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Trip Report: DESY and the ICFA Lugano Workshop on Aperture Limitations

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DESY

Introduction

The HERA tunnel contains two vertically separated machines, for electrons and protons, referred to as HERA-e and HERA-p. HERA-e is mainly being constructed by accelerator physicists from PETRA and the previous electron machines at DESY. HERA-p is designed and constructed by high energy experimentalists. The electron energy is about 30 GeV, and the proton energy about 1.0 TeV (using 4.5 Tesla superconducting magnets). Proton injection is at 40 GeV, for a dynamic range of 25, bigger than the SSC range of 20.

The raison d'etre of HERA is to collide polarised electrons with protons, so the fundamental question, beyond whether the rings will work to specs in general, is whether polarisation will work satisfactorily.

Status of the HERA project

Almost all of the HERA-e magnets are in place, and sector tests over 144 metres have been successfully performed - although not without incident. When the dipole power supply was first turned on, it went out of regulation, and delivered full scale current. The Eddy currents in one of the vacuum chambers were sufficient to eject the center of the chamber sideways out of the magnet! Vacuum chambers are now mechanically constrained at the center of a dipole, as well as at the ends. The chambers are made of two pieces of copper (denser than aluminum, and a better synchrotron light absorber), brazed along two seams in the median plane.

Electron storage tests are scheduled to begin in July, but are realistically expected in September. The intention is only to cursorily confirm storage, in order not to slow down the installation of proton magnets. After this HERA-e personnel will become more and more available to help with HERA-p. Eventually the accelerator physicists will take over running of both rings, and the experimentalists will return to their experiments.

Only two proton magnets are already installed in the tunnel. Industrialisation plans are about a year behind schedule - proton magnets are expected to be arriving in full flux in 1989. HERA-p should be ready to accept protons from DESY-3 in 1990.

Spin

The success of electron polarisation in the HERA-e ring does not seem to be assured, according to separate conversations I had with Mais and Barber.

Mais thinks that contemporary spin theory has too many approximations to be reliable, and he is apprehensive as to successful polarisation. Transverse polarisation was hard enough to set up in PETRA, where conditions were nominally much easier. If you ask the experimentalists how much luminosity they are prepared to give up in order to have polarisation, they say none, but this cannot be true in practice.

Barber continues to work (with Mane and others) to further develop understanding of spin resonant effects. New analyses include nonlinear spin resonances in an analytic program (Mane) and in tracking, showing that the resonances are strong in the non-flat HERA-e, even for an ideal machine. An important parameter is the spin tune spread (proportional to energy spread, and hence unalterable) divided by the separation of nonlinear spin resonances (also unalterable). In SPEAR the ratio was 0.1, in HERA 1.1, and in LEP 1.5 (presumably for a 1 sigma particle). So, unless the nonlinear resonances can be suppressed (there is some hope of this), prospects look bad, and HERA-e will get transverse polarisation, but not longitudinal. Further, polarisation effects for particles in the transverse and longitudinal distribution tails need to be looked at more, since, because the polarisation time is much longer than the damping time, a typical electron may have its polarisation destroyed by nonlinear resonances in weakly populated parts of phase space.

Ground motion

Rossbach has significantly improved our understanding of the effects that ground motion will have on HERA (and the SSC), by successfully comparing an analytical treatment with a tracking program, in a paper which will imminently be published in Particle Accelerators.

The 'nominal' expected rate of increase of the beam emittance is easy to calculate when all the 2N quadrupoles in a ring made of N FODO cells are given random transverse displacements on successive turns. When the transverse displacements are due to a plane wave moving across the ring with a frequency of q (measured in tune units), it is natural to compare the emittance growth rate, as a function of q, with the 'nominal' rate. Roughly speaking, then, if $q < Q$ (the tune of the ring) the motion is adiabatic, and results in no emittance growth, but if $q > Q$, then the growth rate has structure as a function of q, oscillating about the nominal value.

Seismometers placed on top of quadrupoles in the HERA tunnel, about 18 metres below a busy main road - so the surface waves are essentially undamped - show about a 50 dB drop off between the signal at 1 Hz (low frequency cutoff of the device) and about 60 Hz (lowest sensitivity of the device). There is a narrow peak at 50 Hz, but none at 100 Hz. The rms ground (magnet?) motion at 1 Hz is about 0.3 microns.

