



Status and Operational experience of the SuperKEKB positron source

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Overview of KEK e⁺e⁻-Linac and Positron Production



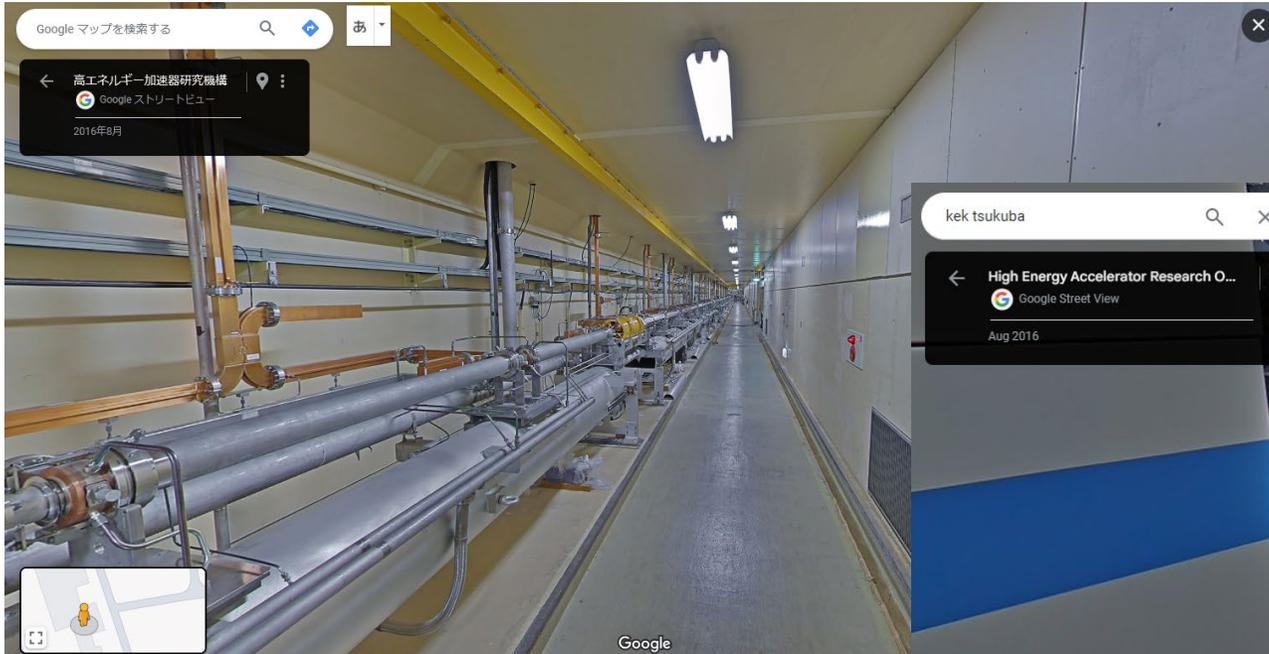
Google Street View@KEK



Zoom and click around here



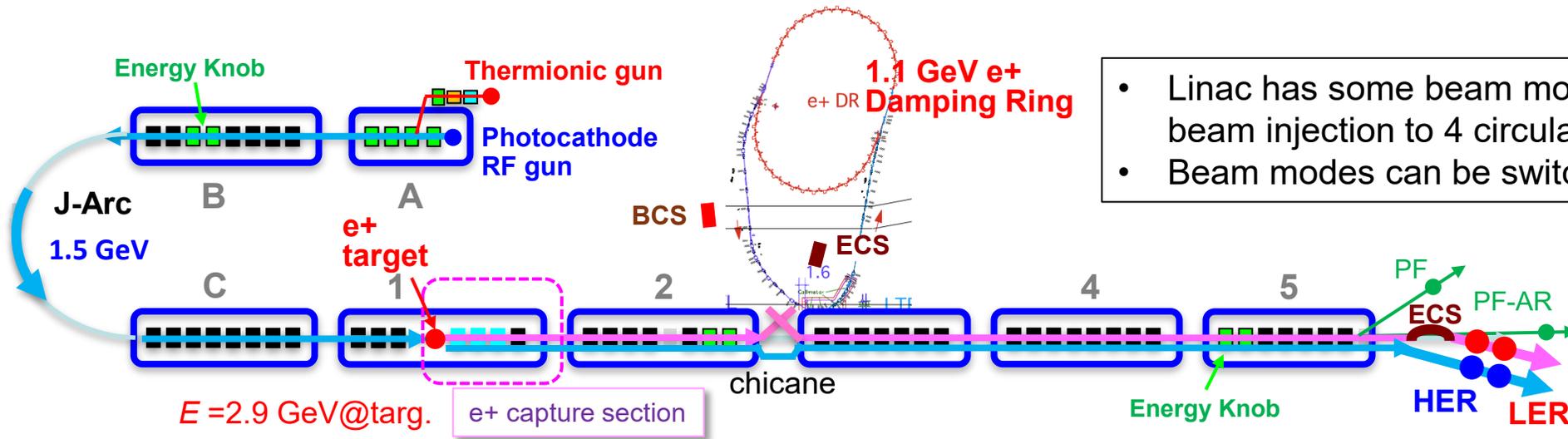
Linac Tunnel



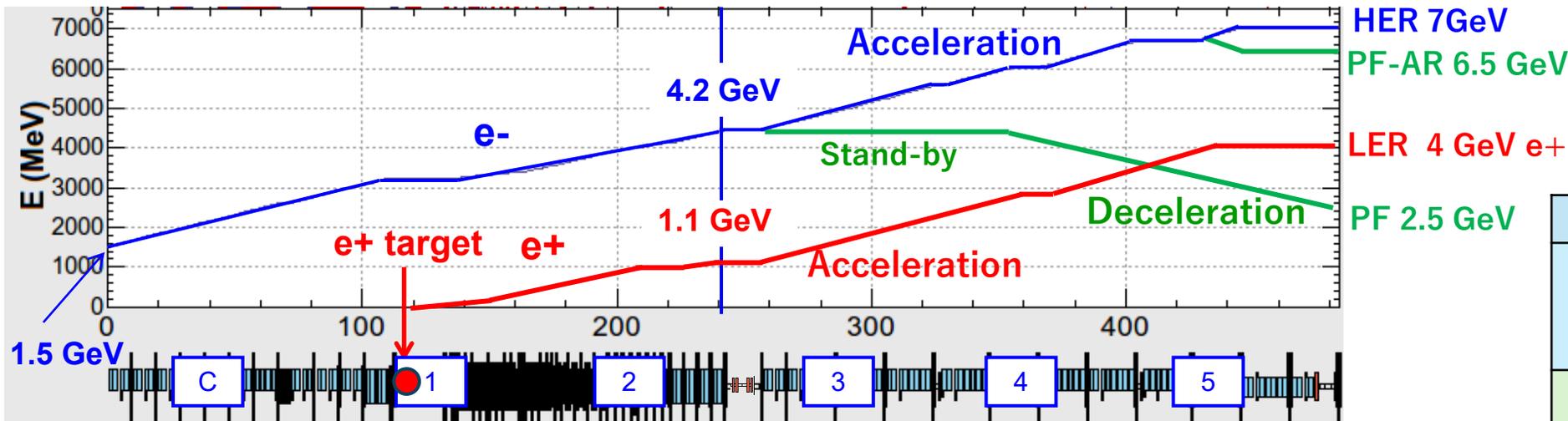
You can see the inside of the tunnel and Klystron Gallery



KEK Linac



- Linac has some beam modes matched beam injection to 4 circular accelerators
- Beam modes can be switched at 50 Hz



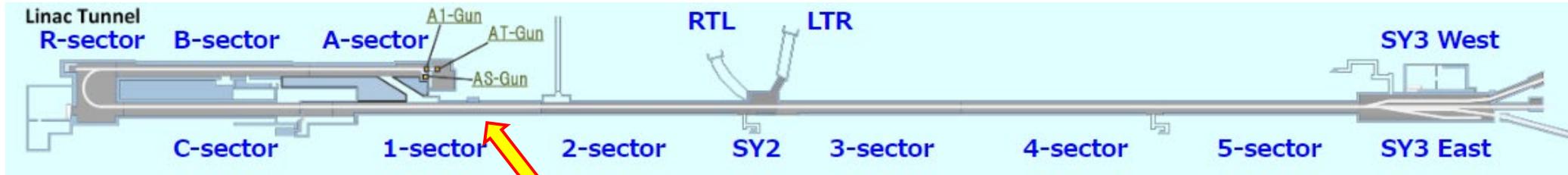
Bunch charge [nC]

HER	2
LER	11 e- for e+ @gun exit
	3.5 nC @end
PF/ PF-AR	0.3

Beam energy for each beam mode along the beam line after the J-Arc.



