FCC-ee positron source

Iryna Chaikovska (IJCLab/CNRS)
on behalf of the WP3 team, FCC-ee Injector update studies

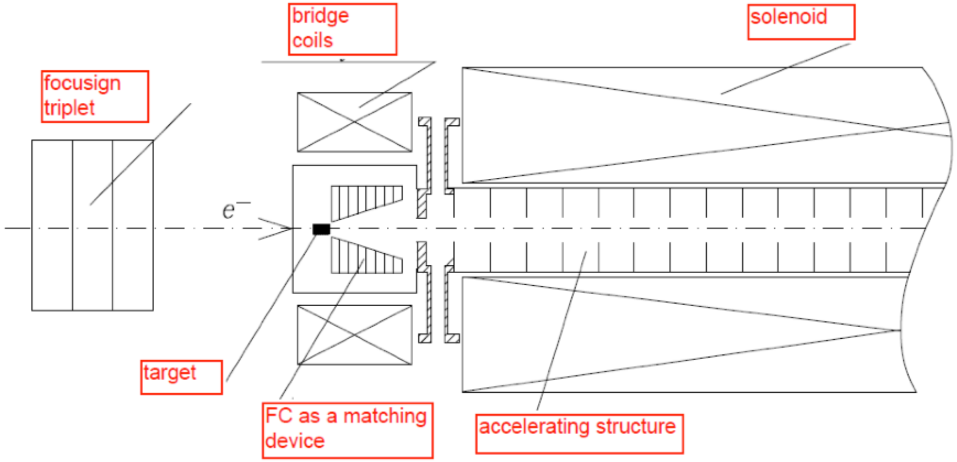
FCC-ee Positron Source: Requirements

The complete filling for Z running => **Requirement @ Injection ~2.1 × 10^{10} e+/bunch (3.5 nC)**

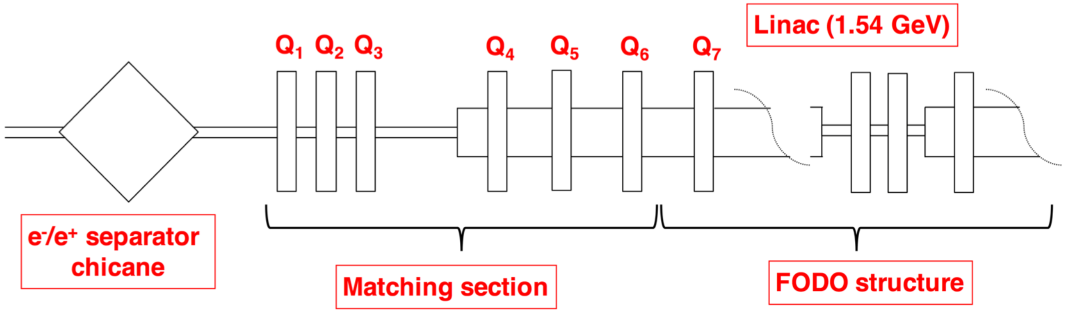
$$N_{e-}/\text{bunch} \times Y_{e+/e-} \geq 3.5\ \text{nC/bunch} \times 2$$

**A safety margin of 2 is currently applied for the whole studies.*

e+ production and capture section

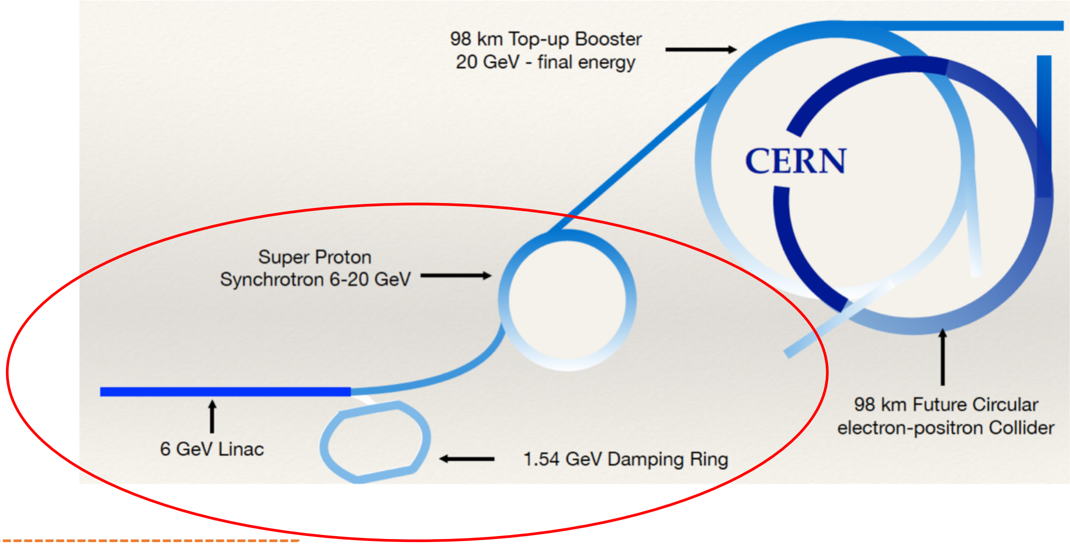


e+ acceleration up to DR energy (1.54 GeV)

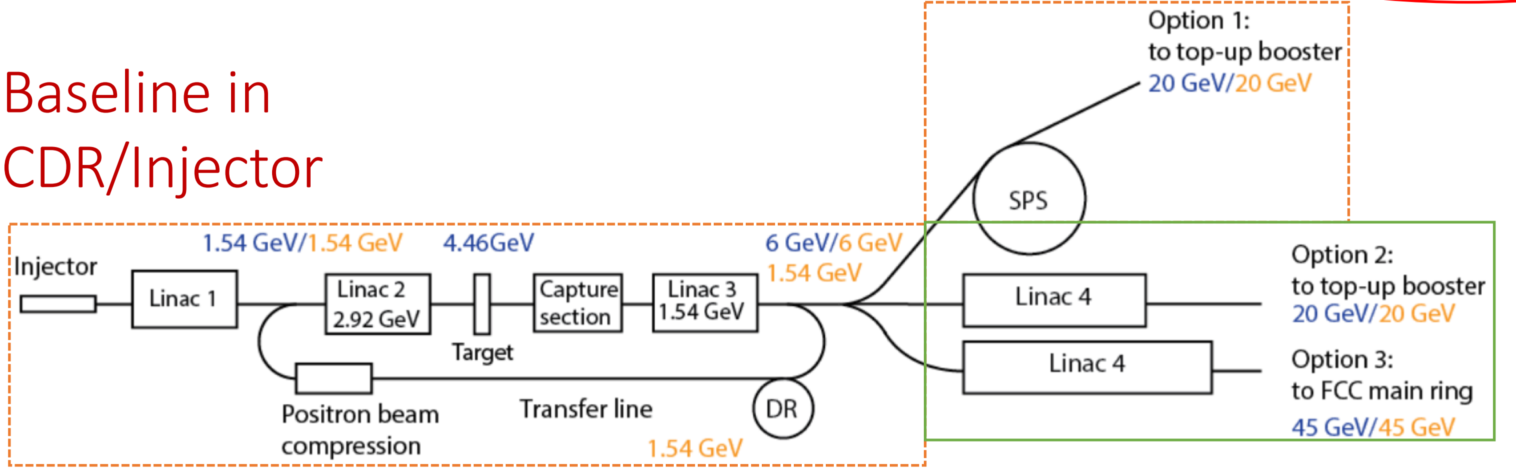


FCC-ee Injector Complex (CDR)

- e-/e+ linac up to 6 GeV, 1.54 GeV Damping Ring
- Pre-Booster Ring (SPS or new ring) (6 - 20GeV)
- Booster Ring (20 → 45 GeV)
- The main 6 GeV linac hosts the positron source. The positrons are produced with 4.46 GeV e- beam



Baseline in CDR/Injector

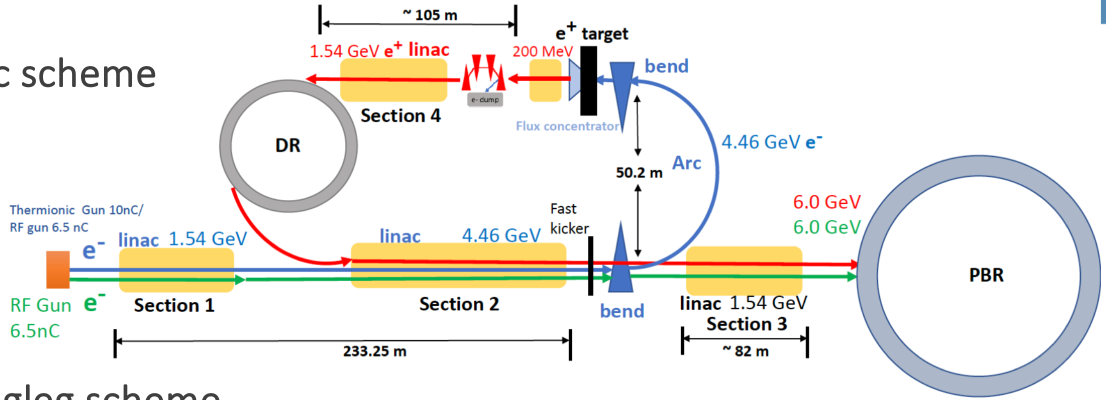


As alternative options for the FCC-ee Injector, a 20 GeV or a 45 GeV linacs are proposed to provide the direct injection into the main booster or main ring

