POSITRON CAPTURE SIMULATIONS OF THE FCC-EE POSITRON SOURCE

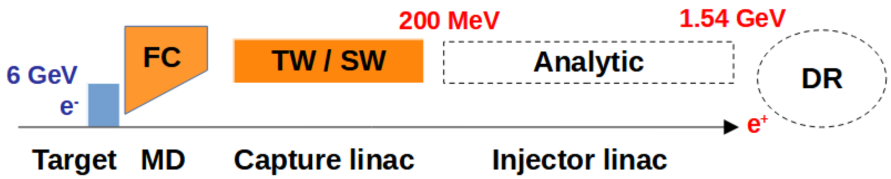
On behalf of the FCC-ee positron source team

Outline

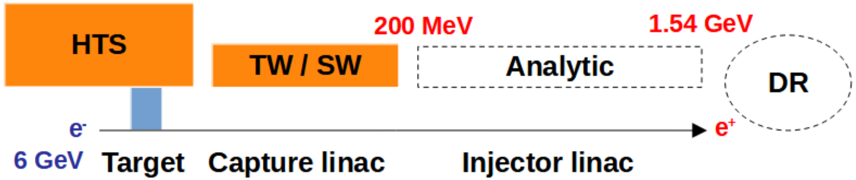
- Introduction to the simulation
- Beam parameters
- Target
- Matching device
- Capture linac
- Optimisation and preliminary results
- Summary

Introduction

- **Layouts used in simulation:**



FC used as MD



HTS solenoid used as MD

- **Important quantities**
  - **Accepted e+ yield:**

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

  - **Peak energy deposition density (PEDD): < 35 J/g**

- **Simulation tools:**
  - **Geant4**: target ("conventional") simulation
    - Gaussian function used for primary e- distributions
  - **RF-Track**: beam tracking in MD and capture linac
  - Tracking in injector linac is longitudinally simulated with **analytic** formula:

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

    - Reference particle with energy around 200 MeV
    - S-band frequency: 2.856 GHz

Beam parameters

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	$6.2 \times 10^{11} / \eta_{e^+}$	$cm^{-}2$
Positrons at the DR entrance		
Bunch charge required	7	nC
Energy window cut	1540 ± 58.5	MeV
Time window cut (total)	17.5†	mm/c

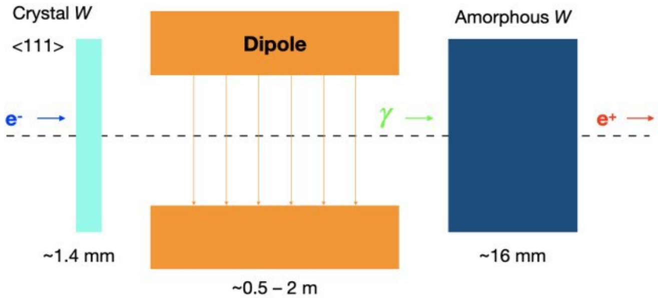
(4.37E+10 e+ / bunch, 3.5 nC safety margin included)

(±3.8% @ 1.54 GeV)

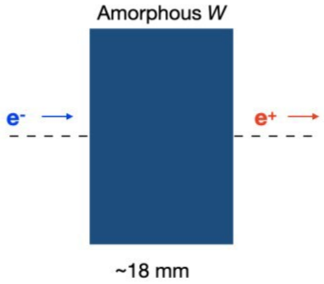
(60° @ 2.856 GHz RF)

- * If larger emittance (60 mm*mrad) assumed for primary e-, the difference in positron yield is negligible
- † Time window might be larger or smaller. To be dsicussed with the DR team for a better definition, as well as the dynamic aperture, matched to the DR acceptance

