SUMMARY FROM WORKING GROUP F: INSTRUMENTATION AND BEAM MATERIAL INTERACTIONS

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Abstract

This workshop on High-Intensity, High Brightness and High Power Hadron Beams, held in East Lansing, MI and hosted by Facility for Rare Isotope Beams (FRIB), included a Working Group which combined the topics of Instrumentation and Beam Material Interactions. Continuing with the HB Workshop series tradition, progress, status and future developments of hadron accelerators in these subfields were presented and discussed. Leveraging off of experiences from existing accelerators including FNAL, IFMIF, JPARC, the LHC, RHIC and the SNS, this workshop provided occasion to discuss new technical challenges for beam instrumentation and beam material interactions as relevant for future high power hadron beam facilities both approved (e.g. FRIB, ESS) and in planning (e.g. CADS). Discussions between this and the other working groups during this workshop were quite lively as necessitated by the need to seriously address strong interdependencies (between beam dynamics, technologies, instrumentation and interaction of the beams with materials such as targets, beam dumps and collimators) in the regime of megawatt beam powers as anticipated in approved and future accelerators.

WG-F ORGANIZATION

At this HB workshop, the topics of Instrumentation and Beam Material Interactions (BMI) were combined into a single working group. Working group F consisted of (1) two sessions with nine talks on Instrumentation, (2) one joint discussion session with working group A (beam dynamics in circular accelerators), (3) one joint discussion session with working groups B (beam dynamics in linear accelerators), (4) one session including discussion with three talks on Beam Material interactions and (5) seven posters contributed to the general poster session.

Since the HB workshop series places strong focus on beam dynamics, the selection of talks for WG-F aimed to reflect this. The instrumentation sessions therefore included topics such as beam profile and halo measurements and their relevance to beam dynamics analyses and simulations as well as comparisons of beam measurements with predictions.

The Beam Material Interactions session included presentations on activation and radiation damage / material response to high-power beams, thermo-mechanical simulations including design tools for targets, collimators and beam dumps, irradiation facilities capable of supporting future desired measurements, and novel materials for interception of high power beams. The orientation of this working group was therefore quite distinct from the IBIC, Linac, Cyclotron or IPAC conferences. Selected highlights from the presentations in WG-F are summarized below.

INSTRUMENTATION

Challenges in existing and future accelerators [1-3]: Experiences at the LHC were presented [1] providing vital input for the design of instrumentation for future high power accelerators (either high in beam current or in beam energy, or both). This includes all aspects related to avoiding uncontrolled beam losses such as measurements of beam loss and halo, sophisticated collimation schemes and machine protection systems. An outstanding challenge at the LHC pertains to precise measurement of the transverse beam emittances of the high brightness beams. Wire scanners are used for profile measurements at low beam intensities and for cross-calibration of other beam size measurements. These include necessarily non-invasive measurement devices including ionization profile monitors, synchrotron light monitors and transverse Schottky measurements. Under development are synchrotron light-based interferometric measurement and, as shown in Fig. 1, a novel non-invasive beam-gas vertex monitor. Based on concepts used by the LHCb vertex detector, this detector will allow measurement of the absolute transverse profiles using reconstruction of the location of inelastic beam-gas interactions based on particle tracking with coincidence detectors [1].

Multi megawatt accelerators of the future require fast beam loss detection (for damage protection) and high dynamic range (to avoid activation) which demands the use

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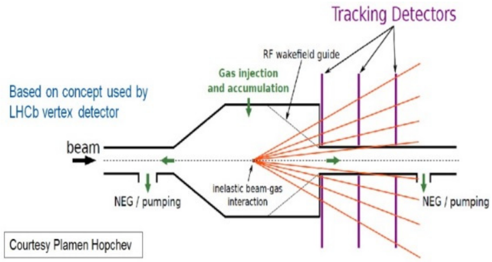
ISBN 978-3-95450-173-1



Courtesy Plamen Hopchev

Figure 1. Novel beam gas vertex monitor being prototyped in the LHC for commissioning in 2015 [1].

of complementary devices to detect errant beams and slow losses [2, 3]. In addition, non-invasive beam profile measurements, both transverse and longitudinal, are needed. Under consideration for transverse profiling at ESS [2] are wire scanners, ionization profile monitors, beam-induced fluorescence monitors, electron beam scanners and possibly gas jets. A challenge unique to FRIB, shown in simulation in Fig. 2, involves the need to monitor and control multi-charge state composite beams in regions of high dispersion [3].

