Optimization of e+ sources for the FCC-ee

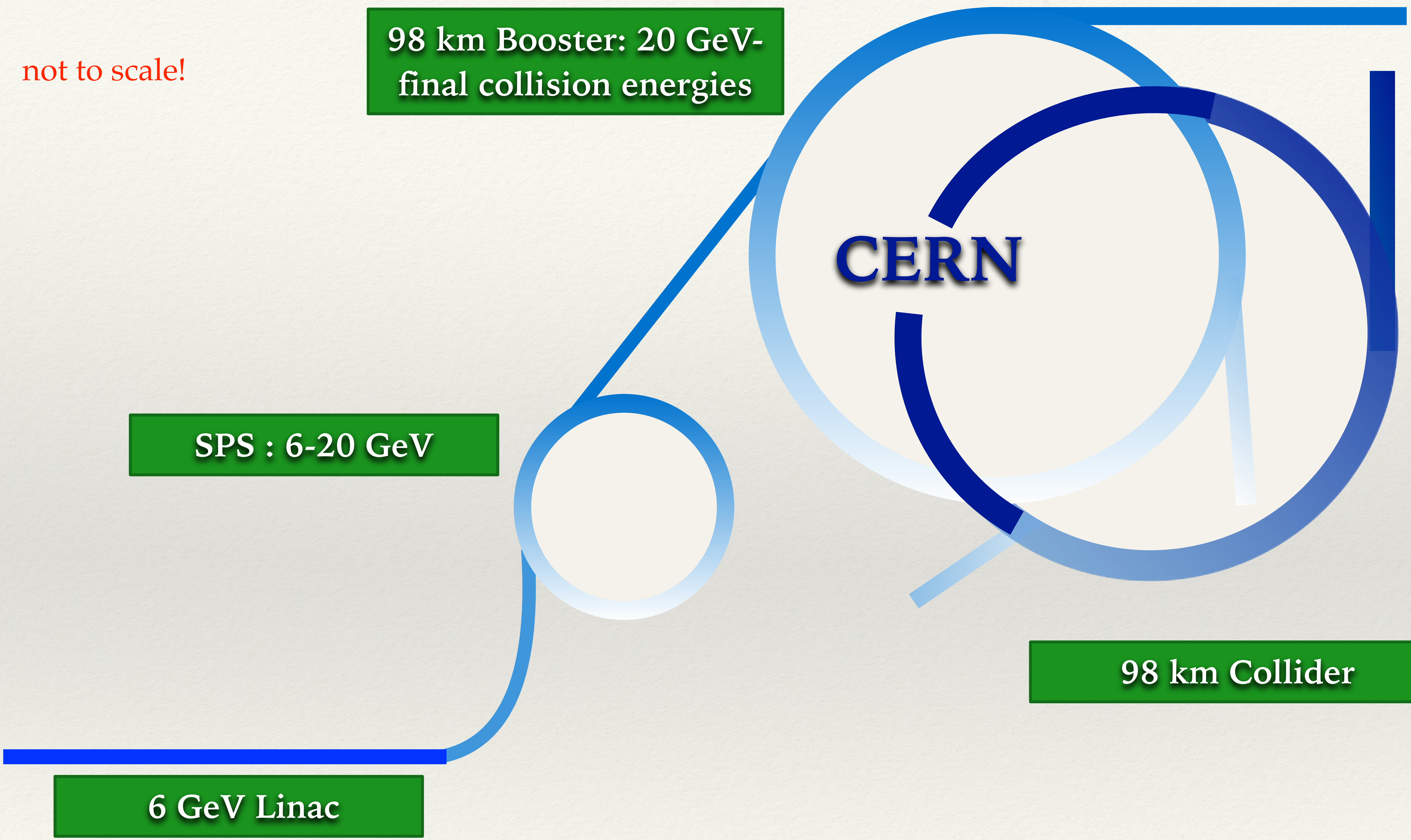
S. Ogur, F. Alharti, I. Chaikovska (leader), H. Guler,
V. Kubytskyi, S. Wallon, R. Chehab (retired).

FCC-France Workshop, 30 Nov 2021

Outline

1) FCC-ee Injectors and Positrons Overview
2) Positron Target and Capture Simulations
3) Beam Tests at Mainzer Mikrotron
4) Conclusions and Outlook

1.1. FCC-ee Injector Complex



1.2. FCC-ee Operational Modes

Operation Type	Final Energy [GeV]	Luminosity Lifetime [min]	Bunches/Beam	Bunch Population
Z	45.6	70	16640	1.7×10^{11}
W	80	50	2000	1.5×10^{11}
H	120	42	328	1.8×10^{11}
tt	182.5	39	48	2.3×10^{11}

- Z-operation is where the highest current of 1.4 A is stored in the collider. For this reason, we take Z-mode which is the most challenging case as reference for the injector.
- Injector for Z-mode, 200 Hz linac with 2 bunches per RF pulse separated by ~50 ns.
- Bunch charge ~2.2E10 particles during the first fill of the collider, and ~2.2E9 during the top-up.

1.2. FCC-ee Operational Modes

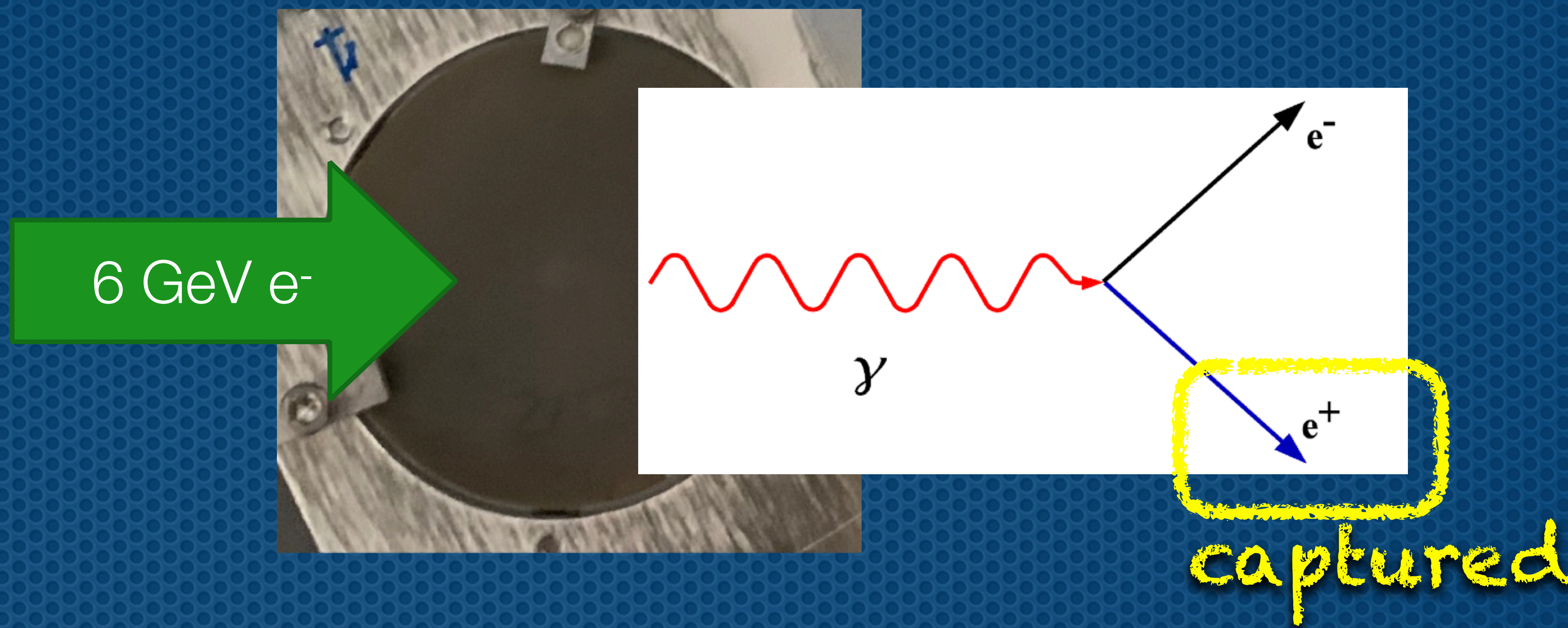
- Z-operation is where the highest current of 1.4 A is stored in the collider. For this reason, we take Z-mode which is the most challenging case as reference for the injector.