Target



Hybrid target scheme



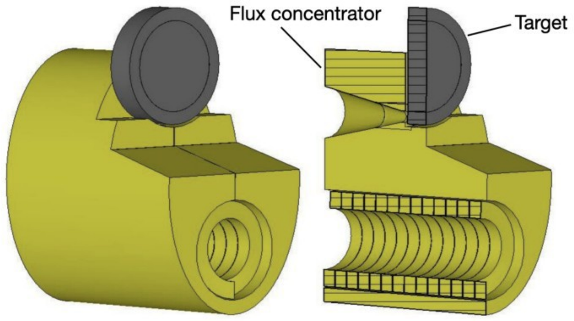
Conventional target scheme

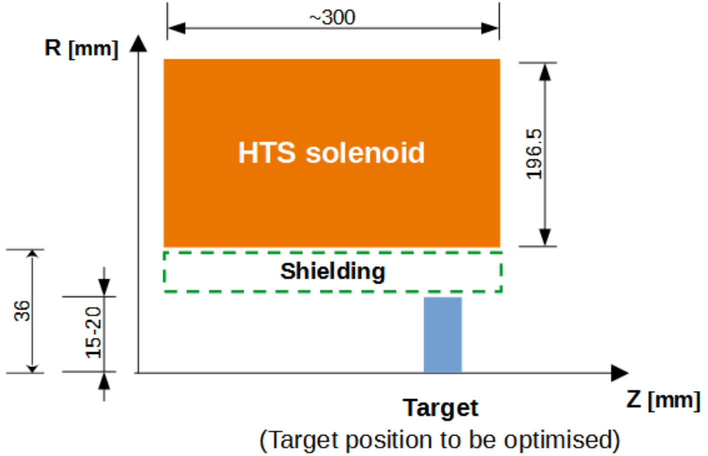
- **Baseline option**
- **High e+ yield**
- PEDD is no more a problem
- **Adopted in this study**

- **Alternative option**, with **potential smaller PEDD and safer radiation and thermal load**, for which the **study is still in progress**
- **Low e+ yield** due to large beam size arriving at the amorphous target
- Therefore, **not adopted in this study**

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

Matching device (MD)





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

Compared with HTS solenoid:

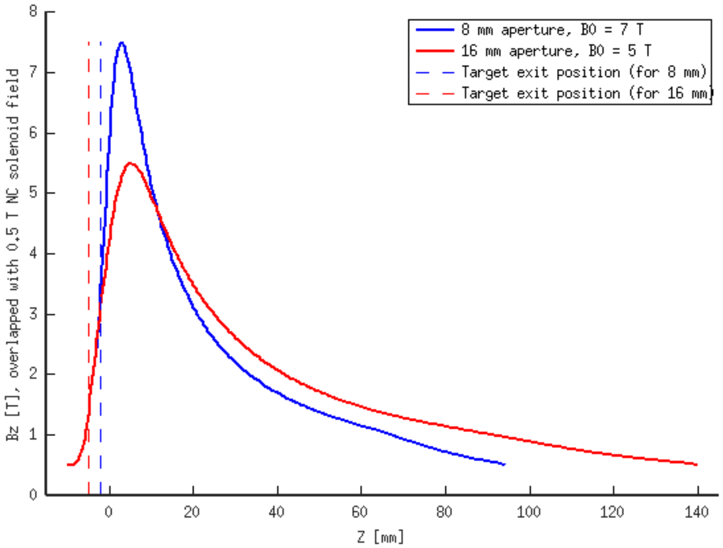
- Low peak field (5−7 T, ~1.5−3 T at target exit)
- Small entrance aperture (Φ = 8−16 mm)
- Fixed target position (2−5 mm upstream)
- Therefore, **low e+ yield**

High-Temperature Superconducting (HTS) solenoid designed by J. Kosse et al. (PSI)

