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HEAVY FLAVOURS

Proceedings of the Third Topical Seminar on
Heavy Flavours
San Miniato, Italy
17–21 June 1991

Edited by
F. GRANCAGNOLO,
F.-L. NAVARRIA
and P. G. PELFER

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PREFACE

The number of heavy particles detected at the $\Upsilon(4S)$ with CESR and DORIS is being surpassed by the statistics collected by CLEO II with a continously upgraded machine. On the high-energy e^+e^- side, owing to the favourable couplings at the Z_0 resonance, the number of b-quarks produced at LEP during two years of operation is becoming comparable. Data are also coming from hadron colliders and fixed target facilities.

The physics of heavy flavours is providing some of the most sensitive tests of the Standard Model and should provide more insight in many of the theoretical puzzles left open by the Standard Model in the near future. Forward–backward charge asymmetry of beauty production and tau polarization are examples of such observables at high energy. Lifetimes and partial widths or branching ratios are important measurements which are pursued both at low energy and at the Z_0 resonance.

B–d mixing seems appreciable and, in the framework of the Standard Model, a substantial B–s mixing and a sizeable *CP* violation is anticipated. Present data are compatible with maximal B–s mixing and the maesurement of *CP* violation is left for the next generation of experiments and machines. The large data samples allow the search for rare decays both at low and high energy. Flavour changing neutral currents in b decays, absent at the tree level in the Standard Model, and predicted rather precisely at the one loop level, could soon provide tests of the physics beyond the Standard Model.

The San Miniato Topical Seminar on Heavy Flavours took place in June 1991 in the Conference Centre "I Cappuccini" of the Cassa di Risparmio di San Miniato. It was attended by about 85 physicists, representing more than 40 laboratories and 9 different countries, and by several representatives of European and American industries. The Seminar was sponsored and supported by the Italian Institute for Nuclear Physics (INFN) together with the Universities of Bologna and Florence, by the Regione Toscana and by the Cassa di Risparmio di San Miniato.

We would like to thank all the sponsoring institutions that made the meeting possible and in particular Prof. N. Cabibbo, President of the INFN, Prof. E. Verondini, Director of the Physics Department of the University of Bologna, Prof. N. Taccetti, Director of the Physics Department of the University of Florence, Dr. P. Benelli, President of the Regione Toscana Council, and Cav. L. Catastini, President of the Cassa di Risparmio di San Miniato.

We would like to thank most warmly the secretaries of the meeting and all the people who helped us with the organization and during the meeting, in particular Mr. A. Bassi, Ms. M. Boldini, Ms. M. Mazerand and Mr. S. Zagato.

The programme was constructed around main lectures followed by shorter talks, leaving in addition ample time for the discussions: Our final thanks go therefore to all the speakers for the quality of their contributions and to all the participants for their enthusiasm which greatly contributed to the success of the meeting.

F. Grancagnolo
F.-L. Navarria
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Part 1

Flavour Factories

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NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Φ-FACTORIES

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A description of the main physical and technical problems of the Φ-factories is given, together with a panoramic view of the proposals presented by different laboratories around the world. The Frascati project DAΦNE is described in more detail.

1. INTRODUCTION

The major physics aim of a Φ-factory is a new precise measurement of CP violation parameters in K-meson decays. The K mesons come from the decay $\Phi \rightarrow K_l^0 K_s^0$, where the Φ is produced at rest in the laboratory frame in e^+e^- annihilations. The first requirement, in order to perform high accuracy CP violation experiments in a Φ-factory, is the achievement of a very high peak luminosity, of the order of 10^{33} cm^{-2} s^{-1}.

Around the world several Φ-factories, based on e^+e^- storage ring colliders at the Φ mass energy (510 MeV per beam), have been proposed. The possibility of using an asymmetric collider (linac plus storage ring) has also been considered, but the proposed solution is not foreseen for the near future.

In storage ring colliders the maximum luminosity ever achieved is 1.8 10^{32} cm^2 s^{-1} and has been obtained at CESR[1] at an energy of 5 GeV. Due to the strong energy dependence of the luminosity it is very difficult to obtain the same luminosity at an energy ten times smaller. The maximum achieved luminosity at the Φ energy is that of the VEPP-2M[2] collider:

$$L = 4.3\ 10^{30}\ \mathrm{cm^{-2}\ s^{-1}}$$

The goal of 10^{33} cm^{-2}s^{-1} is very challenging since a very large factor respect to the performance of the operating machines has to be gained. A world-wide effort is in progress in order to obtain a better understanding of the physics of the beam-beam interaction, which sets the ultimate limit on the maximum luminosity, but the results are not satisfactory.

