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

Report on eeFACT22
ICFA BD Workshop on High Luminosity e^+e^- Factories
LNF Frascati (12th-15th Sept. 2022)

M.E. Biagini, INFN-LNF

CEPC Workshop, October 24th 2022

ICFA 65th Beam Dynamics Workshop

- Biannual meeting, had to skip 2020 and 2021 due to covid-19 pandemic
- 13 Working Groups

WG1	Levichev/Biagini	Overview of colliders (including muon & e-ion colliders)
WG2	Branchini/Dam	Physics & Detector
WG3	Oide/Gao	Optics & Beam Dynamics
WG4	Zobov/Zimmermann	Beam-beam & Instabilities
WG5	Boscolo/Sullivan	Interaction Region & MDI & Backgrounds
WG6	Seeman/Furukawa	Injection
WG7	Ikeda/Wendt	Instrumentation
WG8	Bogomyagkov/Gianfelice	Polarization and energy calibration
WG9	Kersevan/Shibata	Vacuum
WG10	Parker/Koop/Li	Magnets
WG11	Brunner/Rimmer	RF
WG12	Qin/Funakoshi	Infrastructures, Cryogenics, Commissioning & Operation
WG13	Faus-Golfe/Wenninger	Monochromatization

- Indico agenda: https://agenda.infn.it/event/21199/timetable/?view=standard
- Mixed format presence (55%)+remote (45%), 96 talks, 112 registered participants
- Most of talks related to the huge on-going effort for FCCee and CEPC (with some glimpse to EIC). Congratulations!
- SuperKEKB experience presented extensively (very useful for the present work on future colliders)
- 2 EXTRA sessions at the end, focused on "Power issues for future colliders", lead by F. Zimmerman. Please go to Indico for slides
- Summarizing here just a few highlights (mostly from SuperKEKB)

SuperKEKB experience

Y. Onishi

Issues for reaching design luminosity

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.

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These topics should be considered in CEPC present studies

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.
- 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, we need to have large flexibility in these parameters.

SuperKEKB optics tuning and issues

H. Sugimoto

Summary

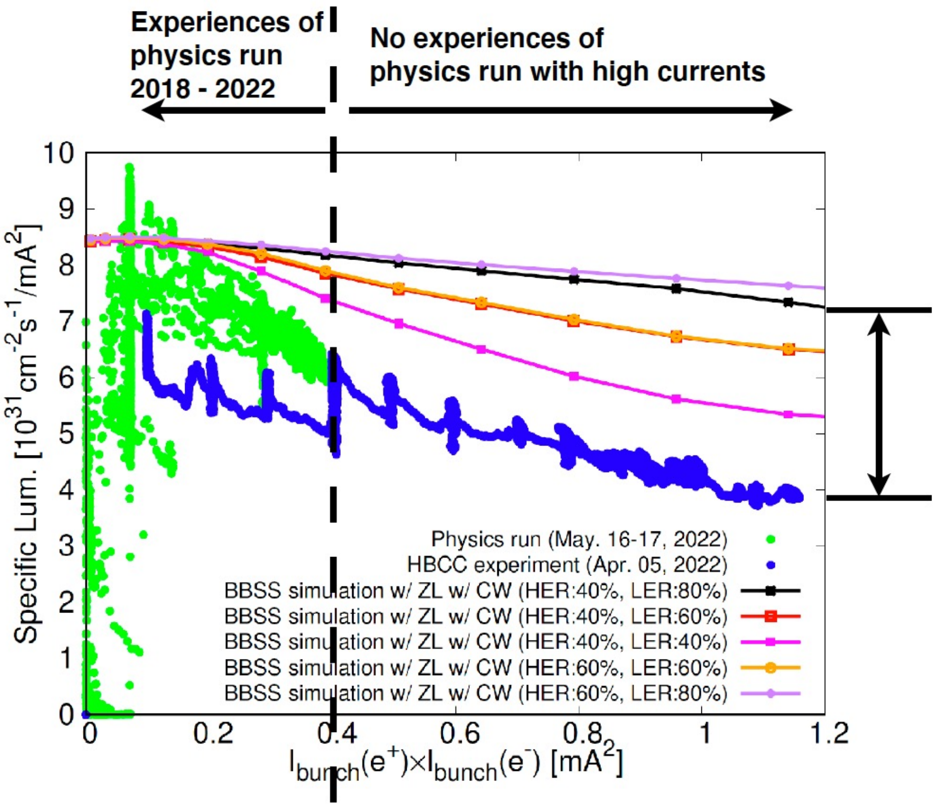
- Global optics tuning is based on analysis of closed orbit response.
- Optics parameters at IP is based on daily IP knob tuning and observed machine performance.
- Tilting sextupole magnets work well in mitigating synchro-beta resonance.
- Field drifting of QCS depending on ramp cycle was observed.
  -> 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 bb simulations

D. Zhou

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.

Lessons from ESRF

P. Raimondi

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

Success is (also) a matter of cost!

CONCLUSION

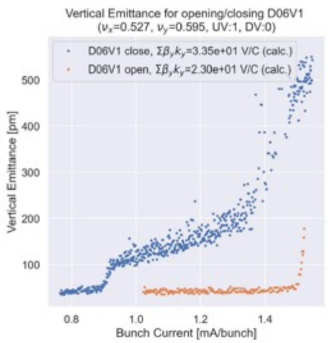
- EBS has been extremely useful to develop system-integration tools that finally allows the realization of a new generation of low emittance rings.
- Our optics know-how and present tuning capabilities are up to the needs to timely achieve and maintain design performances.
- Solutions that implies the use of fewer non-linear elements and local linear and non-linear corrections are extremely effective.
- EBS had some surprise that in principle could have been 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.

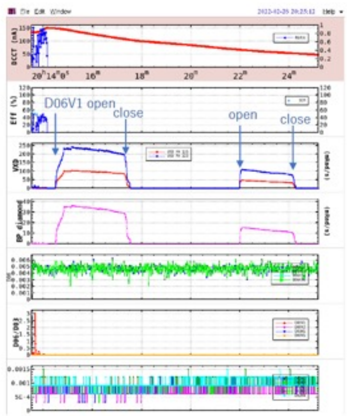
Lessons from ESRF, P. Raimondi

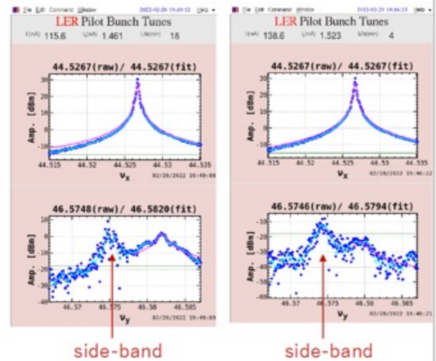
Impedance and instability studies at SuperKEKB

K. Ohmi

Vertical Emittance w/wo D06V1





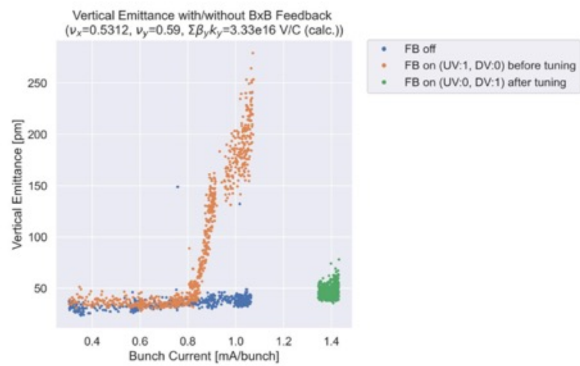


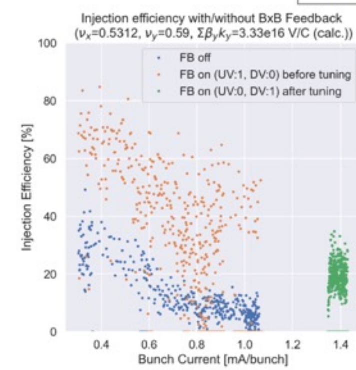
Beam blow-up vs collimator aperture

- 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.

