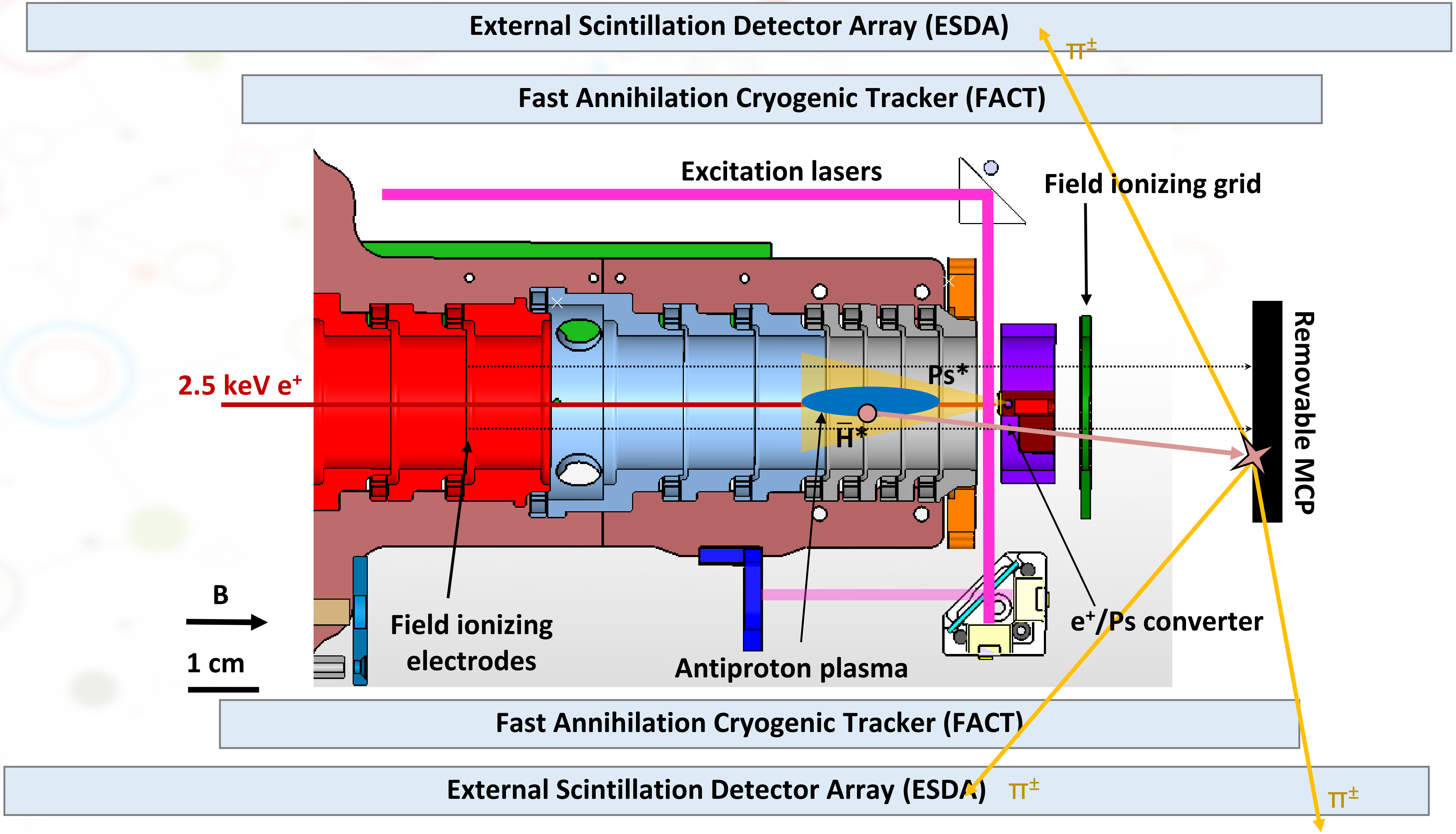
Formation of a forward beam of antihydrogen

Istituto Nazionale di Fisica Nucleare

AEgIS-2 antihydrogen production scheme

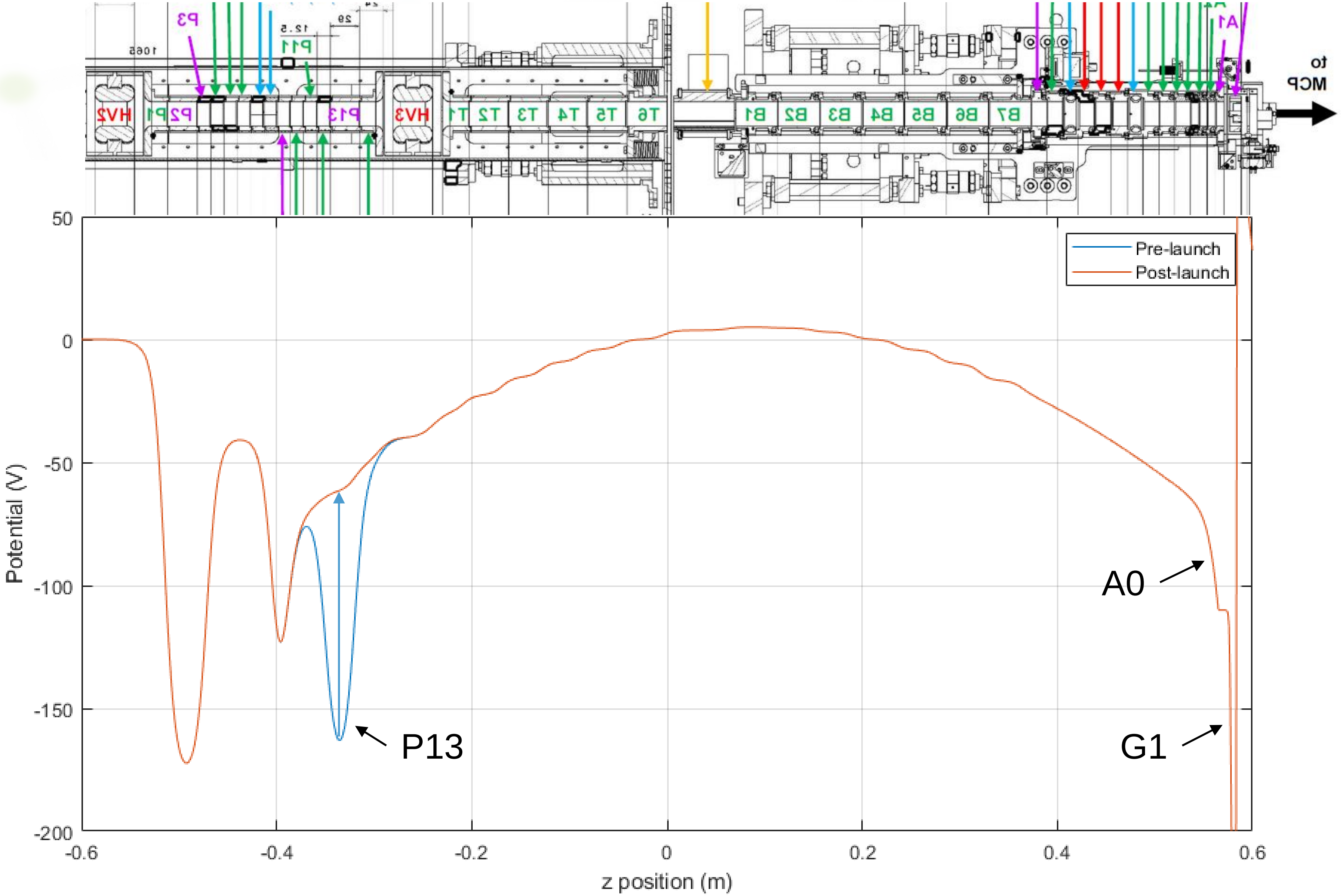

External Scintillation Detector Array (ESDA)

Fast Annihilation Cryogenic Tracker (FACT)

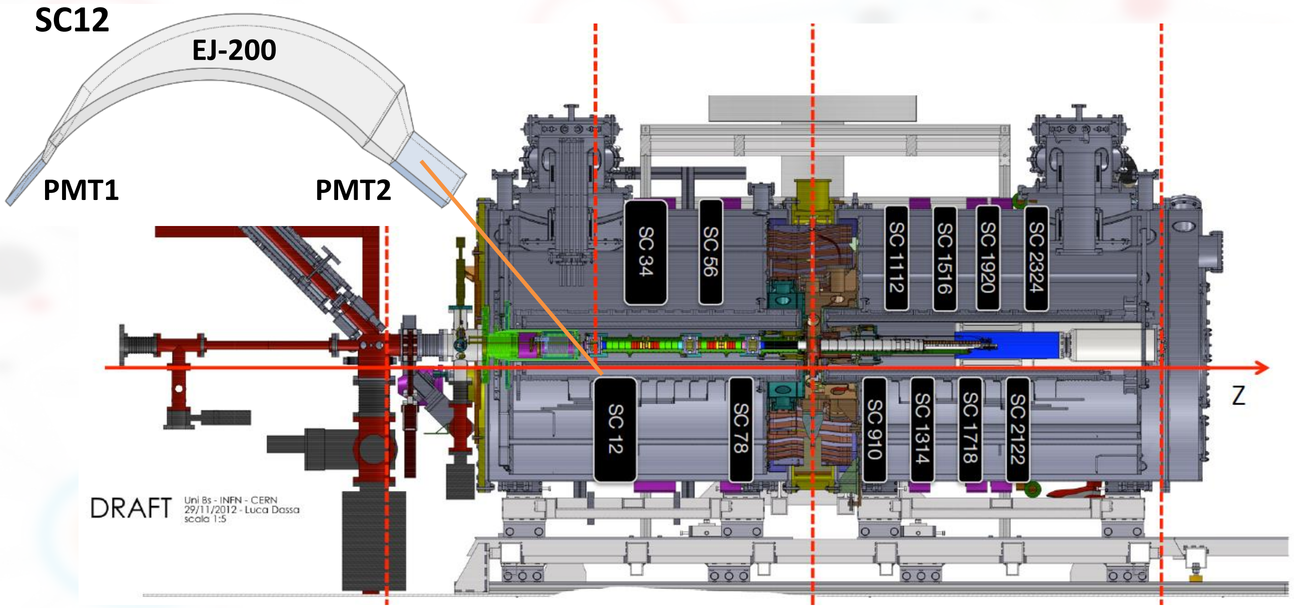
Fast Annihilation Cryogenic Tracker (FACT)

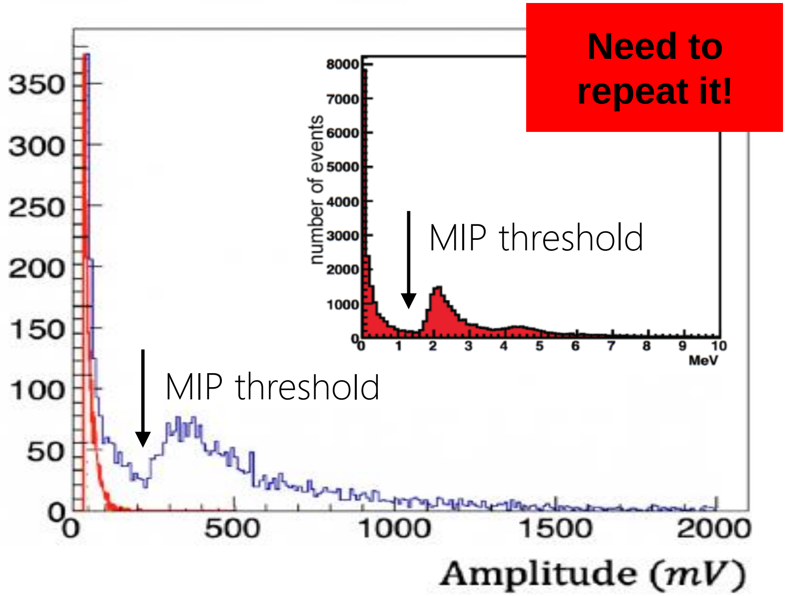
External Scintillation Detector Array (ESDA)

The parabolic transfer potential

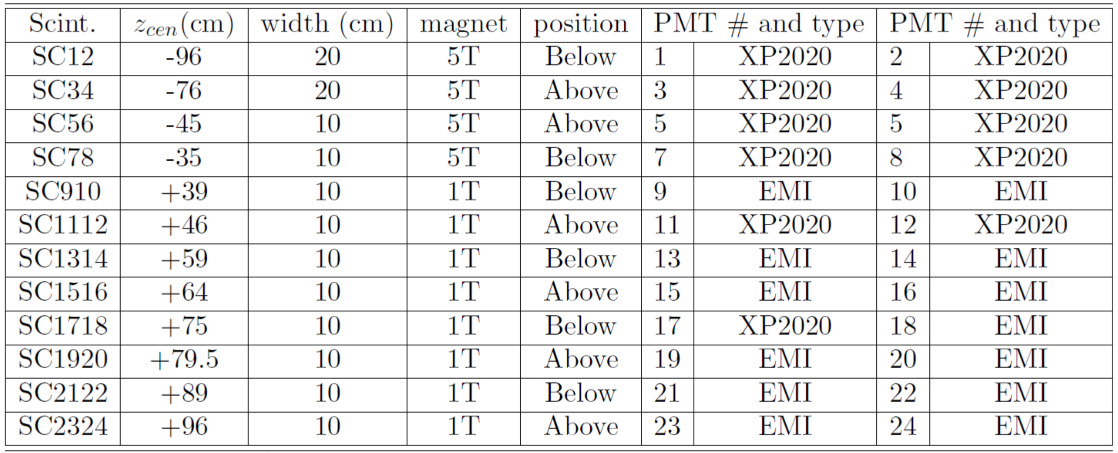


Antihydrogen detector: digitized ESDA





Need to repeat it!



Scint.	z_{cen} (cm)	width (cm)	magnet	position	PMT # and type		PMT # and type	
SC12	-96	20	5T	Below	1	XP2020	2	XP2020
SC34	-76	20	5T	Above	3	XP2020	4	XP2020
SC56	-45	10	5T	Above	5	XP2020	5	XP2020
SC78	-35	10	5T	Below	7	XP2020	8	XP2020
SC910	+39	10	1T	Below	9	EMI	10	EMI
SC1112	+46	10	1T	Above	11	XP2020	12	XP2020
SC1314	+59	10	1T	Below	13	EMI	14	EMI
SC1516	+64	10	1T	Above	15	EMI	16	EMI
SC1718	+75	10	1T	Below	17	XP2020	18	EMI
SC1920	+79.5	10	1T	Above	19	EMI	20	EMI
SC2122	+89	10	1T	Below	21	EMI	22	EMI
SC2324	+96	10	1T	Above	23	EMI	24	EMI

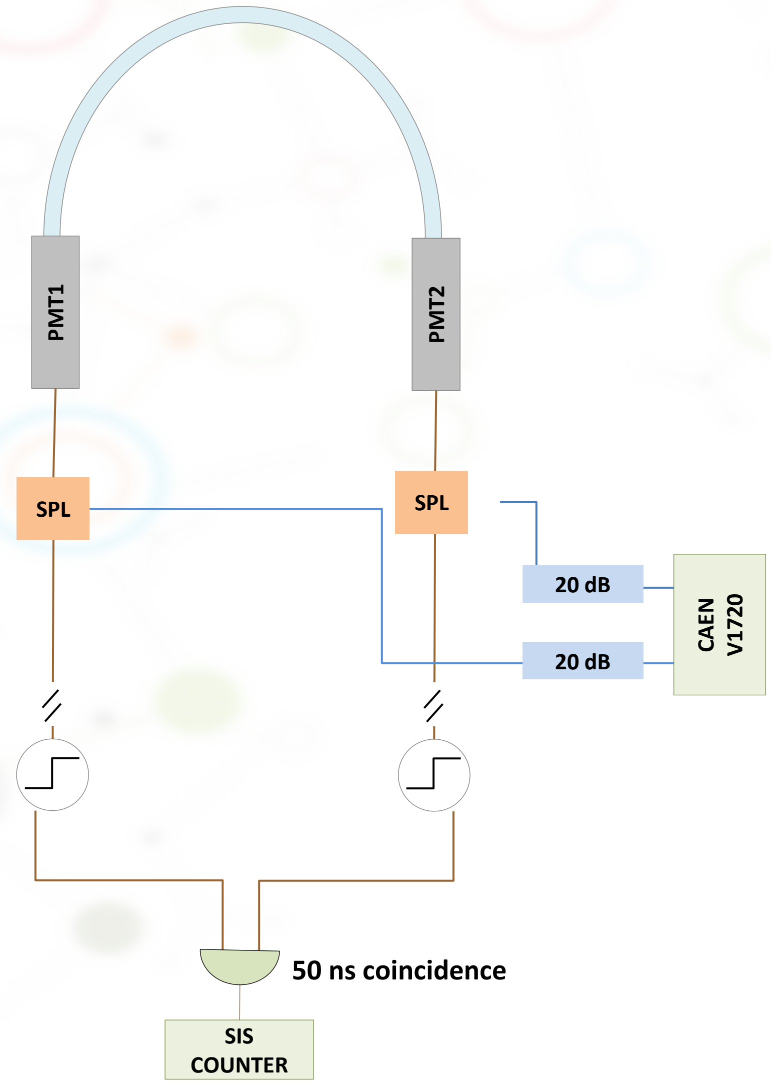
TABLE 1. AE$\bar{g}$IS external scintillators and their respective PMT setup.

