FCC-ee positron capture simulation

Yongke Zhao, CERN

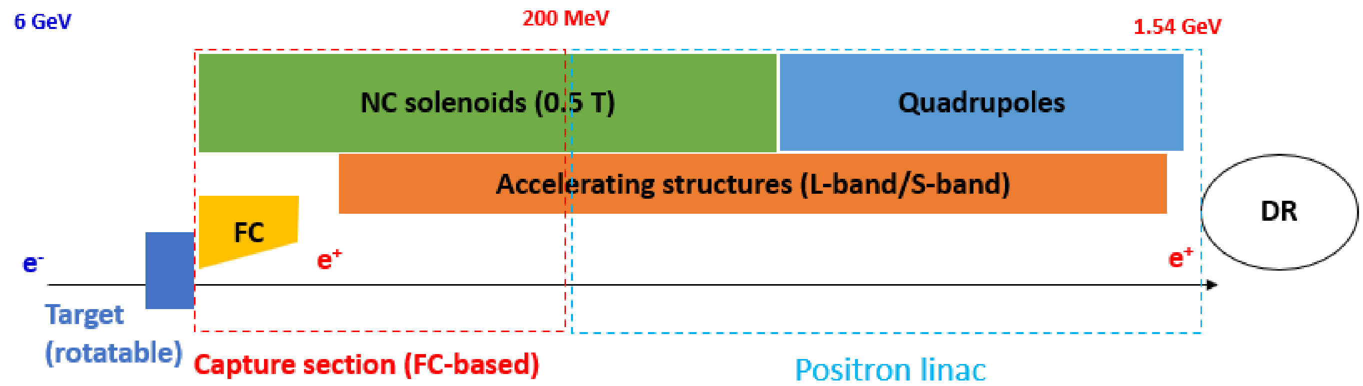
On behalf of the team

FCC-ee Pre-Injector: CHART collaboration meeting

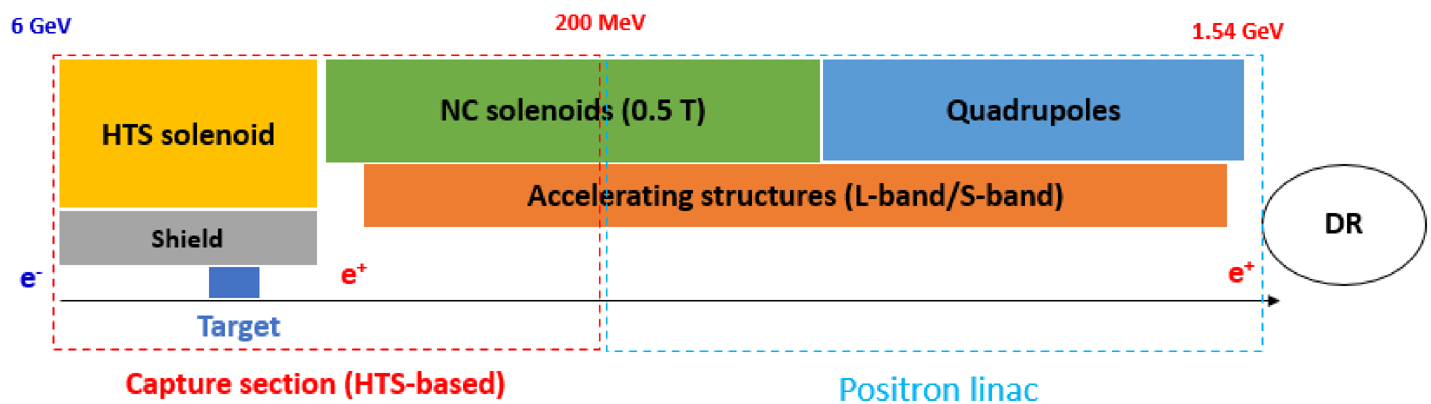
21/04/2023, Frascati

Layout overview

- **FC-based layout (baseline)**



- **HTS-based layout, *V0* (alternative)** ***– study focused on this scenario***



Positron requirements

- Positron requirements

e+ parameters at DR entrance	Values
Repetition rate	200 Hz
No. of bunches (per train)	2
Bunch charge (w/ 100% safety margin)	8 nC
Energy window (@ 1.54 GeV)	±3.8%
Time window (to be discussed)	16.7 mm/c (40° @ 2 GHz)
No transverse cuts (to be discussed)	

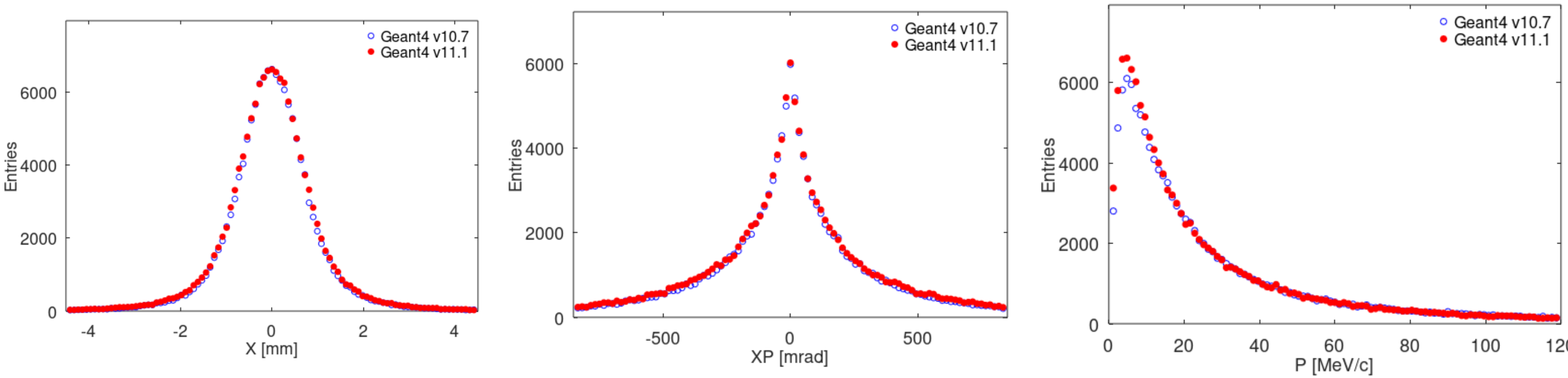
➢ To be matched to DR acceptance (in progress)

- Positron yield (accepted)

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

Simulation tools

- Positron production: **Geant4** (version 11.1.1)
  - Yield increased by ~0.4 after the upgrade from previous version 10.7.2 to current version. Mainly at low energy range



- Tracking in AMD & capture linac: **RF-Track** (version 2.1.6)
- Tracking in e⁺ lianc (longitudinally): **analytic**
  - RF frequency same with capture linac. Reference energy around 200 MeV

$$\Delta E = (1.54\,\mathrm{GeV} - E_{\mathrm{ref}}) \cdot \cos[\omega \cdot (t - t_{\mathrm{ref}})]$$

