65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)

INFN Istituto Nazionale di Fisica Nucleare LABORATORI NAZIONALI DI FRASCATI

ICFA

iFAST

Accelerator physics summary
(WG1, WG3, WG4, WG6, WG8, WG10)

M.E. Biagini, INFN-LNF

Frascati, September 15th 2022

Disclaimer

- SuperKEKB experience was extensively covered
- Most of other talks related to the huge on-going effort for FCCee and CEPC (with some glimpse to EIC). Congratulations!
- Extremely good and interesting talks, but it is impossible to summarize all 45 from WG1, WG3, WG4, WG6, WG8, WG10
- Had to pick just a little portion of the material presented, thanks to all speakers and apologies to those that will not be mentioned here

A recommendation to the “young” people working on FCCee and CEPC

- A lot of theoretical and simulation work is going on for FCCee and CEPC, but a closer collaboration with the SuperKEKB team is needed
- Go to KEK and experience what a real beam looks like (usually a lot different from your simulations…)

SuperKEKB, Y. Onishi

Obstacles to Luminosity Improvement

- Beam blowup in the LER (single beam, non-collision) : "-1 mode instability"
- Sudden beam loss (fast beam loss, especially in the LER)
  - Damage of collimator head due to large beam loss
- Lower beam-beam parameter: ~0.035 at 0.7 mA
- Beam current dependence of beam orbit
  - Orbit deviation at strong sextupoles is caused by beam line deformation due to intense SR heating.
- Short beam lifetime (dynamic aperture, physical aperture) : LER 8 min(1.25 A) / HER 25 min(1 A) n_b=2346
- Beam related background (optimization of collimator, QCS aperture, IR orbit)
  - A. Natochii, Tuesday, September 13 (WG5)
- Beam injection (small physical aperture of injection region, emittance growth in the beam transport line)
  - T. Natsui, Thursday, September 15 (WG6)
- Earthquake : The beam aborts invariably. The ε_y becomes large in the HER. The optics correction is needed.

SuperKEKB, Y. Onishi

Summary

- Peak luminosity of 4.65 (4.71) x 10^{34} $cm^{-2}s^{-1}$ was achieved in 2022.
- Stable operation over 1 A in the LER is possible if the bunch current is smaller than 0.7 mA.
- "Sudden beam loss" is the most serious problem to increase beam current so far.
- Beam blowup in the LER is still unclear. Lower impedance of collimators, BxB FB tuning, and higher vertical tune help to suppress the beam blowup above I_b = 0.8 mA. (single bunch issue)
- Beam line deformation as a function of beam current induces the large beta-beat (change of β_y^*) and global X-Y couplings. The deformation is due to SR heating. The orbit deviation at the strong sextupoles affects optics.
- BPM accuracy for all beam current region is required since the optics correction is performed at 50 mA and physics run is over 1 A.
- High current operation over 1 A is quit different from a few hundreds of mA. The 2022 run was the dawn of a new window for SuperKEKB.
- Short beam lifetime; both of dynamic aperture and physical aperture, need to check crab waist ON and OFF.
- Injection efficiency becomes poor as squeezing β_y^*. It is important to achieve 10^{35} $cm^{-2}s^{-1}$ to solve issues such as emittance growth of injection beams (CSR), injection backgrounds, and so on.

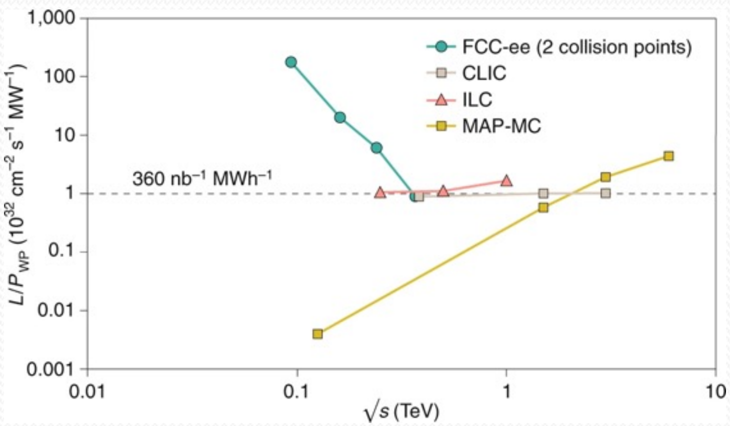
FCCee, F. Zimmermann

FUTURE CIRCULAR COLLIDER

sustainability and carbon footprint studies

highly sustainable Higgs factory

luminosity vs. electricity consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

optimum usage of excavation material

int'l competition "mining the future®"

https://indico.cern.ch/event/1001465/

FCC-ee annual energy consumption ~ LHC/HL-LHC

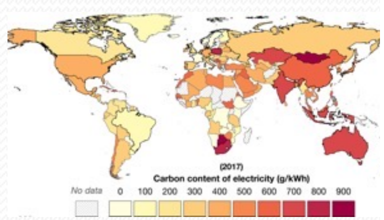
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

J.-P. Burnet, FCC Week 2022

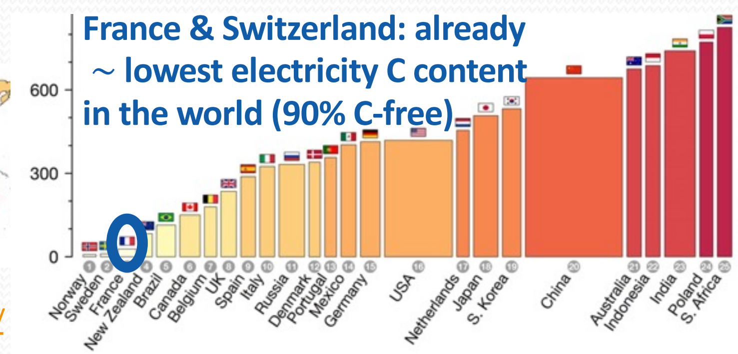
incl. CERN site & SPS

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

powered by mix of renewable & other C-free sources



https://www.carbonbrief.org/



FCCee, F. Zimmermann

sustainability compared with other Higgs factories

FUTURE CIRCULAR COLLIDER

Patrick Janot

https://indico.cern.ch/event/1178975/

P. Janot and A. Blondel, *Who is the greenest? - The environmental footprint of future Higgs boson studies*, arXiv 2208.10466 (2022); https://arxiv.org/abs/2208.10466

TWh / year for the "Higgs factory" centre-of-mass energy

$\sqrt{s}$ = 240 GeV for CEPC/FCC-ee, 250 GeV for ILC/C^3, 380 GeV for CLIC

CLIC	ILC	C^3	FCC-ee	CEPC
0.8	0.9	0.9	1.1	2.0

Energy consumption in MWh / Higgs

CLIC	ILC	C^3	CEPC	FCC-ee
30	20	21	10	3.3

becomes 2 MWh / Higgs for FCC-ee with 4 IPs

Present carbon footprint for electrical energy in tons CO_2 / Higgs

CLIC@CERN	ILC@KEK	C^3@FNAL	CEPC@China	FCC-ee@CERN
2.1	7.8	8.5	6.1	0.24

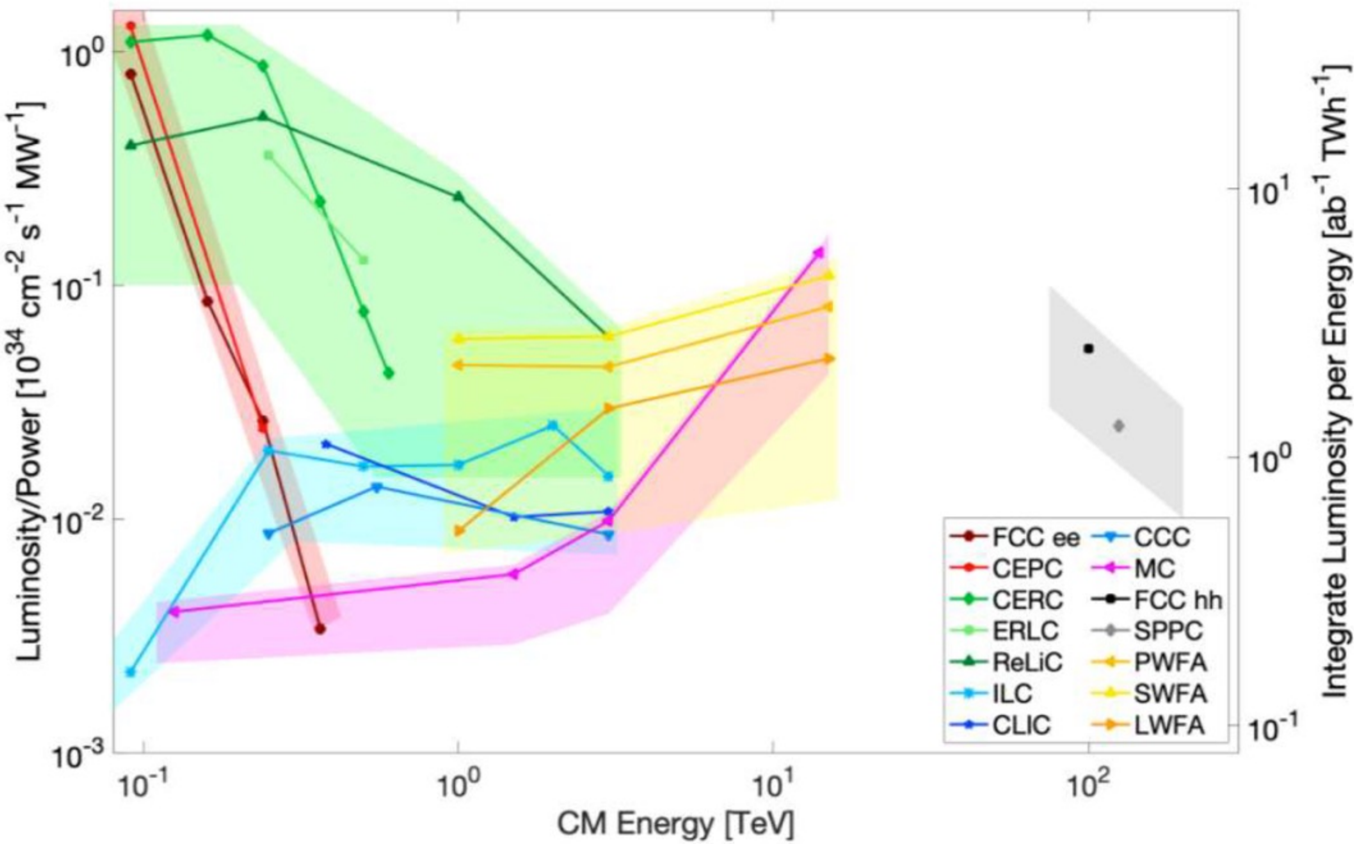
0.14 ton CO_2 / Higgs for FCC-ee with 4 IPs

