[A_RD_22]

Modeling and start-to-end simulation of positron sources for future colliders

Yoshinori Enomoto (Acc. Lab., KEK)

On behalf of collaborators:
I. Chaikovska, Y. Wang (IJCLab),
F. Miyahara, M, Fukuda (KEK)

A_RD_22

French member（2025）		Japanese member	
Iryna Chaikovska	**IJCLab (FCCee)**	**Yoshinori Enomoto**	**KEK(SuperKEKB/ILC)**
Fahad Alharthi	IJCLab (FCCee)	Fusashi Miyahara	KEK (SuperKEKB)
Viacheslav Kubytskyi	IJCLab (FCCee)	Masafumi Fukuda	KEK (ILC)
Viktor Mytrochenko	IJCLab (FCCee)		
Yuting Wang	IJCLab (FCCee)		

Title: Modeling and start-to-end simulation of positron sources for future colliders

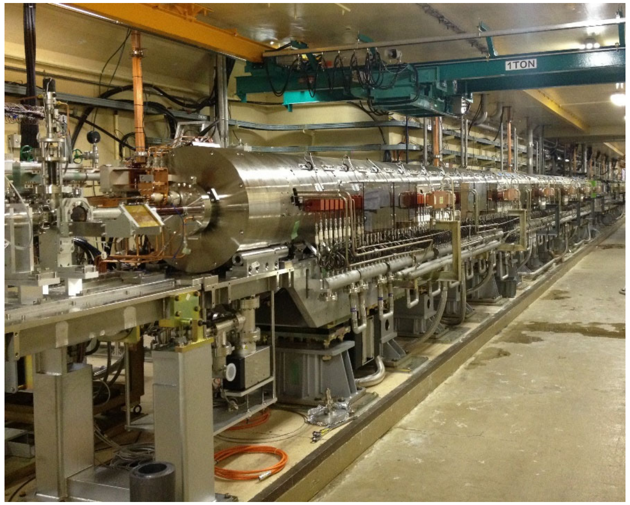
Target: positron sources for ILC and FCCee

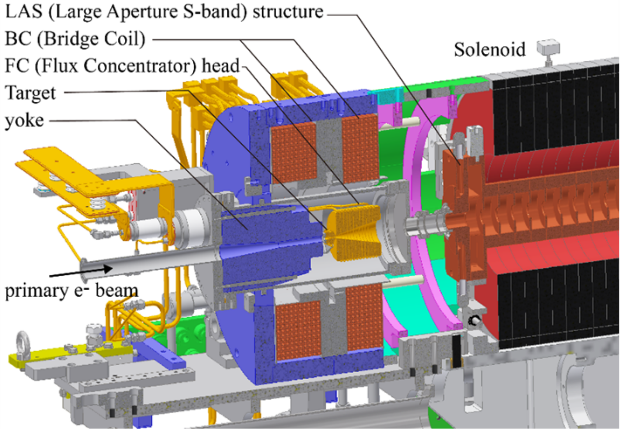
Scope: Design, modeling and simulation of future positron source

Experimental validation of simulation using SuperKEKB

Introduction - positron source

- Positron source is one of the critical component for the future linear and circular collider.
  - To achieve higher luminosity, higher beam intensity is required.
  - e+ are produced within large 6D phase space value (e+/e- pairs produced in a target-converter).
  - Efficient collection and transportation are necessary
  - It's very difficult to develop it step by step using results from beam experiment





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

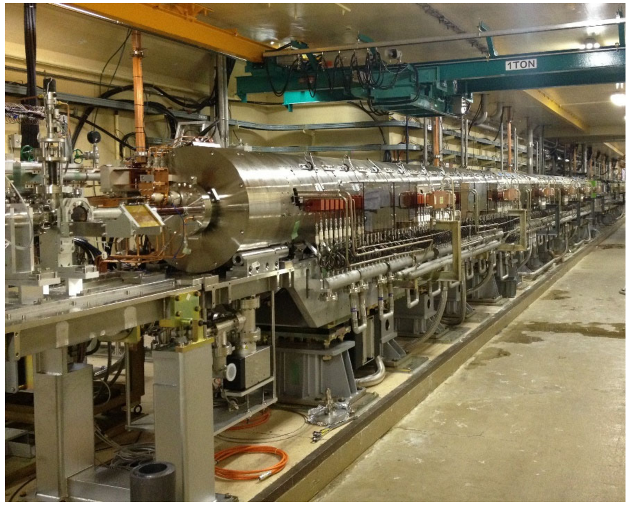
secondary particle source

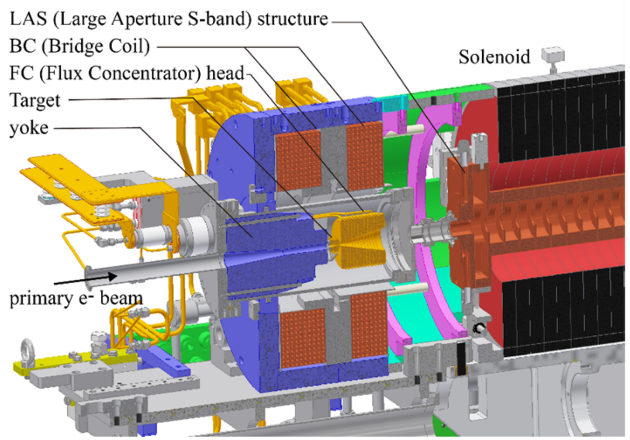
- Neutron source
- Muon source
- Neutrino source

