Radiation Monitoring and Measurements

Presented on behalf of
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by

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Outline

• Introduction
• Monitoring
  – prompt radiation fields
  – induced radiation fields
  – removable radioactive material
Outline

• Monitoring Techniques
  – Active radiation monitoring systems
  – Passive radiation monitoring systems
  – Surveys using hand-held instruments
  – Instrumentation
  – Special measurements
  – Waste characterization for disposal or D&D
Introduction

• Radiation environment at accelerator is discussed in other courses at this school.

• Radiation monitoring
  – Provides current snapshots of radiation environment.
  – Gives accurate picture of rad. Environ. to rad. protection staff, management and workers.
  – Helps in
    • planning activities and doses to workers and public within constraints of regulations and facility policies.
Introduction

• Radiation monitoring
  – Provides the data used for planning activities during accelerator operations and maintenance.
  – Successive snapshots should be scheduled to provide sufficient time resolution to detect significant changes.
  – Good records allow correlation between the beam parameters and the radiation fields.
    • correlation allows dependable estimates of radiation fields during beam operations outside the normal parameters.
Radiation fields

• Types of radiation found at Accelerators
  – Mainly photons
    • $\gamma$, X-rays
      – (Outside shields, activated material & sources)
  – Neutrons
    • (Outside shielding mixed n-$\gamma$ fields)
  – Charged particles
    • Muons (downstream of the beam lines and absorbers)
    • Electrons (activated material, air, water or sources)
    • Alpha particles (sources and radon)
Prompt Radiation Fields
Radiation protection

• Radiation monitoring is an essential component of any radiation protection program

• Measurements of ambient dose provides basic info. required
  – to minimize dose to workers and public.
  – Optimize radiological planning, ALARA
  – Estimating occupancy times for radiological areas.
**Prompt Radiation Fields**

*Regulatory Compliance*

- Monitoring data can be used to show regulatory compliance.
- Monitoring data can be used as technical basis for programmatic decisions.
- Projections based on monitoring data can be submitted to regulators as part of safety analysis prior to operations.
Prompt Radiation Fields
Shielding Verification

Radiation field monitoring:

• Combination of checking the accuracy of calculations: Model, assumptions and input data.

• A way to check as-built versus design

• Requirement as part of commissioning that new accelerators to verify shielding estimates.
Prompt Radiation Fields
Shielding Verification

- Shielding configuration control tool

- Verifying the changes made to accelerators during maintenance has not changed the radiation fields significantly

- Monitoring the radiation fields should be part of routine restarting operations.
Induced Radiation Fields

• Largest fraction of dose from induced radioactivity in materials.
• Maintenance periods are the most dose intensive.
• Induced radioactivity is due to beam losses; intentional and unintentional.
• Beam losses are usually local; require more points to survey than for prompt radiation outside shielding.
Induced Radiation Fields

• In principle the induced radioactivity can be calculated from the first principles.
  (Calculations of induced radioactivity at accelerators discussed by Don Cossairt at another course at this school.)

• Alternatively one of the latest Monte Carlo shielding codes can be used to calculate the induced radiation fields.

• There are limitations to both methods
Induced Radiation Fields

• Limitations:
  - knowledge of basic information,
  - details of the model,
  - details of the calculations,
  - knowledge of actual geometry,
  - limitations of the physical model
  - unknown effects.
Induced Radiation Fields

• A complete model and detailed physical calculations is beyond any existing model.

• In practice beam losses can often not be predicted good enough to warrant the detailed calculation effort.

• Measurements during commissioning at locations of interest is better.
Induced Radiation Fields: example

- Irradiate samples at a loss location. Get beam loss and irradiation interval data.

- Use ionization chamber for simultaneous dose measurements for normalization.

- Analyze samples quickly with a HPGe

- For in situ gamma measurements use low efficiency detector or collimation.
**Induced Radiation Fields: example**

- Analysis gives count rates in photo peaks identified as belonging to specific radionuclides.
- Certain simplifying assumptions about geometry may be needed for calculations.
- Activity in each photo peak is related dose rate by the so called gamma-factor.
**Induced Radiation Fields**: example

- gamma factor $\Gamma_i$ is the activity to dose conversion factor.
- **Total gamma dose is**

$$H = \sum_{i=1}^{n} \Gamma_i A_i = \sum_{i=1}^{n} h_i$$

- Use of activity in photo peak is an underestimation, since scattered photons were ignored.
- Use the ion chamber dose data to normalize to the actual dose.
**Induced Radiation Fields: example**

