STATUS REPORT ON THE UNILAC

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Summary

This paper outlines the present operation mode of the Unilac, including records of beam availability. The beam quality is described in terms of intensity, energy and microstructure. A review of component performance concentrates on problems with the injection and rf system. Comments on the status of the control system are also given.

Introduction

A status report on the start-off[1] and the early operation period of the Unilac[2] was presented in 1976 and 1977. In those papers references are given for a machine description. This paper continues the before mentioned reports, however, the following subjects are left out here and are reported in separate articles in these proceedings: Energy and bunch measurements[3], the Unilac upgrading[4], component improvement[5], beam optimization[6]. In this paper the operational aspects, how they appear after nearly four years of routine service, are described. It is evident, however, that the most significant progress was made in the first year. Imperfections, which were left as problems at that date, still tend to be problems today.

Machine Operation

The Unilac continues to deliver heavy ion beams for fundamental research in nuclear physics, nuclear chemistry, atomic physics and, on a small scale, for practical applications, too. All 20 target stations in the experimental hall are now complete and about 56 proposals for experiments are presently scheduled for obtaining beam. An equal number of experiments already were completed.

The machine is in continuous operation 21 shifts per week. Every fourth week is scheduled for maintenance, minor modifications and accelerator development. This schedule was introduced in January 1979, subsidizing an earlier schedule with one maintenance and one development shift per week and two 6-weeks shut-down periods per year. Those long shut-downs for machine alterations are no longer necessary. For the large number of minor improvements a long shut-down proved to be less efficient and regularly raised coordinative problems. The maintenance weeks now are planned well ahead and each week is exclusively devoted to one particular activity. Due to increased maintenance efficiency, part of this week became available for machine developments jointly with computer program improvements. Interlaced with the research shifts, a few shifts for accelerator experiments are available.

In Fig. 1 a breakdown of the total operation time in the first half year of 1979 is shown and a brief comment on the individual columns should be given In general, the pattern has not changed significantly during the last two years, contrary to what one would have expected. The high fraction of the tune-up time was influenced favorably by the fact that the individual runs on the average last three times longer compared to the early survey experiments. On the other hand the beam quality requirements from the users went up considerably. Tuning the injection to maximum intensities and to perfect isotope separation became laborious. The phasing of bunchers and cavities is much more critical, if a sharp and stable time focus of the bunch structure is essential on the target. A refined adjustment of the beam center in respect to the machine axis is required if the beam splitter is used. Some experiments depend on an extremely clean energy spectrum, which is not a natural feature of a rf linac. The success in attaining those requirements depends on refined diagnostics, human judgement and interaction, which is correlated to the actual status of the hardware. The specific tune-up procedure can hardly be automated.

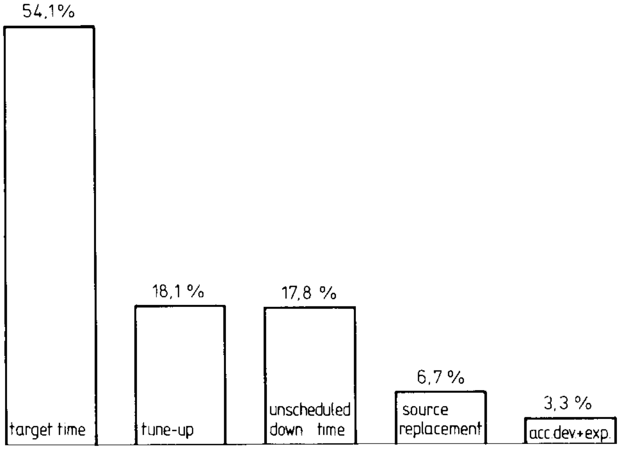

Fig. 1 - Breakdown of Operation Time in the First Half Year of 1979

The fraction of the unscheduled downtime equally is of serious concern. Compared to a proton machine, a heavy ion linac is much more complex and the frequent parameter changes contribute significantly to the amount of fault events. Reviewing the last two years, the weak points in the hardware could not yet be eliminated and every gain in component reliability was spent by increased performance stress. A histogram of the fault sources is given in Fig. 2, the individual deficiencies will be described later.

