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A DISTRIBUTED BEAM LOSS MONITOR BASED UPON ACTIVATION OF OXYGEN IN DEIONISED COOLING WATER*

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Abstract

We propose a novel beam loss detection scheme whereby activation of deionised cooling water is used to observe elevated radiation around the APS storage ring. This is based on radioactivation of oxygen within deionised cooling water by gamma rays above 10 MeV and neutrons above 15 MeV. Losses would be detected using a gamma ray detector monitoring deionised water flow out of the accelerator enclosure. We anticipate that this could be used to provide a segmented, distributed loss monitor system covering the accelerator components closest to locations where radiation is generated.

INTRODUCTION

Particle accelerators are designed to produce beams of collimated ionising radiation. Consequently, when lost, these beams produce showers of particles, including ionising radiation. In order to diagnose accelerator faults, protect people and equipment, ionising radiation monitors ('loss monitors') have been used as diagnostics for accelerators all around the world [1].

Loss monitors can be classified a number of ways. They can be passive and integrate total dose over a long period of time (typically up to months), or have an active detector readout that provides close to real-time measurement of the radiation. They can also be classified as either a point detector (detecting the radiation at a single point), or distributed (detecting radiation over some larger area or distance) [2, 3]. A long ion chamber loss monitor was also designed for the Advanced Photon Source (APS) [4, 5].

The Advanced Photon Source (APS) has Cherenkov loss monitors [6]. Several fibre-based distributed loss monitors have also been tested in the Particle Accumulator Ring and at Storage Ring insertion devices [7]. Both of these systems are fast: able to detect losses within a single turn of the APS storage ring.

We propose a novel detection scheme whereby activation of deionised cooling water is used to observe elevated radiation around the APS storage ring. This is a technique proposed for detection of neutrons at the International Thermonuclear Experimental Reactor (ITER) [8]. In the present work, we summarise the relevant theory, we describe deionised water circuits for the APS storage ring, briefly discuss the time-resolution of the system, and outline a proposed experiment using the APS storage ring.

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THEORY

Cooling water activation is routinely considered as part of the safety assessment of accelerators [9, 10]. Such analyses readily show that activation of deionised water at light source facilities does not present a significant hazard to human health.

Monitoring of cooling water for fission and fusion reactors is not new [11–15]. In particular, it appears that there are a few principal activation reactions of light nuclei in deionised cooling water that may be usable as a distributed loss monitor [16].

In particular, we consider the reactions $^{16}\mathrm{O}(\gamma,\mathrm{n})^{15}\mathrm{O}$ and $^{16}\mathrm{O}(\mathrm{n},\mathrm{p})^{16}\mathrm{N}$. The reaction $^{16}\mathrm{O}(\gamma,\mathrm{n})^{15}\mathrm{O}$ was assessed as the principal radioactivation nuclide present in the APS deionised water system during accelerator operation [17]. The reaction $^{16}\mathrm{O}(\mathrm{n},\mathrm{p})^{16}\mathrm{N}$ appears to be important for reactors, with principally a neutron flux. But this reaction may be relevant at high-energy electron storage rings such as APS [16]. Properties of both reactions are summarised in Table 1 below [8, 18].

We would plan to detect gamma rays as decay products of these reactions. $^{15}\mathrm{O}$ decays via positron emission to $^{15}\mathrm{N}$. The positron annihilates with an electron to produce a pair of 511 keV gamma ray photons [19]. The disintegration of $^{16}\mathrm{N}$ emits gamma ray photons of energy 6.13 MeV (68.8%) and 7.12 MeV (4.7%) [8]. In the absence of energy threshold discrimination, it appears that activity resulting from $^{15}\mathrm{O}$ may dominate a measured count rate [13, 16].

DEIONISED WATER CIRCUITS AT THE ADVANCED PHOTON SOURCE STORAGE RING

Several water circuits are available to measure [20]. Essentially, deionised water for the storage ring is served by a centralised 'primary' system, which distributes water to multiple 'secondary' systems around APS. At APS, there is approximately one secondary system per sector. It appears that there are two circuits of interest: one is the deionised water that goes into the accelerator enclosure to cool accelerator components, and the other circuit is used to cool the magnet power supplies. Additionally, there is also an aluminum deionised water circuit which could be considered. We are principally interested in the 'secondary' circuit, supplying water to the accelerator magnets. The connection between the primary and secondary systems are illustrated schematically in Fig. 1 below.

