WG – F Sessions

Monday: Posters

TUO2AB: F
TUO3AB: Discussions BC&F
WEO2AB: F
WEO3AB: Discussions AC&F

THO4AB: F, F-Discussions

Instrumentation
Beam Material Interactions

WG-F Summary – Part 1: M. Minty
WG-F Presentations

1. A Jansson, "Beam instrumentation and limitations for multi-MW pulsed proton linacs"
2. N. Chauvin, "Halo matching for high intensity linacs and dedicated diagnostics"
3. K. Wittenburg, "Beam diagnostics for the detection and understanding of beam halo"
4. Y. Hashimoto, "Two-dimensional and wide dynamic range profile monitors using OTR/fluorescence screens for diagnosing beam halo of intense proton beams"
5. S. Lidia, "Instrumentation design and challenges at FRIB"
6. M. Sapinski, "Beam loss mechanism, measurements and simulations at the LHC (quench tests)"
7. K. Yamamoto, "Beam instrumentation at the 1 MW proton beam of J-PARC RCS"
8. E.B. Holzer, "Beam diagnostic challenges for high energy hadron colliders"
9. G. Stancari, "Measurements of beam halo diffusion and population density in the Tevatron and in the Large Hadron Collider"
10. G. Skoro, Material response to high power beams
11. A. Konobeev, DPA and gas production in intermediate and high energy particle interactions with accelerator components
12. A. Bertarelli, Novel materials for collimators at LHC and its upgrades
Instrumentation Challenges – Existing Accelerators

High stored energies - both in the beam and in the superconducting magnets, high brightness beams
   Topics: avoiding uncontrolled losses (machine protection, collimation, halo monitoring...), intercepting monitors (quench, need for non-invasive monitors), small beam profiles and sensitivity to systematic errors

E.B. Holzer

“Beam diagnostic challenges for high energy hadron colliders”

Large size of the colliders
   Topics: component numbers, location of electronics, signal transport

High radiation levels

Instruments in cryogenic temperatures
   Topics: new regime BLMs, high dependability,...

Monitoring of beam instabilities
   Topics: bunch-by-bunch and intra-bunch measurements, feedback

Wakefields and rf heating - impedance budget
Challenges to beam instrumentation

- Multi-MW hadron machines need fast loss detection (for damage protection) with high dynamic range (to avoid activation).
- Non-invasive profile (transverse and longitudinal) measurement needed, and is more difficult with protons than H- (and partially stripped ions).
- Halo measurement important, but difficult to predict.
- Diagnostics with machine protection function need to protect even if timing fails.

Design considerations for beam loss monitors

Designs for beam profile monitors

Plans for target imaging

“Beam instrumentation and limitations for multi-MW pulsed proton linacs”

A. Jansson

HB2014, East Lansing, Nov. 10-14, 2014

WG-F Summary – Part 1: M. Minty
FRIB overview
Challenges to beam instrumentation

- Measuring and Tuning High Power Beams
- Accurate Low-β Beam Position Monitoring
- Monitoring Multiple-charge-state Beams
- Measurements Over High Dynamic Range
- Ensuring Machine Protection

Status of requirements, procurements, installations and tests (some already insitu)

Overall instrumentation status

The FRIB instrumentation diagnostic suite
- Designed to provide sensitivity over a large dynamic range to meet the required operational flexibility
- Provides a network of complementary devices to detect errant beam and slow losses
- Meets requirements for commissioning and reliable operation
What is beam halo?

Sources of halo are:
- Space charge forces of the beam
- Mismatch of beam with accel. optics
- Beam beam forces
- Instabilities and resonances
- RF noise
- Scattering (inside beam, residual gas, macroparticles, photons, obstacles (stripping foil, screens etc.))
- Nonlinear forces, e.g. aberrations and nonlinearities of focusing elements
- Misalignments of accelerator components
- Electron clouds
- Beam energy tails from uncaptured particles
- Transverse-longitudinal coupling in the RF field
- etc.
HALO QUANTIFICATION

- There is no clearly defined separation between the halo, tail and the main core of the beam. Consequently, there has been some difficulty identifying a suitable quantitative measure of the halo content of a beam in a model-independent way.
- Methods have been developed, and computationally studied (by simulations), to characterize beam halo.

