Start-to-end simulation of positron sources for future colliders

Fahad A. Alharthi
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab)
CNRS, Université Paris-Saclay
alharthi@ijclab.in2p3.fr

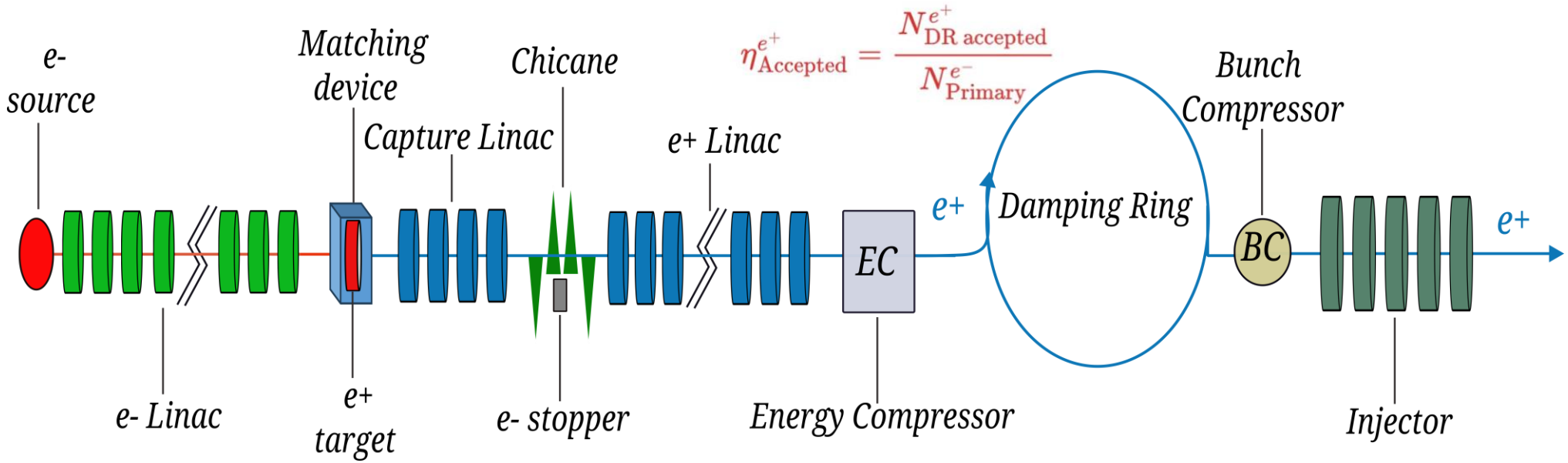
On behalf of: I. Chaikovska, V. Kubytskyi, V. Mytrochenko, Y. Wang (IJCLab), Y.Enomoto, F. Miyahara, M, Fukuda (KEK)

Outline

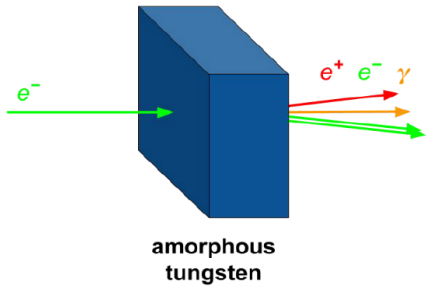
- Positron source for Future lepton colliders
- Toward a start-to-end modeling of the positron source.
- Historical collaboration between KEK and IJCLab
- Recent activities
- Summary and conclusion.

French member		Japanese member	
Iryna Chaikovska	IJCLab (FCC-ee)	Yoshinori Enomoto	KEK(SuperKEKB/ILC)
Fahad Alharthi	IJCLab (FCC-ee)	Fusashi Miyahara	KEK (SuperKEKB)
Viacheslav Kubytskyi	IJCLab (FCC-ee)	Masafumi Fukuda	KEK (ILC)
Viktor Mytrochenko	IJCLab (FCC-ee)		
Yuting Wang	IJCLab (FCC-ee)		

