Overordnet Plan for Drift for ASTRID2

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1: Introduction and general information

This report describes the ASTRID2 facility operated by ISA with the purpose of giving a complete overview of organisation, mode of operation and radiation safety at the facility.

ISA is part of the Institute of Physics and Astronomy (IFA) at the Aarhus University. IFA occupies buildings 1520-1526 in Aarhus land register number 1546n. ASTRID2 is situated in building 1526. A floor plan with room numbers is shown in figure1.

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1.3: Overview of ISA

The accelerator facility ASTRID2 comprises three electron accelerators with associated beamlines:

1: The injector, a 100 MeV electron microtron
2: The ASTRID 580MeV synchrotron/storage ring
3: The ASTRID2 580MeV synchrotron/storage ring

ASTRID2 is used to describe the entire accelerator facility, while the ASTRID ring and the ASTRID2 ring are the two synchrotrons.

The facility is located underground at the Institute of Physics at Aarhus University, in building 1526. The accelerators are placed in room number 112, 113 and 145.

The injector and the ASTRID ring have been in stable operation for about 20 years, and have delivered synchrotron light to a number of experimental beamlines.
The ASTRID2 ring is a new facility which has replaced the ASTRID ring as the source of synchrotron light. The ASTRID2 ring delivers light with a much higher brilliance than the ASTRID ring, and is among the best in the world in its energy range.
An overview of the facility is shown in fig.1.

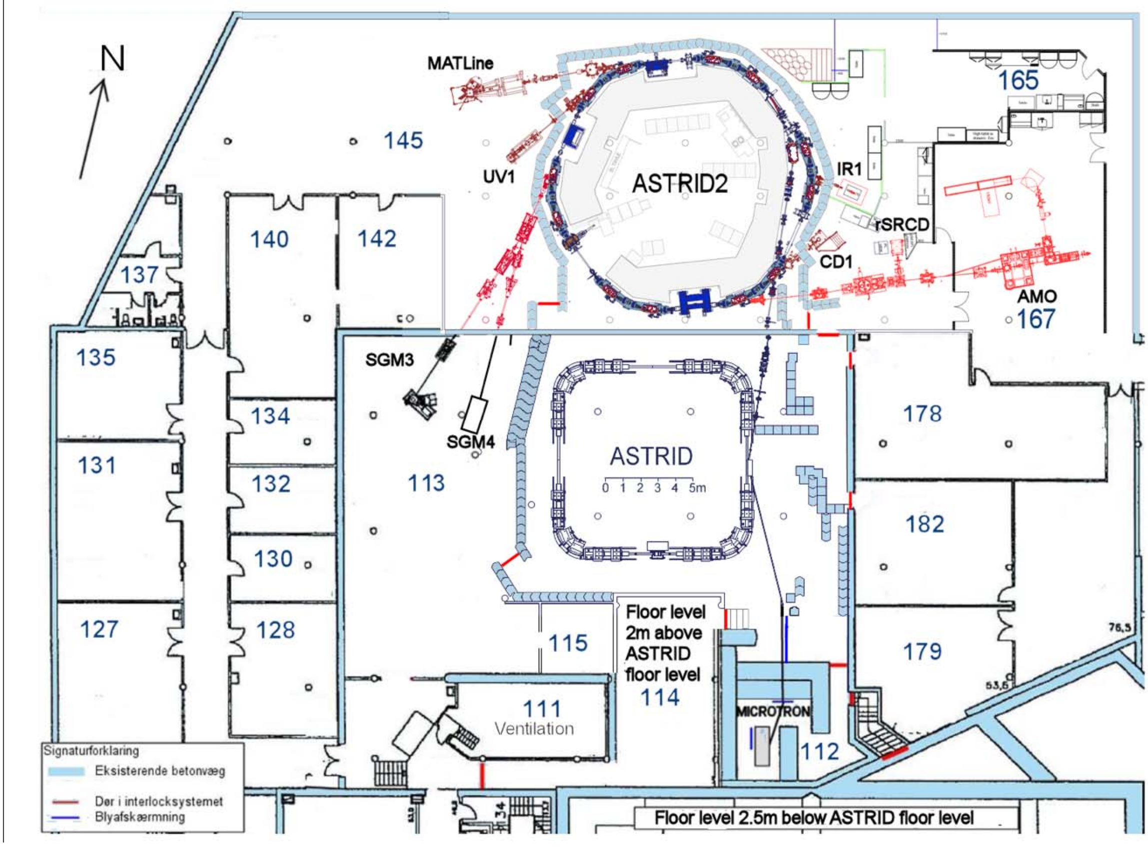

Figure 1: An overview of the ASTRID/ASTRID2 rings and neighbouring labs (Feb. 2020).

In the figure, concrete walls are shown in light blue. Doors marked with red are part of the interlock system, and will stop operation if opened.

1.4: Mode of operation

The ASTRID ring is used as a booster for the ASTRID2 ring, such that when an injection in the ASTRID2 ring is made, an electron beam is first accelerated to 100MeV in the microtron and transferred to the ASTRID ring. In the ASTRID ring the beam is accelerated to 580MeV and transferred to the ASTRID2 ring, where it is stored.

The lifetime (e^{-1}) in the ASTRID2 ring is 2 hours or more with a circulating current of 200mA.We wish to keep the ASTRID2 ring at a high current at all times, which requires a refill of ~5mA from the ASTRID ring every ~180 seconds.

When the ASTRID2 ring is filled from zero, we inject from the ASTRID ring as frequently as possible, which is once every ~35 sec, or about 100 pulses per hour. A complete fill to 200mA requires ~50 pulses and lasts about 30 minutes. An injection from zero only takes place when there has been an intentional or unintentional beam loss in the ASTRID2 ring.

2: Dose rate calculation methods

The calculation of dose rate is based on energy lost from the beam, which may result in ionising radiation, and the radiation dose per unit of energy.
In this report we will use the energy lost per 580 MeV electron. This is simple to calculate, since 1MeV=$1.6*10^{-13}$J, and a 580 MeV electron losing all its energy will therefore lose $9.28*10^{-11}$J.

The number of electrons, n, travelling at the speed of light c (m/s) in a ring with a circumference of L (m) in a beam with current I (A) may be written as n=I/e*L/c, where e is the electric charge of one electron.
Using e=$1.6*10^{-19}$C, c=$3*10^{8}$m/s, L=40.0m and I=0.001A we find that 1mA in the ASTRID ring corresponds to a beam of $8.33*10^{8}$ electrons.
In the ASTRID2 ring, with a circumference of 45.71m, the corresponding number is $9.52*10^{8}$ electrons.

Since each electron carries an energy of $9.28*10^{-11}$J we can calculate the energy lost per mA in the two rings:

In the ASTRID ring, the loss of 1mA at 580MeV corresponds to 0.077J
In the ASTRID2 ring, the loss of 1mA at 580MeV corresponds to 0.088J

This means that 200mA beam of 580MeV electrons stored in the ASTRID2 ring corresponds to a stored energy of ~18J.

Radiation dose per unit energy in the literature is often given in units of Sv/kWh. We find the unit of mSv/kJ (=µSv/J) more convenient, and use that unit in this report. In table 2.1 in the next section, both values are given.