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

Introduction - positron source

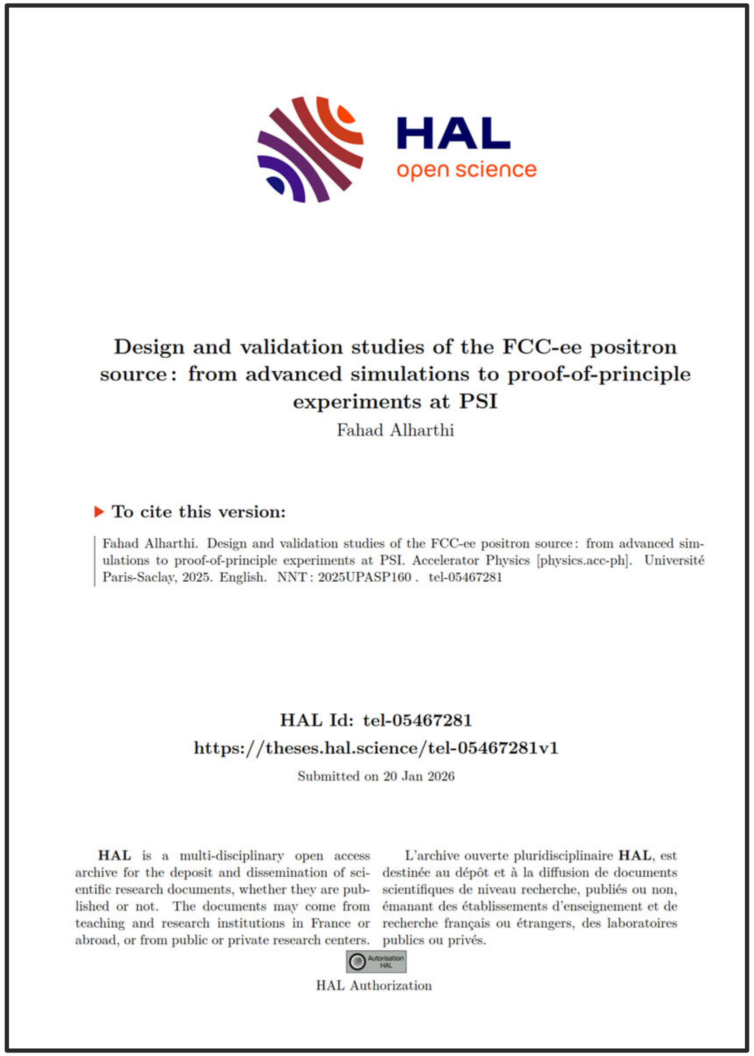
- Positron source is one of the critical component for the future linear and circular collider.
  - To achieve higher luminosity, higher beam intensity is required.
  - e+ are produced within large 6D phase space value (e+/e- pairs produced in a target-converter).
  - Efficient collection and transportation are necessary
  - It's very difficult to develop it step by step using results from beam experiment
  - Importance of detailed simulation is extremely high
  - SuperKEKB is one of a few machine where the high-power positron source for collider is in operation
  - Design and prototyping of positron sources for ILC and FCCee are in progress and similar phase
  - **Maximize the synergy using this collaboration flamework**





Collaboration history of 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.
- 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.
- Now, focus on future collider, FCCee and ILC.
- A graduate student, **Fahad Alharthi,** who is a main player of our collaboration got PhD in 2025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Design and validation studies of the FCC-ee positron source: from advanced simulations to proof-of-principle experiments at PSI

Fahad Alharthi

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Recent situation on positron sources

FCCee

- Design of the positron source for FCC-ee project is actively carried out and summarized in FCCFS published in 2025.
  - IJCLab takes the responsibility of the positron source design
  - Proof-of principle experiment at PSI under the CHART program is in progress

SuperKEKB

- Operation of positron source for SuperKEKB is stable
  - Since major upgrade in 2020, it works almost at the design value without trouble.

ILC

- Design and prototyping of the positron source is in progress
  - 5 years project (2023-2027)
  - Most of the components are delivered and under evaluation.
  - Simulation based on detailed design is in progress

Activity in FY2025

- Recent works were summarized as a PhD thesis by Fahad Alharthi
  - Experimental study of positron source using SuperKEKB
  - Simulation of capture section
  - Essential part was published in PRAB
- Two people from French side stayed in Japan in March.
- Prototyping of positron source ILC got into final phase

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Modeling of the positron sources: Experiment-based benchmarking using SuperKEKB

Fahad Alharthi,[*,†] Iryna Chaikovska, Robert Chehab, and Viktor Mytrochenko
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405, Orsay, France

Fusashi Miyahara, Takuya Kamitani, and Yoshinori Enomoto
High Energy Accelerator Research Organization (KEK), Oho 1-1, Tsukuba, Ibaraki, 305-0801, Japan