Positron Capture Section

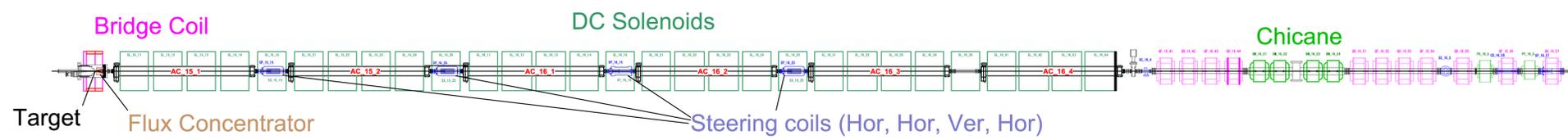
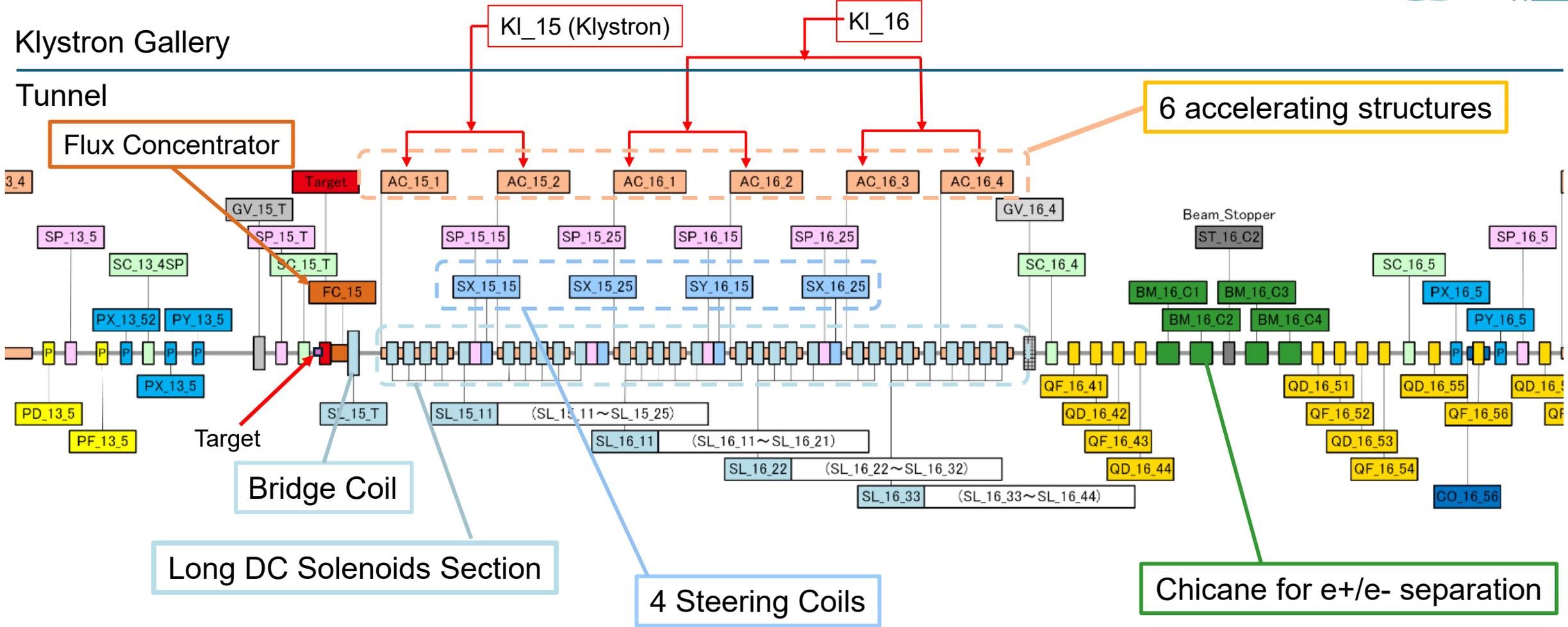




Capture Section Layout

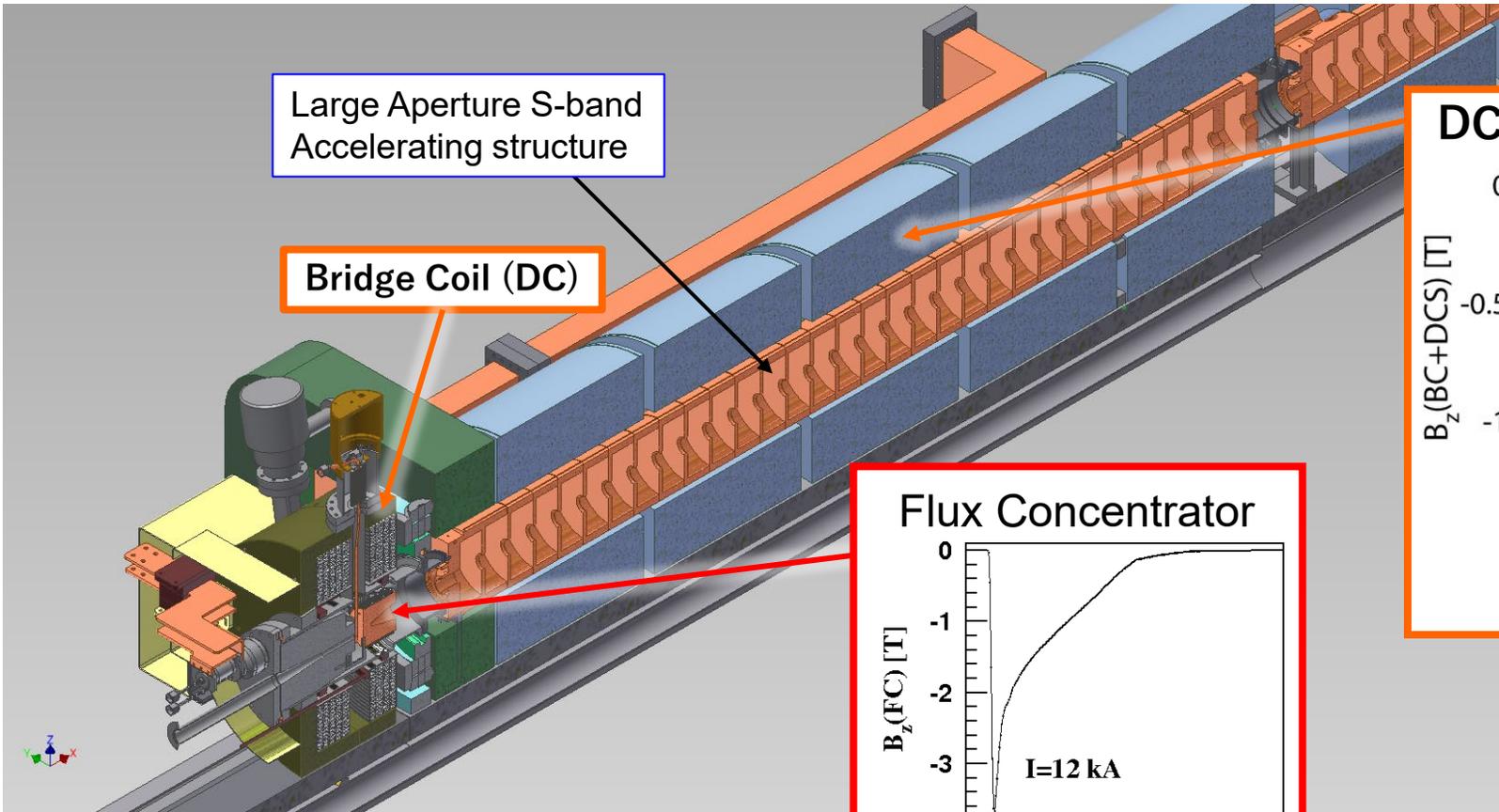
Klystron Gallery

Tunnel



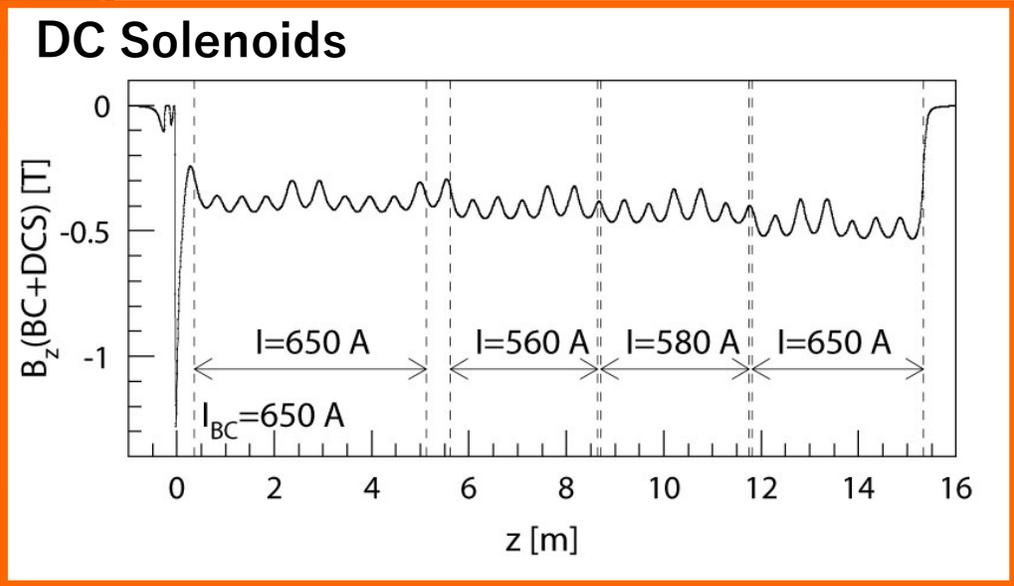
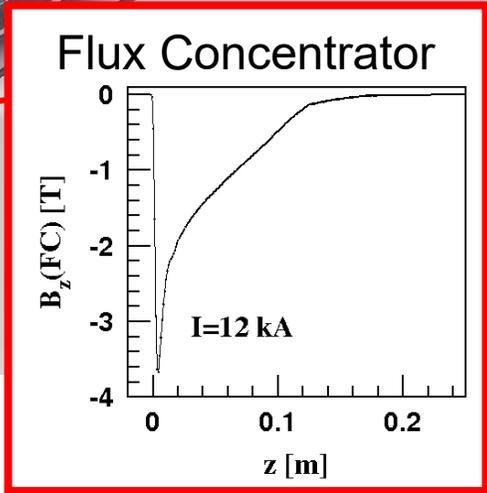


