A new simple strategy for CLIC positron source optimisation

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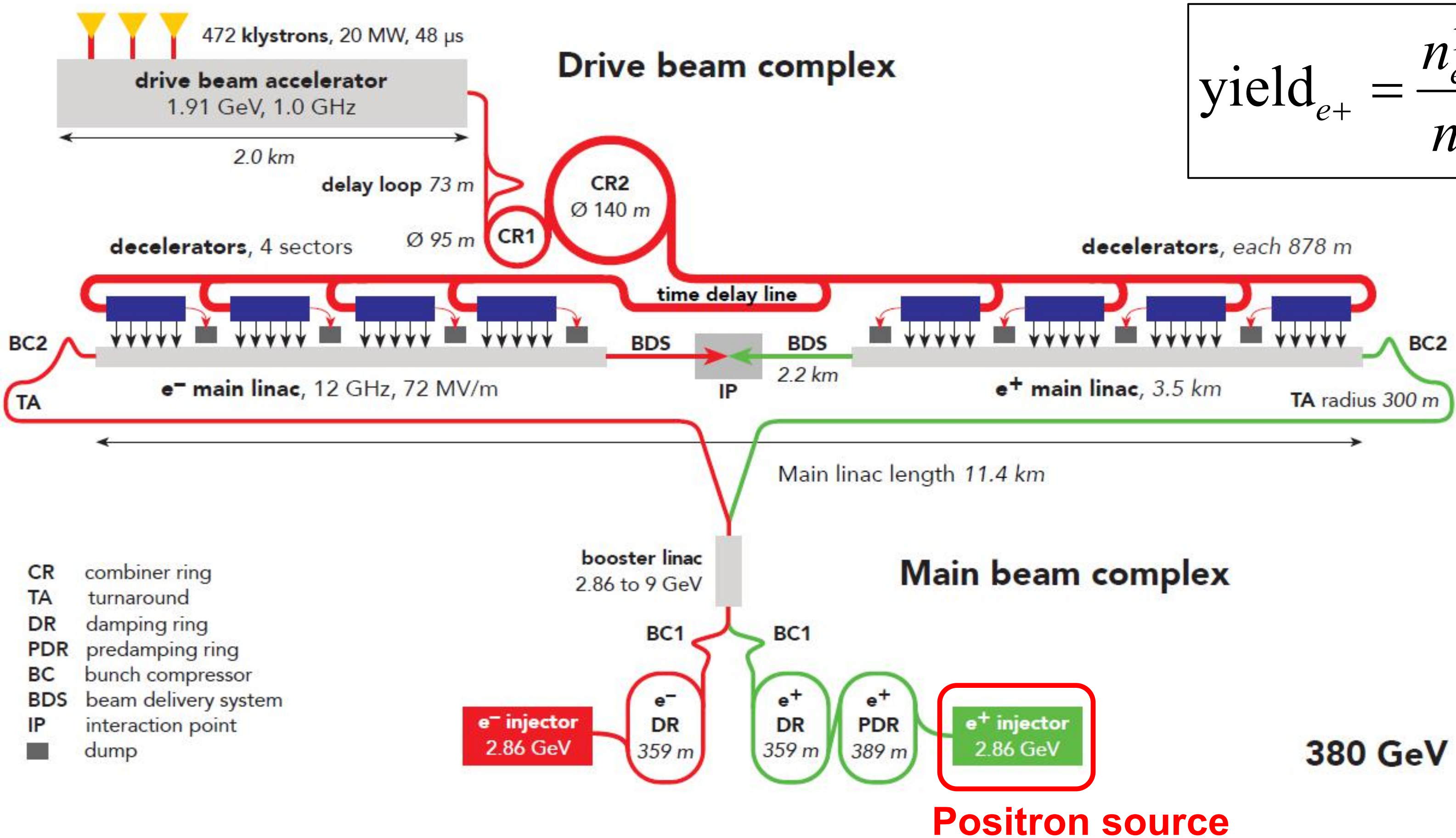
Outline

- Introduction
- Cross-check of ILC and previous CLIC studies
- A new simple optimisation method
- Latest results
- Conclusion

Introduction

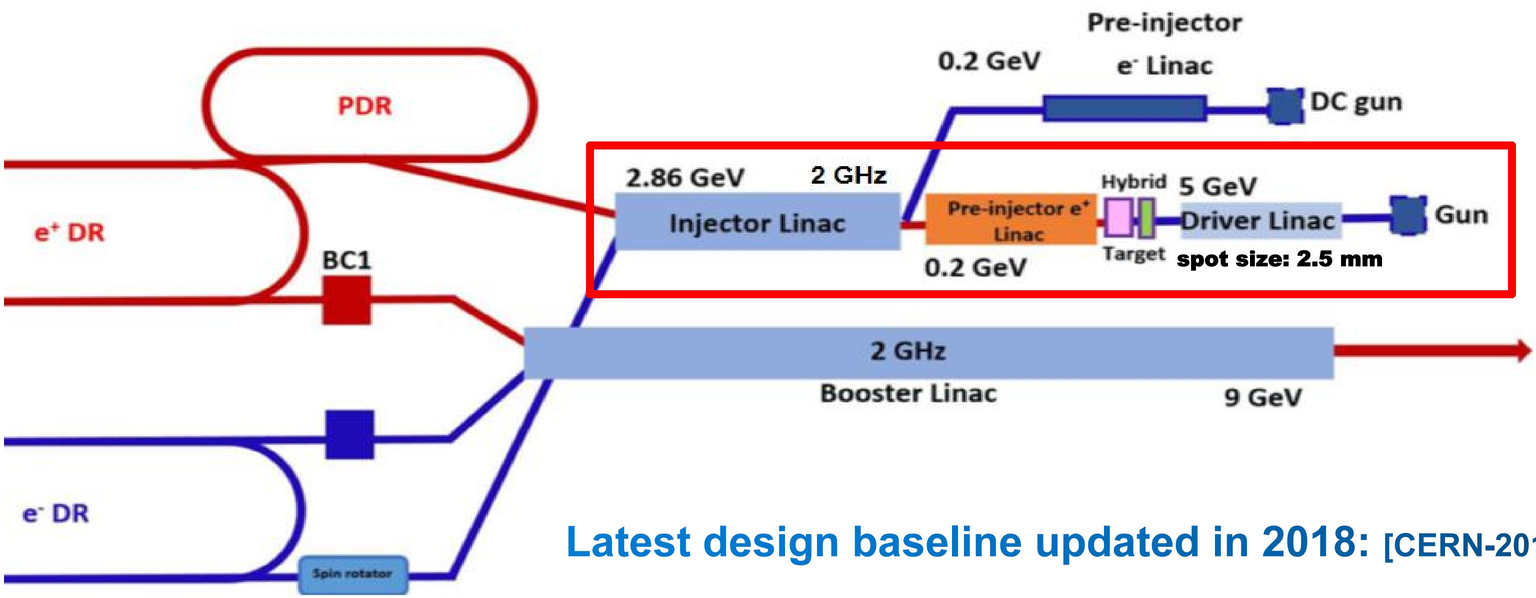
- Motivation: a well optimised positron source is essential to improve positron production efficiency and reduce the positron linac cost. In principle, a higher positron yield is always prefered

$$\text{yield}_{e+} = \frac{n_{e+}^{\text{produced}}}{n_{e-}^{\text{primary}}}$$



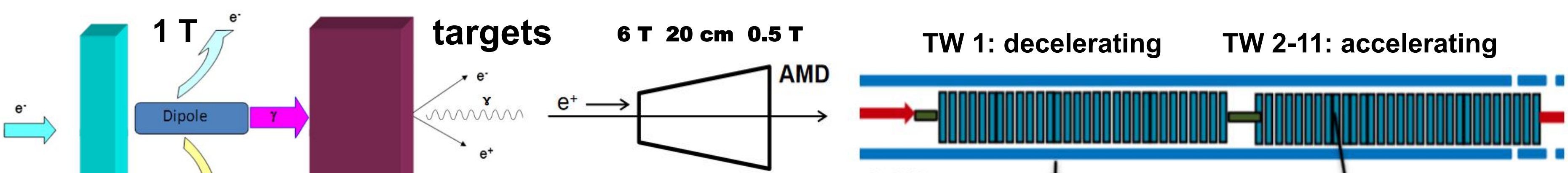
Introduction

- Main components: Primary e^- gun, targets, adiabatic matching device (AMD), travelling wave (TW) structures, injector linac



Latest design baseline updated in 2018: [CERN-2018-010-M]

