FCC-ee positron capture V0 simulation

Yongke Zhao, CERN

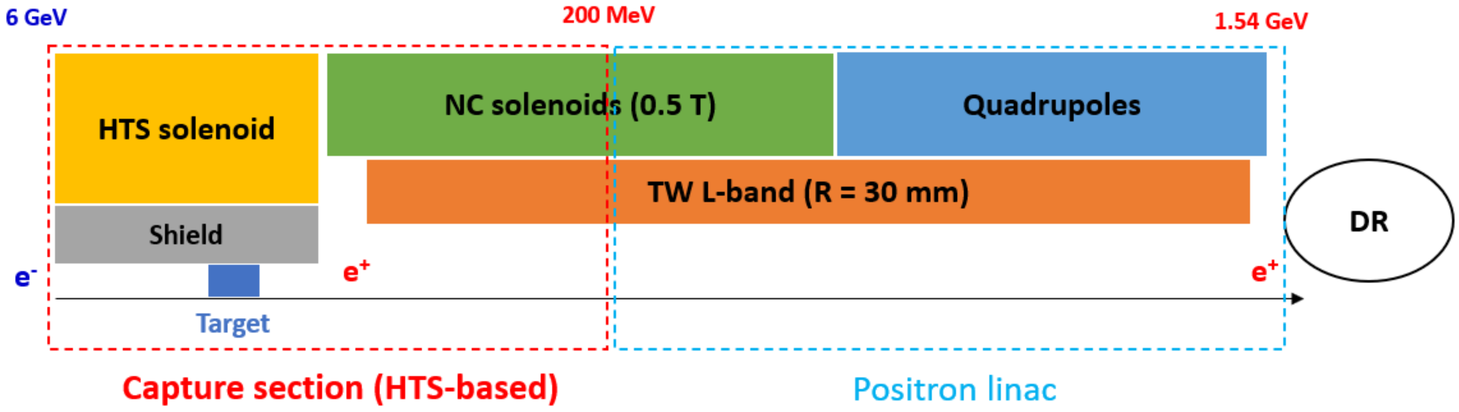
On behalf of the team

FCC-ee Pre-injector Mini-workshop

25/11/2022, Orsay

Overview

- **FCC-ee e^+ source V0 layout:** conventional target + HTS solenoid matching device



- **Simulation tools:** Geant4, RF-Track

- **Accepted e+ yield:**

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

- **Reruirements for e^+:**
  - e^- bunch charge × DR accepted e^+ yield = e^+ bunch charge ≥ **5.6 nC * 2** ≈ 7.0×10^{10} e^+ / bunch
    - ✓ A safety margin of 2 is applied

To be scaled to 4 nC (latest)

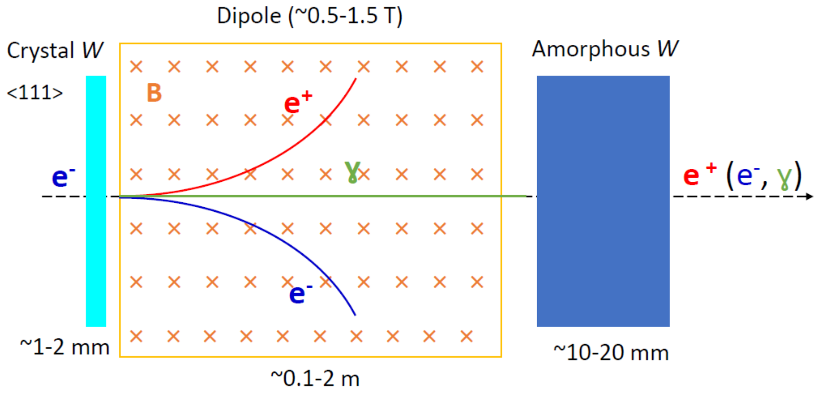
  - **DR acceptance** considered by applying longitudinal **window cuts** on e^+ at DR entrance:
    - ✓ Energy window: 1540 ± 58.5 MeV **(±3.8%** @ 1.54 GeV)
    - ✓ Time window: **16.7 mm/c** (~40° RF @ 2 GHz) in total (to be discussed)

Beam parameters for e^-

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 pulse	2	
Repetition rate	200	Hz
Normalised beam power	$26.8 / \eta_{e^+}$	kW
Normalised beam fluence	$9.9 \times 10^{11} / \eta_{e^+}$	cm^{-2}
For $\eta_{e^+} = 6.8$		
Normalised beam power	3.9	kW
Normalised beam fluence	1.5×10^{11}	cm^{-2}

Target for e^+ production

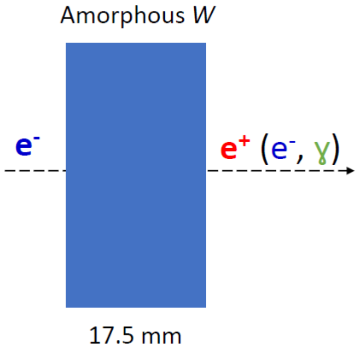
- **Hybrid target**
  - ○ Study in progress



Advantages:

- ○ Promising results (more in the talk of L. Bandiera or their paper: arXiv:2203.07541)
  - ✓ **Lower deposited power** (~30%) and **PEDD** (~60%), assuming same final e+ yield, etc.
- ○ Benchmarking with Geant4 needed?
- ○ Final e+ yield (DR accepted) to be estimated, etc.

- **Conventional target**
  - ✓ Used in **V0** simulation



Target results	**Values**	**Units**
e+ yield at target exit	13.7	e+/e-
Deposited power	6.4 / η_{e+}	kW
PEDD	41.5 / η_{e+}	J/g
For η_{e+} = 6.8 e+/e-		
Deposited power	0.94	kW
PEDD	6.1	J/g

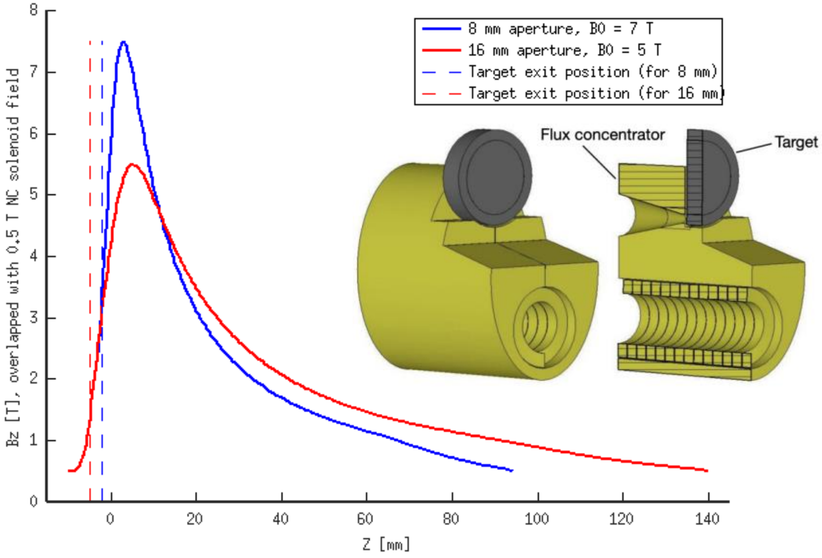
PEDD < 35 J/g required

Advantages:

