Status and prospects of e⁺e⁻ Factories

M.E. Biagini, INFN-LNF & IN2P3-LAL

HEP2017, Venice, July 2017
Luminosity versus center-of-mass energy

past [orange, black, green centre-right], present (2017) [red] and future lepton colliders [blue, purple, green top-left] around the world
Lessons learnt

- **High beam currents possible**
  - Control of trapped HOMs, e-cloud mitigation

- **Crab waist works**
  - Meet sextupoles requirements $\rightarrow$ Dynamic Aperture challenge

- **Top-up injection needed**
  - Reliable injection complex, timing, on-energy injection

- **e-cloud mitigation needed**
  - Solenoids, low SEY pipe material, coating, clearing electrodes, grooves, NEG

- **Bunch-by-bunch Feedbacks work well**
  - Low noise $\rightarrow$ upgrade

- **Backgrounds increase with $I_{beam}$ and $L$**
  - Masking, shielding, beamstrahlung control

- **Emittance tuning needed to achieve low**
  - Errors minimization, fast online procedures for orbit/beta/dispersion/coupling correction

- **IP orbit control needed**
  - IP feedback

- **Nano-beams feasible**
  - Vibrations control and alignment for FF quads
The present:
- Low energy colliders: DAΦNE, VEPP2000, BEPC-II
- Medium energy collider: SuperKEKB
DAΦNE (INFN-Frascati)

- Φ-Factory, 510 MeV/beam, record in electron beam current (2.5 A)
- Novel ideas and R&D:
  - *Large Piwinski angle and crab waist sextupoles* scheme
  - e-cloud clearing electrodes
  - Low impedance pipe design
  - Transverse feedback “*cavity kicker*”
  - Upgraded low noise bunch-by-bunch feedbacks
  - Modified wigglers to compensate for high order multipoles
  - Fast kickers R&D
  - Tests on wires for parasitic beam-beam crossings
Beam transverse size measured at the SLM

Luminosity from 2 different monitors

PC wires test

Kicker

Modified wiggler

e-cloud clearing electrodes
BEPCII (IHEP, Beijing)

Collision Mode
- Beam energy range: 1-2.1 GeV
- Optimized beam energy: 1.89 GeV
- Luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Full energy injection: 1-1.89 GeV

SR Mode
- Beam energy: 2.5 GeV
- Beam current: 250 mA

Q. Qin, Valencia 2017
VEPP-2000 (BINP, Novosibirsk)

VEPP-2000 exploits the **Round Beam Concept**

The X-Y symmetry of both beam-beam force and IP-to-IP transfer matrix introduces partial integrability of motion and results in luminosity increase

<table>
<thead>
<tr>
<th>Design parameters @ 1 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
</tr>
<tr>
<td>Number of bunches</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
</tr>
<tr>
<td>Beam energy range</td>
</tr>
<tr>
<td>Design luminosity</td>
</tr>
</tbody>
</table>

Achieved luminosity (CMD-3 data, 10% best runs)

\[ \beta^* \propto \gamma \]
\[ L \propto \gamma! \]
\[ \beta^* = \text{const} \]
\[ L \propto \gamma! \]

2010–2013

6\(\pi\) cross section drop @ NNbar threshold

3(\(\pi^+\pi^-\))

PLB 723 (2013) 82

Courtesy E. Levichev
SuperKEKB (KEK)

SuperKEKB started **Phase I** (no detector, no FF quads, no beams crossing) in **February 2016** (for 5 months), facing and solving quite a few problems.

Preparation for:
- **Phase II** (detector w/o vertex, detuned lattice, $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), **February 2018**
- **Phase III** (Vertex IN, low-beta, $L = 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$), **Fall 2018**

SuperKEKB parameters are state-of-the-art with respect to KEKB and PEP-II, which twenty years ago were already pushing up their design luminosity and beam currents with respect to previous colliders.