Scintillator array for MIP detection

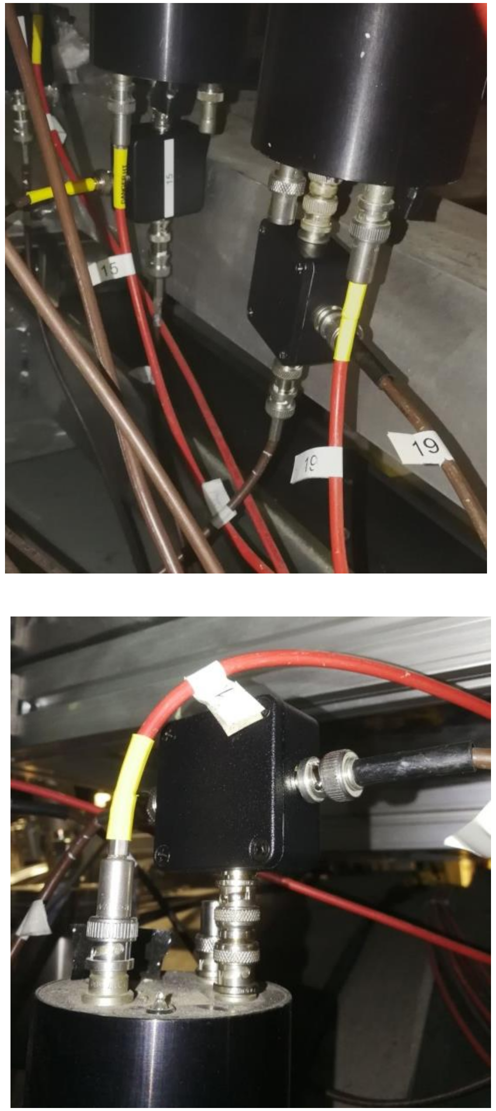
- 4+8 x EJ-200 scintillator slabs
- PMT reading on both ends for coincidences
- Each PMT digitized at 250 Ms, 12 bit
- Software **coincidence** to reject PMT noise
- Amplitude cut to reject **gamma background**

The ESDA digitized acquisition chain in 2023

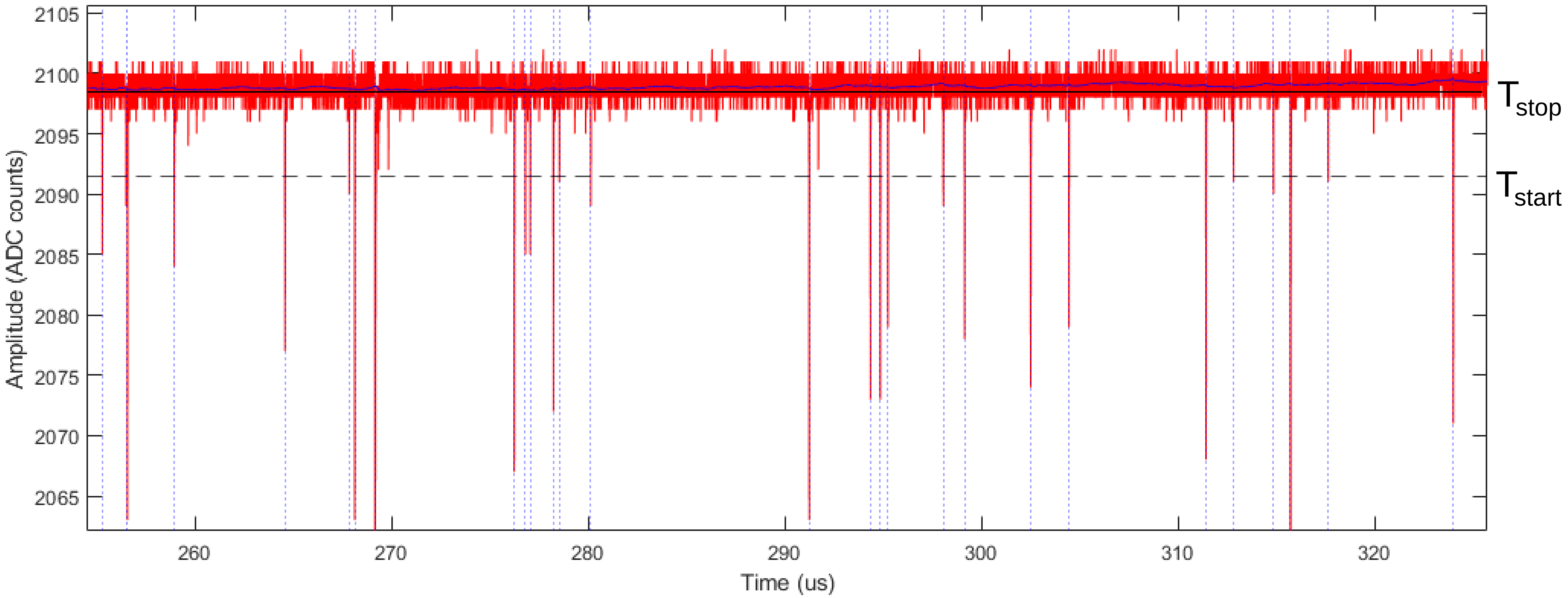
ESDA single slab, 2024 config



- **Standard setup**
  - A 50/50 splitter for each 24 PMT (8 PMT @5Tesla, 16 PMT @1Tesla)
  - Splitter connected directly to PMTs output to minimize ringing due to impedence mismatch
  - **CAEN-digitized r/o**: Other end acquired with 20 dB attenuation and CAEN 1720 250 Ms 12 bit digitizer
  - **SIS-discriminated r/o**: two PMTs of the same slab connected to 50ns coincidence unit + SIS counter
- **SC1920 exception**
  - Standard splitter at both PMTs
  - **CAEN-digitized r/o** as above
  - **No SIS-discriminated r/o on PMT20**
  - **LeCroy-digitized r/o on PMT20:** the second end of the splitter is acquired with 50/50 splitter by LeCroy 2.5 Gs 12 bit oscilloscope ‘Captorius1’



Software trigger and event discrimination



Baseline follower

- Removes HV fluctuations

Threshold discriminator with hysteresis and hold-off

- Robust to noise fluctuat.
- Avoids re-triggersd

Assemble event list

- Compute event charge
- Start time with linear interp.

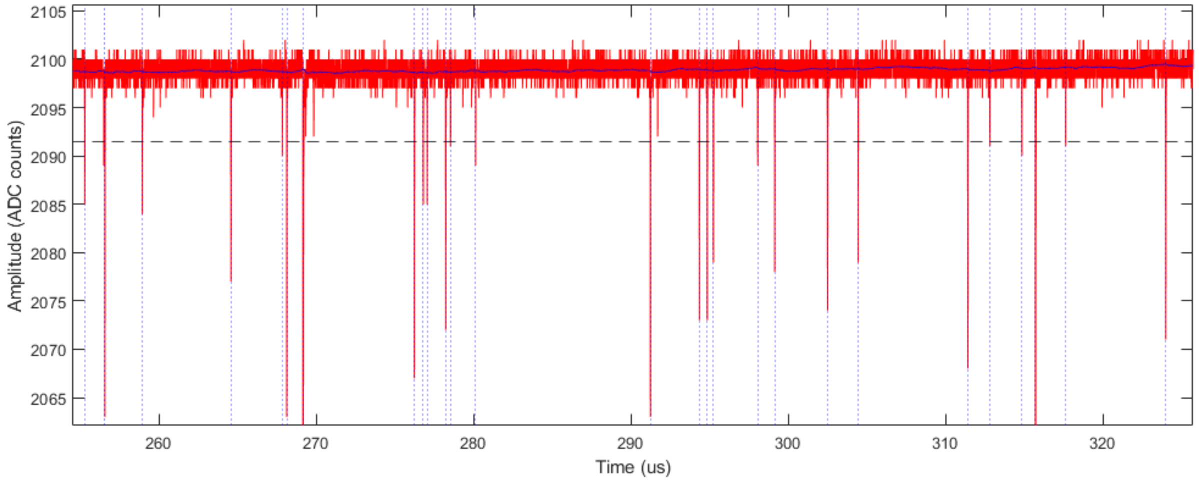
baseline_val = 0.005 .* A(i)
(1.0 – 0.005) * baseline_val

T_{start} = 10 adc, T_{stop} = 1 adc
hold-off = 0.1 us

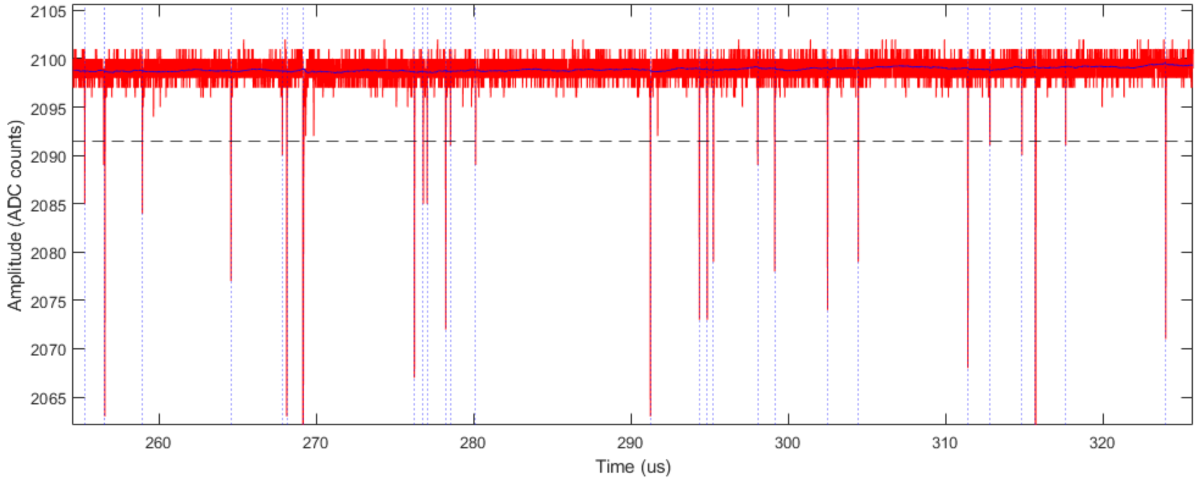
Event: pmt, t_start, t_end, A_peak, charge

Coincidence formation within the same slab

PMT$_n$



PMT$_{n+1}$



Coincidences formation

- AND on the single PMT events
- 50 ns coincidence window

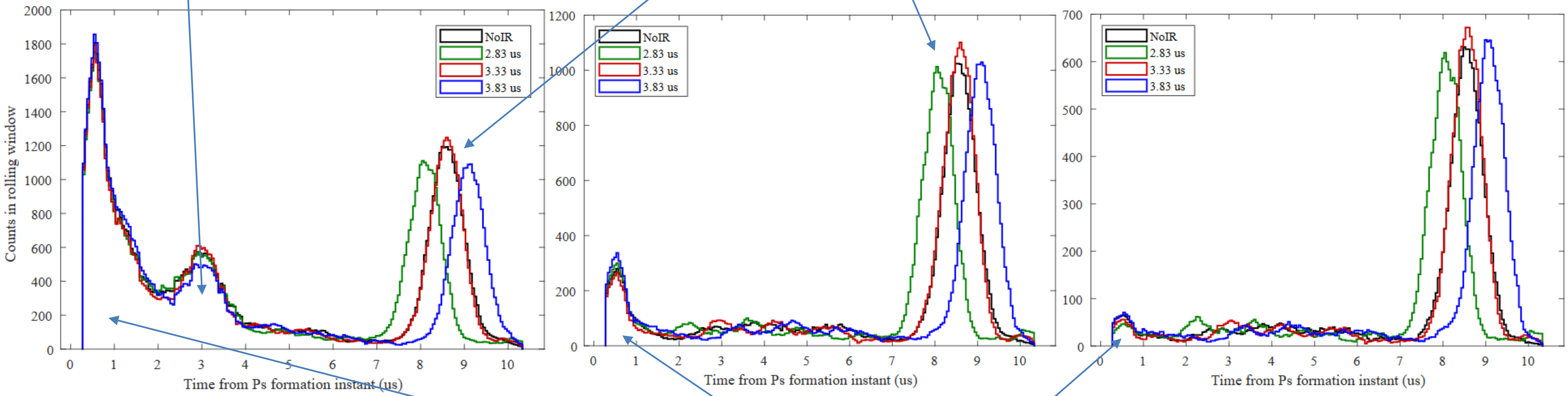
List of coincident events

- Average time-of-arrival
- Time difference between PMTs
- Average deposited charge
- Average amplitude

