ARI – A STORAGE RING FOR NON-INVASIVE CORONARY ANGIOGRAPHY

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Abstract

One of the standard investigations for coronary heart diseases is the invasive coronary angiography, where a catheter is introduced via the arterial system into the origin of the coronary artery of interest. By using high intensity X-ray beams just above and below the K-edge of iodine, the contrast agent, and digital subtraction of the two pictures one can often avoid the use of a catheter and the risks of the conventional method. A 1.6 GeV electron storage ring is described, which is designed as a source for two coronary angiography beamlines. The necessary photon intensity at the K-edge of iodine (33 keV) is provided by two 6 Tesla wigglers and 380 mA beam current intensity.

1 INTRODUCTION

The development of the K-Edge Digital Subtraction coronary Angiography (KEDSA) method started in the eighties at several accelerator laboratories e.g. at BNL in Brookhaven, DESY in Hamburg, KEK in Japan and SLAC in Stanford [1][2]. At HASYLAB, DESY the KEDSA has been developed further during the past years using the X-ray wiggler beamline HARWI at the 4.5 GeV storage ring DORIS.

A field study involving more than 300 patients showed the reliability of the method and the good quality of the images.

The next step should be to build a dedicated angiography facility at a medical centre without the restrictions of a multi user research facility. [3], [4]. To investigate the feasibility of such an installation a detailed study has been performed following the field study in Hamburg[5].

2 REQUIREMENTS FOR THE SOURCE

2.1 Intensity

To obtain clear pictures the flux density fd of the two 33 keV photon beams, necessary for KEDSA, right before the patient must be rather high [1] namely fd = $2.7\cdot 10^{11}$ ϒ/mm^2/sec within 250 eV.

As there are unavoidable losses of photons in the beamline the flux density fdw that the wiggler has to yield must be even larger, namely fdw = L1·L2·L3·L4·fd. Where L1 = 1.401 describes losses due to absorbers necessary to absorb photons of smaller energy than 33 keV, that must not contribute to the heat load of the monochromator. L2 = 1.292 has regard to losses in the monochromator itself. L3 = 2 is given by the principal losses of a monochromator in Laue-geometry and L4=1.77 takes into account the losses at the entrance slit of the monochromator hm = 1.7 mm. So the product of all the loss factors for ARI is 6.4 and the required total flux of one photon beam in front of the patient to be generated by the wiggler must be:

$$\mathrm{flw} = 1.557\cdot 10^{14}\ \mathrm{ph/sec}$$

within the used horizontal opening angle Θ and the local energy band width of the monochromator ($\Delta\omega$ = 41 eV). The photon flux per mA Fw, that a wiggler in combination with a storage ring can provide at the patient, is given [eg. 7] by

$$\mathbf{Fw} = 2.457\cdot 10^{10}\cdot \mathbf{E}[\mathbf{GeV}]\cdot \Phi(\frac{\omega}{\omega\mathbf{c}})\cdot\frac{\Delta\omega}{\omega\mathbf{c}}\cdot \mathbf{np}\cdot\Theta$$

with E the Energy of the storage ring, ω=33.17 keV energy of the photons, ω_c=0.665·E[GeV]^2·B[T] critical photons energy in keV. $\Phi(\omega/\omega_\mathbf{c})$ is the spectral function of the photons, and np the number of radiating poles of the wiggler .

2.2 Resolution

The resolution of the images has its limitation in the pixel size of 0.4·0.4 mm^2. This must not get worse significantly due to the beam properties. The source size transforms to the plane of the detector with the relation Lpd/Lwp with Lwp=12 m (distance wiggler-patient) and Lpd=2.06 m (distance patient-detector). The distance Lpd is given by the experimental setup - Lwp could be increased by the expense of loosing intensity. For the centre of the image the source size is given by the beam size and the amplitude of the beam oscillations in the wiggler. With moderate values for the emittance and low beta functions the beam size can be reduced below 0.3 mm. The amplitude a of the movement depends on the magnetic field and the period length of the wiggler λ:

$$\mathbf{a} = \frac{\lambda^2\cdot\mathbf{c}\cdot\mathbf{B}}{4\cdot\pi\cdot\mathbf{p}_0}$$

For regions at a distance b from the centre of the image, which look at an angle α=b/Lwd to the wiggler, there is another contribution to the source size namely the projection of the wiggler to a plane perpendicular to the beam: $Lw\cdot\alpha$.