A boost in performances is expected by:
- “**large Piwinsky angle**” collision scheme (idea by P. Raimondi, called here “**Nano-beam**”, no crab waist sextupoles)
- major upgrade of the technical systems
- high charge/low emittance RF photo-injector for e⁻
- damping Ring for e⁺
- sophisticated FF layout (quads, solenoid, correcting coils)
# KEKB and SuperKEKB comparison

![Equation](equation.png)

<table>
<thead>
<tr>
<th></th>
<th>KEKB Achieved</th>
<th>SuperKEKB Nano-beam</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{beam}}$ [A]</td>
<td>1.6</td>
<td>3.6</td>
<td>(&gt; 2)</td>
</tr>
<tr>
<td>$\beta_y^*$ [mm]</td>
<td>5.9</td>
<td>0.27</td>
<td>(&lt; 20)</td>
</tr>
<tr>
<td>$\xi_y$</td>
<td>0.09</td>
<td>0.088</td>
<td>~1</td>
</tr>
<tr>
<td>$L$ [cm$^{-2}$s$^{-1}$]</td>
<td>$2.1 \times 10^{34}$</td>
<td>$8.0 \times 10^{35}$</td>
<td>(&gt; 40)</td>
</tr>
</tbody>
</table>

SuperKEKB will be state-of-the-art in 2018
**History of Phase 1 operation**

Red: total beam current  
Purple: vacuum pressure  
Cyan: beam lifetime

HER:
870 mA, 5.7x10^{-8} Pa, ~200 min. (6/17)

LER:
1010 mA, 4.7x10^{-7} Pa, ~60 min. (6/22)
The future:
- Two circular (FCC-ee, CEPC)
- Two “linear” (ILC, CLIC)
Future lepton colliders

**Good for high E**

- **Linear Colliders (energy extendable):**
  - ILC (2x500 GeV) $\rightarrow$ SRF, longer pulse, higher energy efficiency, klystron driven, 1/10 scaled machine done (E-XFEL)
  - CLIC (2 x 1.5 TeV) $\rightarrow$ NRF, High Gradient, 2 beams driven $\rightarrow$ compact

**Good for high L**

- **Circular Colliders (max energy fixed):**
  - FCC-ee (2 x 175 GeV) $\rightarrow$ SRF, higher luminosity efficiency at $<2 \times 175$ GeV, AC power limit/guideline to be mitigated
  - CEPC (2 x 120 GeV) $\rightarrow$ SRF, higher luminosity efficiency at $<2 \times 120$ GeV
Recent changes/staging options

- ILC baseline now 250 GeV c.m.
- CLIC Phase 1 rescaled to 380 GeV, with an option to be fully klystron based
- CEPC now 2 rings, 100 km, FCCee-like
- FCCee injector now 6 GeV linac, CEPC-like
- Remarkably, the cost is now very similar

<table>
<thead>
<tr>
<th></th>
<th>ILC (250 GeV)</th>
<th>CLIC (380 GeV)</th>
<th>CEPC (100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM. Energy</td>
<td>250</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Site Length</td>
<td>~21</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.82</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>AC Power</td>
<td>129</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>Value Cost in TDR</td>
<td>TBD</td>
<td>7.98</td>
<td></td>
</tr>
</tbody>
</table>

FCCee unknown

W. Chou, IAS, HK, 2017
ILC baseline

Physics Detectors

Key Technologies

Nano-beam Technology

SRF Accelerating Technology

Staging option

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Length</td>
<td>31 km</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1.8 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Repetition</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Beam Pulse Period</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Beam Current</td>
<td>5.8 mA</td>
</tr>
<tr>
<td>Beam size (y) at FF</td>
<td>5.9 nm</td>
</tr>
<tr>
<td>SRF Cavity G. $Q_0$</td>
<td>$31.5$ MV/m</td>
</tr>
<tr>
<td></td>
<td>$Q_0 = 1 \times 10^{10}$</td>
</tr>
</tbody>
</table>
ILC staging

