Overview on circular lepton and $\gamma\gamma$ colliders

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Are accelerators still needed for pure physics research?

Particles accelerators have proven to be extremely versatile: from the original purpose of studying particle physics they found many other uses

- Synchrotron radiation facilities with a wide range of applications
  - Rings in their 4th generation
  - Free electron lasers
  - Miniature light sources based on laser, plasma, dielectric and EM technologies under study
- Accelerators for Medical applications
- Accelerator Driven Subcritical Reactor

Some of those kind of facilities are already wide spread over the world, while ADS facilities are under construction (MYRRHA, CiADS, LEHIPA).

What about facilities (colliders) for HEP?

Is the large collider era dead?

- SLAC: after closing the SLC (1998) transformed into a synchrotron light lab.
- DESY: after closing the $p/e^{\pm}$ collider HERA (2007), the lab transformed into a synchrotron light lab.
- Fermilab: after closing Tevatron (2011) the accelerator related activities are focused on the production of neutrinos beams for a variety of on going or under construction experiments.
- BNL: RHIC is still proudly colliding ions and polarized p. The only operating collider in the US!
- CERN: LHC performance as accelerator has surpassed expectations. A luminosity upgrade is in preparation and expected to be operational by the end of 2027 with experiment data taking until $\approx$ 2035.
- ILC: still on "hold", despite energy reduction for reducing costs to $7-billions.

What about the post HL-LHC era?

- HEP research is based on accelerators.
- Development of new accelerators is driven by experimental needs.
- Experimental needs are informed by theoreticians.
- Theoreticians say they need the largest machine we can build!

For making our proposals acceptable to tax payers we must maximize the Benefit-Cost Ratio $\rightarrow$ technological advancements (RF, magnets) and new ideas are key ingredients.

Following rumors on the discovery of the Higgs at LHC, there has been a revival for e^+e^- colliders.
LEP3 was proposed in 2011 (Blondel-Zimmermann): an e^+e^- collider in the existing LHC (LEP) tunnel with $\mathcal{L}=1\times10^{34}$ cm^2/s per IP for studying the Higgs.

The need for a Higgs factory is widely recognized.
In 2012 Fermilab hosted a workshop on Accelerators for a Higgs Factory.

Topics:

- Higgs physics beyond the LHC
- Merits and requirements of each type of Higgs factory
- Linear Higgs factories – ILC, CLIC, SLC, NLC
- Circular Higgs factories: LEP3, TLEP, SuperTristan, Fermilab site-filler, IHEP ring, LBNL/SLAC ring
- Limits of circular e^+e^- colliders
- Muon collider as a Higgs Factory
- γ-γ collider as a Higgs Factory

The **final report** can be found at: www-bd.fnal.gov/icfabd/HF2012.pdf

There were 35 contributions by scientists from Asia, Europe, Russia and US.

Dreaming big...

- DLEP: a 50 Km e^+e^- would allow doubling the current for the same SR power
- TLEP: a 80 Km e^+e^- would allow 3 times larger current for the same SR power
- SuperTRISTAN (40 or 60 Km)
- VLLC in the 233 km VLHC tunnel, the larger ancestor of FCC.

Dreaming small...

- Fermilab 16 Km "SiteFiller"

Luminosity in Circular colliders (head-on):

$$\mathcal{L} = \frac{1}{4\pi}\frac{N^2}{\sigma_x^*\sigma_y^*} n_b f_{rev} R_{hg}$$

particles/bunch (N)

Hourglass (R_{hg})

Beam-beam tune shift:

$$\chi_z = \frac{r_e}{2\pi\gamma}\frac{N}{(\sigma_x^* + \sigma_y^*)}\sqrt{\frac{\beta_z^*}{\epsilon_z}} = \frac{r_e}{2\pi\gamma}\frac{N}{\sigma_x^*(1+r)}\sqrt{\frac{\beta_z^*}{\epsilon_z}}$$

$r \equiv \sigma_y^*/\sigma_x^*$

$$\mathcal{L} = \frac{\gamma}{2r_e}\frac{\mathcal{I}}{e}(1+r)\frac{\chi_y}{\beta_y^*}R_{hg}$$

At high energy luminosity in a e^+e^- circular collider is limited by the radiated power

$$W = \frac{e\gamma^4}{3\epsilon_0}\frac{\mathcal{I}}{\rho_b}$$

In addition

- beamstrahlung (SR emitted in the field of the opposite beam)

$$\frac{1}{\rho_{beam}} \propto \frac{N}{\gamma \sigma_x^* \sigma_\ell}$$

but the critical energy scales as γ^3:

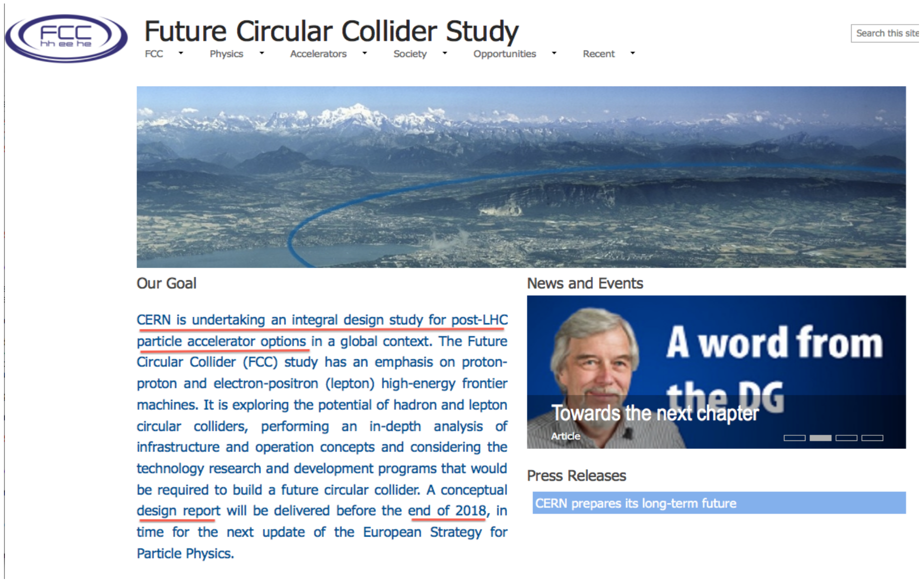
  - it affects lifetime at high energy and the beam parameters (energy spread $\rightarrow \sigma_\ell$);
  - responsible for a new beam-beam instability.

FCCe^+e^-

CERN plans for future at the energy frontier after LHC: CLIC (CDR presented in 2012) and FCC.

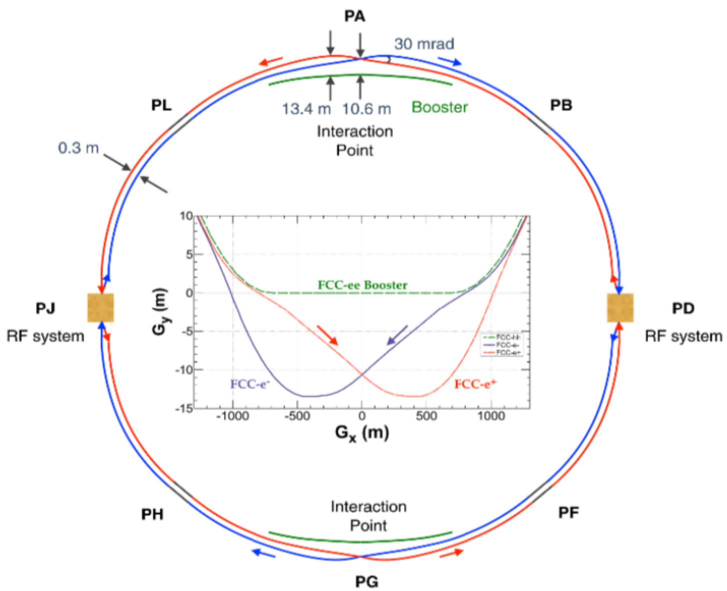
Following 2013 recommendations of the Council on European Strategy for Particle Physics, CERN launched a 5 years international design study for a Future Circular Collider (FCC).

4 volumes CDR has been submitted to the European Strategy for Particle Physics in January 2019.



A 100 TeV c.m. pp collider requires a 100 km tunnel, assuming a dipole field of 16 T.

It would host first a $e^{\pm}$ (double ring) collider with a variety of physics programs.



FCC-ee parameters

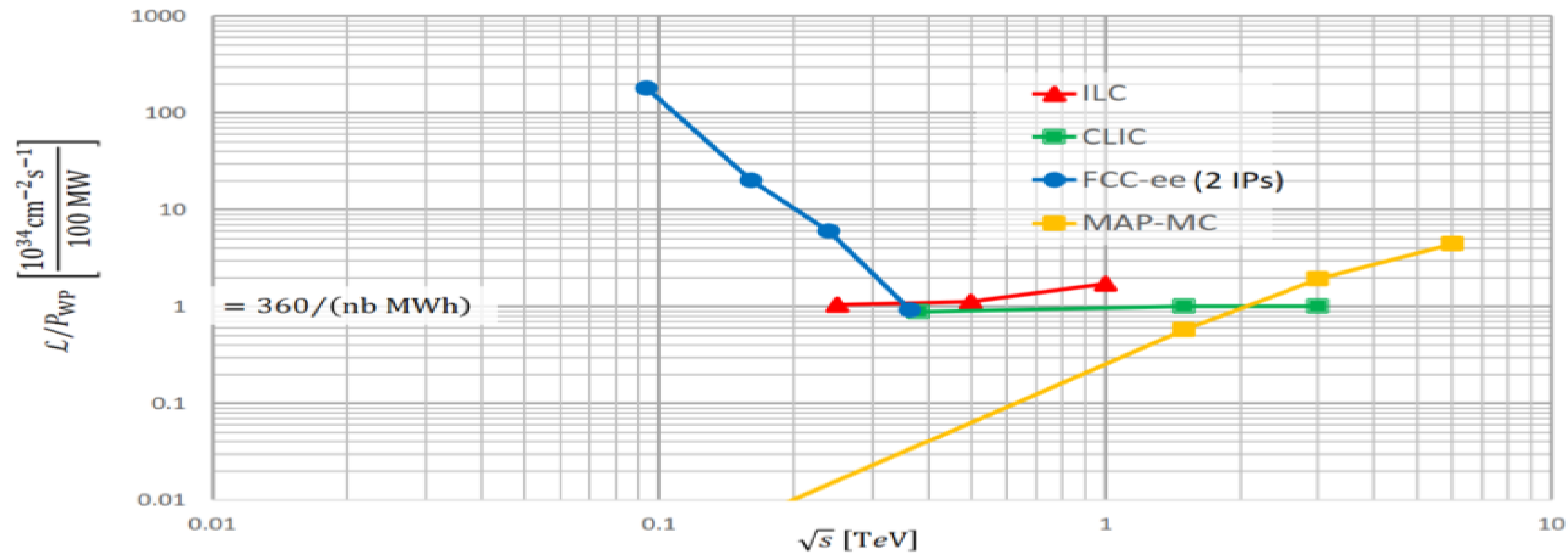
(optimized for max. luminosity at 50+50 MW SR power)