When calculating doses in the user accessible area outside the radiation walls we will calculate the dose for a point 1m outside the wall. This is conservative, since users will spend most of the time at the desks and workbenches which will all be much further away from the wall.

2.1: Source models and attenuation data

High energy electrons may interact with the residual gas molecules in the vacuum tube and with the tube wall. These collisions can result in a loss of electron energy resulting in emission of electromagnetic radiation, or photonuclear reactions which can result in the emission of neutrons. Both mechanisms must be considered in this report because of the high electron energy.

The electromagnetic radiation created is known as Bremsstrahlung with an energy distribution from zero to the energy of the electron. The radiation is extremely forward peaked. The Bremsstrahlung photons interact with accelerator components which results in the development of an electromagnetic shower built up of photons and electron-positron pairs.

Neutrons are produced in photonuclear reactions in the accelerator components. Depending on the reaction mechanism and photon energy, the neutrons may be classified as low energy (<25 MeV), medium (25-100MeV) and high energy (>100MeV). The medium and high energy neutrons are more likely to be emitted in the forward direction, whereas the low energy neutrons are emitted isotropically.
The effective dose rate $H(\theta)$ (Sv/h) at a distance r (m) from a point of loss L (kW) of electrons behind a shielding wall of thickness t is given by

$$H(\theta) = L / r^2 \cdot \sum_j H_j(\theta)\ e^{-t/\lambda_j} \qquad (2.1)$$

The sum is over the different types of radiation j and $H_j(\theta)$ is the so called source term in units of Sv m^2 h^{-1} kW^{-1}, θ is the angle between the electron direction and the dose point. λ_j is the material attenuation length for radiation of type j. If more than one shielding material is present, the expression will contain additional $e^{-t/\lambda}$ factors. Equation 2.1 is used throughout the report for analytical determinations of the dose rates except where explicitly stated otherwise.

There exist different expressions for the source terms H_j. They can differ by more than a factor of two which implies that the uncertainty in the results is at least as large. In table 2.1 below, the data for bremsstrahlung and low energy neutrons are valid for electron energies >50MeV [Ref 1], while the medium and high energy neutron data are valid for 580MeV electrons [See fig 3.2 from Ref 1 reproduced in fig. 2.1 below].

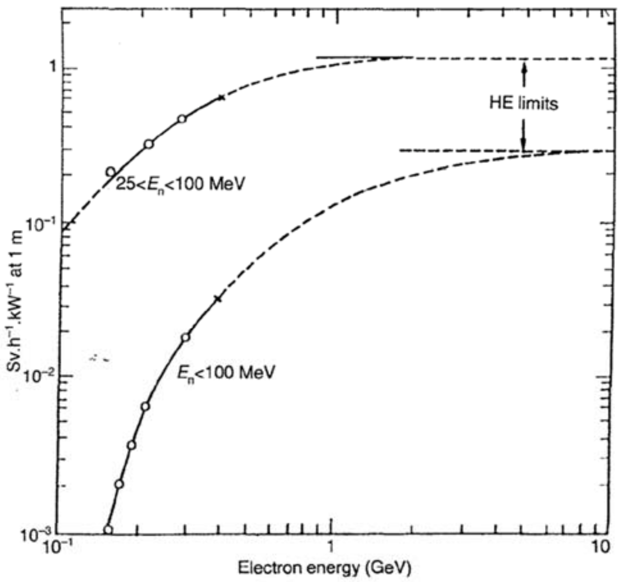

Figure 3.2. Effective source terms for neutrons in the energy range 25–100 MeV and of energy greater than 100 MeV emitted at 90 deg from 1 kW electron power dissipation in a thick copper target as a function of electron energy.

Figure 2.1

Source term	Sv/kWh at 1m, 90°	mSv/kJ at 1m, 90°
Bremsstrahlung	50	14
Neutrons < 25MeV	10	2.8
Neutrons 25-100MeV	0.8	0.22
Neutrons > 100MeV	0.06	0.017

Table 2.1: 90° source terms from Sullivan [1]

The source terms in table 2.1 will be referred to as Brems (Bremsstrahlung), LEN (Low Energy Neutrons, < 25 MeV), MEN (Medium Energy Neutrons, 25-100 MeV) and HEN (High Energy Neutrons, > 100 MeV) in this report. The numbers are valid for an emission angle of 90° and a distance of 1m.

The majority (99.9%) of the Bremsstrahlung emitted at 90° have energies below 10 MeV [2].

The shielding material attenuation lengths λ used in this report were mainly obtained from [3] and are listed in table 2.2.

Material	Brems	LEN	MEN	HEN
Lead	2.2	14	17	17
Iron	4.7	13	18	18
Heavy concrete	14	12	19	34
Concrete	21	17	28	49
Earth	44	21	56	56

Table 2.2: Attenuation lengths in cm for various shielding materials

Using data from table 2.2 we find that the transmission through typical shielding materials used at the ASTRID2 ring is:

Material	Brems	LEN	MEN	HEN
5 cm of Lead	0.10	0.70	0.75	0.75
5 cm of Iron	0.35	0.68	0.76	0.76
50 cm of concrete	0.09	0.05	0.17	0.36
1 m ceiling	0.04	0.005	0.08	0.15

Table 2.3: Transmission through some shielding elements used at ASTRID2.
The bottom row represents the ceiling in the ASTRID2 ring hall,
which consists of ~40 cm of concrete and ~60 cm of earth.

3: Electron loss scenario

Electrons may be lost

1: In the ASTRID ring hall.
2: In the transfer beamline from the ASTRID ring to the ASTRID2 ring
3: At the septum magnet when entering the ASTRID2 ring
4: At a specific location in the ASTRID2 ring
5: Evenly distributed around the ASTRID2 ring

Injections have been shown to have an efficiency up to 75%, such that 75% of the electrons extracted from the ASTRID ring are stored in the ASTRID2 ring while 25% are lost in the first 50ms after injection.