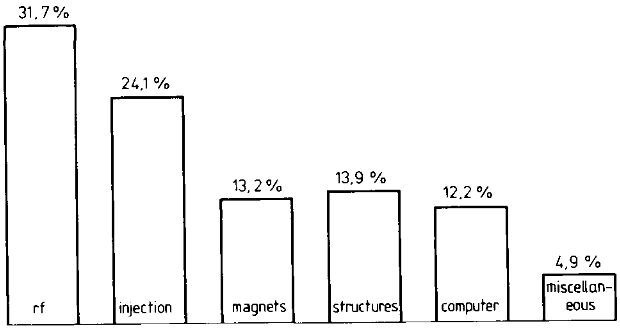

Fig. 2 - Breakdown of Unscheduled Downtime in the First Half Year of 1979

The column "source replacement" only accounts for normal and trouble-free source replacement. If a source turns out to be weak or of unusually short lifetime, this time loss is included under "unscheduled downtime".

The share of accelerator experiments in Fig. 1 seems to be small, but it is actually not unduly low, taking into consideration the limited manpower available for performing and interpretation of those studies.

Not included in Fig. 1 , is the additionally available target time provided by the parasitic beam. This supplementary research time amounts to about one-third of the main beam time.

If one desires to derive conclusions on the beam availability following the data of Fig. 1, only downtime and source replacement are quoted as missing time. Hence the availability, the ratio between obtained and attributed beam time amounts to about 71 %. Bringing up this figure to above 80 % still is a vigorous goal of the Unilac staff.

Beam Properties

The beam intensity remains to be a marginal parameter for all heavy ion accelerators operated so far. Table I lists the optimum values obtained at the Unilac for a variety of ion and isotope species. Compared to the data published in 1977[2], intensities of the very heavy ions went up by about one order of magnitude. This increase could also have been attained for light ions, but was not required. There is no hope for further intensity improvements, except for a factor of 2 or 3 by increasing the injection beam line aperture. The present situation is characterized as follows: The optimum intensity values obtained by the source - although at the expense of source lifetime - just coincides with the intensity limitations of the stripping foil and of the target as well.

Table I

ISOTOPE	POSTSTRIPPER CHARGE STATE	AVERAGE INTENSITY (PARTICLES/S)	ENERGY (MEV/U)
^{40}Ar	10+	$9.4 \cdot 10^{12}$	10
^{46}Ti	13+	$1.4 \cdot 10^{11}$	
^{48}Ti	13+	$1.2 \cdot 10^{12}$	
^{50}Ti	13+	$9.6 \cdot 10^{10}$	
^{56}Fe	14+	$2.8 \cdot 10^{12}$	
^{58}Ni	14+	$4.0 \cdot 10^{11}$	
^{65}Cu	15+	$2.5 \cdot 10^{11}$	
^{84}Kr	17+	$7.0 \cdot 10^{11}$	
^{86}Kr	17+	$2.0 \cdot 10^{11}$	
^{86}Kr	17+/30+	$1.0 \cdot 10^{10}$	13.1 (2.STRIPPER)
^{107}Ag	19+	$3.3 \cdot 10^{11}$	
^{129}Xe	21+	$7.0 \cdot 10^{11}$	
^{132}Xe	21+	$7.0 \cdot 10^{11}$	
^{136}Xe	21+	$2.4 \cdot 10^{11}$	
^{136}Xe	29+/41+	$6 \cdot 10^{10}$	12.0 (2.STRIPPER)
^{154}Sm	32+	$6.0 \cdot 10^{10}$	
^{184}W	34+	$2.0 \cdot 10^{10}$	
^{208}Pb	36+	$4.4 \cdot 10^{10}$	
^{208}Pb	36+/MC	$1.2 \cdot 10^{11}$	10.5 (2.STRIPPER)
^{209}Bi	37+	$8.0 \cdot 10^{10}$	
^{238}U	40+	$9.4 \cdot 10^{10}$	9.0
^{238}U	MC	$4.0 \cdot 10^{11}$	8.8

MC (MULTI CHARGE STATE OPERATION)

Figure 3 shows a histogram of the ion species accelerated in the first half year of 1979 in percent of the obtained target time. During the past years, the peak shifted continuously from the light to the very heavy ions, e.g. from Ar to Pb, W and U, which now are accelerated nearly 60 % of the time. This trend, which still goes on steadily, imposes a high degree of stress on the ion source and most of the accelerator components, which sometimes have to be operated beyond their design ratings. The trend for higher mass numbers, higher intensities and higher energies continues to enforce an exhausting effort in attaining a decent reliability increase on low bid machine components.

