Fermi National Accelerator Laboratory

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Summary Report on Transverse Emittance Preservation

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1 Introduction

In the design of a modern large hadron accelerator, the transverse emittance budget is an essential part. Without cooling, the emittance always grows from the first stages (*e.g.,* an ion source, a linac) to the last one (*e.g.,* a synchrotron or a collider). Careful plan is needed for how much blow up one would allow at each stage. There are two main reasons why the emittance preservation is important.

1.1 Effects on luminosity in a collider

The relation between the luminosity $\mathcal{L}$ and emittance ϵ is:

$$\mathcal{L} \propto \left(\frac{N_b}{\epsilon}\right) \cdot N_b \tag{1}$$

in which N_b is the number of particles per bunch. It is seen that before one reaches the beam-beam limit, the luminosity is proportional to $1/\epsilon$. In other words, in order to have high luminosity, the emittance has to be kept small. One illustrious example is the former SSC. The total beam current in that machine was limited by the cryogenic power (for absorbing the synchrotron radiation energy). The value of N_b was limited by the number of events per crossing. Therefore, to achieve the design luminosity, it was required to have an emittance as small as 1π mm-mrad (normalized), which was about a factor of 3-4 or more smaller than that in any existing collider.

If, however, the beam-beam limit is reached, the ratio N_b/ϵ becomes a constant. The emittance would then be an irrelevant parameter as far as the luminosity is concerned. This was actually the case for the Tevatron at Fermilab during its last collider run. Thus, the luminosity upgrade program calls for an increase of the beam intensity only (which leads to the construction of the Main Injector and Recycler) rather than for a brighter beam.

1.2 Effects on particle losses

In the injector chain of a collider and in a synchrotron, large emittance may lead to particle losses at injection, during acceleration and at extraction. For example,

- AGS Booster at BNL:
  It was shown at this workshop that after ~10 ms during the acceleration, the emittance grows from 60π to 80π mm-mrad (95%). However, the extraction aperture is limited by the septum magnet at 60π. There are appreciable particle losses at extraction.

- Fermilab Booster:
  The bottleneck is again at the extraction region, where there is a "dog leg" structure (2 pairs of orbit deflectors) that limits the aperture and has become a radioactive hot spot. A new "dog leg" is being built for the purpose of providing a larger aperture.

- Fermilab Main Injector:
  This is a new synchrotron, which has a much larger transverse acceptance and momentum aperture than the Main Ring, which it will replace. But still, the aperture of the Lambertson magnets and quadrupoles in the extraction region is a potential concern. If the beam emittance is larger than 40π (95%), particle losses would be foreseen.

2 Emittance tables of existing and planned machines

At the workshop, a survey was conducted for the beam emittance at each stage in the accelerator chain at seven laboratories — Fermilab, CERN, KEK, DESY, BNL, RAL and TSL. The results are listed in Tables 3a-3g. (Note: The number "3" comes from the fact that there are two proton synchrotron data tables compiled at the previous ICFA mini-workshops. One is a performance comparison table, another a particle loss table. All these tables will be put in the database of the ICFA working group on the web. The address is *http://www-bd.fnal.gov/icfa/database/database.html.*)

The data are also plotted in Figure 1 and explained below.

1. The data from RAL and TSL are excluded in Figure 1. This is because the emittance in ISIS/RAL is determined by the beam collimators, and the CELSIUS/TSL is equipped with an electron cooler.

2. Different labs use different ways to describe the emittance (95%, 90% or *rms*). For the purpose of comparison, all have been converted to the equivalent *rms* value in unit μm.

3. When the horizontal and vertical emittances are not equal, their averaged value is plotted.

4. If there is no cooling and the synchrotron radiation damping is negligible (which is true in all these cases), the emittance should either keep a constant value or grow. The decrease at certain stages is believed to attribute to measurement errors.

