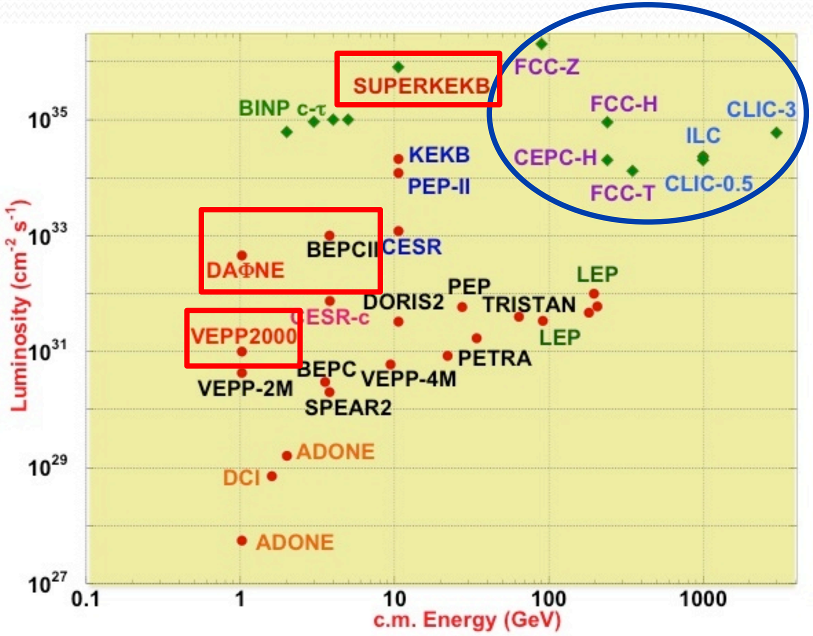
Status and prospects of e^+e^- Factories

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 → 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 → 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

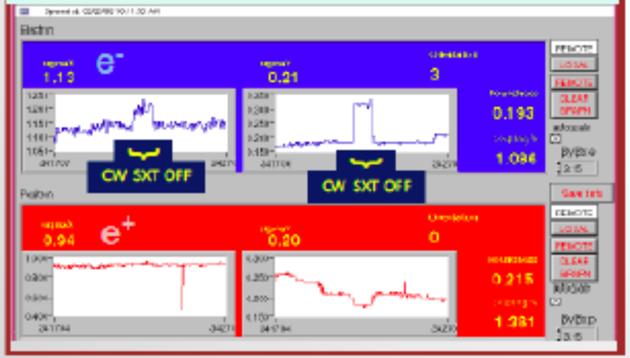
The present:

- Low energy colliders: DAΦNE, VEPP2000, BEPC-II
- Medium energy collider: SuperKEKB

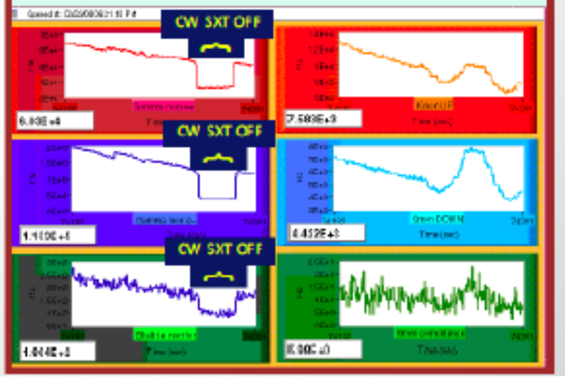
DAΦNE (INFN-Frascati)

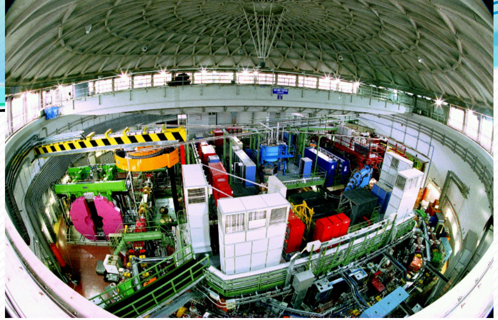
- Φ-Factory, 510 MeV/beam, record in electron beam current (2.5 A)
- Novel ideas and R&D:
  - *Large Piwinski angle and crab waist sextupoles* scheme
  - e-cloud clearing electrodes
  - Low impedance pipe design
  - Transverse feedback "*cavity kicker*"
  - Upgraded low noise bunch-by-bunch feedbacks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

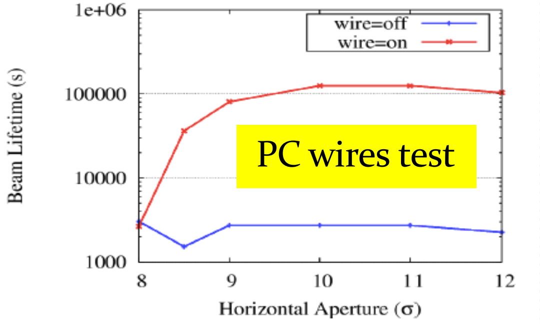
Beam transverse size measured at the SLM

