ILC Damping Rings:
Summary of Configuration Recommendations

December 6, 2005

Contents

Introduction

The recommendations for the configuration of the ILC damping rings presented in this report are the result of discussions held during a meeting at CERN on November 9-11, 2005. The first part of the meeting was devoted to hearing the results of detailed studies of a range of configuration options. These studies were carried out over the previous six months by nearly 50 researchers, and the results of the studies form the basis on which the recommendations for the damping rings configuration have been made. A detailed report of the results of the configuration studies is in progress. Here, we simply present a summary of the issues surrounding each configuration item; an assessment of the risks and costs associated with each option for each configuration item; and recommendations for the baseline and alternative configurations.

The studies of the various configuration options were based on nominal parameter and performance specifications for the damping rings: these specifications are given on page 7. The assessments of the significance of the different issues associated with each configuration item, and the risks associated with the various options for each item, were based on a systematic ranking scheme, given on page 7. We should emphasize that although our systematic approach allows a "score table" for the various options for each item to be drawn up, our recommendations were reached through structured discussion, and not by simply adding up the risk scores for the different options. A number of items requiring R&D were identified during the discussions at the CERN meeting: these are given starting on page 7.

The participants at the CERN damping rings meeting on November 9-11, 2005 were as follows:

David Alesini (INFN)
Desmond Barber (CI/DESY)
Yunhai Cai (SLAC)
Alex Dragt (UM)
Eckhard Elsen (DESY)
Louis Emery (ANL)
Jie Gao (IHEP)
George Gollin (UIUC)
Susanna Guiducci (INFN)
Gilbert Guignard (CERN)
Samuel Heifets (SLAC)
Eun-San Kim (PAL)
Hyoung Suk Kim (CHEP)
Maxim Korostelev (CERN)
Larisa Malysheva (CI/Liverpool)
Oleg Malyshev (ASTeC)
Fabio Marcellini (INFN)
Chad Mitchell (UM)
Janice Nelson (SLAC)
Kazuhito Ohmi (KEK)
Yukiyoshi Ohnishi (KEK)
Toshiyuki Okugi (KEK)
Mark Palmer (Cornell)
Mauro Pivi (SLAC)
Ina Reichel (LBNL)
Marc Ross (SLAC)
Dave Rubin (Cornell)
Daniel Schulte (CERN)
Agoh Tomonori (KEK)
Junji Urakawa (KEK)
Jeremy Urban (Cornell)
Marco Venturini (LBNL)
Rainer Wanzenberg (DESY)
Andy Wolski (LBNL)
Guoxing Xia (DESY)

Summary of Configuration Recommendations

Circumference

The positron damping ring should consist of two (roughly circular) rings of approximately 6 km circumference in a single tunnel. Electron-cloud effects make a single ring of circumference 6 km or lower unattractive, unless significant progress can be made with mitigation techniques. Space-charge effects will be less problematic in a 6 km than in a 17 km ring, and achieving the required acceptance will be easier in a circular ring than in a dogbone ring.

The electron ring can consist of a single 6 km ring, assuming that the fill pattern allows a sufficient gap for clearing ions. The injection and extraction kickers and ion effects are more difficult in a 3 km ring than in a 6 km ring. A 17 km ring could ease ion effects (by allowing larger gaps between minitrains), but would likely be higher cost. We have no recommendation on whether the electron ring needs a separate tunnel from the positron rings.

Although R&D is still required for the injection/extraction kickers for a damping ring with 6 km circumference, it is expected that existing programs will demonstrate a solution.

The exact circumference of the damping rings should be chosen, if possible, to allow flexibility in the fill patterns and number of bunches in a bunch train.

The feasibility of the baseline depends on:

- further progress with developing techniques for suppressing electron cloud (positron rings);
- development of a satisfactory lattice design, e.g. (for electron ring) with properties that mitigate ion effects, etc.
- demonstration of kickers meeting the specifications for rise/fall times, kick amplitude stability and repetition rate.

Alternatives

1. If techniques are found that are sufficiently effective at suppressing the electron cloud, a single 6 km, or possibly smaller, ring can be used for the positron damping ring.

2. If electron cloud mitigation techniques are not found that are sufficient for the baseline positron ring, then a 17 km ring is a possible alternative; this would require addressing space-charge and acceptance issues.

Beam Energy

The damping ring energy should be approximately 5 GeV. A lower energy increases the risks from collective effects; a higher energy makes it more difficult to tune for low emittance, and potentially has an adverse impact on the acceptance.

Injected Emittance and Energy Spread

An injected beam with maximum betatron amplitude up to 0.09 m-rad and energy spread up to 1% (full width) is preferred for the damping rings, over a distribution with larger energy spread but smaller betatron amplitude. Achieving good off-energy dynamics in the damping ring lattices is likely to be more problematic than achieving a large on-energy dynamic aperture. A smaller energy spread is likely to improve the margin for the acceptance of the injected beam.

Alternative

If the acceptance issue can be addressed successfully, a larger energy spread on the injected beam (up to 2% full width) could be accommodated.

Bunch Train Length and Bunch Charge

A train length of around 2800 bunches is preferred because the kickers, ion effects and electron cloud are easier with a smaller number of bunches. If the electron ring is completely filled with no gaps (as may be the case with around 5600 bunches) the ion effects could be extremely difficult. However, there may well be other acceptable options with numbers of bunches between 2800 and 5600: further studies are needed to specify the gaps in the fill needed to keep ion effects under control.

If the positron rings (total circumference 12 km in our recommended baseline) are uniformly filled with 2800 bunches, the bunch separation is around 14 ns. Studies suggest that because of electron-cloud effects, the bunch separation should not be reduced much below this; this would prevent operation with larger numbers of bunches per train.

It is possible that the fill patterns in the electron and positron rings may need to be different, so as to allow a large bunch spacing between positron bunches (because of electron cloud), and gaps between minitrains of electron bunches (because of ions). This would require electron and positron rings with different circumferences, and would limit flexibility on timing solutions.

Alternatives

Increasing the number of bunches beyond 2800 could be possible if electron-cloud and ion effects are found to be manageable, and sufficiently fast kickers can be demonstrated.

Extracted Bunch Length

A 9 mm bunch would be helpful for mitigating single-bunch collective effects in the damping rings (except, possibly, in the case of electron cloud), but a 6 mm bunch also appears to be a viable option.

Injection/Extraction Kicker Technology

The damping ring kickers should be based on “conventional” strip-line kickers driven by fast pulsers, without use of RF separators. The basic technology is available, and is close to a demonstration of most of the performance specifications. Using RF separators has potential cost implications, and could adversely affect the beam dynamics; for these reasons, it is preferred to avoid the need for RF separators if possible.

Alternatives

RF separators may prove useful if it is decided to fill the rings with large numbers of bunches, pushing the bunch spacing to small values. Studies should be continued, to understand fully the beam dynamics and engineering issues.

Because Fourier pulse-compression kickers provide a very different approach, it is worthwhile continuing studies to develop a more complete understanding of the benefits and limitations of these systems.

Damping Wiggler Technology

The damping wigglers should be based on superconducting technology. The requirements for field quality and aperture have been demonstrated in existing designs, and the power consumption is low.

Alternatives

Normal-conducting electromagnetic and hybrid technologies are both viable alternatives. Issues with field quality and aperture can be addressed (at increased cost) in wigglers based on either technology. The power consumption in a normal-conducting wiggler is a concern, though this technology could provide a device with potentially better resistance to radiation damage than the superconducting or hybrid options.

Main (Non-Wiggler) Magnets Technology

We recommend that the main magnets in the damping rings be electromagnets. Using electromagnets simplifies tuning issues, and allows polarity reversal, e.g. for storing electrons in the positron ring.

