dose behind shielding, but this consideration is usually a lesser constraint compared to risk from injection beam losses. Excluding special considerations for SR beamlines addressed below, shielding design for the injector and storage ring requires a careful set of assumptions based on planned modes of operation, expected distribution of beam losses and the total amount of charge injected and ultimately lost.

With the ever increasing sophistication of SR use, there has been an increased demand from the user community for a perfectly stable and constant stored beam, with no exponential decay. This can be achieved in a different mode of operation, the so-called “top-off mode”, in which the ring is being replenished by either continuous injection or a series of very frequent small injections while the synchrotron beam lines are open and operating. In the traditional mode beam lines are shut during injection and in-alcove safety stoppers prevent bremsstrahlung from accidental mis-steering to escape beyond shielding to experimental areas. In the top-off mode this protection is not possible, which presents a challenge and requires additional safety measures as discussed extensively in the beamline section below. Continuous injection is likely to result in higher total charge loss over a period of time compared to traditional operation. As a consequence, a transition to top-off mode usually requires a re-evaluation of the shielding design and implementing more robust safety systems.

Synchrotron Radiation Beamlines

When compared to other types of accelerator facilities, SR beamlines are the most unique features of SR facilities. This section describes the radiation safety and shielding design issues for SR beamlines, mainly SR and gas bremsstrahlung (GB), including radiation source terms and the methodologies for shielding calculations.

Note that, for dose estimation to workers/users/experimenters on the floor, the SR and GB doses from beamlines shall be considered together with the photon and neutron doses from the beam losses in the storage ring. Because it is desired not to subject the users and experimenters to the intense radiation worker training, the dose limit for ring and beamline design is generally set no more than the public dose limit of 1 mSv/y (an occupancy factor of 2000 h/y is also commonly assumed).

Throughout this text, due to the authors' familiarity with SSRL, the design policies and practices, as well as shielding implementation for SSRL are described and used to better illustrate the issues. Readers interested in specific aspects of other SR facilities are encouraged to consult two facility comparison reports (Berkvens 2007; Liu et al. 2007) and the references quoted.

Overview of a SR Beamline

A SR beamline is generally divided into the in-alcove section (the portion that is inside the ring and upstream of ratchet wall) and out-of-alcove section (the portion that is downstream of the ratchet wall – see Fig. 6).

A SR beamline takes the synchrotron light from the source in the ring, an insertion device or a bend magnet, through the in-alcove section and then an optical hutch (downstream of the ratchet wall) into experimental stations. Along each beamline, there are many optical elements that are used to define the SR ray envelope and tune the beam quality and quantity for experiments. The optical components include:

1) Apertures such as masks and movable slits. In many cases, the apertures are the components that intercept most of the SR and GB fans and are the targets of concern.

2) Mirrors (a low-pass filter that removes preferentially high-energy photons). The cut-off energy depends on the mirror's inclined angle and coating material, e.g., a Pt-coated mirror at an inclined angle of 0.16^o has a cut-off of 23 keV, while a Pt-coated mirror at 2.5^o has a cut-off of 1.5 keV. Note that the cut-off energy refers to the energy at which the photon intensity is reduced to 50% of original. Therefore, for shielding design purposes, the presence of high-energy photons beyond the cut-off needs to be considered.

3) Monochromators (called monos hereafter). Mono selects mono-energetic photons (at fundamental and harmonic wavelengths) from the incident beam. Though the harmonic spectrum lines have much lower intensities than the fundamental line, the light from the harmonics may dominate the shielding requirement due to its higher energy.

In addition to the low-energy, high-power SR, the high-energy, low-power GB also channels into the beamline.

Safety Considerations for In-Alcove Section of a SR Beamline

Using SSRL as an example, Figure 9 shows a typical in-alcove layout for a SR beamline, which has a few safety components: a movable water-cooled mask that is used to protect the injection stoppers from possible SR damage, collimator and shadow walls (each consisting of 6"-thick lead followed by 6"-thick polyethylene at SSRL), as well as lead/polyethylene shielding surrounding the beampipe in the hole of the ratchet wall.

Note that the in-alcove safety of a beamline shall be an integral part of the ring safety design. Similar to the lateral and ratchet walls, it is the injection and stored beam losses in the ring (both normal and abnormal cases), as well as GB and credible beam losses in the frontend, that need to be considered for the design of the in-alcove safety components. Analytic codes (*e.g.,* SHIELD11) or general-purpose Monte Carlo codes such as FLUKA, MCNPX or MARS can be used to calculate the shielding requirements.

The beamline portion that is upstream of, and including, the injection stoppers, is called the frontend of a beamline. During beam injection into ring (except in top-off mode), the thick heavy metal injection stoppers (two ~6"-thick Hevimet, tungsten alloy with a density of 17 gm/cm^3, blocks at SSRL) have to be inserted into the frontend to block the injection beam that may be accidentally directed into the beamline. The injection stoppers for each beamline are either locked-in (if the corresponding out-of-alcove section is not completed yet) or interlocked to allow the out-of-alcove section to be operated by experimenters/users when the beamline is ready for beam.

The collimator and shadow walls along the beamline are used to block any secondary photon and neutron radiation from electron beam losses inside the ring that may penetrate the hole in the ratchet wall. The collimator and shadow wall design may be replaced by a single collar (or collimator) design placed near the most downstream end of the in-alcove section.

There are locations where the in-alcove section of a beamline does not exist yet while the corresponding ratchet wall already exists (without the beampipe hole in the ratchet wall of course). In that case, a thick shielding block (4”-thick lead at SSRL) is placed immediately downstream of the beamline exit port of the ring to fully block any forward-angle bremsstrahlung from beam losses in the ring to hit the ratchet wall.

Several reports listed in References (Liu et al. 2003a; Liu et al. 2003b; Rabedeau 2003) can be consulted for detailed design considerations and methodology for the in-alcove section of the beamline.

Safety Considerations for Out-of-Alcove Section of a SR Beamline

For out-of-alcove section of the beamline safety design, it is the SR and GB hazards that need to be considered. There are two categories of SR beamlines that have different beamline layouts, hazards and mitigation methods: hard X-ray (> a few keV) and vacuum ultra-violet/soft X-ray (VUV) beamlines.

As shown in Fig. 2, a hard X-ray beamline generally has an optical hutch downstream of the ratchet wall, followed by one or more experimental hutches. The apertures, mirrors and monos are located in optical hutch, though some beamlines may have apertures and mirrors located in alcove. The hutches are large enclosures with lead or iron shielding walls and roof to attenuate the X rays (up to 1-cm-thick of lead is used at SSRL wiggler beamlines). There are interlocked hutch shutters between optical hutch and an experiment hutch to intercept/block the GB and SR when the experimental hutch is in an accessible state (for optical hutch, the injection stoppers are the hutch shutters).

On the other hand, the energies of the VUV or soft X rays, which come from SR reflected from one or more mirrors at large inclined angles, is so low that the experiment has to be performed inside vacuum. Therefore, the vacuum chamber or beampipe itself (or with additional thin metal wrap) has to be used to attenuate and contain the VUV light. Instead of hutches, a VUV beamline generally consists of free-in-air beam transport pipes only and it utilizes isolation valve as safety shutter.

Compared to the thin SR shielding, mitigation of the GB hazard requires thicker heavy metal shielding. Because the secondary photons from GB hitting a target are very forward-peaked, the GB shielding tends to be thicker in forward angles and thinner at lateral directions (up to 10”-thick of lead at 0-degree and 2”-thick lead for 90-degree at SSRL). Common GB shielding are lead collimators, hutch shutters and beam stops. Local lead shielding around the optical components (e.g., slits, mirror or mono) that are hit by GB may also be needed. Some facilities utilize thick hutch wall and roof (up to 2 inches of lead on the side walls) to shield both GB and SR, particularly for those beamlines with very high SR critical energies (> tens of keV).

In the sections below, a review of the SR and GB hazard calculations and mitigation is given and some reports (Liu and Vylet 2001; Liu et al. 2004; Prinz and Liu 2007) can be consulted for more details.

Synchrotron Radiation. The SR issues can be divided into three light categories:

1) White light (i.e., SR from an ID or bend entering a hutch or beampipe without interacting with any component). This demands up to 1-cm-thick lead shielding at SSRL.

2) Pink light (i.e., photons specularly reflected at a certain angle from a mirror) and the Compton light (photons scattered from a mirror or mono in all directions). These demand up to a few-mm-thick lead shielding at SSRL. Depending on the beam parameters and beamline configuration, e.g., the solid angle subtended by the target downstream of mirror, either pink light or the Compton light from a mirror may dictate the shielding requirement.

3) Mono light (mono-energetic photons from a monochromator). This can be further divided into two types of mono light: unfiltered mono light (mono light without a mirror reflection) and filtered mono light (mono light with a mirror reflection). Filtered mono light at SSRL only needs up to a few-mm-thick iron shielding. Note that a multi-layer mono has a wider band pass and thus higher mono beam intensity than that for ordinary silicon mono.

Most optical hutches are white light hutches, while some optical hutches are pink light hutch (when there is a mirror in alcove). Most experimental hutches are mono light hutches. The SSRL wiggler beamline #11 in Fig. 2 has a white light optical hutch BL11-0 and three experimental hutches: BL11-1 (a filtered mono light hutch on the SPEAR side), BL11-2 (a unfiltered mono light hutch in the end of the central line), BL11-3 (a filtered mono light hutch on the SSRL side), and two transport pipes between hutches.

