ILC Damping Rings:
Configuration, Siting and Staging

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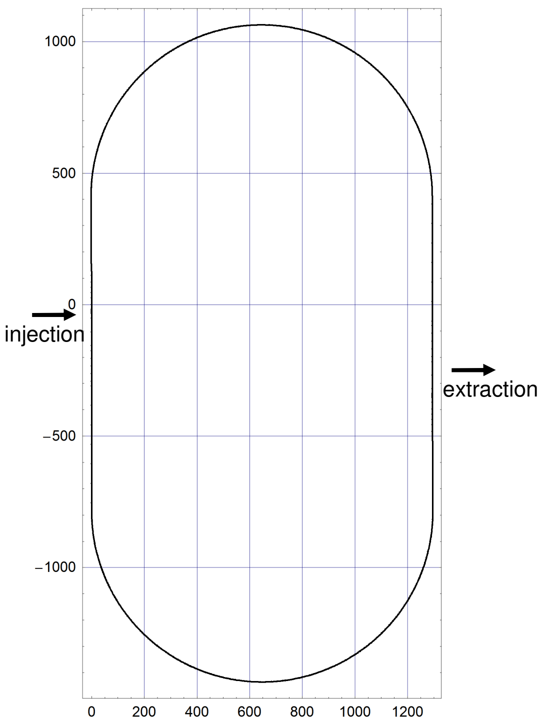
Outline

- Overview of present damping rings baseline configuration.
- Configuration constraints:
  - **timing issues;**
  - **bunch charge, bunch spacing;**
  - **conventional facilities.**
- Potential alternative configurations, and their implications.
  - **Dogbone.**
  - **3 km circumference rings.**
  - **Pre-existing 6 km tunnel.**
  - **Surface construction.**
  - **Reduced specifications for subsystems (wiggler, rf…)**

Present Configuration: Key Parameters

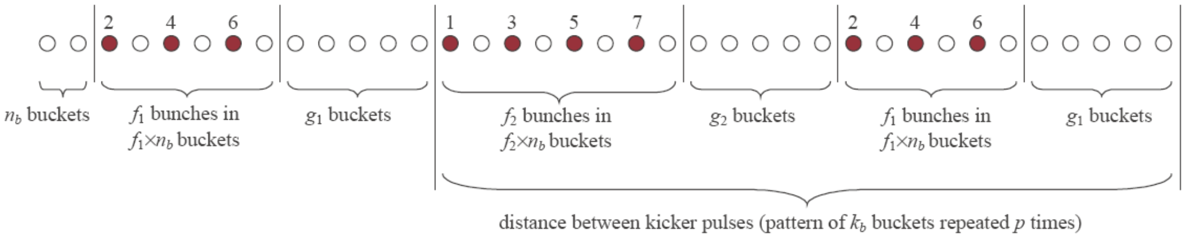
Beam energy	5 GeV
Circumference	6476.440 m
RF frequency	650 MHz
Harmonic number	14042
Transverse damping time	21.0 ms
Natural rms bunch length	6.00 mm
Natural rms energy spread	1.27×10^{-3}

Present Configuration: DCO Lattice



- Two 'identical' rings in a single tunnel.
- Arcs consist of a total of 192 FODO cells
- Flexibility in tuning momentum compaction factor, given by phase advance per arc cell:
  - **72° phase advance: α_p=2.8×10^{-4}**
  - **90° phase advance: α_p=1.7×10^{-4}**
  - **100° phase advance: α_p=1.3×10^{-4}**
- No changes in dipole strengths needed for different working points.
- Racetrack structure has two similar straights containing:
  - **injection and extraction in opposite straights**
  - **phase trombones**
  - **circumference chicanes**
  - **rf cavities**
  - **"doglegs" to separate wiggler from rf and other systems**
  - **wiggler**

Fill Pattern and Harmonic Number, h



$$\left.\begin{aligned} h &= pk_b + n_b \\ g_2 &= 0 \end{aligned}\right\} \qquad f_2 = 0 \qquad (1)$$

