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CRAB-CROSSING IN A TAU-CHARM FACILITY*

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INTRODUCTION

In space-charge limited storage rings, the maximum luminosity can be expressed by

$$L = \frac{\Delta Q^2 \pi \gamma^2 \epsilon_x f}{r_c^2 \beta_{yIP}} \quad , \tag{1}$$

where AQ is the linear tune shift parameter, $\gamma = E/m_0c^2$ is the Lorentz factor, ϵ_x is the horizontal emittance, f is the bunch collision frequency-which is equal to the number of bunches times circumferential frequency, r_c is the classical electron radius, and β_{yIP} is the vertical beta function at the interaction point (IP).

To obtain Eq. (1) it is assumed that the coupling factor $k = \epsilon_y/\epsilon_x << 1$ and that $\Delta Q_x = \Delta Q_y =$ AQ by making $\beta_y/\beta_x = k$ at the IP. It is also assumed that the space charge limits ΔQ_x and ΔQ_y are reached simultaneously for the same value of the bunch current. TO reach the highest luminosity we consider the limits on the parameters involved:

1. The maximum AQ is limited by nonlinear space charge forces. Attempts to cancel these forces with a third and a fourth beam (DCI) have failed. No large gain in luminosity (larger than a factor of two) can be expected when trying to push this number over the presently achievable value somewhere in between 0.02 to 0.05.
2. γ is not a free parameter, but given by the physics requirements.
3. ϵ_x is limited by the dynamical acceptance of the storage ring and/or by the necessary charge which is required to reach the AQ limit. This charge must be stably maintained in each single bunch. Both the dynamical acceptance and the maximum single bunch current depend on many other parameters. It is by no means certain that present

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storage rings have reached the ultimate limit in ϵ_x; but no large luminosity improvement factor is expected by pushing the limit of ϵ_x.

4. β_y has to be substantially larger than the bunch length if the maximum values for AQ are not to be effected in a negative way. Luminosity gains can only be expected by making the bunch length shorter, either by larger RF voltages or by higher frequencies. Factors larger than 3 gained in this way are hard to visualize.

5. f is the parameter which potentially allows large luminosity gains to be made at the cost of large average beam currents. To avoid unwanted beam-beam interactions in a multibunch mode of operation, both beams must be stored in separate rings and should cross each other at the interaction point(s). To ensure high luminosity at each bunch-bunch interaction, the excitation of synchrobetatron resonances in a crossing beam geometry' must be avoided even with modest single bunch currents. That can be achieved by using ***crab-crossing.*** (Head-on collisions with subsequent electrostatic beam-beam separation are also possible. But such schemes never allow bunch frequencies as high as in crab-crossing schemes). Crab-crossing was proposed by Palmer[2] to reach high luminosity in multibunch linear colliders. Oide and Yokoya[3] showed that crab-crossing prevents excitation of synchrobetatron resonances in .a crossing beam geometry.

CRAB-CROSSING

In a crab-crossing beam geometry (beam-crossing half-angle α), bunches are rotated by the angle α around their centers in deflecting RF cavities such that at the IP the two long axes of the bunches (along which phase oscillations take place) are colinear. This changes effectively the crossing beam geometry into a head-on collision geometry with a simultaneous (inconsequential) transverse motion in the laboratory reference system. After having passed through the IP, bunches regain their original orientation along the direction of their flight path in a second crab cavity.

The bunch center traverses the deflecting crab cavity when the beam deflection is zero. Leading (trailing) particles in the bunch located at a distance z from its center gain their deflection angles which manifest as displacement y(z) at the IP. If the crab cavities each are located 90° away from the IP in betatron phase angle, the displacement at the IP is:

$$y(z) = \frac{eU_M\sqrt{\beta_{IP}\beta_c}}{E} \sin \frac{2\pi z}{\lambda} \quad . \tag{2}$$

Here U_M is the amplitude of the RF field in the crab cavity (as seen by a relativistic particle), E is the particle energy, λ is the RF wave length, e is the elementary charge, β_{IP} is the beta function at the IP, and β_c is the beta function at the crab cavity.

For a short bunch (z << X), the crab angle thus produced is:

$$\frac{y}{z} = \frac{2\pi eU_M\sqrt{\beta_{IP}\beta_c}}{E\lambda} \quad . \tag{3}$$

This angle should be equal to the beam-crossing half-angle α.