The SSRL undulator beamline #5 in Fig. 3 has a white light optical hutch BL5-0 and three VUV transport pipes, e.g., pink beampipe for upstream of BL5-1 single-grating mono (SGM) and filtered-mono beampipe for the section downstream of SGM. Note that the SGM acts like a combination of mirror and mono in that both the zero-order pink light and VUV mono lights will be reflected from the SGM. Therefore, the pink light downstream of grating mono also needs to be considered in shielding design. The VUV beamlines also have view ports that are used by beamline physicists/engineers in beamline tuning and their shielding needs should be noted.

Using standard and conservative beam-target-shield geometries in the analytic STAC8 code (Asano 2001a) or Monte Carlo codes, shielding needs for scattered SR for white-light, pink/Compton lights, and mono-light can be calculated. STAC8 is recommended for SR dose calculations as its use is easier than Monte Carlo codes. For example, STAC8 can generate wiggler and undulator source spectrum with user input of electron beam energy, magnetic field, number of pole and fan width. STAC8 can also calculate pink beam, Compton-scattered beam and the mono beam. STAC8 also takes into account of the an-isotropic Compton scattering, SR linear polarization effect, target self-shielding, and build-up factors in the shield.

Generic calculations using STAC8 and FLUKA codes have been performed for SSRL beamlines (Liu et al. 2003c; Prinz et al. 2003a; Fasso and Liu 2003). The ambient dose rates as a function of scattering angle and the thickness of lead shielding were calculated for SSRL beams with 5 critical energies between 3.1 and 12.2 keV. These families of “normalized” attenuation curves allow the estimation of the shielding requirements for beamlines with similar critical energies using a simple linear scaling of the number of ID poles and the horizontal fan width of the white light hitting the target, as well as a scaling of distance using the inverse square law.

In addition to the hutch wall and beampipe shielding, attention should be paid to SR streaming through ventilation and cable penetrations on the hutch walls, as well as groundshine under the hutch doors, in particular for high-power, high-critical-energy ID beamlines.

Synchrotron Radiation Thermal Protection. The SR beam has very high power density that may burn through components that are not properly cooled. It is very essential to ensure every component that may be hit by SR is properly cooled or it can either take the heat load indefinitely. In general, the white-light and pink-light have high power densities that warrant thermal protection, while the mono-light downstream of mono presents no thermal damage issue.

SR ray trace study shall be performed for every beamline to ensure that all possibly mis-steered rays are contained in all operational modes. For example, the pink-light reflected from a mirror in all possible angles (limited by hard stops) shall be contained. When white-light or pink-light is directed onto mono, the monochromatic beam is offset vertically from the direction of the in-coming beam. If the downstream section is not properly shielded and protected for non-monochromatic beams, a SR beam stop shall be placed behind the mono to block the beam in case the mono is mis-placed.

Coolant interlock to prevent burn-through, as well as pressure and/or vacuum interlocks to monitor burn-through, shall be part of the engineered personnel protection system, if the burn-through event has personnel safety implications.

Gas Bremsstrahlung Characteristics. As indicated in (Liu and Vylet 2001), the GB source term has been studied extensively in the literature. This source term has three characteristics:

1) The energy spectrum is $1/k$, where k is the photon energy up to the electron beam energy. Therefore, the GB can create shower in beamline components and is much more difficult to shield than SR. It is conservative and appropriate to use the Compton minimum of the attenuation coefficient of a material (*e.g.*, 24 g cm^{-2} for lead) for the estimation of GB attenuation in both longitudinal and lateral directions of a target.

2) The intensity is highly forward-peaked with an angular characteristic angle θ of $0.511/E$ in radians, where E is the electron energy in MeV. Therefore, the GB hazard occurs mainly along the central-axis beamline (e.g., hutches BL11-0 and BL11-2 in Fig. 2).

3) The un-attenuated GB dose rate is strongly dependent on the dose-scoring area over which the calculation was made, as well as the size, angular divergence, and actual curved trajectory of the stored beam in the air path. In general, the GB dose rate is proportional to $\sim E^{2.5}$, the stored beam current, as well as the mass thickness of the air column in the ring section that stored beam passes through. Therefore, the GB problem is more acute for long insertion devices at high-energy, high-current storage rings.

For SSRL, a 6-m-long straight section houses a 3-m-long ID. Therefore, in the 3-m straight section, the GB is produced in a very small angular cone along the beam direction with a characteristic angle θ_c (0.511/3000 = 0.17 milliradian for SSRL). With the 3-m wiggling path, a horizontal GB fan is also created, the width of which is dependent on the ID's deflection parameter K. Therefore, the actual profile of GB power versus horizontal angle has a peak at 0-degree (from the θ effect) and tail at both ends (from the *K* effect).

Shielding for Zero-Degree Gas Bremsstrahlung. Without shielding, the zero-degree GB dose rate is very high (up to a few Sv/h). Therefore, the beamline shall have GB safety components (e.g., up to 10"-thick lead of collimators, hutch shutters, and beam stops) that can provide enough longitudinal thickness and lateral coverage to block all potential GB rays so that the high forward-angle doses are reduced to acceptable levels. This shall be demonstrated with GB ray trace study. Unlike SR, the GB path is not affected by optical elements. A detailed description of shielding for zero-degree GB is available in a SSRL report (Khater et al. 2003).

Gas Bremsstrahlung Scattered from Beamline Components. The secondary photon and neutron radiation coming out of the downstream and lateral sides of any beamline component (e.g., masks, slits, mirrors, monos) hit by GB also needs to be addressed. Clearly the most accurate method of calculating radiation doses associated with GB is using Monte Carlo codes to model the GB source and beamline layout as accurately as possible. However, this Monte Carlo approach may not be practical or available. In addition, there are cases in which conservative estimation using analytic methods (described below) is sufficient. This is particularly true, considering the fact that one of the largest errors in estimating GB hazard arises from the difficulty in measuring the vacuum pressure in a long straight section, whose uncertainty could be a factor of 2-3.

Gas bremsstrahlung is a thin-target bremsstrahlung process and, thus, the fractional energy transferred from the stored beam to the bremsstrahlung photons, d*E/E*, is equal to the ratio of the thickness, *t*, to the radiation length of the target, *i.e.*, $dE/E = t/X_o$. Therefore, the fractional energy (or power) transferred from the circulating electrons to GB photons is t/X_o, where *t* is the mass thickness of the air path length and X_o is 36.818 g cm^{-2} for air. For example, the stored power of the circulating electrons (500 mA at 3 GeV) at SSRL is 1.5 x10^{9} W. Assuming that the ID straight is 6 m and the vacuum pressure is 0.13 μPa (i.e., 10^{-9} torr), the air mass thickness is 9x10^{-13} g cm^{-2}, and the ratio of the air path to the air's radiation length is then 2.4x10^{-14}. Thus, the power transferred from the SSRL stored beam to the GB in an ID is 38 μW, which is one of the highest GB power of all current SR facilities. The normalized GB power is ~0.1 μW mA^{-1} μPa^{-1} m^{-1}, which is in agreement with the Spring8 measurement of 0.16 μW mA^{-1} μPa^{-1} m^{-1} (Asano 2001b). The ring dipole source is much shorter than an ID source (15-cm-long bending length at SSRL) and, thus, the GB in bend beamlines is generally not a concern, except for zero-degree GB issue.

The GB power estimated above can be used to calculate the scattered GB dose rate, illustrated using SSRL as an example:

1) According to SHIELD11 results, the laterally, scattered dose rate at 1 m for an electron beam hitting a standard iron target (12” long and 2” radius) is about 15 mSv/h/W for photons and 10 mSv/h/W for neutrons.

2) On an equal beam power basis, GB will give similar dose results as an electron beam.

3) With 38 μW of GB, the scattered dose rates at 1 m are 0.6 μSv/h photon and 0.4 μSv/h neutron (these are about the same as the beamline shielding design limit).

The above-estimated scattered dose rates are within a factor of 2-3 from measurements (Liu et al. 1995; Pisharody et al. 1999; Asano 2001c) and those estimated using another estimation method (Liu and Vylet 2001). The main reason for the difference is due to the target size/geometry effects.

The FLUKA Monte Carlo code was used to calculate the photon and neutron dose rates as a function of lead thickness at polar angles from 0-degree to 90-degree from GB hitting 3 types of targets: an inclined 1-m-long mirror, a 1”-cube copper (a shower-maximum target), and a 1”x1”x6” Cu block (simulating a long mask). The results have been used to obtain the shielding requirements for SSRL beamlines (Prinz et al. 2003b).

A medium-energy light source like SSRL tends to have more wigglers (which have high deflection parameter values) than other high-energy (e.g. Advanced Photon Source) or low-energy (e.g. Advanced Light Source) light sources. To maximize the benefit of wiggler, there are generally 2-3 branch lines in a beamline. Therefore, the optical components in the optical hutch of a wiggler beamline may be so close to each other such that GB shielding layout becomes difficult. Thus, it is important that the GB shielding design be considered in the early beamline design stage.

