A new gas attenuator system for the ID17 biomedical beamline at the ESRF

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Abstract. On the biomedical beamline ID17 at the ESRF a gas attenuator system has been installed to complement and protect the standard solid state attenuators (graphite, Al and Cu) against fatigue and damage due to the very high heat load from the beamline's wiggler source. This series of attenuators defines the flux (dose rate) and the X-ray beam spectrum for the Microbeam Radiation Therapy (MRT) research at ID17 which is currently under development towards clinical application. For this, the attenuators at MRT will be crucial elements to guarantee beam- and dose rate characteristics and the new gas attenuator will become a radiation therapy safety device. The installed gas attenuator and its test results will be presented.

1. Introduction

Microbeam Radiation Therapy (MRT) is a novel radiation therapy technique which profits from the high tolerance to radiation of healthy tissue when irradiated by arrays of microbeams(1). MRT clinical trials on large animals, as a milestone before moving to potential human applications, are currently under preparation at the ID17 biomedical beamline(2). MRT utilizes the filtered synchrotron beam generated by a wiggler. At ID17, the total integrated power in the white beam reaches 19.3 kW for 200 mA stored current; the peak power density exceeds 60 W/mm^2 in the (30 x 2) mm^2 beam reaching the optics hutch. For MRT the optimal spectrum is around 100 and 150 keV, low and medium energy photons (< 40 keV) have a too limited penetration depth in tissue and have to be filtered out of the spectrum by a series of attenuators. Dealing with such high powers and power densities is extremely difficult with conventional solid state attenuators (metal, graphite). Even with appropriate cooling the maximum lifetime of the attenuator blades is drastically limited by the stress cycles (including cracks and holes) each time the front end is opened and closed.

Therefore, at ID17 a gas attenuator(3,4) system has been built as a 2.2 m long vessel inserted in the beam path upstream the solid state attenuators. Using a gas attenuator to protect the first solid state attenuator (graphite) has many advantages: with a gas filling well below ambient pressure its safe operation is guaranteed since in case of a leak to the outside of the vessel air will be added to the gas increasing the pressure, thus the beam absorption, in the vessel; it cannot develop cracks as a metal attenuator blade could do inducing local overexposure. This item is particularly important for therapy applications where protection against overexposure is crucial.

2. Gas attenuator, characterization and results

At ID17 the gas attenuator vessel is installed just upstream the primary slits and the solid state attenuators, delimited by Be-windows to separate it from the surrounding UHV sections of the beamline. Between the wiggler source (21 pole, 150 mm period, B_{max} = 1.59 T at closest gap of 24.8 mm) and the gas attenuator vessel a diaphragm is installed to reduce the beam to a solid angle of 1 mrad(hor) x 0.06 mrad(vert) taking already the major part of the source's heat load from the beam (~16 kW at closest wiggler gap and 200mA stored current). Prior to the installation of the gas attenuator, tests have been carried out using Ar- and Xe-gas fillings to verify the feasibility of the concept: within the limitations of attenuator length and pressures well below ambient pressure, 30 – 300 mbar, Ar (with K-edge = 3.2 keV) did not remove enough heat load to efficiently protect the solid state attenuators, whereas Xe (with K-edge = 34.58 keV) absorbed too much the X-rays in the useful part of the X-ray spectrum (> 40 keV). Kr with its K-edge of 14.32 keV turned out to be the best choice for the application.

The gas attenuator was characterized by using one of the ID17 monochromators to analyze the transmitted X-ray spectrum with and without filled gas attenuator under different gas-fillings and heat loads (wiggler gaps): P_{fill} = 100 mbar or 160 mbar, wiggler gaps of 60 mm down to 24.8 mm. Figure 1 shows the ratios of the transmitted intensities at X-rays energies between 25 keV and 80 keV for gas-fillings of P_{fill} = 160 mbar Kr and wiggler gaps of 24.8 mm (left plot) and more relaxed wiggler gaps up to 60 mm (right plot). The data is compared to calculations by XOP 2.3[5] of the X-ray absorption of the 2197 mm long gas attenuator vessel filled with various Kr pressures.