185 days * 10 fills per day * 16640 bunches = 30.8 M Full Charge Annual Hits on e+ Target

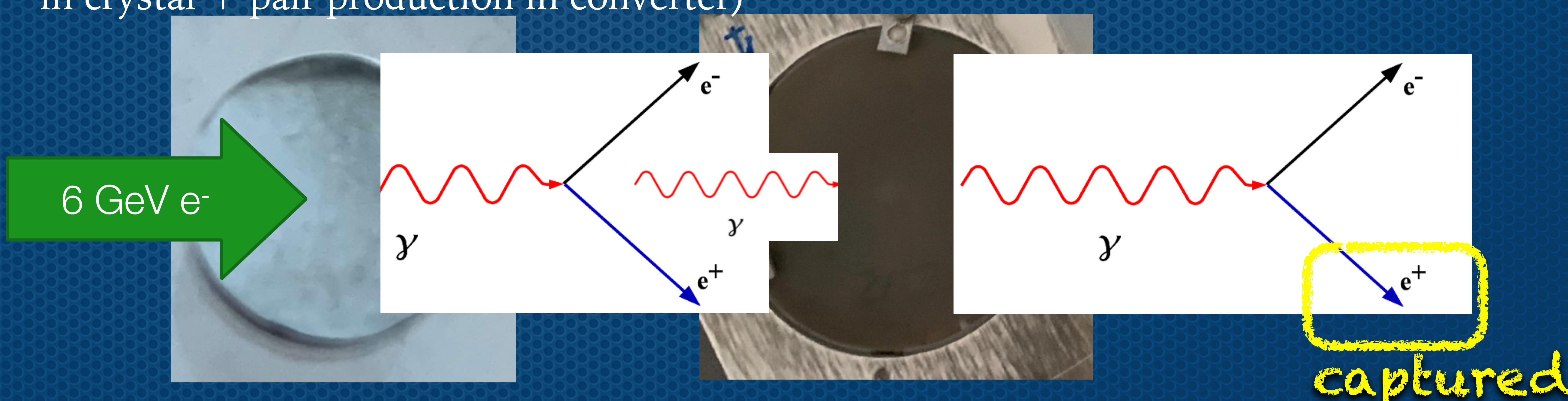
- The annual hits are not necessarily with full injector charge i.e. 2.2E10 e^-/e^+, during top-up the injector may vary around 2.2E9.

1.3. FCC-ee Positron Production

i) Conventional Target:
Amorphous
(e+ are produced by
bremsstrahlung + pair
production)

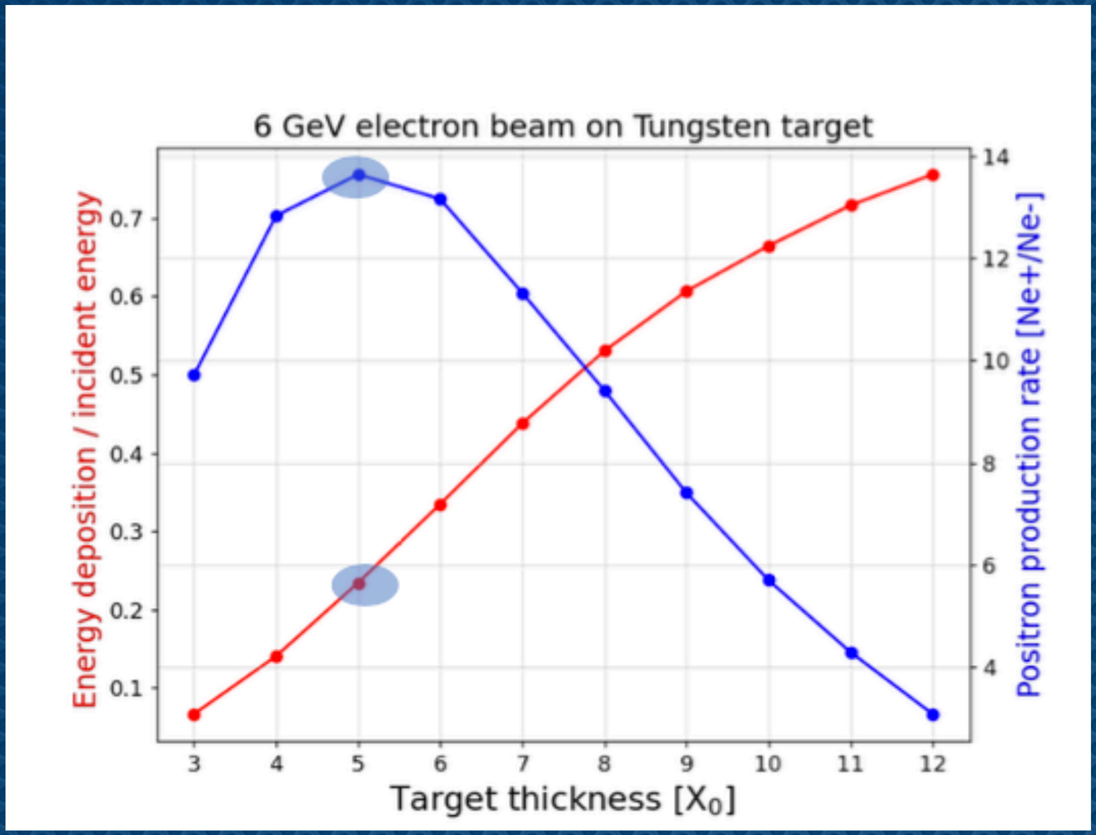


ii) Hybrid Target: crystal + amorphous
(e+: γ are produced by channeling radiation
in crystal + pair production in converter)