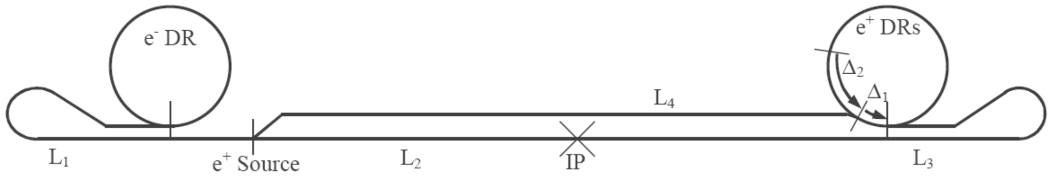
$$\left.\begin{aligned} h &= (p+1)k_b - f_1 n_b - g_1 \\ g_2 &= (f_1 - f_2 + 1)n_b + g_1 \end{aligned}\right\} \qquad f_2 \neq 0 \text{ and } f_2 \neq f_1 \qquad (2)$$

- Also require: linac bunch spacing in linac rf buckets ($= 2k_b$) divisible by 6, 12, 24.

Circumference is Highly Constrained

		A	B	C	D	E	F	G	H	I	J	K	L	M
	1	**Damping Rings Fill Pattern**		**Nominal EDR Circumference**						**RDR Circumference**				
*	2	DR bunch spacing	DR RF buckets	2	2	2	2	4	4	2	2	2	3	4
	3	Pattern repetition factor	p	117	90	78	65	58	32	123	118	82	71	61
	4	Bunches per even-numbered minitrain	f2	0	0	0	0	23	23	0	0	0	22	22
	5	Gaps per even-numbered minitrain	g2	0	0	0	0	30	126	0	0	0	37	32
	6	Bunches per odd-numbered minitrain	f1	45	45	45	45	22	23	44	44	44	22	22
	7	Gaps per odd-numbered minitrain	g1	30	66	90	126	30	122	30	35	89	34	28
	8													
*	9	**Linac average current**	**milli-amps**	**9**	**9**	**9**	**9**	**9**	**5**	**9**	**9**	**9**	**9**	**9**
	10													
	11	**Derived Parameters**												
*	12	**Ring harmonic number**		**14042**	**14042**	**14042**	**14042**	**14042**	**14042**	**14516**	**14516**	**14516**	**14516**	**14516**
	13	DR circumference	meters	6476	6476	6476	6476	6476	6476	6695	6695	6695	6695	6695
	14	DR average current	milli-amps	405	405	405	405	401	226	396	396	396	393	393
	15	Total number of bunches		5265	4050	3510	2925	2610	1472	5412	5192	3608	3124	2684
*	16	Bunch population	1.00E+10	1.04	1.35	1.56	1.87	2.07	2.07	1.02	1.06	1.53	1.75	2.04
	17	Extraction kicker interval	DR RF buckets	120	156	180	216	240	432	118	123	177	203	236
	18	Linac bunch spacing	Linac RF buckets	240	312	360	432	480	864	236	246	354	406	472
	19	Linac bunch spacing	nanoseconds	184.62	240.00	276.92	332.31	369.23	664.62	181.54	189.23	272.31	312.31	363.08
	20													
	21	**Linac pulse length**	**microseconds**	**971.82**	**971.76**	**971.72**	**971.67**	**963.32**	**977.65**	**982.30**	**982.30**	**982.21**	**975.34**	**974.14**
	22													
	23	Average injected power	kW	219	219	219	219	217	122	221	221	221	220	219
	24	Total population of damping ring	1.00E+13	5.46	5.46	5.46	5.46	5.41	3.05	5.52	5.52	5.52	5.48	5.47
	25													
	26	Linac bunch spacing (buckets) mod 6		0	0	0	0	0	0	2	0	0	4	4
	27	Linac bunch spacing (buckets) mod 12		0	0	0	0	0	0	8	6	6	10	4
	28	Linac bunch spacing (buckets) mod 24		0	0	0	0	0	0	20	6	18	22	16

Overall ILC Timing Issues



- To ensure collisions at the IP:

$$L_1 + L_2 = \Delta_1 + \Delta_2 + L_3$$

- For self-reproducing fills in the damping rings:

$$L_1 + L_4 = \Delta_2 + nC \qquad n = 0,1,2\ldots$$

- Hence:

$$L_4 + \Delta_2 + L_3 = L_2 + nC$$

References:
https://wiki.lepp.cornell.edu/ilc/bin/view/Public/DampingRings/WebHome#Damping_Rings_Parameters_and_Lat