1) Kurtosis
2) Ratio of halo to core
3) Ratio of beam core to offset
4) The Gaussian area ratio method

1. Devices that directly measure halo and halo evolution. Examples are Wire Scanners and dedicated Halo Monitors.
2. Devices that contribute to the diagnosis of machine conditions that cause halo formation. An example would be a tune measurement system.
3. Devices that measure the effects of halo development. An example would be the loss monitor system.

Our instruments reach a dynamic range of better $10^6$!

What about the halo simulations?

K. Wittenburg

"Beam diagnostics for the detection and understanding of beam halo"
Recent Simulations: emittance vs halo matching

Particle Swarm Optimization
A population based stochastic optimization technique

N. Chauvin

“Halo matching for high intensity linacs and dedicated diagnostics”

(1) halo and small emittance

(2) no halo and larger emittance


HB2014, East Lansing, Nov. 10-14, 2014
Simulations and Experiments: LHC quench tests

Quench tests are probably most complex beam-loss experiments, their goals:
- determination of quench-preventing BLM beam-abort thresholds
- determination of beam-induced (realistic) quench levels

1. LHC normal losses account for a few percent intensity loss before collisions.
2. Losses have increased by factor 10 after optimization for luminosity-production.
3. Standard BLM system works very well, developments towards fast diagnostics and measurements closer to the loss location.
4. UFO losses maybe the largest thread to physics run at 6.5 TeV.
5. 17 quench tests performed during Run 1, some very sophisticated.
6. Analysis is very complex and multi-disciplinary.
7. Steady-state quench levels: understood within factor 2.
8. UFO-timescale losses (0.1 ms-10 ms) – factor 4 discrepancy.

(experiment and particle shower (with FLUKA) vs electro-thermal analyses)

M. Sapinski

“Beam loss mechanism, measurements and simulations at the LHC (quench tests)”

HB2014, East Lansing, Nov. 10-14, 2014
Simulations and Experiments: LHC ion loss maps

before: standard code ICOSIM for heavy ion loss map simulation

after: SixTrack with ion-equivalent proton rigidities and detailed fragmentation simulation

P. Hermes

“Studies on heavy ion losses from collimation cleaning at the LHC” MOPAB43

HB2014, East Lansing, Nov. 10-14, 2014

WG-F Summary – Part 1: M. Minty
New monitors for further safety/quality of beam

- Monitors for safety/stable operation
  Fast interlock by CT and profile check on target
- Injection halo monitors
  VWM (vibration wire monitor)
  L3BT Scrapers & BLM, CT
- Extraction Halo monitors
  OTR monitor (next slide/talk)
- Delayed proton monitor for $\mu$-e conversion measurement

After correction

wire scraper and scintillators with different sensitivities for simultaneous (?) measurements of both the beam core and halo
New beam diagnostics: 2D core and halo monitor

Y. Hashimoto

“Two-dimensional and wide dynamic range profile monitors using OTR and fluorescence screens for diagnosing beam halo of intense proton beams”

- Motivation

Beam halo: It brings serious activation of the accelerator by beam loss

What to see?
Two-dimensional density distribution from beam core to beam halo of 3GeV Proton Beam.

Beam Intensity ≥ 10^{13} proton/bunch

What kind of instrument?
High Dynamic Range Beam Profile Monitor

Dynamic Range: 10^6

What is carried out?
Beam diagnosing for injection beam of J-PARC MR which is extracted beam from RCS.
Evaluation for validity of beam collimation by the collimator
Beam Halo
Measure Fluorescence From Chromium Doped alumina Screen

Beam Core
Measure OTR From 10 micron Titanium foil

New Four Direction Alumina Screen was installed in 2014
measured profile of beam core and halo with > 1E6 dynamic range

Effect of the beam cut by 3-50 BT collimator (3)

**Horizontal Projection**

- **Dynamic Range**: More than six order obtained
- **Beam Size**: More than 120 mm at 10⁻⁶ order

Collimator-ON
Waist appears at 10⁻⁴
Expansion at 10⁻⁶

Y. Hashimoto
phase space painting: two-dimensional imaging reveals halo rotation

100π Painting

60mm

54mm

50π Painting

Y. Hashimoto

HB2014, East Lansing, Nov. 10-14, 2014

WG-F Summary – Part 1: M. Minty
The electric field of the protons bunch perturbs the trajectories of the to-be-collected electrons.