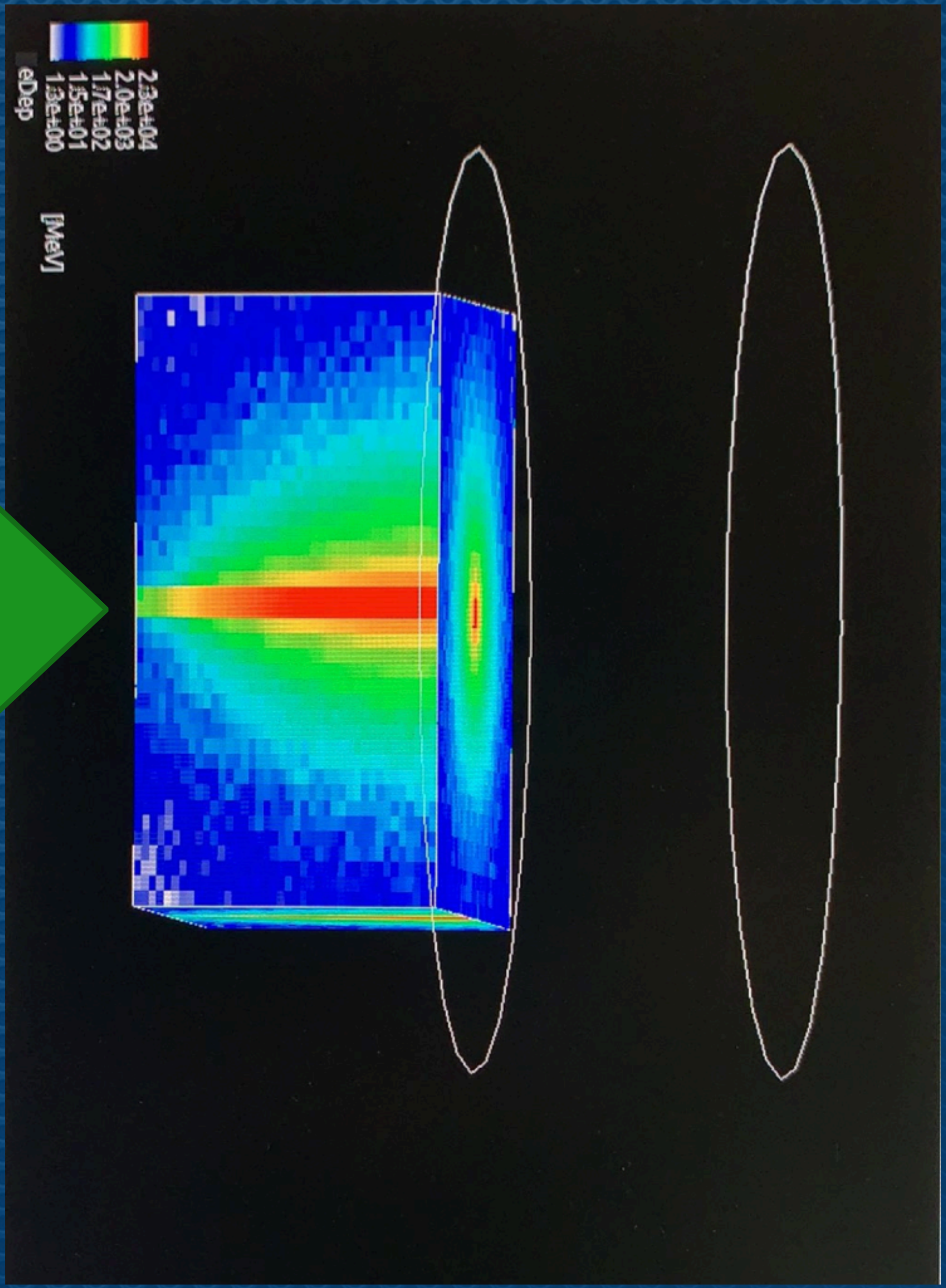


2.1. FCC-ee Conventional Target

- Tungsten is the first candidate for the amorphous target. Simulations on Geant4 showed an optimum thickness of $5X_0$ (5 radiation length of 3.5 mm).



6 GeV e-



- We can achieve 2.2E10 e+/bunch requested by the FCC-ee with conventional target. However, peak energy deposition density (PEDD), cooling, fatigue, atomic disposition etc need to be studied yet regarding the incident beam power.

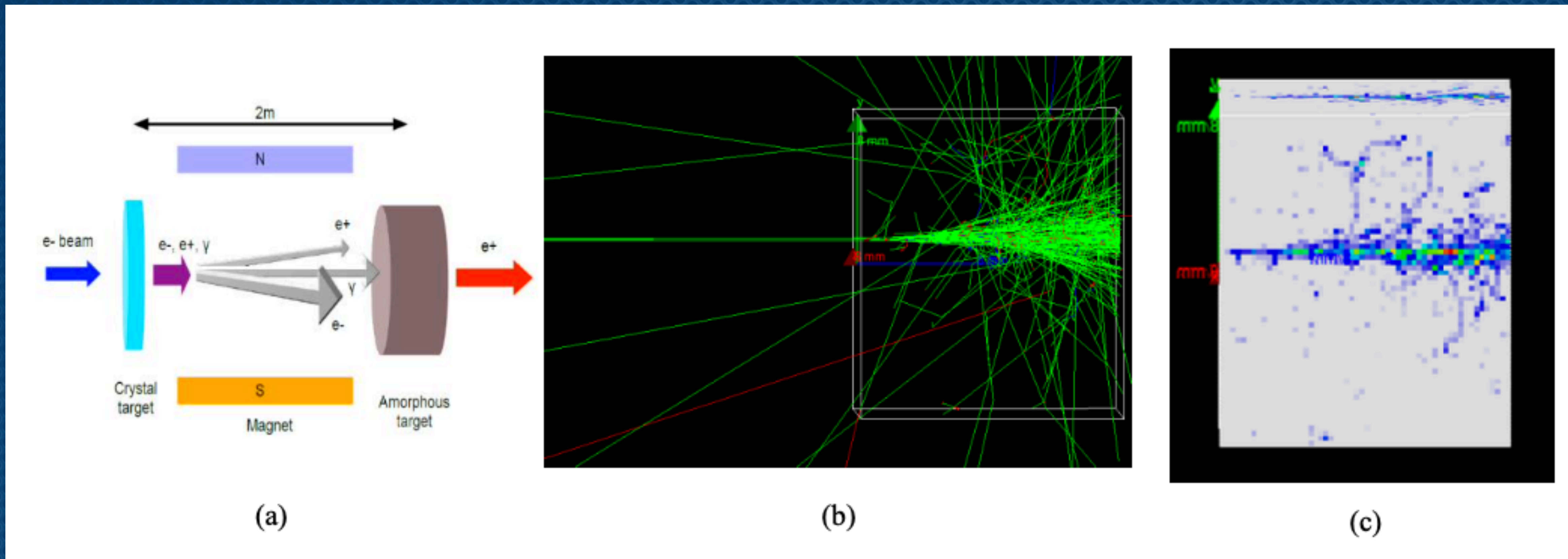
2.1. FCC-ee Conventional Target

- We can achieve 2.2E10 positrons from amorphous W. However, peak energy deposition density (PEDD), fatigue, atomic disposition etc need to be studied yet regarding the incident beam power.