This limits the total length of the wiggler and hence the number of poles. To reach the goal to improve the resolution of NIKOS at DORIS the wiggler had to be shorter than 0.4 m .

2.3 Homogeneity

Since a wiggler has a sinusoidal field variation, the intensity of the radiation drops towards the borders of the radiation fan. In order to get clear pictures only a fraction of the fan can be used where the intensity varies between 100% and 90%.

2.4 Reduction of the 3rd harmonic

The Bragg condition for the reflectivity of crystal planes allows not only the reflection of light with one frequency, but also of the higher harmonics. In this case the second harmonic (66 keV) is suppressed but the 99.5 keV radiation would disturb the imaging if its fraction is more than 2% or 3%. This can be reached by choosing a low critical energy of the radiation.

2.5 Beam Lifetime

The adjustment of all optical elements in the beamline is rather critical and depends strongly on the heat load from synchrotron radiation. For that, only a slow variation of the stored beam current is allowed. If one does not rely on a topping up procedure one has to ensure a sufficient lifetime of at least 5 hours.

3 LAYOUT OF THE FACILITY

The main goals for the design are:

- to get a source of at least the intensity and resolution as at DORIS
- to improve the homogeneity and reduce the 3rd harmonic content
- high reliability
- easy operation
- low cost for installation and operation

3.1 The Beamline

Taking into account the above mentioned restrictions and goals the set of machine parameters showed in table 1 has been found. In order to keep the beam energy low it is necessary to use a superconducting wiggler. A magnet with 6 Tesla peak field and a period length of 120 mm has been designed. With seven main poles it has an active length of 360 mm. The amplitude of the beam orbit is 0.41 mm which results in a sufficiently small source size. The magnet gap of 25 mm leaves room for a cold vacuum chamber with 18 mm clear height. It has been shown[5], that the wiggler chamber can be protected from the radiation of the preceding dipole by vertical absorbers at ±5 mm and a horizontal absorber at 15 mm - both placed 150 mm in front of the cold chamber. Also the radiation from the wiggler itself can leave the chamber without touching the walls if the orbit is controlled to ±2 mm horizontal and ±1 mm vertical.

Table 1 : machine design parameter and parameter of the DORIS beamline for comparison

	ARI	DORIS	
beam energy	1.6	4.45	GeV
hor. emittance	60	400	nm rad
hor. betafunction	1.34	5.9	m
hor. beam size	0.28	1.6	mm
vert. betafunction	1.86	21.9	m
vert. beam size	0.1	0.94	mm
wiggler:			
max. magnetic field	6.0	1.2	Tesla
period length	120	240	mm
no. of main poles	7	20	
wiggle amplitude	0.41	0.12	mm
opening angle	43	6	mrad
radiation:			
critical energy	10.2	16.2	keV
I(99keV) / I(33 keV)	0.24	2.5	%
horizontal homogeneity	91	60	%
resolution (x=0mm)	0.27	0.30	mm
resolution (x=75mm)	0.35	0.34	mm
measuring Time per picture			
needed beam current	380	66	mA

3.2 The Storage Ring

To reach the required intensity a beam current of 380 mA at 1.6 GeV is necessary. The optic has been chosen to reach a moderate low emittance. This helps to reach a good dynamic aperture and a sufficient Touchek lifetime. Small beta-functions in the wiggler reduce the beam size, which is small compared to the other contributions to the source size. The small betafunctions help to reduce the nolinear effects of the wigglers. The dispersion is suppressed in the RF, wiggler and injection straights. In order to reduce the circumference of the ring combined function magnets are used. In order to avoid the problems of ramping the storage ring with the superconducting wigglers a full energy injection with a 50 MeV Linac and a 3 Hz synchrotron is proposed.

The storage ring is designed to store currents up to 500 mA. The total cavity voltage is 1.554 MV. To avoid the excitation of higher order modes in the cavities it is planned to use 3 temperature-controlled cavities of the ELETTRA type [8].

It is proposed to fill 81 buckets out of 116, thus leaving a gap to avoid the trapping of ions. The Touchek lifetime will then be around 60 hours.