Top-off Mode Implications to Beamlines. Problems with the beamline hole in the ratchet wall are escalated if the facility uses the top-off injection mode, which is a much-desired mode of operation for SR facilities. In this mode, users' beam experiments are not interrupted during injection. The stored beam is replenished and maintained at near-constant level by frequent (or quasi-continuous) injections as required, while SR beamlines are open. There are no injection stoppers to block zero-degree bremsstrahlung from injection beam losses in the ring apertures or to intercept possible mis-steering of injection beam into a SR beamline.

The consequences are that the integrated doses on the floor may be higher than that for non top-off mode (particularly when the injection efficiency is poor) and significantly high radiation levels may be produced when the injection beam is mis-steered into the out-of-alcove section. Therefore, the top-off mode requires a more conservative approach to beamline shielding design (as it needs to address the additional forward bremsstrahlung from injection beam losses in the ring on top of the GB from the stored beam). In addition, detailed lattice and ray trace study is needed to ensure that, under some machine bounding conditions, the injection beam can not be mis-steered into the beamlines. Additional safety systems such as the stored beam interlock, injection beam energy interlock, injection efficiency interlock, radiation detectors, etc. can then be identified and implemented to monitor/limit the bounding conditions and to terminate such mis-steered conditions.

Free Electron Lasers and Future Light Sources

Free Electron Lasers

Free Electron Laser (FEL) is a device where coherent light is produced by (free) electrons of an accelerator beam, as opposed by stimulated de-excitation of electrons bound in atoms or molecules of a lasing medium. As discussed above, relativistic electrons traveling through an undulator emit coherent SR in the forward direction. These SR photons can be trapped in an optical cavity formed by a pair of mirrors, like in a conventional laser, and interact with electrons in the following bunches. These electrons are forced to emit stimulated SR like in conventional lasers. A highly coherent SR can be extracted from the optical cavity if the gain of the system exceeds losses. FELs using optical cavities may be used in either one-pass scheme, where electrons after passing through the undulator are deflected into a beam dump, or as part of a storage ring with circulating beam. An example of a ring-based device is the FEL at Duke University presented in Fig. 12. Yet another scheme is is a FEL driven by an energy recovery linac, such as the FEL facility at Jefferson Lab. In this configuration the electron beam, after passing once through one or more insertion devices, is redirected back into the linac with a phase shift such that electrons undergo deceleration instead of acceleration in the waveguide, transferring most of their kinetic energy back to the RF system. This allows to run the accelerator at much higher power levels than would be economically possible in a conventional setup.

In the VUV and X-ray region, where mirrors with sufficient reflectivity are not available, a different mechanism, based on single electron passage and self-amplified spontaneous emission (SASE), is used. This mode is possible in very bright electron beams with high current and low emittance (see definition in the Appendix). In this case the electron beam interacts with its own radiation. This radiation filed causes microbunching of electron bunches where the microbunches are separated by one radiation wavelength. These electrons then emit SR photons coherently (in phase), increasing the intensity of the radiation field. This process leads to an exponential gain along the undulator. Extremely brilliant SASE X-ray FELs based on high-energy linacs are currently under construction: LCLS at SLAC in the USA and the XFEL/TESLA project in Europe. Facilities in this class use undulators in excess of 100 m and will produce extremely short pulses with unprecedented peak power.

From the radiation point of view, it is obvious from the previous discussion of insertion devices in storage rings that the gas bremsstrahlung problem will be amplified in FELs by the even longer straight sections of electron beamline. To illustrate the differences between such facilities, let us compare the gas bremsstrahlung and synchrotron radiation from the LCLS (Linac-based) with that from a typical undulator beamline (5 m long and 0.5 μPa) at the 3 GeV, 500 mA SPEAR (ring-based), as shown in Table 2 (SLAC 1998).

For the gas bremsstrahlung dose source term, the effect from the significantly higher current at SPEAR (which gives the high 1.5×10^9 W stored power) outweighs the combined effects from the higher energy, longer undulator length, and poor vacuum pressure at LCLS.

It is not straightforward to compare the synchrotron radiation from SPEAR with that from LCLS, since every beamline at a storage ring has its own characteristics of intensity and energy of synchrotron radiation, due to different magnetic field strength, period length, and number of periods. However, if it is assumed that the magnetic field strength and period length are the same for the undulators at SPEAR and LCLS, the synchrotron radiation power from a SPEAR undulator would be 3-4 orders of magnitude higher than that from LCLS (see the last row in Table 3). At SPEAR, the total radiated power for synchrotron radiation is between a few kW for an undulator and up to a few hundred kW for a wiggler. On the other hand, the average power of synchrotron radiation at LCLS is only 2.7 W, while the SASE process only increases the total power by 10%, *i.e.*, the SASE gain = 1.1 in Table 2. However, due to its higher beam energy, the critical energy of the LCLS synchrotron radiation is much higher than that of SPEAR and thus the SR from LCLS is more penetrating. Though the average power from LCLS is much lower than that at SPEAR, its peak power is significantly higher due to the SASE process. Consequently, the radiation damage and protection issues are much more severe and challenging at LCLS.

Future SR Sources

Free electron lasers FELs are called the fourth generation light sources. This does not mean that FELs are going to replace 3rd generation facilities based on storage rings. FELs are powerful sources of electromagnetic radiation up to X-ray energy range capable of achieving extremely short pulses (~100 fs), high peak power and brilliance. The unique parameters of FEL light sources open new research possibilities that are complementary to rather replacement of storage rings. Modern storage rings are designed with reasonably low emittance and provide sufficiently high brilliance and high photon flux with a broader distribution in time, which is preferable for certain classes of applications. It is therefore likely that linac-based FELs and storage rings will coexist in the foreseeable future. The advantage of linac-based sources is that a well designed linac, unlike a storage ring lattice, does not degrade the emittance and bunch length of the source. The disadvantage is that linacs require large amounts of power to accelerate electrons to peak energy, which is then wasted only after one pass. Such sources cannot economically operate at high currents needed to achieve very high photon flux. A solution to this problem is use of an energy recovery linac (ERL) mentioned earlier, where most of the electron energy is recovered to replenish the RF power in the linac. ERL can be used as part of a ring containing bending magnets and insertion devices in a similar configuration to a storage ring. ERL facilities have been proposed at Cornell (Gruner 2003) and as an additional phase to the NSLS-II upgrade at BNL. Such facilities have been called generation 3.5 of SR sources, since their capabilities are transitional between modern storage rings and FELs.

Appendix: Flux, Brightness and Brilliance

The following definitions and examples are adapted from Gruner et al. (Gruner 2000). Consider a quasi-monochromatic photon beam with a very narrow energy range of $\Delta E/E$ = 0.1%, or 0.1% bandwidth.

Flux is the number of photons in the beam per second per 0.1% bandwidth. For a given wavelength, the total beam power is proportional to the flux.

Brightness is flux per unit solid angle, or photons per second per unit solid angle per 0.1% bandwidth. Brightness accounts for the divergence of the beam. A perfectly parallel beam would have infinite brightness, regardless of the number of photons in it.

Brilliance is brightness per unit area, or photons per second per unit solid angle per 0.1% bandwidth per unit area. A 5 mW laser pointer beam will be brighter than a 10 W monochromatic lamp because of its low divergence, even though the lamp will produce a higher flux. Out of two 5 mW laser pointers emitting the same number of photons into beams with identical divergence, the one with a smaller emitting area will be brighter.

Emittance. Brilliance is closely related to the emittance of the electron beam, which is the product of beam divergence and transverse size in each direction perpendicular to the direction of electron motion. Low beam emittance is needed to achieve a high brilliance of SR light.

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Tables

Table 1. Characteristic parameters of storage rings at four US synchrotron light facilities.

Parameter	**NSLS**	**ALS**	**APS**	**SSRL**
Ring Circumference (m)	170	197	1104	234
Beam Energy (GeV)	2.8	1.9	7	3
Stored Current (mA)	280	400	100	500
Stored Energy (J)	450	500	2578	1200
Stored Power, Ps (MW)	784	760	700	1500
Design Lifetime, τ (h)	20	8	54	20

Table 2. Comparison of gas bremsstrahlung source term and synchrotron radiation power between SPEAR and LCLS.

Parameters and Ratios	Beam Energy (GeV)	Beam Current (mA)	Undulator Length (m)	Vacuum Pressure (μPa)	SASE Gain	Sum
SPEAR Undulator	3	500	5	0.5	1	---
LCLS	15	0.0001	120	500	1.1	---
SPEAR/LCLS Ratio of Gas Bremsstrahlung Dose	$(3/15)^{2.5}$	$5x10^6$	0.04	0.001	---	3.5
SPEAR/LCLS Ratio of Synchrotron Radiation Power	$(3/15)^2$	$5x10^6$	0.04	---	1/1.1	7300

1) Assuming the magnetic field strength and period length are the same for SPEAR and LCLS undulators.

Figure Captions

Fig. 1. Synchrotron radiaton emission pattern along a curved electron trajectory similar to that caused by a dipole magnet. The figure illustrates SR light cones emitted at five singular points along the trajectory. The integral effect of all emission points along this curvature will result in a continuous horizontal “fan” of SR light.

