FFA Diagnostics

practical examples at KURNS

Ishi, Yoshihiro 11 Sep. 2023

outline

- Introduction: purpose of diagnostics
- Unique characteristics of the beam diagnostics in FFA rings
- Practical examples at KURNS

purpose of diagnostics (in general)

- Beam commissioning

  Understanding the beam characteristics at each stage is essential to complete commissioning in a short period of time.

- Daily operation

  guarantee required beam spec for users

- Upgrade

  An accurate understanding of the machine's current status is important for planning upgrades.

Unique characteristics of the beam characteristics in FFA rings

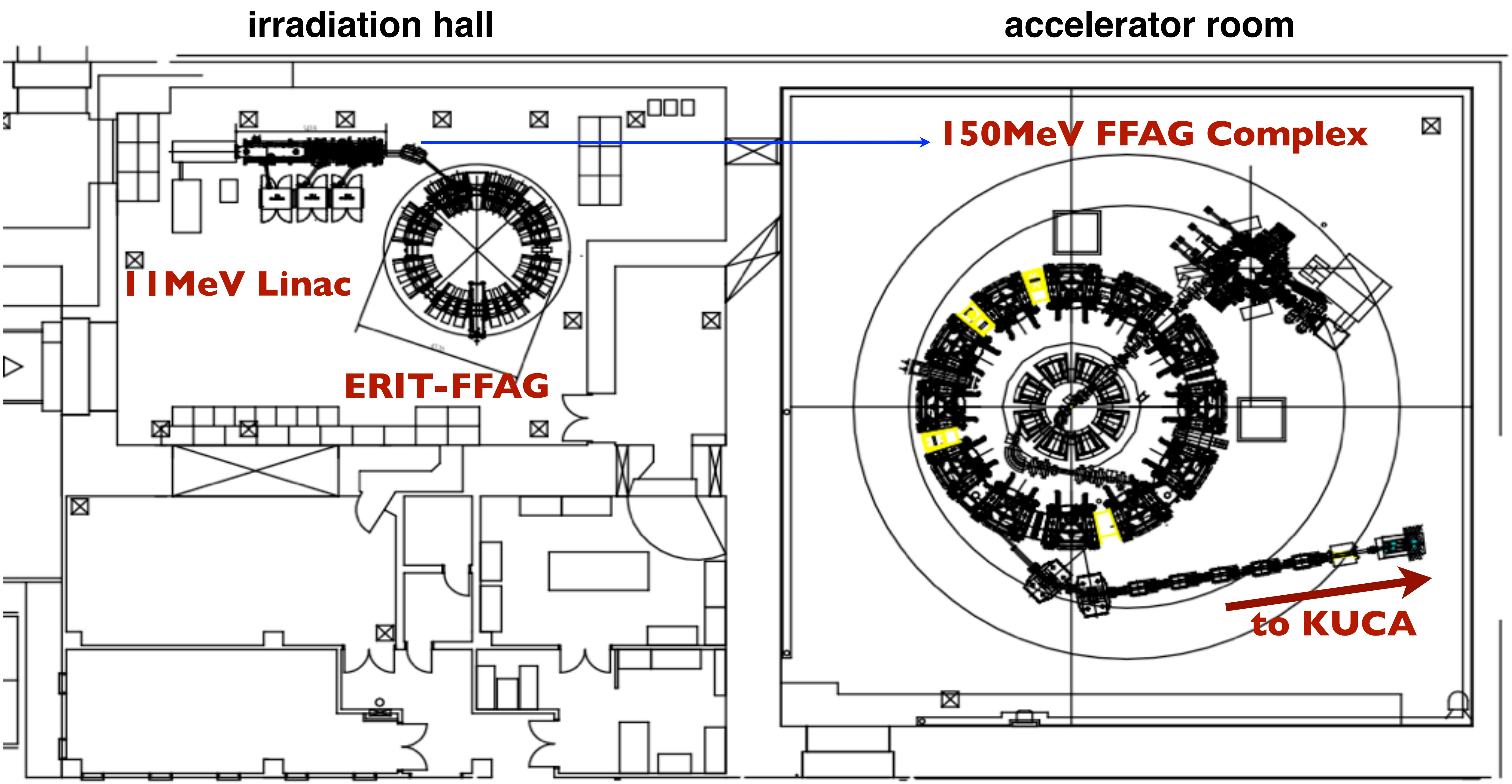
- Orbits move outward(or inward) while acceleration
- smaller turn separation compared with cyclotrons
- Large horizontal aperture available / needed
- This may cause some complications for designing the beam diagnostics system
- Hard to predict the reference closed orbit for certain energy beam → Magnetic field measurement and beam tracking using the field map is essential for the beam commissioning

Practical examples at KURNS FFAs

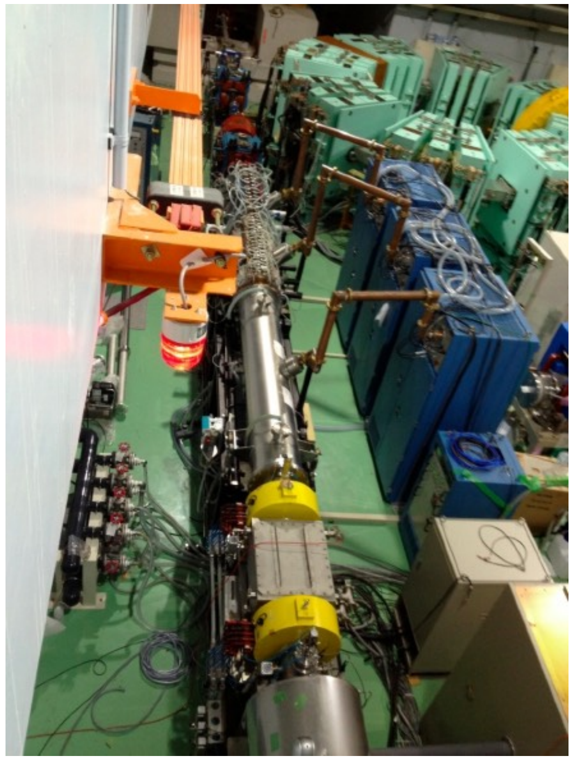
- configuration of the facility
- injection study
- circulating beam current
- betatron tunes
- radial probe measurement
  - beam position
  - beam size
  - COD
- extracted beam characteristics

