Injector, transfer lines and booster summary

Paolo Craievich (PSI)
FCC week, 23 May 2025

3 sessions with 15 talks

FCC-ee injector: Overview (8:30 – 10:00) - M. J. Boland (University of Saskatchewan)

- FCC-ee Injector: overview and outlook, **Paolo Craievich** (PSI)
- Update on the filling scheme, **Hannes Bartosik** (CERN)
- Positron Production for FCC-ee, **Iryna Chaikovska** (CNRS/IJCLab)
- Positron Target Design, Fabrication – Updates on P3 Integration, **Ramiro Francisco Mena Andrade** (CERN)
- FCC-ee top-up operation: photocathodes and laser systems, **Eduardo Granados** (CERN)

FCC-ee injector: Linac and Damping Ring (10:30 – 12:00) – J. T. Seeman (SLAC)

- FCC-ee Injector: New DR at 2.86 GeV, **Antonio De Santis** (INFN/LNF)
- Approach for low impedance design of the FCC DR vacuum chamber, **Shalva Bilanishvili** (INFN/LNF)
- FCC-ee injector linacs: the design and the RF frequency choices for the TDR, **Alexej Grudiev** (CERN)
- FCC-ee injector: linacs design for single- and multi-bunch effects, **Simona Bettoni** (PSI)
- RF-Track development for FCC-ee injector studies, **Andrea Latina** (CERN)

FCC-ee injector: Booster and transfer lines (13:30 – 15:00) – J. Wenninger (CERN)

- Overview of the booster status, **Antoine Chance** (CEA)
- Updates on FCC-ee High Energy Booster collective effects studies, **Adnan Ghribi**
- High Energy Booster Emittance Tuning, **Quentin Bruant** (CEA)
- Injection/extraction systems across the FCCee complex, **Sen Yue** (CERN)
- Swap-out injection with beam recycling in the booster: design and commissioning at the High Energy Photon Source, **Duan Zhe** (IHEP)

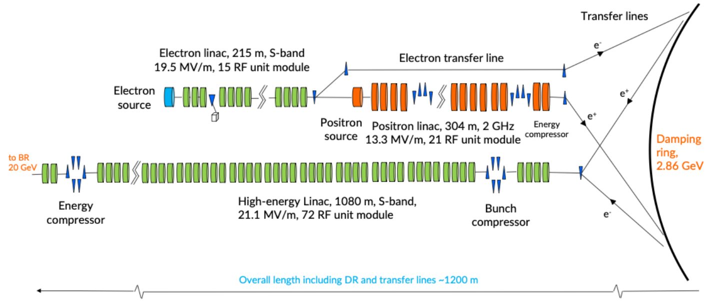
Overviews

FCC-ee Injector overview and outlook

FCC

Future Circular Collider

Feasibility Study Report



Volume 2

Accelerators, Technical Infrastructure and Safety

FCC-ee injector complex is included in

CHART
Swiss Accelerator Research and Technology

CHART Scientific Report (Final Report for Phase 2)

FCC-ee Injector Study and the P^3 Project at PSI

PSI:
P. Craievich, B. Auchmann, I. M. Besana, S. Bettoni, H.H. Braun, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, E. Ismaili, R. Ischebeck, P. Juranic, J. Kosse, F. Marcellini, U Michlmayr, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Reiche, R. Rotundo, S. Sanfilippo, M. Schär, M. Seidel, N. Strohmaier, N. Vallis, M. Zykova, R. Zennaro

CERN:
A. Grudiev, W. Bartmann, H. Bartosik, M. Benedikt, M. Calviani, S. Doebert, Y. Dutheil, J. L. Grenard, B. Humann, A. Kurtulus, A. Latina, A. Lechner, R. Mena Andrade, A. Perillo Marcone, K. Oide, Y. Zhao, T. P. Watson, F. Zimmermann, Z. Vostrel

CNRS-IJCLab:
I. Chaikovska, F. Alharthi, R. Chehab, V. Mytrochenko, Y. Wang

INFN-LNF:
C. Milardi, A. De Santis, O. Etisken, S. Spampinati

SLAC: T. Raubenheimer

KEK: Y. Enomoto, K. Furukawa

PSI CERN IJCLab INFN SLAC KEK

28 October 2024

Towards a "TDR"
CHART 2025-2028

Design phase → Global req. doc. (updated FSR) → Physics req. documents → Engineering specs documents → TDR

Finalizing the baseline layout (design phase)

↓

updating the FSR with new subsystems

↓

(Specific) physics requirements documents

↓

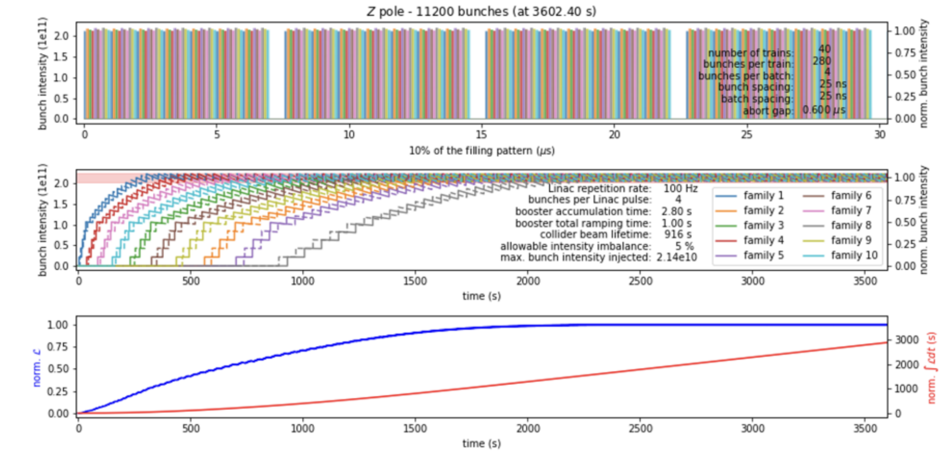
(Specific) engineering specifications documents

Update on the filling scheme

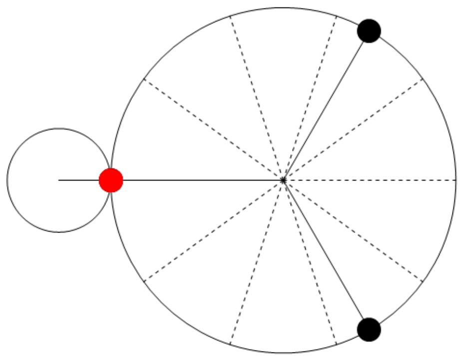
Hannes Bartosik (CERN)

- **The present filling scheme for the Z-pole assumes non-uniform bootstrap injection to mitigate e-cloud instabilities**
  - Not yet updated to latest FCC-ee parameter table (7% more bunches)
  - This scheme is challenging for tune shifts and X-Z instabilities due to large range of bunch populations present in the machine (not possible to find a suitable working point for all bunches)
  - Alternative schemes with bunch spacings down to 5 ns have not yet been studied (this has strong implications for injector complex)
- **Updated filling patterns for W, ZH and tt – no particular issues**

Z-pole: boot-strap and top-up injection



Started looking into synchronisation between pre-injectors and booster, studying the possibilities of injecting into any given bucket.