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

33-bunch operation





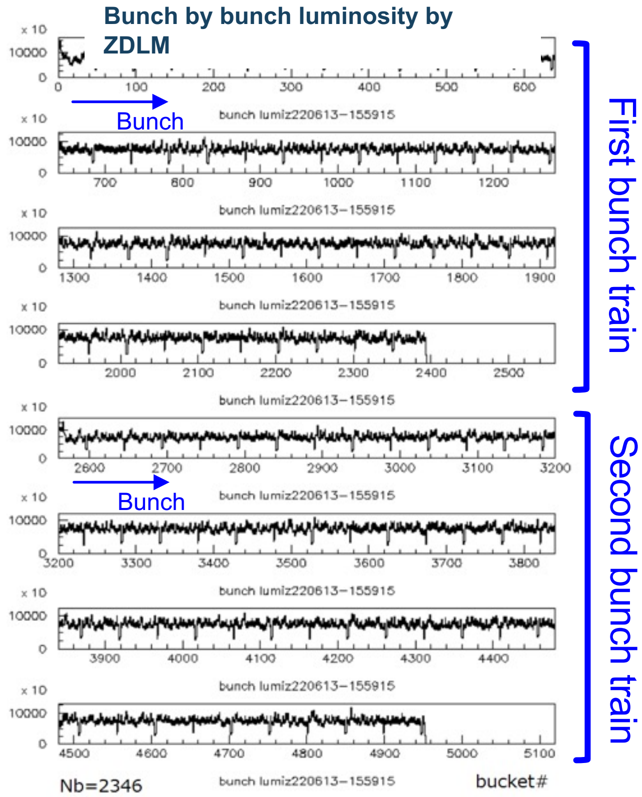
Single bunch instability driven by bunch-by-bunch feedback, corrected by tuning the FB

- 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).

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

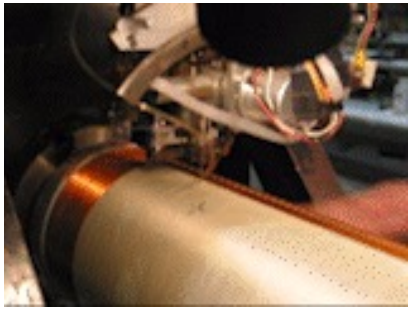


Courtesy of S. Uehara, Belle II

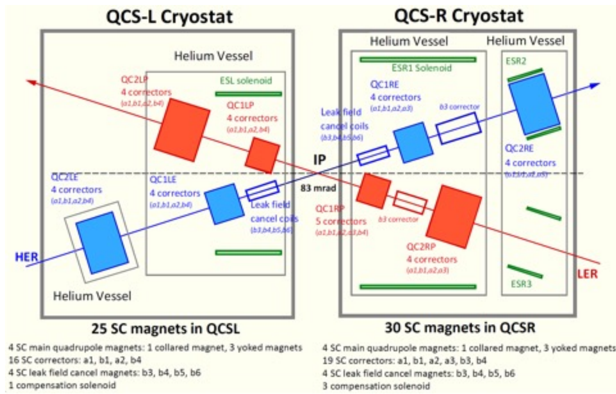
- As seen in the figure, the bunch luminosity seems to be flat along the train, and there is no apparent "long-term" change for each train, which would be resulted in due to the beam-size blow-up caused by the ECE. (2/1173/2.04RF)
  - A piece of supporting evidence that there is no beam size blow-up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

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

How to incorporate Spin Rotators in SuperKEKB!



Direct Wind Corrector for the SuperKEKB IR

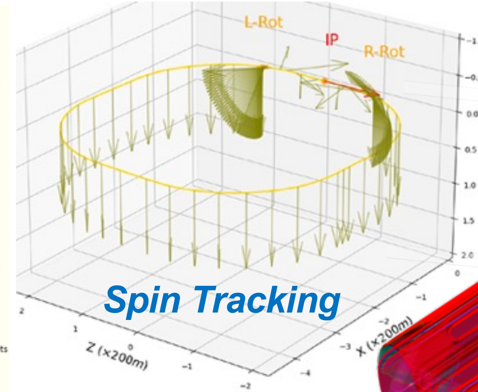


BNL wound the 43 corrector and cancel coils for the SuperKEKB Upgrade.

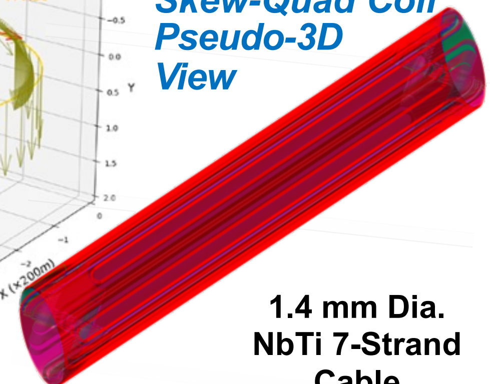
Have US/Japan collaboration funding to explore increasing IR aperture at a critical point with a new corrector package and to wind correction coils for a possible new superconducting LER Crab Waist sextupole.

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.

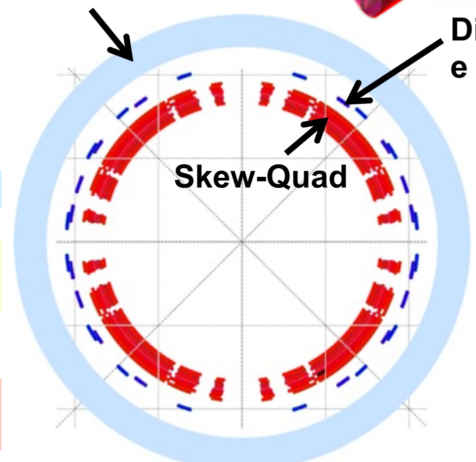
†This multifunction coil configuration was first proposed by Uli Wienands/ANL.