Luminosity per Power

Limits of Colliders, V. Shiltsev

Circular *ee*	ERL based *ee*	Linear *ee*	Muon coll	Wakefield	Hadron *pp*

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Integrated luminosity assumes 10^7 seconds per year.
- The luminosity is per IP.
- Data points are provided to the ITF by proponents of the respective machines.
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



Once again: luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.

Fermilab

ITF Report – T.Roser, et al, arXiv:2208.06030

Limits of Colliders, V. Shiltsev

Main Conclusions:

- **For ultimate high energy colliders:**
  - Major thrust is *Energy*
  - Major concern/limit *is Cost*
  - Main focus is *Luminosity* and *Power*
  - *There are other important factors (CO_2 footprint, etc)*
- **Cost:**
  - Critically dependent on core acceleration technology
  - Existing injectors and infrastructure greatly help
- **High *E*nergy means low *L*uminosity :**
  - Don't expect more than 0.1-1 ab^{-1}/yr at 30TeV - 1 PeV
  - Assume *P*ower limited to 1-3 TWh/yr (1-3 x LHC)

Fermilab

Main Conclusions (2):

- **For considered collider types:**
  - Circular *pp* – limit is ~100 TeV (14 TeV cme per parton)
  - Circular *ee* – limit is ~0.4-0.5 TeV
  - Circular *μμ* – limit is between 30 and 100 TeV
  - Linear RF *ee/γγ* and Plasma *ee/γγ* – limit is between 3 and 10 TeV
  - Exotic crystal *μμ* – promise of 0.1-1 PeV, low *L*uminosity
- **Muons are particles of the future**

PERFORMANCES HIGHLIGTHS

- RF extremely **reliable:** apart the new HOM cavities, the system (power-wise) was dimensioned for the former machine that required about twice more RF power. "A car designed to run at 100km/h seldom fails if runs at 60km/h"

- Power Supplies (more than 600 LGPS) have a MTBF > 500000Hr and in addition an HOT-SWAP system is implemented: **beam losses due to PS failures negligible**

- Vacuum levels and conditioning **at least a factor 2 better than expected**

- Machine alignment **about a factor 2 better then requested => greatly beneficial to commissioning and final performances**

- Beam stability **5 times better than the old machine:** about 15% of the total cost of the project went in the support system (girders, technical choices for magnets supports etc…)

- **Optics very stable in time:** support and diagnostic (5% of the total cost)

ESRF

Lessons from ESRF, P. Raimondi

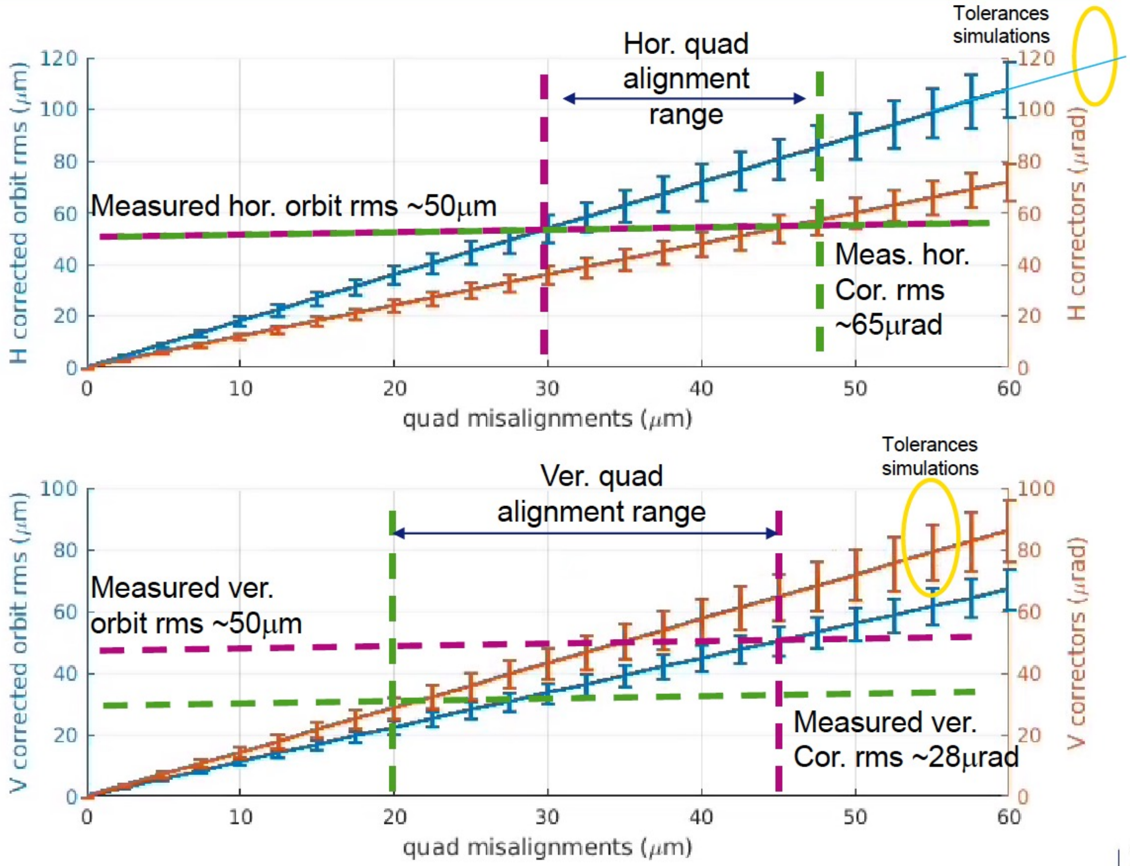
SR ALIGNMENT BETTER THAN EXPECTED

30th Jan 2020 : 26/27 BEAMLINES see Synchrotron radiation at White Beam viewer

From simulations the estimated SR alignment errors are:
H 30-45 μm
V 20-45 μm

The quadrupole alignment tolerances required where:
H 50 μm
V 50 μm

Rough estimation.
Errors only in quadrupoles.



Lessons from ESRF, P. Raimondi

CONCLUSION

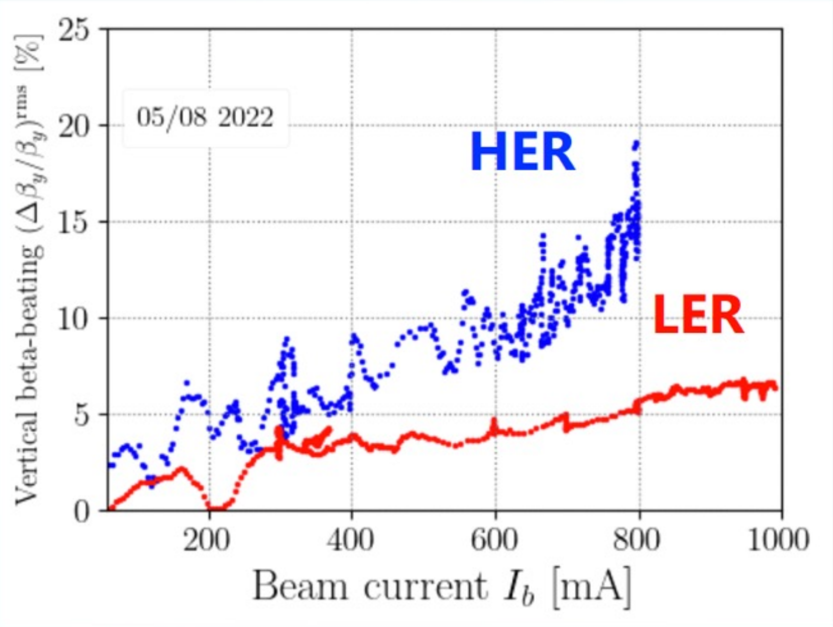
- EBS has been extremely useful to develop system-integration tools that finally allows the realization of a new generation of low emittance rings.
- Our optics know-how and present tuning capabilities are up to the needs to timely achieve and maintain design performances.
-