H. Damerau

Preferred option is careful choice of rational ratio

$C_{booster}/C_{DR} = m/n$

→ n times more azimuthal positions can be reached at expense of transferring within range of n booster turns

→ Requires pulsing Linacs and injector complex non-periodically (from zero to n booster turns)

→ Required flexibility of positioning batches in damping ring reduced to ~ ±180°/n (assuming fixed RF frequency in damping ring)

→ Constrain on the DR circumf.

→ necessary introduce a delay on the timing for RF

→ constrain on the max damping time in DR

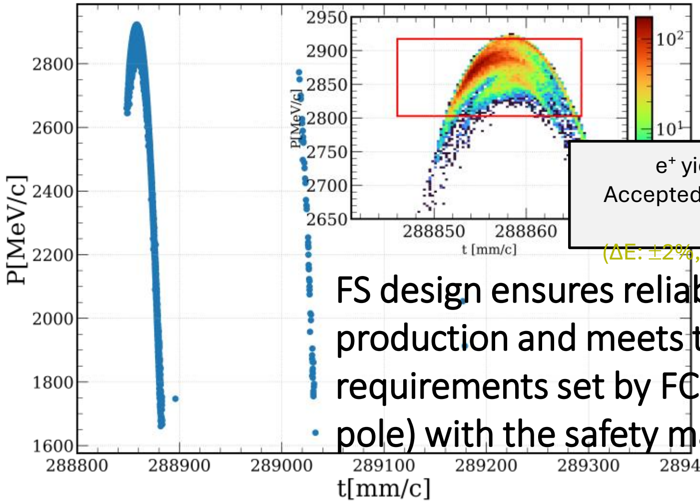
Positron Production for FCC-ee

Iryna Chaikovska (CNRS/IJCLab)

- **FS baseline design** relies on the **HTS solenoid**. The accepted **e^+ yield is ~3 N_{e+}/N_{e-}**. Proof-of-principle with P^3 experiment @PSI starting from 2026.
  - With safety margins, an **e^- drive beam charge of 3.8 nC** is required to meet FCC-ee specifications (**within the current e- source limit ≲ 5 nC**).
- The very first studies to investigate the **feasibility of 3 GHz RF frequency** in the **e^+ capture and 2.86 GeV linac** are started showing:
  - **Reduced e^+ yield** assuming FS solenoidal focusing. Thermionic e^- gun? Clear **preference** for large-apertures **$\Phi \geq 40$ mm.**
  - **ECS** is needed to **match e^+ phase space to DR** acceptance (~15% gain in accepted e^+ yield). DR energy acceptance is a key parameter!
  - **SC solenoids in the capture system** could further **improve efficiency** and should be explored.
- **Conceptual design** studies of the **crystal-based positron source** for the FCC-ee are ongoing. Potential **proof-of-principle** at P^3 experiment 2nd phase (*see F. Alharthi's poster*).

FCC

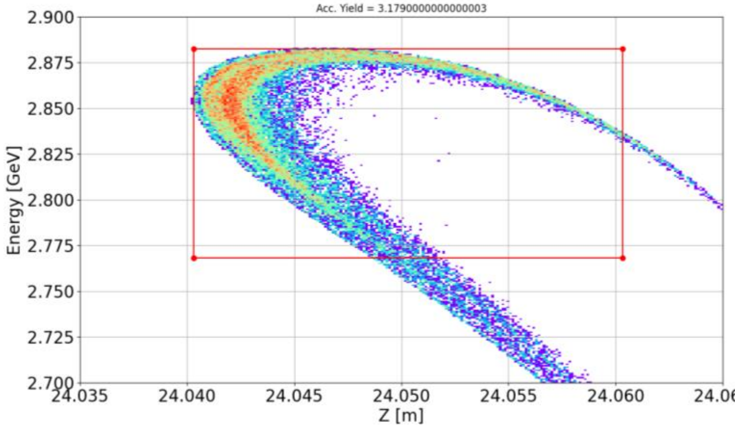
2 GHz



e^+ yield ~ 3.4
Accepted yield @ DR ~ 3.0
(ΔE: ±2%, Δt: 20 mm/c)

FS design ensures reliable e^+ production and meets the requirements set by FCC-ee (Z-pole) with the safety margins