parameter	Z	W	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
circumference [km]	97.8	97.8	97.8	97.8
beam current [mA]	1390	147	29	5.4
bunches / beam	16640	2000	328	48
part./bunch [10^{11}]	1.7	1.5	1.8	2.3
hor. emittance [nm]	0.3	0.8	0.6	1.5
vert. emittance [pm]	1.0	1.7	1.3	2.9
hor. IP beta [m]	0.15	0.2	0.3	1
vert. IP beta [mm]	0.8	1.0	1.0	1.6
lum. [10^{34} cm^{-2}s^{-1}]	>200	> 25	>7	>1.3

(M. Benedikt and F. Zimmermann, IPAC2018)

The cost (tunnel, infrastructures, pp and $e^{\pm}$ colliders) is estimated at 28.6 CHF billions.

FCC-ee efficency drops with energy due to SR



(from E. Jensen, Open Symposium ESPPU, Granada 2019)[a]

[a]data from the proposals submitted to the European Strategy Update and as such of heterogeneous nature.

Linear vs. Circular collider for Higgs studies

Table 1.2. Precision determined in the κ framework for the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240–380 GeV centre-of-mass energy range.

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	<1.7	<2.1	<1.6	<1.2	<1.2	**<1.0**	**<1.0**

(from CDR)

Some like it round...

Main feeatures of FCCee

- Double ring.
- 30 mrad crossing angle collision scheme for overcoming hourglass effect.
  - crab waist crossing for overcoming betatron and synchro-betatron resonances; sextupoles integrated into the LCCS.
- Same layout for all energies; small re-arrangement in the two RF sections at $t\bar{t}$ energy.
  - Tapering of all dipoles and quadrupoles. Those trims are used for optics correction too. Sextupoles have independent p.s.
  - Shared RF cavities at $t\bar{t}$.
- Top-up injection to keep beam current constant:

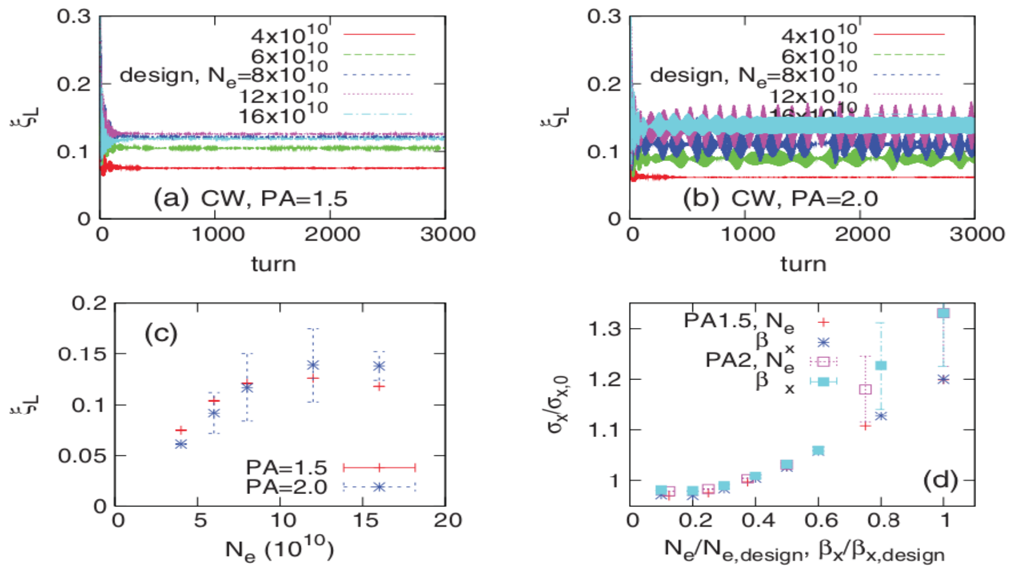
τ(min)	Z	WW	ZH	$t\bar{t}$
Bhabha	68	59	38	40 (39)
Beamstrahlung	> 200	>200	18	24 (18)

$\rightarrow$ full energy booster (in the same tunnel)

Some issues of FCCee.