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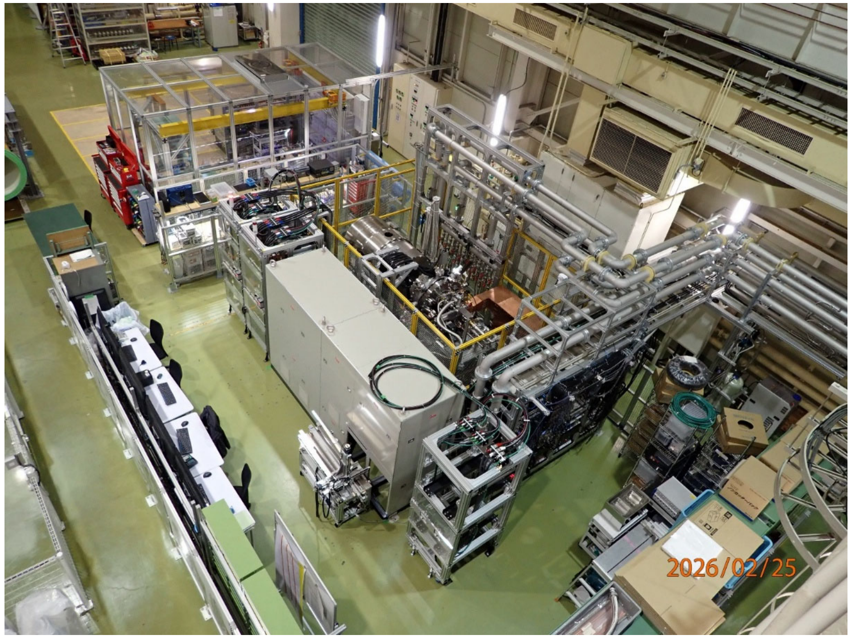
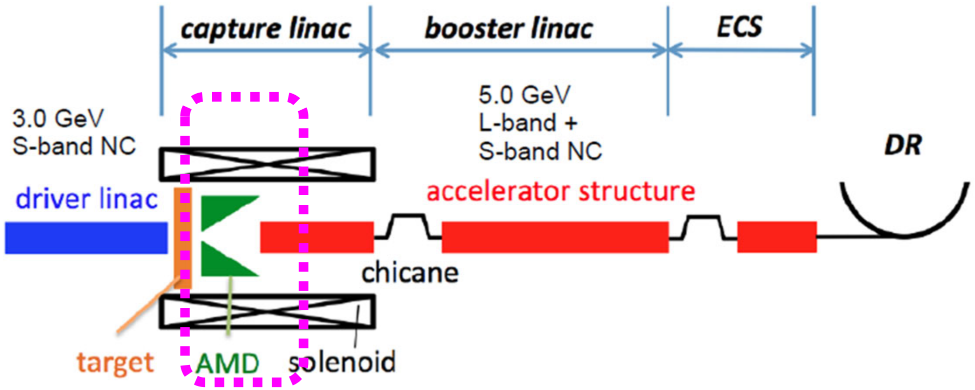
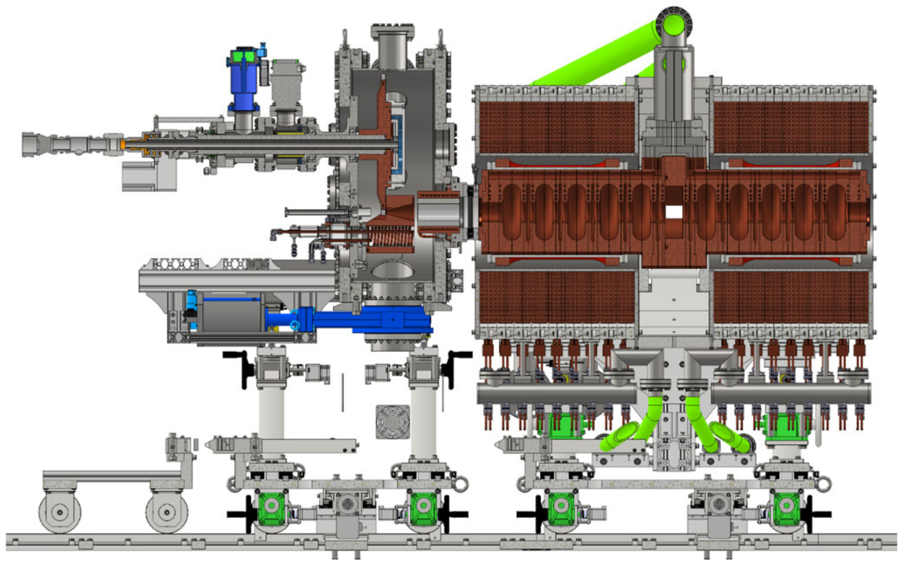
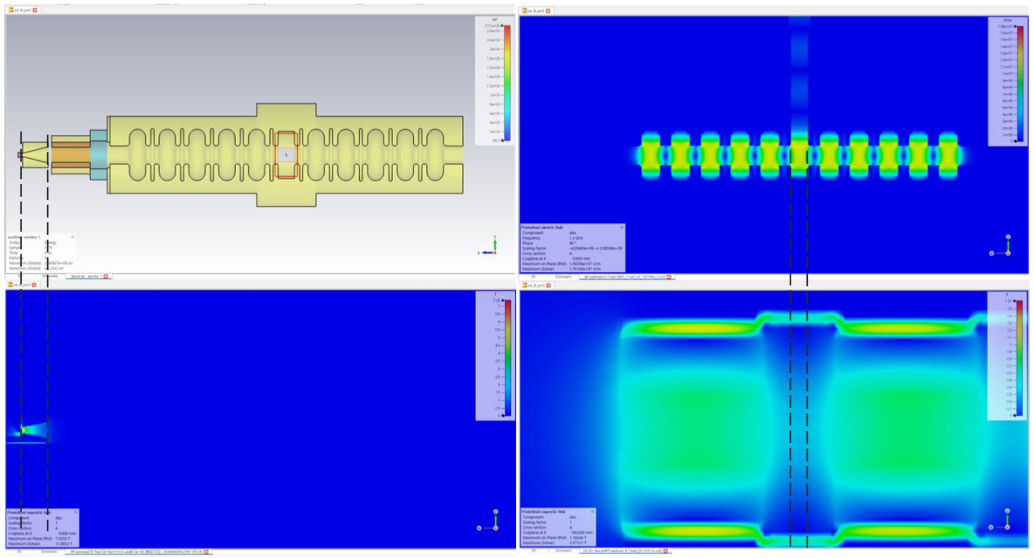


Activity in FY2025 ILC

- Fully 3D tracking simulation using CST studio was performed for ILC positron source design
  - Including beam loading effect
  - Based on real prototype design