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

Direct Wind Application: SuperKEKB IR Correctors and Spin Rotators

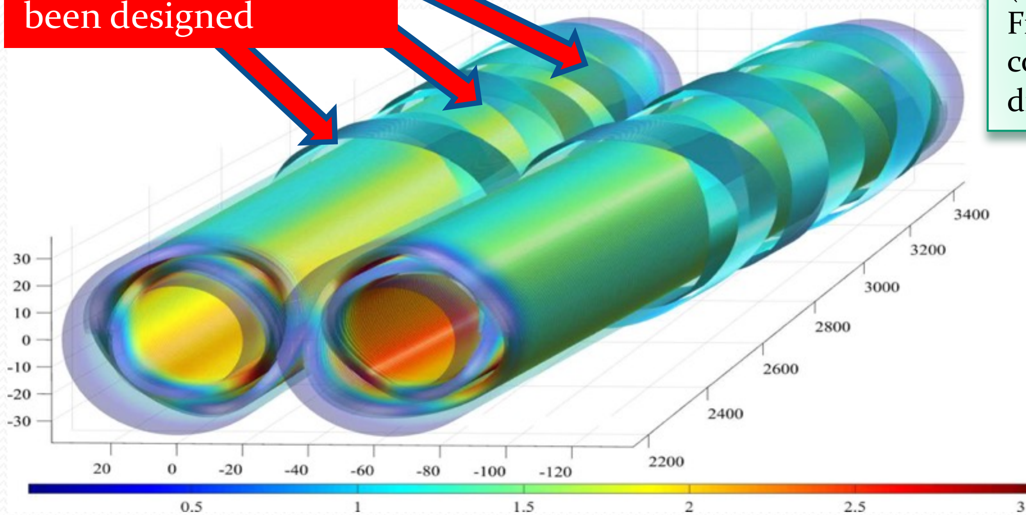
FCCee IR CCT (Canted Cosine Theta Quadrupoles)

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

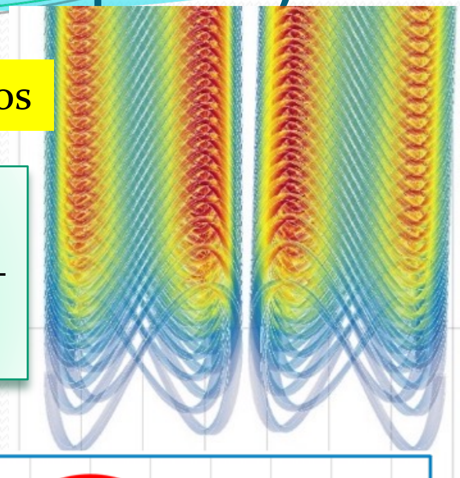
M. Koratzinos

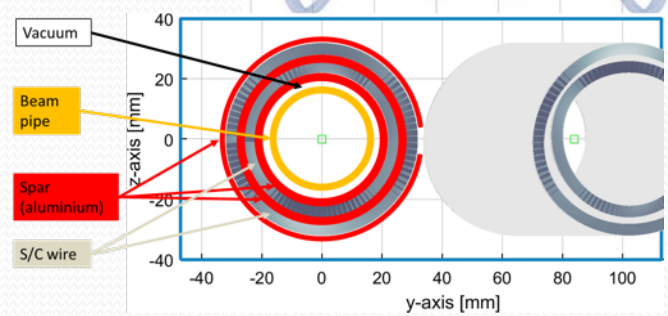
Iron-free design

Correctors have also been designed

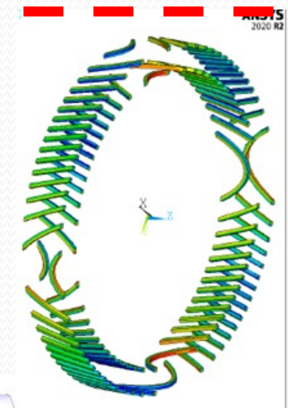


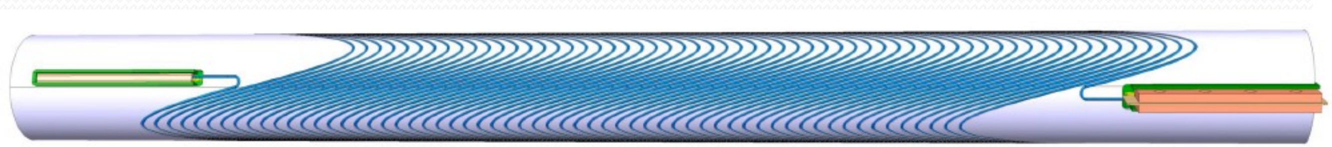
Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm





Inspired by *SuperB* QD0 design, back in 2007 (Paoloni, Raimondi, Fabbricatore, **Farinon**, Musenich et al)



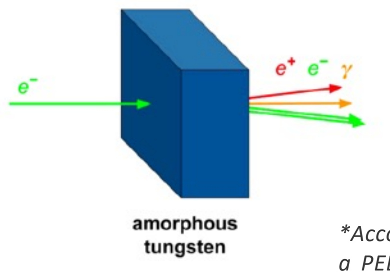


FCC-ee: positron production

Schemes under consideration now

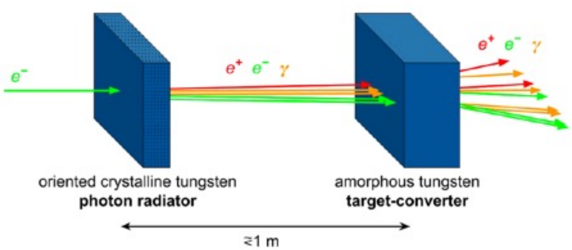
- Conventional scheme: bremsstrahlung and pair conversion (mainly studied until now)
- **Hybrid scheme: two-stage process to generate positron beam. Channeling (crystal target) and pair conversion (amorphous target). Benchmark of simulation codes and first simulation/optimization studies → in progress**

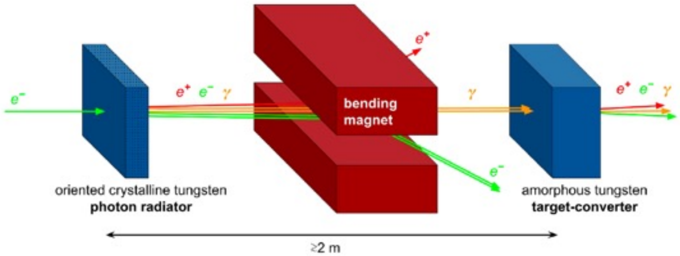
Conventional target



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

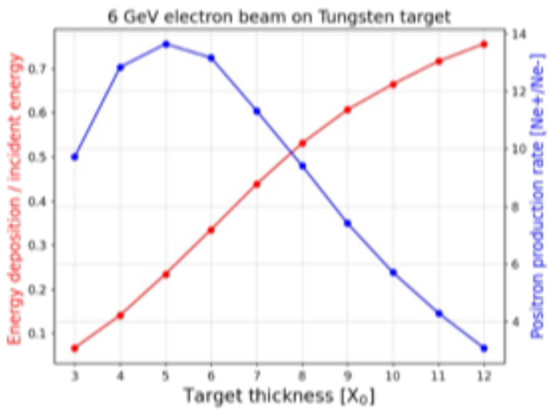
Crystal-based target
Hybrid scheme





The final choice will be done based on the simulated performances

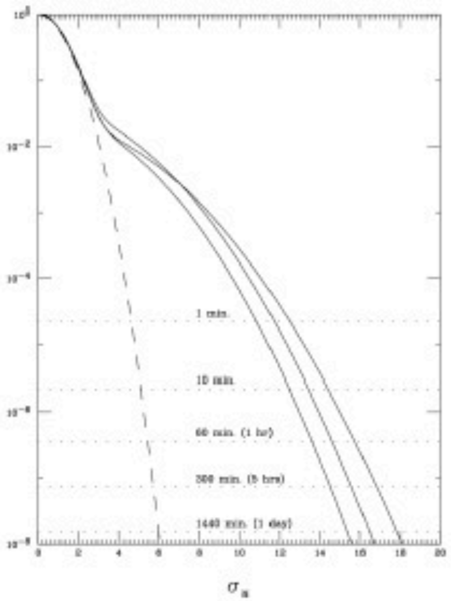
According to SLC experience, $W_{74}Re_{26}$ material has a PEDD limit of **35 J/g (safe value to avoid target failure)*