Bunch Charge and Dimensions

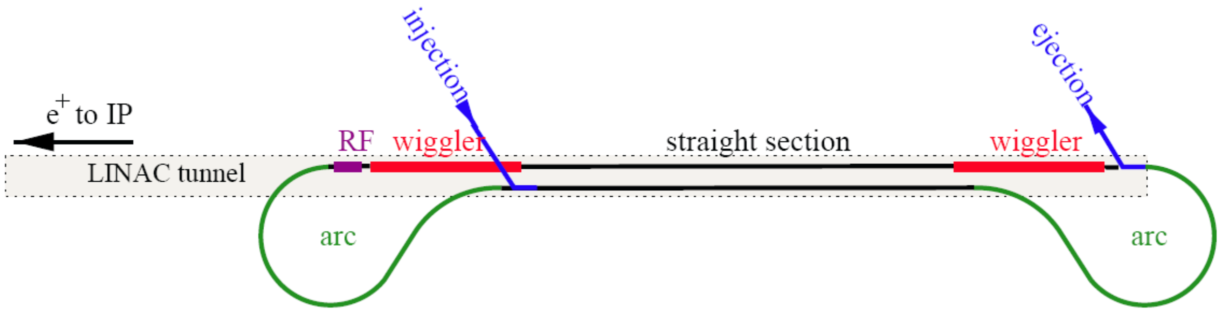
- Damping rings performance ultimately depends on beam quality and stability.
- A range of dynamical effects threaten to cause emittance growth, single-bunch and multi-bunch instabilities…
  - **electron cloud;**
  - **ion effects (ion trapping, fast ion instability);**
  - **impedance effects (short-range and long-range wakes);**
  - **intrabeam scattering;**
  - **space charge.**
- We believe that, in the present configuration, we are in a regime where we can (just about) contain these effects.
  - **Reducing the bunch charge and beam current, or increasing the emittance and bunch length is always desirable…**

Ring Circumference and Beam Energy

- Reducing the circumference will reduce costs.
  - **The lower limit on the circumference comes from kicker performance and length of bunch train.**
  - **6 km is probably the smallest circumference into which we can inject a *full* bunch train of the specified length.**
  - **This already assumes significant progress with kicker R&D.**

- Reducing the beam energy will reduce costs.
  - **Damping time drops: lower energy will need more wiggler.**
  - **Injected beam size becomes larger: dynamic aperture becomes a more difficult issue than it is already.**
  - **All collective effects become more severe (some scale strongly with energy, e.g. space charge, IBS).**

Dogbone Damping Ring



- From TESLA TDR (March 2001).
- Straight sections ~ 7.5 km located in same tunnel as the main linac, joined by 2 arcs ~ 1 km each.
- Reduced total amount of tunnel, while allowing large (20 ns) bunch spacing in the damping rings, relaxing kicker specifications.

Possible Issues with the Dogbone

- Space charge
  - **Parameter regime (bunch charge and dimensions, beam energy, circumference) makes emittance growth a risk.**
  - **Proposed solution: use coupling bumps to generate a "round" beam in the long straights. But the coupling bumps can drive resonances that could themselves result in emittance growth. Also, a round beam could trap ions very efficiently.**
- Dynamic aperture
  - **Non-local chromatic correction (only in the arcs) makes off-energy dynamic aperture a challenge.**
- Stray fields
  - **Large (~ 200 m) beta functions in the long straights makes the beam sensitive to weak magnetic fields.**
  - **A particular concern because of transients during the linac pulse…**
- Would it be any cheaper than the present configuration?

Possible Issues with the Dogbone

- Specific concerns for the dogbone configuration include:
  - **space charge;**
  - **dynamic aperture;**
  - **stray fields.**
- It would be difficult to verify that any design would overcome these issues, without full-scale construction.
- The present baseline is relatively conventional, and limits the risks to issues/components that can be tested in advance:
  - **electron cloud (CesrTA);**
  - **fast injection/extraction kickers (ATF).**
- Of course there are other risks, common to almost any configuration.