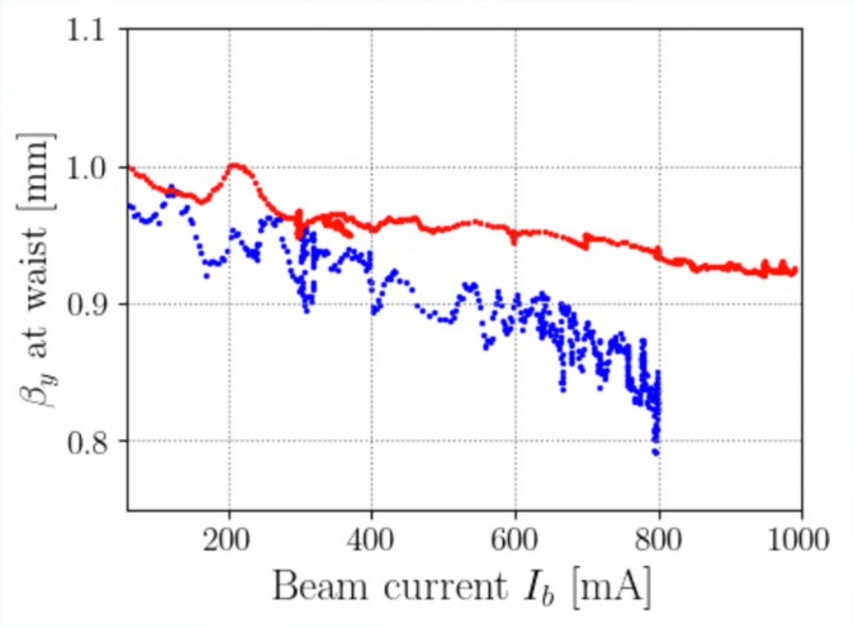
Success is a matter of cost!

- studied/optimized prior construction.
- The need of finalizing the design and start construction imposes limits to the design phase. To cope with the unforeseen, the machines should have a degree of flexibility as large as possible. For EBS this flexibility could be estimated in about 10% (individual PS, extended diagnostic, etc) of the total cost.

Lessons from ESRF, P. Raimondi

Estimated Optics Distortion due to Orbit at SLY Magnets





- Orbit at SLYs causes not only tune shift but also beta-beating.
- Vertical beta function at the waist becomes smaller as beam current becomes higher.
  -> It indicates that we operated SuperKEKB with $\beta_y^* < 1$ mm without knowing.

Fixed by orbit bump (feedback)

SuperKEKB optics tuning and issues, H. Sugimoto

Summary

- Global optics tuning is based on analysis of closed orbit response.
- Optics parameters at IP is based on daily IP knob tuning and observed machine performance.
- Tilting sextupole magnets work well in mitigating synchro-beta resonance.
- Field drifting of QCS depending on ramp cycle was observed.
  -> We modified the ramp cycle in its startup, then the drifting is much reduced.
- Beam current dependency of vertical tune shift is attributed to the beam orbit change at SLYs.
  Where is resistive wall tune shift in vertical direction?
  The mechanism of the beam current dependence is not understood yet.
  (Beamline deformation due to SR and/or HOM heating?)
- The orbit at SLY is very important parameter to be carefully monitored.
- Optics degradation in a few days is one of urgent issues in high beam current operation.
  It seems that beam orbit change of a few ten microns is not negligible.
  More precise orbit control is probably essential.

SuperKEKB optics tuning and issues, H. Sugimoto

major beam frontier challenges

1. synchrotron radiation
2. bending magnetic field
3. accelerating gradient
4. (rare) particle production – e^+ and μ
5. cost and sustainability
6. exploring novel directions

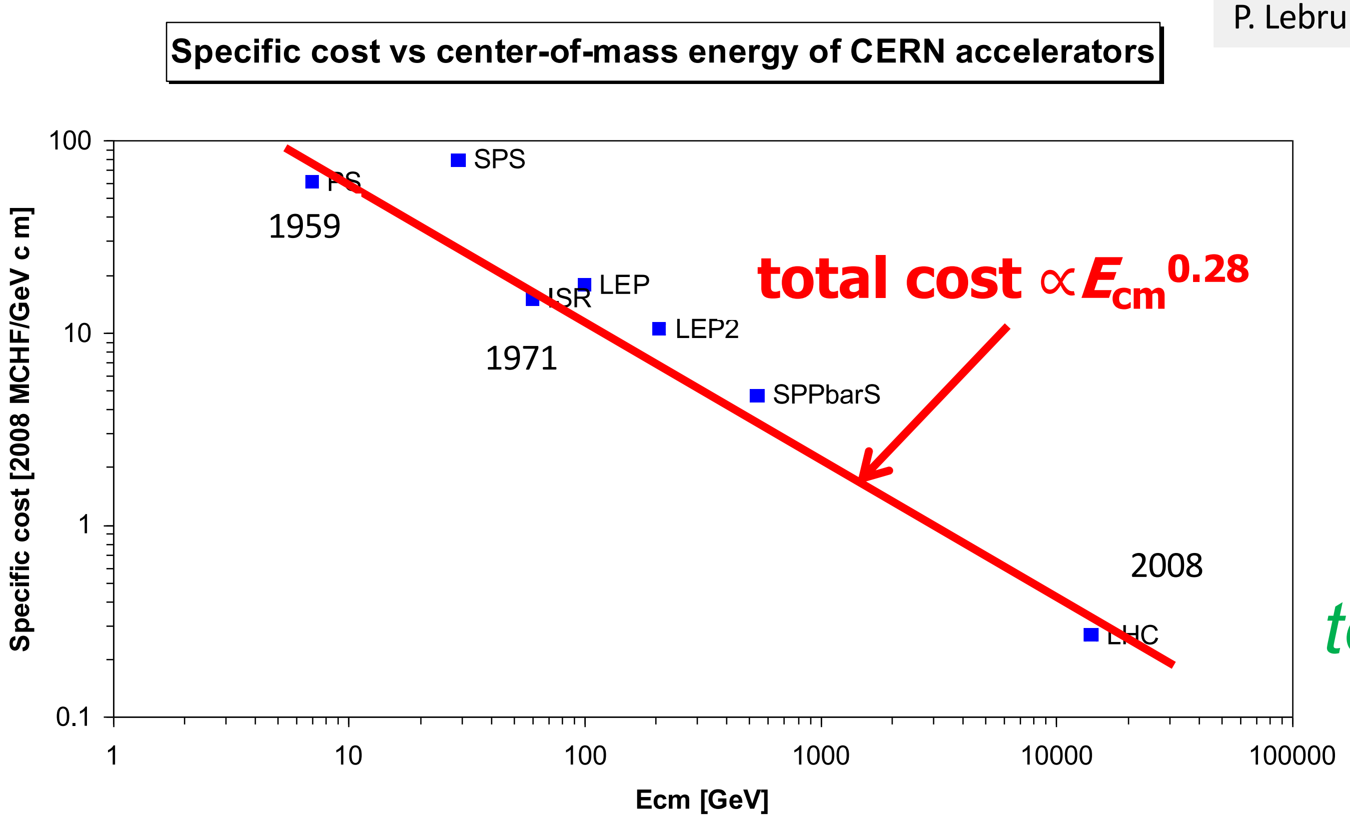
SR in the arcs: possible mitigations (challenge #1)

mitigations:

- **large bending radius ρ**
  → large circular collider
- **linear collider**
  - ”almost” no arcs, but beamstrahlung
- **muon collider**
  - μ ~200 heavier than $e^{\pm}$ → ~10^9x less radiation at same energy and radius, but μ’s decay
- **shaping beam vacuum chamber or the beam itself**
  - tiny vacuum chamber in large ring, $\lambda_{sh} \approx 2\sqrt{d^3/\rho}$ with *d:* pipe diameter
  - beam shaping to suppress radiation; a DC beam does not radiate! explored in EU projects ARIES & I.FAST