Conventional target		DR acceptance 3.8%
Capture Section: FC(7T + 0.75 T) + S-band (LAS)		
		Target: 5X0 (17.5 mm)
FCC-ee		
Beam energy, GeV	6	
Number of bunches	2	
e+ bunch charge @200 MeV, e+	4,2E+10	
Bunch charge, e-	1,77E+10	
Bunch length (rms), mm	1	
Bunch transv. size (rms), mm	0,5	
Bunch separation	wakefiled limit	
Repetition rate (max), Hz	100	
Beam power, kW	3,4	
Emittance (normalsed max), mm.rad	<1	
Energy spread, %	< 1	
PEDD (target), J/g	10,5	
Deposited power (target), [kW]	0,75	

- Peak energy deposition density (PEDD) is calculated to be 10.5 J/g (under study).

2.2. FCC-ee Hybrid Target



❖ Ref: F. Alharti's M.Sc. thesis: hybrid target consisting of 1-2 mm thick W crystal <111> and 14 mm thick W amorphous.

❖ Photons are simulated using code *CRYSTALRAD* by INFN Ferrera.

❖ PEDD has been sharply decreased 1.9 J/g compared to the amorphous-only target (10.5 J/g).

2.2. FCC-ee Hybrid Target

Simulation results	Conventional scheme	Hybrid scheme
Beam energy [GeV]	6	
Beam size [mm]	0.5	
Number of simulated e-	10000	9950
Target material	W	W(crystal) + W(amorphous)
Target thickness	17.5mm	1mm (crystal) +14 mm(amorphous)
Energy deposition [MeV/e-]	1407	984.7
[E_dep/E_incident]	23%	16%
Positron production rate [Ne+/Ne-]	~14	~9
PEDD [J/g]	10.9	1.9

- ❖ Ref: F. Alharti's M.Sc. thesis: hybrid target consisting of 1 mm thick W crystal <111> and 14 mm thick W amorphous.
- ❖ Photons are simulated using code *CRYSTALRAD* by INFN Ferrera.
- ❖ PEDD has been sharply decreased 1.9 J/g compared to the amorphous-only target.

3. Beam Tests at Mainzer Mikrotron

❖ Both options satisfy the FCC-ee positron requirements:

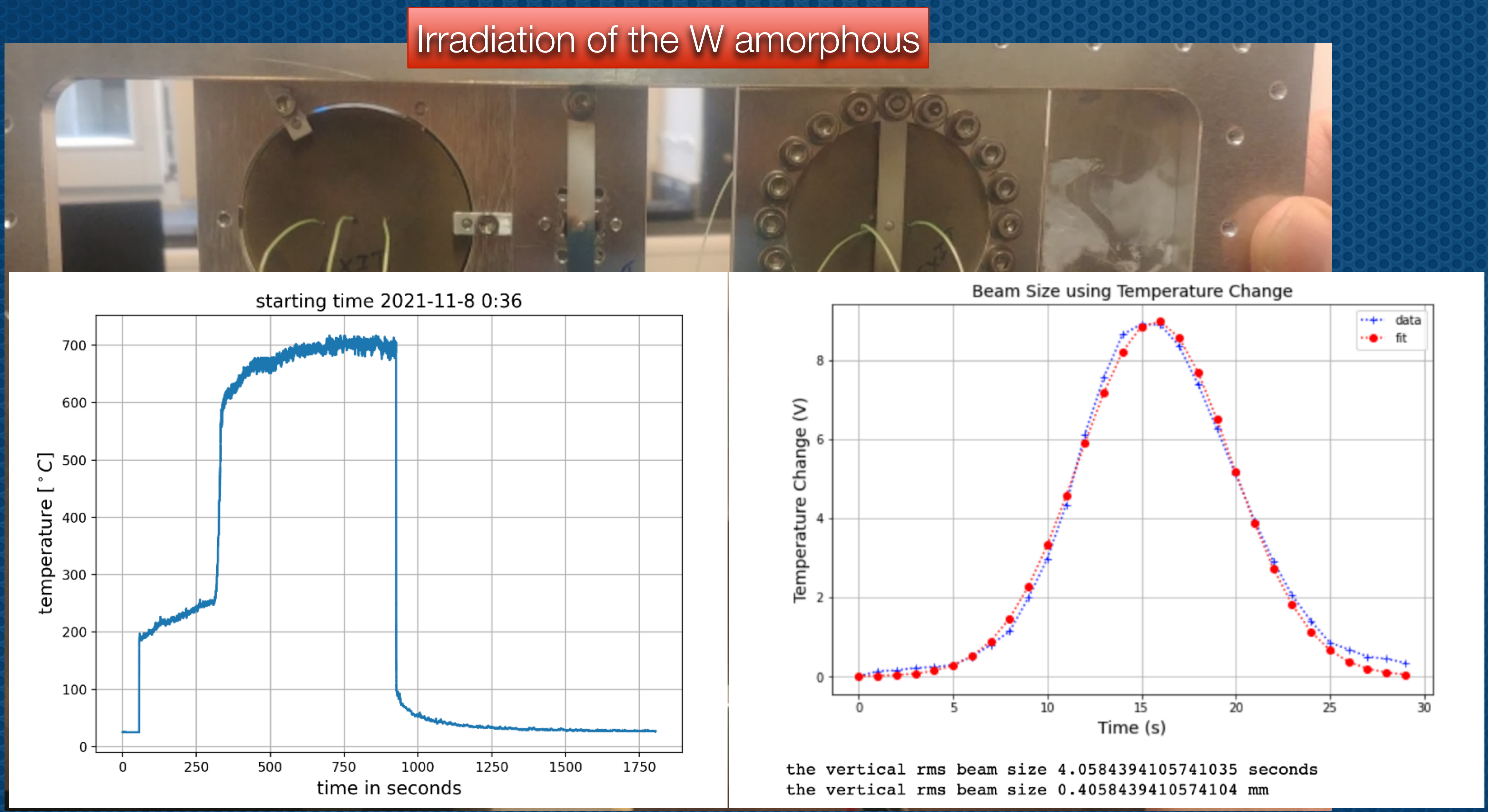
However:

i) Does the conventional target need to be
- stationary like SuperKEKB
- tumbling like SLC
- rotating wheel like ILC
due to the high PEDD; and temperature, fatigue, atomic dispositions?

ii) Does the crystal target keep its photon enhancement after long irradiation?
- SLC fluency of 2×10^{18} electrons/mm^2, crystal structure was still preserved.