Positron source for Future lepton colliders



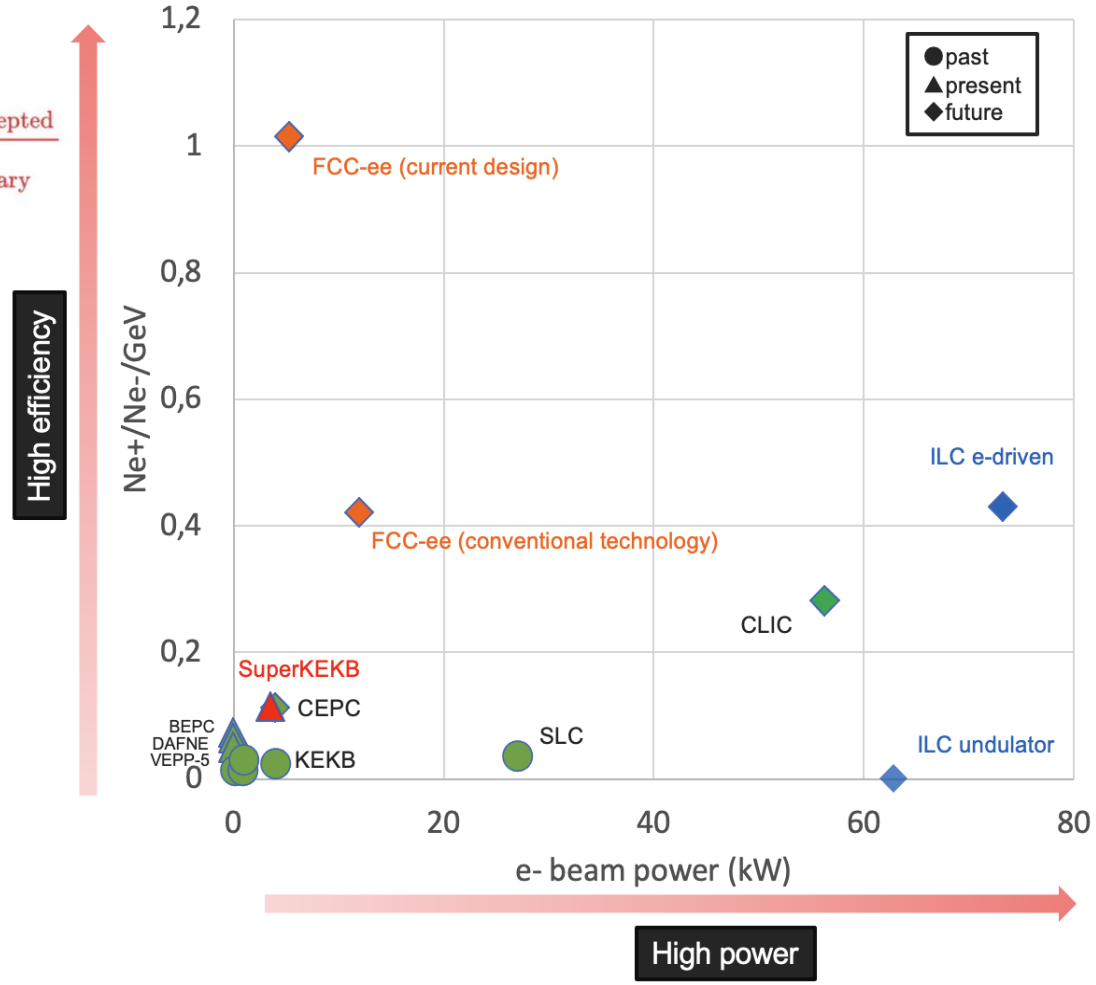
- Positron source is one of the most critical component of the future linear and circular collider.
- Achieving the required Lumosity demands a high positron beam intensity.
- Electron/positron pairs are produced in a target-convertor.
- Positron immerged from the target with a large 6D phase space.
- Efficient collection and transportation are necessary.



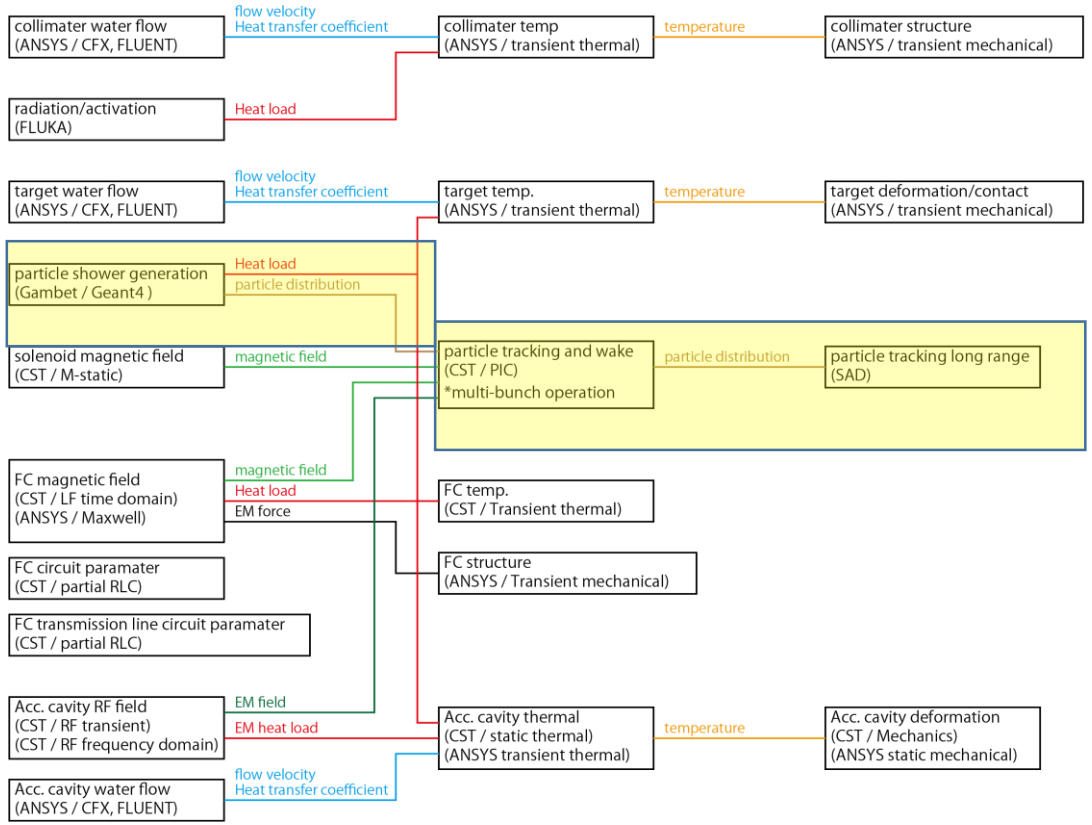
Positron sources performance

- Key factors for high positron yield:
  - Primary e- energy and power $\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$
  - Target design
  - Magnetic strength around the target and capture linac
  - Transverse aperture of the capture linac.

- In the case of FCC-ee positron source, the use of an **HTS solenoid** with a peak field of **~12T** around the target together with large aperture capture linac can substantially increase state-of-the-art e+ yield, by one order of magnitude.



Toward a start-to-end modeling of the positron source.