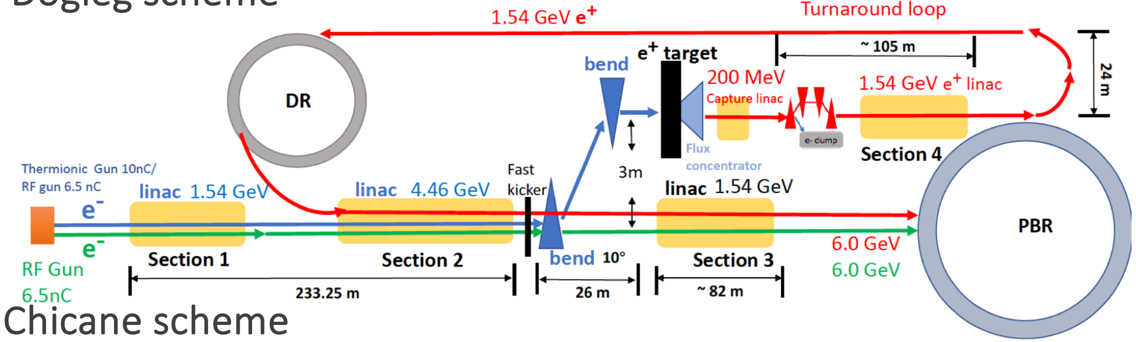
FCC-ee Positron Injector (CDR): Bypass for Positron Production

Courtesy of B.Bai (IJCLab/IHEP)

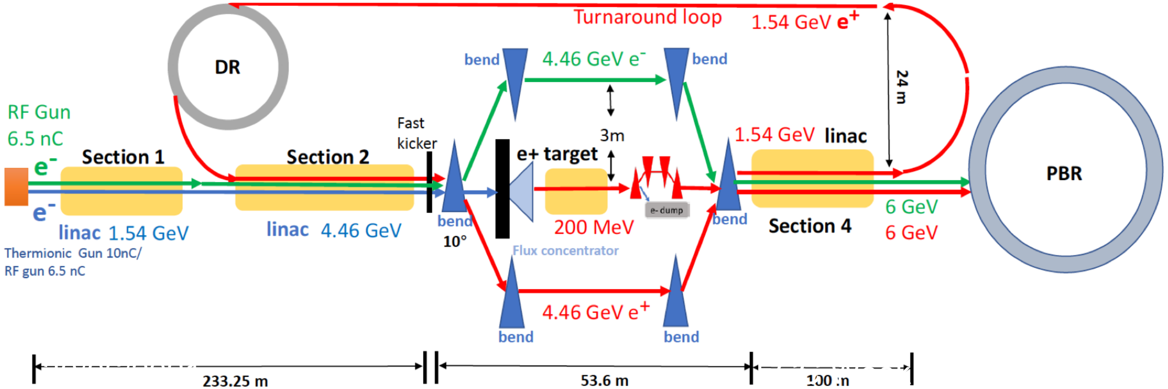
Arc scheme



Dogleg scheme



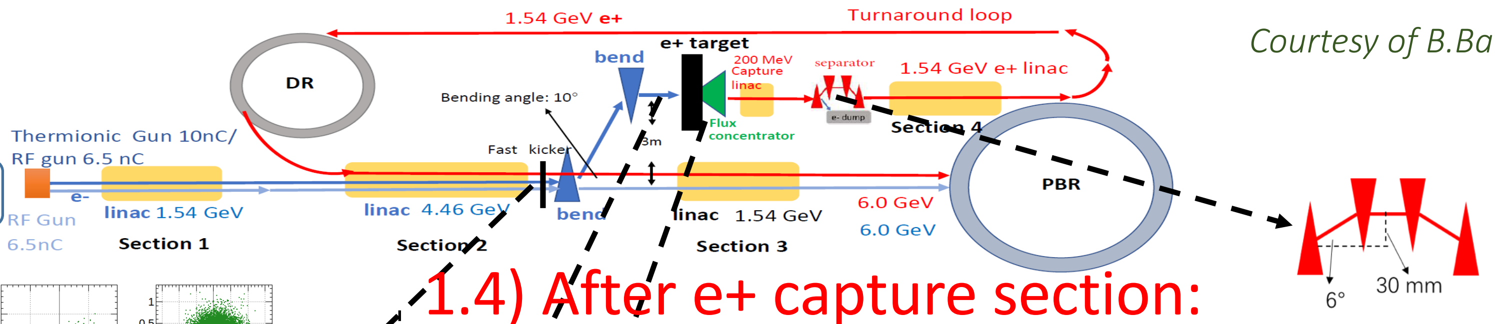
Chicane scheme



- CDR: FCC-ee Injector complex is based on the SuperKEKB scheme with fixed target (has a hole for e- beam passage)
- Positrons from the target share the same linac with electrons
- Additional degradation of the positron yield
- 3 bypass schemes are proposed to achieve better performance and increase flexibility (implementation of the moving target if needed)
- All can meet the requirement of the Z running of the FCC-ee (e+ yield $\gtrsim 1\ N_{e+}/N_{e-}$)

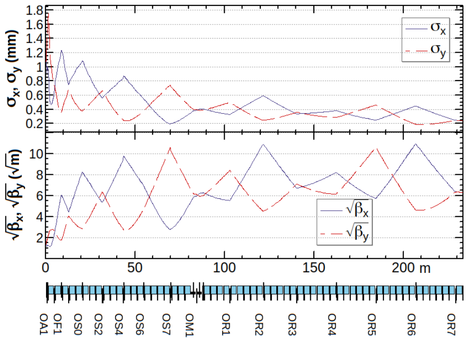
1. Dogleg scheme

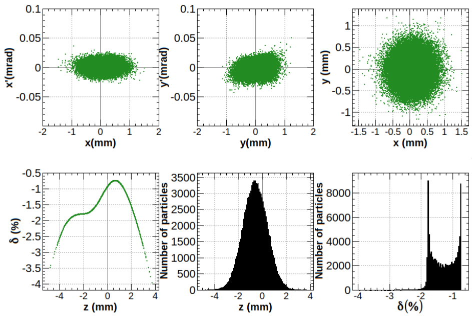
Courtesy of B.Bai



Code: SAD

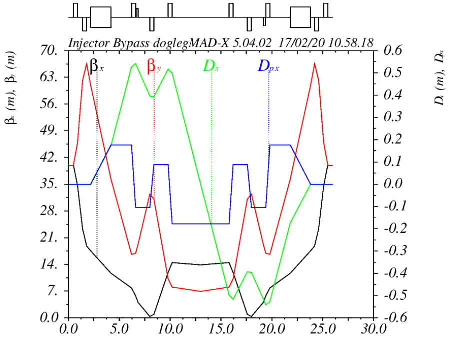
1.1) 4.46GeV e- linac

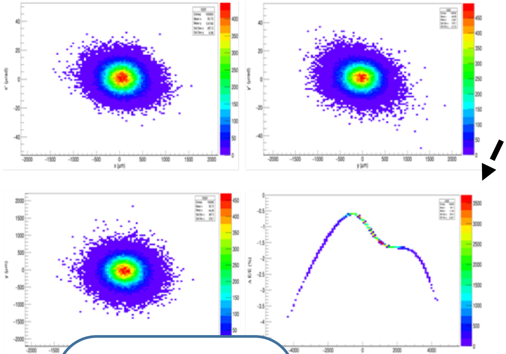




1.2) dogleg bypass

Code: MADX + PLACET



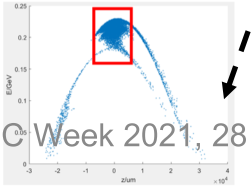


1.3) e+ generation

Results from Dr. Yanliang Han

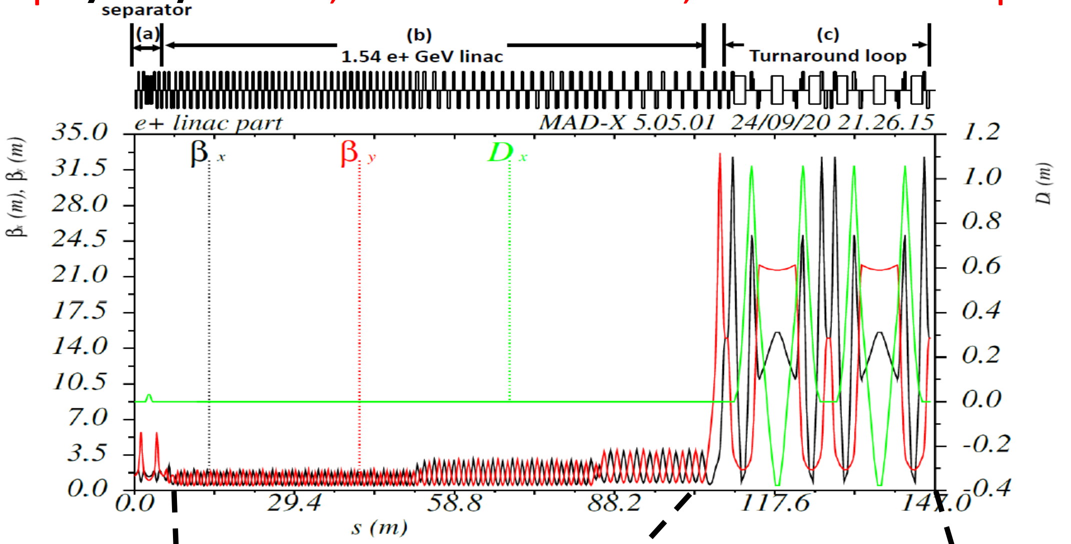
Accelerating mode /decelerating mode
+ Conventional target /hybrid target