3 GHz + SC solenoids

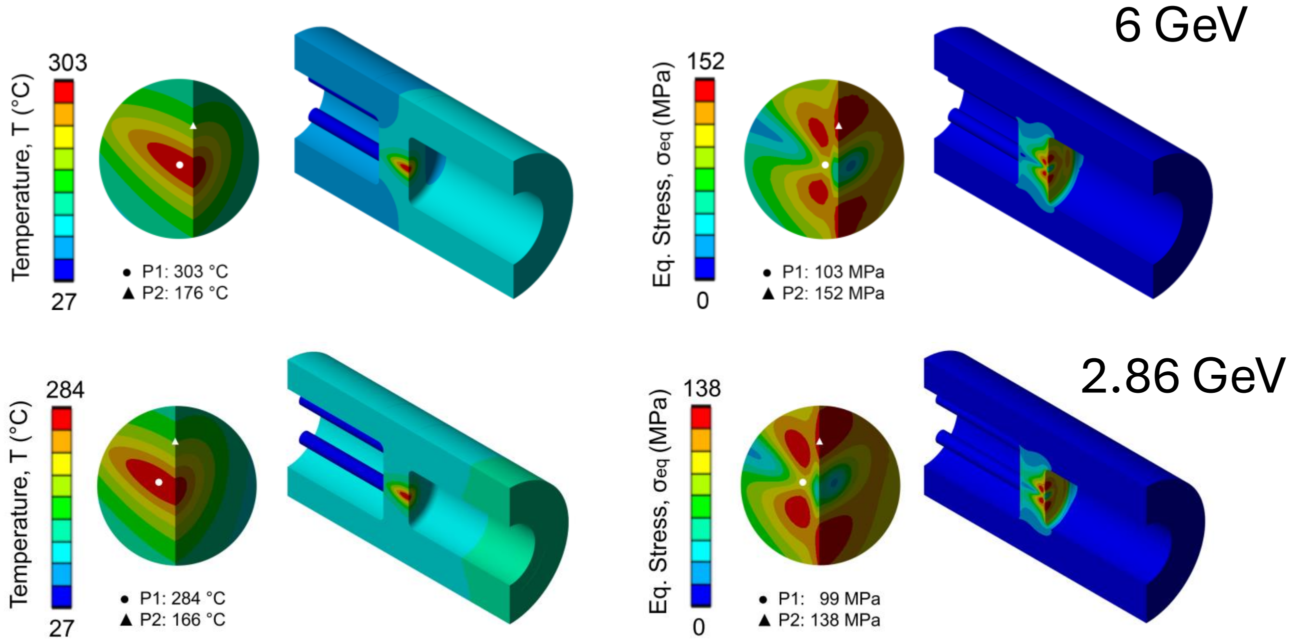


e^+ yield @ Linac end [N_{e+}/N_{e-}]	**3.9**
e^+ yield @ DR accepted/acc. with ECS	**2.7/3.2 (≳ 2.6*)**

Positron Target Design, Fabrication & Updates on P3 Integration

Ramiro Francisco Mena Andrade (CERN)

By moving from 6 GeV to 2.86 GeV, the FCC-ee positron source target (W) improved its thermo-mechanical performance. The obtained reduction in terms of temperature and stresses are beneficial from the operational point of view.



The manufacturing of the target with embedded cooling pipes prototypes are ongoing. Extensive R&D efforts are made to validate the processing route.

Fig. Welding test (left) mock-up of tantalum and (right) stainless steel used for training [A]

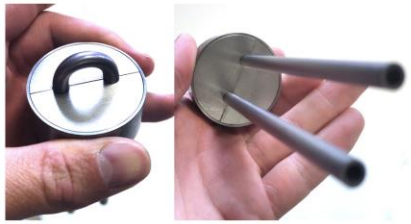


Fig. Target prototype (simplified version)

Fig. Welding test for the Ta-Ta joint on the HIPing capsule (left) mock-up and (right) zoom of the resulting joint [A]

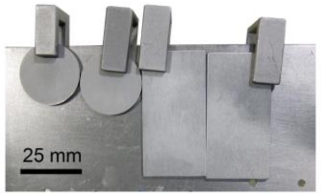
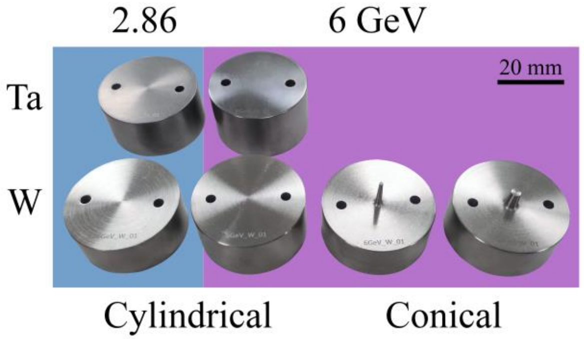


Fig. Ta CVD coating in W substrates [C]

Updates on P^3 Integration

Ramiro Francisco Mena Andrade (CERN)

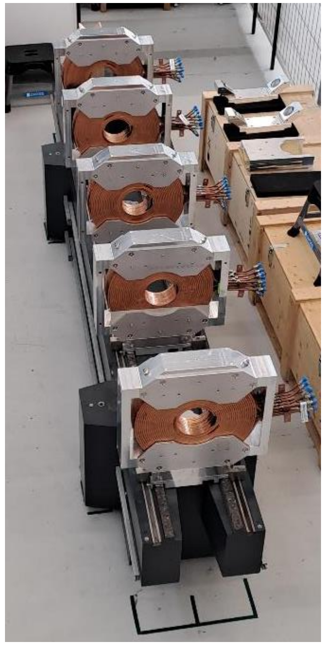
All subsystems are ready, and its installation is foreseen at PSI during the August (and Winter) shutdown(s).
Experiment in 2026 will play a key role for FCC-ee to validate new design concepts and technologies.



Targets

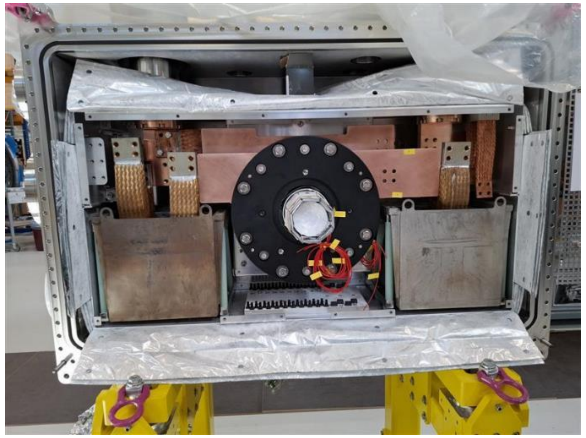

Target Insertion Device

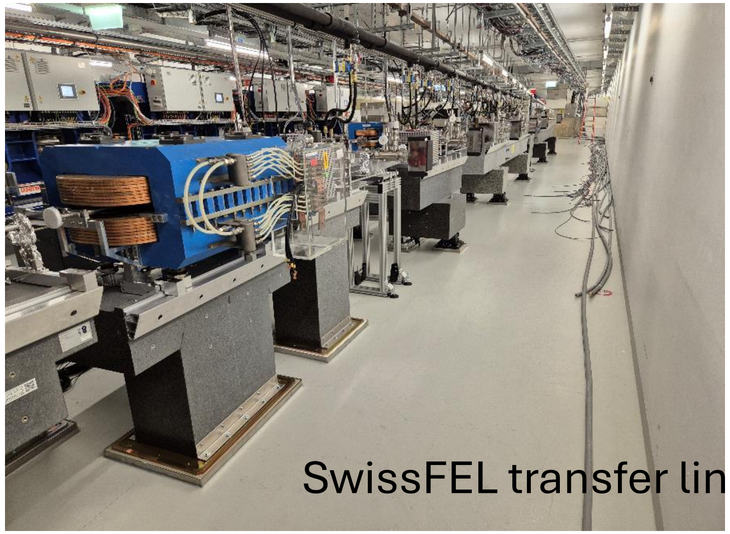
NC sol.