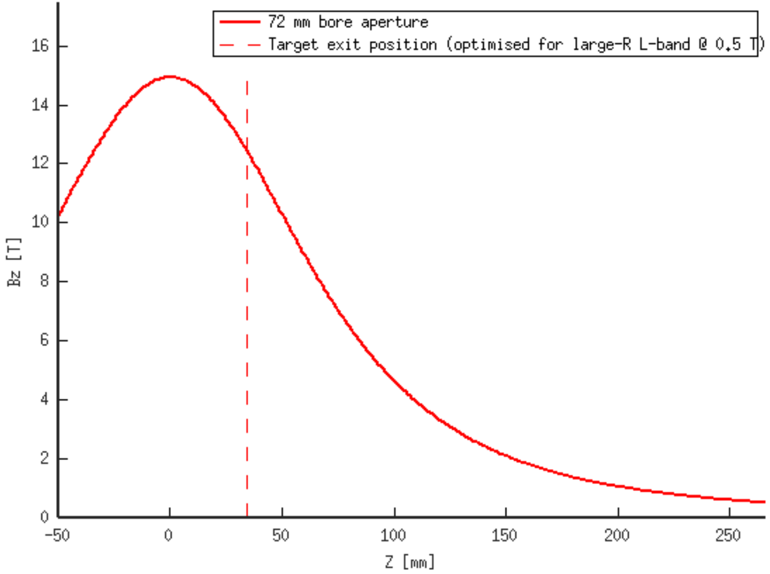
Compared with FC:

- 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, **high e+ yield**

Matching device (MD)

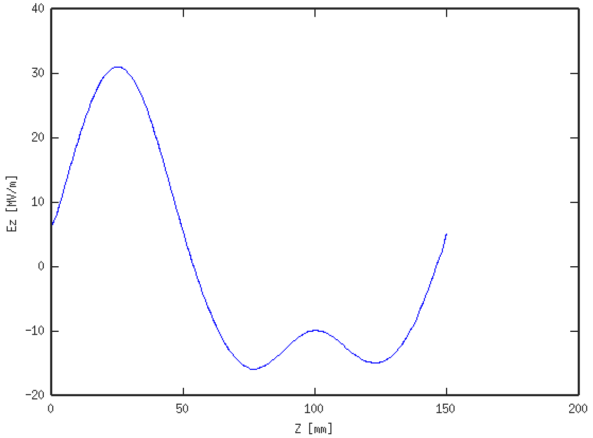


FC on-axis field, with fixed target position (overlapped with a 0.5 T NC solenoid field)



HTS solenoid field, with optimised target position

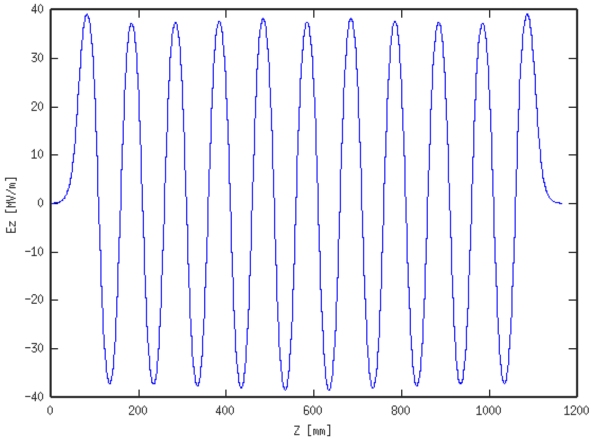
Capture linac



CLIC-style L-band field profile (3 cells)

designed by S. Doebert (CERN)

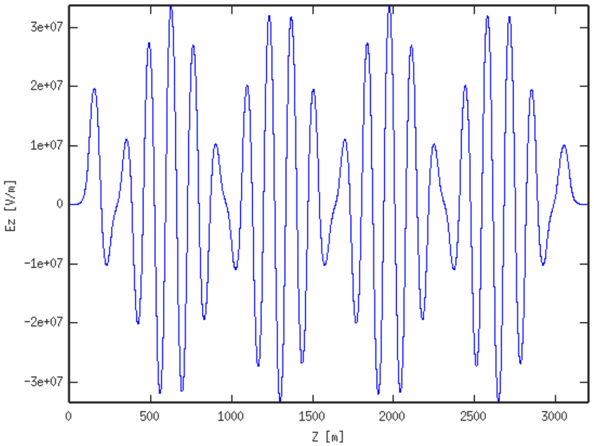
- 2π/3 mode, 2 GHz, 1.5 m long, 20 cm distance
- Aperture diameter: 40−28 mm (**40 mm** assumed, as it's technically possible)
- Number of RF structures: 1 dec. + 10 acc.
- Average gradient: 17.5 MV/m and 21 MV/m
- Solenoid: **0.5 T** NC