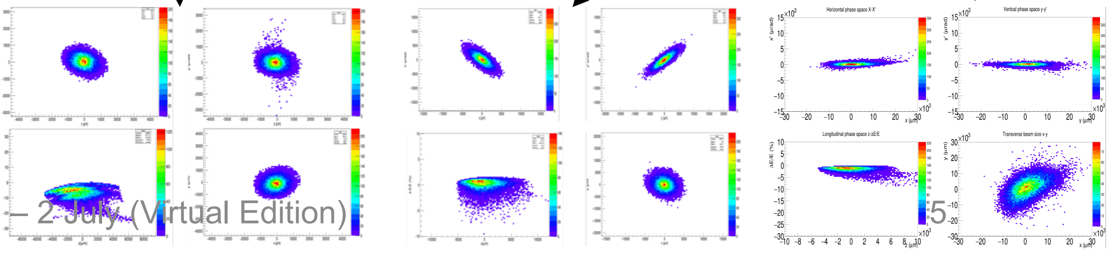
Conventional target
+
deaccelerating mode
Positron yield:
2.3



1.4) After e+ capture section:

separator chicane, 1.54 GeV e+ linac, turnaround loop

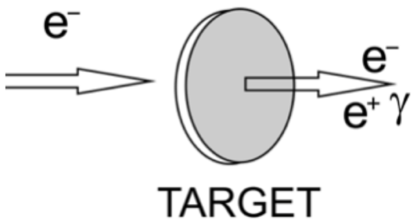




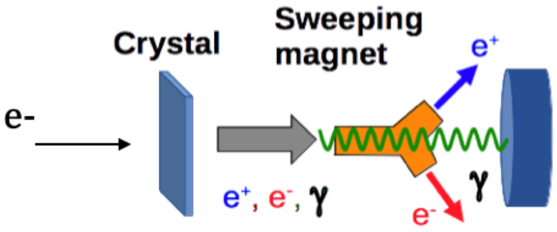
FCC-ee Positron Source: Schemes under Investigation

Production scheme:

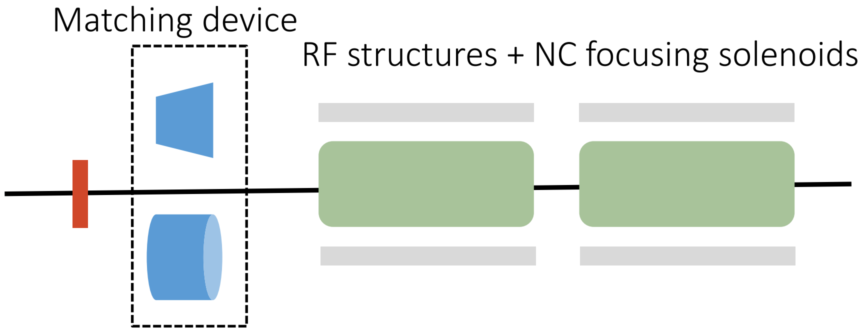
1) Conventional target



2) Hybrid target



Capture system:



2 options to be considered for the Adiabatic Matching Device (AMD):

a. Flux concentrator (pulsed magnet)

b. Superconducting solenoid (new solution)

The capture linac is encapsulated inside the NC solenoid with the axial magnetic field of 0.5-0.8 T.

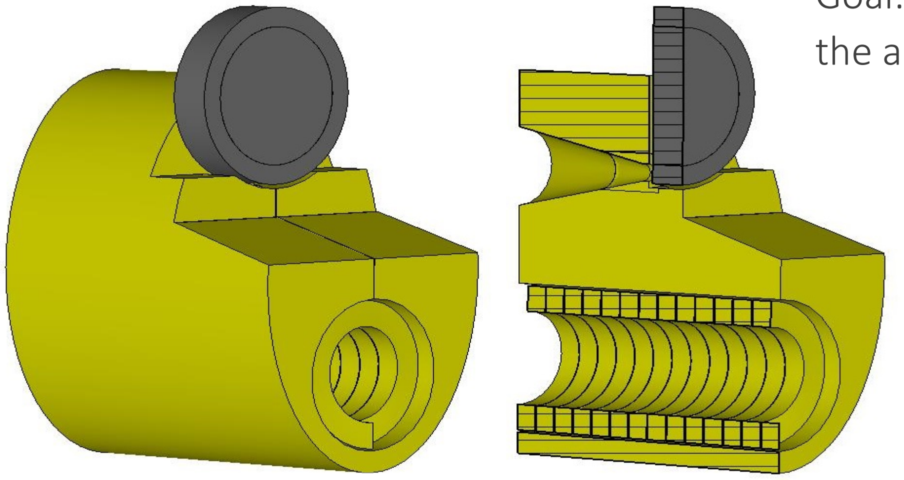
Options to be considered for the RF structures:

L-band (2 GHz) and large aperture S-band structures.

Flux Concetrator – FCC-ee Design (presently)

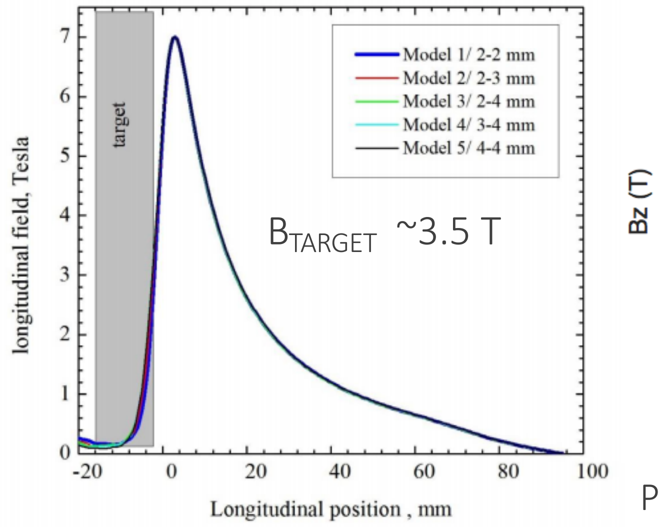
Goal: matching the e+ beam (with very large transverse divergence) to the acceptance of the capture linac.

Courtesy of P. Martyshkin (BINP)

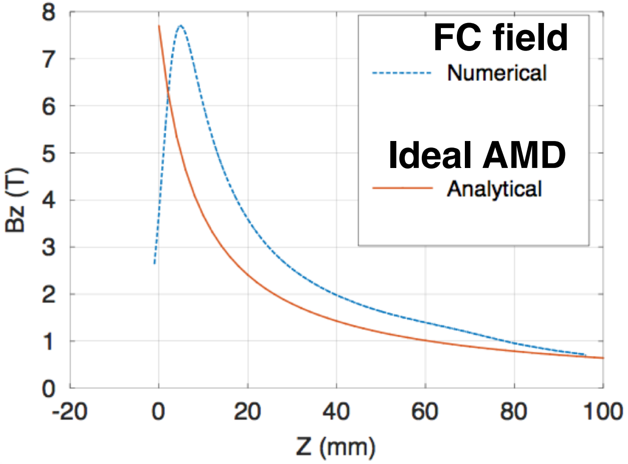


Parameter [unit]	Value
Target diameter [mm]	90
Target thickness [mm]	15.8
Gap between target and FC [mm]	2
Grooving gap between target side face and FC body [mm]	2
Elliptical cylinder size [mm]	120×180
Total length [mm]	140
Conical part length [mm]	70
Min cone diameter [mm]	8
Maximm cone diameter [mm]	44
Cone angle [deg.]	25
Cylindrical hole diameter [mm]	70
Coil turns [-]	13
Current profile pulse length [μs]	25
Peak field [T]	7
Peak transverse field [mT]	135–157
Gap between coil turns [mm]	0.4
Gap between coil and FC body [mm]	1
Turns size	9.6×14 mm

Full 3D magnetic field map is used in the simulations



B_{TARGET} ~3.5 T



Peak of the FC magnetic field is at 5 mm from the target => ~40 % drop in capture efficiency

SC Solenoid as the AMD for the FCC-ee (work in progress)

Advantages => higher field value on the target, DC operation

Promising results of the first tests at KEK (2009-2011)
Beam irradiation experiment of a dummy target installed inside a beam pipe which penetrate a cryostat of a SC solenoid at the beam dump at 1.7 GeV. The solenoid survived at least for 10 minutes at 3.2 T field level with an irradiation of 7 nC x 2 bunch 1.7 GeV beam at 49 Hz. Max field obtained ~4.7 T.

