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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 solid state attenuators is drastically limited by the fatigue of the materials induced by the repetitive thermal 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 air will be added to the gas increasing the pressure, thus the beam absorption. This item becomes particularly important for the clinical 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). Before taking the decision to install a 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 Kr-filled gas attenuator under different gas-fillings and heat loads (wiggler gaps): P_{fill} = 100 mbar (ρ_{Kr} = 0.369 kg/m^3) or 160 mbar (ρ_{Kr} = 0.591 kg/m^3), wiggler gaps of 60 mm down to 24.8 mm. Figure 1 shows the experimental ratios of the transmitted intensities at X-rays energies between 25 keV and 80 keV for gas-fillings of ρ_{fill} = 0.591 kg/m^3 Kr and wiggler gaps of 24.8 mm (top plot) and more relaxed wiggler gaps up to 60 mm (bottom plot). This data (symbols) is compared to calculations (made using XOP 2.3[(5)]) of the X-ray absorption of the 2197 mm long gas attenuator vessel filled with various Kr pressures (lines).

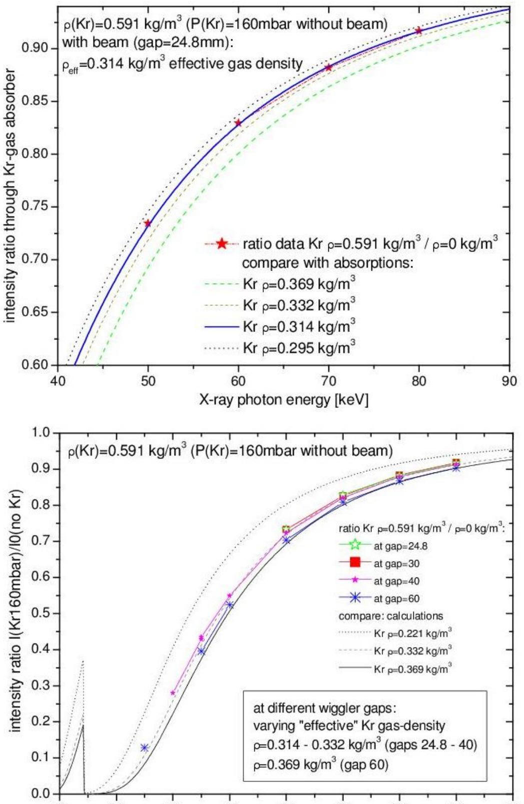

Figure 1. Ratio of the transmitted intensities with and without Kr gas attenuator ρ_{fill} = 0.591 kg/m^3 (P_{fill} = 160 mbar) at different wiggler gaps (symbols). For comparison the calculated X-ray absorptions for Kr at different densities (lines).
Top: wiggler gap 24.8.
Bottom: wiggler gaps 24.8, 30, 40, and 60. Calculations done using XOP 2.3 [(5)].

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 density, ρ_{eff}, than the initial gas filling, ρ_{fill}. At maximum closed wiggler gap one finds a ρ_{eff} of 0.314 kg/m^3 with a filling to ρ_{fill} = 0.591 kg/m^3. 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: ρ_{eff} = 0.369 kg/m^3 with ρ_{fill} = 0.591 kg/m^3).
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. Along the beam path the gas is partially ionized. The ions will repel each other, which will lead to an overall decrease of the gas density along the X-ray beam path. An estimate for the ratio of the repulsion velocity to the thermal ("return") velocity is obtained by considering the respective kinetic energies. The ration is the square root of the potential energy of a pair of ions divided by kT/2. Taking conservative estimates of single ionization, Kr gas density ρ = 0.369 kg/m^3 and a gas temperature of 600 K in the beam volume, the ration is about 6.

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 ρ_{fill} = 0.591 kg/m^3 using ρ_{eff} = 0.314 kg/m^3 (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 reduced by about 40% compared 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, the spectrum is slightly shifted to higher energies and the flux is reduced. Experimentally, a decrease in dose rate of about 16% is observed, which is still compatible with the experimental requirements, e.g. depositing about 300 Gy in the irradiation (as typically used in MRT) in a fraction of a second (in our case: 25 ms). The final dose rate is about 13 kGy/s at 200 mA 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 att. (ρ_{eff}=0.314 kg/m^3)
Be window (0.5 mm)	123 W	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

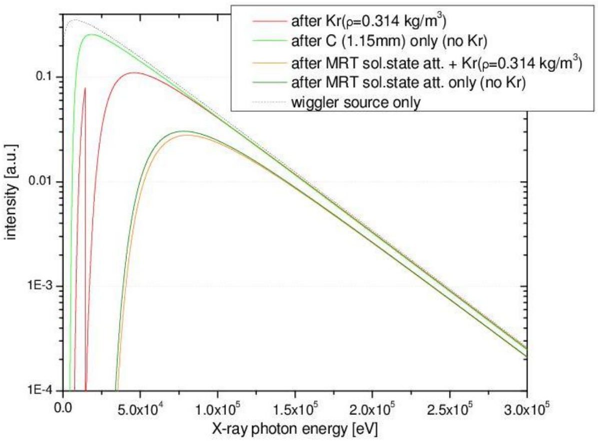

Figure 2. Comparison of the X-ray spectra at MRT/ID17: the wiggler source only (black, dashed), after the graphite attenuator only without gas attenuator (green), after the Kr gas attenuator (red) and after all MRT attenuators (C, Al and Cu) with and without Kr gas attenuator (ochre and dark green, respectively). Calculations done 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 MRT experiments thus receiving the full wiggler flux for about 1370 hours. A recent inspection of the Be-windows enclosing the gas in the gas attenuator, made by endoscopy after about 1300 hours of use, revealed their perfectly clean state with no visible traces or ion-etching effects. This positive result confirms the suitability of the gas attenuator to protect the downstream solid state attenuators, which shape the beam spectrum. 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.

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