5. It is interesting to see that all the five labs start with more or less the same emittance in the linac (about 0.5 μm) and end up with more or less the same emittance in the collider (about 4 μm), while there are large variations in the middle stages (transfer lines, Booster and Main Synchrotron). Part of the reason is probably the limited accuracy of the measurement in these stages.

6. It was pointed out in the workshop that the limited accuracy of the emittance measurements cannot be imputed entirely on the instruments alone. The flying wire, for example, is known to be very precise and yet the uncertainty on the measured emittance can be large. Therefore, a large part of the measurement error can be attributed to the fact that the knowledge of the lattice functions is often insufficient.

3 Sources of emittance blow-up

3.1 During beam transfer

3.1.1 General types of mismatch

The following sources that can cause emittance blow-up during beam transfer have been observed in almost all machines and discussed in some detail at this workshop. The encouraging news is that these mechanisms are relatively simple and, therefore, are calculable. The discouraging news, however, is that the calculations and measurements can disagree with each other.

1. Missteering:
   M. Syphers gave the following expression for estimating the relative increase of emittance due to missteering:
   $$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2} \cdot \frac{\Delta x^2 + (\beta_0 \Delta x' + \alpha_0 \Delta x)^2}{\sigma_0^2} \tag{2}$$
   in which Δx and $\Delta x'$ are the missteering of the position and angle, respectively, β_0 and α_0 are the Twiss parameters, and σ_0 is the rms beam size.

2. β-Mismatch:
   Syphers also estimated the effect due to β-mismatch:
   $$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2} \mid det\ \Delta J \mid \tag{3}$$
   $$= \frac{1}{2} \cdot \frac{(\Delta\beta/\beta_0)^2 + (\Delta\alpha + \alpha_0 \cdot \Delta\beta/\beta_0)^2}{1 + (\Delta\beta/\beta_0)} \tag{4}$$
   where ΔJ is the matrix of the error Twiss parameters:
   $$\Delta J = \begin{pmatrix} \Delta\alpha & \Delta\beta \\ -\Delta\gamma & -\Delta\alpha \end{pmatrix} \tag{5}$$

3. Dispersion mismatch:
   The expression for the dispersion mismatch is:
   $$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2} \cdot \frac{\Delta D^2 + (\beta_0 \Delta D' + \alpha_0 \Delta D)^2}{\sigma_0^2} \left(\frac{\sigma_p}{p}\right)^2 \tag{6}$$
   where σ_p/p is the relative rms momentum spread of the beam.

A general comment is that, among the three sources, missteering seems to be the most critical one, especially at high energy when the beam size is small. For example, at the BNL for a beam of an emittance of 20π, a missteering of $\Delta x = 1$ mm would lead to 2.5% and 25% emittance growth in the AGS and RHIC, respectively. On the other hand, a β-mismatch of as big as 25% only results in 2.5% emittance increase (assuming $\Delta\alpha = 0$). The numerical example of the dispersion mismatch was given for the AGS: For $\Delta D = 2$ m and $\sigma_p/p = 10^{-3}$, the emittance growth would be 10%.

A. Jansson reported his work on the emittance blow-up measurements and comparison with the theoretical predictions using controlled missteering and β-mismatch in the CERN PS. The agreement was rather poor. In particular, when the missteering and mismatch were small, the measured emittance increase was significant. This demonstrated the difficulty of the experimental studies of these seemingly simple phenomena.

3.1.2 Special type of mismatch — Mismatch of the four Booster rings and PS at CERN

In the CERN PS complex, there are four Booster rings. The match between the four rings and the PS presents a specific problem. K. Schindl reported a machine experiment in the PSB and PS using the LHC type beam, *i.e.,* 1.7×10^{11} protons per bunch with small emittance. When only one PSB ring was used, he showed the machines could be well matched so that there was virtually no emittance dilution from the injection to the PSB to the extraction from the PS. (Note: Both horizontal and vertical emittances vary at various stages but the average of the two remains a constant.) This was a respectable accomplishment. But the simultaneous match of the four PSB rings to the PS is a real challenge. Jansson estimated that there could be a 20% emittance blow-up from the PSB to PS if there are no proper corrections to be implemented or no better optics measurements to be taken.