Head of e⁺ Capture Section



Large Aperture S-band Accelerating structure

Bridge Coil (DC)



Cross-section view of the capture section



Target

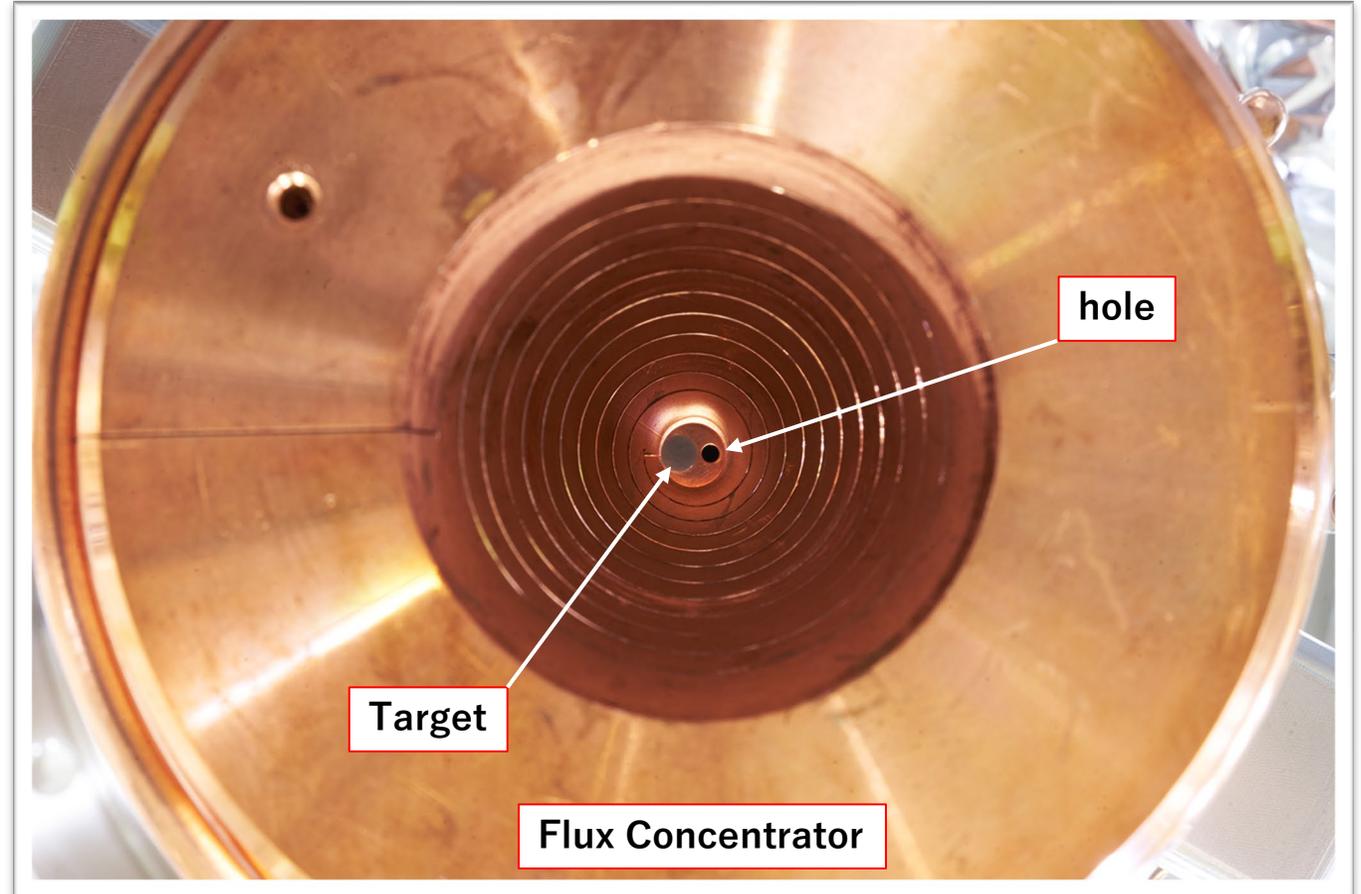
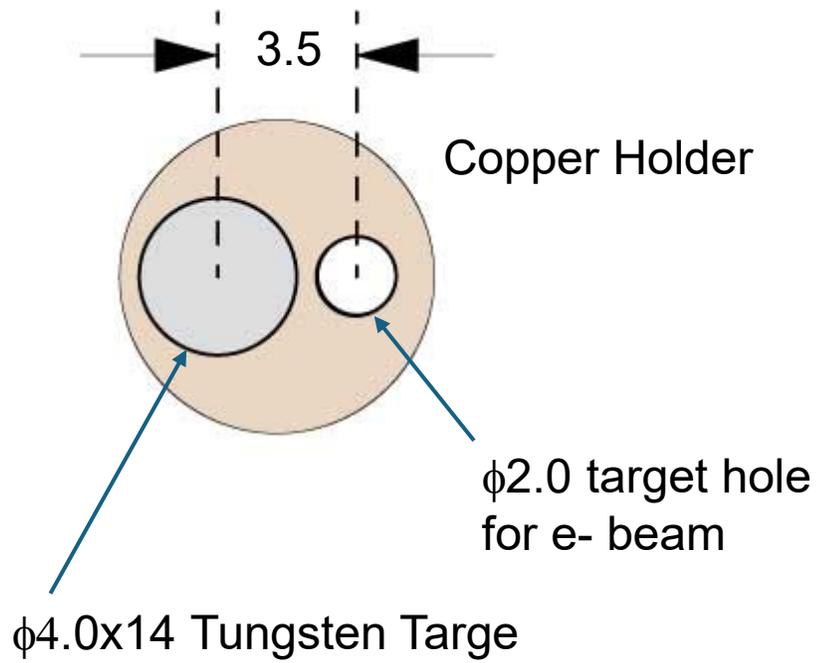


