Damping Rings
Area System Configuration

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on behalf of the Damping Ring Area System Leaders:

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Contents

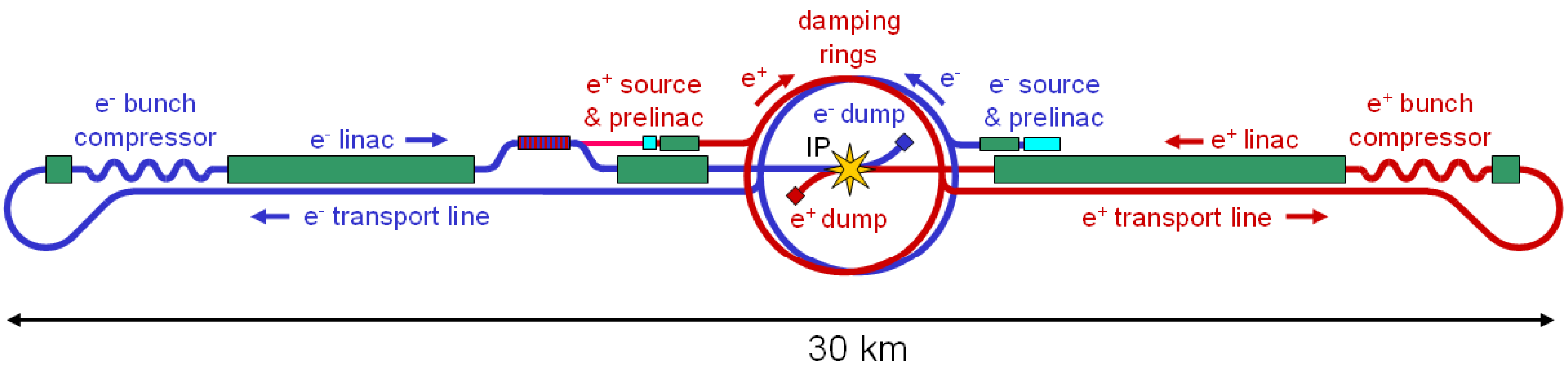
Performance Specifications

The following parameters represent "external" constraints on the damping rings design:

Bunch population	1.0×10^{10} to 2.0×10^{10}
Linac average current	9 mA
Linac RF pulse length	970 μs
Store time	200 ms
Maximum injected betatron amplitude*, A_x+A_y (e^+)	0.09 m
Injected energy spread	1% full width
Extracted normalized horizontal emittance	8 μm
Extracted normalized vertical emittance	0.02 μm
Extracted bunch length	≤ 9 mm
Extracted energy spread	≤ 0.13%

*Note: the betatron amplitude is defined by $A_x = \gamma\left(\gamma_x x^2 + 2\alpha_x x p_x + \beta_x p_x^2\right)$

Damping Rings RDR Configuration



- Two 6.7 km, 5 GeV damping rings.

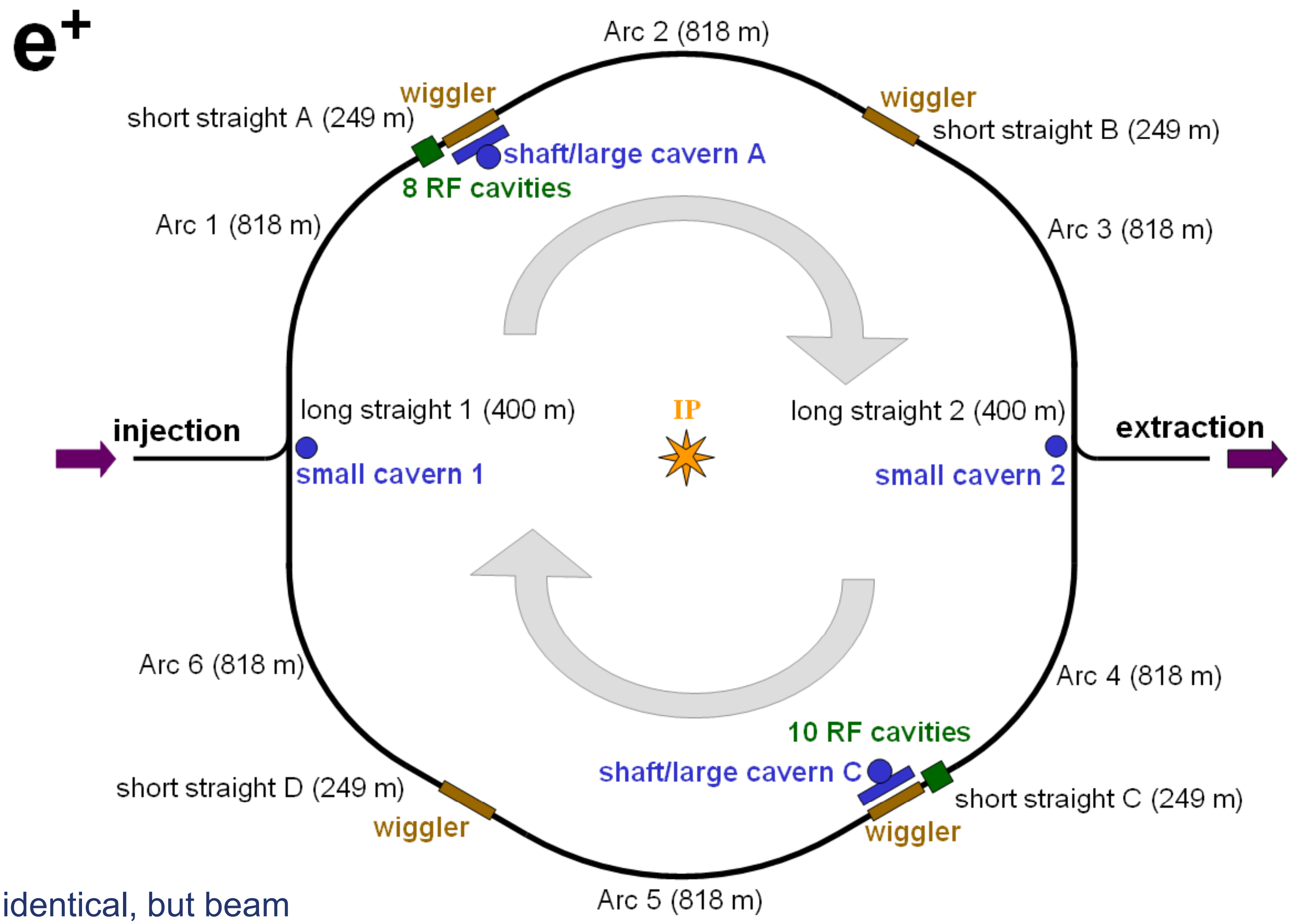
  One electron ring and one positron ring in a shared tunnel around the interaction region.

- Damping rings area system includes short sections of injection and extraction line, connecting each ring with the sources (upstream) and the RTML (downstream).

Documentation

- The intention was to document the reference design and costing using a set of standard "specification sheets".
- Each specification sheet would include information on a single component, or set of components:
  - **classification (beamline, subsystem and component)**
  - **date**
  - **contacts (named people in DR Area System and relevant Technical System)**
  - **principal parameters**
  - **cost (not shown on public versions)**
  - **additional information: cost source, references, drawings…**
- Component specification sheets are archived at:
  https://wiki.lepp.cornell.edu/ilc/bin/view/Public/DampingRings/ReferenceDesignReport
- The system did not work exactly as intended, but was still very helpful.

Schematic Layout: e^+ Ring



e^- footprint is identical, but beam circulates in opposite direction, and RF cavities are always upstream of the wiggler.

Tunnel Cross Section

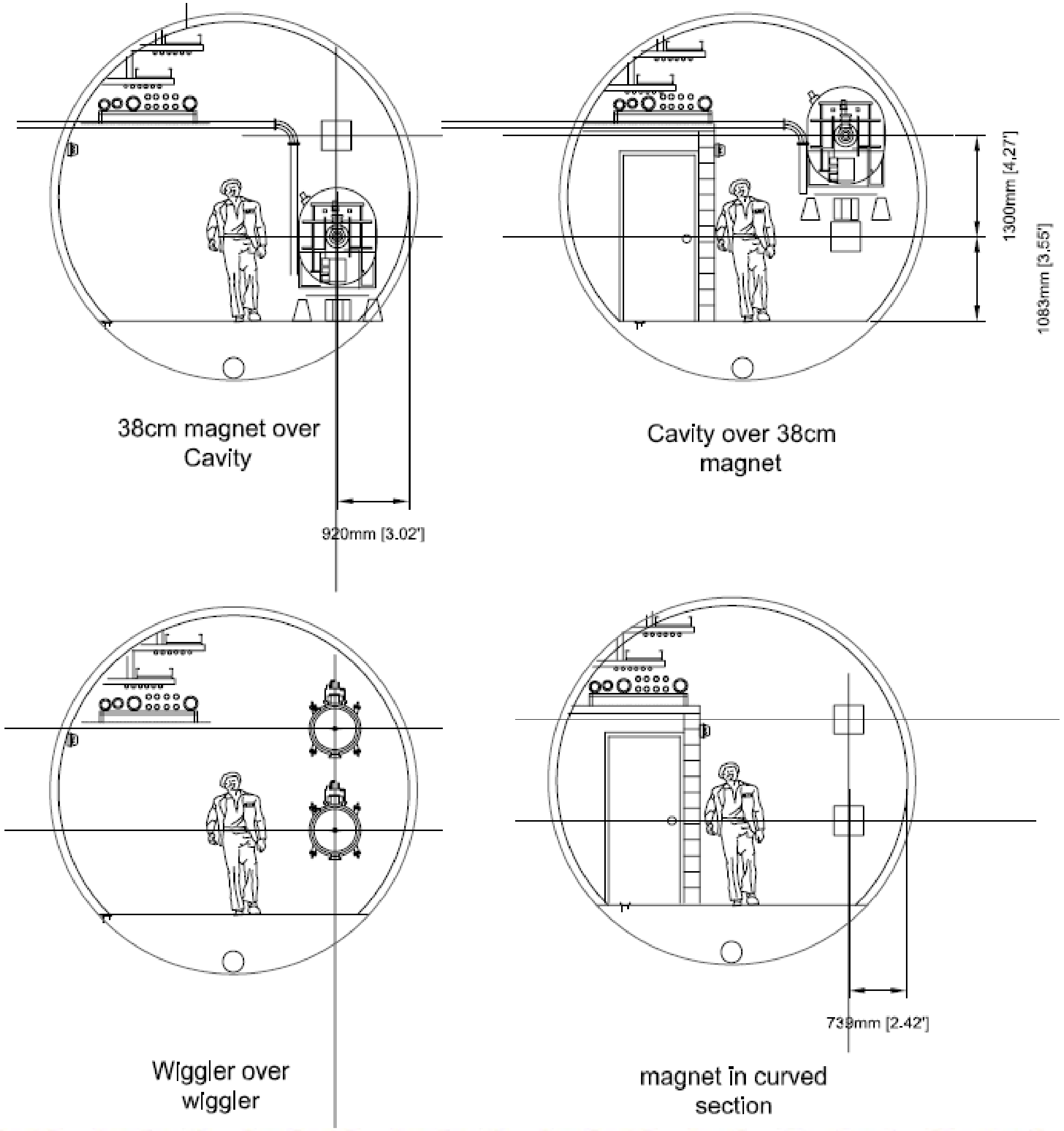
4.5 m tunnel diameter shown.