Practically all runs require isotopically pure beams, which are regularly provided by the isotope separation feature of the low energy beam transport system. The tune up of a pure ^{208}Pb beam sometimes is laborious and time consuming if impaired by unstable source performance. The use of isotopically pure primary material in the ion source so far has been restricted to very few runs,which were dependent on the ultimate beam intensity. The availability of those enriched elements has become increasingly limited on the market.

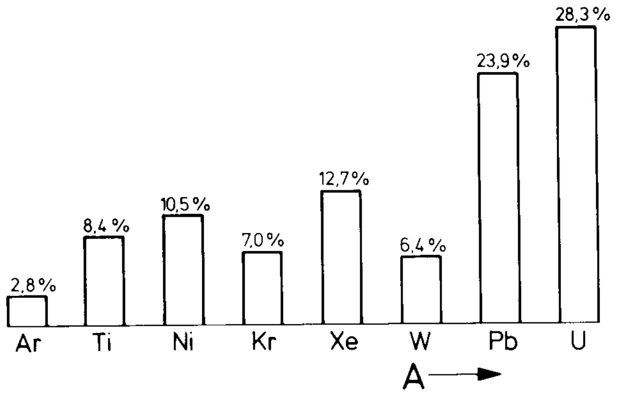

Fig. 3 - Ion Species Accelerated by the UNILAC in the First Half Year of 1979

The duty factor of the machine is set to 25% for all ions. In principle it could be increased to 50 % for medium heavy ions and to 100 % for light ions. But this was not done for a number of minor reasons, which could easily be eliminated, if a higher duty factor would be in heavy demand from the users.

In the past, the required beam energies were concentrated in the range between 4.5 and 5.9 MeV/u. Half of the runs required many energy changes in sometimes very close increments, which now can be quickly adjusted.[6] However, there is a firm trend to higher energies, and the original design aims have been surpassed by inserting a second foil stripper at the entrance of the single-gap cavities. If the charge analysis system in the first stripper section is bypassed , and if the multi-charge state mode is chosen in the Alvarez section, an intensity loss of a factor of only two is encountered by the second stripper. The figures for the maximum energies obtained so far are also listed in Table I. The demand for still higher energies led to an upgrading program[4], which is currently underway on a high priority level.

The excellent energy stability and the small energy spread of 0.1 % was already reported[2] as a result of an improvement effort on rf amplitude control loops. Four helix resonators are in service in the experimental area to refocus the well confined bunch structure of the Unilac to even the most remote target stations, about 80 m away from the machine end. Best values of time focus are about 0.18 ns, and the tune-up[6] is largely computer aided. The occasionally encountered difficulties in obtaining a satisfactory energy spread and time structure could be attributed to ion source instabilities; the interaction mechanism, however, is not yet understood.

Experiments, investigating steep exitation functions near the coulomb barrier, are sometimes fooled by small amounts of satellite energies of the beam. If this occurred, it was hard to eliminate these impurities, the sources of which seem to be numerous, fluctuating and hard to analyze. As a matter of fact, the generally used semiconductor counters tend to read more satellite peaks than the beam actually contains.

The beam splitting system at the end of the Unilac, described in 1977 as a future development[2], has been in use for two years. It provides a continuously variable share of the primary beam into two or three main beam lines of the experimental area. The second beam initially was considered to be a "parasitic beam" for check-out of the experimental set-up. The user of this beam did not have influence on ion species, energy and quality of the beam. As a matter of fact, this parasitic beam was even due to be canceled, if the intensity of the main beam was unsatisfactory. From the standpoint of the users community, the beam splitter is declared as an important success, and the above mentioned understanding of "parasitic" vanished in practice since the second beam really is used for experiments with nearly equivalent priority. On the average, 30 % more target hours have been recorded. The operating crew, however, suggests that this success is not quite real. The cut-down in tune-up time for the machine by a factor of two, as a result of increasing experience and computer based parameter preset, was totally spent by the extremely refined beam centering procedure, which is mandatory for avoiding excessive beam loss on the septum blades. During the run, the operators must keep track of ion source wear-out and must continuously rematch the beam in order to satisfy the extreme beam centering requirement, imposed by the splitting device. It was not entirely clear so far, which particular optical elements should be included in the correcting procedure, therefore a computer-based control loop was not closed at this time.