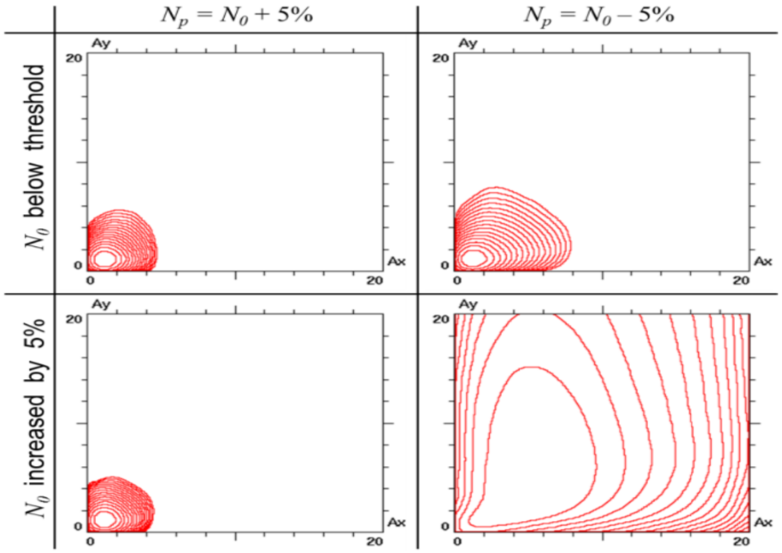
- Beam-beam effects:
  - FCCee test bench for beamstrahlung (high energy and large charge density). It affects the parameter choice in the various operation modes.
  - 2 kinds of instabilities found in simulations related to the crossing angle
    - ∗ beam-beam head-tail instability by "cross-wake" force may limit performance. Confirmed at SuperKEKB (Ohmi et al., eeFACT 2018).

Simulations for $\boldsymbol{H}$ operation with $\boldsymbol{Q_x}/2$=0.54, $\boldsymbol{Q_y}/2$=0.61



$\xi_L \propto \mathcal{L}/N_e$ Ohmi et al., PRL 119 (2017)

* 3D flip-flop instability in presence of beamstrahlung due to asymmetry in the population of the colliding bunches → "bootstrap" injection above the threshold current.



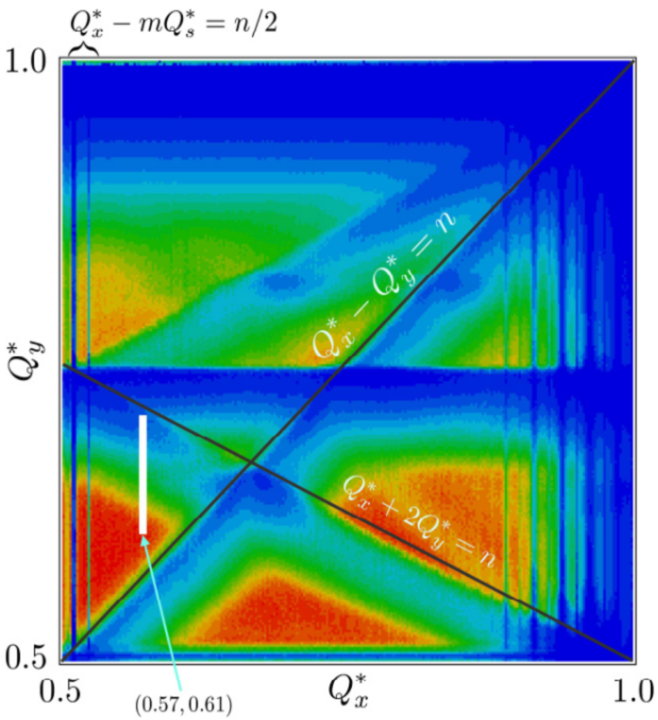
Shatilov (ICFA Newsletter 72)

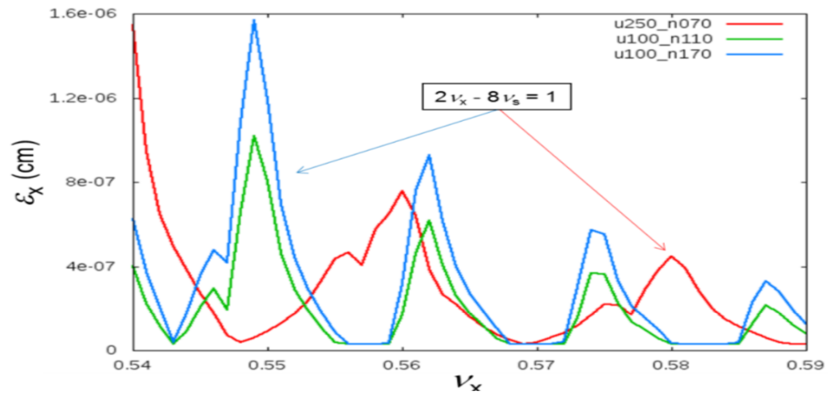
* At $t\bar{t}$ energy the instabilities are suppressed by the large damping, but beamstrahlung requires to increase β^*.