S-band field profile

designed by R. Zennaro (PSI)

- 3 GHz, 1.2 m long, 15 cm distance
- Aperture diameter: **40 mm**
- Number of RF structures: 1 dec. + 12 acc.
- Average gradient: 18 MV/m
- Solenoid: **1.5 T** SC

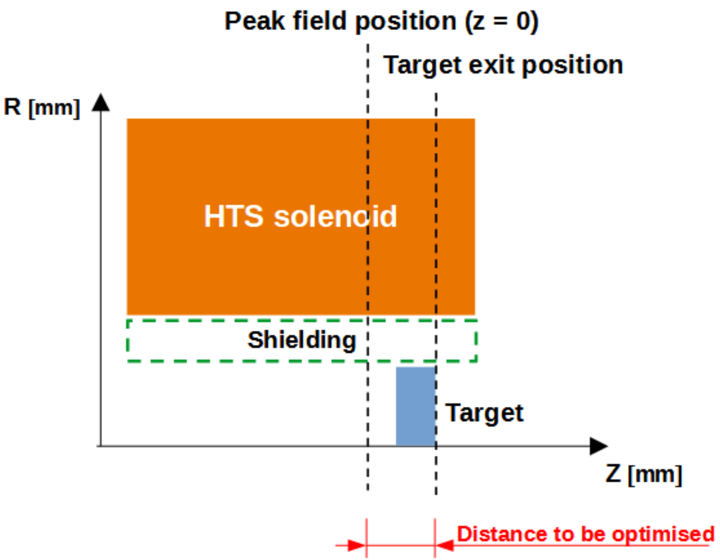


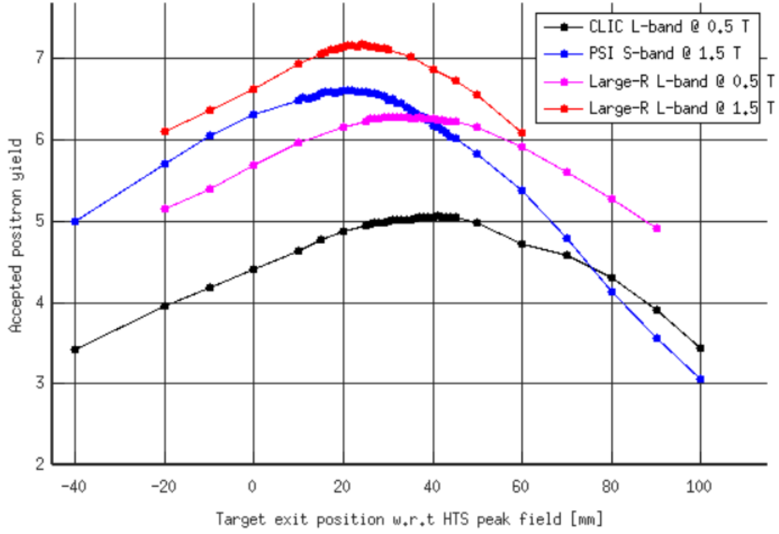
Large-R L-band field profile designed by H. Pommerenke and A. Grudiev (CERN)

- 9π/10 mode, 2 GHz, 3 m long, 24 cm distance
- Aperture diameter: **60 mm** assumed
- Number of RF structures: 1 dec. + 4 acc.
- Average gradient: 20 MV/m
- Solenoid: **0.5 T** NC / **1.5 T** SC

➢ Constant solenoid field assumed so far. Starting to use a more realistic field in following studies