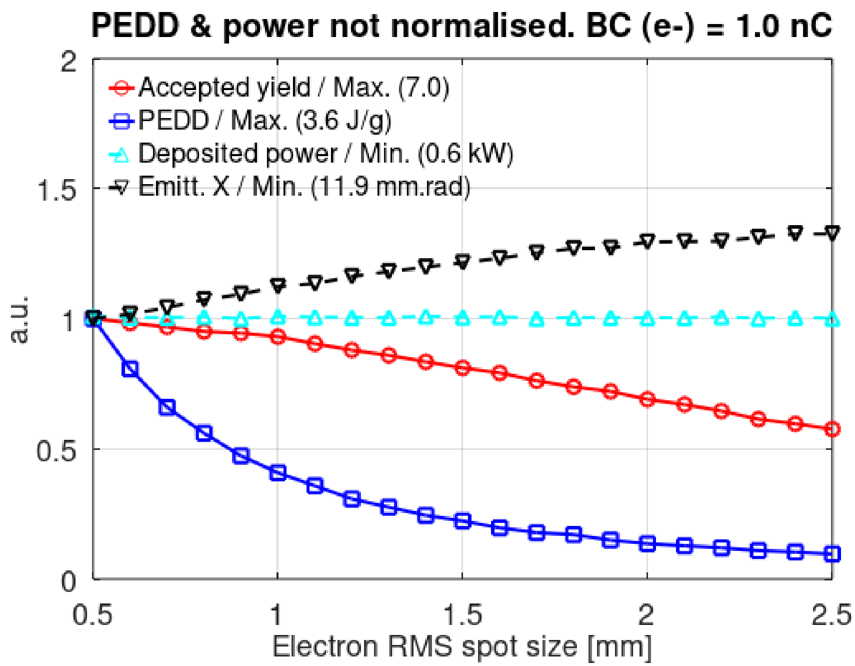
Electron parameters

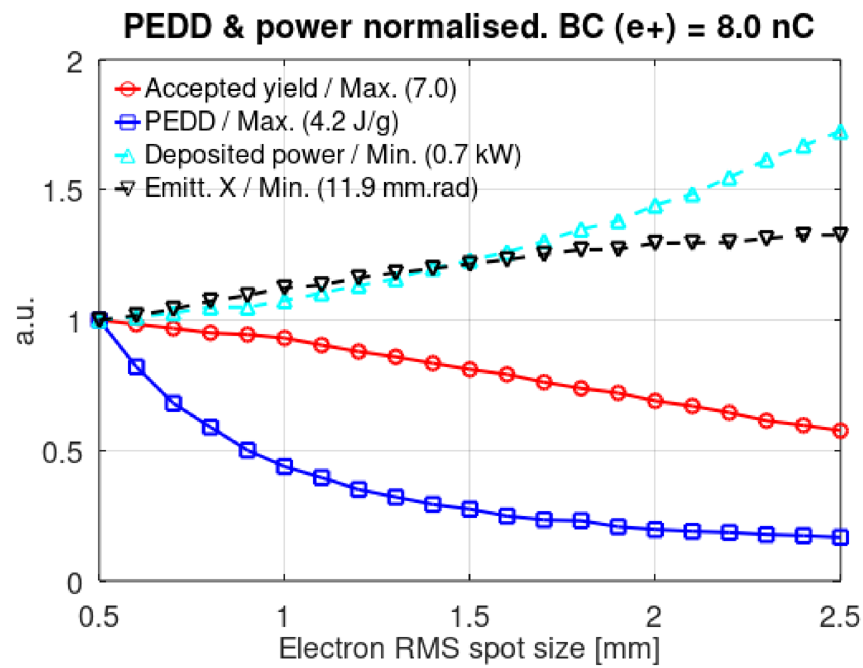
- **Baseline e^- beam parameters:**

Primary e^- parameters	**Values**	**Units**
Beam energy	**6**	GeV
Spot size (rms)	**0.5**	mm
Bunch length (rms)	1	mm
Energy spread (rms)	0.1	%
Normalised trans. emittance (rms)	15	mm·mrad
No. of bunches per train	2	
Repetition rate	200	Hz
Non-normalised beam power (1 nC e^-)	2.4	kW
Non-normalised beam fluence (1 nC e^-)	8.8×10^{10}	cm^{-2}
For η_{e^+} = 7.0, BC_{e^+} = 8 nC		
Normalised beam power	2.7	kW
Normalised beam fluence	1.0×10^{11}	cm^{-2}

Electron spot size

- Scan of e⁻ beam spot size (rms)

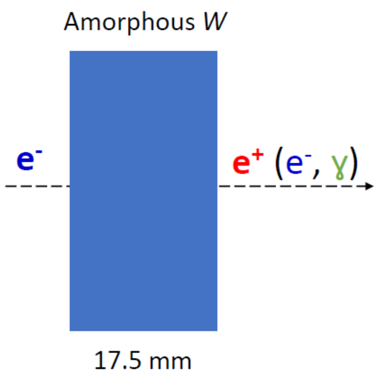




- ❑ To reduce the PEDD, **1 mm** spot size could be a good **alternative**
  - Before 1 mm, PEDD is reduced much faster than the yield
  - After 1 mm, yield reduction is faster while PEDD reduction is slower
- ❑ Nevertheless, 0.5 mm is still used by default in following studies

Target scheme

- **Conventional target (baseline)** *– study using this scenario*



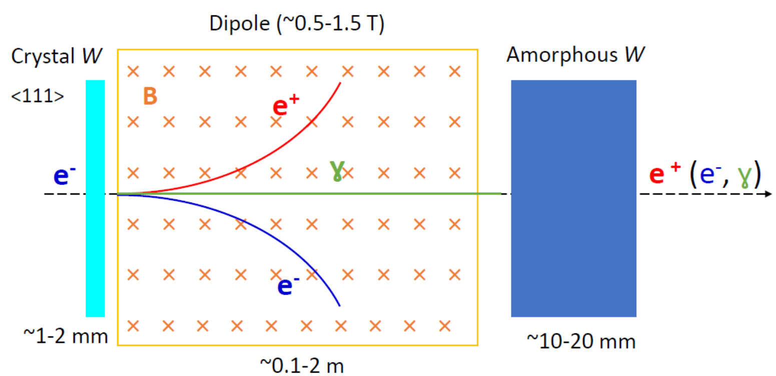
Target results	Value
e^+ yield at target exit	14.1
For η_{e^+} = 7.0, BC_{e^+} = 8 nC	
Deposited power	0.7 kW
PEDD	4.2 J/g

PEDD < 35 J/g required

Advantages:

- **Simple layout** and placement in HTS solenoid matching device
- **Higher e^+ yield** expected (due to smaller e^+ spot size)
- PEDD no more a concern (given high yield and small No. of bunches)

- **Hybrid target (alternative)** *– study in progress*

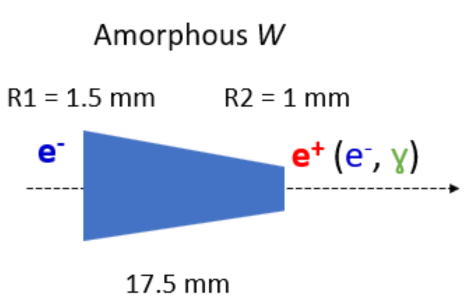


Advantages:

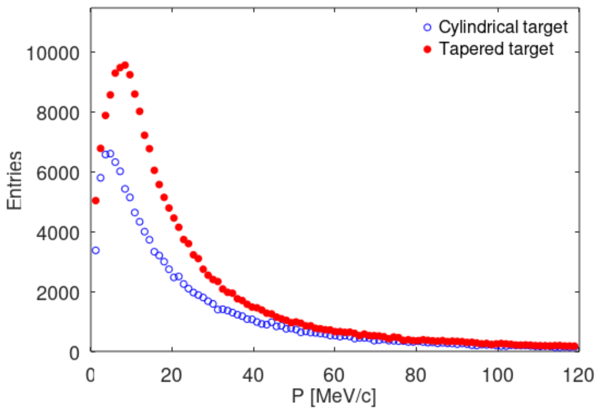
- Promising results (more in the talk of L. Bandiera or their paper: arXiv:2203.07541)
  - ✓ **Reduced deposited power** (~30%) and **PEDD** (~60%), assuming the same e^+ yield, etc.
- DR Accepted e^+ yield to be estimated, etc.

Target shape

- **Significant increase** in e+ yield, using **tapered** target shape, found by ***N. Vallis (PSI)*** for P^3 project with BDSIM (Geant4-based) simulation
  - Confirmed by *A. Lechner (CERN)* and me with Fluka and standalone Geant4 simulations
  - Contribution mainly from lateral e+ production (at low energy range) captured by the HTS solenoid field before deposition in target
  - Only useful for **HTS-based** matching device scenario
  - **Cooling & shielding** design and optimisation for **1 mm spot size** still **in progress**



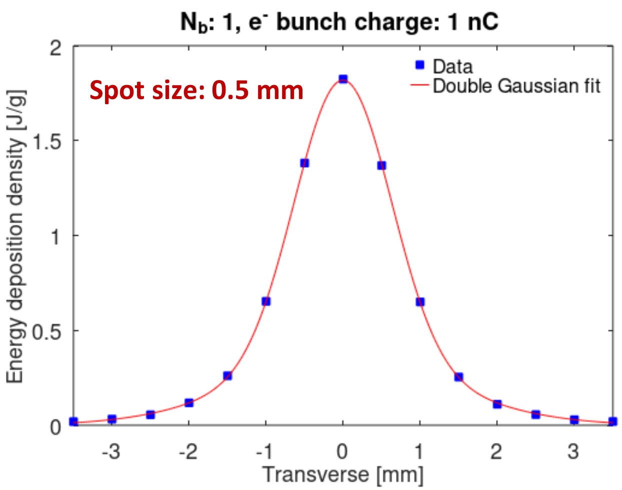
Proposed & optimised by N. Vallis (PSI)