- ○ **Simple layout** and placement in HTS matching device
- ○ **Higher e+ yield** expected (due to smaller e+ spot size)
- ○ PEDD no more a concern (given high yield and only 2 bunches per pulse)

Matching device

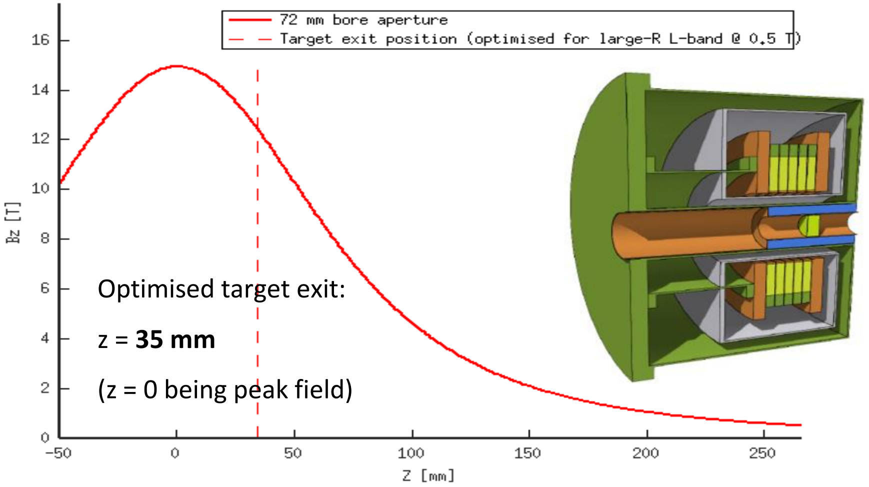
- **<u>FC</u>** <u>option</u>
  - ○ Study in progress



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

- ○ Lower peak field (5-7 T, ~1.5-3 T at target exit)
- ○ Smaller entrance aperture (Φ = 8-16 mm)
- ○ Fixed target position (2-5 mm upstream)
- ○ Therefore, **lower e+ yield**
- ○ Designed for 100 Hz rep. rate? To be re-optimised for 200 Hz?

- **<u>HTS</u>** <u>solenoid option</u>
  - ✓ Used in **V0** simulation



Optimised target exit:

z = **35 mm**

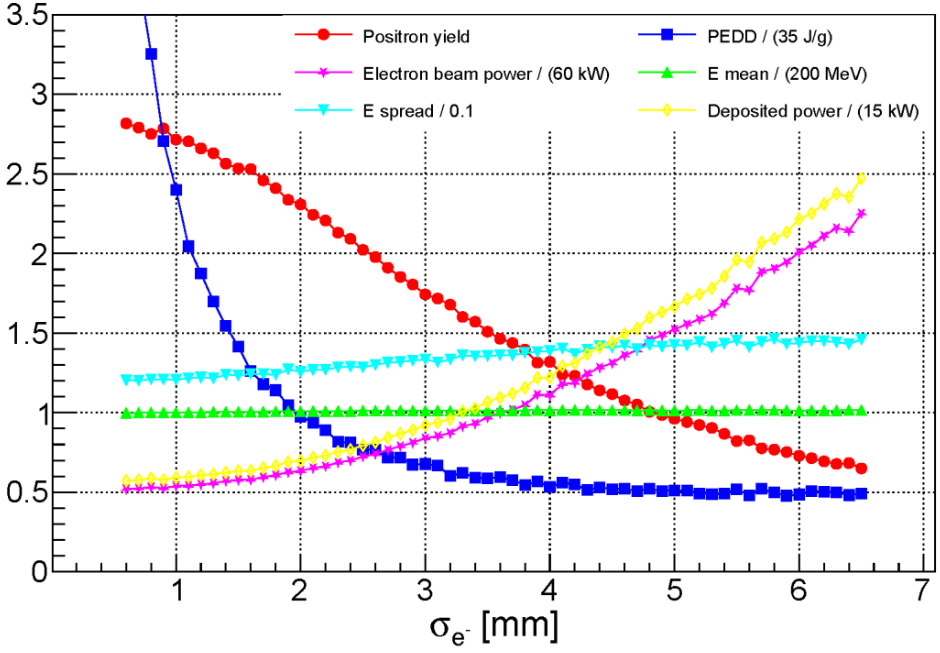
(z = 0 being peak field)

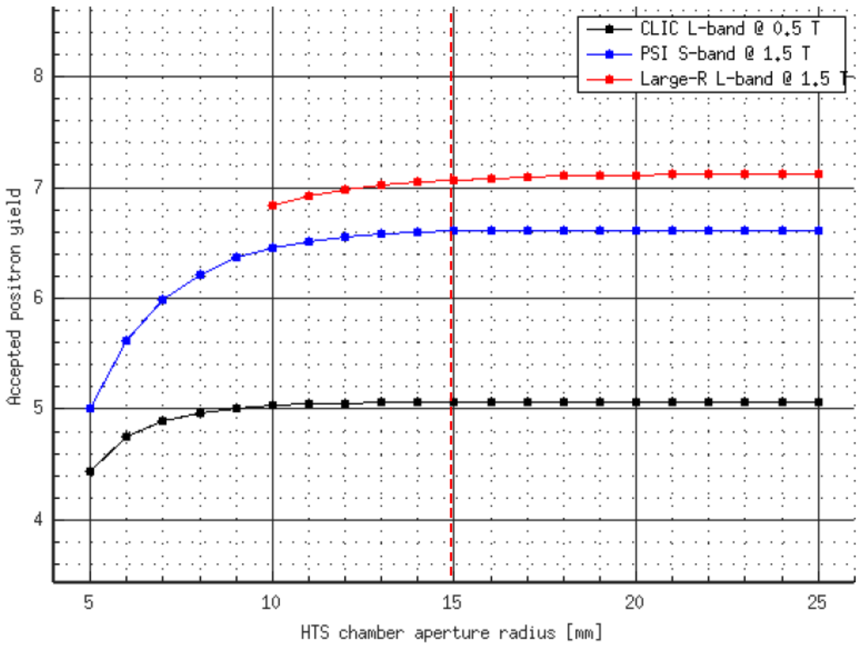
High-Temperature Superconducting (HTS) solenoid
designed by J. Kosse, B. Auchmann and M. Duda (PSI)

- ○ Higher peak field (~15 T, ~12 T at target exit)
- ○ Larger aperture (Φ = ~30 mm, minimised for the shielding)
- ○ Flexible target position
- ○ Therefore, **higher e+ yield** (a factor of > 2 than using FC)

Matching device

- **Ideals** to reduce PEDD in target and radiation in HTS solenoid



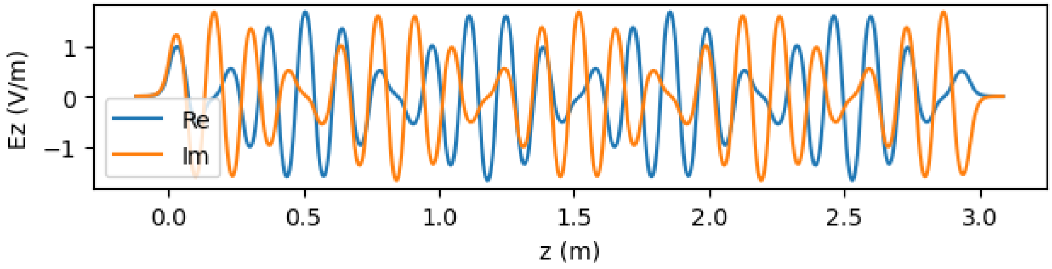


- ➢ **CLIC plot** primary e- spot size scan
- ➢ PEDD (normalised) increased dramatically with smaller spot size
- ➢ Need to study this for FCC-ee (now fixed at 0.5 mm)?