New, advanced concepts for high-rate e^+ production are needed

Machine Detector Interface

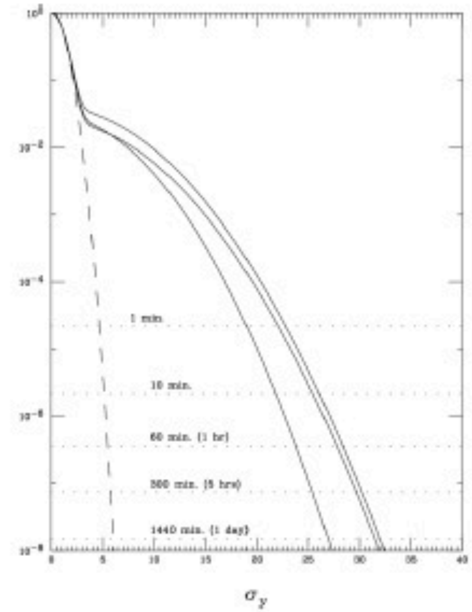
- Mike Sullivan presented some issues regarding high currents and high luminosity
  - High beam currents mean beam pipe “scrubbing” leads to non-gaussian beam tails
  - Large non-gaussian beam tails leads to short lifetimes and high detector backgrounds
  - He showed some examples of second gaussian beam tail models



Tail distributions that can generate the background level seen in the superKEKB pixel detector (PXD) during early running.

They also approximately agree with the measured beam lifetime.

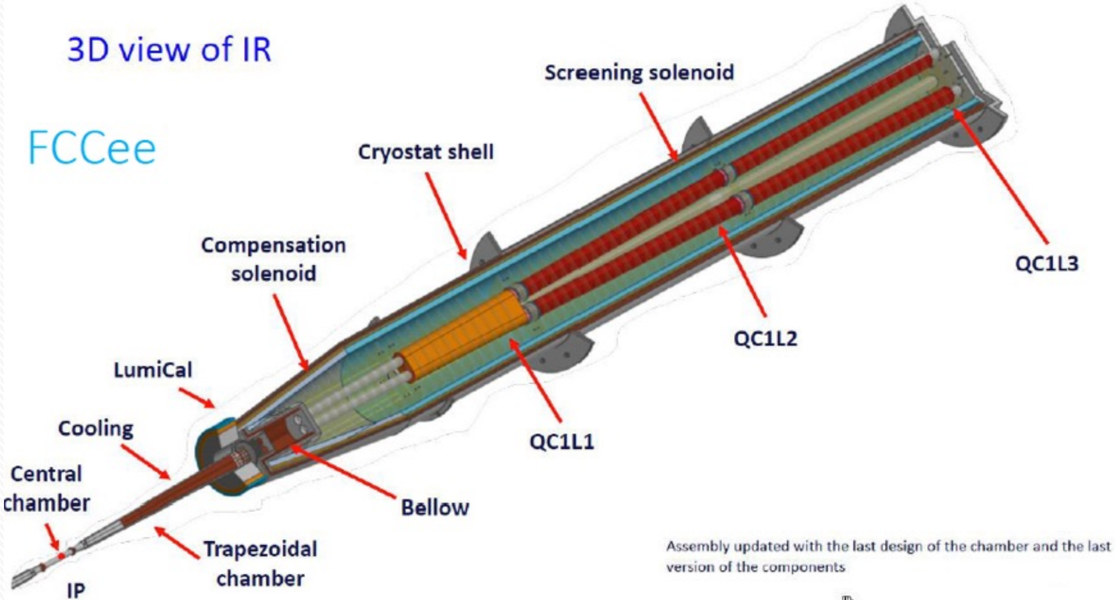
The one-day lifetime is derived by Matt Sands, “The Physics of Electron Storage Rings an Introduction”, 1970, SLAC-121



M. Sullivan

FCCee MDI & IR design

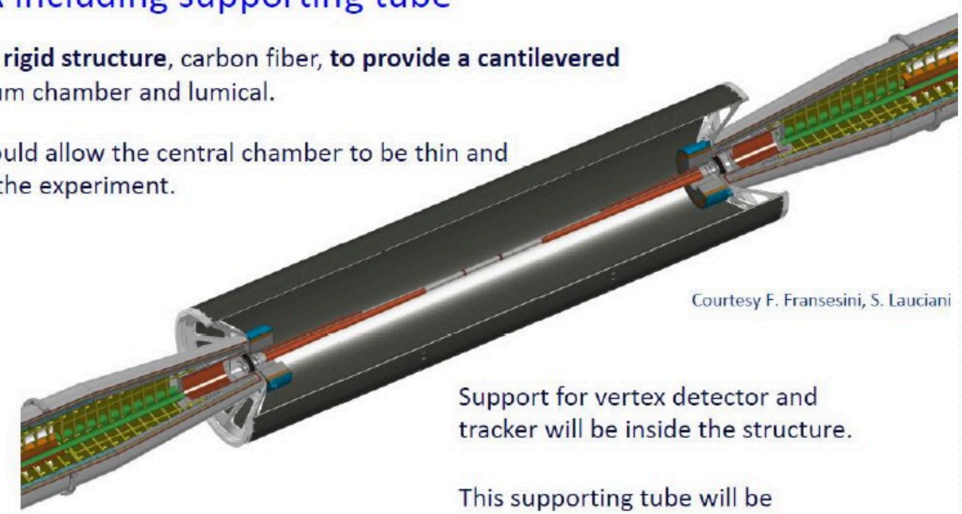
3D view of IR



3D view of IR including supporting tube

Proposed lightweight **rigid structure**, carbon fiber, **to provide a cantilevered support** for the vacuum chamber and lumical.

The rigid structure would allow the central chamber to be thin and light as requested by the experiment.



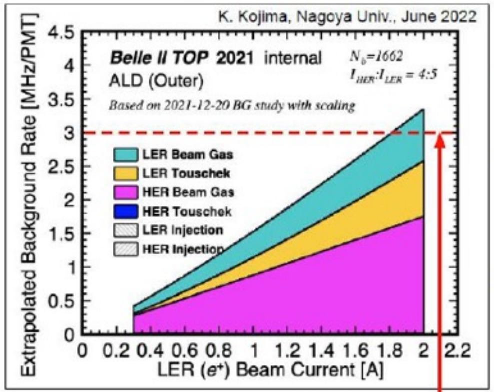
Support for vertex detector and tracker will be inside the structure.