In order to maintain pressure along the secondary circuit, the diameter of the deionised water piping within the accelerator tunnel gradually reduces from 4" to 1" diameter along the length of a sector. For a given loss event, this could

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Table 1: Properties of Radioactivation Reactions in Water

Reaction	Threshold (MeV)	Half-life (s)	Ref.
$^{16}O(\gamma,n)^{15}O$	15.67	123	[18, Table XXXIIa]
$^{16}O(n,p)^{16}N$	10.4	7.13	[8]

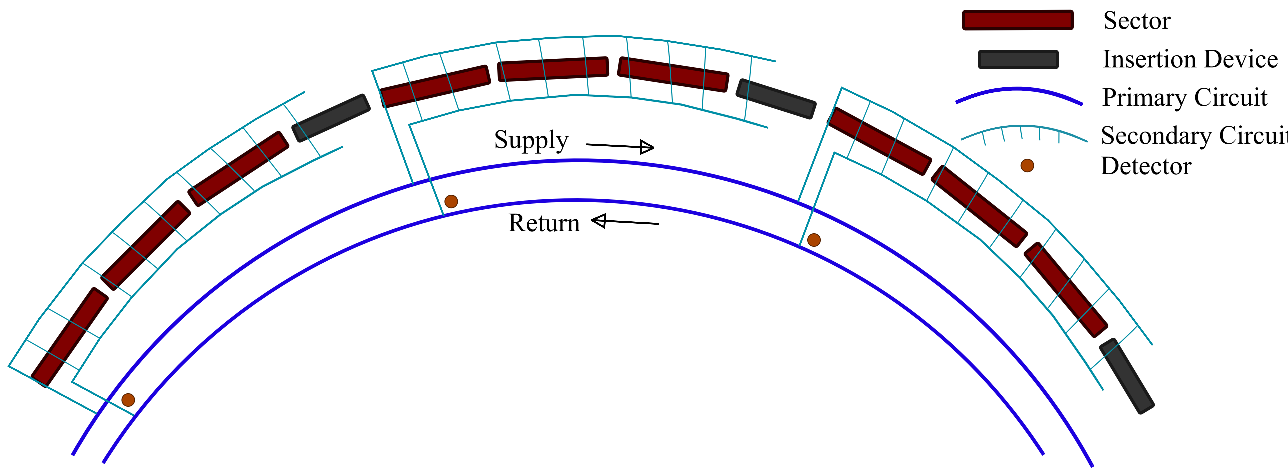

Figure 1: Schematic illustration of primary and secondary water systems. With approximately one secondary system per machine sector, detectors can be placed at each connection to the primary circuit to provide segmented coverage of the entire ring. Short flexible hoses supply and return water from individual accelerator and front-end components.

result in irradiation of a different fraction of the volume of water in the system, based on the longitudinal location of the loss event. However the distribution manifold is relatively far from the centreline of the accelerator – more than 1 m away – at which distance the radiation field at this location is estimated to be four orders of magnitude lower than near the accelerator centreline [17]. Hence the tapering of pipe diameter is in effect negligible. A photo of the system within the tunnel is illustrated in Fig. 2 below [21].

The fire sprinkler water circuit (red piping in Fig. 2) was additionally considered. However the water in such circuits is not routinely moving, and so does not flow past a detector located at a single point. Even in the event of activation of the sprinklers, the water is only flowing *into* the accelerator enclosure, and so is not useful for this diagnostic purpose.

TIME-RESOLVED MEASUREMENTS

In principle, with enough information about the water flow velocity and the path of the water, one can make time-resolved measurements using this apparatus. This was particularly important for the implementation of the detector in fusion experiments, such as ITER [8].

We assume that using the water circuits for the storage ring rather than a dedicated plumbed line results in a complicated water circuit for which it is difficult to reconstruct the loss point and time from a single monitor. Perhaps machine learning algorithms can shed light on this problem.