- Saturation dose rate per unit beam is calculated using

\[
h_{sat,i} = \frac{1}{b} \ast \frac{h_i}{(1 - \exp(\lambda_i \Delta T)}
\]

- Use historical beam loss with time information to calculate saturation values per unit beam loss. Dose rate at any later time \( t \) for an arbitrary irradiation history is

\[
\dot{H} = \sum_{i}^{n} \sum_{j}^{m} b_j h_{sat,i} \left\{ 1 - \exp[-\lambda_i \Delta t_j] \right\} \exp[-\lambda_i (t - t_j)]
\]
Induced Radiation Fields

Process of predicting induced radiation fields

1. Ion chamber
2. Total dose rate
3. Gamma-ray spectrum
4. Normalize
5. Determine partial dose rates for each isotope
6. Determine saturation values per unit beam current for each isotope
7. Allows calculation of induced radiation fields for arbitrary irradiation history

Fig. 1
Monitoring for Removable Radioactive Material

• Much of the activity induced at accelerator facilities is produced by secondary particles in bulk material
  – with the result that the concentration of radioactivity in most materials is quite low,
  – any loose material generated by flaking or scaling etc. will have a corresponding low concentrations of radioactivity.

• Primary beam interactions with components or targets; the concentration of radioactivity will be much greater.
  – Can produce loose material contaminating nearby areas.

• Radioactive material will also be concentrated in vacuum system cold traps, filters and ion exchange columns of cooling-water circuits.
Monitoring for Removable Radioactive Material

• With multiple sources; good practice to institute routine monitoring for removable radioactive material.

• commonly done by paper or cloth ‘smears’ (“wipes”) that are wiped over standardized sampling-areas of the surfaces.

• Accelerator-produced radioactive species decay in different ways: electron, positron, gamma, alpha, etc. Each could be low or high energy.
Monitoring for Removable Radioactive Material

- Common contamination monitors such as thin-window pancake-shaped Geiger counters are not always the right tool.
- These detectors are most efficient for monitoring particle emissions and are not very sensitive to gamma-rays.
- It may be necessary to use a well-shielded NaI detector to obtain sufficient sensitivity for radioisotopes such as $^{57}$Co, $^7$Be.
Monitoring for Removable Radioactive Material

- Advisable to identify the radioactivity found on the smears using an HPGe detector to identify contamination source.

- Knowledge of radionuclides guide the selection of monitoring equipment.

- If loose radioactivity is expected or routinely identified in parts of the accelerator facility, a program of personnel monitoring also needs to be instituted.

- This usually involves the deployment of ‘hand-and-foot monitors or portal monitors at the entrance/exit of the affected areas.
Monitoring for Removable Radioactive Material

• Walk-through portal monitors often being an order of magnitude more expensive than simpler monitors that require ‘frisking’ by hand.
  – it may be required to have a monitor with adequate sensitivity for radionuclides that emit only gamma-rays.

• These monitoring stations together with the change areas for donning protective clothing require a significant floor area and a low-background environment.

• Such space is not always readily available in an operational facility and should be incorporated as part of the design of the facility from the start.
Radiation Fields Monitoring Techniques

- Active radiation monitoring systems
- Passive monitors
- Surveys using hand-held instruments
- Other instrumentation
Active Radiation Monitoring Systems

- Representative monitoring on a continual basis rely on a system of fixed monitors.
- Modern systems are usually computer driven and rely on
  - some type of networking to communicate the monitoring results to a central data processing.
  - Display system that can also generate visual and audible alarms if the radiation fields exceed predetermined levels.
- Type of information to be displayed and the interface with workers and accelerator operators should be specified as verifiable requirements in a human factors engineering plan.
Active Radiation Monitoring Systems

- Typical requirement might for example be
  - A maximum time to evacuate an area once a radiation alarm is generated.
  - A maximum time for accelerator operators to acknowledge a high radiation level and to initiate corrective action.
  - **Automatic removal of beam from an area.**
  - Sensitive to both prompt and induced radiation field to prevent access in the event that induced radiation fields exceed predetermined levels.
  - **All requirements must be verified before commissioning of the system is complete.**
**Active Radiation Monitoring Systems:** *Chipmunk*