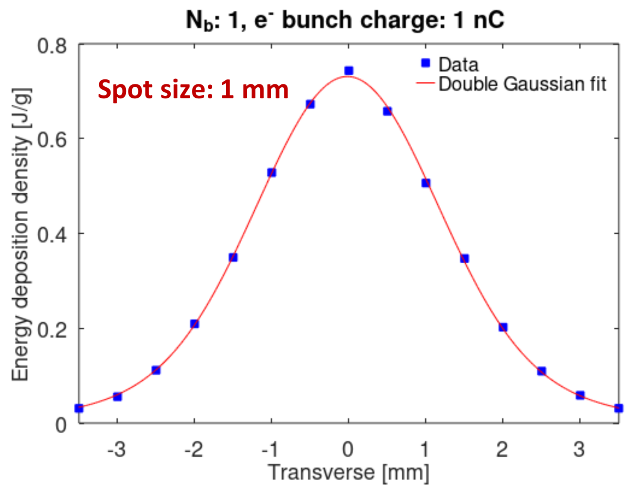


Target shape	Cylindrical	Tapered
Yield @ target exit	14.1	21.1
RMS beam size @ target exit [mm]	1.16	1.95
Yield @ DR entrance	7.0	9.1
Emittance x,y @ DR entrance [mm.rad]	12.0	12.7

Target PEDD

- Mesh grid size (in Geant4): $dx*dy*dz = (0.5\ \text{mm})^3$

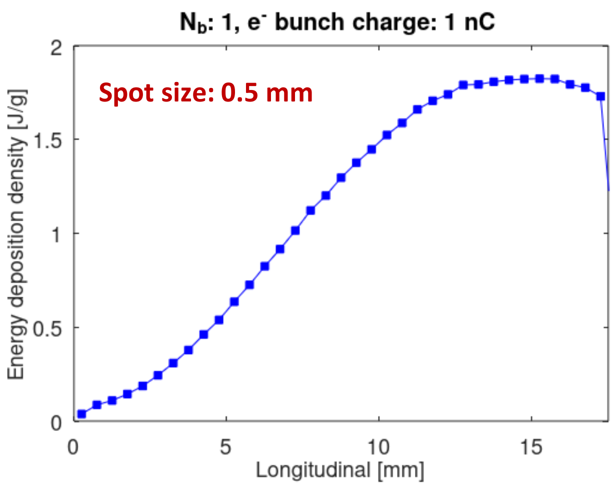


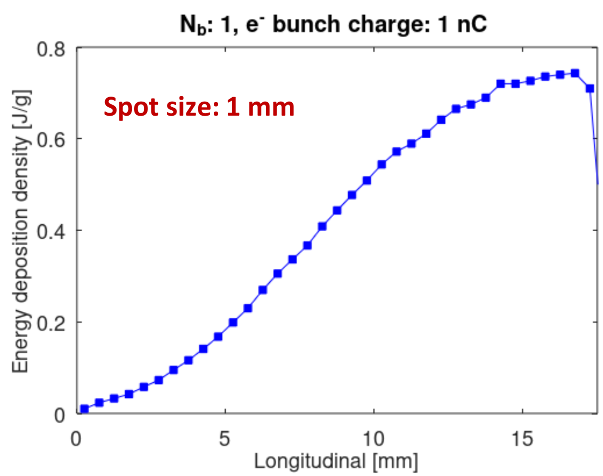


❑ Transverse fit function:

$$f(x) = \alpha \cdot e^{\frac{-(x-\mu)^2}{2\sigma_1{}^2}} + \beta \cdot e^{\frac{-(x-\mu)^2}{2\sigma_2{}^2}}$$

- **Very good agreement** with fit!
- For simplification, **fit is therefore not used** in the results



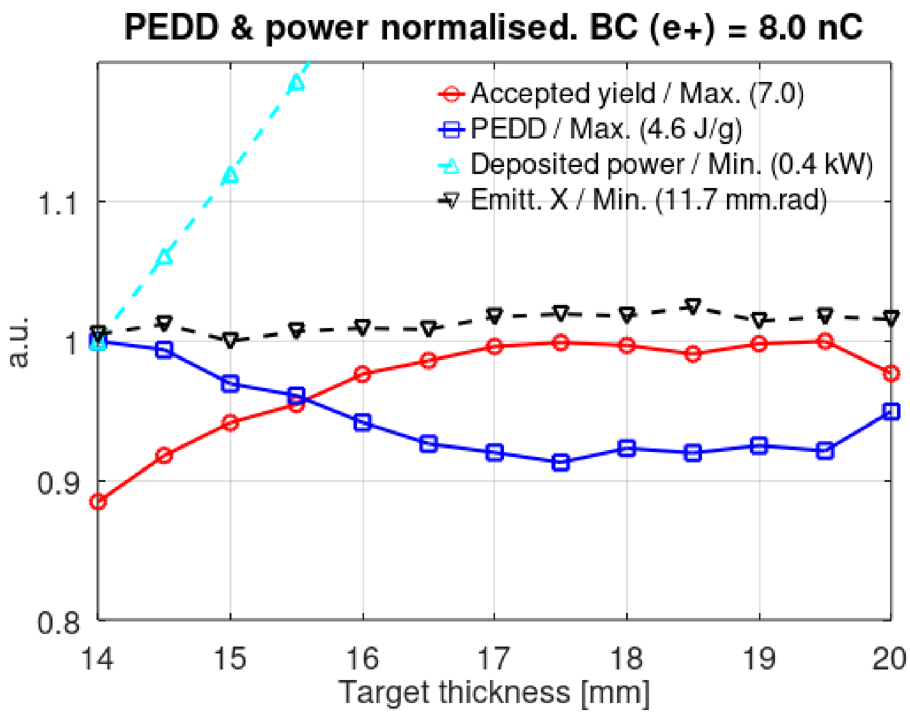


❑ No fit needed longitudinally

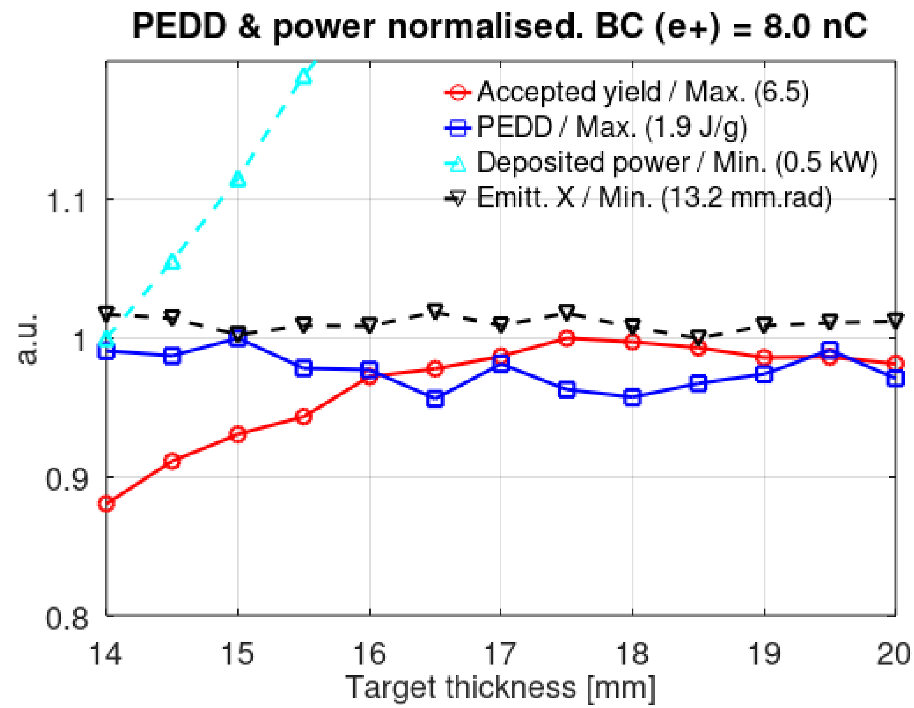
Target thickness

- Scan of target thickness

0.5 mm spot size



1 mm spot size

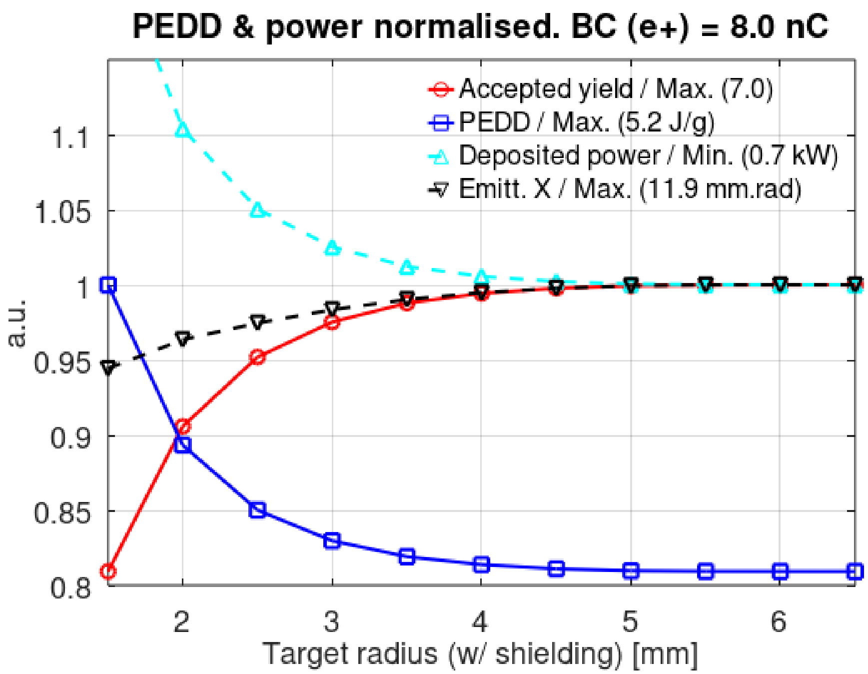


- ❑ **Optimised target thickness** for maximum accepted e^+ yield is still: **17.5 mm**