- Components for optimisation: target, AMD and TW structures



$$B_z = \frac{B_0}{1 + \mu \cdot z}$$

Introduction

- Same simulation tools and configurations used as **Yanliang Han** ([DOI: 10.1016/j.nima.2019.03.044]), who worked on this previously
- Tools: **FOT + Geant4** for targets, **RF_Track** for AMD and TW structures
- **Primary e^-** generated from **gaussian** sampling
- **AMD** simulation simplified using **constant aperture** (2 cm)
- **TW structures** working in 2π/3 mode, each cavity 1.5 m long
- **Injector linac** simulated using a formula **approximation** (assuming no losses, based on previous studies [10.1016/j.nima.2017.07.010])

$$\mathrm{E} = \mathrm{E}_0 + \Delta\mathrm{E}\cdot\cos(2\pi\omega\cdot\Delta t), \quad \Delta\mathrm{E} = 2.86\,\mathrm{GeV} - 200\,\mathrm{GeV}, \ \Delta\mathrm{t} = \mathrm{t} - \mathrm{t}_{\mathrm{ref}}$$

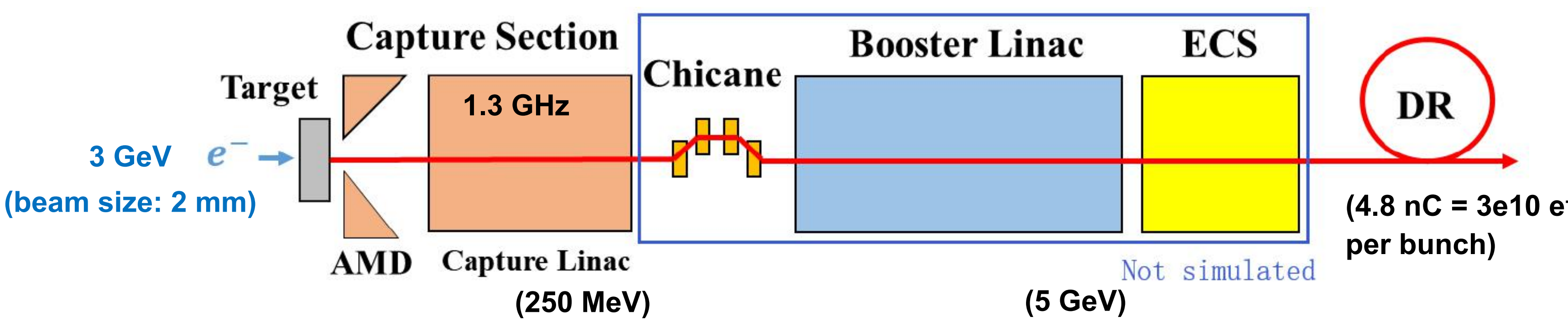
- Final **effective** positrons accepted by the pre-damping ring (PDR): **time window: 20 mm/c, energy window**: 2.86 GeV ± 3σ (σ: 1.2%)
- Peak energy deposition density (**PEDD**) in targets < 35 J/g

$$\mathrm{PEDD} = \frac{\max(\mathrm{E}_{\mathrm{deposited}})}{V_{\mathrm{mesh}}\cdot\rho_W\cdot n^{e^-}_{\mathrm{simulated}}}\cdot\frac{n_{\mathrm{bunch}}\cdot n^{e^+}_{\mathrm{PDR}}}{\mathrm{Yield}^{e^+}_{\mathrm{effective}}}$$

(PEDD always normalised to $n^{e^+}_{\mathrm{PDR}}$, the e^+ bunch population at the entrance of PDR)

Cross-check with ILC

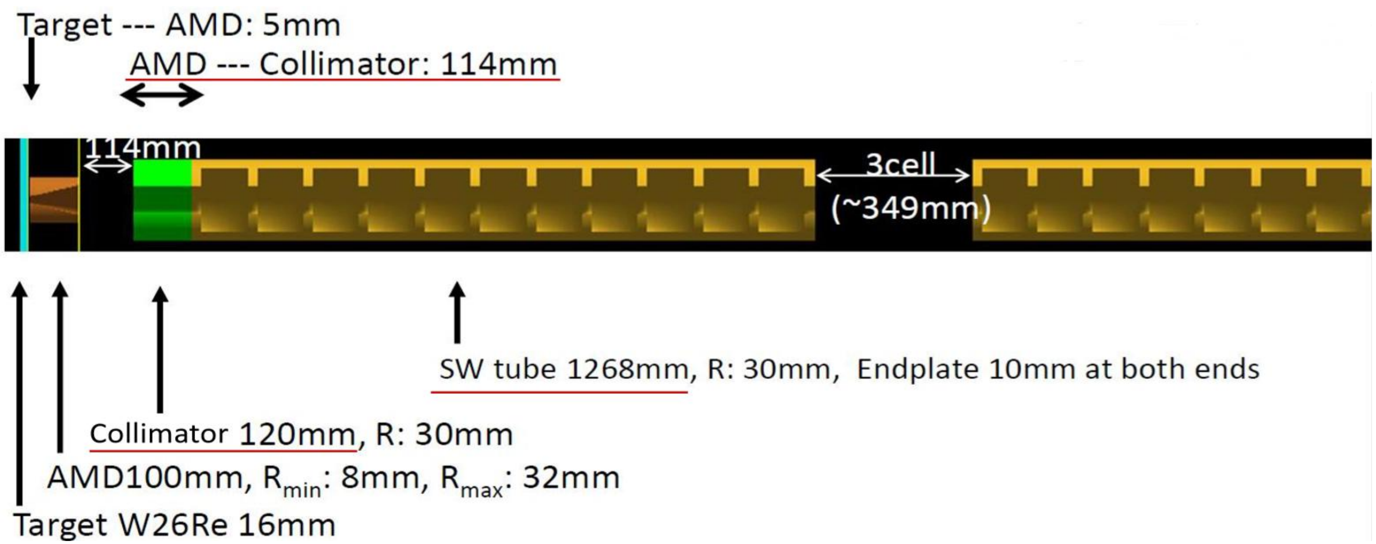
- ILC positron source (**e-driven**) quite similar as CLIC, which can be used to **cross-check** and **validate our code**
- Cross-check based on talks from **Nagoshi-san** and **Fukuda-san** on **LCWS2018**, and discussions with the team (Fukuda-san, Takahashi-san, Kuriki-san, Wanming, etc. To whom I give all my thanks!)
- Main **difference** from CLIC: rotating single target; standing wave (SW) structures used after AMD instead of TW; injector linac replaced by a booster linac in ILC.
- But booster linac is not simulated, a **time window ±7 mm/c** used for damping ring (DR) acceptance instead



Cross-check with ILC

- Simulation tools that are used

	Nagoshi-san	Fukuda-san	Yongke
Targets	Geant4	Geant4	Geant4
AMD & SW tubes	General Particle Tracker (GPT)	Geant4	RF-Track



(Totally 36 SW tubes)

- Number of bunches assumed in **mini-trains** contributed to PEDD: **66** (in ~500 ns, as a conservative estimate for the rotating target)
- Energy and momentum spread not considered in simulation

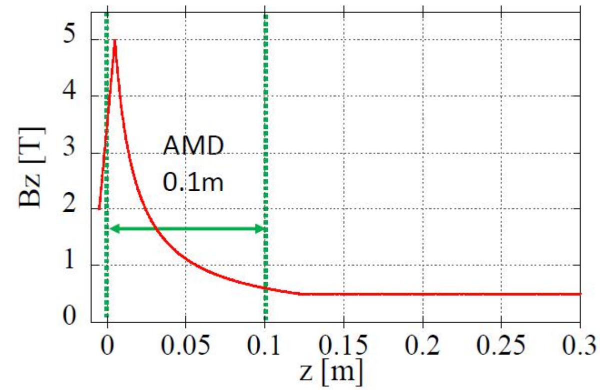
Cross-check with ILC

Analytical field used for AMD

Similar as CLIC AMD field, except for peak not at 0

$$B(z) = \frac{B_{peak}}{1 + \mu(z - 0.005)}$$

$B_{peak} = 5\ [T]$
$\mu = 77\ [1/m]$



Pillbox (TM010) field approximation used for SW tubes

An improved field also studied, but not much difference observed (BACKUP slides)

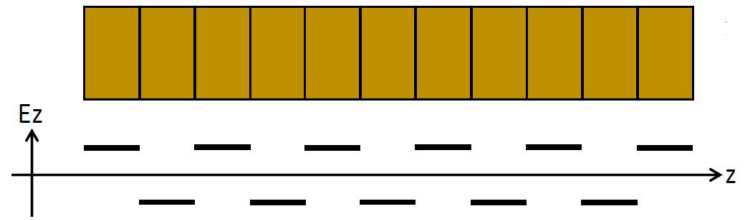
$f = 1.3$ GHz (L-band)
$\lambda = \frac{c}{f} \approx 230.61$ mm
$\varphi = 20°$