- ➢ **Old plot** (needs updates)
- ➢ Currently R=15 mm for target
- ➢ Possible to be further reduced? (compromise between yield and radiation)

Capture linac (200 MeV)

- Linac used in V0
  - Large aperture L-band (**N = 5**)

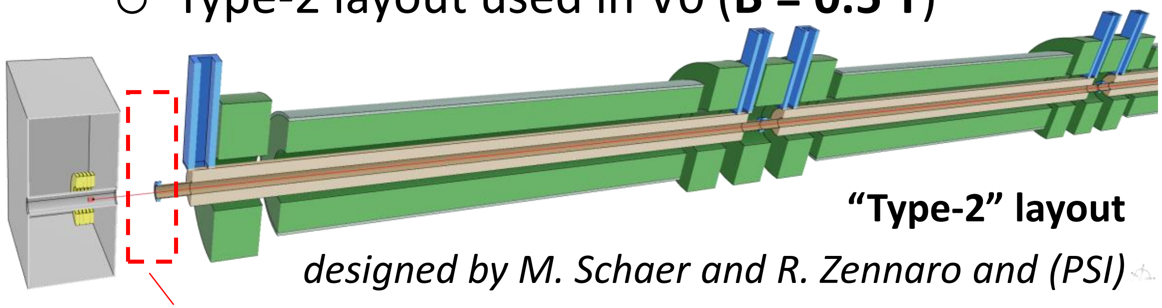


“F3” structure

designed by H. Pommerenke and A. Grudiev (CERN)

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

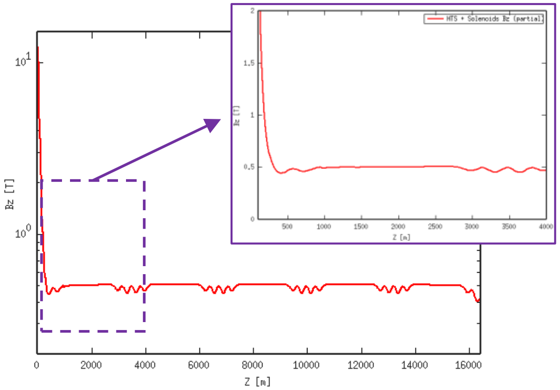
- Solenoid used in V0
  - Type-2 layout used in V0 (**B = 0.5 T**)



“Type-2” layout

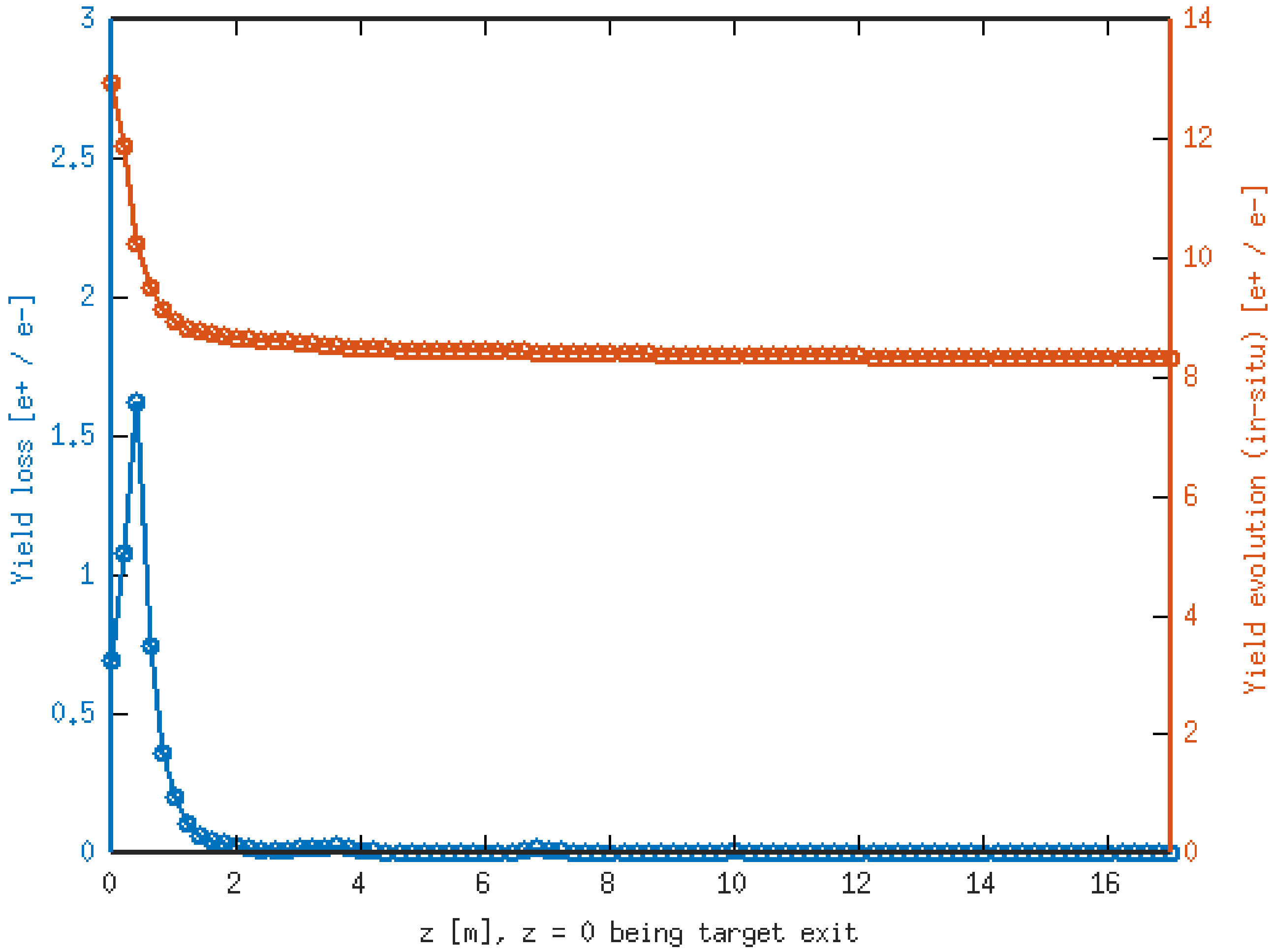
designed by M. Schaer and R. Zennaro and (PSI)