Alternative

Permanent magnets may still be considered as a possibility for the main magnets in the damping rings, if it is decided that polarity reversal is not required.

RF System Technology

Each damping ring should use a superconducting RF system. Compared to a normal-conducting RF system, a superconducting RF system requires fewer cavities, (with advantages for cost and keeping HOMs low); the power dissipation is lower; and smaller phase transients are expected.

Alternative

A normal-conducting RF system could still satisfy the requirements for the damping rings.

RF Frequency

The damping rings RF systems should use an RF frequency of 500 MHz. This is a standard technology; other options would require R&D.

Vacuum Chamber Aperture

A chamber diameter of (not significantly less than) 50 mm in the arcs, 46 mm in the wiggler and 100 mm in the straights is required. The wiggler chamber needs a large aperture to achieve the necessary acceptance, and to suppress electron cloud build-up. The large aperture also reduces resistive-wall growth rates, and eases the requirements on the feedback systems.

Vacuum System Technologies

Recommendations on the various options for the vacuum system technologies are yet to be made.

Summary of Further R&D Requirements

Circumference

Baseline:

- Techniques for mitigating electron cloud to acceptable levels are needed.
- A lattice design is needed that simultaneously satisfies requirements for acceptance and beam stability, and can be tuned easily for low emittance.

Alternative 1 (single 6 km positron ring):

- Techniques for mitigating electron cloud to acceptable levels are needed.
- A lattice design is needed that simultaneously satisfies requirements for acceptance and beam stability, and can be tuned easily for low emittance.

Alternative 2 (17 km positron ring):

- Techniques for suppressing space-charge tune shifts without driving betatron and synchrobetatron resonances are needed.
- A lattice design is needed that simultaneously satisfies requirements for acceptance and beam stability, and can be tuned easily for low emittance.

General R&D requirements

- Kickers that simultaneously meet specifications on rise/fall time, pulse rate and stability need to be demonstrated.
- Ion instabilities are a concern in the electron ring.
- Ion-induced pressure instabilities in the positron ring need to be addressed.
- A range of classical collective instabilities need to be properly understood, with analysis based on a detailed impedance model.
- The effectiveness of low-emittance tuning techniques need to be assessed.

Injected Emittance and Energy Spread

Baseline

Studies of the positron production indicate that an injected full-width energy spread of 1% should be achievable; however, a thorough investigation including realistic models for collimators, energy compressors etc. is still needed.

Alternative

A lattice design is needed that shows an energy acceptance with some margin beyond 2% full-width, while satisfying other requirements.

Bunch Train Length and Bunch Charge

Studies are needed to determine:

- the minimum bunch spacing needed to keep electron-cloud effects under control;
- the minimum gap between minitrains needed to keep ion effects under control.

A demonstration is needed of kickers meeting the specifications (appropriate to each option for the number of bunches in a bunch train) for:

- pulse rise and fall times;
- kick repetition rate;
- kick amplitude stability.

Extracted Bunch Length

Studies of bunch compressors suggest that a 9 mm bunch from the damping ring is acceptable, for a final bunch length of 300 μm. Thorough studies, including tuning simulations for emittance preservation are in progress. Studies of beam dynamics effects in the damping rings with bunch lengths between 6 mm and 9 mm are needed to quantify the benefits (and drawbacks) of longer bunches.

Injection/Extraction Kicker Technology

Baseline

Kickers need to be demonstrated meeting all specifications for:

- pulse rise and fall times;
- pulse repetition rate;
- kick amplitude stability.

Alternative 1 (RF separators):

The beam dynamics and engineering issues associated with the RF separators scheme need to be fully understood, and limitations overcome.

Alternative 2 (Fourier pulse-compression kickers):

A more complete understanding is needed of the technical issues involved in Fourier pulse-compression kickers.

Off-Axis Injection

The usual operation mode of the damping rings requires on-axis injection, which prevents accumulation of current by stacking charge within RF buckets over many turns. Most conventional storage rings - e.g. in synchrotron light sources - use off-axis injection, in which radiation damping is used to merge injected (off-axis) charge with stored (on-axis) charge. The availability of off-axis injection would be of benefit in the damping rings for commissioning and tuning; a high beam current could be stored in the damping rings even with an injector system operating at less than full capacity, or with a separate, low-intensity source.

The possibility of designing the injection system of the damping rings to operate in either on-axis or off-axis mode should be investigated.

Damping Wiggler Technology

Baseline

The CESR-c wigglers have demonstrated the basic requirements for the ILC damping ring wigglers. Designs for a superconducting wiggler for the damping rings need to be optimized.

Alternatives

Designs with acceptable costs for normal-conducting electromagnetic and hybrid wigglers need to be developed, that meet specifications for aperture and field quality. In the case of a normal-conducting electromagnetic wiggler, the design also needs to show acceptable power consumption.

Main (Non-Wiggler) Magnets Technology

Baseline

Designs for electromagnetic dipoles, quadrupoles etc. should be straightforward, but still need to be developed.

Alternative

The problem of polarity reversal needs to be addressed. A demonstration is needed of a permanent magnet with good tunability and resistance to radiation damage.

RF System Technology

The basic requirements of the superconducting RF systems for the damping rings have been demonstrated in existing machines, e.g. KEK-B. A full system specification, design and optimization are needed.

Vacuum Chamber Aperture

Even with a large aperture chamber in the damping rings, a bunch-by-bunch feedback system will be needed in the transverse and longitudinal planes to suppress coupled-bunch instabilities driven by the resistive-wall impedance. Although the required performance of the feedback systems should be within the range of existing technology, studies are needed of the level of residual beam jitter, and possible emittance growth.

Vacuum System

A number of issues regarding the vacuum system remain to be addressed, including:

- What are the required levels of residual gas pressure needed to avoid ion effects?
- What kind of chamber preparation (NEG coating, TiN coating, grooves etc.) is needed for suppressing electron cloud, and what are the implications e.g. for impedance?
- Can (or should) clearing electrodes be used to suppress electron cloud or ion effects?
- What length of time is allowed by the commissioning schedule for conditioning the vacuum system in the damping rings?

Further studies are needed to resolve these issues.

Nominal Parameter and Performance Specifications

	Baseline	Alternative (I)	Alternative (II)
Bunch train length	2820	5640	
Train repetition rate	5 Hz		
Injected bunch separation	330 ns	165 ns	
Maximum injected normalized betatron amplitude (e^+)[1]	0.09 m-rad		
Injected full-width energy spread (e^+)	1%		
Normalized injected transverse emittance, rms (e^-)	45 μm		
Injected energy spread, rms (e^-)	0.1%		
Injected bunch charge	2×10^{10}	1×10^{10}	
Extracted bunch separation	330 ns	165 ns	
Extracted bunch charge	2×10^{10}	1×10^{10}	
Extracted normalized horizontal emittance	8 μm		
Extracted normalized vertical emittance	0.02 μm		
Extracted rms energy spread	1.4×10^{-3}		
Extracted rms bunch length	6 mm		9 mm
Maximum extracted vertical jitter	0.1σ		

[1] The normalized betatron amplitude is defined as A_x+A_y where:

$$\frac{A_x}{\gamma} = \gamma_x x^2 + 2\alpha_x x p_x + \beta_x p_x^2$$

and similarly for A_y. γ is the relativistic factor, and α_x, β_x, γ_x are the Twiss parameters.

