PAUL SCHERRER INSTITUT PSI

FUTURE CIRCULAR COLLIDER

Paolo Craievich (PSI) on behalf of the CHART/FCCee Injector design collaboration

The FCCee (Pre-)Injector Complex

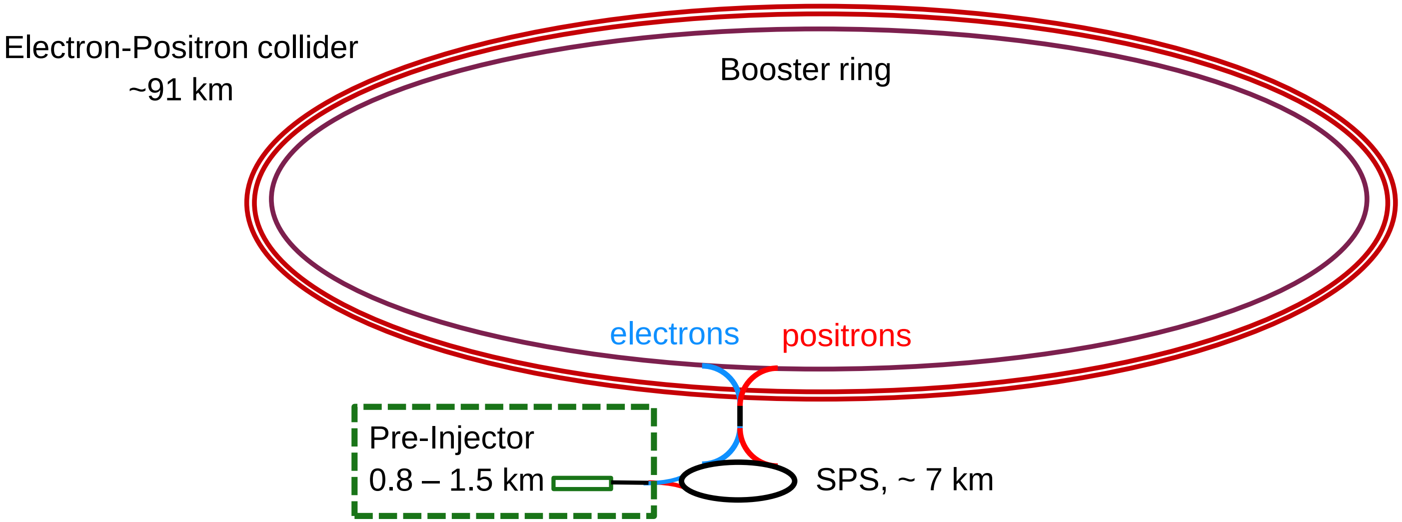
(Diagnostic requirements based on the SwissFEL linac)

1st FCCee Beam Instrumentation Workshop FCC Week, CERN, 21 and 22 November 2022

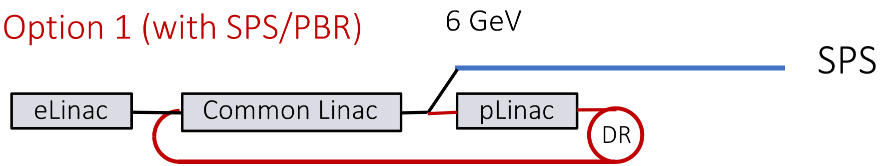
Outline

– **Injector specification**
– **Injector layout**
  - Electron source, Common linac, Positron source, Damping ring
– **General requirements (for diagnostics)**
  - Specifications for diagnostic components
  - Machine protection system
– **Diagnostics for the PSI Positron Source (P^3) project**
– **Conclusion**

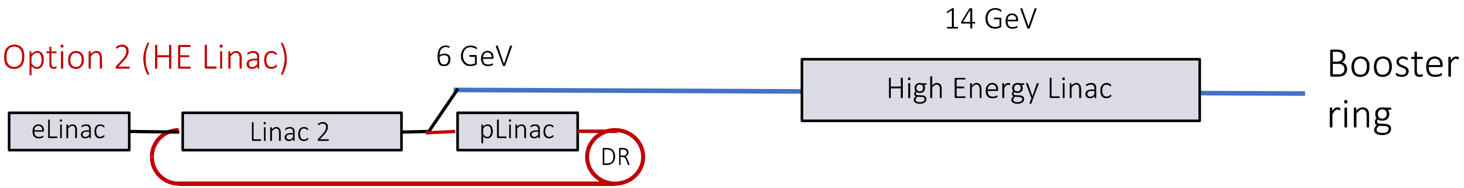
Where are we in FCC-ee?



Option 1 (with SPS/PBR)



Option 2 (HE Linac)



Injector parameters (Z-mode)

FCC Accelerator Pillar meeting #07, 01.11.22

	CDR0	HE Linac	Unit
Ring for injection	SPS/PBR	BR	
Injection energy	6	20	GeV
Bunch charge (max)	4 (5)		nC
Repetition rate	200		Hz
Number of bunches	2		
Bunch spacing	17.5-25		ns
Normalized emittance (x, y) (rms)	10, 10		mm.mrad
Bunch length (rms)	~1		mm
Energy spread (rms)	<0.1		%
Bunches/beam	~10000		

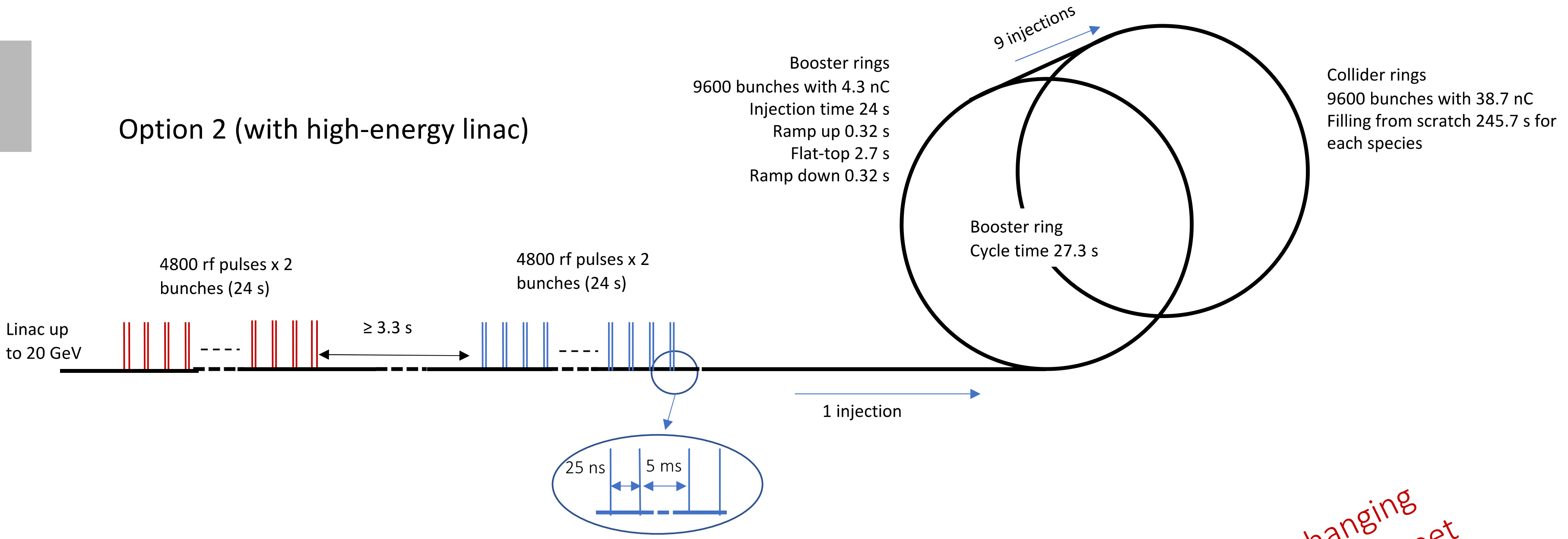
Other important requests:

- The bunch by bunch intensity will **randomly vary 0 (?) to 100%,** depending on the intensity balance between the collider rings
- **Bunch-by-bunch injection intensity fluctuation: 3%**