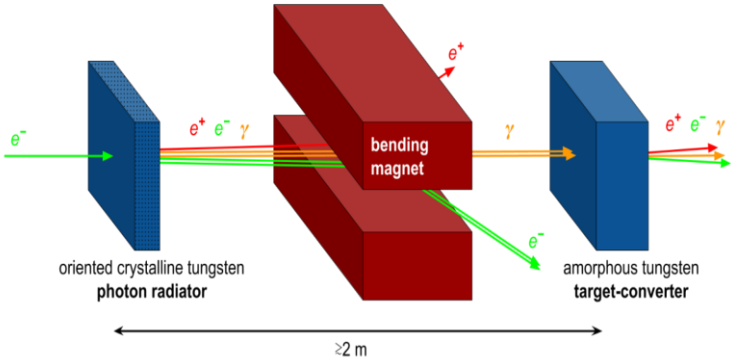


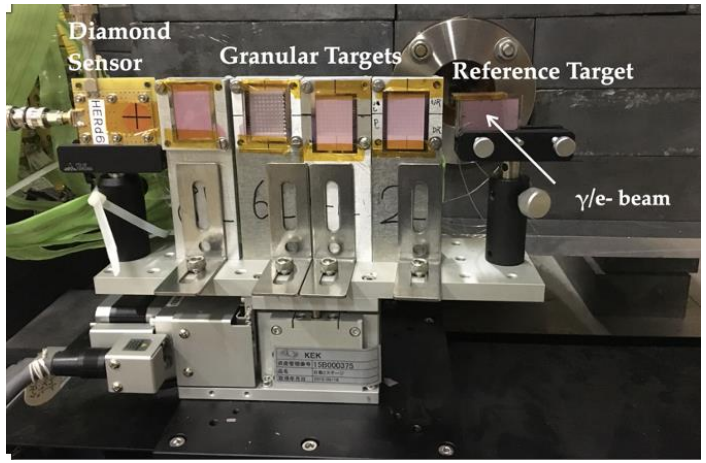
- The simulation chain is complex and interconnected.
- At its core lies the positron production and tracking up to the Damping Ring to estimate the positron yield.
- This yield drives the optimization of all downstream components.
- A flexible experimentally validated, start-to-end simulation framework is essential.

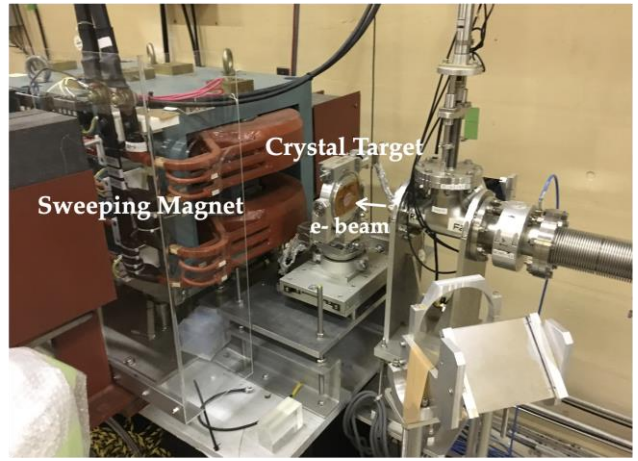
SuperKEKB has the highest-intensity positron source in operation, **serving as a key benchmark for future source development**

Historical collaboration between KEK and IJCLab

- IJCLab and KEK have a long-standing collaboration on the positron source.
  - KEK electron positron injector LINAC has keep producing positrons since 1980's (TRISTAN, KEKB, SuperKEKB), and collaboration started at the beginning.
- For last several years, noble target, such as hybrid target and granular target, are actively studied in our collaboration.
- Previous FJPPL project during 2018 to 2021, (A_RD_13: High Intensity positron sources for Circular colliders (SuperKEKB, FCC-ee)), strengthen mutual relationship very much.