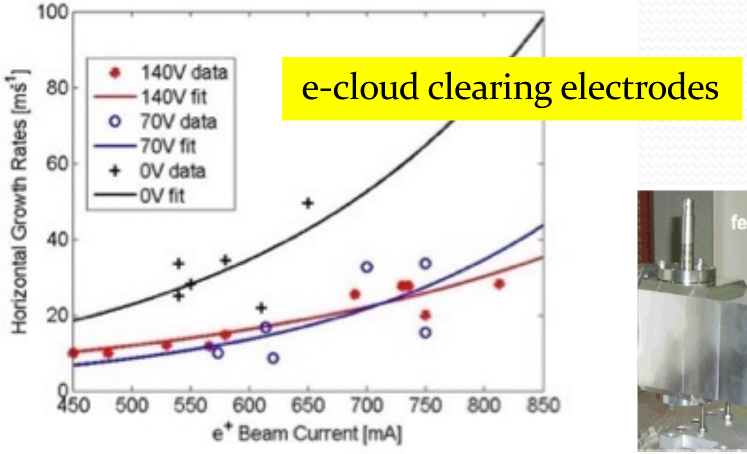


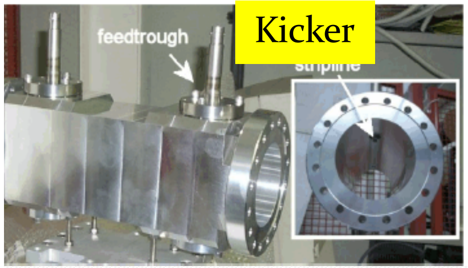
Luminosity from 2 different monitors

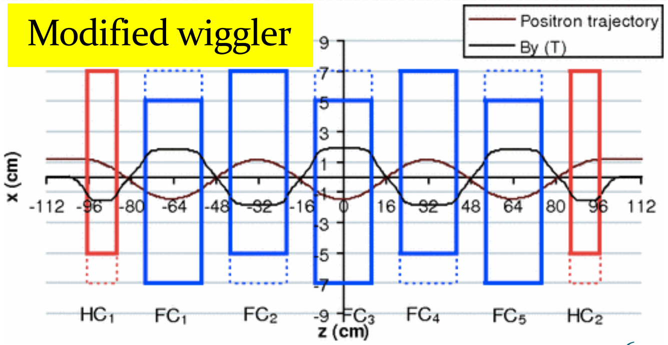




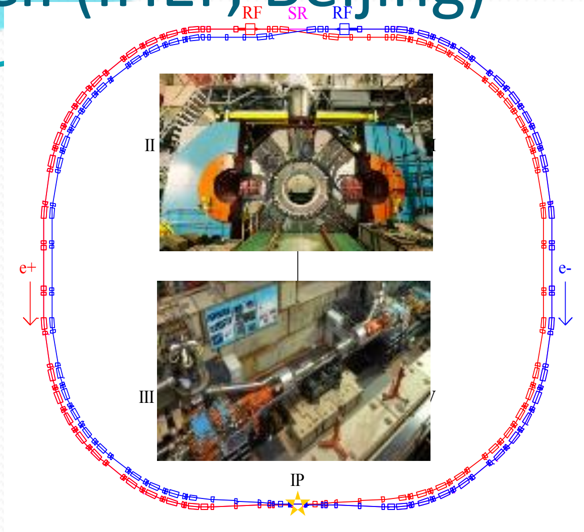


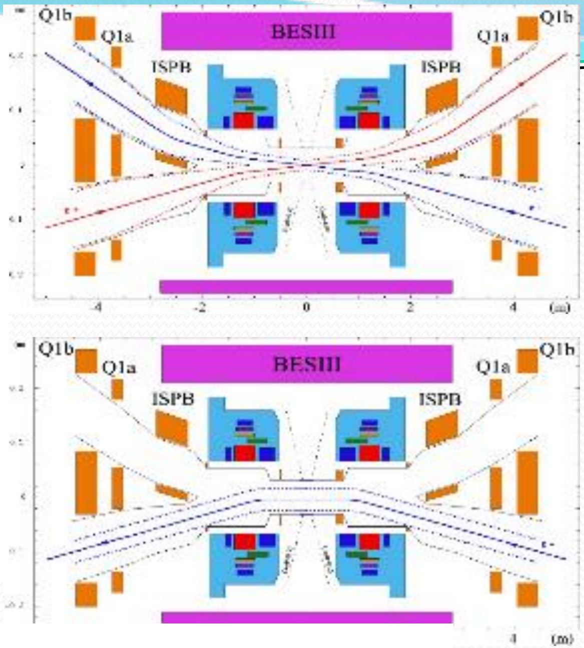


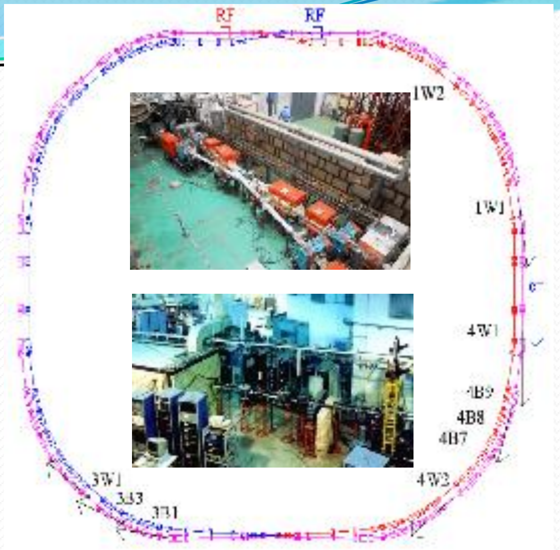




BEPCII (IHEP, Beijing)



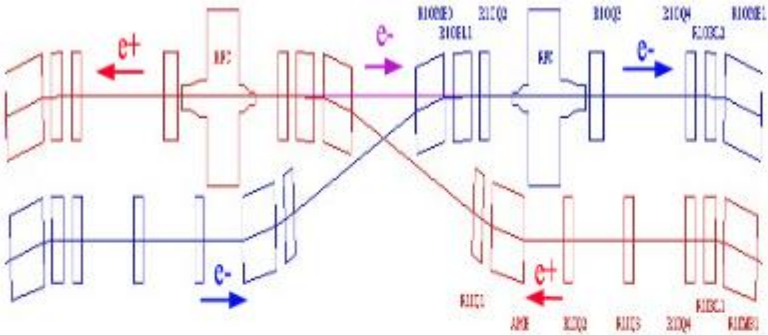




Collider

SR Facility

- Collision Mode
  - Beam energy range 1-2.1 GeV
  - Optimized beam energy 1.89 GeV
  - Luminosity 1×10^{33} cm^{-2}s^{-1} **Design**
  - Full energy injection 1-1.89 GeV
- SR Mode
  - Beam energy 2.5 GeV
  - Beam current 250 mA



Q. Qin, Valencia 2017

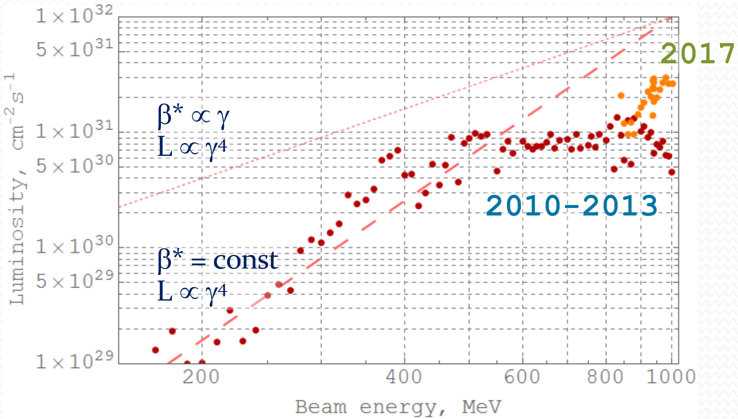
VEPP-2000 (BINP, Novosibirsk)

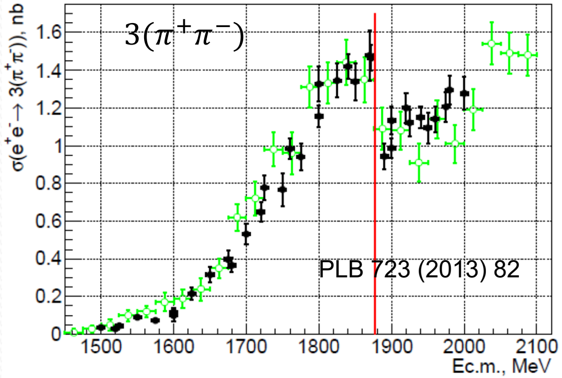
VEPP-2000 exploits the **Round Beam Concept**

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

Design parameters @ 1 GeV	
Circumference	24.388 m
Number of bunches	1×1
Beam-beam parameter	0.12
Beam energy range	150 ÷ 1000 MeV
Design luminosity	1×10^{32} $cm^{-2}s^{-1}$

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





6π cross section drop @ NNbar threshold

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, $L = 10^{34}\ cm^{-2}\ s^{-1}$), February 2018
  - Phase III (Vertex IN, low-beta, $L = 8x10^{35}\ cm^{-2}\ s^{-1}$), 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)

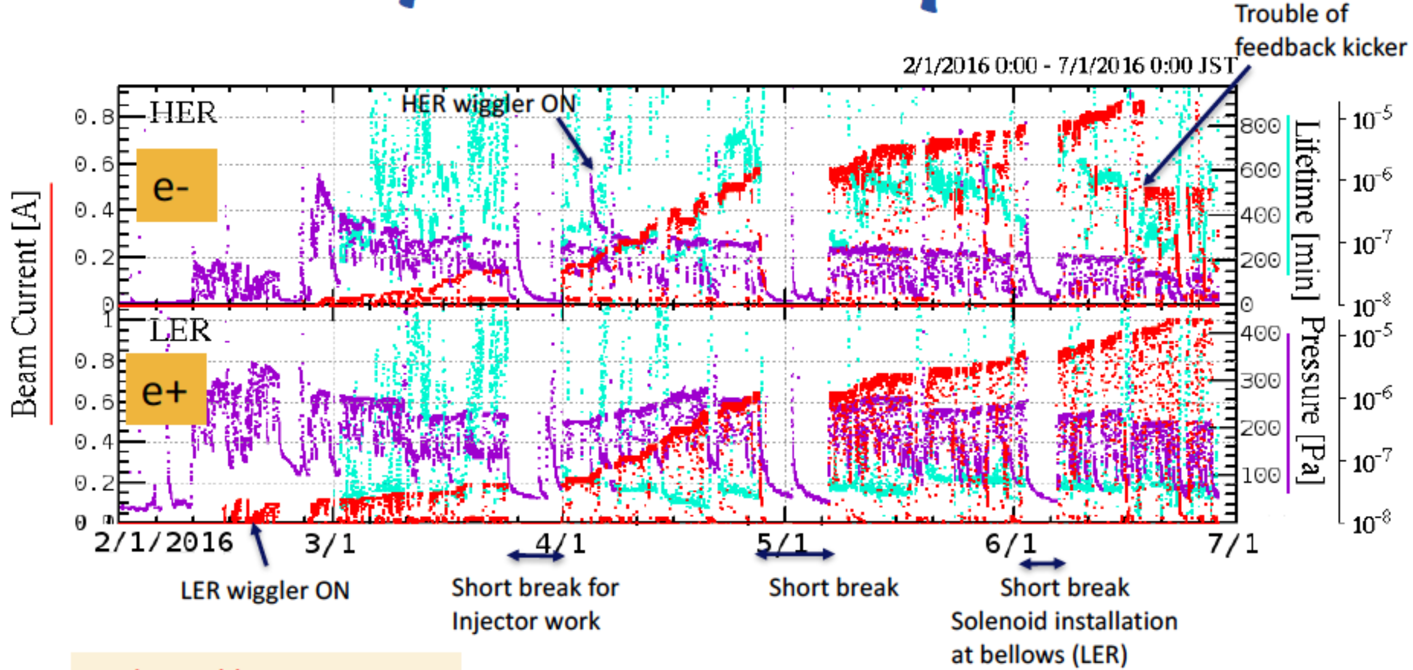
KEKB and SuperKEKB comparison

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

	KEKB Achieved		SuperKEKB Nano-beam		Factor
	LER	HER	LER	HER	
I_{beam} [A}	1.6	1.2	3.6	2.6	(>) 2
β_y^* [mm]	5.9	5.9	0.27	0.30	(<) 20
ξ_y	0.09	0.12	0.088	0.081	~1
L [$cm^{-2}s^{-1}$]	2.1 x 10^{34}		8.0 x 10^{35}		(>) 40

