Optimisation of the FCC-ee positron source

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On behalf of the FCC-ee positron team

CEPC Workshop 2022

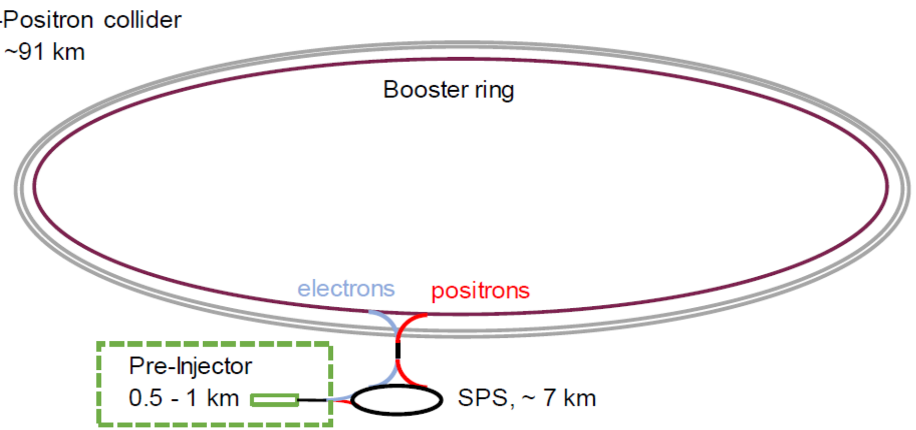
26/10/2022

Many thanks to the FCC-ee Injector team and the CHART project.

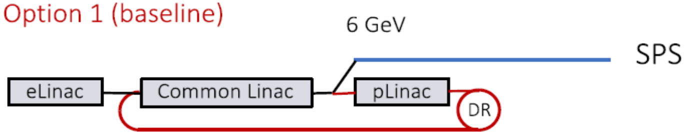
Swiss Accelerator Research and Technology

FCC-ee injector complex

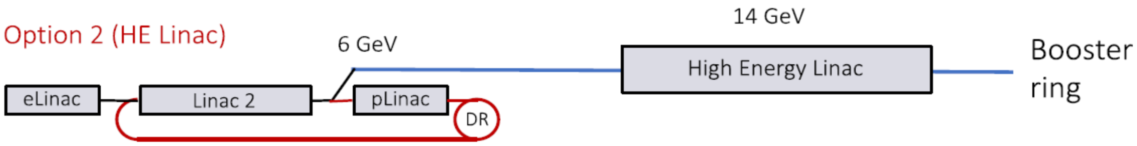
- Pre-injector: e-/e+ linacs up to 6 (20) GeV, 1.54 GeV Damping Ring
- Pre-Booster Ring (SPS or new ring) (6 - 20GeV)
- Booster Ring (20 → 45 GeV)
- The main 6 GeV linac feeds the positron source. The positrons are produced with 6 GeV e- beam.



Option 1 (baseline)

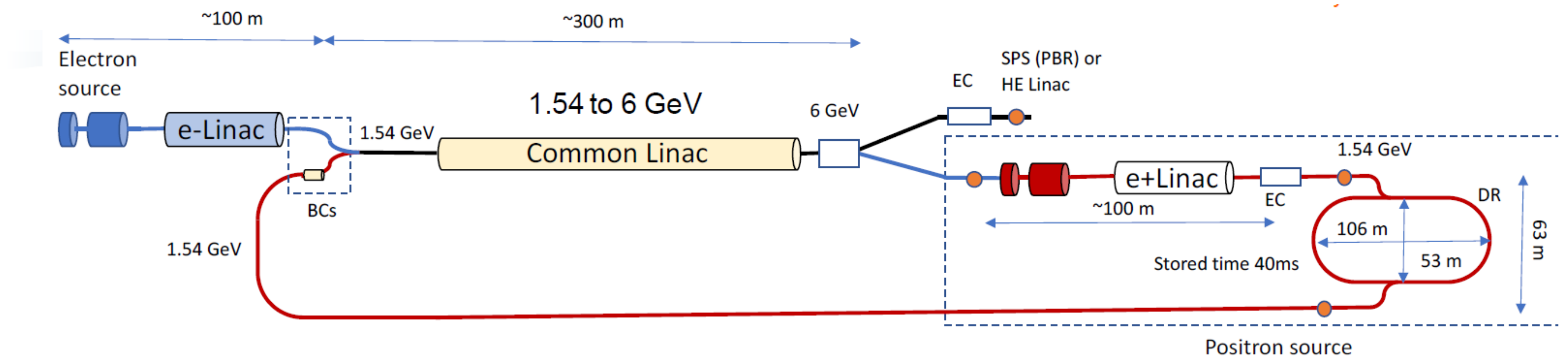


Option 2 (HE Linac)



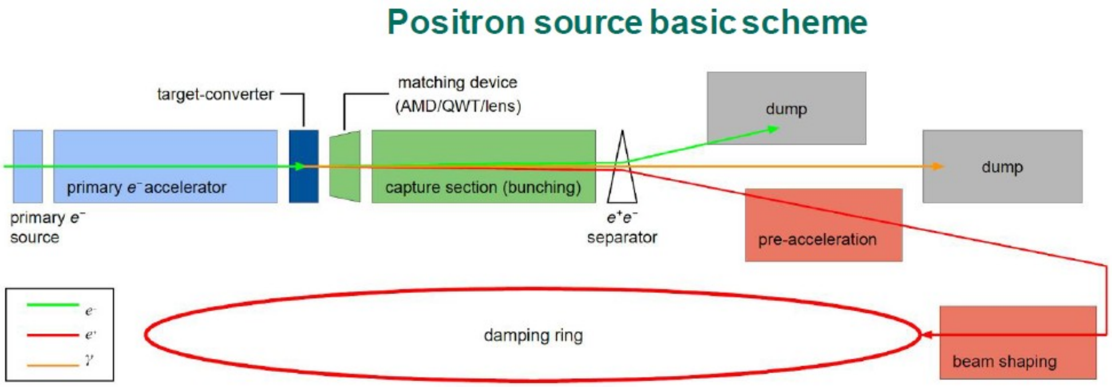
	Baseline	HE Linac	Unit
Ring for injection	SPS/PBR	BR	
Injection energy	6	20	GeV
Bunch population both species	3.47 (5.55)	3.12 (5.0)	1E10 (nC)
Repetition rate	200	200	Hz
Number of bunches	2	2	
Bunch spacing	17.5-50	17.5-50	ns
Normalized emittance (x, y) (rms)	50, 50	50, 50	mm.mrad
Bunch length (rms)	~1	~1	mm
Energy spread (rms)	<0.1	<0.1	%

FCC-ee pre-injector layout (6 GeV option)



- Linac efficiencies optimized: electron/positron beam with same energy, main and drive electron beam with same final energy
- Specifications are fulfilled for the electron bunch (beam dynamics simulations for the e- linac and common linac well advanced)
- e+ Linac: several options of the capture section, RF design well advanced 2 GHz, 200 Hz, large iris aperture, beam dynamics on-going.
- DR provides the damping of the positron beam and delays extraction to allow single species operation for the common linac.