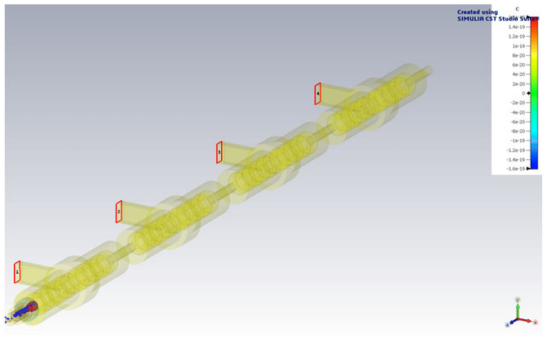


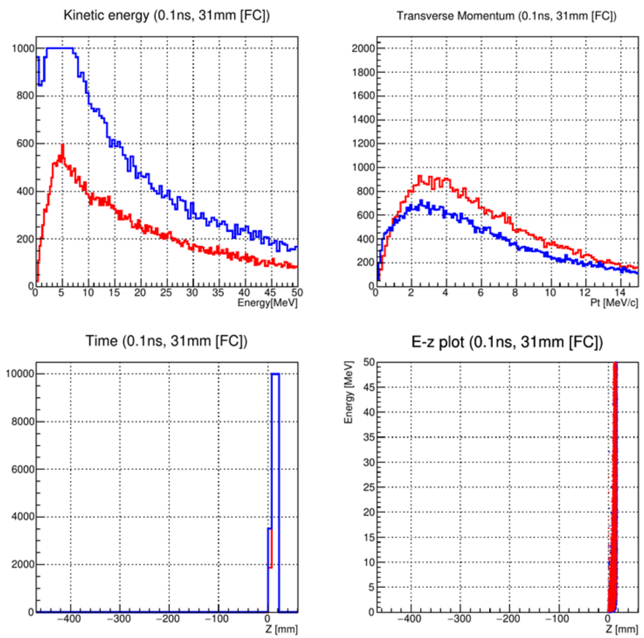


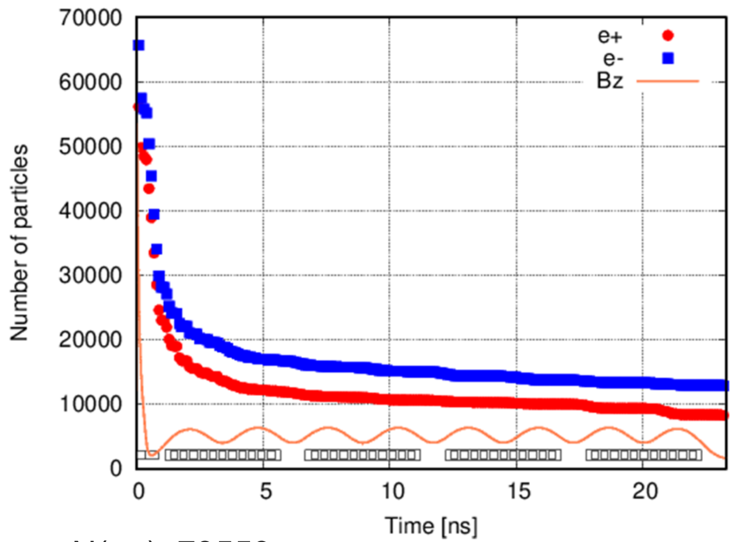


Activity in FY2025　ILC

- Beam tracking was performed using a PIC(Particle-in-Cell) solver.
- Beam tracking starts from the target.
- The simulation extends to the 4th cavity to fully cover the bunch formation process.







N(e+): 73559
N(e-): 93177
at the exit of target.

Number of Primary e-: 10,000

Activity in FY2025 ILC

- Highly multi bunch operation is necessary for ILC
- PIC simulation including beam loading effect using CST studio was performed
  - Fully 3D electric and magnetic field were used
- Strong effect was observed
  - Confirmed to be compensated by simple amplitude modulation

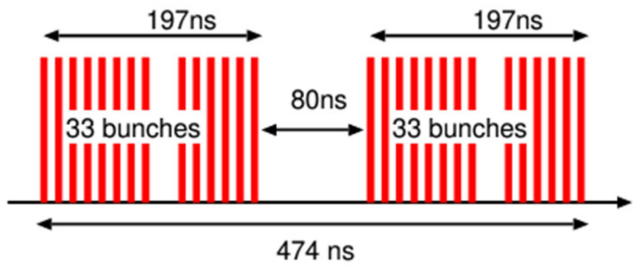
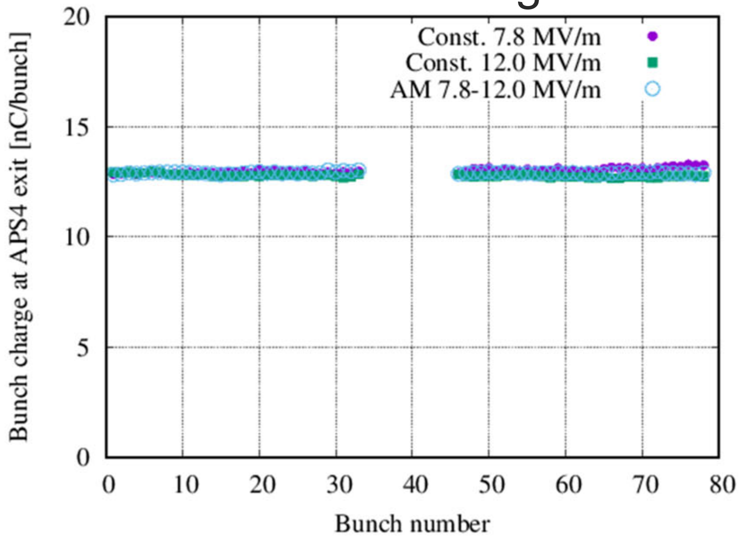


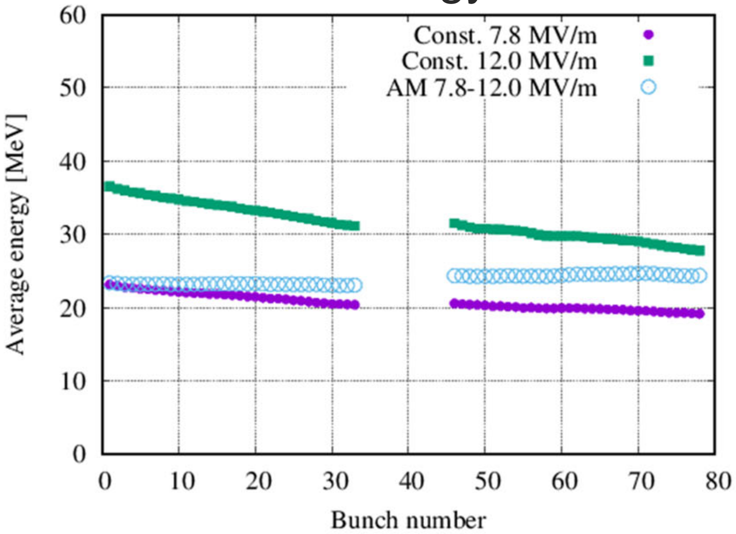
Figure 2: The beam structure in the positron source. Each mini-train contains 33 bunches.