Filling pattern for the Z-mode (an attempt)

Sketch based on the proposal by K. Oide (FCC Accelerator Pillar meeting #07, 01.11.22)

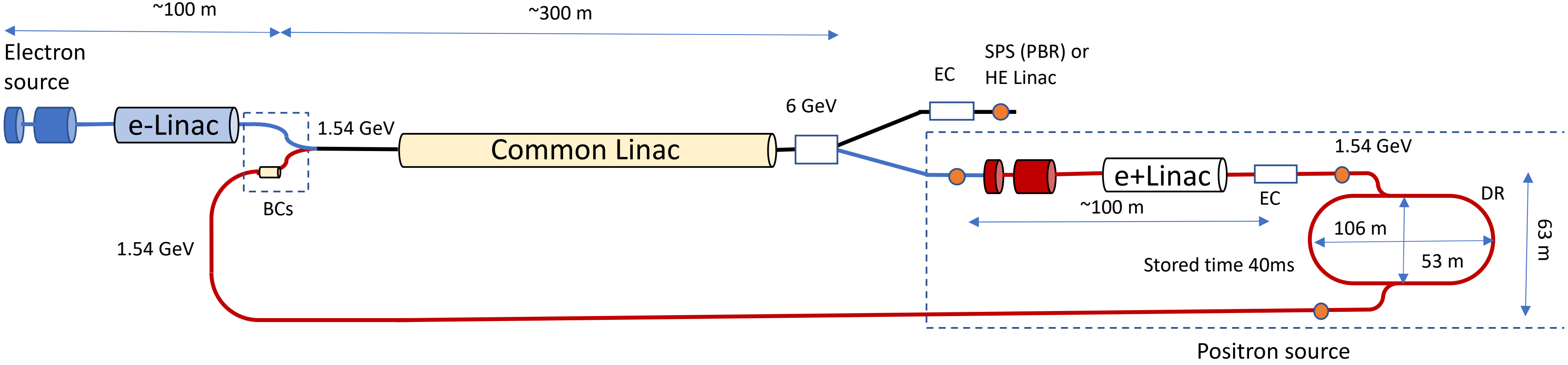
Option 2 (with high-energy linac)



- Total filling time from scratchg for the Z-mode 245.7 s for each species
- Collider filling time for top-up 27.3 s
- Luminosity lifetime 479 s (4 IP)
- Collider top-up interval (between e+ and e-)(4 IP) 24 s

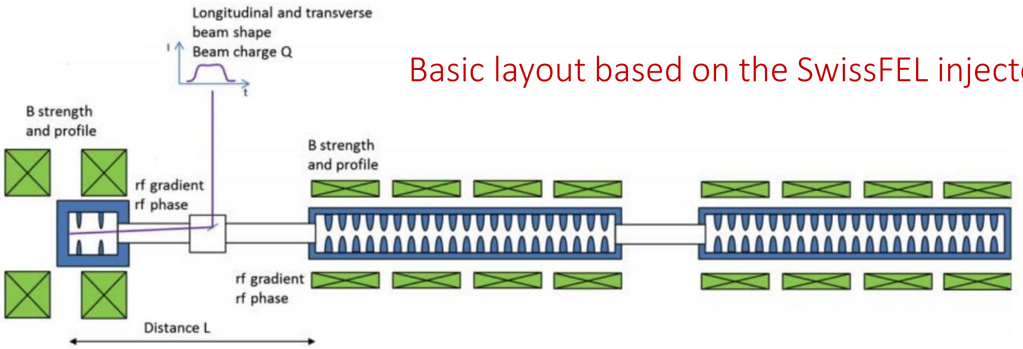
In this phase changing bunches/train can meet the specifications

FCCee Pre-Injector complex (up to 6 GeV)



- Injector is split in WPs:
  - WP1: Electron source, e-linac (2.8 GHz, 200 Hz), common linac (2.8 GHz, 400 Hz), e+Linac (2.0 GHz, 200 Hz), High Energy Linac (2.8 or 5.6 GHz, 200 Hz)
  - WP3: Positron generation and capture (2-bunches, 25 ns, 200 Hz)
  - WP4: DR and transfer lines (Energy Compressor, DR, Transfer line, Bunch Compressor)
- Outstanding question for the layout: is the DR also necessary for electron bunches?

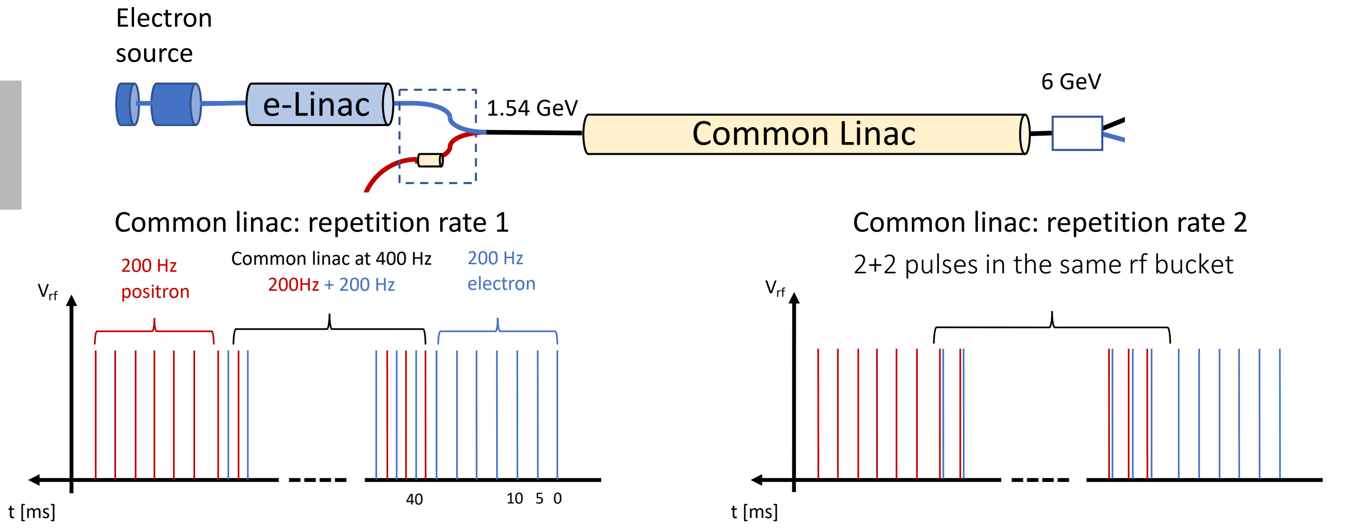
Electron source



Basic layout based on the SwissFEL injector

- Electron source: an injector based on a photocathode RF gun can provide electrons for both ring injection and positron production
- First conceptual design of a photo-injector exists, very good emittance can be achieved even at higher charge
  - DR for electron bunches can be avoided
- Electron source, preliminary: shorter bunch length is possible 1.3 mm → 0.65mm
- The 100% amplitude modulation of the electron and positron charge required for injection into the collider ring could be provided from an optical modulator in the laser system – under investigation

Repetion Rate for the Common Linac



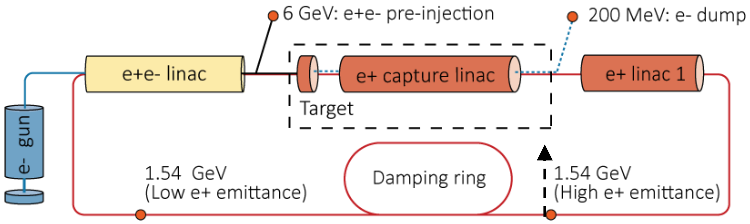
– Baseline: Common linac at 400 Hz, 200 Hz (electrons) + 200 Hz (positrons) when positron are generated

  - Challenging for the RF systems (HV mods and klystrons). Klystron at 400 Hz from CETD could be feasible. HV modulators under development for other projects.