1.3 m vertical separation between beam lines.

RF cryostats are the largest components.

- **Based on CESR-c cryomodules, scaled to 650 MHz.**

Enclosed "tunnel within a tunnel" provides safety egress.



Parameters

Circumference	6695 m			
Beam energy	5 GeV			
Average current	391 mA			
Number of bunches*	2673	3107	3563	5344
Bunch spacing*	6.2 ns	4.6 ns	3.1 ns	3.1 ns
Bunch population*	2.0×10^{10}	1.8×10^{10}	1.5×10^{10}	1.0×10^{10}
Normalized natural emittance	5.2 µm			
Natural bunch length	9 mm			
Natural energy spread	0.13%			
RF voltage	23 MV			
RF frequency	650 MHz			
Momentum compaction factor	4.2×10^{-4}			
Damping times	25.7 ms (x,y); 12.9 ms (z)			

*Note: fill patterns are designed to give constant linac average current of 9 mA and pulse length 970 µs.

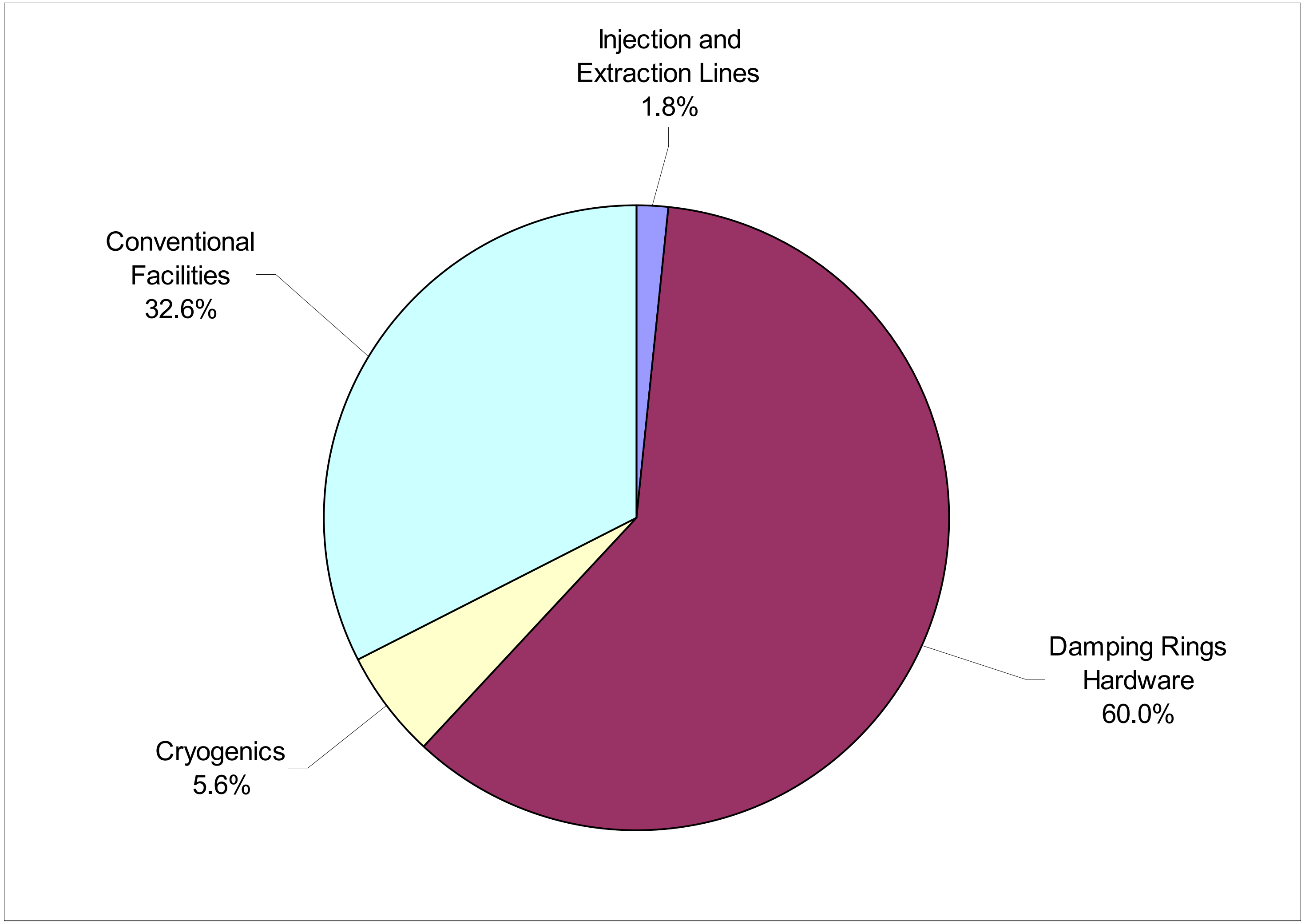
Key Features (quantities per ring)

- Magnets:
  - **114 × 6 m + 12 × 3 m dipoles, 0.146 T (common PS);**
  - **747 quadrupoles, individually adjustable;**
  - **480 sextupoles, individually adjustable;**
  - **300 horizontal and vertical corrector magnets;**
  - **240 skew quadrupoles, adjacent to sextupoles;**
  - **210 m of 1.6 T, 40 cm period superconducting wiggler.**
- RF system:
  - **18 superconducting, 650 MHz RF cavities;**
  - **total voltage 23 MV (upgradeable to 50 MV for 6 mm bunch length).**
- Injection and extraction:
  - **22 × 30 cm stripline kickers driven by fast, high-power pulsers (R&D project).**