The tests reveal a considerably reduced attenuator gas density along the beam path: the gas attenuator behaves as if filled to a significantly lower "effective" gas pressure, P_{eff}, than the initial gas filling, P_{fill}. At maximum closed wiggler gap one finds a P_{eff} of 85 mbar with a filling to P_{fill} = 160 mbar. At more relaxed wiggler gaps, i.e. lower X-ray flux and heat loads, the discrepancy is somewhat reduced but still considerable (gap = 60 mm: P_{eff} = 100 mbar with P_{fill} = 160 mbar).

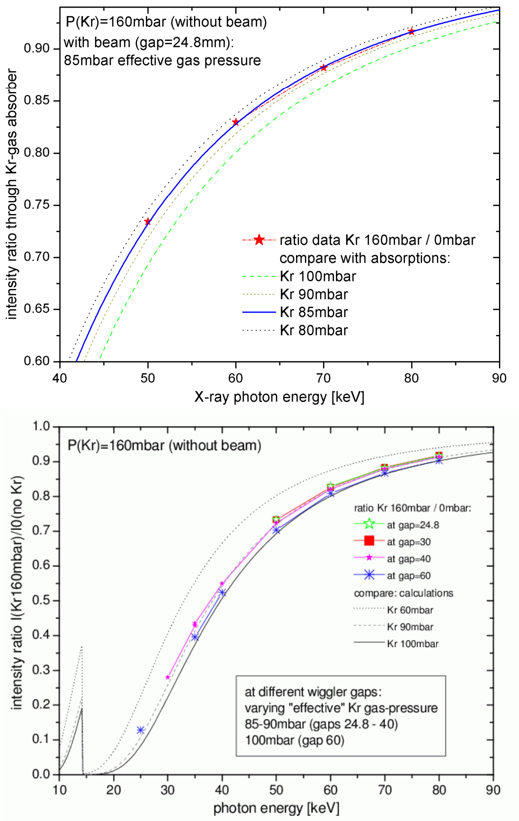

Figure 1. Ratio of the transmitted intensities with and without Kr gas attenuator (P_{fill} = 160 mbar) at different wiggler gaps compared to calculated X-ray absorptions for Kr at different pressures (densities). Left: wiggler gap 24.8, right: wiggler gaps 24.8, 30, 40, and 60. Calculations done using XOP 2.3 [5].

A potential interpretation of this behavior is that although the gas in the attenuator vessel heats up over the complete section of the vessel the gas is heated strongest along the X-ray beam path, thus decreasing locally the gas density. This may account for part of the apparent gas density reduction observed. A second reason may be that along the beam path the gas is partially ionized. The ions will repel each other, thus "dilute" the gas along the X-ray beam path. The speed due to this repulsion should exceed the "return speed" due to thermal motion, which will lead to an overall decrease of the gas density along the X-ray beam path. It seems difficult to quantify these effects with a detailed calculation.

Based on these test results we have calculated and compared the power absorbed in each of the different solid state attenuators and the Be-windows with and without filled gas attenuator. Table 1 shows the calculated powers (heat loads) for a Kr gas filling up to P_{fill} = 160 mbar using P_{eff} = 85 mbar (see Fig 2) for the calculation. Without gas attenuator the solid state attenuators have to cope with several hundreds of Watts up to about 1 kW (Al, Cu), whereas with filled gas attenuator the heat loads for the graphite and the Al-attenuator are reduced by a factor 4 – 6. The Cu-attenuator which mainly determines the final X-ray spectrum for MRT at ID17 still has to cope with more than 600 W but this power is about 40% inferior to the case without gas attenuator. This strong decrease of the heat load on the solid state attenuators reduces significantly the risk of failure due to fatigue with repeated heat load cycles, including potential cracking or breaking. Figure 2 shows the calculated X-ray spectra of the wiggler source (gap 24.8 mm), after the graphite attenuator only, after the Kr-attenuator only and after the complete series of MRT attenuators (Cu 1.04 mm) with and without Kr. For the latter spectra, which describe the X-ray beam finally used for MRT at ID17, a slightly hardened spectrum and a decrease in flux is obtained. Experimentally, a decrease in dose rate of about 16% is observed, which is compatible with the experimental requirements. The final dose rate is about 13 kGy/s at 200mA stored current.