3.1: The ASTRID ring hall

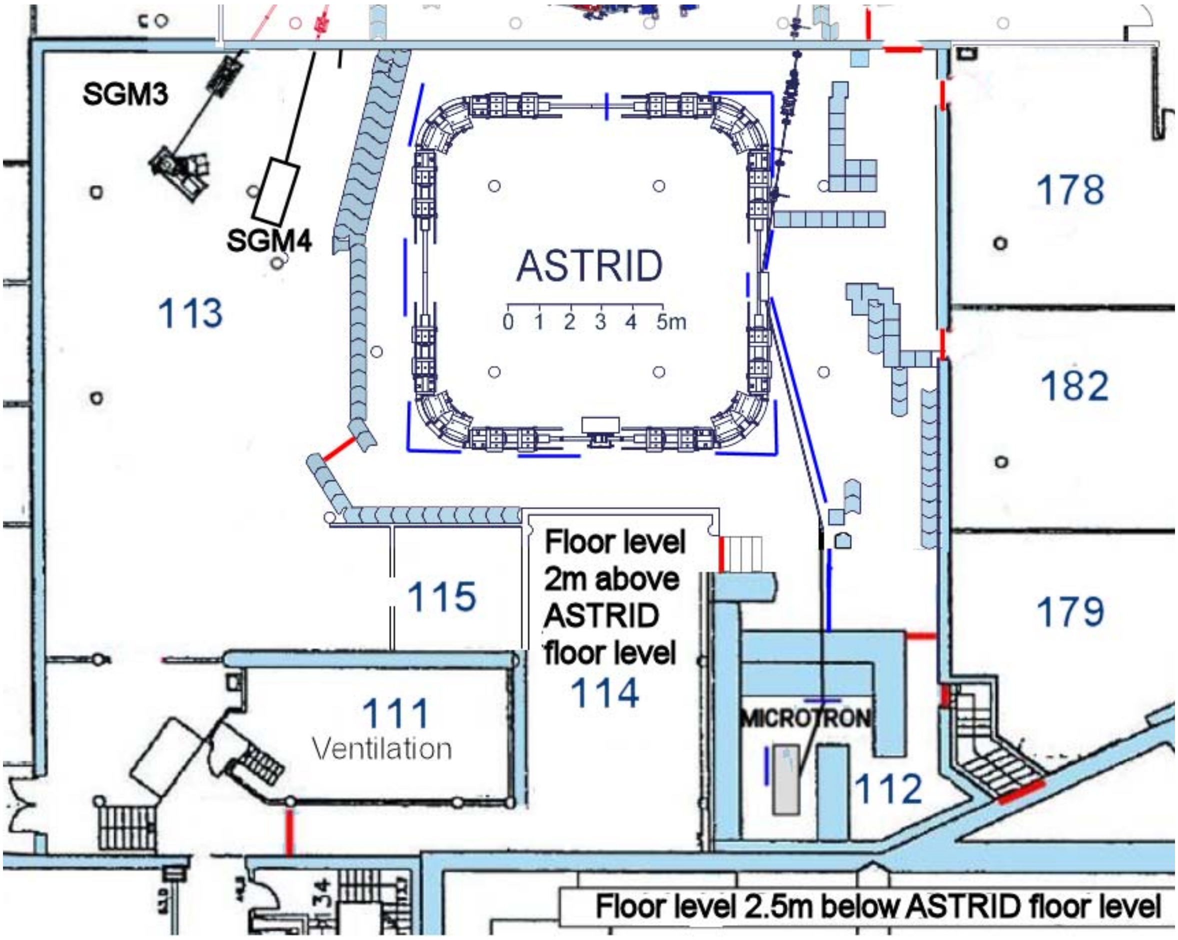

Fig. 3.1: The ASTRID ring hall with the existing (February 2020) concrete walls shown in light blue. Lead shielding is shown in dark blue. North is upwards in the figure.

A 50 – 100 cm thick concrete wall has been built to enable use of the west end of the hall even while ASTRID is delivering beam to the ASTRID2 ring. This part of the room is easy to shield effectively, which has been confirmed by measurements.

Loss calculation:

The 100MeV pulse from the microtron is a 1µs pulse with a pulse current of ~7mA . This corresponds to $4.4*10^{10}$ electrons.
About 5 mA is stored in the ASTRID ring, corresponding to $4.2*10^{9}$ electrons.
This means, that about $4*10^{10}$ electrons at 100 MeV are lost in each injection. A 100MeV electron carries an energy of $1.6*10^{-11}$J, so about 0.64J/pulse are lost at injection, some in the transfer beamline from the microtron to the septum of the ASTRID ring, but the main part in the ASTRID ring and at the ASTRID ring septum.
An energy loss of 0.64J will give a dose of 9µSv at 1m, 90° if it is lost at one place. Based on current experience we estimate that we will operate with about 60.000 pulses a year (2000h), resulting in a total dose of 540mSv/year.
Assume 10% is lost in the injection beamline, 80% at the ASTRID ring septum and 10% distributed around the ASTRID ring. The shielding is based on these estimates.

The injection beamline (10%) is at least 4 meters away from neighbouring labs. In addition, there is 5 cm of lead and a concrete wall of 80cm thickness. This gives a combined reduction factor of 7300, such that the 54mSv/year is reduced to 0.0074mSv/year.

Losses at the septum is 8 times higher than at the injection beamline, the reduction factor is much larger, because the magnet yoke is made of iron, at least 50mm thick, and 50 cm concrete blocks are placed to protect the neighbouring labs. In addition, the distance to other labs is greater, about 6 meters. 6 meters distance, 50mm of Iron and combined concrete thickness of 80cm gives a total attenuation of 4700, reducing 432mSv/year to 0.092mSv/year

The ASTRID ring (10% loss for all sections of the ring): 54mSv/year. After 100cm concrete and 2 m distance this is reduced to 0.13mSv/year for the entire ring. 5-10cm lead walls are placed at critical points, further reducing this number. In straight sections, there is 10 cm of lead in the forward direction.

3.2: Injection and the transfer beamline

About 30% of the beam which is extracted from the ASTRID ring will be not be stored in the ASTRID2 ring.
Assume that 6 mA is accelerated in the ASTRID ring. This corresponds to $5*10^9$ electrons. Only ~11 of the 14 bunches in the ASTRID ring actually enter the extraction beamline due to the ~30ns rise time of the extraction kicker. This will correspond to $3.9*10^9$ electrons. Of these 30 % or $1.2*10^9$ electrons are lost immediately, equivalent to an energy of 0.11J. On a yearly basis, this is a dose of $0.11*10^{-3}*14*60000$μSv = 92mSv in 90°, 1m.

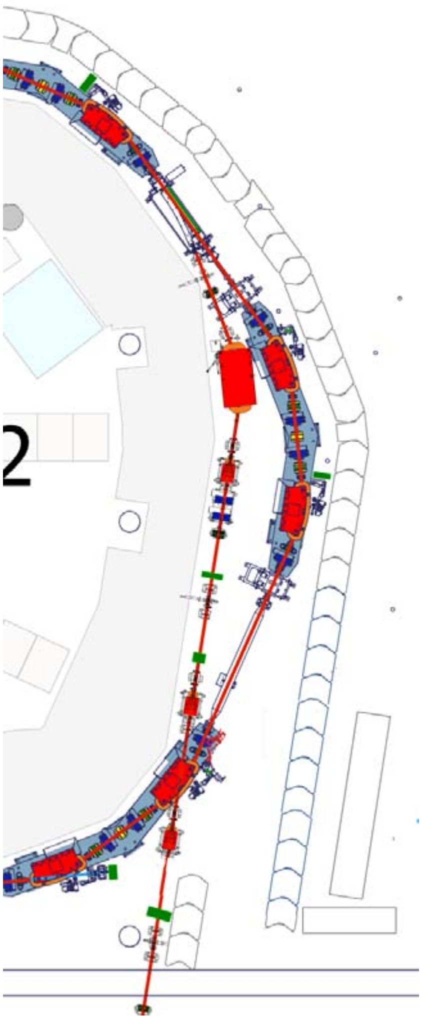

Figure 3.1: The transfer beamline. Local lead shielding is shown in green

We shall assume, that 1/3 of the 92mSv is generated in the transfer beamline, 1/3 at the septum and 1/3 during the first few hundred turns in the ASTRID2 ring. This means, that 31mSv will be generated at each location.