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:
1010mA, 4.7x10^{-7} Pa, ~60 min. (6/22)

Y. Funakoshi, IAS 2017

The future:

- Two circular (FCC-ee, CEPC)
- Two “linear” (ILC, CLIC)

Future lepton colliders

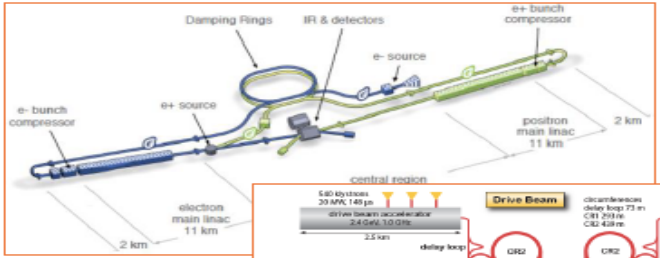
A. Yamamoto, IAS, HK, 2017

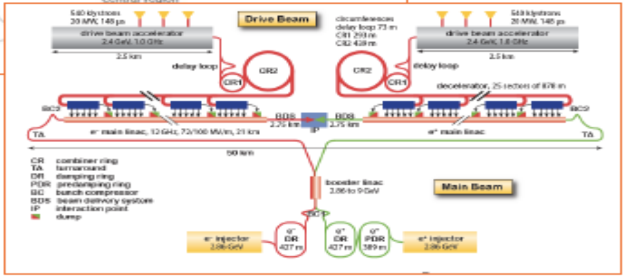
Good for high E

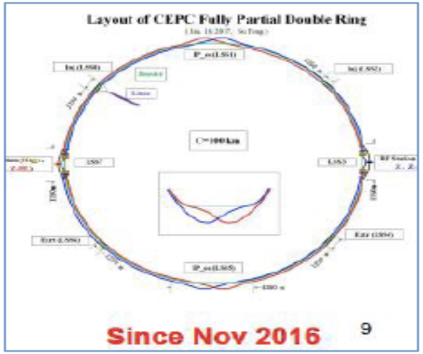
- Linear Colliders (energy extendable):
  - ILC (2x500 GeV) → SRF, longer pulse, higher energy efficiency, klystron driven, 1/10 scaled machine done (E-XFEL)
  - CLIC (2 x 1.5 TeV) → NRF, High Gradient, 2 beams driven → compact

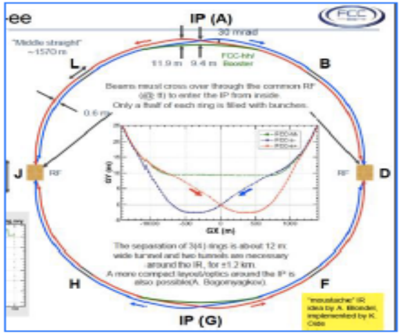
Good for high L

- Circular Colliders (max energy fixed):
  - FCC-ee (2 x 175 GeV) → SRF, higher luminosity efficiency at <2 x 175 GeV, AC power limit/guideline to be mitigated
  - CEPC (2 x 120 GeV) → SRF, higher luminosity efficiency at <2 x 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

ILC (250 GeV)

	ILC	
CoM. Energy	250	500
Site Length	~21	31
Luminosity	0.82	1.8
AC Power	129	163
Value Cost in TDR	TBD	7.98

($5 - 6B)

CLIC (380 GeV)

380 GeV centre-of-mass energy.

	Value [MCHF of December 2010]
	1245
	974
	2038
	132
	2112
ure	216
	6690

CEPC (100 km)

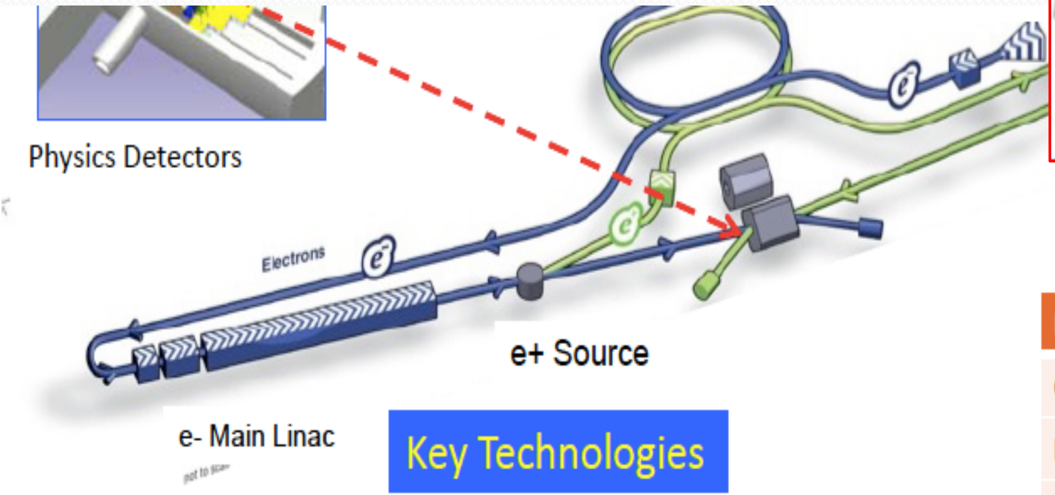
总价（万元）100公里
3606984.81
2323610.85
250227.56
32635.00
1000511.40

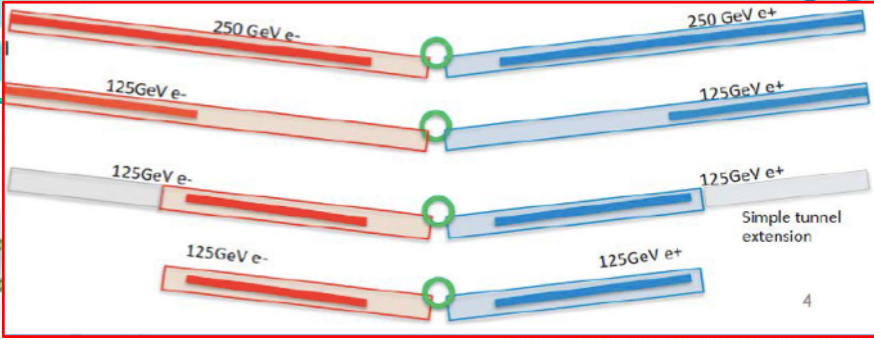
($5.3B)