Optimisation of target position



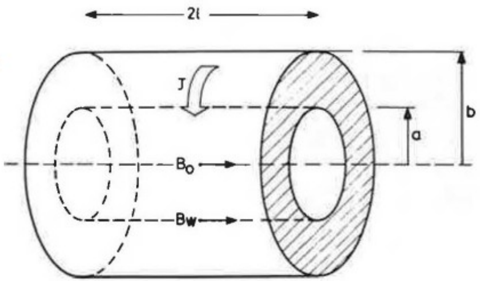


- Max. shielding thickness: ~21 mm
- In case of any big changes, the distance needs to be re-optimised

Capture linac options	Optimised distance [mm]	Accepted e+ yield
CLIC L-band @ 0.5 T	41	5.1
PSI S-band @ 1.5 T	20	6.6
Large-R L-band @ 0.5 T	37	6.3
Large-R L-band @ 1.5 T	24	7.2

Optimisation of analytic HTS solenoid as a cross-check

J: ave. current density
a: Inner radius
b: Outer radius
l: half length



$$B_z = \frac{1}{2} J a [F(\alpha, \beta_1) + F(\alpha, \beta_2)],$$

$$F(\alpha, \beta) = \mu_0 \beta \ln \frac{\alpha + (\alpha^2 + \beta^2)^{\frac{1}{2}}}{1 + (1 + \beta^2)^{\frac{1}{2}}},$$

$$\alpha = b/a \quad \beta_1 = (l - z)/a \quad \beta_2 = (l + z)/a$$

(MARTIN N. WILSON, 1983)

Analytic formula for HTS solenoid

Winding parameters				Target exit position [mm]	Accepted e+ Yield	
J [A/mm²]	a [mm]	b [mm]	l [mm]		Analytic HTS	Designed HTS
580	60	115	30	41	4.9	5.1
890	60	90	196	195	5.5	-

- **Consistent results** between analytic and designed HTS, given similar winding parameters
- Optimisation of analytic HTS (preliminary) using **very loose constraints gains not much (~8%)** in e+ yield improvement, though optimised parameters are more challenging and expensive
- **Therefore, the current HTS design is expected to be optimal** (or close to optimal) **in terms of accepted e+ yield**

Results (preliminary)

- **Positron yield results**

Capture options	MD e+ yield	Capture linac e+ yield	DR accepted e+ yield
FC (7 T) + CLIC L-band @ 0.5 T	9.4	3.5	**3.2** *
FC (7 T) + PSI S-band @ 1.5 T	9.8	6.3	**4.4**
HTS + CLIC L-band @ 0.5 T	13.5	5.9	**5.1**
HTS + PSI S-band @ 1.5 T	13.6	9.7	**6.6**
HTS + Large-R L-band @ 0.3 T	13.5	6.1	**4.7**
HTS + Large-R L-band @ 0.5 T	13.5	8.1	**6.3**
HTS + Large-R L-band @ 1.5 T	13.5	11.6	**7.2**

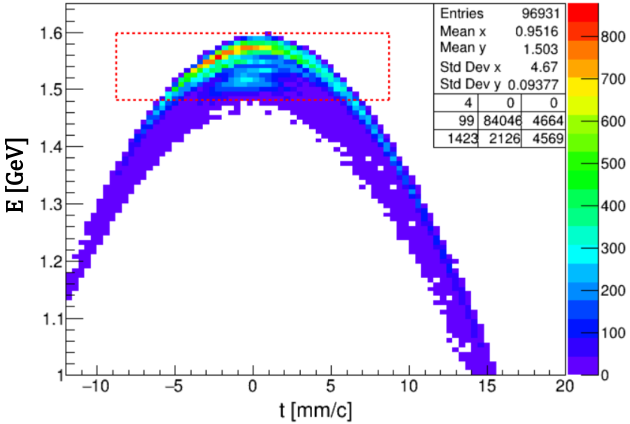
* For comparison, previous result is ~2.4 with larger primary e- beam size (IPAC'21)