Example: effect of coincidence formation and amplitude/charge cutting

Cancelling of PMT afterpulses

No efficiency loss to pbar/Hbar detection



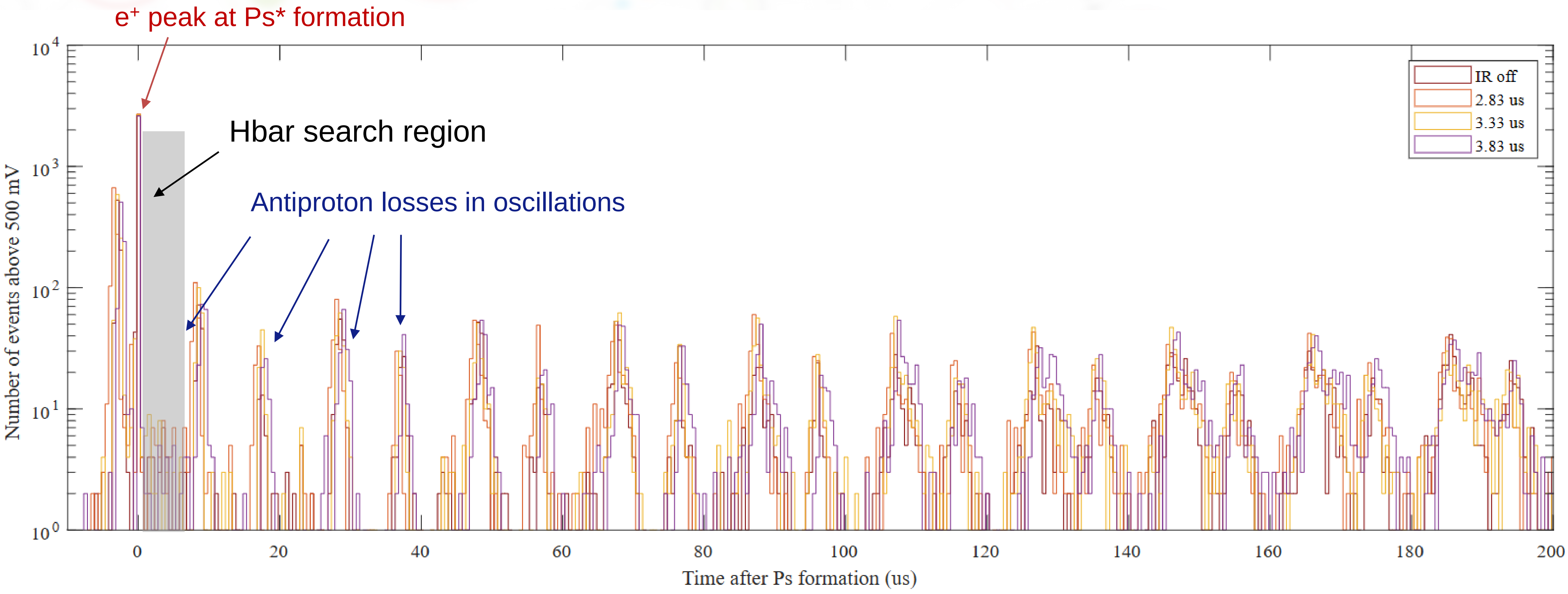
No coincidence, no charge cut

Coincidence, no charge cut

Coincidence, charge cut

Reduction in gamma ray background

Example signal: a beautiful observation of antiprotons swinging



e$^+$ peak at Ps* formation

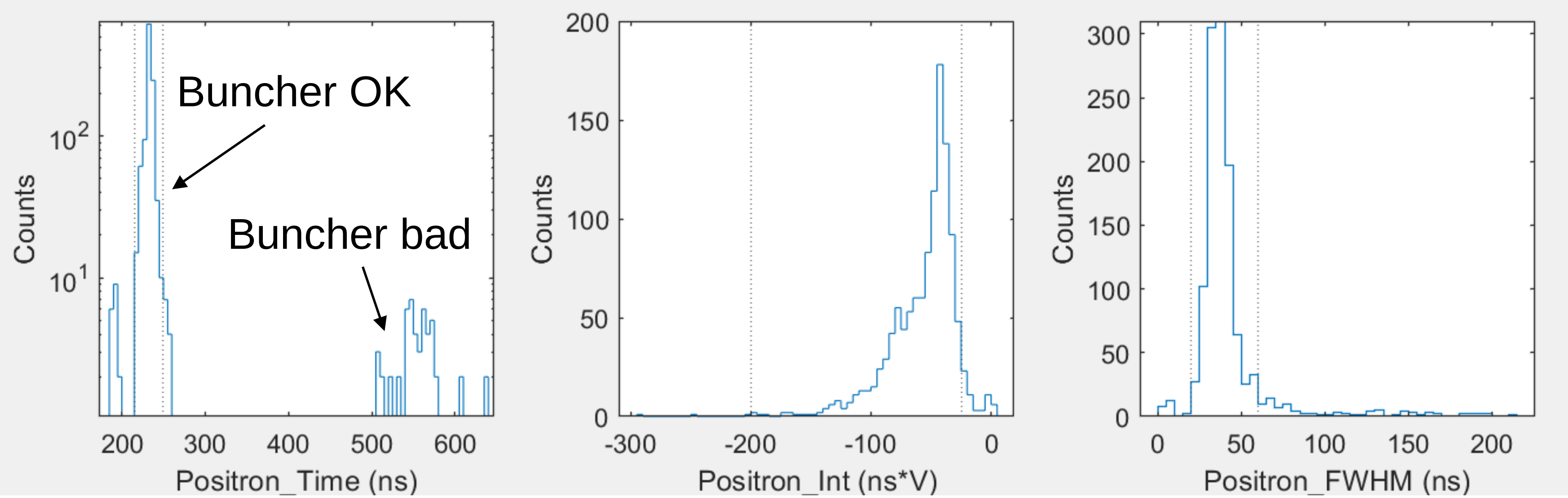
Hbar search region

Antiproton losses in oscillations

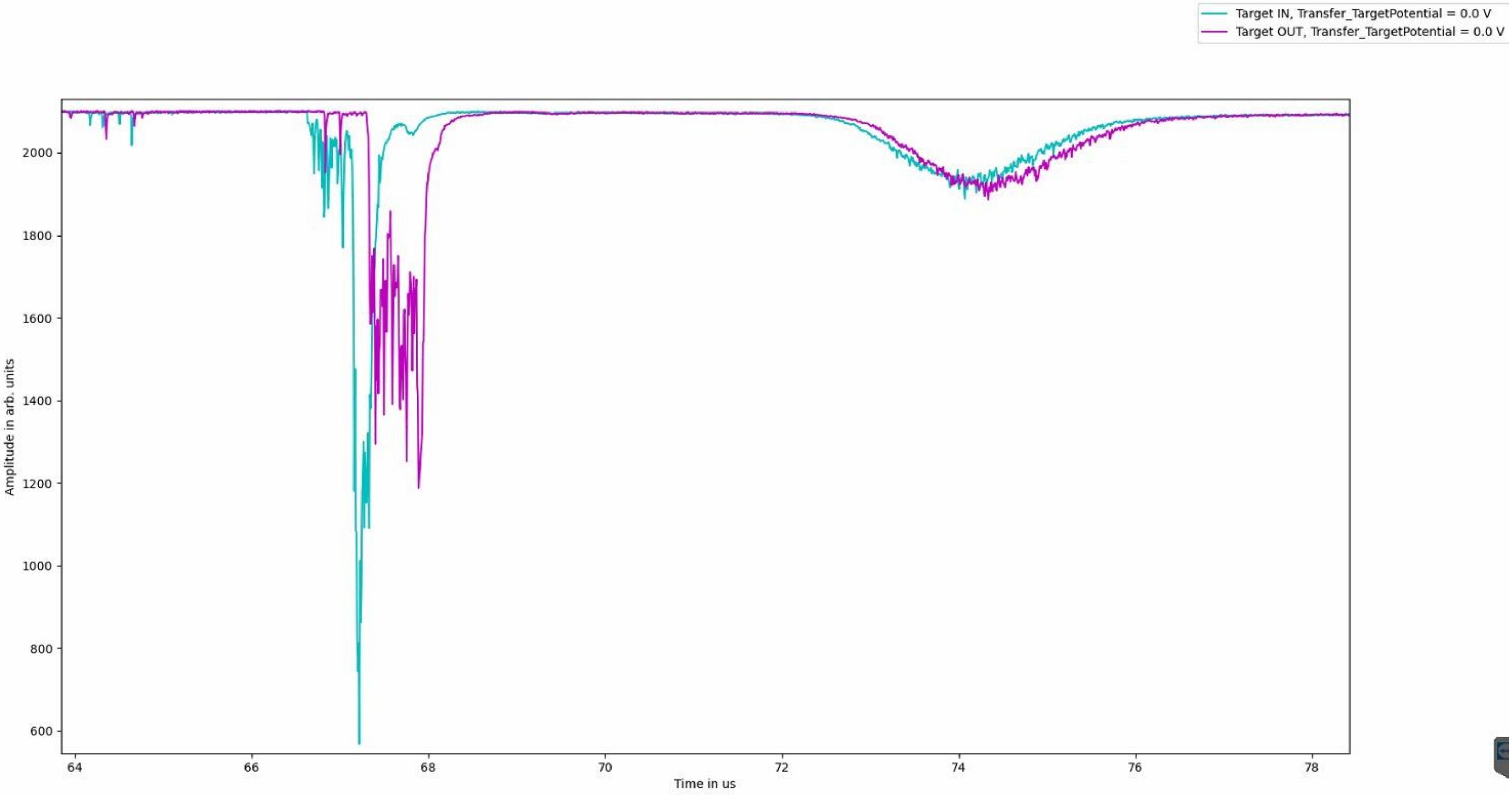
ANTIPROTON/POSITRON SYNC

Step 0: positron impact on target

- The timing on the PMTDigi is **stably 70.7 us**
- Checked manually for sure more than 10/20 runs over the entire dataset
- Captorius1 statistics on positron stability says it’s stable for all the runs with buncher on
- Stability analysis of the positron arrival on the target on PMTDigi

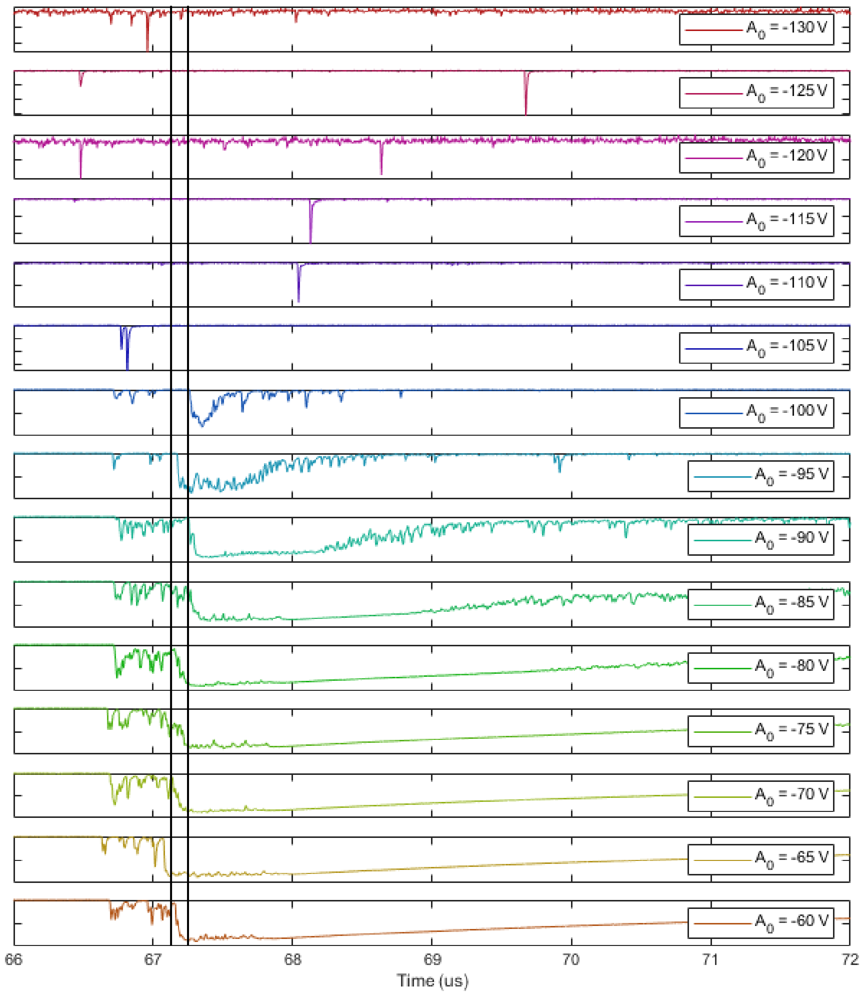


Coarse localization in time of the antiproton peak

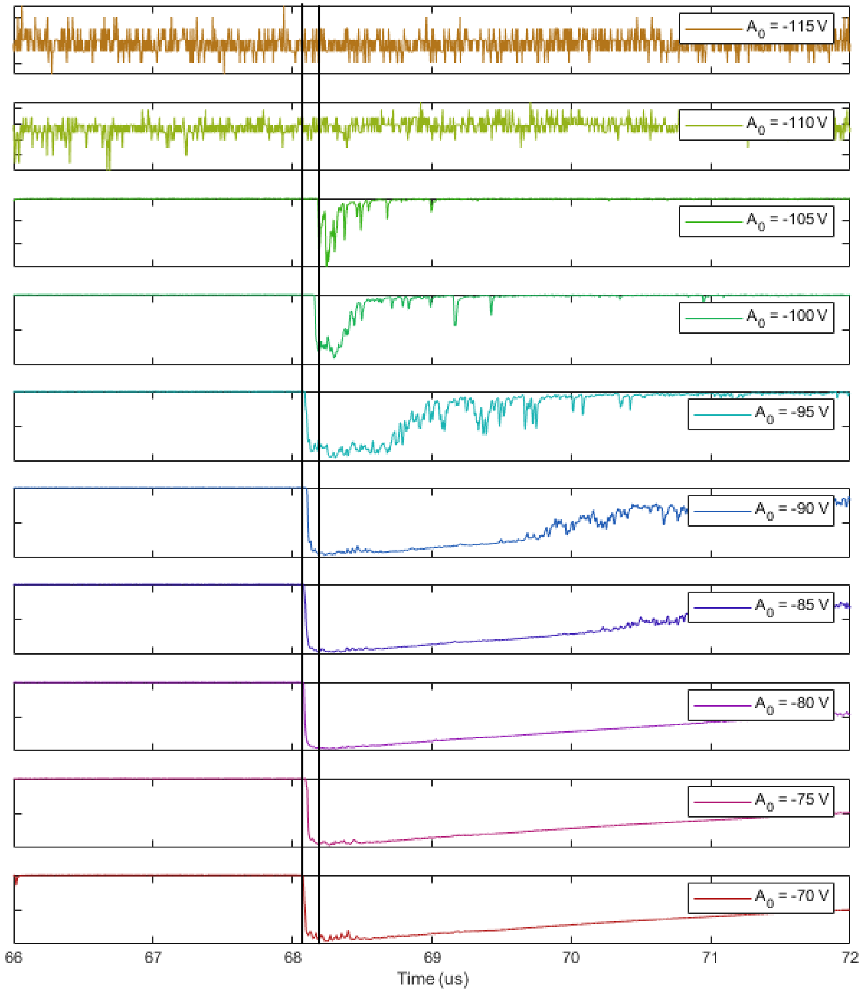


Calibration of antiproton timing

2023



2024

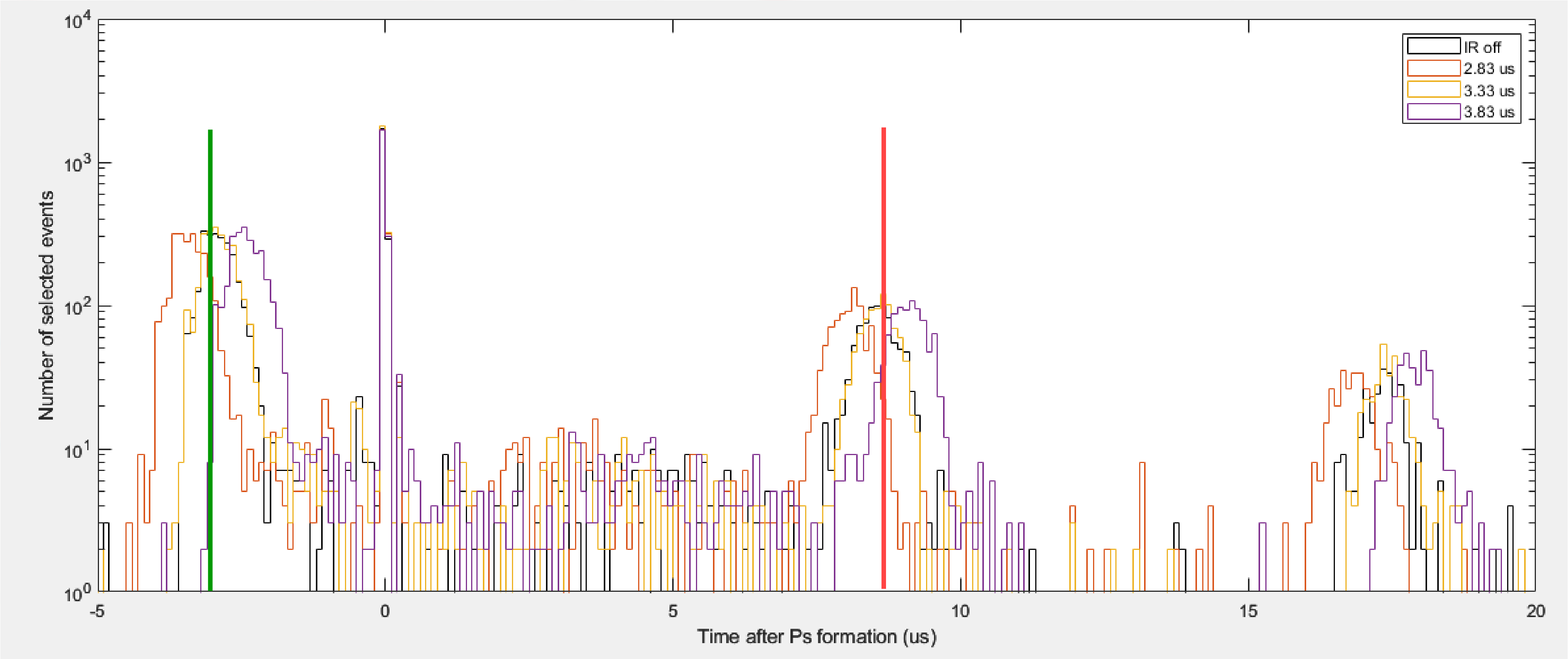


Calibration of antiproton hitting the target by measuring the **Raising edge timing**:
Temptative uncertainty around 100 ns