challenge #5: cost / sustainability

P. Lebrun, RFTech 2013

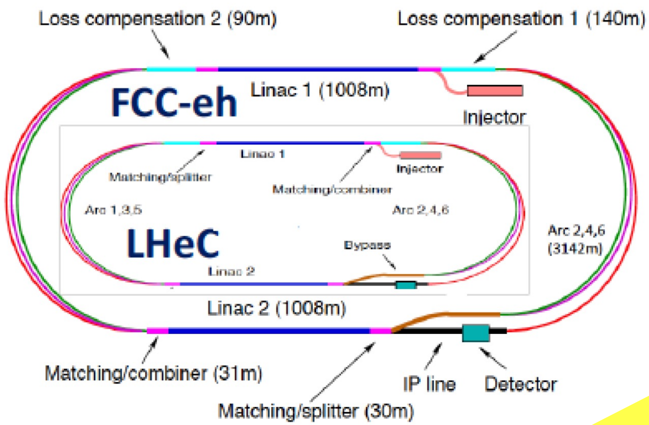


new concepts and new technologies

cost per collision energy greatly reduced

Possible Future Colliders based on ERLs

Energy Frontier Collider Applications of Energy Recovery Linacs

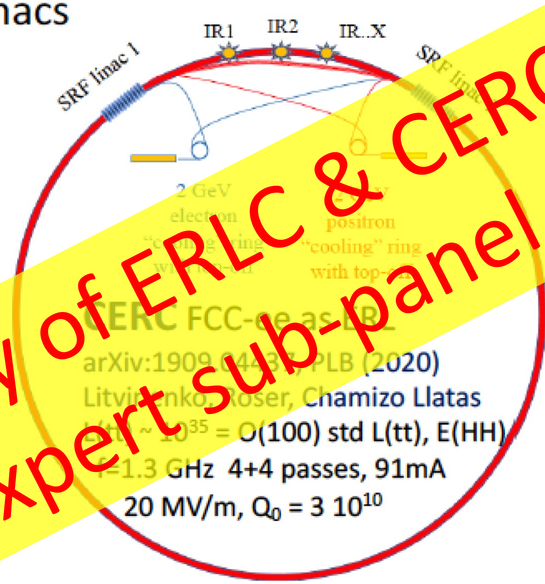


$\mathrm{sqrt}(s_{ep})$ = 1-4 TeV

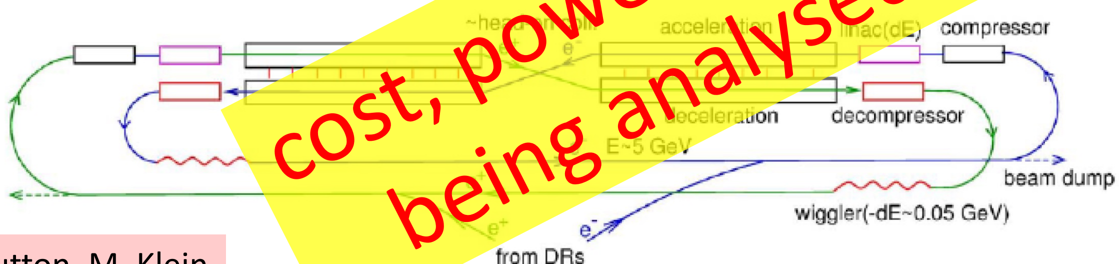
L(HERA) x 1000
(ERL and LHC)

1206.2913, JPhysG
2007.14491, JPhysG

f=802Mz,
3+3 passes: 20mA x 6
20 MV/m, Q_0 ~ 10^{10}



CERC FCC-ee as ERL
arXiv:1909.04437, PLB (2020)
Litvinenko, Roser, Chamizo Llatas
L(tt) ~ 10^{35} = O(100) std L(tt), E(HH)
f=1.3 GHz 4+4 passes, 91mA
20 MV/m, Q_0 = 3 10^{10}



ERLC ILC as ERL
V. Telnov at LCWS → arXiv:2105.11015
L(ERLC) ~ 10^{36} = O(100) std L(ILC)
This yields O(10^7) HZ events in 3 years.
1+1 passes, I =160m
f=750 MHz, 20 MV/m, Q_0 > 10^{10}

A. Hutton, M. Klein

cost, power & feasibility of ERLC & CERC being analysed by expert sub-panel

ee

SuperKEKB beam-beam simulations, D. Zhou

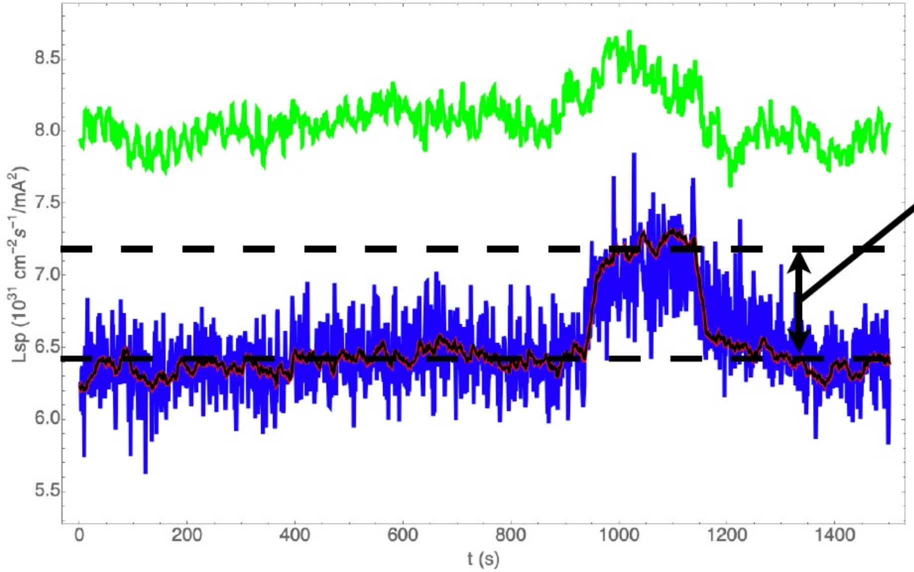
Status of beam-beam simulations

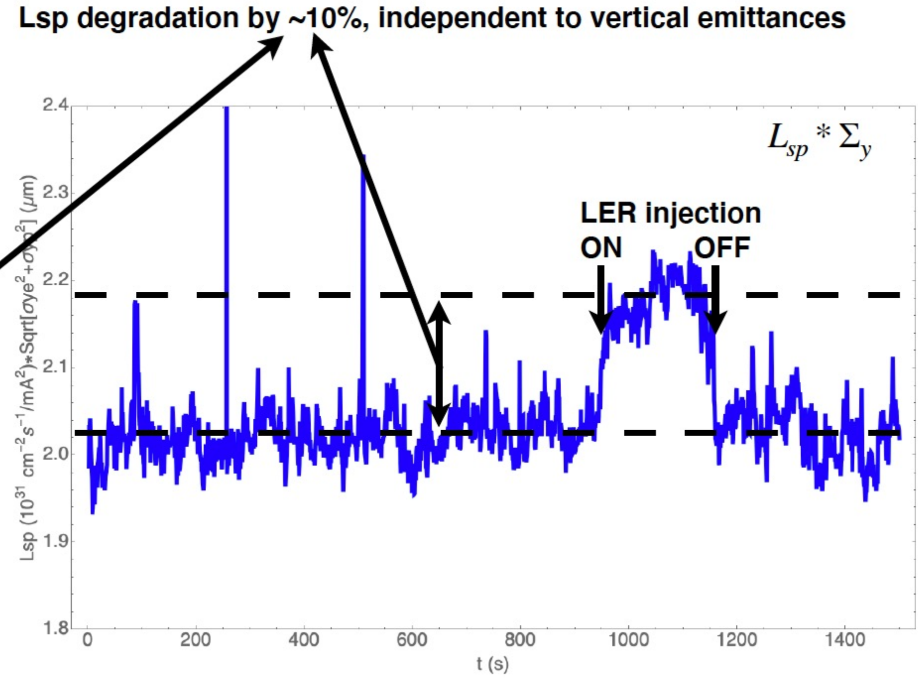
- Beam-beam simulations have shown that multiple factors can strongly interplay with beam-beam interaction
  - Imperfections in linear optics: beta beat, linear couplings, dispersions, etc. at the IP
  - Geometric nonlinearities: It is crucial when $\beta_y^* < 1$ mm
  - Coupling impedances: Longitudinal and transverse (See C. Lin and Y. Zhang's talks)
  - Space charge
  - BxB feedback
- Predictability of beam-beam simulations: The case of SuperKEKB sets demands on
  - Accurate modeling of linear optics
  - Strong-strong model of beam-beam interaction
    - X-Z instability(i.e. Beam-beam head-tail instability)
    - Synchro-betatron resonances with working points near half integers
  - Reliable impedance modeling
    - Longitudinal impedance: potential-well distortion and synchrotron tune spread
    - Transverse impedance: Betatron tune shift and spread
    - Monopolar (longitudinal potential-well distortion and transverse beam tilt), dipole (TMCI), and quadrupolar (tune shift)

Comparison of simulations and experimental results

- A mysterious phenomenon: Lsp is correlated with beam injection
  - All luminosity PVs gave a similar jump-response to injection stop/start.
  - $L_{sp} \cdot \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}$ still shows jump-response. It means there is a geometric loss of luminosity.

Blue: Luminosity by ECL
Red: Luminosity by ECL (averaged)
Green:Luminosity by ZDLM
Black: Lsp