- Strong demand for cost reduction
- Improvement of Linac technology under study (however cost reduction 10-15% at most):
  - Higher gradient: 31 MV/m $\rightarrow$ 35 MV/m
  - Higher Q values: $10^{10} \rightarrow 2 \times 10^{10}$
  - Nitrogen infusion developed at FNAL
- Staging is the option: start at 250 GeV c.m.
- Luminosity simply scaled at lower E is low ($0.82 \times 10^{34} \rightarrow$ needs a “real” 250 GeV design!
- Can be doubled by doubling $N_{\text{bunch}}$ (1312 $\rightarrow$ 2625)
- Another factor of 2 for 10Hz collision (5 Hz for collision, 5Hz for e+ production)
- Positron source with undulator not suitable at low E $\rightarrow$ conventional? (but not polarized)
- Debating if 500 GeV or 250 GeV tunnel
New CLIC layout @ 380 GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>380</td>
<td>1500</td>
<td>3000</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>$G$</td>
<td>MV/m</td>
<td>72</td>
<td>72/100</td>
<td>72/100</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>$\mathcal{L}$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.5</td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity above 99% of $\sqrt{s}$</td>
<td>$\mathcal{L}_{0.01}$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>0.9</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>Main tunnel length</td>
<td>km</td>
<td></td>
<td>11.4</td>
<td>29.0</td>
<td>50.1</td>
</tr>
</tbody>
</table>
CLIC staging

- Optimize cost and power consumption
- Produce optimized, staged design: 380 GeV (optimized for H and top) → 1.5 TeV → 3 TeV (exact choice depends on LHC findings)
- Support efforts to develop high-efficiency klystrons
- Consolidate high-gradient structure test results
- Choose new staged parameter sets, with corresponding upgrade path, considering the possibility to have a klystron-powered initial stage
"Middle straight" ∼1.4 km

"90/270 straight" ∼2.8 km

The separation of 3(4) rings is about 12 m: wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.

A more compact layout/optics around the IP is also possible (A. Bogomyagkov).

Beams must cross over through the common RF (@ tt) to enter the IP from inside. Only a half of each ring is filled with bunches.

The separation of 3(4) rings is about 12 m: wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.

A more compact layout/optics around the IP is also possible (A. Bogomyagkov).
Interaction Region design

(@ top energy)

- central Be beam pipe (0.8 mm thick and |s|< 0.9m from IP)
- luminometres
- Ta (or Pb) shieldings
- 5 mm Au coating in the central chamber

warm pipe:
- water cooling (~ 2mm)

The basic arrangement around the IP has been converged through an MDI workshop in Jan. 2017: https://indico.cern.ch/event/596695/

Large Piwinski Angle and Crab Sextupoles scheme implemented

M. Boscolo, FCC-week, Berlin, 2017
Layout changed many times during design! Finally converged on FCC-ee one.
CEPC RF region

- **Common cavities** for Higgs mode, bunches filled in half ring for e+ and e-.
- **Independent cavities** for W & Z mode, bunches filled in full ring.
- The outer diameter of RF cavity is 1.5m. Distance of two ring is 1.0m.
Beam dynamics challenges (circular)

- Dynamic aperture → crab sextupoles and errors, large energy acceptance
- FF Non-Linearities → FF doublet gradient, $\beta_y^*$, $L^*$
- Beam-beam with Space Charge, NL, CW
- Backgrounds shielding, MDI design (also technical)
- Beam lifetime with BB, CW
- Saw-tooth orbit with energy
- e-cloud mitigation (also technical)
- Large crossing angle → coherent bb instability
- Beamsstrahlung + bunch current asymmetry → 3D flip-flop instability
- Low emittance tuning
- Top-up injection → Injection induced oscillations at IP
- ...


<table>
<thead>
<tr>
<th>Effects</th>
<th>Included?</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchrotron motion</td>
<td>Yes</td>
<td>Essential</td>
</tr>
<tr>
<td>Radiation loss in dipoles</td>
<td>Yes</td>
<td>Essential – improves the aperture</td>
</tr>
<tr>
<td>Radiation loss in quadrupoles</td>
<td>Yes</td>
<td>Essential – reduces the aperture esp. at $\bar{t}$</td>
</tr>
<tr>
<td>Radiation fluctuation</td>
<td>after optimization</td>
<td>Essential</td>
</tr>
<tr>
<td>Tapering</td>
<td>Yes</td>
<td>Essential</td>
</tr>
<tr>
<td>Crab waist</td>
<td>Yes</td>
<td>Transverse aperture is reduced by $\sim 20%$</td>
</tr>
<tr>
<td>Maxwellian fringes</td>
<td>Yes</td>
<td>Small</td>
</tr>
<tr>
<td>Kinematical terms</td>
<td>Yes</td>
<td>Small</td>
</tr>
<tr>
<td>Solenoids</td>
<td></td>
<td>Minimal, if locally compensated</td>
</tr>
<tr>
<td>Beam-beam effects for stored beam</td>
<td>Evaluated separately after optimization (D. Zhou)</td>
<td>Affects the lifetime for $\beta_y^* = 1$ mm at $\bar{t}$</td>
</tr>
<tr>
<td>Beam-beam effects for injected beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher order fields / errors / misalignments</td>
<td></td>
<td>Essential, development of correction/tuning scheme is necessary</td>
</tr>
</tbody>
</table>
FF Non-Linearities