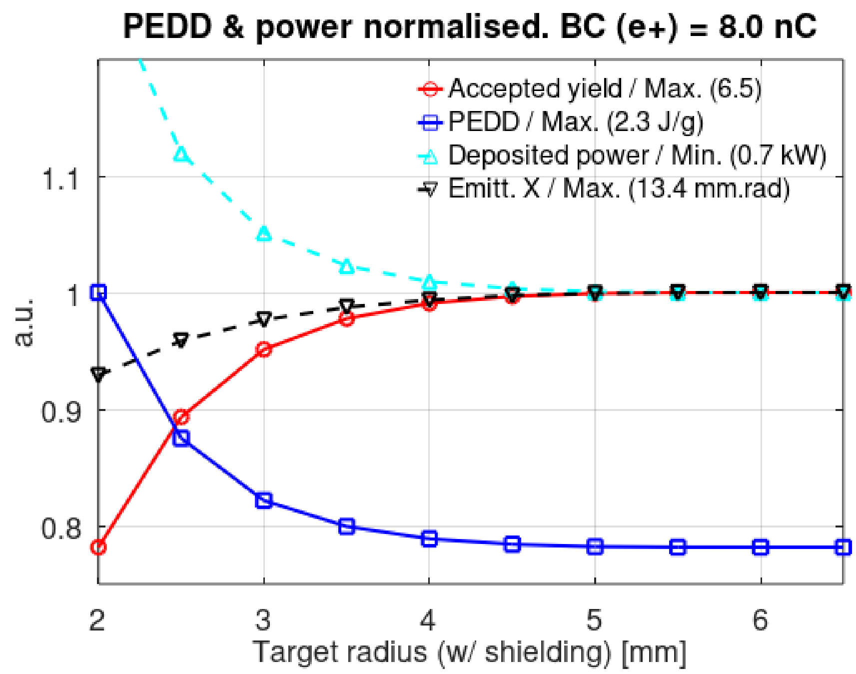
Target radius

- Scan of target radius
  - Aimed to find the minimum radius for better cooling and shielding
  - Assuming that target is surrounded by the shield (no lateral e^+ produced)

0.5 mm spot size



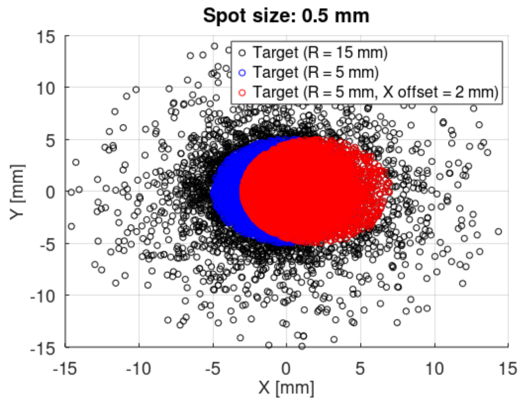
1 mm spot size

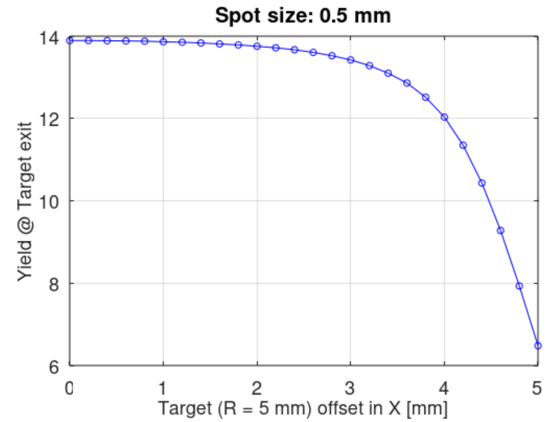


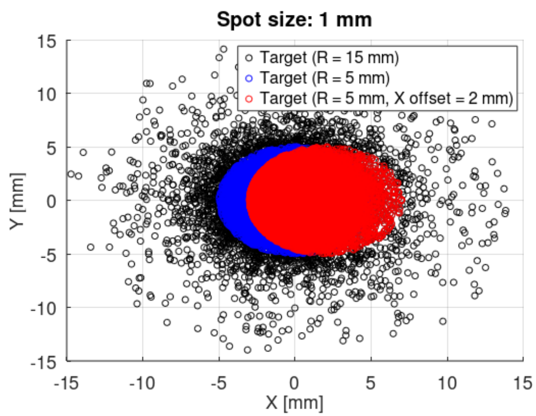
- ❑ **Minimum target radius (w/o significant yield loss): 5 mm**
- ❑ Nevertheless, 15 mm is still used by default in following studies

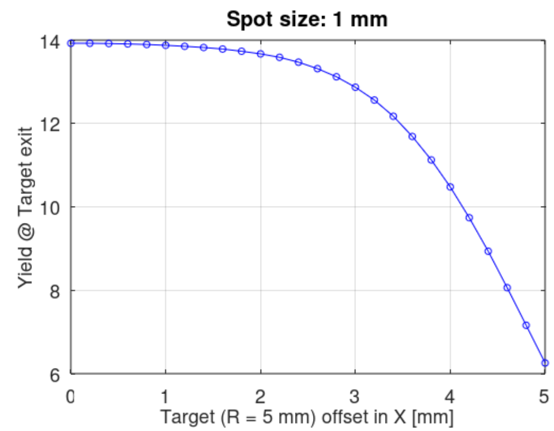
Target misalignment

- Very preliminary test (more in prorgess)







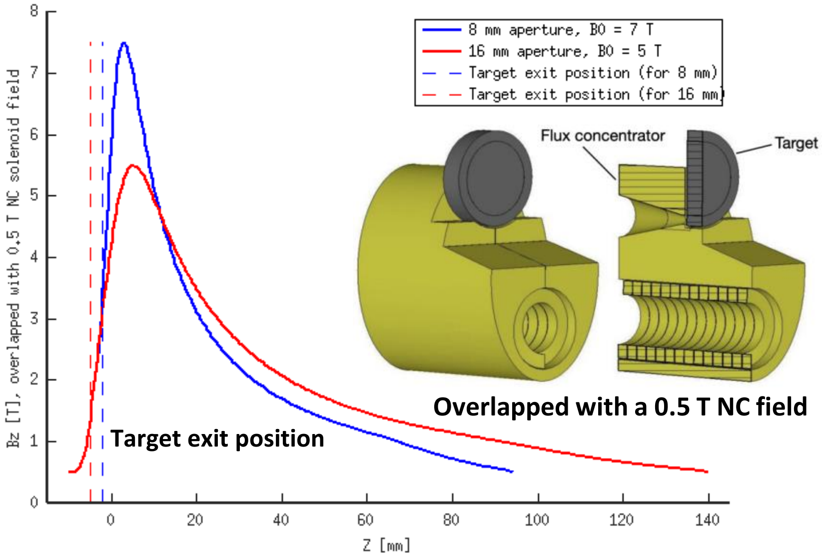


❑ **The effect seems to be small (for example, 1 mm offset)**

❑ **DR accepted yield to be checked. More to be studied**

Matching device

• FC-based (baseline)

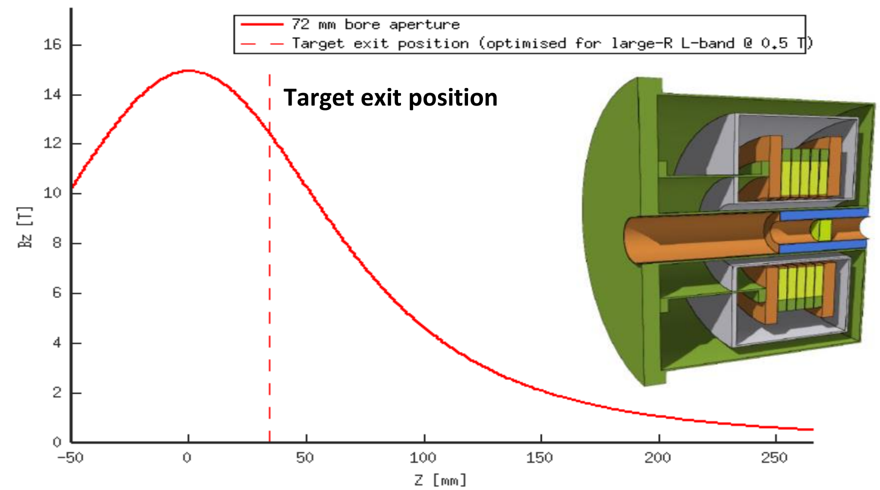


Flux Concentrator (FC)
designed by P. Martyshkin (BINP)