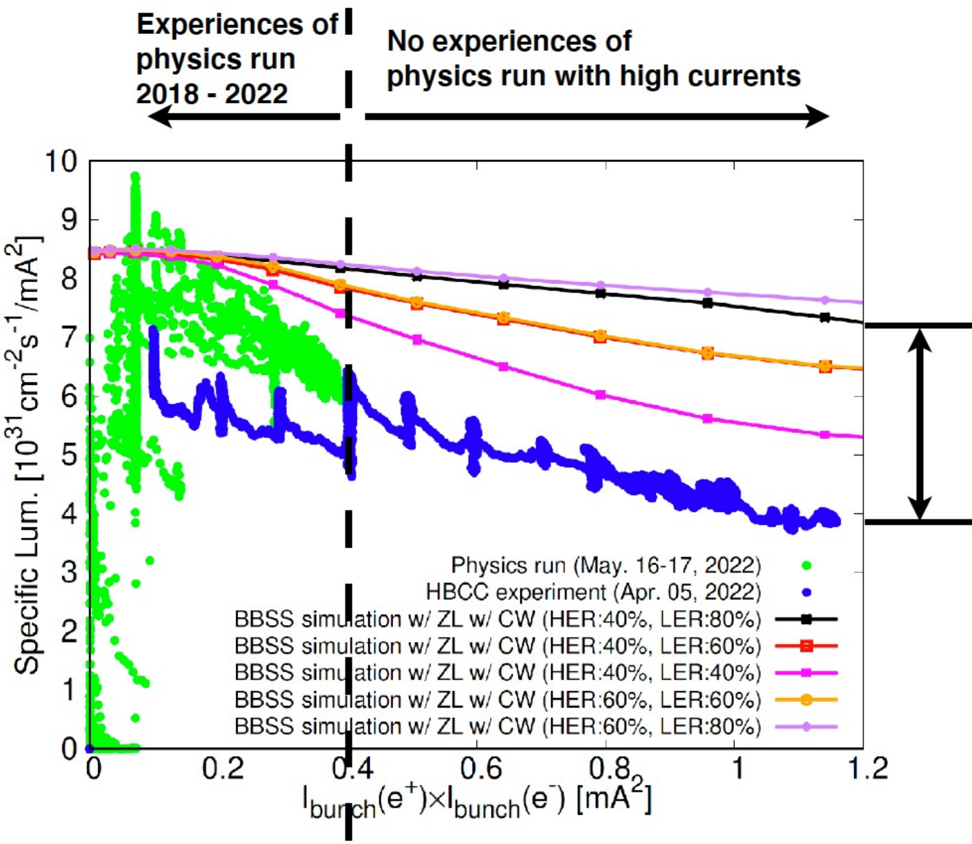




Online data: 2022-06-02 21:05 PM

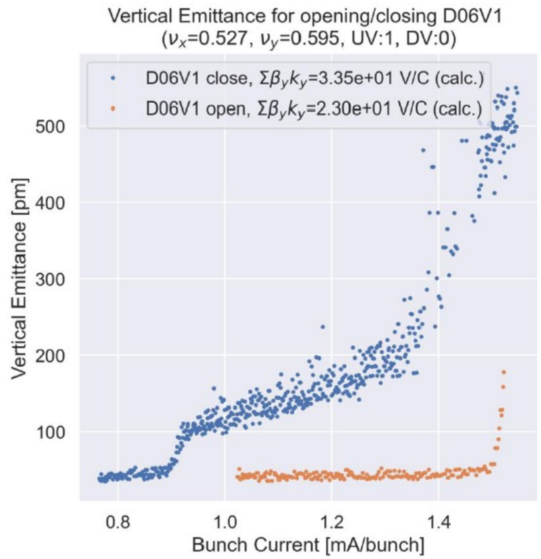
Comparison of simulations and experimental results

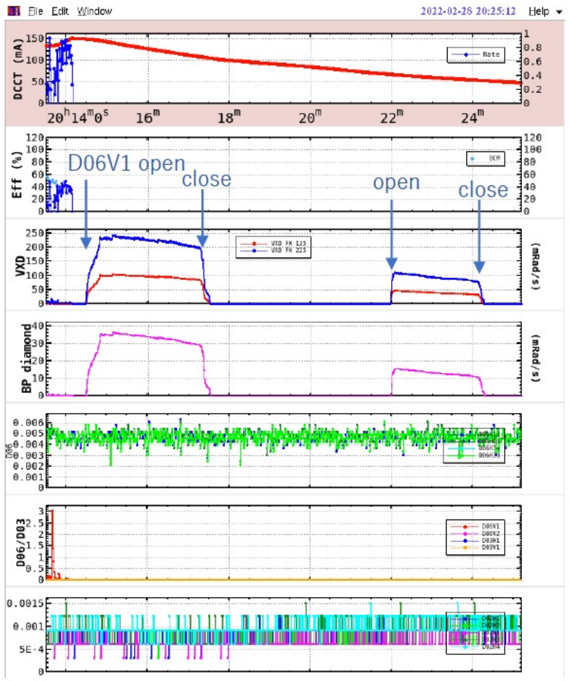
- Filling the gap between simulated and measured Lsp
  - BBSS+PIC simulation showed 5% less Lsp at $I_{b+}I_{b-} = 0.8$ mA^2.
  - Impedance effects:
    - Simulations showed less bunch lengthening than measurements. If measured bunch lengthening is applied, it gives ~10% extra loss of Lsp at $I_{b+}I_{b-} = 0.8$ mA^2.
    - Vertical beam tilt due to monopolar wakes.
    - "-1 mode instability" due to interplay of FB and vertical impedance.
  - Lsp loss correlated with injection: ~10% at $I_{b+}I_{b-} = 0.3$ mA^2 (not sure how much loss at high bunch currents).
  - Other sources of Lsp degradation without quantitative estimate.

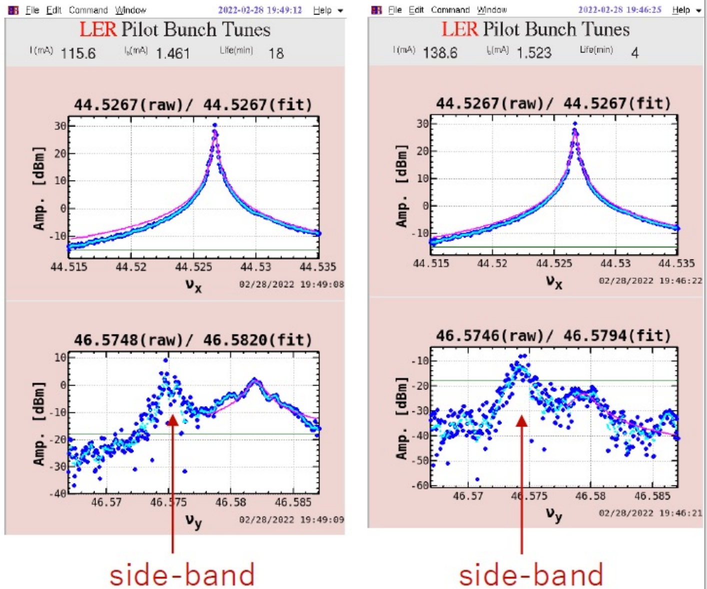


- Prediction of luminosity via beam-beam simulations requires reliable models of 1) beam-beam interaction, 2) machine imperfections, and 3) other collective effects.
- Crab waist is powerful in the suppression of nonlinear beam-beam effects.
- With progress in machine tunings, the measured luminosity of SuperKEKB is approaching predictions of BB simulations (BB + Simple lattice model + Impedance models).
- Many subjects/ideas are to investigated/tried (both simulations and experiments) to achieve higher luminosity at SuperKEKB.

Vertical Emittance w/wo D06V1







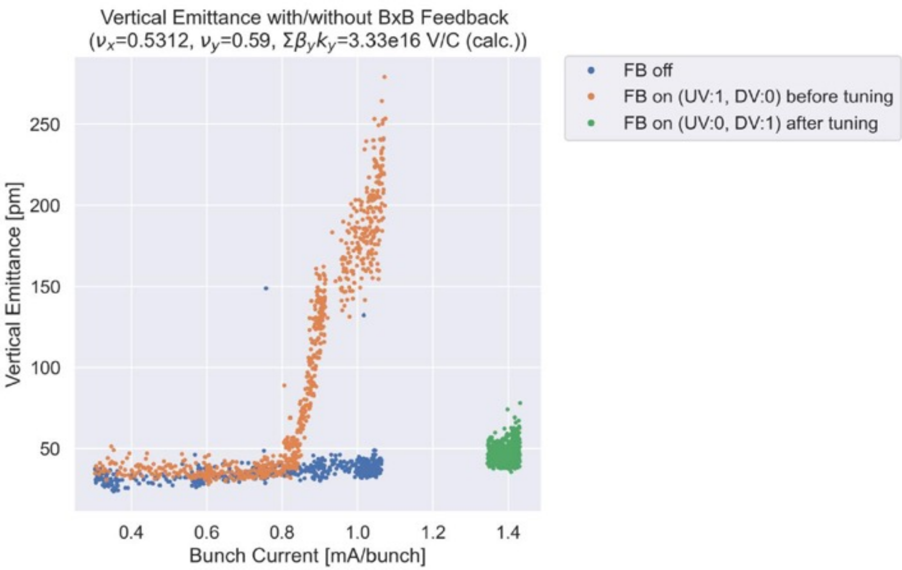
- When we fully opened the aperture of D06V1, the vertical emittance blow-up didn't occur up to ~1.5 mA/bunch.
  - (D06V1 aperture) close: ±2.9 mm, open: ±8 mm
- The background level derived from the storage beam increased when we opened it. We've used D06V1 as a primary collimator to cut off the injection backgrounds, but these observations indicate this collimator contribute to suppress the storage backgrounds too.

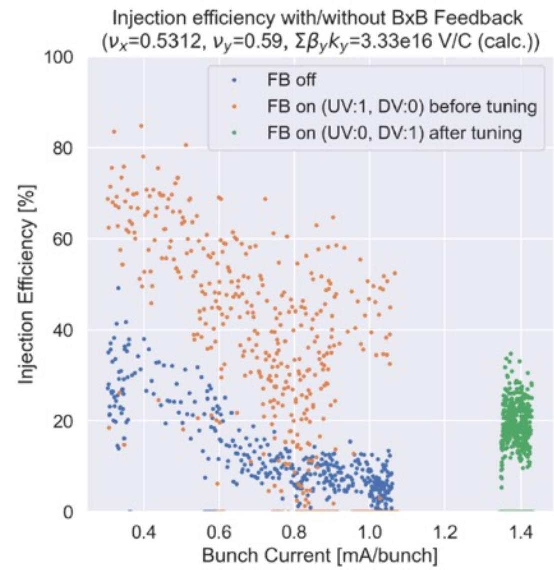
Beam blow-up and collimator aperture

Impedance and instability studies at SuperKEKB, K. Ohmi

Vertical Emittance w/wo BxB FB (Mar. 1st)

33-bunch operation





- We observed the vertical emittance with turning on/off the feedback (FB) with small number of the bunches to avoid multi-bunch instabilities.
- When we turned on the FB, the blow-up occurred around 0.85 mA/bunch.
- When we turned off the bunch-by-bunch FB, the vertical emittance blow-up didn't occur up to around 1.06 mA/bunch (poor injection rate above than this current).
- After the tuning of the FB to suppress the "-1 mode instability", the blow-up didn't occur up to ~1.44 mA/bunch (design bunch current in LER).