This supporting tube will be anchored to the detector.

M. Boscolo

SuperKEKB BKG studies

One of the most vulnerable sub-detectors is the Time of Propagation (TOP) particle ID system



Excludes the luminosity background

Background limit

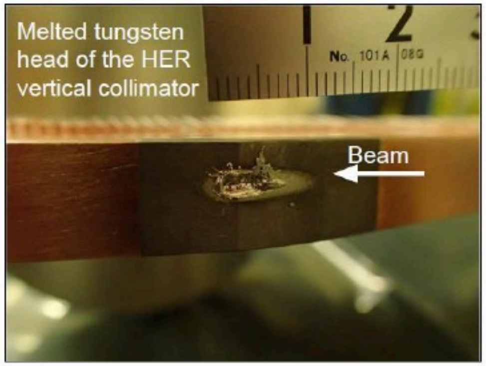
SuperKEKB

- Current background rates in Belle II at ~1.2 A are acceptable and below limits
- Belle II did not limit beam currents in 2021 and 2022
  - It will limit SuperKEKB eventually, without further background mitigation
- To reach the **target** luminosity of 6.3x10^{35} cm^{-2}s^{-1} an upgrade of crucial detector components is foreseen (e.g. TOP short lifetime conventional PMTs)

Snowmass Whitepaper arXiv:2203.11349

superKEKB sudden beam loss event causing coll. damage

- During stable machine operation unexplained beam instabilities and beam losses may occasionally occur in one of the rings causing **sudden beam losses (SBLs)** at a specific location around the ring due to
  - Machine element failure
  - Beam-dust interaction
  - Vacuum element defects
- **Consequences**
  - Detector and/or collimators damage, see Figure
    - Belle II background increase
  - Superconducting magnet quenches
- Usually only a few such catastrophic beam loss events happen per year in each ring
  - In 2022, we had many (>50) SBLs in the LER trying to go beyond 0.7 mA/bunch
- **Cures**
  - Upgraded abort system → fast abort signal
  - Low-Z materials for collimator heads (MoGr, Ta+Gr) → robust collimators
  - Understand the source of the unstable beam (vacuum system inspection, beam dynamics study, installation of additional beam loss monitors around the rings)



A. Natochii

FCCee IR HOMs

FCCee IR HOM: Initial larger IP pipe design needed a HOM absorber

The concept of the HOM absorber

Based on the property of the trapped mode we have designed a special HOM absorber.

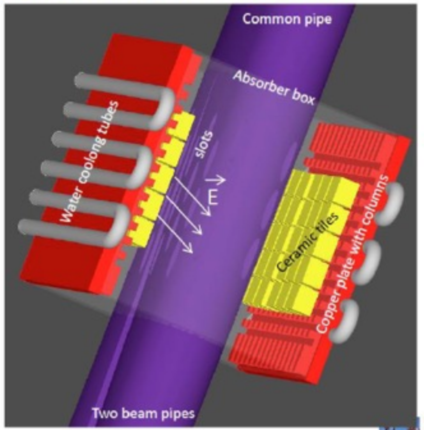
The absorber vacuum box is placed around the beam pipe connection. Inside the box we have ceramic absorbing tiles and copper corrugated plates .

The beam pipe in this place have longitudinal slots, which connect the beam pipe and the absorber box. Outside the box we have stainless steel water-cooling tubes, braised to the copper plates.

The HOM fields, which are generating by the beam in the Interaction Region pass through the longitudinal slots into the absorber box.

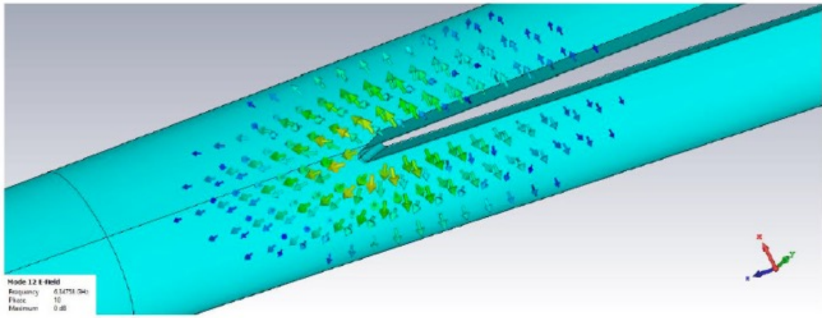
Inside the absorber box these fields are absorbed by ceramic tiles, because they have high value of the loss tangent.

The heat from ceramic tiles is transported through the copper plates to water cooling tubes.



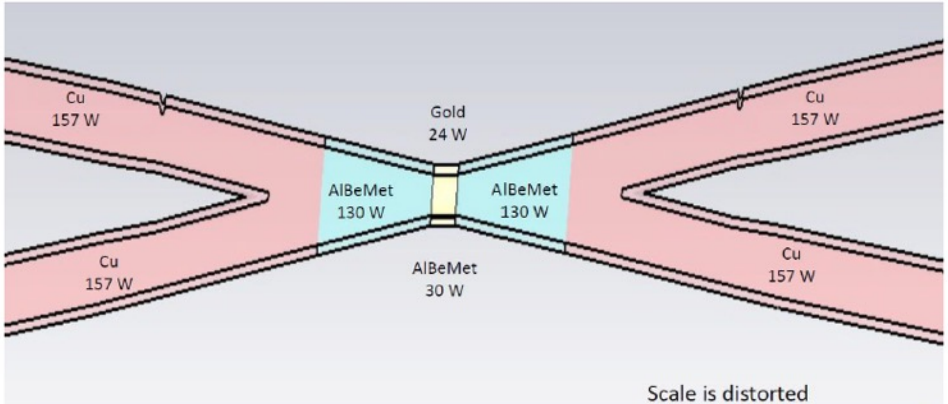
FCCee IR HOM: Smaller IP beam pipe reduces the trapped HOM power

An unavoidable trapped mode still exists, but has much smaller amplitude due to much higher frequency 6.1 GHz



FCCee HOM: The beam pipe discontinuities generate a lot of power but most of it now travels outside of the IR