However, in order to obtain luminosity in the $10^{32} \div 10^{33}$ range, all kind of instabilities which limit the single beam intensities have to be studied and cured.

Finally, the achievement of this ambitious objective requires technological improvements to push all the parameters of the machine at their limit and at the same time to maintain the machine operation very reliable, in order to get also a very high average luminosity.

2. REQUIREMENTS

A high average luminosity at an energy of 510 MeV is then the main requirement. Obviously to get a high average luminosity one has to get a very high peak luminosity, but this is not enough, since other important factors play a role in it. They are the following:

- good beam lifetime
- fast injection and topping up
- reliable operation.

Moreover, to exploit the machine features, a very high detection efficiency in the apparatus is needed. Therefore, the interaction region design has to take into account the constraints of the apparatus and has to be done in very strict connection with the experimental group. In particular a very large solid angle has to be left free and this makes the design of the low-β insertion difficult.

The interest for the CP violation experiment is to have the results in 5 or 6 years from now. This eliminates some ideas which require a long period of R&D in accelerator physics. It is therefore important to design a very flexible machine in order to adjust the various parameters to optimize the luminosity and, eventually, to adopt new ideas coming out in the near future.

3. DESIGN STRATEGIES

The luminosity is given by:

$$L = hL_0 = hf_0 \frac{N^2}{A}$$

where L_0 is the single bunch luminosity, h the number of bunches, f_0 the revolution frequency and $\frac{N^2}{A}$ the transverse beam density.

To obtain a high luminosity the number of particles per bunch and the collision frequency have to be very high. The transverse beam density is essentially limited by the beam-beam interaction and by the available aperture, therefore the only parameter which can be strongly pushed in order to gain the enormous factor we need is the collision frequency.

At this low energy, two very different strategies are possible: the first one is to increase the revolution frequency making a very small storage ring with few bunches, the second one is to make a large ring and a high number of bunches. The second solution allows to reach a much higher value of the collision frequency (~ 500 MHz), but it requires a more complicated design in order to avoid the beam-beam limit (the bunches must interact just at the interaction point and two different rings is the only choice).

The main difference between small ring and larger one is that in the first case one tries to push the single bunch luminosity L_0 well beyond the limit of existing machines. The ultimate limit to this value is then the beam lifetime acceptable for the experiment. In the second case one chooses a value of L_0 of the order of that achieved in the operating machines and increases the number of bunches. The main limitation that one has to face is due to multibunch instabilities, a problem which poses a technological challenge. Intense R&D programs on this argument are in progress in many laboratories because it is important also for Beauty factories and Synchrotron Light machines.

In the following we summarize the advantages and drawbacks of both solutions.

3.1. Short ring

The shortest is the machine, the highest is the collision frequency but, in practice, the maximum frequency achievable is of the order of 30 MHz, which corresponds to a circumference of the order of 10m. In such a machine the space available for the apparatus is very restricted.

A small machine has very high bending fields and gradients. This makes the lattice design and the construction of the magnetic elements more difficult. In particular, in order to obtain small bending radii, superconducting magnets are needed, which have nonlinear field components stronger than conventional magnets. These can lead to a reduction of the dynamic aperture. However the strong synchrotron radiation due to the high fields is favourable for the beam dynamics and for high luminosity.

In a small machine it is more difficult to get a low impedance vacuum chamber and therefore a very short bunch, which is required for the high luminosity.

The number of circulating particles is small, this makes much easier the RF, and vacuum system and in particular the injection system, which is mainly limited by the positron production rate.

This choice is very interesting from the accelerator physics point of view because it exploits new ideas to increase L_0. Anyway the increase of L_0 is always obtained by an increase of the bunch density, and therefore at the expense of the beam lifetime. Moreover for luminosities of the order of $10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ the beam-beam bremsstrahlung becomes important for the beam lifetime.

The beam-beam bremsstrahlung lifetime is proportional to the total number of particles in the ring and inversely proportional to the luminosity. This is a strong argument against the choice of a machine with a small number of particles in a very dense bunch.

This argument and the limited space available for the experimental apparatus are the major drawbacks of the small ring solution.

3.2. Large ring

At the Φ energy, a large ring is a machine with a circumference of the order of 100 m, i.e. much smaller than most of the existing e^+e^- storage rings.