Single bunch instability driven by multi-bunch feedback, corrected with tuning FB

WG8 Polarization and polarimetry

WG8 Conclusions

- Progress in upgrading computational tools shown by Oleksii Beznosov for EIC and Yi Wu for FCCee.
- Update of achievable polarization of the EIC ESR in presence of realistic misalignments: less spin diffusion prone optics allows to relax closed orbit correction (talk by Vahid Ranjbar).
- Clever lattice design allows large polarization preservation by fast crossing of resonances during acceleration (talks by Vahid Ranjbar and Zhe Duan).
- Stringent requirements for e^- polarimetry at EIC can be met (talk by Dave Gaskell).
- New approach to polarization at CEPC: polarized e^-source, damping ring with wigglers for polarizing e^+, solenoid rotators for physics (Zhe Duan).

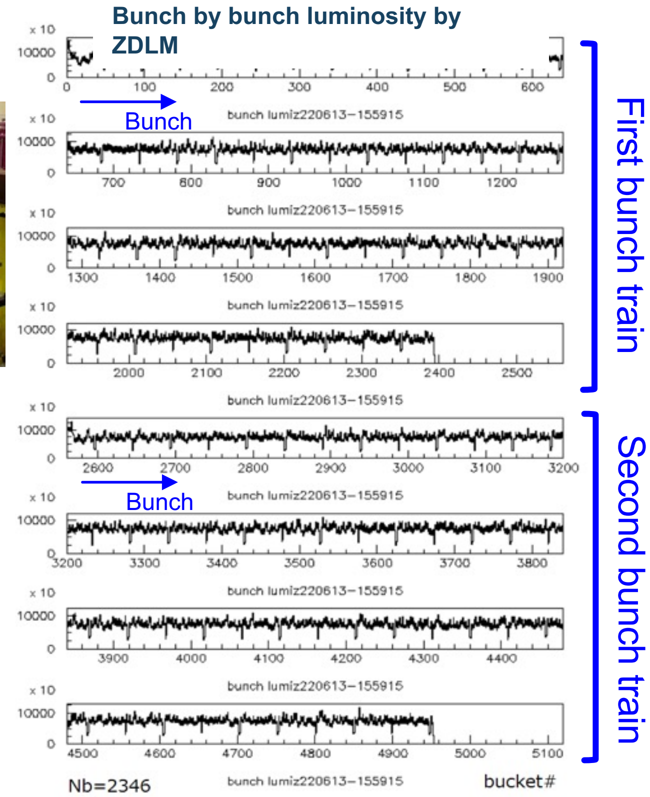
Thanks to E. Gianfelice for this summary

ECE in SuperKEKB, Y. Suetsugu

ECE in Phase-3 commissioning (2022)

- The luminosity of each bunch was measured by ZDLM (Zero Degree Luminosity Monitor).
  - The electromagnetic calorimeters which aim to measure the bunch-by-bunch luminosity.
  - The calorimeters detect electromagnetic showers induced by photons or positrons from the radiative Bhabha scattering.

ZDLM



Courtesy of S. Uehara, Belle II

- As seen in the figure, the bunch luminosity seems to be flat along the train, and there is no apparent "long-term" change for each train, which would be resulted in due to the beam-size blow-up caused by the ECE. (2/1173/2.04RF)
  - A piece of supporting evidence that there is no beam size blow-up caused by the ECE during the physics run.

Mitigation of ECE very successful, what about with design beam current?

FCCee parameters for luminosity, D. Shatilov

Lattice Errors and Misalignments

- Misalignments and errors can lead to a significant decrease in the DA and momentum acceptance. This limits the luminosity per IP even in the case of ideal super-periodicity.
- The full beam-beam footprint from 2 or 4 IPs can cross a number of strong resonances, e.g. 1/2, 1/3, etc. The width of these resonances depends on the level of symmetry breaking, which depends on the magnitude of misalignments and the quality of corrections.
- Ways to solve the problem: improve the quality of corrections, and reduce the magnitude of misalignments (can be expensive!). Perhaps the increased accuracy of the alignment will be required only for some sections, and not for the entire ring – this needs to be clarified.
- Error correction should consist of several stages: obtain a stable orbit and designed emittances, then enlarge the DA and momentum acceptance, and special attention must be paid to obtaining designed lattice parameters at the IPs and crab sextupoles (dedicated knobs at the IR). This work is ongoing and notable progress has been made recently.
- A realistic assessment of the beam dynamics, luminosity and lifetime is possible only in simulations, taking into account all errors, corrections and beam-beam effects.

FCCee parameters for luminosity, D. Shatilov

Conclusion

- The main parameters of FCC-ee (lattice, RF, beta-functions at the IP, etc.) are more or less defined. Further optimization is mainly related to misalignments and errors, and it will affect only the bunch population N_p (and, accordingly, the number of bunches n_b and luminosity).

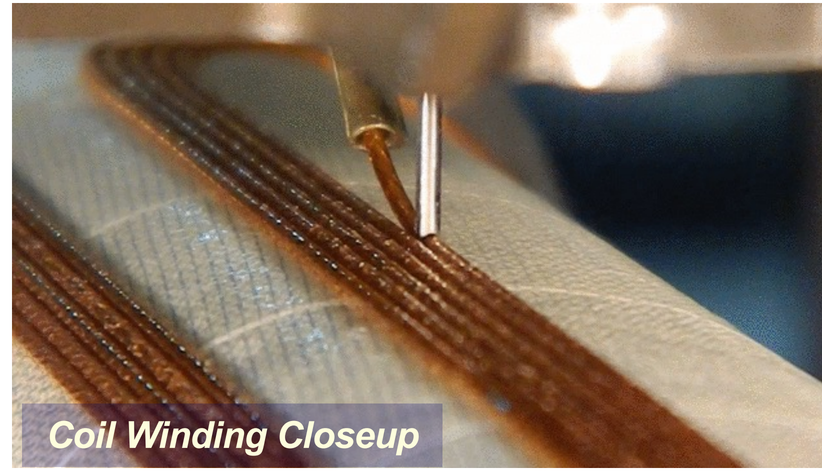
- There are many other things that depend on N_p and n_b. For some of them (i.e. electron clouds and ion instabilities, mainly at Z), an increase in N_p and, consequently, a decrease in n_b are beneficial. For impedance-related phenomena, the opposite is true. In any case, <u>we need to have large flexibility in these parameters</u>.

- Perhaps as we resolve the current issues, new ones will be discovered. Parameter optimization is a very interesting and exciting (and maybe endless) process, the work continues...

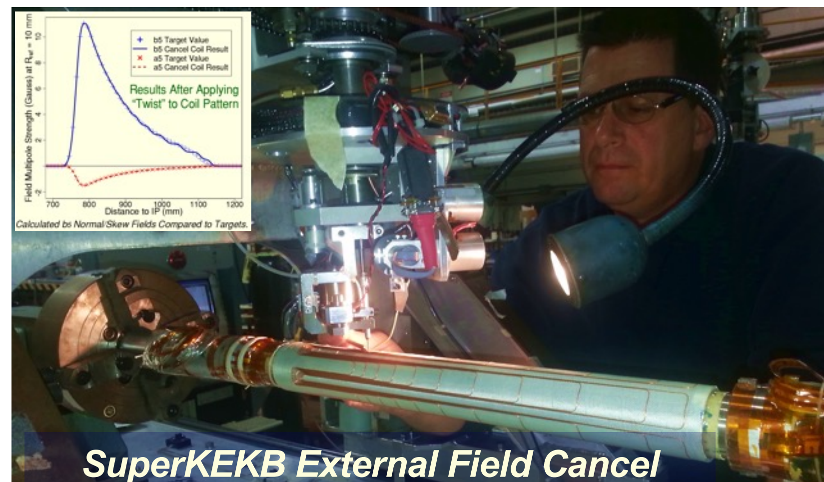
Direct Wind Magnets, B. Parker

- Review motivation and development of BNL Direct Wind.
- Compare / contrast Planar and Serpentine Patterns.
- Show ILC QD0 Direct Wind active shielding configuration.
- Compare / contrast Serpentine and Double Helical (CCT) approaches for performing localized field profile tailoring.
- Propose using Direct Wind for making FCC-ee IR correctors.
- Show some future applications for SuperKEKB and the EIC.

1. Temporarily bind round conductor/cable to a substrate covered support tube.
2. Fill empty space in coil pattern with G10/Nomex/epoxy.
3. Wrap with fiberglass roving under tension to provide prestress after which cure the epoxy.
4. In multilayer structures, make magnetic field harmonic measurements that are then used to fine tune ultimate field quality by adjusting later coil windings.