The design of a micro-bunch suppressor also mentioned as a further improvement[2] in 1977, was completed. The specifications are briefly as follows: Travelling wave deflector, at a phase velocity v/c = 0.005, to be inserted into the injection beam line. Total length: 0.7 m, deflection at ± 600 V and 2 cm spacing of the deflection electrodes: 30 mrad; switching time: 6 ns. Investigations of commercially available wide band amplifiers and measurements of delay line samples confirmed the feasibility of the system. This universal beam chopper, which equally would have served as a convenient tool in particle dynamics studies , was never built. Because of the increasingly broad application of the beam splitting system in the last two years, it was felt unreasonable to shape the time structure of the beam for the main experiment and make it less useful at the same time for the parasitic experiment. Instead of an universal beam chopper in front of the accelerator, it is now stated as a general rule that the users should provide dedicated deflectors in the high energy beam line, leading to their individual target set-up. In one case, so far, where such a deflector was built, it turned out to be simple and highly successful.

Hardware Performance

Since a separate report[5] is given on achieved improvements of a few components, this paragraph will concentrate on operation experiences of most critical subsystems and will equally outline proposed measures for further reduction of still existing deficiencies. According to Fig. 3, mostly the rf and injection system deserve further comments.

A few general remarks: The continuing high fraction of downtime as marked in Fig. 2 seems to compare unfavorably with other linacs, even with heavy ion linacs. But since there is no unified accounting scheme among all accelerators, the figures do not entirely bear evidence. Technically it is clear that amplifiers and power supplies can be trimmed to operate safely and stably at one particular set value, as in proton accelerators. However, it is technically non-comprehensive that amplifiers from a supplier X behave much more reliably than those procured from company Y under essentially identical operating circumstances. Therefore an assessment on the state of the art is readily available. The operations budget of the Unilac in the last years would have allowed for elimination of faulty equipment to some extent, but in most cases it was not clear whether the equipment was inherently underdesigned, or whether it could be made to give satisfactory service. For this analysis, available maintenance time never sufficed. As a result of an excellent collaboration with the users' representative, runs of various degrees of difficulty for the linac performance could mostly be scheduled according to the operational status of the machine or its particular subsystems. This situation however, will change in the future. Plans for a heavy ion synchrotron facility, for which the Unilac is included as an injector, clearly imply the need for a vigorous reconsideration of the reliability aspect. This is mandatory since fewer maintenance people will be available then for the linac.

Injection

The ion source and electronic equipment contribute nearly equally to the problems in the injection system. The duoplasmatron, earlier reported as an alternate source, was abandoned completely in favor of the Penning source. The latter shows much better beam currents for metal ions and equal properties for gaseous elements. No drastic progress can be reported for the source lifetime and there is no meaningful figure on an average value. Instead, there is a broad distribution almost from zero to 8 hours, if it was pushed hard, or to 40 hours, if it was run decently. The output intensity runs up slightly during the first two hours, then drops steadily, until the intensity becomes intolerably low for the particular experiment or until a short develops between anode and sputter electrode. A continuous monitoring and retuning of the source and beam matching elements is necessary on a trial and error basis. Spurious plasma oscillations, apparently giving rise to considerable energy oscillation of the beam, sometimes prevent an acceptable beam quality in terms of time structure and energy spread. Eliminating this behavior is by trial and error adjustment of source and extractor parameters, rather than a rationally substantiated operation. There are good and bad sources, differing by a factor of 5 in beam intensity, though they are fabricated or refurbished from precisely identical pieces and assembled with well controlled clearance settings. This inconvenient operation behavior was not previously experienced during the long years of test bench investigations, because more fundamental questions had to be pursued. Recent emittance measurements, performed on the high voltage terminal of the injector, revealed an incredibly erratic reaction of the emittance shape on incremental variations of the magnetic field and the extractor position. An emittance break-up by a factor of five can easily occur, accounting probably for the above mentioned intensity discrepancies from source to source. Taking into account the already laborious operation of charge state optimization and isotope selection, it is deemed unreasonable to implement a sophisticated emittance shaping effort into the routine procedure for beam tune-up. Instead, an ECR source is under development and is expected to replace the PIG source in a few years. This new source is not supposed to yield much higher brilliance figures, but it is a promising candidate for a stable and a long life device.