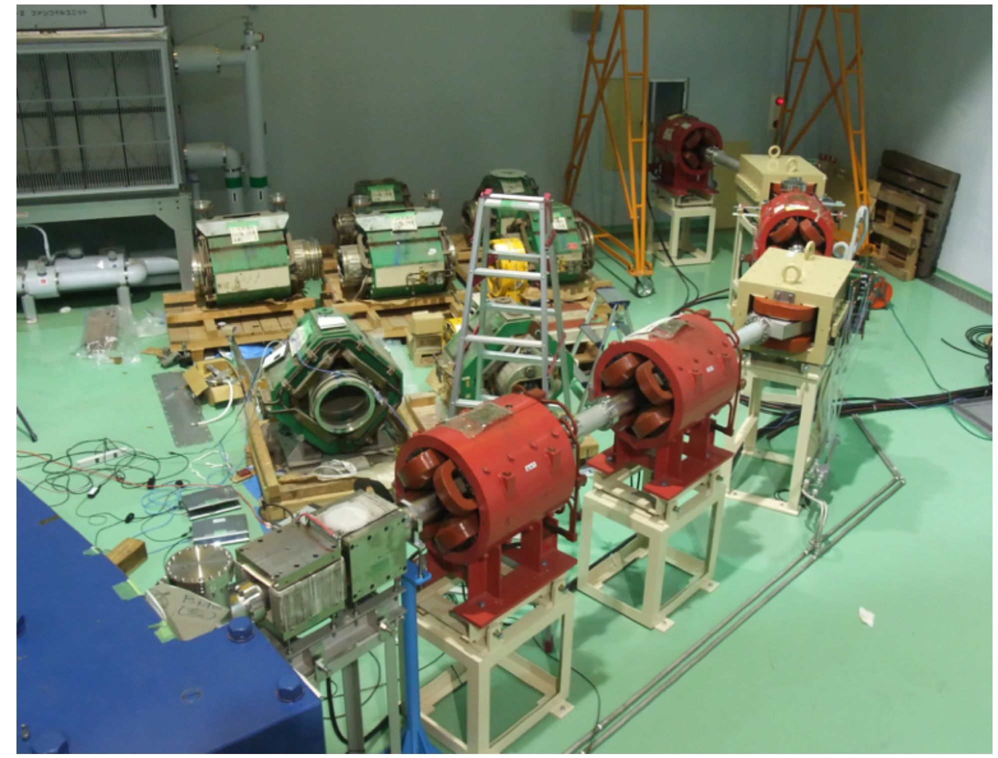
Configuration of the facility

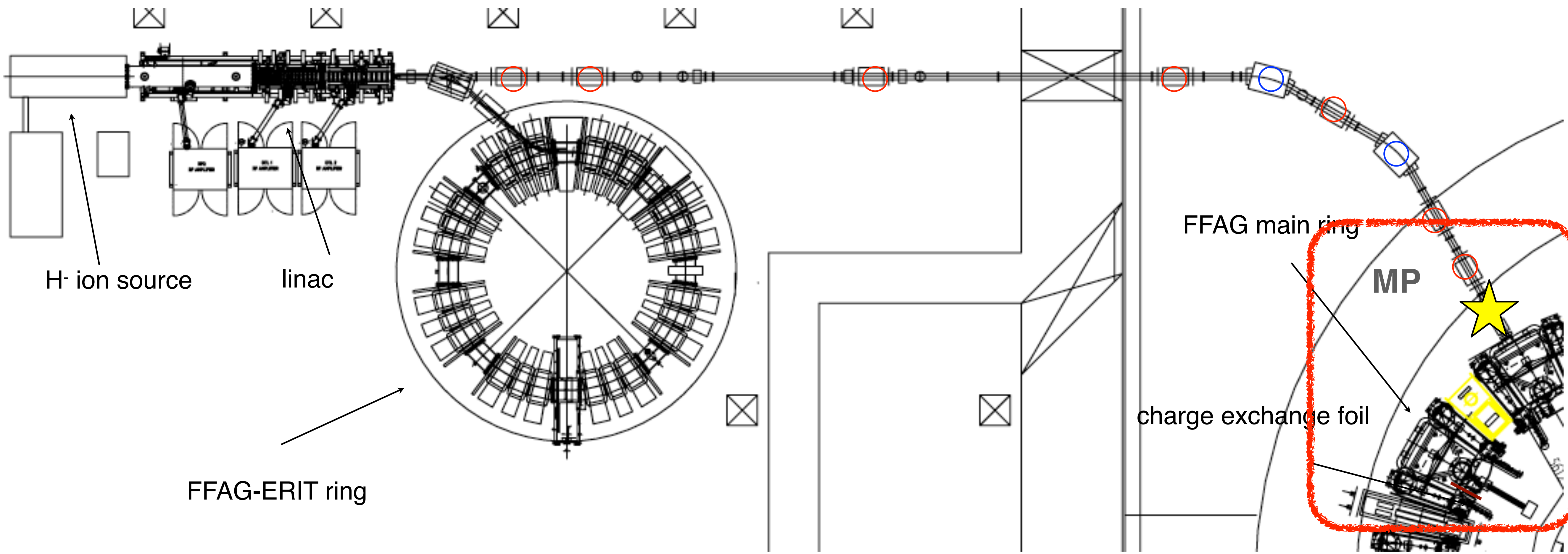
Layout of the accelerator complex at KURNS