Differences between the two IPs: a potential source of troubles?

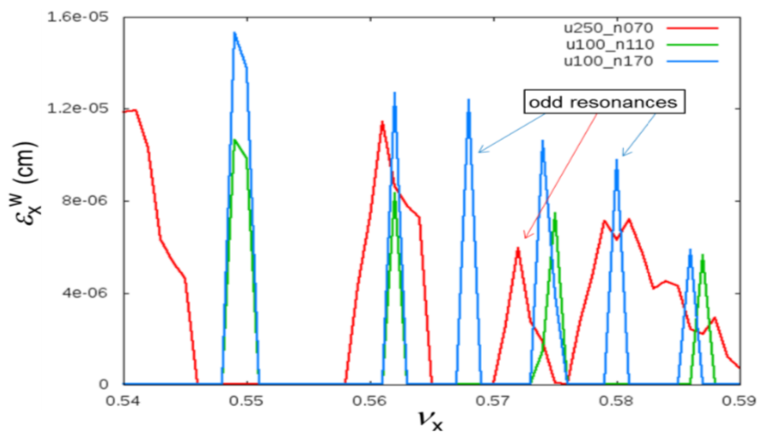
The instabilities related to the crossing angle have informed the choice of beam parameters at the different energies.

Parameter optimization for Z operation.





x-z instability



flip-flop

— ± 5%

— ± 3%

Shatilov (ICFA Newsletter 72)

- The very small β_y^* causes large chromaticity and response to vertical misalignments:
  - The IRs quadrupoles have a huge effect on the closed orbit.
  - It is crucial to have near-by BPMs and correctors to compensate their effects *locally*.
- Beam offsets in the sextupoles , in particular the LCC ones, produce tune shift and betatron coupling:
  - dipole and skew trim windings on the sexts are used for correcting orbit and coupling
  - trims on quads (needed for tapering) are used for optics correction
  - tricky correction procedure with errors and corrections in steps to get a stable machine and achieve the small ϵ_y in presence of reasonable misalignments

	Δx [μm]	Δ_y [μm]	Roll [μrad]
Arc quads	100	100	100
Sexts	100	100	0
IP quads	50	50	50

from CDR, studies to relax conditions still going on

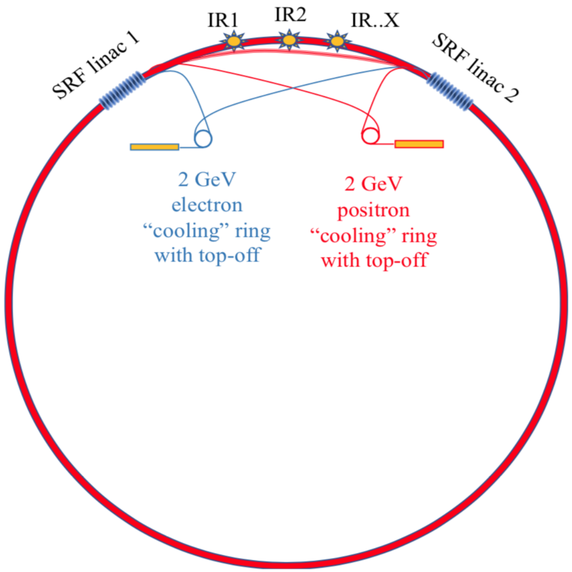
- Large momentum acceptance needed because of beamstrahlung
  - -2.8% – +2.5 % at $t\bar{t}$
  - at lower energy because of the increased $\Delta p/p$
- Large DA ($\gtrsim 12\sigma_x$) to accommodate top-up injection.
  - Sexts strengths optimized by down-hill simplex method in SAD.
    PSO (BESSYII) also suggested.
- e-clouds.
- Longitudinal bunch-by-bunch feed-back design, particularly demanding at Z operation (large number of bunches): Q_s=0.025 $\rightarrow$ 80 turns fastest manageable growth time.

- Beam polarization for precise energy calibration through resonant depolarization required at 45 GeV and 80 GeV:
  - wigglers needed at 45 GeV to reduce $\tau_{10\%}$ introduce more complexity to operation: they can be switched on only in the beginning of the injection with few bunches stored;
  - colliding bunch lifetime forces use of non-colliding bunches;
  - the required precision (better than 100 KeV for Z) calls for evaluation of possible biases and errors.
  - Computational problem: SITROS doesn't have all MADX features (no thin lenses, for instance); upgrade of computational tools desirable (BMAD).