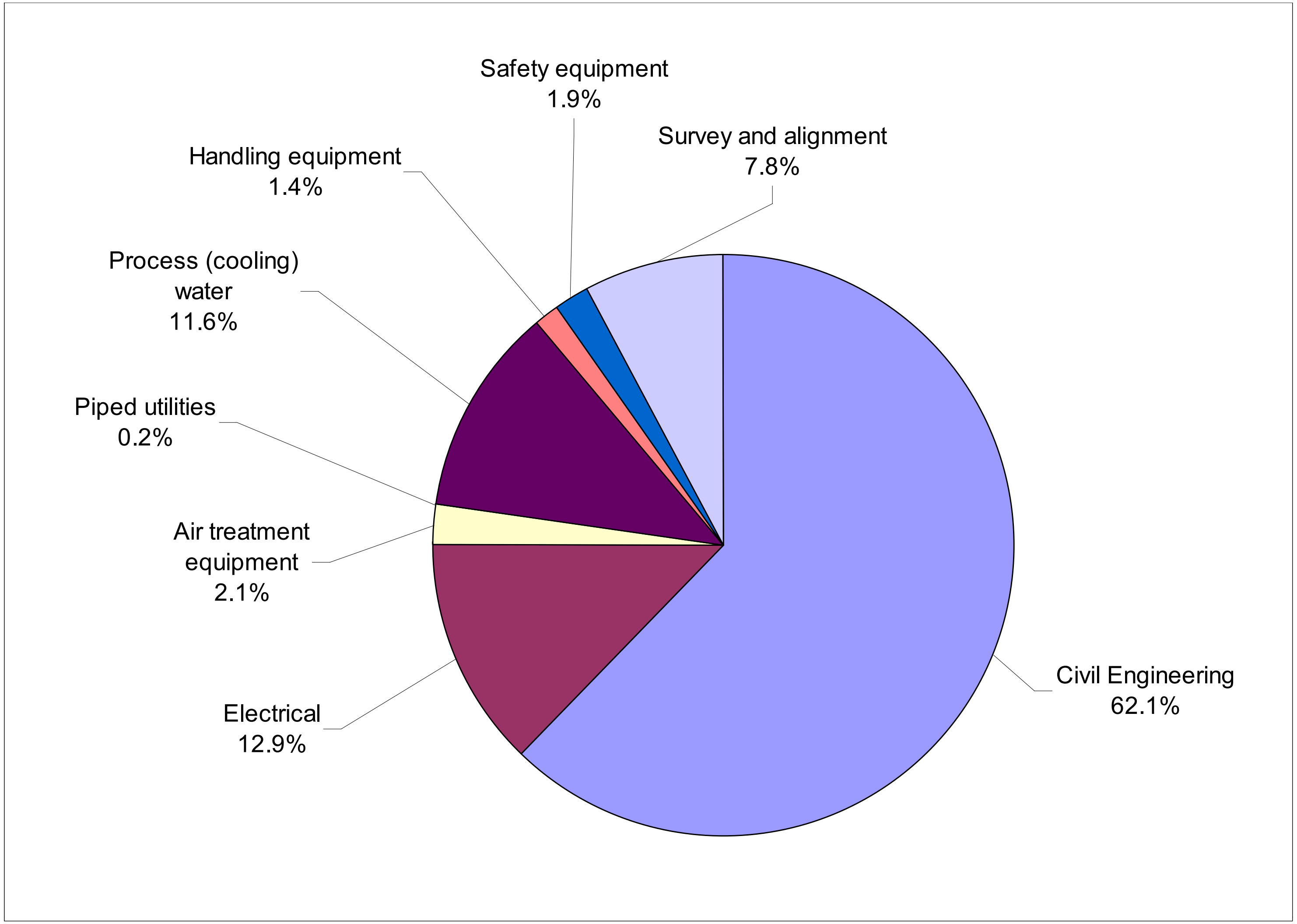
Key Features

- Vacuum system:
  - **specified for 0.1 ntorr in straights, 0.5 ntorr in arcs, 1 ntorr in wiggler (driven by ion effects);**
  - **NEG-coated aluminum cylindrical pipe in straights and arcs with in-situ “bake-out”; antechamber in wigglers;**
  - **possible e-cloud prevention measures include grooved chamber and clearing electrodes.**
- Instrumentation, coupling correction etc:
  - **747 turn-by-turn BPMs in each ring;**
  - **laser wire, SR beam-size monitor, streak camera, beam loss monitors…**
- Fast feedback systems:
  - **digital systems (x, y and z) specified to damp coupled-bunch instabilities with growth times ~ 20 turns.**

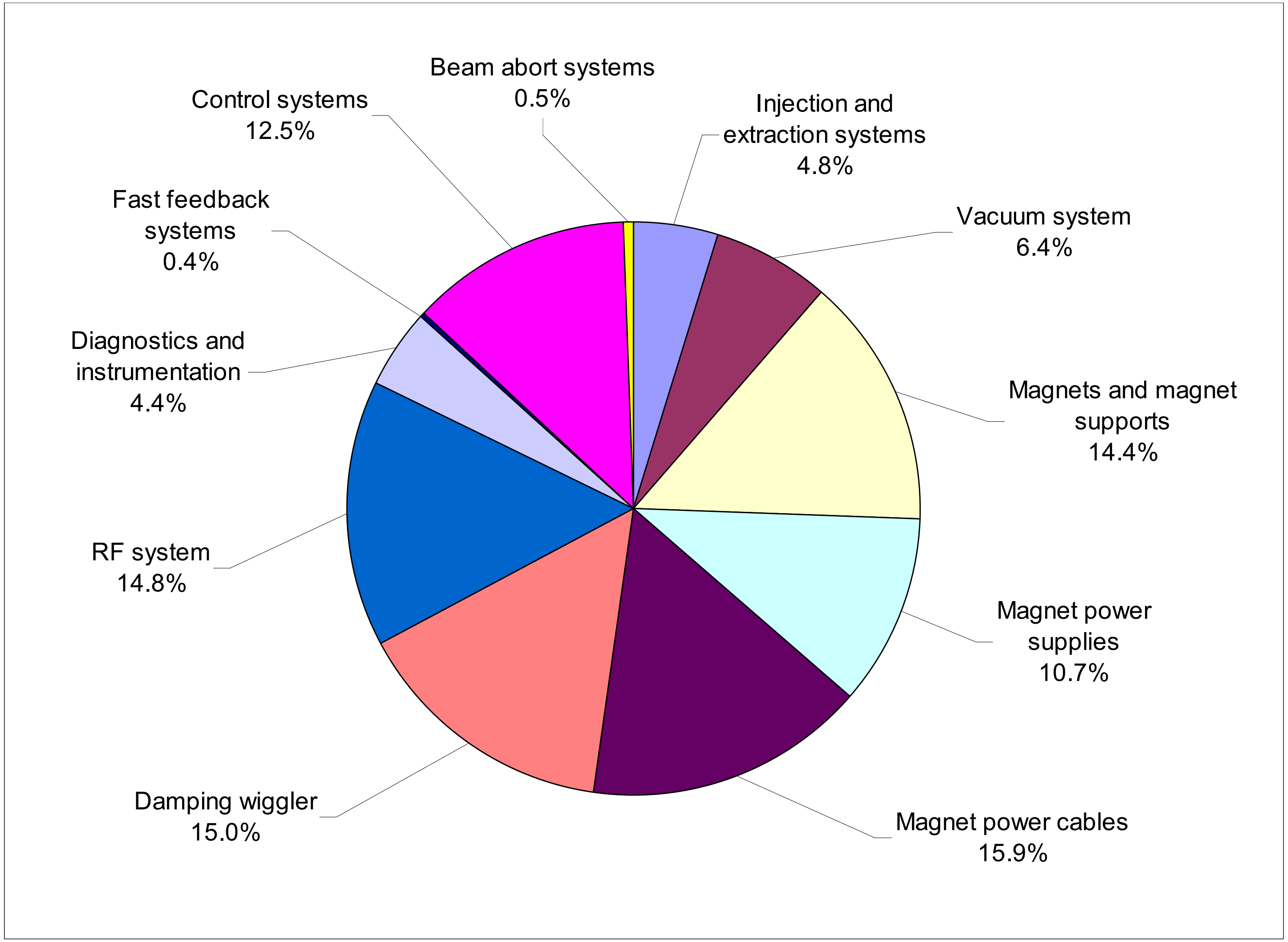
Relative Costs



Relative Costs: CF&S Portion



Relative Costs: DR Hardware



Configuration Choices

The key parameters of the baseline configuration were chosen following detailed studies (in 2005) of a range of configuration options.

- **Many issues were considered, including: beam dynamics, performance of technical subsystems and components, operability and reliability, and costs.**
- **Studies involved a team of 50 people, most of whom were involved in choosing the final recommendations.**
- **Results of the configuration studies and the configuration recommendations are documented in a detailed report (LBNL-59449, February 2006).**

Continuing studies in 2006 led to a number of configuration changes, mostly to reduce costs.

Evolution of the DR Configuration

- RF frequency changed from 500 MHz to 650 MHz.
  - **Original choice was intended to reduce amount of R&D required, by specifying a standard RF frequency.**
  - **A frequency of 650 MHz will improve phase synchronisation with linac RF (1.3 GHz), and provides more flexibility in the timing solution by increasing the harmonic number for a given circumference.**
- Circumference fixed at 6695 m.
  - **Harmonic number of 14516 provides good flexibility in fill patterns and bunch charges, for fixed pulse length and average current in the main linacs.**
  - **This choice was based on a machine configuration with two IRs with some longitudinal separation. With one IR, other choices should be reconsidered.**

Evolution of the DR Configuration

- Number of positron damping rings reduced to one.
  - **Original (February 2006) specification was for two positron damping rings, to reduce the average current, and mitigate electron cloud effects.**
  - **Continuing studies (through 2006) of techniques to suppress build-up of electron cloud indicated good prospects for being able to operate with a single positron damping ring (see later slides in this talk).**
  - **Benefits include reduced cost, and elimination of separator/combiner systems.**
- Two rings located in a single tunnel.
  - **With a single positron ring, locating the positron and electron rings in a single tunnel (thereby eliminating an entire 6.7 km tunnel) became a realistic possibility.**
  - **Two rings makes the tunnel more crowded, but we were already prepared to accept this with two positron rings.**

Evolution of the DR Configuration

- Number of access shafts and caverns reduced to two.
  - **Connected with lattice symmetry and dynamic aperture.**
  - **Limits the number of locations for the RF, but seems an acceptable solution.**
- Bunch length specification increased from 6 mm to 9 mm.
  - **Reduces required RF voltage from 50 MV to 24 MV for a fixed "nominal" momentum compaction factor.**
  - **Reduced peak current raises thresholds for single-bunch instabilities.**
  - **Increased bunch length from the damping rings puts additional pressure on the bunch compressors, but it appears that solutions do exist.**
  - **Rings should be designed so that additional RF can be added at a later date, to reduce the bunch length.**

Other Possible Changes

A number of changes to reduce costs further were considered, but not (so far) adopted, including:

- **Reduction of momentum compaction factor, allowing reduction in RF voltage for a given bunch length. This was considered too risky for the instability thresholds.**
- **Higher-harmonic RF to reduce bunch length, allowing reduction in main RF voltage. Attractive in some respects, but has technical disadvantages; higher-harmonic cavities are costly; would require significant R&D.**
- **Reduction of RF cavity temperature from 4.5 K to 2 K, allowing operation at same total power with half the number of cavities. Would require significant R&D.**
- **Development of lattice design to reduce the number of magnets. Still attractive: requires time to look at properly.**
- **Reduction in circumference to ~ 3 km, with accompanying reduction in luminosity by a factor of two. Potentially upgradeable by adding additional 3 km rings – but such an upgrade would be a big deal.**

Injection and Extraction Systems

- Injection and extraction systems consist of:
  - **short (~ few hundred meters) of transport line connecting the damping rings with the sources (upstream) and the RTML (downstream); including 90° bends, matching sections, dispersion suppression for kickers/septa etc.;**
  - **ultra-fast kickers;**
  - **(pulsed) septa.**
- Most technically challenging specifications are set by the positron injection system:
  - **large beam (0.01 m normalised rms emittance) requires large apertures;**
  - **on-axis injection of individual bunches is the only realistic method.**
- For smaller beams, such as the injected electrons, techniques (such as closed orbit bumps) may be possible that ease the requirements on the kickers.