3.2 Space charge and intrabeam scattering

3.2.1 Space charge effects

The space charge is a principal source causing emittance growth when the beam energy is low. Although this has been known for decades, the status of the theoretical study of this phenomenon is not satisfactory. One knows how to calculate the incoherent space charge tune shift, but doesn't know how to estimate the emittance growth in an analytical way. The alternative is computer simulations. But this usually requires substantial computing resources (cpu power and run time). Several codes have been written. S. Machida reported his work using the code SIMPSON. It is a 3-D code. There is a 2-D module that can study the coherent modes due to the space charge. For a debunched beam, his results showed coherent dipole mode, which was previously studied by I. Hofmann, and also quadrupole, sextupole modes, *etc.* At this moment, except the dipole mode, his results are not easy to be checked by experiments because of the lack of appropriate pickup instrumentation. (Note: CERN PS is in the process to develop a quadrupole pickup.) However, this by no means suggests that one could overlook this study. On the contrary, these coherent modes play an important role in high intensity accelerators. The ISIS at RAL is an example. It operates at 50 Hz and delivers 2×10^{13} protons per pulse, *i.e.,* 1×10^{15} protons per second. The loss at extraction is remarkably low at 0.01%. G. Rees commented that this is mainly due to the good control of the closed orbit, which prevents the image current-induced coherent dipole mode from occurring.

3.2.2 Intrabeam scattering

The intrabeam scattering is another source of emittance growth. One usually treats it separately from the space charge effect, even though both are closely related. In the study of the space charge effect, each particle is in an electromagnetic field, which represents the smoothed forces of all the other particles. The Coulomb collisions are neglected. In the analysis of the intrabeam scattering, on the other hand, each particle collides with another particle at a time. The forces of all other particles are neglected. Unlike the case of the space charge, there are two existing theories — Piwinski's [1] and Bjorken-Mtingwa's [2] — that tell how to estimate the emittance growth rate due to intrabeam scattering. At high energies and above transition, these theories give similar results and are in agreement with machine experiments. However, at low energies and especially when below the transition, the two theories could give quite different results. To make things more complicated, there is no conclusive machine measurements (to the authors' knowledge) below transition for checking the theories. The difference is not just quantitative. It is in some sense fundamental. This can be explained as follows. When $\gamma < \gamma_t$ (below transition) and $\beta' = D' = 0$ (ignoring variations of the β- and dispersion-function in the machine), Piwinski predicts the existence of an equilibrium distribution in the 6-D phase space, while Bjorken-Mtingwa says this will almost never happen. (It only happens when all the three eigenvalues of the matrix L in Ref. [2] are equal. But this condition will almost never be met in any machine.) It should be mentioned that this conceptual confusion is not merely of academic interest. It has consequences in the design of real machines. For example, Fermilab is building a Recycler to recycle and accumulate antiprotons. It will operate below transition and will use stochastic and/or electron cooling. The intrabeam scattering is considered to be one major source of emittance growth in this storage ring. A correct estimate of the growth rate is essential to the design of the cooling facility. The different estimates from the two theories make the design difficult. As part of the efforts to resolve this problem, a machine experiment is being carried out on the Accumulator Ring at Fermilab. The measured data will be analyzed and compared with the theories.

3.3 Other sources

The following sources can also cause emittance growth. But they were not carefully discussed at the workshop due to time limitation.

