Brief History of e+e- Circular Colliders
Emphasizing Future Applications

John Seeman,
SLAC
IAS Workshop HKIST
January 2015
# List of e+e- Colliders

<table>
<thead>
<tr>
<th>Collider</th>
<th>Laboratory</th>
<th>Date start-end</th>
<th>Circumf. (type)</th>
<th>Beams</th>
<th>$E$ [GeV]</th>
<th>Luminosity $[10^{30} \text{ cm}^{-2} \text{s}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADA</td>
<td>Frascati, Italy</td>
<td>1961-1964</td>
<td>3 (SR)</td>
<td>$e^-/e^+$</td>
<td>0.25</td>
<td>Measured</td>
</tr>
<tr>
<td>VEP-1</td>
<td>BINP, Russia</td>
<td>1962-1967</td>
<td>2.7 (DR)</td>
<td>$e^-/e^-$</td>
<td>0.13</td>
<td>0.003</td>
</tr>
<tr>
<td>CBX</td>
<td>Stanford, USA</td>
<td>1963-1967</td>
<td>12 (DR)</td>
<td>$e^-/e^-$</td>
<td>0.5</td>
<td>0.0017</td>
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<tr>
<td>VEPP-2</td>
<td>BINP, Russia</td>
<td>1967-1970</td>
<td>11.5 (SR)</td>
<td>$e^-/e^-$</td>
<td>0.13</td>
<td>0.02</td>
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<tr>
<td>ACO</td>
<td>Orsay, France</td>
<td>1967-1972</td>
<td>22 (SR)</td>
<td>$e^-/e^+$</td>
<td>0.5</td>
<td>0.1</td>
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<tr>
<td>VEPP-2M</td>
<td>BINP, Russia</td>
<td>1974-2000</td>
<td>17.8 (SR)</td>
<td>$e^-/e^+$</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>ADONE</td>
<td>Frascati, Italy</td>
<td>1969-1993</td>
<td>105 (SR)</td>
<td>$e^-/e^+$</td>
<td>1.5</td>
<td>0.6</td>
</tr>
<tr>
<td>CEA Bypass</td>
<td>Cambridge, USA</td>
<td>1971-1974</td>
<td>225 (SR)</td>
<td>$e^-/e^+$</td>
<td>3.0</td>
<td>10</td>
</tr>
<tr>
<td>SPEAR</td>
<td>SLAC, USA</td>
<td>1972-1988</td>
<td>234 (SR)</td>
<td>$e^-/e^+$</td>
<td>2.5</td>
<td>12</td>
</tr>
<tr>
<td>DORIS</td>
<td>DESY, Germany</td>
<td>1973-1993</td>
<td>288 (DR,SR)</td>
<td>$e^-/e^+$</td>
<td>6.0</td>
<td>33</td>
</tr>
<tr>
<td>DCI</td>
<td>Orsay, France</td>
<td>1977-1984</td>
<td>95 (DR)</td>
<td>$e^-/e^+$</td>
<td>1.8</td>
<td>1.4</td>
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<tr>
<td>PETRA</td>
<td>DESY, Germany</td>
<td>1978-1986</td>
<td>2304 (SR)</td>
<td>$e^-/e^+$</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>CESR</td>
<td>Cornell, USA</td>
<td>1979-2008</td>
<td>768 (SR)</td>
<td>$e^-/e^+$</td>
<td>6.0</td>
<td>1100</td>
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<tr>
<td>VEPP-4</td>
<td>BINP, Russia</td>
<td>1979-present</td>
<td>366 (SR)</td>
<td>$e^-/e^+$</td>
<td>7.0</td>
<td>50</td>
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<tr>
<td>PEP</td>
<td>SLAC, USA</td>
<td>1980-1988</td>
<td>2200 (SR)</td>
<td>$e^-/e^+$</td>
<td>15</td>
<td>59</td>
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</table>
### List of e+e- Colliders (cont)