If the crab cavity frequency is the same as that of the main RF system, the maximum acceleration voltage occuring in such cavity must be

$$U_M = \frac{E\alpha\lambda}{2\pi e\sqrt{\beta_{IP}\beta_c}} \quad . \tag{4}$$

If the crossing angle is sufficiently small, both beams can go through the same crab cavities. By having them located at an integral number of RF half-wavelengths from the IP, two bunches of opposite beams cross the cavities at the same phase.

HORIZONTAL VERSUS VERTICAL BEAM CROSSING

The purpose of the beam crossing is to make sure that beam-beam interactions take place only at the IP and that beams can be guided in a natural way into their separate storage rings. There are four strong reasons why horizontal beam crossing is to be preferred:

1. At the IP, the natural beam divergence is given by $\sqrt{\epsilon/\beta_{IP}}$. To cleanly separate both beams, the crossing angle α should be one order of magnitude larger than the natural beam divergence. Since β had been adjusted to be proportional to ϵ (see above), one could assume that the required crossing angle is the same for horizontal and

vertical crossing. This is not true, however, because for safe operation the vertical aperture requirement is much larger than that defined by the value of the coupling k. To avoid beam losses, α_y has to be much larger, thus making the requirements on the crab cavity more severe. It is also conceivable to keep α just large enough to limit beam-beam interactions at a distance to a tolerable amount and to have further beam-beam separation at more favorable places with large beta functions. But this means greater complexity, adding electrostatic plates or RF beam separators to the system.

2. The power requirements for the crab cavities for a given crossing angle are inversely proportional to the beta function at the IP [see Eq. (4) above]. The larger value for the horizontal beta function clearly favors the horizontal crossing.

3. In an optical arrangement with much smaller vertical beta functions compared to the horizontal ones at the IP, the first quadrupole following the IP is normally vertically focusing, i.e., horizontally defocusing. In a horizontal beam crossing scheme, the beam-beam separation increases rapidly after the first quadrupole magnet, making the beam-beam effects at adistance much smaller.

4. It can be shown that for very small crossing angles, the force which drives synchro-betatron resonances is smaller in horizontal crossing compared to vertical crossing by $\sqrt{\epsilon_y/\epsilon_x}$. At first sight, this is a strong argument for horizontal crossing (similar to that proposed for the original SPEAR rings), as compared to the original DORIS rings with their vertical crossing. But this argument is erroneous because, for practical crossing angles ($\alpha \geq \sqrt{\epsilon/\beta}$), the driving term quickly saturates, particularly in the vertical plane.[4] Without the crab arrangement, there seems to be no large advantage of horizontal over vertical crossing. But with crab cavities, a small error in the strength of these cavities is equivalent in its effect to a very small crossing angle without crab cavities. The horizontal crossing has the advantage of a smaller driving force; the tolerances for crab cavity voltage control are thereby larger by $\sqrt{\epsilon_x/\epsilon_y}$.

A CRAB-CROSSING ARRANGEMENT FOR A TAU-CHARM FACILITY

Figure 1 shows a straight section which makes use of crab-crossing. The general assumed beam parameters are given in Table 1.

The assumed horizontal crossing angle is ±6 mrad. This makes it possible to steer both beams into two separate rings without additional beam-beam separation. Each beam can have a free aperture close to ±12 standard deviations. Figure 1 also gives values for horizontal and vertical beta functions, betatron phase advances and beam-beam separation. The triplet optics is adjusted such that both crab cavities are approximately 90° away from the IP. At the same time, their physical distance is 510 cm from the IP, equal to 12 RF half-wavelengths. It is important that both crab cavities are 180° apart in betatron phase space. In this case, the crab angle produced by one crab cavity is cancelled by the other.

Following the crab cavities at f510 cm from the IP are thin-walled double-septum magnets which guide each beam into its separate half-storage-ring. In the straight section on the opposite sides of the storage rings, beams must cross again to get each into the correct half-storage-ring. If there is to be only one experimental interaction region, this second crossing can easily be arranged in such a way that the beams do not interact.

The parameters in Table 1 are chosen to give some feeling for the luminosity which can be reached, if it is possible to reach the corresponding average currents. At the beginning it may be easier to start with a smaller number of bunches, i.e., with smaller average currents and proportionally smaller luminosities. As one learns to control and avoid the coupled bunch instabilities, one will be able to increase bunch numbers and thereby average currents and luminosity.

The choice of the beta functions at the IP and the choice of the RF frequency are rather arbitrary. The numbers in Table 1 are conservative. Smaller values of the beta functions at higher RF frequencies certainly can be considered with correspondingly larger luminosity.