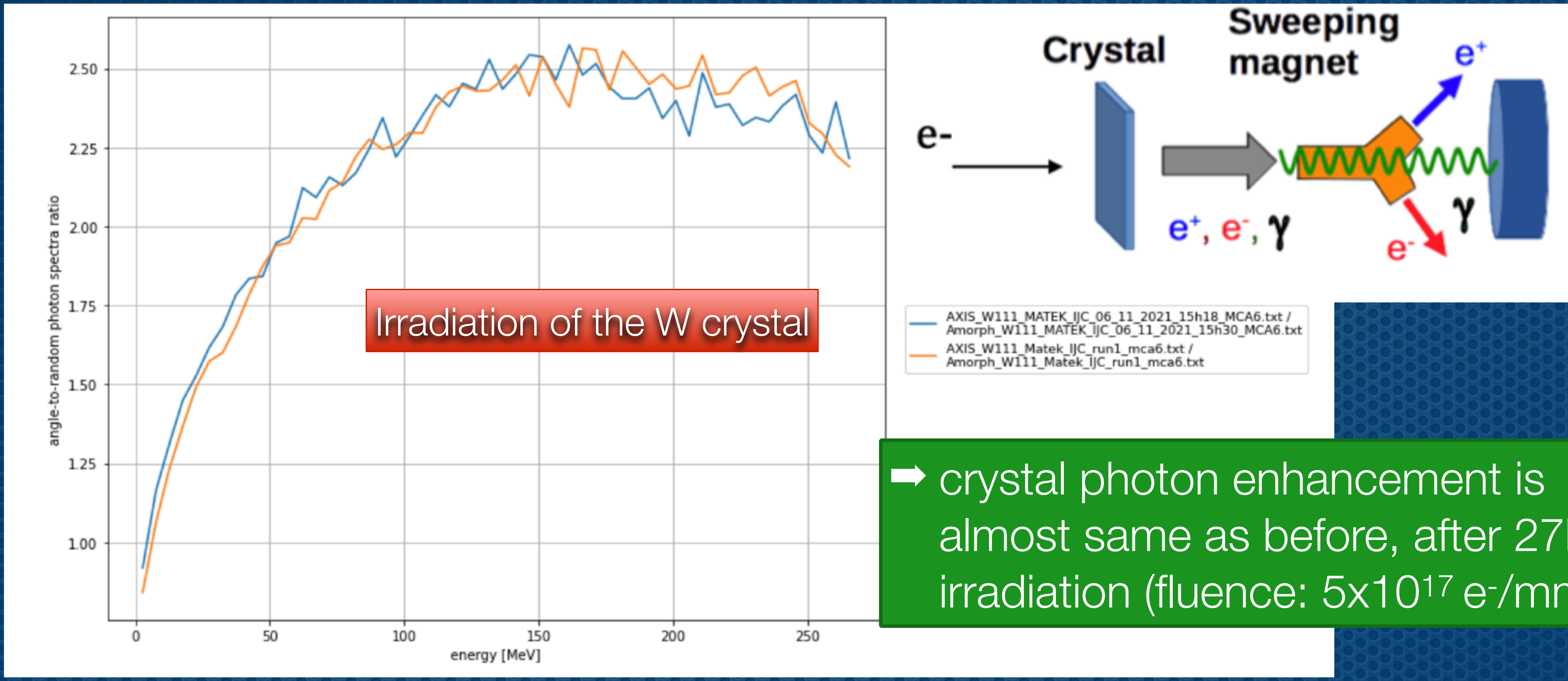
3.1. Beam Tests at MAMI (Amorphous)

❖ Thermocouples are used for temperature measurements on the target exit, even for the beam size measurements, very fresh and preliminary results.



1 μA beginning, switch (jump can be seen) to 4 μA average, well-aligned, 20k Samples/sec @855 MeV.

3.2. Beam Tests at MAMI - Crystal



➡ crystal photon enhancement is almost same as before, after 27h irradiation (fluence: 5×10^{17} e^-/mm^2)

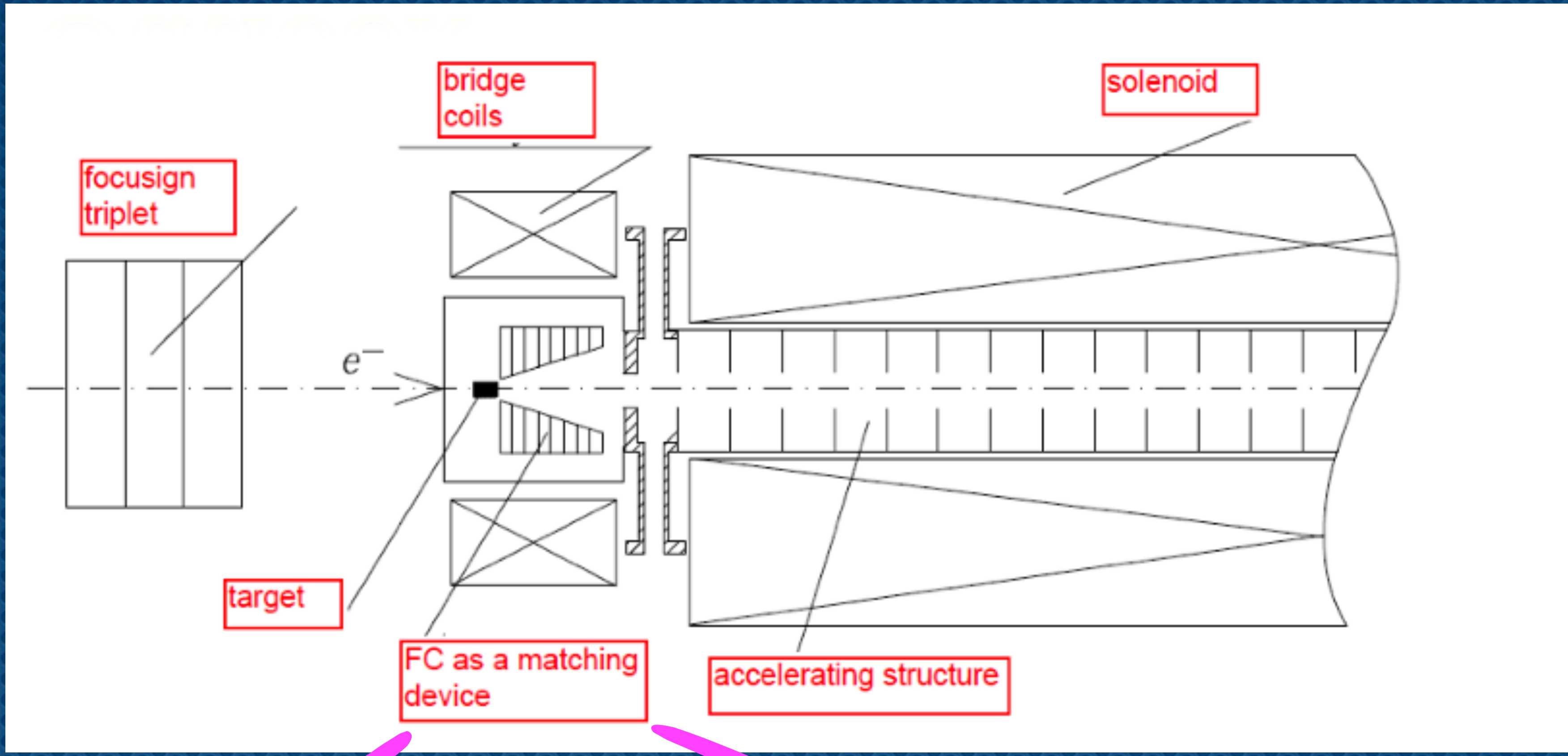
i) Crystal for FLUENCE† test to surpassed the SLC limit 2×10^{18} e^-/mm^2 by by factor 2.5!

ii) X/γ-ray diffractometry, electron microscope/laser scanning microscope in ~ Mid 2022 to study radiation damage on our targets once they are 'radiationally cooled'.