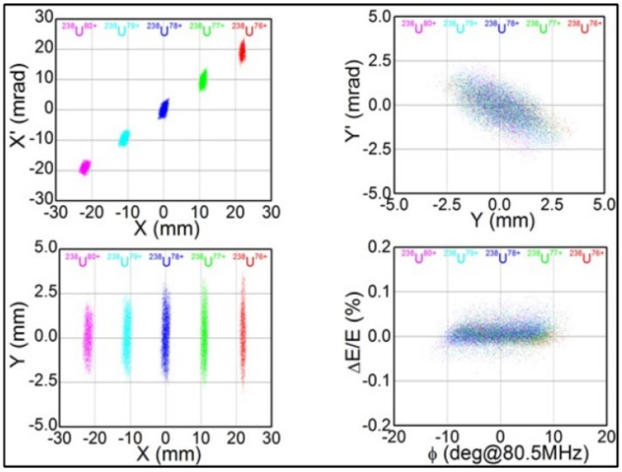


Figure 2. Phase space and physical space for a five-charge-state beam in the first folding segment with high dispersion at FRIB [3].

Developments in simulations of beam loss [4, 5]: New simulation results were presented on the topic of beam losses in high intensity linacs. As applied to IFMIF, a “Particle Swarm Optimization” (stochastic optimization technique), was utilized to optimize simulated transport of high intensity beams through a linac in the presence of multiple, operationally-realistic machine errors.

A "catalogue of detailed losses" was developed using simulations for all phases of accelerator operation [6, 7] at IFMIF and CADS [8]. Low loss tuning strategies aim to use densely placed "micro-loss monitors", such as crystalline CVD diamond detectors, capable of detecting fractional beam losses of <1E-6. While acknowledged that the simulations are not precise at this level, such simulations will be invaluable during commissioning and operation of future high power accelerators.

Developments in simulations of beam loss with comparisons between simulation and experiment [9, 10]: In preparation for LHC operation with 6.5 TeV beams and as partially motivated by recent observations of “unidentified falling objects”, very challenging studies were presented involving comparison of extensive simulations to detailed beam experiments performed to determine thresholds for quench-preventing BLM-based beam-aborts and for determining BLM thresholds for real beam-induced quenches [9]. In the steady-state, quench levels were understood within a factor of two while on the short time scales of UFO-induced beam losses (0.1-10 ms), the comparisons between experiment and simula-tions of particle loss are not yet consistent with those from detailed electro-thermal analyses [9].

On the topic of ion-induced beam losses at the LHC [10], detailed studies of ion beam losses from collimation cleaning were presented. Standard code (ICOSIM) for heavy ion loss map simulation was shown to not explain certain features of the measured beam losses. The agreement between measurement and simulation was signifycantly improved, as shown in Fig. 3, using SixTrack with ion-equivalent proton rigidities and a very detailed simulation of fragmentation [10].

Beam halo considerations including definition [4, 11]: With accelerator designs aiming for increased total intensity and/or beam energy, unintentional beam losses become even more important as even a very small fraction of the total beam can lead to component damage and/or practical difficulties related to serviceability of accelerator components. Particles not following the design trajectory and/or not having design beam focussing properties may eventually contribute to the “beam halo” and cause unintended beam loss.

The sources of beam halo fall into two categories [11]: those with unavoidable physical origins (such as space charge, beam-gas scattering in an imperfect vacuum) and those of practical origin as resulting for example from small deviations from design parameters (e.g. errors in magnet alignment, parameter mismatches both transverse and longitudinal between linear and circular accelerators) and consequences of external perturbations including noise in power supply currents, rf cavity voltages, environmental factors leading to vibrations in component position, etc. Many diagnostics have been implemented world-wide to enable detection of the beam profile over a wide dynamic range to include measurement of the beam halo. A broad overview was given in Ref. [11].