- Kinematic terms and FF quads fringe fields introduce NL which affect beam dynamics
- Increase with low-\( \beta \)

K. Ohmi and H. Koiso, IPAC’10 (2010)

\[
J_y \leq \frac{\beta_y^2}{(1 + 2|K|L^3/3)L^*} A(\mu_y)
\]

<table>
<thead>
<tr>
<th>Ring</th>
<th>( \beta_y^* ) (mm)</th>
<th>( K_1 ) (m(^{-2}))</th>
<th>( L^* ) (m)</th>
<th>( J_y/A ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKEKB-HER</td>
<td>0,3</td>
<td>3,05</td>
<td>1,22</td>
<td>0,02</td>
</tr>
<tr>
<td>SKEKB-LER</td>
<td>0,27</td>
<td>5,1</td>
<td>0,76</td>
<td>0,03</td>
</tr>
<tr>
<td>CEPC</td>
<td>1,2</td>
<td>0,176</td>
<td>1,5</td>
<td>0,76</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>1</td>
<td>0,336</td>
<td>2,2</td>
<td>0,22</td>
</tr>
<tr>
<td>KEKB</td>
<td>5,9</td>
<td>1,78</td>
<td>1,76</td>
<td>4,22</td>
</tr>
<tr>
<td>SuperB-HER</td>
<td>0,253</td>
<td>4,6</td>
<td>0,6</td>
<td>0,05</td>
</tr>
<tr>
<td>SuperB-LER</td>
<td>0,21</td>
<td>4,4</td>
<td>0,6</td>
<td>0,036</td>
</tr>
</tbody>
</table>

Should:
- increase \( \beta_y^* \)
- decrease gradient and \( L^* \)
Space charge tune shift

- Linear tune shift
  - Same order for SC and BB
  - But have opposite signs

<table>
<thead>
<tr>
<th></th>
<th>SuperKEKB(^1)</th>
<th>KEKB(^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER(^2)</td>
<td>HER(^3)</td>
</tr>
<tr>
<td>(\varepsilon_x) (nm)</td>
<td>3.2</td>
<td>4.6</td>
</tr>
<tr>
<td>(\varepsilon_y) (pm)</td>
<td>8.64</td>
<td>11.5</td>
</tr>
<tr>
<td>(\xi_x)</td>
<td>0.0028</td>
<td>0.0012</td>
</tr>
<tr>
<td>(\xi_y)</td>
<td>0.0881</td>
<td>0.0807</td>
</tr>
<tr>
<td>(\Delta v_x)</td>
<td>-0.0027</td>
<td>-0.0004</td>
</tr>
<tr>
<td>(\Delta v_y)</td>
<td>-0.0943</td>
<td>-0.0121</td>
</tr>
</tbody>
</table>
Tapering mitigates the sawtooth in FCC-ee

indeed double ring and magnet tapering
remove energy sawtooth due to SR

Comparison:
8 RF w/o tapering
2 RF with tapered dipoles
Coherent bb instability (head-tail mode)

- Discovered by K. Ohmi in strong-strong simulations (BBSS code)
- Reproduced in quasi-strong-strong simulations by D. Shatilov (Lifetrac). Good agreement between 2 codes
- Effect is 2D, due to large Piwinski angle, important for Z running. Main consequences:
  - the bunch crabbing (tilt) oscillates with large amplitudes, comparable to $\theta/2 \rightarrow$ luminosity drops by $20\div40\%$
  - $\varepsilon_x$ increases in $5\div15$ times. Itself, it is not a problem, but betatron coupling leads to $\varepsilon_x$ growth in the same proportion $\rightarrow$ luminosity drops $2\div3$ times

Mitigation:
- decrease $\beta_x$ and double the momentum compaction at low energy, or...
- increase bunch current and decrease $\sigma_z$, but HOM may be a problem

Can be studied at SuperKEKB!