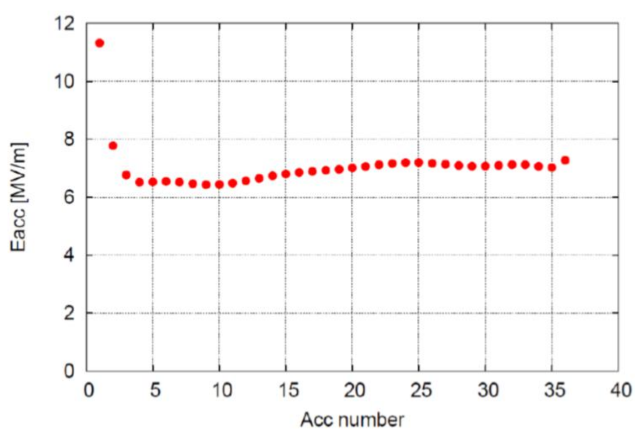
$$E_z = \frac{\pi}{2} E_{acc} \cdot J_0\left(\frac{2\pi}{\lambda} r\right) \cdot \sin(\omega t + \varphi)$$

$$E_x = E_y = 0,\ B_z = 0.5\ \mathrm{T}$$

$$B_{\emptyset} = \frac{\pi}{2} E_{acc} \cdot J_1\left(\frac{2\pi}{\lambda} r\right) \cdot \cos(\omega t + \varphi) \cdot \frac{1}{c}$$

$$B_x = -\frac{y}{r} \cdot B_{\emptyset},\ B_y = \frac{x}{r} \cdot B_{\emptyset}$$





Cross-check with ILC

Positron yield comparison

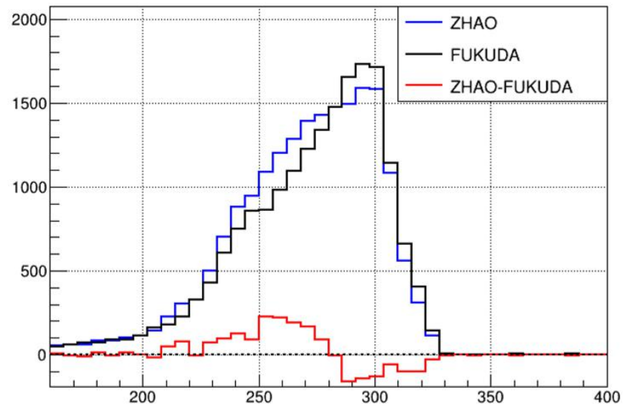
e+ Yield	Ne-simulated	After target	After AMD	After 1st SW tube	After all SW tubes	Matched to DR acceptance
Nagoshi-san	1,000	7.29	4.48	2.14	1.90	**1.00**
Fukuda-san*	10,000	7.13	5.09	2.58	1.94	**1.03**
Yongke	10,000	7.06	4.48	2.03	1.96	**1.09**
Difference (N.-san)		3%	0	5%	3%	**9%**
Difference (F.-san)		1%	12%	21%	1%	**6%**

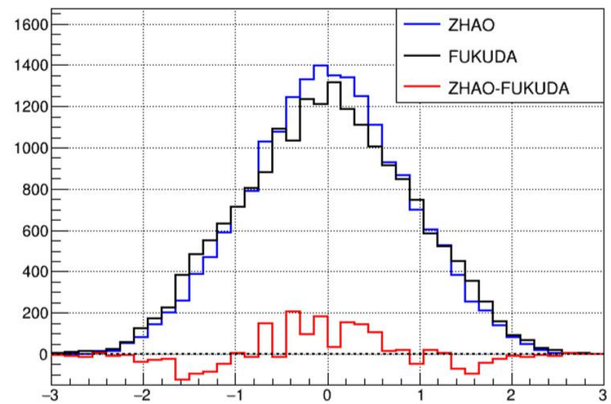
* We reproduced Fukuda-san's results in the table using ILC code. Many thanks to him for providing the code

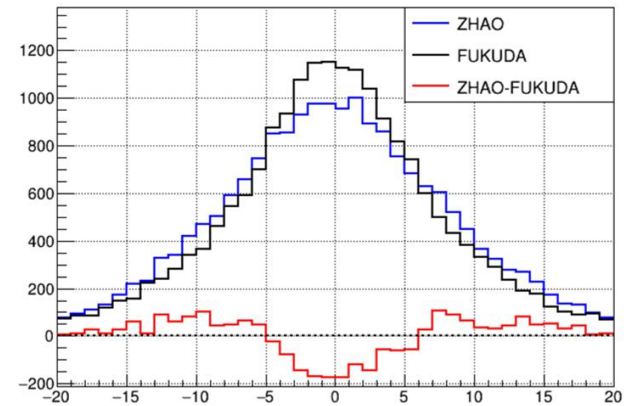
- Very **good agreement** after targets (since the same simulation tool used)
- Visible **difference** found **during the transport** between **Geant4** and **other simulation tools**. But difference **eliminated** at the end after a long travel
- Nevertheless, a more detailed study is needed to investigate the difference
- For the **final yield**, the discrepancies between the 3 studies found to be **< 10%**

Cross-check with ILC

- Positron energy, momentum and position distributions and comparisons between Fukuda-san's results and my results (after all SW tubes)

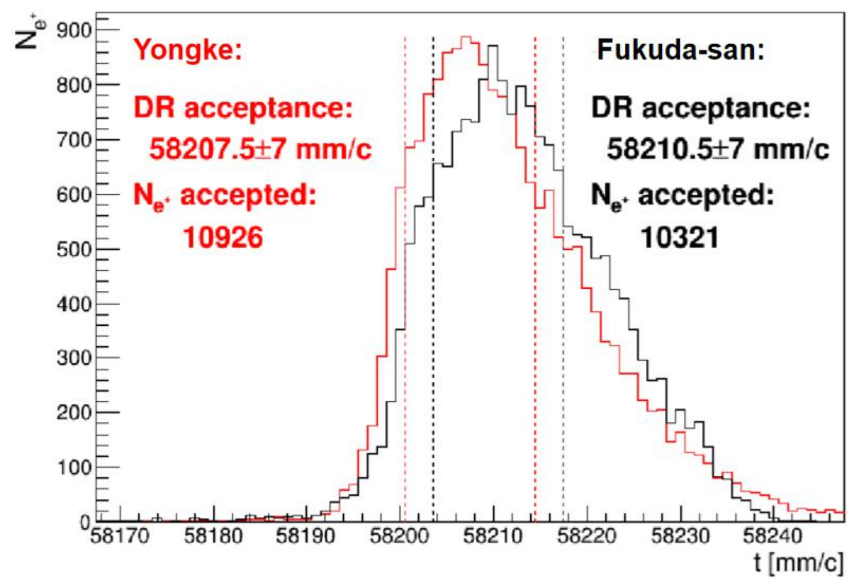






- Positrons with the DR acceptance ($\pm$7 mm/c)

More comparison plots in BACKUP slides



Cross-check with ILC

- Target PEDD comparison
  - for **2.4 nC** e$^-$ bunch (equivalent to a final e$^+$ **yield** of **2**)

Target PEDD	Ne- simulated	PEDD for 2.4 nC e- bunch / [J/g]
Nagoshi-san	1,000	**19.20**
Takahashi-san (previous)	10,000	**18.75**
Takahashi-san (latest*)	1,000	**22.00**
Yongke	10,000	**23.73**

* In previous ILC result, PEDD **underestimated** compared to CLIC. **In the latest ILC result, this is improved**. However still some differences in the estimation between ILC and CLIC, e.g. ILC **mesh volume** size 2 times larger than CLIC

- Finally a **difference** of **8%** is found
- We think CLIC PEDD calculation **more conservative** and will **stick to it**
- Nevertheless, the **agreement is good**, given that our PEDD **statistical uncertainty** is **6%** (see BACKUP slides)

Cross-check of previous results

- The latest previous study on CLIC positron source is from **Yanliang Han**, etc. (publication: [DOI: 10.1016/j.nima.2019.03.044])
- Reproduction of Yanliang's results (using same parameters):

Reproduction		Primary e- energy / [GeV] & spot size / [mm]			
		5 & 2.5	5 & 1.25	3 & 2.5	3 & 1.25
Yanliang	Yield	1.30	1.94	0.76	1.03
	PEDD / [J/g]	17.7	29.3	17.1	26.7
Yongke	Yield	**1.28**	**1.86**	**0.71**	**0.96**
	PEDD / [J/g]	**17.7**	**30.9**	**16.4**	**28.4**

- PEDD normalised to the same **e^+ bunch population** 5.6e9 (~ **0.9 nC** bunch charge)
- Same **mesh volume** size used for PEDD calculation:

$$\Delta x \cdot \Delta y \cdot \Delta z = \frac{4\sigma_{xy}}{25} \cdot \frac{4\sigma_{xy}}{25} \cdot \frac{X_0}{4}, \text{ where } \sigma_{xy} \text{ is spot size, } X_0 = 3.5 \text{ mm is } W \text{ radiation length}$$