In principle, two completely identical injectors are available. It is still the aim to have a pretuned source on stand-by in the second injector, if the source in the first one expires. This might not be advisable, if simple beam quality without isotope separation is sufficient. In this case a source change in the same injector may be effected in half an hour and easily coordinated with a target change. But those easy runs are becoming rare. In the case of an ion change, a pretuned stand-by source certainly will save 3 - 5 hours of tune-up time. After a completed pretune, with the optimized beam stopped in front of the switching magnet, filament and discharge current are run down. The source then comes right on with the same beam parameters if turned on again. Thus far, frequent breakdowns in electronic equipment on the source platform or in the high voltage supply prevented the success of the envisaged twin injector concept. Semiconductor circuitry, in the sophisticated data transmission chanels and power supply control units, are highly susceptible to nearly unavoidable high voltage transients and discharges. Two injectors present nearly twice the probability for break downs and present also the need for nearly twice the maintenance effort.

A rigorous reconstruction of the injection beam lines, extending from the DC gap to the switching magnet is under consideration, eliminating in the future inconvenient acceptance constraints imposed by the isotope separator optics. In the original design the actual source emittance has been underestimated and adequate reserves for a a less ideal beam centering were not included. Thus, an increase of magnet and lens aperture from the present 4 to about 8 cm is planned. This will alleviate the presently encountered beam loss of a factor of 3 and will considerably simplify the tune-up of the beam through the injection lines. In addition, this alteration is indispensable for the application of a multi mA source for singly charged Ne ions, which is a substantial tool in future investigations of the longitudinal and transverse space charge limits of the Wideröe structure.

Rf-System

The Wideröe rf amplifiers, built by a commercial company specializing in industrial heat application, continue to operate as reliably as communication equipment. Anode and grid voltages have been increased in order to obtain the excess power, especially in module No. IV, for the acceleration of U^{9+} instead of the design charge state U^{11+}.

Irrespective of an elaborate test bench program, the situation of the Alvarez amplifier system remains unchanged: The tetrodes in the final amplifiers become unstable beyond one quarter of their design power ratings. The implementation of sophisticated protection circuitry did not inhibit tube damage but seems to shut off the system too often. If a tube becomes defective, crowbar firing becomes more frequent even at decreased power levels. Inspection of the interior structure of a broken tube does not reveal the fault causes. It is still believed that parastitic oscillations inside the tube initiate the damage. Sensing circuits, tuned to 0.76 and 1.2 GHz indicate a coincidence of microwave signals with an over-current trip-off. A large variety of attenuating measures have been applied without conclusive success. This activity will be continued until alternate approaches, which are pursued in parallel, result in an ultimate solution. The design aim still remains to obtain 1.6 MW pulse power at 25 % duty out of one single amplifier. The achievement of this goal is crucial for the Unilac upgrading program[4], for which the space for two amplifiers per Alvarez cavity will not be available. In the meantime nearly two tubes per stage have to be replaced in one year, and the useful tubes have to be selected properly.

As a consequence of the rf power shortage in the Alvarez section, foil stripping has to be used for ions heavier than Xe. In case of a high current run, for instance with a few μA Uranium beam, foils of 40 $\mu g/cm^2$ are damaged in less than one hour. This damage is not visible, nor does it result in a drastic drop of charge state abundance. It is mostly a pile up of energy straggling, which inhibits a proper phase space matching after the flight path between stripper and Alvarez tank I.

The amplifiers for the single-gap cavities and the re- and debunchers, altogether 30 identical units, perform nearly acceptably. After the elimination of several systematic failure sources, the required maintenance effort is still high: two technicians just manage to have on the average 28 out of the 30 units operational.

The replacement of the rf power lines for the Alvarez and for the single-gap cavity section was delayed, since a complete rearrangement of the line routing has to be effected anyway for the upgraded machine. A satisfactory design for the supporting insulators[5] has been found. Meanwhile, the fault rate drastically decreased, as a result of a yearly line inspection and replacement of deficient parts.