Kicker Specifications

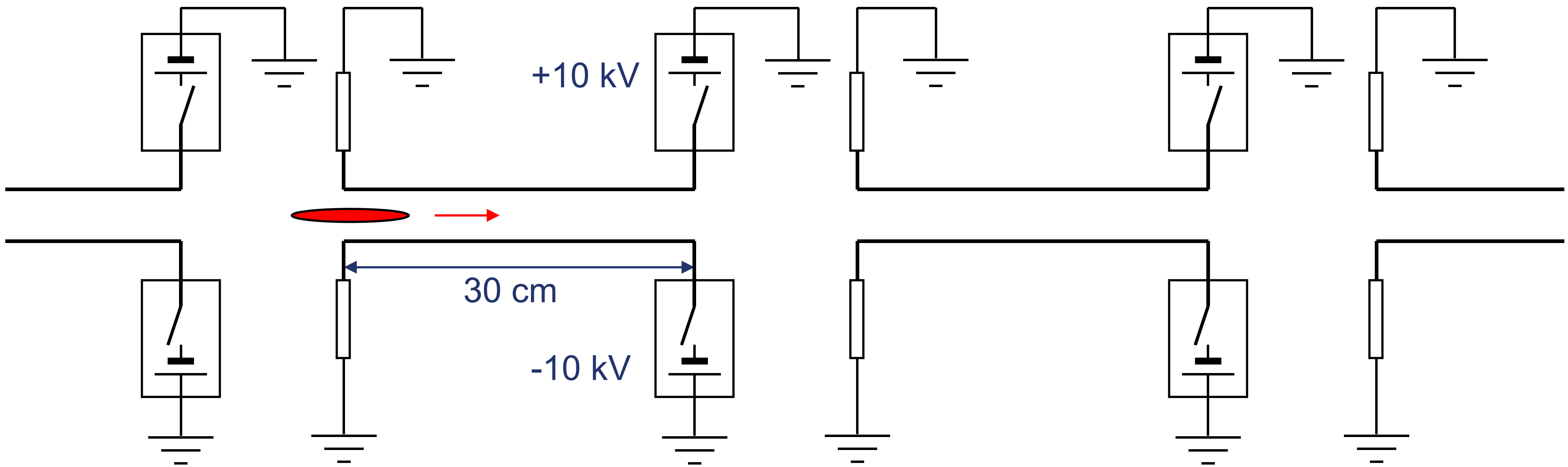
The kickers will consist of strip-lines fed by ultra-fast, high-voltage pulsers. The integrated voltage required is determined by the acceptance specification:

$$V \times L = \frac{2}{k} \frac{A_{x,\max}}{\gamma} \frac{E}{e}$$

where V is the voltage between the strip-lines, L is the strip-line length, k is a geometry factor (~ 0.7) determined by the strip-line shape, $A_{\max}$ (~ 0.09 m for injected positrons) is the maximum betatron amplitude, E is the beam energy and γ is the relativistic factor.

Integrated voltage	> 132 kV-m
Rise and fall times	< 3 ns
Repetition rate	5.5 MHz
Pulse length	970 μs
Stability	< 0.1%

Kicker Systems

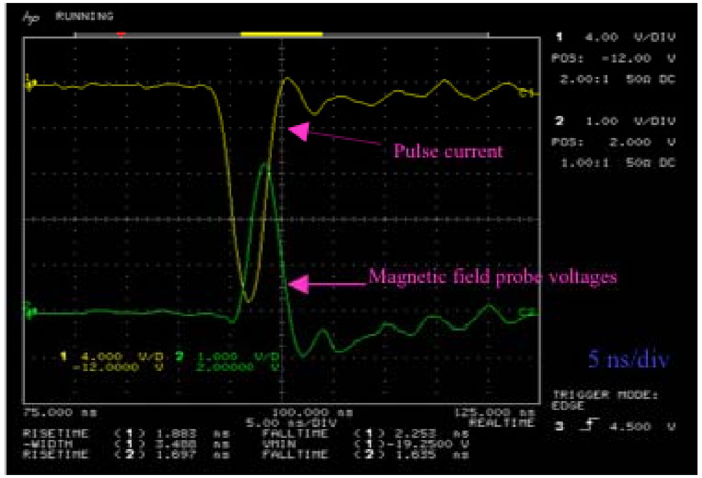


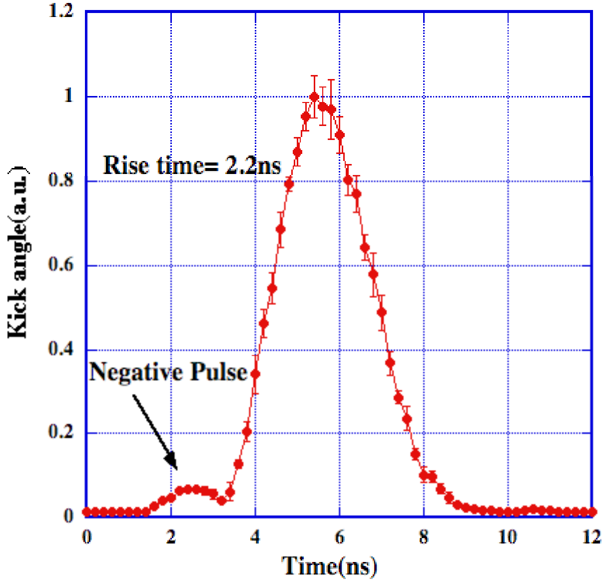
The length of each stripline is limited by the rise and fall time specifications. We assume a maximum length of 30 cm. Each stripline is driven by two pulsers operating at ±10 kV, providing a voltage between the electrodes of 20 kV. A complete kicker is made up of 22 such units.

Kicker Systems

- There is a continuing R&D program to develop a pulser that meets the specifications for amplitude, rise and fall time, repetition rate, and stability.
- Several technologies look promising, including:
  - **fast ionization dynistor (FID);**
  - **drift step recovery diode (DSRD);**
  - **"inductive adder" (MOSFET).**
- There is a commercial FID device available that comes close to meeting the specifications. Costs for the RDR have been based on the price of this device.

Tests of FID Pulser at KEK-ATF





Magnets

The "main" magnets in the lattice (dipoles, quadrupoles, sextupoles, orbit correctors, skew quadrupoles) are normal-conducting electromagnets, and are unremarkable in terms of size and field strength.

Magnet type	Length	Pole-tip radius	Max. pole-tip field
Dipole	6 m	30 mm	0.16 T
Quadrupole	300 mm	30 mm	0.47 T
Sextupole	250 mm	30 mm	0.0072 T

Outline designs, sufficient to allow costing and specification of power requirements etc. have been produced.

Main issues are:

- **field quality (impacts dynamic aperture);**
- **stability (impacts beam jitter);**
- **power: designs must be optimized for low current.**

Magnets

- Dipoles will be powered on "strings", from power supplies located in the two large caverns.
  - **Large cables (23 mm Ø) are required to provide the necessary current (320 A) with minimal power losses.**
- Individual control of field strength in quadrupoles and sextupoles is a necessity, for flexibility of optics, tuning, and beam-based alignment. Options for power distribution are:
  - **"Cable-based" system: Individual cables from power supplies (in large caverns) to each magnet. Total cable length over 5,000 km for two rings.**
  - **"Bus-based" system: Water-cooled bus providing power to local DC-DC converters at each magnet. (As used, for example, at CESR).**

Magnets: Cable-Based System Power

- Power requirements per ring (in kW):

Magnet type	Magnet power	Cable power loss	PS power loss
Dipole	1,394	43	215
Quadrupole	185	163	6
Sextupole	2	15	0.02
Orbit corrector	44	19	0.06
Skew quadrupole	12	13	0.02

- Totals per ring (in kW):