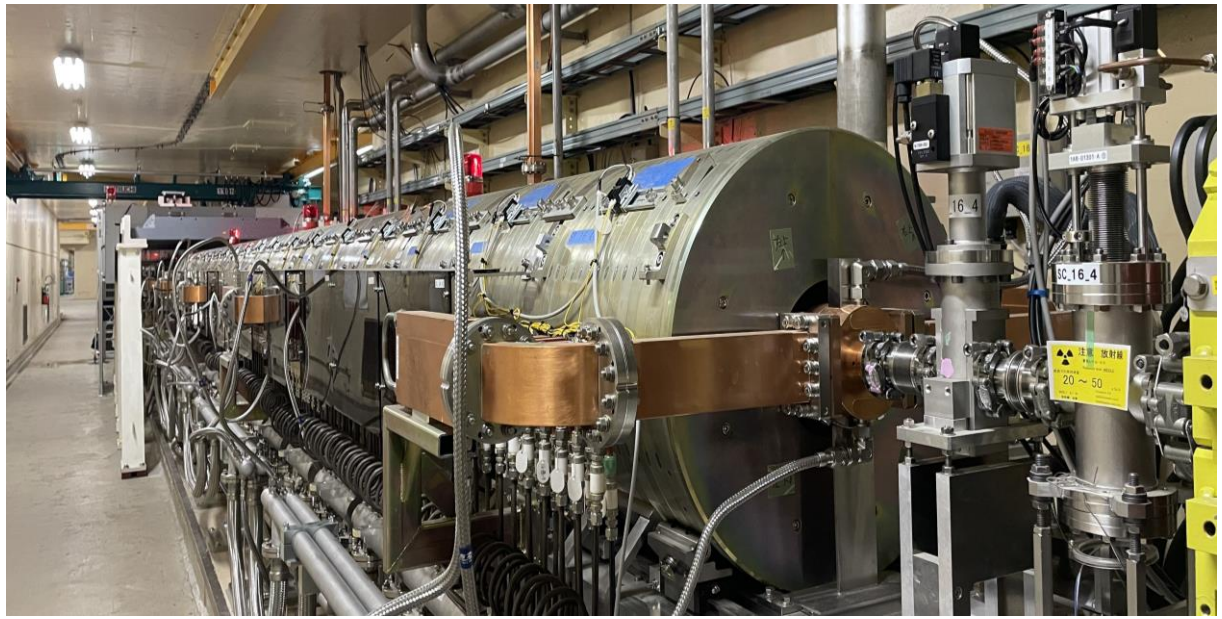




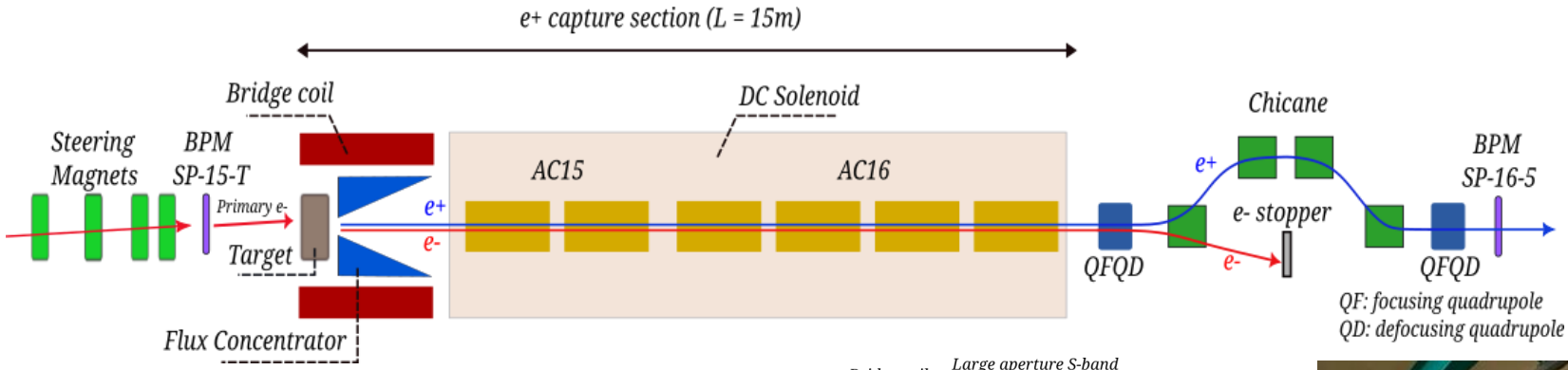


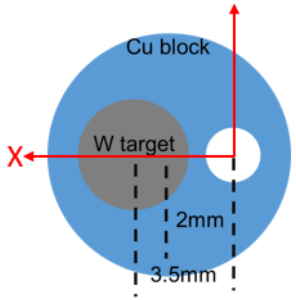
Recent activities (2022 - 2024)

- IJCLab team is responsible for designing the positron source for FCC-ee.
- A start-to-end simulation framework has been developed starting from the target until the entrance of the Damping Ring.
- Since the positron source at SuperKEKB is the only high intensity positron source in operation, the IJCLab team visited KEK Nov/Dec in 2022 and 2023 and early 2025, with the goal to validate the model experimentally.