**Electron Sieve Concept**

sieve filters electrons of different gyration radii
original partial profile constructed by deconvoluting the PSF

**Novel Readout Design**

Timepix3 ultrahigh BW
Hybrid pixel detector

- Fast readout speed enabling bunch-by-bunch measurement
- Reduced thickness with respect to an optical readout
- No need for MCP amplification
- Low RF coupling
- Highly radiation hard system

**MOPAB41** “Feasibility Study of a Novel, Fast Read-out System for an Ionization Profile Monitor Based on a Hybrid Pixel Detector”

**MOPAB42** “Investigation of the Effect of Beam Space-charge on the trajectories in ionization profile monitors”
Giulio Stancari

“Measurements of beam halo diffusion and population density in the Tevatron and in the Large Hadron Collider”

Beam halo diffusion rates in the Tevatron and in the LHC

Effect of beam-beam is 1-2 orders of magnitude

Near core, diffusivity consistent with emittance growth

Very low noise and nonlinearities in LHC

curves from measured core emittance growth

\[ D_J = \dot{\epsilon} \cdot J \]
Effect of hollow electron lens on diffusion in the Tevatron

Giulio Stancari

To our knowledge, first direct observation of controlled diffusion enhancement in specific amplitude range!
New diagnostics: electron back scattering detector

- New tool for the precise alignment of electron with ion beam
- Small plastic scintillator installed close to the e-gun
  - Measures back-scattered electrons
- Automatic procedure for beam alignment by maximizing eBSD counting rates

Backscattered electron detector in RHIC electron lenses

- Might also be used for hollow electron lens considered as option for HL-LHC (CERN_LARP collaboration), based on Tevatron lens design

Slide with theory and demonstration of truly parasitic beam-gas scattering data (appended)
Discussion

*a question to beam dynamics / simulation:*

what quantity and quality of information beam diagnostics have to deliver ...

**covered dimensions**

- \(6D\) \((x, x', y, y', z, \varphi)\)  
  ideal
- \(4D\) \((x, x', y, y')\)  
  emittance pepper pot
- \(2D\) \((x, x') + 2D\) \((y, y')\)  
  emittance slit-grid
- \(2D*\)(x, y)  
  SEM foil (+ electron optics) / gas sheeth fluoresce.
- \(2D*\)(x, y) only tail  
  screen / scanning ionization chamber
- \(2D*\)(x, z) + \(2D*\)(y, z)  
  wire + TOF (bunch shape)
- \(1D\) \((\varphi)\)  
  spectrometer
- \(1D*\)(x) + \(1D*\)(y)  
  wire scanner
- \(1D*\)(x) + \(1D*\)(y) only core  
  residual gas fluorescence
- \(~0.5D*\)(x) + \(~0.5D*\)(y)  
  4-segment foil or collimator
- \(1D*\) \((\varphi)\) only lost tail  
  micro loss monitors (circumferential)
- \(~0.5D*\)(\(\varphi)\) only lost tail  
  4-segment loss monitors (circumferential)
- \(0D*\) only lost tail  
  external loss monitor
- \(~0D*\) \((<x>) + <0D*\) \((<y>)\)  
  BPM
- \(~0D*\) \((<z>)\)  
  phase probe
- \(~0D*\) \((<\varphi>)\)  
  current monitor

* usable while beam delivered  
Rudolf Dölling, HB2014

number of measurement locations along beam path

one / few / many / continuous

quality

dynamic range
accuracy

added up

all information useful? and "digestable"?  
quality weighting?

what (exactly) is enough? (if at all)

... to allow the prediction of beam losses?

(of the order of 10 nA)
Experience from existing high power accelerators shows that reliability may be compromised by not anticipating or realizing the impact of certain physical phenomena (SNS: space charge, intrabeam stripping, LHC: unidentified falling objects, electron clouds, fast ion instabilities...). Are we doing enough to ensure that future accelerators are not unexpectedly compromised?