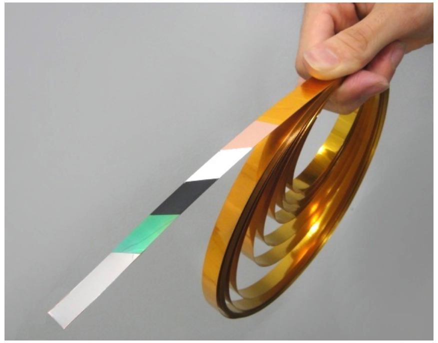
For the FCC-ee positron source application: shared effort of the CERN-STI and PSI magnet group on the conceptual design of the SC solenoid and target integration (coil geometry, power deposition, annual dose…).

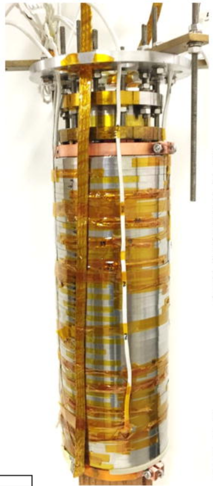
Optimization of the magnetic field profile in the vicinity of the target to maximize the capture efficiency.

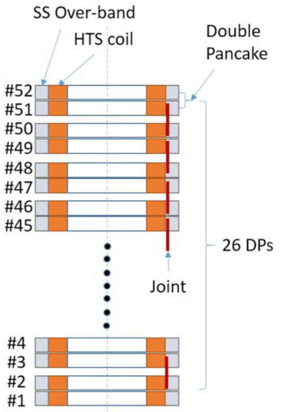
Design studies started @PSI

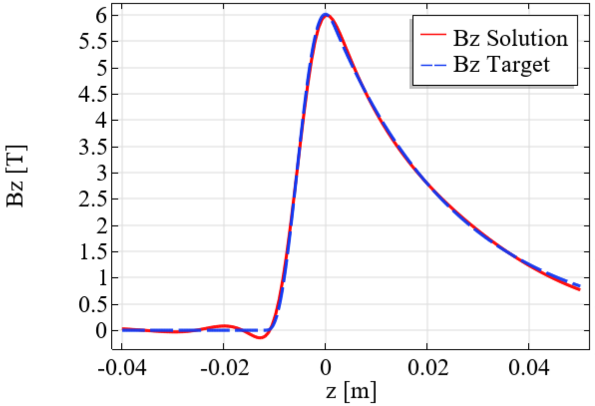
Courtesy of J. Kosse and B. Auchmann (PSI)

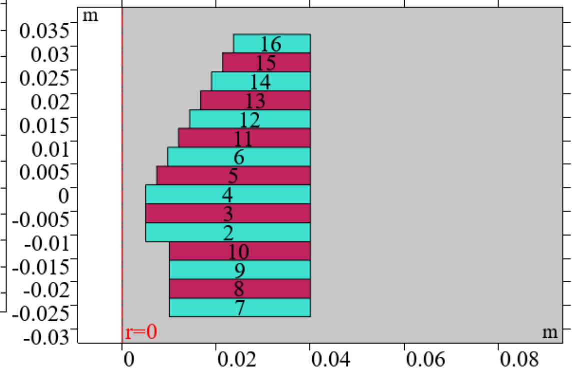
HTS solenoid











FCC-ee Positron Source (CDR): Simulation Results

Preliminary

Primary e- beam for e+ production	
Beam energy	4.46 GeV
Bunch charge	4.2 × 10^{10}
Bunch length (rms)	2 mm
Bunch transv. size (rms)	0.5 mm
Bunch separation	~60 ns
Nb of bunches per pulse	2
Repetition rate	100-**200** Hz
Beam power	12 kW

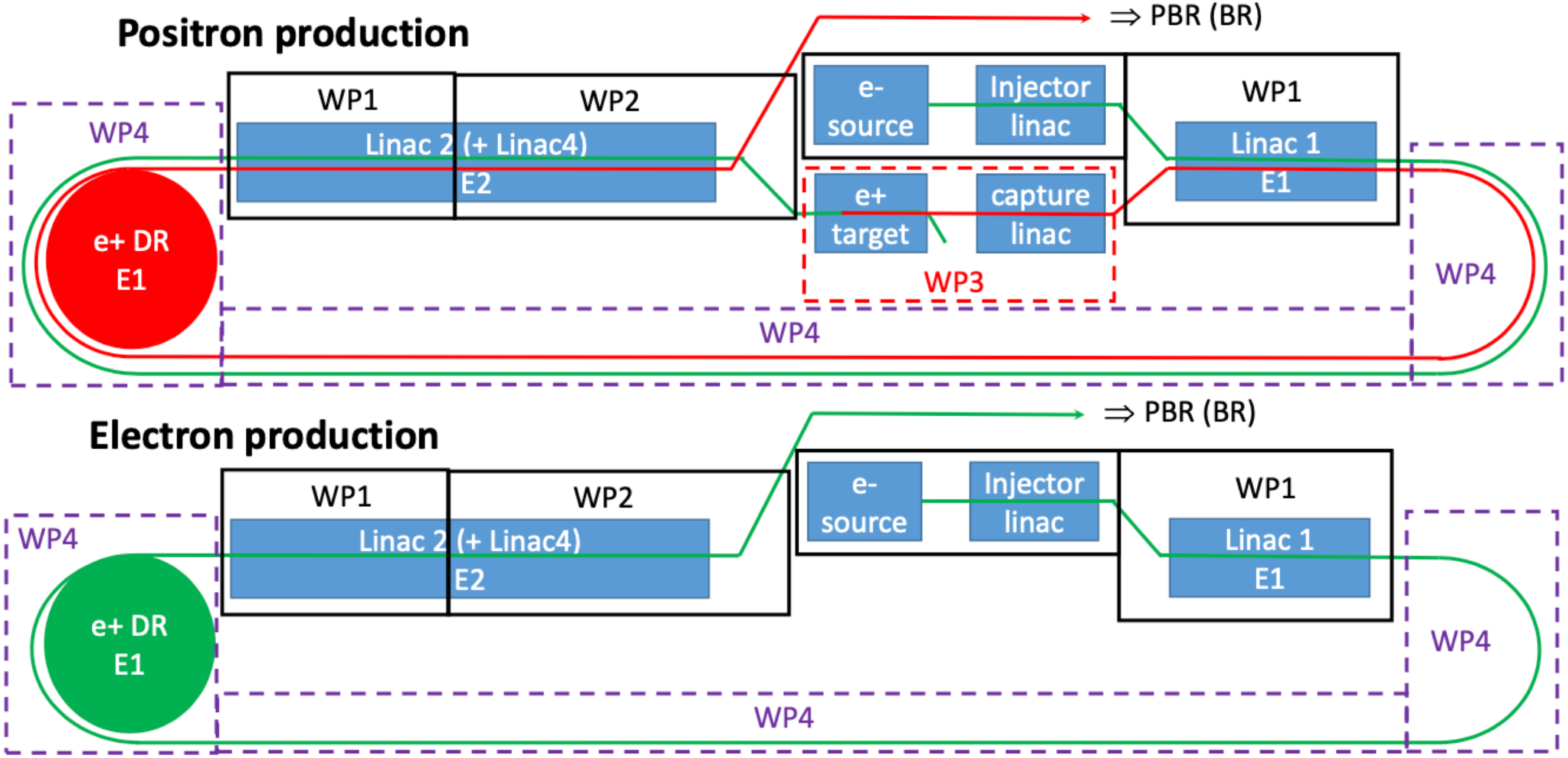
- Requirement @ Injection: ~2.1 × 10^{10} e+/bunch (3.5 nC)
- With electron bunch charge of 7 nC, it gives ~0.5 N_{e+}/N_{e-} without safety factor or 1 N_{e+}/N_{e-} taking into account 2 as a safety margin.