Fig. 2. Universal SR spectrum (adapted from Cossairt 2007)

Fig. 3. Symbolic drawing of an insertion device. Alternating magnetic field created by a periodic array of permanent magnets imparts cause electrons to “wiggle” or “undulate” along the axis of the device, emitting SR in the forward direction.

Fig. 4. Comparison of the angular distribution of SR from a wiggler and from an undulator. In a wiggler electron trajectories are subject to angular path deflections that are greater than $1/\gamma$, which widens the SR emission pattern (adapted from Winick 1994).

Fig. 5. A small section of a storage ring beamline showing the high density of beamline devices. The two largest objects are bending dipole magnets with a special C-shape geometry (schematically shown in the inset) with an opening towards the outside of the ring that allows easier extraction of SR into dedicated SR beamlines.

Fig. 6. A generic schematic of a section of a storage ring with a ratchet-type shielding wall, illustrating multiple components of the safety system. Adapted from (NCRP 2003).

Fig. 7. Drawing of the National Synchrotron Radiation Research Center (NSRRC) facility in Taiwan. The linac and booster synchrotron are situated in the smaller structure on the right side (courtesy of NSRRC).

Fig. 8. Drawing of the planned National Synchrotron Light Source (NSLS-II) at Brookhaven National Laboratory. Linac and booster are contained inside the storage ring perimeter (courtesy of Robert Casey).

Fig. 9. Using SSRL as an example to show a typical in-alcove layout of a SR beamline, which has a few safety components: a movable mask to protect the 2 injection stoppers from possible SR damage, lead/polyethylene collimator and shadow walls, and lead/polyethylene shielding surrounding the beampipe in the hole of the ratchet wall. Concrete lateral wall and ratchet wall are also shown.

Fig. 10. Top: typical layout of an SR beamline, showing the hutches (outlined in red) outside the storage ring. The one labeled “BL11-0” is the optics hutch. The other three (BL11-1, BL11-2 and BL11-3) are experiment hutches. Bottom: view of BL11 optics hutch showing locations of optical elements and GB shielding.

Fig. 11. Vacuum-ultraviolet beamline BL5 at SSRL. The optics hutch is downstream of the concrete ratchet wall and there are three VUV lines: BL5-1, BL5-2 and BL5-4..

Fig. 12. Schematic drawing of the Duke FEL facility. The FEL is located in the south straight section of the electron storage ring designed for electron energies up to 1.2 GeV. Besides FEL photons in the IR – VUV range, this facility also produces mono-energetic gamma rays by back-scatter of FEL photons off the relativistic electrons. This gamma beam, directed into the HIGS line in the south section, is tunable from 1.4 MeV to ~200 MeV (Litvinenko 1997).

Fig. 13. Jefferson Lab FEL after planned upgrade contains two optical cavities for IR and UV light. This facility uses a superconducting recovery linac. After acceleration to 125 MeV electrons pass only once through one or the other optical cavity and reenter the linac where they are decelerated, supplying their energy back into the RF system. This device is designed

to operate in quasi-continuous mode (500 fs bunches at 74.5 MHz bunch rep rate), with a high average current of 10 mA. (reproduced with kind permission of G. Neil, Jefferson Lab).

Figures

Fig. 1.

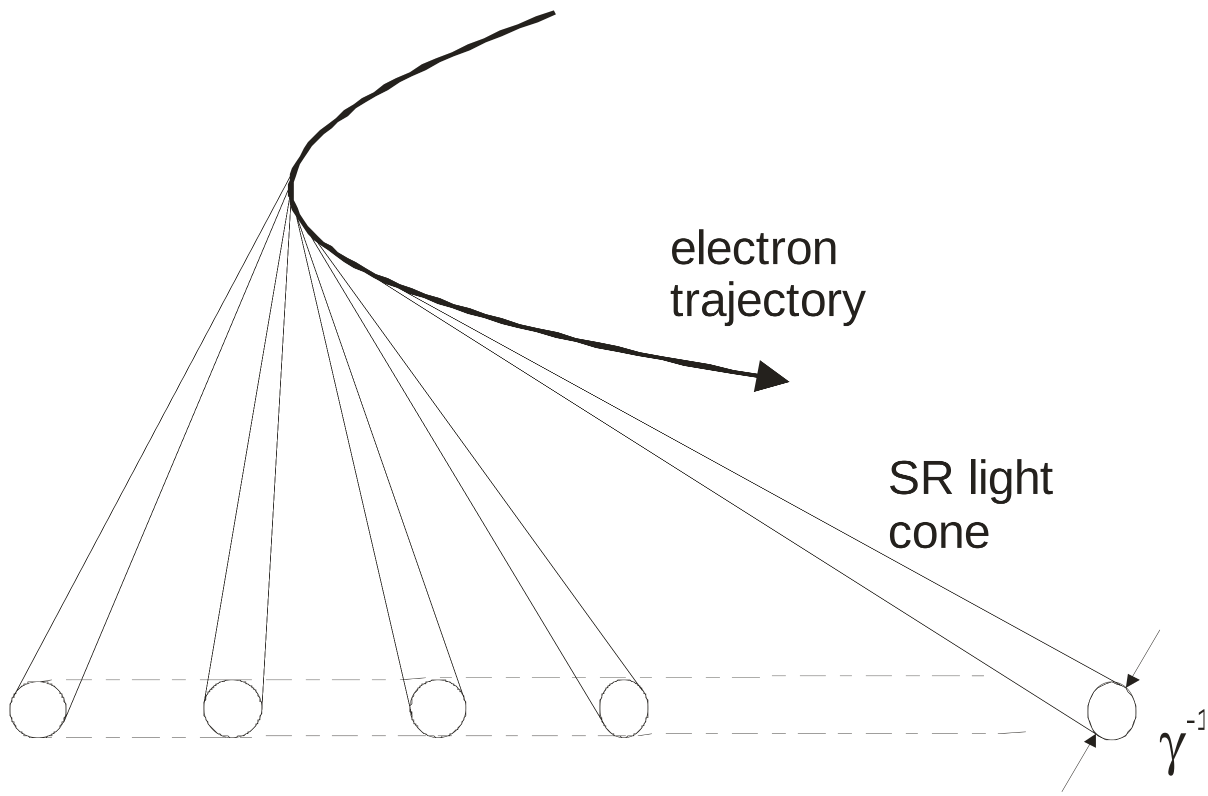
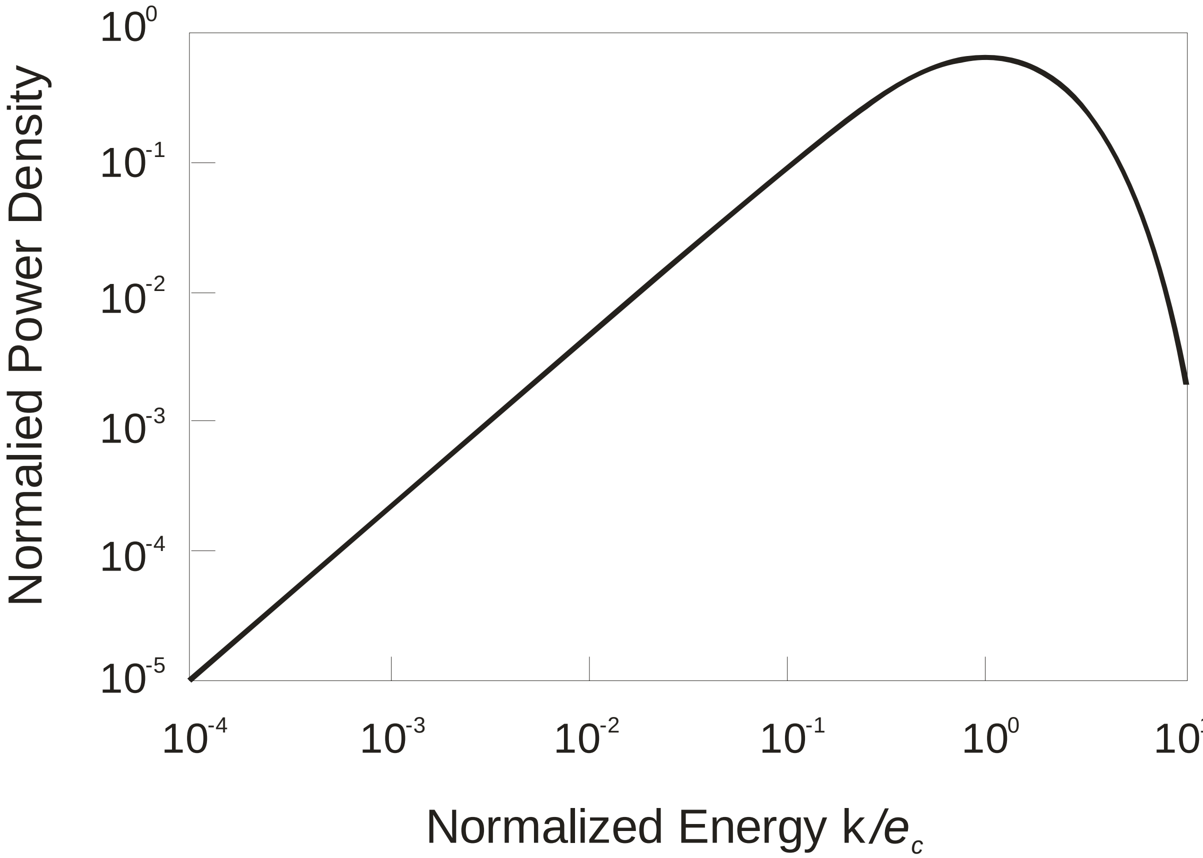


Fig. 2.