Safety margin criteria for future accelerators often cited in terms of figures of merit; e.g. permissible maximum beam loss = $1 \times 10^{-6} \times$ total beam current
maximum power deposition = 1 W/m

These are too general (and should not be interpreted as specifications by physicists or engineers).

A fractional beam loss is not the appropriate measure for a safety margin. It is the total absolute beam loss and/or total power deposition that is relevant.
The success of the LHC collimator design (with 100+ collimators) is truly noteworthy (no unintentional quenches to date). The designing methodologies should be “kept alive” and, if not already done, applied to collimation system designs for future accelerators.

At the Halo’03 workshop, available computing power was considered a limiting factor for understanding beam halo and its evolution. With today’s technologies, is this still the case? Has our understanding of beam halo improved commensurately? Do we still think to need such simulations?

Will simulations guarantee that we can achieve the requirements on maximum allowable beam loss in future accelerator designs (FRIB, ESS, ADSs)? Should we expect them to?

On the topic of “what is halo”:

(my view) need to expand to multiple definitions which depend on context the definition of dynamic aperture seemed also not so clear
Working Group-F Summary
Part 2: Beam-Material Interactions

Nikolai Mokhov
Fermilab
G. Skoro: Material Response to High-Power Beams

• **Solids: thermal stress**
  - Minimization via segmentation, no stress concentration, compressive preloading, beam size/shape, material selection
  - Stress quality factor
  - Stress test Lab at RAL: direct measurements of material strength
  - Dynamic measurements
  - Material fatigue

• **Liquids**
  - Mercury jet

• **In between**
  - Fluidized tungsten powder
Stress test Lab @ RAL

Coaxial wires
(current from power supply)

Test wire

Vacuum chamber
Hole

LDV = Laser Doppler Vibrometer

3 different decoders: VD-02 for longitudinal, DD-300 and VD-05 for radial oscillations

Schematic circuit diagram of the wire test equipment
Test wire, 0.5 mm Ø
Pulsed Power Supply:
0-60 kV; 0-10000 A
300 ns rise and full time
800 ns flat top
Repetition rate 50 Hz or sub-multiples of 2

Vacuum chamber, 8x10⁻⁷ to 1x10⁻⁵ mbar

LDV
Proton Beam Window (PBW) for ESS

- the PBW separates the accelerator vacuum from the helium atmosphere in the target room at 1 bar
- Al6061-T6 is the preferred material for the PBW
- helium at 10 bar is used for PBW cooling (customer request: no water cooling!)
- Maximum time-averaged heat deposition @ beam center: 0.5 kW/cm³
- Pulsed operation at 14 Hz & beam trips => risk of fatigue

New concept: panpipe design
J-PARC Mercury Target:
Detection of vibration induced by proton beam

In-situ measuring system

Micro-machining tech was applied to a new mirror.

Bubbling mitigation effect on pressure waves
Between Solid and Liquid: Fluidized Tungsten Powder

**Motivation:** Material already fragmented; no cavitation; thermal stress contained within grains; target can be continuously reformed; can be ‘pumped’ away, externally cooled and recirculated.

- Potential solution for applications requiring highest pulsed beam powers e.g. alternative to Neutrino Factory liquid mercury jet
- Pneumatically (helium) recirculated tungsten powder

**HiRadMat Beam Parameters:**
- A high-intensity beam pulse from SPS of proton or ion beams is directed to the HiRadMat facility in parasitic mode, using the existing fast extraction channel to LHC.
- **Beam Energy** 440 GeV
- **Pulse Energy** up to 3.4 MJ
- **Bunch intensity** $3.0 \cdot 10^9$ to $1.7 \cdot 10^{11}$ protons
- **Number of bunches** 1 to 288
- **Maximum pulse intensity** $4.9 \cdot 10^{13}$ protons
- **Bunch length** 11.24 cm
- **Bunch spacing** 25, 50, 75 or 150 ns
- **Pulse length** 7.2 μs
- **Beam size at target** variable around 1 mm²

HiRadMat: very interesting and important results (characterisation of novel, more robust materials for beam collimation at higher power).
A. Konobeev: DPA and gas production in intermediate and high energy particle interactions with accelerator components