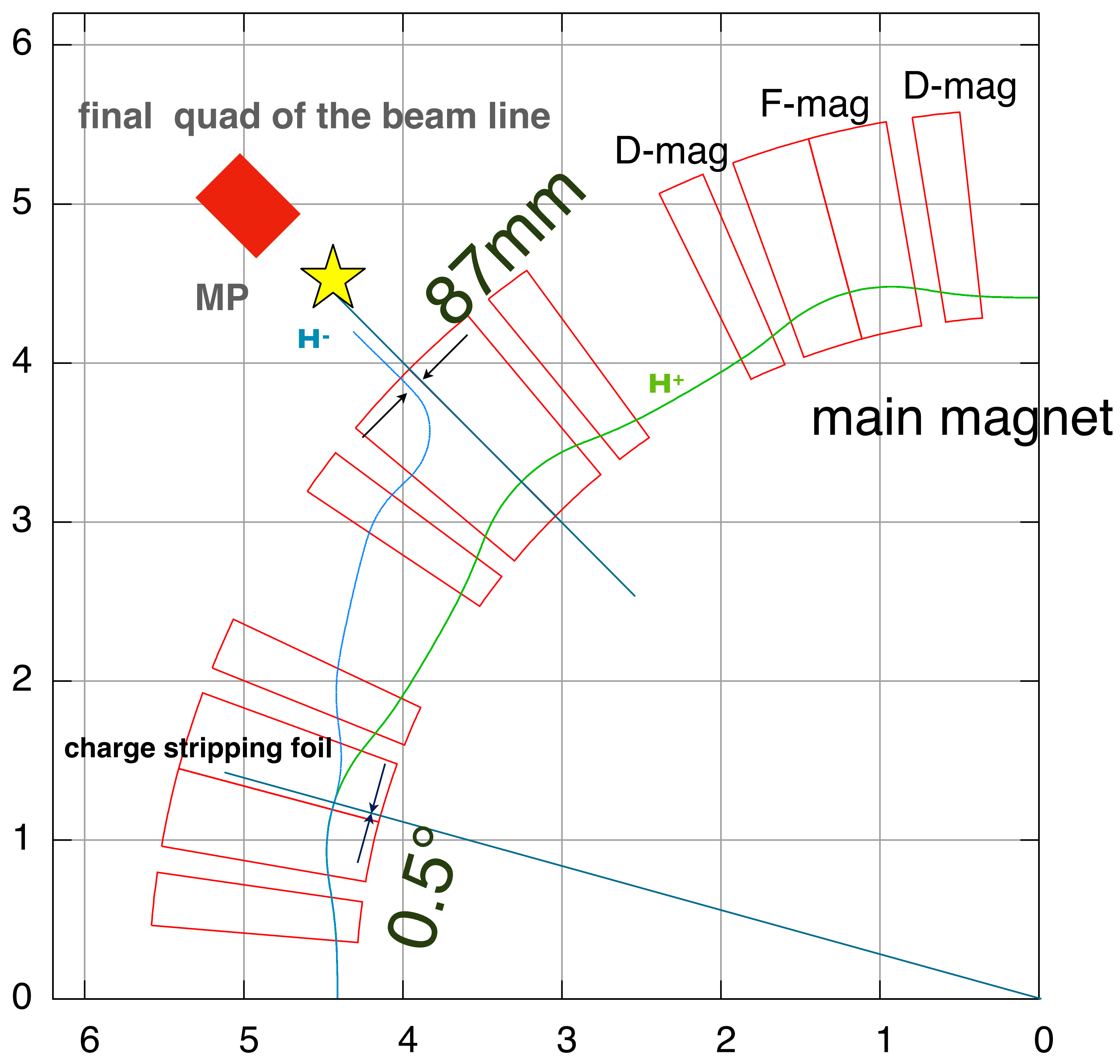


LINAC and transport line



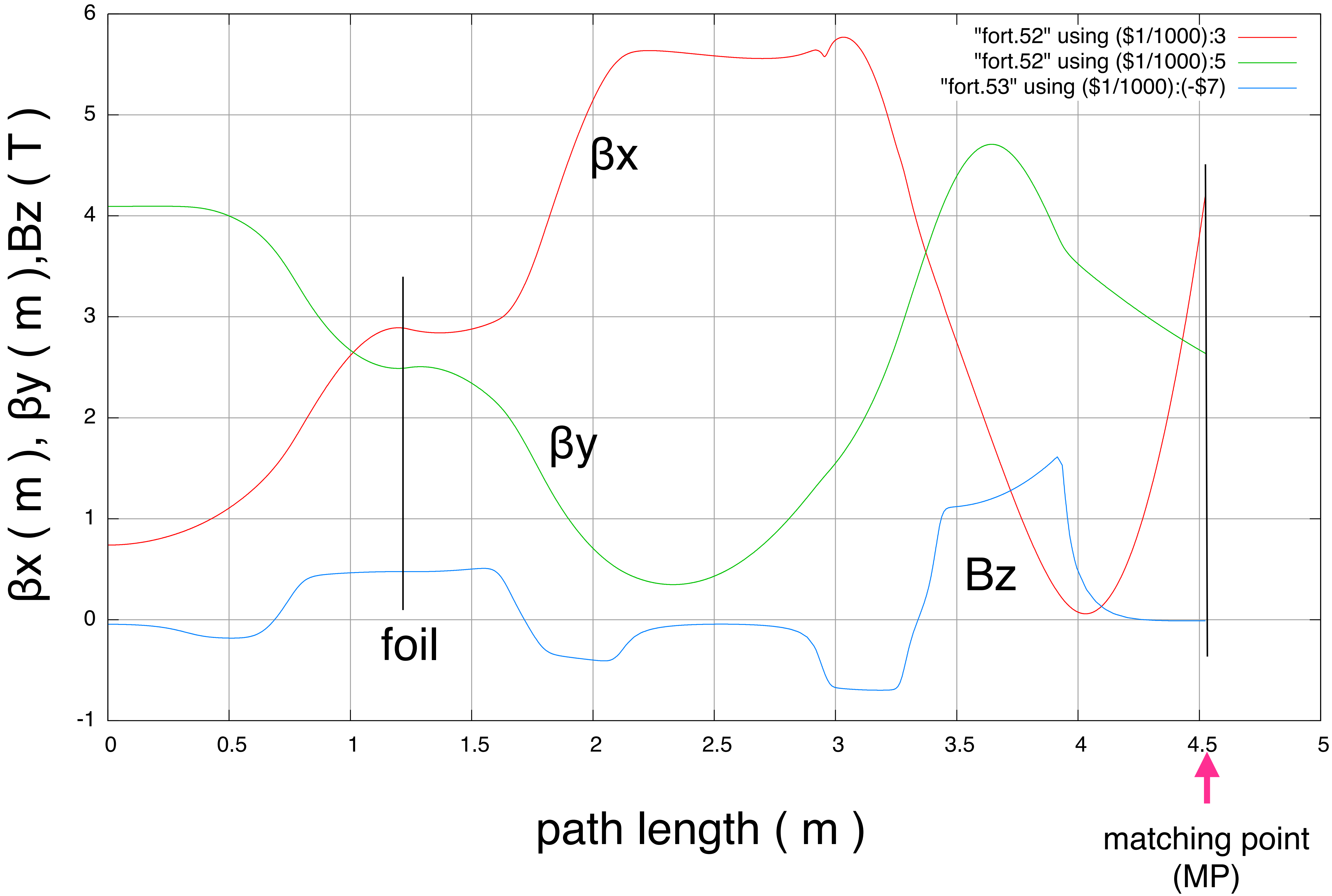




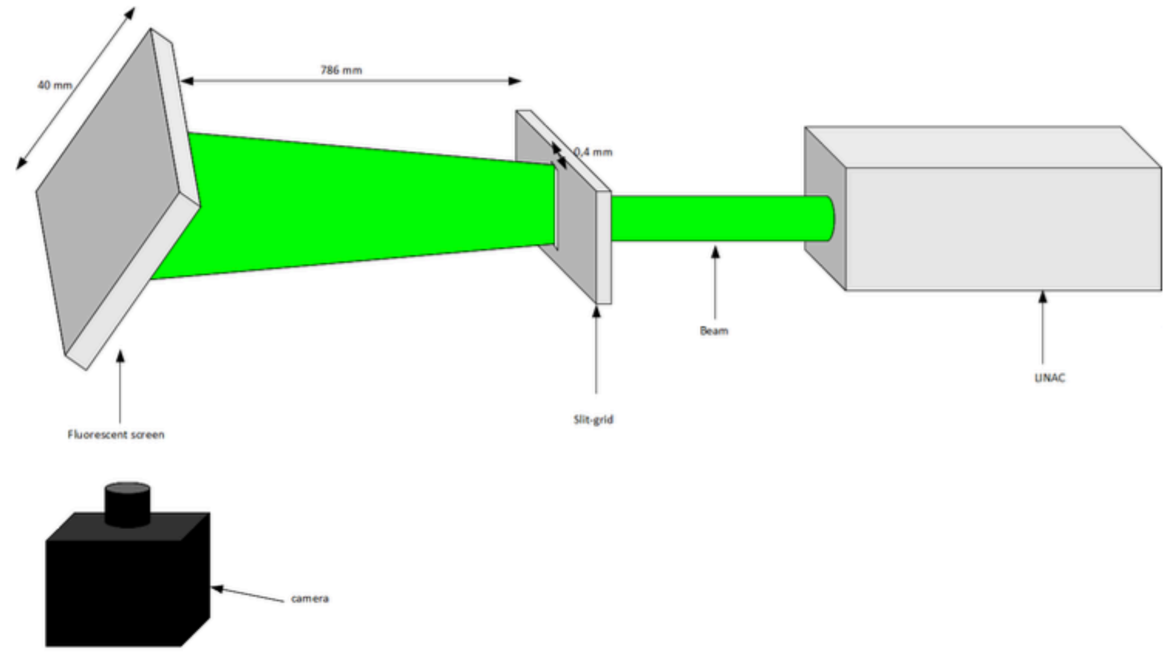


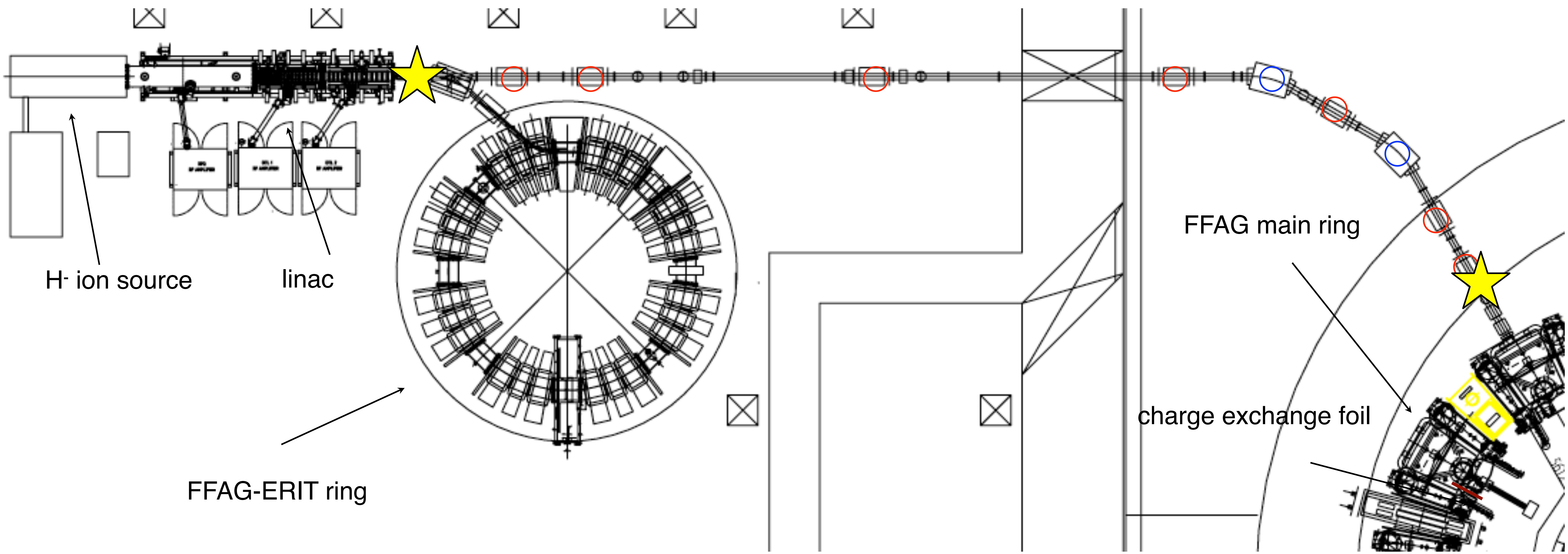
final quad of the beam line