- Fixed target position (2-5 mm upstream), but allowing for rotating target with lower PEDD
- Lower peak field (5-7 T, 1.5-3 T at target exit)
- Smaller entrance aperture (Φ = 8-16 mm)
- Therefore, **lower e^+ yield, smaller emittance**
- Designed for 100 Hz rep. rate. To be optimised for 200 Hz

• HTS-based (alternative)

– study focused on this scenario



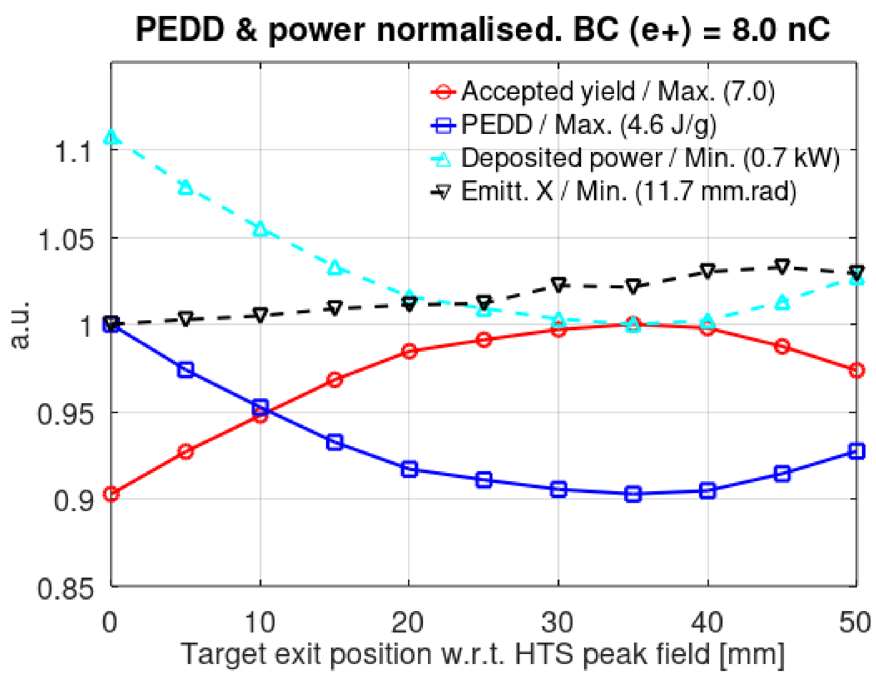
High-Temperature Superconducting (HTS) solenoid
designed by J. Kosse, B. Auchmann and M. Duda (PSI)

- Flexible target position, but not rotatable
- Higher peak field (15 T, 12 T at target exit)
- Larger aperture (warm bore: Φ = 72 mm, minimum beam aperture: Φ = 30 mm)
- Therefore, **higher e^+ yield, larger emittance**

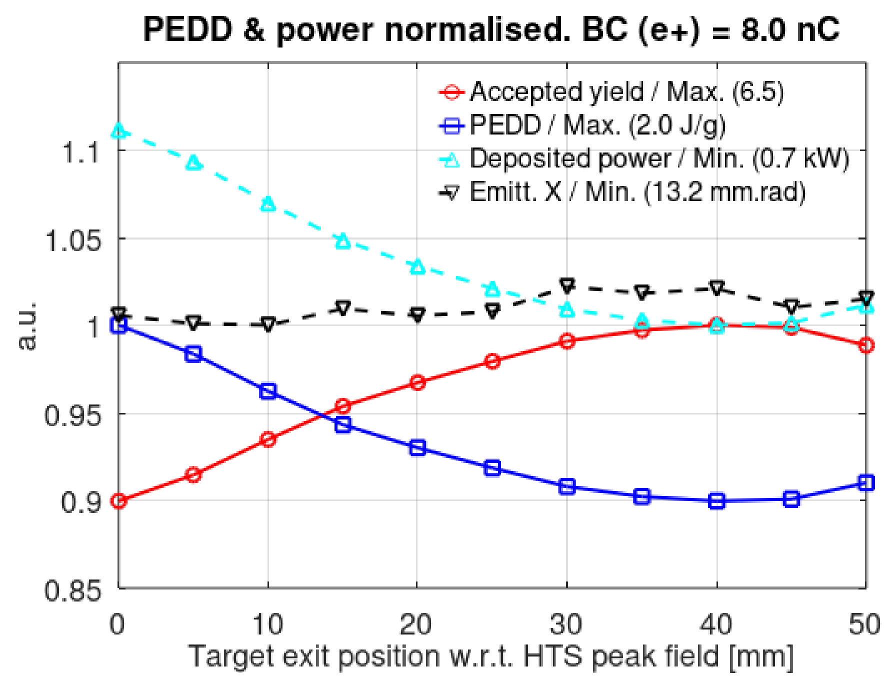
Target position in HTS solenoid

- Scan of target position in HTS solenoid

0.5 mm spot size



1 mm spot size



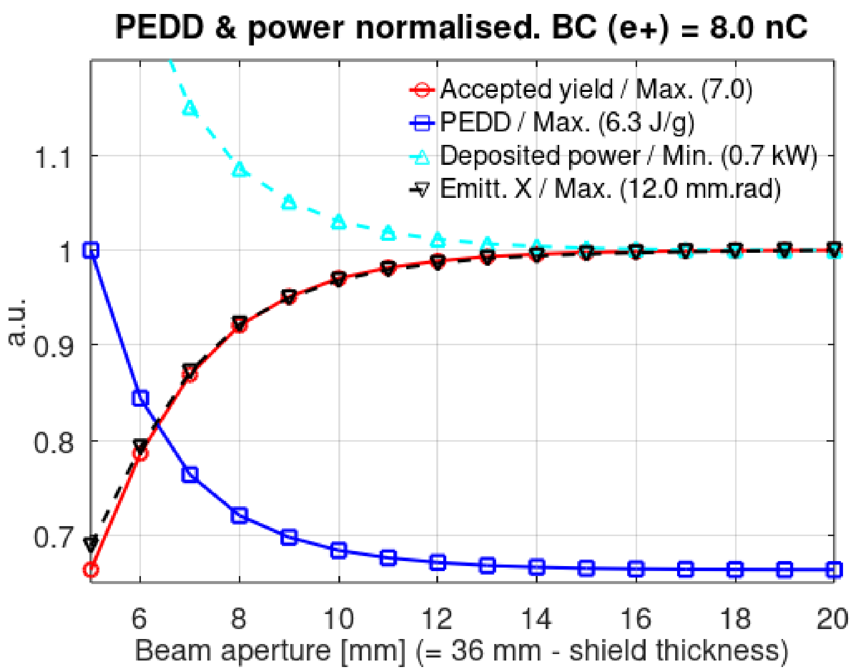
- **Optimised target exit position** for maximum accepted e^+ yield:
  - **0.5 mm spot size: z = 35 mm**
  - **1 mm spot size: z = 40 mm**

(z = 0 being HTS peak field)

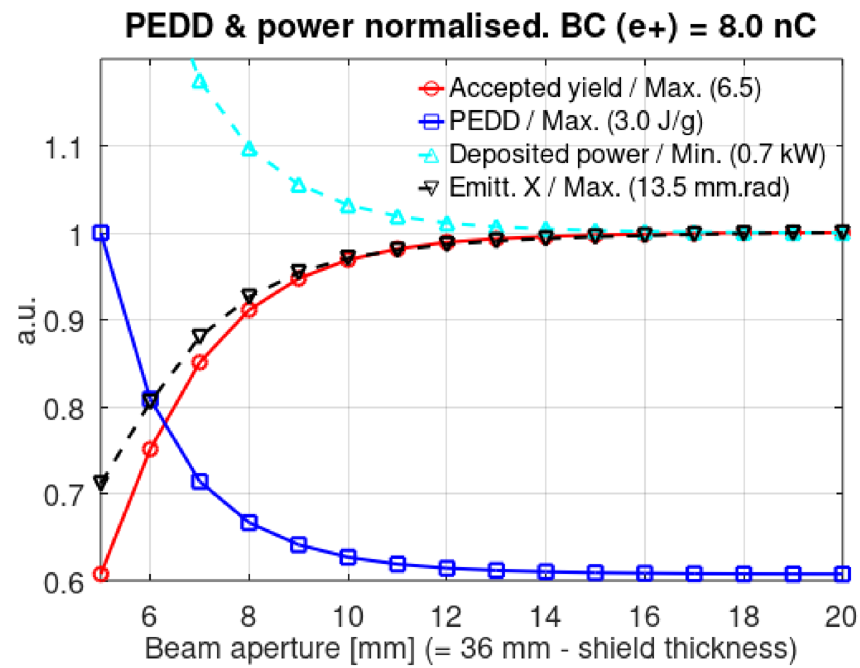
Shielding thickness in HTS solenoid

- Scan of beam aperture radius (in HTS solenoid)
  - Aimed to find the maximum shielding thickness (downstream target)