- Power supply noise (*e.g.,* which was identified as one of the major causes of the emittance blow-up in the Tevatron at Fermilab).
- RF noise.
- Rolled quadrupole (which was found in the Tevatron/FNAL and was the cause of large optical distortion and reduction of luminosity).
- Beam instabilities.
- Stacking (coalescing) and cogging.
- Beam-beam effect (*e.g.,* which was believed to cause emittance dilution in the HERA at DESY), *etc.*

4 Measures to control emittance blow-up

4.1 Better steering and better match

The followings were discussed at the workshop:

1. Better understanding of the optics:
   This is essential to the better steering and better match. It means better instrumentation and more careful measurement. B. Autin introduced the ABS project (Automated Beam Shaping and Steering) in the PS complex. It requires a dispersion-free section for the measurements, which, however, does not exist in the rings nor in the beam lines. He argued that this was crucial to a better understanding of the optics

so it is worthwhile considering a modification of the present PS complex for creating zero-dispersion regions.

2. Installation of correctors.

3. Compensation of the end fields:
M. Giovannozzi studied the non-linear end field of the PS magnets near the transfer line to the SPS. This field can change the optics of the beam line and lead to the mismatch between the beam line and SPS. The resulting emittance blow-up could be as big as 15-20% during the SPS injection. During the discussion, it was pointed out that special care was needed in analyzing the end fields, because they are 3-D. The field harmonics used in 2-D analysis (*i.e.,* the b_n's and a_n's) should be replaced by the pseudo-harmonics or by their integrated values (integration from the longitudinal component of the field $B_z = 0$ somewhere inside the magnet to $B_z = 0$ somewhere outside the magnet).

4.2 Injection damper

This is important for minimizing the emittance blow-up at injection due to missteering. The damping time has to be shorter than the beam decoherence time. The bandwidth is determined by the batch spacing (not the bunch spacing). In other words, it does not need to be bunch-by-bunch, but should be able to damp the coherent motion of each individual batch.

W. Hofle reported that the injection damper in the SPS works fine for the normal short bunches (5 ns long). But the horizontal emittance blow-up of the long (25 ns) bunches can not be reduced by this damper. The cause is not clear.

4.3 Improving bunching factor

One effective way for reducing the space charge effect is by improving the bunching factor. There are two examples.

1. KEK PS:
K. Shinto reported that, at the injection of the KEK PS, a longitudinal phase error of 90° was intentionally introduced for increasing the bunching factor. As a result, the beam intensity was increased by 25% while the transverse emittance remains about the same. The advantage of this method is that it does not need any additional hardware. The concern is, of course, the quality of the beam (*e.g.,* the filamentation).

2. CERN PSB:
The second harmonic rf cavity has been used for years in the PSB for increasing the bunching factor. The voltage ratio of the fundamental and second harmonic rf cavities has been optimized by analytical method. But the experimentally observed improvement in bunching factor is somehow lower than the theoretical prediction. The reason is unknown. At present, the system consists of h = 5 and h = 10 cavities. But they will soon be replaced by h = 1 and h = 2 cavities in 1998.

4.4 Low noise feedback system

This is critical for control of emittance dilution due to external noises (*e.g.,* ground motion and power supply ripple) in a large collider, such as the LHC. There have been extensive studies on this subject both theoretically and experimentally. But it was not discussed at this workshop because the focus was on synchrotrons and beam transfer lines.

5 Conclusions

During the past years, significant progress has been made in understanding the beam transverse emittance blow-up and its preservation. However, one often finds him-/herself ignorant when he/she tries to explain what was observed in an existing machine or to predict what will happen in a machine under design. There are a number of such examples given in this report. Some of them are even fundamental. These are the challenges. But they are also the directions leading to new achievements. The workshop gladly acknowledged them and promised to work on them.

6 Acknowledgements

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References

[1] A. Piwinski, *Proc. 9th International Conf. on High Energy Accel.*, pp. 405-409, SLAC (1974).

[2] J.D. Bjorken and S.K. Mtingwa, *Particle Accelerators,* Vol. 13, pp. 115-143 (1983).