Beam energy, GeV	**4,46**		
	Conv	**Conv**	**Hybrid**
Number of bunches	**2**	**2**	**2**
Bunch charge, e-	**4,2E+10**	**4,2E+10**	**4,2E+10**
Bunch length (rms), mm	2	2	2
Bunch transv. size (rms), mm	**0,5**	**0,5**	**0,5**
Bunch separation	tens of ns	tens of ns	tens of ns
Repetition rate (max), Hz	**200**	**200**	**200**
Beam power, kW	12	12	12
Emittance (normalsed max), mm.rad	<1	<1	<1
Energy spread, %	< 1	< 1	< 1
Target thickness	16 mm (4.5X0)	16 mm (4.5X0)	1.4/12 mm (L=1.5 m)
Positrn yield at target	~11	~12	~7
PEDD (target), J/g	**20**	**17**	**2**
Deposited power (target), kW	**2.7**	**2.1**	**1.5**
Capture linac	L-band (2a = 40)	S-band (2a = 30)	L-band (2a = 40)
Energy gain, MeV/m	16 (average)	20 (average)	16 (average)
e+ yield	**2,5**	**1,4**	**0.9**

New Layout of the FCC-ee Injector 6 GeV (20 GeV)

A full injector energy (6 or 20 GeV) can be used for the positron production

Courtesy of A. Grudiev (CERN)



Electron driver: 6 (20) GeV, 100-200 Hz, up to 7nC/bunch, 2 or multi-bunch injector operation

Positron Production/Capture Simulations (work in progress)

Conventional target
Capture Section: FC (7T => 0.7 T) + S-band (LAS)

DR acceptance 3.8%

Target: 5X0 (17.5 mm)

Courtesy of P. Martyshkin (BINP)

Beam energy, GeV	**6**					
Number of bunches	**2**	**10**	**15**	**20**	**30**	**40**
e+ bunch charge @200 MeV, e+	4,2E+10	4,2E+10	4,2E+10	4,2E+10	4,2E+10	4,2E+10
e+ yield	2,3	2,3	2,2	2,1	1,8	1,2
Bunch charge, e-	**1,8E+10**	**1,8E+10**	**1,9E+10**	**2,0E+10**	**2,4E+10**	**3,4E+10**
Bunch length (rms), mm	1	1	1	1	1	1
Bunch transv. size (rms), mm	**0,5**	**0,65**	**0,9**	**1,15**	**1,7**	**2,5**
Bunch separation	tens of ns	tens of ns	tens of ns	tens of ns	tens of ns	tens of ns
Repetition rate (max), Hz	100	100	100	100	100	100
Beam power, kW	3,5	17,3	27,4	38,4	69,1	130,6
Emittance (normalsed max), mm.rad	<1	<1	<1	<1	<1	<1
Energy spread, %	< 1	< 1	< 1	< 1	< 1	< 1
PEDD (target), J/g	**8,6**	**32**	**32**	**32**	**32**	**32**
Deposited power (target), kW	**0,6**	**3,3**	**5,1**	**7,2**	**13**	**25**

ILC
3
33*2 => x20 (1320)
2,9E+10
2,2E+10
1
2
6 ns with 80 ns gap
300 (5)
74,0
<1
< 1
33.6 (for 66 bunches)
18.8

Beam energy, GeV	**20**					
Number of bunches	**2**	**10**	**15**	**20**	**30**	**40**
e+ bunch charge @200 MeV, e+	4,2E+10	4,2E+10	4,2E+10	4,2E+10	4,2E+10	4,2E+10
e+ yield	6,6	6,5	6,1	5,8	4,7	3,4
Bunch charge, e-	**6,4E+09**	**6,5E+09**	**6,9E+09**	**7,3E+09**	**8,9E+09**	**1,2E+10**
Bunch length (rms), mm	1	1	1	1	1	1
Bunch transv. size (rms), mm	**0,5**	**0,7**	**0,95**	**1,2**	**1,75**	**2,5**
Bunch separation	tens of ns	tens of ns	tens of ns	tens of ns	tens of ns	tens of ns
Repetition rate (max), Hz	100	100	100	100	100	100
Beam power, kW	4,1	20,8	33,1	46,7	85,4	157,4
Emittance (normalsed max), mm.rad	<1	<1	<1	<1	<1	<1
Energy spread, %	< 1	< 1	< 1	< 1	< 1	< 1
PEDD (target), J/g	**9,6**	**32**	**32**	**32**	**32**	**32**
Deposited power (target), kW	**0,5**	**2,5**	**3,7**	**5,3**	**10**	**18,5**

@ILC
FC: 5 T -> 0.5 T + L band
1.3GHz, 2a=60 mm

Target: W26Re, 16mm

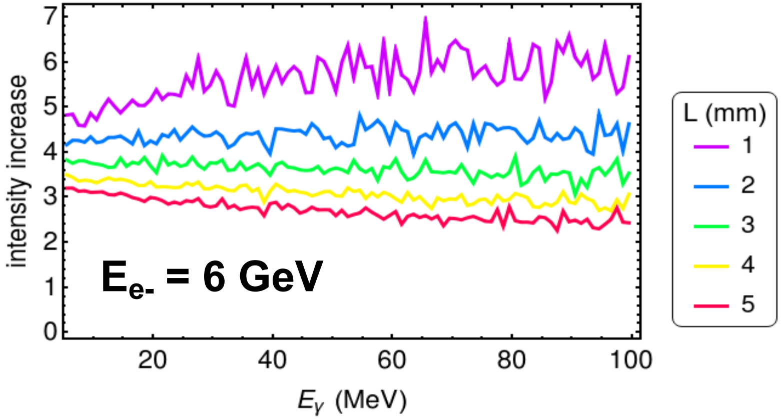
Nb. bunches: 66 in ~0.5 µs
and 1320 in 63 ms

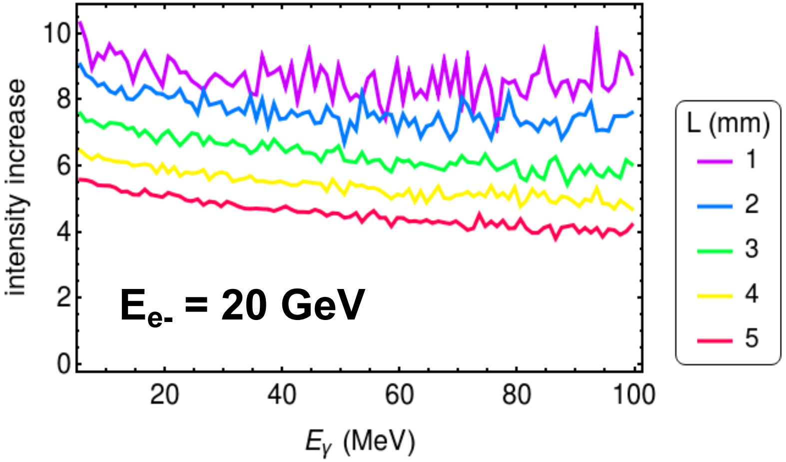
e+ yield: 1.25-1.28

FCC-ee Positron Source: Hybrid Target (work in progress)

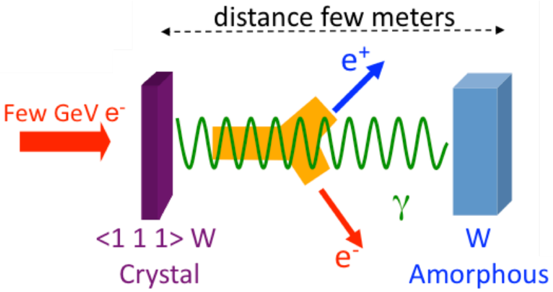
Preliminary

Crystal optimization for axially oriented <111> W crystal





Courtesy of L. Bandiera and A. Sytov (INFN Ferrara), V. Tikhomirov (INP Minsk)



Optimization studies for the hybrid target is ongoing (**crystal**, distance between the targets, target-converter, drive beam parameters, capture)

N (5 MeV<E<60 MeV) per incident e-	1 mm	2 mm	3 mm	4 mm	5 mm
6 GeV (amorphous)	0.96	2.2	4.0	6.4	9.6
6 GeV (crystal)	5.0	9.5	14.9	21.3	28.7
20 GeV (amorphous)	0.71	2.0	4.2	7.6	12.4
20 GeV (crystal)	6.4	16.2	29.2	45.1	63.9

Up to 1 order on magnitude increase of the radiation intensity by using an oriented crystal!

Target Thermal Load: Target Design and Cooling System

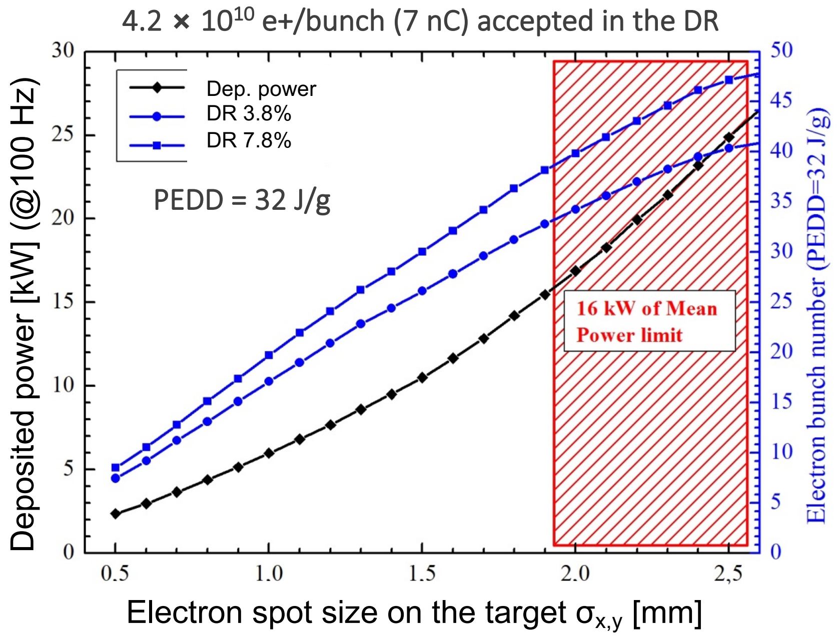
@ E = 6 GeV and 100 Hz

<u>With 2 bunches per pulse</u>

Power deposited in the target @ 100 Hz is 0.6 kW => average heating.
PEDD with σx/σy ~ 0.5 mm is 8.6 J/g => thermo-mechanical stress and fatigue.