Heat load distribution

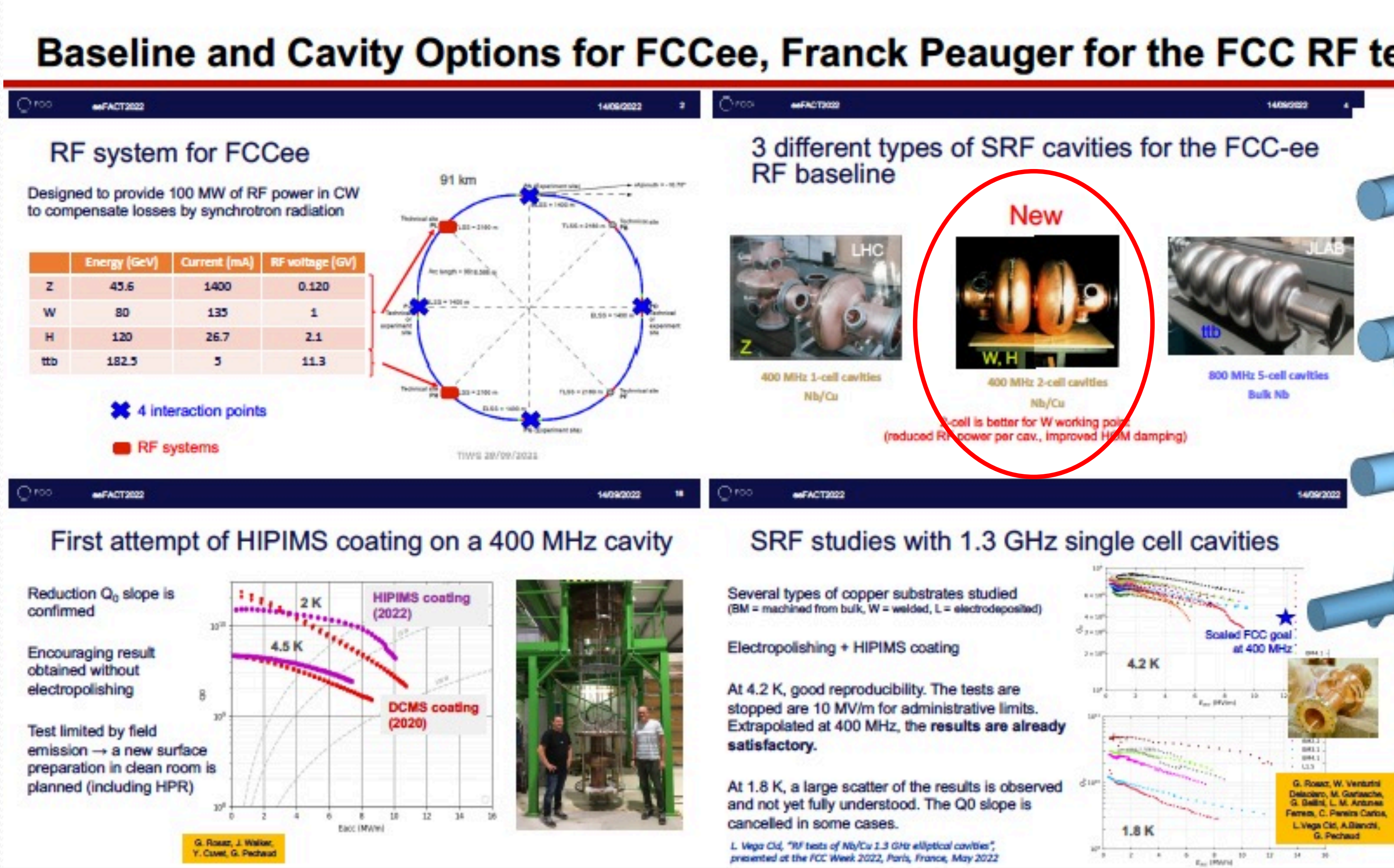


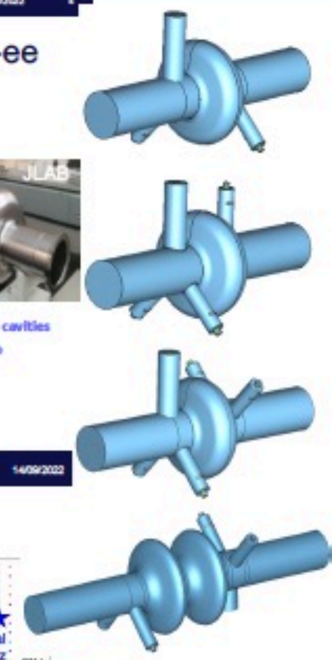
All of this power must still be accounted for

A. Novokatski

FCCee cavities options

F. Peauger

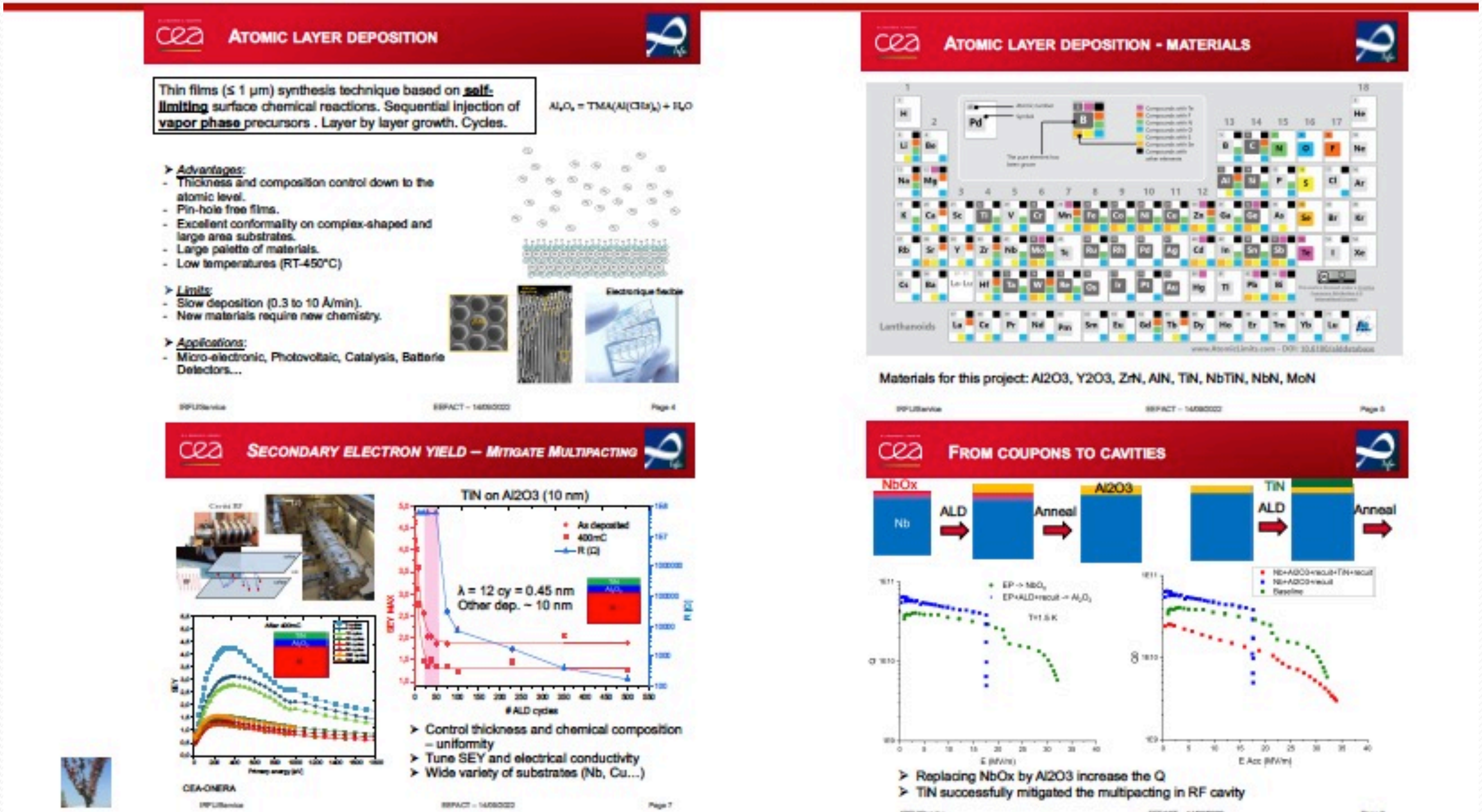




SFR atomic layer deposition

T. Proslier

Atomic layer deposition for SRF cavities, Thomas Proslier (CEA)