Ranking of Issues and Risks

The significance of the issues relevant to each configuration item are ranked as follows:

Rank	Meaning
A	This issue: • is critical to the corresponding item in the configuration decision; • has significant technical, operational or cost implications associated with it; • is likely to be a key consideration in choosing between the various options.
B	This issue is important for the corresponding item in the configuration decision, but should not be considered a decisive factor.
C	This issue has only a minor impact on the corresponding item in the configuration decision.

The risks associated with the various options are ranked as follows:

Rank	Meaning
1	The performance requirements of this option have been demonstrated, or studies indicate little risk.
2	Some R&D is required to demonstrate performance requirements, but with a likelihood of successful outcome; *or* low technical risk, and a practical fix will likely be found in event that a problem occurs.
3	Significant R&D is required to demonstrate performance requirements; *or* high technical risk, with likelihood to cause ongoing problems.
4	There is unlikely to be an acceptable technical solution.

The cost impacts of the various options are ranked as follows:

Rank	Meaning
1	Lowest cost option, or close to lowest cost.
2	Up to roughly factor of two greater cost than lowest cost option.
3	Up to roughly factor of three greater cost than lowest cost option.
4	More than a factor of three greater cost than lowest cost option.

Configuration Couplings

In a storage ring, many of the parameters and systems are connected either directly, or indirectly. The table below is intended to illustrate the *principal* couplings between configuration items in the damping rings.

	Circumference	Beam energy	Injected emittance/energy spread	Bunch train length/bunch charge	Extracted bunch length	Injection/extraction kickers	Damping wiggler	Multipole magnets	RF system technology	RF frequency	Vacuum chamber aperture
Circumference	▨	●	●	●	●	●	●				
Beam energy	●	▨	●	●	●		●				
Injected emittance/energy spread	●	●	▨				●				●
Bunch train length/bunch charge	●	●		▨	●	●				●	
Extracted bunch length	●	●		●	▨						
Injection/extraction kickers	●			●		▨					
Damping wiggler	●	●	●				▨				●
Multipole magnets								▨			
RF system technology									▨		
RF frequency				●						▨	
Vacuum chamber aperture			●				●				▨

Circumference

The choice of ring circumference is strongly coupled to the choices of:

- **beam energy**: a shorter ring will have a lower space-charge tune shift, that may make a lower energy feasible;
- **injected emittance and energy spread**: a large energy acceptance can be difficult to achieve in a dogbone lattice;
- **bunch train length**: if a large number of bunches (5600) is needed, a larger circumference will make the injection/extraction kickers easier;
- **bunch length**: a longer bunch reduces the charge density, which will reduce the space-charge tune shift that may be a problem in a 17 km ring;
- **injection/extraction kickers**: the kickers become more difficult in shorter rings, and other options may become more attractive if a short circumference is chosen;
- **wiggler technology**: a larger circumference requires a longer wiggler, which can affect the relative cost impact of the different options for the wiggler technology.

Options

Configurations with circumferences of roughly 3 km, 6 km and 17 km have been considered. It is also possible to stack several rings in a single tunnel, dividing the bunch train between the different rings to reduce the average current in any given ring. A further option would be to use RF deflectors to separate alternate bunches down different beamlines for injection and extraction: this would ease the kicker requirements by increasing the bunch spacing locally in the injection/extraction regions, and could be used with any ring circumference.

Rings up to 6 km can be built in (roughly circular) tunnels separate from the main linac. 17 km rings would have a “dogbone” layout, with long straight sections sharing tunnel with the main linac to reduce costs.

Issues

Electron cloud effect (Significance: A)

Shorter rings have a closer bunch spacing, which greatly enhances the build-up of electron cloud. Electron cloud can be difficult to suppress in the dipole and wiggler regions where it is expected to be most severe, and the instabilities associated with electron cloud could significantly affect the performance of the damping rings.

Injection and extraction kickers (Significance: A)

Shorter rings have shorter bunch spacing, and place higher demands on the injection and extraction kickers. For rings of 17 km and 6 km circumference, the required rise and fall times are considered achievable, though a full demonstration (including repetition rate, pulse length and amplitude stability) is still required. 3 km rings have a shorter bunch separation requiring faster rise and fall times, so the kickers are more demanding. It may be possible to use RF deflecting cavities to separate bunches between different beamlines for injection and extraction, easing the kicker rise and fall time requirements. Kicker performance is critical to the production of a stable beam from the damping rings.

Acceptance (Significance: A)

Given the high average injected beam power, beam losses in the ring could rapidly damage critical components (e.g. the wigglers) and adversely affect diagnostics, making the ring difficult to operate. The design criterion is a lattice that achieves (in simulation) 100% injection efficiency for a nominal injection distribution, including physical apertures and tuning errors. Lattice designs have been developed for 6 km rings that have good acceptance for the baseline positron distribution. The long straight sections in the dogbone damping rings break the lattice symmetry, and generate chromaticity that is difficult to correct locally. As a result, it is difficult to achieve the dynamic aperture needed to accept cleanly the large positron beam from the source.

Cost (Significance: A)

A 3 km ring would have rather a lower cost than 6 km or 17 km rings. The additional tunnel in the 6 km rings makes the costs comparable to the 17 km rings. Estimates suggest that using two 6 km rings in a single tunnel is a higher cost than a 17 km ring.

Ion effects (Significance: B)

Accumulation of ions in the vacuum chamber can drive instability. Ion effects are complex, particularly in the damping rings where the beam sizes can be very small. Gaps in the fill and very low vacuum levels will be necessary to mitigate ion effects. Present understanding is that the style of lattice, fill pattern and vacuum pressure are more significant than the circumference for the severity of the effects; however, longer rings have a lower current than shorter rings, making it easier to achieve lower vacuum pressures. A larger circumference could help by allowing larger gaps in the fill for a given bunch spacing.

Space-charge (Significance: B)

The incoherent space-charge tune shift is proportional to the ring circumference. The coupling bumps used to reduce this effect in the dogbone ring could be some risk for the vertical emittance.

Tunnel layout (Significance: B)

Sharing the linac tunnel increases the time taken for commissioning and reduces the availability. Stray fields in the linac tunnel could adversely affect the vertical emittance of the extracted beam (though it may be possible to use feed-forward systems to correct the effects of stray fields). Coupling between the straights in a dogbone lattice is a potential issue.

Availability (Significance: C)

The larger number of components in a larger ring is likely to have an adverse impact on reliability.

Classical collective effects (Significance: C)

A variety of classical collective effects are of potential concern, including resistive-wall instability, coupled-bunch instabilities driven by higher-order modes, microwave instability, and intrabeam scattering. Studies show that these effects should be manageable in rings with any of the proposed circumference options. The severity of these collective effects tends to be dominated by issues such as bunch charge, bunch length, lattice design (momentum compaction), beam-pipe diameter etc., rather than by the circumference.

Low-emittance tuning (Significance: C)

Achieving the specified vertical beam emittance in the damping rings is important for producing luminosity. However, there is an additive emittance dilution in all the systems downstream of the damping rings; and the luminosity depends on the beam size at the interaction point, which scales with the square root of the emittance. There is little evidence that the circumference of the damping ring in itself has an impact on the emittance sensitivity to misalignments and tuning errors.

Polarization (Significance: C)

Studies suggest that depolarization should not be a major issue in any of the configuration options under consideration.

Issues Ranking

Issue	Significance	Risks			
		3 km	6 km	2×6 km	17 km
Electron cloud (positron ring)	A	4	3	2	2
Kickers	A	3	2	2	2
Acceptance	A	2	1	1	2
Cost	A	1	2	3	3
Ion effects (electron ring)	B	3	2	2	2
Space-charge	B	1	1	1	2
Tunnel layout	B	1	1	1	2
Availability	C	1	1	1	1
Classical collective effects	C	2	2	2	2
Low-emittance tuning	C	2	2	2	2
Polarization	C	1	1	1	1

Comment: Use of RF deflecting cavities locally to separate alternate bunches down different beamlines would reduce kicker risks for any of the circumference options, though potentially with some impact on the acceptance.