The transfer beamline is typically 2 m away from the radiation wall, such that a point 1 m outside the 0.5m concrete wall will receive a dose of $31\text{mSv}*0.09/3.5^2$ = 0.23mSv/2000h. At critical points along the beamline, this is brought further down by the use of local lead shielding. This will be the maximum dose for a person if the loss occurs at one spot, if no additional lead shielding has been placed at that spot, and if the person is located 1 m outside the wall 2000h/year at a position perpendicular to this spot. At other positions outside the wall, the dose will be smaller because of a greater distance to the source point and the oblique angle under which the wall is hit.

At the septum, the distance to the wall is smaller, but here a 5 cm thick wall of lead bricks has been placed along the septum towards the wall, reducing the 90º dose to ~0.07 mSv/year.

Injection losses in the ring will have the same characteristics as losses in the injection beamline, but since the ring is closer to the wall, the distance is reduced and the dose is therefore ~4 times higher than at the injection beamline, 0.6mSv/2000h, if all is lost at one point. Again, lead is placed at critical points, which will reduce the radiation level further. This is possible, since it is known where the beam is largest, and therefore most likely to be lost.

Radiation in the forward direction in case of beam loss is far more intense, but here several factors help to reduce the dose: The beamline is bent downwards before entering the ASTRID2 ring hall. After passing under the ASTRID2 ring, it is again bent upwards, and is only horizontal in the last part, just before the large 30° magnet and from there on to the septum.

In order to reduce potential forward radiation, lead walls have been built at three places along the beamline, and in addition the optical elements all have a considerable amount of iron and/or copper close to the beamline.

Forward losses at the septum are more critical, so here a 5 cm thick wall of lead bricks has been placed. This is hit under an angle of 15°, increasing the effective thickness to 19.3cm, giving a transmission of $\sim 10^{-4}$. The concrete wall is hit under an angle of about 20° resulting in a transmission of ~10^{-3}. As a further barrier to the forward radiation cone, a 150 mm thick lead wall is placed in the continuation of the first part of the ring which the beam will pass.

The dose rate is checked for each beamline as it is set up to confirm, that the shielding is sufficient.

3.3: The ASTRID2 storage ring

The storage ring has a circumference of 45.71m.
The optical elements (dipoles, quadrupoles, sextupoles and correction dipoles) are mounted on 6 girders). The ring has a six-fold symmetry with 6 long (4.25m) straight sections connecting the 6 girders, 6 short (1.67m) straight sections in the middle of the girders and 12 curved sections (0.85m) in the 30 degree dipoles. This is illustrated in figure below:

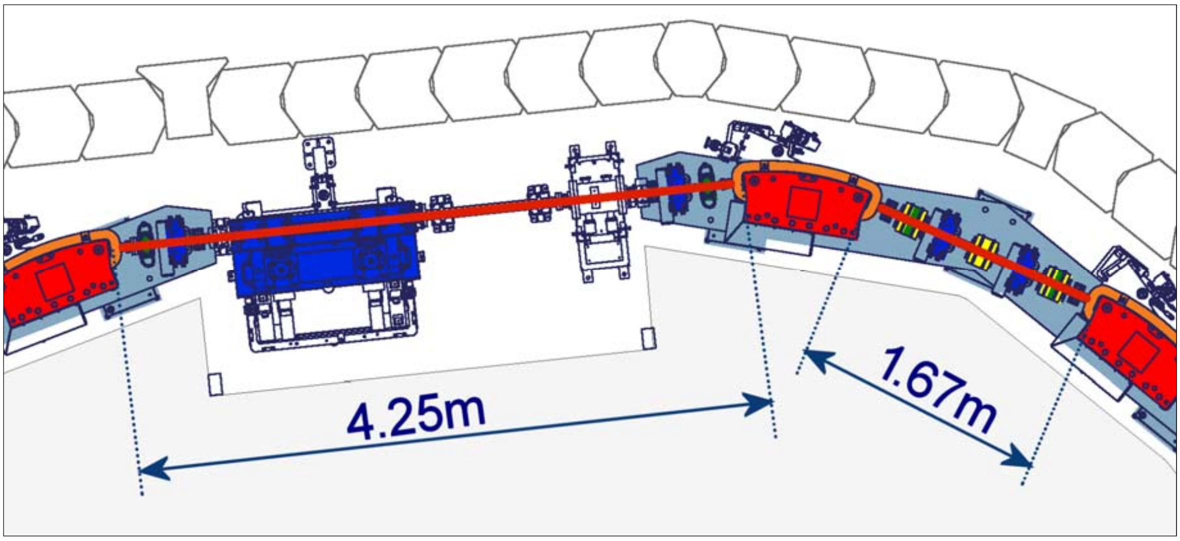

Figure 3.2

During normal top-up operation, we will maintain 180mA in the ASTRID2 ring by injecting ~5mA from the ASTRID ring every 180 seconds with a lifetime of ~2 hour. Every two hours, ~180 mA will be injected and therefore also lost in the ASTRID2 ring. This loss is caused by changes in momentum of individual electrons caused either by collision with molecules in the residual gas in the vacuum system (vacuum losses), or with other electrons in the beam (beam-beam collision losses). Following a sufficiently large momentum change, the electron will move to a new trajectory resulting in a collision with the physical aperture of the vacuum chamber.
The number of ‘fatal’ collisions with residual gas molecules at a given spot is directly proportional to the local pressure in the system. These collisions will also give rise to an immediate emission of radiation from the point of the collision.
The number of beam-beam collisions depends on the size of the beam, which varies around the ring, being smallest in the long straight sections.

Collisions with the physical aperture of the ring will take place either where this aperture is small or when one of the off-momentum particles mentioned above is far from the central orbit of the machine, which is in the centre of the short straight sections where the momentum dispersion is largest. The smallest aperture is found in two of the long straight sections where small-aperture chambers have been mounted to accommodate special devices for generating synchrotron light (insertion devices).

In case of a system failure causing the injected pulse to be lost at some point in the ring or injection beamline, the system will shut down the injection cycle if the injections fail. Injection step size and efficiency are both continuously calculated and logged.

Concluding, part of the radiation is emitted more or less (depending on local vacuum) evenly distributed around the ring, and part is emitted from the locations with small physical aperture or large beam excursions from the central orbit.

To estimate the radiation dose, we use the fact, that 100mA are lost every hour. This corresponds to 9J lost every hour, with a resulting dose at 90°, 1m distance of 125µSv/h or 250mSv/year.

Assuming that radiation is emitted 1 m from the concrete wall (transmission 0.09), the dose at 1 m from the outside of the wall will be $250/2.5^2*0.09$ mSv/year = 3.6mSv/year. This number is for the entire ring, for electron losses by any mechanism and for a radiation path perpendicular to the wall. At points where it is known that the continuous loss will be higher (narrow chambers, middle of girder straight sections) a 50mm lead wall is mounted, reducing the dose by a factor of 10.