FCC-e^+e^- using ERLs

Proposal by Litvinenko, Roser and Chamizo-Llatas of using ERLs.

Schematic layout with two ERLs inside the FCC tunnel.

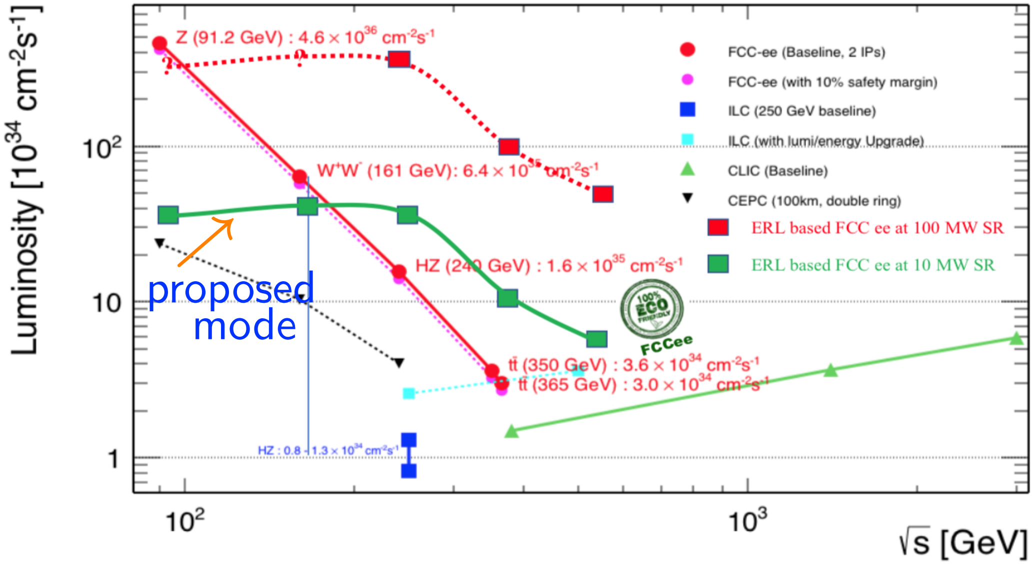


- Injection of $e^{\pm}$ from 2 GeV DRs into the SRF ERLs.
- Acceleration to top energy in the ERLs (4 or 6 turns).
  - IP is by-passed during beam acceleration.
- Deceleration of used beams to 2 GeV into the ERLs and injection in the DRs.

FCC arcs filled by combined function magnets with sextupole components.

Expected advantages:

- very small beam size,
- no beam-beam tune shift limitations,
- beam energy recovery,
- recycling of $e^{\pm}$ in ≈2 GeV damping rings.



- It opens the possibility of reaching ≈ 500 GeV in CM for ZHH production.
- Lower luminosity at 45 GeV, but 5 MW/beam radiated power.
- Possibility of injecting polarized beams.

- No possibility of high precision energy calibration through resonant depolarization.

Concept under test at CBETA, full energy recovery on one pass demonstrated in June.

Extremely small emittances:

- ϵ_x^N =4 μm $\rightarrow$ ϵ_x=17 pm at 120 GeV (vs. 600 pm original FCCee)
- ϵ_y^N =8 nm $\rightarrow$ ϵ_y=0.034 pm at 120 GeV (vs. 1.3 pm original FCCee)

Are they feasible in practice?

Linacs:

- ΔE=248 GeV (ZH) with 31 MV/m requires 8 km active length (w/o SR) $\rightarrow \approx$ 1 Km linac (each) in the 4 turns scenario.
  - The geometry must be compatible with the pp layout.

$\gamma\gamma$ colliders

$\gamma\gamma$ collider proposed in 1980 as extension for SLC and VLEPP physics program.
The idea got a new boost after the Higgs discovery as a cheaper way to build a Higgs factory.

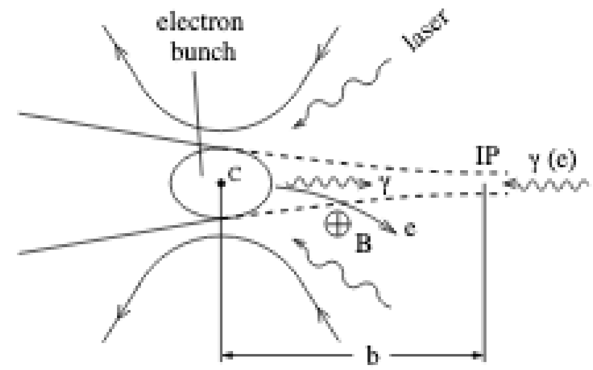
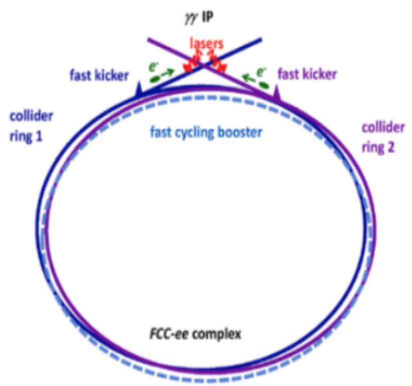


Figure 1: Scheme of $\gamma\gamma$, γe collider.