It is not enough to know the ground motion, since the magnets may resonate and amplify the motion at some frequencies. Nor is it only the ground motion which causes the magnetic field that the beam sees to fluctuate with time, since local noise sources (for example, pumps) can excite acoustic modes in magnets. In the SSC the betatron frequency will be about 1 kHz. Is it possible to measure field fluctuations at this frequency and above inside real magnets, either on a test stand or in the actual tunnel environment, by inserting a motionless coil and observing the induced voltages?

Wake Field Transformer

Decker discussed the status and future of the WFT during a tour of the facility.

So far there has been a limit of 2 transformer plates in their studies, because the 'witness' electron beam is non-relativistic, and quickly gets out of phase with the 'ring' electron beam. However, an ingenious technician has recently made a compact cathode which can be placed just before an RF cavity in the tightly packed center of the structure, enabling the witness beam to be relativistic at the entry to the transformer. Plans are now being drawn up to make a 25 plate transformer which, unlike its predecessor, will be 'resonant' - with the plates extended outside the ring beam to an outer cylindrical wall. The motivation for this is as follows.

The ring beam is created by a pulse of laser light striking a cathode. The laser pulse is much longer than the 2 centimetre structure of the transformer plates, so the ring beam is prebunched into a train of rings separated by 2 cm. In the original tests of the WFT, the witness beam saw an accelerating gradient about 4 times greater than naively expected, because the fields due to many preceding bunches bounce around between the plates, and interfere constructively with the field due to the properly synchronised ring bunch. It is hoped to capitalise on this effect by making a resonant transformer with an enclosed cylinder with many plates, a central hole for the witness beam, and an azimuthal slot for the ring beam. The radius of the azimuthal slot will probably be chosen so that the 2nd radial mode is most strongly excited by a passing ring bunch. There is also an intention to make the laser pulse stronger and longer.

Systematic dipole magnet errors

Two sources of systematic errors in HERA dipoles have recently been recognised to need urgent attention, according to conversations with Brinkmann, Harrison (at Lugano), Herb, and Willeke.

Tracking studies performed in the last 2 or 3 months have revealed that systematic 10-pole and 14-pole errors need to be corrected, in order to have sufficient aperture in HERA-p at injection. (Caveat - a minor bug which was very recently found and removed in RACETRACK is not expected to qualitatively affect the tracking results.) So far only 6-pole errors have been considered. The additional bore tube windings which are being designed at this late stage to compensate for these effects will probably not have a serious effect on the schedule of the project.

The importance of the drifting 'persistent' 6-pole field at injection energy is only being fully perceived as a result of discussions of the effect in the Tevatron at the Lugano workshop. Calculations and observations at the Tevatron show that the chromaticity shifts by about 50 units during the first 2 seconds of ramping, after an injection pause of about an hour. The effect is somewhat stronger at HERA - and is about 100 times stronger at the SSC. Starting the ramp off slowly will help the situation, but the main problem is one of diagnostics. Interest was shown in the MIRABILE instrumentation which has been used at Fermilab primarily for the E778 experiment, but which has also been used for rapid chromaticity measurements.

There is confident conjecture, especially at Fermilab, that the 'persistent' sextupole drift is due to movement of the 'Eddy' currents from the outer surface of the individual superconducting filaments towards the interior (paper by Anderson in 1962 in Phys Rev). Perhaps it will soon be possible to remove a large part of the perturbation by dead reckoning.

Narrow band multi-bunch feedback system

Kohaupt has a scheme to suppress multi-bunch coherent modes, without using broad band feedback systems, which could be useful at the SSC.

The theory of the scheme, and an experiment testing the scheme in PETRA, have recently been published in two articles in Particles and Fields. The idea is to produce a spread in synchrotron tune between different bunches, by retuning one of the RF cavities to a slightly different harmonic number. Only the 'barycentric' mode - the center of gravity motion of the bunches - is damped by feedback, avoiding the need to distinguish individual bunches. In an analogy to stochastic cooling, the bunches correspond to macro-particles, and the tune spread across all the bunches corresponds to the inverse of the mixing time. The scheme may be used in HERA-e.

The damping rate of such a scheme is slower than a broadband scheme, but usually sufficient. Although multibunch problems are usually worse in electron rings, proton rings can also benefit from such schemes - for example, the Fermilab proton booster spreads the synchrotron tunes in order to suppress coherent excitations, without using feedback at all.

Drawbacks are that only half a ring can be filled with bunches, unless the low frequency modes don't matter (probably true for the SSC), and that it is necessary to match schemes in both injector and acceptor rings, unless the retuned cavity is turned off during beam transfer.