MP
H-
87mm
D-mag
F-mag
D-mag
H+
main magnet
charge stripping foil
0.5°
6
5
4
3
2
1
0
6
5
4
3
2
1
0

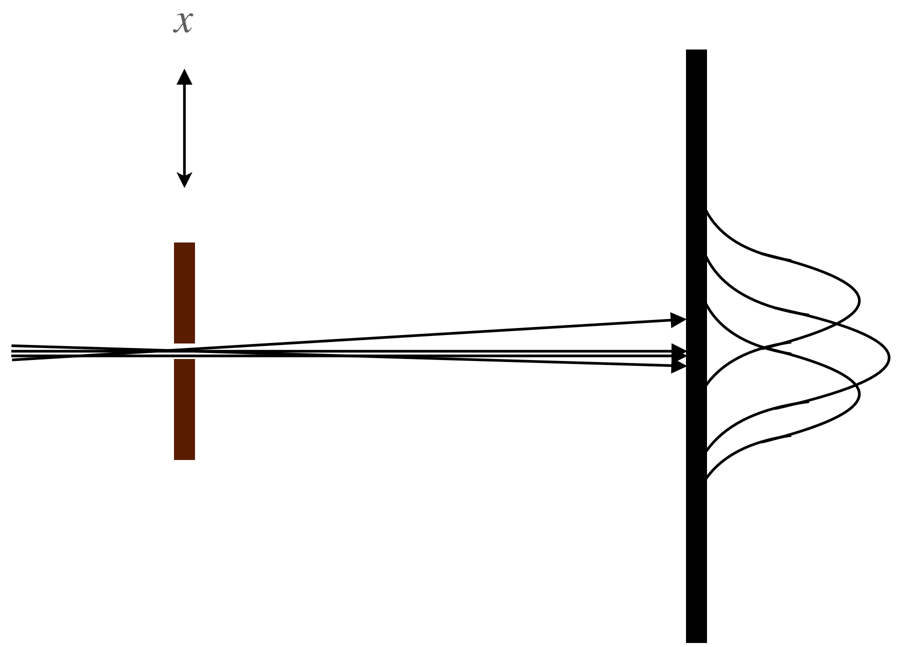
Beta functions calculated from backward tracking in the main ring