The suppression of rf leakage is a lengthy story of only a partly technical nature. The choice of the Unilac frequencies, 27.12 MHz for the prestripper and 108.48 MHz for the poststripper, was based on a recommendation of the German communication authority. They only lately discovered that the upper frequency falls into the air navigation band and drew the attention of the air control authority to this fact. An avalanche of bureaucratic reactions was the result, though this particular channel is not occupied by the near-by Frankfurt Airport.

GSI finally was assigned to suppress the radiation of the 27.12 MHz harmonics "only" to below the legally admitted level. This turned out to be an extremely tedious and laborious undertaking, which took almost three years. About 20 leaks had to be fixed on the 34 amplifier chains, each of them having additionally very special leakage sources. A series of mechanical parts had to be redesigned and remade. The problem was not so much the fixing of the leaks, as their detection.

Magnetic and electric probes, when used for scanning the metal surfaces and leads, are unable to discriminate irrelevant leaks from relevant leaks. This determination can only be made by a test antenna in the remote field, scanning the radiation pattern and polarization. Leaks tend to be quite frequency selective, and leakage generally is much more intense for higher harmonics than for the fundamental, for which chokes and traps already had been designed in the circuit. This subject gives rise to the question about the frequency selection for future accelerators. So far, there is no optimum choice. Any fundamental below a few 100 MHz will imply harmonics, which fall into broadcasting bands, for which the restrictions are more severe than for the communication bands. In the far future, multiples of 27.12 MHz will be a perfect selection, because the association of industrial rf heat equipment manufacturers argue strongly on international frequency allocation committees in favor of a cancellation of limitations for the 27.12 MHz harmonics out of channels.

Computer Control

The Sigma 6 computer facility was upgraded to its ultimate configuration and capacity and it no longer is shared with the users taking data. It is extremely useful for off-line programs supporting accelerator operation and optimization[3,6]. It provides convenient and highly instructive information on the machine status via display screens in the main control room. The following data are presently available: all faraday cup and profile harp signals along the machine, all magnet currents referenced to the optimized set values, a pattern of the beam current along the machine, derived by nondestructive probes, a read out of interlock events, charge and isotope spectra of the injection beam line, charge spectrum after the stripper, display of source parameters, printout of energy measurements. On-line programs, which really are meant by the word "computer control", are limited to a few examples: The run-up of the source until striking the arc is automated, all magnet currents can be set as computed values or as stored data from earlier runs, the beam can automatically be centered in the injection and at the high energy end of the machine.

The envisaged superiority of the computer facility, namely a drastic saving in tune-up time, can not yet be reported. The use of the computer as an intelligent switchboard and as a convenient display processor are not considered to be control functions. Mainly two reasons prevented the envisaged saving in set-up time: first, the steadily changing hardware imperfections of the machine (disabled elements, misalignments, current offsets, non linear reactions of magnet power supplies etc.) are not registered or updated in the data base. The second reason is the lack of a reproducible emittance pattern as a start-off basis for lens current determination. It is possible in fact, to measure the emittance and to let the computer evaluate the particle dynamics and set the beam optical parameters, but this procedure does not save much in tune-up time.

A general short coming of the existing computer facility with the highly centralized scheme of one powerful computer and a few small non-self-sustaining satellites is the slow reaction time, especially for automated optimization loops. An improvement of the system software and an increased assignement of control functions to decentralized microcomputers is under consideration, along with a continuous stabilization effort of hardware components and a more thorough understanding of the accelerator behavior.

References

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Discussion

L. Teng, FNAL: Could you tell us something about your future development program especially in connection with heavy ion fusion? I understand you have a project actually funded for heavy ion fusion.

Böhne: Compared to the plans here in the States, ours is a very limited and preliminary undertaking. We are looking at very particular developments which we feel we can easily do because they are on the line which we have to follow for the synchrotron project anyway. We have a high intensity ion source under development, presently delivering about 60 mA Xenon. We will make accelerator experiments on the Unilac when the acceptance of the injection beam line is increased, so we can do space charge experiments on the Wideröe,a so-called low beta structure, to evaluate emittance growth and space charge thresholds if they exist with our beam intensities of about 10 mA. A high intensity low beta structure is under consideration and R.W. Müller will report on this study. We don't have activities in storage rings or in final beam transport or anything else.