- ➔ **HTS solenoid improves final yield by ~50–60%** compared with FC (3.2→5.1, 4.4→6.6)
- ➔ **SC solenoid field (capture linac) improves final yield significantly** compared with NC field
- ➔ **Larger aperture (R = 30 mm) L-band improves final yield by ~10–25%** compared with normal aperture (R = 20 mm) (5.1→6.3, 6.6→7.2)
- ➔ Larger aperture **also allows to reduce NC solenoid from 0.5 T to 0.3 T** without much loss (~10%) in final yield compared with normal aperture (R = 20 mm) (5.1→4.7)

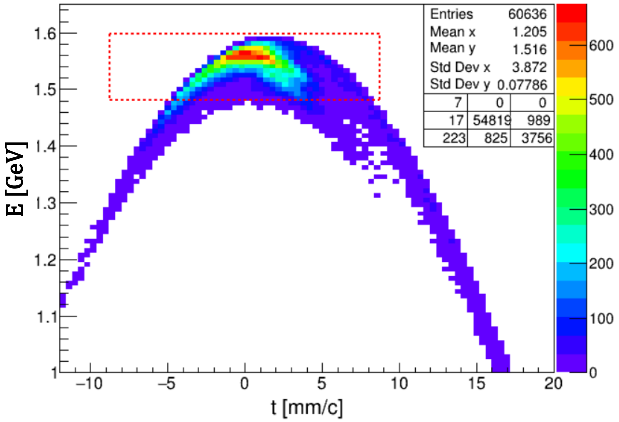
Results (preliminary)

- **Longitudinal phase space at DR entrance**

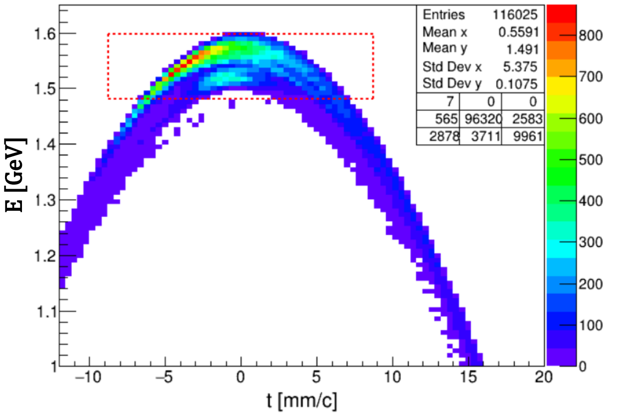
✔ Reference time (window center) set to 0
✔ Energy & time cut window also displayed
✔ 10,000 primary e- simulated
✔ Overflow & underflow positrons beyond the plotting ranges also displayed in the statistics box



HTS + PSI S-band @ 1.5 T
(Yield: 6.6)



HTS + Large-R L-band @ 0.3 T
(Yield: 4.7)



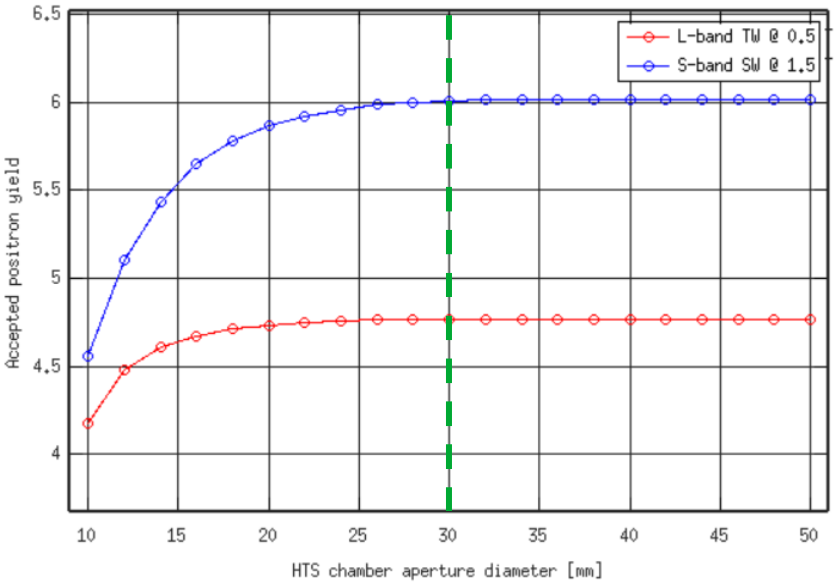
HTS + Large-R L-band @ 1.5 T
(Yield: 7.2)