- Example of a stationary rad. Monitor (developed at Fermilab)
  - TE ion chamber
  - Stable indoors & outdoors
  - Used both *beam-on* and *beam-off*
  - Detects: $n$, $\gamma$, charged particles
  - Adjustable trip level
  - Adjustable QF: 1, 2.5, 5, 10
  - Range: 0-100 mrem/hr (dial)
    - 0-900 mrem/hr (direct readout)
Active Radiation Monitoring Systems

• Save active monitoring system data
  – To be used for diagnostic purposes.
  – For generating periodic radiological records.
  – Proof that radiation fields were safely kept to the design levels.
  – (Permanent) legal records that the facility operated within the administrative and legal restrictions.
Passive Monitors

• Active monitoring yield information on dose rates
• Passive monitors provide an integrated dose - potential doses to personnel over the required time span.
• Examples are area dosimeters and personal dosimeters typically films, TLDs, OSL, foils and track etch combinations etc.
• Passive detectors are not sensitive to beam structure and can sometimes be used to correct active monitoring results.
Surveys Using Hand-held Instruments

In many cases fixed radiation monitoring does not provide a complete picture.

• Usually fixed radiation monitoring detectors are not placed where they can become radioactive.

• Important to obtain more detailed information than can be provided at a fixed set of points by the radiation monitoring system.

• Especially true during commissioning and whenever a change has been made to the accelerator configuration or shielding.
Surveys Using Hand-held Instruments

- GMs
  Log Survey Meter (LSM)
  Beam-off area survey (2-2000 mR/hr)

- Frisker, E140N
  • Beam-off contamination and activation monitor

Fig. 3
Surveys Using Hand-held Instruments

• Measuring contact doses is tricky and hard to reproduce
  – different technicians may get very different results depending on their interpretation of “contact”, especially for point sources.
  – At close distances both geometry and distance can change significantly.
  – Don’t want to contaminate the survey meter
  – Better to specify a standard distance (e.g. 30 cm) from activated components to be reproducible.
Surveys Using Hand-held Instruments

• Care must be taken in the documentation of the results of such surveys. Record
  – time and date of survey,
  – Monitor type
  – Calibration due date
  – serial numbers
  – Initials, ID number or the name of the surveyor
  – More detailed records may include
    • relevant accelerator parameters
    • the time the last beam was accelerated.
Surveys Using Hand-held Instruments

• Some thought must be given to how
  – the data is recorded/saved
  – made available to workers and accelerator operators.

• Usual practice is to display the data in the form of maps that may be
  – posted in the areas affected
  – post additional conditional signs when field deviates from normal.
**Instrumentation**

- Radiologically **neutrons** are the most important radiation to shield.
- Neutrons require more shielding than photons and most charged particles.
- Have to deal with neutron transparency
- Neutrons usually dominate the radiation field outside proton or high energy electron accelerator shields.
- At high energy accelerators **muons** can also leak out of the shielding.
**Instrumentation: for neutrons**

- Dose measured by ion chamber related to DE by QF

  \[ H = \bar{Q}D \]

- GM not good in mixed fields
- GM could be used to quickly find flaws in shielding

- For monitoring neutron fields thermal neutron detectors $^6\text{Li}(\text{Eu})$ scintillator, BF$_3$ or $^3\text{He}$ proportional counter in spherical or cylindrical moderator gives reasonable response
Instrumentation

- Some detectors use boron-loaded polyethylene to shape the low-energy response so that it approximates the dose equivalent.

![Graph showing neutron energy vs. dose equivalent](image)

**Fig. 4**

- Neutron energy (MeV)
- Dose equivalent (μSv cm⁻²)

- **H**(10)
- "Snoopy" response
**Instrumentation**

- A monitor of this type is the Andersson-Braun monitor, colloquially referred to as ‘SNOOPY’
Example of a Rem-meter: WENDI

Other improved examples are LINUS and WENDI.
Energy Response of Rem-meters

Fig. 7

improvement
Instrumentation for neutrons

Long Response Counter

Fig. 8
**Instrumentation:**

**Recombination Chamber**

- Operates in the recombination and saturation region

![Fig. 9](image-url)
**Instrumentation: Recombination Chamber or REM-2**

Ratio of response at recombination region to response at saturation is related to the QF.
**Instrumentation: Recombination Chamber or REM-2**

- Based on columnar recombination is more severe for high LET (neutrons, heavy ions)

\[ i = kV^n \text{ for a given QF} \]

\[ n \text{ is proportional to QF, } k= \text{ constant for specific field} \]

\[ i_c = kV_c^n \text{ and } i_{sat} = V_{sat}^n \]

\[ R = \frac{i_c}{i_{sat}} = \left(\frac{V_c}{V_{sat}}\right)^n \]