<u>With 30-40 bunches per pulse</u>

Power deposited in the target @ 100 Hz is 13-25 kW => average heating.
PEDD with σx/σy ~ 1.7 - 2.5 mm is 32 J/g => thermo-mechanical stress and fatigue.



4.2 × 10^{10} e+/bunch (7 nC) accepted in the DR

- Depending on the scenario, a dedicated target and cooling system should be designed *(at high rep. rate and with large number of bunches => larger targets and more sophisticated solutions).*
- Peak stress and fatigue limit resulting from cyclic loading (target lifetime) should be evaluated. *With high rep. rate and large number of bunches => beam should be spread out over a wide target => moving/rotating target.* The rotation velocity and target size should be calculated to avoid the pile-up (temperature, stresses).
- Shock waves and thermal dynamics: in principle should be OK. In our case, target should survive one shock, no pile up between successive shock waves between 10 ms. Enough time for the shock wave to be damped (µs time scale).

Considerations on the Target Design

Preliminary

2 bunches/pulse:

A stationary target of about 2-4 cm in a diameter can be water cooled. However, the number of pulses/year reaches extreme values of ~ **5×10^9** thermal cycles (@200 Hz). Therefore, the stationary target with 2 bunches will have a limited lifetime. To prolongate this lifetime, a moving or trolling SLC-like target should be envisaged.

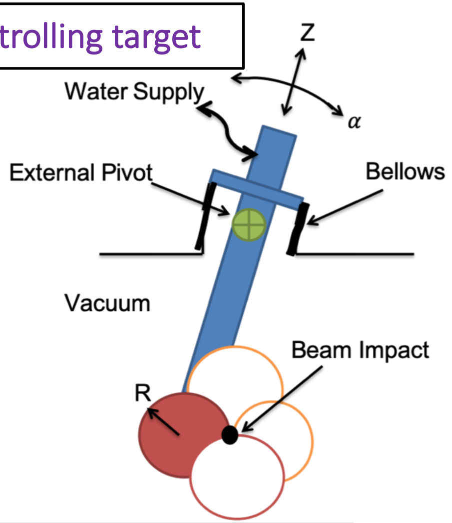
Multi-bunch operation:

SLC-like trolling target @ 0.5 - 1 Hz, may work for ~10 bunches/pulse. Removing more than 5 kW (deposition from ~15 bunches/pulse) becomes difficult, would require large target => lots of weight to tumble.

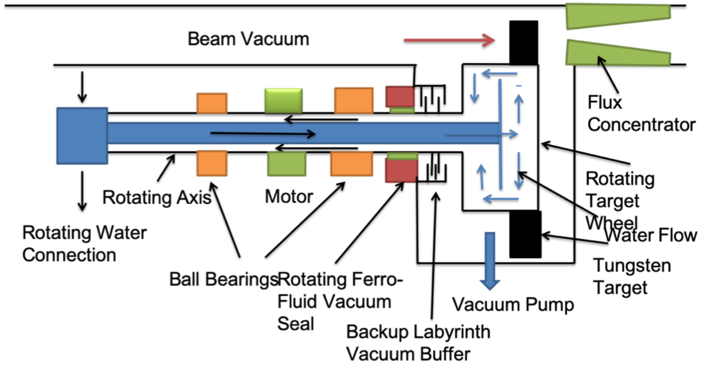
For > 15 bunches/pulse: need for a truly rotating, water cooled target, including a rotating vacuum seal (rotating wheel as in the ILC e- driven positron source).

Courtesy of P. Sievers (CERN)

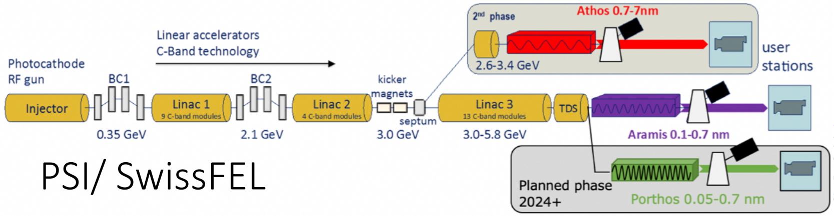
SLC trolling target



ILC target (e- driven scheme)



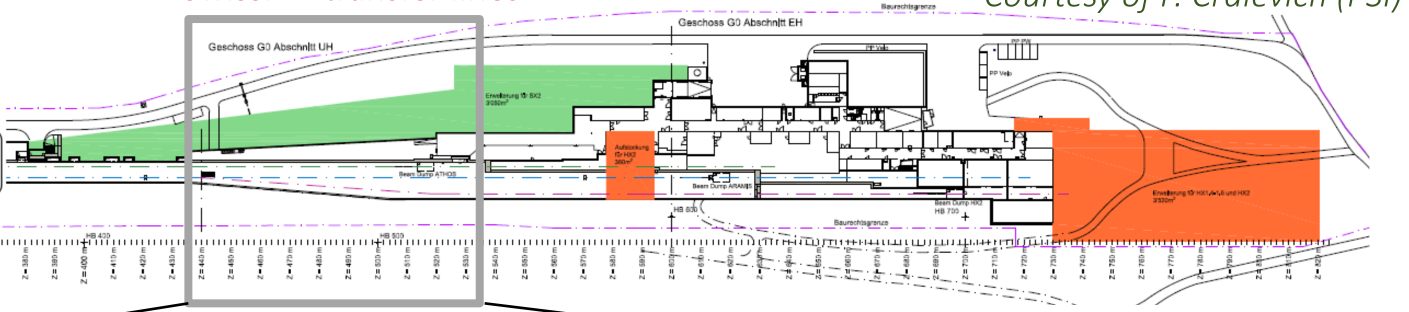
Positron production and capture: demonstrator @PSI (WP6)



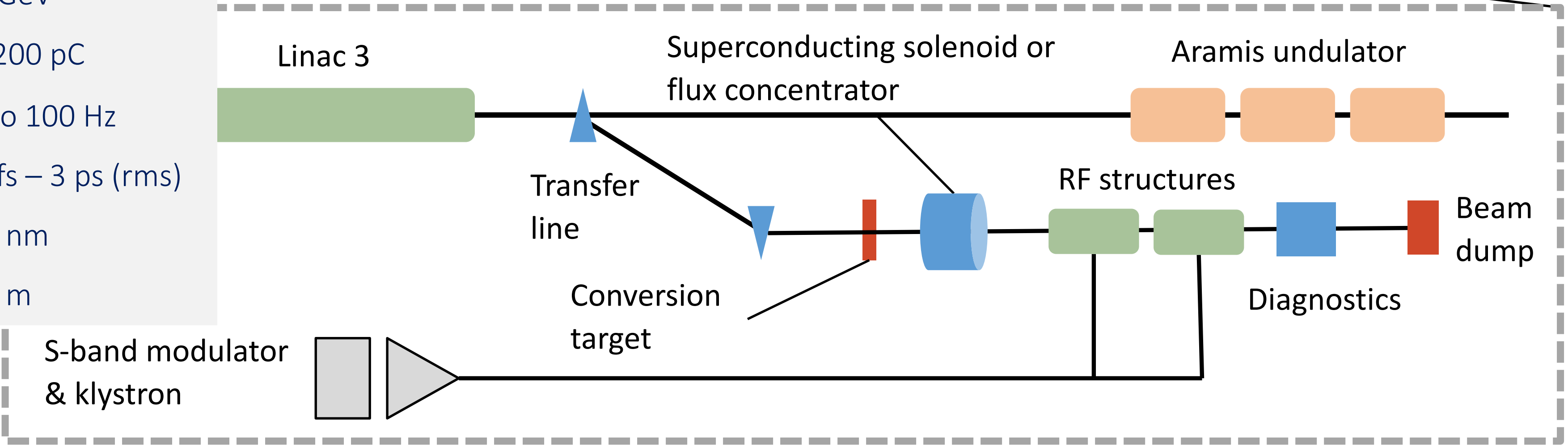
PSI/ SwissFEL

SwissFEL transfer lines

Courtesy of P. Craievich (PSI)



Main parameters	
Beam energy	6.2 GeV
Bunch charge	10-200 pC
Repetition rate	up to 100 Hz
Pulse duration	<1 fs – 3 ps (rms)
Norm. emittance	400 nm
Overall length	740 m



Demonstrator for novel target and capture system using the 6 GeV linac of the SwissFEL facility at PSI will be realized to validate the proposed concept for the FCC-ee positron source.

Summary

The studies on the FCC-ee positron source are ongoing (positron production, capture, SC technology feasibility for matching device, design and optimization studies).

- CDR injector layout (@ E = 4.46 GeV, 2 bunches/pulse, 200 Hz)
  - 3 bypass schemes for positron production/capture have been designed.
  - Preliminary simulations have been done for the conventional and hybrid targets.
  - Target design: robust solution with existing technology (fixed or moving).
- New injector layout (@ E = 6 GeV, 2 bunches/pulse or multibunch operation, 100-200 Hz)
  - Positron generation with capture section are naturally separated.
  - Full energy can be used for positron generation. Positron production and capture studies ongoing.
  - Multi-bunch operation => Target design: challenging engineering & prototyping.
- 20 GeV injector option
  - Positron production increase ~linearly with e- drive beam energy.
  - Lower drive beam charge & target thermal load.
- Demonstrator for novel target and capture system will be realized at SwissFEL facility at PSI. Beam tests are foreseen also to study the target materials and hybrid production scheme (KEK, MAMI, DESY…).