– DR has to provide a delay of 2.5 ms (more complicate timing) to allocate the positron bunches on the on the right rf bucket

Positron source

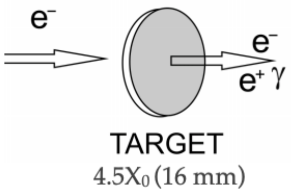
Positron yield up to 7 (Y. Zhao FCC week 2022)



Schematic of FCC-ee Injecor Complex

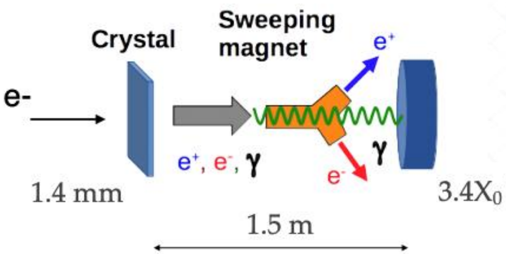
- Target
- Adiabatic Matching Device
- 10 RF Cavities surrounded by solenoids

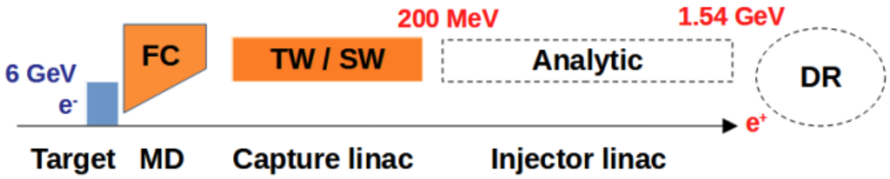
Conventional scheme (baseline for FCCee)



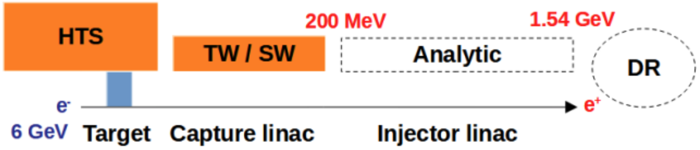
e-
1.4

Hybrid scheme





FC used as AMD

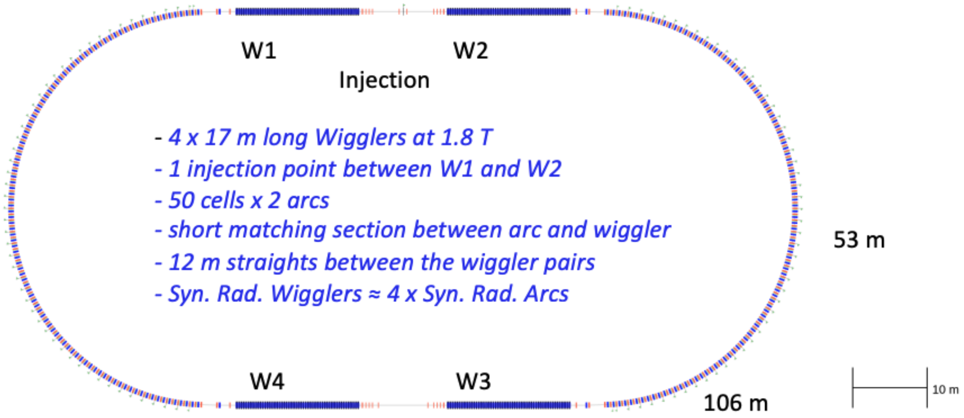


HTS solenoid used as MD

I. Chaikovska, Y. Zaho et al.

Damping ring

Parameters from the WP4 - Damping ring and transfer lines meeting on 11.11.22



Required Parameters		
Energy [GeV]	1.54	
Circumference [m]	~250 m	
Stored time [ms]	40	
Damping time (hor.) [ms]	≈10	→ ~5 ms
Extraction geo. emittance (hor.) [nm.rad]	≈5	→ ~1.7 nm.rad
Number of bunches	16	
Energy spread @ extraction [%] (rms.)	-	
Injection type	on axis	
Number of straight sections	3	→ more
Injected Parameters		
Injected emittance (h) (e-/e+) [nm.rad/μm.rad]	5.5/1.29	
Injected emittance (v) (e-/e+) [nm.rad/μm.rad]	6/1.22	
Injected momentum spread [%] (e-/e+) (rms.)	0.2/5	
Injected bunch length (e-/e+) (mm)	1/3.4	

Parameters	CDR	After CDR	New
Bending magnet quantity*	232	232	72
Dipole magnet length [m]	0.21	0.21	0.28
Bending angle [degree]	1.55	1.55	5
Dipole magnetic field [T]	0.66	0.66	1.8
Filling factor	0.2	0.2	0.07
Damping wiggler magnet	26.5 m / 1.8 T	68 m / 1.8 T	18 m / 2 T
Robinson wiggler magnet	-	-	3.8 m / 1.2 T
Circumference	242 m	240 m	257.31 m
Emittance	2 nm.rad	1.25 nm.rad	4.89 nm.rad
Damping time	10.5 ms	5.9 ms	6 ms
Energy loss per turn	0.255 MeV	0.47 MeV	0.253 MeV

- The concepts for the DR and the return transfer line are still working in progress (specification are still changing…)
- RF systems to be decided (most likely 400 MHz)
- Positron bunch has higher emittance and energy spread → DR acceptance has to be verified

C. Milardi, A, De Santis, O. Etisken

General requirements (for diagnostics)

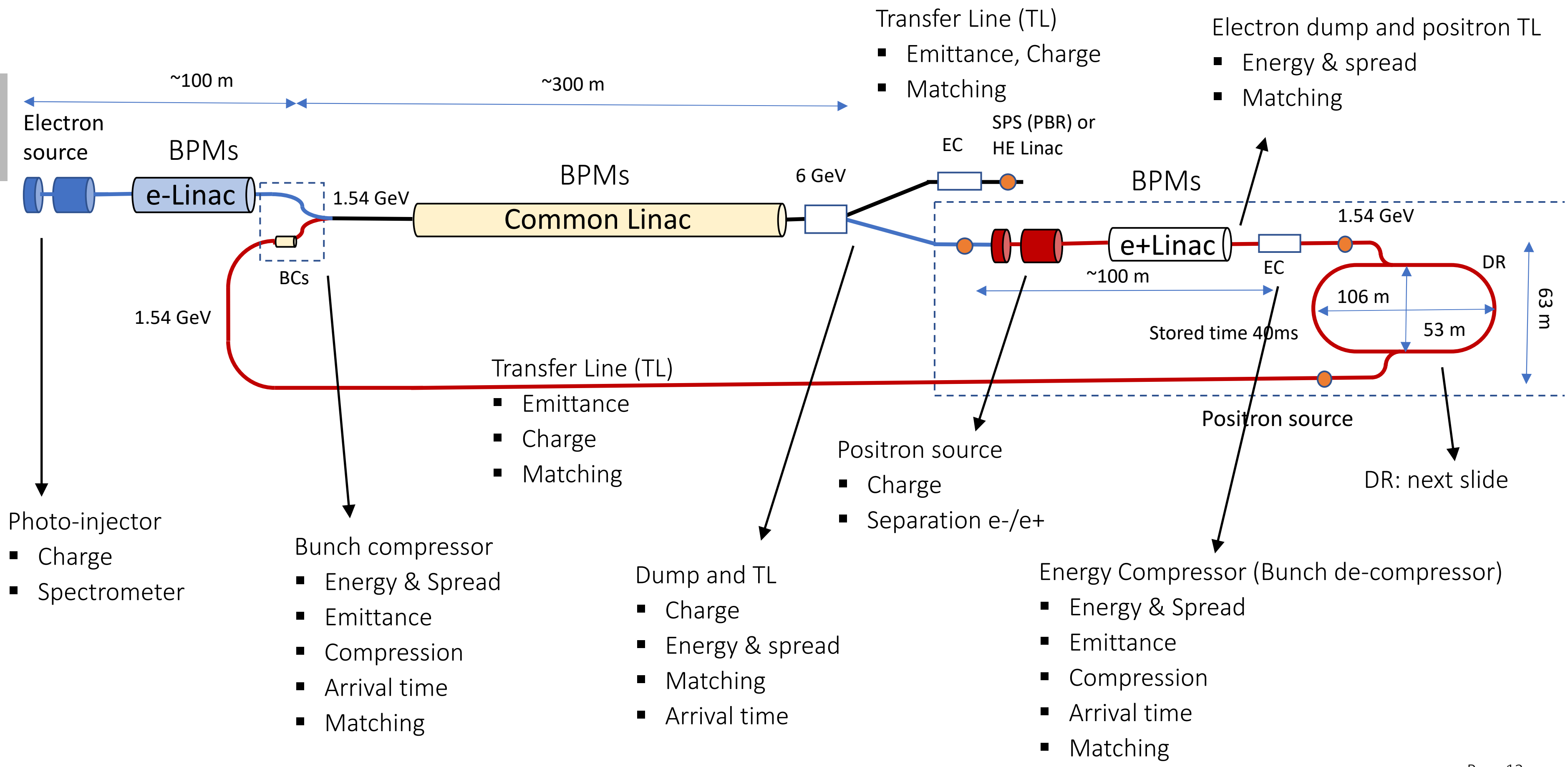
Based on the experiences in SwissFEL at PSI

