

Diagnostics Summary – Working Group T9

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I. Survey of Machines

The diagnostics T9 group was charged with reviewing the diagnostic requirements of the proposed accelerators for the future. The list includes the e+ e- colliders, Muon Neutrino source, NLC, Proton Driver, Tesla, and the VLHC. While the machines vary widely on diagnostic requirements, there are many similarities that were discovered. The following sections will attempt to point out the similarities and requirements for R&D for these future accelerators.

To answer the Charge to the group we organized joint sessions with most of the machine groups and several of the technical groups. In addition, due to their overwhelming importance, we held a special session on position monitor systems. For each of the joint machine group sessions we generated a table of required diagnostic systems, selected the highest priority items using a ranking based on need and RD effort, and pondered a RD path leading from the present state of the technology to a system satisfying the requirement. We used the joint technical group sessions to collect up to date RD plans and to assess the applicability of new ideas in a broad range of topics. As required by our Charge, we have also tried to include promising new ideas.

As can be seen from the comments below, there is ample opportunity for the accelerator community to work together on common challenges. In the current era of political competition, this may prove difficult. Nonetheless, cooperation and exchange of ideas should be strongly encouraged. It was clear from all of the presentations and discussions that all of the future projects are short of sufficient funds and resources. For the continued health of the high energy physics accelerator community, a strong spirit of collaboration should be fostered.

II. Common diagnostic requirements.

Luminosity, beam current, beam power, beam size, duty cycle, peak RF gradients, magnetic fields, of all the machines of the future exceed those of present operating machines by as much as one or two orders of magnitude. Most of the machines have extensive lengths of beam pipe or power delivery systems that extend hundreds of kilometers. The beam energies involved are impressive and have the power to melt beam pipes or anything in their way with just one pulse. This makes the role of diagnostics a challenging one in that they are no longer just a means of commissioning and trouble shooting accelerator operations, but also fundamental to the protection of personnel, environment, and accelerator hardware.

Certainly the list of conventional BPMs, profile scanners, beam current monitoring, and longitudinal diagnostics exist for each of the machines. Due to the large physical size of many of the proposed future accelerators, the number of channels of such conventional diagnostics is substantially larger than current installations. As such, reliable engineering is required to sustain system performance. In applications that require protection of personnel or the environment, redundant systems will be necessary. A level of engineering reliability approaching that of a "NASA" type system may be required. A case in point might be the beam diagnostics required for the NuMI project at Fermilab. The restrictions of activation of the groundwater for a lost beam pulse are on the order of one or two pulses of beam at full current. Such a beam loss could shut down operations for weeks. The diagnostics for such a system play a vital role in the operation of the machine. Beam powers of the future accelerators dwarf those of the NuMI project. Will the HEP community be able to afford the reliability value engineering that goes into the space program? With all the talk of a "global" accelerator network, reliability will be of paramount importance. The accelerator community has not operated on the high quality control level required for such extensive systems in the past because it is cost prohibitive. It may be a good idea to investigate what has been done in the space programs and perhaps the communications industry. If one were to extrapolate current reliability data for operational HEP facilities and add the appropriate multiple for a larger installation, it is clear that the up time of any such facility would be dismal. Fermilab data shows a typical percentage "up time" of approximately 65% of that scheduled. A linear collider or large hadron facility ten times the size of Fermilab would then yield a comparable "up time" of 1-2% if system reliability were not improved. This is not an acceptable value considering the expense of operating such large accelerator complexes.

For most of the accelerator installations, an extensive amount of diagnostics must be located in potentially high radiation areas of the tunnel. There are plans for installing hardware in caverns excavated into the tunnel walls. Issues associated with power distribution, heat dissipation, and communication links must also be addressed. This is an area where all the machine design groups could benefit from collaboration. Diagnostics specialists should consider having a workshop specifically to address this problem. Work this early in the design process could easily save each of the collaborations considerable time and expense.

The precision and resolution of the diagnostics have been defined by the machine designers, but with little input or feedback from the diagnostics designers. This lack of symbiotic approach has led to shortcomings that will be difficult to overcome once the machines are built. One example is the space provided for beam diagnostics in the Muon cooling channel for the neutrino source. Once the RF and target designs are proposed, the space left for diagnostics is on the order of one inch of longitudinal space in the lattice. That space is also further restricted by the fact that it is in an intense magnetic field at a temperature of 20 deg K. Historically, the accelerator physics community has handed down specifications for diagnostics without consulting the engineering community that has the expertise of executing the designs. This appears to continue in the design of new accelerators. Technical reviews of design specs and machine requirements should take place well before requesting project funding.