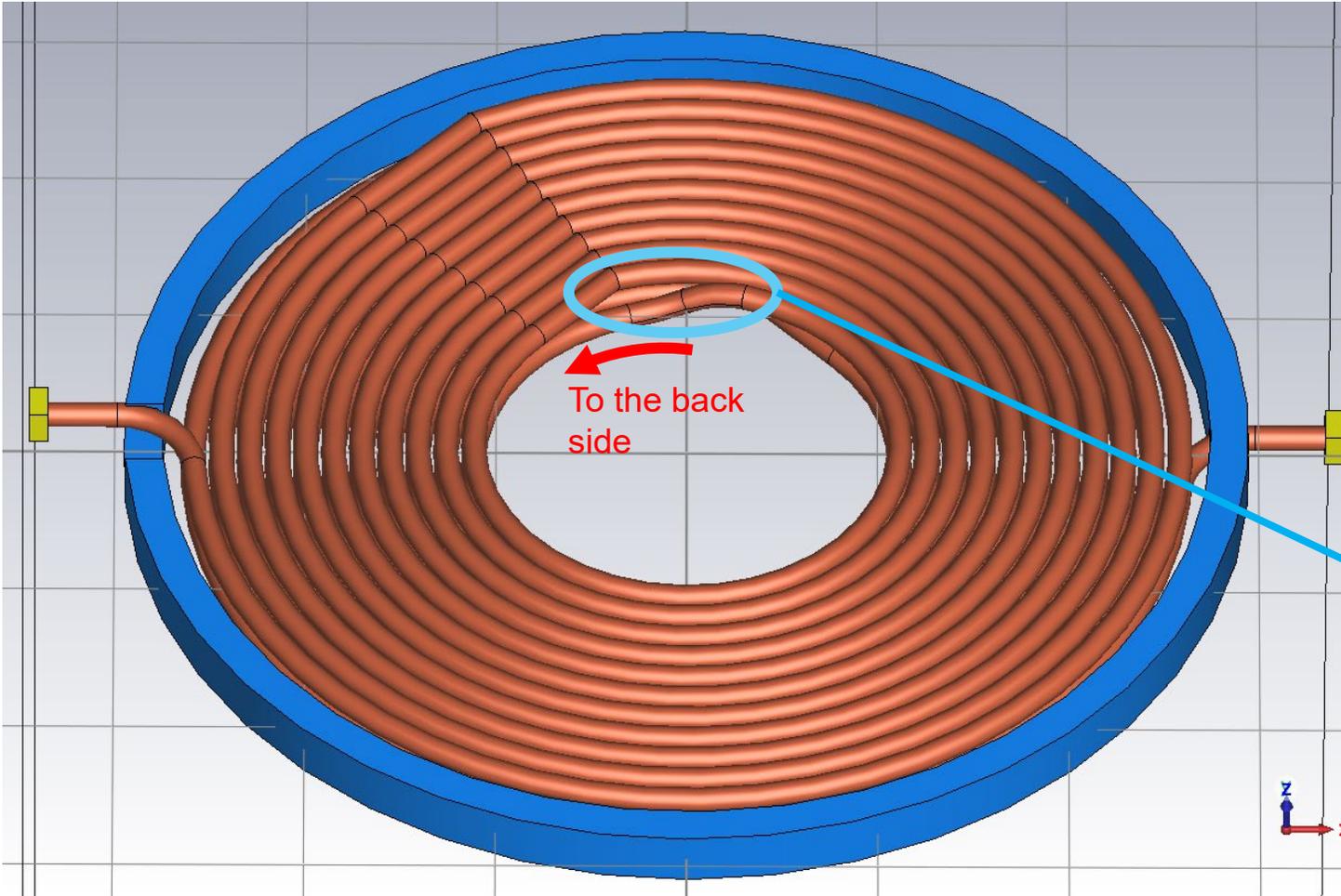
Photo looking at FC from beam exit



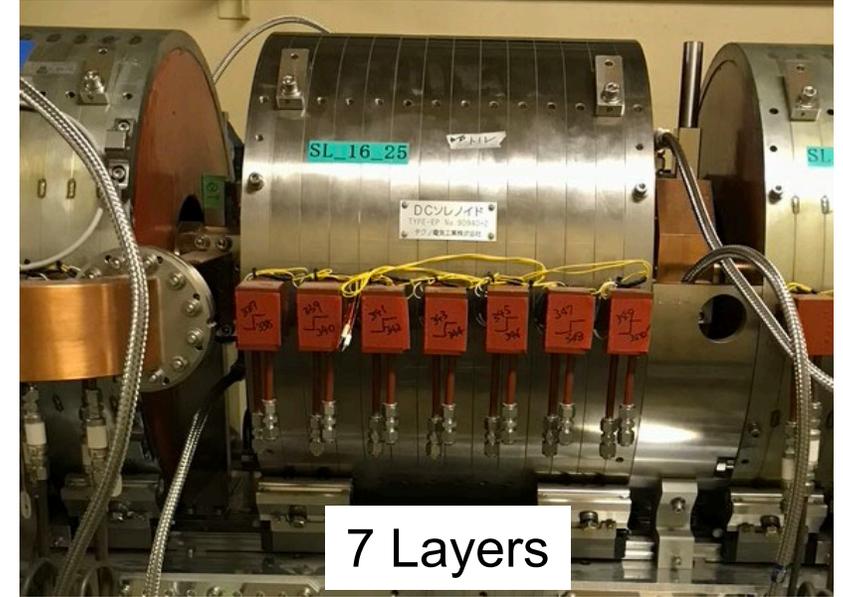
DC Solenoid



A. Enomoto



Two-layer structure of hollow-conductor



Axial symmetry of the magnetic field is broken due to this part



Steering Coils

4 Steering coils to compensate for kicks caused by non-axisymmetric magnetic fields

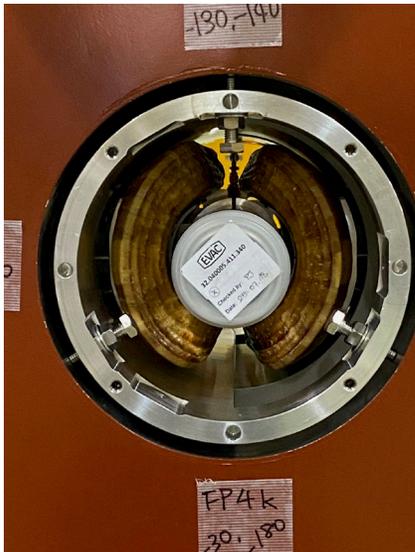
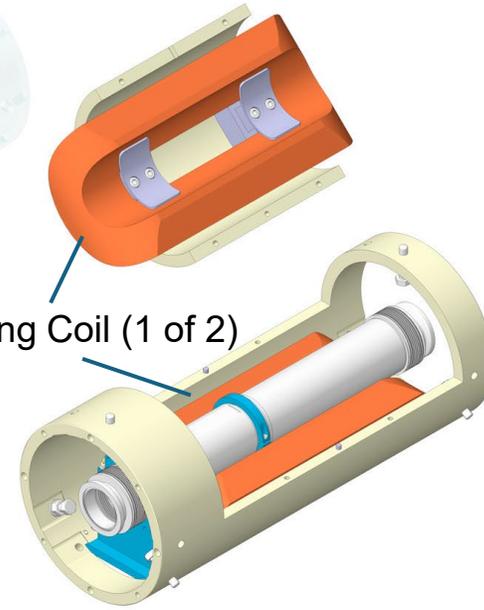
K. Kakihara, K. Yokoyama



Beam Position Monitor



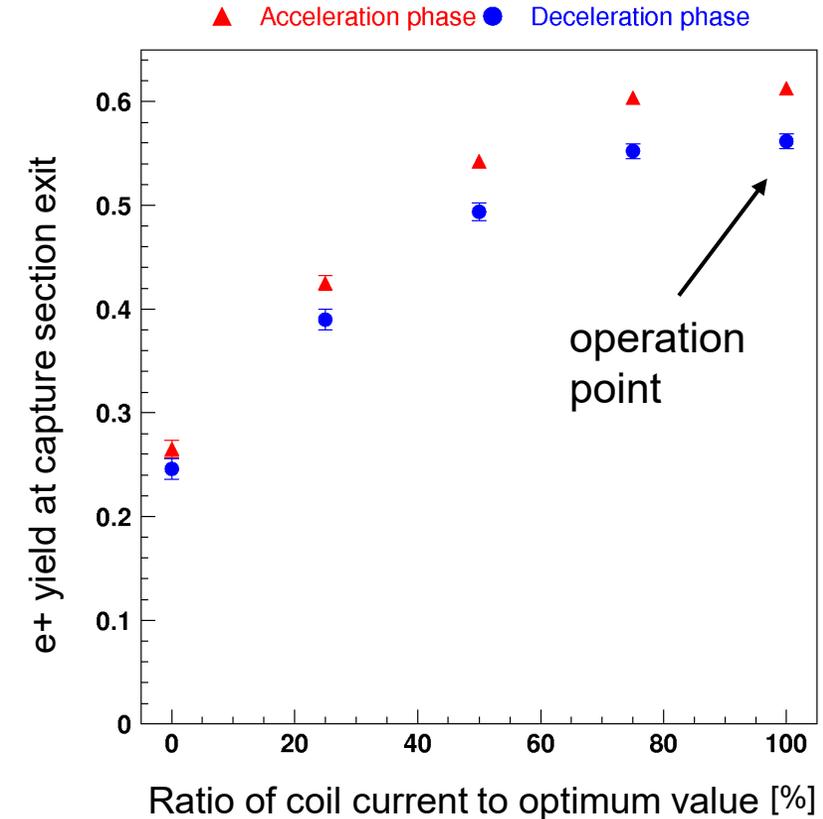
Steering Coil (1 of 2)



The electron beam through the hole shifts by up to 3.8 mm compared to the solenoid OFF



Steering coils were installed in 2020.



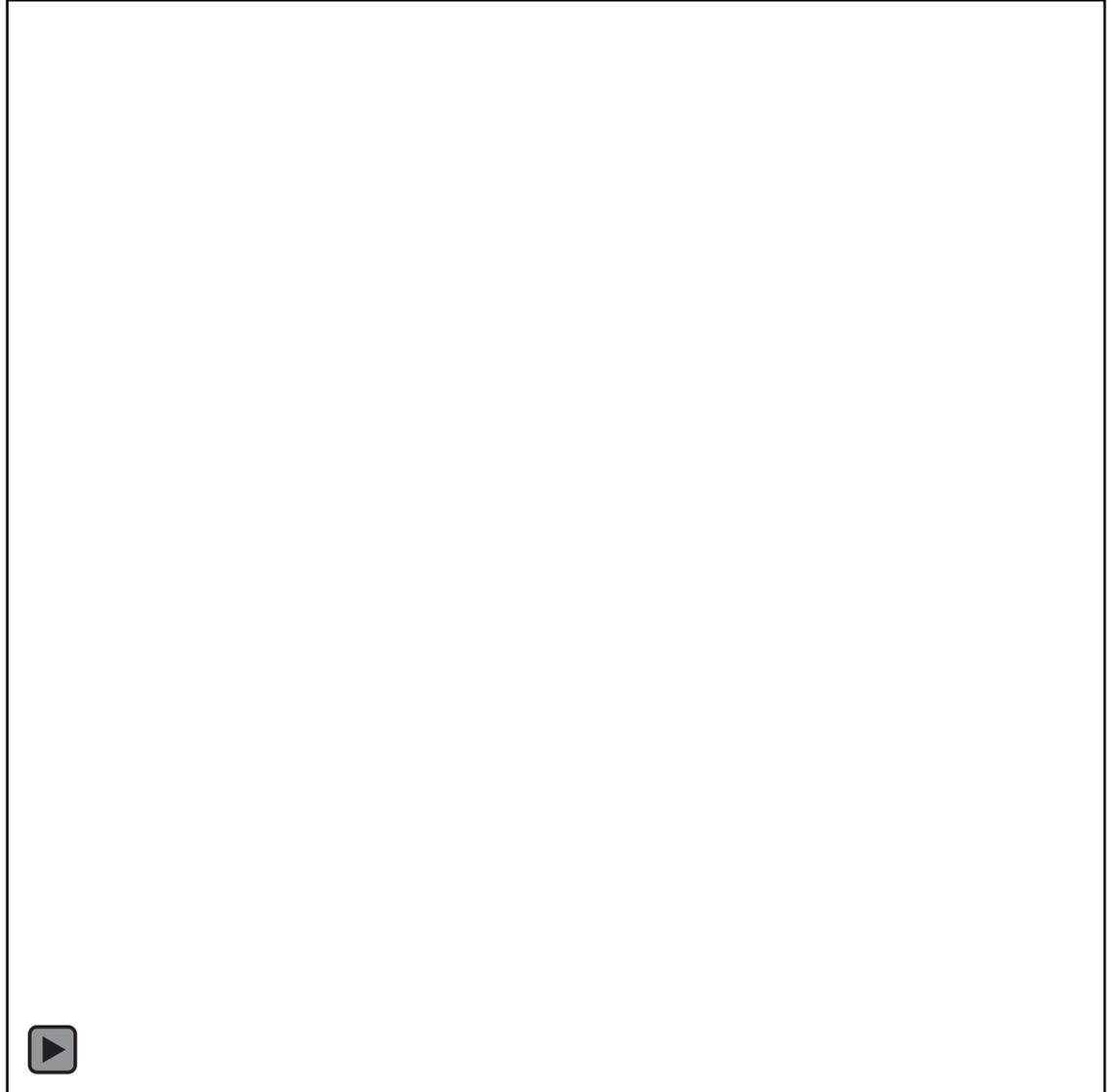
Steering coils are very important for positron capture section