– Role for FCCee Pre-Injector Diagnostics:
  - Allows for successful commissioning of the electron source, linacs, positron source and DR
  - Fast and reliable set-up of the machine for operation (filling pattern and top-up for different collider operational modes)
  - Monitor possible drifts (non-invasive) for feedback systems

– How much diagnostics?
  - Avoid operating the different injector sections blindly
  - Decoupling of machine sections (in accordance with piece-wise commissioning of the injector)
  - Reducing the impact of model-derived assumptions (beam parameters derived from simulation)

Balance between Instrumentation and Costs

Injector Layout & Diagnostic locations



Damping ring, injection and extraction

For commissioning and daily operation a beam diagnostics for the following parameters are required (16 bunches, 4 nC per bucket, 80 mA):

- transverse emittance and energy spread (emittance and energy spread monitors)
- charge and charge loss (beam loss monitor)
- beam size and position (BPM)
- beam current and filling pattern
- bunch length (streak camera)

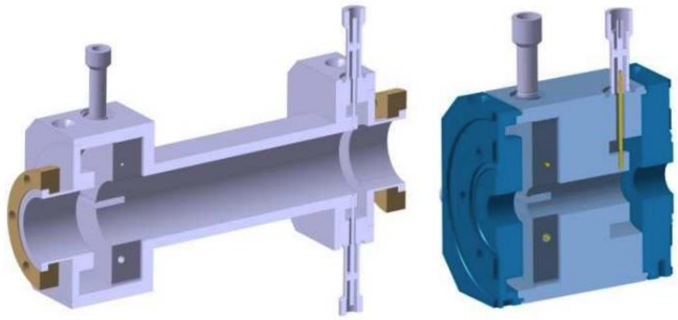
Transfer line Diagnostics:

- BPMs and optical screens

→ To be defined the requirements in term of minimum beam size, resolutions, field of view

Injector and Linacs BPMs

- Resolution of 5 μm (?)
- 200 Hz Readout of the 2 bunches
- Charge range 0(?) - 5 nC per bunch
- Valid Range +/- 1 mm (just a number here, to be defined from the trajectory jitter studies)
- It has to resolve both bunches

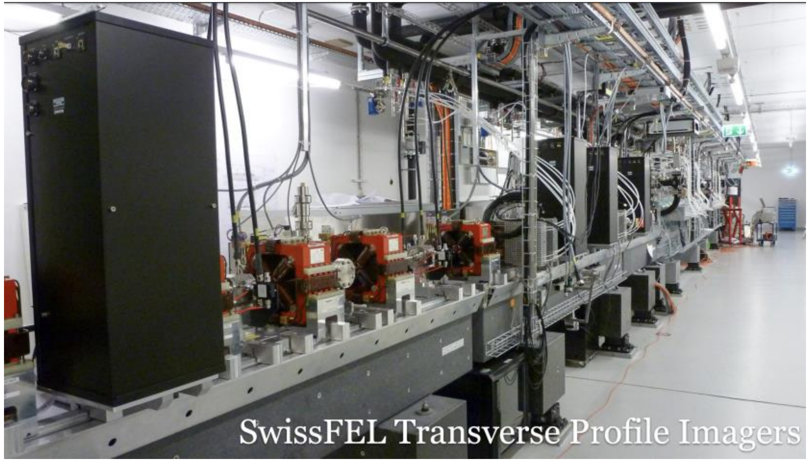


SwissFEL Cavity BPM, low Q, bunch spacing 28 ns, 100 Hz (Ref. F. Marcellini and B. Keil)

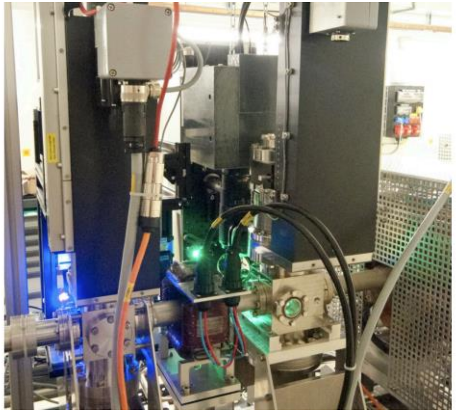
Beam size, matching

- Transverse Profile Screens (Destructive, assume 100% losses):
  - Typical beam sizes
    - β: 5-100m, ε_n: 1-5 mm mrad, E: 0.2 – 6 – 20 GeV → σ: 25-1100 μm
  - Avoid unnecessary losses → beam synchronous acquisition
  - Long term insertion of screen with low rep rate

R. Ischebeck



Test of different cameras, different scintillators and imaging geometries

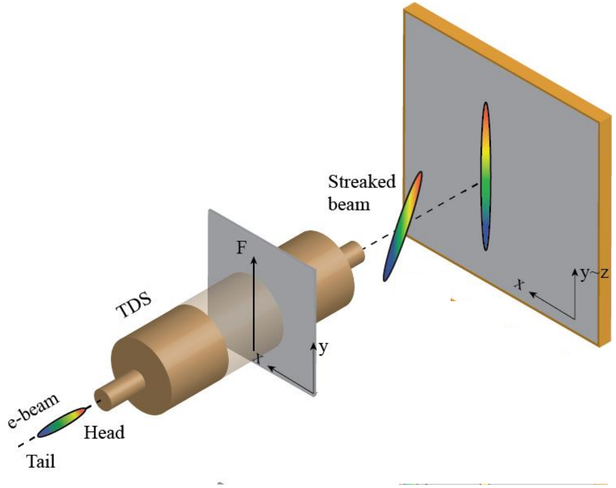


Compression and de-compression

- Compression & de-compression (energy compression) monitors
  - Compression: from ~20 ps to ~3 ps
  - De-compression (energy compression): to be studied
  - Dynamic range:
    - Expected range of bunch lengths for commissioning/tuning
- Bunch Compression Monitor
  - Relative measurement with CSR at some bending magnets
  - Locked (Calibrated) with Bunch Profile Measurements?
  - Needed for Feedback, it has to resolve both bunches in main linac

Bunch Length and Arrival time

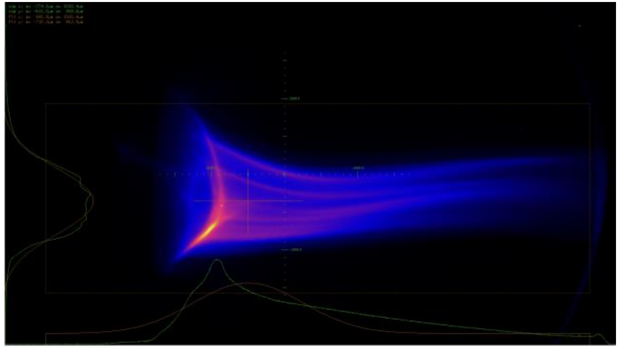
- Bunch Profile Measurements:
  - Streaking Bunch Profile with TDS
  - Location:
    - After electron linac and after Common linac
    - After positron linac?
  - Resolution: ~200 fs at 6 GeV – challenging 20 GeV



- Arrival time
  - Needed for feedbacks
    - Non-destructive
    - Resolves both bunches
    - Resolution: 50-200 fs (to be studied)
  - Injector: Measurement of electron beam and gun laser (LAM) to separate laser drift and phase drifts in the injector