Miscellaneous

Dipoles in HERA-e are sorted only by minimising the $\Delta\beta/\beta$ wave.

A canonical 6-dimensional formalism recently developed by Ripken and others naturally describes longitudinal betas, satellite sideband resonances, and more.

Ways to correctly calculate the 2nd order strength of sextupole island resonances are reported in a thesis by Schmidt, but are still not completely correct.

It was recently realised that ground loops must be avoided in the DESY-3 vacuum chamber, if very large tune shifts are to be avoided during ramping. There will be protons in DESY-3 in late 1988.

Drift tube problems in the proton linac have been overcome.

RMS errors in the location of the HERA-p sextupole bore tube windings, nominally large enough to cause very large tune shifts (and linear coupling?) through multipole feeddown, are being reduced.

The HERA-e and HERA-p control systems are converging on a common design using NORD-10 console computers, connected to each other and a NORD 100 (or 500) computer by slow network links.

All HERA beam position monitors will be capable of storing many turns of information.

RF noise in HERA-e can lead to coherent oscillations which couple through the beam-beam effect to cause emittance blow up in HERA-p. It is not very hard to suppress this effect.

ICFA Workshop on "Aperture-Related Limitations of the Performance Beam Lifetime in Storage Rings"

Introduction

The avowed purpose of this workshop was to "survey and advance present knowledge, both experimental and theoretical, of those aperture-related effects which limit the performance of storage rings, and in particular the lifetime of the stored beams". To this end we broke into 4 working groups,

1) criteria (spokesman: Alex Chao)

2) theory (Swapan Chattophadyay)

3) correction schemes (Ferdi Willeke)

4) experiments (Jaques Gareyte)

From the SSC/LBL, Etienne Forest was in the theory group, Dick Talman was in the corrections group, and I was in the experiments group.

Despite the regrettable absence of computers and reference books, the workshop was quite useful in the exchange of information and ideas, scoring perhaps 7 on a scale of 0 to 10 . The word 'workshop' should be reserved, perhaps, for meetings where a narrowly defined concrete subject matter allows individuals to go off and work by themselves, for a significant fraction of the time.

Approximately 55 people attended the workshop, mostly from European laboratories. There was a striking demographic split between accelerator physicists from large, mainly proton, storage rings (SSC, SPS/LHC, HERA, LEP) and from small synchrotron light rings (ALS, BESSY/COSY, Daresbury/Helios, ESRF) plus the rest (mainly theorists). Three expatriate russians were present (Kheifets, Heifets and Orlov), but the 3 russians who were expected from Novosibirsk (Dikansky, Gerasimov and Temnykh) failed to show up, for unknown reasons, as did the expected participant from the Peoples Republic of China.

There was debate in all of the working groups about the complementary roles of linear aperture and dynamic aperture in describing storage ring behavior. Linear aperture and smear appear to be gaining more general acceptance, for example at the CERN-SPS. This was the first time that many of the electron light community were exposed to smear and linear aperture, with a mixed response. Certainly it is true that small electron machines care more about lifetimes and dynamic apertures than do large proton machines.

Other reported nonlinear experiments

The three presentations made to the general audience about the E778 experiment, by Don Edwards and myself, were well received. Presentations were also made about dynamic aperture experiments at the SPS, about turn-by-turn measurements in the CERN p-bar accumulator, and about dynamic aperture/lifetime experiments in BESSY. The SPS results have been reported elsewhere, and need not be discussed here.

A small amount of data was taken by Krejcik and his colleagues in the CERN accumulator with an injected beam oscillating in 2 degrees of freedom, and being recorded for 1024 turns. One way this data was presented was in the form of 2 Fourier spectra, with a comparison between real data and tracking data which was not quantitative - the initial amplitudes did not agree. A second, innovative, way to present the data was as two 3-D wire frame plots of horizontal (vertical) amplitude, versus horizontal and vertical phases. Something like this should be incorporated into E778 analysis software in any future two-degree-of-freedom (2 DOF) runs. With these exceptions, the analysis software for the CERN accumulator experiment did not seem to be well developed.

The BESSY experiments reported by Kuske and Simon consisted mainly of measuring the current lifetime versus horizontal or vertical scraper position. Listening to their description illustrated how small synchrotron light rings are much different from large rings. For example, when all the chromatic sextupole are turned off in BESSY, the lifetime decreases by only about 30 per cent. The dependence of lifetime on vertical aperture is quantitatively well understood as being due to gas scattering, while the dependence on horizontal aperture is only qualitatively understood as being due to a mixture of Touschek scattering, radiative damping, and phase space nonlinearities. The shape of the non-gaussian tails in the horizontal beam distribution is not well understood.