FCCee unknown

W. Chou, IAS, HK, 2017

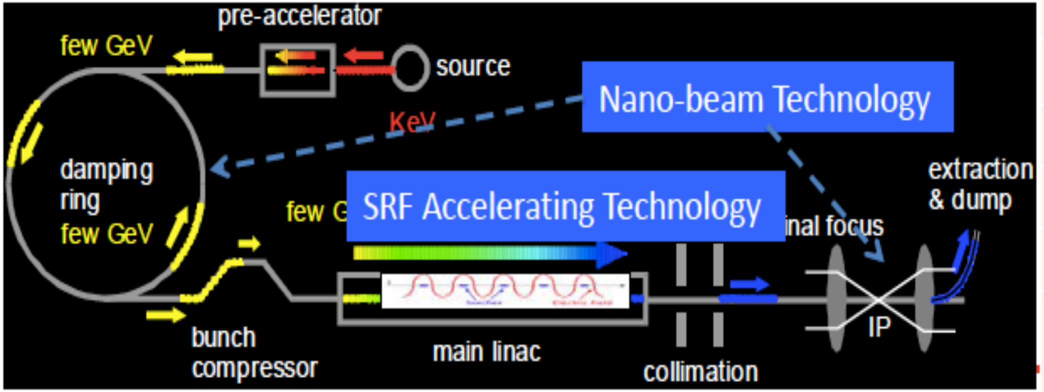
ILC baseline





Staging option

Key Technologies



Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10^{10}

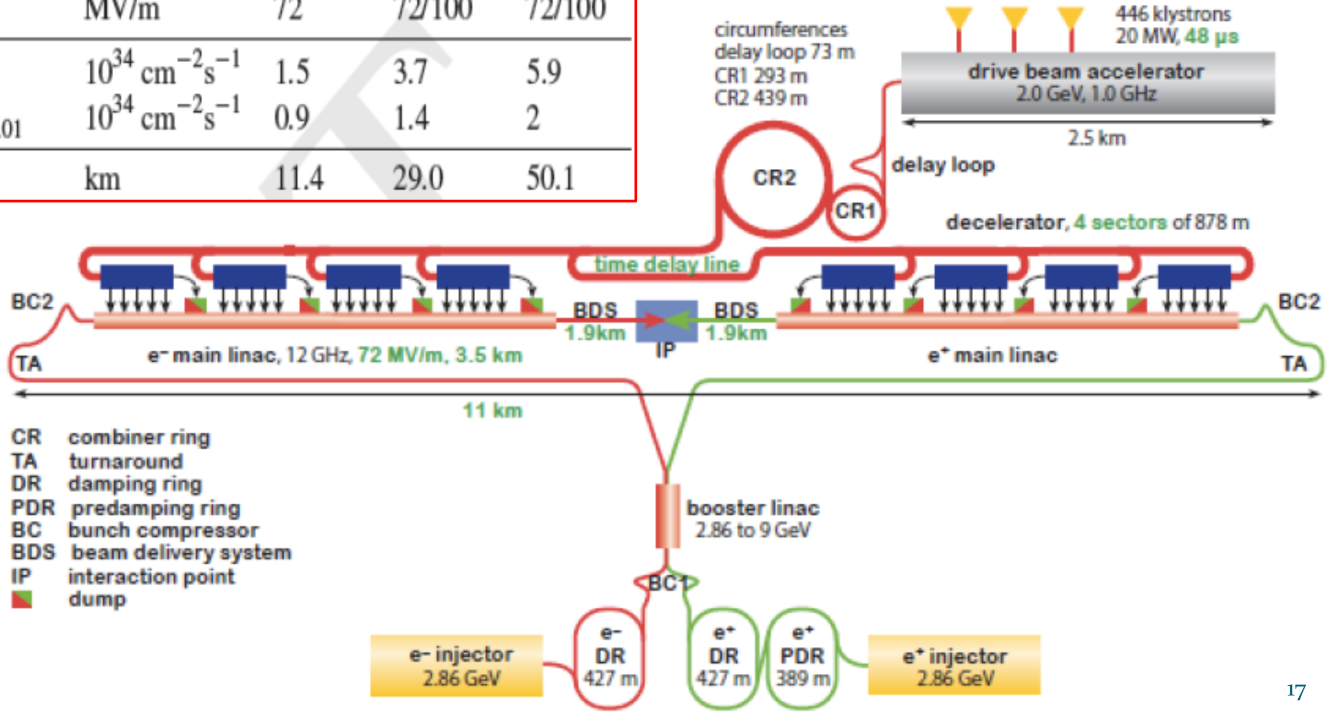
ILC staging

- Strong demand for cost reduction
- Improvement of Linac technology under study (however cost reduction 10-15% at most):
  - Higher gradient: 31 MV/m → 35 MV/m
  - Higher Q values: 10^{10} → 2×10^{10}
  - Nitrogen infusion developed at FNAL
- Staging is the option: start at 250 GeV c.m.
- Luminosity simply scaled at lower E is low (0.82×10^{34})→ needs a "real" 250 GeV design!
- Can be doubled by doubling N_{bunch} (1312 → 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 → conventional? (but not polarized)
- Debating if 500 GeV or 250 GeV tunnel

New CLIC layout @ 380 GeV

Same option for CLIC

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

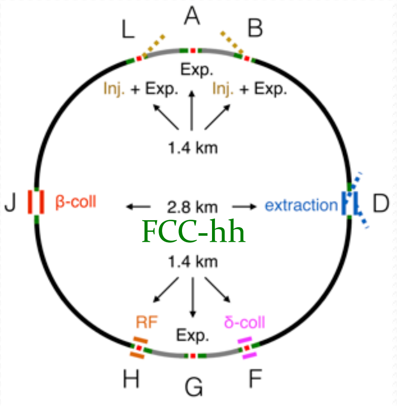


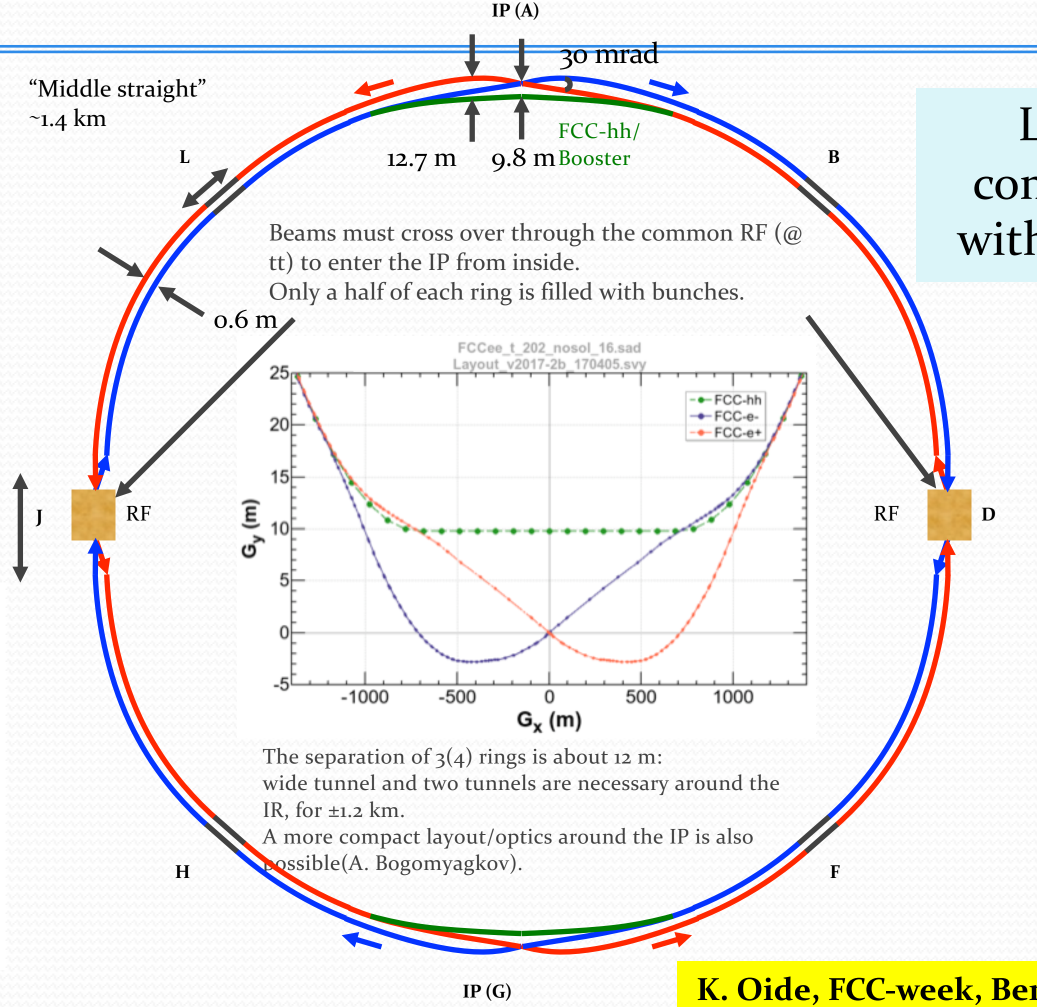
P. Burrows, JAS, 2017

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

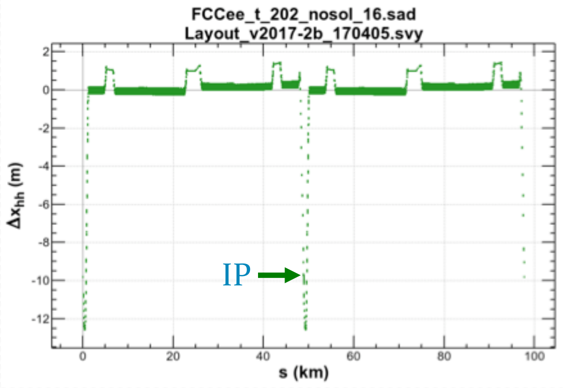
Layout of FCC-ee





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).