Many of the proposed new diagnostics are quite complicated devices in themselves. From the operational aspect of the machine, the diagnostics cannot be an "experiment" that requires as much tender loving care as the accelerator itself. A case in point is the use of laser wires. The need for non-intercepting profile monitors is universal. Laser wires are a demonstrated technology, but one that has also proven to be finicky. Linear colliders of the future will require tens of channels of such diagnostics. They would be critical to performance and quite a challenge to keep operational. Diagnostic designers also tend to add numerous features that may look attractive, but in actual operations are only applicable by the designer himself. With the advent of cheap digital signal processing, designers tend to lean toward "highly flexible" architecture for their signal processing needs. The amount of software support necessary to maintain such systems is substantial. While such systems do yield to changes, they should not be a substitute for good thorough initial design. These large accelerators of the future will need to be simple by design so that all diagnostics are available to the commissioners at all times.

The data collection and communication systems will need to have considerable bandwidth. Thousands of channels of BPMs or profile monitors will need to be networked with countless feedback loops. This could be a control engineer's dream or nightmare depending on the implementation. The communications industry has opened a world of enormous bandwidth by utilizing fiber optics. Unfortunately, much of the area necessary for data collection is in the radioactive regions of the accelerator enclosure where fiber optics have a limited lifetime. Some R&D for high bandwidth data collection should be initiated, as it would serve each of the new proposed accelerators.

III. Commissioning

Almost uniformly, each of the proposed machines has not prepared an extensive commissioning scenario. This shortfall will mean that the required diagnostics may not be available when startup commences. Each of the future accelerator collaborations should assemble a commissioning team early in the development process. Most of the "what if ..." questions associated with commissioning should be posed and addressed. This is routinely done for magnet, power supply, cryogenic, RF, vacuum systems and the like. For some reason, the accelerator community does not take commissioning as seriously as the accelerator hardware. This must change in the future.

Historically, diagnostics have not been given the priority of other accelerator systems. Diagnostics critical to commissioning are often not necessary on a daily operational basis in current accelerators, hence, they are de-emphasized. When budgetary limitations are imposed, diagnostics are the first system to be cut. A case in point might be the Recycler ring at Fermilab. The diagnostics in that machine were minimal at startup due to such budgetary constraints. The result has been very slow commissioning progress some two years after first beam. These future machines will more than likely require all of the system diagnostics on a daily basis. Whether there are alignment

problems from ground motion or finesse required to keep beams in collision, the diagnostics will be on line full time.

With beam powers capable of rupturing the vacuum system, pilot beam pulses orders of magnitude below design operation values will be used initially for commissioning. The diagnostics hardware will be expected to perform with the same precision and resolution, making strong demands on hardware dynamic range. Detailed analysis of precision monitoring versus beam currents must be part of the diagnostic specifications. High precision is always necessary at full beam current, but what value is tolerable for startup? Understanding the perceived dynamics of the diagnostics systems should not be delayed to the time when the first beam pulses provide the clarity of this important point.

IV. Focus

All of the proposed machines have focused on main subsystems such as RF power sources, accelerator structures, magnets, ... Each of these areas are consuming most of the monies and resources. Before the conceptual design report is completed, similar attention must be given to diagnostics. The costs associated with each of the proposed accelerators are larger than anything the field has experience. These large machines will also be very expensive to operate. A strong diagnostic system will allow for the most efficient use of the funds allocated to future projects. Time is money, time saved is valuable, and time to invest in diagnostics is at the beginning. The historical "cowboy" approach to commissioning is not viable for such large installations.

There is also a need to do substantial prototyping of the hardware. Once prototypes have been built, they will need to be tested in environments that simulate the future machines. This means putting hardware in radiation environments, high magnetic fields, cryogenic environments, and commensurate beam tests. Some of these tests will necessitate the use of current operational accelerators or beam experiments. HEP should invest in the future by accommodating requests for such specific testing.

Accelerators of the future will take full advantage of the experience of building the machines of the past. What must change is the attitude toward accelerator diagnostics. Repeating the "sins" of the past will certainly have serious consequences for the success of HEP in the 21st century.

V. Recommendations for research and development

Although the linear collider (LC), with its emphasis on small beam sizes and extensive use of beam instrumentation based feedback, makes the heaviest use of beam diagnostics of all of the reviewed machines, it is not far removed from them. Experience with third generation synchrotron light sources, some of which have been operating for almost ten years, has shown that the role of beam diagnostics has become central in machine design and operation. Even the term 'diagnostic', which implies revealing a shortcoming or failure of some sort, is misleading because it de-emphasizes the level of integration that such systems have in all modern machines. In this context, 'integration'

refers to the software and hardware that bring the position monitor data, calibration and control into the control system at large. See recent review publications (SLAC PUB 8437 May 2000).