2023

LOOKING FOR ANTIHYDROGEN

A beautiful observation of antiprotons swinging



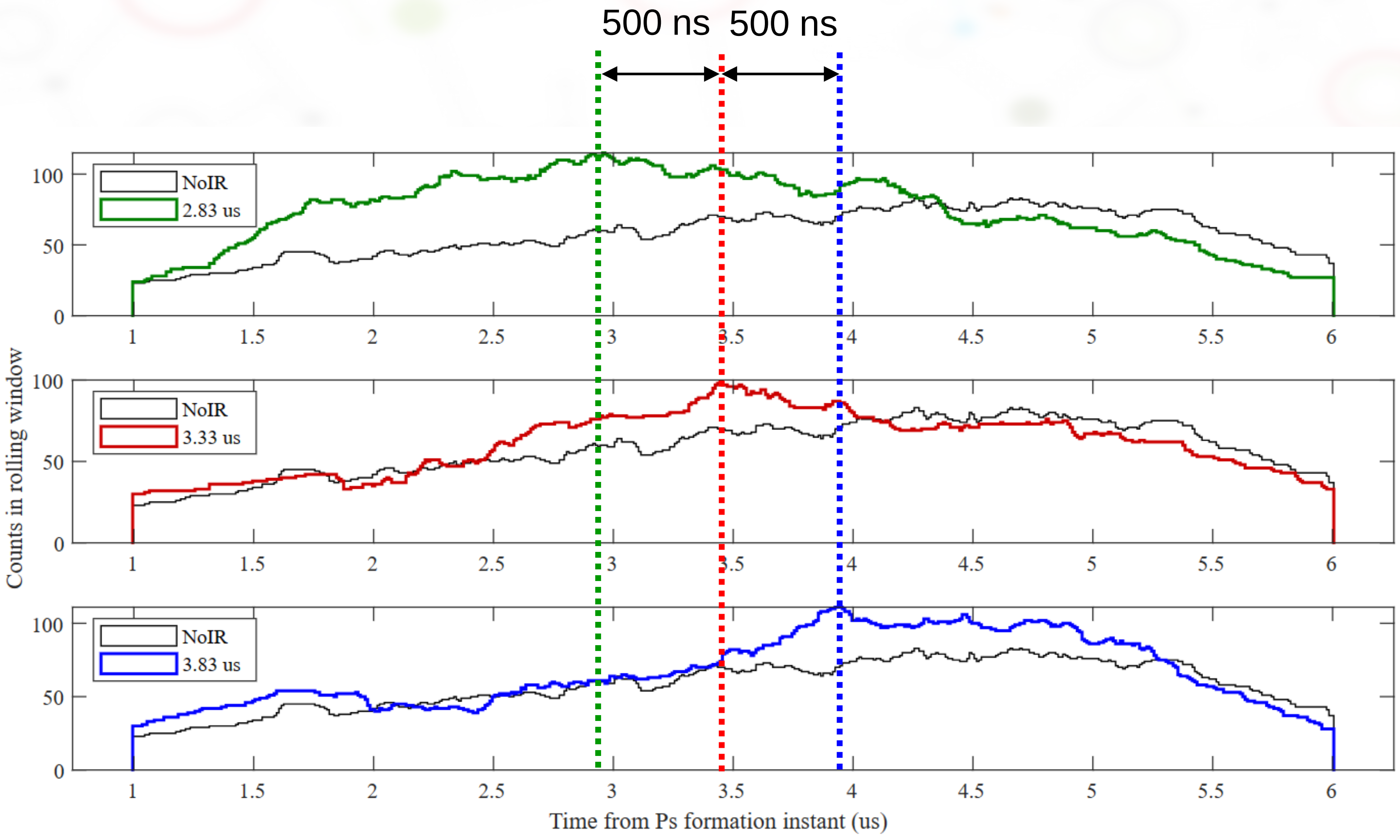
→ From 5T to 1T

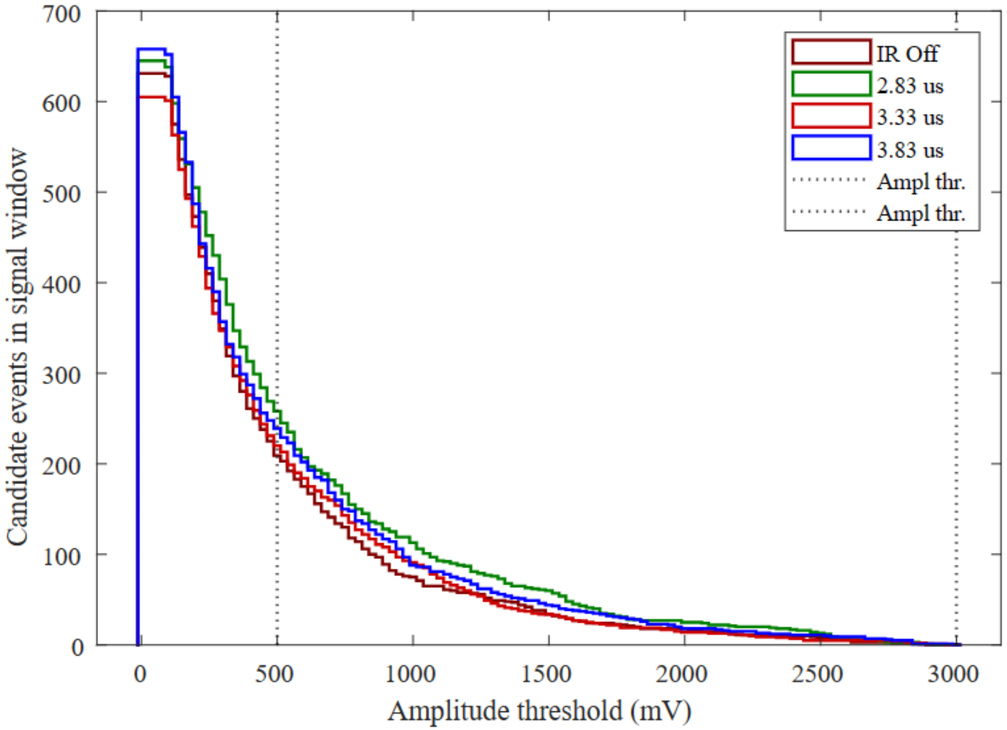
← From 1T to 5T

▪▪▪▪▪ Midpoints

Hypothetical conclusion: time calibration procedure was off by us
we were always sending positrons too early, i.e. with a forward boost

Evidence of some antihydrogen produced in 2023





All antihydrogen was hitting obstacles in the production region

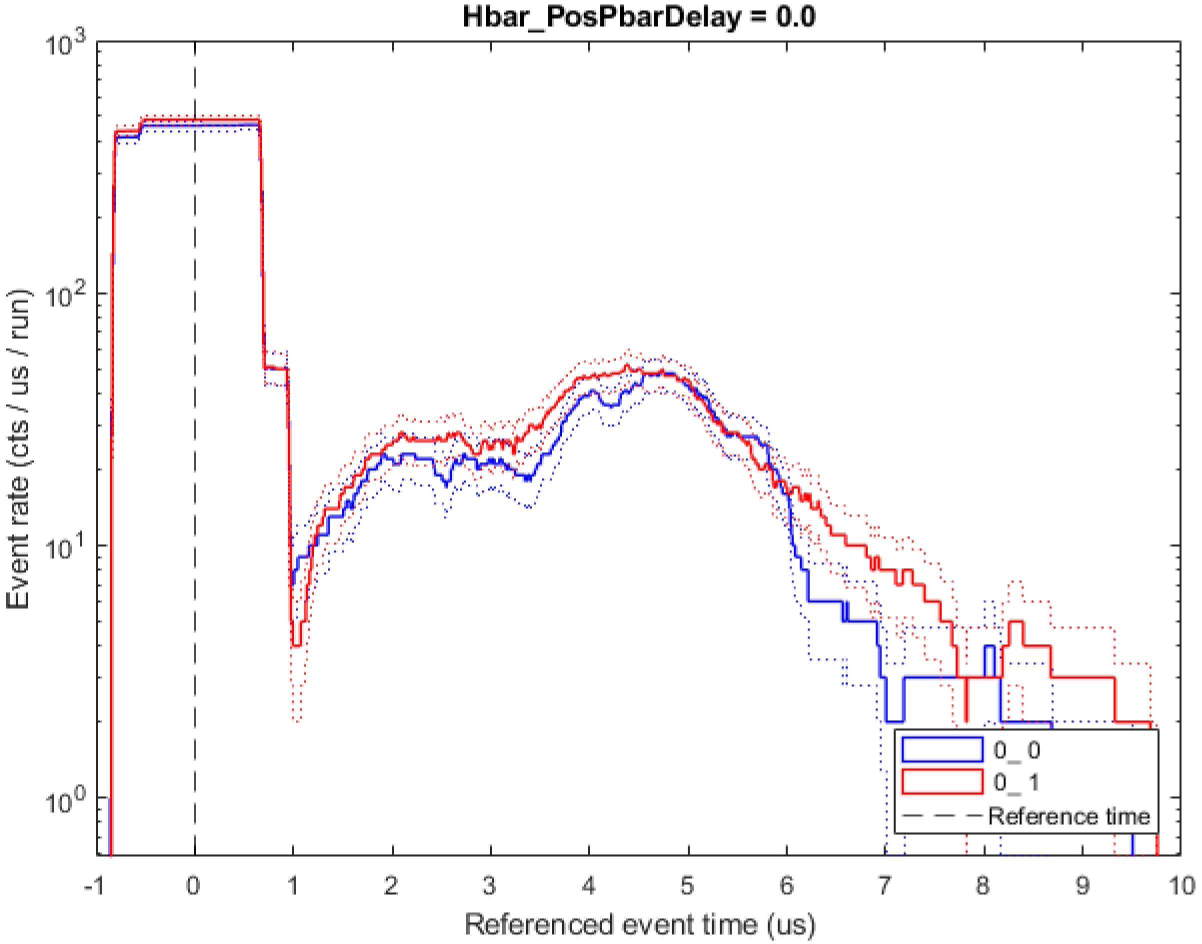
Antihydrogen 2024 dataset summary

Dataset	IonGrid	Setting	Comment
HbarLog154	OUT		No Ps
HbarLog155	OUT		No Ps
HbarLog156	OUT		No Ps
HbarLog157	OUT	2/3/4	No Ps
HbarLog158	OUT		No Ps
HbarLog159	YES		No Ps
HbarLog161	**YES**		**No pbars**
HbarLog163	**YES**	**0 us**	
HbarLog164	**YES**	**-1 us**	
HbarLog165	**YES**	**-2 us**	
HbarLog166	**YES**	**-3 us**	
		-4 us	
HbarLog167	YES		Centr. sep.
HbarLog168	YES		Centr. sep.
HbarLog170	YES		Centr. sep.

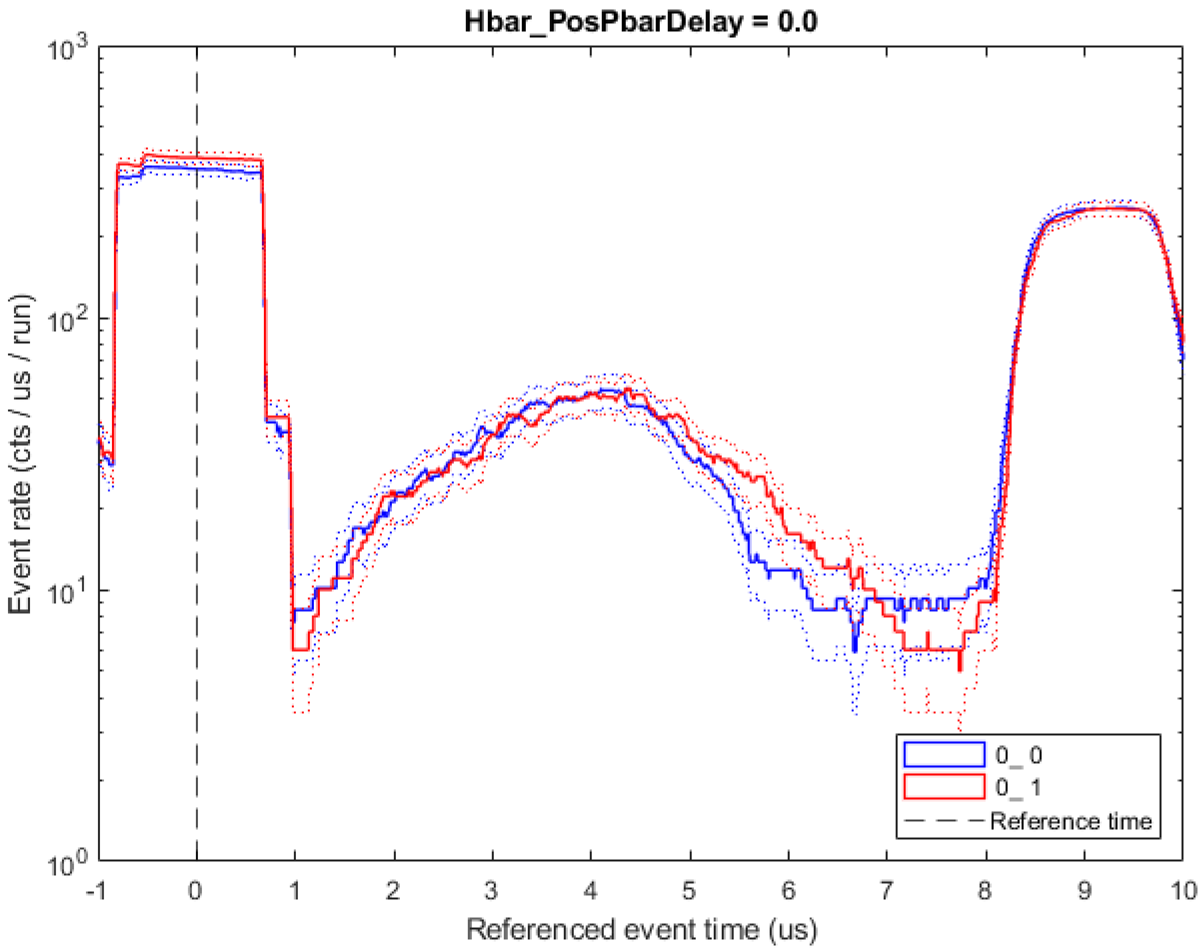
Analysis ToDo

- PMTDigi
  - Discriminated events
  - Analog excess
- PCOEdge
  - Search for tracks
  - Analog excess
- Captorius 1
  - 1TMCP search for events
  - 1TMCP analog excess
- Captorius 3
  - UV amplitude & timing
  - Amount of e^+ and Ps
  - SSPALS laser excit.
- Avantes
  - Calibration & IR bandwidth
- SIS
  - Antiprotons at Catch
  - Antiprotons at HD
  - Antiprotons in Swing
  - Hbar search?

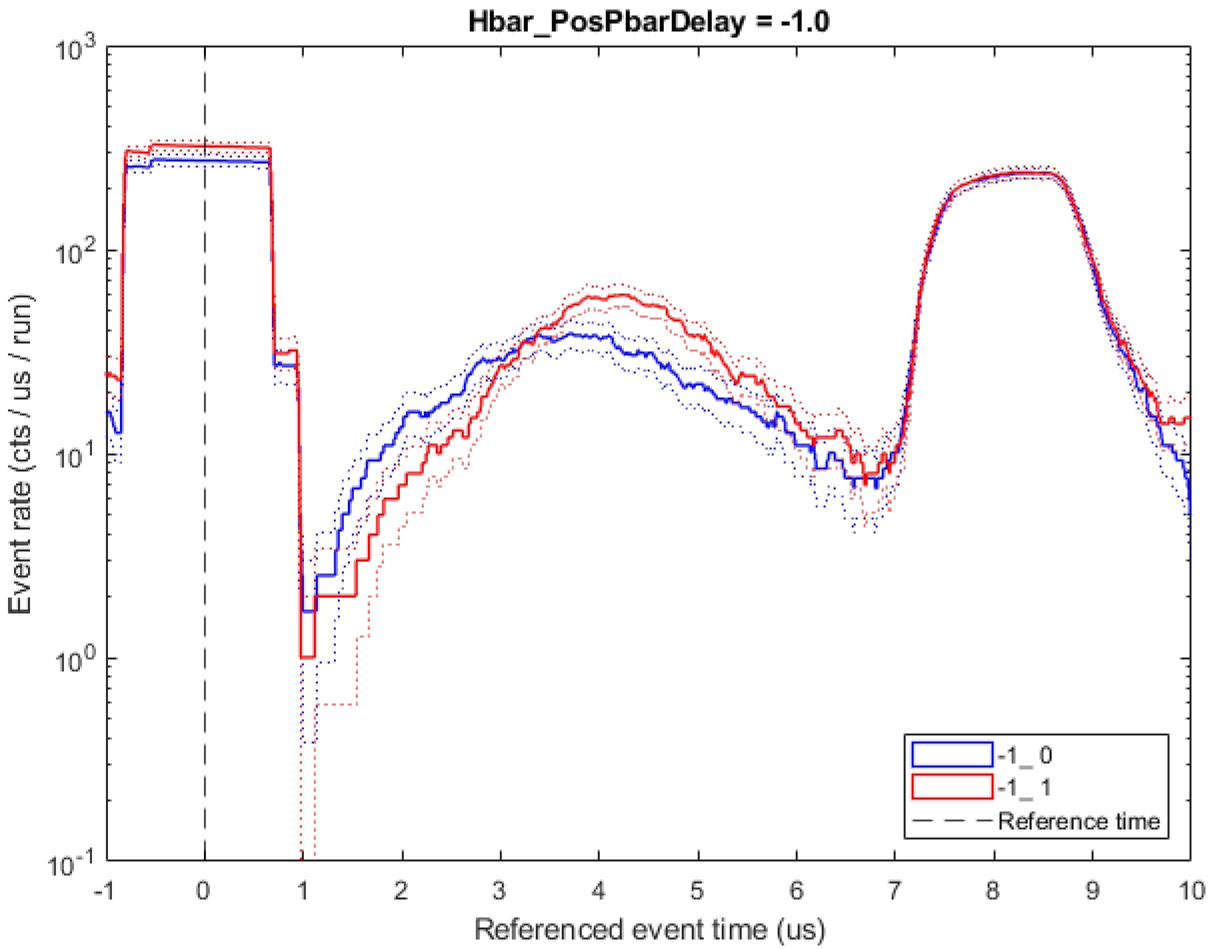
RunLog161 – background (no pbars)