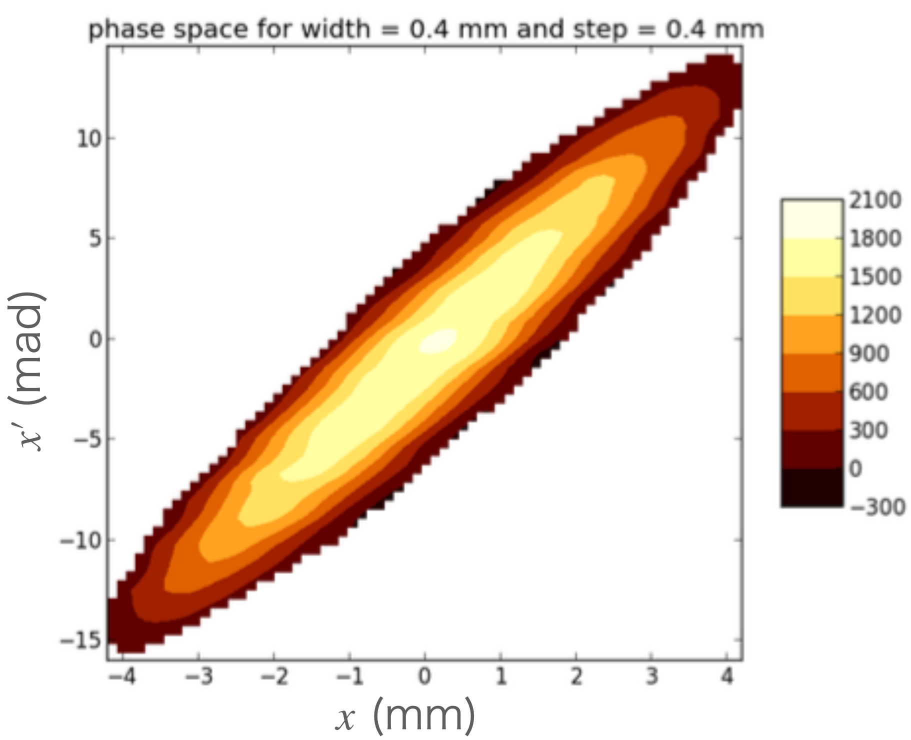


Measurement of Beam Emittance and the Twiss parameters in the beam line









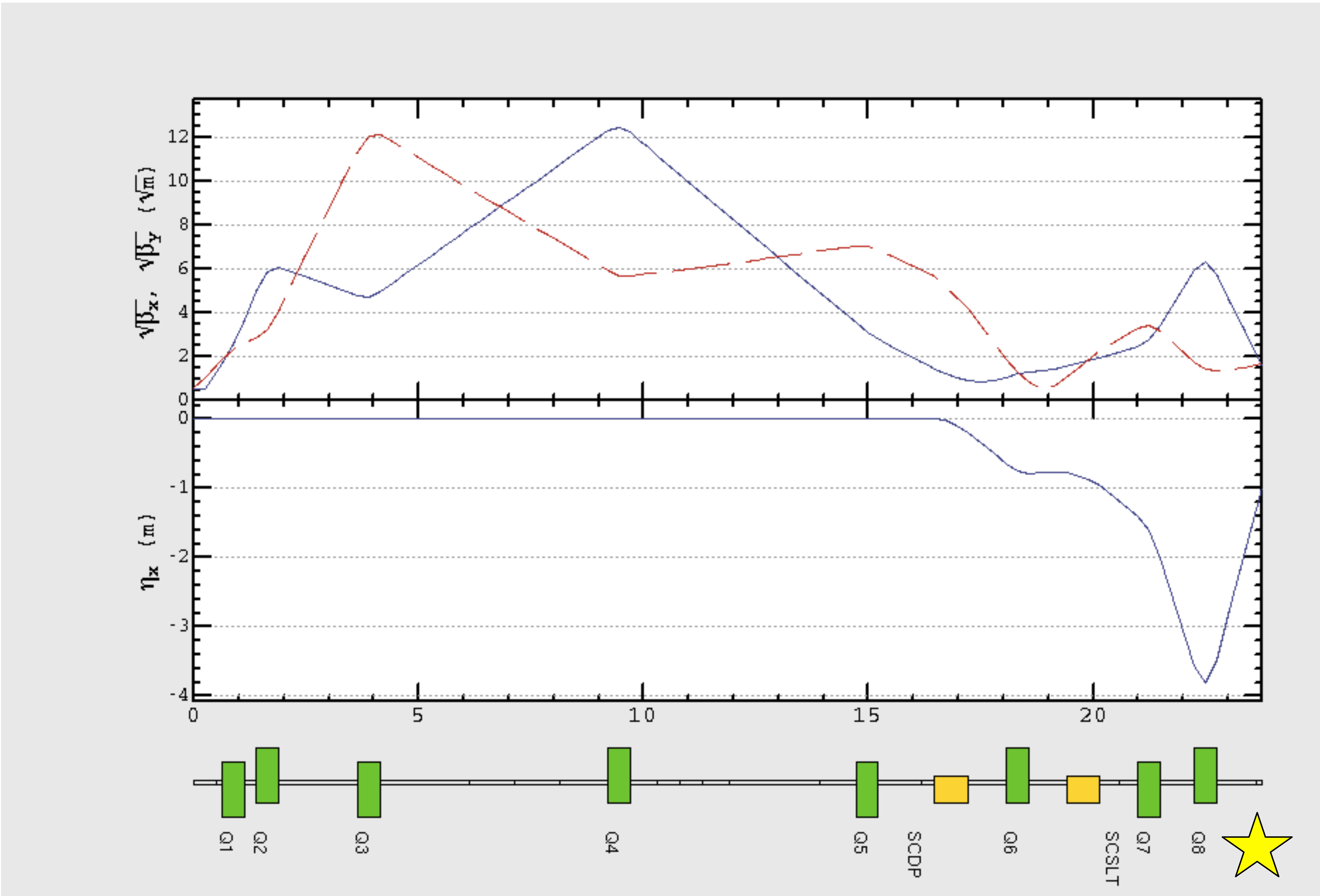
1. For each position of the slit, a beam distribution will be obtained as an image on the fluorescent screen.
2. Reconstruction of the phase space distribution can be obtained from these distribution.
3. From the phase space distribution, the emittance and the Twiss parameters can be obtained by using the beam covariance matrix.

$$\mathbf{\Sigma} = \begin{bmatrix} \sigma_x^2 & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'}^2 \end{bmatrix} = \epsilon_{\mathrm{rms}} \begin{bmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{bmatrix}$$

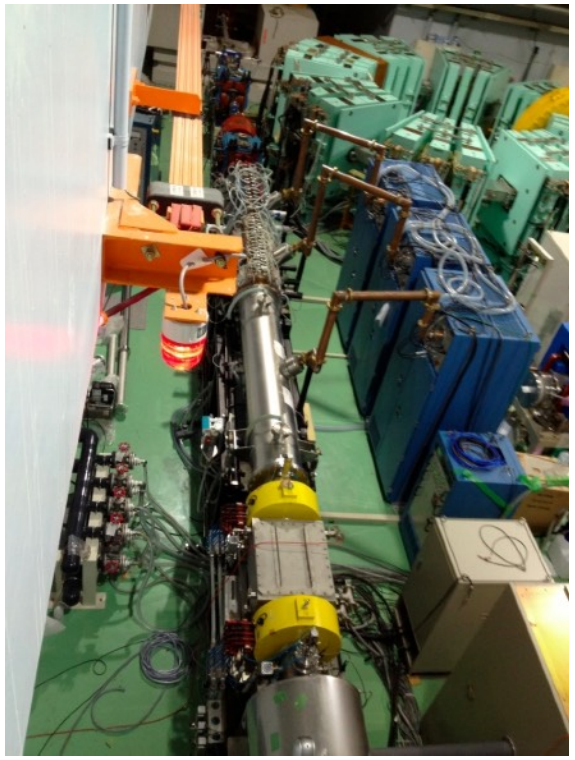
$$\epsilon_{\mathrm{rms}} \equiv \sqrt{\det \mathbf{\Sigma}}$$