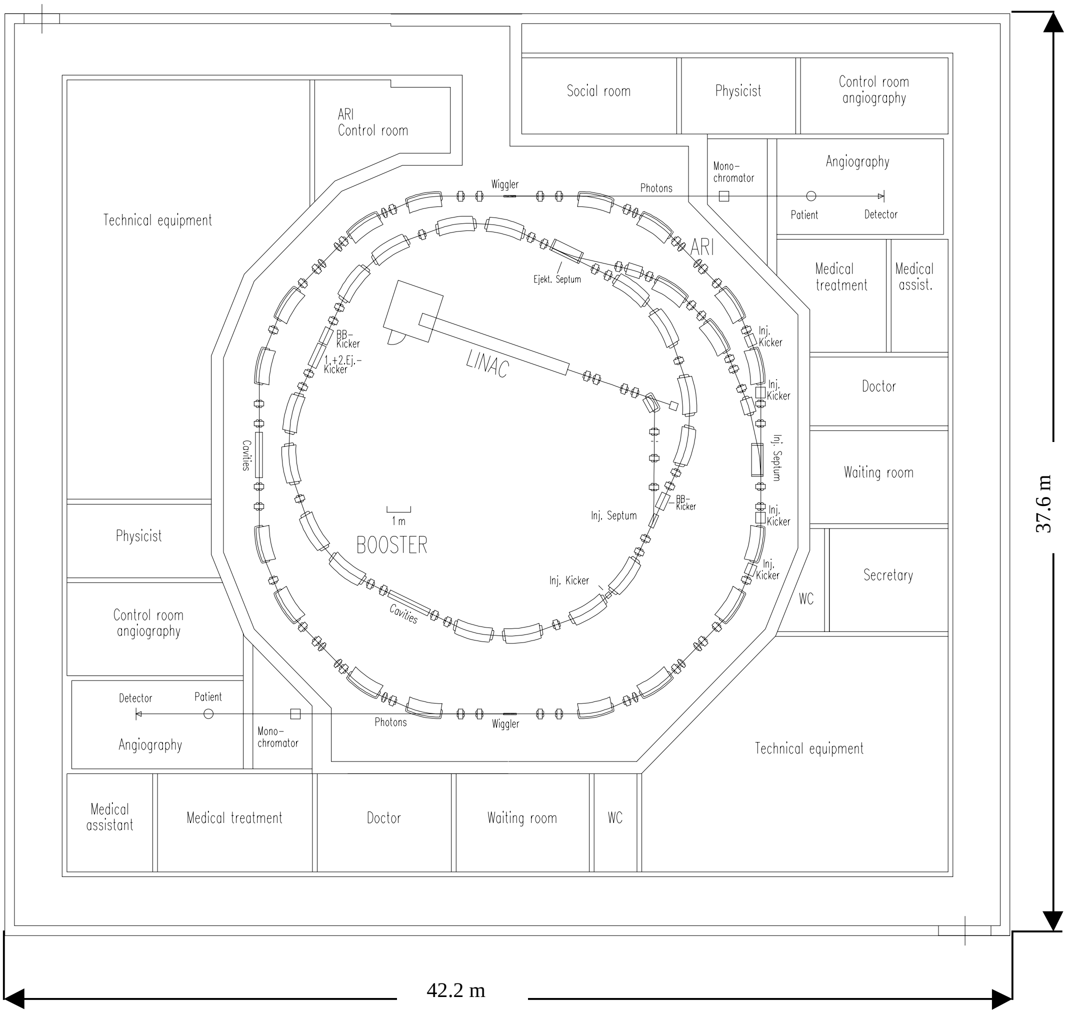

Figure 1 : Layout of the angiography facility

In order to reach a sufficient vacuum lifetime the vacuum system has to be carefully designed. Either chambers which let the synchrotron light pass to a crotch absorber where it is absorbed locally, or a system with integrated NEG or sputter-ion-pumps. With both systems a mean pressure of $2.5\cdot10^{-7}$ Pa is possible.

4 DISCUSSION

The facility outlined here is one example of a dedicated light source for angiography. Obvious variations of this design are to use an existing injector if it is placed at an accelerator centre or to expand the ring and install more beamlines for angiography or other synchrotron light applications.

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