FCC-ee positron source requirements



Accepted e⁺ yield is a function of **primary beam characteristics** + **target** + **capture system** + **DR acceptance**

To estimate the accepted yield:
energy window cut: (1540 ± 58.5) MeV → (±3.8% @ 1.54 GeV)
time window cut: 40° RF (~16.7 mm/c @2 GHz)

The complete filling for Z running => Requirement ~3.5 × 10^{10} e⁺/bunch (5.6 nC)

$$N_{e-}/\text{bunch} \times \eta^{e+}_{Accepted} \geq 5.6\ \text{nC/bunch} \times 2$$

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

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

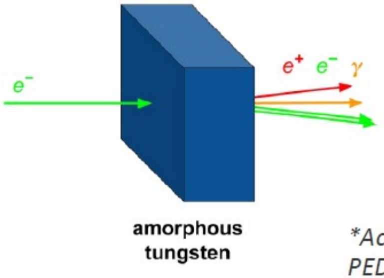
All the studies are focused on the operation scheme: 6 GeV, 2 bunches/pulse, 200 Hz rep. rate, the max e- bunch charge is 5.6 nC → ~1.4 × 10^{13} e⁺/s

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



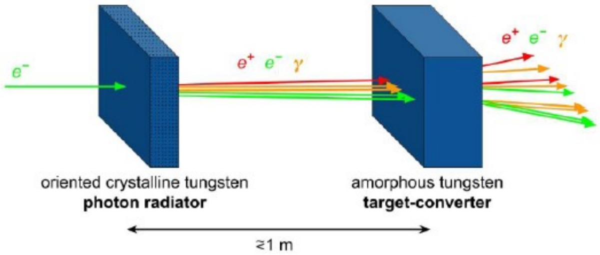
Target ("conventional" scheme)		
Thickness	17.5	mm
Positron yield at target exit	13.7	e^+/e^-
Normalised PEDD	$25.6 / \eta_{e^+}$	J/g
Normalised deposited power	$4.0 / \eta_{e^+}$	kW

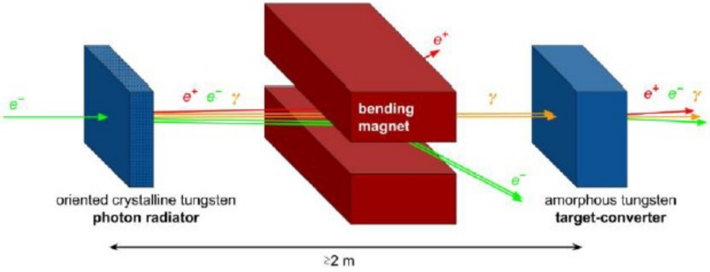
Geant4 used for target simulation

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

Crystal-based target
Hybrid scheme

L. Bandiera et al., Eur. Phys. J. C (2022) 82:699)



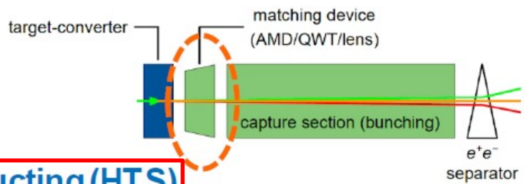


The final choice will be done based on the simulated performances

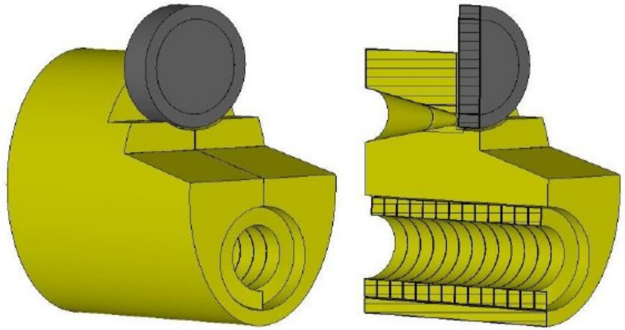
Parameters	Values	Units
Primary electrons at the target entrance		
Beam energy	6	GeV
Spot size (RMS)	0.5	mm
Bunch length (RMS)	1	mm
Energy spread (RMS)	0.1	%
Normalised transverse emittance (RMS)	15	mm·mrad
Number of bunches per pulse	2	
Repetition rate	200	Hz
Normalised beam power	$16.8 / \eta_{e^+}$	kW
Normalised beam fluence	$6.2 \times 10^{11} / \eta_{e^+}$	cm⁻2

FCC-ee positron capture system: matching device

Matching device => a fast phase space rotation to transform the small size and high divergence in big sizes and low divergence beam.



Flux Concentrator (FC)
designed by P. Martyshkin (BINP)



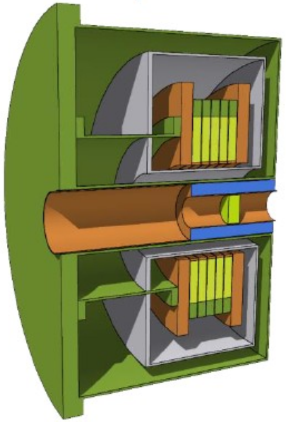
Compared with HTS solenoid:

- Low peak field (5−7 T, ~1.5−3 T at target exit)
- Small entrance aperture (Φ = 8−16 mm)
- Fixed target position (2−5 mm upstream)

Therefore, lower e+ yield

In case used, needs to be optimised for 200 Hz rep. rate

High-Temperature Superconducting (HTS) solenoid designed by J. Kosse, B. Auchmann and M. Duda (PSI)



Compared with FC:

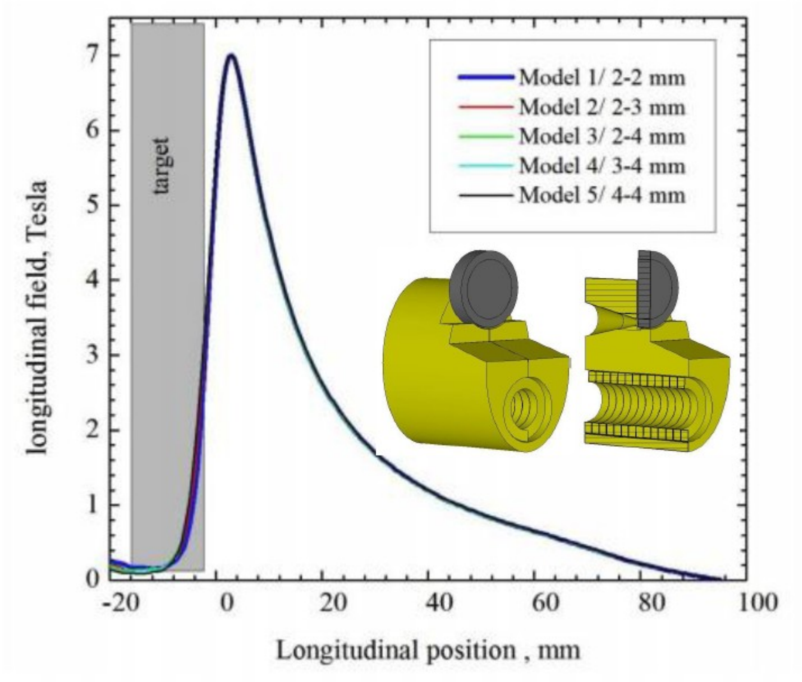
- High peak field (~15 T, ~12 T at target exit)
- Large aperture (Φ = ~40 mm)
- Flexible target position (can be placed inside the bore)

Therefore, higher e+ yield

Yield higher than using FC with a factor of > 2.
We currently focus on studies using HTS solenoid.

FCC-ee positron capture system: matching device

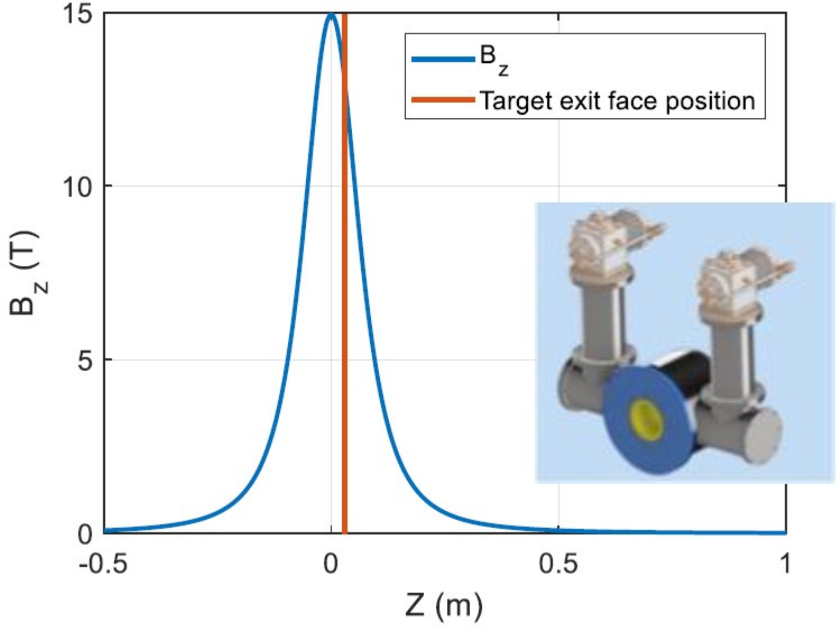
Flux Concentrator (FC)



FC on-axis field, with fixed target position

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

High-Temperature Superconducting (HTS) solenoid



HTS solenoid field, with optimised target position

Target located inside HTS solenoid.

Position optimised for maximum DR accepted e+ yield.

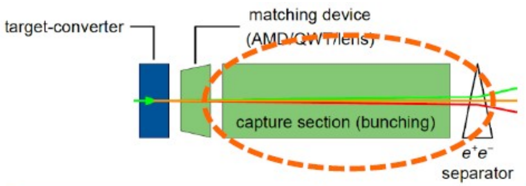
FCC-ee positron capture system: capture linac

The capture linac is encapsulated inside a solenoid with the axial magnetic field of ~0.5 T (NC)

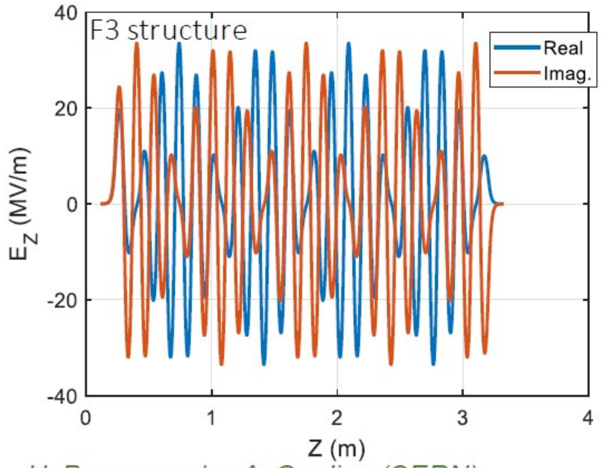
(usually with constant solenoid field and recently, more realistic field profiles started to be used)

- 1.5 m long, ~21 MV/m, TW 2 GHz L-band structures, (Φ = 40 mm)
- 3 m long ~20 MV/m, TW 2856 MHz S-band structures (Φ = 30 mm),
- 1.5 m long ~18 MV/m, SW 2998 MHz S-band structures (Φ = 40 mm) -> P^3 project
- 3 meter long ~20 MV, TW 2 GHz large aperture structures (Φ = 60 mm)

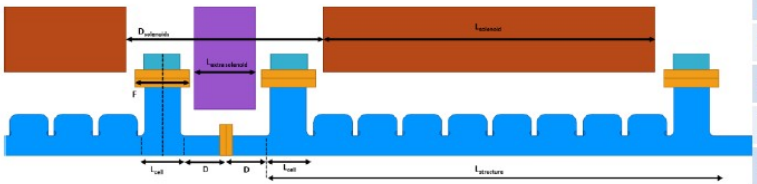
We currently focus on this structure



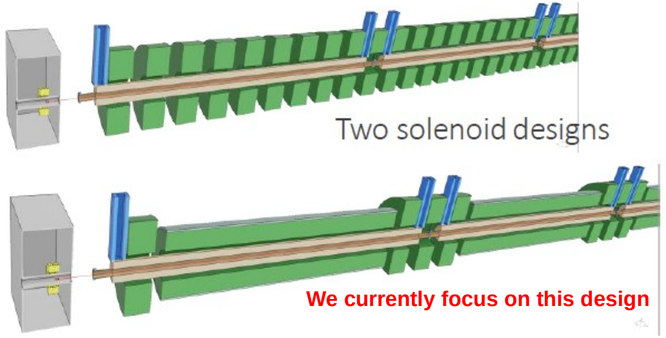
	F3 („baseline")
Frequency	**2.0 GHz**
Constant aperture	**30 mm = 0.2 λ**
Phase advance	**9π/10**
Length	**3.0 m = 44 cells**
Entr., exit iris thickness	14.3 mm, 20.0 mm
Transverse wake at 17.5 ns	0.13 V/pC/mm/m
Filling time	447 ns
Min. group velocity	1.9 % c
Largest cell radius	**61 mm**
SLED coupling	17
Eff. shunt impedance	**39 MΩ/m**
Average gradient	**15 MV/m**
E_{max} (instant.)	58 MV/m
$S_{c,max}$ (instant.)	329 mW/μm²
Klystron pulse length	5 μs
Klystron power per structure	17 MW