V. Telnov (KEK-Preprint 98-163)

Recent proposals as addition to (but using only e^-)

- CLIC and ILC
- FCC and CEPC.



Dedicated facilities

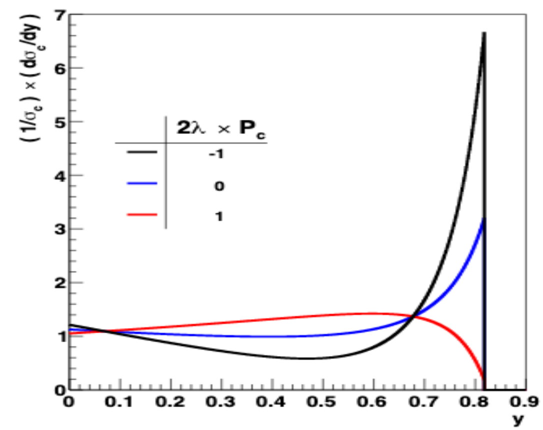
- SAPPHiRE
- HFiTT

The cross sections for Higgs production (ZH channel for e^+e^- and s-channel for $\gamma\gamma$) are similar for 120 GeV/beam and photon energy of 63 GeV.

The *maximum* energy of the inverse Compton scattered photon is

$$\hat{E}_\gamma = \frac{x}{1+x} E_e \qquad x \equiv \frac{4\hbar\omega_L E_e}{(m_0 c^2)^2}$$

x=4.48



$y \equiv E_\gamma / E$

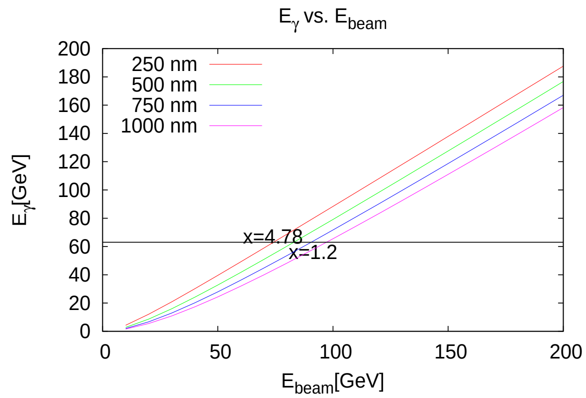
J. Gronberg (World Scientific, 2014)

The photon energy distribution depends on the product of longitudinal beam and circular laser polarization.

The best running mode is for $2\lambda \times P_c$=-1.

- The photon spot size at IP is about the same as that computed for the e^-, depending on the traveled distance to the IP and energy spread.
  - The luminosity is the "geometrical" one (no beam-beam effects).
- The parameter x should not exceed $\approx$ 4.8, above the photons produce e^+e^- pairs.

Setting x ≈4.6, 63 GeV photons can be produced with a 80 GeV beam; laser wavelength: 351 nm.

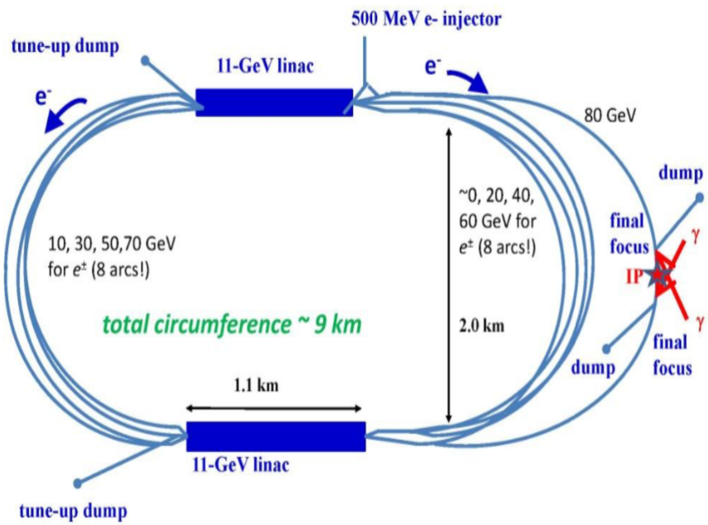


- No e^+ needed and only one DR for the linear collider option. No DR at all if source provides low emittance beams.

But...

- Only a fraction of the e^- will produce a photon: conversion efficiency ≈63%.
- The photons have a relatively large energy tail.
  - Actual luminosity: $\mathcal{L}_{eff} \approx 0.1 \times \mathcal{L}^{ee}_{geom}$.
  - The laser must match the e^- beam time structure, bunch size and length.