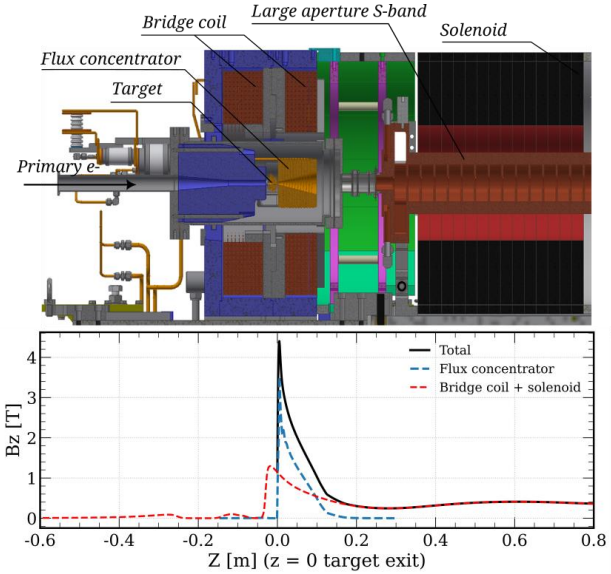


Positron source at SuperKEKB





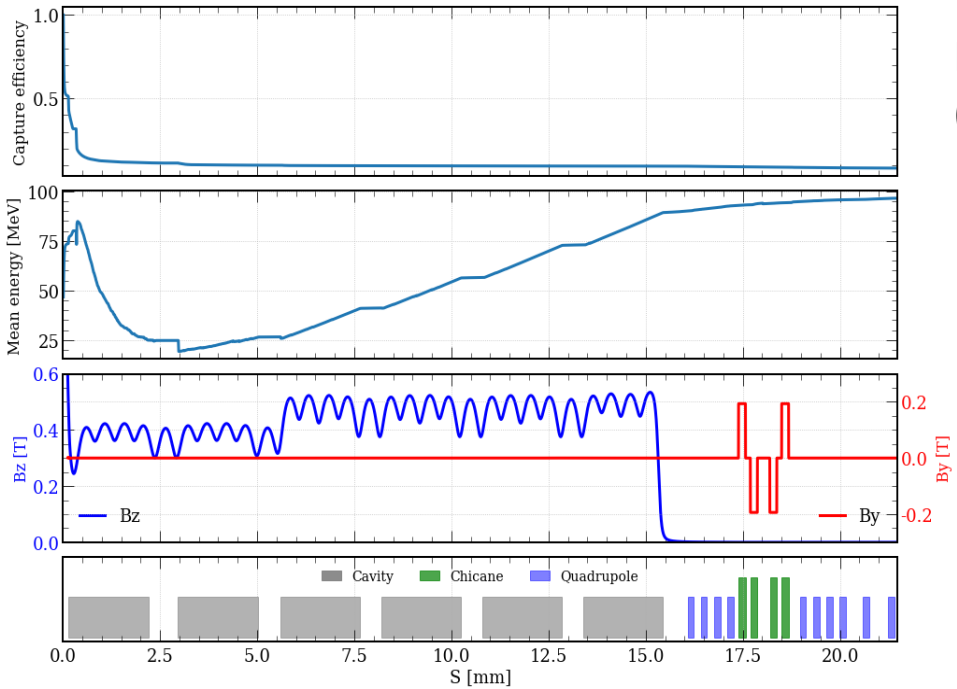
- Several experiments conducted at SuperKEKB positron source:
  - Impact position on the target.
  - RF phase of the capture linac.
  - Magnetic fields of solenoids and Flux concentrator.
- The benchmarking also include comparison between different simulation tools.



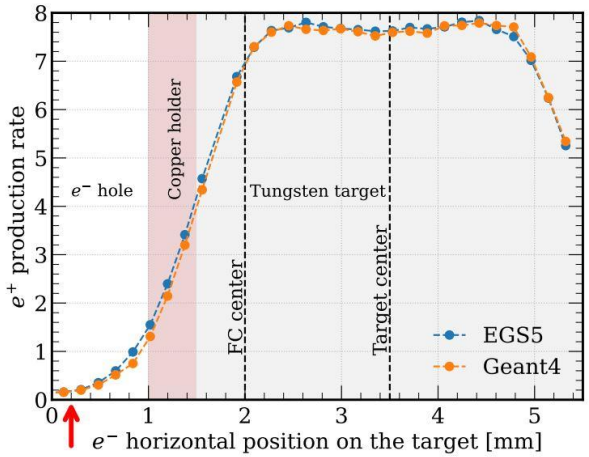
Recent activities (2022 - 2024)

- Testing the start-to-end tracking model at the SuperKEKB positron source.

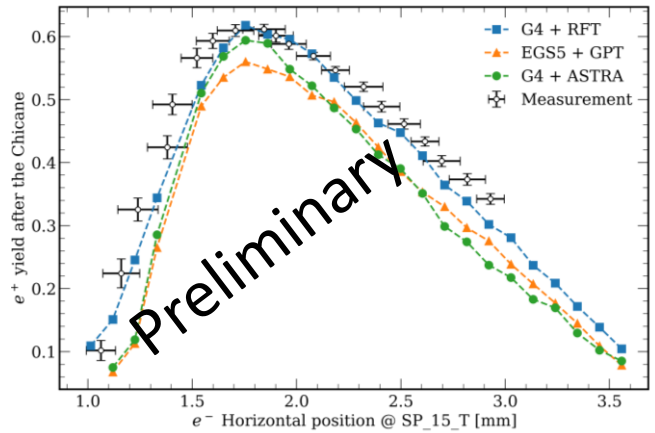
Tracking simulation results in the capture section.



Positron production rate (Geant4 and EGS5).

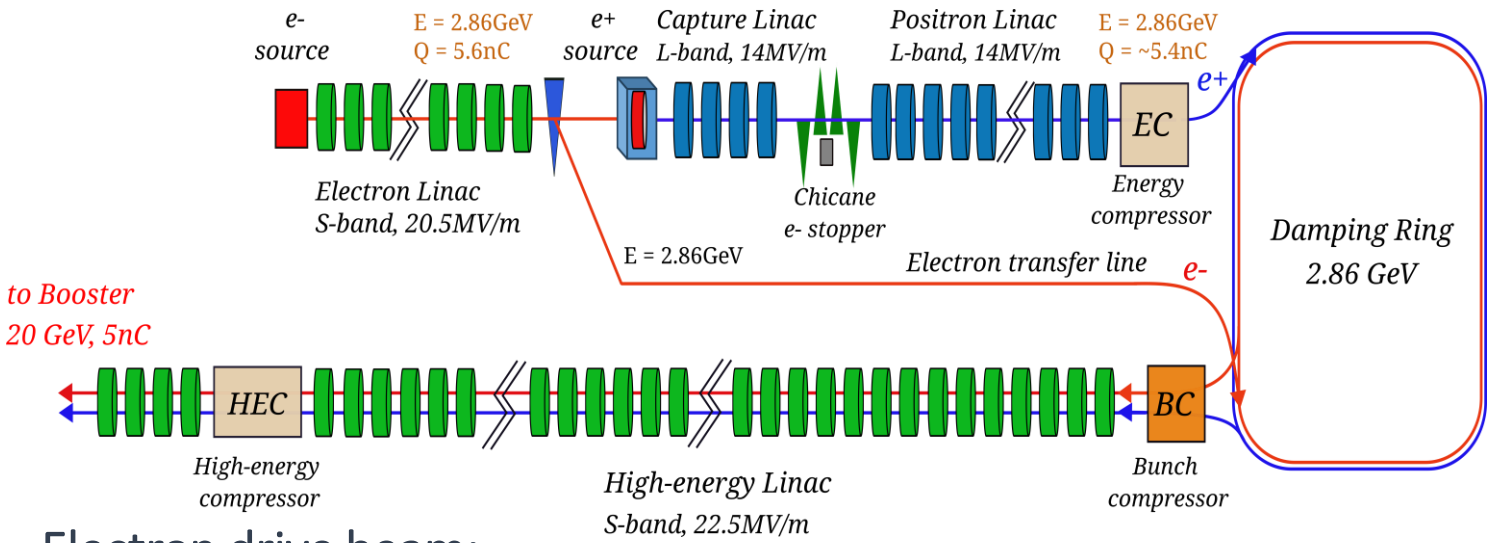


Horizontal impact position of the e- on target.