Baseline Recommendation

The positron damping ring should consist of two (roughly circular) rings of approximately 6 km circumference in a single tunnel. Electron-cloud effects make a single ring of circumference 6 km or lower unattractive, unless significant progress can be made with mitigation techniques. Space-charge effects will be less problematic in a 6 km than in a 17 km ring, and achieving the required acceptance will be easier in a circular ring than in a dogbone ring.

The electron ring can consist of a single 6 km ring, assuming that the fill pattern allows a sufficient gap for clearing ions. The injection and extraction kickers and ion effects are more difficult in a 3 km ring than in a 6 km ring. A 17 km ring could ease ion effects (by allowing larger gaps between minitrains), but would likely be higher cost. We have no recommendation on whether the electron ring needs a separate tunnel from the positron rings.

Although R&D is still required for the injection/extraction kickers for a damping ring with 6 km circumference, it is expected that existing programs will demonstrate a solution.

The exact circumference of the damping rings should be chosen, if possible, to allow flexibility in the fill patterns and number of bunches in a bunch train.

The feasibility of the baseline depends on:

- further progress with developing techniques for suppressing electron cloud (positron rings);
- development of a satisfactory lattice design, e.g. (for electron ring) with properties that mitigate ion effects, etc.
- demonstration of kickers meeting the specifications for rise/fall time, kick amplitude stability and repetition rate.

Alternatives

1. If techniques are found that are sufficiently effective at suppressing the electron cloud, a single 6 km, or possibly smaller, ring can be used for the positron damping ring. This will save costs.

2. If electron cloud mitigation techniques are not found that are sufficient for the baseline positron ring, then a 17 km ring is a possible alternative; this would require addressing space-charge and acceptance issues.

Required R&D

Baseline:

- Techniques for mitigating electron cloud to acceptable levels are needed.
- A lattice design is needed that simultaneously satisfies requirements for acceptance and beam stability, and can be tuned easily for low emittance.

Alternative 1 (single 6 km positron ring):

- Techniques for mitigating electron cloud to acceptable levels are needed.
- A lattice design is needed that simultaneously satisfies requirements for acceptance and beam stability, and can be tuned easily for low emittance.

Alternative 2 (17 km positron ring):

- Techniques for suppressing space-charge tune shifts without driving betatron and synchrobetatron resonances are needed.
- A lattice design is needed that simultaneously satisfies requirements for acceptance and beam stability, and can be tuned easily for low emittance.

General R&D requirements

- Kickers that simultaneously meet specifications on rise/fall time, pulse rate and stability need to be demonstrated.
- Ion instabilities are a concern in the electron ring.

- Ion-induced pressure instabilities in the positron ring need to be addressed.
- A range of classical collective instabilities need to be properly understood, with analysis based on a detailed impedance model.
- The effectiveness of low-emittance tuning techniques need to be assessed.

Beam Energy

The choice of beam energy is strongly coupled to the choices for:

- **circumference**: a shorter ring will have a lower space-charge tune shift, that may make a lower energy feasible;
- **injected emittance and energy spread**: lowering the beam energy increases the injected emittance and energy spread, and makes a larger acceptance necessary;
- **bunch train length and bunch charge**: single bunch collective effects become less severe at lower bunch charge, and may make a lower energy feasible;
- **bunch length**: a longer bunch length reduces the charge density in the bunch, reduces the severity of single bunch collective effects, and may make a lower energy feasible;
- **wiggler technology**: a lower beam energy requires a longer wiggler, which can affect the relative cost impact of the different options for the wiggler technology.

Options

Beams at low energy are sensitive to collective effects. At higher energies, it is difficult to achieve the equilibrium emittances in a lattice of reasonable size. The energy choices are restricted by the need to avoid depolarization resonances, which occur roughly at intervals of 440 MeV. We may consider energies in the range (roughly) 3.7 GeV to 6.8 GeV. Most of the detailed configuration studies have been performed for lattices designed for 5 GeV beam energy. There is also the possibility of bunch spacing resonances affecting the electron cloud effect.

Issues

Longitudinal emittance (Significance: A)

An increase in the longitudinal emittance (from an increase in either or both of the bunch length and energy spread) has an impact on the bunch compressors and the spin rotators making their design and operation more difficult. Assuming that the damping wiggler dominates the energy loss of the beam, the equilibrium relative energy spread increases linearly with the beam energy. At 5 GeV, the damping rings will have a natural energy spread of around 0.13% (which is within the nominal value of 0.15% specified for the bunch compressors). An energy spread of 0.18%, which would be expected in a damping ring at 6.8 GeV, may be acceptable for the spin rotators and (assuming a 6 mm bunch length) for the bunch compressors, but lower values are desirable. The strength needed for the spin rotator solenoid also depends directly on the beam energy: at 5 GeV, this solenoid is already large; an increase in energy would make the solenoid more difficult.

Collective effects (Significance: A)

The impact of collective effects (growth rates, thresholds etc.) often scales inversely with the energy: higher energies will reduce growth rates and/or raise thresholds. At a beam energy of 5 GeV, some of the collective effects look challenging (given the baseline circumference). Space-charge problems get worse with lower energy. The emittance growth from intrabeam scattering scales inversely with the fourth power of the energy, and would likely have a significant impact on performance at energies below 5 GeV.

Acceptance (Significance: A)

The particle sources produce beams with given normalized emittances and absolute energy spread. Increasing the ring energy provides a benefit from adiabatic damping: the transverse beam sizes scale inversely with the square root of the energy, and the relative energy spread decreases linearly with increasing energy. However, there is a competing effect: a higher energy ring may have a more challenging lattice design to achieve the required equilibrium emittances, which could adversely affect the acceptance.

Transverse emittance (Significance: B)

The normalized natural emittance scales with the third power of the energy. An increase in energy can be compensated to some extent by increasing the number of arc cells in the lattice; however, this tends to reduce the momentum compaction, which can lower the thresholds for some collective instabilities. Lattice changes could also adversely affect the acceptance.

Low-emittance tuning (Significance: B)

The specification on the extracted vertical emittance applies to the normalized emittance. Reducing the beam energy for a fixed normalized vertical emittance increases the allowed geometric emittance, and would ease the tuning requirements.

Damping rates (Significance: B)

Higher energies increase the radiation damping rates, which may allow reduction in wiggler length.

Cost (Significance: B)

The construction cost and operating cost of a storage ring generally increase with energy. Although the wiggler length would be reduced at higher energy, the cost savings would likely be offset by higher costs of other systems, including vacuum and RF.

Issues Ranking

Issue	Significance	Risks		
		3.7 GeV	5 GeV	6.8 GeV
Longitudinal emittance	A	1	1	2
Collective effects	A	3	2	1
Acceptance	A	2	1	2
Transverse emittance	B	1	1	2
Low-emittance tuning	B	1	2	3
Damping rates	B	1	1	1
Cost	B	1	1	2

Baseline Recommendation

The damping ring energy should be approximately 5 GeV. A lower energy increases the risks from collective effects; a higher energy makes it more difficult to tune for low emittance, and potentially has an adverse impact on the acceptance.

Injected Emittance and Energy Spread

The specifications for the injected emittance and energy spread are strongly coupled to the choices for:

- **circumference**: a large energy acceptance can be difficult to achieve in a dogbone lattice;
- **beam energy**: lowering the beam energy increases the injected emittance and energy spread, and makes a larger acceptance necessary;
- **vacuum chamber aperture**: a larger transverse emittance requires a larger physical aperture for good injection efficiency;
- **wiggler technology**: a larger transverse emittance needs a larger physical aperture, which is easier to achieve in some wiggler technologies than others.