Capture Section Particle Motion



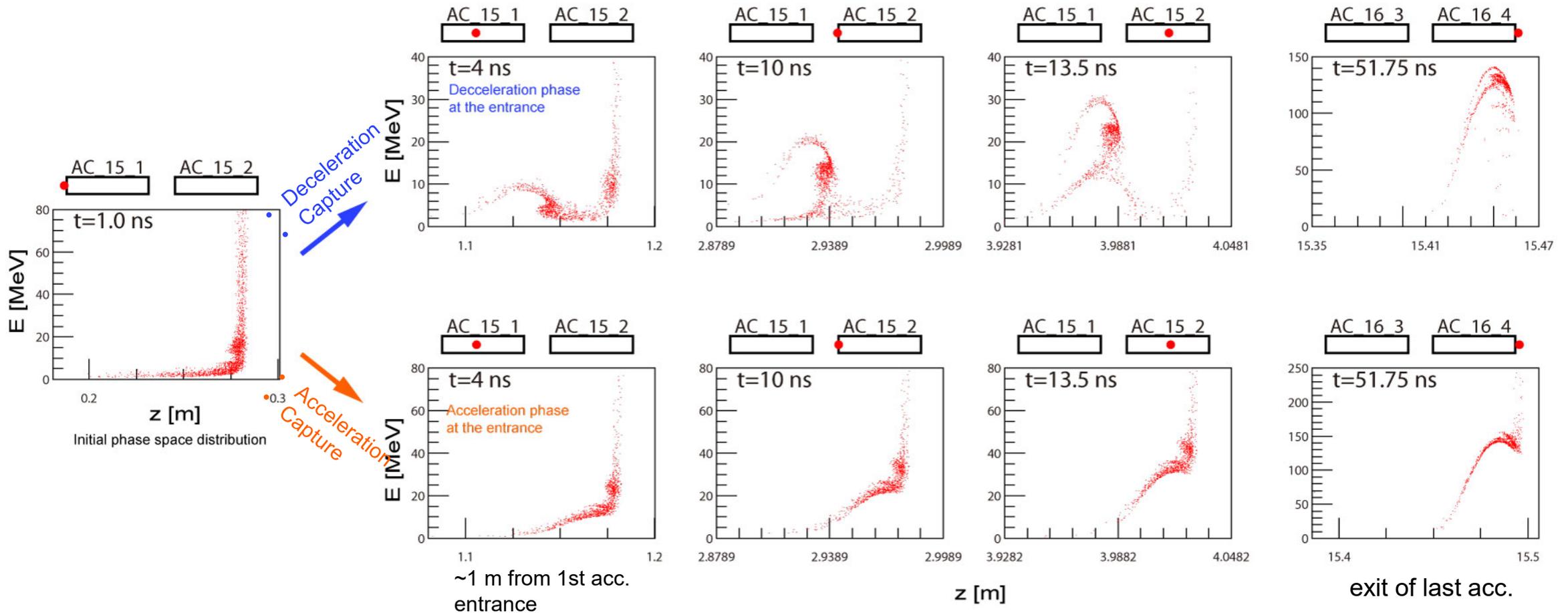
1. e^+ are captured in a deceleration phase of first accelerating structure
2. Decelerated e^+ move to the acceleration phase



Deceleration @1st Acc. Capture



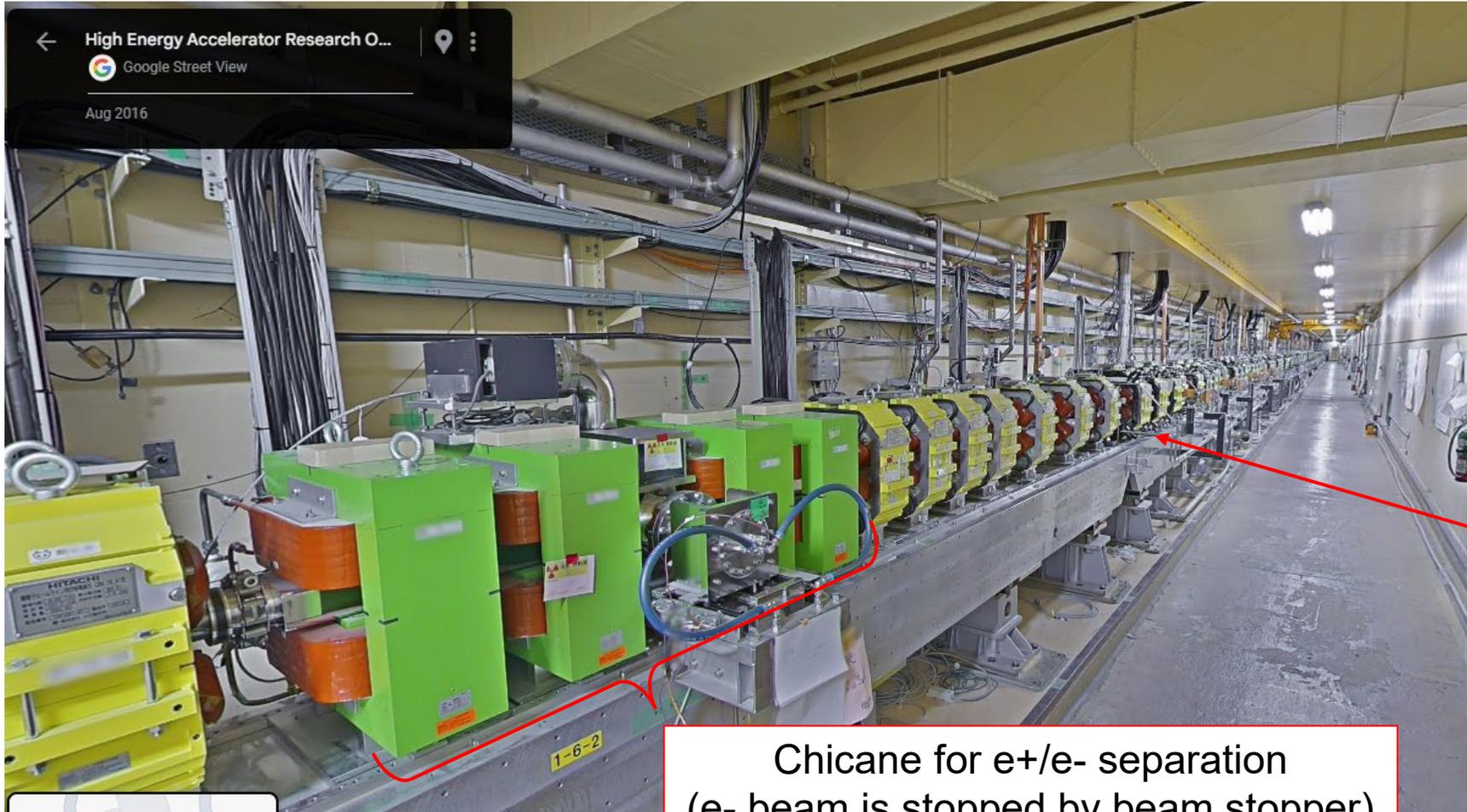
Longitudinal Phase Space



- Acceleration capture has a large energy spread →
- Difficult to transport beam up to DR with small beam loss.
 - Beam transport line to the DR has only a 10% energy aperture



Beam line after the Cap. Sec.



Chicane for e^+/e^- separation
(e^- beam is stopped by beam stopper)

Many quadrupoles are installed at short intervals up to the Damping Ring



Positron Beam Tuning



Beam tuning procedure



Beam tuning procedures after long-term shutdown

1. RF phase and beam orbit rough tuning

→ Beam reaches up to DR and Linac End (Beam loss is OK)

2. RF Phasing

Change the RF phase to find the crest phase from the position change at a Beam Position Monitor where the dispersion is large

3. Manual beam tuning

Operator loads previously best parameters.

→ Energy and beam orbit tuning

4. Fine tuning with a machine learning (ML tuning)



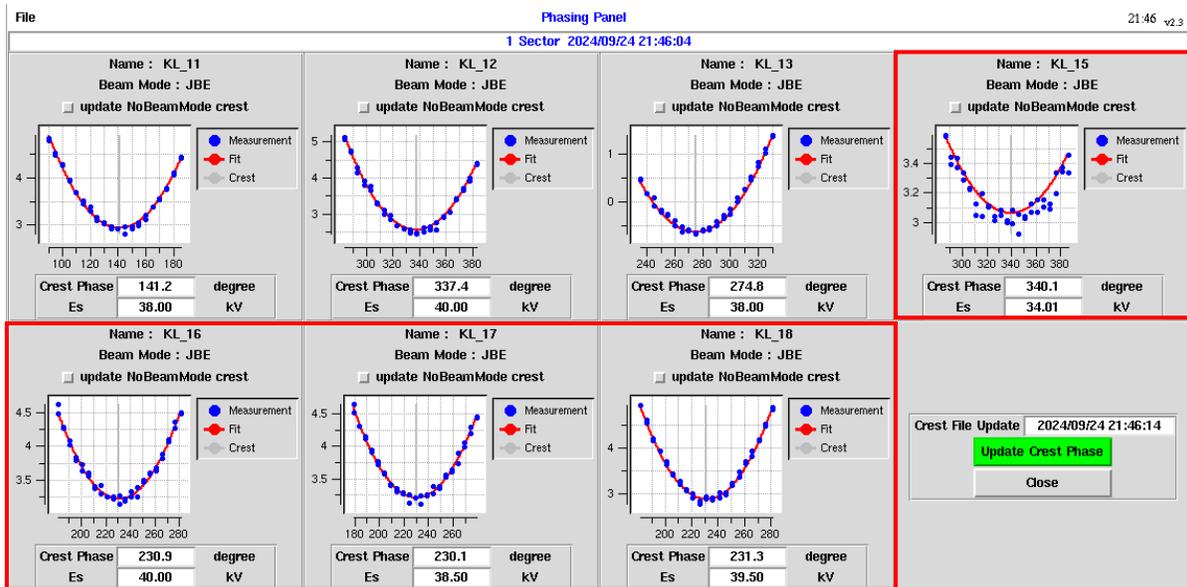
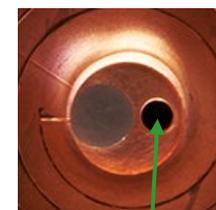
RF Phasing after the cap. section