Extra solenoid



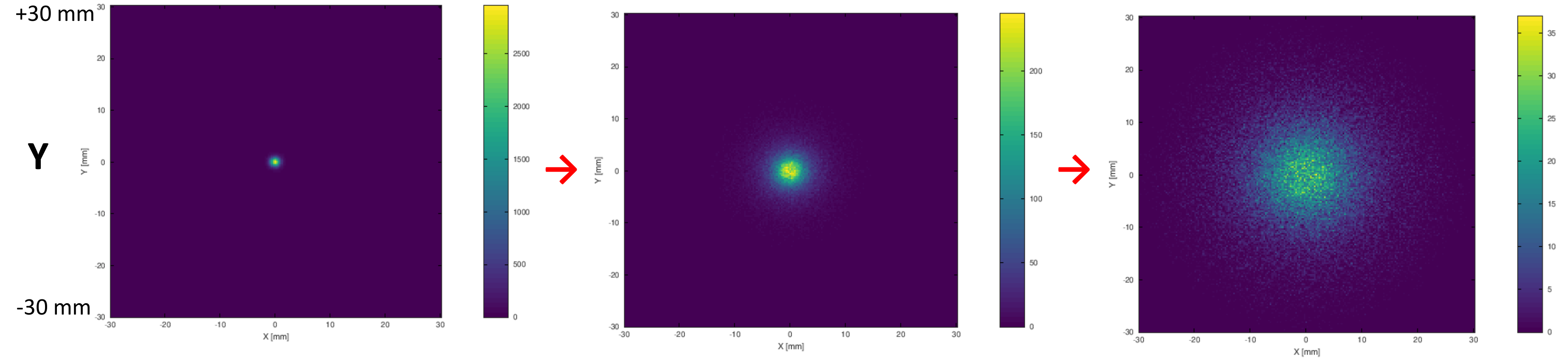
Capture linac (200 MeV)

- Yield losses in capture system:

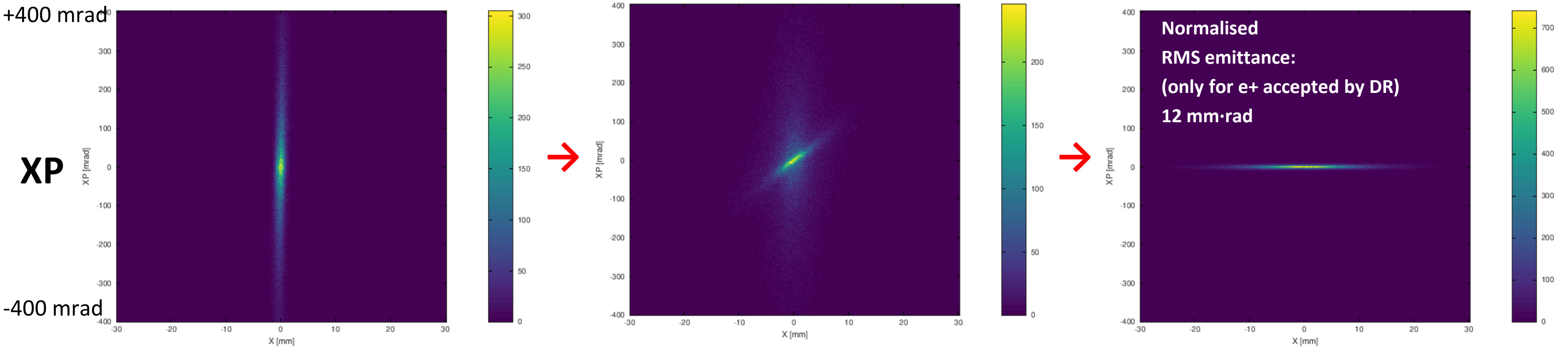


Capture linac (200 MeV)

- Transverse phase spaces



X (-30 mm to 30 mm)



Normalised RMS emittance:
(only for e+ accepted by DR)
12 mm·rad

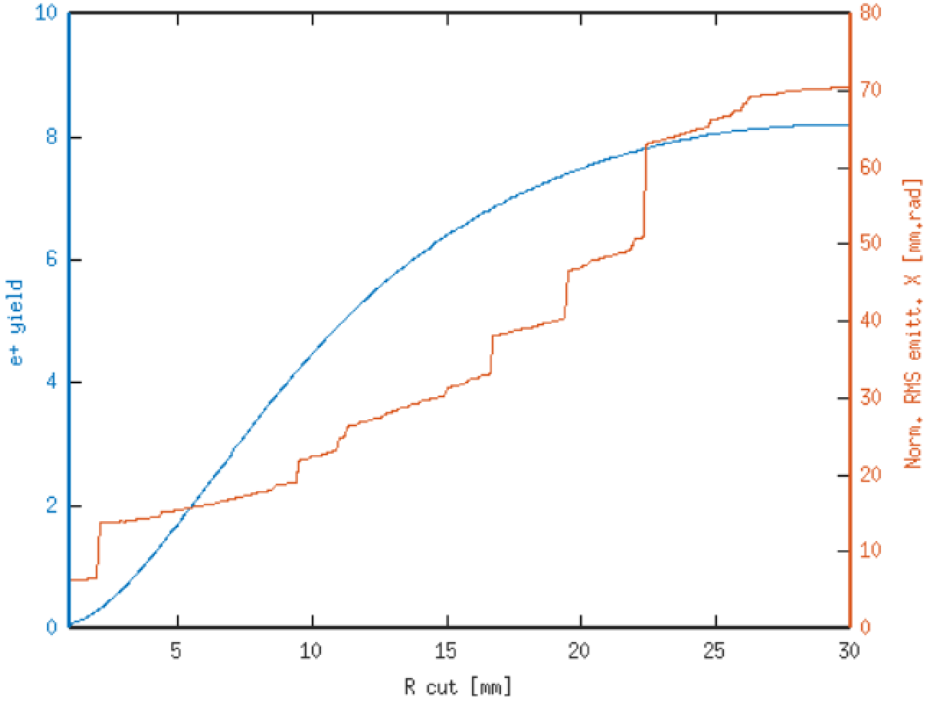
X (-30 mm to 30 mm)

Target exit → **HTS solenoid cryostat exit** → **Capture linac exit**

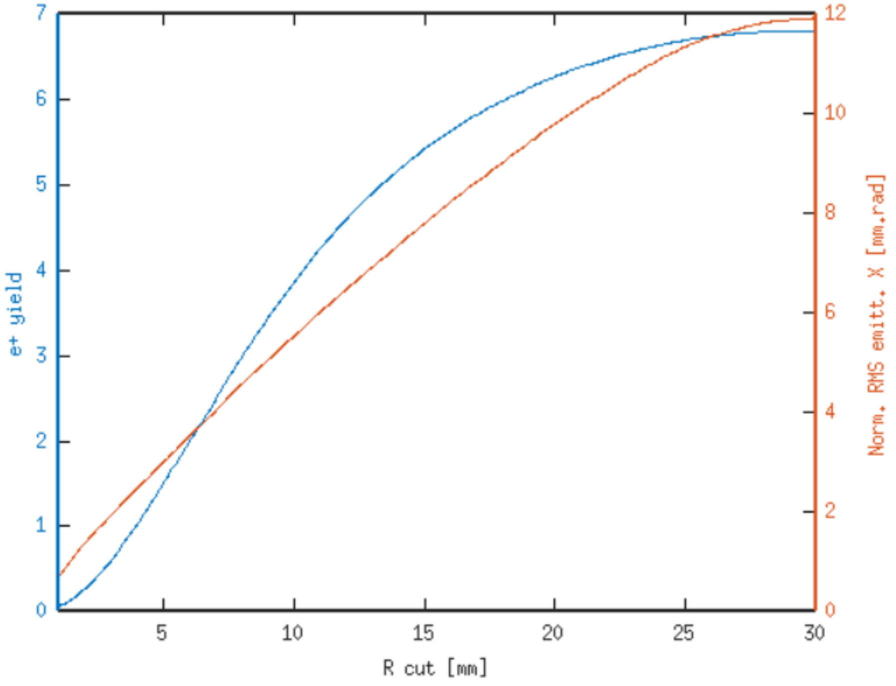
Capture linac (200 MeV)