0.5 mm spot size



1 mm spot size



- ❑ Minimum beam aperture radius (w/o significant yield loss): 16 mm (15 mm is also OK)
  - ✓ **Maximum shielding thickness: 36 - 16 = 20 mm**

HTS fringe field

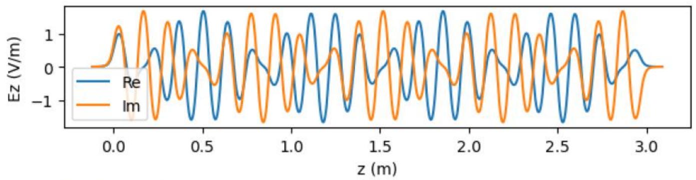
- For simplification, **upstream HTS fringe field** is not simulated
- The effect of fringe field on the results is nevertheless studied:
  - **Case A: w/o upstream HTS fringe field**
  - **Case B: w/ fringe field in target**
  - **Case C: w/ fringe field in target and e^- beam pipe**

Results	**Case A**	**Case B**	**Case C**
Spot size @ z = -300 mm and @ z = 17.5 mm (target entrance) [mm]	0.5, 0.5	0.5, 0.5	0.5, 0.5
Emittance x,y @ target entrance [mm.mrad]	15	15	**2015**
Yield @ target exit	14.1	14.2	14.1
Normalised PEDD in target [J/g]	4.2	4.2	4.2
RMS beam size @ target exit [mm]	1.16	1.14	1.15
Yield @ DR entrance	**7.0**	**7.1**	**7.0**
Emittance x,y @ DR entrance [mm.rad]	12.0	12.0	12.0

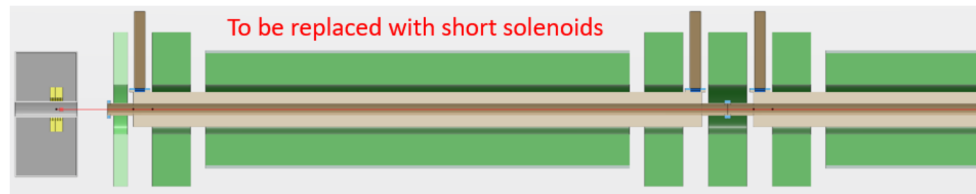
❑ **HTS fringe field effect on final results is negligible (though e^- beam emittance increased a lot)**

Capture linac

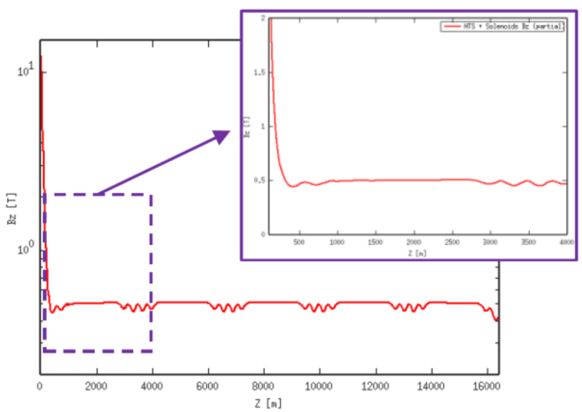
- **Baseline** structure ***– study focused on this scenario***
  - Larger aperture (Φ = **60 mm**) **TW L-band** (CERN) @ 2 GHz, 9π/10, 3 m, **20 MV/m**



“F3” structure
designed by H. Pommerenke and A. Grudiev (CERN)



NC solenoids (0.5 T), *designed by M. Schaer and R. Zennaro and (PSI)*



HTS + NC solenoids field

- No. of structures used: 5
- Distance between structures: 240 mm
- Same RF structure and NC solenoid used in e^+ linac
- For simplification, **0.5 T uniform NC field used** (as the difference was found small with the realistic field)

- **Alternative** structures
  - Normal aperture (Φ = **40 mm**) **TW L-band** (CERN, used for CLIC) @ 2 GHz, 2π/3, 1.5 m, **16-20 MV/m**
  - Normal aperture (Φ = **40 mm**) **SW S-band** (PSI, used for P^3 project) @ 2998.8 MHz, 1.5 m, **18 MV/m**
  - Smaller aperture (Φ = **30 mm**) **TW S-band** @ 2856 MHz, 3 m, **20 MV/m**

Capture linac

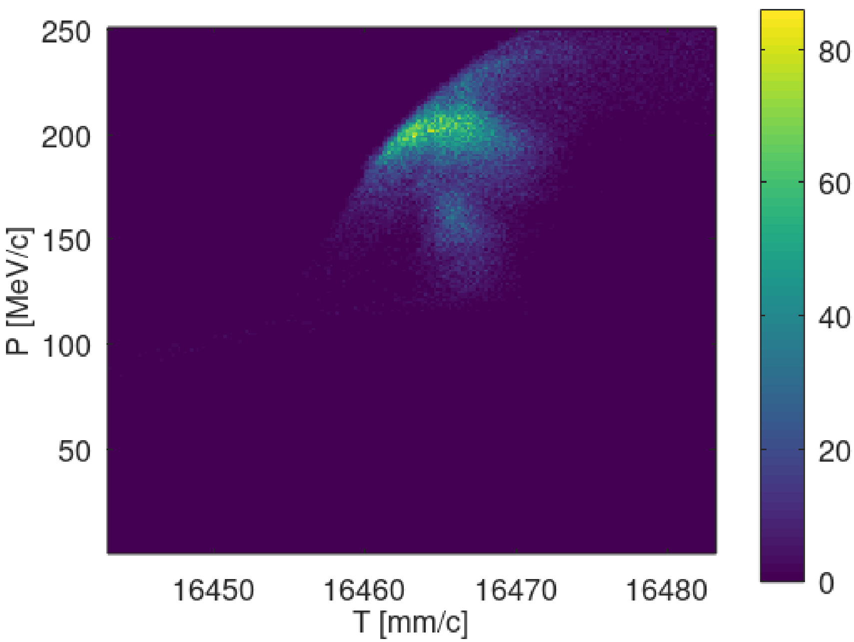
- **1D field map** has been used for the **baseline structure** (larger aperture L-band)
- **2D field map** was found to be helpful to reduce the **energy spread and correlation** in the **e^+ linac**, therefore the effect is studied for capture linac

Larger-R L-band e^+ results	1D field map	2D field map
Yield @ 200 MeV	8.5	8.5
Mean energy @ 200 MeV [MeV]	195	208
Energy spread @ 200 MeV [%]	23.4	22.4
Accepted bunch length [mm]	3.1	2.9
Accepted energy spread [%]	1.6	1.5
Accepted emittance x,y [mm.rad]	12.0	12.3
Accepted yield	7.0	7.0

- ❑ The **difference** between 1D and 2D field maps seems to be **small** for **capture linac**
- ❑ Nevertheless, 1D is still used in the study (due to limited time for updates)