H. Pommerenke, A. Grudiev (CERN)
M. Schaer, R. Zennaro (PSI)

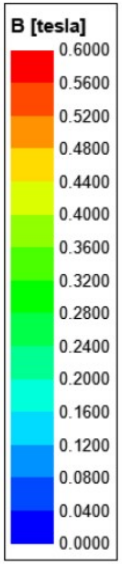


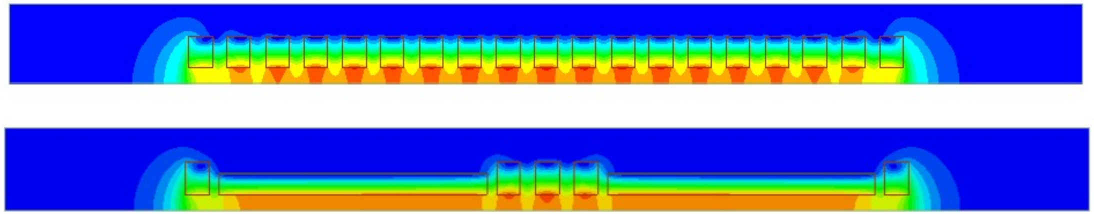
Up to 200 MeV, 1+4 structures used in simulation



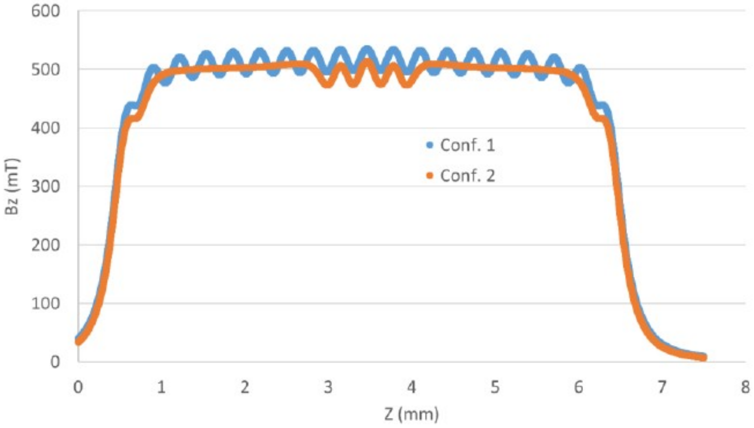
FCC-ee positron capture system: capture linac

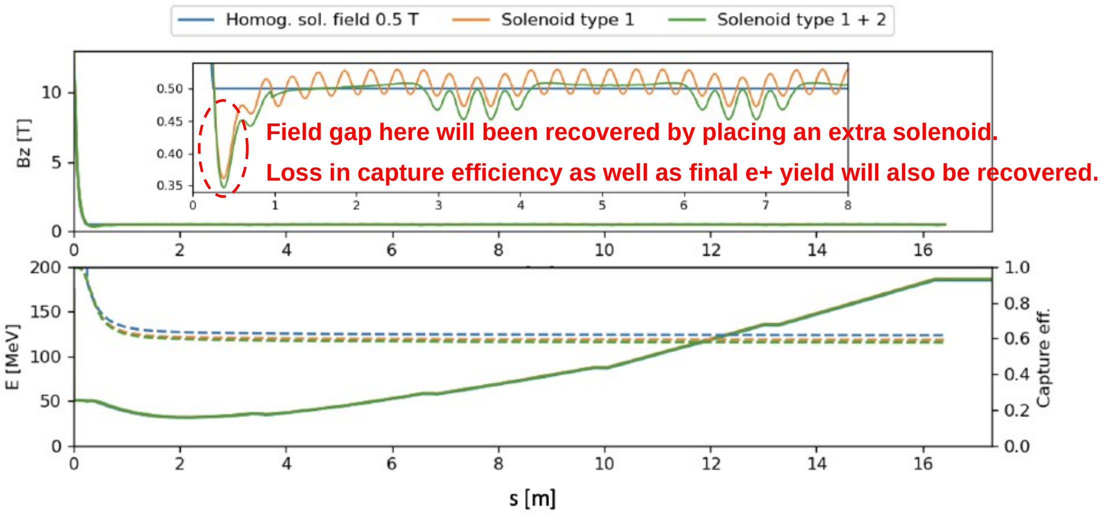
Maxwell 2D simulation for solenoid over 2 RF structures





Minimal reduction in capture efficiency between homog. channel (0.618) and realistic solenoids (0.593 and 0.579)





M. Schaer, R. Zennaro (PSI)

FCC-ee positron capture system: preliminary results

The first results (preliminary)

- Capture efficiency @ 200 MeV: ~0.6
- e+ yield @1.54 GeV: 6.4 Ne+/Ne- (*)
- e+ norm. emittance: ~12 mm.rad