At the prototype linear collider SLC, most of the position monitors downstream of the damping rings, where emittance propagation is critical, were used in a feedback or monitor loop. The primary purpose of the loops was to maintain stability so that higher level, more complex beam optics optimization could be done without concern for basic trajectory stability problems. In order to achieve the best possible performance of the profile monitors, (wire scanners in the case of SLC), a close connection to the position monitor system was required.

In the case of the Spallation Neutron Source, scheduled for completion in 2005, nearly 20 years after the completion of SLC construction, diagnostic devices are intended to provide insight into high power proton linac beam halo generation and propagation. Indeed, almost 70 such devices are planned along the 1 GeV linac.

The two examples given illustrate the two primary metrics used to assess the potential value of the instrument systems presented. Namely, 1) the extension of machine performance based directly on the use of highly integrated instrumentation systems and 2) the furthering of understanding of perceived critical technical limits. A good example of 1), the LC must include instrumentation performance expectations in the design in order to relieve tight tolerances on mechanical and high power RF systems. High power proton linacs are a good example of 2), where diagnostic RD will prove vital and innovative diagnostic technology will provide insight into present performance limits, paving a path to future high(er) performance machines.

In view of the focus of the Snowmass 2001 meeting, we start with an evaluation of LC diagnostics.

1. Linear Collider

The linear collider requires precision diagnostics because of its small beams and pulsed operation. Key parameters used to describe performance requirements are 1) resolution, indicating signal to noise and smallest detectable change, 2) accuracy, indicating measurement performance with respect to an external standard and 3) stability, indicating the rate at which re-calibration procedures should be performed. The most expensive and most highly integrated instrumentation subsystem is the beam position monitor (BPM), with several thousand of various types required. BPMs perform the function of intensity monitors as well. Next on the list, in terms of importance, is the transverse profile monitor system, used basically as a predictor of luminosity and a monitor of emittance propagation. The last system that completes the basic set is the bunch length monitoring system that is also used for understanding emittance propagation problems. More specialized instruments provide 1) details of the beam-beam interaction, 2) beam x - y , y - z , E - z etc. correlation data, 3) insight into damping ring physics and 4) beam loss data. A summary of next generation linac instrumentation requirements can be found in SLAC-PUB-8826 (May 2001).

A. BPM requirements and technology

The LC BPM system is the cornerstone beam instrumentation system. Compared with existing BPM systems at, for example, SLC or high intensity B-factory rings, the BPM system must 1) perform to tighter specifications, 2) include internal diagnostics and 3) be much more reliable. With regard to the latter, it can be shown that beam based feedback and alignment processes are easily fooled by incorrect or corrupted input from the front end BPM system. While it is possible to evaluate and model the impact of simple failures such as missing data or poorer than expected resolution on the higher level processes, it is harder to estimate the impact of various complicated failures or data corruption. Perhaps more importantly than the above system-specific issues is the question of integration. In addressing this, experience from third generation light sources, factories and the SLC is insufficient due to the significantly increased requirements.

It is probable that several types of BPMs will be required for an LC. At NLC, four systems were presented, intended for use 1) to correct magnetic alignment, 2) to correct structure alignment, 3) to correct bunch-to-bunch offsets, within the train and 4) for the damping ring. For TESLA, with 337 ns interbunch spacing and somewhat reduced resolution performance requirements, the technology is somewhat different. For both NLC and TESLA, however, there appear to be no fundamental limitations that would prevent operation of any of the systems.

Research and development for BPMs is urgently required to prove technological choices and provide an experience base from which to develop a mature system. It is important to note that it may matter little if a final system flaw results from a fundamental limitation of a chosen technology or an underlying engineering error; the cost to fix it may be the same. Table 1 lists technical challenges for both NLC and TESLA.

Table 1: Technology issues for LC BPMs

Problem	System	RD needs	TESLA/NLC
Micron long term stability	Magnetic alignment	Also needed for B-factories	Both
Micron to submicron resolution	All except structure	micron stability beams (ATF)	Both
High bandwidth multibunch	Bunch to bunch intra-train correction	stable multi-bunch beams (B factory/ATF)	NLC
Structure HOM	Structure BPM	define system signal processing	NLC
Cryogenic interface /cleanliness requirements	TESLA linac	Determine construction / testing techniques	TESLA

Table 2: NLC QBPM system requirements (used to do Quad alignment).

Parameter	Value	Conditions
Resolution	300 nm rms	@ 10^{10} e ⁻ single bunch
Position Stability	1 μ m	over 24 hours (!)
Position Accuracy	200 μ m	With respect to the quad magnetic center
Position Dynamic Range	± 2 mm	
Charge Dynamic Range	5×10^8 to 1.5×10^{10} e ⁻ per bunch	
Number of bunches	1 - 95 or 1 - 190	
Bunch spacing	2.8 ns or 1.4 ns	

Requirements for the NLC linac Q-BPM system, to be used for magnet beam-based alignment (BBA), are summarized in Table 2. BBA will take some time and will most likely not be possible during production operation. In order to address the most difficult requirements (resolution and stability), a cavity-based monitor has been proposed. Stripline monitors, proved at FFTB to 1 μ m resolution, were rejected because of the large common mode signal and because of mechanical complexity. Cavity BPMs may provide much better resolution, even beyond the required 0.3 μ m.