- Normalised RMS transverse emittance as a function of cut on beam radius (R)

Blue color: e+ yield   Orange color: emittance



All positrons

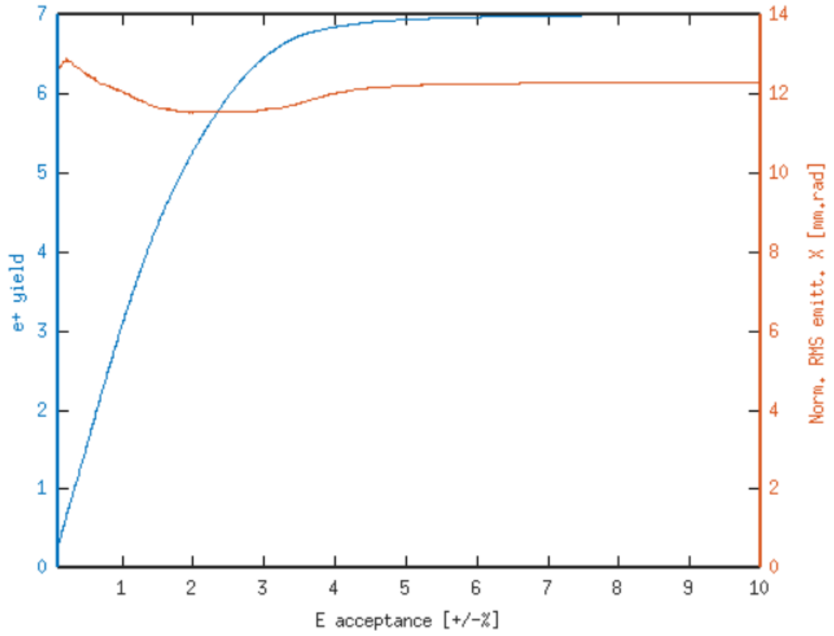


Positrons accepted by DR E & time cut window

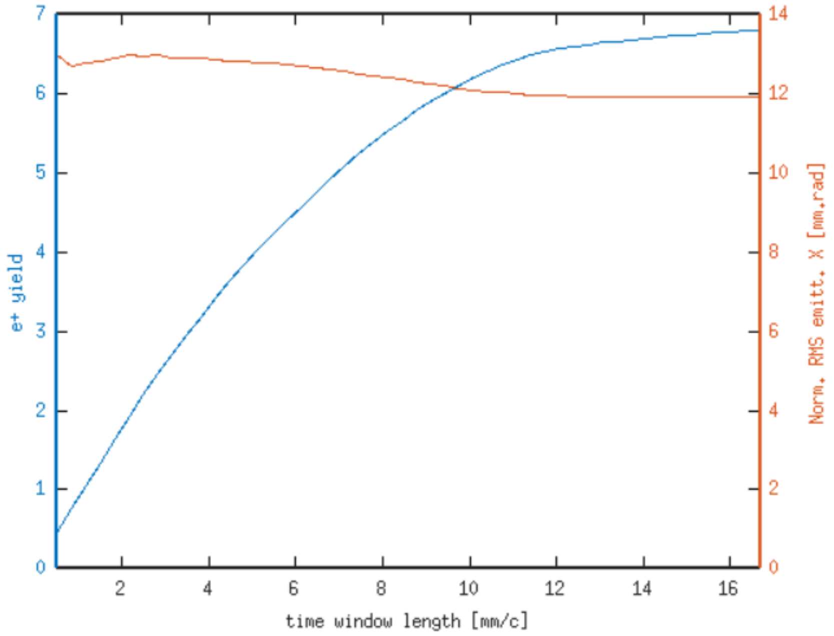
Capture linac (200 MeV)

- Normalised RMS transverse emittance as a function of DR cut window

Blue color: accepted e+ yield Orange color: emittance



Scan of E acceptance
(16.7 mm/c time cut applied)