Normalied Power Density
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
Normalized Energy k/e_c

Fig. 3.

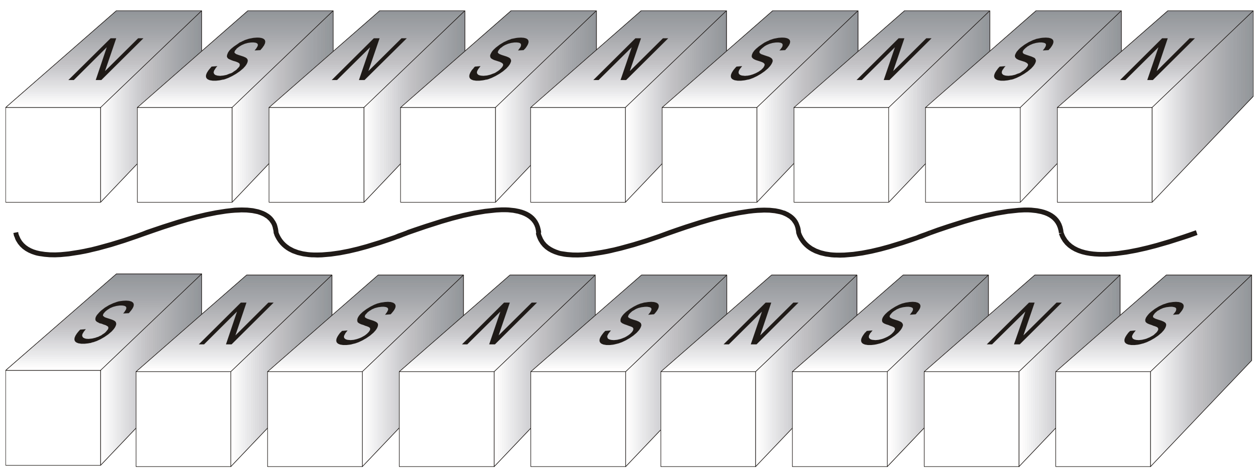


Fig. 4.

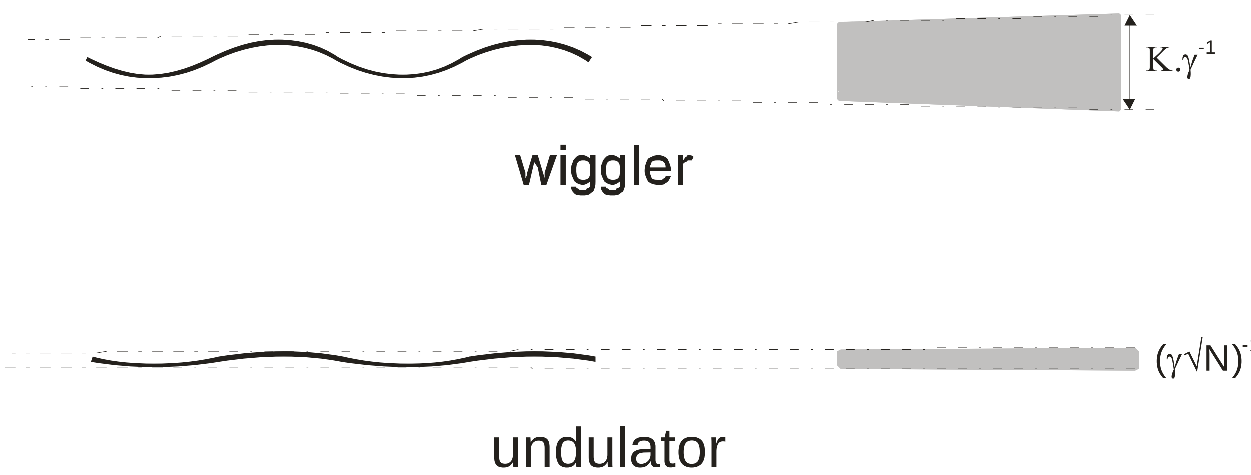


Fig. 5.

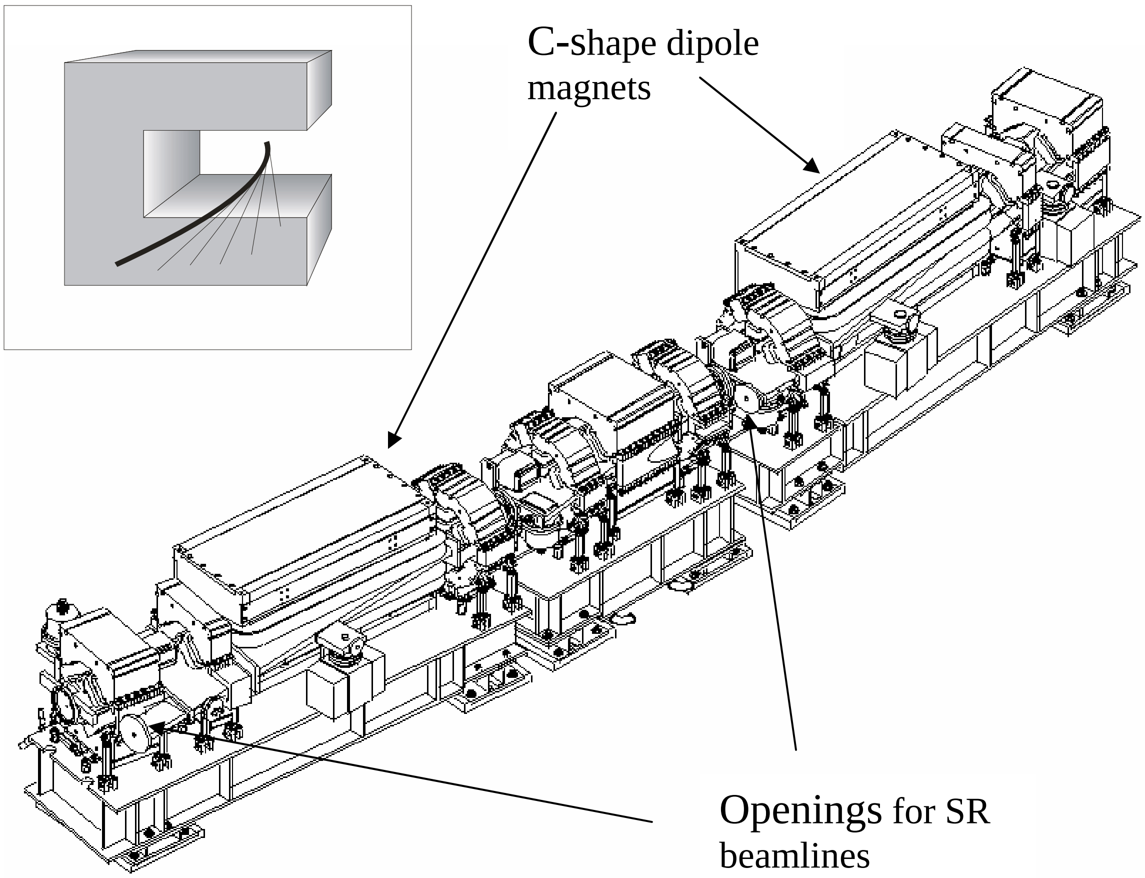
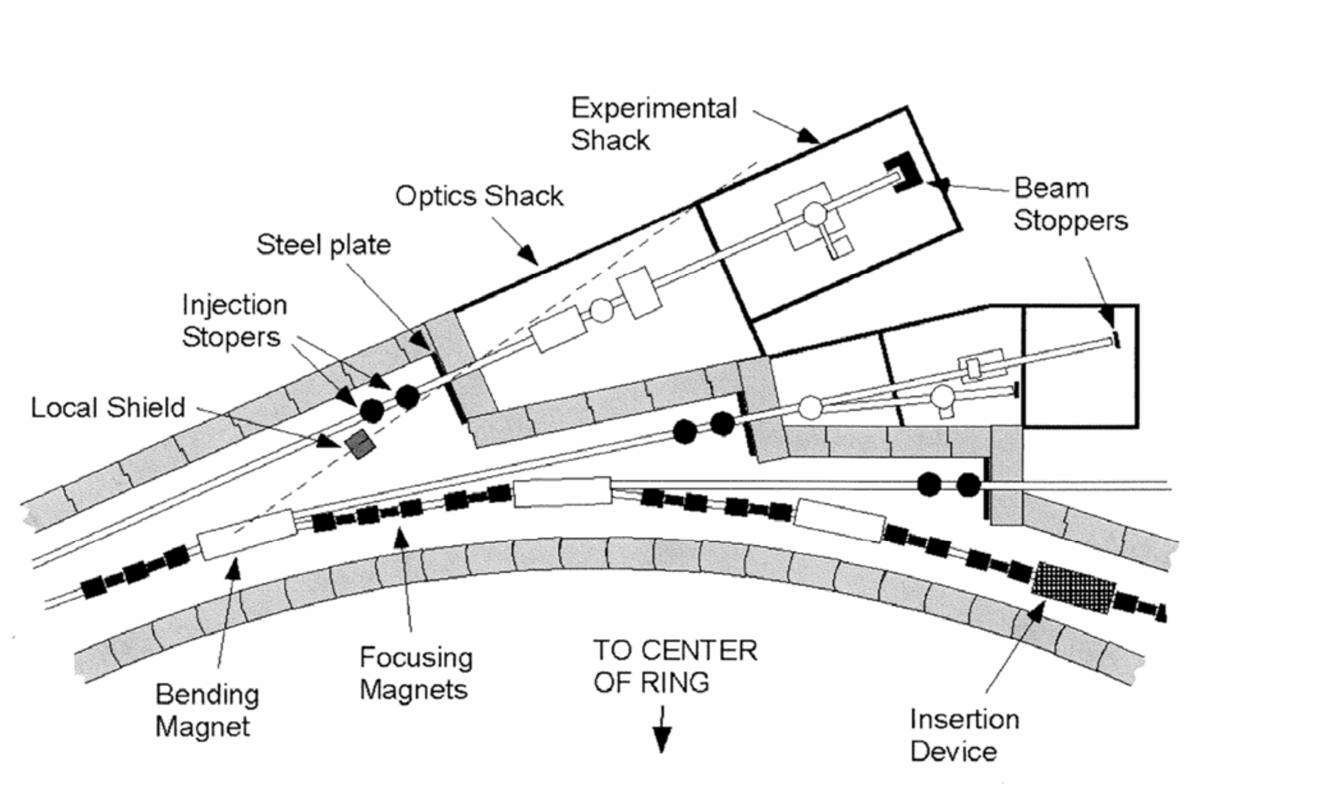