D. Shatilov, K. Ohmi, FCC Week 2017, Berlin
Technology related challenges

- Magnets (warm/cold SC, IR doublets, SC wires)
- Radiation damage on magnets
- Beam pipe & vacuum system (material, coating, low impedance, HOM,...)
- Injectors (high reliability, top-up, full energy booster in same tunnel?)
- Positron source (high number of e\(^+\), polarization?)
- High efficiency klystrons
- High field accelerating sections (X-band, ...)
- SRF cavities (single/multi-cells, cryogenics, 400/650/800 MHz)
- Two beams in same RF cavity
- Beam loading and beam transient in RF cavities
- IP feedback and vibrations \(\rightarrow\) alignment, control
- Energy saving options \(\rightarrow\) minimize costs
- Civil Engineering
- ...

...
Twin Aperture Arc Magnets

- An idea of “twin aperture quadrupole” has been developed by A. Milanese (CERN) to save the power consumption of quadrupole magnets.
- The currents in the magnet are always surrounded by iron to maximize the usage.

Dipole:
- twin aperture yoke
- single bus bars as coils

Quadrupole:
- twin 2-in-1 design

An example of the cross section of a twin aperture dipole and quadrupole for FCC-ee. The separation between two beams is 30 cm.

- The power consumption of the twin aperture quad: 22 MW at 175 GeV with Cu coil = half of single-aperture quads.
- Dipoles are also “twin”: power consumption = 17 MW at 175 GeV with Al bus bar.

A. Milanese, FCC Week 2017, Berlin
400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)
- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)
- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)

400 or 800 MHz multi-cell cavities preferred for ee-ZH, ee-tt and ee-WW
- Baseline options 400 MHz Nb/Cu @4.5 K, 800 MHz bulk Nb system @2K
- R&D: High Q0 cavities, coating, long-term: Nb3Sn like components

O. Brunner, A. Butterworth, R. Calaga
Injector complex issues

- Top-up requires high reliability and resistance to stresses (non stop operation)
- Photo-injector for low emittance/high charge electrons
- Damping Ring (electrons too?)
- Booster at full energy in same tunnel → IPs layout?
- High repetition rate
- Positron source (undulator, conventional, polarized)
- Control of injected beam oscillations at IP
High efficiency klystrons

- Beams require significant RF drive power (CLIC 180 MW, FCC-ee 100 MW, ILC 88 MW)
- An RF source with high efficiency is preferable to minimize the overall power required
- Klystrons with the current state of the art are operating at efficiencies of up to 70%
- Novel bunching methods are being investigated and promise to deliver 90% efficiency:
  - “congregated bunch”, V.A. Kochetova, 1981
- International collaboration on R&D

Excessive electricity bill, M Euro

FCC e+e- at 50 Euro/MWh and 5000 hours/year:

- 10.7 M Euro
- 9.3 M Euro

Efficiency impact on operation cost

I. Syratchev, FCC-ee Week, 2017
ILC civil engineering

A good fraction of costs

- Assembly Place: Surface Building/AH
- Access way to DHL underground
  - only Inclined Access Tunnel (AT)
  - Transport. by special long trailer

- Assembly Place: Underground/DH
- Access way to DH underground
  - mainly Vertical Shaft (VS)
  - Transport. by Gantry Crane

Assembly Yard
DR Yard

Access Tunnel W11m Grad 7%
Access Tunnel W8m Grad 10%

Vertical Shaft Main shaft D18m
Vertical Shaft Utility shaft D10m
Conclusions

- The future of lepton colliders, linear and circular, depends on solving both the pending technological issues and the beam dynamics ones.

- Technology moves fast, and worldwide collaborations already in place will help solving the most "hot" issues in the next 20 years or so → in this case time is a friend!

- The success of B-Factories was also due to the healthy competition between PEP-II and KEKB.

- Two linear and two circular projects are being proposed and the synergy between their communities, as well as with the Synchrotron Light Sources one, will be crucial for the success of hopefully at least one of each.