Energy and Energy Spread

- Energy Measurement
  - BPMs in dispersive dominated location (e.g. bunch compressors, transfer lines)
  - Resolution: to be defined (i.e. <1e-4 for dispersion of 0.1 m and higher)
  - Needed for Feedback, measurement of both bunches
  - Cross-check with Spectrometer dumps (Gun, Injector, BC, Common linac etc..)
- Energy Spread Measurement
  - Incoherent SR port in dispersive section
  - Needed for Feedback 200 Hz, resolving 2 bunches



Beam based Feedback/Monitoring

- Most of the time the machine will run in user operation with the needs to monitor important beam parameters and apply feedback to it:
  - Orbit, Compression, Energy, Energy spread, Charge, Transmission, Emittance, Matching, Arrival Time
- DR: fast orbit feedback system, transverse and longitudinal multi-bunch and fill pattern feedback

Machine Protection System (MPS)

Beam power levels

Location	Beam parameters	Beam power
Injector/e-linac/e+linac	200 Hz, 5 nC, 1.54 GeV	2 x 1.54 kW = 3.08 kW
Common linac/positron source	200 Hz, 5nC, 6 GeV	2 x 6 kW = 12 kW
HE linac/trasfer lines	200 Hz, 5 nC, 20 GeV	2 x 20 kW = 40 kW

The following systems will be used to detect an improper state of the machine:

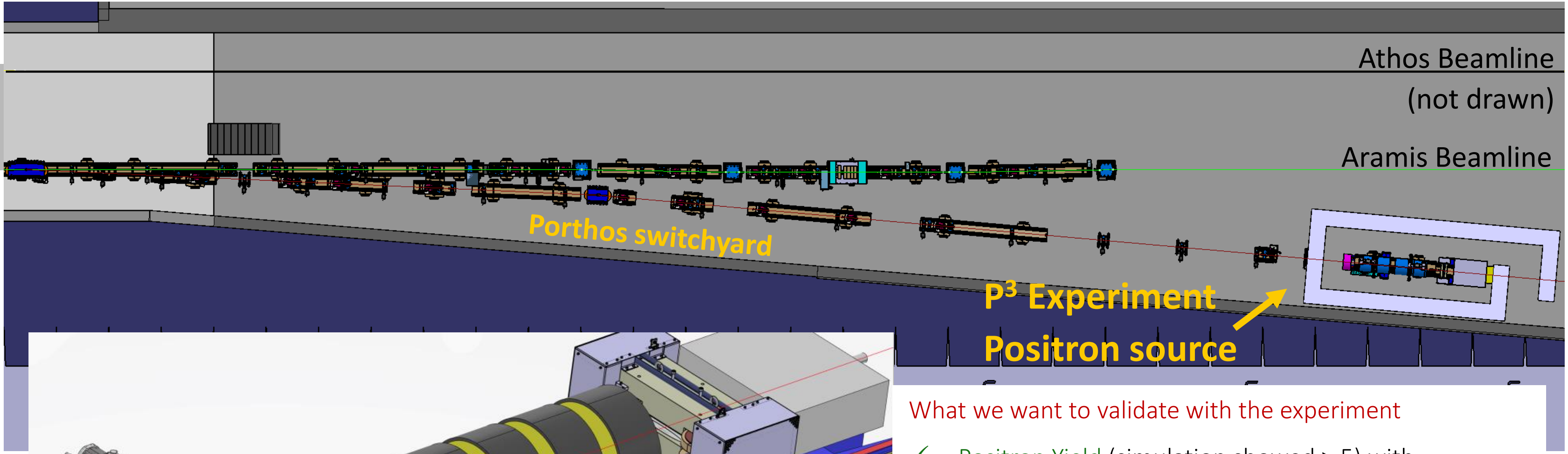
a. Beam modes
b. Differential charge monitoring
c. Beam loss monitoring
d. Monitoring of average beam current
e. Radiation dose monitoring