Options

	Option I	Option II
Maximum injected normalized betatron amplitude	0.045 m-rad	0.09 m-rad
Injected full-width energy spread	2%	1%

Issues

Acceptance (Significance: A)

For a given acceptance, the injection efficiency will improve with smaller injected betatron amplitude and energy spread. With the damping ring lattices considered for the configuration studies, the energy spread was the more important quantity in most cases: a better injection efficiency was found using a simulated positron distribution corresponding to Option II, compared to Option I. The impact on the positron source is not clearly understood at the present time.

Injection systems (Significance: B)

A smaller injected emittance allows a narrower aperture in the injection components, which could simplify their design.

Issues Ranking

Issue	Significance	Risks	
		Option I	Option II
Acceptance	A	3	2
Injection systems	B	1	2

Baseline Recommendation

An injected beam with maximum betatron amplitude up to 0.09 m-rad and energy spread up to 1% (full width) is preferred for the damping rings, over a distribution with larger energy spread but smaller betatron amplitude. Achieving good off-energy dynamics in the damping ring lattices is likely to be more problematic than achieving a large on-energy dynamic aperture. A smaller energy spread is likely to improve the margin for the acceptance of the injected beam.

Alternative

If the acceptance issue can be addressed successfully, a larger energy spread on the injected beam (up to 2% full width) could be accommodated.

Required R&D

Baseline

Studies of the positron production indicate that an injected full-width energy spread of 1% should be achievable; however, a thorough investigation including realistic models for collimators, energy compressors etc. is still needed.

Alternative

A lattice design is needed that shows an energy acceptance with some margin beyond 2% full-width, while satisfying other requirements.

Bunch Train Length and Bunch Charge

The specifications for the bunch train length and bunch charge are strongly coupled to the choices for:

- **circumference**: if a large number of bunches (~5600) is needed, a larger circumference will make the injection/extraction kickers easier;
- **beam energy**: single bunch collective effects become less severe at lower bunch charge, and may make a lower energy feasible;
- **bunch length**: a longer bunch reduces the charge density, and may make a higher bunch charge possible before reaching limits from collective effects;
- **injection/extraction kickers**: the kickers become more difficult with a larger number of bunches, which must be packed more closely into the ring;
- **RF frequency**: the flexibility in the number of bunches in a train depends to some extent on the RF frequency.

Options

	Option I	Option II
Bunch train length	2800	5600
Injected bunch separation	330 ns	165 ns
Injected bunch charge	2×10^{10}	1×10^{10}

Issues

Injection and extraction kickers (Significance: A)

It is possible to store 5600 bunches in a ring with approximate circumference 6 km and with a 4 ns bunch spacing; this bunch spacing is expected to be possible with the proposed baseline kicker technology. However, the kickers do get more difficult as a higher rep rate – with same pulse length – is required. A lower number of bunches (2800) allows gaps between “minitrains” of bunches in the ring, which could provide for a slow fall-time kicker. The gaps get shorter as the number of bunches is increased, and may be reduced to zero with the largest number (5600) of bunches in the ring.

Ion effects (Significance: A)

We assume fill patterns for bunch train lengths between 2800 and 5600 bunches, satisfying the following conditions:

- the bunch spacing is independent of the number of bunches (roughly 4 ns in a 6 km ring);
- bunches are arranged in “minitrains” in the ring, with gaps between minitrains;
- additional bunches are accommodated by increasing the number of minitrains, and reducing the gap between minitrains.

The average current is independent of the total number of bunches. In the assumed fill scheme, increasing the number of bunches reduces the gap between minitrains, which could result in the ion effects becoming more severe.

Electron cloud effects (Significance: A)

Electron cloud effects are strongly dependent on bunch spacing. To keep these effects under control, it might be necessary always to maintain the largest possible bunch spacing in the positron ring. This means that the number of bunches in each of a pair of 6 km rings may be limited to around 1400, to maintain a bunch separation of 14 ns.

Single-bunch collective effects (Significance: A)

Single-bunch effects such as the microwave instability, space-charge tune shifts and emittance growth from intrabeam scattering are mitigated by a lower bunch charge.

Resistive-wall instability (Significance: B)

With a fixed average current in the ring, the resistive wall instability will not be significantly affected.

Issues Ranking

Issue	Significance	Risks	
		Option I (2800 bunches)	Option II (5600 bunches)
Injection and extraction kickers	A	2	3
Ion effects (electron ring)	A	2	4
Electron cloud (positron ring)	A	2	3
Single-bunch collective effects	A	2	1
Resistive wall	B	1	1

Baseline Recommendation

A train length of around 2800 bunches is preferred because the kickers, ion effects and electron cloud are easier with a smaller number of bunches. If the electron ring is completely filled with no gaps (as may be the case with around 5600 bunches) the ion effects could be extremely difficult. However, there may well be other acceptable options with numbers of bunches between 2800 and 5600: further studies are needed to specify the gaps in the fill needed to keep ion effects under control.

If the positron rings (total circumference 12 km in our recommended baseline) are uniformly filled with 2800 bunches, the bunch separation is around 14 ns. Studies suggest that because of electron-cloud effects, the bunch separation should not be reduced much below this; this would prevent operation with larger numbers of bunches per train.

It is possible that the fill patterns in the electron and positron rings may need to be different, so as to allow a large bunch spacing between positron bunches (because of electron cloud), and gaps between minitrains of electron bunches (because of ions). This would require electron and positron rings with different circumferences, and would limit flexibility on timing solutions.

Alternatives

Increasing the number of bunches beyond 2800 could be possible if electron-cloud and ion effects are found to be manageable, and sufficiently fast kickers can be demonstrated.

Required R&D

Studies are needed to determine:

- the minimum bunch spacing needed to keep electron-cloud effects under control;
- the minimum gap between minitrains needed to keep ion effects under control.

A demonstration is needed of kickers meeting the specifications (appropriate to each option for the number of bunches in a bunch train) for:

- pulse rise and fall times;
- kick repetition rate;
- kick amplitude stability.

Extracted Bunch Length

The specification for the extracted bunch length is strongly coupled to the choices for:

- **circumference**: a longer bunch reduces the charge density, which will reduce the space-charge tune shift that may be a problem in a 17 km ring;
- **beam energy**: a longer bunch length reduces the charge density in the bunch, reduces the severity of single bunch collective effects, and may make a lower energy feasible;
- **bunch train length and bunch charge**: a longer bunch reduces the charge density, and may make a higher bunch charge possible before reaching limits from collective effects.

Options

The nominal specification on the bunch length has been 6 mm. It is possible to consider bunch lengths up to 9 mm. In principle, the bunch length can be varied independently of other parameters (such as the energy spread) by varying the RF voltage.

Issues

Bunch compressors (Significance: A)

For a given energy spread, the bunch compressors get more difficult with increasing bunch length. The following bunch compressor configurations have been considered, and are deemed practical:

Stages of compression	Initial energy spread	Initial bunch length	Final bunch length
Two-stage	0.15%	≤ 9 mm	300 μm
Two-stage	0.15%	≤ 6 mm	150 μm
One-stage	0.15%	≤ 6 mm	300 μm

A two-stage bunch compressor is presently recommended for the ILC baseline configuration, with a one-stage compressor as a lower cost alternative.