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<th>Luminosity $[10^{30} \text{ cm}^{-2}\text{s}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tristan</td>
<td>KEK, Japan</td>
<td>1986-1995</td>
<td>3016 (SR)</td>
<td>$e^-/e^+$</td>
<td>32</td>
<td>140</td>
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<tr>
<td>SLC</td>
<td>SLAC, USA</td>
<td>1989-1998</td>
<td>4000 (linear)</td>
<td>$e^-/e^+$</td>
<td>49</td>
<td>2.8</td>
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<tr>
<td>BEPC</td>
<td>IHEP, China</td>
<td>1989-2004</td>
<td>240 (SR)</td>
<td>$e^-/e^+$</td>
<td>2.8</td>
<td>8</td>
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<tr>
<td>LEP</td>
<td>CERN, Switzerland</td>
<td>1989-2000</td>
<td>26659 (SR)</td>
<td>$e^-/e^+$</td>
<td>104</td>
<td>100</td>
</tr>
<tr>
<td>DAFNE</td>
<td>Frascati, Italy</td>
<td>1998-present</td>
<td>98 (DR)</td>
<td>$e^-/e^+$</td>
<td>0.7</td>
<td>453</td>
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<tr>
<td>PEP-II</td>
<td>SLAC, USA</td>
<td>1998-2008</td>
<td>2200 (DR)</td>
<td>$e^-/e^+$</td>
<td>3.1x9.0</td>
<td>12069</td>
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<tr>
<td>KEKB</td>
<td>KEK, Japan</td>
<td>1999-2009</td>
<td>3016 (DR)</td>
<td>$e^-/e^+$</td>
<td>3.5x8.0</td>
<td>21083</td>
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<tr>
<td>BEPC-II</td>
<td>IHEP, China</td>
<td>2008-present</td>
<td>240 (DR)</td>
<td>$e^-/e^+$</td>
<td>2.1</td>
<td>293</td>
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<td>VEPP-2000</td>
<td>BINP, Russia</td>
<td>2006-present</td>
<td>24.4 (SR)</td>
<td>$e^-/e^+$</td>
<td>1.0</td>
<td>100</td>
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</tbody>
</table>

→ **SuperKEKB**  KEK, Japan  7x 4 GeV Spring 2015!
Circular Electron Positron Collider Family

$L \text{ (cm}^{-2} \text{ s}^{-1})$

$E \text{ (GeV)}$

C. Biscari
Luminosity Scaling with Beam Energy (M. Zanetti)
Earliest Colliders (Early 1960’s)

ADA e+e- Frascati
(Touschek scattering discovered)

CBX e-e- Stanford
(Stored 1 Amp/per beam, beam-beam tune shift observed)
Low energy colliders (1970s)

ADONE Frascati
(Longitudinal feedback, adjustable damping partitions)

ACO Orsay
(Ring based FEL studies)
Intermediate Energy Colliders (1980s)

PEP, SLAC
(Three bunches per beam, Mitigations for head-tail microwave instability)

PETRA, DESY
(Seven cell RF cavities, Positron pre-damping ring)
Phi-Tau-Charm Colliders

- **SPEAR** (Flexible Lattice)
- **DAFNE** (Crab waist)
- **VEPP-2000** (Round beams)
- **BEPC-I&II** (SC RF)
Asymmetric Energy B Factories (1998-2010)

PEP-II, SLAC
(1722 bunches,
3 Amps stored,
Top-up injection,
bunch feedback)

KEKB, KEK
(Low emit lattice,
record luminosity,
ARES RF cavities,
Crab cavities)
Z Colliders