- **Good agreement (diff. < 10%)** found between reproduction and previous study
- An **alternative mesh volume** (**0.5*0.5*0.5 mm³**) is tested and **small effect** found on PEDD (corresponding PEDD values: 17.2, 31.4, 17.5, 27.2 [J/g])

A new simple optimisation method

- The new method is a **global** optimisation (parameters optimised **simultaneously**), based on the '**start-to-end**' optimisation used by previous studies
- But instead of using **Nelder-Mead** algorithm (used by Yanliang), we propose a **new strategy** based on a simultaneous scan:
  ① Provide initial values as a **starting point**, and **Scan** parameters **separately but simultaneously**, and find optimised parameters (during a scan of one parameter, the other parameters are fixed)
  ② Use **all optimised parameters** (or **best one from scan** if it's better) as a **new starting point** for the next scan
  ③ Continue the **iterations** of scan until we find **final** optimal parameters (parameters are **stable** and results can not be improved)
- **Advantages** of the new strategy:
  - ✓ **Much faster** (**weeks → hours !**) and **simpler**
  - ✓ More **reliable and convincing** results (**visual** scan plots, not like Nelder-Mead algorithm which is a black box)
  - ✓ Allow us to see **individual effects** from parameters

Re-optimise previous results

- Previous results (from **Yanliang**) **re-optimised** using the new method, **as an example** to show how the method works
- **Same configuration** (more details in his publication) are used, except for free parameters to be optimised
- Primary **e^- energy** fixed to **5 GeV**
- Mesh volume size: 0.5*0.5*0.5 mm^3 ; e^+ bunch population: 4.3e9 (~0.7 nC)
- For the **1st iteration**, a **starting point** chosen arbitrarily:

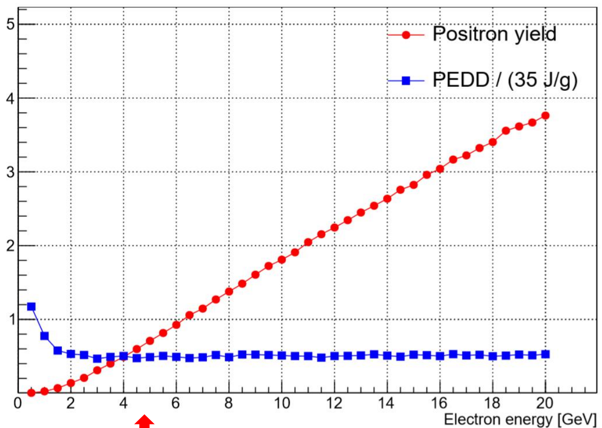
Free parameters	Primary e- energy (E_{e-})	Spot size (σ_{xy})	Crystal thickness (W_{xtal})	Target distance (D_{targ})	Dipole field (B_{targ})	Amorphous thickness (W_{amor})
Initial values	5 GeV	2.5 mm	1.5 mm	2 m	1 T	15 mm

AMD B_0 (B_0)	AMD length (L_{AMD})	TW dec. phase (φ_{dec})	TW acc. phase (φ_{acc})	TW dec. gradient (E_{dec})	TW acc. gradient (E_{acc})
6 T	20 cm	150°	250°	15 MV/m	15 MV/m

- Final e+ **yield: 0.70**, **PEDD: 17.5 J/g**

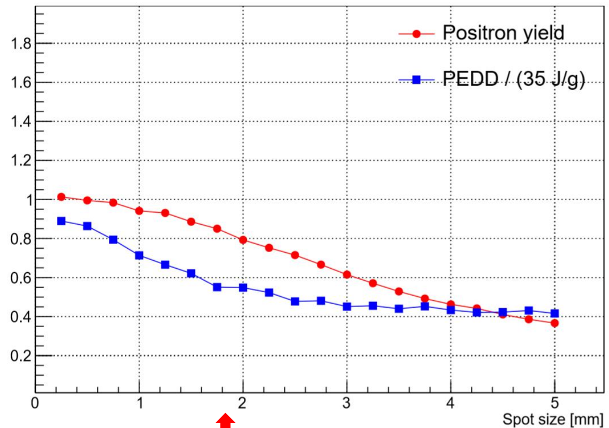
Re-optimise previous results

- **Scanning results** of the **1st iteration** (3 parameters as an example)
  - more plots in BACKUP slides



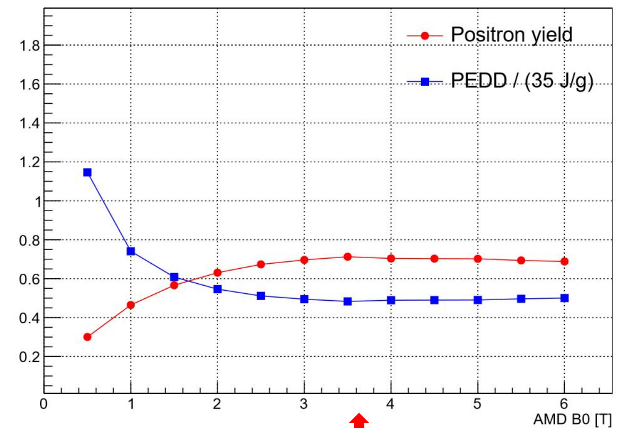
(5 GeV, 0.70 e^+/e^-)

Primary e^- energy [GeV]



(1.75 mm, 0.85 e^+/e^-)

Spot size [mm]



(3.5 T, 0.72 e^+/e^-)

AMD B_0 [T]

- Optimised parameters of 1st iteration and results

Par.	E_{e-}	σ_{xy}	W_{xtal}	D_{targ}	B_{targ}	W_{amor}	B_0	L_{AMD}	φ_{dec}	φ_{acc}	E_{dec}	E_{acc}	**All**
Opt.	5 GeV	1.75 mm	1 mm	0	0	14 mm	3.5 T	15 cm	140	280	10 MV/m	20 MV/m	
Yield	0.70	0.85	0.72	**1.83**	0.84	0.72	0.72	0.70	0.80	0.95	0.76	0.87	**1.38**
PEDD [J/g]	17.5	19.3	18.2	**20.0**	16.8	16.5	16.8	17.5	15.4	14.0	15.8	14.0	**45.8**

Best result from scan taken for next iteration

Re-optimise previous results

- After 3~4 iterations of scan, we got the **final optimal results**:

E_{e-}	σ_{xy}	W_{xtal}	D_{targ}	B_{targ}	W_{amor}	B_0	L_{AMD}	φ_{dec}	φ_{acc}	E_{dec}	E_{acc}	Final Yield	PEDD [J/g]
5 GeV	1.75 mm	1.5 mm	0	0	15 mm	6 T	20 cm	150°	250°	15 MV/m	20 MV/m	**2.9**	**23**

- **Short summary**: **hard to say the new method is absolutely better** than previous methods, since **considerations could be different**. But we are **so far satisfied and prefer to apply** it in our study

- Things to mention:

- Final **yield allowed to be changed flexibly** by loosening / tightening some **constraints** (e.g. linearly increased with primary e^- energy)
- To perform a **fair comparison**, **AMD** still simulated with a **constant inner aperture** (although this is improved in latest RF-Track code with tapered aperture)
- Beam **emittance** actually **floated** depending on beam spot size, since **transverse momentum spread** is fixed to **0.001%·E_{e-}** in Yanliang's study
- Optimised beam **spot size** chosen to be **1.75 mm**, for the reason that, starting from this value, **yield drops faster than PEDD** (as shown in last slide)

Latest results (preliminary)

- A few **improvements** w.r.t previous study
  - Aimed at **380 GeV** stage instead of 3 TeV. N_{bunch} per train: **352**. e+ population: **6.24e9** (=**1nC**, 20% safe margin included). For 1.5 TeV & 3 TeV, PEDD simply scaled by 0.63
  - **AMD** simulated with **tapered inner aperture**

$$R_{entrance} = \sqrt{\frac{B_{exit}}{B_0}} \cdot R_{exit} = \sqrt{\frac{0.5\ T}{B_0}} \cdot 20\ mm$$

  - Beam **emittance**, ε, specified (transverse momentum floated instead) to be **80 mm mrad**, and set free to be optimised

$$\varepsilon = \sigma_{XY} \cdot \frac{\sigma_{p_x, p_y}}{m_e c}$$

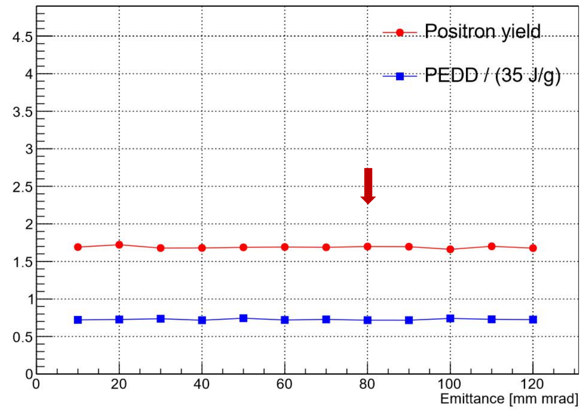
  - Others still the same, e.g., energy spread & beam length: $0.1\% \cdot E_{e-}$ & 1 mm