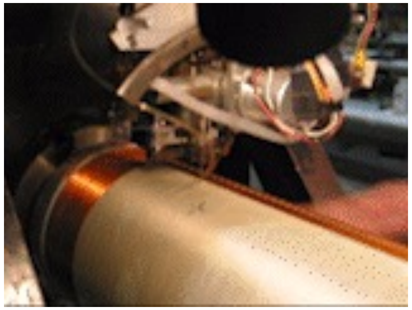
Coil Winding Closeup



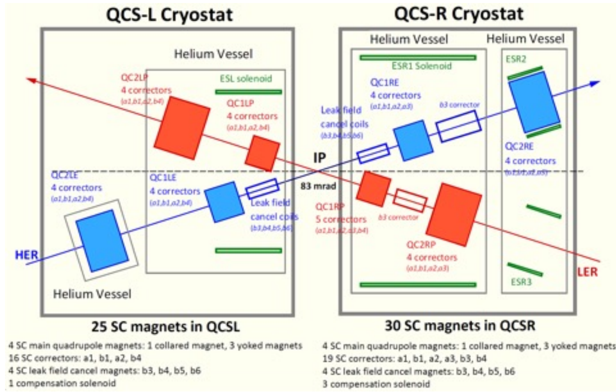
SuperKEKB External Field Cancel Coil

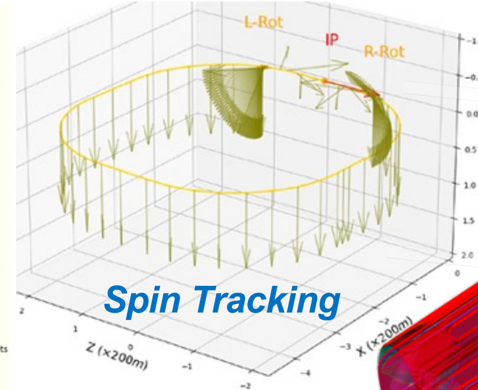
Outline: Direct Wind Magnets for ILC, SuperKEKB, FCC-ee and EIC

How to incorporate Spin Rotators in SuperKEKB!



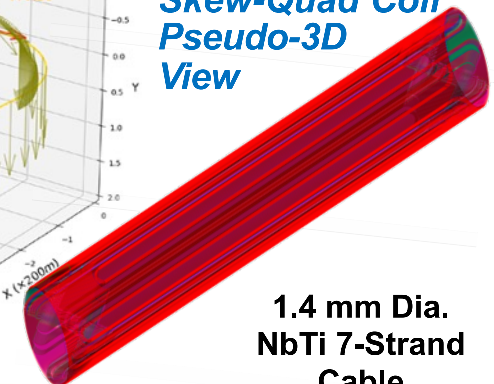
Direct Wind Corrector for the SuperKEKB IR



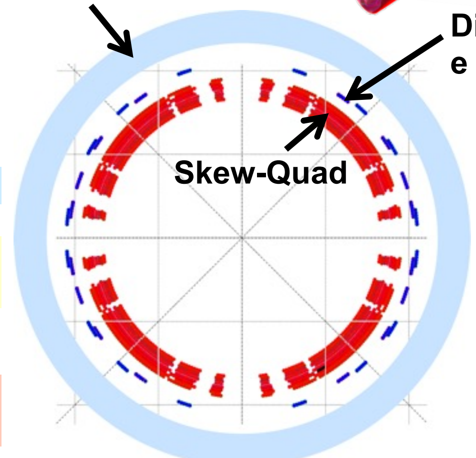


Spin Tracking

Skew-Quad Coil Pseudo-3D View



1.4 mm Dia. NbTi 7-Strand Cable



Solenoid Field 4.85 T
Skew Gradient 24 T/m
Dipole Field 0.2 T

Combined Field @ Skew-Quad is 6.15 T
I_{op} = 729 A
I_q = 1050 A
for 69% Short Sample

Coil Cross Section at Skew-Quad Center

BNL wound the 43 corrector and cancel coils for the SuperKEKB Upgrade.

Have US/Japan collaboration funding to explore increasing IR aperture at a critical point with a new corrector package and to wind correction coils for a possible new superconducting LER Crab Waist sextupole.

Another interesting prospect allows Belle II to explore a new spin physics frontier by having longitudinally polarized electrons at the IP. We want to do this, without moving magnets in the tunnel, by replacing pairs of warm dipoles on either side of the IR with new superconducting multifunction, standalone spin rotator magnets.† These spin rotator modules overlay solenoidal field on the existing dipole bend and a set of integrated skew-quadrupoles correct the local optics coupling. BNL Direct Wind is a natural candidate for producing the required multi-function magnetic field configuration.

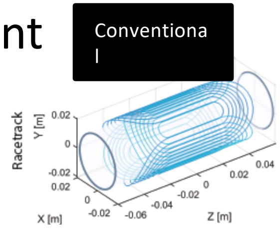
†This multifunction coil configuration was first proposed by Uli Wienands/ANL.

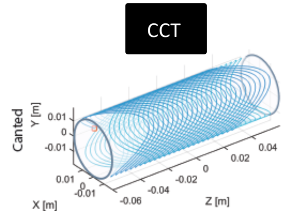
Direct Wind Application: SuperKEKB IR Correctors and Spin Rotators

FCCee IR Quadrupoles, M. Koratzinos

CCT accelerator magnets

- A CCT (Canted Cosine Theta) is a type of accelerator magnet where the multipole mix is a *local* attribute of a magnet. (One can trivially design a magnet which is a dipole on one side and a quadrupole in the other.)
- The QC1L1 magnets are NOT quadrupoles. They are quads minus the field due to the other aperture. But together they make two nearly perfect quadrupoles
- Other important advantages of CCTs:
  - Cheap to make – from the magnet design program to CAD to CNC machine with no manual interventions
  - Easy to make – no pre-stress! Stress management is trivial in CCTs
  - Fast to make – few steps, no expensive equipment
  - Excellent field quality – please see further



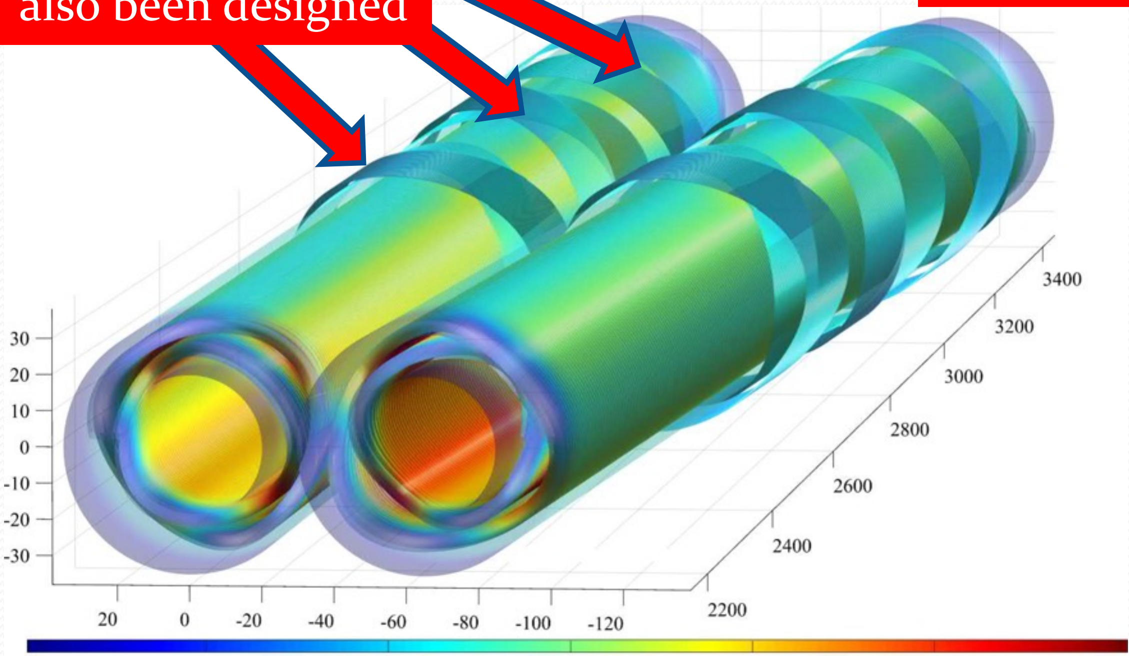


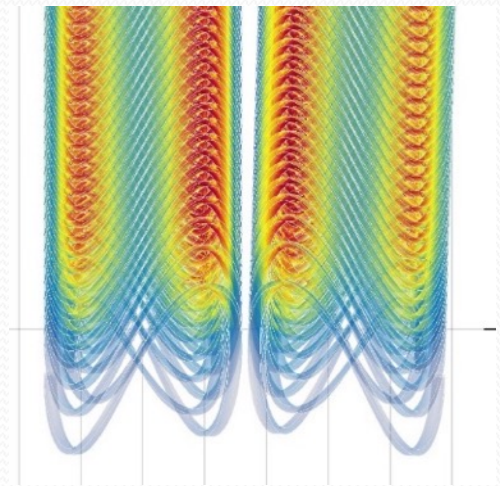
QC1L1

QC1L1 is the first and most demanding pair of quadrupoles of the final focus system of FCC-ee

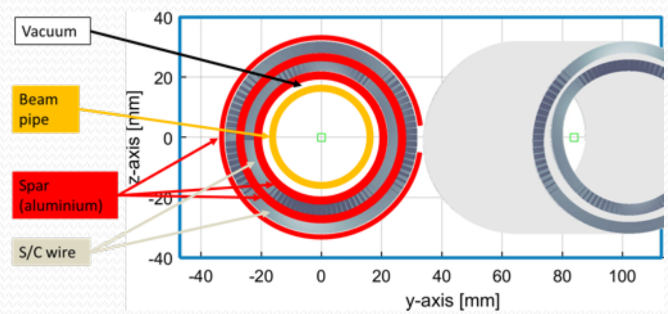
Correctors have also been designed

Iron-free design





Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm



Future e+ sources, J. Seeman

Conclusions

Bunch pulse structure of the collider drives the technical design of the positron complex.