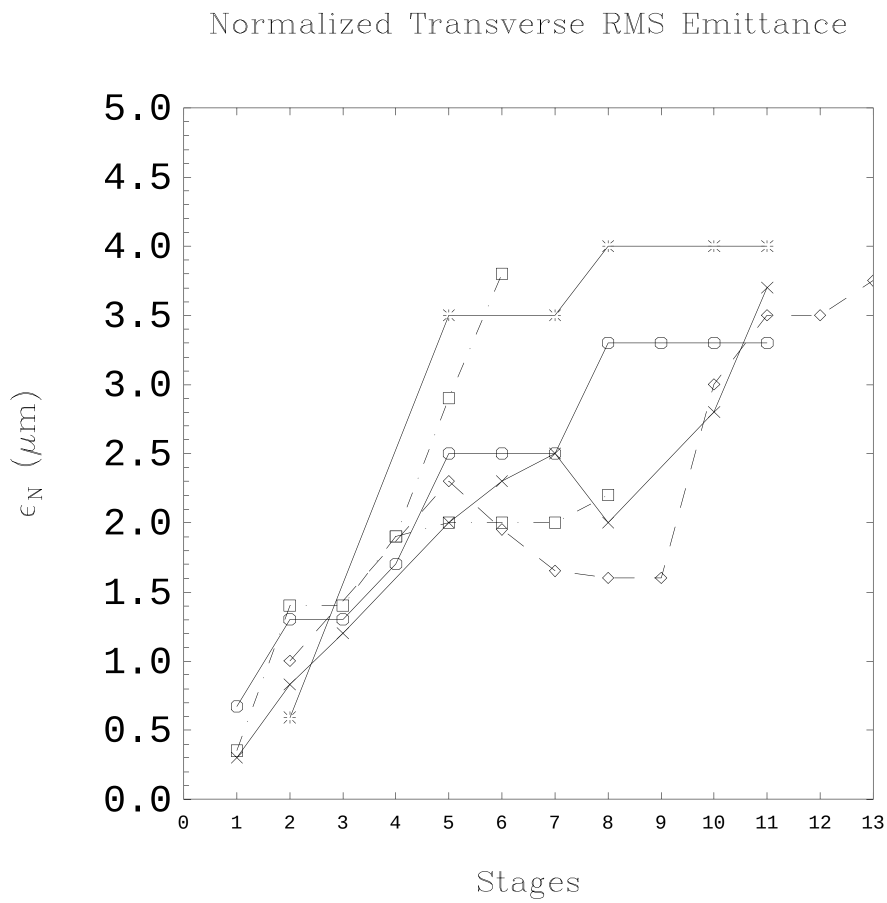

Figure 1. Normalized transverse *rms* emittance at each stage: 1. Linac in; 2. Linac out; 3. Transfer line from linac to Booster; 4. Booster in; 5. Booster out; 6. Transfer line from Booster to Main synchrotron (Main Ring/FNAL, PS/CERN, PS/KEK, Petra/DESY, AGS/BNL); 7. Main synchrotron in; 8. Main synchrotron out; 9. Transfer line from Main synchrotron to collider (or SPS/CERN); 10. Collider (or SPS/CERN) in; 11. Collider storage; (or SPS/CERN out) 12. LHC in; (CERN only) 13. LHC storage (CERN only).

The data are from five laboratories:

FNAL – diagonal cross and solid line;
CERN – diamond and dashed line;
KEK – square and dotdash line; (4-8: upper/lower line for high/low intensity beam)
DESY – star burst and solid line;
BNL – octagon and solid line.