Fig. 6.



Experimental
Shack
Optics Shack
Beam
Stoppers
Steel plate
Injection
Stopers
Local Shield
Focusing
Magnets
TO CENTER
OF RING
Bending
Magnet
Insertion
Device

Fig. 7.

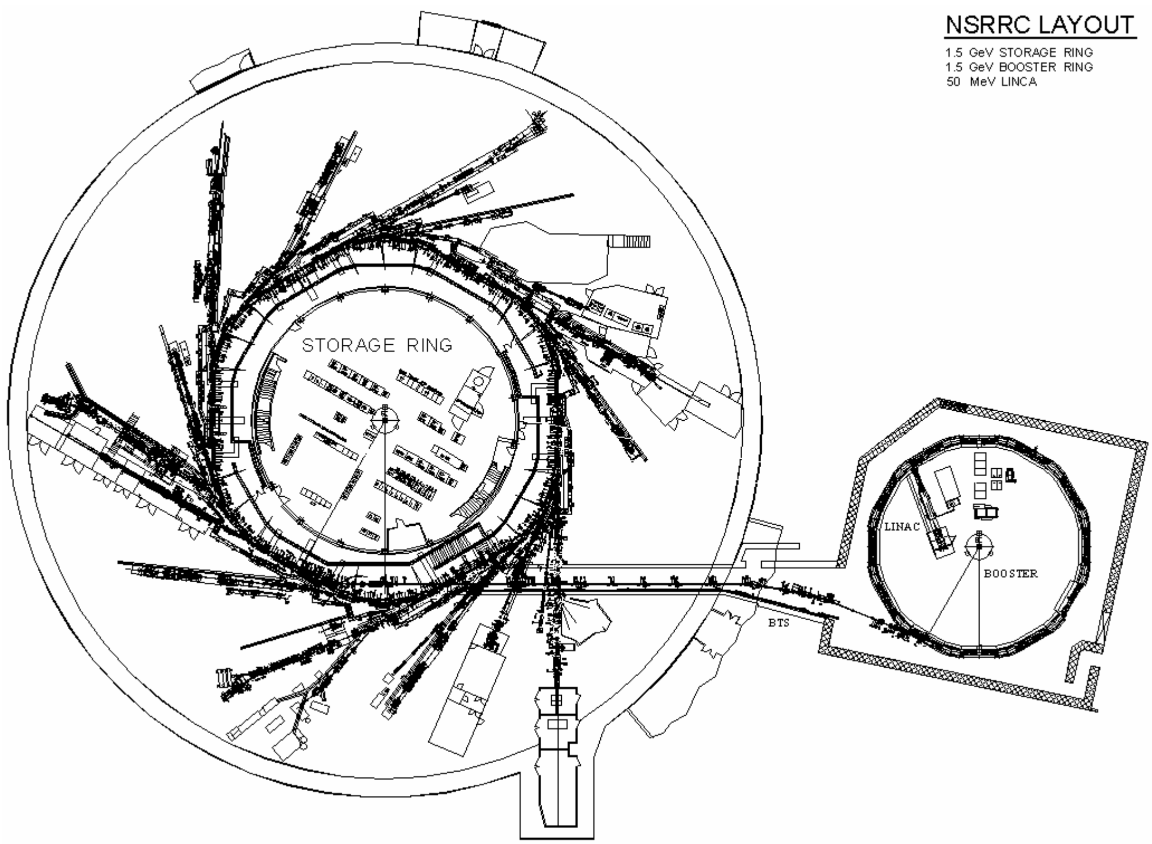

NSRRC LAYOUT
1.5 GeV STORAGE RING
1.5 GeV BOOSTER RING
50 MeV LINCA
STORAGE RING
LINAC
BOOSTER
BTS

Fig. 8.