A topic of ongoing discussion concerns how to quantify beam halo. Methods used in the past for characterization include definition in terms of the kurtosis of the density profile, ratio of halo to core, ratio of beam core to offset and the Gaussian area ratio method [11]. Recent work with focus on high power beam transport in linear accelerators offered a new measure of beam halo: definition of the core-halo limit as the location of biggest

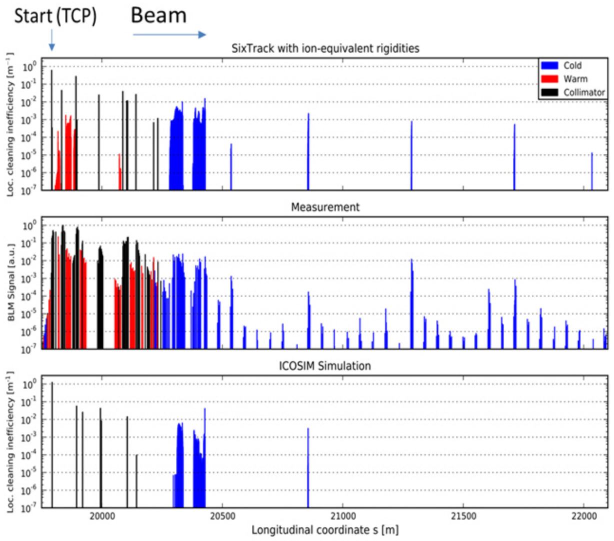


Figure 3. Simulations of ion beam losses in the LHC before (bottom) and after (top) code refinements compared with measurements (middle) from Ref. [9].

slope variation in the beam density profile, e.g. where the second derivative of the density is a maximum [4]. Concerning future designs, the need for clear specifications for the required measurements was emphasized and these should be agreed upon by accelerator physicists, collimation experts and beam diagnostics specialists [11].

Beam halo dynamics in linear transport lines [4-8]: As shown in Fig. 4, results from the Particle Swarm Optimization (see developments in simulations of beam loss above), revealed that off-axis particle transport (beam "halo") could be minimized at the expense of non-preservation of the rms beam emittance, an observable often used as a measure in quantifying the efficiency of beam transmission. This simulation results are not inconsistent with beam tuning experiences at the SNS [4].

Beam halo dynamics in circular accelerators [12]: Simulations and experimental results of beam halo diffusion and population density in the Tevatron and the LHC were presented. As a function of normalized action, measured diffusion coefficients were measured for both colliding and non-colliding beams at the Tevatron and the LHC, as shown in Fig. 5. At the LHC with collisions, the diffusivity was reported to be consistent with emittance growth. At the Tevatron, by comparing data with antiprotons only and colliding beams, the measured diffusion coefficient revealed a 1-2 order of magnitude increase attributed to the beam-beam interaction. In a separate set of measurements utilizing a hollow electron beam in the electron lens at the Tevatron, the measurements of diffusion coefficient versus vertical collimator position revealed what is believed to be a first time direct observation of controlled diffusion enhancement in a specific amplitude range.

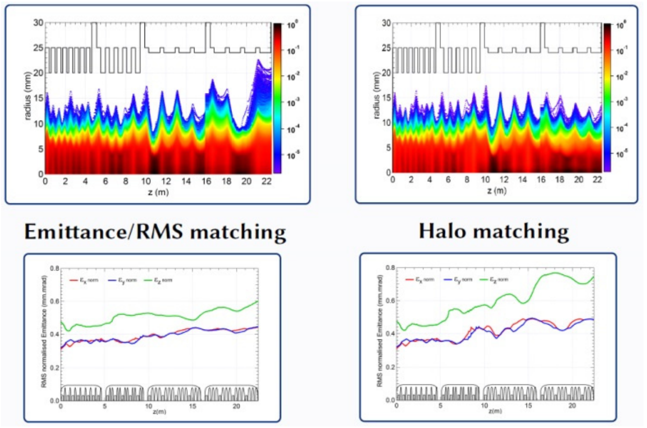
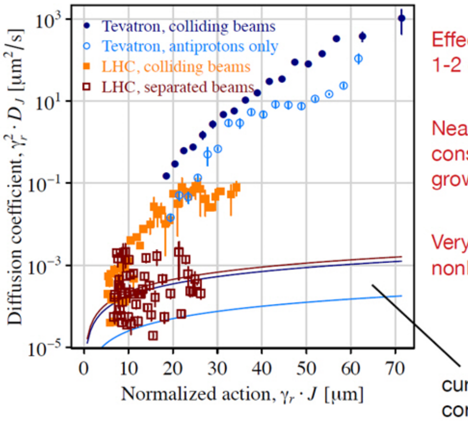


Figure 4. Simulation results (Particle Swarm Optimization) for the IFMIF linac [4, 5].