Table 2: LEP Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design (55 / 85 GeV)</th>
<th>Achieved (45 / 95 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch current</td>
<td>0.75 mA</td>
<td>1.00 mA</td>
</tr>
<tr>
<td>Total beam current</td>
<td>6.0 mA</td>
<td>8.4 / 6.2 mA</td>
</tr>
<tr>
<td>Vertical beam-beam parameter</td>
<td>0.03</td>
<td>0.045 / 0.043</td>
</tr>
<tr>
<td>Emittance ratio</td>
<td>4.0 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Maximum luminosity</td>
<td>$16 / 27 \times 10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>$23 / 100 \times 10^{30}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>IP beta function $b_x$</td>
<td>1.75 m</td>
<td>1.26 m</td>
</tr>
<tr>
<td>IP beta function $b_y$</td>
<td>7.0 cm</td>
<td>4.0 cm</td>
</tr>
</tbody>
</table>

LEP, CERN
(high beam energy 104 GeV
Pretzel orbit, concrete dipoles)

SLC, SLAC
(First linear collider,
BNS damping, e- polarization at IP)
SuperKEKB nearing completion

(nano-beam emittances, mm level IP vert betas)
Future New e+e- Colliders (Higgs, Top)

FCCee

CEPC

A hypothetical location of the CEPC ring on the Qinghuangdao area
How to get more luminosity?

Luminosity equation

\[ L = 2.17 \times 10^{34} \frac{n \xi_y E I_b}{\beta_y^*} \]

Parameters:

- \( \xi_y \): Vertical beam-beam parameter
- \( I_b \): Bunch current (A)
- \( n \): Number of bunches
- \( \beta_y^* \): IP vertical beta (cm)
- \( E \): Beam energy (GeV)

Answer:

- Increase \( I_b \)
- Decrease \( \beta_y^* \)
- Increase \( \xi_y \)
- Increase \( n \)
General Observations e+e- Colliders (1)

**Lattices:**
- x-y chromatic coupling in the IR is important: \(\rightarrow\) skew sextupoles.
- Sextupole and skew quadrupole coupling corrections in IR
- More studies of IR error tolerances needed.

**Instabilities:**
- More work on e-cloud to allow more bunches.

**Beam-Beam Calculations:**
- Need more studies of non-linear beam dynamics.
- Parasitic crossing studies

**Beam lifetimes:**
- Short beam lifetimes expected in the next collider (\(~10\) minutes) with continuous top-off needed.
Tunes:

For best collisions: \(v_x = \sim 0.505, \ v_y = 0.512-0.518\),

Crab cavities:

Crab cavities tilt bunches as expected at IP. 
Expected luminosity gains not, so far, fully achieved. 
Must include dynamic beta effects with respect to ring apertures. 
Crab cavity trip rates need some additional study.

Large Piwinski Angle:

Works in a collider. 
Allows \(v_x > 0.505\)

Crab waist:

Crab waist can potentially improve the luminosity. 
Effects of crab sextupoles on dynamic aperture needs work.

Round beams:

Initial beam tests look promising. 
Additional tolerance studies are needed.
Interaction Point Design

Key issues: 1 mm to 300 micron scale $\beta y^*$, large betas in IR quadrupoles, quadrupoles inside the detector, collision feedback, vacuum chamber design, magnet tolerances, alignment and jitter tolerances, crab cavities, crab waist

Test accelerators/facilities: SuperKEKB, CESR-TA, PETRA-3, vibration stabilization facility

Technologies:

100+ Hz IP dither feedback on luminosity
Superconducting magnets
Permanent magnets
Power supply stability
Vibration control
Non-linear optics
Superconducting quadrupoles
In the interaction region
Two beam passages
Need to shield stray fields.

Magnet inner radius=22 mm,
Outer radius=27.86 mm
Magnet current=1622 A
Field gradient=80.63 T/m
Machine Detector Interface

Key issue: Synchrotron radiation backgrounds, lost particle backgrounds, SR heating of vacuum chambers, radiation damage/lifetime of detectors, sensor occupancy, luminosity measurement.

Test accelerators/facilities: SuperKEKB, LHC, lab tests of high power vacuum chambers, lab tests of detector lifetime

Technologies:
- IP vacuum pumping
- Advanced masking
- Rapid luminosity feedback
- Detector design
IP Vertex Be Chamber Bellows Cooling (PEP-II, 5 Amps)
SuperKEKB Fast Dither Feedback (Wienands, Funakoshi)
Low Emittances

Key issue: Component tolerances, vibration control, emittance measuring hardware, active feedbacks, field nonlinearities.