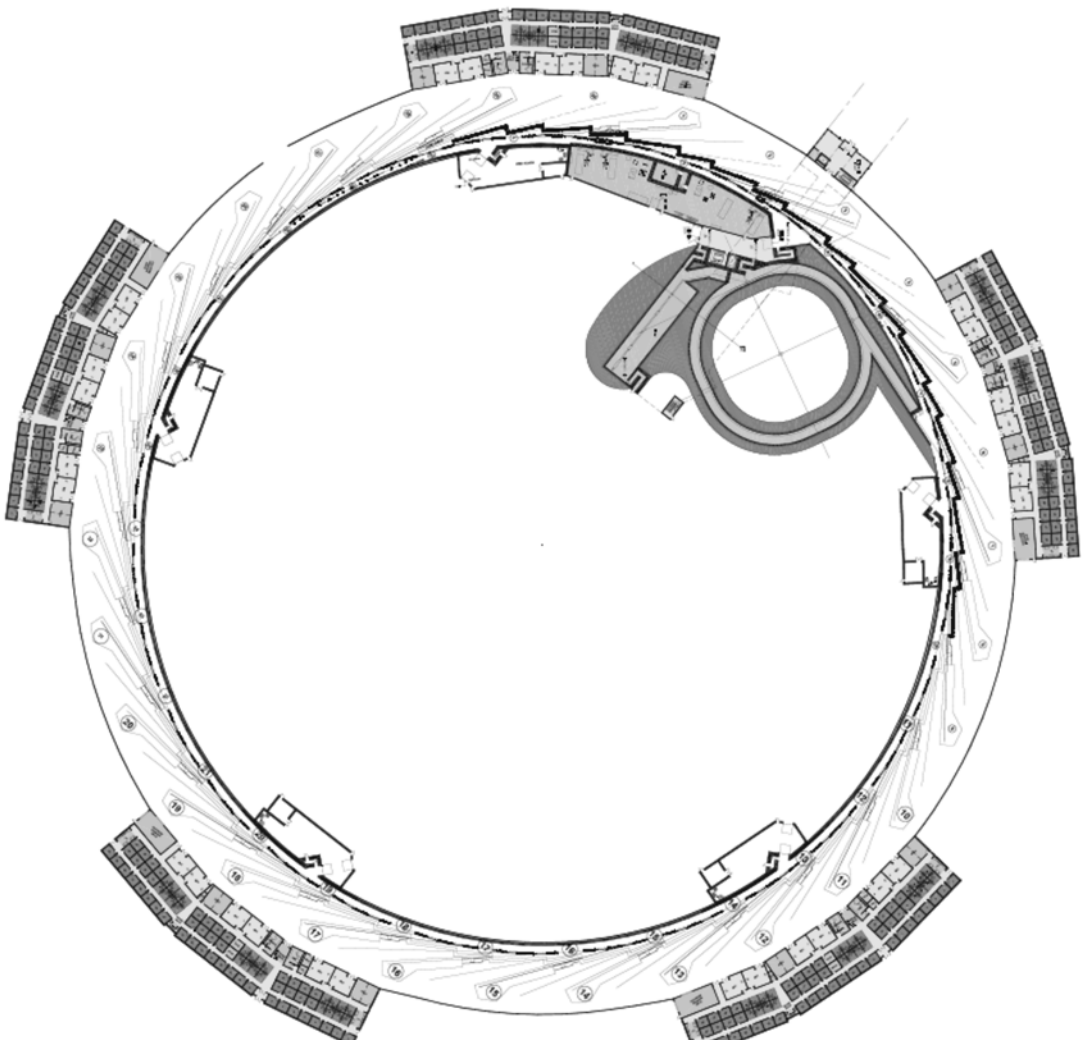
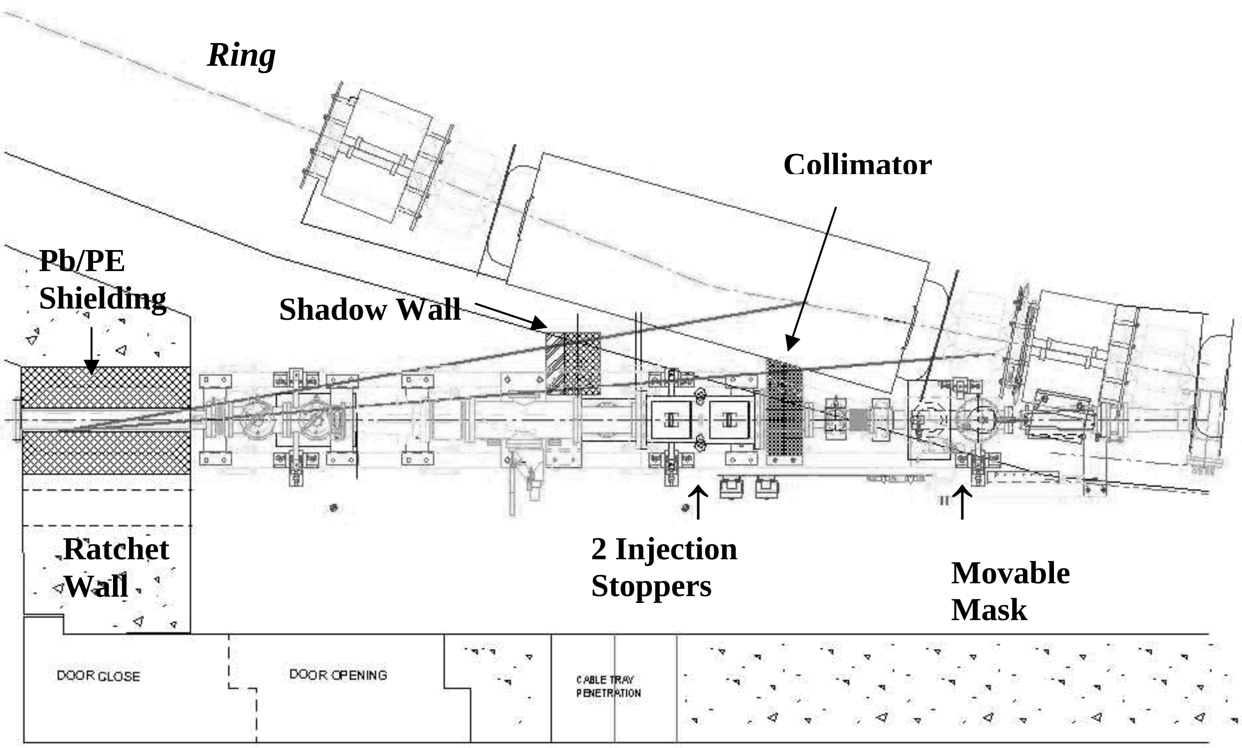
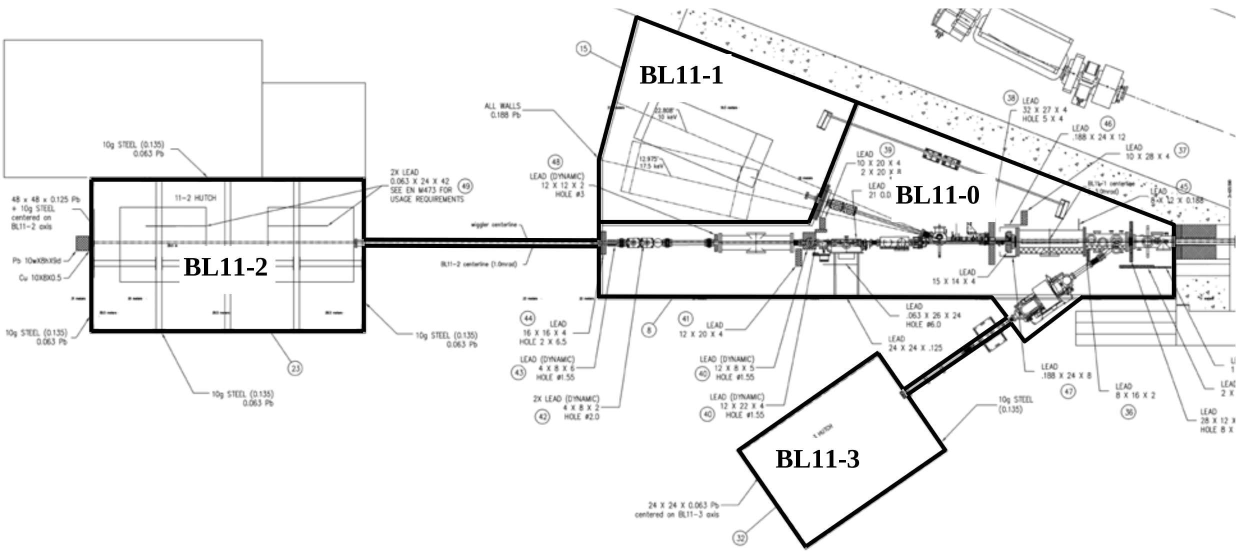


Fig. 9.



Ring
Collimator
Pb/PE
Shielding
Shadow Wall
Ratchet
Wall
2 Injection
Stoppers
Movable
Mask
DOOR CLOSE
DOOR OPENING
CABLE TRAY
PENETRATION

Fig. 10.


BL11-1
BL11-0
BL11-2
BL11-3

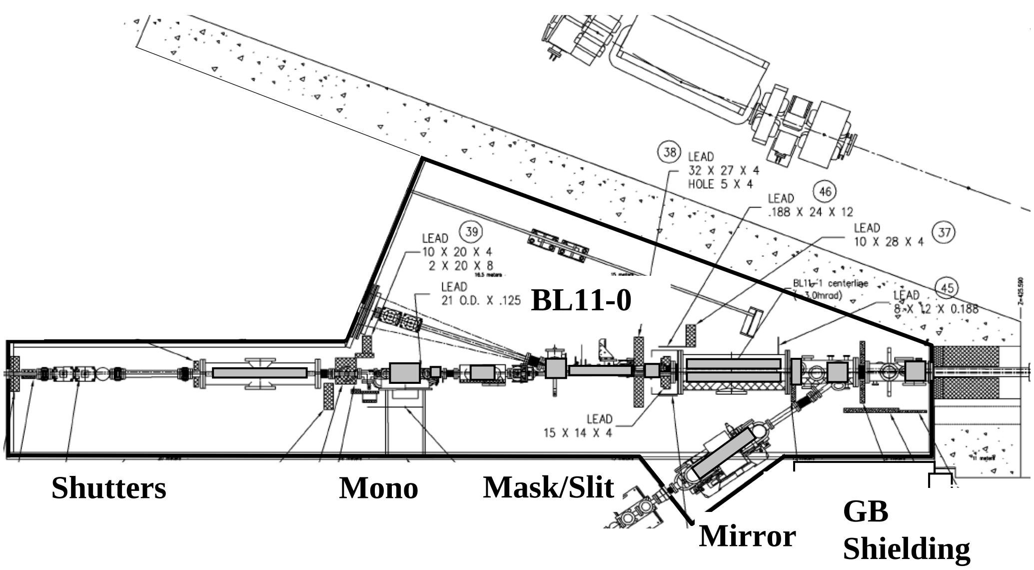

38
LEAD
32 X 27 X 4
HOLE 5 X 4
46
LEAD
.188 X 24 X 12
LEAD
10 X 28 X 4
37
39
LEAD
10 X 20 X 4
2 X 20 X 8
LEAD
21 O.D. X .125
BL11-0
BL11-1 centerline
(1.0mrad)
45
LEAD
8 X 12 X 0.188
LEAD
15 X 14 X 4
Shutters
Mono
Mask/Slit
Mirror
GB
Shielding