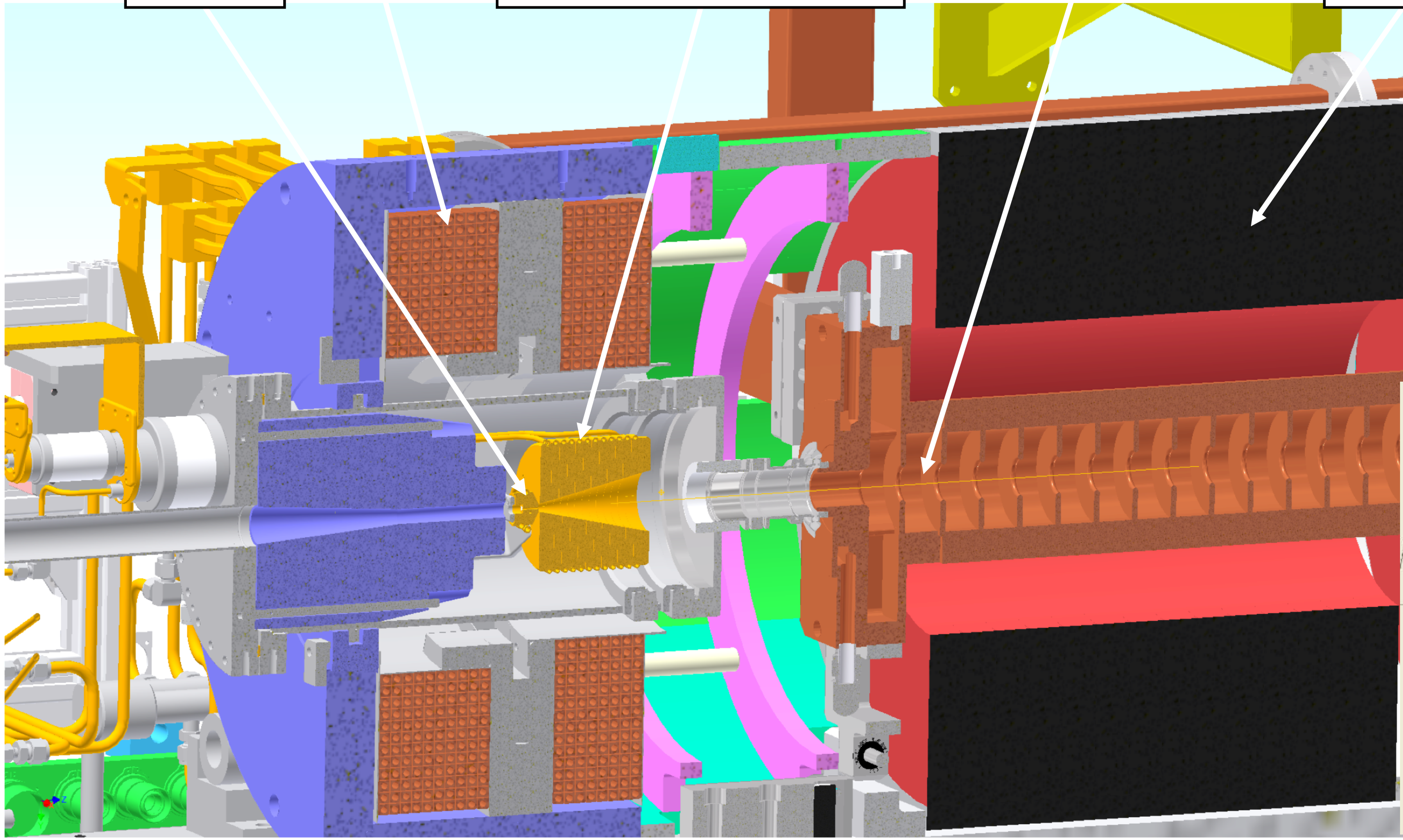
BACKUP

Existed and future positron source parameters

	SLC	SuperKEKB	FCC-ee (conv.)	FCC-ee (conv.) multi-bunch	ILC
Incident e- beam energy	33 GeV	3.3 GeV	6 GeV	6 GeV	3 GeV
e-/bunch [10^{10}]	3-5	6.25	1.8	2	2.2
Bunch/pulse	1	2	2	20	33*2 => x20 (1320)
Rep. rate	120 Hz	50 Hz (25 Hz)	100 Hz	100 Hz	300 (5)
Incident Beam power	~20 kW	3.3 kW	3.5 kW	38.4 kW	74 kW
Beam size @ target	0.6 - 0.8 mm	~0.5 mm	0.5 mm	1.15 mm	2
Target thickness	$6X_0$	$4X_0$	$5X_0$	$5X_0$	$4.6X_0$
Target size, diameter	70 mm	4 mm	XXX	XXX	500 mm
Target	Moving	Fixed	Moving	Moving (wheel ?)	Moving (225 rpm)
Deposited power	4.4 kW	0.6 kW (0.3 kW)	0.6 kW	7.2 kW	18.8 kW
PEDD	~30.5 J/g	29 J/g	8.6 J/g	32 J/g	33.6 J/g
Positron yield @ DR	$\sim 1.1\ N_{e+}/N_{e-}$	$0.4\ N_{e+}/N_{e-}$	$2.3\ N_{e+}/N_{e-}$	$2.1\ N_{e+}/N_{e-}$	$\sim 1.25\ N_{e+}/N_{e-}$
DR energy acceptance	+/- 2.5 %	+/- 1.5 % (1 σ)	+/- 4 %	+/- 4 %	+/- 0.75 %
Energy of the DR	1.15 GeV	1.1 GeV	1.54 GeV	1.54 GeV	5 GeV

SuperKEKB Positron Source

Courtesy of Y. Enomoto (KEK)



BC (bridge coil)

LAS (large aperture S-band)

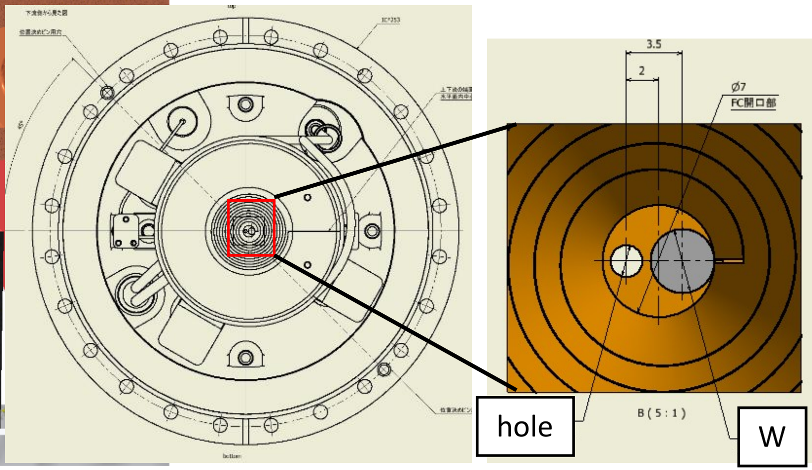
W target

FC(flux concentrator) head

solenoid

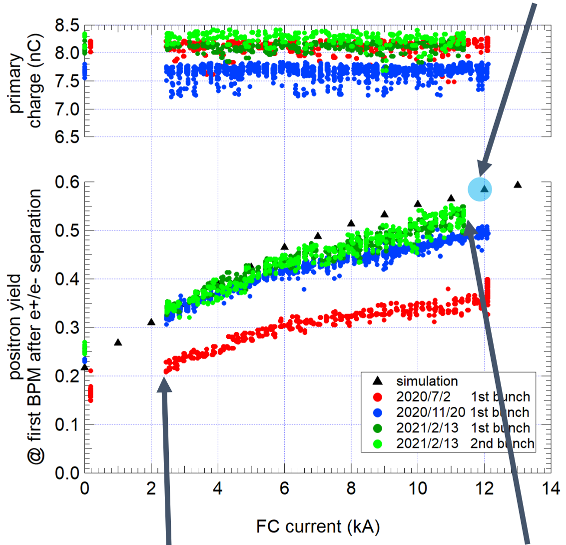
Target material : W
Target size : Φ4 x 14
Inserted in the pule Cu block
Connected by HIP process