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

$D_J = \dot{\varepsilon} \cdot J$

Figure 5. Measurements of beam halo diffusion rates in the TeVatron and in the LHC [12].

Developments in combined beam core and beam halo diagnostics [11, 13-15]: Qualitative measures of the portions of the beam contained within the undesired beam "halo" require absolute calibration most easily determined by additional measurement of the beam core (defined here as those particles contained within the area of interest).

From J-PARC two diagnostics each combining different measurement techniques provide large dynamic range [13-15]. From the J-PARC rapid cycling synchrotron (RCS), with results shown in Fig. 6, scintillator-based measurements of the beam core were combined with data from wires applied as scrapers to sample the beam halo and a portion of the beam core. With this topology, a dynamic range of 1E4 was demonstrated [13].

Also from J-PARC, state-of-the-art high dynamic range beam profile measurements were presented using beams extracted from the RCS prior to injection into the J-PARC main ring [15]. The beam core was measured using optical transition radiation from a thin (10 μm) Titanium

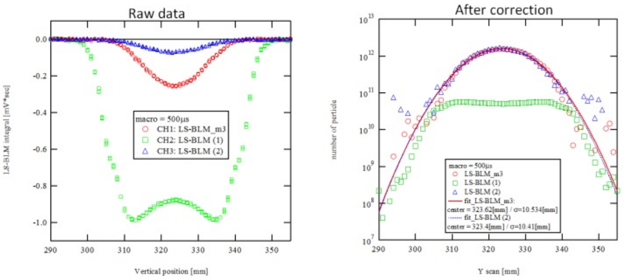


Figure 6. Measurements of beam core and halo from the J-PARC RCS [13].

foil while the beam halo was measured using fluorescence from a chromium doped Aluminum screen. Measurements (see Fig. 7) demonstrated >1E6 dynamic range achieved by this composite diagnostic. This device is unique in that it measures the two dimensional distribution of the beams as shown in Fig. 8. The measurements revealed different properties of the beam core and halo depending on the details of the beam injection scheme (target admittance of phase space painting). From Figs. 7 and 8, more than six orders of dynamic range for the projected profile have been reached and four to five orders for the two-dimensional profile.

Another beam halo diagnostic: the electron back–scattering detector [1, 11]: Numerous presentations included mention of a relatively new development, presented first at IBIC14 [16] with adaptation aspects presented at the Beam Halo Workshop [17]. This novel detection concept utilizes Compton backscattered electrons generated by grazing collisions between a hadron (proton or ion) beam and an electron beam provided in this application by an electron lens. Recent data from RHIC confirmed more than sufficient measurement sensitivities with counting rates consistent with expectation. The design features an elegantly simple detection technique (scintillators and photomultipliers) and has provided already meaningful data derived from beam-gas scattering. The concept is being considered for use as an option for the HL-LHC together with the hollow electron lens design from the Tevatron [1].

Other non-intercepting beam diagnostics [18, 19]: Recent developments in ionization profile monitors were presented as relevant in the context non-invasive beam size monitoring at the LHC. Simulations showed that the electric field of the proton beams perturbs the to-be-collected electrons (those released in the ionization process) at high particle beam brightness. To combat this, an electron "sieve" will be used to filter out electrons of different gyration radii. This should allow for a correction of the disturbance. In addition, the Timepix3 ultrahigh bandwidth, radiation hard, hybrid pixel detector developed at CERN (CERNs Medipix chip) will be used to enable bunch-by-bunch beam profile measurements.

A concept and simulations for an improved version of an existing beam current monitor at PSI were presented [20, 21]. The device, presently under construction, will be used in a location with high heat load from secondary particle showers. It is based on a low-Q resonator made from graphite. The new design with increased and fixed gap width should be less sensitive to drifts caused by unequal thermal expansion [20, 21].