Loss of the entire beam will probably also happen at several points in the ring at the same time, but may in principle happen at any spot. Every time this happens, a dose of 250µSv will result, equivalent to 2 hours extra of continuous beam loss. This happens unintentionally when a component fails (In 2019 we had 9 total and 4 partial beam losses), and intentionally every time it is necessary to enter the ring for repairs/installation of new components etc (estimated to happen ~50 times/year).
Monitors placed around the ring integrate the dose, and on these monitors a beam dump does not contribute significantly to the integrated dose. The largest observed increase in dose was <0.1µSv. This shows, as expected, that beam losses do not add significantly to the dose in the area outside the radiation walls. Using the above estimates, the yearly dose resulting from beam dumps will be <7.5µSv.

The radiation emitted in the forward direction requires more attention because of its intensity, and because some synchrotron radiation beamlines are passing through holes in the wall and are extensions of the long straight sections of the ring. As in the case of the injection beamline, this radiation is reduced by the optical elements of the ring, except in the direction through the beam tube. The beam tubes pass through a 100-150mm lead wall mounted on the inside of the concrete wall. The radiation passing through the beam tube itself can only be removed after the first mirror chamber where the light beam changes direction, making shielding the forward direction possible.

3.4: Skyshine

The ASTRID2 facility is housed underground, below a parking area.

The ceiling is 1 m of concrete and earth, with a transmission of 0.04. The distance from the ring(s) to 1m above ground level in the parking area is 4.5m. Together, this attenuates the radiation by a factor of $0.04/4.5^2 = 2*10^{-3}$ relative to the 1m, 90° values.

In section 3.3 it was found, that the yearly dose at 1m, 90° for the entire ring was 250mSv/year. From the injection beamline it was found to be ~138mSv/year.

Using the attenuation value found above, the dose 1m above ground level for **the entire ring** is 0.8mSv/year. Given that the radiation is lost over a very large area and that the occupancy factor is low for the parking lot (1/40), the dose received by any individual in the parking lot will be far below 0.1mSv/year.

4: Neutrons

Using data from tables 2.1 and 2.3 it becomes clear that neutrons will give only a minor contribution to the radiation dose, as long as the bremsstrahlung is properly shielded with concrete.

The neutron emission from loss of 580MeV electrons will be dominated by low energy neutrons, which are emitted isotropically. The dose in mSv/kJ is 5 times lower than that of bremsstrahlung, and the transmission through 50cm of concrete is half that of bremsstrahlung, totally making LEN doses about 11% those of bremsstrahlung.

Medium and high energy neutrons will contribute to the total dose by 3 and 0.8% respectively, relative to the dose from bremsstrahlung, again using data from, tables 2.1 and 2.3.

The above assessment is supported by a 6-month neutron TLD survey in 2014/2015, which showed a dose of zero (detection limit 0.1mSv) for all measurements in the open area.

5: Safety assessment:

Below, the risk of radiation exposure and the precautions taken in each case is evaluated for three different modes of operation:

Routine operation:

Risk**:**

1. Loss during injection, acceleration and extraction in the ASTRID hall
2. Loss during injection in the ASTRID2 hall
3. Continuous beam loss in the ASTRID2 ring

Safety assessment:

1. These losses will affect the experimental area in the ASTRID hall, the labs in rooms 178,182 and 179, and parts of the ASTRID2 hall. As calculated in section 3.1, the dose rate at the above locations will be less than 0.3mSv/year. This is supported by measurements as shown in table 6.1 on page 17.

2. Injection losses in ASTRID2 and the injection beamline are calculated in sections 3.2 and 3.3. These losses mainly affect the eastern part of the ASTRID2 hall and the corridor in the northern part of the hall. Calculations show that yearly doses will be below 0.3mSv in open areas when we reach full current (180mA). Levels at 120mA have been measured to be below 0.3mSv/year at all existing work places (See table 6.1 on page 17).

3. In section 3.3 the dose rate outside the concrete wall for the entire ring is estimated to be in the order of 3.6mSv/year for radiation with a direction perpendicular to the wall. If losses were evenly distributed, this would not present a problem anywhere on the >50 m long wall. However, continuous losses occur at positions which are partly predictable, but are easy to locate with a radiation monitor during routine use with a large current in the ring.
   At all identified loss points, additional lead is placed, keeping the dose at 1 m distance to the wall <0.3 mSv/year.

Non-routine operation

Risk

1. Modifications/installation of beamlines. All synchrotron radiation beamlines pass through holes in the concrete wall, and several point directly to the ASTRID2 beam tube, allowing radiation to pass the wall.

2. Authorized access to the ring while beam is circulating, but no injections taking place, involves risking a beam dump while a person is inside the concrete wall.

3. Adjustments of the injection beamline and ring may give rise to higher doses.

Safety assessment

1. All work on beamlines where they pass through the wall is done without beam in the ring. A beam is not injected until lead shielding has been mounted around the beam tube. Every beamline is carefully checked with dose rate monitors when beam is first injected. Beamline scientists and technicians know the procedure well, and in order to keep others away, we will permanently fence off the front end of all beamlines.

2. The persons authorized to enter the ring compound while a beam is circulating run a small risk of an uncontrolled total or partial beam loss taking place while they are inside. Such events are rare in general and while authorized access to the compound during operation is also rare, an overlap cannot be excluded.
    a. Ring centre: The radiation generated from a beam dump of 180mA shows an integrated dose of up to 6μSv in some spots in the centre of the ring. In most locations, e.g. the computer desk inside the ring, the dump is not detectable using a radiation monitor. In the centre – near racks – the continuous dose rate levels from a stored beam of 180mA levels are not discernible from the natural background levels with zero beam. Considering that the maximum time a person is in the ring centre with a stored beam in the machine is less than one hour/year, and that the probability for a beam dump while being there is low, this is not a serious risk.
    b. Outside ring (inside compound): The continuous dose rates due to steady losses from 180mA of stored beam has been measured to be about 30μSv/h (excluding injections). As for the sudden loss of the full beam, an increase in the integrated dose is not observed. It should be noted that the loss pattern may depend heavily on the cause of the uncontrolled loss. As detailed in Sec. 6: Radiation protection, access to the area outside of the ring during full-beam operation is prohibited, but should this not be respected, the risk is still low due to modest impact and very low incidence.

3. The purpose of adjusting ring parameters is to make injections more efficient or to increase beam lifetime. However, while a parameter is being changed, mis-steering could take place, resulting in higher dose rates. It is estimated that dose rates could be up to 10 times the dose rates calculated for routine operation in section 3. This gives dose rates up to 1.5mSv/year, but since adjustments take place at an estimated 1hour/week=40 hours/year, the effective dose is 0.03mSv/year or less.

Accidents and system failure

Risk

1. Power failure, vacuum failure or human error can lead to total or partial beam losses, poor beam lifetime, low injection efficiency and mis-steering of the beam.

2. People not associated with the ASTRID2 facility may make an unauthorised access to radiation areas.

Safety assessment

1. As shown in section 3.3, a total beam loss does not contribute significantly to the radiation level in the open area.
   Mis-steering or low injection efficiency will be detected by the control system, which after a short time will stop the injection cycle and alert the ring operators via SMS. The system's monitoring scope is continuously expanded to detect ever more fault scenarios and act accordingly.