The main features of such a machine are the following:

- easy lattice design and flexibility;
- good beam lifetime;
- large volume available for the apparatus;
- technological problems due to the high number of particles in each ring;
- higher cost.

Here we want to stress one of the main problems of these machines, the multibunch instabilities, which set a limit on the total current and then on the maximum luminosity. A great effort has to be addressed to the design of RF cavities in order to suppress the HOMs responsible for the coupled bunch instabilities. On the other side the development of a powerful feedback system has to be envisaged.

Another difficult point of the design is the separation scheme. For a symmetric machine, where the two beams have the same energy, there are two possible choices: head-on collision with electrostatic separators or crossing at an angle. In the second case an opportune choice of the beam parameters at the IP or the adoption of a crab-crossing scheme are necessary in order to avoid a luminosity reduction.

4. DESIGN PARAMETERS

At the space charge limit the luminosity can be written as:

$$L = hL_0 = \pi\left(\frac{\gamma}{r_e}\right)^2 hf_0 \frac{\xi^2\,\varepsilon(1+\kappa)}{\beta_y}$$

where:

γ	beam energy in units of the rest mass
r_e	classical electron radius
ξ	linear tune shift
ε	beam emittance
β_y	vertical β-function
κ	coupling factor.

The above formula is written in the hypothesis of equal tune shift in both planes:

$$\kappa = \frac{\beta_y}{\beta_x} = \frac{\sigma_y}{\sigma_x} = \frac{\varepsilon_y}{\varepsilon_x}$$

4.1. Linear tune shift

The beam-beam interaction sets a limit on the linear tune shift ξ:

$$\xi = \frac{r_e}{2\pi\gamma}\,\frac{N}{\varepsilon}$$

The maximum achievable linear tune shift determines the maximum luminosity. It cannot be calculated theoretically. To estimate the luminosity in a collider project an average value from the data of the existing machines is taken:

$$.03 < \xi_{max} < .05.$$

Some simulation studies predict that for round beams a much higher value of the tune shift can be achieved. For the Novosibirsk Φ-factory project it is assumed that, with round beams, a value of $\xi_{max} \geq .1$ can be achieved, but such a high value has never been reached in an operating storage ring collider.

4.2. Low-β

The β-function at the IP has to be as low as possible. This requires very strong focusing elements near the IP, which limit the solid angle for the apparatus and give a high chromaticity and then a reduction of the dynamic aperture. Due to the parabolic increase of the β-function in the interaction straight section, to take advantage of the low-β value the bunch length has to be very short:

$$\sigma_z \leq \frac{2}{3}\beta_y.$$

This is a further difficulty in the machine design, in fact very short bunches mean high RF voltage, low impedance of the ring, high bunch peak current and instability problems.

4.3. Emittance

The emittance has to be as large as possible, compatibly with the physical and dynamic aperture of the ring. Practical values are in the range:

$$10^{-7} < \varepsilon < 10^{-6} \text{ m rad}$$

4.4. Coupling factor

Two different solutions are possible:
round beams ($k \sim 1$) or flat beams ($k \ll 1$). The first one gives a gain of a factor two on the luminosity but requires the same low-β value both in the horizontal and in the vertical plane. This makes more difficult the design of the low-β insertion and gives a higher chromaticity and, as a consequence, a reduction of the dynamic aperture of the ring. It has been adopted in the Novosibirsk design where very high field superconducting solenoids (11T) are used to focus the beam at the IP in both planes.

The second solution means relatively large values of the horizontal β_x and σ_x at the IP. It allows crossing at an angle without exciting synchrobetatron resonances, which limit the maximum achievable tune shift. In case of crab crossing the voltage of the crab cavity is reduced by a factor $\sim\sqrt{\kappa}$.

5. DIFFERENT PROPOSALS

Various Φ-factory proposals have been presented in laboratories all over the world. Two of them (Novosibirsk[3] and UCLA[4]) are based on short machines and two (Frascati[5], KEK[6]) on large ones.

The parameters of the various designs are shown in Table I.

The Novosibirsk Φ-factory is an eight shape machine, the design is based on the idea that round beams can get a higher value of ξ_{max}. Solenoidal magnets are used to exchange the horizontal and vertical plane and create the same emittance in the two planes. They are also used to focus the beam at the IP. Both the solenoids and the bending dipoles are superconducting. From the layout of the ring, shown in Fig.1, we can see that the size of the apparatus is very small. The beam-beam bremsstrahlung lifetime is of the order of ten minutes, and therefore injection each few minutes is foreseen.