RF structures

HTS solenoid (for matching device)

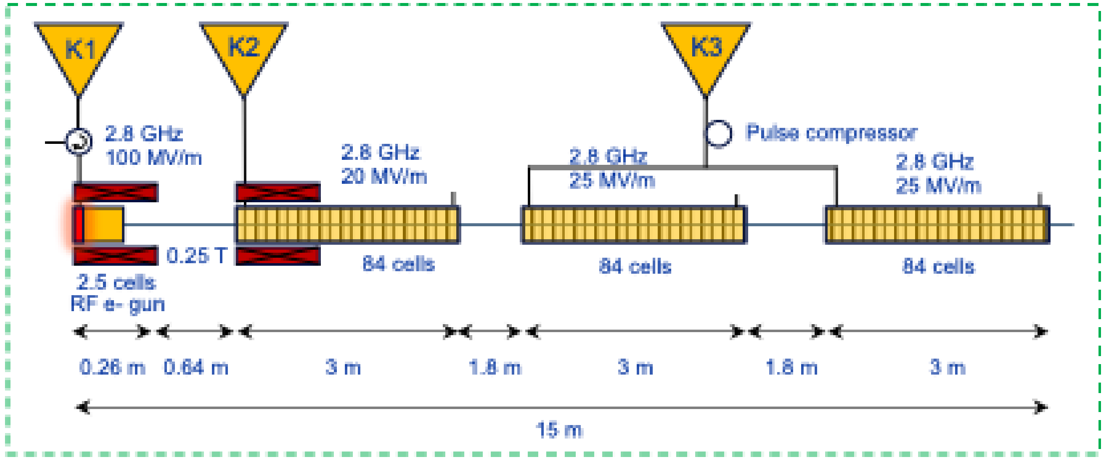



SwissFEL transfer line to the exp.

FCC-ee top-up operation: photocathodes and laser systems

Eduardo Granados (CERN)

200 MeV electron source

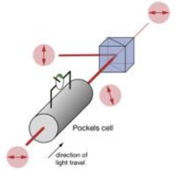
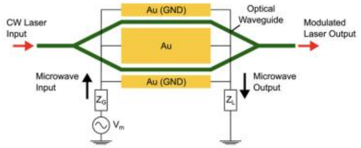
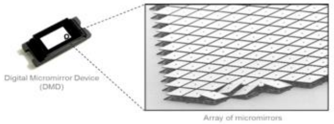


Top-up operation in the CR needs a 100% charge modulation at 100 Hz → this poses a challenging on the electron source.

Present baseline: 4 lasers systems

Next steps: Design and test hardware to demonstrate top up mode charge variation (key development for FCC-ee)

UV laser beam shaping techniques for FCC-ee top-up

	PSI	CERN
On-demand amplitude modulation	Pockels cell 	Electro-Optic front-end laser (MZM) 
Transverse profile shaping devices	Deformable mirror 	Digital micromirror device 

Photocathodes

- Choice is influenced by **quantum efficiency, lifetime**, vacuum requirements, fabrication method, and properties of the electron beam to be produced (for example, **spin polarization**).
- For tests, **Cs_2Te** and **Cu** are currently available, in the meantime we need to consider the production of alloy photocathodes (**Ir_7Ce_2**) with "infinite" lifetime and **Cs-GaAs** options for polarized photoinjector.

Laser and optical systems

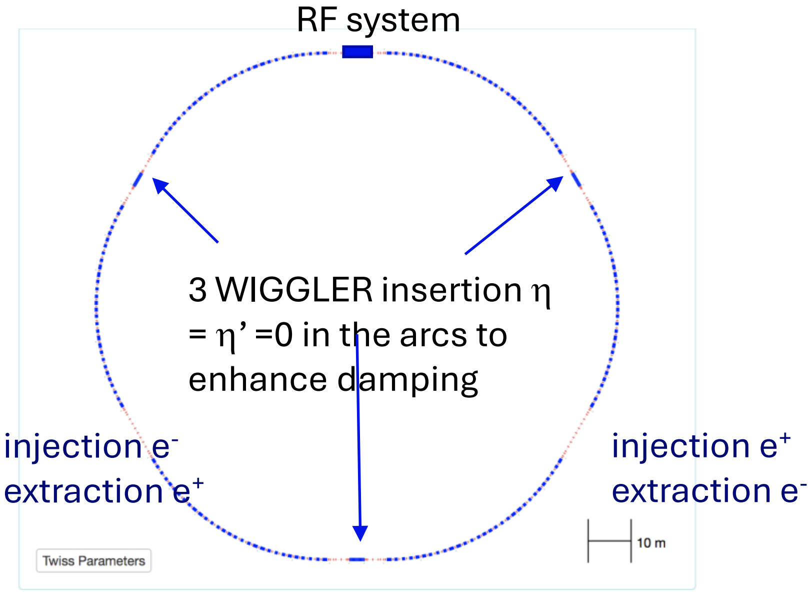
- For producing the temporal bunch structure, the options currently considered for testing are:
  - **MOPA architecture** with multiple laser lines, then recombine them at the photocathode level (well established). Tests will be carried out at **PSI**.
  - **Electro-Optic front-end** in combination with burst amplifiers (experimental). Tests will be carried out at **CLEAR**.
- In terms of the UV shaping technique, two approaches will be explored:
  - **Deformable mirror**, which allows for high pulse energy on photocathode (suitable for low QE photocathodes)
  - **Digital Micro-mirror Device (DMD)**, which allows fast masking of the UV beam profile (*higher resolution* but more lossy, works better with high QE photocathodes)

Linac and Damping Ring

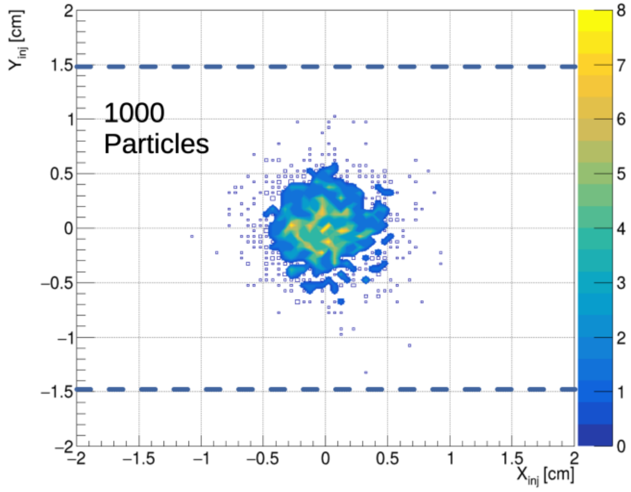
New FCC DR at 2.86 GeV and approach for low impedance design of VC

Antonio De Santis (INFN/LNF)/Shalva Bilanishvili (INFN/LNF)

- General layout established
- Preliminary optics evaluated
- DA/MA smaller than needed
- Timing and synchronization under study
- TL (injection/extraction) needs update