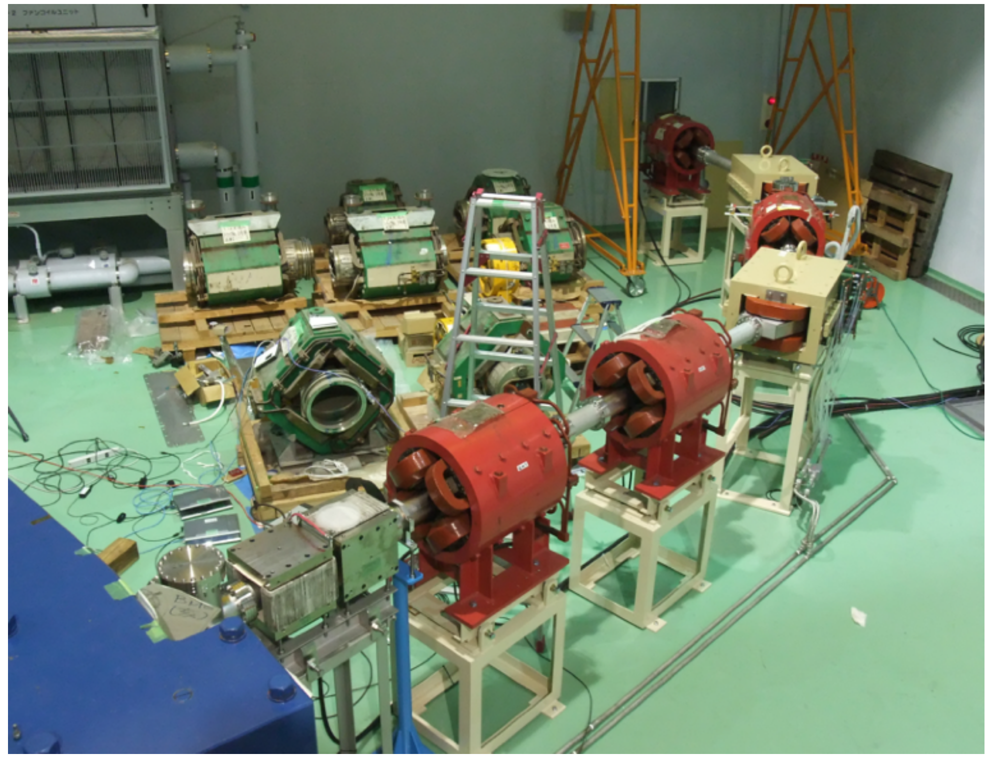
$$\sigma_{xx'} = \int (x - <x>)(x' - <x'>)\rho(x, x')\,dx\,dx'$$

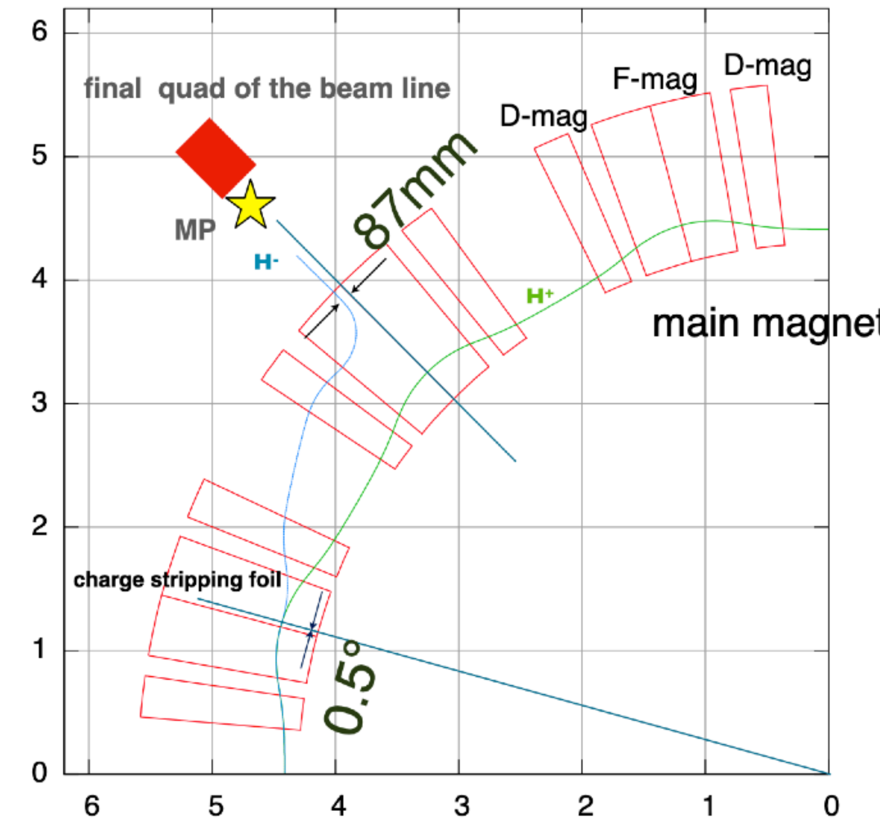
H- beam line beta functions calculated using SAD