Table 3a

Proton Beam Emittance Evolution and Measurement at Fermilab

P. Lucas

Location	**Linac**		**T-line**	**Booster**		**T-line**	**Main Ring**		**T-line**	**Tevatron**	
	IN	OUT		IN	OUT		IN	OUT		IN	OUT
kinetic ***E***	750 *keV*	400 *MeV*	400 *MeV*	400 *MeV*	8 *GeV*	8 *GeV*	8 *GeV*	150 *GeV*	150 *GeV*	150 *GeV*	900 *GeV*
ε_N in μm	0.3	0.66 (H) 1 (V)	1.2	*0.25*	2	2.8 (H) 1.7 (V)	2.5	2		2.8	3.7
method	emittance probe	wire scan	multiwire	IPM	IPM	multiwire	Sampled Bunch Display, flying wire	SBD, flying wire		SBD, flying wire	SBD, flying wire synch light
precision	a few %	50% systematic			few % relative	few %	10% (rel) 25% (abs)	same		same	same
cause of growth	space charge	lattice irregularity bunching, rf non linearity		space charge, transition, rf noise			injection line match	coalescing, cogging		matching, 150 GeV lifetime	beam-beam, intra beam, instabil. power supply noise
comments		quad. param. and spacing		wrong !		lattice dependant	values are function of booster turns				

$\varepsilon_N = (\beta\gamma)\sigma^2/\beta_{Twiss}$

Table 3b

Proton Beam Emittance Evolution and Measurement at CERN

K-H. Schindl, L. Vos

Location	**Linac**	**Booster**		**T-line**	**PS**		**T-line**	**SPS**		**LHC**	
	OUT	IN	OUT		IN	OUT		IN	OUT	IN	OUT
*kinetic**E***	50 *MeV*	50 *MeV*	1.4 *GeV*	1.4 *GeV*	1.4 *GeV*	25 *GeV*	25 *GeV*	25 *GeV*	449 *GeV*	449 *GeV*	7 *TeV*
ε_N in μm	1		3 (H) 1.6 (V)	2.7 (H) 1.2 (V)	1.9 (H) 1.4 (V)	1.2 (H) 2 (V)	1.6	3	3.5	3.5	3.75
method	slit, multiwire		*beam scope*	multiwire	flying wire	same	multiwire, OTR screens	flying wire	same	same	same + synch light, lum mon.
precision	10-20%		10-25%	same	10-20%	same	10-25%	20%	same		
cause of growth	space charge [180 *mA*]		hor.stacking, space charge		missteer. (kickers), mismatch (dispersion)	space charge coupling		missteer., mismatch	feedback res.	missteer., mismatch	feedback res.
comments	input LINAC = 750 keV RFQ $\varepsilon_N \sim 0.5\ \mu m$		measured with 1 booster ring in 1993	same	same	same	design: $\varepsilon_N \sim 3\ \mu m$	design figures	same	same	needs low-noise feed back at collision

$$\varepsilon_N = (\beta\gamma)\sigma^2/\beta_{Twiss}$$

Table 3c

Proton Beam Emittance Evolution and Measurement at KEK

Y. Mori

Location	**Linac**		**T-line**	**Booster**		**T-line**	**P S**		**T-line**	**Collider**	
	IN	OUT		IN	OUT		IN	OUT		IN	OUT
kinetic ***E***	750 *keV*	40 *MeV*	40*MeV*	40 *MeV*	500*MeV*	500 *MeV*	500 *MeV*	12 *GeV*	12 *GeV*		
ε_N in μm	0.35	1.5 (H) 1.3 (V)	1.5 (H) 1.3 (V)	2 (H) 1.8 (V)	3 (*2*)(H) 2.8 (*2*)(V)	4.3(*2*)(H) 3.3(*2*)(V)	2	? (H) 2.2 (V)			
method	emittance probe(*)	same	same	beam scope	same	multiwire	flying wire(V), IPM	same			
precision	a few %	same	same	<10%	same	few %	few % (wire), 20% (IPM)	same			
cause of growth	space charge	lattice irregularity bunching, rf non linearity		mismatch	space charge		space charge				
comments	(*) slit + Faraday cup				(*x*) for N=5 10^{11} ppp	same	IPM 20% rel, 250% abs	same			