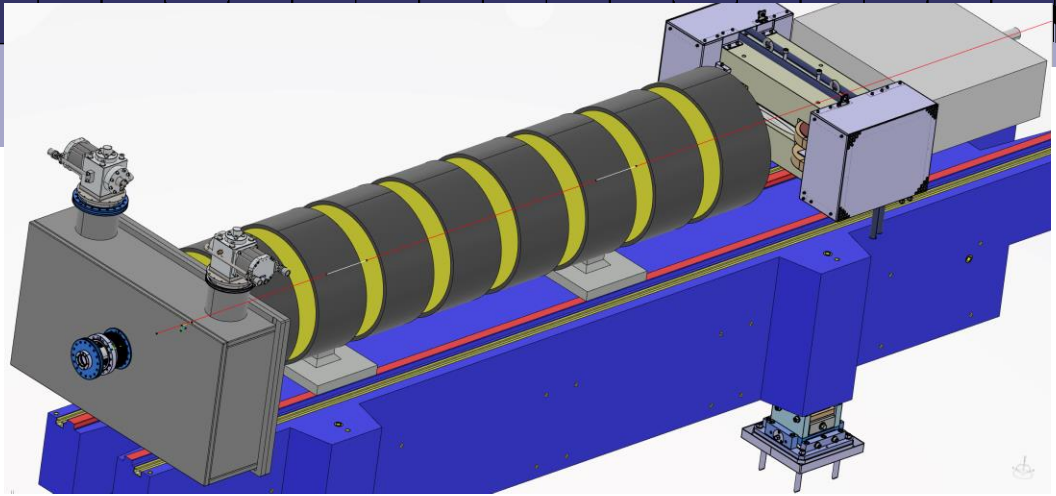
Beam loss monitor

- Redundant Cherenkov fibers along the entire machine
- Scintillating fibers

→ Protection of the machine from radiation! This is NOT a personal safety system

PSI Positron Production (P³) Experiment in SwissFEL

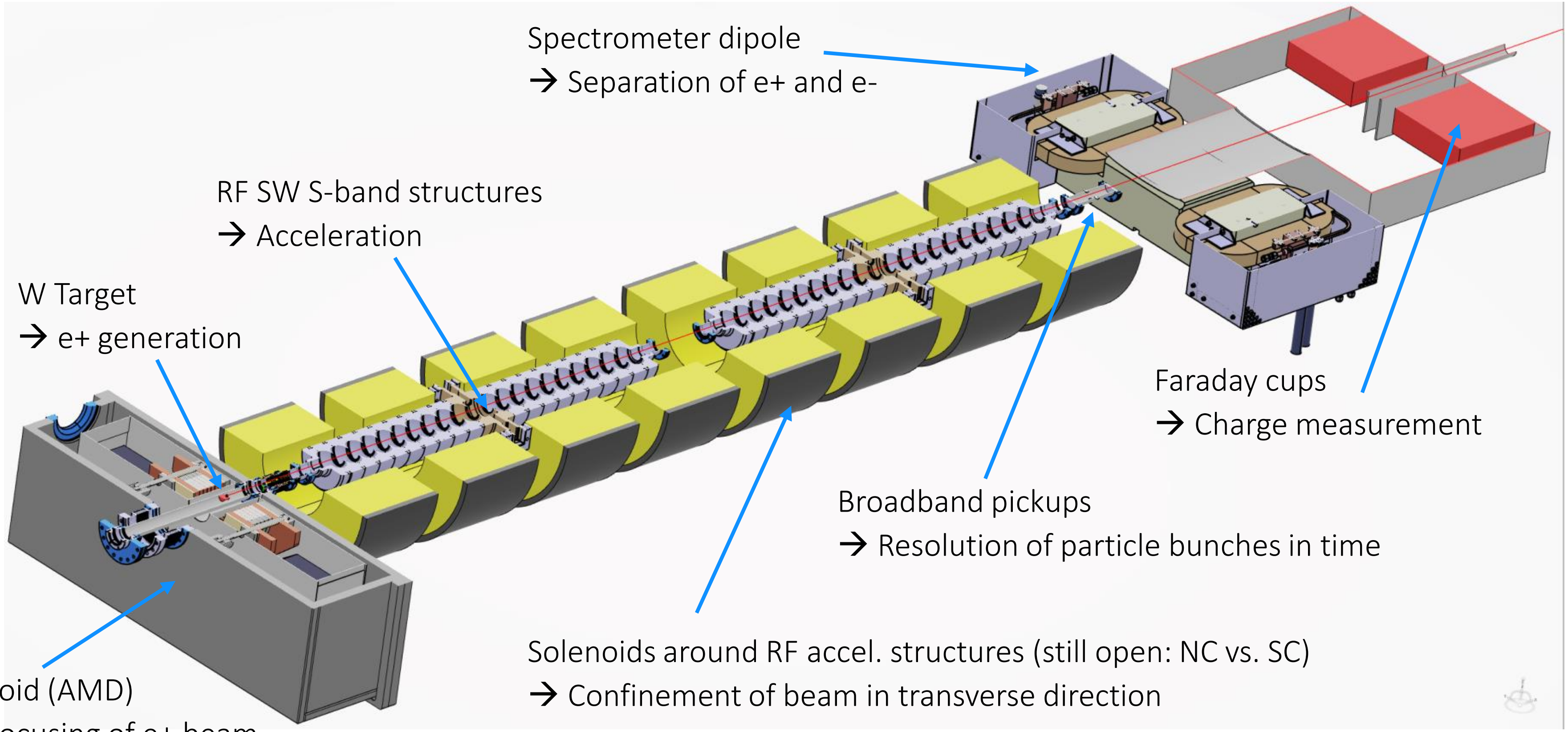




What we want to validate with the experiment

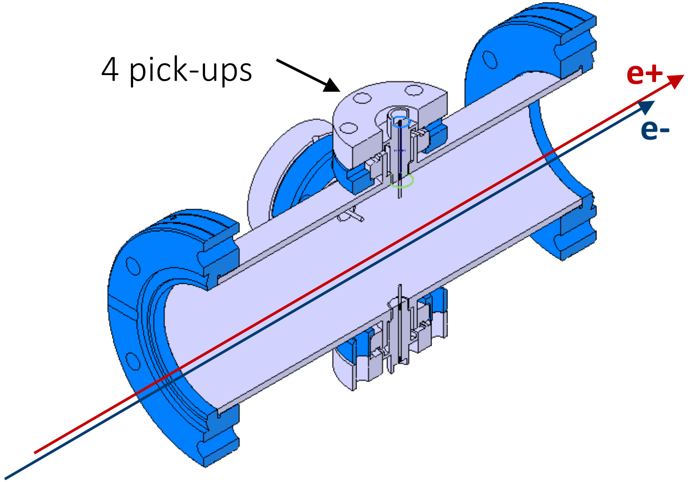
- ✓ Positron Yield (simulation showed > 5) with conventional scheme (simulation vs measurement)
- ✓ AMD: SC Solenoid with HTS technology including mech. and thermal (cryostat) concept
- ✓ RF structures: large iris aperture
- ✓ Diagnostics for positron bunches (cloud)
- ✓ Phase 2: hydride scheme with crystal

P3 = PSI Positron Production



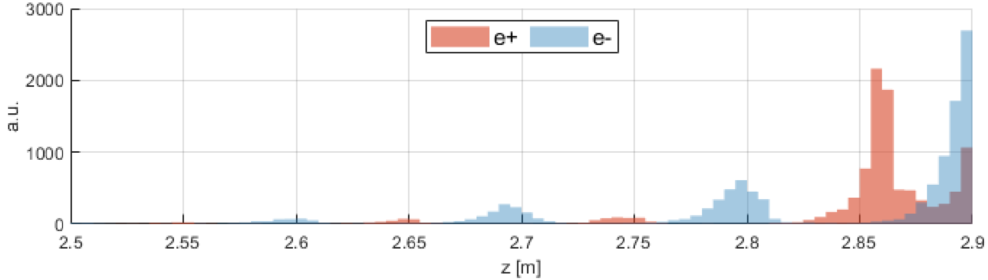
Time resolution with broadband PickUp

- Very broadband pickups (bandwidth > 40 GHz) can measure the time structure of the beam
- e+ and e- buckets are separated by 167 ps
- Based on SuperKEKB diagnostic

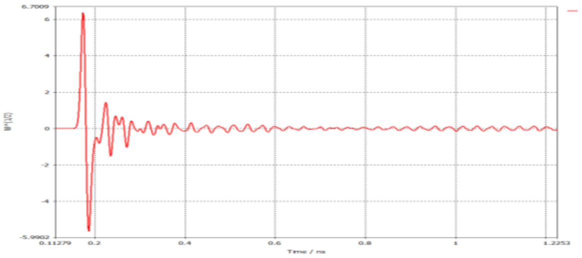


Development of fast BPM (summer student project), based on T. Suwada et al., Sci Rep 11, 12751 (2021)

Time structure of the beam

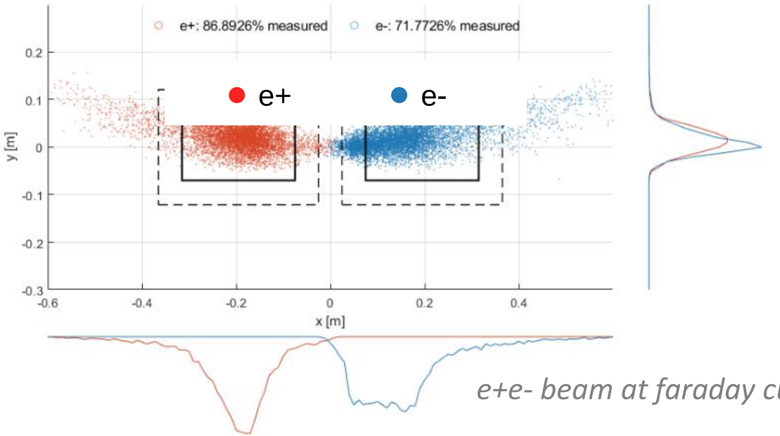


Simulated signal at BBPs (E. Ismaili)

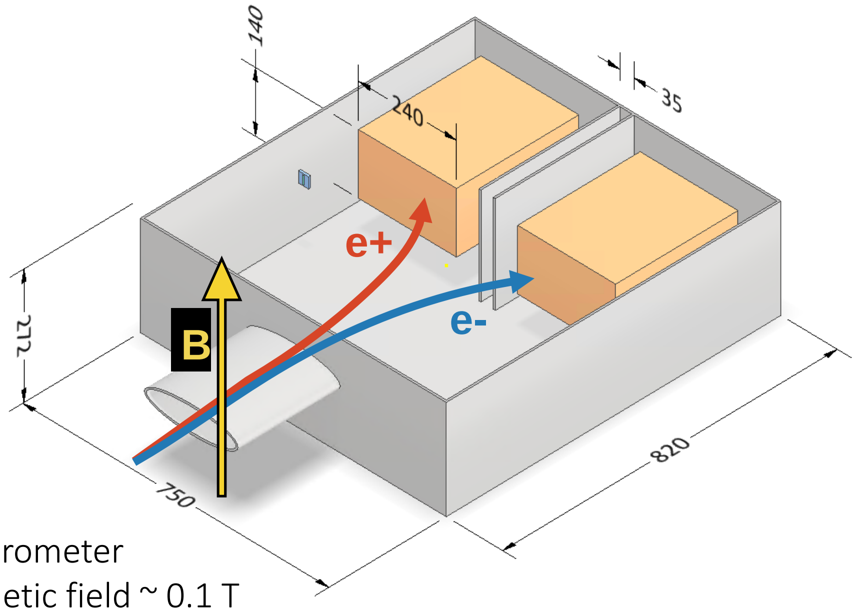


Charge measurement with Faraday Cups

- Measurement of e+ and e- charge separately
- 2 parallel 25 Ohm connectors each
- Negligible backscattering



e+e- beam at faraday cups

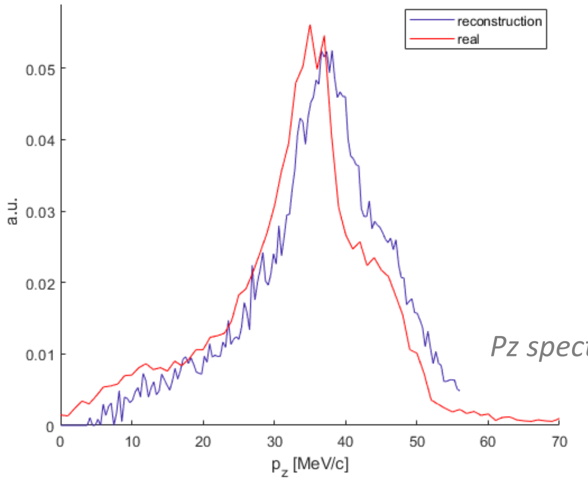


Spectrometer magnetic field ~ 0.1 T

Optimized dimensions of diagnostics chamber.