- **Final optimal results**

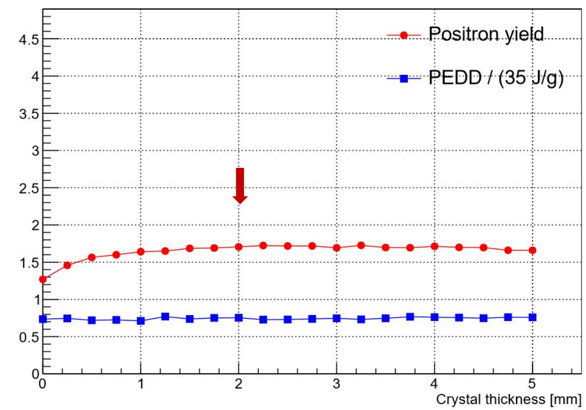
E_{e-}	σ_{xy}	ε	W_{xtal}	D_{targ}	B_{targ}	W_{amor}	B_0	L_{AMD}	φ_{dec}	φ_{acc}	E_{dec}	E_{acc}	Final Yield	PEDD [J/g]
5 GeV	3 mm	80 mm ·mrad	2 mm	**0**	0	13 mm	**3 T**	25 cm	150°	270°	11 MV/m	16 MV/m	**1.67**	**25.4**

Latest results (preliminary)

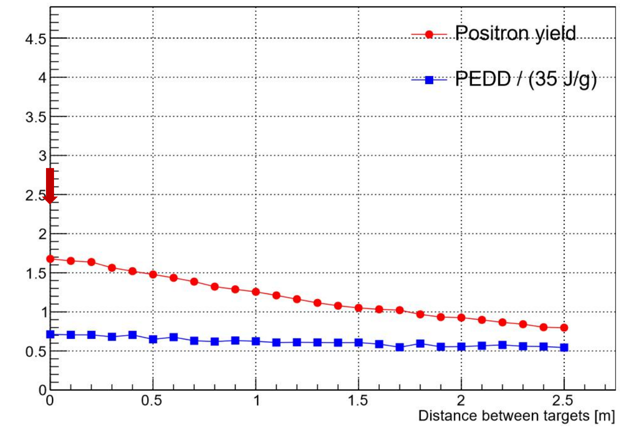
- Some **scanning plots** of the **final iteration**
  - more plots in BACKUP slides



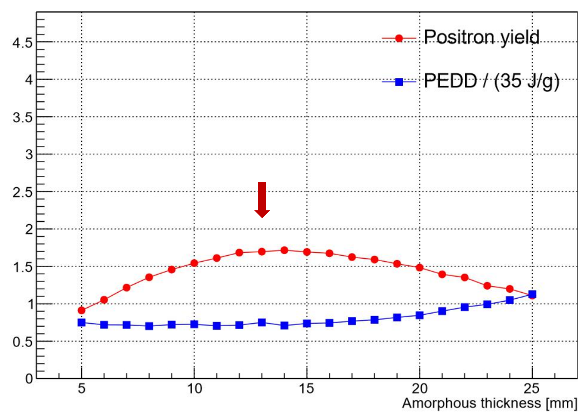
e- beam emittance [mm mrad]



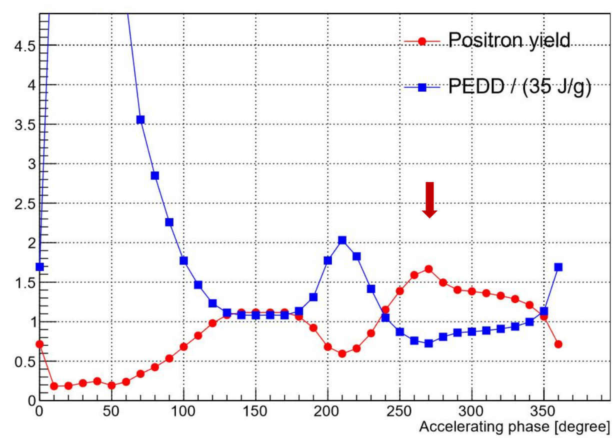
Crystal target thickness [mm]



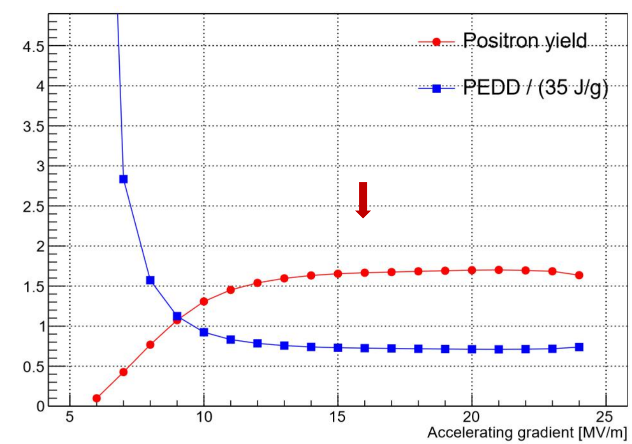
Distance between targets [m]



Amorphous target thickness [mm]



TW accelerating phase [degree]



TW accelerating gradient [MV/m]

Latest results (preliminary)

Comparison with previous results

- **PEDD** for previous studies all **scaled to current 380 GeV** stage baseline (Nb*Np = 352*6.24e9, as listed in last slide)

Parameters & results	Primary energy	Spot size	Distance between targets	AMD B_0	Final e^+ yield	PEDD [J/g]
CDR (2012)	**5 GeV**	2.5 mm	2 m	6 T	**0.39**	**49.2**
Implementary plan report (2018)					**0.97**	**19.8**
Yanliang's publication (2019)	**5 GeV**	2.5 mm	~0.65 m		**1.30**	**22.2**
	5 GeV	1.25 mm			1.94	36.8
	3 GeV	2.5 mm			**0.76**	**21.5**
	3 GeV	1.25 mm			1.03	33.6
Yongke (preliminary)	**5 GeV**	**3 mm**	**0**	**3 T**	**1.67**	**25.4**
	(4GeV)				1.40	
	(3GeV)				1.10	

- Injector linac always optimised automatically by searching for the best time window accepted by the PDR, therefore not included in common optimisation

Conclusion & outlook

- A **cross-check** with ILC and previous CLIC studies on positron source shows a good agreement
- A **new simple optimisation method** is proposed and applied to CLIC positron source study with some **advantages**
  - E.g. much faster and simpler, more reliable and convincing results
- Latest **preliminary results** using the new method **presented** and **compared with previous CLIC results** for the **380 GeV** stage, with final e^+ **yield** and **PEDD** improved to about **1.7** and **25 J/g**. And final yield found to be **linearly increased** with primary e^- energy (**~0.35·E**, PEDD not changed much)
- Next steps
  - Find the reason and understand **difference** in ILC cross-check
  - Double-check and **understand the results** (especially when distance=0)
  - Investigate and study to find a proper **PEDD mesh volume** size
  - Check effects from **AMD design** with Opera (talk from Hugo this afternoon)

BACKUP

Improved SW field check for ILC

Improved field:

Quantity	Value
q_n	$\sqrt{\left|\left(\frac{\omega}{c}\right)^2 - \left(\frac{n\pi}{L}\right)^2\right|}$
$\boldsymbol{E}_z(r,z,t)$	$\sum_{n=1}^{\infty} a_n Sin\left[\frac{n\pi(z+L/2)}{L}\right] Sin[\omega t+\phi_0] \times \begin{cases} J_0(q_n r) & \frac{\omega}{c} \geq \frac{n\pi}{L} \\ I_0(q_n r) & \frac{\omega}{c} < \frac{n\pi}{L} \end{cases}$
$\boldsymbol{E}_r(r,z,t)$	$-\sum_{n=1}^{\infty} a_n \frac{n\pi}{L q_n} Cos\left[\frac{n\pi(z+L/2)}{L}\right] Sin[\omega t+\phi_0] \times \begin{cases} J_1(q_n r) & \frac{\omega}{c} \geq \frac{n\pi}{L} \\ I_1(q_n r) & \frac{\omega}{c} < \frac{n\pi}{L} \end{cases}$
$\boldsymbol{B}_\phi(r,z,t)$	$\sum_{n=1}^{\infty} a_n \frac{q_n^2 + \left(\frac{n\pi}{L}\right)^2}{\omega q_n} Sin\left[\frac{n\pi(z+L/2)}{L}\right] Cos[\omega t+\phi_0] \times \begin{cases} J_1(q_n r) & \frac{\omega}{c} \geq \frac{n\pi}{L} \\ I_1(q_n r) & \frac{\omega}{c} < \frac{n\pi}{L} \end{cases}$