Report on the ILC Positron Source, PUBDB-2019-00651, 2018.

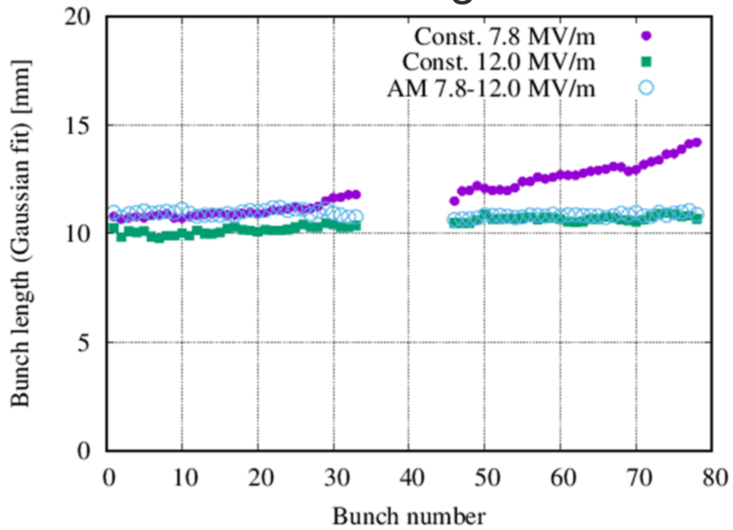
Bunch charge



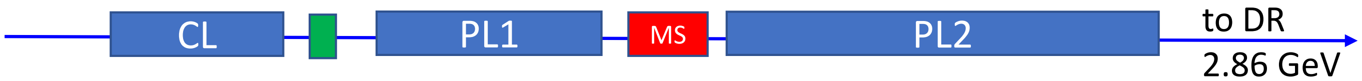
Energy

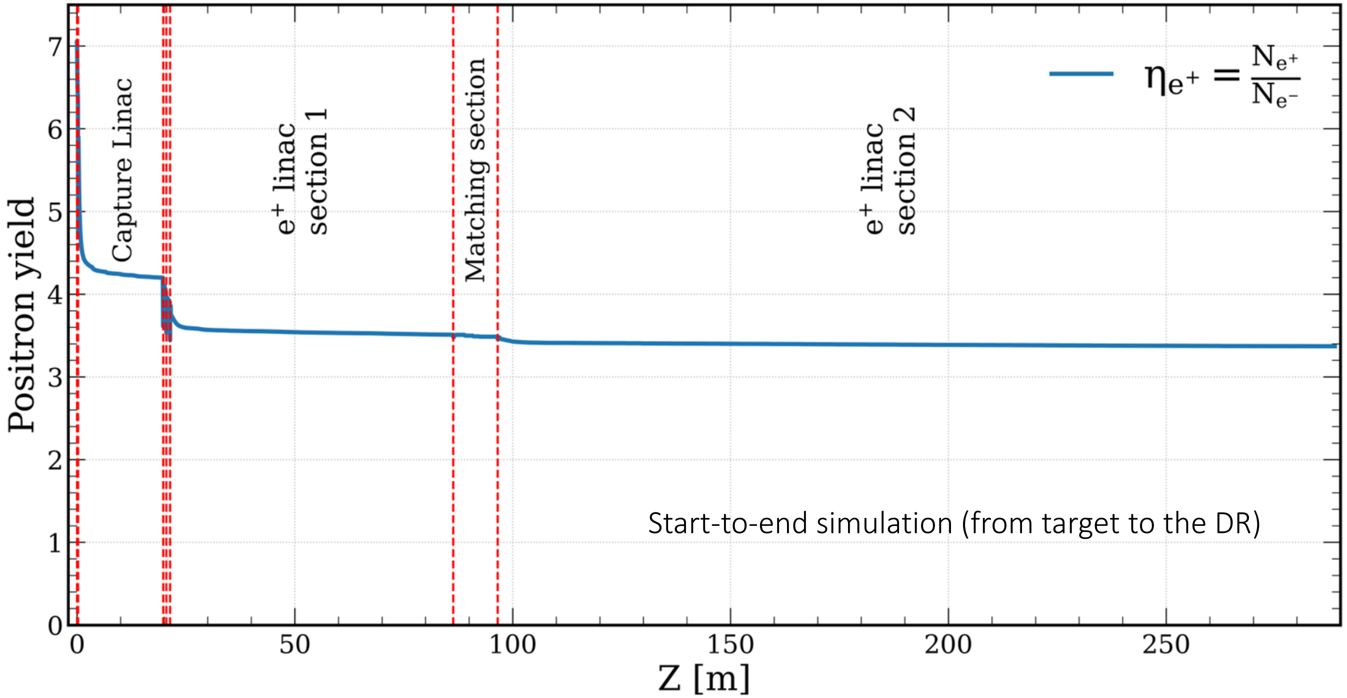


Bunch length

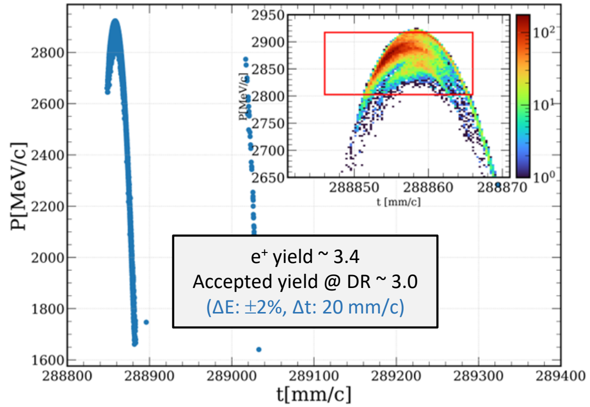


Positron Source for FCC-ee: Feasibility Study (FS) Configuration





The positron yield at a given location $\eta = \frac{N_{e^+}}{N_{e^-}}$ is defined as the ratio of the number of positrons to the numbers of incoming electron