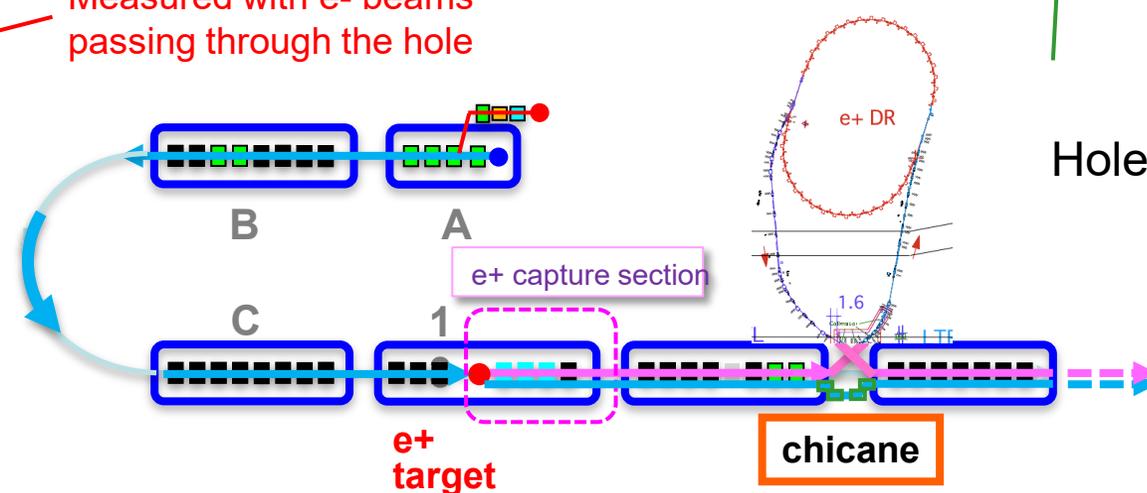
The RF crest phase is found by varying the RF phase and measuring the beam position at location with a large dispersion function.

e+ beam in/after capture section has a large energy spread and it's difficult to transport

→ Using low charge primary electron beams passing through the target hole (e+ crest phase = e- crest phase + 180 deg.)



Measured with e- beams passing through the hole



Klystron phase and e- beam position in the center of the chicane

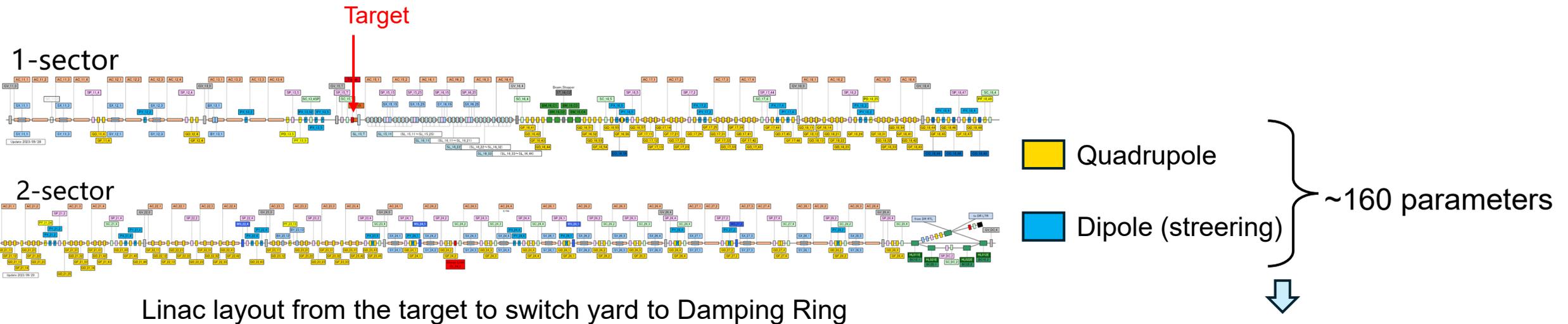


Fine tuning with ML



Why use machine learning?

- After the capture section, energy spread, beam size and emittance are very large (Design optics are no longer relevant for fine tuning)
- ML tuning can be worked all the time
- ML tuning does not depend on the skill of the operator
- Too many parameters (← depends on the goal)



Manual tuning is almost impossible



Optimization Program

Files with list of magnets

Using **Bayesian optimization**, or Downhill simplex

T. Natsui

The screenshot shows the 'General Optimizer UI' with the following components:

- Open dialog:** Directory: /nfs/linacfs-users/tp/natsui/KBP_afterTarget_wPulseQ. Files listed include SP_17_4.txt, SP_22_4.txt, SP_28_2.txt, etc.
- Parameters table:**

PV name	min	max	init
x0: LIIMG.PX_22_4:IWRITE:KBP	-3.978	-1.9780	-2.978
x1: LIIMG.PV_22_4:IWRITE:KBP	3.306	5.306	4.306
x2: LIIMG.BX_22_12:IWRITE	-1.8	0.1999	-0.800
x3: LIIMG.BV_23_13:IWRITE	-2.5	-0.5	-1.500
x4: LIIMG.QF_23_11:IWRITE	43.122	53.122	40.122
x5: LIIMG.PF_23_13:IWRITE:KBP	102.61	152.61	127.61
x6: LIIMG.QF_23_22:IWRITE	44.843	54.843	49.843
x7: LIIMG.QD_22_43:IWRITE	34.158	44.158	39.158
x8: LIIMG.QD_23_12:IWRITE	46.759	56.759	51.759
x9: LIIMG.QD_23_21:IWRITE	49.822	59.822	54.822
- Y settings table:**

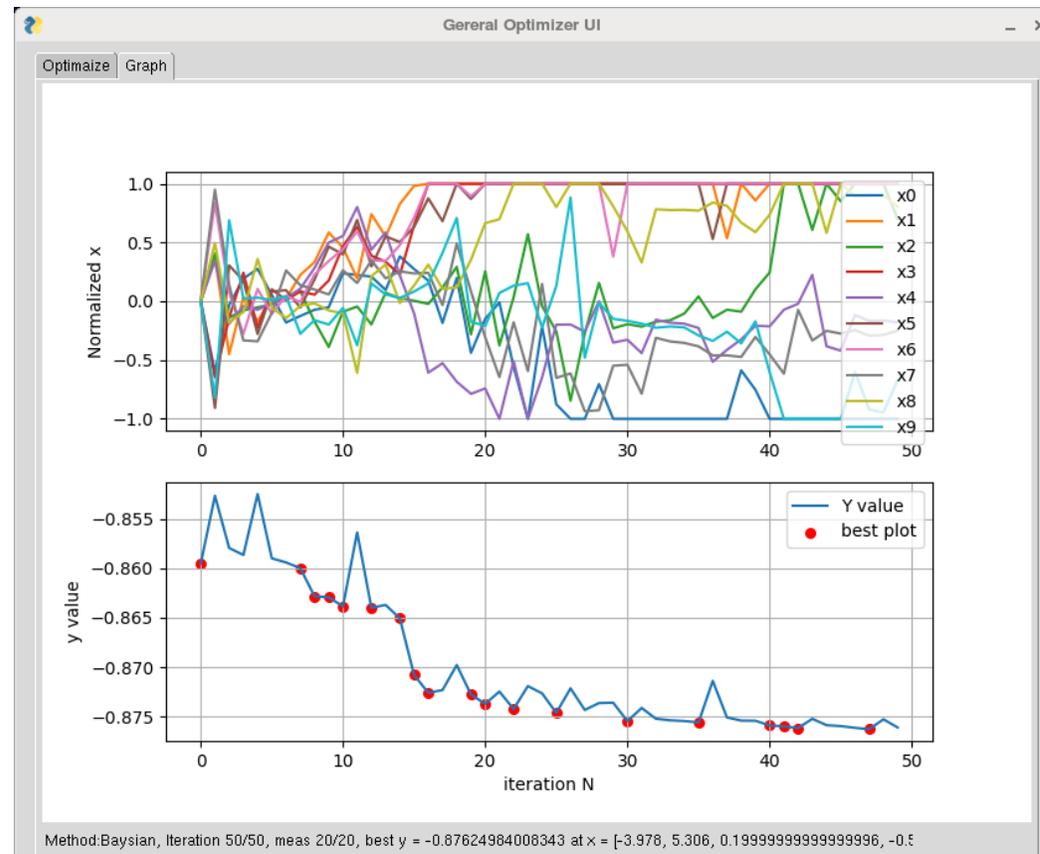
PV name	alias
LIIBM.SP_16_5_1:ISNGL:KBP	Qref
LIIBM.SP_23_2_1:ISNGL:KBP	Q1
LIIBM.SP_23_4_1:ISNGL:KBP	Q2
LIIBM.SP_24_1_1:ISNGL:KBP	Q3
- Objective Function:** Evaluate function: $-(Q1+Q2+Q3)/3/Qref$
- Optimize method:** Bayesian optimization (selected), acquisition_weight: 1.0, default: 2, exploration: 3.