The UCLA project is also based on a small machine with SC bending magnets. Three phases are foreseen. In phase I the design

TABLE I

	L 10^{-33} $cm^{-2}s^{-1}$	h	L_0 10^{-30} $cm^{-2}s^{-1}$	f_0 MHz	ξ	ε 10^6 m rad	κ	β_y cm	τ_{bb} h
Novosibirsk	1	1	1000	17.1	.1	.47	1	1	.2
UCLA	.2	1	200	17.2	.05	3.2	.2	3.9	2.5
KEK	3	300	10	2.50	.03	1.1	.01	1	4
DAFNE	.5	120	4.5	3.17	.04	1.0	.01	4.5	24
VEPP-2M	.0043	1	4.3	16.8	.02-.05	.46	~.01	4.5	6

parameters are chosen in order to reach a luminosity of 2 10^{32} cm^{-2} s^{-1}. To get a higher luminosity in phases II and III (i.e. on a time scale longer than 5-6 years) they plan to exploit new ideas like the quasi-isochronous ring or a linac against ring collider scheme. The quasi-isochronous ring is a machine with an almost vanishing momentum compaction to obtain an extremely short bunch and have the possibility to design a micro-β (~1 mm) insertion. The study of beam stability in such a ring is a hard problem due to the extremely high value of the peak current in the bunch (~ KAmpere).

The Frascati project DAΦNE is described in more detail in the next section. It is a double ring collider with horizontal crossing angle at the IP and the high luminosity is mainly obtained with a high number of bunches.

The KEK design philosophy is very similar to the Frascati one, with a different choice of some parameters, as it can be seen from Table I.

6. THE DAΦNE Φ-FACTORY

The DAΦNE project has been approved and funded in June1990, commissioning is foreseen to start in 1995. The accelerator

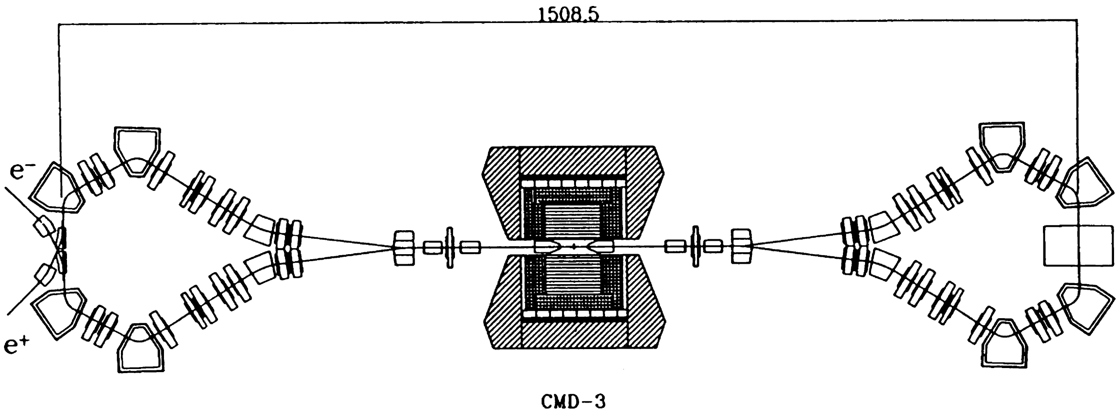

FIGURE 1
Layout of the Novosibirsk Φ-Factory

complex consists of the double ring collider, an accumulator and a linac. It will be housed in the existing LNF buildings, after the decommissioning of Adone.

Luminosity is optimized at 510 MeV and the maximum energy (not yet defined) will be around 700 MeV.

6.1. Design criteria

The main features of the design are:

- many bunches
- very flat beams
- high emittance.

To separate the bunches out of the interaction region, the two beams cross at an angle in the horizontal plane.

For flat beams, the horizontal crossing should not excite synchrobetatron resonances, which limit the maximum achievable tune shift, due to the reasonable small value of the geometrical factor $a = \theta_x \frac{\sigma_z}{\sigma_x}$.

In Table II the values of the parameters relevant to the luminosity are given. The single bunch luminosity L_0 is nearly the same as that achieved in the VEPP-2M machine and the maximum number of bunches is 120. Therefore filling all the buckets a luminosity as high as 5.4 10^{32} cm^{-2} s^{-1} can be achieved. However the design has enough flexibility to fine tune the parameters in order to optimize L_0 and try to go over the design value.