TESLA BPM system requirements are based on a similar assessment of BBA. Because the beam line apertures are larger, the requirements are somewhat relaxed compared to NLC. The TESLA group has tested cavity BPMs at TTF with resolution approaching that required for the main linac.

Challenges for cavity BPMs are: 1) suppression of the common mode using mode-selective coupling antennas or an external circuit (or both), 2) minimization of the long range wake effects of the BPM cavity on the beam, 3) manipulating high frequency signals locally, (in moderate to high radiation areas), and 4) operation in cryogenic systems.

Multi-bunch BPMs are to be used to determine bunch to bunch differences due to, for example, DR beam loading or long range wakes. The requirements for TESLA are much easier to meet because of the large bunch spacing. Report TESLA-2000-41 describes the tests. Tests of an NLC multi-bunch prototype have begun using the 2.8 ns spaced bunches at KEK ATF (ATF internal report ATF-00-17). The prototype relies on a high sampling rate digitizer, similar to those found in modern high performance digital oscilloscopes, and it is this component that appears to be the most serious impediment to achieving the desired performance.

Successful RD proving the principle of structure BPMs has been done at ASSET. The tests relied upon laboratory instrumentation. RD is needed to determine limits in resolution and appropriate electronics.

As noted above (section II) the problem of housing and shielding tunnel electronics and cable connections is common to other proposed projects, such as VLHC.

B. Profile Monitor requirements and technology

Transverse profile monitors fall into two categories: 1) particle density samplers (e.g. wire scanners) and 2) optical devices (imagers of phosphorescence, transition radiation or synchrotron radiation). They complement each other in several ways.

The beam size in an LC is a critical operational parameter. In practice, once the machine is built, the beam size is controlled more effectively (and also requires more attention) than other parameters such as intensity or repetition rate. Since there is no transverse equilibrium condition in a linac, $\sigma_{x,y}^*$ (* means at the IP) is determined by the beam source and the sum (or product) of dilutions in the acceleration and delivery system. The primary function of the transverse profile monitor is as a predictor of $\sigma_{x,y}^*$. Second, implemented in groups along the linac length, they can be used to determine sources of emittance dilution.

Given the sparse distribution of profile monitors it is difficult to verify their performance. In contrast, the ubiquitous BPMs can be used to cross check each other and can be compared with the expected beam motion from magnetic field changes. Techniques for verifying profile monitor performance include 1) redundancy, 2) using the centroid motion as a BPM, 3) comparing monitors built with different technologies and 4) use of flexible beam optics for producing a variety of beam conditions. A good example of the implementation of these checks can be seen at the KEK ATF where a sequence of five wire scanners is used for measuring $\epsilon_{x,y}$.

LC requirements for precision and durability force the use of laser-based profile monitors (laserwire). The combination of small beam size and large aspect ratio make the readily achievable laserwire resolution greater than $\sigma_y/3$ unless a very short wavelength laser is used. In contrast to the conventional wire scanner, used extensively at SLC, the laserwire has an optical waist and therefore does not sample the particle beam with a cylindrical uniformity. This problem, illustrated in Table 3, is common to all LC designs. The table, done for only select locations, must be completed in order to evaluate the optics and the required laser performance throughout the machine. From the point of view of the LC design, it is clear that there are fundamental beam size monitor performance questions, for each design (NLC, TESLA, and CLIC), that must be addressed with RD. Laserwire limitations may force the use of dedicated particle beam optics systems. If this were true, it would greatly reduce the flexibility of the monitor by restricting its use to very few parts of the LC.

Profile monitor RD is needed for other devices, some of which are promising new technology: 1) Optical Transition Radiation (see section 6) has been used to image beams well below 10 μm at the KEK-ATF (ATF Internal report ATF-01-05), ODR (diffraction radiation similar to transition radiation but without an actual impacted target), and 2) X-ray interferometry may be useful down to IP sizes.

Table 3: Laserwire parameters for various systems and locations, normalized to the detectable scattered Compton signal. Resolution of ‘s_y/2’ ($\sigma_y/2$) is unacceptable.