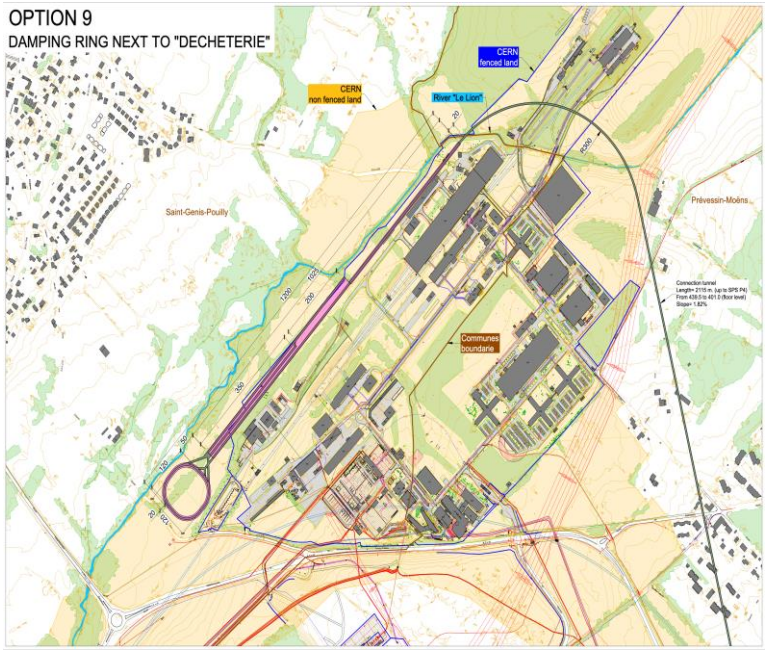


The FCC-ee positron source model (Geant4 + RF-Track) has been successfully validated experimentally at SuperKEKB. (Paper is finished and will be submitted soon.)

FCC-ee injector layout (Current baseline)



H. Bartosik, T. Watson, P. Craievich



Electron drive beam:

Beam energy	2.86 GeV
Bunch charge	~5.6 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

Nb of bunches per pulse	4
Bunch separation	25 ns
Repetition rate	100 Hz
Beam power	~6.4 kW

$$\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$$

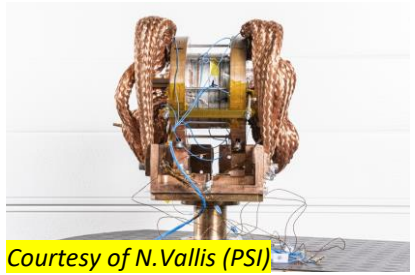
**50% losses for injection in the DR + 20 % losses from target up to the end of the e+ linac*

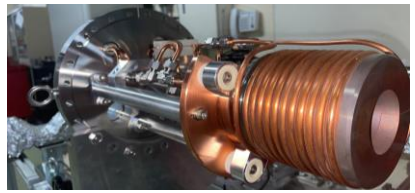
- Latest proposal: injector complex on the Prévessin site with damping ring next to the "Decheterie"
- High energy linac next to North Area and Beam Dump Facility

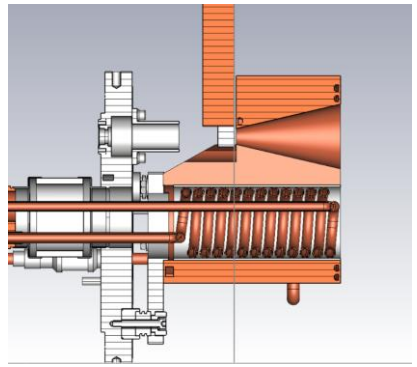
FCC-ee positron source matching device options (joint investigations)

- KEK shared the field maps of the Flux concentrator with IJCLab.
- IJCLab carried out the tracking simulation and compared it with the baseline option.

Parameters	Flux concentrator		HTS
Matching Device (MD)	ILC-KEK FC	SuperKEKB FC	HTS solenoid
MD aperture [mm]	2a=12-64	2a=7-52	$2a_{min}$=60
MD peak magnetic field (@Target) [T]	5.3 (0.95)	4.5 (1.1)	15 (12)
e- bunch charge [nC]	**11**	**7.9**	**3.8**
Deposited power [kW]	2.9	2.1	1
PEDD [J/g]	16.4	11.8	5.8
e+ yield @Target [Ne^+/Ne^-]	7.07		
e+ yield @ CS [Ne^+/Ne^-]	1.3	1.7	4.1
e+ yield @DR [Ne^+/Ne^-]	**0.8**	**1.49**	**3**
e+ bunch charge @ DR [nC]	**5**		


Courtesy of N.Vallis (PSI)