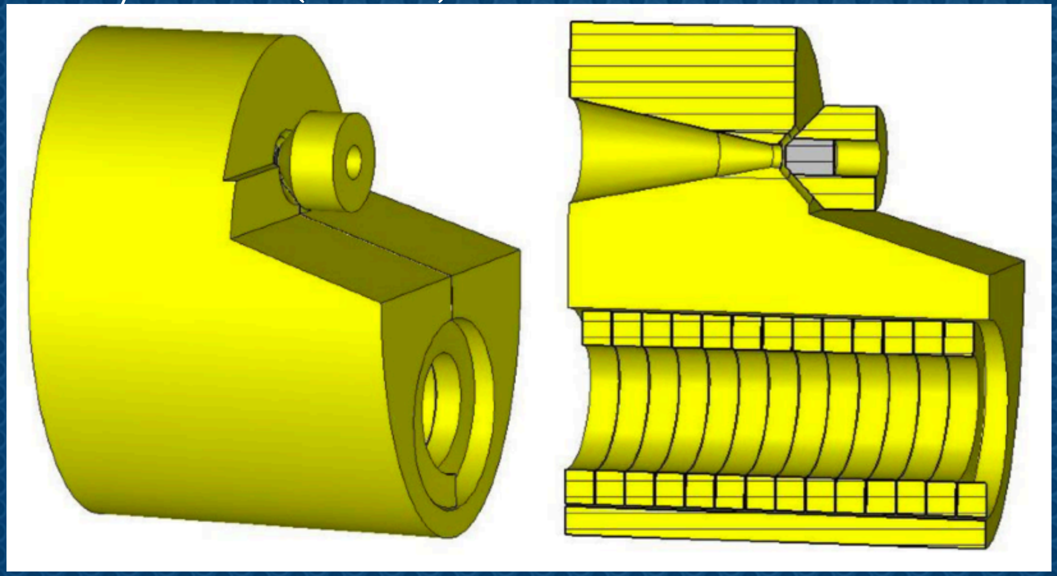
iii) Crystal we have: 8 mm diameter 1, 1.4, 2 mm thick Tungsten.

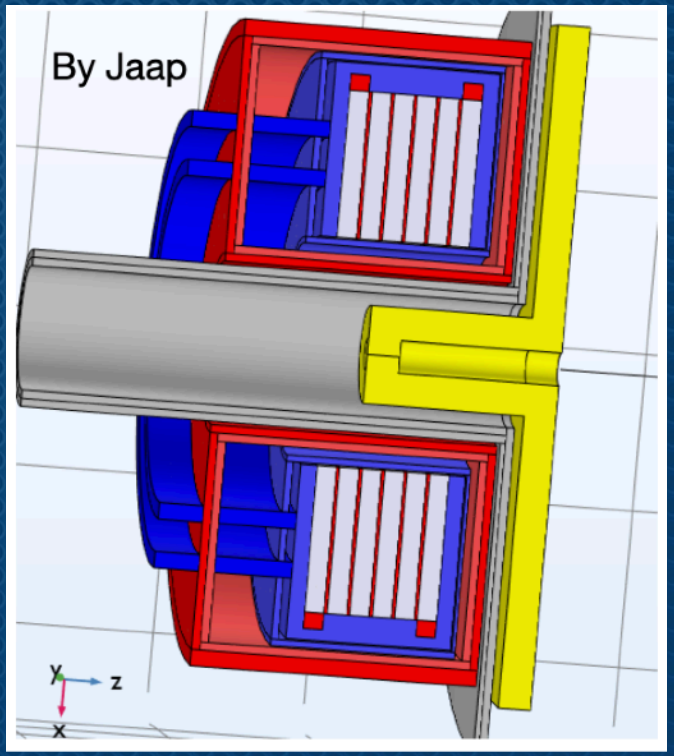
† X. Artru, R. Chehab et al., Radiation-Damage Study of a Monocrystalline Tungsten Positron Converter, LAL-RT-98-02.

4.1. Outlook



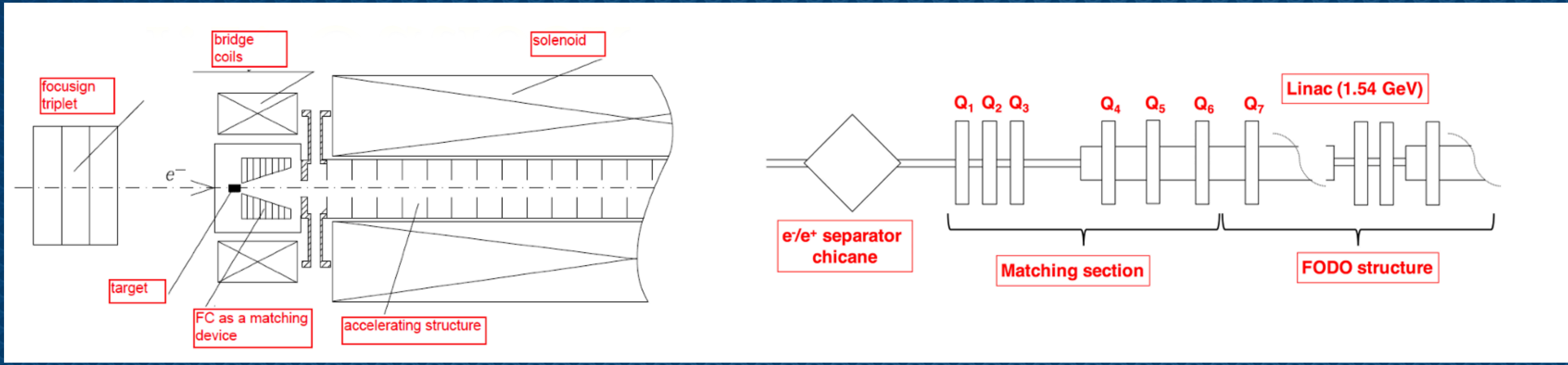
Normal Conducting Flux Concentrator by P. Martyshkin (BINP)





Super Conducting Matching Device by J. Kosse (PSI)

4.1. Outlook



Geant4
- Primary Beam Size
- Target Material
- Target Thickness

Already existing Python Script

RF- Track
- FC, SC or NC
- FC location
- FC aperture

RF-Track Enables Python or Octave

RF- Track
- Cavities Frequency
- Cavity Length, Phase
- Cavity aperture

RF- Track, MADx
- Linac Optics
- Damping Ring Optics

MADX can be used in Python as CPYMAD library

Start to end simulation in Python (AI Controlled Optimization ?)