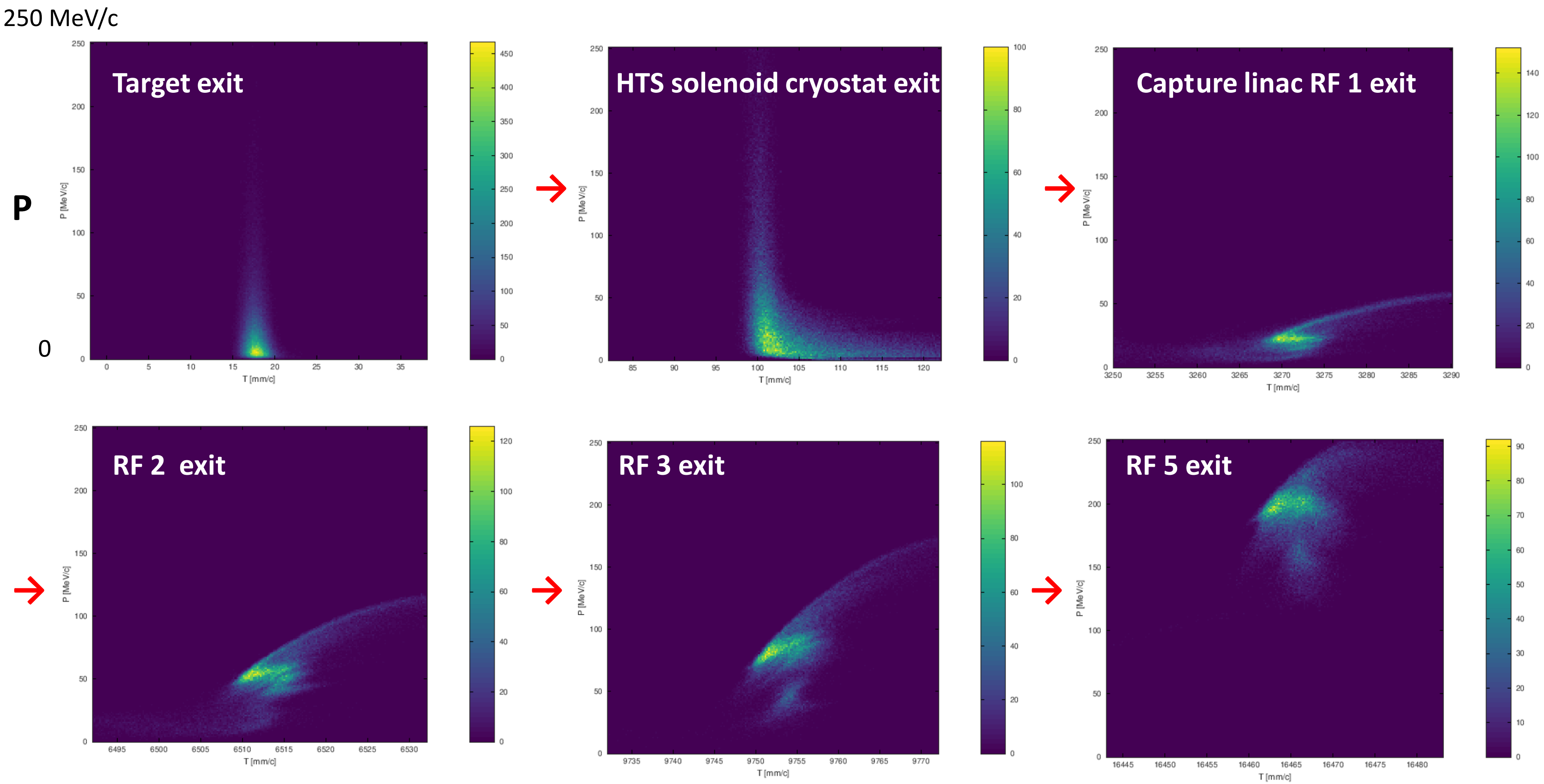


Scan of time cut window length
(±3.8% E acceptance applied)

✓ These are just **analytic** results. Need to check with Mattia (who showed realistic simulations yesterday the emittance seems to be sensitive to E acceptance)

Capture linac (200 MeV)

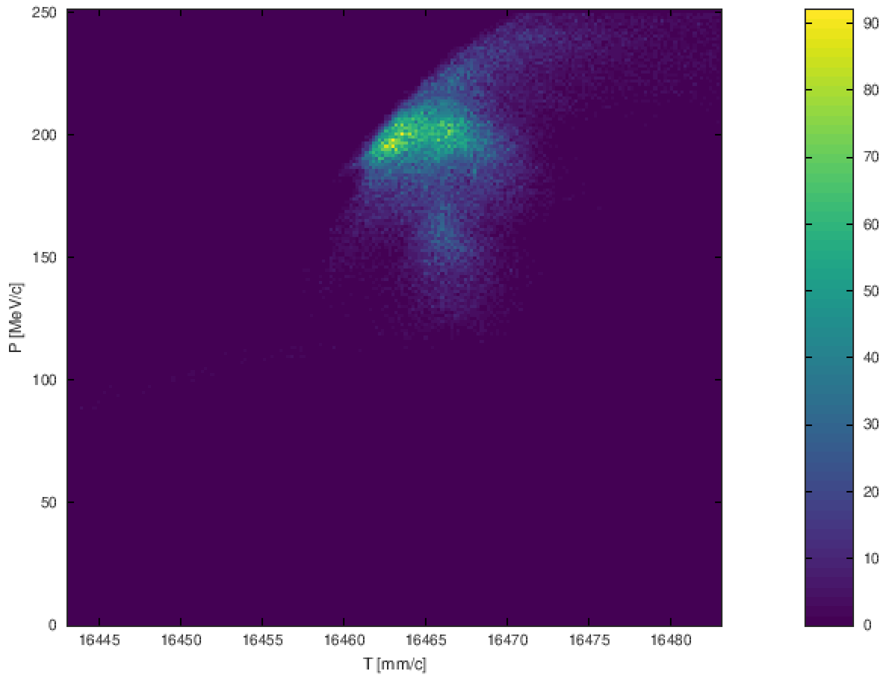
- Longitudinal phase spaces



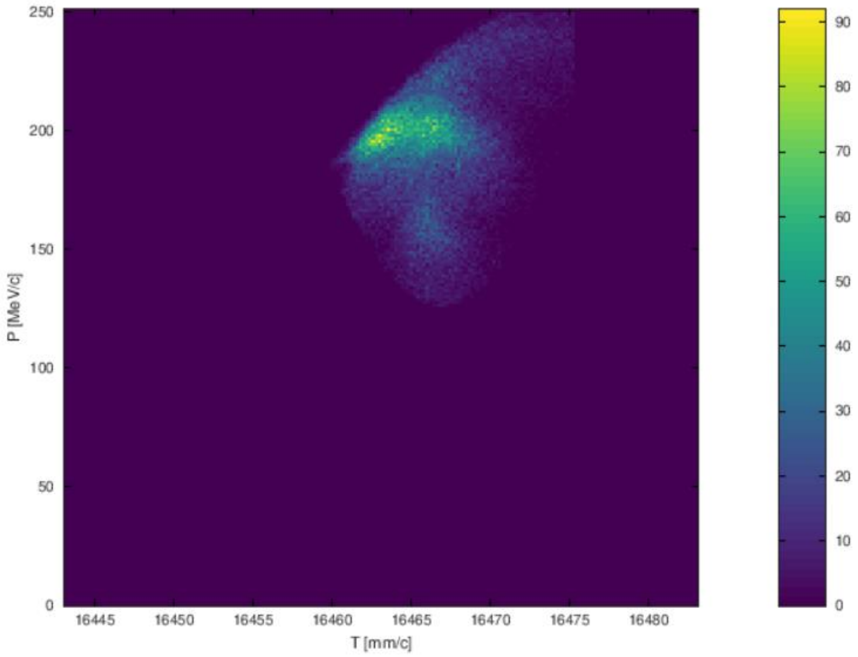
Peak time (±20 mm/c)

Capture linac (200 MeV)

- Longitudinal phase spaces (at the end of capture linac)



All positrons



e+ accepted by DR E & time cut window

Positron linac

- Simulated **longitudinally** with an **analytic** formula:

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

  - Reference energy: ~185 MeV (a bit optimised)
  - Reference time: scanned for max. e+ yield
  - RF frequency: 2 GHz (same with capture linac)

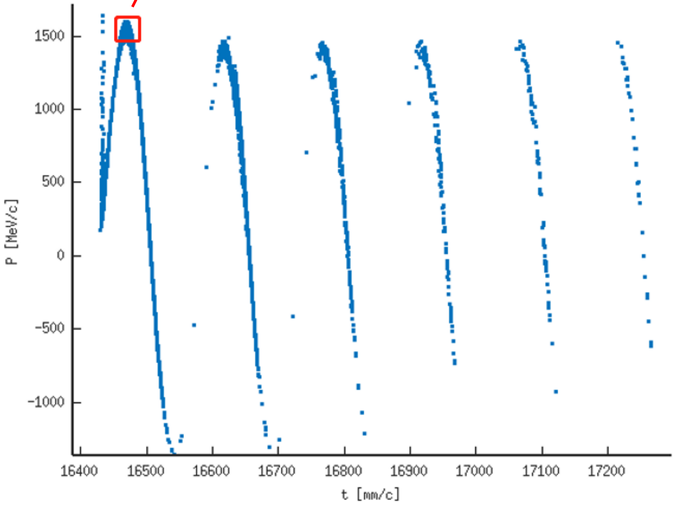
See *M. Schaer*'s talk for more realistic simulations of e+ linac