Fig. 11

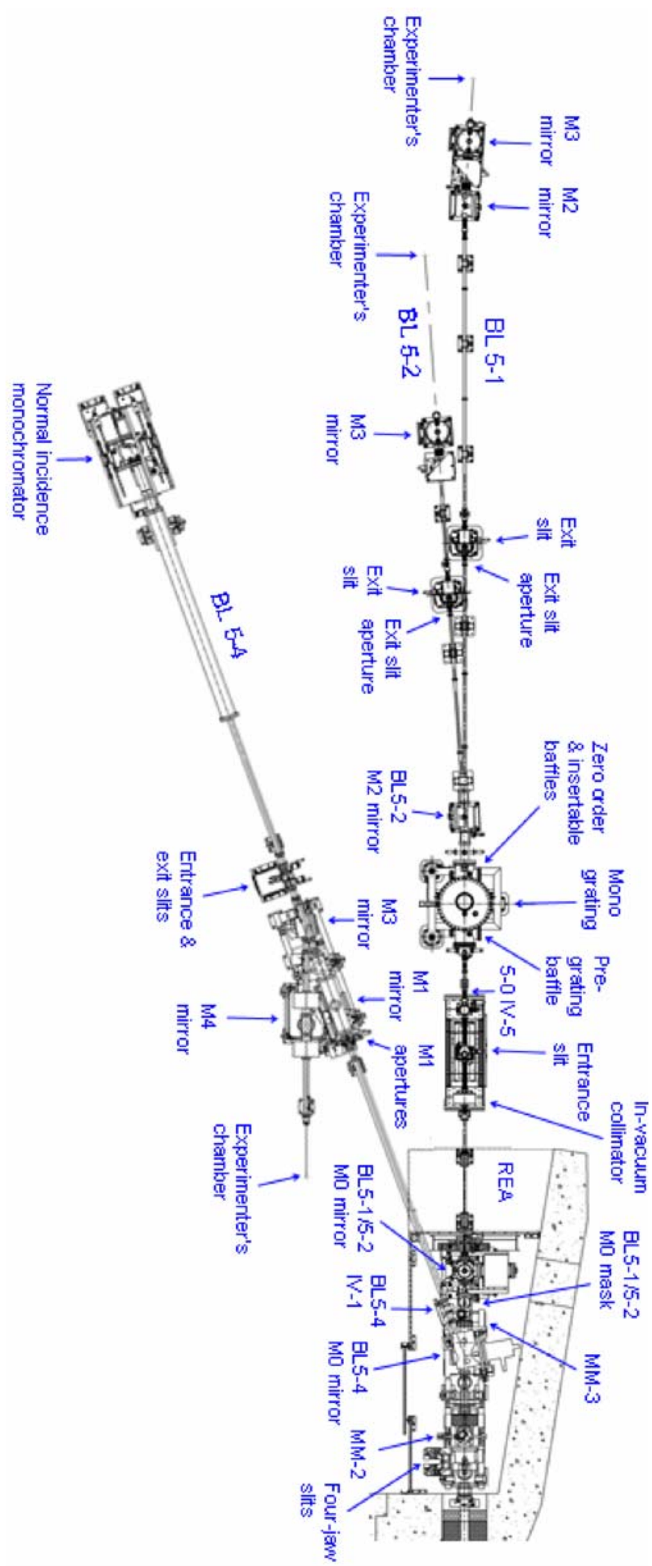
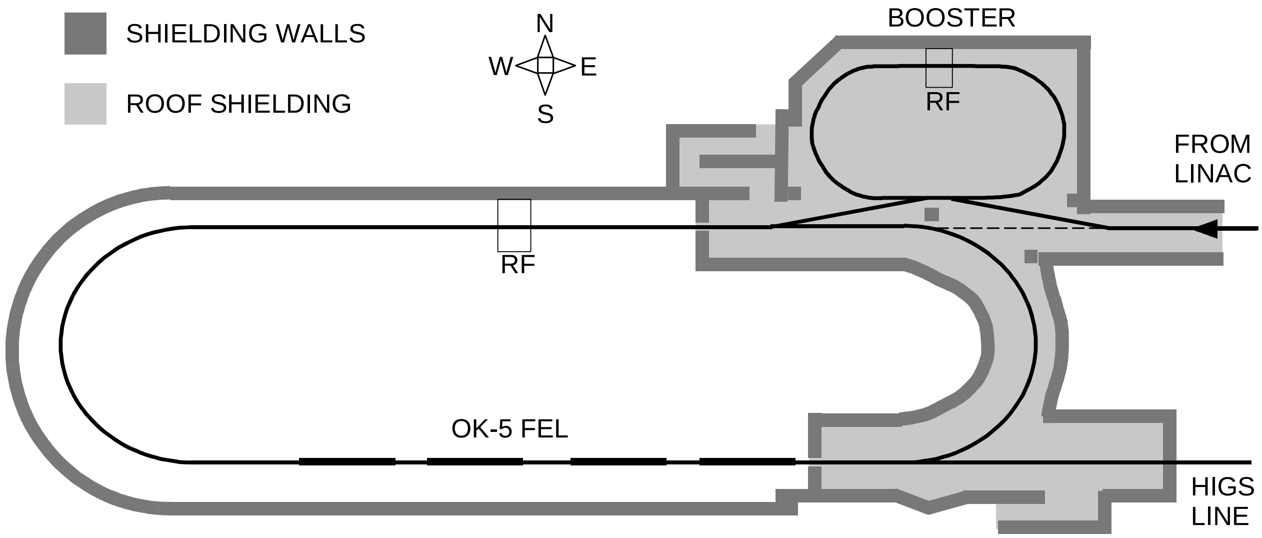
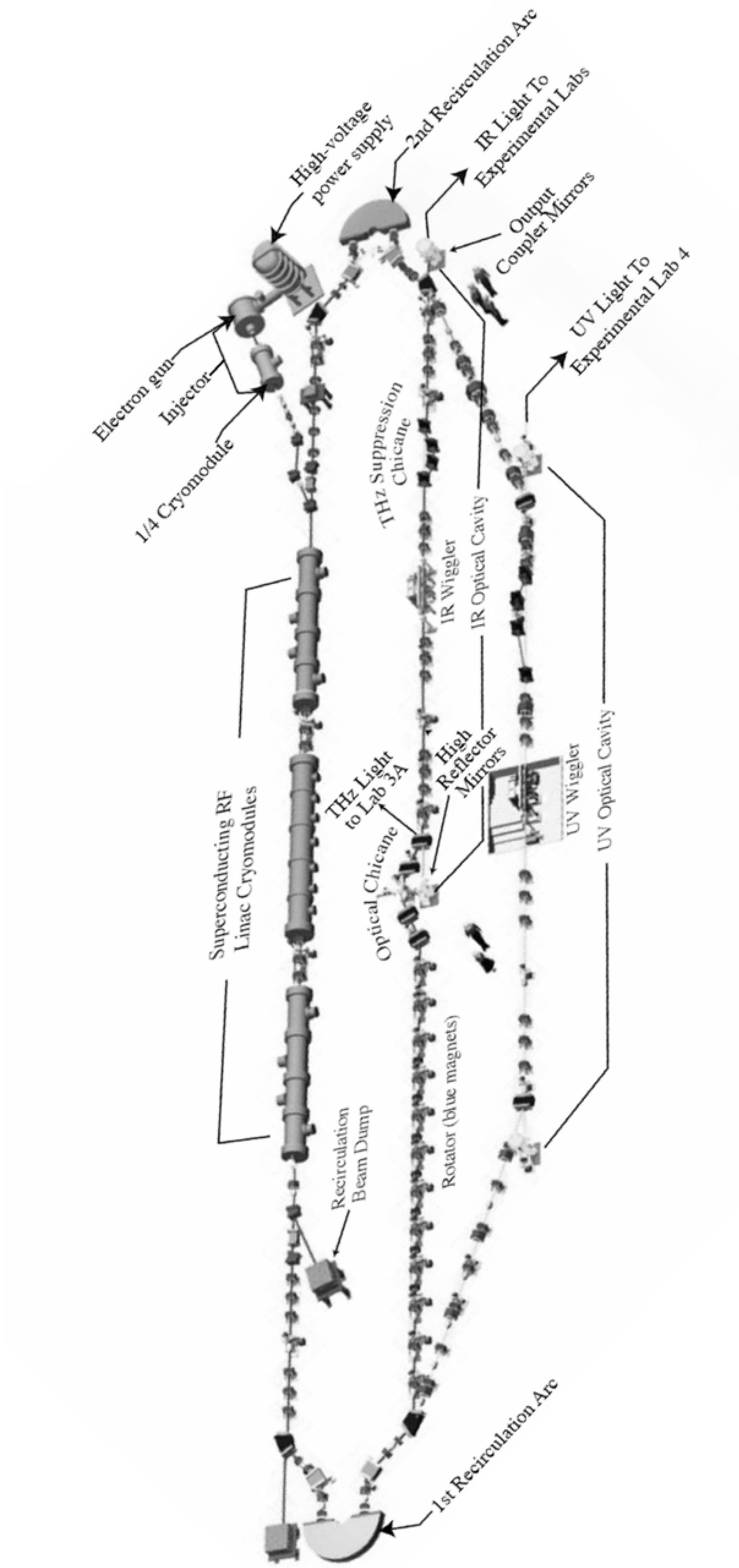

Experimenter's chamber
M3 mirror
M2 mirror
Experimenter's chamber
BL 5-1
BL 5-2
Normal incidence monochromator
M3 mirror
Exit slit
Exit slit aperture
Exit slit
Exit slit aperture
BL 5-4
Zero order & insertable baffles
BL5-2 M2 mirror
Mono grating
Entrance & exit slits
M3 mirror
Pre-grating baffle
5-0 IV-5
M1 mirror
M4 mirror
Entrance slit
M1 apertures
In-vacuum collimator
REA
Experimenter's chamber
BL5-1/5-2 M0 mirror
BL5-1/5-2 M0 mask
BL5-4 IV-1
MM-3
BL5-4 M0 mirror
MM-2
Four-jaw slits

Fig. 12



SHIELDING WALLS
ROOF SHIELDING
N
W
E
S
BOOSTER
RF
FROM
LINAC
RF
OK-5 FEL
HIGS
LINE

Fig. 13



2nd Recirculation Arc
IR Light To
Experimental Labs
High-voltage
power supply
Output
Coupler Mirrors
UV Light To
Experimental Lab 4
Electron gun
Injector
1/4 Cryomodule
THz Suppression
Chicane
IR Wiggler
IR Optical Cavity
Superconducting RF
Linac Cryomodules
THz Light
to Lab 3A
High
Reflector
Mirrors
UV Wiggler
UV Optical Cavity
Optical Chicane
Recirculation
Beam Dump
Rotator (blue magnets)
1st Recirculation Arc