Power to cooling water	Power to tunnel air	Power to cavern air
1,637	253	221.1

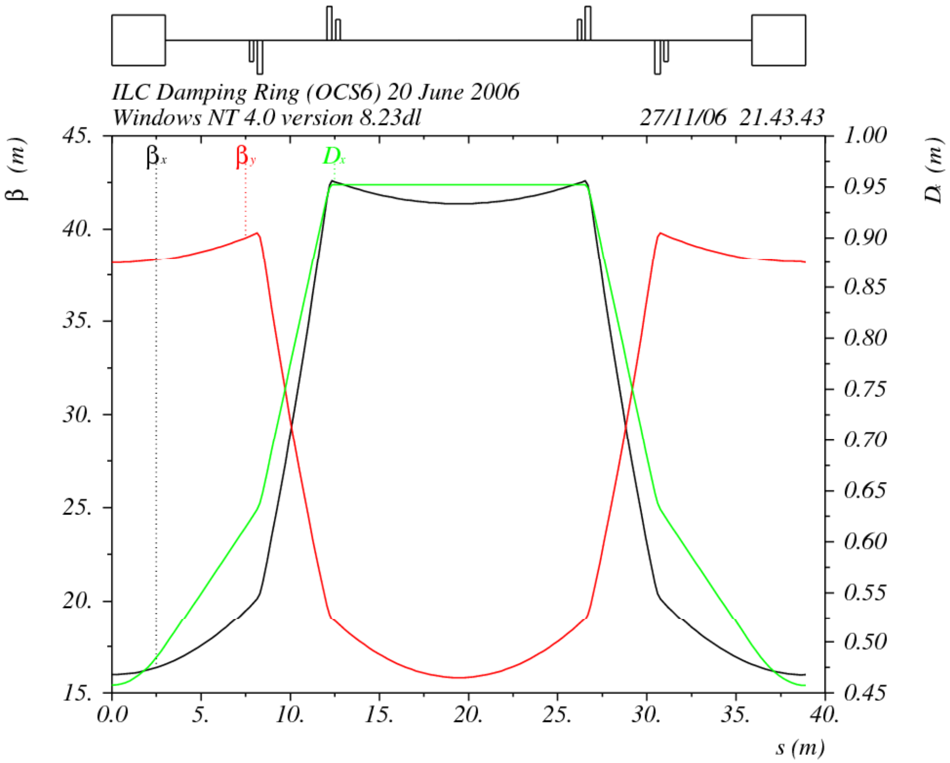
38 W/m

Magnets: Bus-Based System Power

- The cable-based system will dump around 76 W/m of heat to the air in the tunnel. It is considered highly desirable to reduce this as far as possible, to ease the requirements on cooling and temperature regulation.
- A power distribution system using a water-cooled bus provides an alternative:
  - **total volume of copper and power losses will be roughly the same as in the cable-based system, however…**
  - **…heat losses will be mostly dumped to water, rather than to the air in the tunnel;**
  - **specification and costing of the bus-based system is in progress.**

Magnet Support Stands

- Alignment and stability of magnets will be a critical issue for achieving and maintaining 2 pm vertical emittance, and for minimizing beam jitter.
- The concept for support stands, used for costing, involves:
  - **single stand supporting two quadrupoles (one directly above the other);**
  - **single stand supporting two quadrupole/sextupole pairs (one pair directly above the other).**
- There are other possible approaches: designs will be developed in conjunction with (very high priority) R&D into low-emittance tuning.

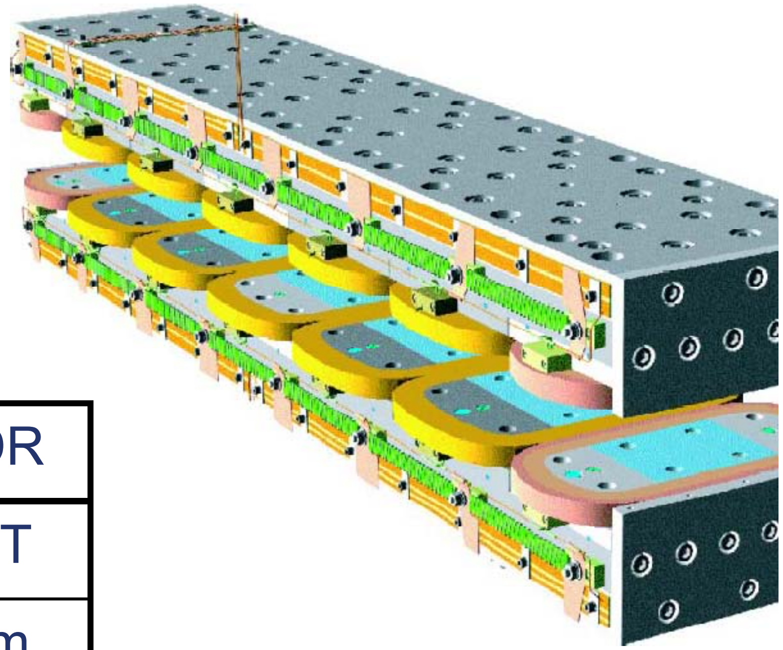


Wigglers

- Each damping ring requires 200 m of wiggler with peak field of approximately 1.6 T, to achieve damping times less than 25 ms.
- Options considered for the wiggler technology were:
  - **permanent magnet;**
  - **normal-conducting electromagnet;**
  - **superconducting.**
- Based on a range of considerations, including radiation resistance, physical aperture, field quality, construction costs and operating costs, the decision was made to specify a superconducting wiggler in the baseline configuration.
- The CESR-c superconducting wigglers provide a good prototype: good aperture, very good field quality and proven performance.

CESR-c and ILC Wigglers

Parameters of CESR-c and ILC DR wigglers are sufficiently close to allow reliable costing. Some optimisation for the ILC is possible.

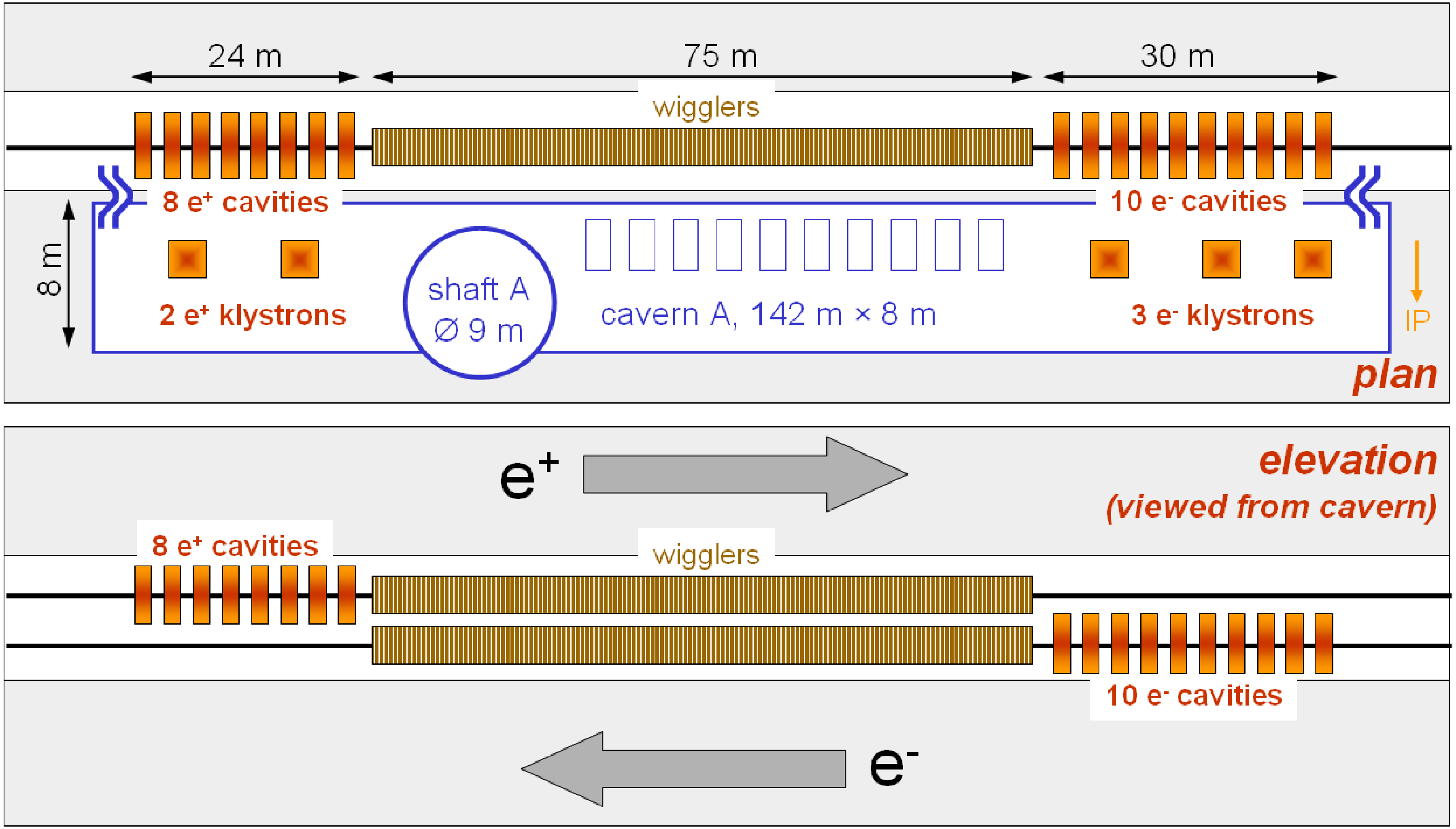


	CESR-c	ILC DR
Peak field	2.1 T	1.67 T
Period	40 cm	40 cm
Length	1.3 m	2.5 m
Vertical aperture	5 cm	5 cm
Pole width	23.8 cm	20 cm

RF System

- The original choice for the RF frequency was 500 MHz: such an RF system would be, in may respects, "standard".
- The frequency was changed (in March 2006) to 650 MHz, for reasons including the improvement of phase-locking to the main linac.
- Design work is needed for 650 MHz, HOM-damped superconducting cavities.
- An industrial source has expressed willingness to develop and supply klystrons with appropriate parameters.
- System parameters are based on scaling from 500 MHz model.
- Costs include:
  - **RF cavities/cryomodules;**
  - **klystrons;**
  - **modulators;**
  - **waveguide;**
  - **low-power electronics.**

Schematic Layout: Straight "A"