H- injection






final quad of the beam line
D-mag
F-mag
D-mag
MP
87mm
H-
H+
main magnet
charge stripping foil
0.5°
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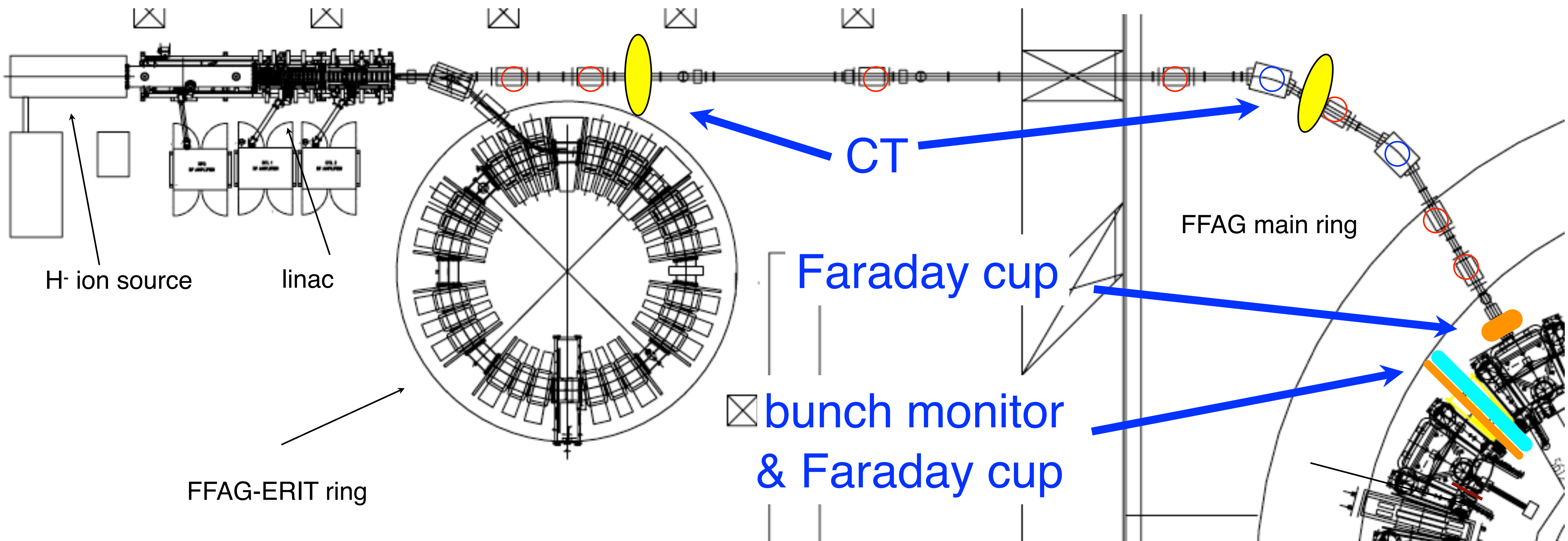
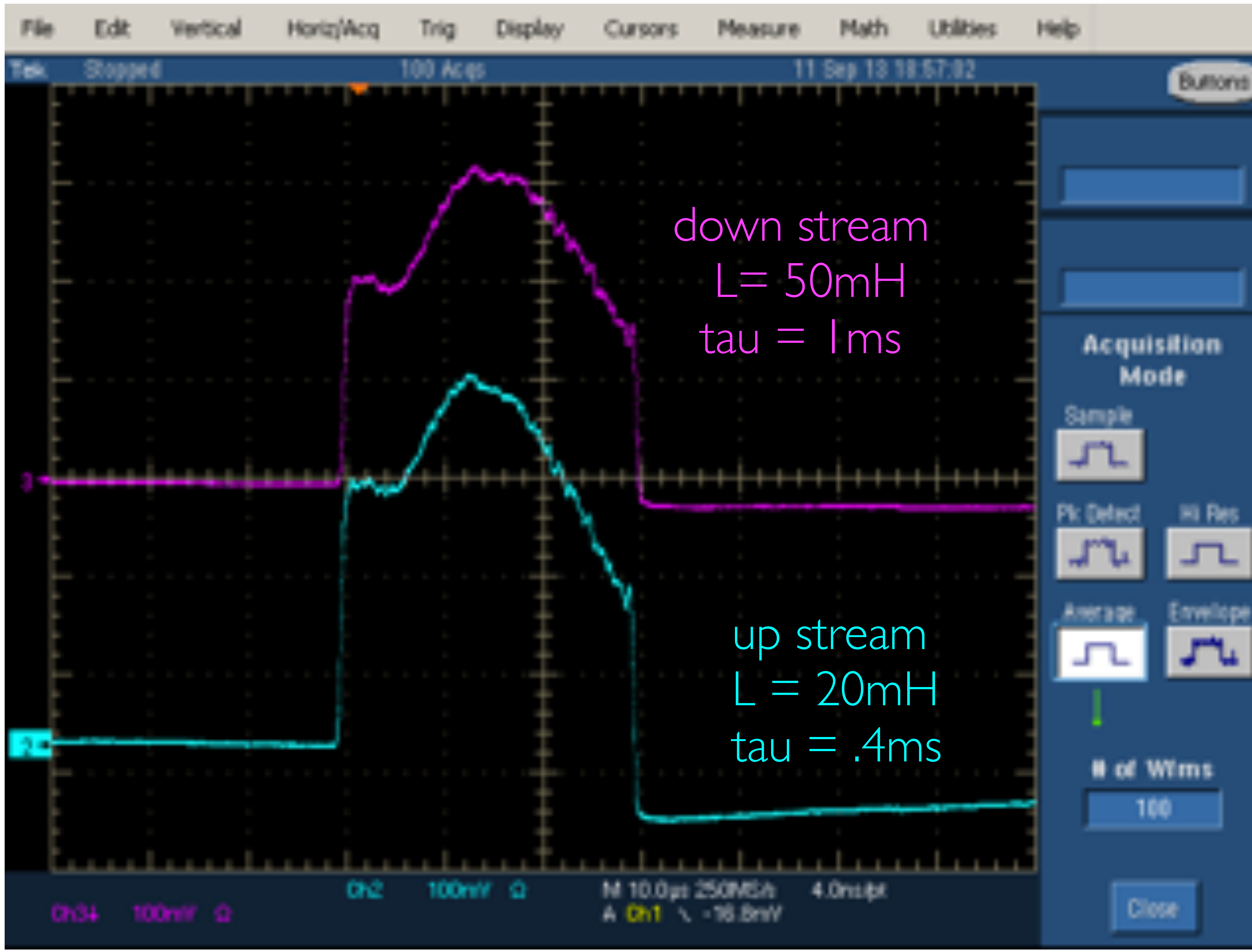
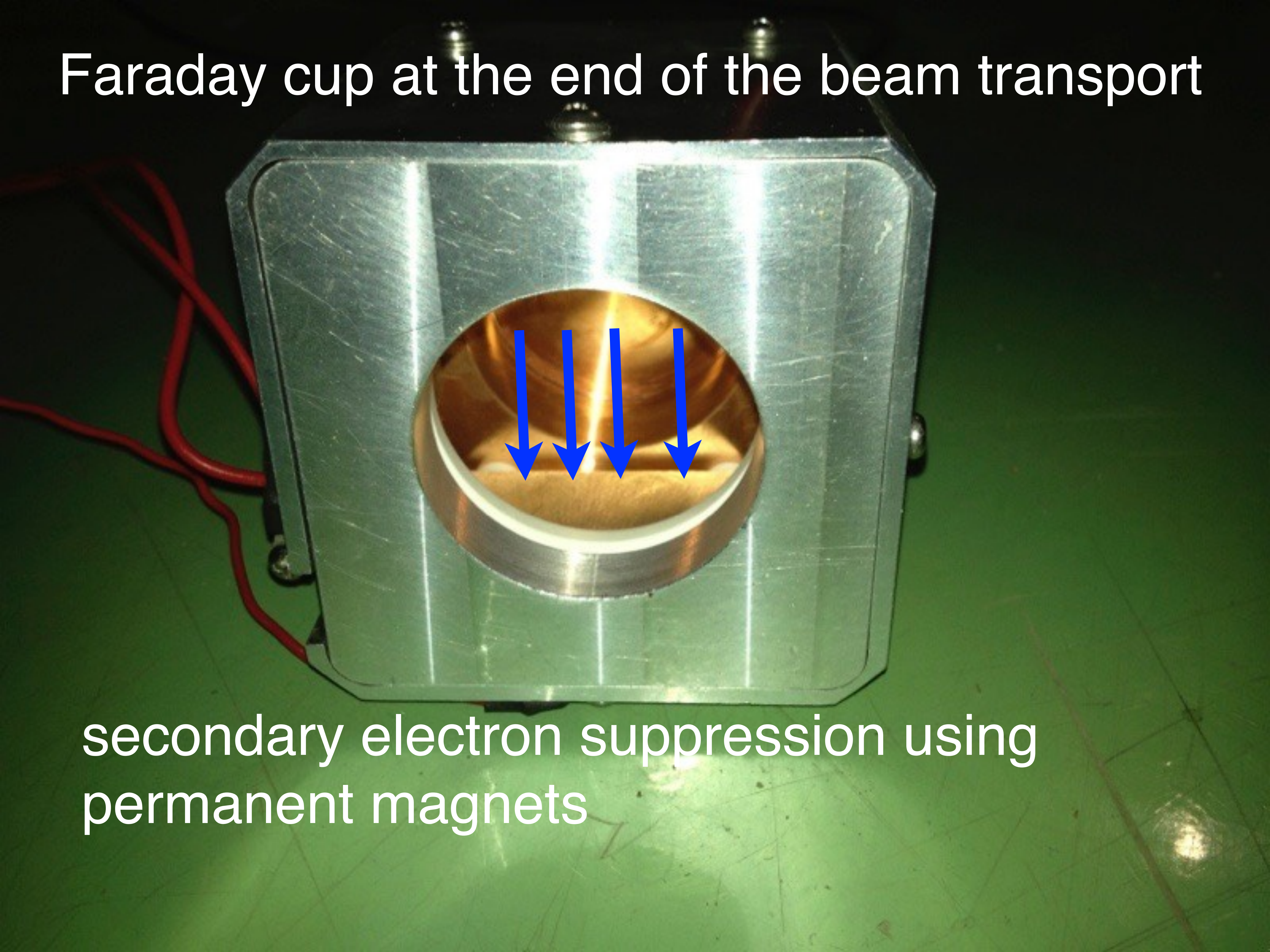
1
0