Test accelerators/facilities: SuperKEKB, PETRA-3, CESR-TA, NSLS-II, lab tests of x-ray size monitors

Technologies:

- 300 to 1 emittance tuning techniques
- Coherent Synchrotron Radiation CSR simulations and measurements
- Fast Ion Instability FII simulations and measurements
- Intra-Beam Scattering IBS simulations and measurements
- Electron Cloud Instability ECI simulations and measurements
- Effects of spin rotators.
- Effects of beam-beam interaction on spin
Comparison of Emittances of Colliders

Future colliders

Existing colliders

LEP3

K_\varepsilon=100

K_\varepsilon=500

Vertical Emittance [pm]

Horizontal Emittance [nm]

Courtesy of F. Zimmermann, H. Burkhardt and Q. Qin
### Vertical rms IP spot sizes in nm

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEP2</strong></td>
<td>3500</td>
</tr>
<tr>
<td><strong>KEKB</strong></td>
<td>940</td>
</tr>
<tr>
<td><strong>SLC</strong></td>
<td>500</td>
</tr>
<tr>
<td><strong>FCC</strong></td>
<td>250</td>
</tr>
<tr>
<td><strong>CEPC</strong></td>
<td>150</td>
</tr>
<tr>
<td><strong>ATF2, FFTB</strong></td>
<td>73 (35), 77</td>
</tr>
<tr>
<td><strong>SuperKEKB</strong></td>
<td>50</td>
</tr>
<tr>
<td><strong>ILC</strong></td>
<td>5 – 8</td>
</tr>
<tr>
<td><strong>CLIC</strong></td>
<td>1 – 2</td>
</tr>
</tbody>
</table>

$\beta_y^* :$

5 cm $\rightarrow$ 1 mm

F. Zimmermann
Lattice and Dynamic Aperture Calculations

Figure 4.2.3: The beta functions and dispersion function of a short straight section in the CEPC ring.

Figure 4.2.4: The dynamic aperture of the CEPC ring.

Chao, Cai)
SuperB LER FF optics

- Similar layout as in HER except that matching section is shorter to provide space for spin rotator optics.

(Cai, Ramondi, Biagini)
Ohmi, Cai, et al. showed that the linear chromaticity of x-y coupling parameters at IP could degrade the luminosity, if the residual values, which depend on machine errors, are large.

To control the chromaticity, skew sextupole magnets were installed during winter shutdown 2009.

The skew sextupoles are very effective to increase the luminosity at KEKB.

The gain of the luminosity by these magnets is ~15%.
Crab Cavities in KEKB at 2 x 11 mrad crossing

From simulation BB Parameter increases 0.06 → 0.15

(Funakoshi)

(Ohmi)
Crabbed Waist Scheme

Sextupole

\[ K = \frac{1}{2\theta} \frac{1}{\beta_y^* \beta_y} \sqrt{\beta_x^*} \]

\[ \Delta \mu_y = \frac{\pi}{2} \]

\[ \Delta \mu_x = \pi \]

Equivalent Hamiltonian

\[ H = H_0 + \frac{1}{2\theta} xp_y^2 \]

\[ \beta_y = \beta_y^* + \frac{(s - x/\theta)^2}{\beta_y^*} \]

(Anti)sextupole

\[ \beta_x^*, \beta_y^* \]

IP

\[ \beta_x, \beta_y \]
DAFNE Crab Waist:

1. Small emittance $\varepsilon_x$

2. Large Piwinski angle $\Phi >> 1$

3. Larger crossing angle $\theta$

4. Longer bunch length $\sigma_z$

5. Strong nonlinear elements (sextupoles)

(Zobov)
How the crabbed waist works

Crab sextupoles OFF: Waist line is orthogonal to the axis of the beam

Crab sextupoles ON: Waist moves parallel to the axis of other beam: maximum particle density in the overlap between bunches

All particles in both beams collide in the minimum $\beta_y$ region, with a net luminosity gain

Plots by E. Paoloni
**Frascati: DAFNE: Large Piwinski angle and crab waist**

DAFNE will run for luminosity for at least the next two to three years.