Collective effects (Significance: A)

Most single-bunch effects become less severe as the bunch length increases (including space-charge tune shifts, microwave instability thresholds, emittance growth from intrabeam scattering). Touschek lifetime benefits from a longer bunch. Many of these effects are of concern in the damping rings, and a 9 mm bunch would therefore provide a potentially useful safety margin over a 6 mm bunch.

Electron cloud (Significance: A)

It is possible that electron-cloud effects get worse with increasing bunch length. This issue requires further study.

RF system (Significance: B)

The RF voltage needed in a storage ring is inversely proportional to the square of the bunch length. Allowing a longer bunch also allows a larger momentum compaction (which is helpful for suppressing instabilities) for a given voltage. A lower RF voltage reduces costs. However, if the RF voltage is too low, the RF energy acceptance can be small, and this can limit the Touschek lifetime, and the injection efficiency.

Issues Ranking

Issue	Significance	Risks	
		6 mm	9 mm
Bunch compressors	A	1	2
Electron cloud	A	2	2
Collective effects	A	2	1
RF system	B	1	1

Baseline Recommendation

A 9 mm bunch would be helpful for mitigating single-bunch collective effects in the damping rings, but a 6 mm bunch also appears to be a viable option.

Required R&D

Studies of bunch compressors suggest that a 9 mm bunch from the damping ring is acceptable, for a final bunch length of 300 μm. Thorough studies, including tuning simulations for emittance preservation are in progress. Studies of beam dynamics effects in the damping rings with bunch lengths between 6 mm and 9 mm are needed to quantify the benefits (and drawbacks) of longer bunches.

Injection/Extraction Kicker Technology

The choice of technology for the injection/extraction kickers is strongly coupled to the choices of:

- **circumference**: the kickers become more difficult in shorter rings, and other options may become more attractive if a short circumference is chosen;
- **bunch train length**: the kickers become more difficult with a larger number of bunches, which must be packed more closely into the ring.

Options

The principal options for the kicker systems are:

- a conventional stripline kicker driven by a fast pulser;
- a "Fourier" kicker, using (for example) a transverse deflecting RF cavity driven by an RF pulse compressed in a highly dispersive waveguide.

RF separators provide a further option that may be combined with either kicker scheme but would more likely be used with the conventional stripline kickers. The RF separators could be used to increase the bunch spacing in the injection/extraction region, by channeling alternate bunches down separate beamlines.

Issues

Rise/fall times and beam stability (Significance: A)

The rise and fall times must be sufficiently short as to provide deflection for the target bunch, while not kicking any of the adjacent bunches. The use of RF separators eases the requirements on the rise and fall times. Fast pulsers are available that can provide rise times of around 3 ns. The fall time is likely to be longer; however, the consequences of this may be corrected.

Impedance (Significance: A)

The vacuum system of the damping rings will have tight limits on the acceptable impedance, so as to stay below instability thresholds. Systems using RF deflecting cavities potentially add greater impedance than stripline kickers.

Impact on beam dynamics/acceptance (Significance: A)

Some studies have shown that the bypass lines associated with RF deflecting cavities may have an adverse impact on the energy acceptance of the damping ring; this issue needs further study.

Kick amplitude stability (Significance: A)

There are demanding requirements on the pulse-to-pulse stability of the kick amplitude. It may be possible to design a turn-around in the extraction line, allowing a feedback system to correct bunch-to-bunch extraction jitter. However, this will likely add cost to the machine and will be accompanied by its own set of technical issues.

Kick amplitude (Significance: B)

The kickers must be capable of providing sufficient amplitude for clean injection and extraction. Injection of positron bunches sets the amplitude goal, since larger clearance is needed for the large beam from the positron source. In principle, it is possible to use a sequence of kickers, each powered independently, to achieve the required amplitude. The optics of the lattice must be designed to meet the requirements of the injection and extraction components.

Reliability (Significance: C)

The kickers must operate reliably. Lifetime is a potential issue for high-power fast pulsers. However, since the number of pulsers required will be limited, it should be possible to maintain a reasonable redundancy in the number of pulsers available at any time.

Cost (Significance: C)

The basic stripline kicker scheme uses relatively conventional components. Use of RF separators would incur additional cost because of the extra beamlines required in the damping ring.

Issues Ranking

Issue	Significance	Risks		
		Conventional	Conventional + separators	Fourier
Rise/fall time; beam stability	A	2	1	3
Impedance	A	2	2	2
Beam dynamics	A	1	2	1
Kick amplitude stability	A	3	3	3
Kick amplitude	B	1	1	1
Reliability	C	1	1	1
Cost	C	1	3	3

Baseline Recommendation

The damping ring kickers should be based on “conventional” strip-line kickers driven by fast pulsers, without use of RF separators. The basic technology is available, and is close to a demonstration of most of the performance specifications. Using RF separators has potential cost implications, and could adversely affect the beam dynamics; for these reasons, it is preferred to avoid the need for RF separators if possible.

Alternatives

1. RF separators may prove useful if it is decided to fill the rings with large numbers of bunches, pushing the bunch spacing to small values. Studies should be continued, to understand fully the beam dynamics and engineering issues, and resolve problems.

2. Because Fourier pulse-compression kickers provide a very different approach, it is worthwhile continuing studies to develop a more complete understanding of the benefits and limitations of these systems.

Required R&D

Baseline

Kickers need to be demonstrated meeting all specifications for:

- pulse rise and fall times;
- pulse repetition rate;
- kick amplitude stability.

Alternative 1 (RF separators):

The beam dynamics and engineering issues associated with the RF separators scheme need to be fully understood, and limitations overcome.

Alternative 2 (Fourier pulse-compression kickers):

A more complete understanding is needed of the technical issues involved in Fourier pulse-compression kickers.

Off-Axis Injection

The usual operation mode of the damping rings requires on-axis injection, which prevents accumulation of current by stacking charge within RF buckets over many turns. Most conventional storage rings - e.g. in synchrotron light sources - use off-axis injection, in which radiation damping is used to merge injected (off-axis) charge with stored (on-axis) charge. The availability of off-axis injection would be of benefit in the damping rings for commissioning and tuning; a high beam current could be stored in the damping rings even with an injector system operating at less than full capacity, or with a separate, low-intensity source.

The possibility of designing the injection system of the damping rings to operate in either on-axis or off-axis mode should be investigated.

Damping Wiggler Technology

The choice of wiggler technology is strongly coupled to the choices of:

- **circumference**: a larger circumference requires a longer wiggler, which can affect the relative cost impact of the different options for the wiggler technology;
- **beam energy**: a lower energy requires a longer wiggler, which can affect the relative cost impact of the different options for the wiggler technology;
- **injected emittance**: a larger transverse emittance needs a larger physical aperture, which is easier to achieve in some wiggler technologies than others;
- **vacuum chamber aperture**: the wiggler must have sufficient aperture to accommodate the vacuum chamber.

Options

There are three principal options for the damping wiggler:

- electromagnetic, normal-conducting (EM/NC);
- electromagnetic, superconducting or superferric (EM/SC);
- permanent magnet with steel poles ("hybrid").

Issues

Field quality (Significance: A)

A high quality field is needed to achieve the dynamic aperture necessary for good injection efficiency. The field quality depends on the geometry of the wiggler: increasing the gap between the poles, increasing the period, or increasing the pole width can generally improve the field quality. However, increasing the gap and pole width can add considerably to the power consumption for a normal-conducting electromagnetic device, or to the cost of magnetic material for a hybrid device. So far, only a superferric design has been demonstrated that has a satisfactory field quality; however, it is possible that other types of wiggler could be developed into satisfactory designs.