Example of an optimization

Objective Function

$$f = -(Q(\text{BPM1})+Q(\text{BPM2})+Q(\text{BPM3}))/Q(\text{BPM0})$$

Minimizing this function is equivalent to maximizing beam transmission



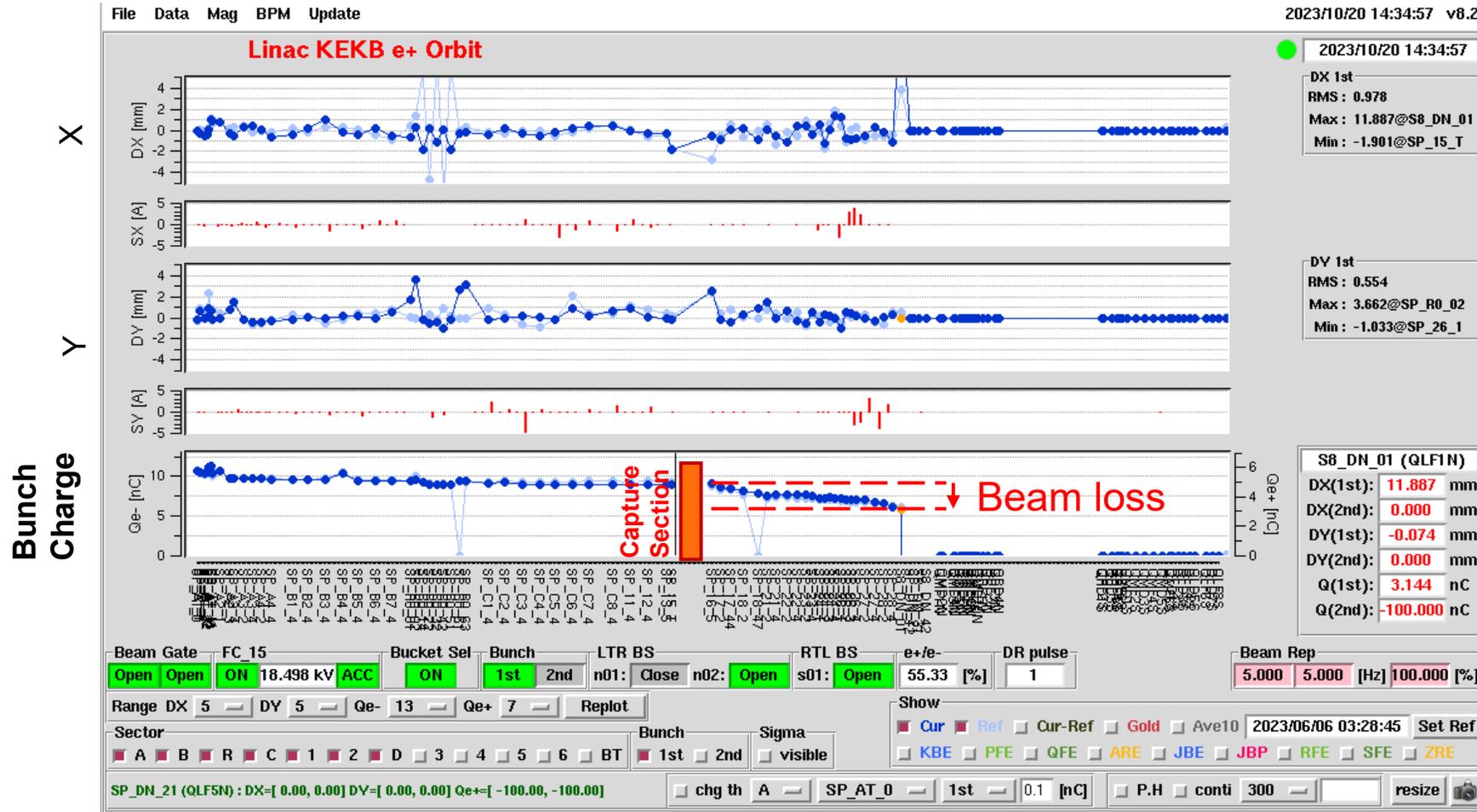
The process of the objective function decreasing during an optimization.



Tuning of Quadrupole, Steering Magnets



Goal: Minimize beam loss up to the DR beam transport line



Beam orbit and charge before ML tuning

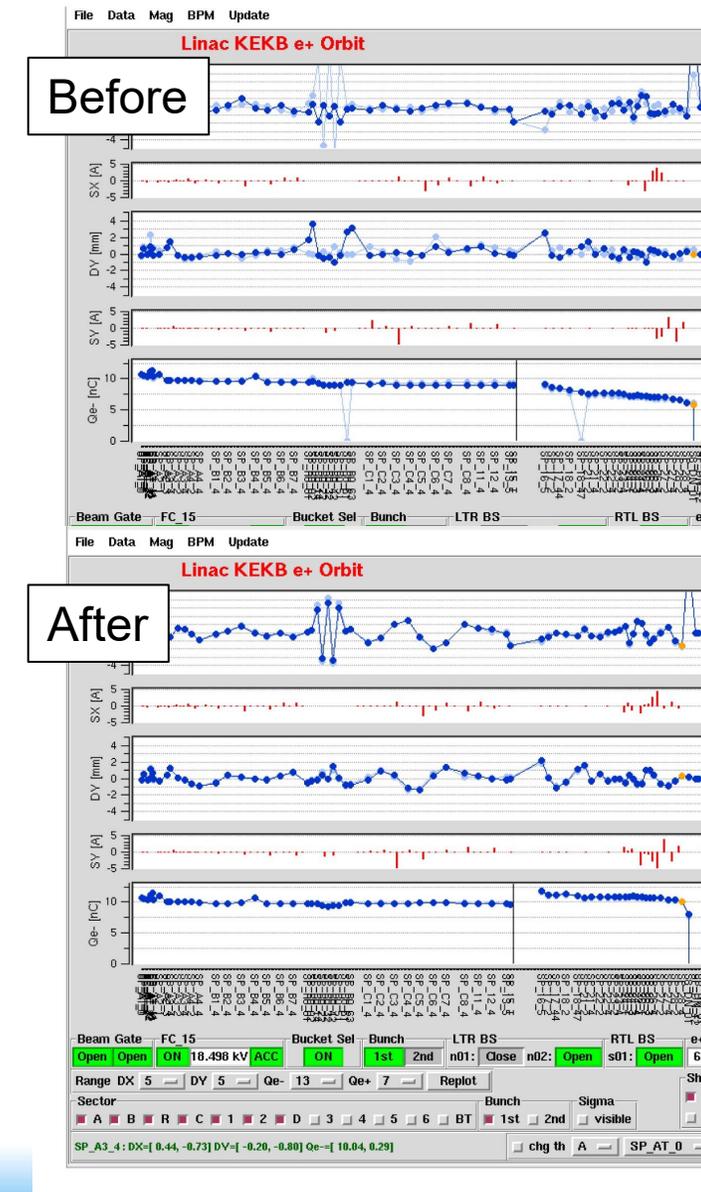


Improvement of transmission



Progression of tuning process

This tuning process (~160 parameters) takes a few days, so we have only done it once so far.





Optimization to keep the condition



Bayesian optimization moves parameters significantly

➔ The downhill simplex method is used when condition deviates slightly from best ones

General Optimizer UI

Optimize | Graph

Setting file name : /nfs/linacs-users/tp/natsui/KBP/16_5/KBP_16_5_RC1sec_knob16.txt

OpenSetting SaveSetting Y setting text ON OFF

X	PV name	min	max	init
x0:	LIIEV.SH_A1_S1.KBPPHASE	52.0	54.0	53.000
x1:	LIIEV.SH_A1_S8.KBPPHASE	95.5232	105.5232	100.5232
x2:	LIIMG.PD_R0_61.IWRITE.KBP	354.293	374.293	364.293
x3:	LIIMG.PF_R0_61.IWRITE.KBP	364.852	364.852	374.852
x4:	LIIMG.PD_R0_63.IWRITE.KBP	169.897	189.897	179.897
x5:	LIIMG.PX_R0_63.IWRITE.KBP	-3.458	-1.4580	-2.458
x6:	LIIMG.PV_R0_63.IWRITE.KBP	-1.87	0.13	-0.870
x7:	LIIMG.PX_C7_4.IWRITE.KBP	-3.88	-1.88	-2.880
x8:	LIIMG.PV_C7_4.IWRITE.KBP	-2.659	-0.6590	-1.659
x9:	LIIMG.PV_12_2.IWRITE.KBP	-2.6	-0.6000	-1.600
x11:	LIIMG.PX_13_2.IWRITE.KBP	1.612	3.612	2.612
x11:	LIIMG.PX_13_5.IWRITE.KBP	-9.5590	0.44093	-4.559
x11:	LIIMG.PV_13_5.IWRITE.KBP	-1.0979	0.90200	3.902
x11:	LIIMG.PD_13_5.IWRITE.KBP	105.243	125.243	115.243
x11:	LIIMG.PF_13_5.IWRITE.KBP	135.482	155.482	145.482
x11:	LIIEV.SB_C.KBPPHASE	86.5	96.5	91.500

Y settings

PV name	alias
LIIBM.SP_15_T_1.SINGL.KBP	Q1
LIIBM.SP_16_S_1.SINGL.KBP	Q2

Limitation : -(Q1/4+Q2)