4.2. Conclusions

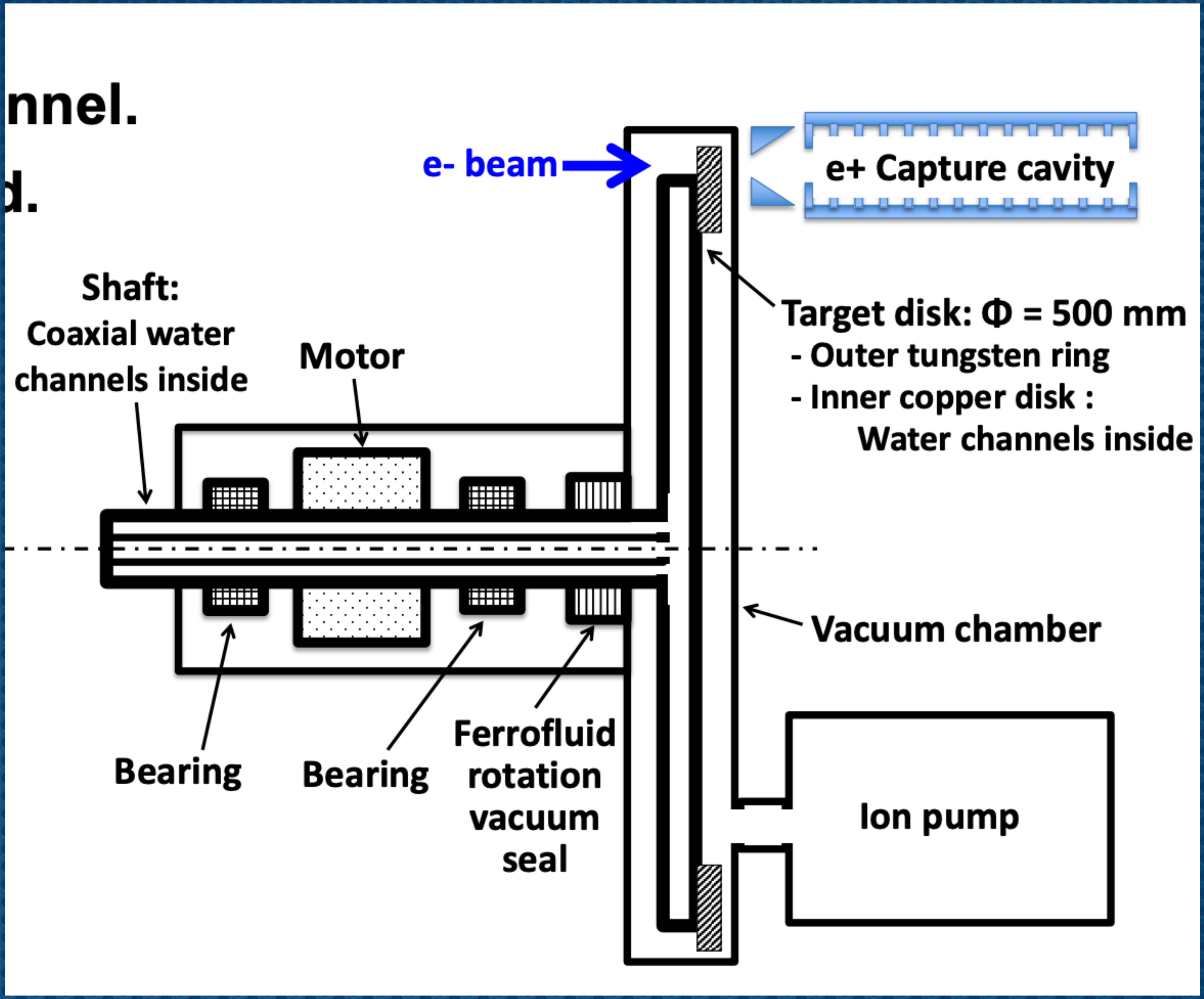
❖ We are considering both conventional and hybrid targets for the FCC-ee positron production. Final choice to be done for the FCC-ee CDR+.

❖ Our very preliminary beam tests of the W samples are promising, final conclusions will be drawn after targets are radiationally cooled and the detailed material analysis are performed.

❖ For capture and optics, we will be implementing machine learning.

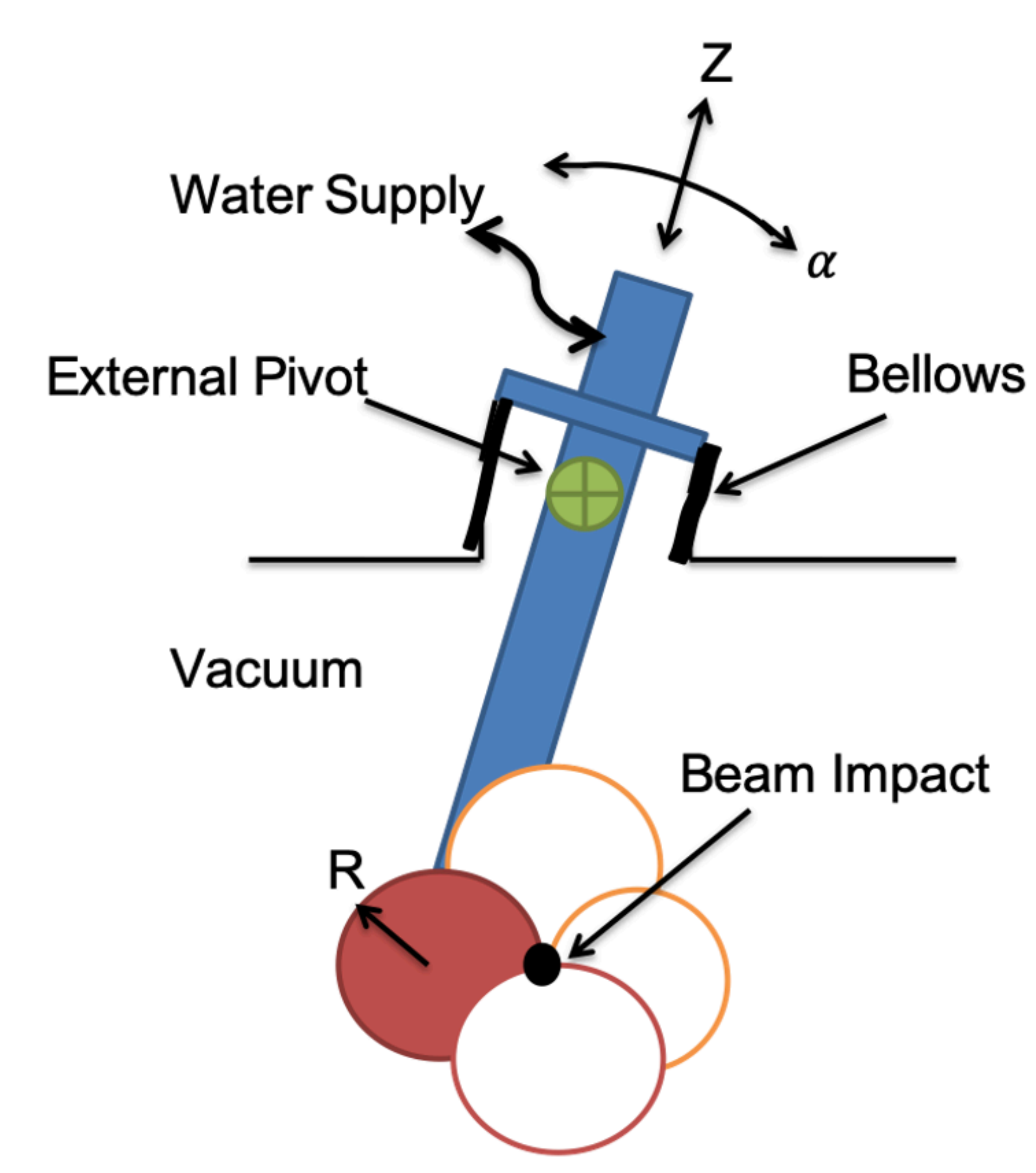
❖ Collaboration between PSI and CERN with several external partners (IJCLab, INFN-LNF, INFN-Ferrara, BINP, KEK…) => demonstrator for e+ production and capture to be built at PSI/SwissFEL in 2024-2025.