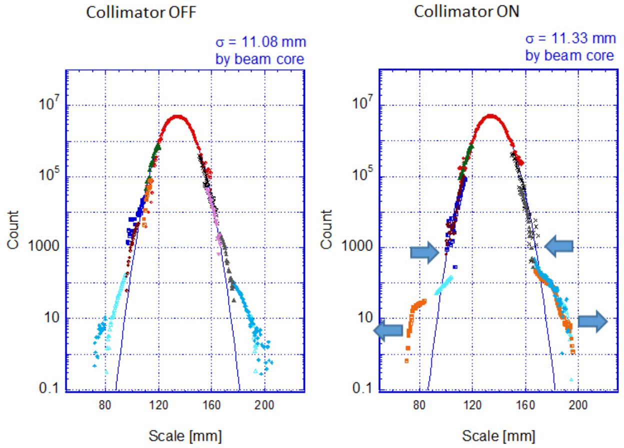


Figure 7. Horizontal projections from a high dynamic range beam profile monitor from J-PARC [14].

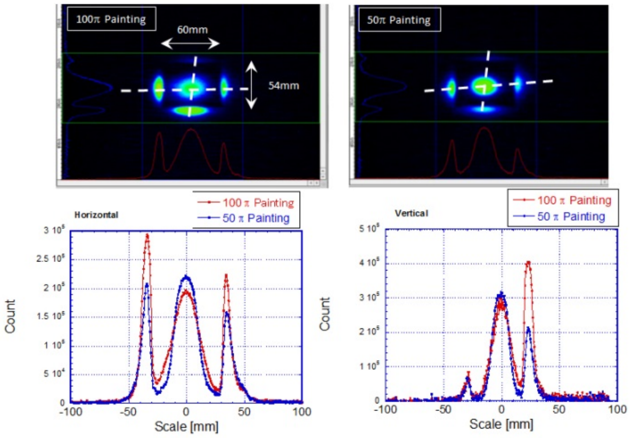


Figure 8. Measurements of the two-dimensional beam profile including the beam core and beam halo in a wide dynamic range diagnostic developed at J-PARC [14].

BEAM MATERIAL INTERACTIONS

The consequences of impact of high-intensity or/and high-power hadron and heavy-ion beams – or just their fraction – on components of accelerators, beam-lines, target stations, collimators, absorbers, detectors, shielding, and environment can be quite severe or even catastrophic. Depending on material, level of energy deposition density and its time structure, one can face a variety of effects in materials under irradiation affecting their lifetime (melting, thermal shocks and quasi-instantaneous damage; critical property deterioration; and radiation damage to inorganic materials due to atomic displacements and helium production) and component performance (superconducting magnet quench; single-event effects in electronics; detector performance deterioration as well as radioactivation, prompt dose and impact on environment).

Therefore, these effects along with the progress towards the ways to mitigate and model these are traditionally considered at the HB workshops. Three original talks were presented at this one followed by discussions.

Material response to high power beams [22]: The techniques to measure and characterize changes of material properties under intense beam impact were described for the three states of targets. For solid materials, the key phenomenon is material stress. The studies include its minimization via target segmentation, avoiding the stress concentration, compressive preloading, optimization of beam size/shape, and appropriate material choice. The characterization of the materials is done via a stress quality factor. Direct measurements of material strength are done at the Stress Test Lab at RAL. These include dynamic measurements as well as studies of material fatigue. The example that illustrates the latter phenomenon is the proton beam window for the ESS beams. The fatigue is related the peak power deposition of 0.5 kW/cm^3 under a pulsed operation at 14 Hz. Al6061-T6 was found to be the preferred material for the window cooled by Helium at 10 bar.

A second state of the target is liquids. A typical representative of this type is flowing mercury used at the Spallation Neutron Sources. A quite interesting technique was developed at J-PARC for the in-situ measurements of vibration induced by a proton beam. The bubbling mitigation effect on pressure waves was confirmed in these studies. A third type of targets – between solid and liquid – is studied at RAL for the fluidized tungsten powder recirculated in helium pneumatically. The advantages of this technique are that material is already fragmented, there is no cavitation, thermal stress is contained within grains, and the target can be continuously reformed, pumped away and externally cooled.