Cavities are always upstream of wiggler

RF System Estimated Parameters

Frequency	650 MHz	
Active cavity length	0.23 m	
R/Q	89 Ω	
Operating temperature	4.5 K	
Standby losses at 4.5 K	30 W	
No of operating SC modules per ring	18	14
Accelerating gradient	5.8 MV/m	7.5 MV/m
Accelerating voltage	1.33 MV	1.72 MV
Q_0 at operating gradient	0.6 x 10^9	0.6 x 10^9
Cryo-RF-losses per cavity	33 W	50 W
Total cryo-losses per straight	1130 W	1120 W
Beam power per cavity	194 kW	250 kW
Number of klystrons per ring	5	4
Klystron output RF power	780 kW	1000 kW

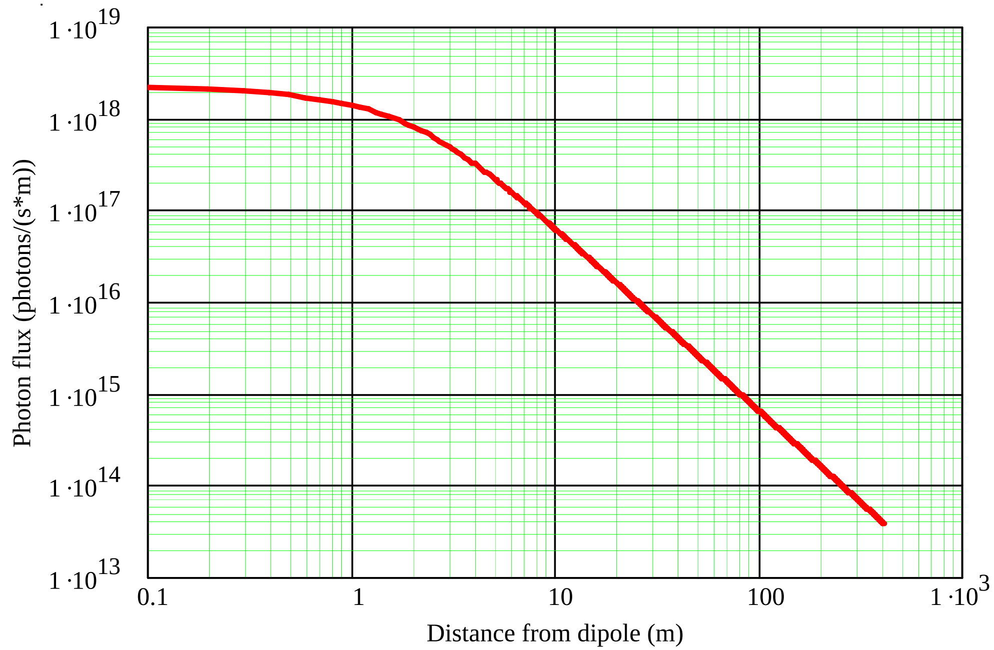
all RF stations operational ↑ ↑ one RF station off-line

Vacuum System

- Vacuum requirements in the electron damping ring are driven by the need to avoid ion effects.
  - **Fill structure will include many gaps for ion clearing; but a low pressure (< 1 ntorr in the arcs and < 0.1 ntorr in the straights) will still be needed to avoid fast ion instability (FII).**
  - **There is still some uncertainty in the impact of FII.**
- In the positron damping ring, electron cloud effects are a major concern for the vacuum system.
- Issues for the apertures include beam acceptance, magnet designs, diagnostics (particularly BPMs), wake fields.
- Options for the vacuum system have been considered:
  - **choice of chamber material (stainless steel, aluminium…);**
  - **whether or not to use an antechamber;**
  - **type and location of pumps;**
  - **use of NEG coating for pumping, and reducing SEY.**
- Various methods for suppressing e-cloud are under study.

Vacuum System

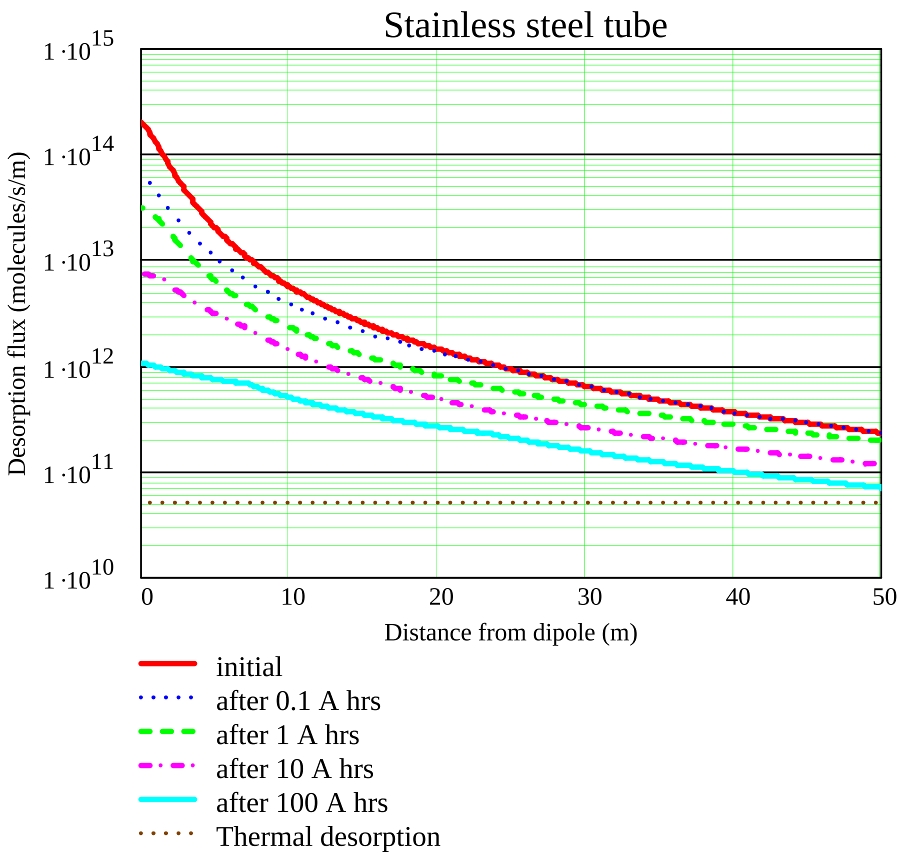
Estimates of the performance of the vacuum system with various design options have been made for different sections of the rings (arcs, straights, wiggler), including the effects of photon-stimulated desorption, thermal desorption, and conditioning.

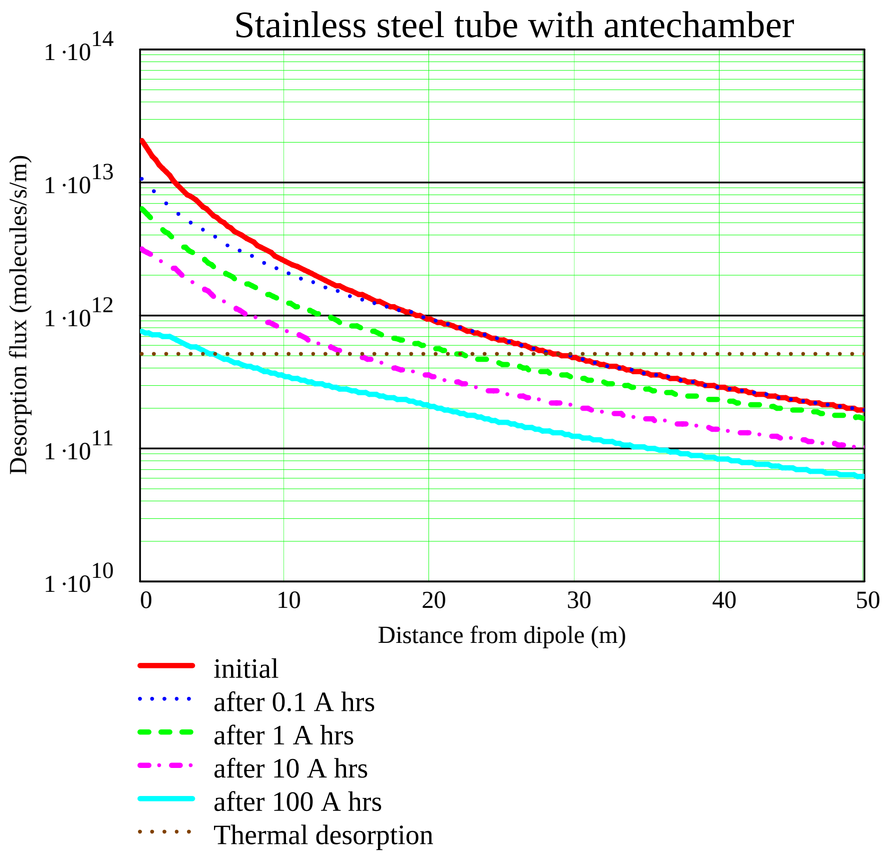


Photon flux downstream of a dipole in an arc section. The critical photon energy is 2.4 keV.