Our principal goal is to obtain coverage of the accelerator with radiation monitors. If fast (< 1 s) time-resolved measurements are needed, other approaches such as a fibre-based beam loss monitor may be better suited [7].

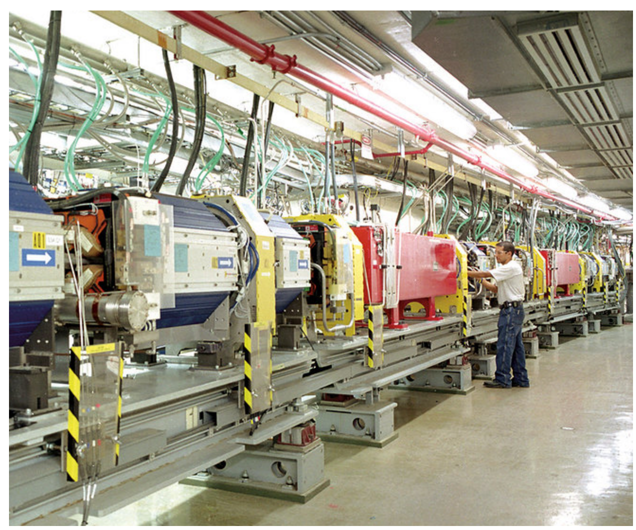

Figure 2: Photo of the APS storage ring within the accelerator enclosure [21]. Prominent in this image are the flexible tubing (aqua) serving individual accelerator components, connected to the water manifold at the ceiling. The fire sprinkler piping (painted red) is also visible along the ceiling. [Adapted under CC BY-NC-SA 2.0 license from Ref. [21].]

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PROPOSED EXPERIMENT

We consider a proposed experiment using the APS storage ring. We propose positioning a gamma ray detector outside the accelerator enclosure at the locations indicated in Fig. 1.

We assume that a staged approach would be taken to experiments. Initially, one might use a handheld survey meter to determine a proposed detector location along the water line, in particular as it relates to shielding of the accelerator enclosure.

A comparison of a few different sectors around the ring could be instructive. For instance, we could compare the storage ring injection straight to a sector on the other side of the ring.

A few types of loss studies may be instructive as initial examples. We may want to compare the performance of such a detection scenario to existing point detector loss monitors (Cherenkov loss monitors, area radiation monitors), as well as handheld survey instruments. In particular, we consider using various horizontal corrector magnets to steer the beam to create losses along a single storage ring sector ('painting' the losses longitudinally along a sector).

Additionally, we expect that the activation of cooling water provides a benefit in having a detection scheme that effectively 'flattens the curve' of a full electron beam loss. Essentially, we expect that mixing of water within the pipe will spread out the volume of activated water as it arrives at a detector. This may provide a complementary and different way to measure the full energy deposited at different locations around the ring.

SUMMARY

We propose a novel detection scheme whereby activation of deionised cooling water is used to observe elevated radiation around the APS storage ring. This is based on radioactivation of deionised cooling water by gamma rays and neutrons above about 10 MeV, and detected using a gamma ray detector monitoring water flow out of the enclosure. We outlined the deionised water distribution for the APS storage ring, and propose a staged experimental plan to test the feasibility of the concept. We anticipate that this could be used to provide a segmented, distributed loss monitor system covering the accelerator components closest to locations where radiation is generated.

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REFERENCES

[1] K. Wittenburg, "Beam Loss Monitors", in *Proc. CAS - CERN Accelerator School: Beam Instrumentation*, Tuusula, Finland, Jun. 2018, arXiv:2005.06522 [physics.acc-ph]. doi:10.48550/arXiv.2005.06522

[2] W. K. H. Panofsky, "The Use of a Long Co-Axial Ion Chamber Along the Accelerator", SLAC, Menlo Park, CA, USA, Rep. SLAC-TN-63-057, Jul. 1963.

[3] H. DeStaebler, "Note on Panofsky's Long Ion Chamber", SLAC, Menlo Park, CA, USA, Rep. SLAC-TN-63-063, Jul. 1963.

[4] D. R. Patterson, private communication, Nov. 1991.