Relative distance to FCC-hh

Layout compatible with FCC-hh

K. Oide, FCC-week, Berlin, 2017

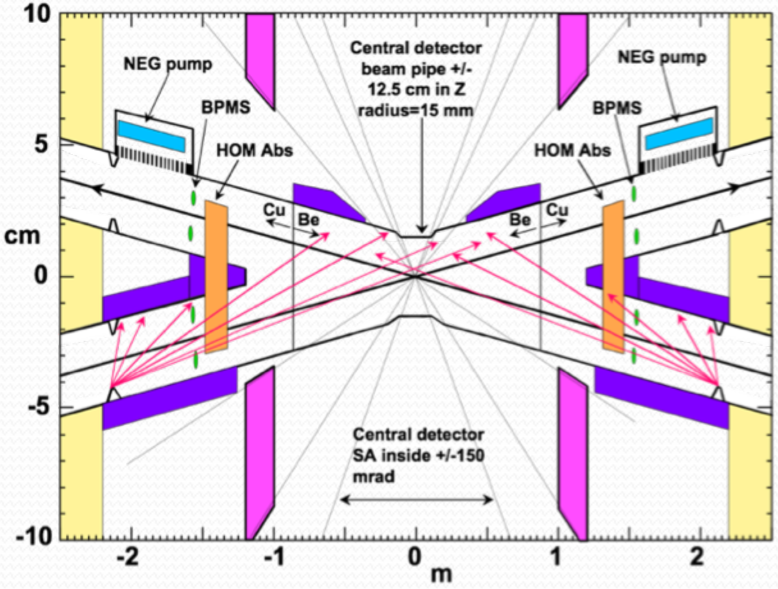
Interaction Region design

(@ top energy)

- central Be beam pipe (0.8 mm thick and |s|< 0.9m from IP)
- luminometrs
- **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

ullivan

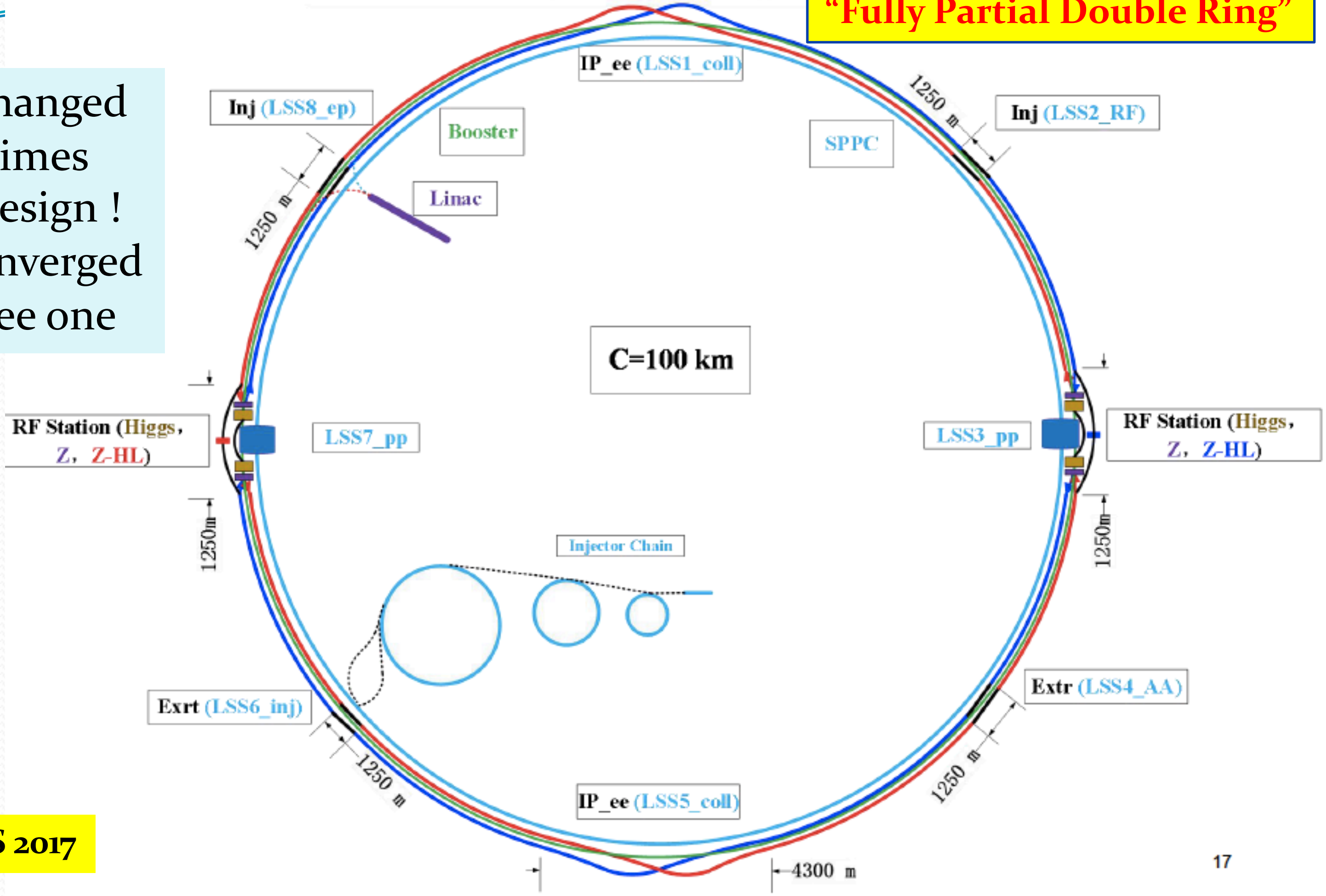
M. Boscolo, FCC-week, Berlin, 2017

Layout of CEPC-SPPC

(Jan. 18, 2017, Su Feng)

"Fully Partial Double Ring"

Layout changed many times during design ! Finally converged on FCC-ee one



J. Gao, IAS 2017

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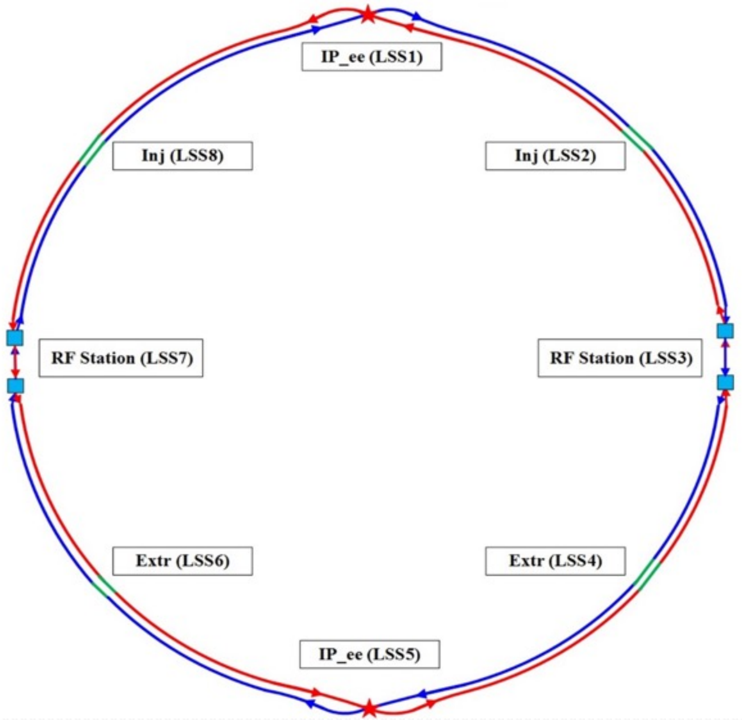
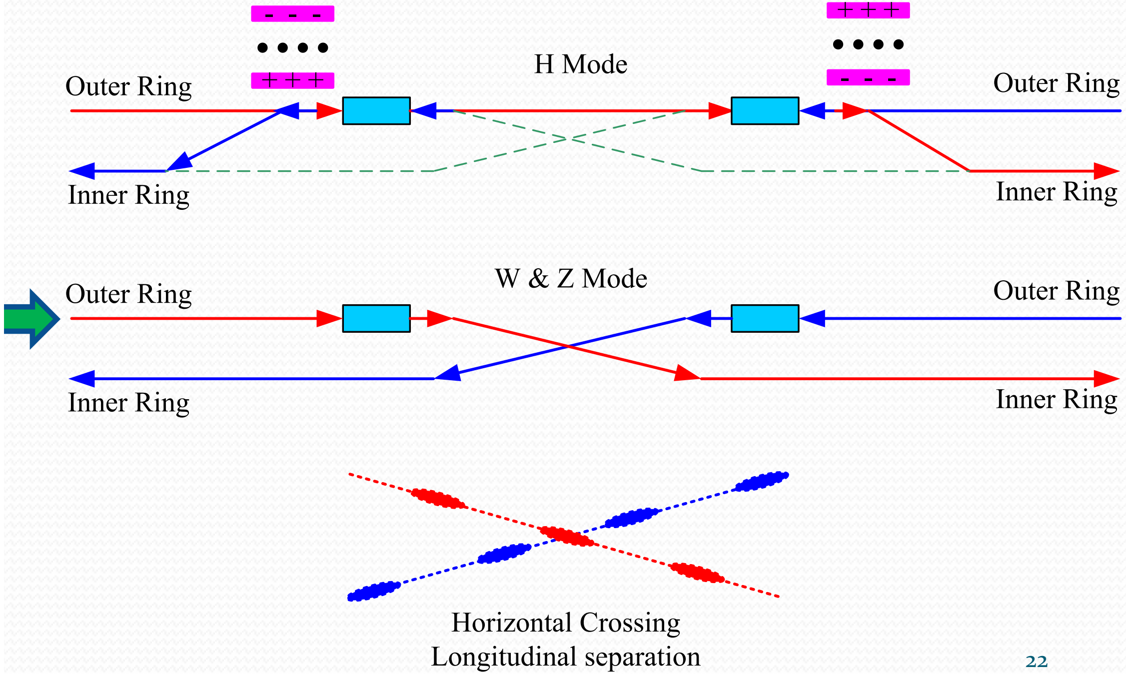
CEPC RF region