Parameters	Value
Energy [GeV]	2.86
Circumference [m]	373.46
Arc Cell	multi-bend
Lattice shape	six-fold symmetry
Nat. emittance [nm rad] (WGL on/off)	1.3 / 2.3
Bunch Lenght [mm]	5.1
Damping time $\tau_{x,y}$ (WGL on/off) [ms]	16.9 / 29.4
Nat. Cromaticity (x/y)	-38.2/-28.3
Nat. energy spread (WGL on/off) [10^{-4}]	7.1 / 5.2
Betatron amplitude max (x/y) [m]	9.66 / 6.49
Betatron amplitude min (x/y) [m]	0.5 / 1.1
Tune (Q_x,Q_y)	27.8707 / 22.3728
Momentum compaction (WGL on/off) [10^{-3}]	1.55 / 1.57
Revolution period [μs]	1.2457
Dipole #, length [m], field [T]	180 , 0.7 1.13, 0.34 0.39
Wiggler #, length [m], field [T]	3, 3.5 , 1.8
Cavity #, length, voltage [MV]	1.5, 4
Max. # Bunch stored, Bunch Curr. [mA]	40 / 4
Store time	5 τ_y
Energy loss per turn (WGL on/off) [keV]	422.2 / 246.7
SR power loss wiggler [kW]	27.83
Kicker rise time [ns]	50



Only Transverse motion (4D)

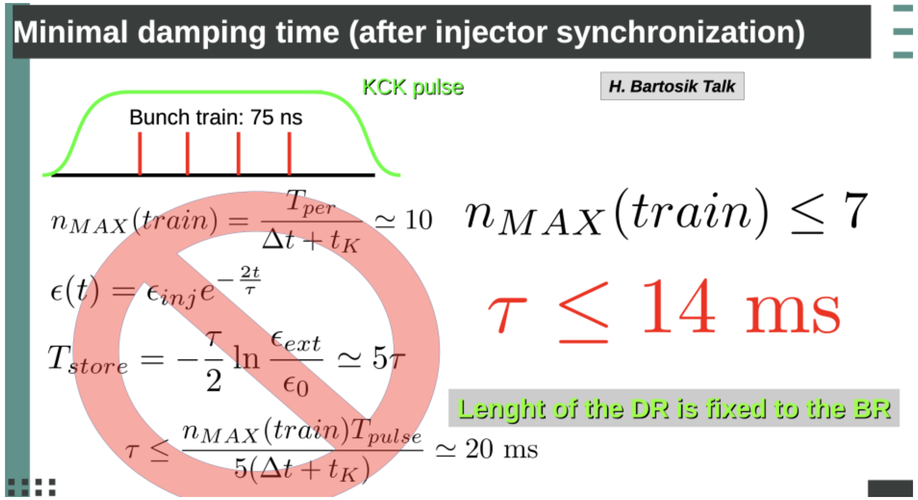
SXP ON

Beam injected in SS section with expected emittance (2.36/2.32 mm mrad) in x/y planes [FS].

Tracked for 1000 Turns

Beam Pipe physical apertures:
Horizontal: ± 3.0 cm
Vertical: ± 1.5 cm

$$\varepsilon_{acc} = \frac{472}{1000} = 47\%$$

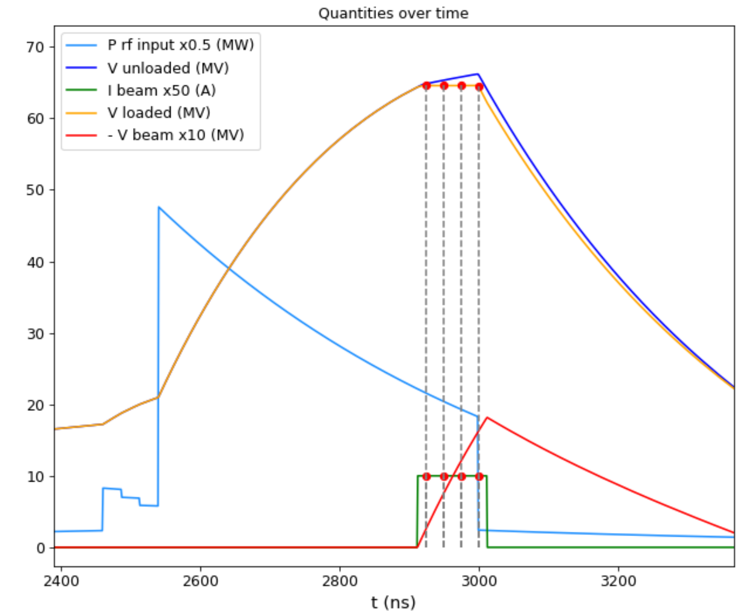


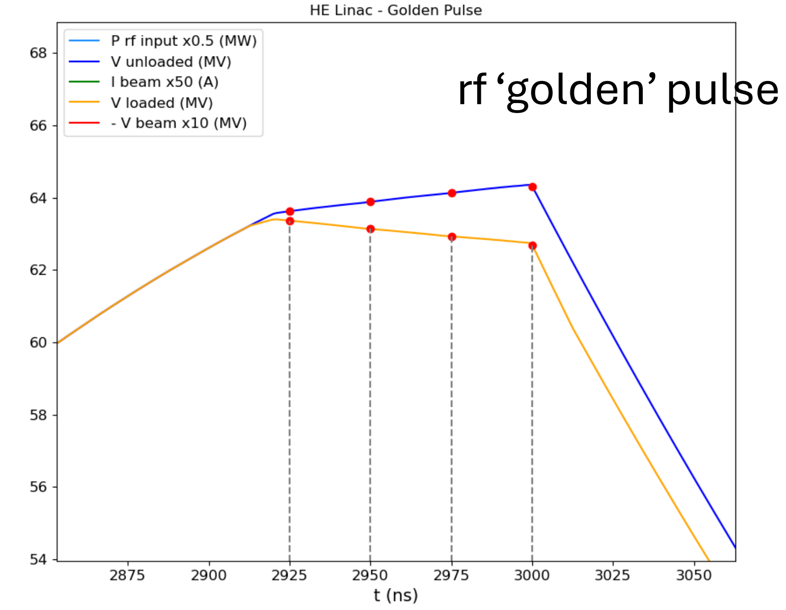
Low-impedance design of vacuum chamber: the talk highlights both proven solutions, already validated in existing accelerators, and new design concepts (e.g. BPM)

FCC-ee injector linacs: the design and the RF frequency choices for the TDR

Alexej Grudiev (CERN)

- Robust design of the FCC-ee injector linacs has been done for the Feasibility Study Report
- It must be adjusted and reoptimized for the TDR to address several changes including new RF frequency, new DR acceptance, site constraints
- It seems that the choice between European S-band 2998.5 and the CR harmonic 3006.9 MHz favor the latter one due to simpler overall compatibility of the linacs and rings with minimum impact on the RF power systems
- The design for the TDR is a chance to push the sustainability of the FCC even further by developing a high efficiency (>70%) multi-beam klystron as RF power source for the injector linacs. New design of high efficiency S-band Multi Beam Klystron (MBK) for KEK injector linac: KMS80
  - rf ‘golden’ pulse: compensation of the beam loading and rf pulse shape, energy variation between 4 bunches below ±1.5% (also also with intensity modulation of the 4 bunches).