3 km Damping Rings

- Purely from point of view of the lattice design, a 3 km ring is probably feasible.
  - **We considered a 3 km lattice (PPA) in the 2005 Configuration Studies.**
- We can't put the bunches any closer together.
  - **kicker performance, electron cloud, ions…**
- If we halve the circumference, this must be achieved in one of two ways:
  - **Halve the bunch train length (halves the luminosity?)**
  - **Stack two electron rings and two positron rings all in the same tunnel (save on the tunnel costs, but not on the component or power costs).**
- 3 km rings may provide a possibility for a staged solution.
  - **Start with a single 3 km tunnel with one electron and one positron damping ring, providing half the present baseline design luminosity.**
  - **Upgrade by adding additional rings in a new tunnel, or (less desirably) installing additional rings in existing tunnel.**

Pre-existing 6 km tunnel

- Precise circumference is critical to timing issues.
  - **The harmonic number does not have to be exactly 14042, but we will lose some, or even all, operational flexibility (fill patterns, bunch charge) if it is not.**
- Any proposed tunnel would need to be carefully evaluated from point of view of space, services, installation, survey and alignment etc.
- Geometry is a tight (and often unpleasant) constraint on the lattice design.

Surface Construction

- Main drawback of construction at ground level would be sensitivity to environmental changes.
  - **Temperature.**
  - **Rainfall.**
- Vertical emittance is sensitive to magnet alignment at the level of a few microns.
  - **Tuning for 2 pm vertical emittance could be a lengthy process, which we don't want to do too often.**
- Changes in circumference lead to changes in beam energy, which should be avoided.
  - **Lattice design includes circumference chicanes, which allow correction in circumference at the level of a few millimeters.**

Reduced Wiggler

- Wiggler provides around 90% of the radiation damping.
- Reducing wiggler length increases damping times, roughly in proportion.
  - **Extracted vertical emittance will be larger.**
  - **Equilibrium horizontal emittance will be larger.**
  - **Extracted energy spread would be smaller.**
  - **Effects such as intrabeam scattering will have a larger impact.**
- Cost saving will be relatively small.

Reduced RF

- RF voltage determines the bunch length.

$$\sigma_z \propto \frac{1}{\sqrt{V_{rf}}}$$

- Bunch length also depends on other parameters, including the momentum compaction factor.
- Momentum compaction factor was initially specified at a relatively large value (4×10^{-4}) because of concerns over instabilities.
- More detailed studies of instabilities suggested the momentum compaction factor could be relaxed. Present specification is for 2×10^{-4}, which allows a 6 mm bunch length with reasonable (25 MV) rf voltage.
- Present lattice design allows tunability in the optics, to cover a range of momentum compaction factors.
  - **This provides the possibility of "staged" installation...**

Staging the RF Installation?

Phase advance per arc cell (approx)	72°	90°	100°
Momentum compaction factor	2.80×10^{-4}	1.73×10^{-4}	1.29×10^{-4}
Normalised natural emittance	6.53 μm	4.70 μm	4.27 μm
RF voltage	31.6 MV	21.1 MV	17.2 MV
Bunch length (rms)	6 mm	6 mm	6 mm
RF acceptance	2.35%	1.99%	1.72%
Synchrotron tune	0.061	0.038	0.028
Horizontal tune	64.750	75.200	80.450
Natural horizontal chromaticity	-76.5	-95.1	-106.9
Vertical tune	61.400	71.400	75.900
Natural vertical chromaticity	-75.6	-93.4	-103.5

Possible scenario: start with low momentum compaction factor and (if necessary) low bunch charge; then upgrade rf and momentum compaction factor to push for higher bunch charge.

Conclusions (1)

- Present baseline configuration has been developed to balance cost and technical risk.
  - **Key issues related to the baseline configuration, such as kicker performance and electron cloud, can be addressed at test facilities.**

- Alternatives are possible, and should be considered as we learn more about costs and technical possibilities and limitations.
  - **Dogbone damping ring: costs should be looked at again; a number of dynamical issues may be difficult to address before construction.**
  - **3 km damping rings: provide the possibility of a staged installation; somewhat nervous about four rings in a single tunnel.**

Conclusions (2)

- Pre-existing 6 km tunnel provides the potential for significant cost savings...

  ...but could also impose potentially difficult constraints on geometry and circumference.

- Surface construction may impact operational performance, by adversely affecting beam stability, and requiring more time for tuning.

Conclusions (3)

- Scope for reducing technical subsystems and component specifications is rather limited.
- In many cases, a "full complement" is necessary for the damping rings to work at all.
  - **e.g. vacuum system and magnets.**
- There are a couple of possibilities for cutting specifications, at least in the early stages...
  - **Reducing the wiggler: would impact extracted emittances, and increase vulnerability to collective effects.**
  - **Reducing the rf: may be an option if operation at low momentum compaction factor is possible (e.g. at low bunch charge, or if instabilities are not too severe).**
- ...but cost savings will be rather modest.