$\varepsilon_N = (\beta\gamma)\sigma^2/\beta_{Twiss}$

Table 3d

Proton Beam Emittance Evolution and Measurement at DESY

J. Maidment

Location	**Linac**		**T-line**	**DESY 3**		**T-line**	**PETRA**		**T-line**	**HERA-p**	
	IN	OUT		IN	OUT		IN	OUT		IN	OUT
kinetic ***E***	750 *keV*	50 *MeV*	50 *MeV*	50 *MeV*	6.6 *GeV*	6.6 *GeV*	6.6 *GeV*	39 *GeV*	39 *GeV*	39 *GeV*	819 *GeV*
ε_N in μm		0.63 (H) 0.54 (V)			3.5 (H) <3.5 (V)		4 (H) 3 (V)	5 (H) 3 (V)		3->5	4
method		3 harp		IPM	flying wire IPM	scintillator	flying wire IPM	same	scintillator	flying wire	flying wire lum. mon.
precision		>20%		>20%(H) 10% (V)				>20%(H) < 5% (V)		>20%	same
cause of growth					space charge			none detectable			transverse instab.
comments		non gaussian		intensity dependant	1.3 10^{11} ppb						

$\varepsilon_N = (\beta\gamma)\sigma^2/\beta_{Twiss}$

Table 3e

Proton Beam Emittance Evolution and Measurement at BNL

M. Syphers

Location	**Linac**		**T-line**	**Booster**		**T-line**	**AGS**		**T-line**	**RHIC**	
	IN	OUT		IN	OUT		IN	OUT		IN	OUT
kinetic ***E***	750 *keV*	200 *MeV*	200 *MeV*	200 *MeV*	1.6 *GeV*	1.6 *GeV*	1.6 *GeV*	24 *GeV*	24 *GeV*	24 *GeV*	250 *GeV*
ε_N in μm	0.67	1.3	1.3	1.7	2.5	2.5	2.5	3.3	3.3	3.3	3.3
method	wire scan	same	multiwire, scintillator	IPM	same	multiwire, scintillator	IPM, flying wire(fut.)	same	scintillator, OTR	IPM	same
precision	>20%	same	same	same	same	same	same	same			
cause of growth		mismatch		mismatch, space charge	space charge		mismatch	space charge			
comments	**polarized proton beam**									future	

$\varepsilon_N = (\beta\gamma)\sigma^2/\beta_{Twiss}$

Table 3f

Proton Beam Emittance Evolution and Measurement at RAL

G. Rees

Location	**Linac**		**T-line**	**ISIS**	
	IN	OUT		IN	OUT
kinetic ***E***	660 *keV*	70 *MeV*	70 *MeV*	70 *MeV*	800 *MeV*
ε_N (*100%*) in μm	~1.5	6	6	110	120
method	slit, Faraday cup	wire scan	same	defined by collimators	harps in extraction line
precision	~40%	~30%	same		~20%
cause of growth	intensity dependant matching	same	no growth	painting	little growth
comments	effects of missteering	10 MeV focusing transition Tank/Tank2	difficult line to understand	H^- injection ΔQ~0.4 for 2 10^{13} ppp	very low loss with fast extraction (< 10^{-4})

Table 3g

Proton Beam Emittance Evolution and Measurement at TSL

V. Ziemann

Location	**Cyclotron**		**T-line**	**CELSIUS**	
	IN	OUT		IN	OUT
*kinetic **E***		180 *MeV*	180 *MeV*	180 *MeV*	≤1.3*GeV*
ε_N in μm		3	5	50	emittance damped !
method		quad scan wire scan	Al-pin on stripper mechanism +scintillator	injection process fills aperture of CELSIUS	
precision		~20%	50% unreliable. bad backgrd		
cause of growth		large tails due to multiturn extraction	vacuum ?		
comments				CELSIUS is a ring equipped with an electron cooler that handles a variety of particles (p,α,Ne,O,Xe)	

$\varepsilon_N = (\beta\gamma)\sigma^2/\beta_{Twiss}$