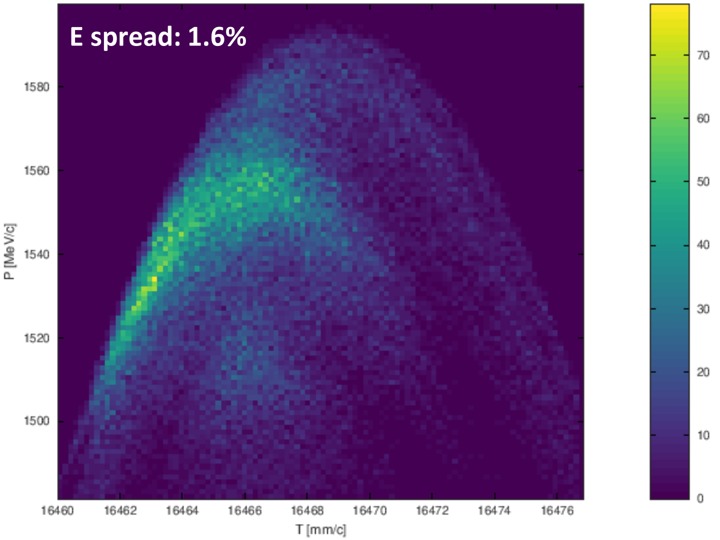
Accepted e+ yield: 6.81

- Longitudinal phase space:

Only E cut: 84.4% e+ selected
Only time cut: 85.4% e+ selected
E & time cut: 83.0% e+ selected

E & time cut window




E spread: 1.6%

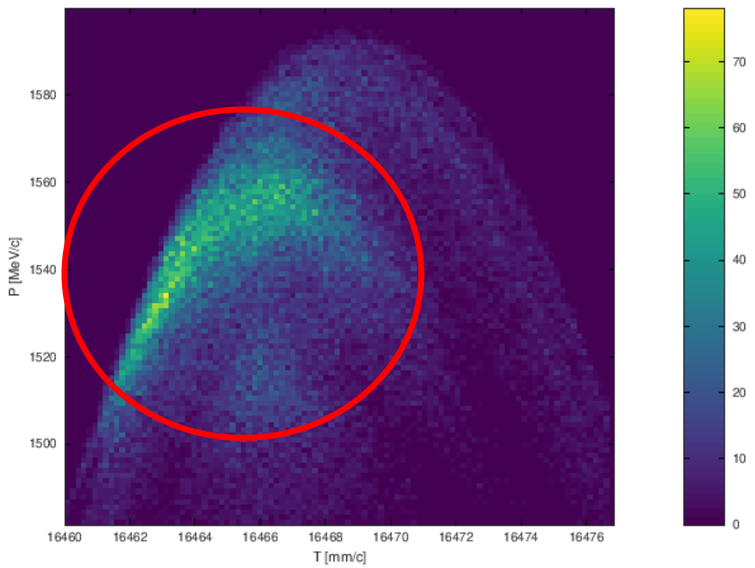
Summary

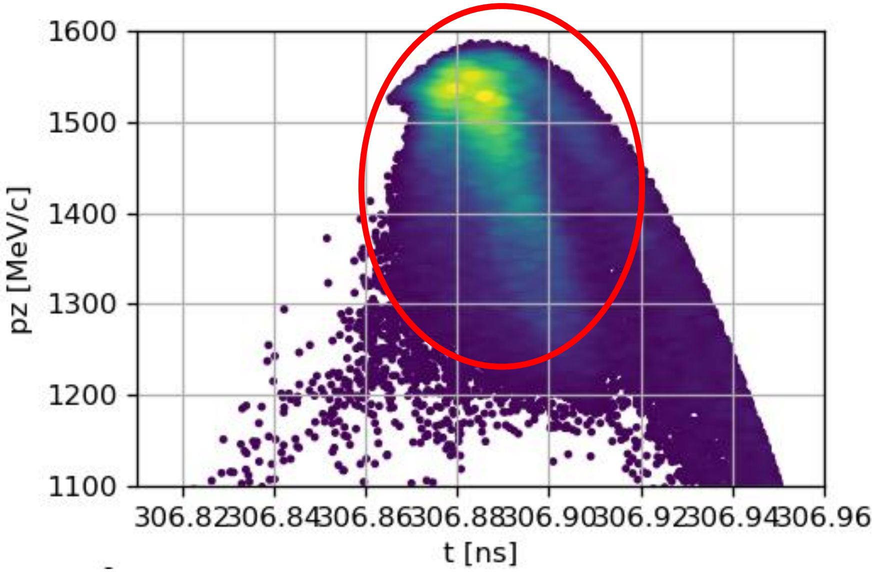
- Simulation of capture system ("**V0**") presented
- **Conventional *W* target** is used
- **HTS solenoid** used as matching device
- New large aperture (R = 30 mm) **TW L-band** (2 GHz) used as capture linac
- Realistic **0.5 T NC solenoid** field used, with layout optimised to improve the field (close to the constant field)
- **Positron linac** (200 MeV -- 1.54 GeV) longitudinally simulated using analytic formula (assuming the same 2 GHz L-band to be used)
- Effective e+ yield accepted by DR: **6.81**

BACKUP

Positron linac

- Some comments to Mattia’s talk yesterday:





Analytic (longitudinally) calculation

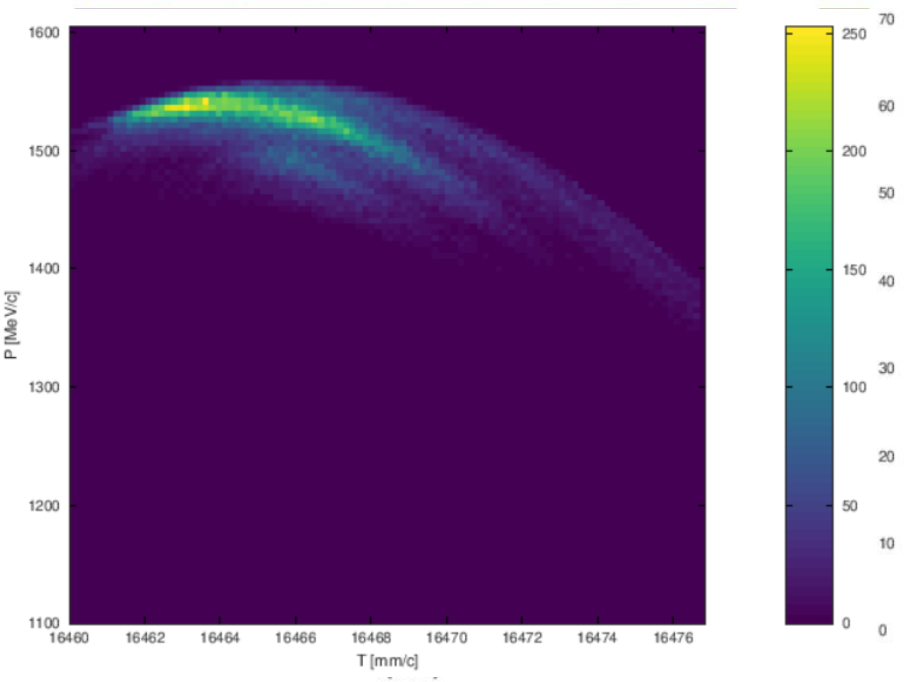
Full simulation by Mattia

- ➢ A possible reason for the difference: I’m actually not doing exactly on-crest acceleration:
  - ✓ reference energy in the formula (not the reference particle energy): E_ref = 184.3 MeV (instead of exactly 200 MeV), which requires ~1.2% higher energy gain or gradient than using 200 MeV
  - ✓ Reference time (same with reference particle time): 16467 mm/c, which gives +9.6° offset in phase (assuming peak time at 16463 mm/c)