- Overview of recent developments in modeling of primary radiation damage relevant to dpa rate calculations

Corrections to the reference NRT model: BCA, MD, BCA-MD (IOTA code at KIT) and various forms of defect production efficiency. Most recently by Nordlund:

$$\xi(E) = \frac{1-c}{(2E_d/0.8)^b} E^b + c$$

Kinetic Monte Carlo (up to $10^4$ s cf to ns in MD): Individual defects, clusters, impurities, annealing

Complete simulations: particle interaction and transport codes coupled to BCA+MD(+KMC)
3. Modeling using pre-calculated $\xi(T)$ dependence

$\xi(T)$: parameterized or pointwise

Implemented: MARS15, FLUKA, PHITS

Simulation: BCA-MD

Correction: measured $\langle \xi \rangle$ values, *JNM* 328, 197 (2004)

Important

- Evaluated data at low energies (ENDF/B, JEFF, JENDL etc): processing dpa- cross-sections with $\xi(T)$
- $\xi(T)$ dependence for various PKA
4. Modeling using pre-evaluated $\sigma_d$ cross-sections

The most flexible way to keep

- justified theoretical information
- experimental data

DXS data file (KIT, 2011-2014) (IAEA)

Projectile: neutron, proton
Energy: $10^{-5}$ eV to 3 GeV
Target: Al, Ti, V, Cr, Fe, Ni, Cu, Zr, W
Gas Production: p, d, t, $^3$He and $^4$He

Nuclear models implemented in popular computer codes predict gas production cross-section with varying degrees of success depending on the energy of projectiles.

The use of cross-sections evaluated using nuclear model calculations and measured data is one of the most reliable and flexible approach for advanced calculation of gas production rate, certainly at intermediate energies. KIT: 278 targets from $^7$Li to $^{209}$Bi; incident proton energies: 62, 90, 150, 600, 800, 1200 MeV.
Challenging applications - LHC collimators. Key properties to be optimized to meet the requirements (no existing material can simultaneously meet all the requirements):

- **Electrical Conductivity** \((g)\) Maximize to limit Resistive-wall Impedance
- **Thermal Conductivity** \((l)\) Maximize to maintain geometrical stability under steady-state losses
- **Coefficient of Thermal Expansion** \((a)\) Minimize to increase resistance to thermal shock induced by accidental beam impact.
- **Melting/Degradation Temperature** \((T_M)\) Maximize to withstand high temperatures reached in case of accidents.
- **Specific Heat** \((c_p)\) Maximize to improve thermal shock resistance (lowers temperature increase)
- **Ultimate Strength** \((R_M)\) Maximize to improve thermal shock resistance (strain to rupture)
- **Density** \((r)\) Balance to limit peak energy deposition while maintaining adequate cleaning efficiency
- **Radiation-induced Damage.** Minimize to improve component lifetime under long term particle irradiation
Novel Materials R&D Program

- Extensive materials R&D program in collaboration with EU institutes and industries (EuCARD, EuCARD2, HiLumi)

- Aim: explore composites combining the properties of graphite or diamond (low $\rho$, high $\lambda$, low $\alpha$) with those of metals and transition metal-based ceramics (high $R_m$, good $\gamma$)

- Materials investigated are Copper-Diamond (CuCD), Silver-Diamond (AgCD), Molybdenum-Copper-Diamond (MoCuCD), Molybdenum Carbide-Graphite (MoGr)

- Production techniques include Rapid Hot Pressing, Liquid Phase Sintering and Liquid Infiltration

- Most promising are CuCD and (especially) MoGr
Comprehensive beam test program:

- 450-GeV protons, HiRadMat at CERN
- 10 MeV to 1.2 GeV C to U, UNILAC at GSI
- 100 to 200 MeV protons, BLIP at BNL
Discussion: Issues and Questions

- **DPA, gas production, fluence and dose**
  - Material and environment
  - Beam energy and particle type (e.g., accelerators vs reactors)
  - Energy deposition density level
  - Irradiation time structure
  - Observations (e.g., accelerators, RRR at cryo temperatures)

- **Model/code capabilities, uncertainties and questions**
  - EDD, dose, fluence, DPA and He/H₂ gas production
  - Corrections to the reference NRT model: BCA, MD, BCA-MD (IOTA code at KIT) and various forms of defect production efficiency.
  - Data needs

- **Link of calculated quantities (DPA etc) to observable changes in critical properties of materials remains on the top of the wish-list (coupling EDD codes and MD?)**
Data Needs & Further Issues

• Well-thought experiments – covering various regions of the parameter space - are extremely desirable, including measurements with charged particle beams, their relation to neutron data and degradation measurements at cryogenic temperatures.