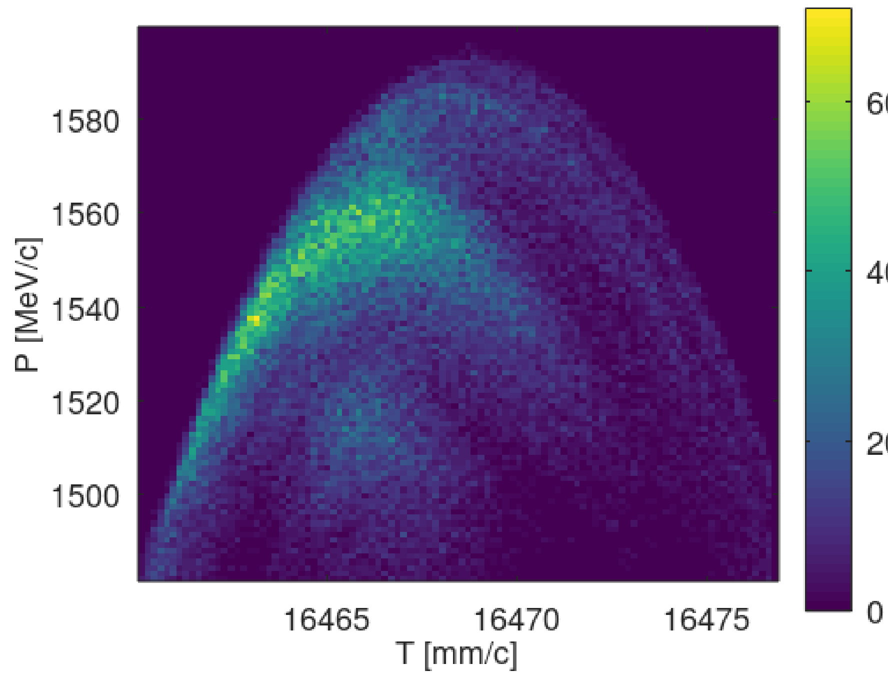
Longitudinal phase spaces

- @ 200 MeV (capture linac exit)



No cuts

- @ 1.54 GeV (DR entrance)



P & T cuts applied

Results

- Comparison of some selected scenarios
  - ✓ Format: "**Spot size** + **AMD** type + **Capture linac** type"

Scenarios	Accepted e^+ yield	Norm. PEDD in target [J/g]	Norm. Emitt. X,Y [mm.rad]
0.5 mm + FC (7 T) + L-band (60 mm)	4.4	6.7	11.4
0.5 mm + FC (7 T) + L-band (40 mm)	3.7	8.0	7.3
0.5 mm + FC (7 T) + S-band (40 mm)	3.3	9.0	6.7
0.5 mm + HTS + L-band (60 mm)	**7.0**	**4.2**	**12.0**
0.5 mm + HTS + L-band (40 mm)	5.6	5.2	7.0
0.5 mm + HTS + S-band (40 mm)	4.9	6.0	6.5
1 mm + HTS + L-band (60 mm)	**6.5**	**1.8**	**13.5**
1 mm + HTS + L-band (40 mm)	4.9	2.4	7.7
1 mm + HTS + S-band (40 mm)	4.2	2.9	7.1

- PEDD for FC-based scenarios can be reduced with rotating target
- **L-band (40 mm)** gradients & phases have been **very briefly reoptimised**
- More detailed parameters & results can be found at: FCC-ee CERNBox: WP3/Task3.4

Summary & next steps

- Simulation results presented for **many different capture scenarios**
- **Target optimised** for maximum yield and better shielding & cooling
- Work (**simulations, optimisations, shielding & cooling, e^+ linac design, etc.**) currently mainly focused on: "***conventional** target*" + "***HTS** AMD*" + "***larger aperture L-band** structure*" (current layout referred to as "***V1***")
- **Alternative e^- spot size** (1 mm) for **reduced PEDD** (for HTS-based scenario)
- A new **tapered target** shape proposed and being studied in **PSI** with **higher yield**
- **To-do's**
  - Reconsideration of **DR acceptances** (longitudinal & transverse)
  - **FC** studies (design optimisation for 200 Hz, R&D, etc.)
  - **Reoptimisations** (N_structures, gradients, phases, etc.). Difficult to reoptimise all scenarios. Once decided which scenario to use, a more detailed final reoptimisation is probably needed
  - **Misalignment** study (beam & target, position & direction, etc.) to be continued
  - Etc.

BACKUP

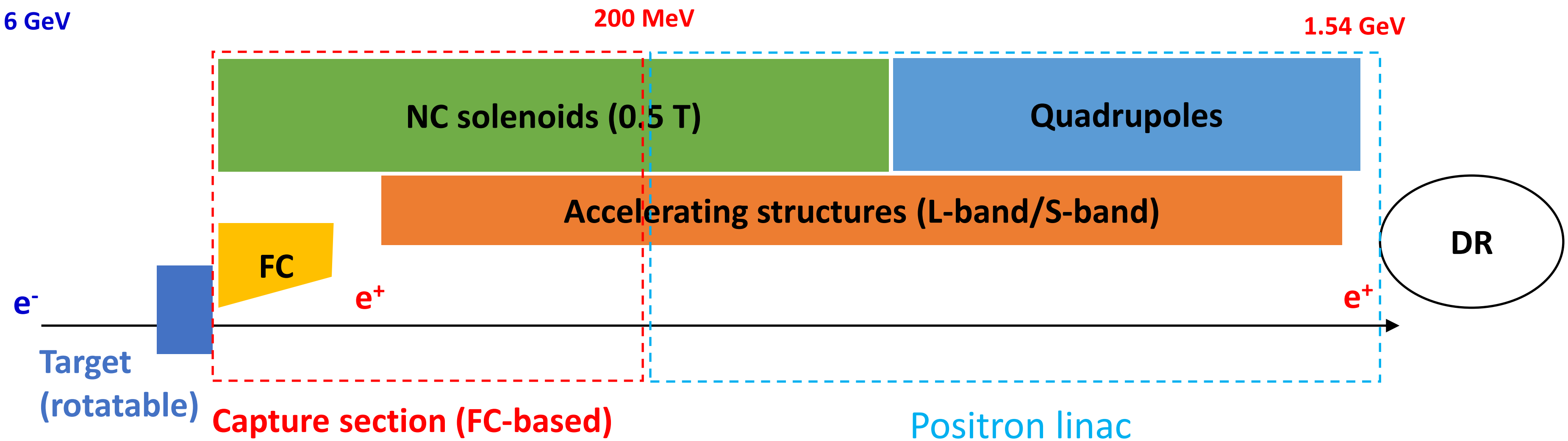
Misalignment study (in progress)

Misalignment

- Config
  - Beam size: 0.5, 1 mm
  - Target radius: 5 mm

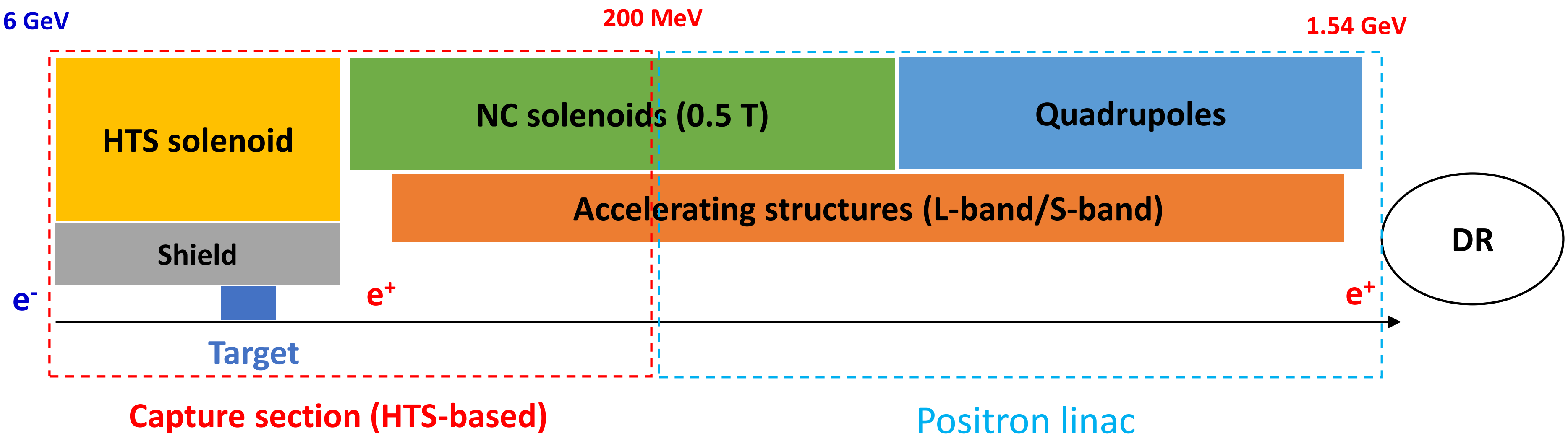
- Target trans. position offset
  - X0 = [0:0.2:1] mm
- Target direction offset (tilt)
  - Theta: [0:0.2:1] mrad
- Beam trans. position offset
  - X0 = [0:0.2:1] mm
- Beam direction offset
  - Theta: [0:0.2:1] mrad