RF-Track used for tracking simulation

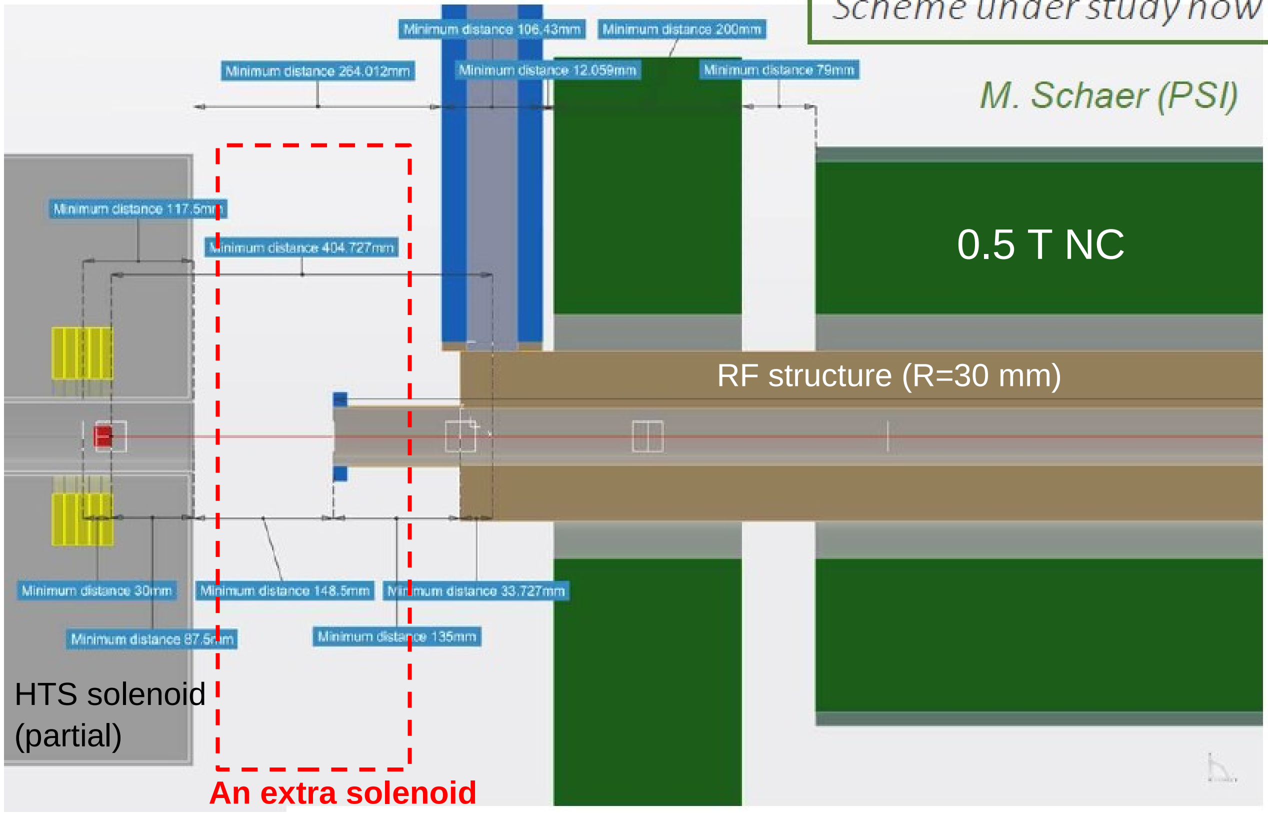
- In the coming update, an extra solenoid between HTS and RF linac will be placed, which will improve the final e+ yield to ~6.6-6.8 (*)

(*) Depending on simulation tools and codes, the yield might be slightly different.

FCC-ee e+ capture system "version 0"

Scheme under study now

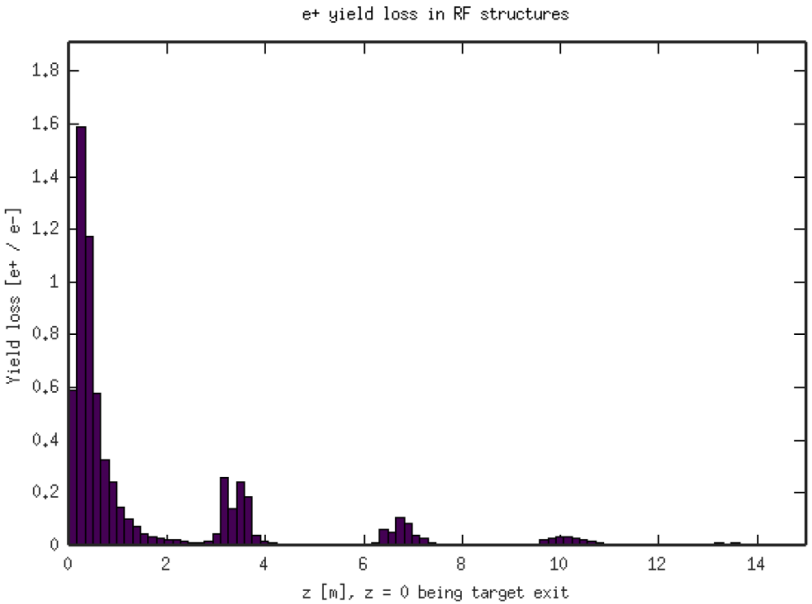
M. Schaer (PSI)



An extra solenoid will be placed here

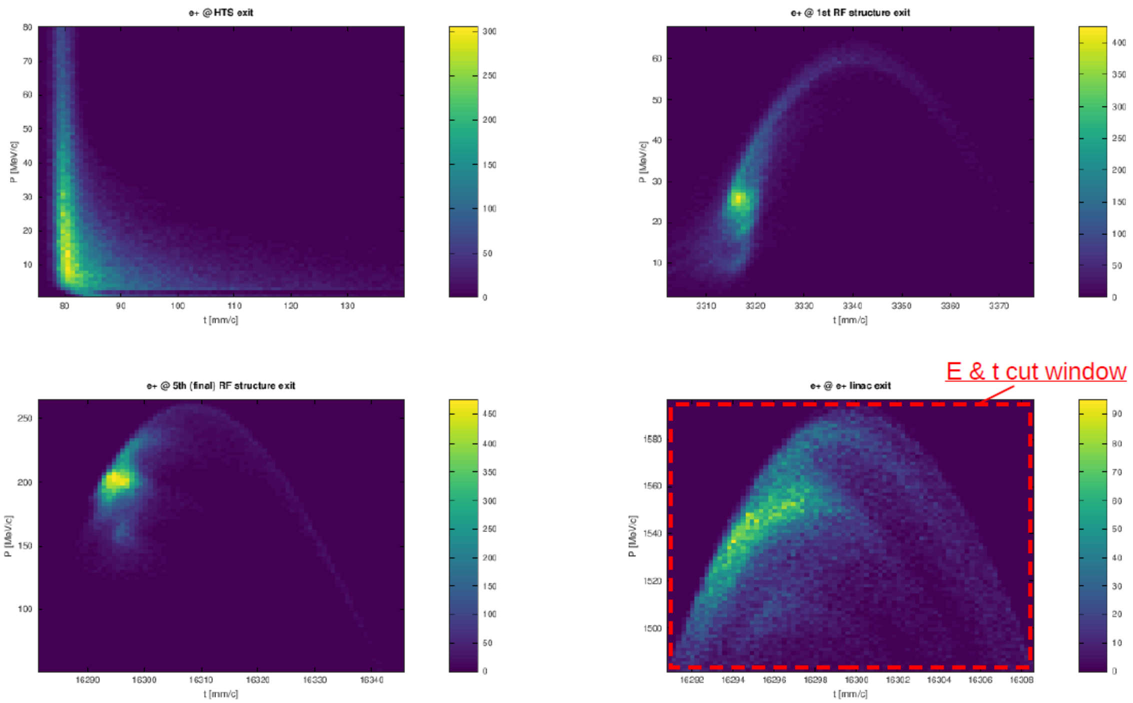
FCC-ee positron capture system: preliminary results

Yield loss in RF structures (up to 200 MeV)