FCC-ee injector: linacs design for single- and multi-bunch effects

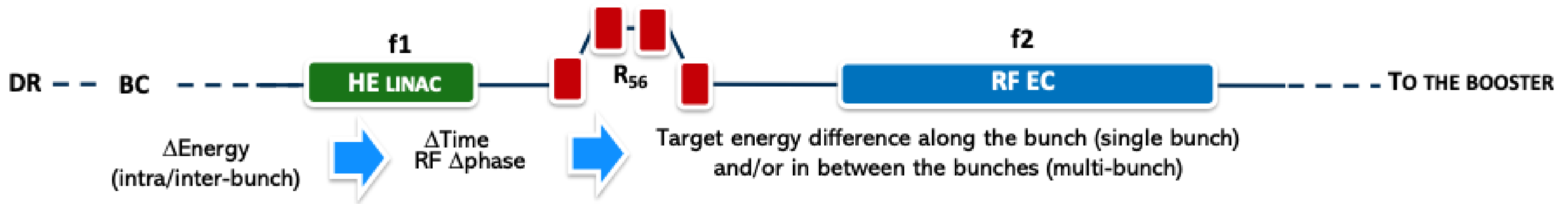
Simona Bettoni (PSI)

- **Transverse dynamics (static): emittance growth**
  - Defined the RF structures aperture along all the linacs
  - Achieved ***40% margin*** on the target emittances for the booster injection
- **Transverse dynamics (dynamic): jitter**
  - The full linac chain (single and multi-bunch) has an acceptable transverse jitter amplification for the injection to the booster
  - Used a kind of "BNS damping" which even reduces the jitter at the HE linac exit, AND operating on-crest the RF cavities

The present design fulfills the design requirements with some margin

Experimental tests to verify some of the outcomes from the simulations are essential

- **Longitudinal dynamics: energy spread and bunch length**
  - *Without the energy compressor:* solution with RF cavities operated around 10 degrees ***off-crest*** (worse for acceleration efficiency and transverse emittance growth)
  - *With the energy compressor:* RF cavities operated ***on-crest***, target parameters achieved (with even a margin for the energy spread), and independently tunable without varying the linac's settings (important for the bunch charge scan)
  - *Multi-bunch*: presented the results corresponding to the possibility of using the EC also for the beam loading compensation, to avoid the implementation of a LLRF system adjusting for each charge variation (scan from "0" nC to 5 nC)



20 GeV

RF-Track development for FCC-ee injector studies

Andrea Latina (CERN)

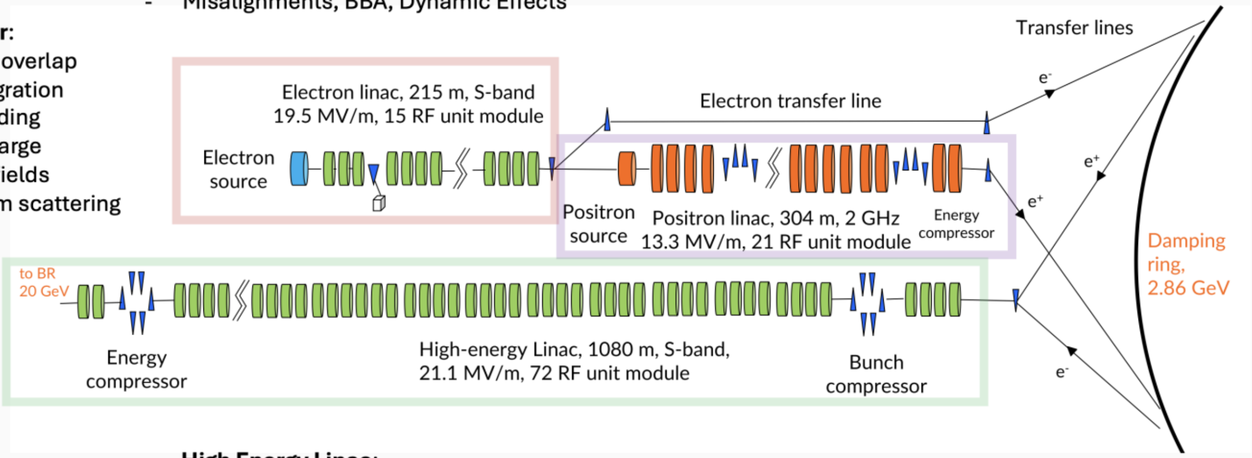
FCC

RF-Track for the FCCee Injectors

Positron source and Positron Linac:
- Elements overlap
- Time integration
- Realistic fields
- Coherent Synchrotron Radiation (EC)
- Beam loading from electrons and positrons
- Misalignments, BBA, Dynamic Effects

Electron Linac:
- Beam loading
- Multi-bunch beam loading
- Short- and Long-range wakefields
- Misalignments, BBA, Dynamic Effects

Photoinjector:
- Elements overlap
- Time integration
- Beam loading
- Space-charge
- Realistic fields
- Intra-beam scattering



High Energy Linac:
- Short- and Long-range wakefields
- Multi-bunch beam loading
- Coherent Synchrotron Radiation (BC, EC)
- Misalignments, BBA, Dynamic Effects

Damping Ring: DA studie
- Dynamic aperture
- Intra-beam scattering

Key Capabilities

- Tracking in **time** and **space** of **any particle** at **any energy**
- **Realistic fields** and **arbitrary field maps**
- **Overlapping** elements
- **Space-charge effects**
- **Beam-beam effects**
- **Intra-beam scattering**
- **Wakefields** (short- and long-range)
- **Synchrotron radiation emission**
- **Multi-bunch Beam loading** in **SW** and **TW structures**
- **Particle-matter interaction**
- Arbitrary **element misalignments**
- **Beam-based alignment** algorithms
- **Back-tracking** in the presence of collective effects

New capability for polarized electron and positron pilot bunches at the injector. Spin polarization tracking (under testing for positron linac start-to-end simulaiton)

Booster and transfer lines

Overview of the booster status (1)

Antoine Chance (CEA)