“No man is an island entire of itself; every man is a piece of the continent, a part of the main” (J. Donne, 1572-1631)
Acknowledgments

Material for this talk from:

- M. Boscolo (INFN-LNF)
- P. Burrows (IAI)
- W. Chou (IHEP)
- S. Fukuda (KEK)
- Y. Funakoshi (KEK)
- J. Gao (IHEP)
- M. Koratzinos (Un. Geneva)
- E. Levichev (BINP)
- K. Oide (CERN)
- K. Ohmi (KEK)
- Q. Qin (IHEP)
- D. Shatilov (BINP)
- M. Sullivan (SLAC)
- A. Yamamoto (KEK)
- K. Yokoya (KEK)
- M. Zobov (INFN-LNF)
- D. Zhou (KEK)
- F. Zimmermann (CERN)
Backup slides (topics I could not cover in 20’)
<table>
<thead>
<tr>
<th>Factories</th>
<th>Design Luminosity</th>
<th>Achieved Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEKB</td>
<td>1.0 x 10^{34}</td>
<td>2.1 x 10^{34}</td>
</tr>
<tr>
<td>PEP-II</td>
<td>3.0 x 10^{33}</td>
<td>1.2 x 10^{34}</td>
</tr>
<tr>
<td>DAΦNE phase I</td>
<td>1.0 x 10^{32}</td>
<td>1.6 x 10^{32}</td>
</tr>
<tr>
<td>DAΦNE upgrade</td>
<td>5.0 x 10^{32}</td>
<td>4.5 x 10^{32} (*)</td>
</tr>
<tr>
<td>BEPCII</td>
<td>1.0 x 10^{33}</td>
<td>1 x 10^{33}</td>
</tr>
</tbody>
</table>

(*) without detector solenoid
## Beam Current Records at Factories

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PEP-II</th>
<th>KEKB</th>
<th>DAΦNE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER</td>
<td>HER</td>
<td>e+</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>3016</td>
<td>97.69</td>
</tr>
<tr>
<td>Circumference, m</td>
<td>2200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy, GeV</td>
<td>3.1</td>
<td>3.5</td>
<td>0.51</td>
</tr>
<tr>
<td>Damping time, turns</td>
<td>8.000</td>
<td>4.000</td>
<td>110.000</td>
</tr>
<tr>
<td>Beam Currents, A</td>
<td>3.21</td>
<td>1.70*</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Maximum positron beam current

Maximum currents with SC cavities

* 2.00 A and 1.40 A without crab cavities

Maximum electron beam current

Courtesy M. Zobov
VEPP-4M goes to high energy

VEPP-4 is an old collider with low luminosity but advanced accelerator technologies (resonant depolarization, unique e+e- tagging system, etc.) allow us performing some number of experiments (particles mass measurement, two-photon physics, etc.)

<table>
<thead>
<tr>
<th>Design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
</tr>
<tr>
<td>Number of bunches</td>
</tr>
<tr>
<td>Beam current</td>
</tr>
<tr>
<td>Beam energy range</td>
</tr>
<tr>
<td>Design luminosity (@5 GeV)</td>
</tr>
</tbody>
</table>

Record accuracy J/ψ mass measurement. →

The next run relates to the beam energy increase up to 5.5 GeV for γγ-physics and Y-mesons study.

Hardons production at VEPP-4M @4 GeV, 2017
## Parameters comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>ILC - TDR</th>
<th>CLIC – CDR+</th>
<th>CEPC</th>
<th>FCC-ee tt-bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td></td>
<td>Linear SRF, Klystron driven</td>
<td>Linear NRF, 2-beam driven</td>
<td>Circular SRF</td>
<td>Circular SRF</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>250</td>
<td>500</td>
<td>380</td>
<td>500 – B/A</td>
</tr>
<tr>
<td>Acc. Length</td>
<td>km</td>
<td>~21</td>
<td>31</td>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td>Lumin. / IP</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>0.82*</td>
<td>1.8</td>
<td>3.6</td>
<td>1.5*</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>MV/m</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5/45</td>
<td>72</td>
</tr>
<tr>
<td>Res. Frequency</td>
<td>GHz</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>12</td>
</tr>
<tr>
<td>IR, v. beam-size</td>
<td>nm</td>
<td>7.7</td>
<td>5.9</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Beam Power</td>
<td>MW (2-beams)</td>
<td>2 x 2.9</td>
<td>2 x 5.2</td>
<td>2 x 13.6</td>
<td>2 x 4.7</td>
</tr>
<tr>
<td>SR loss</td>
<td>MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Power</td>
<td>MW</td>
<td>129</td>
<td>163</td>
<td>300</td>
<td>252</td>
</tr>
<tr>
<td>L / AC</td>
<td>Relative</td>
<td>0.64</td>
<td>1.1</td>
<td>1.2</td>
<td>0.60</td>
</tr>
</tbody>
</table>