looking from downstream side



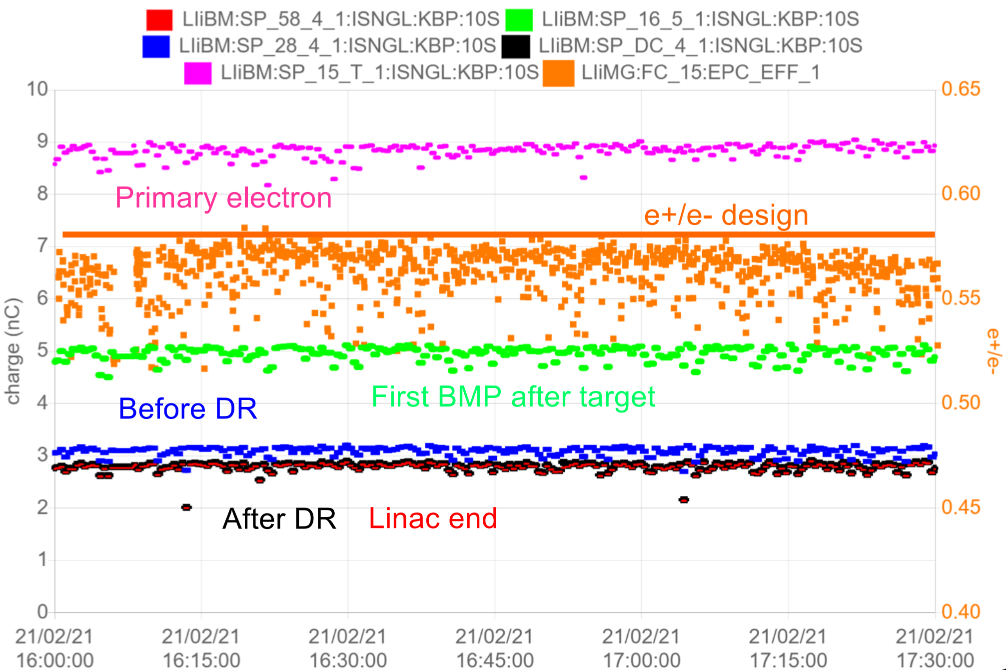
SuperKEKB Positron Source: Latest situation

Design (0.58)



Present

Before upgrade
(To avoid discharge,
FC current was limited very low)



- Primary beam
  - 90% (9 nC / 10 nC)
- Positron yield（e+/e-）
  - 100% (0.58 / 0.58)
- transport
  - Assuming 5.8 nC (design value) @ first BPM after the target and present transport efficiency, charge @ Linac end is expected to be 3.3 nC.
  - There is still room for improvement

Hardware upgrade

Further beam tuning

	design	2020ab	2020c	2021a	2021a (10 nC, 0.58)
Energy (e-)	3.5 GeV	3.5 GeV	3.5 GeV	**3.5 GeV**	
primary charge (e-)	10 nC	8.4 nC	8 nC	**9 nC**	
e+/e-	0.58	0.24	0.51	**0.58**	
e+ @ first BPM after the target	5.8 nC	2.0 nC	4.1 nC	**5.1 nC**	*5.8 nC (assume)*
e+ @ before DR	-	1.6 nC	2.5 nC	**3.2 nC**	4.2 nC
e+ @ after DR	-	1.4 nC	2.1 nC	**2.9 nC**	3.3 nC
e+ @ Linac end	4 nC	1.4 nC	2.1 nC	**2.9 nC**	3.3 nC

Courtesy of Y. Enomoto (KEK)

SLC Positron source

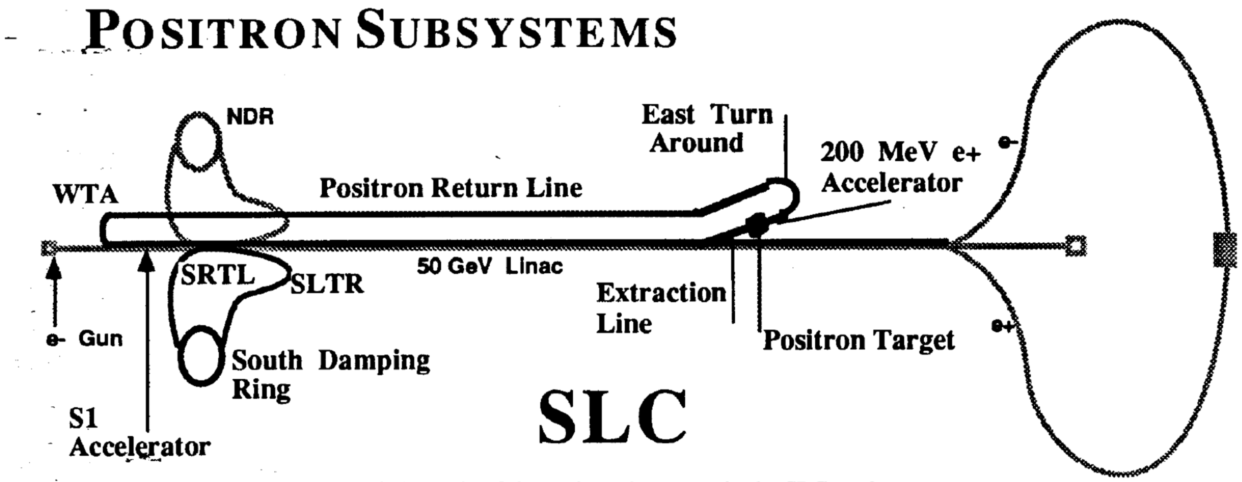


Figure 1: Schematic of the major subsystems in the SLC positron system.

P. Krejcik, J. Corbett, S. Ecklund, P. Emma, T. Fieguth, R. Helm, A. Kulikov et al.
Recent improvements in the SLC positron system performance.
SLAC-PUB-5786; CONF-920315-3. SLAC, Menlo Park, CA (United States), 1992.

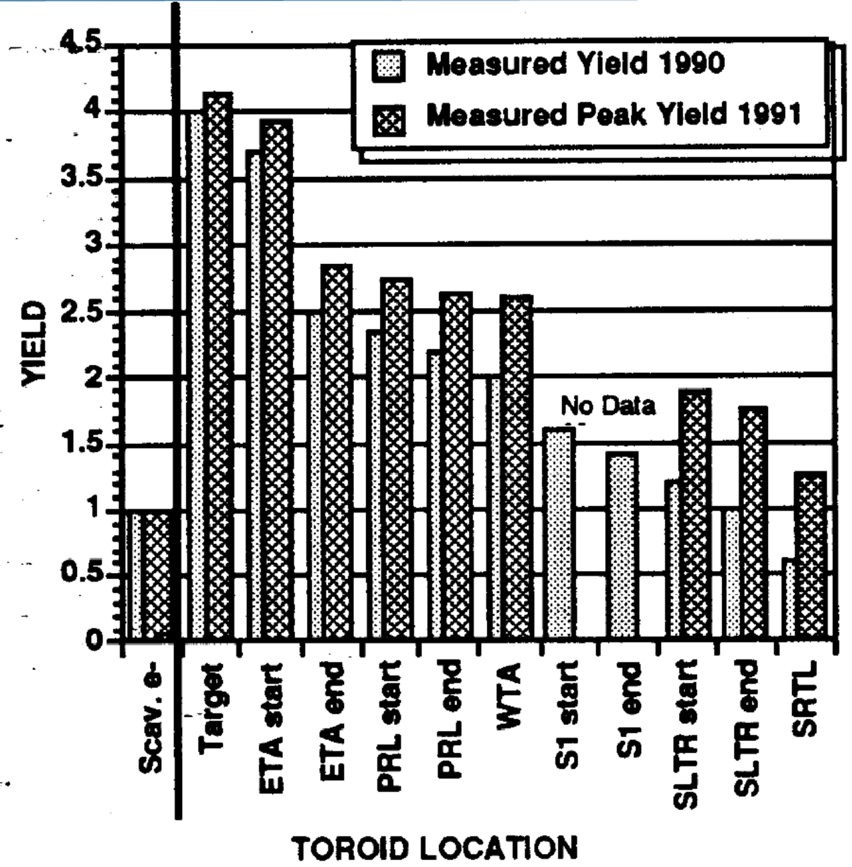


Figure 2: Positron yields measured for each subsystem normalized to the electron intensity hitting the target. The earlier 1990 data are chosen as typical rather than the best achieved.

Annual number of hits on the target

Courtesy of S. Ogur

The CDR injector was supposed to hit the target with electrons at 200 Hz with 2 bunches:

400 Hits/s * 3600 s *24 h* 185 days * 0.804 = **5.1E9 Hits/year**

The first fill from scratch (daily few times). The required positron charge during top up may vary between 0 to 100% of the nominal charge.
Roughly, we expect <10% of the nominal positron charge to be top-upped.
Therefore, we expect after first fill in 17 mins, the injectors carries ~2E9 e+/e-.

The new injector option may hit the target with electrons at 100 Hz with 20 bunches (number of bunches is not fixed yet):

2000 Hits/s * 3600 s *24 h* 185 days * 0.50 = ~**1.6E10 Hits/year**

The first fill from scratch (daily few times), the required positron charge during top up may vary between 0 to 100% of the nominal charge.
Roughly, we expect <5% of the nominal positron charge to be top-upped.
Therefore, we expect after first fill in 5 mins, the injectors carries ~1E9 e+/e-.

Assumption: the collider will work 185 days per year (Z-operation).

The linac is OFF when the synchrotrons are filled, therefore the linac duty cycle is 80.4%

1 hit = 1 bunch

The linac is OFF when the synchrotrons are filled, therefore the linac duty cycle is 50%

SLC (rotating target, 365 days):
~4E9 Hits/year