Optics

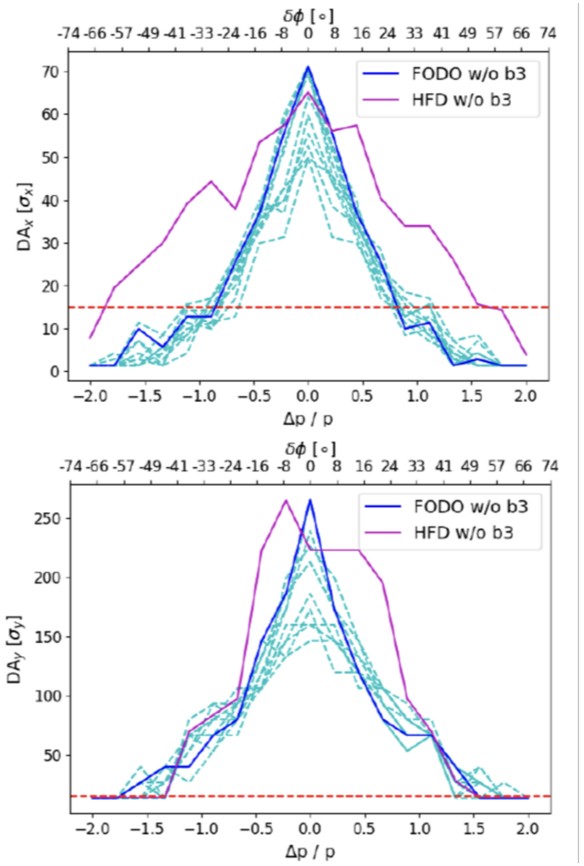
- Integration of the injection/extraction optics.
- The dynamic aperture and momentum acceptance stay large (thanks to second-order matching in the insertions).
- More work is under progress to understand the driver of the dynamic aperture and momentum acceptance and how to correct in in presence of errors.

Operation

- **New baseline RF system**: reverse phase operation in Z, WW, and ZH operation modes.
- The ramping is under progress (study of the use of wigglers to damp coupled bunch instabilities).

Other opportunities

- The use of the booster as a light source is under study. Space charge effects may be a limitation.

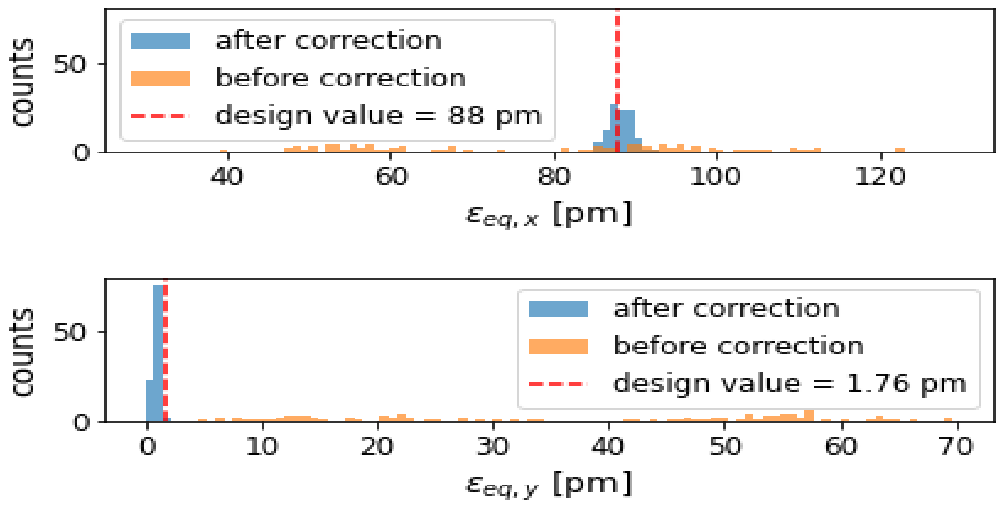


High Energy Booster Emittance Tuning

Quentin Bruant (CEA)

Great progress: beta-beating, dispersion beating, and coupling are now corrected. The equilibrium emittance in presence of errors is near the target.
Study on the tapering has begun: first results show that it is possible to have a residual and that it can be managed by using the dipole correctors + dipole sectoring in the dipoles.

Equilibrium Emittances



Updates on High-Energy Booster collective effects studies,

Adnan Ghribi (GANIL)

A robust design with respect to collective effects :

- ☑ Single bunch instabilities mitigated ;
- ☑ Transverse coupled bunch instabilities mitigated ;
- ☑ Collective effects interplay at injection not critical.

But we still need to :

- Add a complete and realistic impedance budget ;
- Study the evolution of collective effects with respect to the cycling strategy.

Baseline

Assumptions

- Only resistive wall effects taken into account (round vacuum pipe);
- Baseline PA31 optics including booster updates [a] ;
- Longitudinal impedance and wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations ;
- Studies of instabilities at injection energy.

[a] see A Chance prsentation

Overview of the booster status (2)

Antoine Chance (CEA)

Emittance evolution: Total cycling: 0.746 (ramp-up) +0.1 (flat-top) + 0.294 (ramp-down) = 1.14 s

- We use the double parabolic ramp + energy overshoot. Wigglers can help mitigating coupled bunch instabilities at injection. Consideration for **0/1/2 permanent wigglers**.
- Initial beam parameters: **20 μm x 2 μm x 1e-3**
- Final beam parameters: Hor. Emittance: **113 pm / 95 pm / 81 pm**, Vert. Emittance: **2.69 pm / 1.93 pm /1.38 pm**, Energy spread: **0.383e-3, 1.109e-3, 1.437e-3**
  - Because of the I_3 increase, the energy spread is too large at extraction. How to get a smaller energy spread at extraction is under investigation.