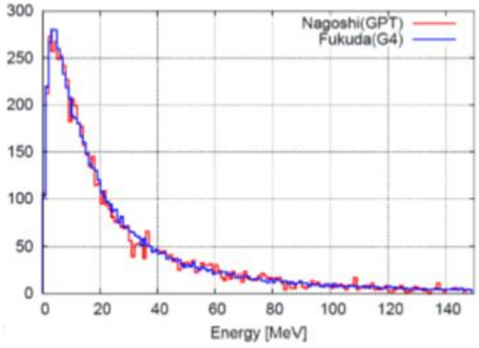
Results	After SW 1st tube	After 36 SW tubes	Within ±7 mm from z_peak
CLIC code (pillbox approximation)	2.03	1.96	1.09
CLIC code (improved SW field)	2.04	1.97	1.09

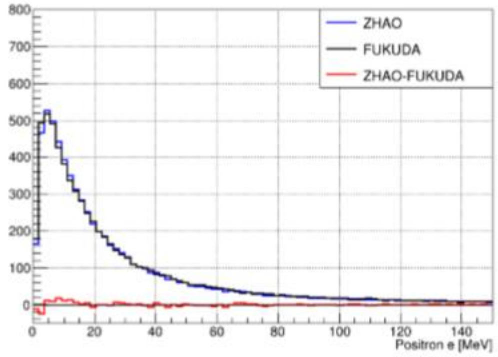
Positron energy & pz after target

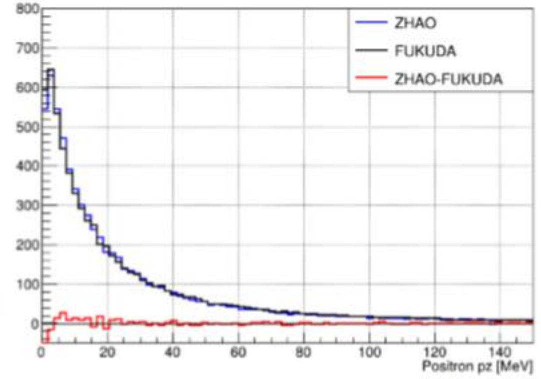
- Energy distribution comparation

Nagoshi: **1000** events

Fukuda & Zhao: **10,000** events, **scaled to 1000** (applies to all the related plots in the following slides if not otherwise specified)





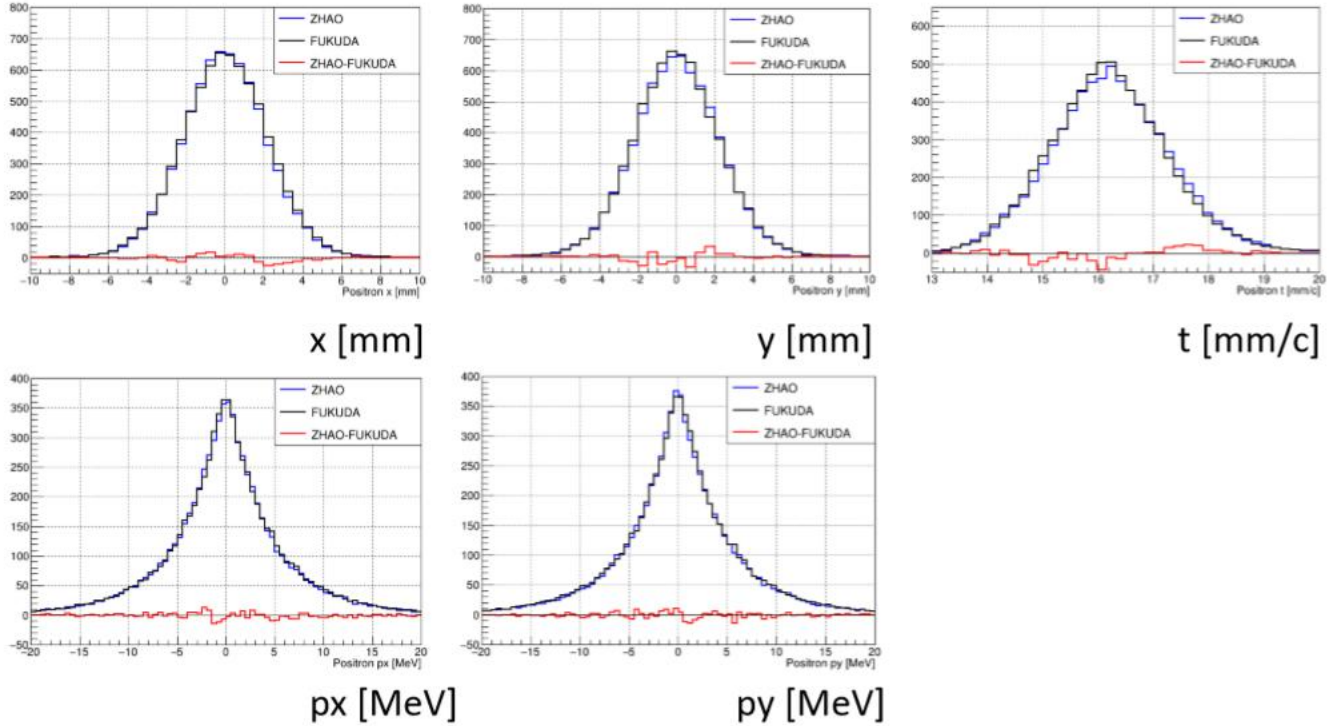


e [MeV] e [MeV] pz [MeV]

❑ **Good agreement** found in positron **energy** and **pz** distributions at the **target exit**

Comparison plots for ILC

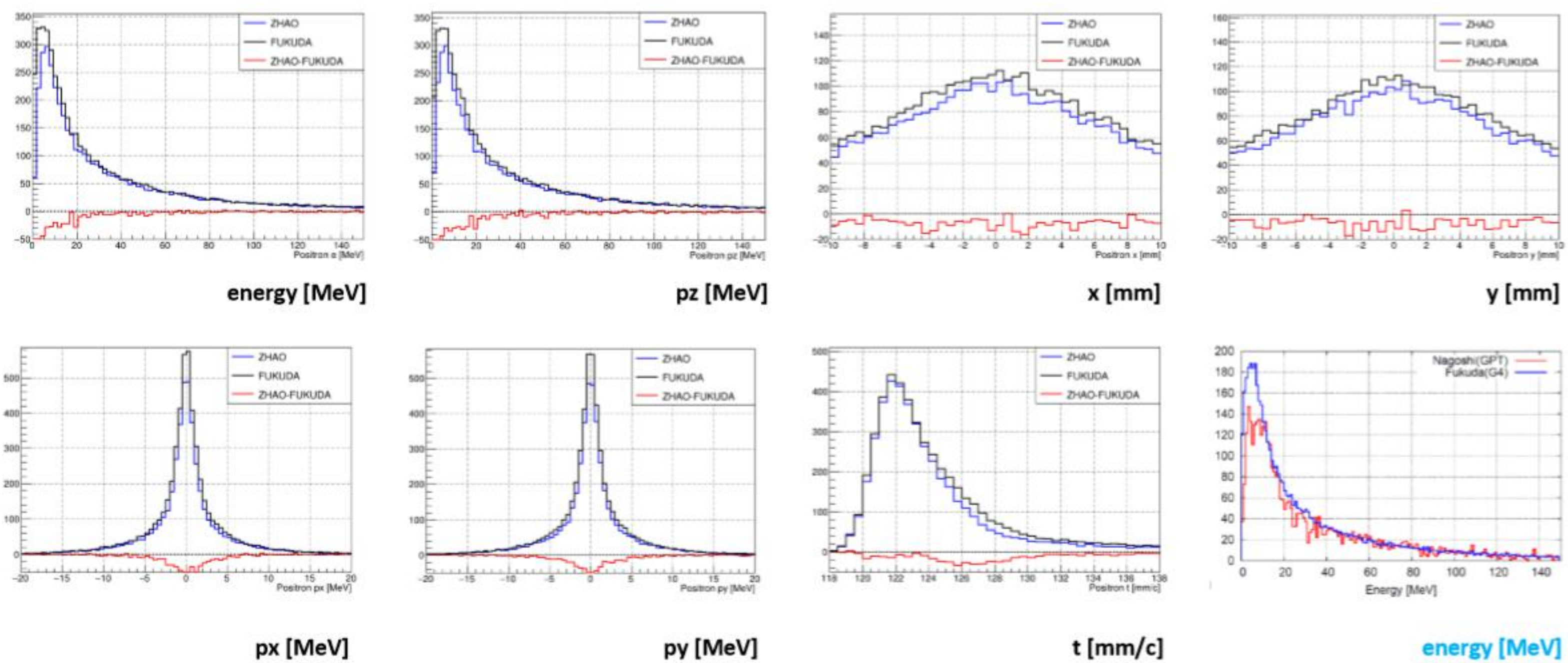
Positrons after target



❑ A **Good agreement** found in positron **x, y, px, py** and **t** distributions at the **target exit**