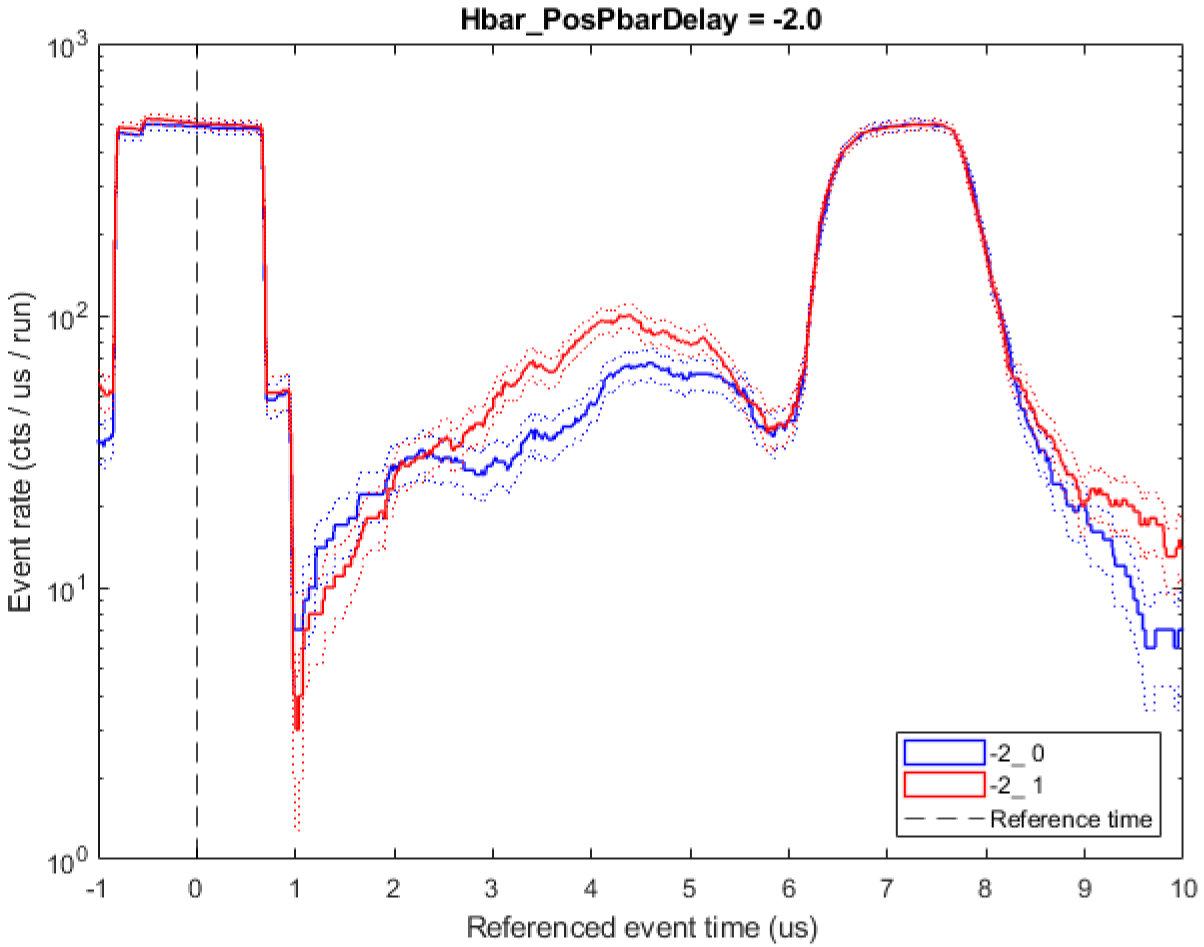
RunLog163 – very late antiprotons



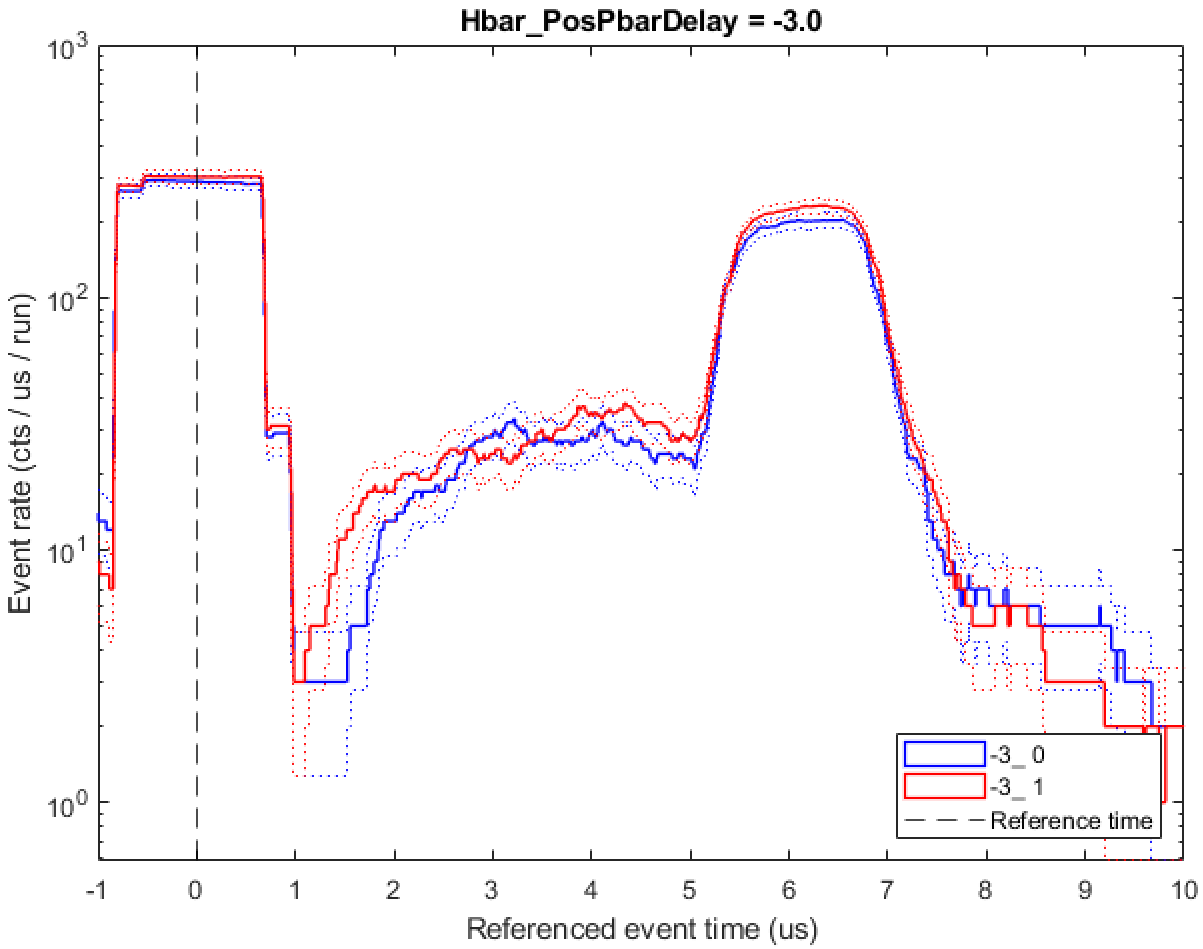
RunLog164 – late antiprotons



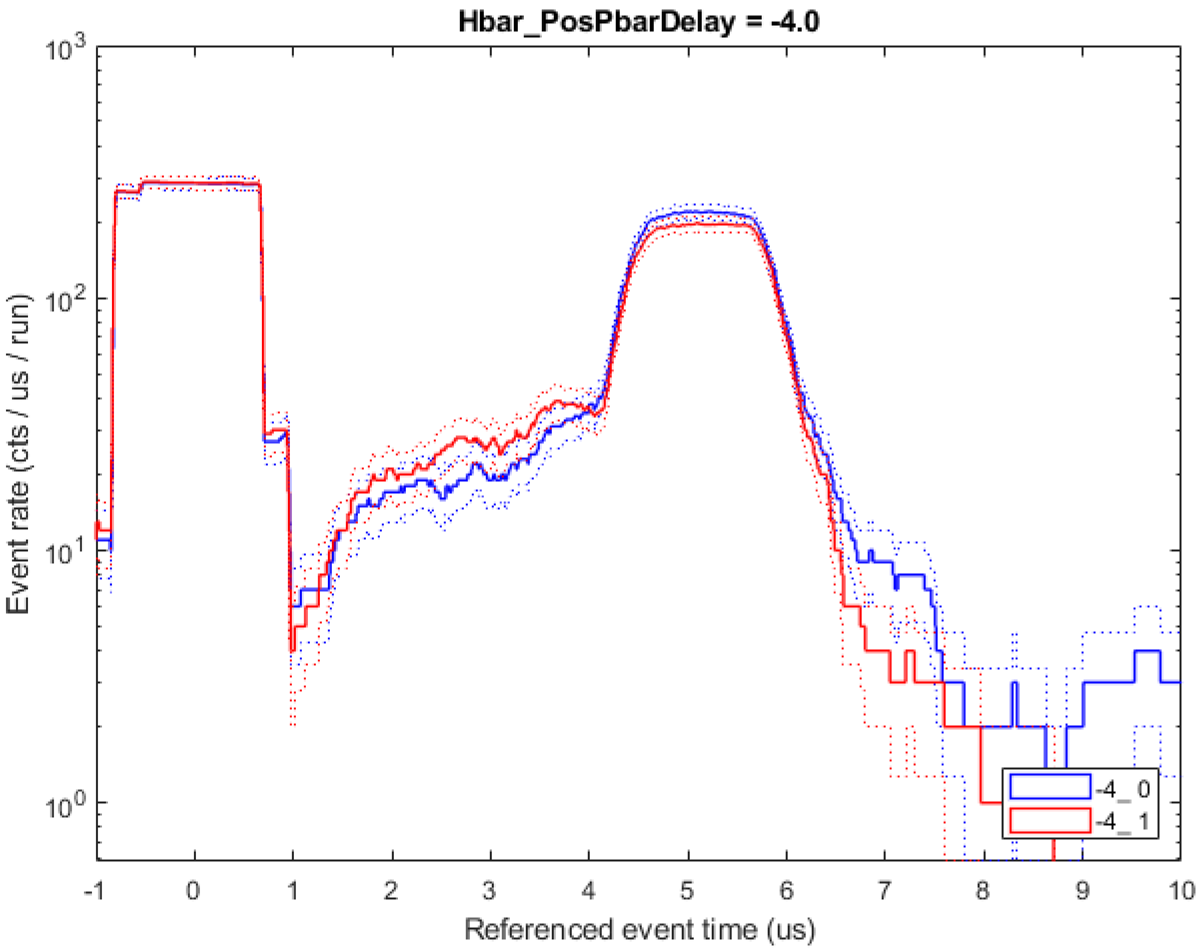
RunLog165 – early antiprotons



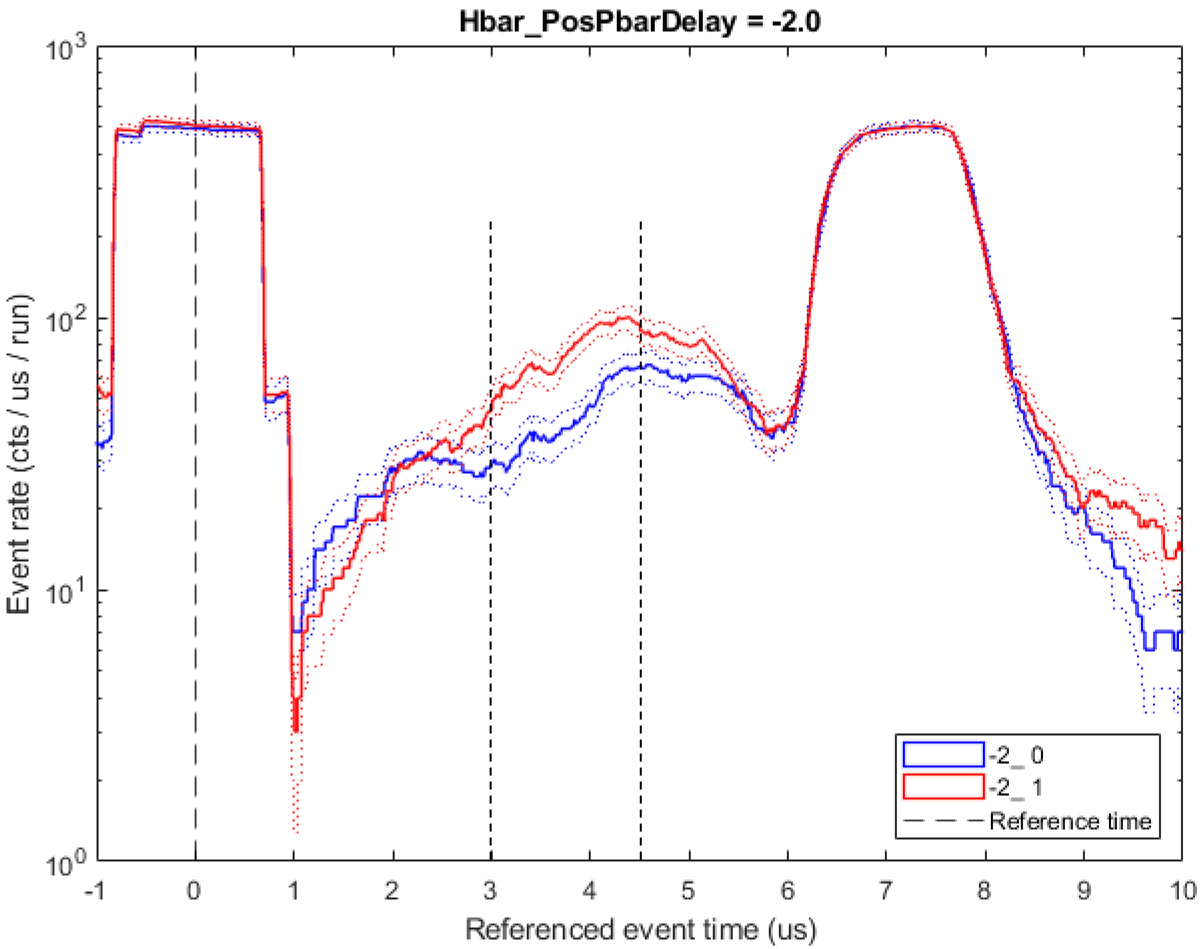
RunLog166a – very early antiprotons

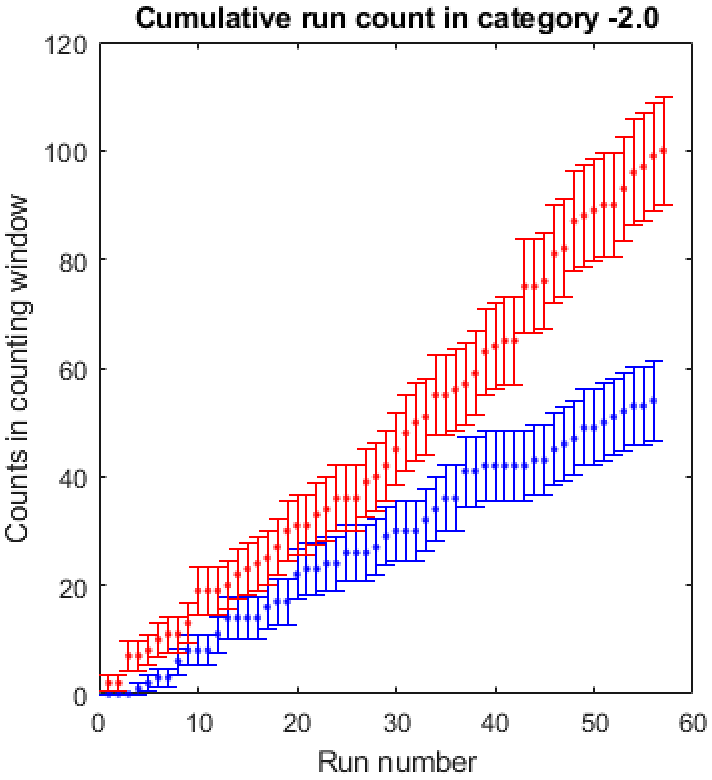


RunLog166b – even earlier antiprotons

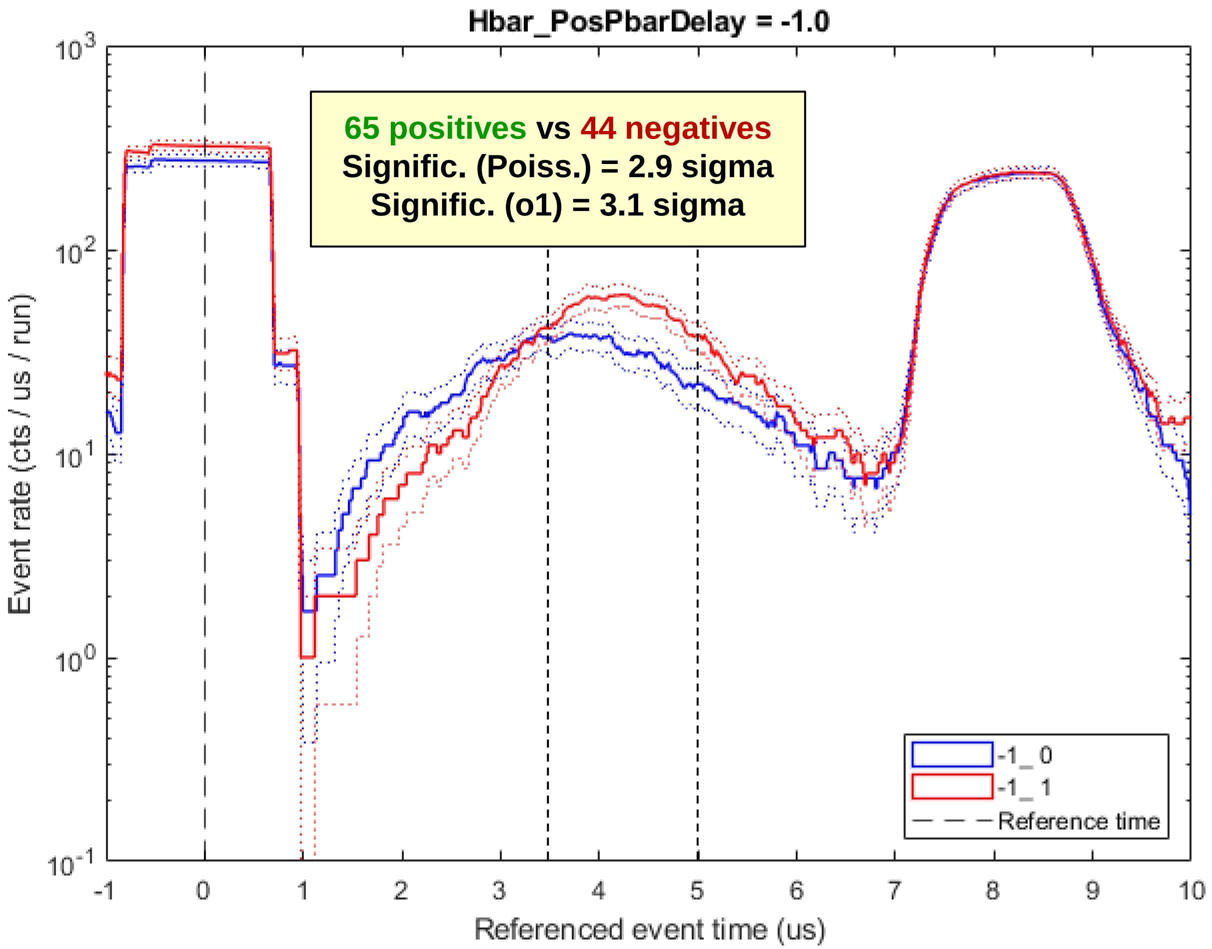


Sanity checking





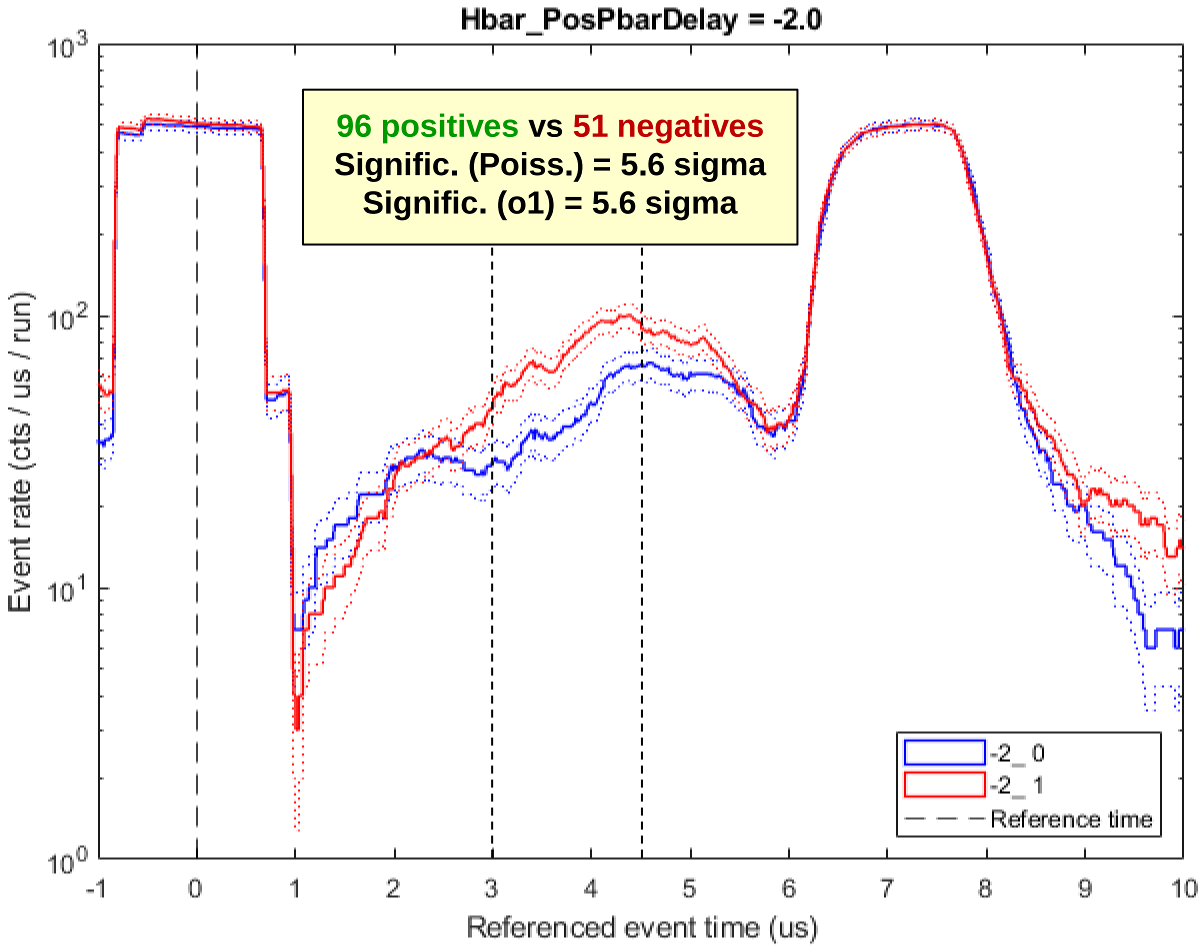
RunLog164 – late antiprotons



- **21 events in 36 runs**
- **0.6 events per run**
- **40% det. Efficiency**

.: 1.5 Hbar produced per run :.

RunLog165 – early antiprotons

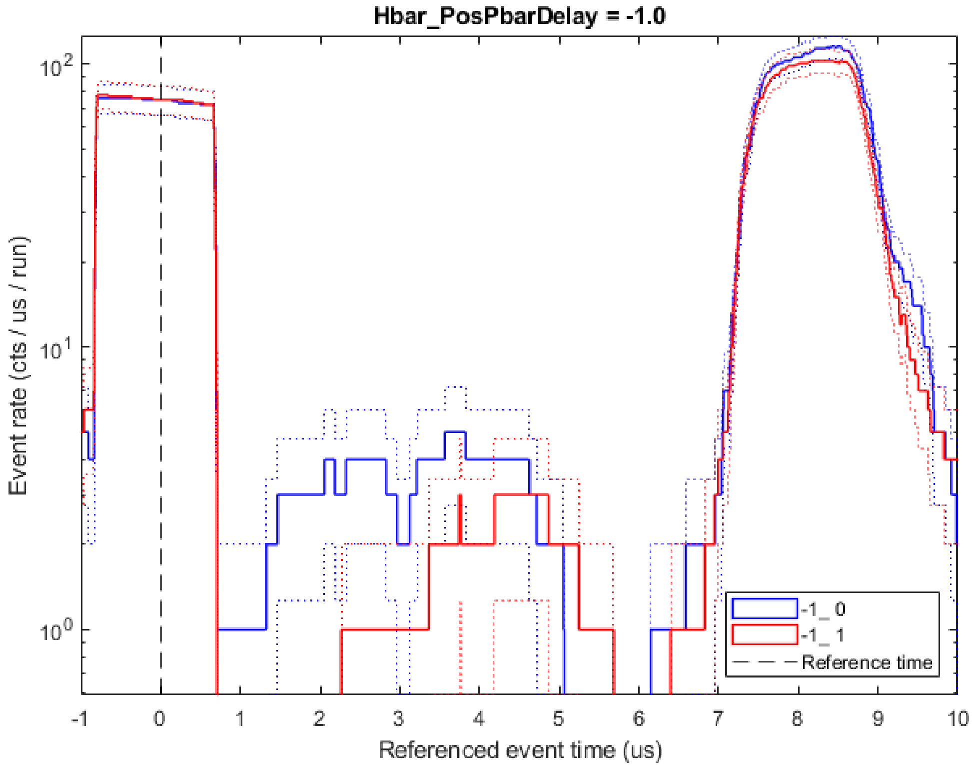


- 45 events in 56 runs
- 0.8 events per run
- 40% det. Efficiency

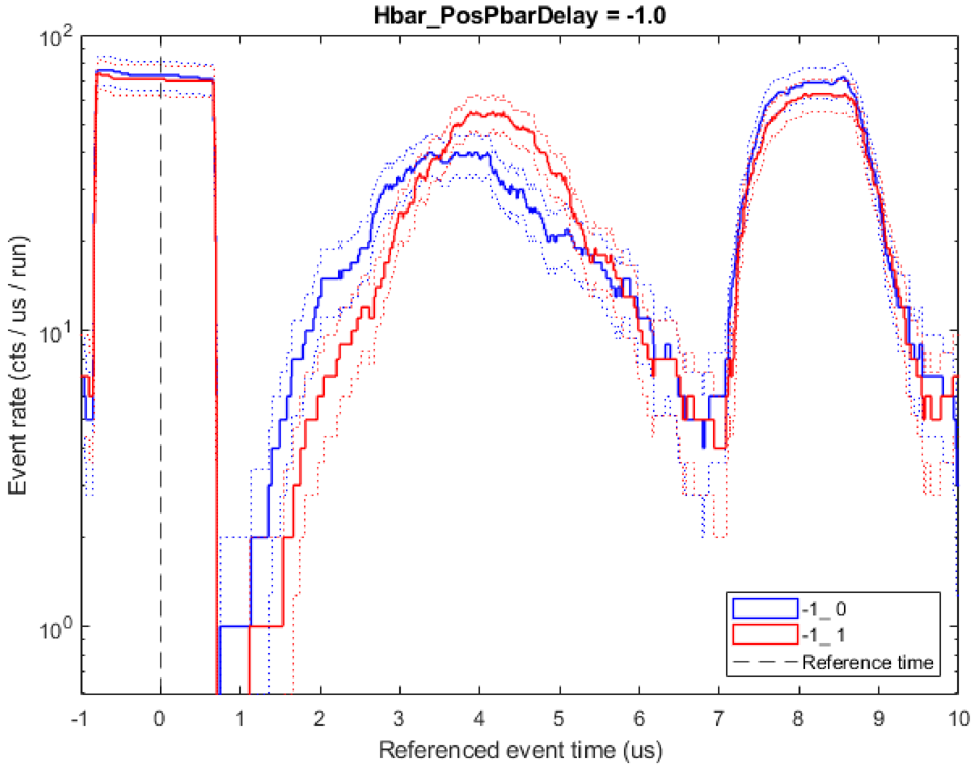
.: 2.0 Hbar produced per run :.

RunLog165 – late antiprotons

SC1314, SC1516

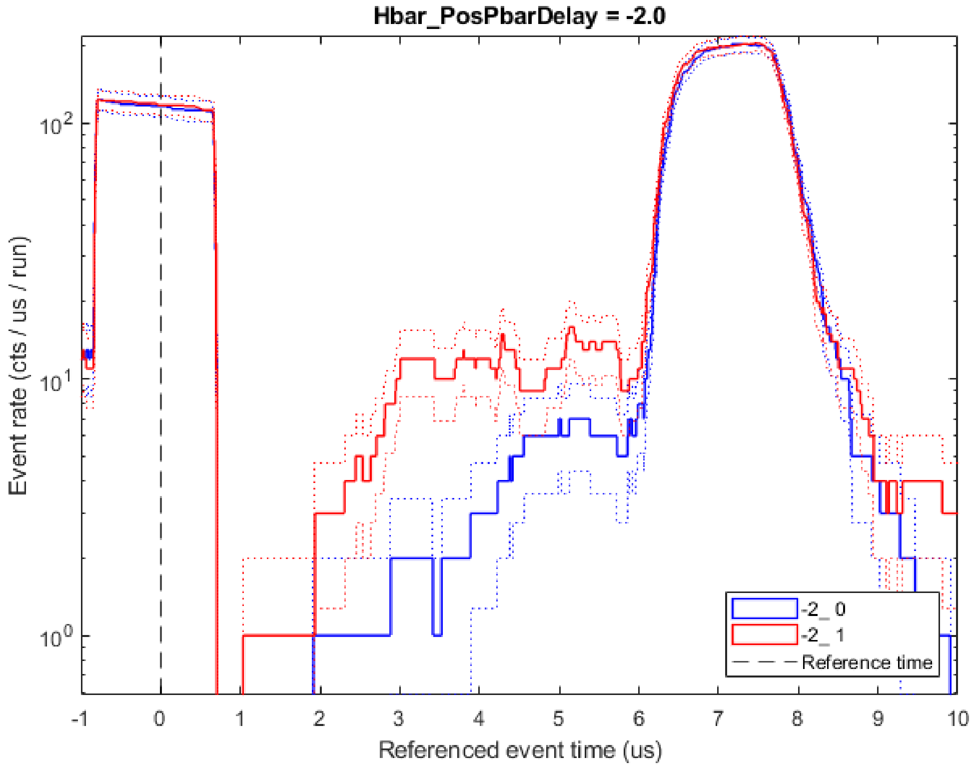


SC2122, SC2324

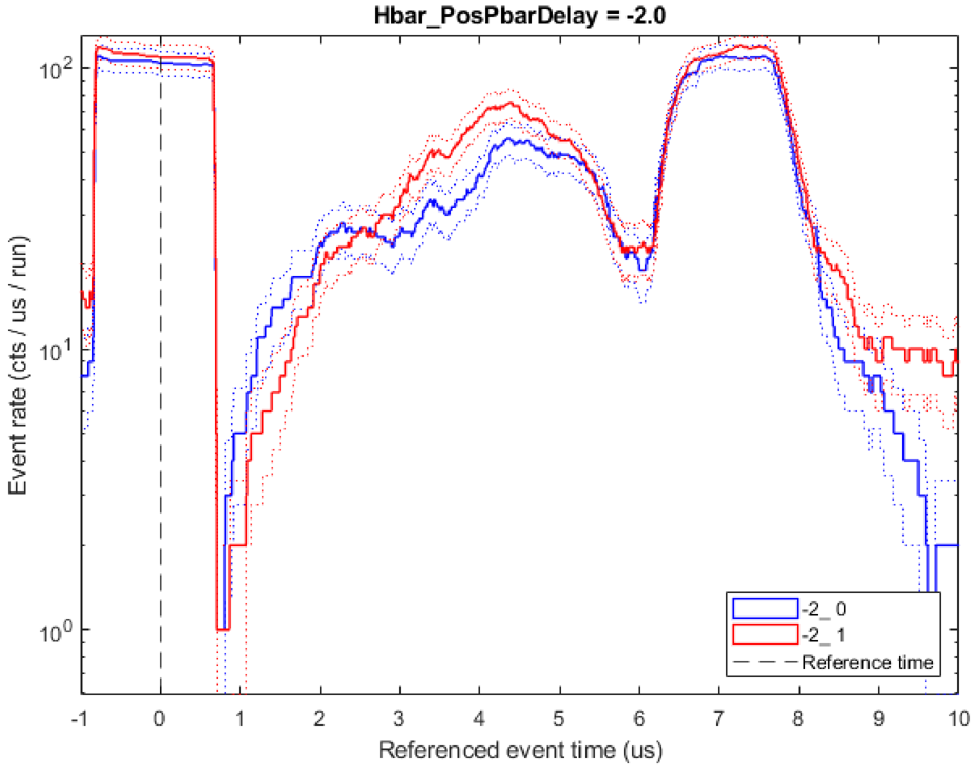