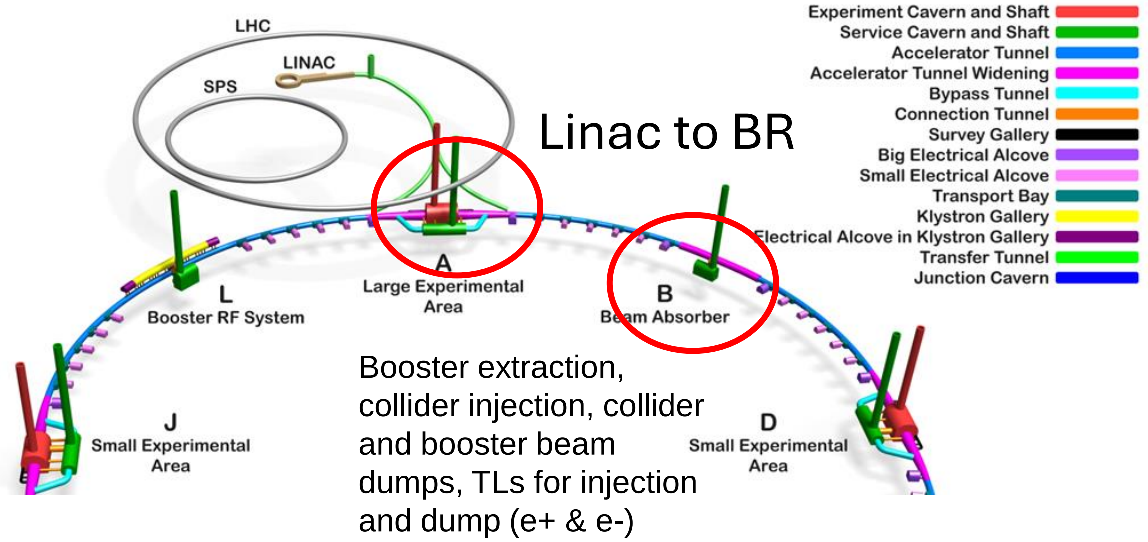
Perspectives

- Update the lattice to follow the changes in tunnel geometry or in collider lattice.
- Continue the good work on optics tuning (including tapering), collective effects (to study space charge effects and IBS together with a refined impedance budget), operation with an optimized ramp, integration of the insertions (injection, extraction, …), spin transport, and feed the database and the global parameter tables.
- Impact of the leaking field of the detector solenoid on booster optics.

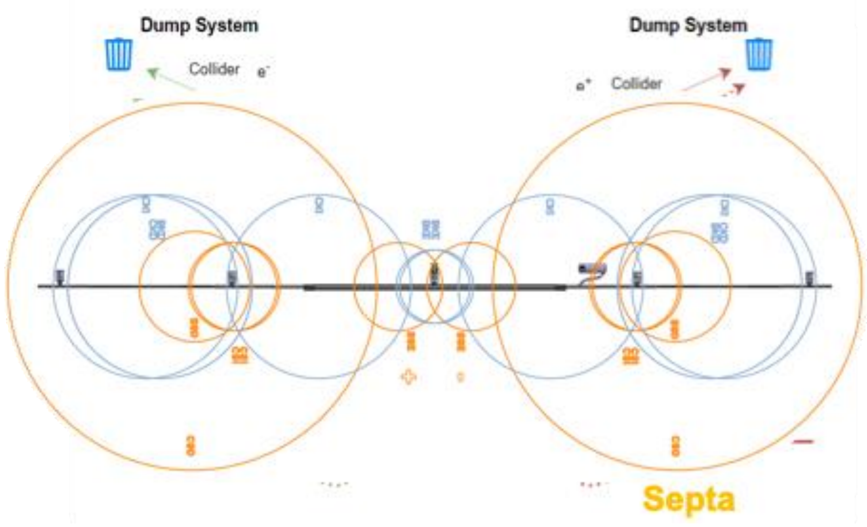
Injection/extraction systems across the FCCee complex

Sen Yue (CERN)

- **Requirements from TL & Booster injection:**
  - Survey point and optics parameters at the end of HE linac
  - Alcove location for booster injection design
  - Beam time jitter from HE linac, damper in booster ring



- **Booster extraction (PB):**
  - Symmetric design for e- and e+ extraction
  - Precise vertical dispersion control in the transfer line to the collider injection
- **PB Integration:** Further in-depth integration studies are required due to the high system density and interdependence

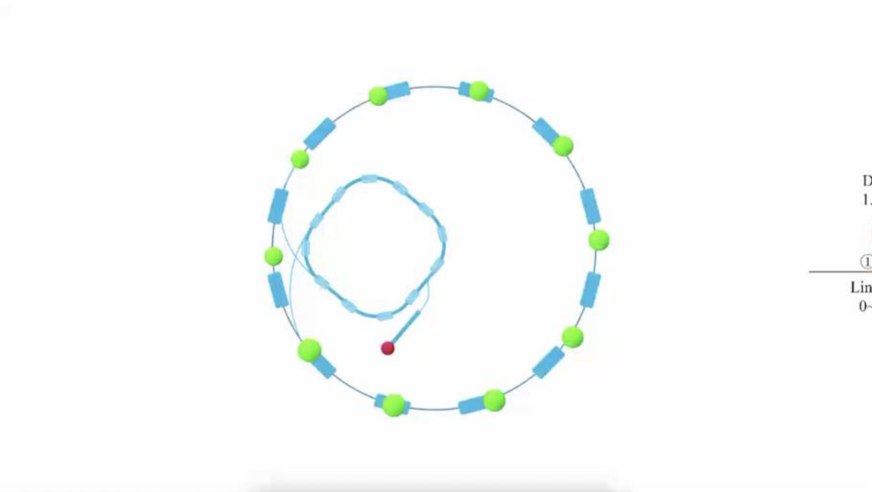


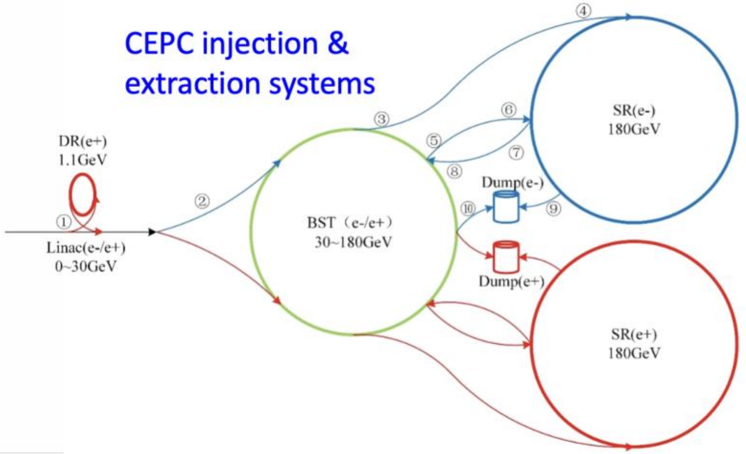
Swap-out injection with beam recycling in the booster @ the High Energy Photon Source (HEPS)

Zhe Duan (IHEP)

- The swap-out injection scheme with beam recycling in the booster has been demonstrated and utilized in routine operation at HEPS
- Novel injection hardware (stripline kicker module, half-in-vacuum Lambertson, HV pulser based on DSRD & inductive adder) has been fully tested and running smoothly

- Swap-out injection, with bunch recycling in the booster as a full energy accumulator ring
  - save ¾ costs relative to the scheme with a dedicated accumulator ring
  - Decrease the bunch charge requirement of booster LE by ½, improving the reliability of booster design





HEPS HIGH ENERGY PHOTON SOURCE

Note: similar injection scheme is adopted for CEPC at the Higgs energy

That’s all, thank you!!