DPA and gas production in intermediate and high energy particle interactions with accelerator components [23]: A brief overview of recent developments in modelling primary radiation damage relevant to Displacement-per-Atom (DPA) calculations was presented. Problems and perspectives of advanced radiation damage and gas production calculations at intermediate beam energies were also discussed. The author has described the key features of the existing approaches to estimate the number of stable defects. The methods include:

- Norgett, Robinson, Torrens (NRT) model, widely used as is or with various corrections.
- Binary collision approximation (BCA) model.
- Molecular dynamics (MD).
- MD extrapolation to high energies using various assumptions.
- BCA-MD combination with BCA used above a critical energy (~30-60 keV) and MD below this energy. Similar to NRT, this method is easily implemented in Monte-Carlo particle transport codes.
- Kinetic Monte Carlo (KMC), a promising method to simulate the long-term defect evolution.

Although quite different with respect to capabilities, complexity of code implementation and accuracy of predictions, the methods find their ways in numerous applications related to material damage by high-intensity beams.

At accelerators, radiation damage to structural materials is amplified by increased hydrogen and helium gas production for high-energy beams. In SNS-type beam windows, the ratio of He/atom to DPA is about 500 of that in fission reactors. These gases can lead to grain boundary embrittlement and accelerated swelling. 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 approaches for advanced calculation of gas production rate, certainly at intermediate energies. The database created at KIT includes 278 targets from ^{7}Li to ^{209}Bi, and incident proton energies: 62, 90, 150, 600, 800, 1200 MeV.

Novel materials for collimators at LHC and its upgrades [24]: This presentation was focused on materials for one of the most critical and – at the same time – very challenging components of the Large Hadron Collider (LHC), its beam collimation system. The following key properties of the materials are to be optimized to meet the LHC operation, performance and lifetime requirements:

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

It is realized that no existing material can simultaneously meet all the requirements. Therefore, the extensive R&D program on novel materials has been launched at CERN in collaboration with EU institutes and industries (EuCARD,

ISBN 978-3-95450-173-1

EuCARD2 and HiLumi). Its aim is to explore composites combining the best properties of graphite and diamond with those of metals and transition metal-based ceramics (high ultimate strength and good electrical conductivity). Materials investigated include Copper-Diamond (CuCD), Silver-Diamond (AgCD), Molybdenum-Copper-Diamond (MoCuCD), and Molybdenum Carbide-Graphite (MoGr). Production techniques include rapid hot pressing, liquid phase sintering, and liquid infiltration. It has already been found that the most promising ones are CuCD and (especially) MoGr.

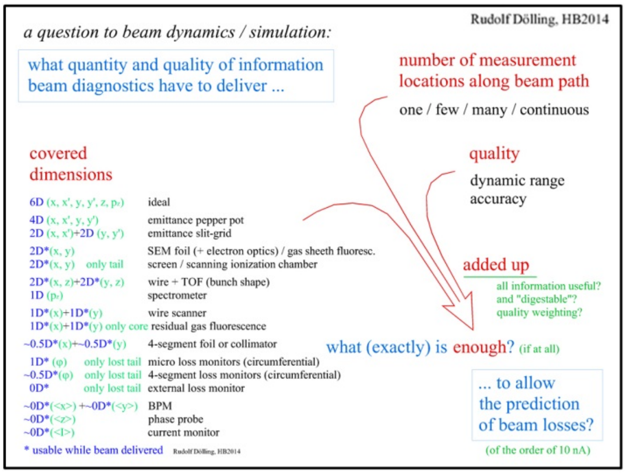
To compare and rank materials against the most relevant requirements, several Figures-of-Merit (FOM) have been derived. These are: (a) Thermomechanical Robustness Index (TRI) related to the ability of a material to withstand the impact of a short beam pulse; (b) Thermal Stability Index (TSI) related to the ability of the material to maintain the geometrical stability of the component under irradiation; and (c) Electrical Conductivity, with resistive-wall impedance being inversely proportional to electrical conductivity and therefore the highest electrical conductivity is sought for materials sitting closest to circulating beams.

The highlights on the comprehensive beam test program have been given which include HiRadMat at CERN with 450-GeV protons, GSI with 10 MeV to 1.2 GeV ion beams ranging from carbon to uranium, and BLIP at BNL with 100 to 200 MeV proton beams.

The Beam-Materials Interactions session was wrapped-up by discussions. It was stressed that material response to the beam impact depends on variety of factors: material, level of energy deposition density (EDD), its time structure, environment and many others. The issues and questions were outlined such as quantities responsible for radiation damage (DPA, gas production, fluence and dose), as well as model/code capabilities and uncertainties in prediction of these values. It was stressed that the link of calculated values to observable changes in the critical properties of the materials remains on the top of the wish-list. The group has agreed that the 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.