Laser Wires, Power scaled to produce 1000 scattered photons						
	CLIC	NLC	TESLA	TTF2	PETRA	ATF
E [GeV]	500.00	250.00	250.00	1.00	4.50	1.28
N [10⁹]	20.00	20.00	20.00	6.00	5.00	6.00
#Bunches	154.00	95.00	2820.00	2820.00	40.00	1.00
s_x [um]	3.40	7.00	20.00	55.00	300.00	50.00
s_y [um]	0.34	2.00	2.00	55.00	30.00	5.00
For Resolution = s_y / 2						
lambda [nm]	53.41	532.00	355.00	1064.00	1064.00	532.00
w_o [um]	0.17	1.00	1.00	27.50	15.00	2.50
2*y_R [um]	13.60	47.24	70.80	17863.38	5314.72	295.26
f#	6.37	3.76	5.63	51.69	28.20	9.40
P [MW]	19.40	1.59	2.94	21.82	14.72	4.02
For Resolution = s_y / 5						
lambda [nm]	8.55	143.62	50.27	1064.00	532.00	125.66
w_o [um]	0.07	0.40	0.40	11.00	6.00	1.00
2*y_R [um]	13.60	28.00	80.00	2858.14	1700.71	200.00
f#	15.92	5.57	15.92	20.68	22.56	15.92
P [MW]	497.01	11.45	68.26	19.90	27.85	16.61
Calculations by Thorsten Kamps						

C. Bunch Length Monitor requirements and technology

No adequate bunch length monitor is available. An accurate, conservative design using transverse deflection cavities exists but is expensive (SLAC-PUB-8864). RD is needed to evaluate parameters, determine applicability and test the deflection structure design. It will be straightforward to modify the design for the measurement of $y - z$ correlations, as required, to counter the ‘banana’ effect in TESLA (see the section below on correlation monitors). RD for the study of other bunch length monitor strategies is focused on electro-optic sampling field probes (M. Huning, TESLA, DIPAC 2001), mm wave interferometry and synchrotron light techniques. Several of the above are very promising, but none have demonstrated the utility and ease of operation needed for a reliable device.

All LC designs include one or more stages of bunch length compression, where the bunch is rotated in longitudinal phase space, exchanging energy spread for bunch length. Each stage is followed by a linac section, which reduces the fractional energy spread. An aggressive bunch compression scheme, involves generating a strong correlation between E and z with offset phase RF and using a sequence bend magnets or chicane to provide different path lengths for the head and tail particles. The scheme relies on careful cancellation between the longitudinal beam wakefield and the slope of the S-band RF. Because the beam is far from the RF crest in the section of linac where the

correlation is generated, the pulse-to-pulse phase stability and beam loading stability tolerances can be extreme.

The z distributions can be rather asymmetric and skewed, greatly increasing the challenge of measuring the bunch length. It is clear that the two traditional methods of bunch length monitoring, the streak camera and the inverse transform of the emitted radiation do not have the required resolution. The best streak cameras have resolution approaching 0.3 fs, $\sim 100 \mu\text{m}$, or about the effective σ_z of NLC. Coherent radiation may be a significant source of emittance dilution, as at a short wavelength FEL. Coherent synchrotron radiation has been developed for diagnostic purposes and, in contrast to streak cameras, tends to perform better for shorter bunches. Because of this coherent radiation monitors will be used in some capacity in the LC. However, since coherent radiation monitors provide only radiated power spectrum information, without phase, they will not yield shape information for the highly asymmetric bunches with close to $10 \mu\text{m}$ detail required.

The design parameters of the deflection cavity bunch length monitor proposed for test at SLAC are shown in Table 4. The S-band TM₁₁ deflecting field is used to tilt the beam, introducing a $y - z$ correlation. The phase of the deflection is offset slightly so that the centroid of the beam receives a small kick directing it onto a downstream screen. This allows operation of the monitor in ‘parasitic’ mode, so that only those machine pulses during which the deflection RF is on are intercepted by the screen and all other beam pulses proceed as they do on nominal pulses. By alternating the sign of the $y - z$ correlation, incoming correlations, such as those generated by wakefields, can be checked and corrected for.

Table 4: SLAC FEL LCLS bunch length monitor parameters for the SLAC S-band 8 foot TM₁₁ deflecting structure.

RF deflector voltage	20 MV
Peak input power	25 MW
RF deflector phase (crest at 90°)	3.3 deg
Nominal beam size	$80 \mu\text{m}$
Beam size with deflector on (two-phase mean)	$272 \mu\text{m}$
Beam energy at deflector	5.4 GeV
RMS bunch length	$24 \mu\text{m}$

D. Correlation monitors

Control of emittance propagation within the LC linac will require specialized monitors. For TESLA, which depends strongly on the pinch effect at the IP, a very small linear y - z correlation, increasing the projected emittance by only 1%, is enough to degrade the luminosity by over 30%. Two ideas for directly measuring the correlation were proposed: 1) using the transverse deflecting structure described in section C above and 2) a cavity BPM set to operate as an ‘inverse crab structure’. The latter is quite interesting since it holds the possibility for adapting cavity BPMs or NLC structure BPMs in a widespread fashion, throughout the complex. A signal from a tilted beam has been clearly seen at the ASSET test structure BPMs. RD is needed to prove this promising, vital, technology.