TABLE II

L_0 (cm^{-2} s^{-1})	4.5 10^{30}
h^{max}	120
ξ	.04
ε^{max} (m-rad)	10^{-6}
κ	.01
β_x (m)	4.5
β_y (m)	.045
σ_x (mm)	2
σ_y (mm)	.02
σ_z (m)	.03
θ (mrad)	10
Nmax	8.9 10^{10}
f_0 (MHz)	3.17
τ_{bb} (h)	24

The commissioning strategy is to optimize the single bunch luminosity and then increase the total luminosity increasing the number of bunches as far as the multibunch instabilities are overcome.

6.2. The main rings

The layout of the two rings is shown in Fig. 2. Each ring has a circumference of the order of 100 meters with two 10 meters long interaction regions. In Fig. 3 the beam sizes and the half separation of the beams in the interaction region are shown. The low-β quadrupoles are .45 m far from the IP and are confined in a cone of 8.5° half aperture, leaving a free solid angle for the apparatus of 99%. The time separation between two bunches at the maximum collision frequency is 2.7 ns.

The novel lattice design is a modified Chasman-Green with electromagnetic wigglers in the arcs to control the emittance and to increase the radiation damping and fluctuations. In Table III a complete list of the single ring parameters is shown.

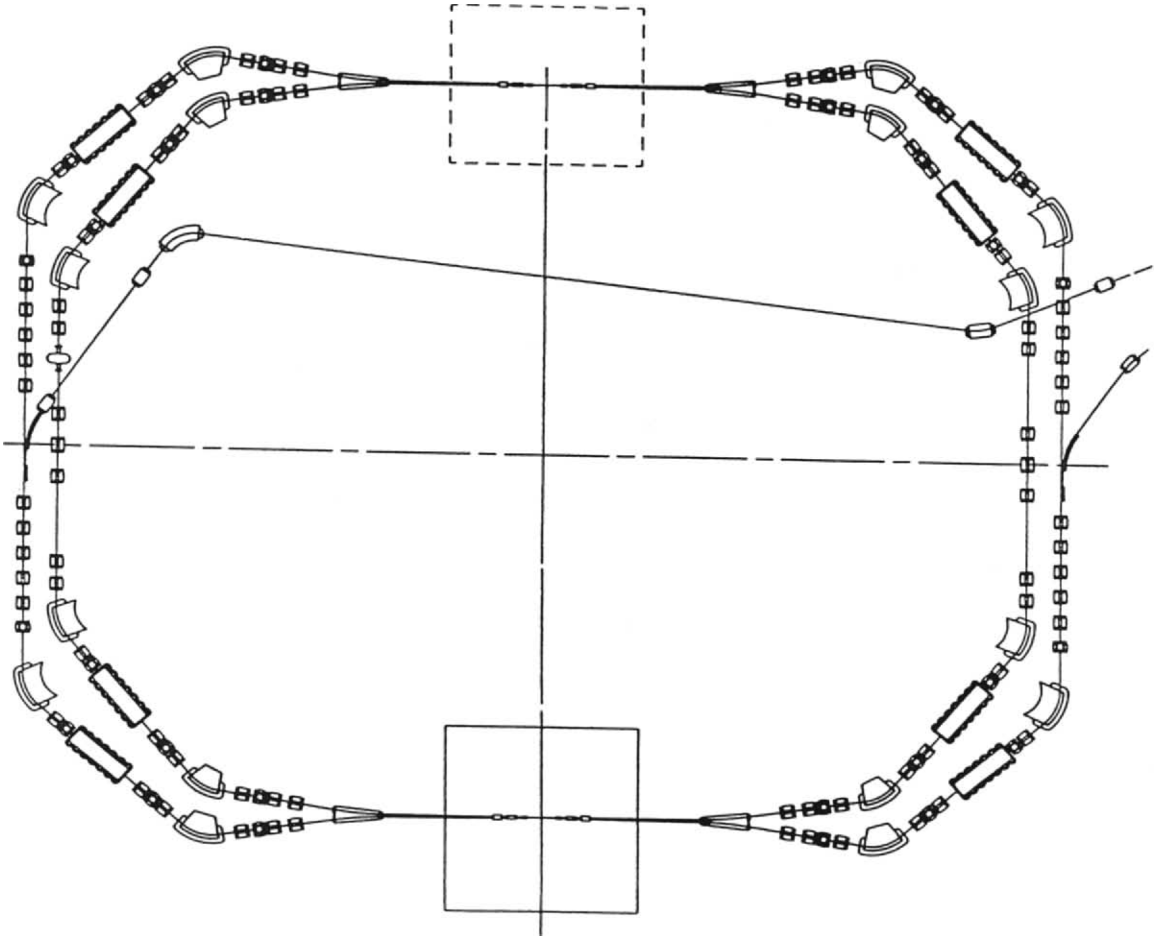

FIGURE 2
DAΦNE Magnetic Layout