*Simulations include collective effects (space charge and short-range wakefield)

Imperfection	Unit	Value
Transverse position error	μm	100
Transverse angular error (soleoids and dipoles)	μrad	200
Transverse angular error (other elements)	μrad	100
Magnetic strength error	%	0.1
RF gradient error	%	1
RF phase error	°	0.1
Beam position error	μm	100
Beam divergence error	μrad	100

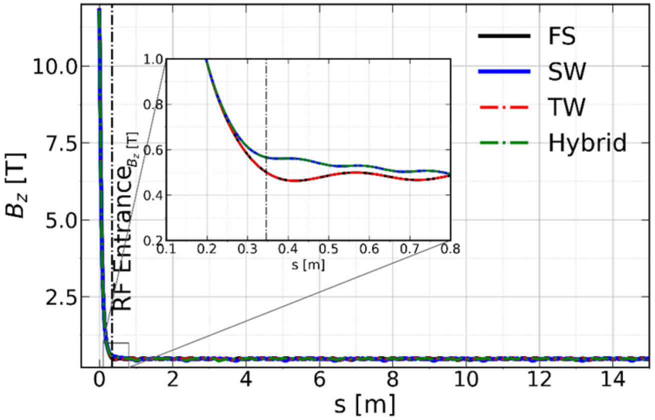
The impact of these imperfections is found to be negligible: e^+ yield ↓1.3%, emittance x/y ↓0.4/0.8 %

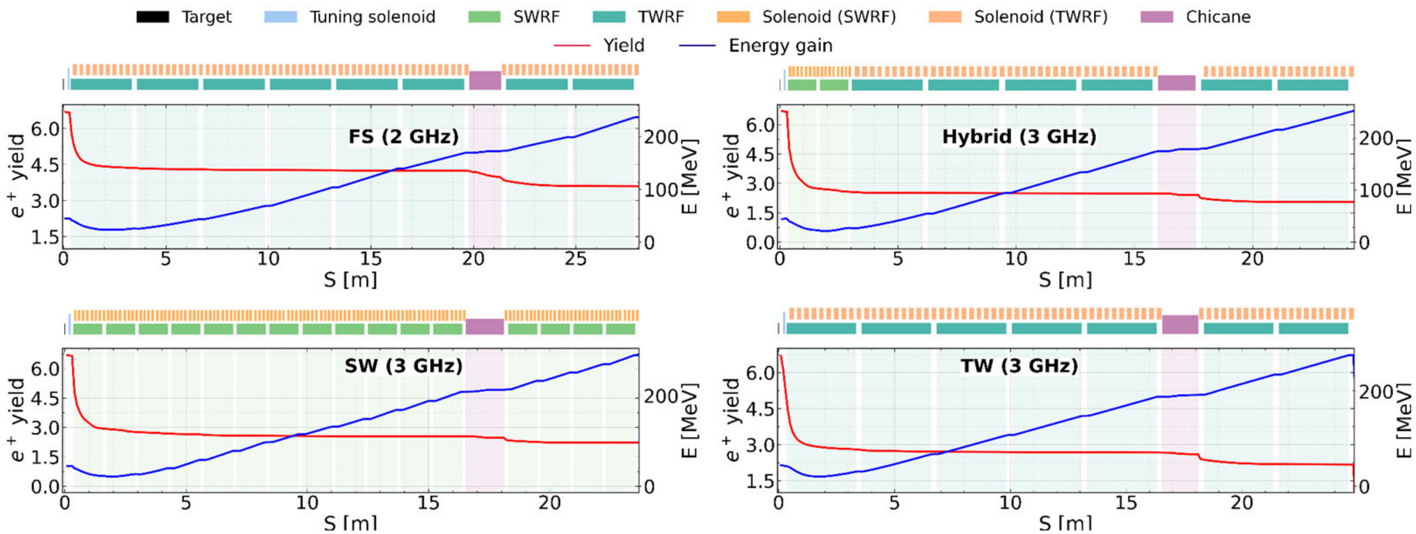
FS design ensures reliable e^+ production and meets the requirements set by FCC-ee (Z-pole) with the safety margins

Positron Source for FCC-ee: Toward 3 GHz RF

Alongside the baseline in FS, alternative 3GHz capture-linac solutions are being explored as part of the ongoing optimization of the FCC-ee injector chain. These options are attractive because they could benefit from the mature and widely available S-band RF technology high power source.

On-axis solenoid magnetic field profile Bz





Comparison of the considered layouts in terms of positron yield and beam energy evolution

The reference case is the 2 GHz FS capture scheme with six TW structures.

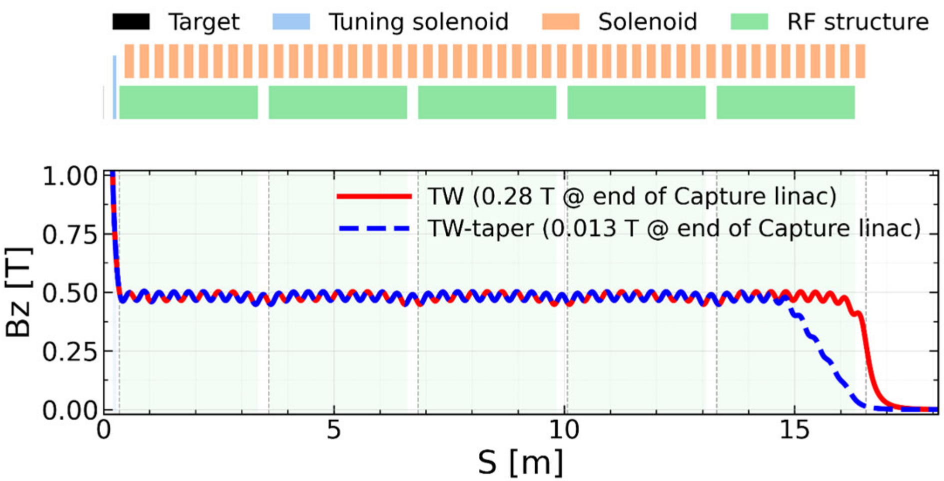
Three alternative 3 GHz capture layouts are considered: a pure TW scheme (five TW structures), a hybrid scheme (two SW followed by four TW structures), and a pure SW scheme (twelve SW structures).