2. Proton drivers

Bob Webber, FNAL

The Proton Source Working Group defined its R&D categories as:

- a.) beneficial to existing and future machines
- b.) critical for new machines
- c.) useful but long term and lower immediate priority.

A. Linac and Transport Lines

The acceleration and transport of high power beams present new challenges for beam diagnostic systems. Conventional measurements will continue to be required, but not all traditional methods are acceptable in the presence of high power beams. Operating conditions may need to be modified to permit use of traditional instruments. New measurements will be required to detect, diagnose, and prevent small fractional beam losses that can damage accelerator components and produce unacceptable levels of residual radiation in high power machines. Monitors that can directly measure beam halo must be developed because the performance of new high power machines may well be halo dominated. If the new machines are to operate as expected at as yet unachieved performance levels, the diagnostics must keep pace. The working group was reminded, "If you keep doing what you've been doing, and you will keep getting what you've got."

Devices that can produce credible profile measurements of high power and high space charge beams are critical to beam emittance and other transverse parameter measurements. Beam mis-matches that couple to space charge distribution oscillations have been determined to be a major factor in beam halo development. Traditional multi-wire or scanning wires are time-proven devices for profile measurements, but they exhibit severe shortcomings for application to high power beams and in superconducting Linacs. BNL, as part of the SNS project, is currently researching "laser wire" techniques as a solution to this problem for H- beams. Good progress has been made and the technique appears to be an attractive potential solution though measurement of high energy beams with suitable resolution has yet to be demonstrated. We strongly encourage that work to be continued. At the same time, R&D into other innovative solutions to this very important problem should not be neglected. Ion profile monitors and fluorescence based monitors are options that deserve continued development, although high space charge beams present particular difficulties to these methods. Full transverse emittance measurements are most important and perhaps only obtainable at either end of a long Linac structure. With suitable beamline design, laser-based extraction of short pulses may be used for emittance measurements without interrupting normal operation. This is an example where beamline designs may need to include specific considerations for particular measurements. Problems using wire harps immediately upstream of targets or beam dumps due to back-scatter was noted.

Diagnostic systems with sufficient bandwidth to observe beam parameter variations during the pulse will be especially important for long pulse Linacs. With chopped Linac beams, multi-MHz bandwidth may be necessary to observe the transients due to chopping.

The trend toward superconducting hadron Linacs will have a major impact on beam instrumentation. There are serious concerns related to contamination of the superconducting cavity surfaces during equipment installation and operation. Moving parts in traditional instrumentation like wire scanners, harps, and emittance monitors pose the threat of liberating dust, flakes, or other particulates that can migrate into the cavities. Intercepting devices with the potential for breakage, ablation or sputtering of material heated by the beam also risk contamination. All devices to be installed in the vicinity of superconducting RF, even non-intercepting and non-moving devices, will be subjected to stringent cleansing requirements prior to installation. SNS will be at the forefront of this new challenge for hadron machines.

Longitudinal measurements of Linac beams shall become more important as demands for enhanced performance are to be met. On-line energy measurements and energy spread measurements will be important to SNS beam transport and ring injection commissioning and operation. Precision beam phase measurement may permit time-of-flight energy measurement methods to be used. It is quite possible that the shape resonance bump in the cross section near the $2p$ threshold can be used for H- beam energy spread measurements. The laser-excited $H0^*$ shape resonance can also be used for absolute beam energy measurements, to complement time of flight or beam rigidity measurements. Beam energy jitter, which can be measured in a high-dispersion point in an arc, is a more important measurement than absolute energy. Thin halo scraper foils at a high dispersion point can measure momentum halos.

Development of an on-line, non-invasive bunch length/shape measurement would be valuable. Some form of a pulsed-mode-locked laser may be useful for bunch length measurement, but the issue of $H0$ background from residual gas stripping must be considered. The shape resonance (see above) may be useful. One approach was demonstrated at the LANL LINDA experiment. Specific recommended R&D activities by priority category are:

- a.) Non-invasive beam profile measurements.
Accurate on-line beam energy and energy spread measurements.
- b.) Specific beam halo monitors.
Instrument compatibility with superconducting RF environments.
- c.) Longitudinal bunch shape monitors with around 10 picosecond resolution.