Physical aperture (Significance: A)

A large gap is needed to achieve the necessary acceptance for the large injected positron beam. Increasing the gap adds to the power consumption of a normal-conducting electromagnetic device, and to the cost of permanent magnet material in a hybrid device. Acceptance studies indicate that a beam stay-clear of at least 32 mm is required in the wiggler in the positron ring, though a smaller beam stay-clear may be acceptable in the electron ring. A large physical aperture is also desirable from point of view of electron-cloud and resistive-wall effects. So far, only a superferric design has been demonstrated that shows a good physical aperture; however, it is possible that other types of wiggler could be developed into satisfactory designs.

Power consumption/running costs (Significance: A)

The operating costs associated with power consumption of the wiggler are an issue. For a hybrid wiggler, the power consumption is essentially zero. For a superconducting device, the power consumption is primarily in the cryogenics. The power consumption of a normal-conducting electromagnetic wiggler is likely to be considerable.

Resistance to radiation damage (Significance: A)

The damping rings are likely to be high radiation environments. Permanent magnet materials can be sensitive to radiation, and long-term damage is an issue. Power deposition from radiation can cause quenching of superconducting magnets, but operational experience suggests this may not be a real issue. Normal-conducting electromagnets are generally more resistant to radiation damage, than superconducting or hybrid devices.

Materials and construction costs (Significance: A)

Construction of a normal-conducting electromagnetic wiggler is relatively straightforward, and requires no special materials. The cost of the permanent magnet materials in a hybrid wiggler (given the expected pole-width and aperture requirements) may be considerable. The cryogenic systems needed for a superconducting wiggler add to the cost compared to a normal conducting device.

Requirements for auxiliary systems (Significance: B)

Electromagnetic wigglers require power supplies, cooling systems and controls; superconducting wigglers require cryogenics, low-voltage power supplies and controls. Hybrid wigglers require essentially no additional systems.

Flexibility (Significance: B)

It may be useful to be able to vary the field strength in the wigglers for tuning and machine studies. The field strength in an electromagnetic (normal conducting or superconducting) device can be varied easily; a hybrid wiggler would require a mechanism for varying the gap, which would add cost to the device.

Availability (Significance: C)

The wigglers are not expected to cause any significant downtime in the damping rings. Hybrid magnets have the advantage of not requiring power supplies, cooling or control systems.

Issues Ranking

Issue	Significance	Risks		
		EM/NC	EM/SC	Hybrid
Field quality	A	2	1	2
Physical aperture	A	2	1	2
Power consumption	A	3	1	1
Resistance to radiation damage	A	1	2	2
Materials and construction costs	A	1	2	3
Auxiliary requirements	B	1	1	1
Flexibility	B	1	1	2
Availability	C	1	1	1

Baseline Recommendation

The damping wiggler should be based on superconducting technology. The requirements for field quality and aperture have been demonstrated in existing designs, and the power consumption is low.

Alternatives

Normal-conducting electromagnetic and hybrid technologies are both viable alternatives. Issues with field quality and aperture can be addressed (at increased cost) in wigglers based on either technology. The power consumption in a normal-conducting wiggler is a concern, though this technology could provide a device with potentially better resistance to radiation damage than the superconducting or hybrid options.

Required R&D

Baseline

The CESR-c wigglers have demonstrated the basic requirements for the ILC damping ring wigglers. Designs for a superconducting wiggler for the damping rings need to be optimized.

Alternatives

Designs need to be developed with acceptable costs for normal-conducting electromagnetic and hybrid wigglers that meet specifications for aperture and field quality. In the case of a normal-conducting electromagnetic wiggler, the design also needs to show acceptable power consumption.

Main (Non-Wiggler) Magnets Technology

Options

The main magnets (dipoles, quadrupoles, sextupoles) may be electromagnets, or permanent magnets.

Issues

Tunability for beam-based alignment (Significance: A)

The challenging goal for vertical emittance makes high-precision beam-based alignment of the quadrupoles essential. Variation of the magnetic center of a quadrupole with magnet strength will contribute to the systematic errors, and limit the accuracy of the results. This is potentially a greater concern with permanent magnets (where variation in field strength generally requires mechanical movement) than in electromagnets.

Flexibility for polarity reversal (Significance: A)

It may be desirable to operate the positron damping rings with an electron beam, for example during commissioning, or for e^-e^- collisions. The design of the vacuum chamber (in particular, the location of the photon stops) will likely prevent reversal of the direction of travel of the beam in the ring, so magnet polarities will need to be reversed when switching from a positron beam to an electron beam. This will be more easily achieved with electromagnets than with permanent magnets.

Tunability for optics flexibility and energy variation (Significance: A)

It will likely be desirable to have the flexibility to adjust the optics in the damping rings, for example for tuning the emittance and the momentum compaction. Tunability will be more easily achieved with electromagnets than with permanent magnets.

Although the ring energy is nominally fixed in operations, there are circumstances under which it may be useful to vary the energy, perhaps by as much as 10% from the nominal value. Some increase in energy may be helpful to raise the threshold for some collective instabilities, or to increase the damping rates; some reduction in energy may be helpful to reduce the equilibrium emittances. Additionally, although depolarization is not expected to be a significant problem, small adjustments in energy may be necessary to avoid spin resonances. Adjustments in magnet strength to accommodate changes in beam energy may be more easily achieved in electromagnets than in permanent magnets.

Reliability (Significance: B)

Failure of a single power supply for an electromagnet will render the damping ring inoperable. Failure of the mechanism for strength adjustment of a permanent magnet will inhibit tuning procedures, but would likely allow operation of the damping ring to continue.

Resistance to radiation damage (Significance: B)

Radiation damage is a potential problem for permanent magnets. This issue may be less critical than in the wiggler, since the narrower physical aperture in the wiggler will likely lead to higher radiation levels in that region.

Cost (Significance: C)

The cost of permanent magnet materials is high. If the magnet strengths are to be adjustable, then permanent magnet multipoles need precision mechanical tuning systems. Electromagnets need power supplies and cooling systems. Overall, there is unlikely to be any significant difference in cost between the two options.

Issues Ranking

Issue	Significance	Risks	
		EM	Permanent magnet
Tunability for BBA	A	1	2
Flexibility (polarity reversal)	A	1	4
Tunability (for optics or energy variation)	A	1	2
Reliability	B	2	2
Resistance to radiation damage	B	1	2
Cost	C	1	1

Baseline Recommendation

We recommend that the main magnets in the damping ring be electromagnets. Using electromagnets simplifies tuning issues, and allows polarity reversal, e.g. for storing electrons in the positron ring.

Alternative

Permanent magnets may still be considered as a possibility, if it is decided that polarity reversal is not required.

Required R&D

Baseline

Designs for the main damping ring magnets should be straightforward, but still need to be developed.

Alternative

The problem of polarity reversal needs to be addressed. A demonstration is needed of a permanent magnet with good tunability and resistance to radiation damage.

RF System Technology

Options

The RF system could, in principle, use either normal conducting or superconducting RF cavities.

Issues

Higher-order modes (Significance: A)

Higher-order modes (HOMs) in RF cavities can have adverse effects on the beam dynamics. Normal-conducting and superconducting cavities can be designed to have HOMs of low amplitudes, but it is still preferable to keep the number of cavities as small as possible. The gap voltage per cell in a normal-conducting RF cavity is typically around 0.7 MV (limited by cooling); in superconducting cavities, voltages as high as 3 MV have been demonstrated. This means that up to four times as many cavities would be needed in a normal-conducting RF system as in a superconducting system.

Power dissipation (Significance: A)

In a normal-conducting cavity, the power dissipated in the cavity wall may be as large as the power supplied to the beam. In a superconducting cavity, the power dissipation is negligible; power is required by the cryogenics, but this is still expected to be less than the power dissipated in a normal conducting cavity.