- **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, β_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
- …

Effects included in Dynamic Aperture studies for FCCee

Effects	Included?	Significance
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture esp. at $t\bar{t}$
Radiation fluctuation	after optimization	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by $\sim 20\%$
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Solenoids	Evaluated separately	minimal, if locally compensated
Beam-beam effects for stored beam	after optimization (D. Zhou)	affects the lifetime for $\beta_y^* = 1$ mm at $t\bar{t}$
Beam-beam effects for injected beam	Not yet	
Higher order fields / errors / misalignments	Not yet	**Essential**, development of correction/tuning scheme is necessary

K. Oide, FCC-week, Berlin, 2017

FF Non-Linearities

- Kinematic terms and FF quads fringe fields introduce NL which affect beam dynamics
- Increase with low-β

K. Oide and H. Koiso, Phys. Rev. E47 (1993)
K. Ohmi and H. Koiso, IPAC'10 (2010)

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

Ring	β_y^* (mm)	K1 (m^{-2})	L* (m)	J_y/A (mm)
SKEKB-HER	0,3	3,05	1,22	0,02
SKEKB-LER	0,27	5,1	0,76	0,03
CEPC	1,2	0,176	1,5	0,76
FCC-ee	1	0,336	2,2	0,22
KEKB	5,9	1,78	1,76	4,22
SuperB-HER	0,253	4,6	0,6	0,05
SuperB-LER	0,21	4,4	0,6	0,036

Should:
- **increase β_y^***
- **decrease gradient and L***

Space charge tune shift

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

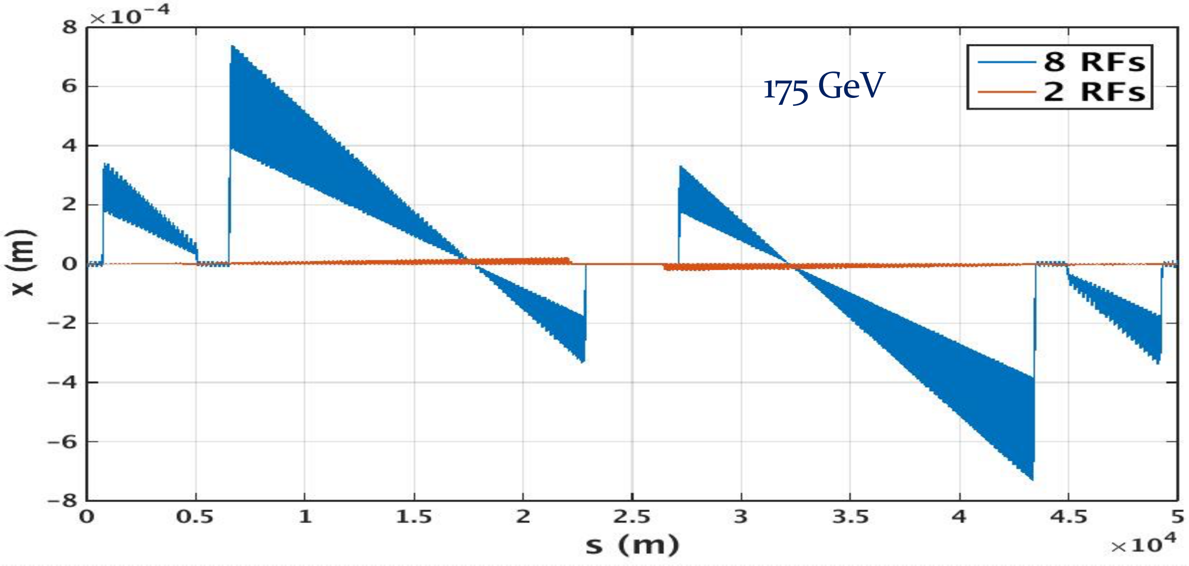
	SuperKEKB[1]		KEKB[4]	
	LER[2]	HER[3]	LER	HER
ε_x (nm)	3.2	4.6	18	24
ε_y (pm)	8.64	11.5	180	240
ξ_x	0.0028	0.0012	0.127	0.102
ξ_y	0.0881	0.0807	0.129	0.09
$\Delta\nu_x$	-0.0027	-0.0004	-0.0005	-3E-05
$\Delta\nu_y$	-0.0943	-0.0121	-0.0072	-0.0004

D. Zhou

Tapering mitigates the sawtooth in FCC-ee

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

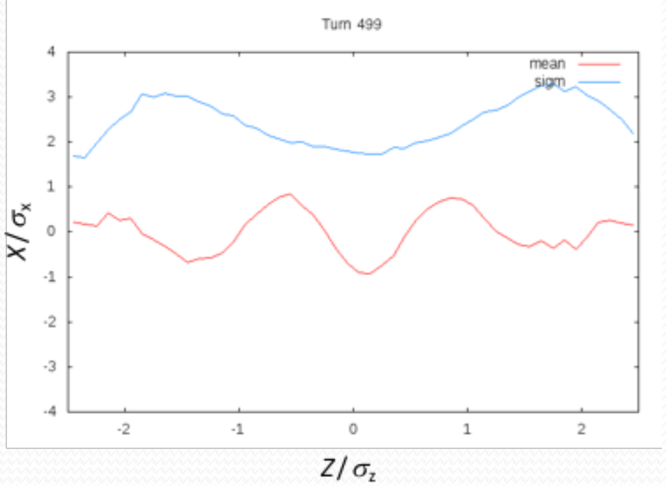
Comparison:
8 RF w/o tapering
2 RF with tapered dipoles

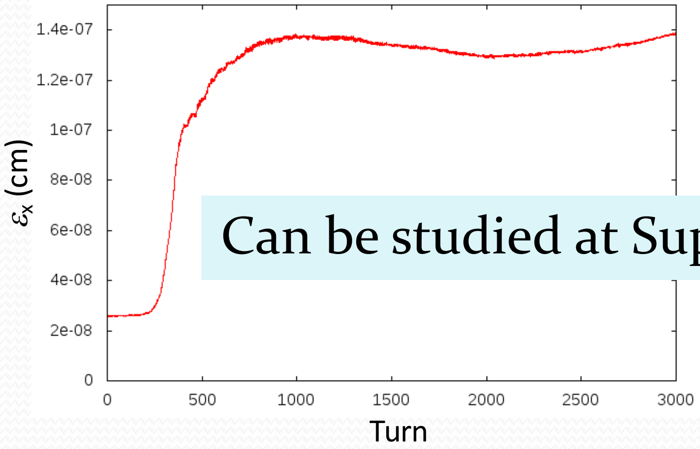


S. Aumon, B. Härer,
A. Doblhamer, B. Holzer

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 $\theta/2$ → luminosity drops by 20÷40 %
  - ε_x increases in 5÷15 times. Itself, it is not a problem, but betatron coupling leads to ε_x growth in the same proportion → luminosity drops 2÷3 times





Can be studied at SuperKEKB !

Mitigation:

- decrease β_x^* and double the momentum compaction at low energy,

or…

- increase bunch current and decrease σ_z, but HOM may be a problem

D. Shatilov, K. Ohmi, FCC Week 2017, Berlin

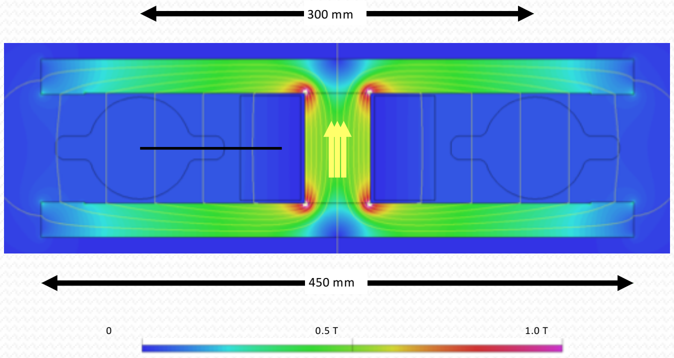
Technology related challenges

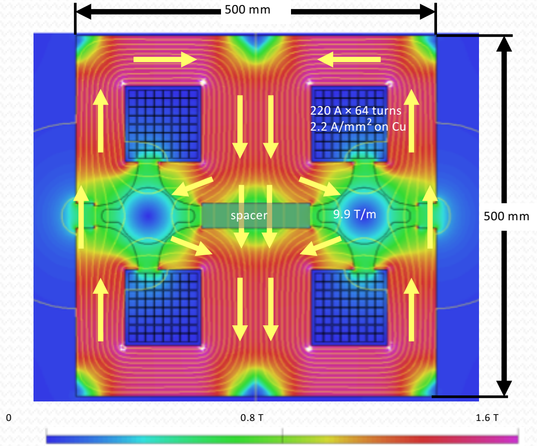
- Magnets (warm/cold SC, IR doublets, SC wires)
- Radiation damage on magnets
- Beam pipe & vacuum system (material, coating, low impedance, HOM,…)
- Injectors (high reliability, top-up, full energy booster in same tunnel?)
- Positron source (high number of e^+, polarization?)
- High efficiency klystrons
- 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 → alignment, control
- Energy saving options → 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.