RunLog166 – early antiprotons

SC1314, SC1516



SC2122, SC2324



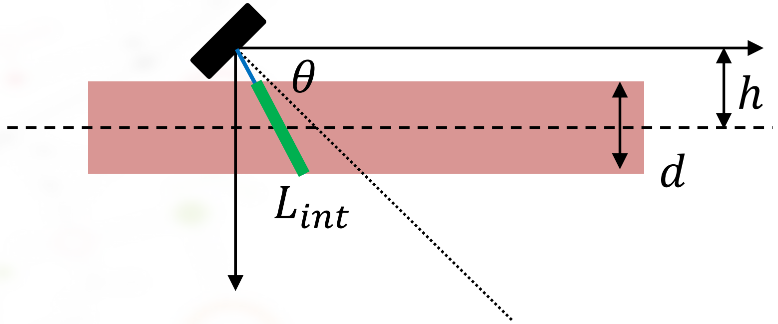
MODELING

Antihydrogen formation modeling

1. Generate Ps* trajectories according to know distributions
    1. Axially, Asym2Sigmoid
    2. Radially up, normal distribution without selection
    3. Radially side, normal distribution with laser selection
2. Rotate trajectories by angle theta in the lab frame
3. Compute $v_\perp$ and motional electric field $F(v_\perp)$
4. Compute Ps ionization rate with the n-dependent but sublevel-averaged Damburg and Kolosov formula
5. Sort each track travel distance from lifetime
6. Calculate ray-cylinder intersection, entrance and terminal points, and interaction length with plasma
7. Approx. uniform plasma density, compute Hbar formation probability from cross-section

$$\frac{\sigma_{\bar{H}}}{n^4} := (10^{-19}\,\mathrm{m}^2)\,\frac{1.2 + 0.1\,k_v(n,v)^{-2}}{1 + (k_v(n,v)/1.84)^{18}}\,, \qquad k_v(n,v) := \frac{v}{v_{e^+}} = \frac{2\,n\,v}{\alpha\,c}\,.$$