Intense work in progress also in collaboration with CERN (IFAST project)

Vacuum studies for FCCee

R. Kersevan

WG9: Vacuum System of the FCC-ee, R. Kersevan, TE Dept., CERN

FCC eeFACT-2022, Frascati The Vacuum System of FCC-ee, *R. Kersevan, TE-VSC*

Prototyping, experiments, as per FCC Week 2021 PRESENT STATUS/PLANS

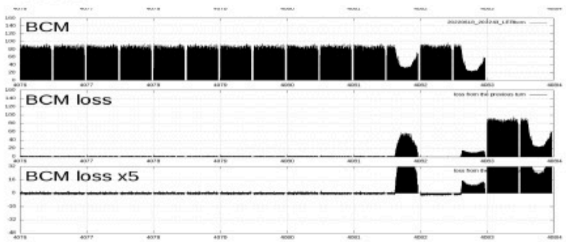
1. Design prototype vacuum chambers with and without SR absorber (~ 2 m-long) and test them at light source (KARA/KIT?) UNDERWAY
2. Test behavior of thin NEG-coating at light source SCHEDULED EXPERIMENTS TO TEST REFLECTIVITY AT "BEAR" BEAMLINE, ELETTRA LIGHT SOURCE, TRIESTE, Sept-Oct 2022
3. Define deposition technique for dipolar ~ 12 m-long vacuum chambers (horizontal sputtering with mole?, other techniques?) DESIGN OF 12 m-LONG COATING BENCHES UNDERWAY
4. In-situ measurement of photoelectron yield at light source CONCURRENTLY WITH No.2
5. Test other thin-films with potential application to FCC-ee: amorphous carbon (a-C), hydrophobic silicon films (to reduce pump down time without bakeout); test surface texturing techniques (e.g. LASE) WILL PRODUCE SEVERAL 2m-LONG PROTOTYPES FOR KARA's "BESTEX" TEST STAND OR OTHER FACILITY
6. Determine material and fabrication technology of SR absorbers and bonding technique to the vacuum chamber (surface power density above 100 W/mm^2 at the ttbar energy) UNDER DESIGN & THERMAL ANALYSIS, SEE NEXT SLIDES
7. Design, fabricate, and test bellows with RF fingers, under elongation and misalignment conditions similar to those expected for FCC-ee, BPM blocks SEVERAL DESIGN OPTIONS UNDER ANALYSIS, SEE NEXT SLIDES
8. Continue collaboration with FLUKA team (see B. Humann/F. Cerutti), magnet group, tunnel integration working group, and machine optics group (plus MDI) TO BE RESUMED, IMPLEMENTING NEW 92 km LATTICES

We have come to the conclusion that the aggressive experimental program with large integrated luminosity values within a rather short amount of time (4 yrs for the Z-pole starting from an unconditioned machine) require two things:

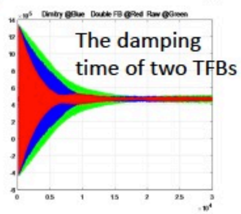
1. NEG-coating of the chamber
2. Localized ("lumped") SR absorbers

Beam instrumentation

- H. Ikeda: SuperKEKB beam instrumentation
  - SR monitors, BLMs
  - Unexplained sudden beam losses
    - Appears in both rings HER & LER
    - Within a single turn
    - High damage potential, collimators, QCS quench, large bg. to Belle-II



- Y. Sui: CEPC beam instrumentation
  - Challenging systems: BxB FB, BPMs, bunch size & length, BxB electronics
  - Yanfeng gave many details on trans. and long. FB, BxB and narrowband
    - To fight resistive wall coupled bunch instabilities and HOM CBI



Pillbox cavity with ridged waveguides type kicker

Challenge: large scale systems, electronics, beam size and length measurements

- D. Gassner: EIC beam instrumentation
  - Challenges: Large scale system - BPMs: quantity, variety, requirements Pandemic-related, e.g., chip shortage, raw materials, manpower & staffing
  - BxB BPMs with narrow bunch spacing, 5 & 10 ns, ADC peak detection
  - Crabbing angle measurements

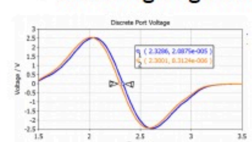


Figure 4: Particle Studio output for the two, opposite, horizontal PUEs when using a 60 mm diameter BPM with 10 mm diameter PUEs with a simulated crabbed bunch input described in Fig. 3.

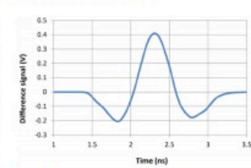
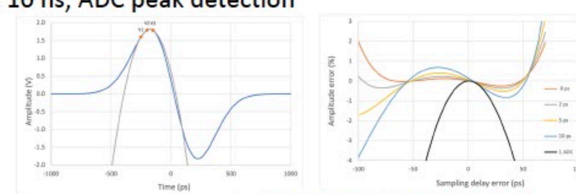
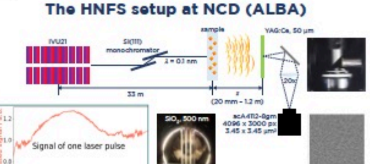


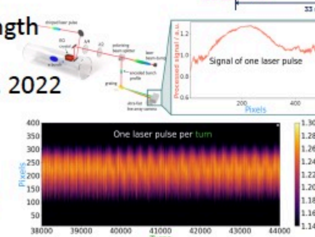
Figure 5: Difference signal obtained by using the simulation output shown in Fig. 4.



- M. Wendt: FCC-ee beam instrumentation
  - Challenges: BPMs, BLMs, beam size, bunch length communication, manpower, budget
  - FCC-ee BI Mini-Workshop@CERN, 21.-22. Nov. 2022
    - Identify FCC-ee BI requirements and most critical R&D activities
  - Discussion: BI cost profile for e+/e- collider?
    - 5% of the total costs? With or w/o tunnel costs?