Less units to manufacture, transport, install, align, remove,…

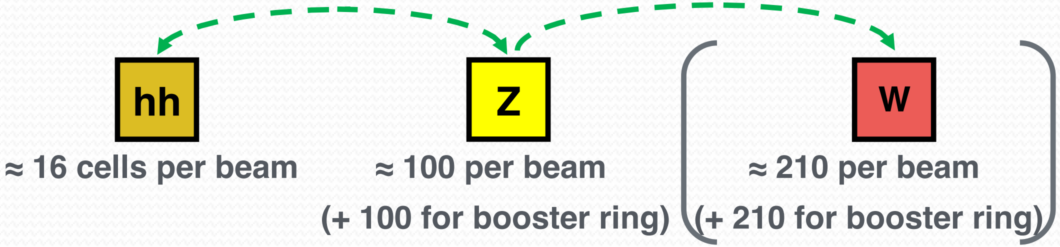
- The power consumption of the twin aperture quad: 22 MW at 175 GeV with Cu coil = half of single-aperture quads.
- Dipoles are also "twin": power consumption = 17 MW at 175 GeV with Al bus bar.

A. Milanese, FCC Week 2017, Berlin

FCC-ee RF system R&D lines

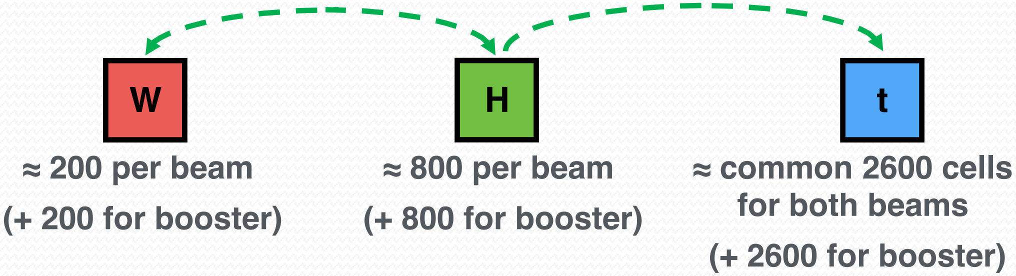
400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- 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 Qo 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

HEIKA

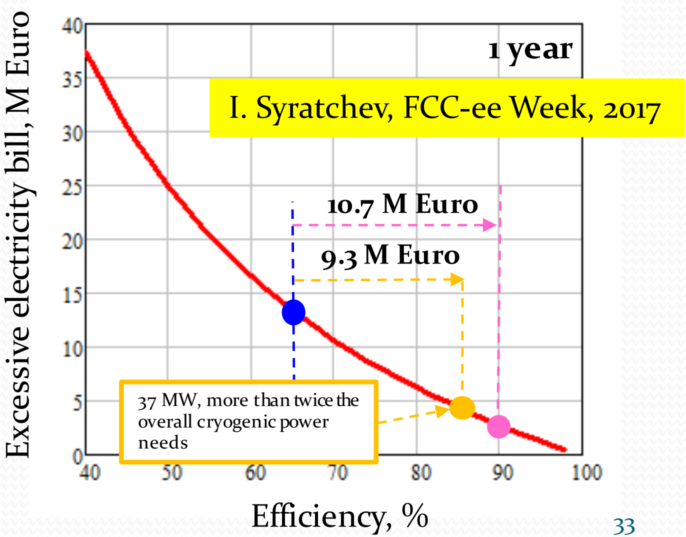
High Efficiency International klystron activity Since 2013

J. CAI, CERN
C. Marrelli, ESS
A. Baikov, MUFA
D. Constable, Lancaster U
V. Hill, Lancaster U
G. Burt, Lancaster U
R. Kowalczyk, SLAC

- 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
  - "bunch core oscillation", A.Yu. Baikov et al, 2014
  - "BAC method", I.A. Guzilov, O.Yu. Maslennikov, A.V. Konnov, 2013
- International collaboration on R&D

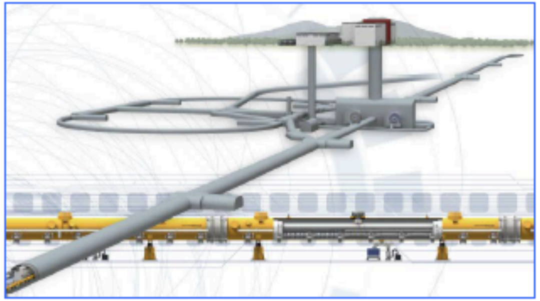
Efficiency impact on operation cost

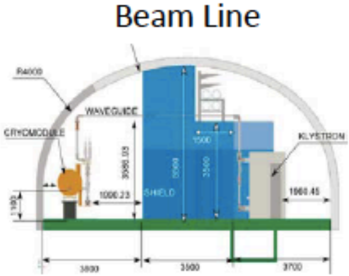
FCC e+e- at 50 Euro/MWh and 5000 hours/year:

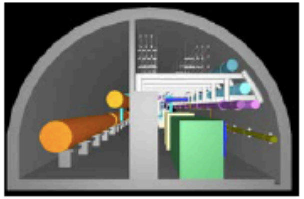


ILC civil engineering

A good fraction of costs

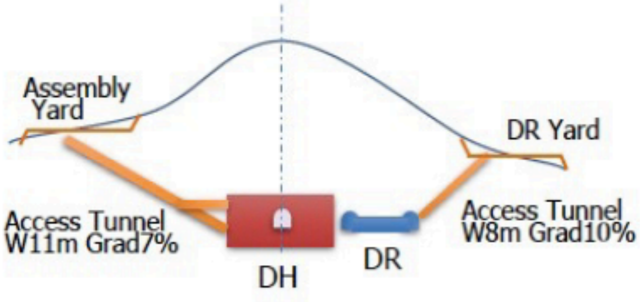


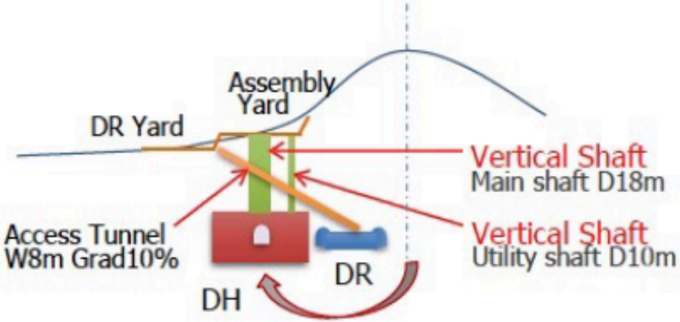




- Assembly Place: Surface Building/AH
- Access way to DHl underground
  - only Inclined Access Tunnel (AT)
  - Transport. by special long trailer

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





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:
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  - K. Ohmi (KEK)
  - Q. Qin (IHEP)
  - D. Shatilov (BINP)
  - M. Sullivan (SLAC)
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  - M. Zobov (INFN-LNF)
  - D. Zhou (KEK)
  - F. Zimmermann (CERN)

Backup slides (topics I could not cover in 20’)

Factories		Design Luminosity	Achieved Luminosity
KEKB	B-Factory KEK, Japan	1.0×10^{34}	2.1×10^{34}
PEP-II	B-Factory SLAC, USA	3.0×10^{33}	1.2×10^{34}
DAΦNE phase I	Φ-Factory Frascati, Italy	1.0×10^{32}	1.6×10^{32}
DAΦNE upgrade	Φ-Factory Frascati, Italy	5.0×10^{32}	4.5×10^{32} (*) 2.1×10^{32}
BEPCII	C-Tau-Factory Beijing, China	1.0×10^{33}	1×10^{33}

(*) without detector solenoid

Beam Current Records at Factories

Parameters	PEP-II		KEKB		DAΦNE	
	LER	HER	LER	HER	e+	e-
Circumference, m	2200 2200		3016	3016	97.69 97.69	
Energy, GeV	3.1	9.0	3.5	8.0	0.51	0.51
Damping time, turns	8.000	5.000	4.000	4.000	110.000	110.000
Beam Currents, A	3.21	2.07	1.70*	1.25*	1.40	2.45