Comparison plots for ILC

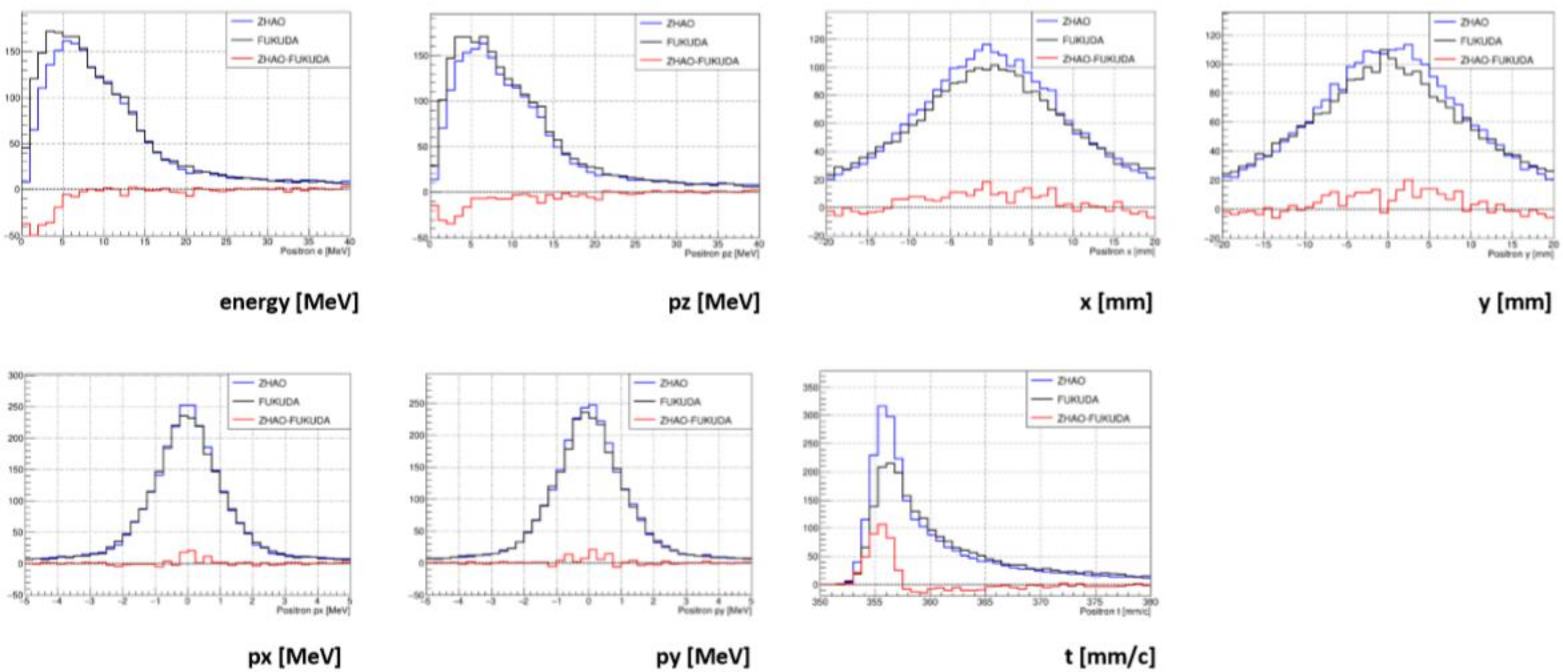
Positrons after ILC AMD



- Difference mainly distributed at **very low four-momentum** range
- An internal comparison from ILC (the last plot) shows even larger difference

Comparison plots for ILC

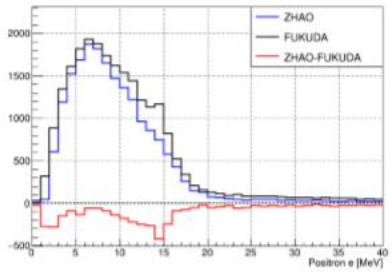
Positrons after Collimator



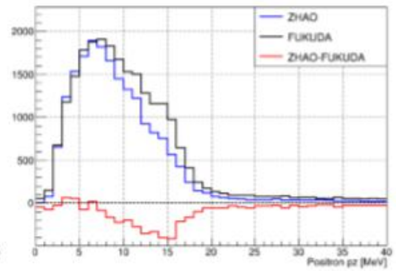
- Difference mainly in **time** distribution and **low energy** range
- An **in-situ check** performed (in **backup slides**), confirms that the **difference comes mainly from the simulation of Collimator** itself, instead of inheriting mostly from the difference in AMD

Comparison plots for ILC

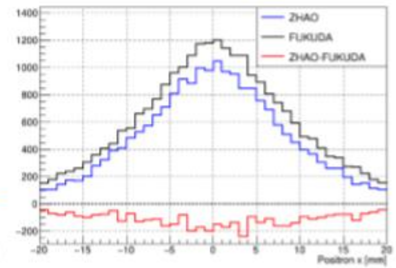
Positrons after the 1st SW tube



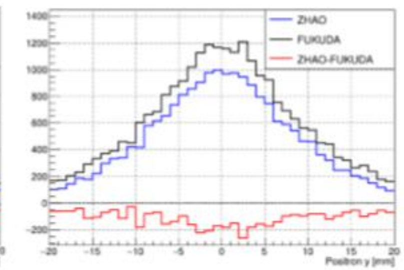
energy [MeV]



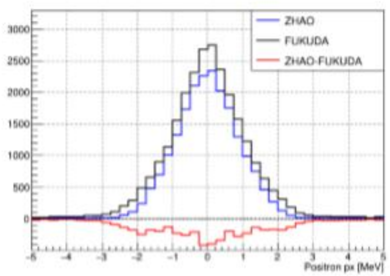
pz [MeV]



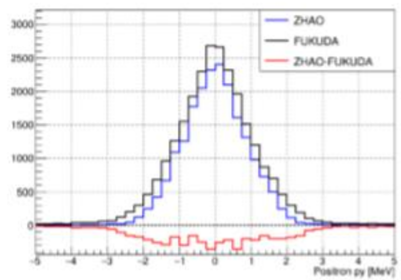
x [mm]



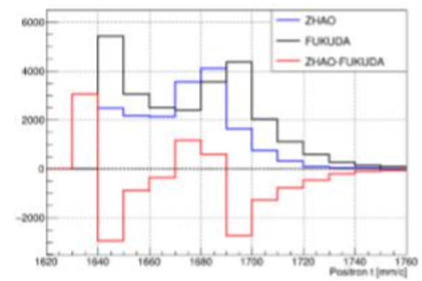
y [mm]



px [MeV]



py [MeV]