Evaluate function :

Beam repetition: 5.0 Hz data N at a point: 20 Iteration N : 200 Wait Time [sec]: 3.0

Optimize method

Bayesian optimization acquisition_weight: 1.0 default:2, exploration:3

Downhill simplex initial value range: 20.0 %

Start with set current and shift Stop Restart Set Best and Finish Abort

Method:Downhill, Iteration 200/200, meas 20/20, best y = -7.444428038597107 at x = [52.97743081 100.18156906 364.9725

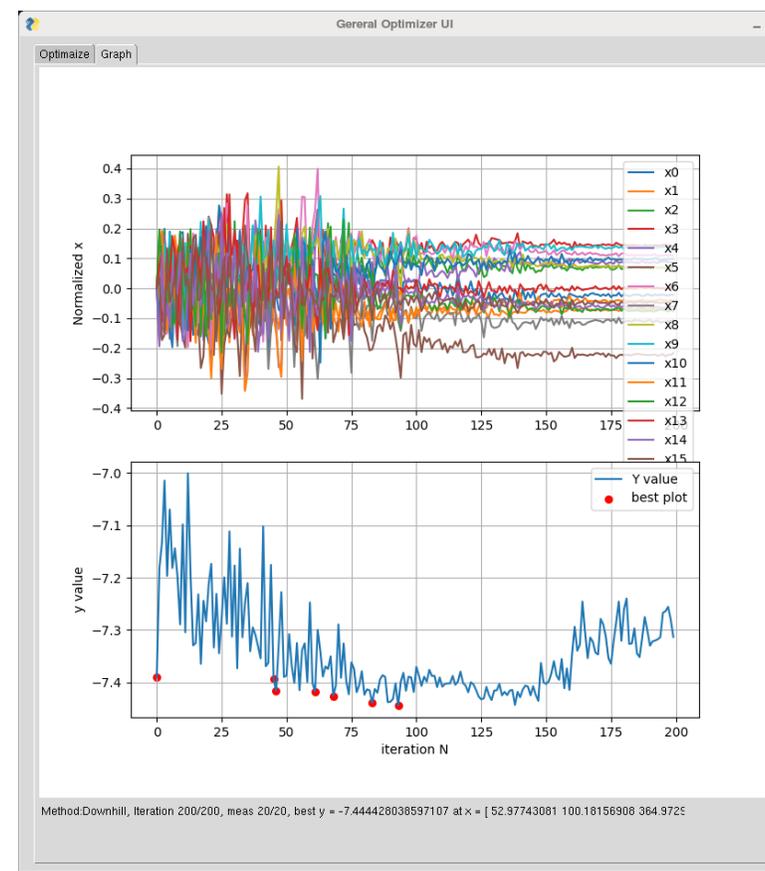
start

Repetition 5.0, dataN 20, IterN 200

Method:Downhill, Iteration 1/200, meas 1/20, best y = 9999 at x = []

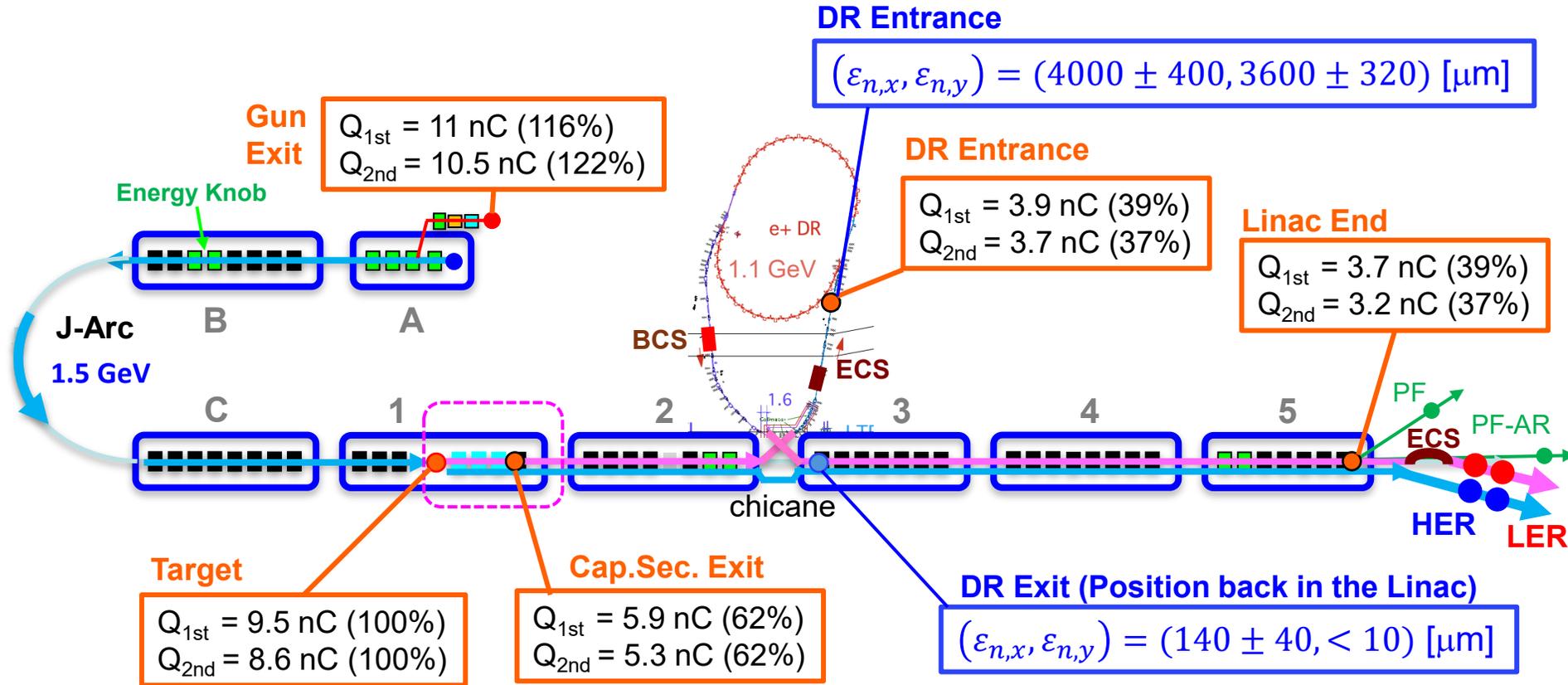
set x [83.0, 100.52320795204973, 364.293, 374.852, 179.897, -2.458, -0.87, -2.88, -1.659, -1.6, 2.612, -4.559, 3.902, 115.243, 145.482, 91.5]

Downhill simplex





Current Status



Bunch charge and normalized emittance

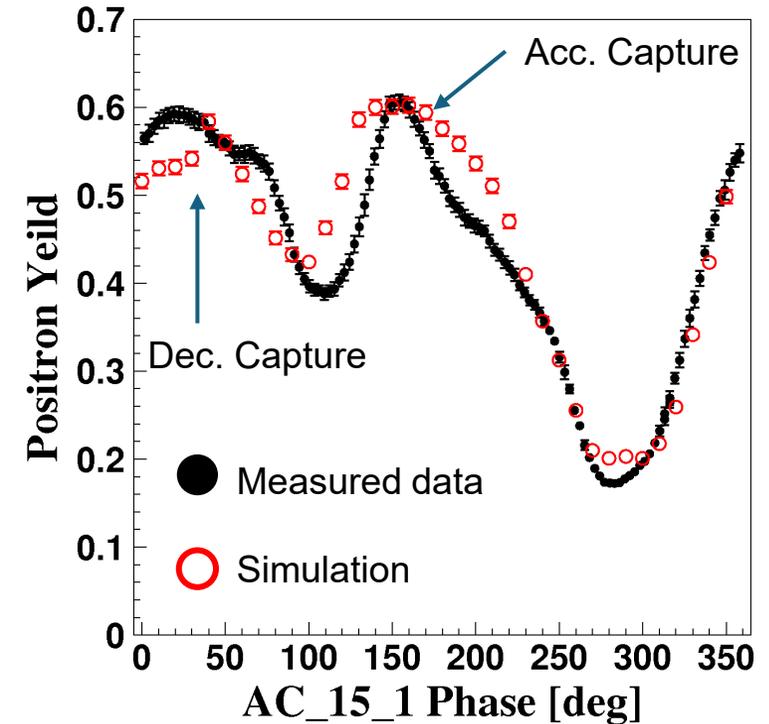
- Primary electron beam has large energy spread and emittance, so it loses about ~20% up to the target
- Conversion efficiency of primary electron beam to positron beam is ~60%
- 30% of the beam is lost in the Beam transport line (SY2 to DR) → Bunch charge decreases to ~40% at the end



Comparison of simulated and measured data



- Simulation (EGS5 and GPT) roughly reproduce experimental values for the phase dependence of yield
- Slightly different phase-dependent structure
→ Simulation studies are needed
(Fahad will reports on this topic on Friday)



Klystron phase of 1st accelerating structure and positron yield



Summary



- KEK e+e- Linac and Positron Capture Section Overview
- Positron beam tuning : Manual and machine learning are used together
 - Bayesian optimization is very useful in improving position yield and beam transmission
 - If the parameters deviate slightly from the optimum, Downhill Simplex is effective
- Current Status of the positron beam
 - Bunch charge : 11 (Gun Exit) → 9.5 (Target) → 3.9 (DR) → 3.7 (Linac end) [nC]
 - Normalized Emittance (x,y) : (~4000, ~3600) @DR, (~140, ~10) @Linac end [μm]
- Measurements and Simulation
 - Simulation roughly reproduces experiment
 - However, differences also exist, and further investigation is needed