8. Sum all probabilities over Ps tracks to get the Hbar formation amount.
9. Generate Hbar trajectories and propagate until a collision occurs



$$P(n, v_{\mathrm{rel}}, \rho, L_{\mathrm{int}}) = 1 - e^{-\sigma(n, v_{\mathrm{rel}})\,\rho\,L_{\mathrm{int}}},$$

Damburg and Kolosov

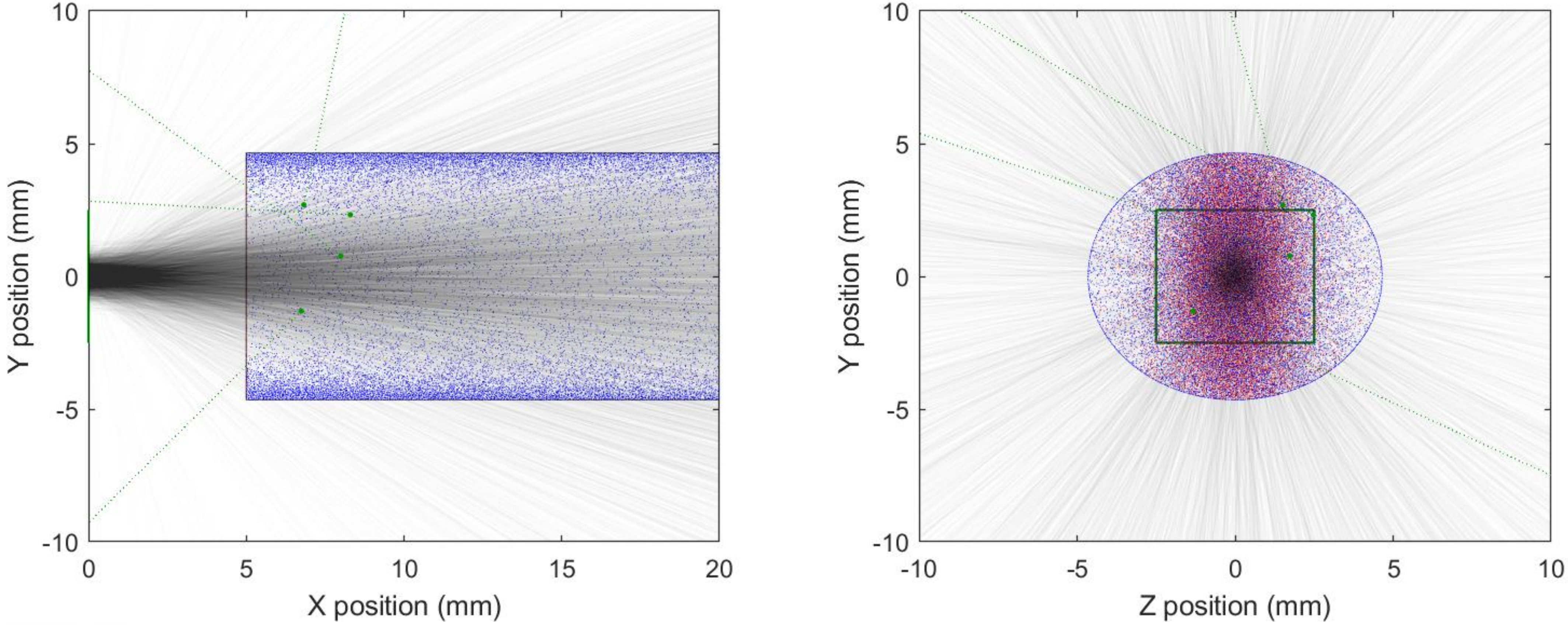
$$\Gamma_{n\,n_1\,n_2\,m} = \frac{E_{\mathrm{h_{Ps}}}}{\hbar}\,\frac{(4R)^{2n_2+m+1}}{n^3\,n_2!\,(n_2+m)!} \times \exp\left[-\frac{2}{3}R - \frac{1}{4}n^3\,\frac{e\,a_{0_{\mathrm{Ps}}}|\vec{F}|}{E_{\mathrm{h_{Ps}}}}\left(34n_2^2 + 34n_2 m + 46n_2 + 7m^2 + 23m + \frac{53}{3}\right)\right], \tag{5}$$

$$R = \frac{1}{e\,a_{0_{\mathrm{Ps}}}\sqrt{E_{\mathrm{h_{Ps}}}}}\,\frac{(-2E_{n\,n_1\,n_2\,m})^{3/2}}{|\vec{F}|} \tag{6}$$

N. Zurlo et al. (AEgIS collaboration), Hyperfine Interactions 240 (2019), 18

An example of simulation result: Hbar in 2024

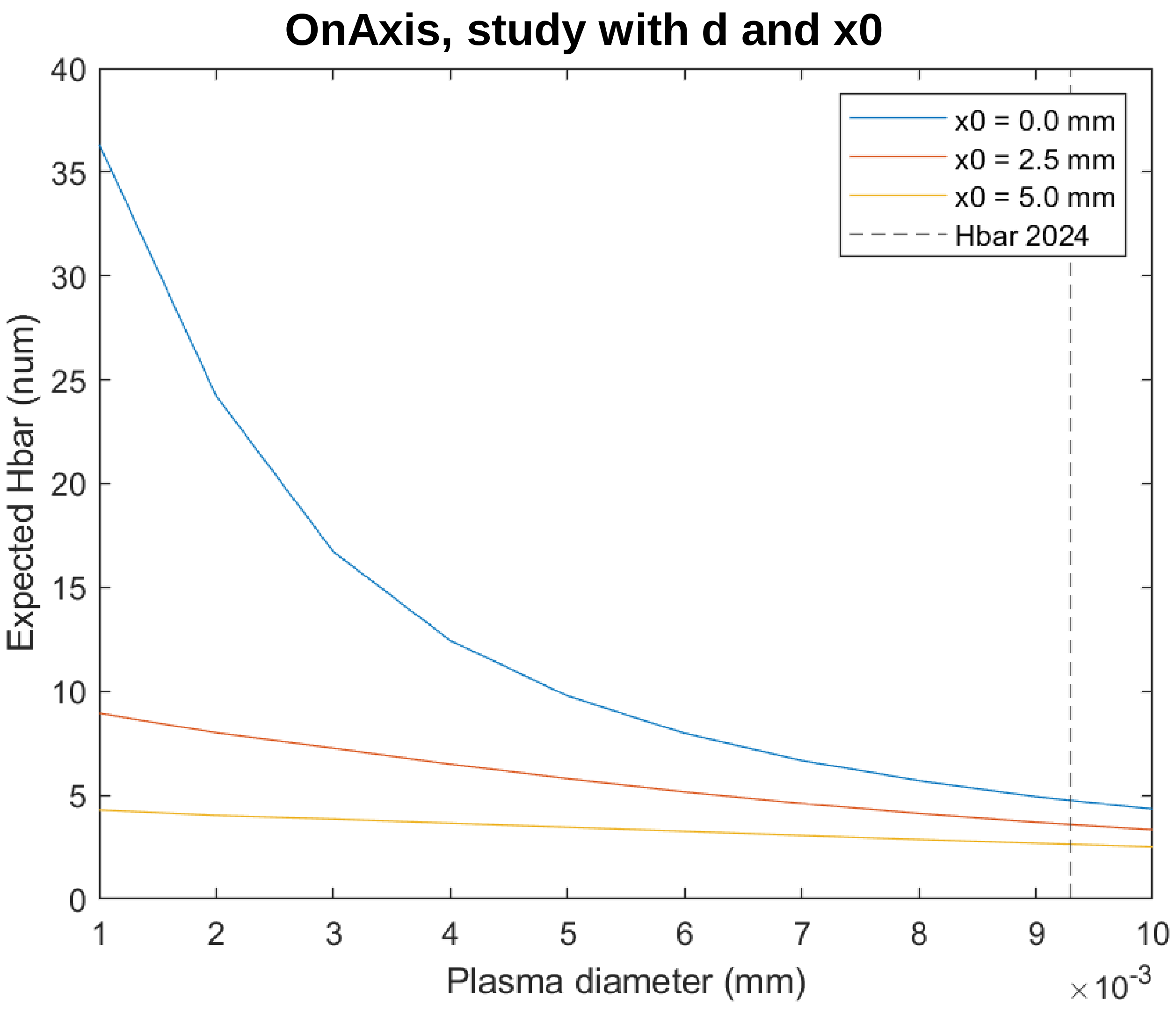
$N_{Ps*} = 0.8 \cdot 10^5$ $N_{pbar} = 2.0 \cdot 10^6$ $L_p = 20$ mm $d_p = 9.3$ mm



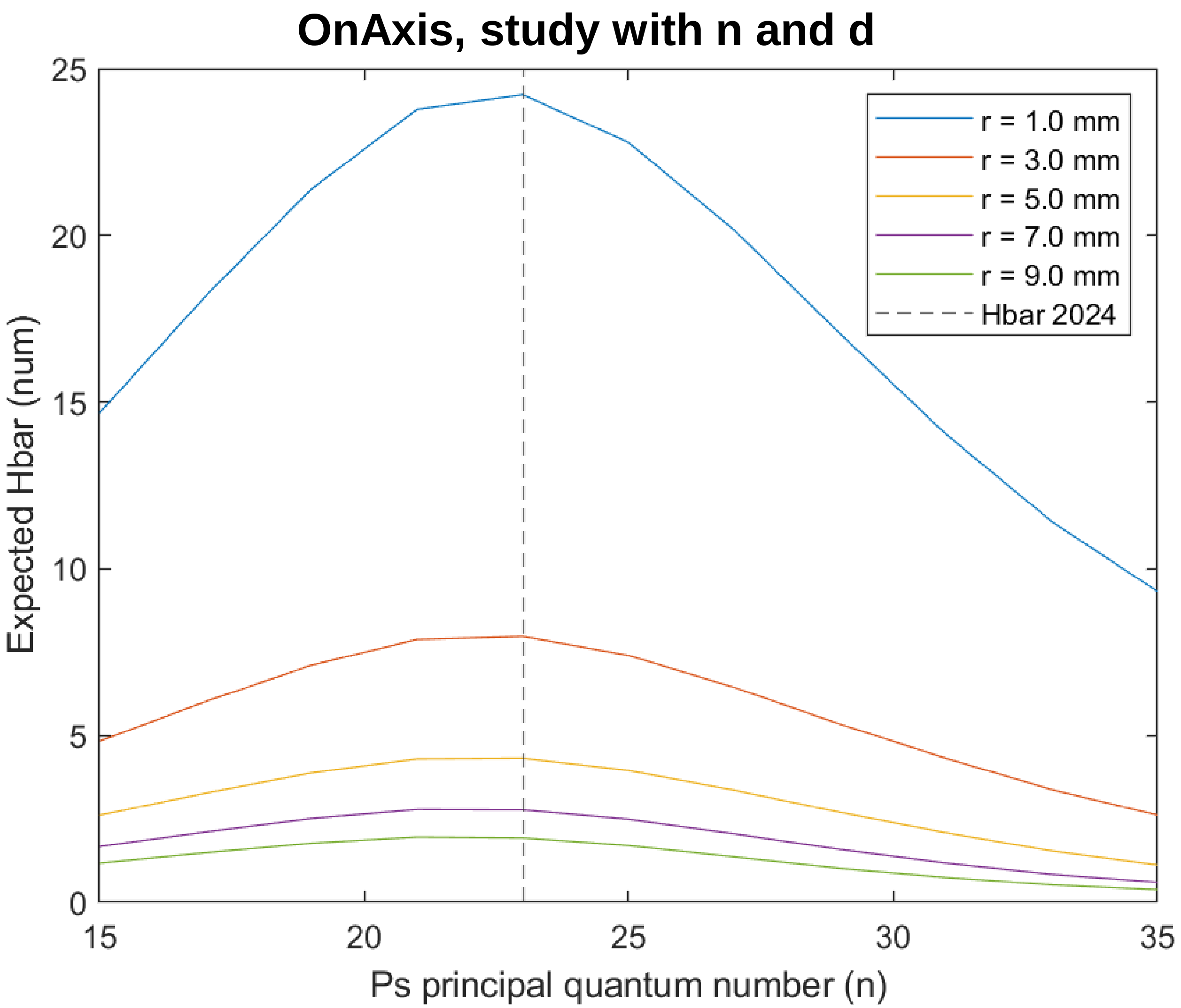
Computed Hbar production rate: 2.6 per run

NEXT STEPS

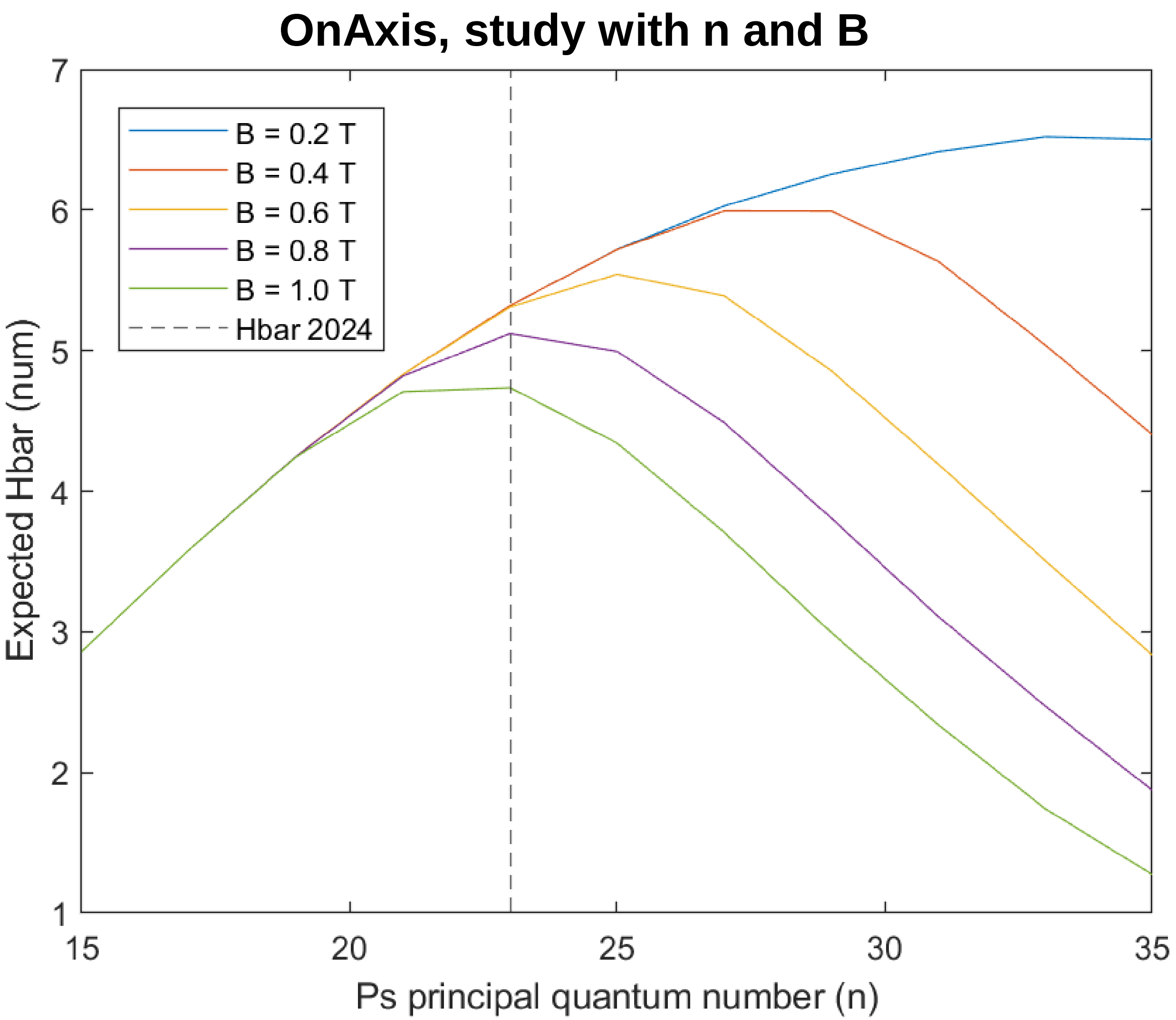
What happens if we leave all as is, and we compress the pbars?



How much antihydrogen should we expect if we increase Rydberg level?