These discussions underlined two defects in the way that accelerator physicists continue to investigate storage rings. First, controlled experiments (where predictions are compared with reality as a function of one or more control variables) are much more desirable, and, unfortunately, much rarer, than passive measurements. Second, the need for significant investments of time and intellectual effort in analysis software is often underestimated.

Gareyte's concluding presentation as spokesman of the working group began with the statement that "existing nonlinear dynamics are notably insufficient to predict observed behavior". He continued to say that tracking studies are OK to map phase space in the short time scale, for 10^3 - 10^4 turns, but that more experimental checks are necessary. In the longer time scale, 10^8 turns, where emittance and current lifetimes are the relevant experimental parameters, experiments need to be done, but tracking is more difficult and time consuming.

Future development of E778

Two natural topics for continued study in E778-like experiments at Fermilab, using methods which have already been developed, are to test other sextupole configurations in which the 1/3 resonance is not so strongly excited, and to better understand resonance islands and tune modulation behavior. The most obvious extension of E778 is to measure smear, and examine the linear aperture, in 2 degrees of freedom (2 DOF), that is, with horizontal and vertical oscillations in the excited beam. A more speculative extension is to try to measure diffusion enhancement factors in the presence of known nonlinearities - long time scale effects. Both of these extensions require the development of new analysis software tools, and the latter requires new experimental techniques.

In 1 DOF experiments the smear can be measured by fitting phase space data in the time domain, using the knowledge that the decoherence is gaussian. However, in 2 DOF experiments the decoherence is more complicated, and the frequency domain description becomes more appealing. Krejcik suggested in Lugano, as did Talman at Snowmass in 1986, that the smear could be measured as the root of the sum of the powers under all the Fourier peaks except the fundamental. However, it is necessary to keep track of the phases of the Fourier peaks (which are broadened by the decoherence process), as well as their powers. These ideas suggest a way to reconstruct the turn-by-turn motion in 2 DOF with the decoherence removed, enabling smears to be measured simply.

1 measure Q_x and Q_y accurately, as the phase advance divided by the number of turns

2 calculate a power and a representative phase for each broad Fourier peak, for example around $Q = m\,Q_x + n\,Q_y$, for all beam position monitors (BPMs)

3 rebuild the spectra using delta function Fourier peaks, with the same power and phase as the broad original, at a tune of exactly $Q = m\,Q_x + n\,Q_y$

4 transform the new spectra into periodic turn-by-turn time series, with decoherence removed

5 calculate the smear, et cetera.

This algorithm can be tested on tracking data, and on the limited amount of 2 DOF data already available from E778, to evaluate it for future use in an E778-like experiment.

Diffusion enhancement factors might be measured as follows. A high order (about 20th order) resonance is excited in one dimension at a moderately large amplitude, with a known strength which is measured by persistent signal techniques. A beam which is hollow in phase space is constructed by kicking the beam outwards to (or near) the resonance island chain, and letting it decohere. The response of this beam to known levels of white noise (or narrowband noise) is observed. Possible diagnostics include

1 power spectrum of the response
2 transfer function measurements of (response output) / (noise input) as measured on sensitive BPMs.
3 current lifetime from beam current transformers
4 loss rates from loss monitors (can they be calibrated to give current lifetime?)

5 flying wires, to measure the evolution of the distribution, and movement of the beam edge

While there is much work to be done here, it is worth noting that experiments were performed in the CERN-ISR to observe diffusion and resonances by measuring the power spectrum of the beam.

Compact light sources

COSY, the compact light source at BESSY, in West Berlin, has been successfully run with conventional 180 degree dipoles, and trials will soon begin with a superconducting version. The trials have been delayed because the magnet cryostat had to be sent back to England for defects to be corrected. Now they find that the magnets themselves, built by Siemens in Germany, have a deliberately inbuilt sextupole component of the wrong sign.

HELIOS, the compact light source being built under contract to IBM by Oxford Instruments, with consulting connections to Daresbury, is expected to begin commissioning with 4.5 Tesla superconducting dipoles in spring 1989. IBM are building an experimental factory for it somewhere in the US (Wisconsin?), including a 200 MeV linac, in a conservative approach which does not rely on a lower energy microtron for injection.