BEAM INSTRUMENTATION DISCUSSION SESSIONS

During the first shared Instrumentation and Beam Dynamics discussion session P. Nghiem presented more on the topic of beam halo definition, which resulted in lively discussion. Next, the slide shown in Fig. 9 was used to introduce the topic of what types and quality of measurements, including correlations, would be most desired for furthering and validating simulations. Topics discussed included the types and numbers of measurements needed to predict subsequent beam loss and the degree of coordination between simulations and experiments as desirable to motivate specifications for instrumentation requirements and new instrumentation designs.



Rudolf Dölling, HB2014

a question to beam dynamics / simulation:

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

number of measurement locations along beam path

one / few / many / continuous

quality

dynamic range
accuracy

covered dimensions

6D (x, x', y, y', z, p_z)		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 fluoresc.
2D*(x, y)	only tail	screen / scanning ionization chamber
2D*(x, z)+2D*(y, z)		wire + TOF (bunch shape)
1D (p_z)		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* (φ)	only lost tail	micro loss monitors (circumferential)
~0.5D*(φ)	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*(<I>)		current monitor

* usable while beam delivered Rudolf Dölling, HB2014

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)

Figure 9: A very general and simple question. Answers, seemingly elusive, could help focus further developments in beam diagnostics (and simulations).

During the second discussion session, a by-request presentation by P. Hermes on the topic of comparisons between measurements and simulations as well as developments in simulation strategies for heavy ion beams in the LHC was presented (see developments in simulations of beam loss with comparisons between simulation and experiments, above). In the short amount of time remaining, two questions were posed. The first, raised by Working Group A, Beam Dynamics in Circular Accelerators, concerned the ability of beam diagnostics to discern space-charge related effects from beam instabilities. Responses pertained to beam loss minimization (difficult with instabilities that saturate) and impedance detection (coherent oscillations). The second provocative question concerned whether or not simulations of beam loss for future accelerators are sufficiently mature so as to guarantee successful commissioning and operation of future multi-Megawatt accelerators. The often cited specification of beam loss at the level 1E-6 and energy loss levels of 1 W/m were stated, by the conveners with audience corroboration, as too general.

For these discussion sessions topical questions (http://frib.msu.edu/misc/hb2014/QuestionABCF.html) were distributed in advance of the conference soliciting input. This strategy was marginally (at best) successful, maybe because of the many different backgrounds (machines, reasons for halo formation, interests and ways to consider these topics) which makes it more difficult to find a common starting point. (However, this is at the same time a potential source for collaboration and finding fresh views.) It remains the feeling that the organisation of these sessions must be improved in order to use the precious time similar effectively as it is done in the many bilateral

ISBN 978-3-95450-173-1

discussions during coffee or other "unplanned" times, and that we have not yet found the optimal Ansatz.

OTHER

As topics in beam instrumentation and dynamics were presented in many other talks – both plenary and in the parallel working group sessions - this report, regrettably, does not include all great contributions to this conference. Pertaining to a subset of that, select additional important findings from the conference includes:

- The success of the LHC collimator design (with 100+ collimators) is truly noteworthy with no unintentional quenches to date. The design methodologies should be kept alive and, if not already done, applied to collimation system designs for future accelerators.
- Experience from existing high power accelerators shows that reliability may be compromised by not anticipating or realizing the impact of certain physical phenomena with examples including SNS (space charge, intrabeam stripping), LHC (unidentified falling objects, electron clouds)
- Safety margin criteria for future accelerators are often cited in terms of figures of merit (maximum permissible beam loss = 1E-6 of total current, maximum power deposition of 1W/m). These are too general and should not be interpreted as specifications by engineers.
- A fractional beam loss is not a good measure for a safety margin, rather the total absolute beam loss and/or total power deposition.
- The available computing power was considered a limiting factor for understanding beam halo transport in the past. With today's technologies, is this still the case? Has our understanding of beam halo improved commensurately? Do we think to still 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": perhaps need to expand to multiple definitions which depend on context, definition of dynamic aperture also in question.

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ISBN 978-3-95450-173-1