B. Rings

Serious attention should be paid to diagnostics necessary during multi-turn injection when beam signals are complex and dynamic. Separating information of the most recent injected turn from that of previous turns is very difficult. Residual Linac bunch structure on the beam dies out after a few turns in the ring. Intentional beam modulation to "tag" specific parts of the beam may be used. The dynamic range of beam intensity can vary by three orders of magnitude during the injection/accumulation time. Separating injection mismatch from intentional painting from emittance blow-up is a difficult diagnostic. Beam size can, by design, vary by up to a factor of thirty during injection and accumulation.

e-p instabilities have been shown to be important in some high intensity proton accumulator/compressor rings. Research into instrumentation that can clearly diagnosis

this problem is important. The Los Alamos PSR group has led the way in this effort in recent years and has demonstrated one such electron diagnostic instrument that they have developed. Fourier-transform analysis of high-harmonic betatron sideband signals from a wideband BPM is another technique that may be applicable to e-p diagnostics.

Credible beam profile measurement in circulating hadron machines is not regularly (if ever) achieved. Profile and halo measurements are important for diagnosing emittance growth and other historically nuisance problems that will result in significant beam power loss in high power machines. Turn-by-turn profile measurements are important to see injection evolution and envelope resonances. Other, non-intercepting, transverse "quadrupole moment" monitors that are sufficiently sensitive to typical beam aspect ratios should be developed. IPMs with strong magnetic fields seem to hold some promise for fast, unambiguous profile measurements but may impact sensitive machine lattice parameters. Specific halo monitors should also be developed.

Large tune adjustment range in the SNS ring may have impacts on diagnostics and especially feedback systems that depend on betatron phase differences. It is important that these lattice design flexibilities are appropriately conveyed to and understood by the beam instrumentation and feedback engineers.

Compressor rings, like SNS or PSR, find measurement of "beam in the gap" to be an important measurement since that beam will be lost at extraction and produce unacceptable radiation. Measurements at the level of $1\text{E-}5$ on the sub-microsecond time scale are sought. This is a problem unique to accumulator rings, and not rapid cycling synchrotron rings.

Fast, accurate on-line transverse tune measurement and beam transfer measurements are useful. Many techniques are known for these measurements, but incorporating them into easy-to-use, on-line systems has proven difficult.

All time and frequency domain diagnostic signals become considerably more complex to deal with in rapid cycling synchrotrons in the intermediate energy range due to the fast velocity change of the beam. Specific recommended R&D activities by priority category are:

- a.) The whole area of diagnosing beam parameters (injection matching, painting, possible emittance blow-up, incremental intensity, etc.) during multi-turn injection.

Circulating beam profile monitors that will produce credible results over a significant dynamic range and with turn-by-turn speeds. Fast and accurate non-invasive tune measurements.

- b.) see a.) above

C. General

The interaction between lattice/optics design and beam instrumentation crucial for machine commissioning, operation and development is important to be considered early in the design stage. This requires early and continued interaction between physicists and instrumentation designers through the time of machine commissioning. SNS has made considerable progress in this regard, especially in the HEBT beamline design. Future machines should take this into account and further the early design stage integration of machine/beamline design with beam diagnostics requirements.

Integration of diagnostics systems (hardware and software) into control systems with easy-to-use interfaces and unambiguous results is critical to making the diagnostics part of operational machines. The best diagnostic is the diagnostic that gets used! Diagnostics that require operation by an expert will get used only by that expert. Development of the integration of instrumentation into controls systems is an area that requires continued and intensified attention.

It is imperative to strive for instrumentation that is able to make beam parameter measurements at the diagnostic and predictive level as opposed to simply measuring end results of important beam processes.

3. Mu/nu factories

Beam profile and emittance diagnostics are vital for the muon ionization cooling demonstration projects. A number of promising proposals are in progress; each of which entails substantial innovation and development in their own right. Perhaps tightest of all is the requirement to measure the decrease in muon emittance to an accuracy of a few percent.

4. VLHC

RD is needed for 1) control of fast instabilities at injection, 2) for diffusion processes in general and 3) for tune/chromaticity control during ramping (Schmickler DIPAC 2001).

At VLHC injection, the resistive wall instability growth rate is substantially less than one turn. A conventional multi-bunch feedback scheme, which relies on signals from successive turns, will not be effective. The proposed scheme uses a sequence of feedback loops, installed one after the other. RD is required to prove that all the loops can work properly in concert.

Understanding of diffusion related emittance growth is a priority for large hadron machines, as it is for proton drivers. Instrumentation RD is needed for more accurate, more sensitive beam size monitors. There is promising RD at RHIC using crystal extraction in order to analyze phase space density at large amplitudes.

Finally, but perhaps most critical, the control of beam optics during ramping is an ongoing operational problem for superconducting rings with low injection energy. HERA experience reinforces this. RD on the development of an online, real-time chromaticity monitor that could be used in an electronic feedback is underway for LHC.