[5] D. R. Patterson, private communication, Jan. 1993.

[6] A. Pietryla, W. Berg, and R. Merl, "A Cerenkov Radiation Detection System for the Advanced Photon Source Storage Ring", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper TPAH304, pp. 1622–1624. doi:10.1109/PAC.2001.986768

[7] J. C. Dooling, W. Berg, L. Emery, and B. X. Yang, "Development of a Fiber-Optic Beam Loss Position Monitor for the Advanced Photon Source Storage Ring", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH5RFP003, pp. 3438–3440.

[8] T. Nishitani, K. Ebisawa, S. Kasai, C. Walker, "Neutron activation system using water flow for ITER", *Rev. Sci. Instrum.*, vol. 74, pp. 1735-1738, 2003. doi:10.1063/1.1534398

[9] "Advanced Photon Source Safety Assessment Document", Argonne National Laboroatory, Lemont, IL, USA, Rep. APS-3.1.2.1.0 (Rev. 5), Jun. 2017.

[10] P. K. Job, W. R. Casey, "Preliminary Activation Analysis of Soil, Air Water Near the NSLS II Accelerator Enclosures", Brookhaven National Laboratory, Upton, NY, USA, Rep. BNL-210948-2019-TECH, Aug. 2006. doi:10.2172/1493193

[11] A. Žohar, L. Snoj, "On the dose fields due to activated cooling water in nuclear facilities", *Prog. Nucl. Energy*, vol. 117, p. 103042, 2019. doi:10.1016/j.pnucene.2019.103042

[12] W. K. TenBrook, "Research reactor coolant monitoring using automated gamma ray spectrometry", Masters Thesis, Oregon State University, Corvallis, OR, USA, May 1986. http://hdl.handle.net/1957/40112

[13] O. Kum, "Estimation of cooling water activation in high-energy heavy ion medical accelerator", *Rad. Phys. Chem.*, vol. 181, p. 109258, 2021. doi:10.1016/j.radphyschem.2020.109258

[14] Y. Verzilov, K. Ochiai, T. Nishitani, "A New Approach to the D-T Neutron Monitor using Water Flow", *J. Nucl. Sci. Technol.*, vol. 41, pp. 395-398, 2004. doi:10.1080/00223131.2004.10875730

[15] Y. Verzilov, T. Nishitani, K. Ochiai, C. Kutsukake, Y. Abe, "Development of a new fusion power monitor based on activation of flowing water", *Fusion Eng. Des.*, vol. 81, pp. 1477–1483, 2006. doi:10.1016/j.fusengdes.2005.08.061

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA37

[16] F. Masukawa, Y. Nakane, Y. Iwamoto, H. Nakashima, "Estimation of Radioactivity Produced in Cooling Water at High-Intensity Proton Accelerator Facility", *Nucl. Technol.*, vol. 168, pp. 680–684, 2009. doi:10.13182/NT09-A9289

[17] H. J. Moe, "Radiological Considerations for the Operation of the Advanced Photon Source Storage Ring - Revised", Argonne National Laboratory, Lemont, IL, USA, Rep. APS Note LS-295 (Rev. 1), Sep. 1997. doi:10.2172/795063

[18] W. P. Swanson, "Radiological Safety Aspects of the Operation of Electron Linear Accelerators", International Atomic Energy Agency, Vienna, Austria, Technical Reports Series No. 188 (STI/DOC/010/188), Feb. 1979.

[19] F. Ajzenberg-Selove, "Energy levels of light nuclei A = 13-15", *Nucl. Phys. A*, vol. 523, pp. 1–196, 1991. doi:10.1016/0375-9474(91)90446-D

[20] E. Swetin, M. Kirshenbaum, C. Putnam, "Cooling Water Systems for Accelerator Components at the Advanced Photon Source", in *Proc. 2nd International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI02)*, Argonne, IL, USA, Sep. 2002, pp. 445–453.

[21] Argonne National Laboratory, Advanced Photon Source storage ring, Apr. 2007. https://www.flickr.com/photos/advancedphotonsource/5936640399/. Adapted under CC BY-NC-SA 2.0 license: https://creativecommons.org/licenses/by-nc-sa/2.0/.