If all RF buckets are filled, there are 12 “near collisions” on either side of the IP where bunches of both beams come close and can interact with each other at a distance. The quadrupole field of one beam produces additional vertical focusing for the other beam, corresponding to a vertical tune shift of 0.046, and a very small horizontal defocusing, corresponding to a horizontal tune shift of about -0.002. The tune shifts can be corrected, if necessary, by changing the quadrupole currents in the straight section. The effect of the dipole field (both bearns attract each other outside of the IP) is canceled at the IP and is very small in both rings (of the order of 1 mm orbit distortion). This effect could also be corrected with steering coils, if necessary.

TOLERANCES

The tolerances imposed on the various elements of the crab-crossing scheme must be checked to make certain that the proposed scheme is feasible:

1. The RF phase of each crab cavity has to be adjusted with respect to the bunches so as not to deflect the centers of the bunches.

   A phase error of the RF in a crab cavity produces a transverse deflection of the bunch and thereby an orbit distortion. As far as both beams see the same field, their orbit distortions are the same. A phase error of 10° may cause horizontal orbit distortions of less than 1 mm and seems to be of no significance.

2. The betatron phase angle between both cavities has to be 180°, otherwise there is some crab angle left, leading to synchrobetatron excitation in a single beam.

   A betatron phase angle between both crab cavities not equal to 180° produces an RF phase-dependant horizontal orbit distortion and can cause single beam blow-up due -to the excitation of synchrobetatron resonances. To maintain lifetime in the case where the operating point was on the first satellite side-band of an integral resonance would require a cancellation of any leftover crab angle larger than about 10^{-3} to 10^{-4}. Higher satellite side-bands are produced by the nonlinearity of the RF potential. These nonlinearities for single-particle motion are most likely determined by higher-order mode losses in the vacuum chamber or in the RF cavities, and are current-dependant. Considering the relatively modest single-bunch current of 14 mA and the small number of cavities in each ring (six single cells designed to have small higher mode losses), it may be justified to assume that the strength of higher satellite side-bands is considerably smaller than the number given above for the first side-band. The tolerances for cancelling the crab angle would be correspondingly more relaxed. If the crab angle has to be compensated to within 1%, the betatron phase angle between both cavities has to be correct to better than 0.5'.

3. Both cavities must have the same voltage, otherwise excitation of synchrobetatron oscillations takes place in a single beam.

   The effect of unequal deflecting power in both cavities is comparable to the effect of a betatron phase angle different from 180° between crab cavities. In both cases, the crab angle produced by one cavity is not compensated for by the other, and synchrobetatron resonances can be excited. A 1% voltage unbalance corresponds in our example to a betatron phase error of 0.5’.

4. Both cavities must have the right voltage, otherwise some crab angle is left at the IP, leading to lower limits on AQ.

   If the crossing angle is not completely compensated for by the right deflecting angle, the situation is comparable to crossing without crab cavities at very small angles. Here it is advantageous to have horizontal instead of vertical crossing. Using the maximum AQ in a vertical crossing beam geometry found at the DORIS’ storage ring to be 0.01, one can estimate the maximum crossing angle which would allow a value of AQ of 0.04.[4] That angle would be roughly 0.1 mrad in the vertical plane or 0.5 mrad in the horizontal plane. The voltage in the crab cavity apparently needs to be correct only to within 10%.

5. Deflection as a function of the phase position has to be a linear function, otherwise particles with large phase deviations find themselves transversely displaced at the IP. This also can lead to beam loss through the excitation of synchrobetatron resonances.

If a crossing angle of f0.5 mrad is tolerable without crab-crossing, we might also assume that the dependance of crab angle on phase is only linear within 8% (0.5 mrad/6 mrad). This corresponds to an RF phase acceptance angle of smaller than 45°. Particles with six standard phase deviations (the largest we have to consider) should therefore have distances from the bunch center of smaller than 10.6 cm (45° of λ equals 85 cm). The bunch length should therefore be smaller than 1.8 cm (1 st.d.). By overpowering the crab cavities by 10%, one might be able to extend the acceptable bunch length to 2.3 cm.

BEAM LOADING AND AVERAGE CURRENT LIMITATIONS

If all RF buckets are filled in both rings so as to reach the maximum luminosity, the average current will be 6.5 A in each ring. This is almost an order of magnitude larger than in rings built to date, and certainly presents new and challenging problems. The single-bunch current of 14 mA (6500:444) is not unusually high and should be manageable in a ring with smooth vacuum chambers and only a few RF cavities (each beam might “see” only as few as six single cell cavities including the two crab cavities); but beam loading in RF cavities and bunch-bunch interaction through higher cavity modes will need close attention.