Table 1. Power absorbed in the MRT attenuators with and without gas attenuator. The wiggler delivers 19.3 kW at maximum closed gap (24.8mm), 3.1 kW pass the first diaphragm (1 mrad(h) x 0.06 mrad(v). Calculated using XOP 2.3 [(5)].

	Without Kr gas attenuator	With Kr gas attenuator (P_{eff} = 85 mbar)
Be window (0.5 mm)	123W	123 W
Gas attenuator (2197 mm)	-	**1.51 kW**
Be window (0.5 mm)	90 W	18 W
Vitreous graphite (1.15 mm)	372 W	64 W
Al (total = 1.78 mm)	896 W	204 W
Cu (total 1.04 mm)	1032 W	626 W
Transmitted through all attenuators	405 W	374 W

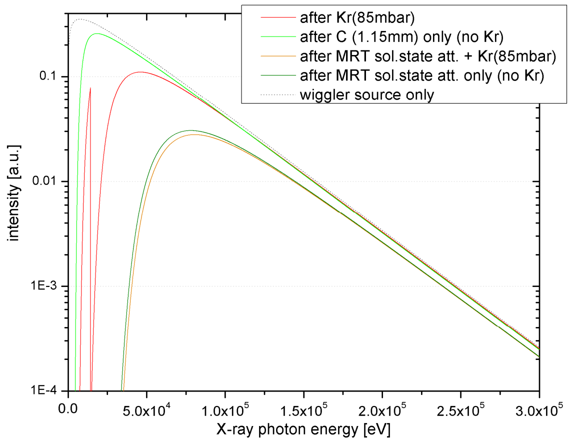

Figure 2. Comparison of the spectra from the wiggler source only (black, dashed), after the graphite attenuator with gas attenuator (green), after the Kr gas attenuator (red) and after all MRT attenuator with and without Kr gas attenuator (ochre and dark green, respectively). Calculations don using XOP 2.3 [(5)].

3. Conclusion

Since its installation in September 2009 and modification and re-commissioning in May 2010 the gas attenuator has been in use in about one third of all beamtimes of MRT at ID17 receiving full flux, i.e. full heat load accumulating to about 1370 hours. A recent inspection, after about 1300 hours of use, of the Be-windows of the Kr gas attenuator by endoscopy revealed a perfectly clean state of the Be-windows with no visible trace of use or ion-etching. This confirms its suitability to protect the downstream solid state attenuators, which shape the beam spectrum and determine the dose rate for MRT. These points are of extreme importance for an application of MRT for clinical use where reliability, even safety on both spectrum and dose rate is critical. In preparation for the planned clinical trials at MRT at ID17 the gas attenuator has been included in the “Patient Safety System”, a hardware-based system defining the conditions (verified dose rate, beam stability, etc.) under which a radiation therapy treatment could be launched.

References

[1] E. Bräuer-Krisch et al., Phys. Med. Biol. 50 (2005) 3103.
[2] M. Renier et al., Eur. J. Radiol. 68 (2008) S147.
[3] P. Suortti and W. Thomlinson, Brookhaven National Laboratory report #34934 (July 1984)
[4] P. Suortti and W. Thomlinson, Nucl. Instr. Methods A 269 (1988) 639.
[5] M. Sanchez del Rio et al., SPIE proceedings 5536 (2004) 171.