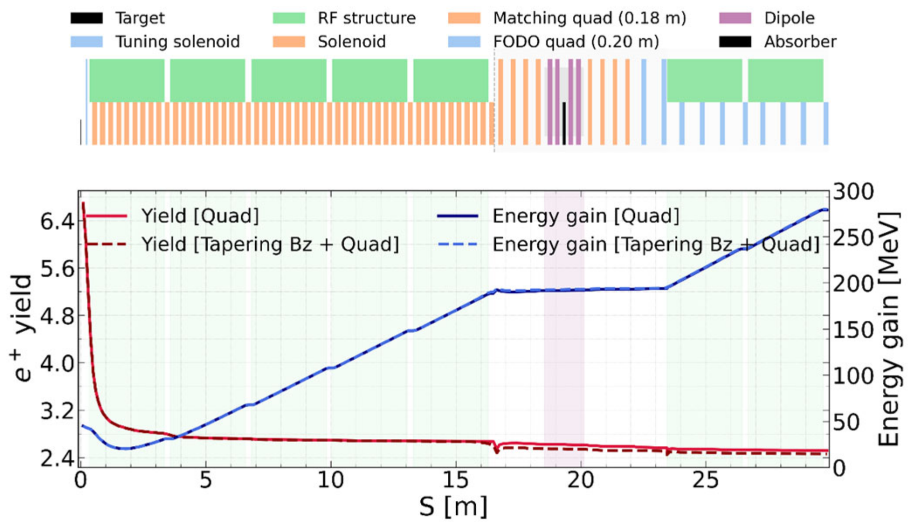
The positron yields after the second accelerating structure downstream of the chicane are 3.59 (FS), 2.04 (Hybrid), 2.17 (TW), and 2.22 (SW).

Alternative downstream optics based on quadrupole focusing

A dedicated study of the downstream optics was carried out using the 3 GHz TW capture scheme as the reference. The downstream solenoid channel was replaced by a quadrupole-based lattice, requiring dedicated matching between the coupled solenoidal channel and the uncoupled quadrupole optics. Two transition strategies were investigated: direct matching upstream of the chicane with a residual solenoid field of 0.28 T, and a tapered-solenoid approach reducing the field to 0.013 T at the end of capture linac.

With this procedure, the TW+Quad and tapered-solenoid TW+Quad configurations achieve main-bucket yields of 2.47 and 2.41, respectively, indicating that the field transition has a negligible impact on the positron yield (@ 0.5 T).





Summary table for the 3 GHz capture system

@ S0 (after the second RF structure downstream of the chicane

Current baseline

	FS	TW – 0.5T	Hybrid - 0.5 T	SW – 0.5T	TW - 0.5 T QUAD
G [MV/m]	13.3	15	18/15	18	15
Yield @ S0	3.57	2.11	1.95	2.11	2.47
Beam size [mm]	9.89/8.12	6.55/5.95	7.18/5.96	6.28/6.37	3.62/4.70
Energy [MeV]	243.32	278.61	243.58	290.85	279.86
Energy spread [%]	13.17	9.99	12.44	12.63	8.23
Emittance rms [mm.rad]	12.13/11.20	6.67/5.58	6.34/6.20	5.81/5.69	6.49/6.44
Bunch length [mm]	8.09	5.47	5.83	6.17	5.21

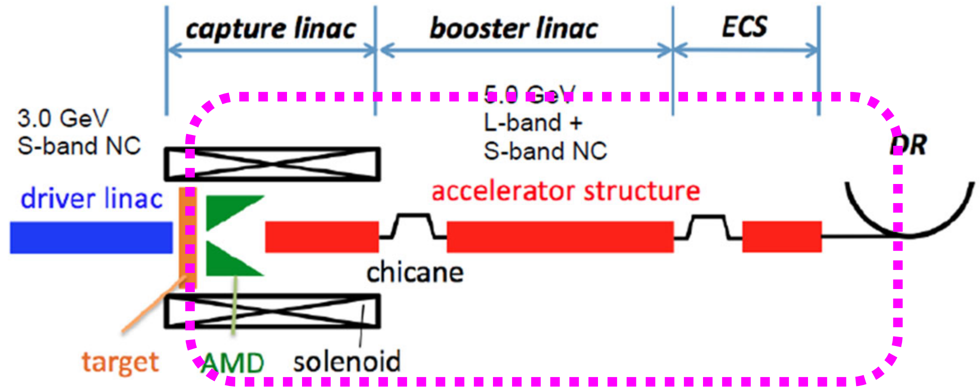
Solenoid focusing downstream the chicane