Vacuum System: Arcs & Straights

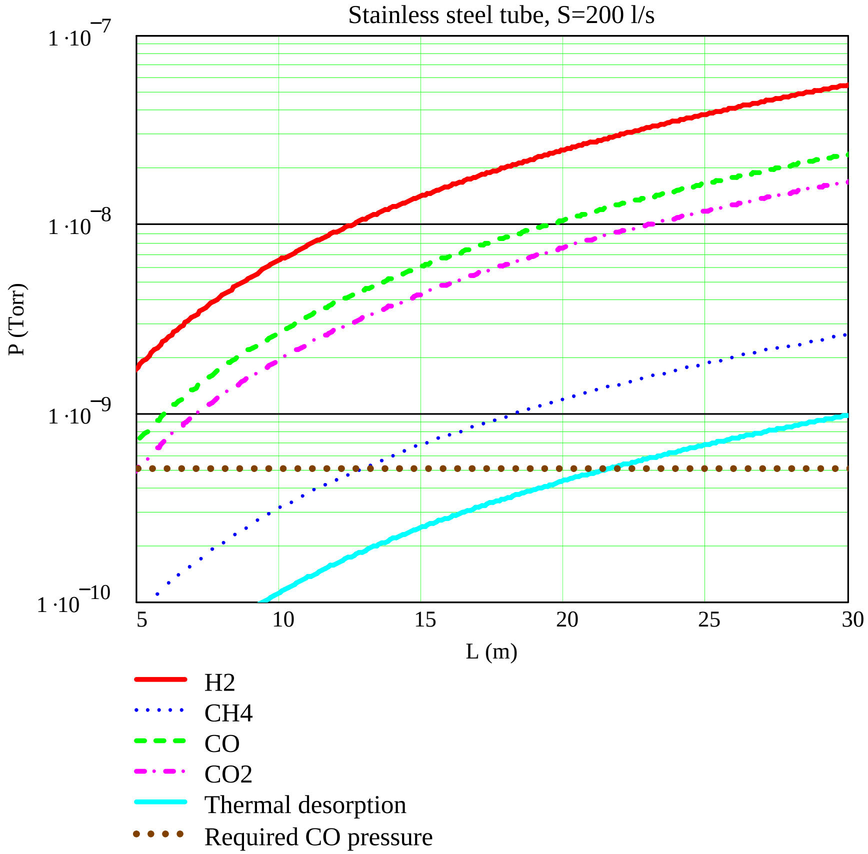
Antechamber provides little reduction in desorption flux (after conditioning of chamber surface).

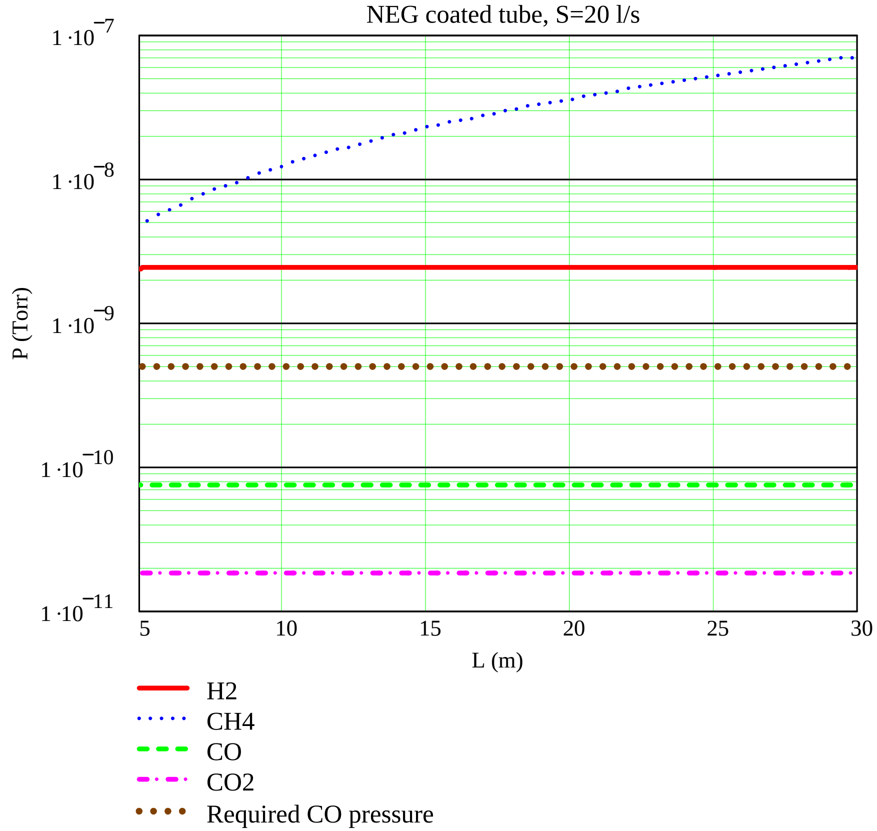




Vacuum System: Arcs & Straights

NEG coating provides significantly lower vacuum pressure, after conditioning and activation.



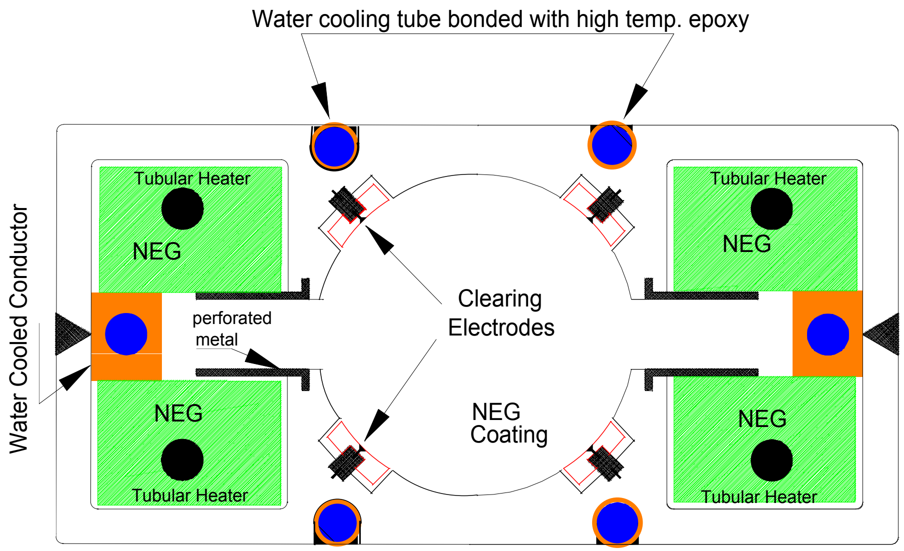


Vacuum System: Arcs & Straights

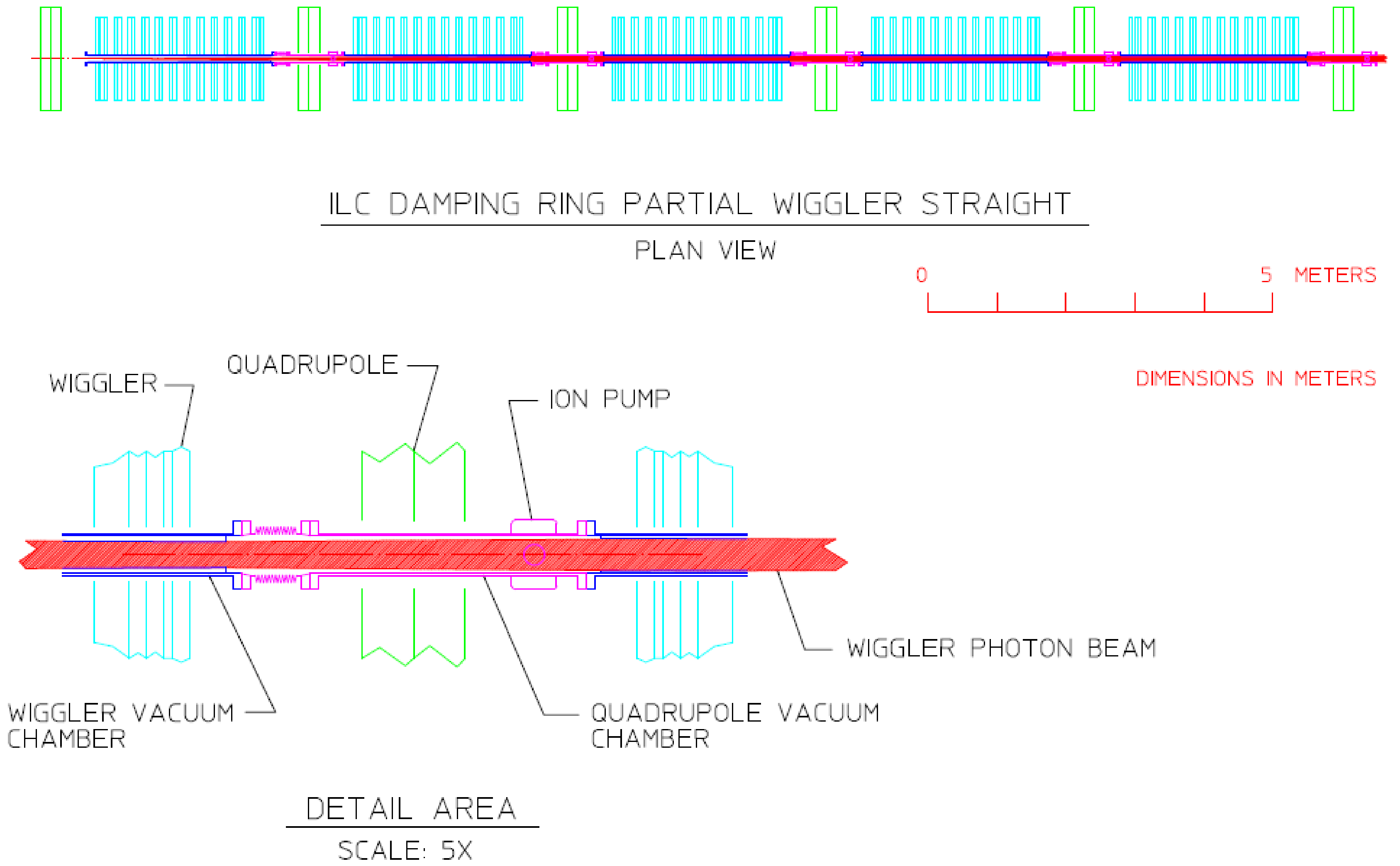
- The vacuum system specified for the arcs and the straights consists of:
  - **extruded aluminium tube, without antechamber;**
  - **NEG coating;**
  - **in-situ bake-out (for activation of NEG);**
  - **ion pumps (20 l/s), one per arc cell (~ 40 m), and every 20 m in the long straights.**
- Estimated costs include NEG licence and coating rig, chambers, pumping chambers, pumps, controllers, gauges, valves, flanges, bellows, etc.
- Extensive use of NEG coating makes the system very inexpensive.