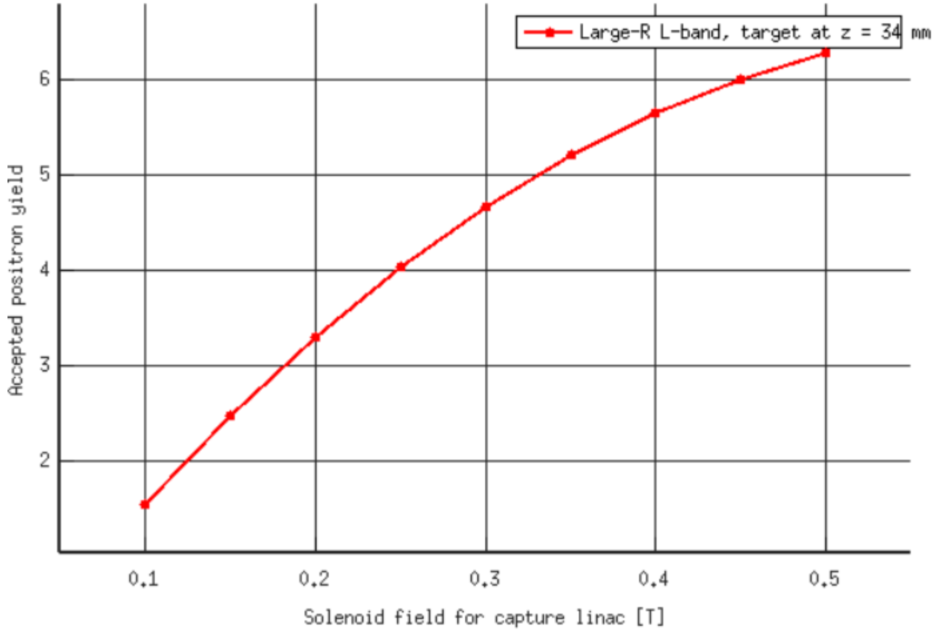
Summary

- **Preliminary results** presented for different capture options. Compared with previous results, **yield improved significantly**, due to **new beam parameters** or **SC implementation** or **larger RF aperture**
  - ✔ **HTS solenoid improves final yield by ~50−60%** compared with FC
  - ✔ **Larger aperture (R = 30 mm) L-band improves final yield by ~10−25%** compared with normal aperture (R = 20 mm)
  - ✔ **SC solenoid field (capture linac) improves final yield significantly** compared with NC field
  - ✔ Larger aperture also **allows to reduce NC solenoid from 0.5 T to 0.3 T** without much loss (~10%) in final yield compared with normal aperture (R = 20 mm)
- **Next step:**
  - ➔ Discuss with the DR team for a **better match to DR acceptance**: time window, dynamic aperture, XY emittances, etc.
  - ➔ **More realistic solenoid field** to be implemented for capture linac (now using constant field for simplicity in optimisation)
  - ➔ RF **gradients & phases** are **preliminary** and can still be re-optimised a bit
  - ➔ To be presented at **IPAC'22** but using smaller time window and large-R L-band not included. To update if time allows
  - ➔ **Cooperate on other on-going studies**: radiation load, linac design, magnet design and e+ transport in injector linac, etc. Find more details in other talks this afternoon

Thank you for your attention.

Scan of shielding thickness for HTS solenoid and NC solenoid field





- Smaller time window (9.3 mm/c) still used in left plot, but not changing the conclusion