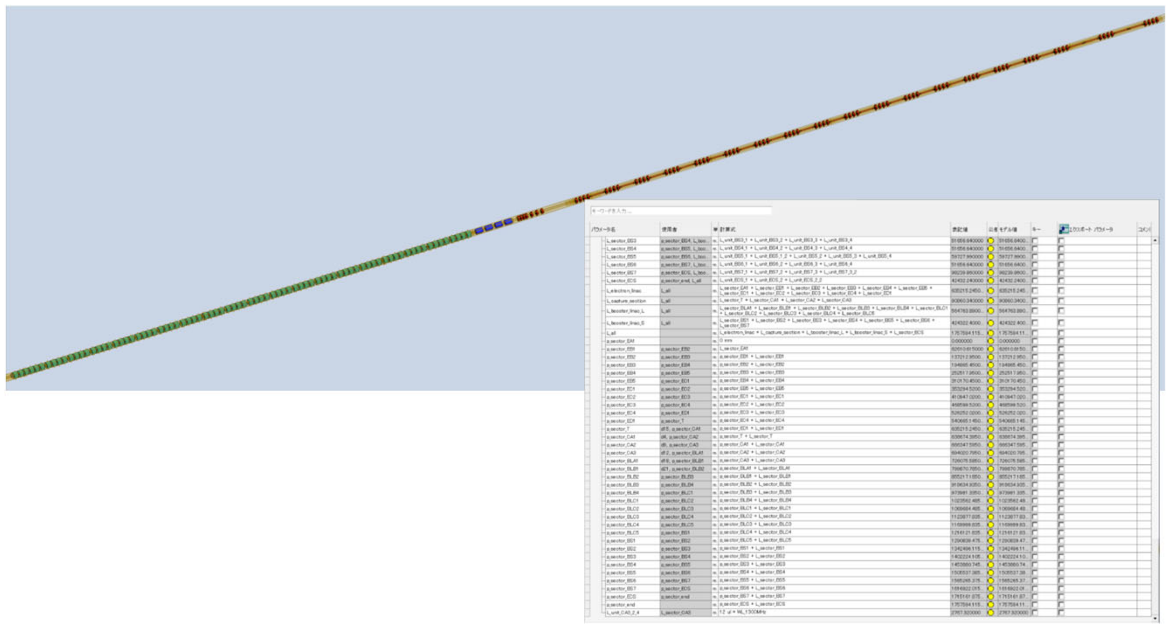
QUAD focusing

- The FS scheme provides the highest positron yield, while the 3 GHz layouts reduce the positron emittance by nearly a factor of two, offering an improved yield–emittance trade-off

Activity plan in FY2026

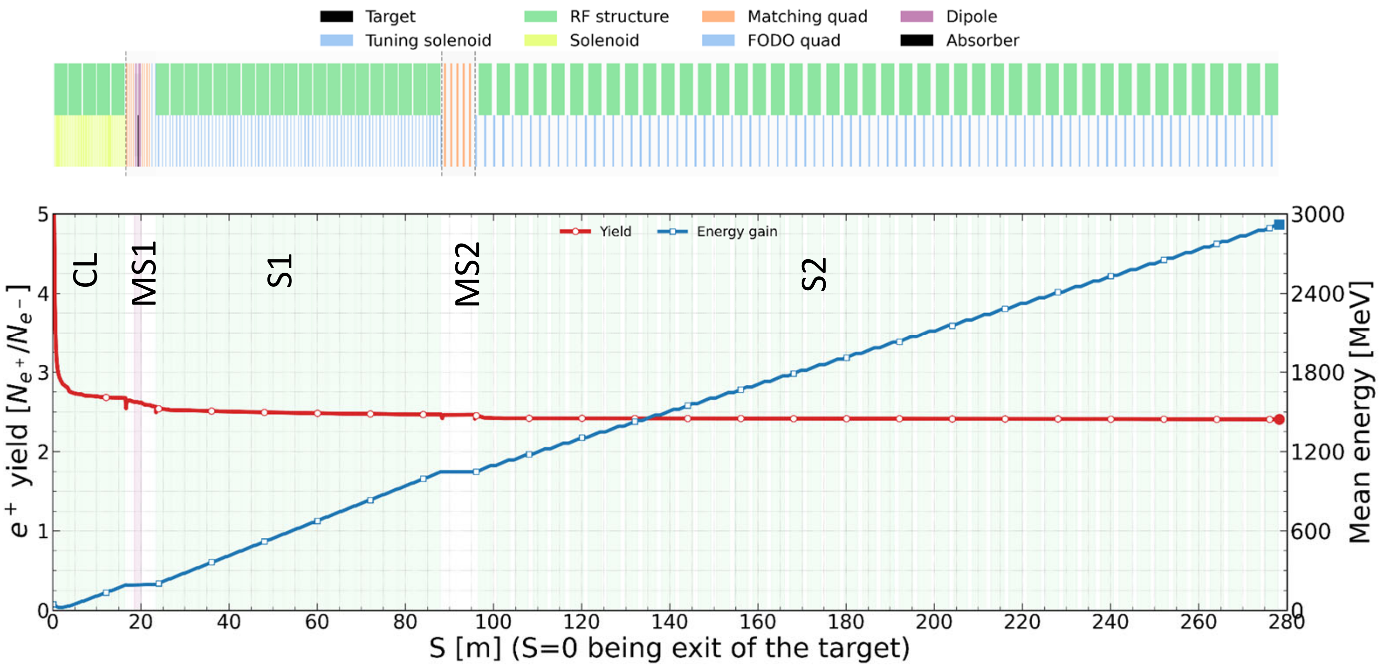
- Extend tracking simulation up to DR
  - Establish simulation method flexibly compatible with layout update
  - Cross check KEK and IJCLab using the same layout
  - Validate simulation by beam experiments in SuperKEKB
  - Extract layout parameters from 3D cad model





3 GHz positron linac

- **RF structures**: 3 GHz TW with aperture (2a) = 40 mm , 3 m long and 15 MV/m.



- As a continuation of the benchmarking studies at SuperKEKB, we now aim to extend the studies downstream of the capture section up to the Damping Ring.
- Implementation of the SuperKEKB linac sectors and transfer line is in progress.
- This will allow a more complete validation of the modeling and simulation environment, including injection into the Damping Ring.

- The positron yields at the end of S2 are 3.4 for the FS scheme and 2.41 for the 3 GHz scheme. However, the 3 GHz layout achieves nearly a factor-of-two reduction in emittance while maintaining comparable bunch length and energy spread. After 1000 turns, the accepted positron yields are 1.33 for the FS scheme and 1.96 for the 3 GHz scheme

Summary

- FY2025 was important year for our collaboration
  - Published several documents, FCCFS, PhD thesis, PRAB paper
  - Prototyping of the positron source for ILC reached evaluation phase after design and construction phase
  - Simulation method in capture section was established
  - Detailed simulation based on real design
- Next focus will be on the tracking simulation up to DR
  - Using established collaboration framework
  - Extend scope from capture section to downstream part
  - Integrate each results and maximize synergy