BACK UP 1 - ILC Rotating Wheel



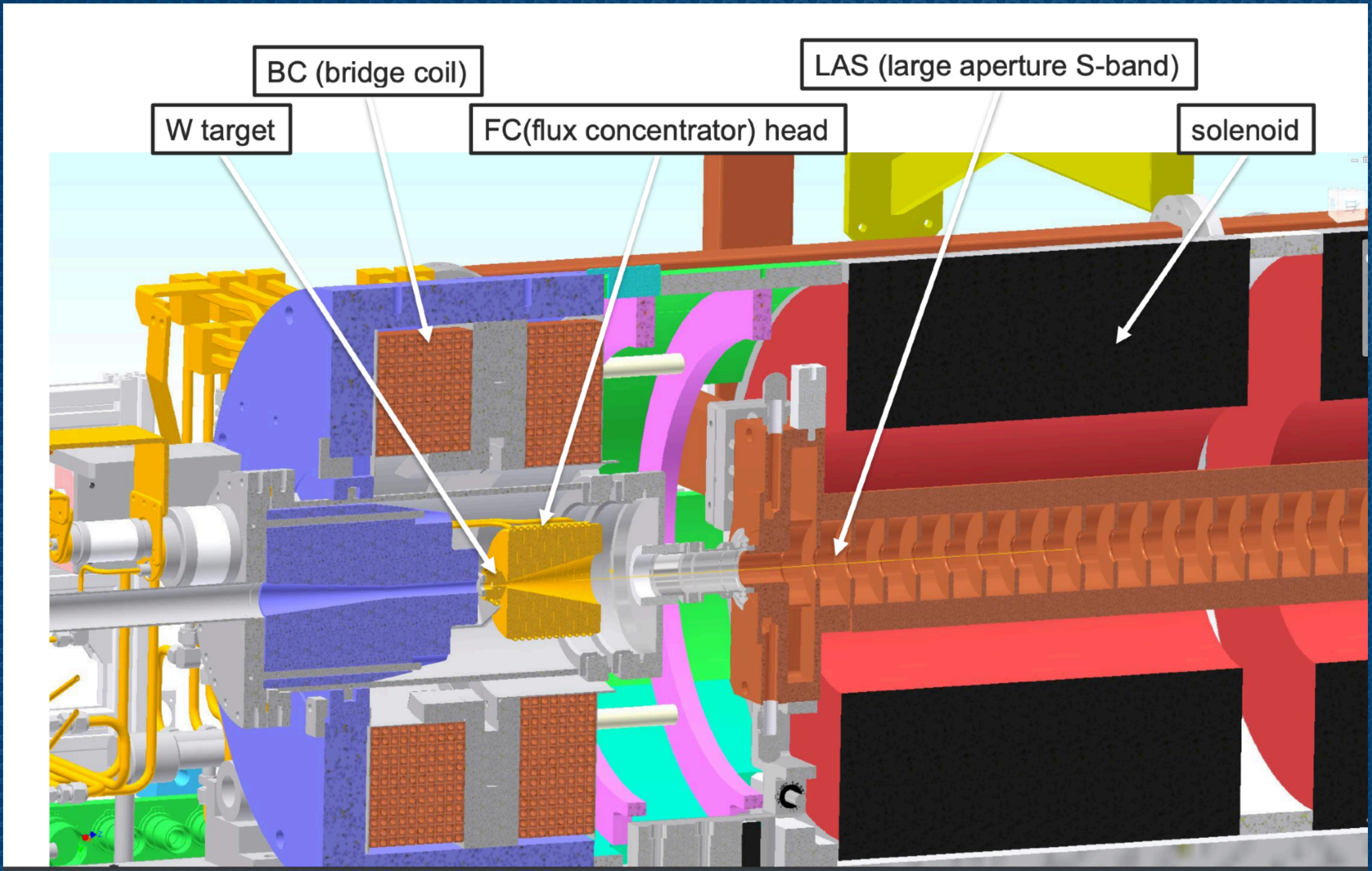
❖ T. Omori (KEK), ILC e-driven e+ Source (AWLC2020), link.

BACK UP 2 - SLC Rotating Wheel



❖ E. Reuter et al, " Mechanical Design and Development of a High Power Target System for the SLC Positron Source, SLAC-PUB-5369.

BACK UP 3 - SuperKEKB Fixed Target



❖ Y. Enomoto, "Status of SuperKEKB positron source" link

BACK UP 4

❖ We aim to test our materials without external cooling. With the 2 mm thick diameter 25-50 mm disk, we can achieve the FCC-ee foreseen PEDD and push even for the target PEDD limits.

S. Wallon

Material	Diameter	Thickness	Avg. power at 10.5 J/g	Temp. Max	Avg. power at 35 J/g	Temp. Max
W	25 mm	2 mm	5.1 W	239 °C	17.1 W	510 °C
Ta	25 mm	2 mm	3.9 W	217 °C	13.2 W	490 °C

BACK UP 5

❖ 10'000 macroparticles can be used for simulation mesh size would be kept at 0.05^3 mm^3 less than $\sigma_{rms}/2$ as CERN suggests.

❖ Yields statically fluctuates for **W material with thickness 2 mm**: 0.3147, 0.3129, 0.3245, 0.3186, 0.3161

PS: E_{cell}^{max} [MeV] is the max energy deposited in a scorer mesh for 10k particles!

Rms beam size	E_{dep}^{mean} [MeV]	E_{cell}^{max} [MeV]	$PEDD^{e-}$ [J/g]	Pulse Duration	Current (@200 Hz)	Power for 10.5 J/g	Power for 35 J/g
0.1 mm	7.02	68.42	4.6×10^{-10}	60 μs	0.6 μA	5.1 W	17.1 W
0.2 mm	7.02	22.58	1.5×10^{-10}	182 μs	1.8 μA	15.8 W	52.5 W
0.3 mm	7.13	13.05	8.7×10^{-11}	315 μs	3.2 μA	27.6 W	92.0 W
0.4 mm	7.08	9.54	6.4×10^{-11}	418 μs	4.3 μA	37.1 W	124 W
0.5 mm	7.08	7.15	4.8×10^{-11}	571 μs	5.7 μA	49.6 W	165 W