Total number of positrons/second drives the target and capture section design.

Number of simultaneously stored positron bunches dominates the damping ring length.

Some of the advanced colliders need new and enhanced concepts for positron production.

Demonstrated (a world record for existing accelerators): SLC e+ source ~6e12 e+/s

Facility	SLC	SuperKEKB	DAFNE	BEPCII	LIL	CESR	VEPP-5	DCI
Research center	**SLAC**	**KEK**	**LNF**	**IHEP**	**CERN**	**Cornell**	**BINP**	**LAL**
Repetition frequency, Hz	120	50	50	50	100	60	50	50
Primary beam energy, GeV	30–33	3.5	0.19	0.21	0.2	0.15	0.27	1
Number of e^- per bunch	5×10^{10}	6.25×10^{10}	$\sim 1 \times 10^{10}$	5.4×10^{9}	2×10^{11}	3×10^{10}	2×10^{10}	–
Number of e^- bunches /pulse	1	2	1	1	1	7-21	1	1
Incident e^- beam size, mm	0.6	~ 0.5	1	1.5	~ 0.5	2	~ 0.7	–
Target material	W-26Re	W	W-26Re	W	W	W	Ta	W
Target motion	Moving	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Target thickness/size, mm	20, r=32	14, r=2	-	8, r=5	7, r= 8	7, r=10	12, r=(~ 10–>2.5)	10.5, r= –
Matching device	AMD (FC)	AMD (FC)	AMD (FC)	AMD (FC)	QWT	QWT	AMD (FC)	AMD (Sol.)
Matching device field, T	5.5	3.5	5	4.5	0.83	0.95	8.5 (10 max.)	1.25
Field in solenoid, T	0.5	0.4	0.5	0.5	0.36	0.24	0.5	0.18
Capture section RF band	S-band	S-band	S-band	S-band	S-band	S-band	S-band	S-band
e^+ yield, N_{e^+}/N_{e^-}	0.8-1.2 (@DR)	0.4 (@DR)	0.012(@LE)	0.015(@LE)	0.006 (@DR)	0.002(@LE)	~ 0.014 (@DR)	0.02 (@LE)
e^+ yield, $N_{e^+}/(N_{e^-}E)$ 1/GeV	0.036	0.114	0.063	0.073	0.030	0.013	0.05 (@DR)	0.02 (@LE)
Positron flux,* e^+/s	$\sim 6 \times 10^{12}$	2.5×10^{12}	$\sim 1 \times 10^{10}$	4.1×10^{9}	1.2×10^{11}	7.6×10^{10}	1.4×10^{10}	–
Damping Ring energy, GeV	1.19	1.1	0.510	No	0.5	No	0.51	No
DR energy acceptance $\frac{\Delta E}{E}$, %	±1	±1.5	±1.5	No	±1	No	±1.2	No

What are the main challenges?

High intensity

Emittance

Polarization

Reliability and radiation environment

e+ source for FCCee, I. Chaikovska

Future collider project challenges

Demonstrated (a world record for existing accelerators): SLC e+ source ~6e12 e+/s

Project	CLIC	ILC	LHeC (pulsed)	LEMMA	CEPC	FCC-ee
Final e^+ energy [GeV]	190	125	140	45	45	45.6
Primary e^- energy [GeV]	5	128** (3*)	10	–	4	6
Number of bunches per pulse	352	1312 (66*)	10^5	1000	2	2
Required charge [10^{10} e^+/bunch]	0.4	3	0.18	50	1.88	~3.5
Horizontal emittance $\gamma\epsilon_x$ [μm]	0.9	5	100	–	16	24
Vertical emittance $\gamma\epsilon_y$ [μm]	0.03	0.035	100	–	0.14	0.09
Repetition rate [Hz]	50	5 (300*)	10	20	100	200
e^+ flux [10^{14} e^+/second]	1	2	18	10–100	0.04	~0.1
Polarization	No/Yes***	Yes/(No*)	Yes	No	No	No

* The parameters are given for the electron-driven positron source being under consideration.
** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.
*** Polarization is considered as an upgrade option.

Linear Collider projects: high request for polarization, requested intensity should be produced in "one shot".
Circular Collider projects: polarization is under discussion, requirements are relaxed due to stacking and top-up injection

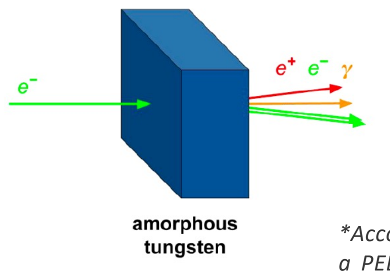
e+ source for FCCee, I. Chaikovska

FCC-ee: positron production

Schemes under consideration now

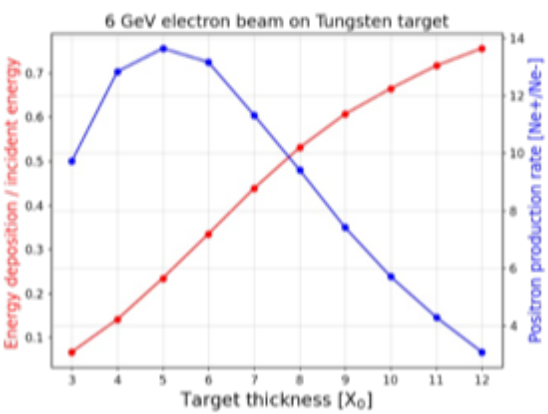
- Conventional scheme: bremsstrahlung and pair conversion (mainly studied until now)
- Hybrid scheme: two-stage process to generate positron beam. Channeling (crystal target) and pair conversion (amorphous target). Benchmark of simulation codes and first simulation/optimization studies → in progress

Conventional target

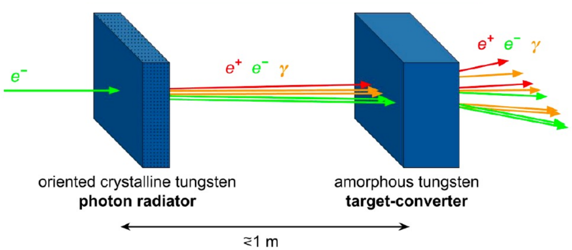


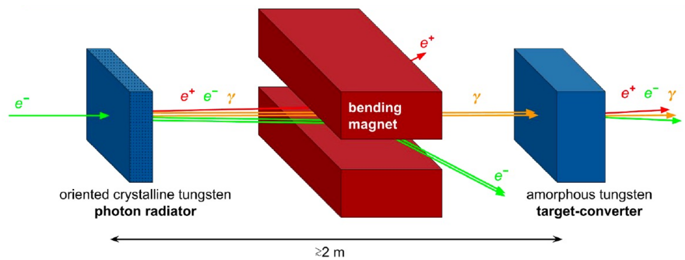
Target thickness	5 X_0 17.5 mm
Production rate	~14 Ne+/Ne-
PEDD*	f(e- beam)
Deposited power	f(e- beam)

*According to SLC experience, $W_{74}Re_{26}$ material has a PEDD limit of **35 J/g** (safe value to avoid target failure)*



Crystal-based target Hybrid scheme





The final choice will be done based on the simulated performances

e+ source for FCCee, I. Chaikovska

Conclusions (personal) (1)

- Future colliders luckily can profit from SuperKEKB experience, they should make good use of it. Some examples:
  - Chromatic X-Y coupling correction (rotating sextupoles in IR)
  - Minimum impedance to minimize beam blow-up and TMCI
  - Clever design of collimators (NLC,..?)
  - Orbit control (night/day, strong sextupoles,…)
  - Perfect alignment (ESRF experience)

- Beam-beam simulations must become faster (how?) and must include several effects (see again SuperKEKB experience):
  - Impedance (transverse, longitudinal)
  - BxB Feedback
  - Injection
  - Coupling in IR
  - Instabilities
  - Realistic bunch length
  - BB and non-linear lattice interplay
  - Machine imperfections (vertical emittance)
  - …

- Simulations: set up an International Task Force to join forces on building/improving ONE code for SS BB and for Impedance Modeling?

Conclusions (personal) (2)

- Work hard on the injection chain:
  - future machines will operate in "ramp-up&top-up" mode, we saw how injection affects SuperKEKB luminosity performances (just in top-up!)
- Be realistic in parameters list and peak luminosity:
  - SuperKEKB, in spite of the huge effort, clever beam understanding, and sophisticated correction methods still is far below the design luminosity
  - Max bunch current seems limited in SuperKEKB (may improve with new collimator materials and new ideas?) → how to reach design L?
- Integrated luminosity is what really counts: a lower luminosity goal with shorter commissioning/tuning time can increase the actual data taking time
  - ESRF has 99,7% up time (paying user machine)
  - Perfect alignment (ESRF experience)
  - Large peak luminosity means large backgrounds in detector !
- **Flexibility** (in design) and **stability** are the keys to efficient operation and happy users → it is not cheap!
- We need brilliant **young** people (in view of the timeline of future colliders) with brand new and (revolutionary) ideas