- Innovative, DC operation

High-Temperature Superconducting (HTS) solenoid designed by PSI => HTS:FCC

Current baseline option

- Classical, Pulsed

Originally designed by KEK for the SuperKEKB => FC:SKEKB-KEK

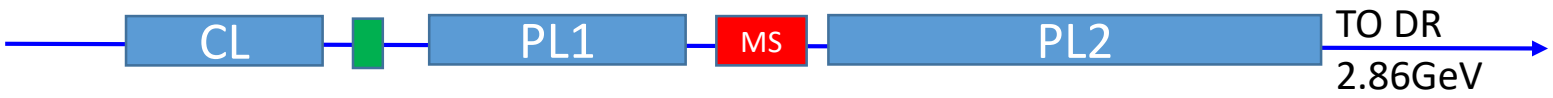
Under consideration for the FCC-ee (with and w/o Bridge Coils)

- Classical, Pulsed

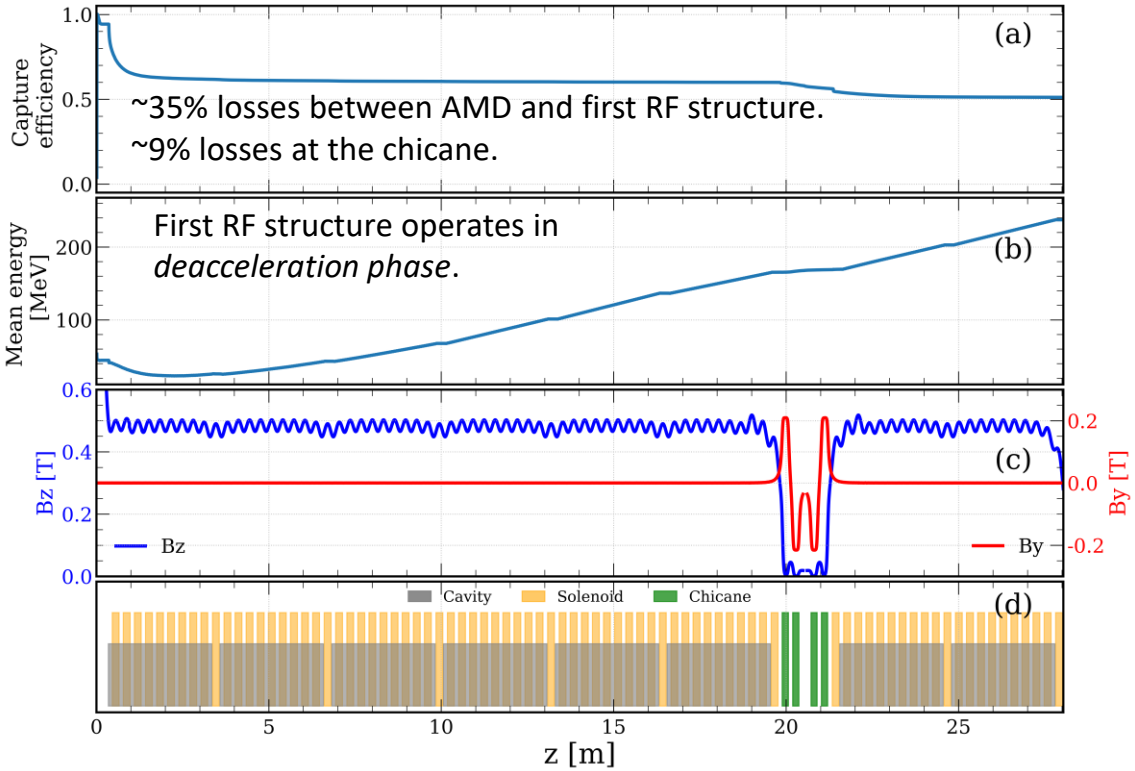
Designed by KEK for the ILC (Y. Enomoto) => FC:ILC-KEK

Under consideration for the FCC-ee

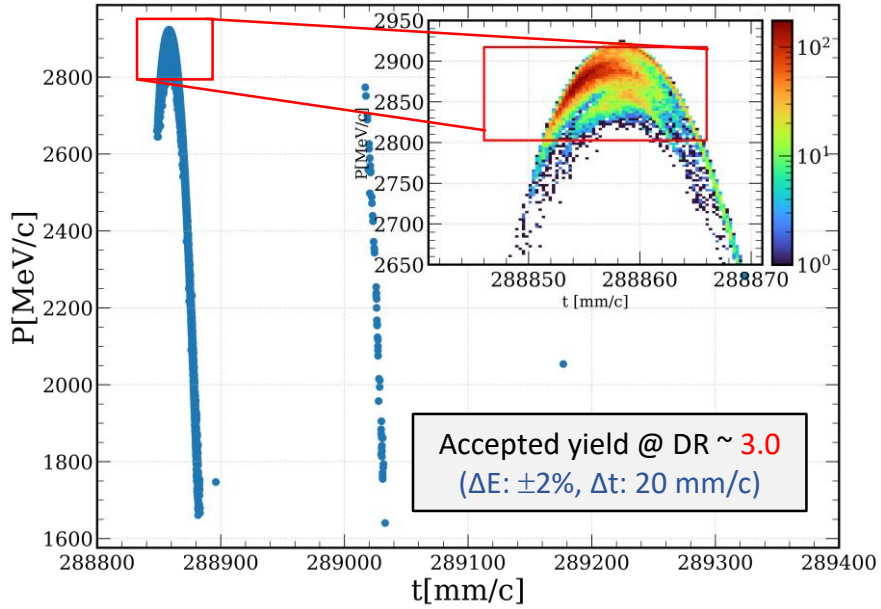
FCC-ee positron source simulation: based on Geant4 + RF-Track (HTS)



- **RF structures**: 2GHz L-band with aperture (2a) = 60mm , 3m long and 13.3 MV/m.