**Luminosity** [10^{28} cm^{-2} s^{-1}]

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Value</strong></th>
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</thead>
<tbody>
<tr>
<td>Energy per beam</td>
<td>510 [MeV]</td>
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<tr>
<td>Machine length</td>
<td>97 [m]</td>
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<tr>
<td>Max. beam current (KLOE run)</td>
<td>2.5(e-)1.4(e+) [A]</td>
</tr>
<tr>
<td>N of colliding bunches</td>
<td>100</td>
</tr>
<tr>
<td>RF frequency</td>
<td>368.67 [MHz]</td>
</tr>
<tr>
<td>RF voltage</td>
<td>200[kV]</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>120</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>2.7[ns]</td>
</tr>
<tr>
<td>Max. ach. Luminosity (SIDDHARTA run)</td>
<td>4.5 \cdot 10^{32} [cm^{-2}s^{-1}]</td>
</tr>
</tbody>
</table>
Dynamic aperture studies with crab waist (SuperB studies)

Piminov, Chancé

Comparison (Piminov) codes and few discrepancies (MADX more realistic model) → corrected, now in agreement

Found that, as expected, crab-waist sextupoles reduce dynamic aperture between MADX (Chancé) and Acceleraticum.
Luminosity and Beam-Beam Interaction

PEP-II Luminosity versus \( N^+ \times N^- \)
**IHEP: BEPC-II: Crossing angle and new sextupole families**

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.89 GeV</td>
<td>$\nu_s$</td>
<td>0.034</td>
</tr>
<tr>
<td>Beam Current</td>
<td>910 mA</td>
<td>$\alpha_p$</td>
<td>0.024</td>
</tr>
<tr>
<td>Bunch Current</td>
<td>9.8 mA</td>
<td>$\sigma_{x0}$</td>
<td>0.0135 m</td>
</tr>
<tr>
<td>Bunch Number</td>
<td>93</td>
<td>$\sigma_z$</td>
<td>0.015 m</td>
</tr>
<tr>
<td>RF Voltage</td>
<td>1.5 MV</td>
<td>Emittance</td>
<td>144 nmrad</td>
</tr>
<tr>
<td>$\beta_x/\beta_y$</td>
<td>1.0/0.015 m</td>
<td>Coupling</td>
<td>1.5%</td>
</tr>
<tr>
<td>$\nu_x/\nu_y$</td>
<td>6.53/5.58</td>
<td>$\xi_y$</td>
<td>0.04</td>
</tr>
<tr>
<td>Crossing Angle</td>
<td>$2 \times 11$ mrad</td>
<td>$\tau_x/\tau_y/\tau_z$</td>
<td>3.0e4/3.0e4/1.5e4 turns</td>
</tr>
</tbody>
</table>

BEPC-II will run for luminosity for the next ~five years, then look at upgrades.
Simulations: Beam-beam tune plane scan

**CDR, \( \xi_y = 0.17 \)**

**CDR2, \( \xi_y = 0.097 \)**

Crab waist gives better performance.
Synchro-betatron resonances are still present.

\( L \text{ (red)} = 1 \cdot 10^{36} \)
High Current Effects

Key issues: Beam stability, high power RF, high power vacuum components, AC wall efficiency, injector capabilities, I > 1 A.