* enable to be further optimized for staging
** effectively x $N_{IR}$
3D Flip-Flop instability

• Flip-flop instability is normally 1D, bb interaction of flat bunches does not affect $\sigma_z$ and only slightly affects $\varepsilon_x$. The perturbations occur mainly in the vertical direction.
• In FCC-ee 3D flip-flop: beamstrahlung affects $\sigma_z$, which in turn depends on all 3 sizes of the opposite bunch. Instability is triggered by asymmetry in the bunch currents. But even in symmetrical case the 3D flip-flop was observed (with larger bunch population)

- Asymmetry in the bunch currents leads to asymmetry in $\sigma_z$ due to beamstrahlung
- In collision with LPA, asymmetry in $\sigma_z$ leads to increase in $\xi_x$ and amplification of synchro-betatron resonances for the “weak” bunch $\rightarrow$ its $\varepsilon_x$ increases
- Due to betatron coupling, $\varepsilon_y$ of the “weak” bunch also increases
- The blowup of $\varepsilon_y$ enhances beamstrahlung for the “weak” bunch and its lengthening, while beamstrahlung for the “strong” bunch weakens and its $\sigma_z$ shrinks

Decrease in $\beta_x$ helps to suppress this effect. On the other hand $\sigma_x$ decreases, that leads to magnification of beamstrahlung.
Emittance evolution after injection, with and without crab sextupoles

Beneficial effect of crab sextupoles on vertical emittance during injection

D. Shatilov, 2009
Framework of the study of the RF system

- Define “ideal” RF system for each machine
- Identify technology choices and R&D perspectives
- Propose optimum baseline scenario (fabrication, installation, cost)

<table>
<thead>
<tr>
<th>Machine</th>
<th>$V_{tot}$ (GV)</th>
<th>$N_{bunch}$</th>
<th>$I_{beam}$ (mA)</th>
<th>$\sigma$ (mm)</th>
<th>$E_{turnloss}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-hh</td>
<td>0.032</td>
<td>50180 / 91500</td>
<td>500</td>
<td>0.9 / 1.6</td>
<td>0.03</td>
</tr>
<tr>
<td>Z</td>
<td>0.4 / 0.2</td>
<td>50180 / 91500</td>
<td>1450</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.8</td>
<td>5260</td>
<td>152</td>
<td>2</td>
<td>1.67</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
<td>780</td>
<td>30</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>10</td>
<td>81</td>
<td>6.6</td>
<td>2.1</td>
<td>7.55</td>
</tr>
</tbody>
</table>

- 8 months operation
- 4 months shutdown

O. Brunner
Electricity bill

- **Fermilab:**
  - $440k per MW-year
  - $20M a year (~5% of lab budget)
  - (5 US cents per kWh)

- **CERN:**
  - 1,200 GWh/year
  - CHF 65M a year (~5% of lab budget)
  - (5 Swiss cents per kWh)

- **BEPC II: (Qing Qin)**
  - Annual machine operation: 100M yuan
  - Electricity: 40M yuan a year (US$ 6M)
    - (~3% of lab budget)

---

For a 500 MW collider in China:

To reach the required integrated luminosity, we need at least 4,400 hours for operation each year:

\[
500 \text{ MW} \times 4,400 \text{ hours} = 2.2 \times 10^9 \text{ kW-hr}
\]

Annual electricity cost: **RMB 2.2B (US$ 320M)**

(RMB 1 yuan per kWh for industry, 3 times higher than in the US or France)