Vacuum System: Wigglers

- The wigglers in each ring generate 3.4 MW of synchrotron radiation power, compared to 200 kW generated by the dipoles.
- Safe handling of the radiation from the wigglers is an important issue, and presents technical challenges.
- Present vacuum chamber concept uses an antechamber, with water-cooled copper absorbers, and vanes of NEG to provide distributed pumping.

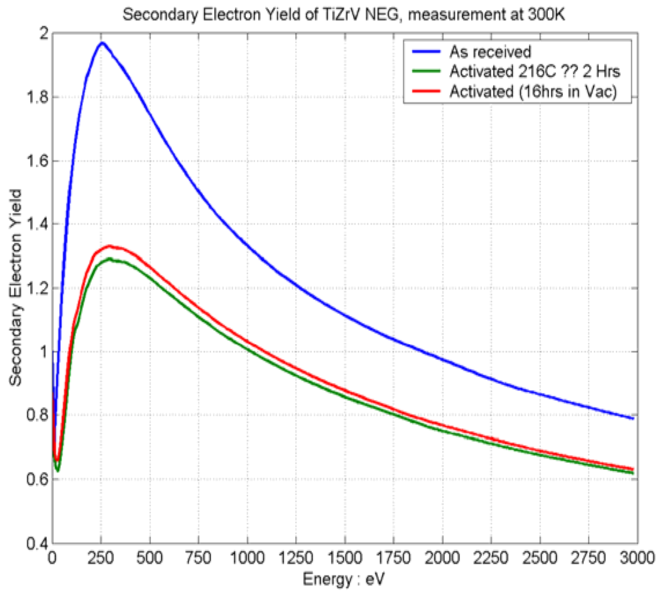


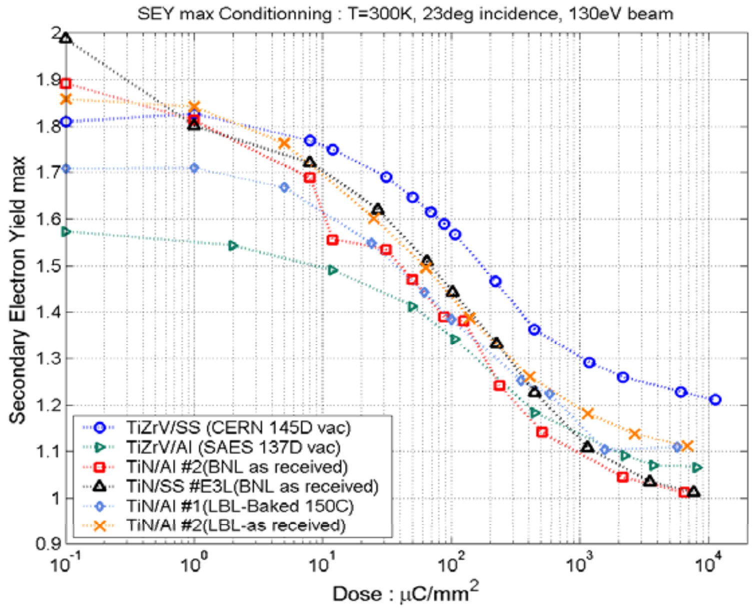
Vacuum System: Wigglers



Vacuum System: Electron Cloud

- Electron cloud could drive instabilities in the positron beam, if allowed to develop to a sufficiently high level.
- Coating with NEG may be sufficient to suppress build-up of electron cloud in the field-free regions (by reducing peak SEY < 1.2); solenoids may also be helpful in these regions.

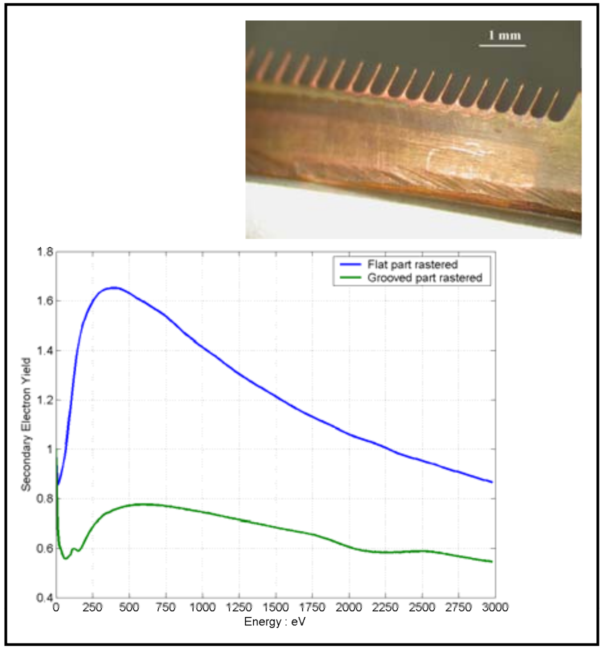


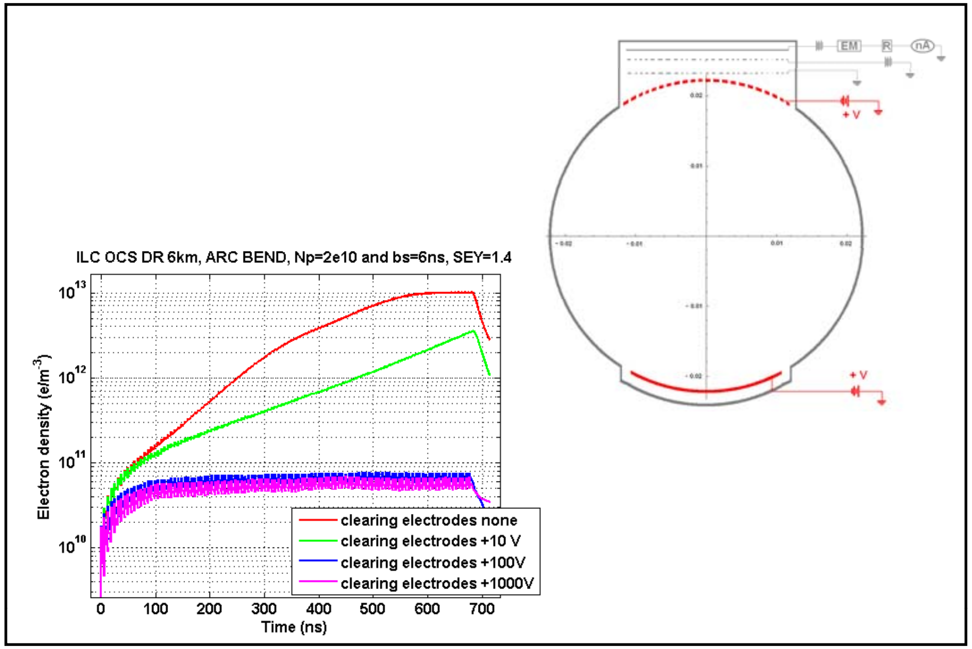


- Suppressing the build-up of electron cloud in the dipoles and wiggler could be more challenging.

Vacuum System: Electron Cloud

- Techniques being explored for suppressing electron cloud in the dipoles and wiggler include:
  - **grooved surfaces for the vacuum chamber;**
  - **clearing electrodes.**
- These techniques look promising, and studies are planned to verify their effectiveness under operational conditions.





Instrumentation and Diagnostics

Present specifications include the following instrumentation and diagnostics:

- **747 BPMs; turn-by-turn capability, resolution ~ few μm;**
- **laser wire for beam size (emittance) measurements; emittance resolution < 1 pm;**
- **synchrotron light monitors, for fast beam-size measurements, including damping rates;**
- **fast feedback systems, for damping instabilities with growth times of order 20 turns;**
- **streak camera;**
- **bunch-by-bunch current monitors;**
- **tune monitors;**
- **beam loss monitors;**
- **fast orbit feedback.**

R&D Issues

- The RDB S3 group has reviewed 76 R&D objectives for the damping rings, and identified 11 as "Very High Priority". These fall in the categories of:
  - **injection/extraction kickers;**
  - **lattice design (for good dynamic aperture);**
  - **tuning and maintaining low vertical emittance;**
  - **electron cloud and ion effects;**
  - **impedance and impedance-driven instabilities.**
- Development of a detailed R&D plan is in progress, detailing objectives, resources, milestones and timescales.
  - **So far, draft work packages have been produced for the electron cloud studies, and for studies of impedance and impedance-driven instabilities.**
- The R&D program at present test facilities (notably, KEK-ATF) could be strengthened by future test facilities (e.g. CESR-ta and HERA-DR).
- With over 25 institutions and 150 people interested or already involved, coordination of R&D efforts is a significant issue.

Summary

- The present baseline configuration has evolved from detailed studies of beam dynamics and performance of technical subsystems, considering a wide range of configuration options.
- As a detailed understanding of the costs has developed, changes to the configuration have been made after careful consideration of the impact on the costs and the technical performance.
- The RDR configuration represents the outline of what we believe will be a technically feasible design.
- Exploration of different options will continue in parallel with R&D and design work, to optimise cost and performance.

Acknowledgements

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ANL	FID	LLNL
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Efremov Inst.	LBNL	U. Illinois UC
		YerPhI