Test accelerators/facilities: SuperKEKB, CESR-TA

Technologies:
- Better bunch feedbacks
- Electron cloud instability control
- Intra-beam scattering mitigations
- Fast ion instability mitigations
- More efficient klystrons
- High power cavities
- Longitudinal beam feedback
New transverse kicker electrodes (SLAC, KEK)
HOM Absorbing Bellows

HOM tiles

Shield fingers
Three methods used, all in good agreement:

- **Allows** for emittance growth rates estimate and for emittance time evolution estimate
- **6D MonteCarlo** → more accurate, all of above, will include non-gaussian tails

\[ \varepsilon_{x,z} \text{ vs bunch current} \]
RF Systems

KEKB

LEP

ILC

PEP-II
High Beam Power Recipe

Higher currents and shorter bunches lead directly to much higher wake-field effects

- HOM power and CSR

Vacuum chamber impedances must be minimized

- Causes bunch lengthening
- Hard to do a lot better than present B-factories

All components must be water-cooled

- Again, difficult to do much better than present B-factories

SR power levels increase with higher beam currents causing higher total beam losses

- More RF power needed to restore the lost beam energy – more plug power
RF System Overall for FCC/CEPC

An RF system based on about 700 MHz SC cavity technology seems reasonable.

- ongoing R&D at BNL, CERN, ESS for 704 MHz cavities and components
- RF wall-plug to beam efficiency around 55 % (w/o cryogenics)

Open questions and R&D necessary

- fundamental power couplers: R&D ongoing
- HOM damping scheme: study needed
- low level RF & feedback requirements: study needed
- construction and testing cost are an issue.

Butterworth, Jensen, etc
Longitudinally Polarized e- Beam at the Interaction Point

Key issue: Injected polarization, beam lifetime, polarization lifetime, spin rotators, polarization measurements, effect on IP optics, beam-beam effect on polarization.

Technologies:

- Siberian snakes
- Solenoidal rotators
- Beam-beam depolarization diagnostics
- Spin manipulation in the Damping Ring and Linac.
- e- polarized source
Longitudinal Polarization at the Interaction Point with Vertical in the ARCs needing Spin Rotation (SuperB)

90° spin rotation about x axis
• 90° about z followed by 90° about y
“flat” geometry => no vertical emittance growth
Solenoid scales with energy => LER more economical
Solenoids are split & decoupling optics added.

S.r. solenoids (90° spin)
S.r. dipoles (270° spin)
Beam Lifetime

CEPC-FCC:

Lifetime limit due to beam-beam, luminosity (Bhabha), beamstrahlung, Touschek, and vacuum.

\[ \tau_{\text{beam}} \sim 16 \text{ minutes} \]

SuperKEKB: \( \tau \sim 6-10 \text{ minutes!} \)

Required: Full energy and Top-Up Injection.
Top-Up or Continuous Injection In PEP-II

PEP-II: ~5 Hz continuous
KEKB: at ~5-10 min intervals

U. Wienands
"Synchrotron" as a CEPC-FCC Top-Up Injector

Top-up injection = 50 bunch / pulse
Cycle rate = 3 Hz
Injection rate: 1 Hz e+, 1 Hz e-, 1 Hz e- to make e+
Particles per injection: $4 \times 10^9$ / pulse over 50 bunches
with 90% injection efficiency
$\Rightarrow 8 \times 10^7$ / bunch $\Rightarrow$ means low instability effects and RF.
Bunch injection controller: Tailor the charge of each bunch
Magnet laminations same as AC transformers.
Injection kicker pulse length = 183 $\mu$sec (= 53 km)
Kickers = 13 stronger than PEP-II but 7 times slower.
Ring path length = 183 $\mu$sec (53 km)
$\Rightarrow$ Luminosity stays within 0.12% of the peak.

Cornell synchrotron: 768 m
Sine wave-magnet excitation
0.2 GeV to 12 GeV in 8.3 msec at 60 Hz.
Does not affect CESR storage ring operation just 2 m away.
Conclusions

e+e- colliders have had a spectacular history.

Very mature knowledge base on which to design the next accelerator.

Many new accelerator physics and technology discoveries and solutions were found over the years. We need to continue to pursue new R&D and required technologies to make the next round of colliders viable.

Any new large accelerator should have a bold but achievable energy-physics reach.

Every geographical region should design to world high energy physics goals while making use of local advantages.