Crab cavities could perhaps be built similar to the “single mode cavities” proposed by Weiland.[5] Such cavities resonate only on a fundamental accelerating mode (here at a lower frequency than the basic RF frequency of 353 MHz) and one deflecting TM_{110} mode tuned to 353 MHz. Because of the crossing angle of ±6 mrad, both beams do not go through the center of the cavity, but 1.5 cm off-axis. Beams couple to the electric fields. Each beam by itself may produce as much as 2 MV in the cavity, but the voltages produced by both beams cancel each-other. This also means that one beam is accelerated, while the other one is decelerated, as they traverse a crab cavity. Because it is off-axis, in the second crab cavity each beam sees again some of the accelerating E-field, although this time with changed polarity. This means that beams will not suffer a net energy change in the crab system. A very tight feedback system for phase and amplitude control will be necessary, nevertheless.

The accelerating voltage of 2 MV in each ring required to produce a bunch length smaller than 2.3 cm (1 st.d.) can be produced with four normal conducting single cells, each of the “single mode type.” In order to combat longitudinal and transverse multibunch instabilities, a number of conceivable remedies have been proposed?

1. Active or passive damping systems on the cavities should be used to keep any higher mode excitation to a minimum.
2. If the cavities have only one higher mode with sufficiently high Q, it may be possible to tune the cavities such that the corresponding mode is not excited.
3. Broad band or narrow band[7] feedback systems for the beams should be developed to combat multibunch instabilities.

The success of these measures, as expressed in average current, will determine the achievable luminosity.

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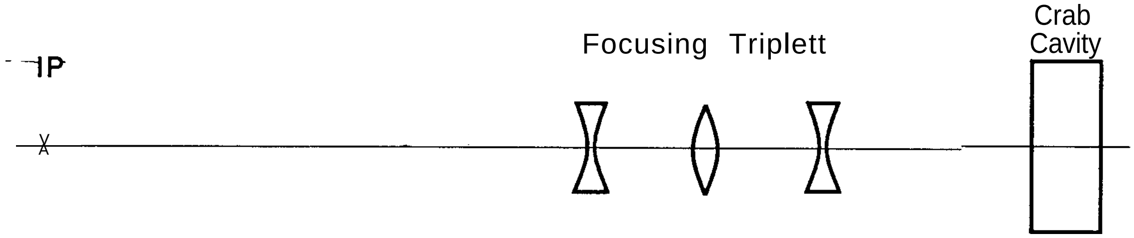
Table 1. Parameters of a Tau-Charm Facility with crab-crossing.

N	Parameter	Value	Unit
1	Maximum energy	2.2	GeV
2	Maximum current at 2.2 (1.5) GeV	$2 \cdot 6.5$ ($2 \cdot 4.4$)	A
3	Luminosity at 2.2 (1.5) GeV	$4.6 \cdot 10^{33}$ ($2.1 . 10^{33}$)	cm^{-2} s^{-1}
4	Circumference	377.4	m
5	Horizontal emittance	$2.5 \cdot 10^{-5}$	cm
6	Horizontal beta function at the IP	100	cm
7	Vertical beta function at the IP	3	cm
8	Coupling factor k	3	%
9	Beam size at the IP $(w \cdot h \cdot l)$	$0.05 \cdot 0.0015 \cdot 2.1$	cm^3
10	Horizontal crossing angle	±6	mrad
11	Linear tune shift $\Delta Q_x = \Delta Q_y$	0.04	
12	Energy loss at 2.2 (1.5) GeV	174 (38)	keV/turn
13	Synchrotron radiation power at 2.2 (1.5) GeV	$2 \cdot 1100$ (2.162)	kW
14	Accelerating frequency	353	MHz
15	Accelerating voltage	2	MV/turn
16	Harmonic number	444	
17	Momentum compaction factor	0.026	
18	Natural energy spread at 2.2 GeV	$5.4 \cdot 10^{-4}$	
19	Bunch length at 2.2 GeV	2.1	cm
20	Maximum crab cavity voltage	0.71	MV



	Focal length (cm) (horizontal)	f=−113	f=70.5	f=−113	
0	Distance from IP (cm)	200.0	250.0	300.0	510.0
0	Beam-beam Separtation (cm)	2.4	4.06	2.84	3.01
1.0	Horizontal beta function (m)	5.0	13.5	6.35	6.3
0	Hor. betatron Phase Shift (°)	63.0	66.9	70.0	90.0
0.03	Vertical beta function (m)	133.0	87.0	187.0	42.0
0	Vert. betatron Phase Shift (°)	89.1	89.4	89.6	91.2

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Fig. 1. Parameters of the IP straight section.