- Calibrate QF curve with different combination of neutron and gamma sourced.
  - Generate n vs. QF curve.
  - Measures response in an unknown mixed field.
  - Fit response → QF for unknown field.
**Instrumentation: Recombination Chamber or REM-2**

Fig. 11
**Instrumentation**

- Muon detectors
  - Thin plastic scintillator paddle pairs with a metal discriminator in between.
  - Charged particles produce light in plastic.
  - Photomultipliers amplify the light signal.
  - Plastic has low sensitivity to neutrons and gammas.
  - **Two types are used at Fermilab**
    - Muon telescope
    - Moun finder
Instrumentation: Muon Telescope

Fig. 12
Instrumentation: muon finder

Fig. 13
Instrumentation: muon finder
Special Measurements

Neutron Spectrum Measurements

• No single detector can measure the whole spectrum.
• Each detector has a useful response in a limited portion of the energy spectrum
• Need multiple detectors
Special Measurements

Neutron Spectrum Measurements

• Activation foils

• Bonner spheres set

• Additional variations of above (balls covered with lead, copper or cadmium) and additional detectors to extend the range; plastic scintillator and liquid Scintillator (NE213).

• Super saturated drop detector set, fission counters, proton recoil counters, TEPC, etc.
# Activation detectors

- **Important characteristics of various activation detector nuclear reactions**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Reaction</th>
<th>Energy Range (MeV)</th>
<th>Half-Life</th>
<th>Cross Section-High Energy (mb)</th>
<th>Particle Detected</th>
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<td>sulfur</td>
<td>$^{32}$S(n,p)$^{32}$P</td>
<td>&gt; 3</td>
<td>14.26 d</td>
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<td>$^{27}$Al(n,α)$^{24}$Na</td>
<td>&gt; 6</td>
<td>14.95 h</td>
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<td>aluminum</td>
<td>$^{27}$Al(n,x)$^{22}$Na</td>
<td>&gt; 25</td>
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<td>plastic scint.</td>
<td>$^{12}$C-&gt;$^{11}$C</td>
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<td>copper</td>
<td>Cu-&gt;$^{54}$Mn</td>
<td>&gt; 80</td>
<td>312.1 d</td>
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<td>$\gamma$</td>
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Threshold detectors and foils

Fig. 15

[Graphs showing cross sections and fission cross sections as functions of energy for different reactions and isotopes.]
## Threshold detectors foils

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<th>Foil</th>
<th>(n, γ)</th>
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55
Threshold detectors and foils: Bismuth

Fig. 16

Cem (n, nx) Cross Sections for a Bismuth Activation Inside a 5 Inch Lead Covered Bonner sphere
Threshold detectors and foils: Gold

Bertini \((n, nx)\) Cross Sections For a Gold Foil Centered in a Lead Covered Bonner Sphere

Fig. 17
Neutron Spectrum Measurements
Moderation mechanism

Fig. 18
Neutron Spectrum Measurements

- Bonner spheres set
- Different sizes of polyethylene balls
- Detector in the center of the ball
- Typical set: bare detector, 2”, 3”, 5”, 6”, 10”, 12” and 18”. 
Neutron Spectrum Measurements

Fig. 19

Polyethylene set

Examples of modified spheres
Neutron Spectrum Measurements

- Bonner spheres detectors
- $^6$LiI(Eu) crystal
  - Phoswich detectors
- BF$_3$ counter
- $^3$He proportional counter detector
- TLD 600 and TLD700 chip sets ($^6$LiF, $^7$LiF)
Neutron Spectrum Measurements

Thermal neutron detection reactions

- $^6\text{Li}(n,\alpha)^3\text{H}$ $Q=4.78$ MeV $E_\alpha=2.05$ MeV
- $^{10}\text{B}(n,\alpha)^7\text{Li}$ $Q=2.79$ MeV $E_\alpha=1.47$ MeV
- $^3\text{He}(n,p)^3\text{H}$ $Q=0.77$ MeV $E_p=0.57$ MeV
Detection reactions cross sections
A Phoswich detector

Fig. 21
**Analysis of neutron measurements**

Neutron count rates in a set of detectors are related to the neutron spectrum through the Fredholm equation.

\[
a_i = \int_{0}^{\infty} \phi(E) \rho_i(E) \, dE
\]