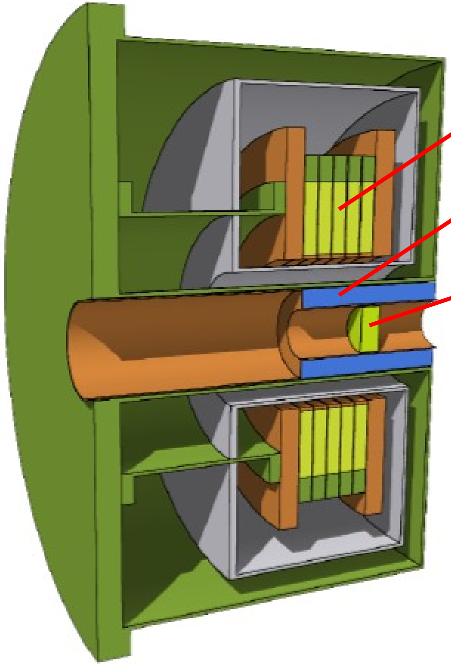


- The RF phases of the 5 capture linac structures are all optimised for the maximum e+ yield

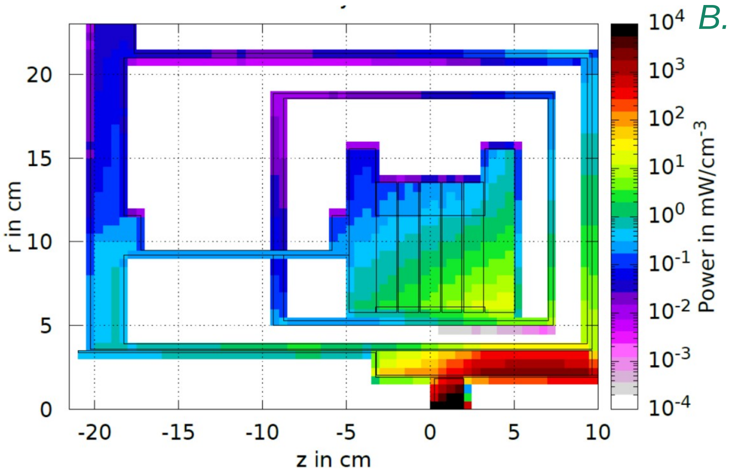
Longitudinal phase spaces at the exits of the HTS solenoid, 1st RF structure, 5th RF structure (200 MeV) and e+ linac (analytic)



Radiaton load study: HTS solenoid



PSI HTS solenoid design



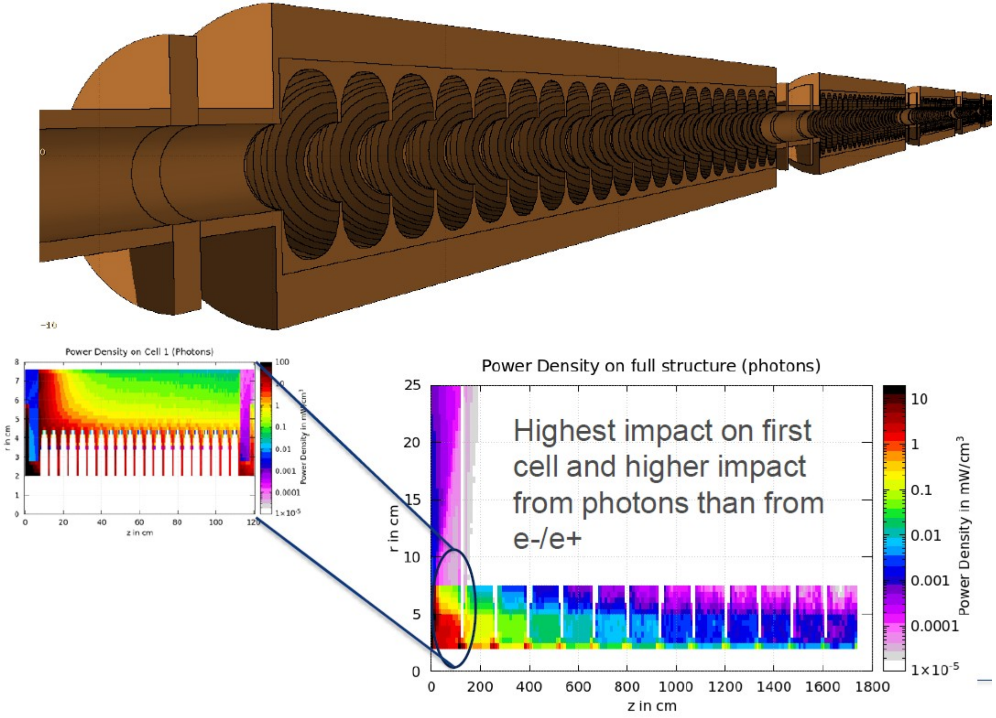
B. Humann, A. Lechner (CERN)

- **Electron beam**: 6 GeV. Assuming 1.43 nC bunch charge and 3.43 kW beam power
- **Target**: W-26Re. Peak power density ~21 kW/cm^3 at the center position. Damage: 3 DPA/year
- **Shielding**: thermo mechanical studies needed. Can be thicker without loss in e+ yield
- **HTS coils**: peak power density seems OK. 10^{-4} DPA/year. Ionizing radiation dose up to 22 MGy/year. Being discussed with experts. More shielding optimisations needed

Preliminary results! Study still on-going! Layout and results to be updated shortly!