2. Since the experimental areas are open, anybody can in principle enter these areas. The areas immediately around the rings are completely enclosed, and entry must take place via doors which are interlocked, such that the opening of a door will make an immediate (< 50ms), controlled dump of the beam and shut down injections. This safety measure is part of the annual machine interlock inspection but is verified more often than that.
   There are also small areas around the front end of beamlines which have an increased dose rate immediately around the beam tube (Up to a few µSv/h at distances less than 10cm). These areas are being protected by a wire fence with signs prohibiting access. These fences also serve the purpose of keeping people away from the often very mechanically sensitive beamline front ends.

6: Radiation protection

Classification of areas

According to the assessments of radiation levels in section 3, the areas around both the microtron, ASTRID and ASTRID2 are controlled areas (>6mSv/year). These areas are enclosed by concrete walls and doors are all interlocked.
The remaining area (the experimental area) is not classified as a radiation area (<0.3mSv/year).

Classification of persons

The following group of persons are classified in radiation risk group B. People in this group will receive information on the area classification and must wear a radiation badge. A list of these people will be kept by the radiation co-ordinator:

1. Permanent IFA and iNano staff working on the accelerators
2. IFA and iNano researchers working on beamlines
3. Students working on beamlines

The following groups of persons with access to the complex are not classified as being exposed to a radiation risk:

4. Guests working on beamlines
5. Staff and students passing through the open areas
6. The cleaning staff
7. External technicians

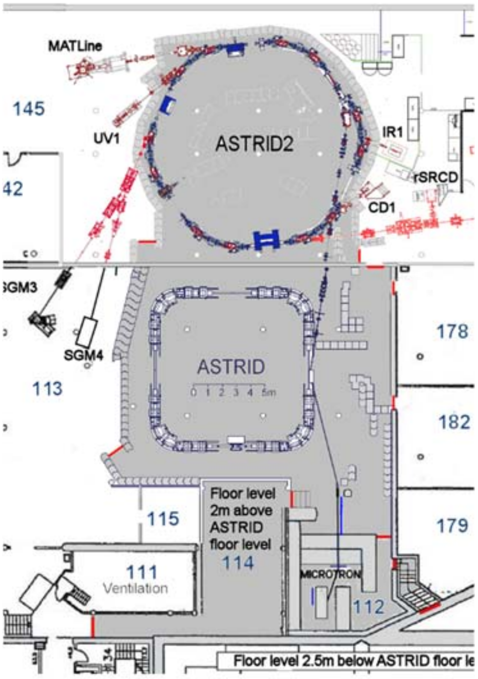

Figure 6.1: The controlled area is shown shaded in grey. All other areas are open.

6.1 The open area:

In this area we must ensure that a person will receive less than 0.3mSv/year. This is achieved by placing sufficient radiation shielding at all places where beam losses are expected and known to occur, and where such losses would give radiation in the open area. All planned shielding is in place, and a 6-month TLD survey from 1/11 2014 to 30/4 2015 shows that doses are well below 0.3mSv/2000h at all the measured locations, which covered the open areas around the rings plus neighbouring labs 178, 179 and 182.

The ASTRID2 ring:

The shielding is composed of three elements: Lead bricks (50*100*200mm) and 2 kg bags with lead pellets close to potential loss points, concrete walls with 0.5 or 1m thickness and finally distance from the outside of the wall to the source point. Together, these three elements will ensure a reduction factor of at least 1000. This can for example be realized by 50mm of lead, 0.5 m of concrete and a distance of 3m. In places where the beam is closer to the concrete wall, more lead will compensate for the reduced distance.

The reduction in dose rate by 1000 will reduce the estimated dose perpendicular to the beam tube from 100mSv/year to 0.1mSv/year.

In the extension of the straight sections, the radiation will in almost all cases traverse the concrete wall at an oblique angle thereby increasing the effective thickness. In addition, the distance to a person in the open area will often be greater than 3m, and more lead (at least 100mm) will be used. Together, this will increase the attenuation by at least another factor of 1000, enough to compensate for the higher intensity in the forward direction.

At three locations, synchrotron radiation beamlines pass through the wall in the extension of long straight sections. In these cases, 200mm of lead bricks surround the beam tube near the concrete wall, and bags with lead pellets are placed immediately around the beam tube where it passes the hole in the wall. These beamlines will all be bent by a small angle in a mirror chamber inside or outside the wall, enabling additional lead bricks in the 0° direction. All front ends of beamlines will be surrounded by a wire fence to prevent general access to the area.

One area may exceed 0.3mSv/year: The corridor along the north side of the ASTRID2 ring is narrow (~1m), so people must pass close to the wall, which is also close to the ring. The reduced distance may increase the dose rate by a factor of 4, but with the standard occupancy factor for corridors of 20% (in reality much less, probably 1%, since 20% is 1.6h in the corridor/day), and additional 50mm of lead in place, the yearly dose will still be below 0.3mSv/h.

The ASTRID ring:

The ASTRID ring is now used solely as a booster for the ASTRID2 ring. The maximum repetition rate is ~170 pulses/h. During routine operation we expect a repetition rate of ~10-30 pulses/h, depending on beam lifetime in ASTRID2.

The affected areas are the experimental area in room 113 west of the ASTRID ring, room 115 south of the ASTRID ring, and rooms 178, 182 and 179 east of the ASTRID ring hall, and the area east of the ASTRID2 ring close to the doors to the ASTRID ring hall.

As with the ASTRID2 ring, we aim for a damping factor of 1000 for losses perpendicular to the beam direction, and 100-1000 times more in the forward direction. This is achieved by a combination of lead, concrete and distance.

The visitor platform:

In December 2015, a visitor platform was constructed outside the concrete wall north-east of the ASTRID2 ring, allowing visitors a direct view over parts of the ring. The platform was constructed after receiving approval for the plan by SIS (J.Nr. 1-5811-838/7/, Ref. CASG). The platform is included in figure 1 on page 3.

The floor of the platform is raised 1.1m above the hall floor, and since the wall is 2.2m high, an average person can easily see parts of the ring. The edge of the platform facing the ring is 0.5m from the wall, so it is not possible to see the closest part of the ring.

The radiation level has been measured by an integrating monitor placed on top of the wall directly in front of the platform. The dose measured over 24 hours of routine operation (Top-up 120mA) was 10.5µSv, giving a dose of ~0.44µSv/h, or 0.875mSv/2000h including background.
A similar measurement was made at the edge of the platform closest to the ring, at a height of 1.80m above the platform floor, i.e. at eye height of a tall person. The dose rate at this point was measured to be 0.55µSv/h or 1.1mSv/2000h including background.

Signs at the platform inform about the increased level of radiation, and the guides normally accompanying visitors are informed about the radiation level and the rules for entering the platform. People usually stay on the platform about a minute, so the increased level of radiation does not contribute significantly to the yearly dose received. Other signs at the platform instruct visitors to use it only for brief visits, and not to lean over the wall.

In case the ring is running in a non-routine mode which may increase the level of radiation, access to the platform is blocked by a chain.