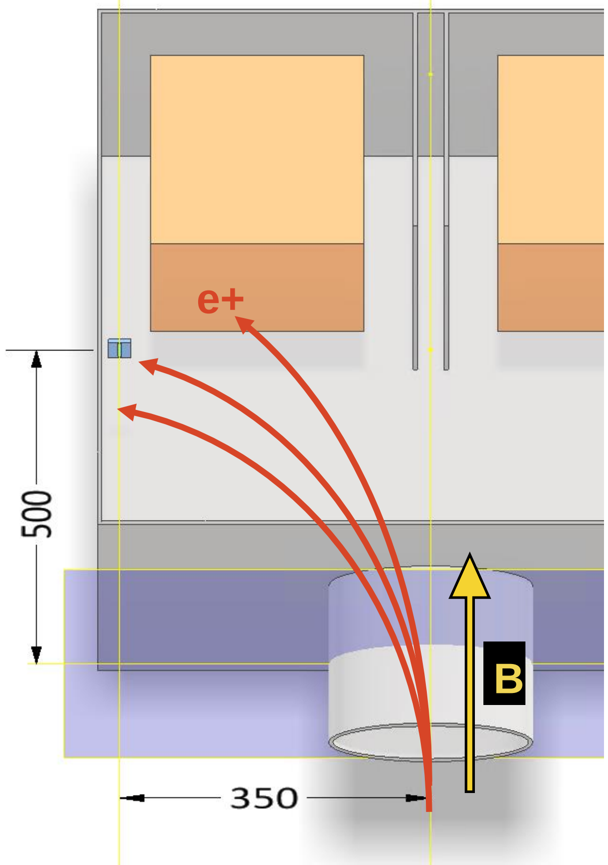
Spectrometer and Charge Detector

- Dipole strength scanned to measure e+ energy profile
- e+ at different p_z detected by narrow screen
- Technology of the detector under investigation (we are planning to test a scintillating fiber).



Pz spectrum reconstruction

Schematic of energy spectrum measurement



Concluding remarks

- The pre-injector is still in the design phase and there are still some outstanding questions to be addressed
- Some specifications of the pre-injector were frozen in view of the next year mid-term cost review (second half 2023)
- As deliverable for the review, we must provide a cost estimate for the injector. So, after the design phase we must start with a cost model for the different part of the injector (including diagnostics)!
- The type and technology for diagnostics fairly defined based on the experiences of SwissFEL (2-bunches, smaller charge), BUT the number of components and their specifications still to be defined
- PSI Positron production (P^3) project
    - ❖ Some key diagnostics for the positron source will be tested, broadband pickups, energy spread and charge measurements

Credits

PSI: R. Zennaro, M. Schaer, N. Vallis, B. Auchmann, I. Besana, S. Bettoni, H. Braun, M. Duda, D. Hauenstein, E. Hohmann R. Ischebeck, P. Juranic, J. Kosse, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Reiche, S. Sanfilippo, all the technical groups involved in the P^3 experiment

IJCLab: I. Chaikovska, F. Alharthi, V. Mytrochenko, R. Chehab

CERN: A. Grudiev, W. Bartmann, M. Benedikt, T. Brezina, M. Calviani, S. Doebert, Y. Duthell, O. Etisken, J.L. Grenard, B. Humann, A. Latina, A. Lechner, A. Marcone, H. Pommerenke R. Ramjiawan, Y. Zhao,, R. Mena Andrade, Z. Vostrel, F. Zimmermann

SLAC T. Rauberheimen

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

KEK: K. Oide, Y. Enomoto, K. Furukawa

Swiss Accelerator Research and Technology

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FCCIS: 'This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.'

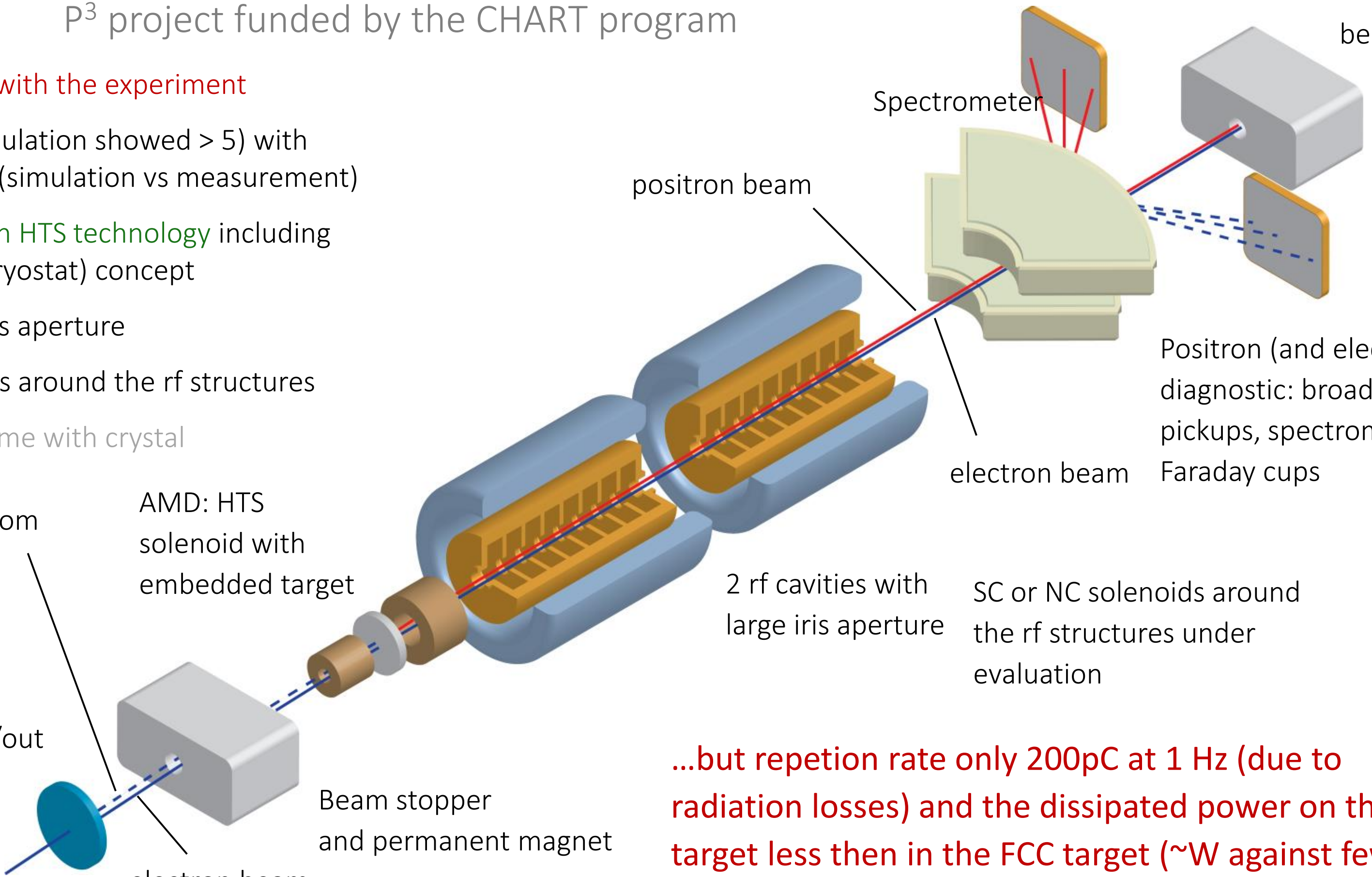
Backup slides

PSI Positron Source Experiment at PSI

P[3] project funded by the CHART program

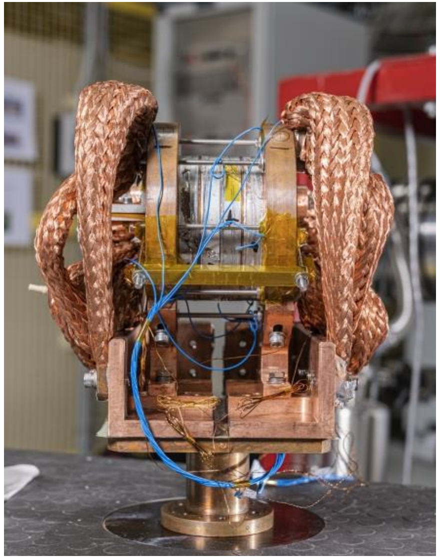
What we want to validate with the experiment