Drawing



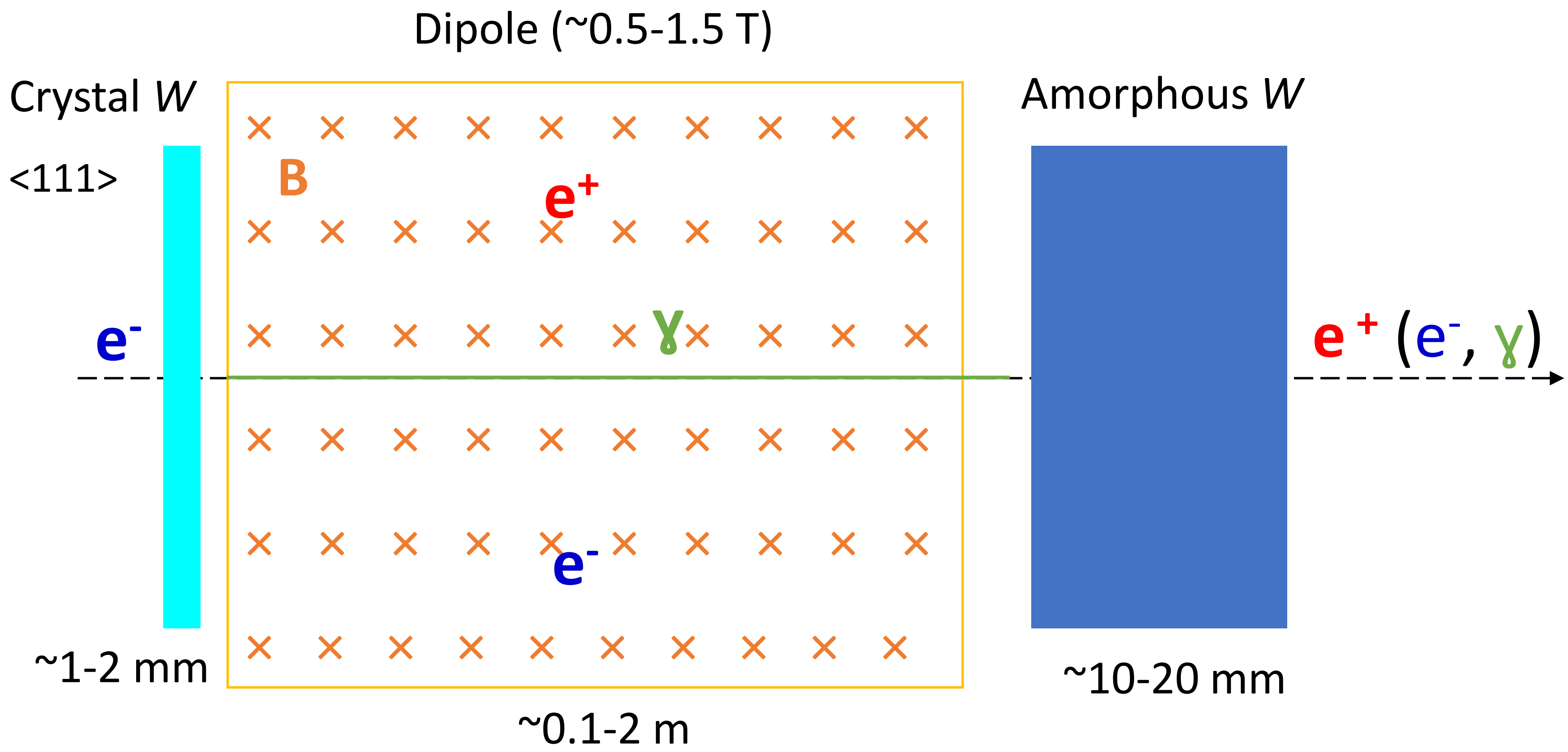
6 GeV
200 MeV
1.54 GeV
NC solenoids (0.5 T)
Quadrupoles
Accelerating structures (L-band/S-band)
FC
DR
e-
e+
e+
Target
(rotatable)
Capture section (FC-based)
Positron linac

Drawing



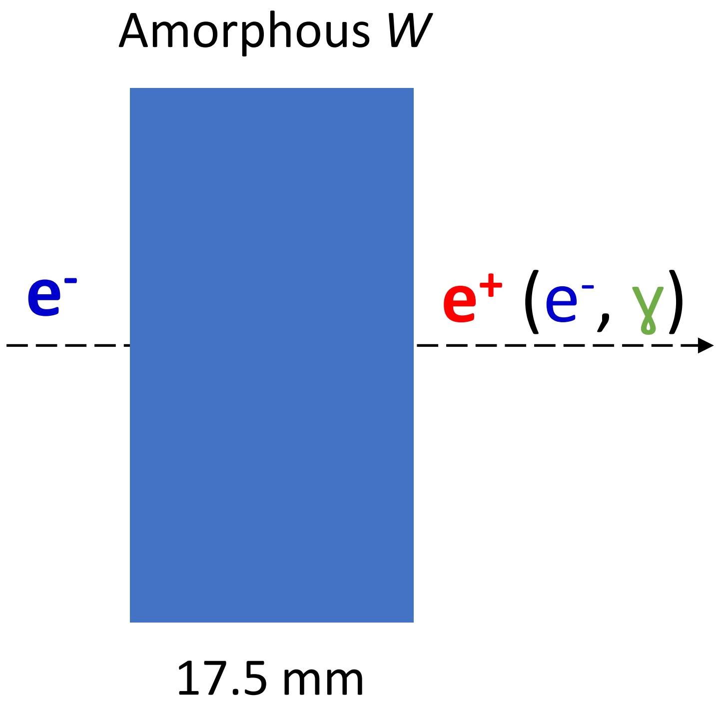
6 GeV
200 MeV
1.54 GeV
HTS solenoid
NC solenoids (0.5 T)
Quadrupoles
Accelerating structures (L-band/S-band)
Shield
DR
e-
e+
e+
Target
Capture section (HTS-based)
Positron linac

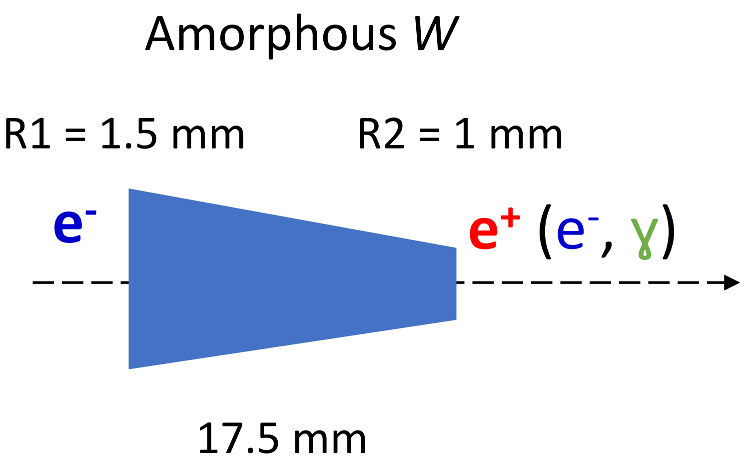
Drawing



Dipole (~0.5-1.5 T)
Crystal W
<111>
B
e+
Amorphous W
e-
γ
e + (e-, γ)
e-
~1-2 mm
~10-20 mm
~0.1-2 m

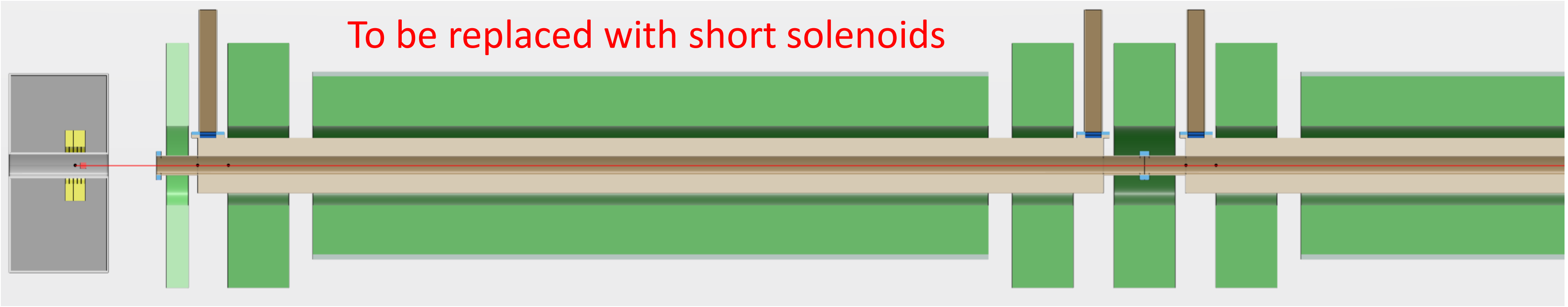
Drawing





Proposed & optimised by N. Vallis (PSI)

Drawing



NC solenoids (0.5 T), *designed by M. Schaer and R. Zennaro and (PSI)*