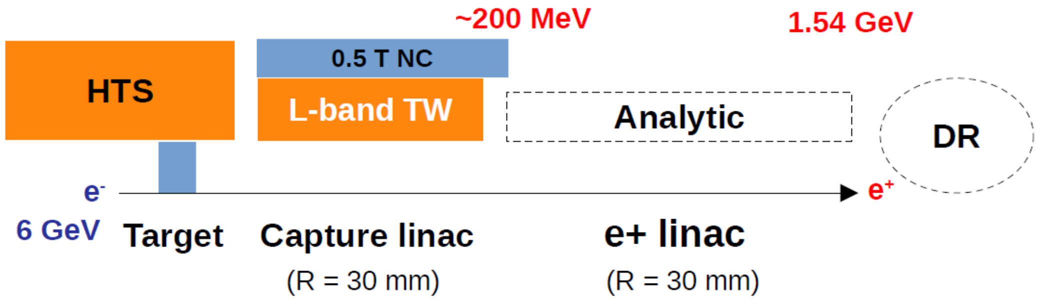
Radiaton load study: RF structures

B. Humann, A. Lechner (CERN)



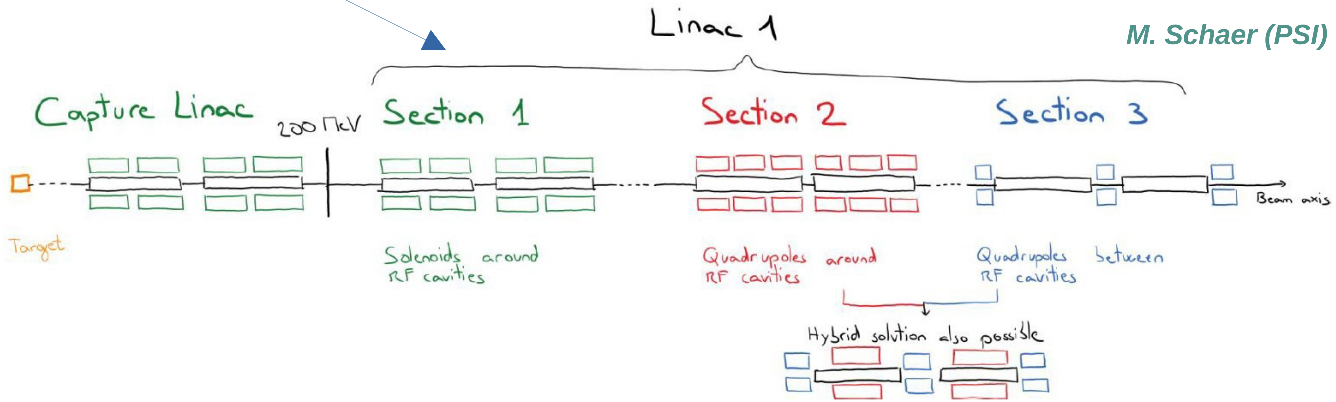
- **Study still on-going!**
- Only **S-band** RF structure (as shown on the left) studied so far (for the PSI P[3] e+ source project). To study the new L-band structure (larger aperture)
- Simulation planned to see the impact and efficiency of a **mask** in front
- Radiation protection being studied with the experts (might be a mid-term plan)

FCC-ee positron linac (Linac 1)



- The same RF structure will be used in capture linac and e+ linac
- In Section 1 of e+ linac, 0.5 T NC solenoid can be extended to be used
- Quadrupoles used in Sections 2 and 3
- Study in progress!

M. Schaer (PSI)



Summary

- In the latest version of FCC-ee pre-injector, e+ produced by **6 GeV, 2 bunches/pulse e- beam at 200 Hz** (cf. CDR version is 4.46 GeV)
- FCC-ee positron source **studies well advanced**: e+ production, SC technology (HTS) feasibility for matching device, capture linac (RF structure & solenoid), etc. Studies **in progress**. **No showstoppers found that prevent HTS solenoid from being used as matching device**
- e+ linac and DR designs well-established and advanced. Studies **in progress**. DR dynamic aperture to be optimised. DR filling schemes under investigation
- **Radiation load** studies **in progress**: layout & results to be updated (e.g. increasing shielding thickness or aperture). Energy deposition in RF structures (if mask is needed)
- Design of the **target** mechanical system **in progress**
- A demonstrator for the FCC-ee positron production and capture will be realised at SwissFEL facility at PSI (CHART **P^3 project**)
- Next deliverables (CHART and FCC FS): inputs for mid study costing exercise in summer 2023, final project cost update and feasibility study report in 2025

BACKUP

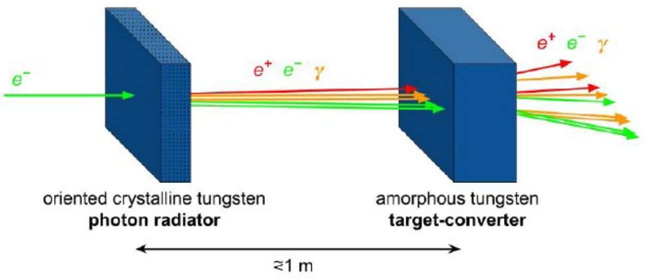
Hybrid FCC-ee target scheme: preliminary simulations

L. Bandiera et al., Eur. Phys. J. C (2022) 82:699)

e- beam energy = 6 GeV, angular divergence 0.1 mrad and with the r.m.s. transverse beam size of 0.5 mm. W crystal oriented in <111> (θc ≈ 0.6 mrad).

A 2 mm thick crystal has been selected to be used as a radiator for the hybrid positron source.

→ good photon yield, moderate values of photon divergence and energy deposition in the crystal.

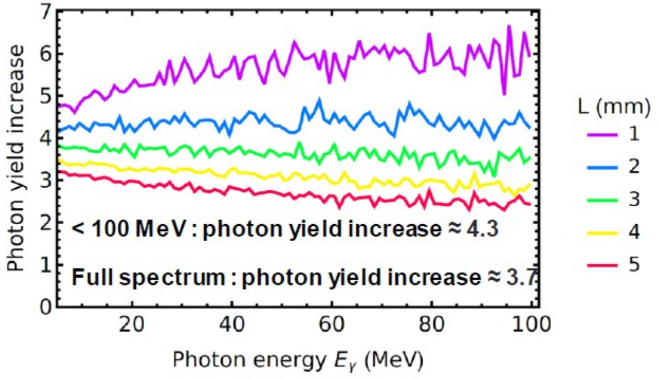


Results for the positron production simulations

scheme	conventional	hybrid[1]
target thickness [mm]	17.6	2 + 10
e^+ production rate $[N_{e^+}/N_{e^-}]$	14.4	15.1
target deposited energy $[\mathrm{GeV}/e^-]$	1.44	0.946
PEDD $[\mathrm{GeV}/\mathrm{mm}^3/e^-]$	0.0416	0.0156