Positron linac

- Still analytic results, but using different reference energies and times

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

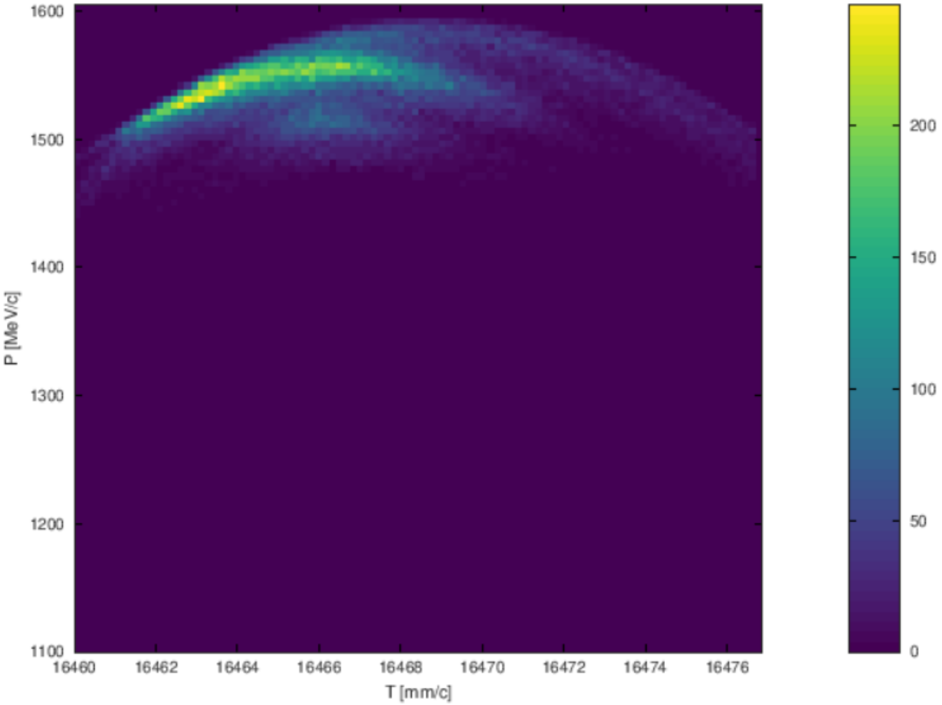


E_ref = 200 MeV

t_ref = 16463 mm/c

(might be different from Mattia)

OK. Effect seems small. Maybe it's not the reason ..



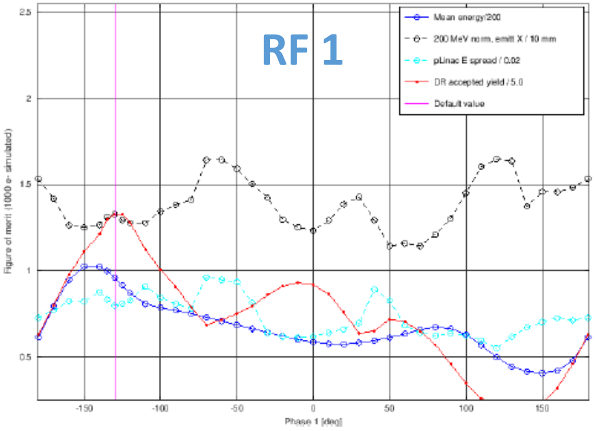
E_ref = 184.3 MeV

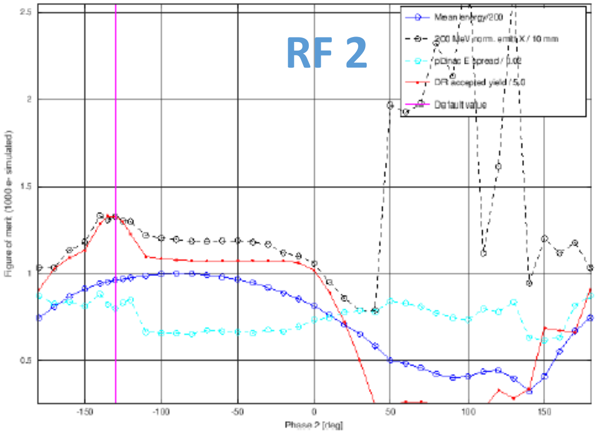
t_ref = 16467 mm/c

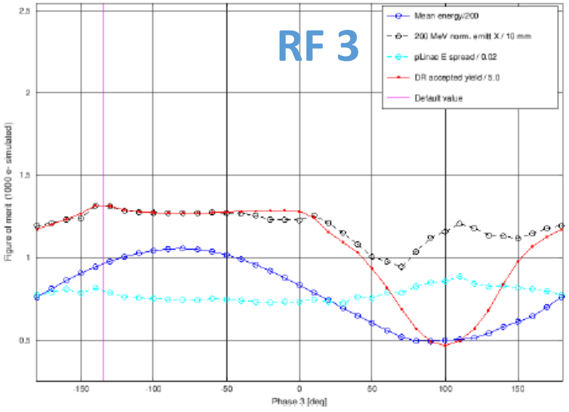
(a bit optimised)

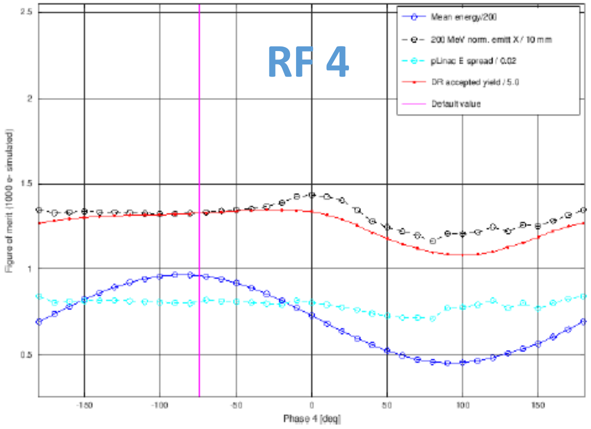
Capture linac (200 MeV)

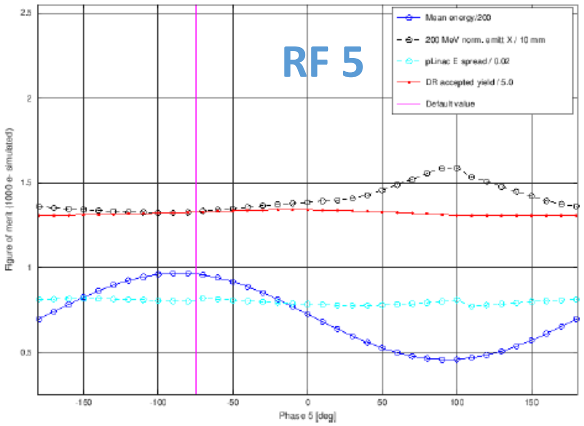
- RF phase optimisation (final iteration of scan)
  - Constant (instead of realistic) solenoid field of 0.5 T assumed











Ref. particle: x=x'=y=y' = 0

t = 248.8 mm/c, P = 100 MeV

Optimised phases:

-130 -130 -135 -75 -75

degrees