• Annealed versus non-annealed defects.

• Low-energy neutron DPA in compounds.
1) **Is it possible to understand the beam losses in detail and to predict them?**
- at a level of $10^{-5}$ to $10^{-6}$ of the beam current
- from different loss mechanisms/with protons and ions/at different machines
- examples pro/con from existing accelerators; examples of comparison between simulation and measurement
- open questions for future accelerators?

2) **What really has to be provided by simulation and diagnostics to make this possible?**
- what information is really needed/sufficient/can be digested by simulations?
- dynamic range/precision of transversal/longitudinal profile/halo measurement? of simulation?
- emittance measurement, tomographic methods, full 6D phase space, projections?
- losses, how detailed?
- requirements of future accelerators?

3) **What seems actually feasible/has been delivered?**
- dynamic range/accuracy of transversal/longitudinal profile/halo measurement? of simulation?
- emittance measurement, tomographic methods, full 6D phase space, projections?
- examples of comparison between simulations and measurement
- is there recent progress? what can we hope for/dream of? what are the bottlenecks?

4) **If a detailed understanding of losses were possible, affect on operation/tuning/hardware improvements?**
- commissioning strategy integrating beam dynamics/diagnostics
- strategy if simulation and measurement disagree?
- can we overcome empirical tuning?
- different requirements to simulation for support of tuning and support of hardware changes?

5) **How important is a detailed understanding for decreasing/limiting the beam losses?**
- for improvements at existing accelerators/for future accelerators
- is what we have reached already good enough?
- are we optimistic/pessimistic on the further development?
- is a better coordination of beam dynamics/diagnostics needed?
Coulomb scattering calculations

\[ p = \text{momentum} \quad E = \text{energy} \quad \Theta = \text{angle of the electron in the ion frame} \]

\[ \frac{d\sigma}{d\Omega} = \frac{Z^2}{4} \left( \frac{e^2}{E} \right)^2 \frac{1}{\sin^4(\Theta/2)} \times \left[ 1 - \left( \frac{pc}{E} \right)^2 \frac{\sin^2 \Theta}{2} \right] \times \left[ 1 + \frac{2E \sin^2(\Theta/2)}{M_p c^2} \right]^{-1} \times \left[ 1 - \frac{q^2 \tan^2 (\Theta/2)}{2M_p^2} \right] \]

Rutherford \quad Quantum corr. \quad Recoil corr. \quad Magnetic moment corr.

Small deflections in the ion frame leads to large deflections in the lab.

Time-resolved eBSD counts

<table>
<thead>
<tr>
<th>Ion Beam:</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy:</td>
<td>100 GeV/u</td>
</tr>
<tr>
<td>Bunch intensity:</td>
<td>1.1*10^9</td>
</tr>
<tr>
<td># of bunches:</td>
<td>2</td>
</tr>
</tbody>
</table>

The background is due to electrons from the residual gas (\( \sim 5\text{E-10 Torr at pump} \))

P. Thieberger

“Scattered electrons as possible probes for beam halo diagnostics”
New beam diagnostics design: current monitor at PSI

**ID: 1101 – MOPAB47/48 Simulation/Design of a New Beam Current Monitor Under Heavy Heat Load**

**PSI**  
**J. Sun**

**Summary**

- **Part 1: M. Minty**
- Should be less sensitive to drifts caused by unequal thermal expansion under heating by particle shower

**Detailed Design**

- **Ceramic Ring**
  - Acts as a thermal bridge
  - High permittivity to increase the capacity gap (relax the mechanical tolerances)

- **Passive Compensation**
  - 2 mm Aluminum shim for self-compensation, since Aluminum’s Thermal Expansion Coefficient is 3 times higher than Graphite