5. Electron positron circular colliders

Factories are faced with coupling/optical correction, two-stream instability and strong beam-beam effects. The BPM system is the most critical diagnostic in factories, with difficult bunch-to-bunch, front-end signal processing and stability requirements. Strong integration of the BPM system with controls is needed to tightly control the ring optics. Typically, there are 2 systems: 1) narrowband with tight stability tolerances installed throughout the ring and 2) wideband, capable of resolving individual bunches but installed only in a few places. Because of the optical complexity of the IR, absolute stability of $1\mu\text{m}/24\text{hrs}$ is important near the IP, a requirement today's systems don't meet. While no fundamental limits are foreseen, RD is needed improve performance on several fronts: 1) resolution, 2) long term stability, 3) integration (measurement validation and

error handling) and 4) bunch-bunch cross talk and signal separation. Table 5 shows requirements for circular collider BPMs.

Table 5: e+ e- circular collider BPM system requirements.

Parameter	Value	Conditions
Resolution	1 μm rms	Narrow band
Resolution	10 μm rms	Wide band
Position Stability	1 μm	over 24 hours (!)
Bunch spacing	> 2 ns	wide band

Transverse profile requirements are well below the limits of optical synchrotron radiation diffraction. RD is required to improve the utility of devices such as the interference fringe monitor. The most serious instability encountered in these machines is the electron cloud instability; detailed RD is required to understand this serious limitation. Several cloud monitors have been proposed and are being tested.

6. Advanced Optical Diagnostics for Particle Beams: an Incomplete Survey

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Much progress has been made in advanced optical diagnostics for particle beamsⁱ, to diagnose the beam quality and characteristics of advanced acceleratorsⁱⁱ. Examples of recent experimental results for 50 MeV-30 GeV electron beams follow. Shot noise-driven fluctuations in incoherent radiation from electrons has been used to extract bunch length and spot size for 2-5 ps electron beams at 50 MeV, in agreement with independent measurementsⁱⁱⁱ (BNL/LBNL collaboration). The requirement on spectral resolution relaxes as the bunch length gets shorter, and with appropriate choice of wavelength and sufficiently high charge levels, it can be implemented with any source of incoherent radiation^{iv}. A review of bunch length measurement techniques can be found in ref [v]. Optical transition radiation has been used for spot size, bunch length and slice emittance at energies ranging from a few MeV to 30 GeV^{viii}. First OTR-based diagnostic measurements at 30 GeV have been recently carried out at the FFTB at SLAC^x. At these energies, the usual expression for formation length, $L_f = (\lambda/\pi)(\gamma^2 + \theta^2)^{-1}$, reduces to $L_f = \lambda/\pi \theta^2$ for $\theta \gg 1/\gamma$. Operating in this γ independent limit allows compact setups to be used for interference-based measurement of beam divergence of ultra-relativistic beams. This was experimentally demonstrated^x recently using a 30 GeV e-beam and 0.5 m double-foil separation. Also, in this limit, transverse resolution is simply determined from $\lambda/2\pi\theta$, where $\theta \gg 1/\gamma$ is the collection angle. Transverse profiles of 10's of microns have been routinely measured at 30 GeV. These techniques have provided the tools to study betatron oscillations^{xi}, tails and equivalent bending radius of the plasma/beam interaction in a plasma wakefield experiment at 30 GeV (E157; LBNL/SLAC/UCLA/USC collaboration). The use of coherent OTR to measure ultrashort bunches^{xii} is being explored for laser wakefield acceleratorsⁱⁱ.

Spatial profiles which contain phase-matched cone angles and color-coding have also been used to measure beams. As an example, visible radiation from a microwiggler has been used to characterize 50 MeV beams at the ATF at BNL with better than 0.5% energy resolution and to extract single shot calibrations of beam divergences of $250 \mu\text{rad}$ ^{xiii}. In addition, energy spreads of 0.5-2% and beam steering have been measured. As another example, the Cerenkov phase-matched cone angles at 30 GeV have been used to extract time and space-synchronized plasma and neutral density for plasma wakefield applications (E157) by making use of the index of refraction dependence near an atomic spectral line, and the fact that they are γ -independent^{xiv}.

Laser-based diagnostics such as Thomson scattering (BTF at LBNL) or the Shintake monitor^{xv} (FFTB at SLAC) have provided high resolution probing of electron beams. Using a tightly focused laser beam, with a spot size much smaller than the electron beam dimensions, Thomson scattering has been used to measure longitudinal profiles at 50 MeV, to tune and remove chromatic aberrations and to measure beam divergence for 300 fs slices. In combination with this optimization, transverse profiles have been diagnosed with Thomson scattering and found to agree with OTR. Application of these diagnostics is being explored for laser wakefield accelerator-produced beams^{xvi}.

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