The HNFS setup at NCD (ALBA)





EOS Near-Field at KARA

Turn-by-turn single bunch profile measurements

Conclusions (1)

- Future colliders can profit from SuperKEKB experience, they should make good use of it
- Beam-beam simulations must become faster (how?) and must include many new effects (SuperKEKB experience)
- Accurate design of IR for (different) backgrounds and HOMs mitigation is essential
- Machine alignment is crucial to good performances
- The injection chain design needs attention, the collider performances will also depend on it (ex. 30GeV Linac for CEPC is a good choice)
- Flexibility (parameters, lattice design) and stability are the keys to efficient operation and good performances → it is not cheap!
- Success will depend (also) on the money spent (see ESRF experience)

Conclusions (2)

- New and innovative RF solutions are still being developed
- SuperKEKB and LHC are providing essential lessons
- Forward planning such as Snowmass and European strategy emphasize R&D, facilities, workforce development, collaborations and energy efficiency
- New materials and processes are essential for realizing ambitious new projects, R&D now will make that possible (needs funding!)
- High efficiency RF sources are becoming reality, including klystrons and SSA's
- Beam instrumentation and diagnostics should be planned ahead, not as an afterthought
- Vacuum design relies more and more on advanced materials and coatings. (NEG, amorphous Carbon, beam screens etc.), e.g. ESRF

EXTRA sessions

(EXTRA) Discussion on luminosity and electrical power projections for various ee Factories

Conveners: FRANK ZIMMERMANN (CERN) , Vladimir Shiltsev (Fermilab)

17:00 **Power limit concerns**
Speaker: Vladimir Shiltsev (Fermilab)
LandPchallenges_e...

17:10 **C^3** ¶
Speaker: Emilio Nanni (REMOTE) (SLAC Natinoal Accelerator Laboratory)
CCC Power Discussi...

17:30 **CERC and ReLiC**
Speaker: Vladimir Litvinenko (REMOTE) (Stony Brook University)
CERC and RELIC ICF...

18:00 **HELEN**
Speaker: Sergey Belomestnykh (REMOTE) (FNAL)
HELEN Collider - eeF...

18:20 **EIC**
Speaker: Todd Satogata (REMOTE) (Jefferson Lab)
2022-09-15-eeFACT-... 2022-09-15-eeFACT-...

FRIDAY, 16 SEPTEMBER

(EXTRA) Discussion on luminosity and electrical power projections for various ee Factories

Conveners: FRANK ZIMMERMANN (CERN) , Maria Enrica Biagini (Istituto Nazionale di Fisica Nucleare)

09:00 **FCCee**
Speaker: FRANK ZIMMERMANN (CERN)
eeFACT22-power.pptx

09:30 **CEPC**
Speaker: Jie Gao (REMOTE) (Institute of High Energy Phyics, CAS)
CEPC Accelerator T...

10:00 **CLIC**
Speaker: Steinar Stapnes (REMOTE) (CERN)
CLIC_eefact22_lum...

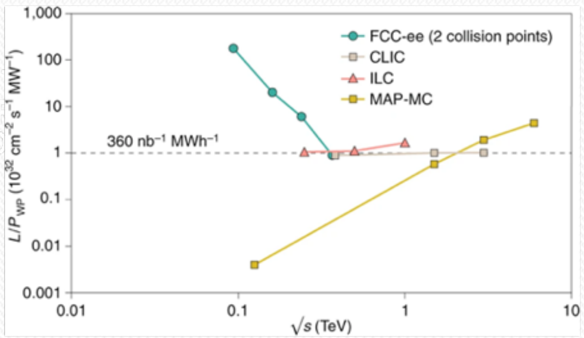
10:30 **ILC**
Speaker: Benno List (REMOTE) (DESY -IPP-)
eeFACT_ILC-Power_...

Backup

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

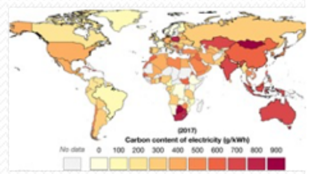
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880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

J.-P. Burnet, FCC Week 2022

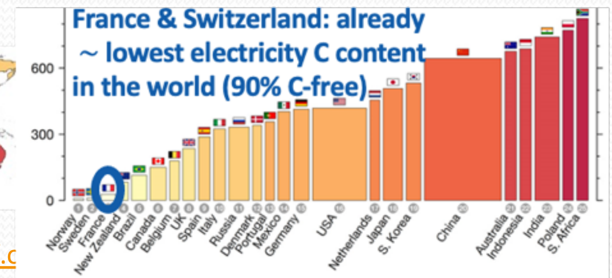
incl. CERN site & SPS

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.c



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

$\sqrt{s}$ = 240 GeV for CEPC/FCC-ee, 250 GeV for ILC/C³, 380 GeV for CLIC

CLIC	ILC	C³	FCC-ee	CEPC
0.8	0.9	0.9	1.1	2.0

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

Energy consumption in MWh / Higgs

CLIC	ILC	C³	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	C³@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

F. Zimmermann

EIC RF cavities

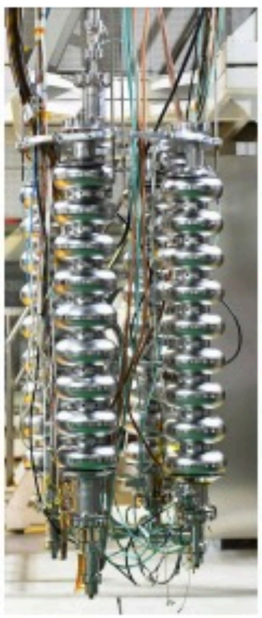
R. Rimmer

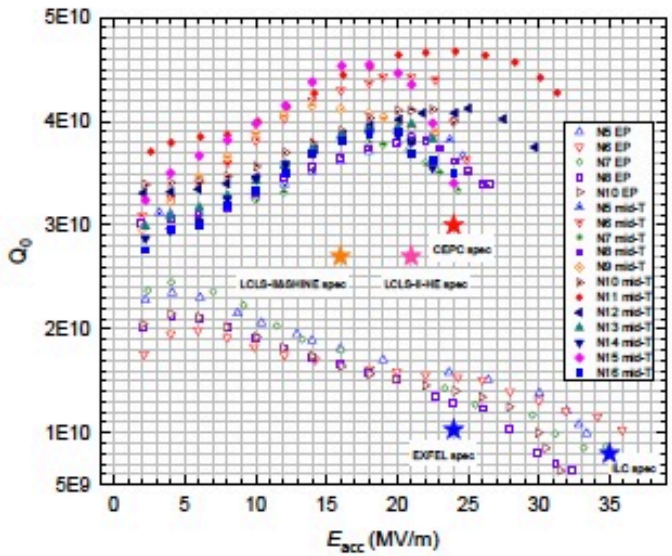
CEPC 1.3 GHz cavity

J. Zhai

Cavity and Cryomodules Developments for CEPC, Jiyuan Zhai (IHEP)

World Leading Mid-T High Q 1.3 GHz 9-cell Cavity





2 K VT	1st batch average	2nd batch average
E_{acc} (MV/m)	24	27.7
Q_0@16 MV/m	3.8E10	4.1E10
Q_0@21 MV/m	3.8E10	4.1E10

First batch (6 cavities): N5-N10

Second batch (8 cavities): N11-N18 (N11-16 tested)

- Best Cavity (N11): 4.6E10@21 MV/m, 4.3E10@31MV/m
- Q spread due to cool down difference?
- One of the best high Q 1.3 GHz 9-cell cavities and cavity batches in the world.
- Will install to high Q module at IHEP PAPS