The SGM4 beamline:

In 2019, a new beamline was installed on ASTRID2, the SGM4 (SGM: Spherical Grating Monochromator) beamline. This beamline shares its front-end with the SGM3 beamline. In the front-end, mirrors can be adjusted to send the light from ASTRID2 either to SGM3 or to the new SGM4. Therefore, SGM4 does not introduce anything new regarding radiation, since the UV light it receives from the front-end has an energy less than 200eV.

The microtron modulator in the ASTRID hall

Preventive maintenance plans were made to replace the ageing microtron modulator and klystron with a modern solid-state klystron modulator in the autumn of 2022. While the present klystron is placed inside the microtron controlled area, the new modulator and klystron is located just outside the microtron bunker (i.e. contained in the ASTRID controlled area).

The new klystron is very similar to the present one, relying on a concept of RF power amplification in an electron beam of ~143kV, 93A for only a very short duration of 5µs at a maximum of 10Hz (typically a shorter pulse and much less frequent). The beam is disposed inside the klystron, thus generating up to ~143 keV bremsstrahlung photons. An effort is made to make the modern klystrons for particle accelerator applications self-contained in terms of radiation, thus enabling feasible service of these and their concomitant modulators by allowing to place the devices in open areas. Integrated lead parts are used to efficiently self-shield the klystron:

- The single-pass electron beam in the klystron is dumped in a lead-insulated collector at the top.
- The body of the klystron is enclosed by a sheet of lead.
- Lead-based brackets (X-ray shield kit, VT-69133) are placed near the RF output window. Adding additional shielding here will be considered during installation.

A radiation survey report of a modulator + klystron (completely identical to the future installation) has been provided by the supplier [4]. Operating at 200Hz, 8.5 µs pulse width (more than 20x the max. operation of the future device at the microtron), <=38µSv/h is measured at 1.00 m from the klystron. Scaling to our operation, the expected levels are less than 1.9µSv/h, i.e. small.

With the former PFN modulator it was safe and possible to operate the microtron, while the ASTRID area is open, since its klystron was contained in the microtron compound. During Factory Acceptance Test at the supplier (preceding delivery) and during the early commissioning after installation, radiation levels were monitored closely. They were in both cases found to be very modest during nominal operation, ~1µSv/h, at maximum. As a general precaution, a chain and sign were established early to maintain a distance to the equipment during operation (despite the very low levels observed), in the rare operational case where the ASTRID compound is open for access. The klystron modulator has a dedicated stack light to indicate the operational state of the modulator.

6.2 The controlled area:

The controlled area is the area inside the shielding walls. Unauthorized access to this area is through doors equipped with switches such that opening a door disables the machine operation and dumps the beam immediately. Coloured lights outside the doors show the status of the area. The controlled area is really a set of adjacent or overlapping controlled areas:

1. Microtron: enclosed by 1-2 m concrete walls (floor to ceiling) and contains 2 interlocked doors (1 towards the ASTRID area and 1 emergency exit).
2. ASTRID: enclosed by 0.5-1 m concrete walls and contains 6 interlocked doors (to open area, adjacent labs, etc.).
3. ASTRID2: enclosed by 0.5-1 m concrete walls and contains 2 interlocked doors (to open area).

When there is no beam in the machines, the areas can be open to anyone, since no radiation is generated, and only few, marked components are radioactive.

Search procedures

To close off a controlled area, an operator is forced to perform an extensive search of the entire area (ensuring that no one is left inside) by pressing a dedicated number of distributed search buttons in a set order.

- Storage rings (ASTRID, ASTRID2): All interlocked doors must be closed to initiate a search. Opening a door during a search will necessitate a restart of the search procedure. When a search is initiated, a siren sounds to alert people in the area. When the last button has been pressed and the operator has left the area and closed the exit door, the area is secured, and the machine may be started.
- Microtron: one search button is located at the far end of the small microtron area and this initiates the search procedure and a timer relay. The operator now has 15s to evacuate and close the doors of the area. Failing to do so will leave the area open and make the accelerator inoperable. When the microtron modulator high-voltage is enabled, a siren inside the microtron area alerts people.

Procedure for authorized access to controlled areas

It is possible for a few ISA staff members to make an authorised access to the ASTRID2/ASTRID areas by bypassing a door switch using a fingerprint reader. When entering the areas in this way, injections are stopped immediately. The stored beam in ASTRID2 (and resulting dose rate levels) will, however, generally be maintained. In particular in the case of ASTRID2, this type of access is thus only justified by:

- *Brief, urgent interventions due to unexpected problems that occurred during accelerator operation*
- *Mechanical adjustments or calibrations that necessitates a beam.*
- *The intervention must require local access, i.e. intervention is not possible from outside the walls.*

Facility operation schedules allow for at least a weekly controlled dump of the beam in ASTRID2, during which all other maintenance activities necessitating access are scheduled. Examples of operations that do *not* justify authorized access during beam operation could be non-urgent maintenance, inspections, fetching equipment, etc. This is to be avoided and postponed for a maintenance period.

During an authorized access:

- ASTRID: Stored beam – currently in the machine – is dumped in a safe, controlled manner, thus bringing the radiation levels down to the natural background level.
- ASTRID2: Stored beam is maintained. While there are no additional injections, the stored beam still leads to slow, steady beam losses related to the beam lifetime.
    - The steady losses and resulting dose rates at nominal operation and 180 mA beam are lowest in the centre of the storage ring (<1μSv/h) and high near the actual ring elements and RF cavity (<100μSv/h at contact). Localized, elevated levels should be expected outside the ring – between the ring and its concrete shield wall. Here, the circulating beam gives rise to ~30μSv/h, measured at 0.5 m from beam axis using radiation monitors at two similar locations along the ring, near the point of entry during an access (BMH141 and BMH142).
    - A complete loss of the full 180 mA beam cannot be discerned from the continuous losses on either monitor, and the impact of such an event is thus not considered severe. Although this has been the case for a few different controlled and uncontrolled loss mechanisms, it cannot be excluded that the loss could lead to elevated localized losses. The loss pattern is known to change with accelerator operation in ways that are difficult to predict.

    Authorized access to ASTRID2 is typically very brief (max. a few minutes) and the operator enters the ring centre, where the levels are lowest. Such access is made available to three people, Jørgen S. Nielsen, Heine Thomsen and Søren Vrønning Hoffmann. These persons have an intimate knowledge of radiation levels and the location of radiation fields in the closed area. It is estimated, that each person will spend a maximum of 5 minutes/month in the centre area while the machine is running, which will contribute minimally to the yearly dose. All three wear TLD dosimeters. General guidelines:

    - Working near the ring elements is allowed for very brief periods but requires bringing a radiation monitor to provide an online reading of the dose levels.
    - Working on the outside of the ring is prohibited when the stored beam is more than 10 mA.
    - Other technicians cannot enter alone and must not be left unsupervised.
- Microtron: There is no measure to conduct an authorized access to the microtron area; opening either of the doors will halt beam and radiation production immediately. This interlock is routinely verified.

6.3 Dose monitoring and documentation:

To ensure that doses in the open area are within the 0.3mSv/year limit, measurements are made at selected points around the ring and in neighbouring labs using portable dose rate meters.