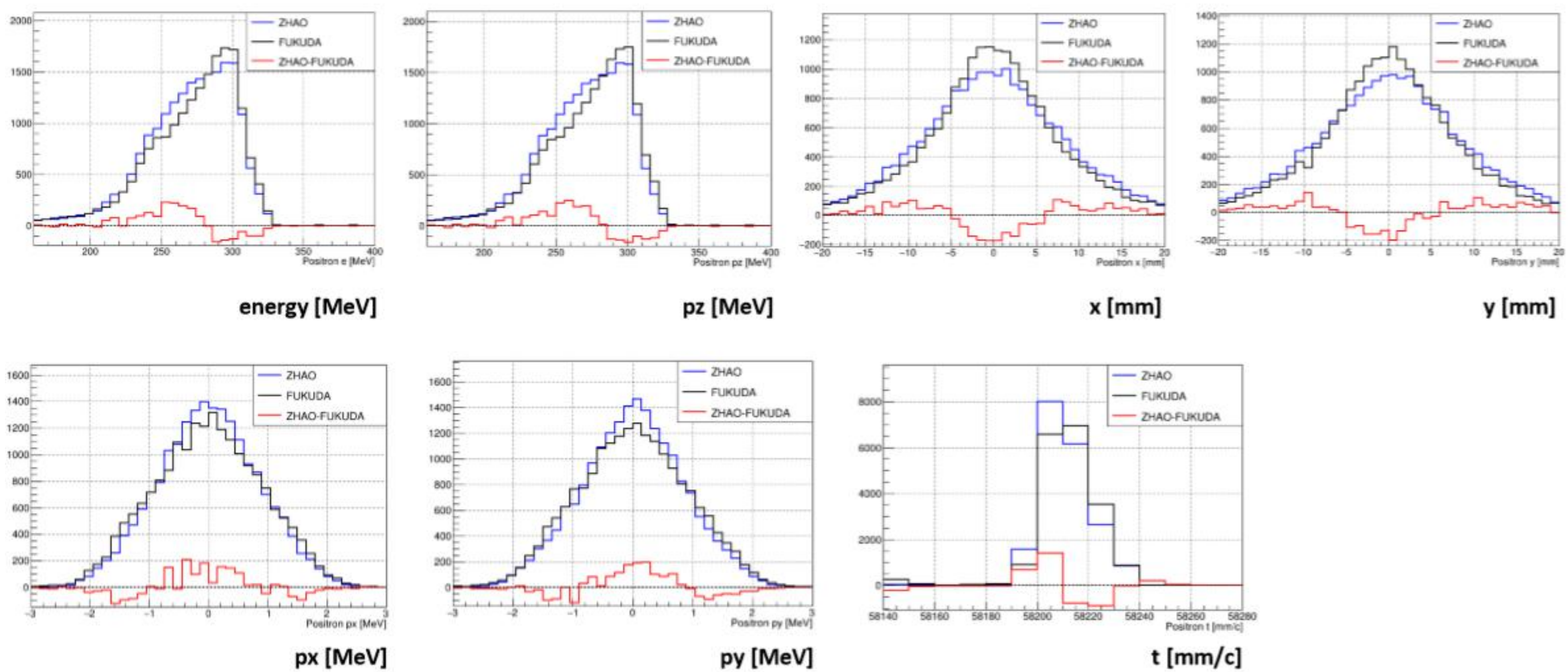


t [mm/c]

- ❑ Difference mainly in **time** distribution and range around **pz=15 MeV** and **p_T=0**
- ❑ An **in-situ check** performed (in **backup slides**), confirms that the **difference comes mainly from the 1st SW tube** itself, instead of inheriting mostly from the difference in Collimator

Comparison plots for ILC

Positrons after all the 36 SW tubes

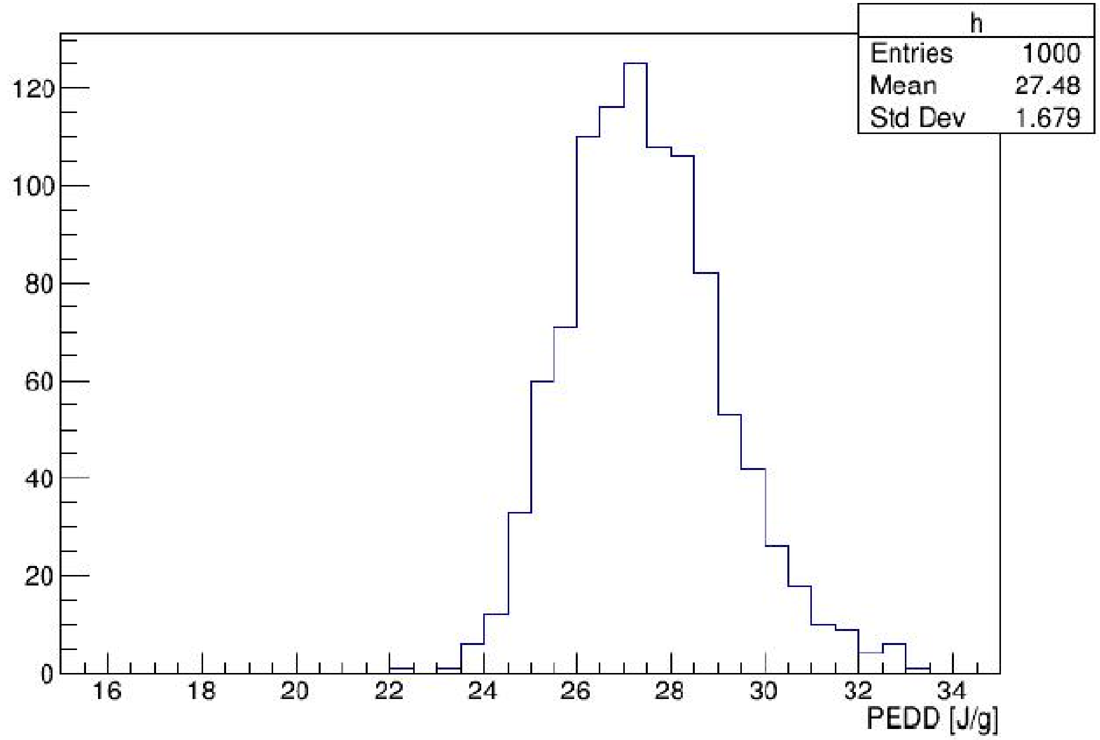


- **Small differences:** our results have a bit larger **energy and momentum spread** and **beam size**

PEDD uncertainty

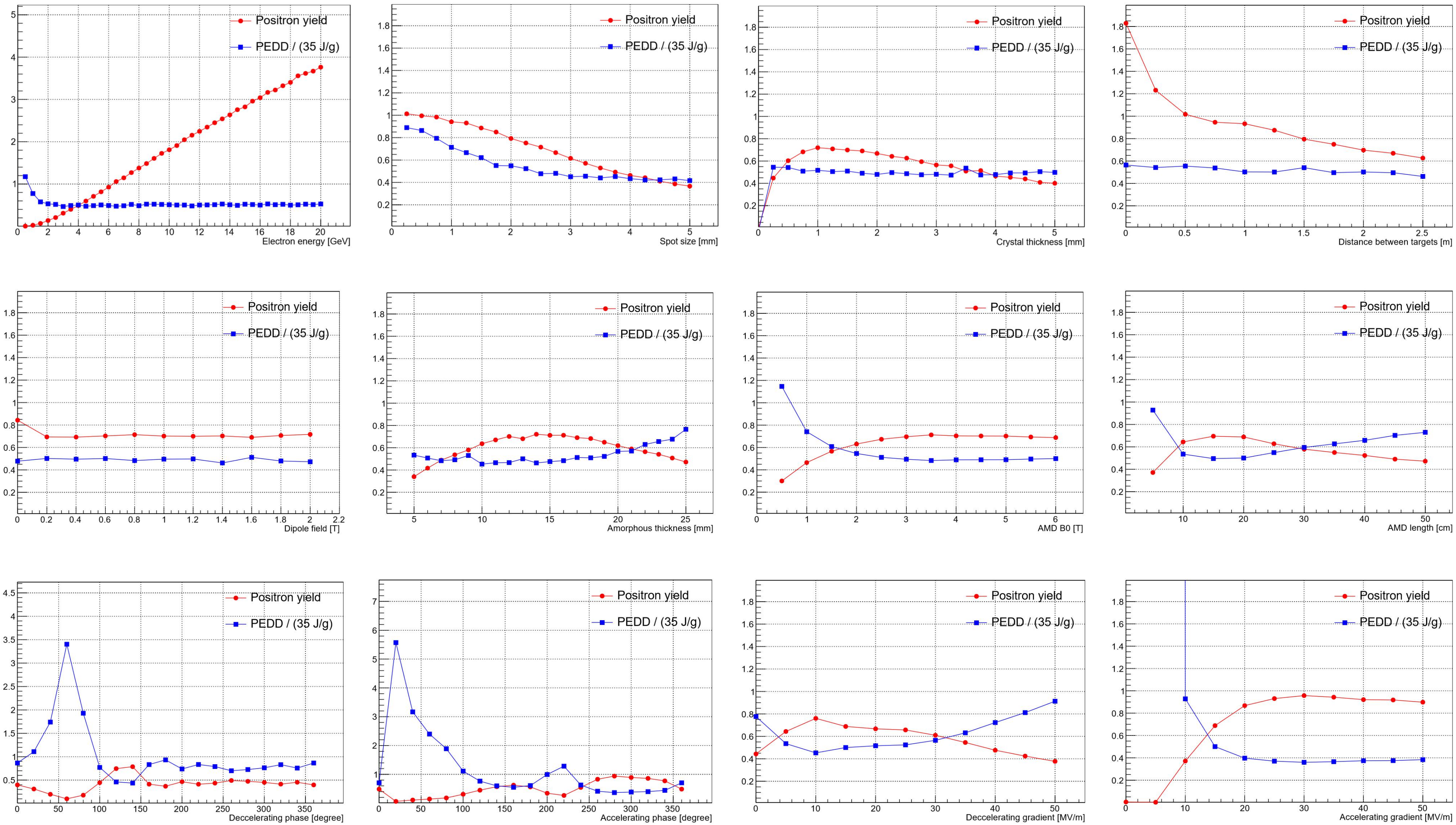
PEDD uncertainty for cross-check with ILC

- PEDD uncertainty for 1000 events: 6.1% (1 sigma, 1000 electrons simulated also, and 1000 times of simulation with different random seed).



Re-optimise previous results

- **Scanning results** of the **1st iteration** for the free parameters



Latest results (preliminary)

- Other **scanning plots** of the **final iteration**