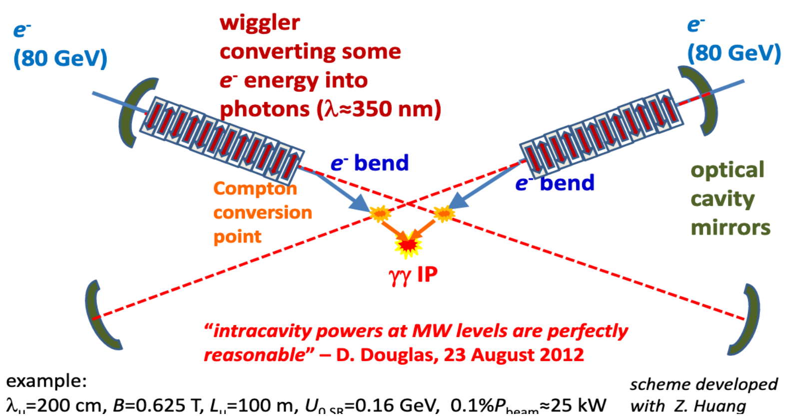
SAPPHiRE: 80 GeV recirculating linacs for a photon collider (SAPPHiRE)[a].



F. Zimmermann (Fermilab-TM-2558-APC)

Recent developments

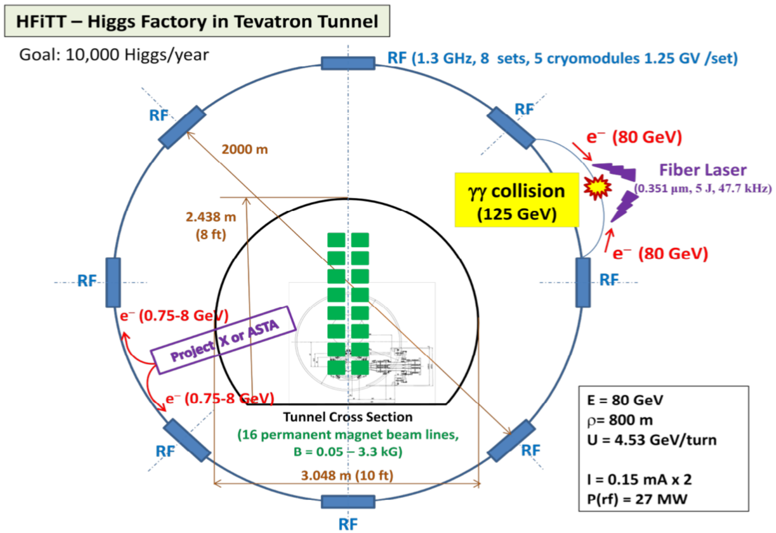
- use of fast kicker for avoiding beams circulating in opposite direction and reduce number of loops.
- FEL instead of laser: self-generated or driven by lower energy e^- beams.



F. Zimmermann (Photon Beams Workshop, 2017)

[a] Small Accelerator for Photon-Photon HIggs production using Recirculating Electrons

- Re-use of existing facilities (Tevatron tunnel)
  - HFiTT: a kind of (vertical) RL
    - 8 passes per beam (10 GeV/pass), ≈ 96 Km of beamline.



W. Chou et al. (Fermilab-TM-2558-APC)

Main parameters

Parameter	HFiTT	Sapphire	SILC	CLICHE
cms e-e- Energy	160 GeV	160 GeV	160 GeV	160 Gev
Peak $\gamma\gamma$ Energy	126 GeV	128 GeV	130 GeV	128 GeV
Bunch charge	2e10	1e10	5e10	4e9
Bunches/train	1	1	1000	1690
Rep. rate	47.7 kHz	200 kHz	10 Hz	100 Hz
Power per beam	12.2 MW	25 MW	7 MW	9.6 MW
L_ee	3.2e34	2e34	1e34	4e34
L_gg (E$\gamma\gamma$ > 0.6 Ecms)	5e33	3.5e33	2e33	3.5e33
CP from IP	1.2 mm	1 mm	4 mm	1 mm
Laser pulse energy	5 J	4 J	1.2 J	2 J
ε_x / ε_y [μm]	10/0.03	5 / 0.5	6 / 5	1.4 / 0.05
β_x / β_y at IP [mm]	4.5/5.3	5 / 0.1	0.5 / 0.5	2 / 0.02
σ_x / σ_y at IP [nm]	535/32	400 / 18	140 / 125	138 / 2.6

W. Chou (ICFA Mini-Workshop on $\gamma\gamma$ colliders, Beijing 2017)

Big technical challenges for all proposals:

- Laser parameters need (much) R&D. 2017 Beijing mini-Workshop: one session dedicated to lasers for various applications, no solutions prospects for $\gamma\gamma$.
- IR needs a careful design:
  - Focusing of the laser spot at the $e^-\gamma$ IP may interfere with the detector;
  - Background from spent electrons and dump of photons.

In addition for the recirculating linacs:

- e^- source
  - low emittance (1 μm);
  - highly polarized;
  - large charge (1.6 nC for SAPPHiRE);
  - high repetition rate (200 KHz for SAPPHiRE).
- Emittance dilution, in particular for HFiTT, from energy spread, chromaticity, optics mis-match, transfer from one arc to the next. Some studies done for SAPPHiRE.

Thanks!