At ISA, four gamma and one neutron dose rate meter are used:

1. Inovision 451P, a portable gamma ray dose rate meter which uses a high pressure (8 bar) ionization chamber to measure dose rates and integrated doses.
   The energy range is from ~20keV to ~10MeV.
2. Ludlum 9DP-1. Similar to our Inovision 451P, but uses a low pressure (1 bar) ionization chamber, more suitable than the Inovision instrument for pulsed radiation fields. We have three of these.
3. Alnor neutron dose rate meter 2202D (Studsvik type). This instrument can measure neutron doses from thermal energies (<1eV) up to ~20MeV.

The gamma monitors have a minimum readout of 0.01µSv/h, and will, when compared to background measurements at the same locations, be able to ensure that levels are below 0.15µSv/h (0.3mSv/2000h). The instruments used were last calibrated by the manufacturer in September 2014.
The instruments are placed in a position and set to integrate. They can be connected to our control system to provide continuous readout and make it possible to set up alarms in case of unexpected large doses. These data are saved in our database and will be available at any time. The monitors are not yet mounted in permanent positions, but are set up at various locations to give an overview of the dose in the hall.

The results of the most recent measurements are summarized in the table below. The background level is 0.8mSv/year. Numbers are given in mSv:

Location	Scaled to full year	Corrected for background	Scaled to 2000h
1526-182 at wall to ASTRID	0.8	<0.1	<0.1
1526-182 at door to ASTRID	0.8	<0.1	<0.1
1526-179 at wall to ASTRID	0.7	<0.1	<0.1
SGM3 beamline table centre	0.8	<0.1	<0.1
CD1 beamline work table	1.1	0.3	<0.1
MatLine beamline work table	0.8	<0.1	<0.1
UV beamline work table	0.85	<0.1	<0.1

Table 6.1: Summary of measurement results (2014).

As seen in table 6.1, the measurements confirm the effectiveness of the radiation shielding. During the entire measurement period, the machines were running top-up at 120mA. As this current will be increased later, measurements will be repeated, especially at locations where doses greater than 0.1mSv/2000h were measured. Additional shielding has been mounted at critical locations to lower the doses reported in the October 2014 report. The radiation shielding is unchanged since then. After changes in the machine setup or shielding walls, dose rates in the area are always checked.

Records of radiation measurements, changes in shielding etc. relevant to radiation safety are stored in our electronic logbook. All documents are stored in a document archive on our file server and are linked to from the ISA website, which can be seen by anyone.

All ISA staff members and most of the users of synchrotron radiation and people working in neighbouring labs (room 178, 179 and 182) wear TLD dosimeters. These may serve as an additional check of radiation levels, since especially some ISA staff members spend a considerable amount of time in the open areas of the complex. The person receiving the results from readout of TLD dosimeters at the Institute of Physics and Astronomy has not seen any readings higher than 0.1mSv during the past 12 months.

In case of radiation events in which doses surpass the accepted limits, the authorities will be notified, operation will be suspended or personnel from the affected area evacuated until the cause of the event has been found and eliminated.
The level at which notification will take place is if readouts from TLDs exposed for 6 months

indicate that people without dosimeters in the area can have received ≥0.2mSv, or 0.5mSv if only people wearing dosimeters use the area. The detection limit of the TLD dosimeters is 0.1mSv.

7: Radioactive materials

There are no radioactive sources in use in our accelerator complex, but electron irradiation may produce low levels of short-lived isotopes in the accelerator components. This production is a result of both gamma and neutron irradiation.

The highest saturation activity is reached in Aluminium and Copper, in the form of the isotopes ^{26}Al, ^{62}Cu and ^{64}Cu, having a half-life $T_{½}$ of 6.4 s, 9.8 min and 12.8 h respectively. We have Al chambers at several places in the ring, and our RF cavity is made of Cu. This does not present a problem, since levels are low and decay quickly.
Only at the electron microtron and at the ASTRID ring septum magnet have we been able to detect low levels of radiation (<5µSv/h) immediately after using the machine. This comes from the copper RF-structure which is mounted inside a vacuum chamber on the microtron, and the copper coil on the septum magnet.

These locations are marked with *'Radioactive material'* labels and technicians are instructed not to dismount ring components without the knowledge of the responsible operator.

8: Decommissioning:

As mentioned in section 7, no long-lived isotopes are produced by the accelerators. However, parts which can be activated (especially Copper structures close to the beam) will not be scrapped, but stored locally and marked as contaminated material, in accordance with current legislation, or passed on to Dansk Dekommissionering.

Dose rates from these parts will be lower than the detection limit of our instruments shortly (< 1 day) after their last use in the running facility.

9: References

[1] A guide to radiation protection and radioactivity levels near high energy particle accelerators
A. H. Sullivan, *Nuclear Technology Publishing*, 1992

[2] 90 degrees bremsstrahlung source terms produced in thick targets by 50MeV to 10GeV electrons
X. S. Mao et al., *SLAC-PUB-7722*, 2000

[3] NSLS-II Preliminary design report
Brookhaven National Laboratory, 2007

[4] Radiation measurement K100 (DOC-016239-00), *ScandiNova Systems, Internal report*, December, 2020. Available on request.

Appendix A: Warning signs and emergency numbers

On all entrances to the controlled areas, we have put up yellow/black DS signs with the text 'Ioniserende stråling' and the symbol for radiation, as shown below.

On the entrances to the halls is a list of telephone numbers to call in case of an emergency, and names of the personnel responsible for safety in connection with activities relevant for the ASTRID2 facility (e.g. fire, cooling water, mechanical problems, radiation etc.).

In addition, the sign below is put up on all entrances to the controlled areas.

Appendix B: Log of changes to ASTRID2:

Modifications to this document, July 2024:

- Inserted Birgit Schiøtt as dean

Modifications to this document, July 2023:

- Inserted Søren Vrønning Hoffmann as ISA Director
- Updated information about the solid state klystron modulator

Modifications to this document, March 2022:

- Detailed information about measured dose levels to safety assessment (Sec. 5) and procedure for authorized access (Sec. 6.2).

Modifications to this document, December 2021:

- Added a section in Sec. 6.1 about the future project of installing a new klystron modulator for the microtron.
- Rewritten Sec. 6.2 to reflect the authorized access to the 3 distinct compounds of the facility (ASTRID2, ASTRID, microtron).

Modifications to this document, February 2020:

The new SGM4 beamline on ASTRID2 has been included in this document. The figures on page 3 and 14 have been updated, and a short description of radiation aspects of the beamline has been included in section 6.1 on page 16.

The sign with the text *Strålingsgenerator, Overvåget område, Risiko for ekstern bestråling* has been updated to a new version supplied by SIS. The new sign is shown in Appendix A, page 20.

A few numbers have been updated in order to match current operational parameters:

> In earlier versions it was assumed that we would be maintaining 200mA in ASTRID2. The actual number is 180mA, and there are currently no plans to increase this number (Page 10, just below figure 3.3)
>
> The estimate of the number of beam losses has been replaced with the actual losses in 2019 (page 11, paragraph 4).

Sentences have been reworded for clarity in many places.

This document will be revised no later than 12/7 2025.