In practice the spectrum is subdivided into \( n \) energy groups and the discrete form of the equation is used.

\[
a_i = \sum_{j=1}^{n} \phi_j \rho_{i,j} \Delta E_j
\]
Example of calculated Bonner Spheres response functions with $^6\text{Li(l(Eu)}$ detector

![Graph showing response functions for different sphere sizes.](image)
Example of calculated Bonner Spheres response functions with $^3$He detector

Fig. 23

Standard set

Modified set
Neutron Spectrum Measurements

Analysis of Neutron Spectrum data
• Usually will try to reconstruct a spectrum with finite number of energy bins
• Still have more unknowns than equations
• Use a priori constrains to help define the solution:
  – Solution is positive (no negative flux)
  – First derivative is smooth
  – Spectrum is continuous
  – Solution not differ greatly from predetermined energy spectrum, such as 1/E slowing-down spectrum
  – The highest energy possible….
Neutron Spectrum Measurements

Codes

• Several algorithms → Several computer codes
• Direct inversion (matrix, Fourier, derivative)
• Least-squares (LOHI)
• Iterative recursion (BUNKI, SAND-II, Gold, SPUNIT)
• Parameter estimation (Expansion of basis, Bayesian)
• Regularization (LOHI78)
• Monte Carlo (SWIFT)
• Recent developments
  – Genetic algorithms
  – Neural networks
Neutron Spectrum Measurements

Analysis of Neutron Spectrum data

• Codes use known/measured response function of detector to a typical radiation field

• Fermilab: measurements behind thick shields n-spectra similar to $^{241}$Am-Be source.

• In general, codes agree best for properties determined by integrating over spectrum: average QF, total $\Phi$, and total D and DE.
Neutron spectrum measured vs. FLUKA simulation

Fig. 24

Neutron energy (MeV)

Fluence rate (n cm\(^{-2}\) s\(^{-1}\))

- Multisphere unfolding
- FLUKA simulation
# Recombination Chamber vs. Unfolding Technique

<table>
<thead>
<tr>
<th>Description of Radiation Field</th>
<th>Unfolding</th>
<th>Recombination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed field of neutrons and muons (Co 87)</td>
<td>1.4 ± 0.2</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>Iron leakage spectra before shielding was added (Fig. 6.8b) (El86)</td>
<td>5.4 ± 0.2</td>
<td>6.0 ± 0.6</td>
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<tr>
<td>Iron leakage spectra after shielding was added (Fig. 6.8c) (El86)</td>
<td>2.5 ± 0.3</td>
<td>3.0 ± 0.3</td>
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<tr>
<td>Spectrum in a labyrinth (Fig. 6.7) (Co85b)</td>
<td>3.1 ± 0.7</td>
<td>3.4 ± 0.1</td>
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</table>
Waste Characterization for Disposal or Decommissioning

• Two waste categories
  – Compactable waste: PPE, cleaning waste products, …
  – Solid materials: magnets, beam pipes, magnet stands, other accelerator parts, concrete blocks

• Strictly speaking no disposal of such waste is permitted.

• Radioactive waste may only be sent to approved, long-term storage sites.
Waste Characterization for Disposal or Decommissioning

• Disposal sites require
  – physical, chemical characterization and inventory of radioactivity content.

• Compactable waste is shipped in standardized containers such as 55 gal. steel drums.
  – Waste is assayed by placing each drum on a turntable at a fixed distance from an HPGGe detector.
  – Set-up may be calibrated by a mock-up drum with randomly distributed calibration sources.
Waste Characterization for Disposal or Decommissioning

- Assaying the non-compactables more difficult; geometry.
- Generate a database of radionuclides in materials used.
- Generate a relation between the radioactivity concentration and the contact dose-rate for different materials.
- Use relation to estimate the radioactivity content based on the dose-rate.
- The information generated extremely useful in planning D&D.
Waste Characterization for Disposal or Decommissioning

- Estimates of the radioactivity induced in shielding using core samples to verify calculated estimates.

- Can calibrated using similar slugs of concrete spiked with a broad-spectrum gamma-emitter such as $^{152}$Eu.
Waste Characterization for Disposal or Decommissioning

Typical setup for assaying concrete cores
Assay results of typical concrete shield used for 30 years of 500 MeV operation
Waste Characterization for Disposal or Decommissioning

- Better use of measurements need to have life history of the beam (losses)
- Similar technique may be used to predict the radioactivity inventories at D&D.
Acknowledgements
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