- ✓ Positron Yield > 3 (simulation showed > 5) with conventional scheme (simulation vs measurement)
- ✓ AMD: SC Solenoid with HTS technology including mech. and thermal (cryostat) concept
- ✓ RF structures: large iris aperture
- ✓ NC versus SC solenoids around the rf structures
- ✓ Phase 2: hydride scheme with crystal



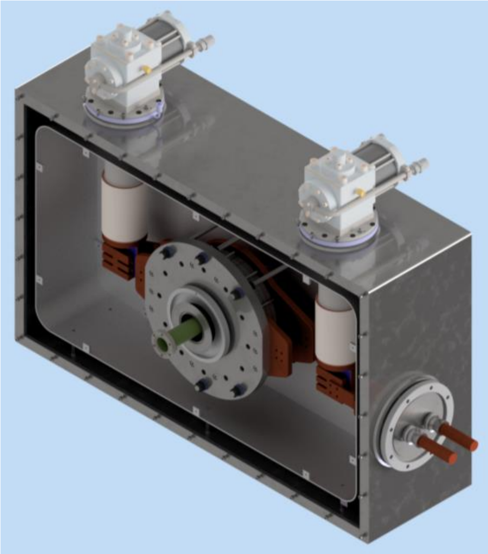
…but repetion rate only 200pC at 1 Hz (due to radiation losses) and the dissipated power on the target less then in the FCC target (~W against few kW)

HTS Solenoid as AMD



HTS demonstrator at PSI (M. Duda et al.)

- HTS demonstrator developed at PSI (left)
  - 4 ReBCO tape coils at 2kA
  - Operation at 18.2 T, on-axis peak
  - Temperature 20 – 30 K, no need of He cooling
  - Quench self-protected
- Technical design of cryostat for P^3 in development at PSI (right)
- CW operation, ramp-up time of magnetic field ~ 2 days

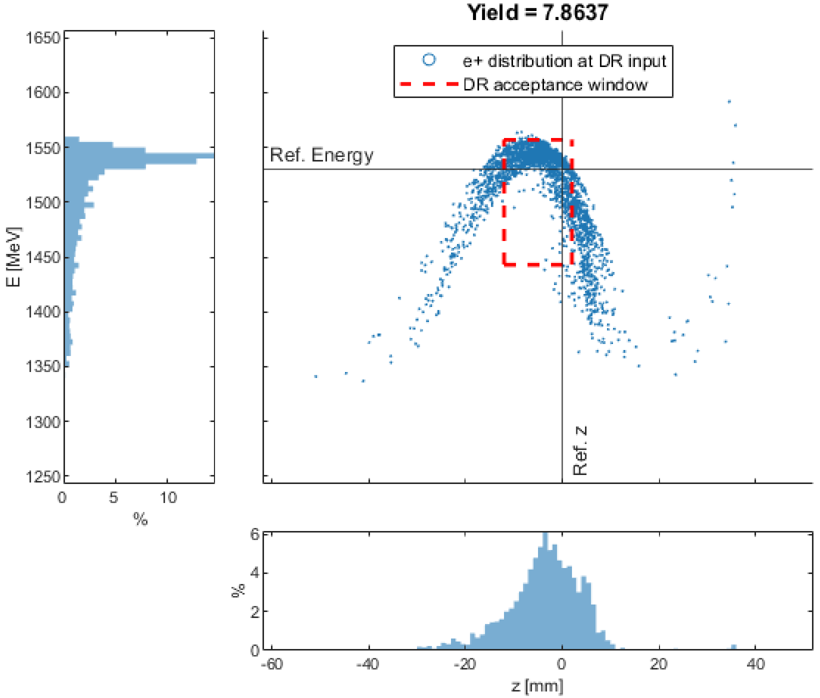


Preliminary model of the AMD for P^3 (H. Garcia Rodrigues)

PSI P^3 exp., N. Vallis, R. Zennaro, M. Schaer et al.

Estimated yield

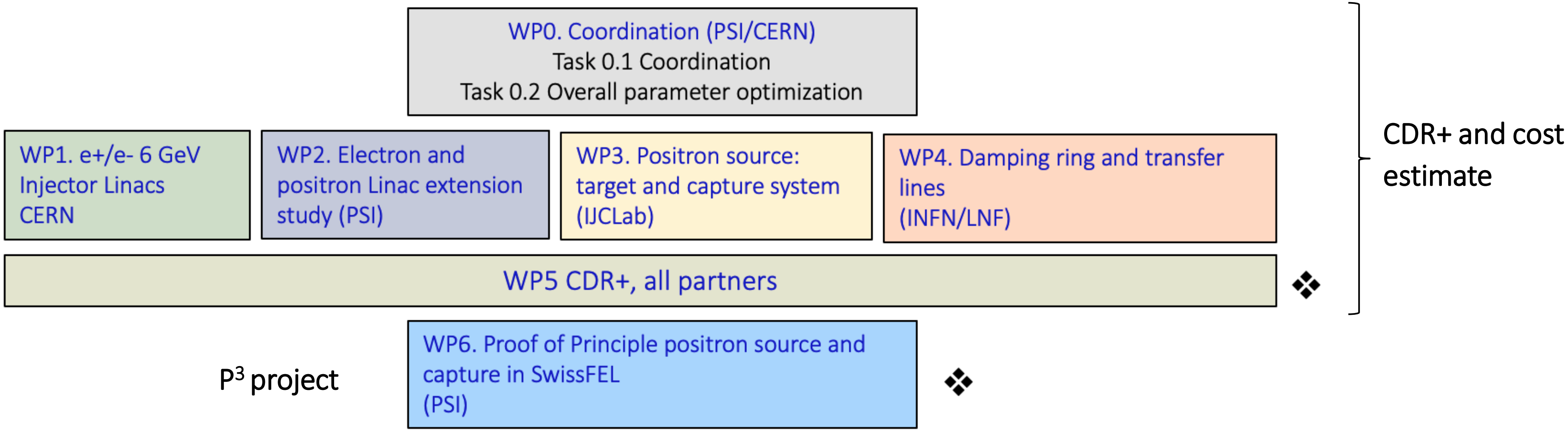
Energy (capt. LINAC)	197.8 MeV
e+ capture (capt. LINAC)	75 %
emittance (capt. LINAC)	≈ 15000 pi mm mrad
Energy spread (c. LINAC)	≈ 50 MeV
AMD max field	12.54 T
Solenoid strength	1.5 T
Decelerating mode	Yes
Yield	**7.86**



FCC-ee injector study (Project in CHART)

Collaboration between PSI and CERN with external partners:

CNRS-IJCLab (Orsay), INFN-LNF (Frascati), SuperKEKB as observer (also interested in the P^3 project), INFN-Ferrara – radiation from crystal



What is CHART?

– CHART (Swiss Accelerator Research and Technology): umbrella collaboration for accelerator research and technology activities in Switzerland

– The mission is to support the future oriented accelerator project FCC at CERN and development of accelerator concepts beyond the existing technology

– The activities are focused on the support of the FCC project. I.e. High-field magnet R&D complemented by beam dynamics studies for FCC-ee, FCC-hh and FCC-ee Injector and positron production test facility

→ CHART is contributing to the FCC Feasibility Study to be delivered in 2025

Reference: https://chart.ch/