Phase transients from beam loading (Significance: B)

If there are gaps in the fill, variations in beam loading will result in phase transients along each minitrain. The transients depend on the R/Q of the cavities and the total voltage. Since a superconducting RF system would have fewer cavities, the phase transients should be smaller.

Reliability (Significance: C)

The superconducting RF system in KEK-B has a trip rate of the order of one trip per day. In PEP-II, the normal-conducting RF system has a trip rate of between three and five trips per day. The system can be designed so that a trip would result in loss of a small number of machine pulses. Trips are not expected to have a significant impact on operation of the damping rings, provided there is some reserve in the amount of RF voltage available.

Cost (Significance: C)

The RF system is expected to be a small contribution to the cost of the damping rings. A superconducting system could have some advantage from the smaller number of RF cavities that would be required.

Issues Ranking

Issue	Significance	Risks	
		Normal-conducting	Superconducting
Higher-order modes	A	2	1
Power dissipation	A	2	1
Phase transients	B	2	1
Reliability	C	1	1
Cost	C	1	1

Baseline Recommendation

Each damping ring should use a superconducting RF system. Compared to a normal-conducting RF system, a superconducting RF system requires fewer cavities, (with advantages for cost and keeping HOMs low); the power dissipation is lower; and smaller phase transients are expected.

Alternative

A normal-conducting RF system could still satisfy the requirements for the damping rings.

Required R&D

The basic requirements of the superconducting RF systems for the damping rings have been demonstrated in existing machines, e.g. KEK-B. A full system specification, design and optimization are needed.

RF Frequency

The choice of RF frequency is strongly coupled to the choice of:

- **bunch train length**: the flexibility in the number of bunches in a train depends to some extent on the RF frequency.

Options

An RF frequency of 500 MHz is a common choice for synchrotron light source storage rings. It is possible to consider other choices, for example 650 MHz.

Issues

Cost (Significance: A)

500 MHz RF systems are standard, and will therefore be lower cost. A 650 MHz system would need to be designed from scratch.

Bunch length (Significance: B)

A higher frequency makes it possible to achieve the desired bunch length at a lower voltage. A reduction in voltage has advantages in saving cost; but in the case of the options considered here, the cost savings of the lower voltage of the 650 MHz system compared to the 500 MHz system would be outweighed by the required R&D.

Phase locking with linac RF (Significance: C)

The damping ring RF must be phase locked to the linac RF, to ensure that bunches extracted from the damping ring arrive at the correct phase of the main linac RF. An RF frequency of 650 MHz is a simple subharmonic (1/2) of the main linac RF frequency of 1.3 GHz. A 500 MHz RF system is at a more complex subharmonic (5/13). However, either frequency can easily be locked to the main linac RF.

Issues Ranking

Issue	Significance	Risks	
		500 MHz	650 MHz
Cost	A	1	3
Bunch length	B	1	1
Phase locking with linac	C	1	1

Baseline Recommendation

The damping rings RF systems should use an RF frequency of 500 MHz. This is a standard technology; other options would require R&D.

Vacuum Chamber Aperture

The specifications for the vacuum chamber aperture are strongly coupled to the choices for:

- **injected emittance and energy spread**: a larger transverse emittance requires a larger physical aperture for good injection efficiency;
- **wiggler technology**: the wiggler must have sufficient aperture to accommodate the vacuum chamber.

Options

The vacuum chamber will have a complicated geometry, and comprehensive studies of issues related to the geometry are not possible without detailed designs. However, it is possible to consider the impact of chambers of different diameters (assuming a circular cross-section) in different sections of the damping rings. We consider three representative cases:

Section	Chamber diameter [mm]		
	Option: 44/16/100	Option: 50/32/100	Option: 50/46/100
Arc	44	50	50
Wiggler	16	32	46
Straight	100	100	100

Issues

Acceptance (Significance: A)

The large beam from the positron source needs a large chamber aperture for good injection efficiency. Tracking studies in the reference lattices indicate that in most cases, a diameter of 32 mm in the wiggler would be sufficient, while a diameter of 24 mm would be insufficient. Reducing the beta functions in the wiggler would help with the acceptance, but the beam size varies only as the square root of the beta function, and reducing the beta functions would increase the local chromaticity.

Cost (Significance: A)

Increasing the chamber diameter in a storage ring generally increases the cost of the machine, since magnets with larger aperture are required, which are more expensive. In the three options considered here, the difference between 44 mm and 50 mm in the arcs is not likely to be significant. A superconducting wiggler (as in the recommended baseline) can accommodate a chamber with 46 mm aperture; in any case, the wiggler chambers are a relatively small contribution to the cost of the whole vacuum system.

Electron cloud (Significance: A)

A larger chamber helps to reduce the build-up of electron cloud from multipacting. With the baseline of two 6 km rings for the positron damping ring, the necessary chamber aperture in the wiggler is likely to be no less than 46 mm. In an alternative 17 km ring, a smaller chamber aperture could be tolerated.

Resistive-wall instability (Significance: A)

The resistive-wall wake field drives coupled-bunch instabilities. The strength of the transverse wake is inversely proportional to the cube of the chamber diameter; increasing the diameter by a factor of 2 reduces the wake field by nearly an order of magnitude. Bunch-by-bunch feedback systems can be used to suppress coupled-bunch instabilities, as long as the growth times are above approximately 20 turns. With small chamber diameter (44/16/100), the growth times in the damping rings are of this order; a larger chamber would provide some margin.

Gas conductance (Significance: B)

Ion and electron cloud effects place demanding requirements on the residual gas pressure in the vacuum chamber. Increasing the chamber diameter increases the conductance, which helps to achieve a lower average pressure with a given number of pumps; this could be particularly helpful in the wiggler.

BPM performance (Significance: B)

Achieving good BPM performance becomes more difficult as the chamber aperture increases.

Issues Ranking

Issue	Significance	Risks		
		Option: 44/16/100	Option: 50/32/100	Option: 50/46/100
Acceptance	A	4	2	1
Cost	A	1	1	1
Electron cloud	A	3	3	2
Resistive-wall instability	A	3	2	2
Gas conductance	B	2	1	1
BPM performance	B	1	2	2

Baseline Recommendation

A chamber diameter of (not less than) 50 mm in the arcs, 46 mm in the wiggler and 100 mm in the straights is required. The wiggler chamber needs a large aperture to achieve the necessary acceptance, and to suppress electron cloud build-up. The large aperture also reduces resistive-wall growth rates, and eases the requirements on the feedback systems.

Required R&D

Even with a large aperture chamber in the damping rings, a bunch-by-bunch feedback system will be needed in the transverse and longitudinal planes to suppress coupled-bunch instabilities driven by the resistive-wall impedance. Although the required performance of the feedback systems should be within the range of existing technology, studies are needed of the level of residual beam jitter, and possible emittance growth.

Vacuum System Technologies

Vacuum chamber material

Options for the chamber material are:

- stainless steel;
- copper;
- aluminum.

Treatment for suppressing electron cloud

There are options for treating the chamber to suppress electron cloud, including:

- coating with titanium nitride;
- coating with NEG, e.g. TiZrV;
- using a grooved surface.

Different treatments may be used in different parts of the damping ring.

Pumping technology

Options for pumping technology include:

- use of conventional pumps;
- use of NEG coating.

Antechamber

An antechamber may be needed in some sections of the damping ring, and not in others.

In-situ baking

It may be desirable to have a vacuum chamber that is capable of being baked in-situ.

Baseline Recommendations

Recommendations for the vacuum system for the baseline configuration have not yet been made.