BNL-224863-2023-TECH

EIC-ADD-TN-073

Tritium Production Estimates in EIC Cooling Water Systems

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March 2025

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DISCLAIMER

Annual tritium production in EIC cooling water has been estimated in one sextant cooling system from expected electron beam and proton beam losses in the tunnel. Beam losses and the secondary particles they produce are the only source within the RHIC Tunnel for producing radioactivity in cooling water, including tritium. The need to estimate tritium production supports decisions on whether cooling water systems are required to meet Suffolk County Article 12 requirements (e.g., double-walled piping, leak detection and containment, etc.). Results are extended to the remaining sextant cooling water systems because of the similarity in tunnel cooling water loads and system volumes.

Production from ESR Losses

The creation of unstable nuclei in water is a function of beam interactions with the water oxygen molecules. Electron losses produce an electromagnetic shower. The Bremsstrahlung yield photoneutrons when they interact with oxygen nuclei. The threshold for this reaction is about 15.6 MeV[1]. Implicit in the release of neutrons is the formation of unstable nuclei which may be radioactive.

M. Chin previously performed a FLUKA simulation[2] to estimate tritium production in the electron storage ring (ESR) Transfer Absorber cooling water system where the electron beam losses are in very close proximity to the Absorber cooling water. The sextant cooling water loads are assumed to have similar geometries meaning the location of cooling water is in the same relative position with respect to the beam. The supply and return headers, which contain most of the system's cooling water volume, will be located radially further away from the ESR. Scattered secondaries from beamline losses and water activation potential will be considerably lower in these areas and have been ignored.

Approximately 95% of ESR beam losses are expected to occur on the Absorber (personal communication from M. Vallette[3]). The result of 0.1 µCi/yr. per continuous 1 Watt loss of beam (Figure 4 of Reference 2) was used as the basis to estimate tritium production in the sextant cooling water system. The Absorber simulation was for 3.06E+11 18-GeV electrons lost per second (500 Watts) for 40 weeks.

The electron beam losses in the sextant cooling water locations that feed the ESR beam line components will be much lower since the non-Absorber electron beam losses will mostly occur at the intersecting region and collimators. The assumption is that each of the six sextant cooling water systems will sustain a total of 1 W of continuous beam loss. Scaling from the Absorber simulation, this equates to 0.1 µCi/year tritium production.

The total sextant supply and return header water volume in the tunnel is approximately 1.74E+04 liters[4]. The tritium production rate from electron losses is therefore estimated to be:

[(0.1 µCi/y) / (1.74E+04L)] x (1E+06 pCi/µCi) = 6 pCi/L per year

The remaining sextant cooling water systems have similar volumes and similar tritium production rates and concentrations from electron beam losses in these sextants are expected.

Production from HSR Losses

Determining absolute beam losses from RHIC measurement systems has proved challenging. Areas of beam loss at the collimators are known with greater accuracy than other locations, but integrated beam losses over a running cycle have not yet been determined.

Proton and heavy ion losses result in hadronic cascades. Above incident energies of 100 MeV, production cross sections are practically independent of energy. Sullivan[5] provides a tritium production rate of 1.8 Bq sec^{-1} for 1E+12 high energy hadrons traversing 1 cm of water per sec.

Each high-energy proton that is lost and interacts with accelerator components will produce a shower of hadrons whose number scale with proton energy. Sullivan[5] provides an estimate of the total number of spallation interactions in a cascade initiated by a proton of energy of E_o:

$$N = 3.5(E_0)^{0.92}$$

For E_0 = 275 GeV, N = 610 spallation interactions. Not all interactions will occur in cooling water circuits since some fraction of the particles will be emitted in other than the forward direction. We will assume that 10% of the interactions occur in cooling water.

A. Drees has estimated average HSR losses as 0.1% over 4 hours (personal communication[6]). The Master Parameters Tables for EIC[7] indicate a proton bunch intensity of 6.9E+10 and 1.16E+03 bunches for a total of 8E+13 stored particles for electron-proton operation in high divergence operation mode. A loss rate of 0.1% over 4 hours equates to a loss rate of 5.6E+06 protons sec^{-1}. Multiplying by 610 spallation interactions per proton results in 3.4E+09 interactions sec^{-1} inside the tunnel or 5.7E+08 interactions sec^{-1} per sextant. This equates to 5.7E+07 interactions sec^{-1} in cooling water after applying the 10% water interaction rate.

We will assume each cooling water sextant contains one meter of cooling water channels that are available for hadron spallation interactions. We will further assume that the accelerator operates at 80% efficiency for 8 months annually (2.1E+07 sec).

The annual tritium production rate (Bq/yr.) per sextant is then:

(1.8Bq/sec-cm) (5.7E+07/1E+12) (100 cm) (2.1E+07 sec) = 2.15E+05 Bq/yr (5.8 μCi)

This equates to a quadrant cooling water concentration of 330 pCi/L per year. Again, this considers only the volume of cooling water in the tunnel and not the full system volume.

As a quality check on the results, one can compare these estimates to the measured values obtained in RHIC cooling water systems. All systems are sampled annually, and results are posted on C-AD’s intranet. Most system results have been below environmental laboratory detection limits of 300 pCi L^{-1}. Three systems have consistently shown small but detectable concentrations between 300 and 1000 pCi L^{-1}: RHIC Injection (ATR), RHIC Cavity Cooling, and RHIC Spin/E-Lens, indicating low annual production rates.

Summary

After one year or normal beam operations the expected sextant cooling water tritium concentrations are expected to be very low and close to the analytical laboratory detection limit of 300 pCi L^{-1}. Low concentrations are a consequence of low beam losses experienced by well-designed particle colliders. Annual sampling will be performed to validate this finding. Additionally, cooling water systems are periodically flushed and refilled as part of the maintenance program so no significant buildup of a tritium inventory is expected.

References

1. Neutron Activation Cross-Section Measurements from Threshold to 20 MeV for the Validation of Nuclear Models and Their Parameters, Nuclear Energy Agency (NEA/WPEC-19)
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5. Sullivan, A.H. *A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators*, 1992, (page 137)
6. Personal Communication from A. Drees. 6/13/2023
7. Master Parameter Tables for the EIC. September 2022