Longitudinal phase space and window acceptance

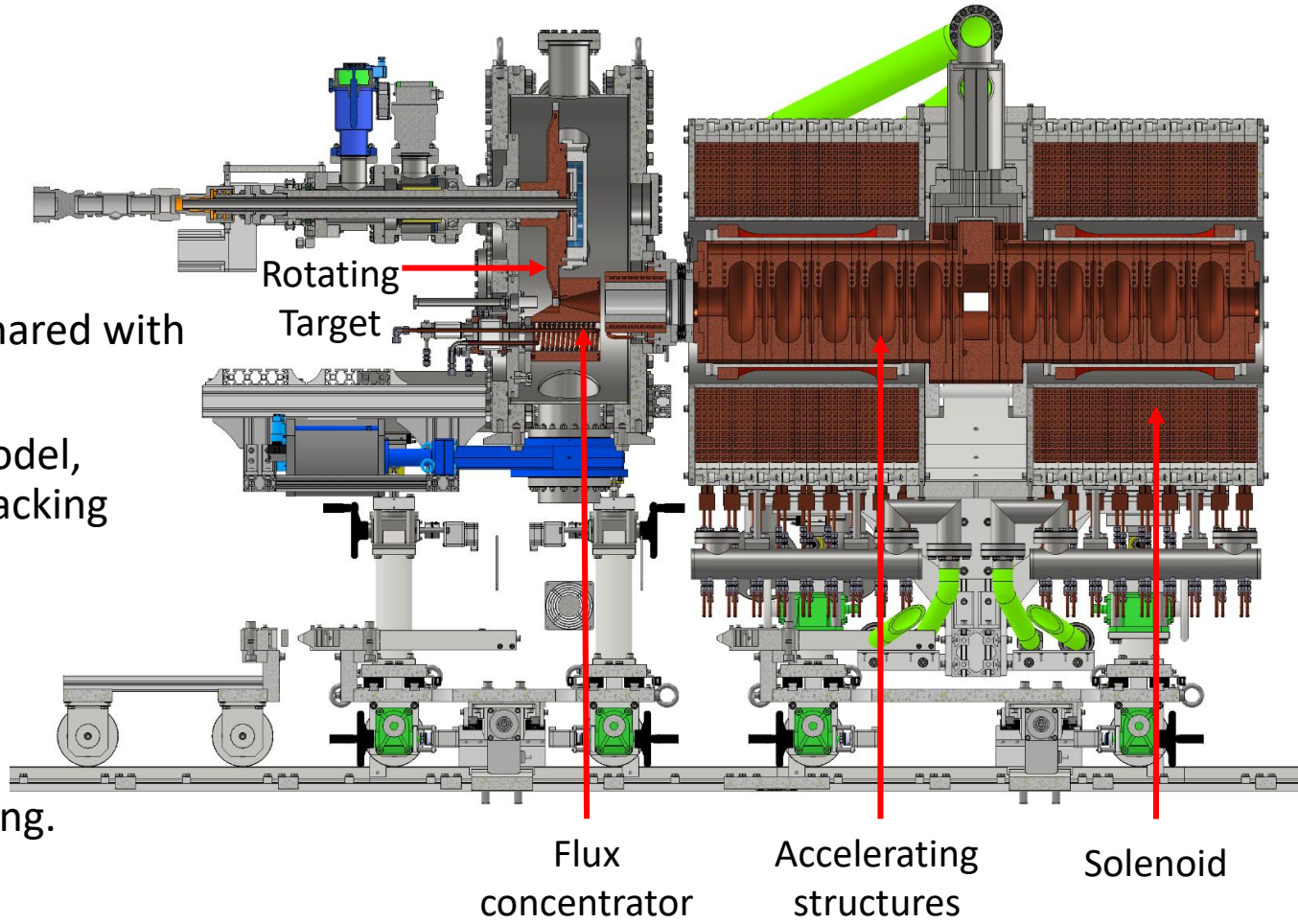


The design is finished and included in the FCC Feasibility Study report [ref].

Activity plan in FY 2025

KEK group is actively designing the positron source prototype for ILC.

- Key technologies:
  - Flux concentrator.
  - Capture cavity.
  - Rotating target.
- All the field maps and design layout are shared with IJCLab.
- Talking advantage of the benchmarked model, IJCLab is contributing to do the particle tracking simulations.
- The primary focus is on:
  - Multi-bunch simulations
  - Beam loading simulations.
  - Simulation to simulation benchmarking.
  - Overall optimizations.



Prototyping of positron source for ILC

- Prototyping of positron source for ILC has been progressing rapidly since 2023.
  - Validation of design is important to support simulation results.
  - Mechanical and thermal tests of the rotating target are in progress.
  - High power test of the FC with the rotating targe is foreseen.

Conclusion

- IJCLab and KEK share a strong, long-standing collaboration, leading global efforts in positron source development for future lepton colliders.
- A comprehensive start-to-end simulation framework has been developed and validated using data from SuperKEKB.
- This model has been adopted for the FCC-ee positron source design and is included in the FCC Feasibility Study Report (March 2025).
- Regarding Linear Colliders, KEK and IJCLab are actively collaborating on the design and beam tracking simulations for the ILC positron source prototype being under construction at KEK.

Thank you for your attention!

Backup.

Particle sources and positron source

Primary particle source

- Electron source
- Ion source

- High quality beam for acceleration
- Stand alone test is possible
- No radiational, thermal requirement

Accelerator

Positron source source

- Positron source is installed in the middle of accelerator
- Collection and acceleration of secondary beam
- need high power primary beam for full test
  - Usually impossible before construction

Secondary particle source

- Neutron source
- Muon source
- Neutrino source

- Low beam quality is acceptable
- Need high power primary beam
- Severe radiational, thermal requirement