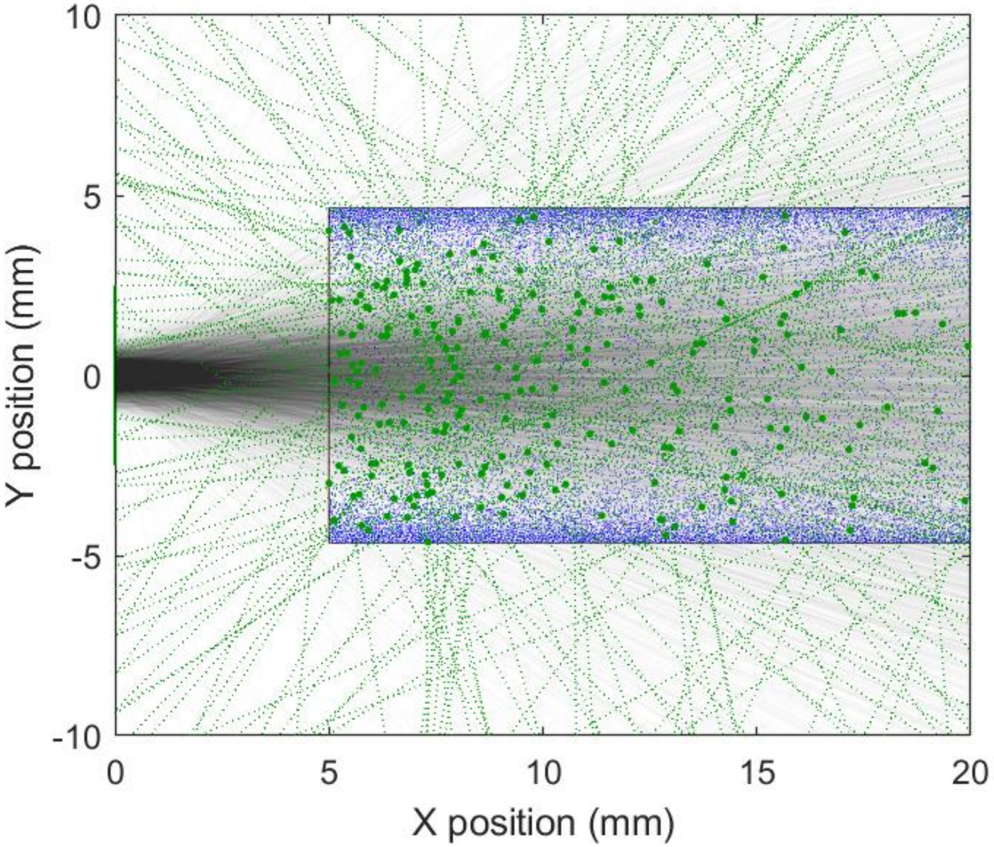


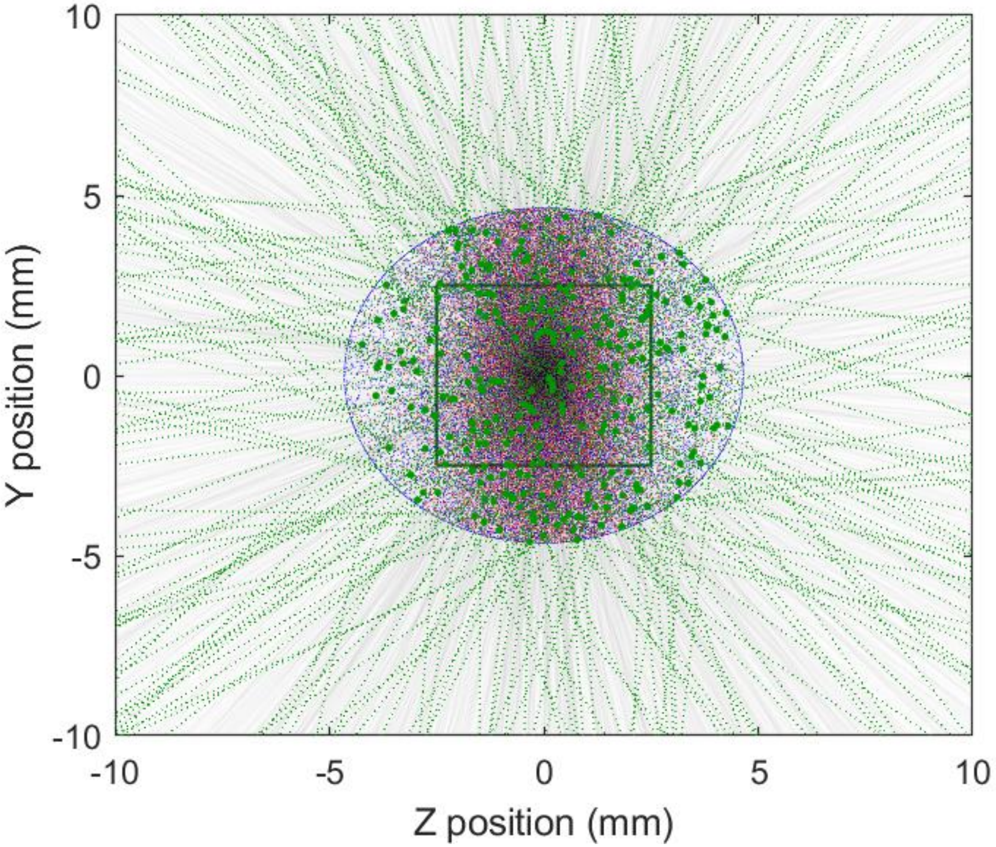
How much antihydrogen should we expect if we increase Rydberg level?



Estimating the forward-produced antihydrogen

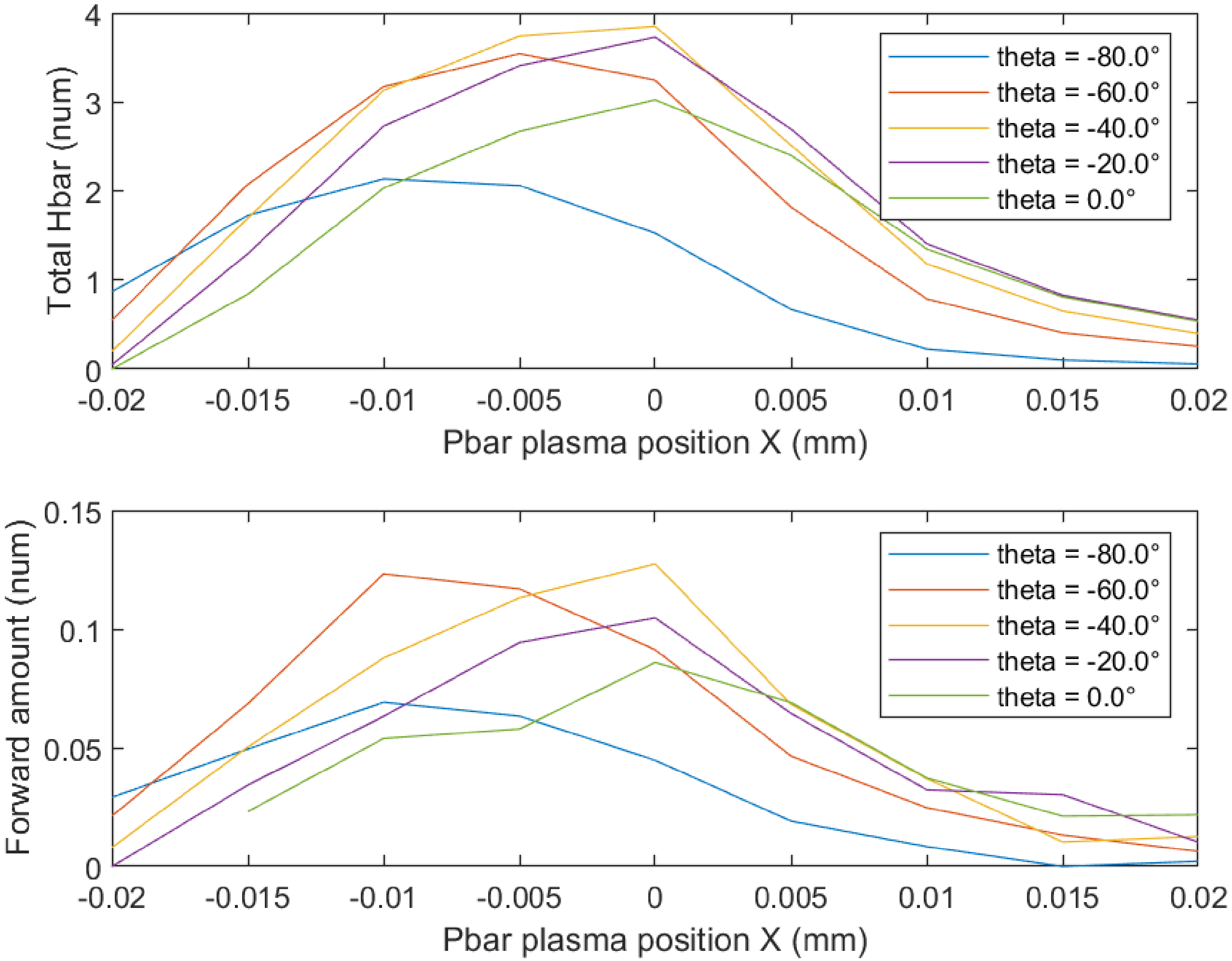
- Trick: oversample the number of produced antihydrogens, sorting on the same Ps* trajectories
- Compute collision with the target (rotated rectangle) and with the domain (cylinder)
- Define forward/backward fractions according to the traject. angle wrt the axis (10 cm / 88 cm)





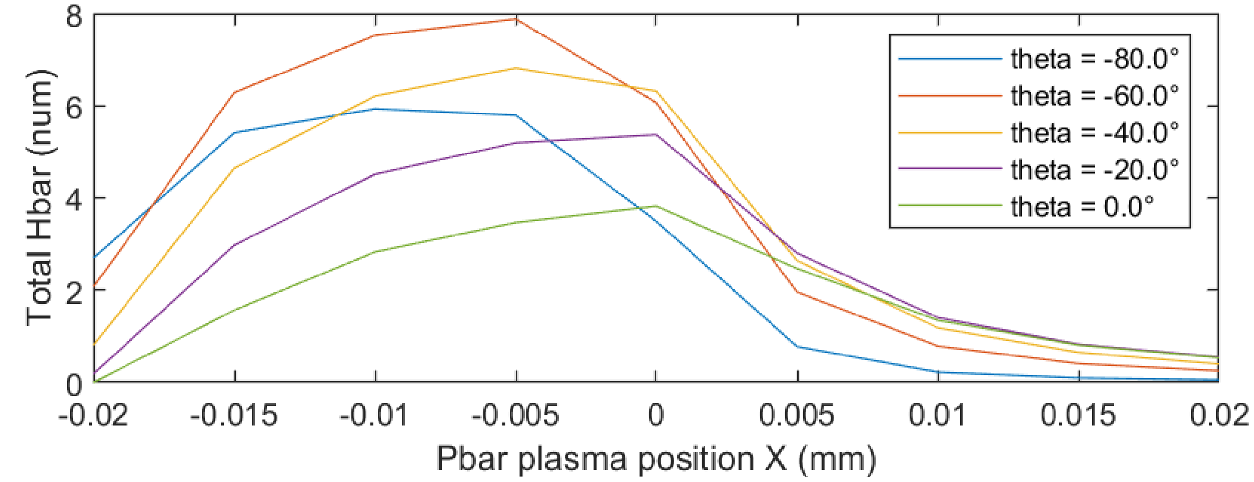
How much antihydrogen should we expect if we go off axis?

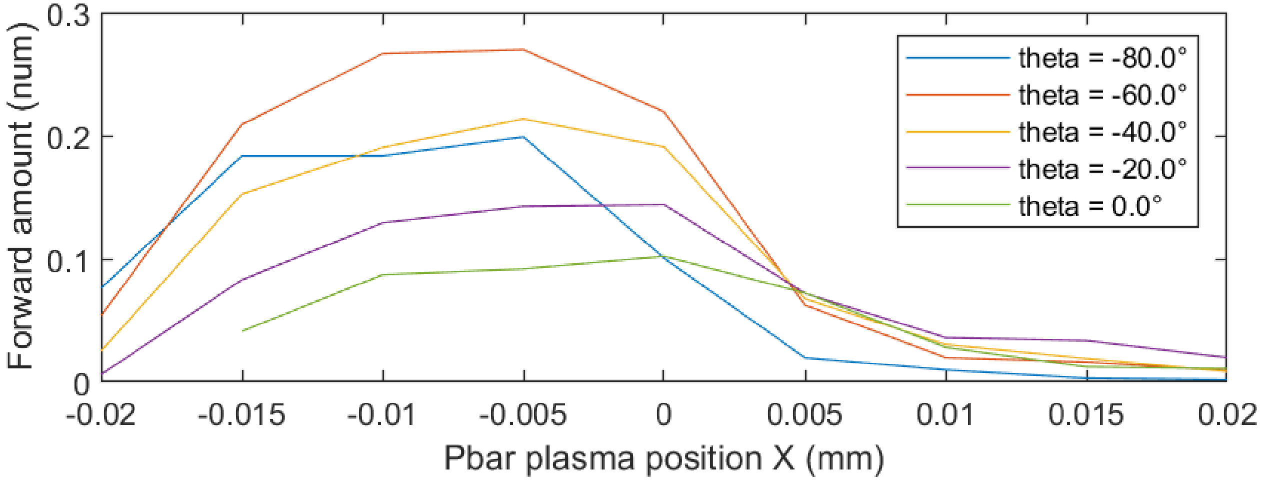
Study with B = 1 T, h = 4 mm, d = 4 mm



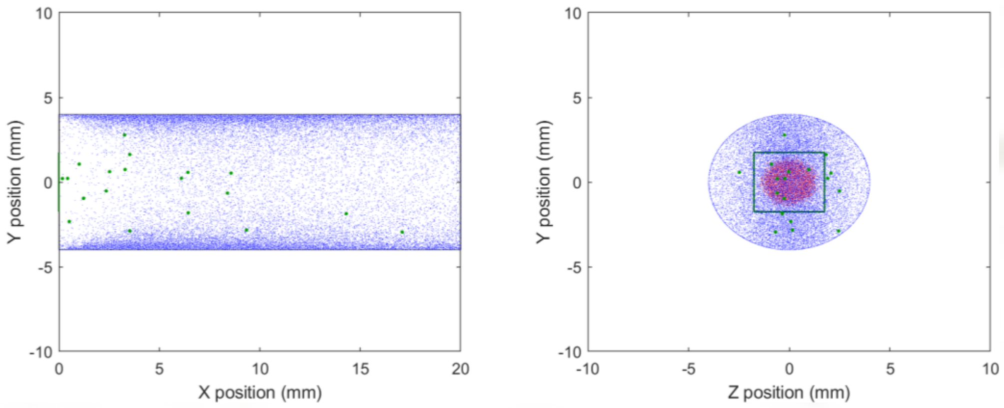
How much antihydrogen should we expect if we go off axis?

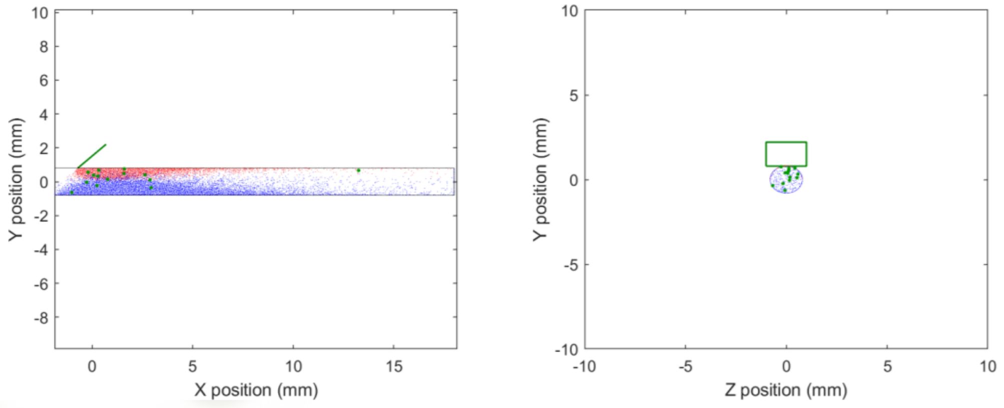
Study with B = 0.2 T, h = 4 mm, d = 4 mm





Considered scenarios





Stacking

A. On-axis, B = 1 T, n = 22, d = 4.0 mm, N_{stack} = 4, L = 3.5 mm
=> 21.6 Hbar/shot, 0.32 forward (2.1 %)

B. On-axis, B = 0.2 T, n = 32, d = 4.0 mm, N_{stack} = 4, L = 3.5 mm
=> 27.7 Hbar/shot, 0.40 forward (1.4 %)

Pbar RW

C. Off-axis, B = 1 T, n = 19, d = 0.8 mm, h = 1.5 mm, $\theta = 45°$
=> 15.0 Hbar/shot, 0.43 forward (2.9 %)

D. Off-axis, B = 0.2 T, n = 32, d = 2.0 mm, h = 3.2 mm, $\theta = 60°$
=> 10.5 Hbar/shot, 0.33 forward (3.2 %)

Modeling of the plasma E x B is completely missing at the moment