Maximum positron beam current

Maximum currents with SC cavities

* 2.00 A and 1.40 A without crab cavities

Maximum electron beam current

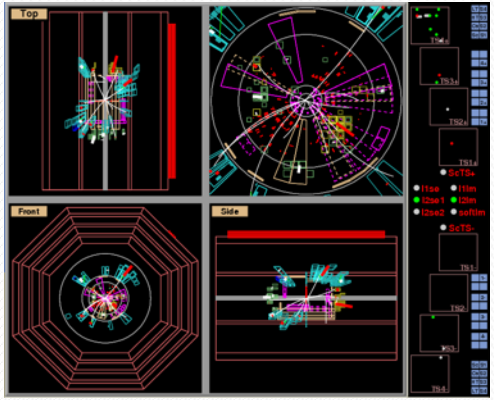
Courtesy M. Zobov

VEPP-4M goes to high energy

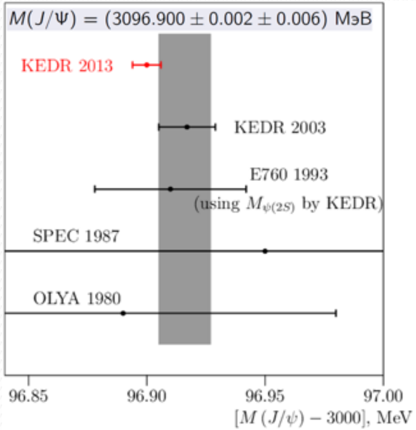
VEPP-4 is an old collider with low luminosity but advanced accelerator technologies (resonant depolarization, unique e+e- tagging system, etc.) allow us performing some number of experiments (particles mass measurement, two-photon physics, etc.)

Design parameters	
Circumference	366 m
Number of bunches	2×2
Beam current	25 mA
Beam energy range	1 ÷ 5.5 GeV
Design luminosity (@5 GeV)	4×10^{31} $cm^{-2}s^{-1}$

Hardons production at VEPP-4M @4 GeV, 2017



Record accuracy J/ψ mass measurement. →



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

Parameters comparison

	Unit	ILC - TDR			CLIC – CDR+			CEPC	FCC-ee tt-bar
Technology		Linear SRF, Klystron driven			Linear NRF, 2-beam driven			Circular SRF	Circular SRF
Energy	GeV	250	500	1,000	380	500 – B/A	3,000	240	350
Acc. Length	km	~21	31	50	11	13	48	100	100
Lumin. / IP	10^{34} $cm^{-2}s^{-1}$	0.82*	1.8	3.6	1.5*	2.3	5.9	3.3 / 5.4 **	1.9 **
Acc. Gradient	MV/m	31.5	31.5	31.5/45	72	100/80	100	14	
Res. Frequency	GHz	1.3	1.3	1.3	12	12	12	0.65	0.65
IR, v. beam-size	nm	7.7	5.9	2.7	2.9	2.3	1	--	--
Beam Power	MW (2-beams)	2 x 2.9	2 x 5.2	2 x 13.6		2 x 4.7	2 x 14	--	--
SR loss	MW							30 / 50	100 (tbc)
AC Power	MW	129	163	300	252	271	589	210 / 350 (tbc)	364
L / AC	Relative	0.64	1.1	1.2	0.60	0.85	1.0	1.6 / 1.5	0.52**

* enable to be further optimized for staging

** effectively x N_{IR}

A, Yamamoto, 17/01/26

3D Flip-Flop instability

- Flip-flop instability is normally 1D, bb interaction of flat bunches does not affect σ_z and only slightly affects ε_x. The perturbations occur mainly in the vertical direction
- In FCC-ee 3D flip-flop: beamstrahlung affects σ_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)

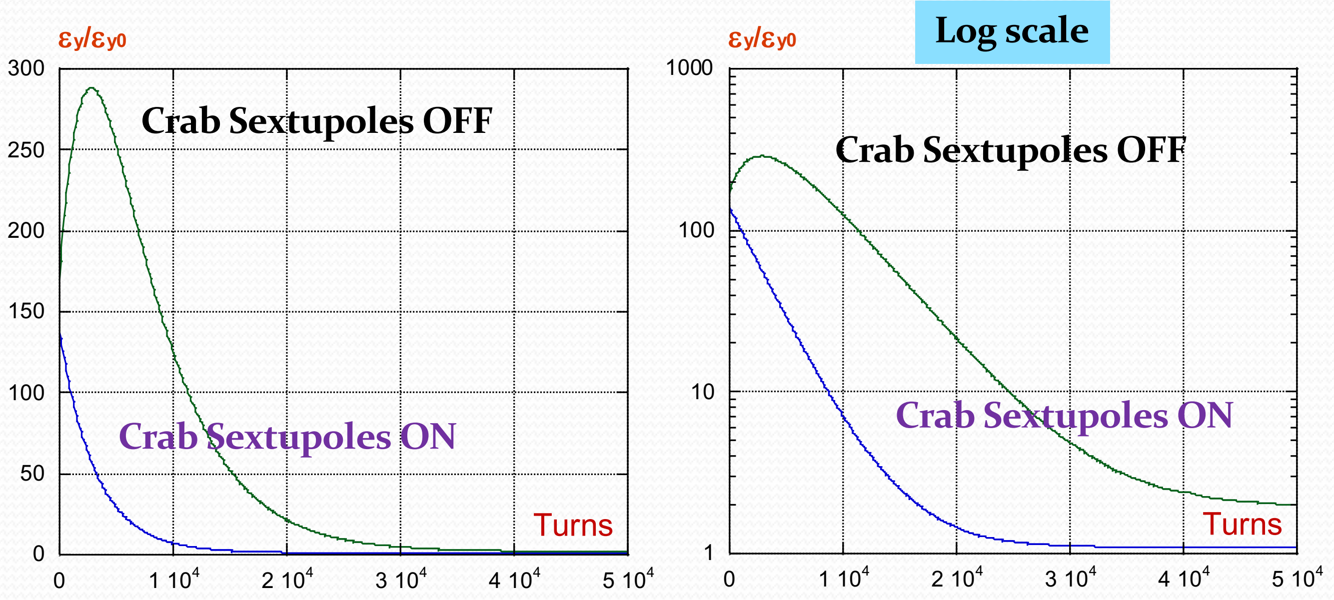
  - Asymmetry in the bunch currents leads to asymmetry in σ_z due to beamstrahlung
  - In collision with LPA, asymmetry in σ_z leads to increase in ξ_x and amplification of synchro-betatron resonances for the "weak" bunch → its ε_x increases
  - Due to betatron coupling, ε_y of the "weak" bunch also increases
  - The blowup of ε_y enhances beamstrahlung for the "weak" bunch and its lengthening, while beamstrahlung for the "strong" bunch weakens and its σ_z shrinks

Decrease in β_x helps to suppress this effect. On the other hand σ_x decreases, that leads to magnification of beamstrahlung.

D. Shatilov, FCC Week 2017, Berlin

Emittance evolution after injection, with and without crab sextupoles

Beneficial effect of crab sextupoles on vertical emittance during injection



D.Shatilov, 2009

CABIBBO LAB
Laboratorio Nicola Cabibbo

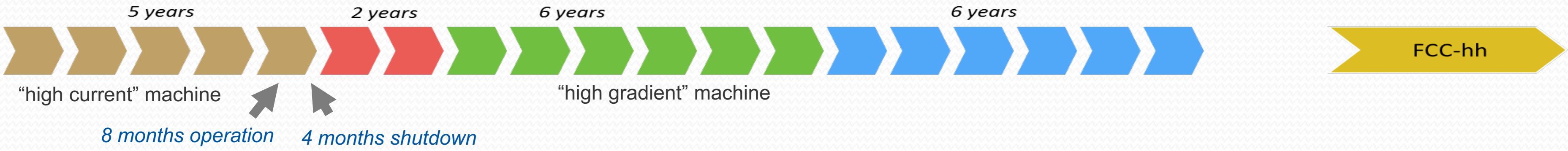
Framework of the study of the RF system

“high current” machine

	V_tot (GV)	n_bunch	I_beam (mA)	σ (mm)	E_turnloss (GeV)
FCC-hh	0.032		500		
Z	0.4 / 0.2	30180 / 91500	1450	0.9/1.6	0.03
W	0.8	5260	152	2	0.33
H	3	780	30	2	1.67
t	10	81	6.6	2.1	7.55

FCC-ee (Z, W, H, t)

“high gradient” machine



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

O. Brunner

Electricity bill

W. Chou, IAS, HK, 2017

- 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 MW x 4,400 hours = 2.2 x 10^9 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)