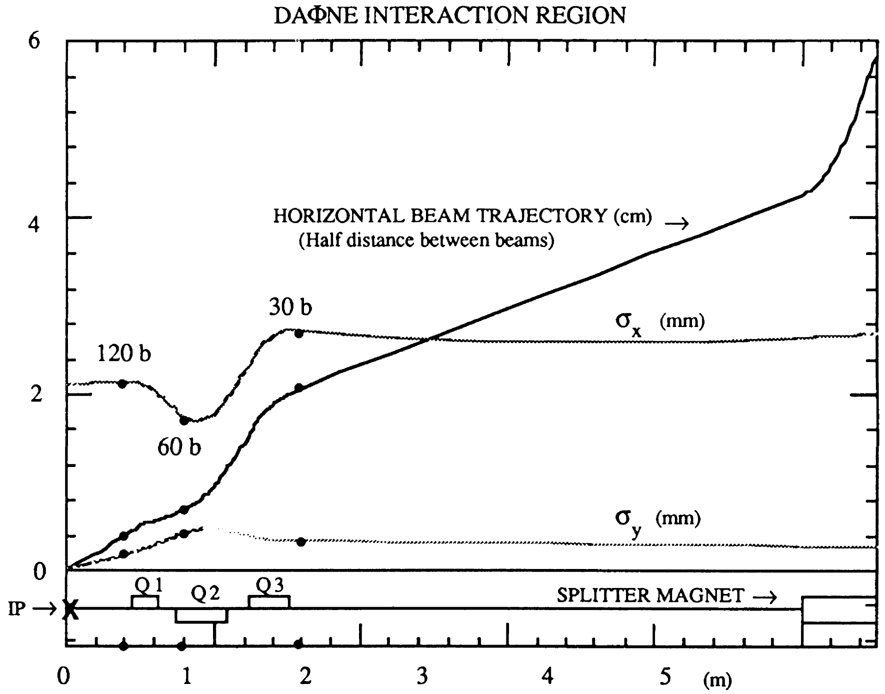

FIGURE 3

DAΦNE: Beam half-separation and beam dimensions in the low-β region. The heavy dots mark the parasitic crossing points for different bunch pattern configurations.

TABLE III

Energy (MeV)		510
Circumference (m)		97.69
Dipole bending radius (m)		1.400
Wiggler bending radius(m)		0.94
Wiggler length (m)		2.0
Wiggler period (m)		.66
Horizontal β-tune		4.87
Vertical β-tune		4.85
Natural chromaticities:	Horizontal	-6.5
	Vertical	-16.7
Momentum compaction		.017
I_2 (m^{-1})		9.69
I_3 (m^{-2})		8.05
Energy loss/turn (KeV):	Bend.magnets	4.27
	Wigglers	4.96
	Total	9.3
Damping times (msec):	τ_s	17.8
	τ_x	36.02
	τ_y	35.73

Natural emittance (m-rad)		10^{-6}
Natural rms energy spread		$3.94\ 10^{-4}$
β_y @ IP (m)		.045
β_x @ IP (m)		4.5
σ_y @ IP (mm)		.021
σ_x @ IP (mm)		2.11
κ		.01
Bunch length σ_z (cm)		3.0
Crossing half angle (mrad)		10.0
f_{RF} (MHz)		368.25
Harmonic number		120
Number of bunches		1 ÷ 120
Maximum number of particle/bunch		9.10^{10}
Maximum bunch peak current (A)		57
Maximum average current/bunch (mA)		46
Maximum total average current (A)		5.5
Maximum synchrotron power/beam (KW)		75
V_{RF} (KV)	@ $Z/n = 2\ \Omega$	254
	@ $Z/n = 1\ \Omega$	127
Parasitic losses @ $\sigma_z = 3$ cm (KeV/Ω)		7