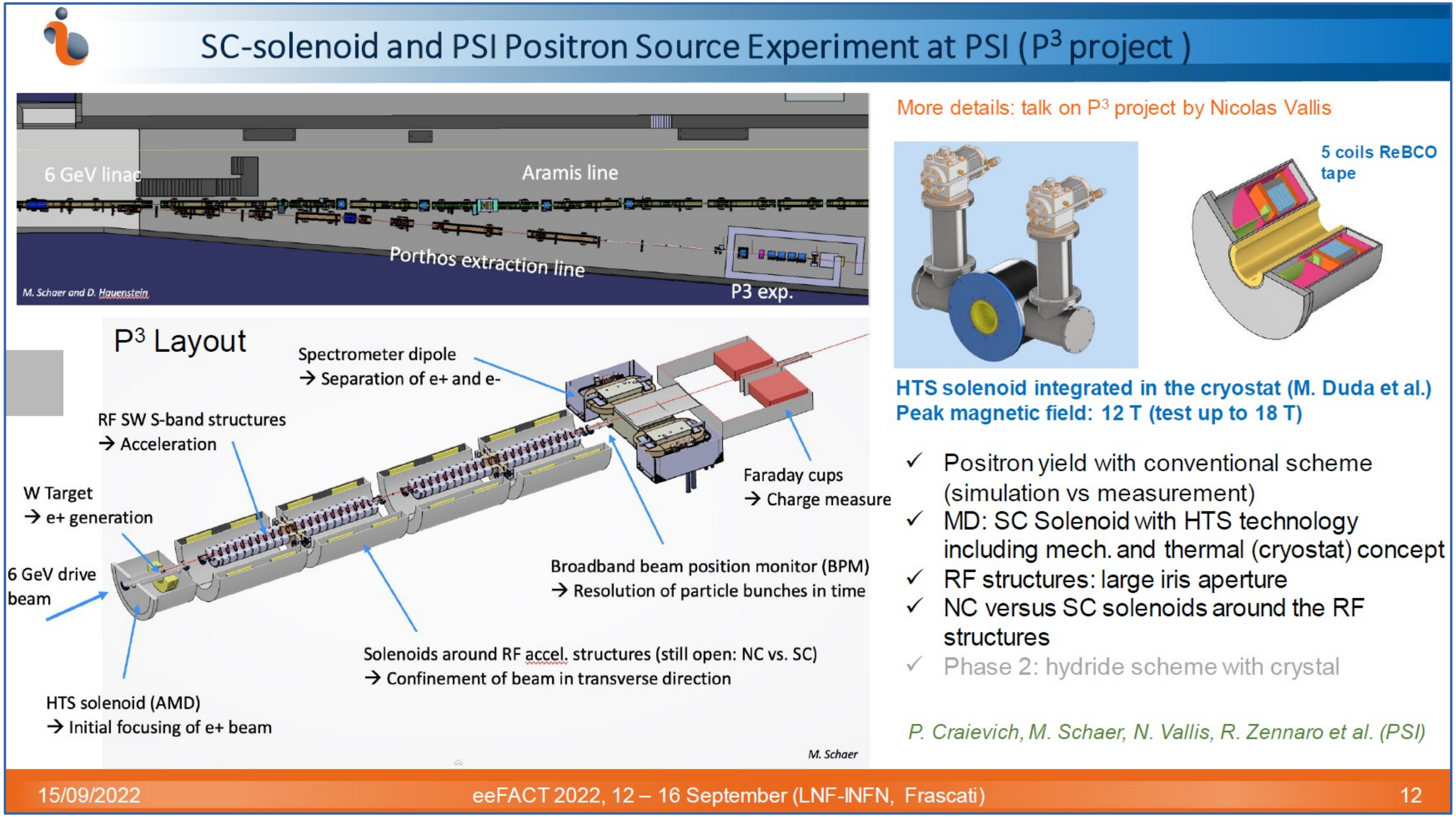
[1]The values are given for the amorphous target-converter installed after the crystal target.

Radiation enhancement in the tungsten (W) crystals aligned along <111> axes



Final yield accepted by DR to be compared (since increased beam size leads to lower final yield)

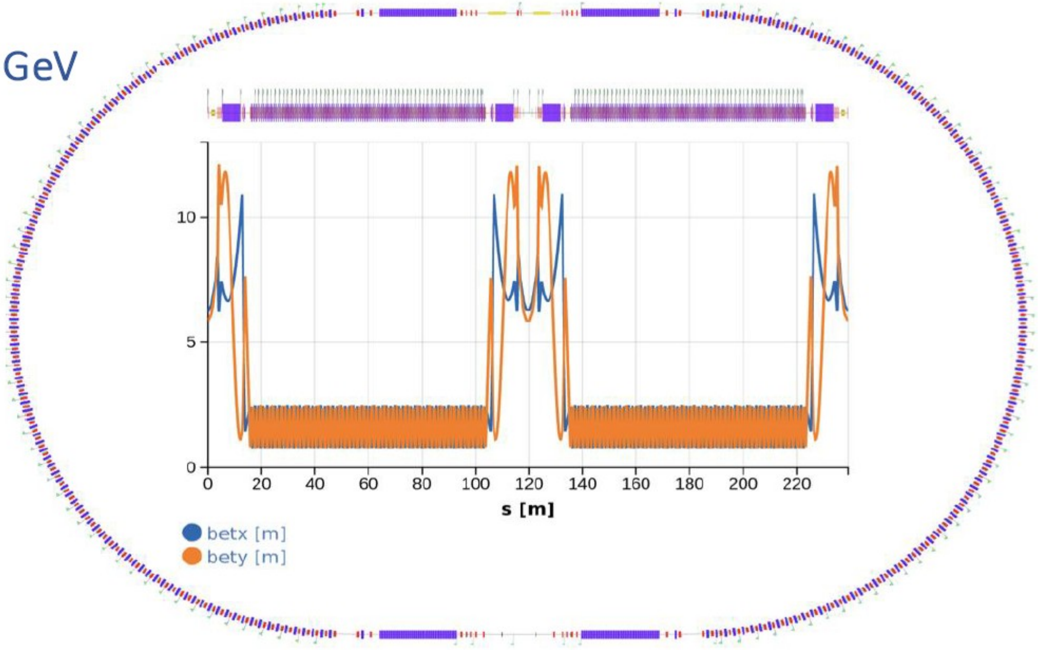
The Swiss CHART P^3 project at PSI



FCC-ee Damping Ring design studies

Studies of the DR dynamical aperture are in progress ➔ start-to-end simulations for the positron source

E = 1.54 GeV



2 wigglers each in straight sections
400 MHz LHC like 2 SC cavities

A. De Santis et al. (LNF)

Parameter	FCC_ee DR
Circumference	239.2 m
Harmonic number	319
Eq. Emittance (x/y/z)	1.01 nm/ - / 1.46 μm
Dipole length, Field	0.21 m, 0.66 T
Wiggler #,Lenght, Field	4, 6.64 m, 1.8 T
Cavity #, Lenght, Voltage	2, 1.5 m, 4 MV
Bunch stored #, charge	18 , 4.0 nC
Damping Time (x/y/z)	10.8 / 10.8 / 5.4 ms
Store Time	42.5 ms
Energy loss per turn	0.227 MV
SR Power Loss (WGL)	15.7 kW

	V= 8MV	V= 6MV	V= 4MV	V= 2MV
U_0 [KeV]	227.1			
DE/E_s	$0.71 \cdot 10^{-3}$			
Ω_s [KHz]	25.313	21.918	17.888	12.618
T_0 [μsec]	0.79801			
ω_0 [s^{-1} rad]	$7.87\ 10^6$			
ν_s	0.003215	0.00278	0.002272	0.0016
L_{bunch}[m]	**0.00207**	0.00239	0.00293	0.00415
φ_s [rad]	0.0283967	0.0378663	0.0568164	0.113817
$(E - E_s)$ [GeV]	0.124	0.107	0.0862	0.058
$\Delta\varphi$ [unit of π]	1.8	1.7769	1.7269	1.6016
L_{bucket}[m]	0.6788	0.6664	0.6476	0.6006