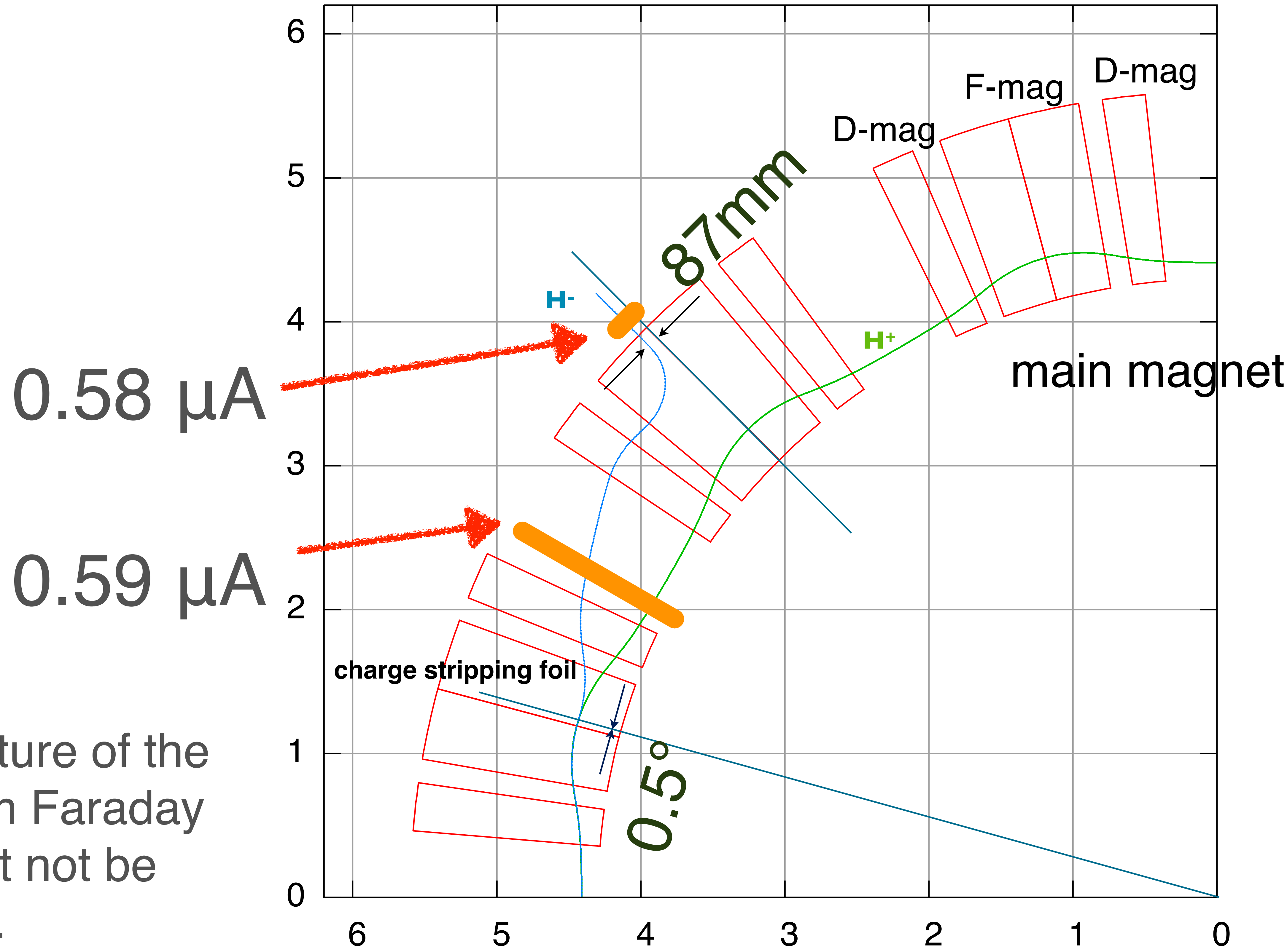

H- ion source
linac
FFAG-ERIT ring
CT
FFAG main ring
Faraday cup
bunch monitor
& Faraday cup

CTs installed in vacuum



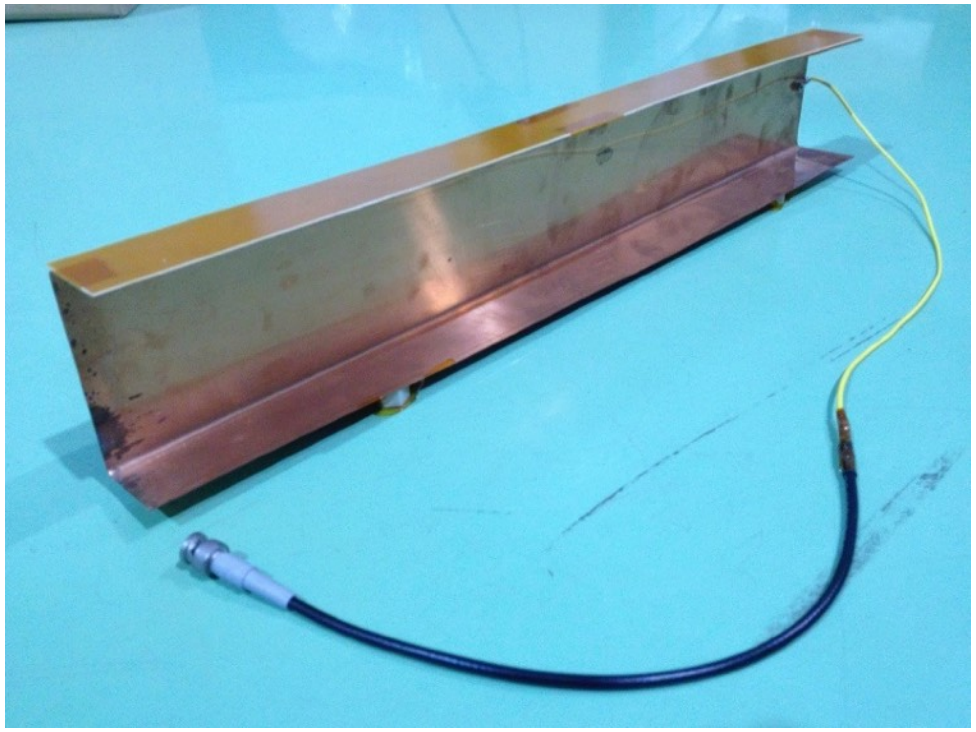

Faraday cup at the end of the beam transport
secondary electron suppression using permanent magnets

Beam injection to the main ring



The aperture of the up stream Faraday cup might not be sufficient.

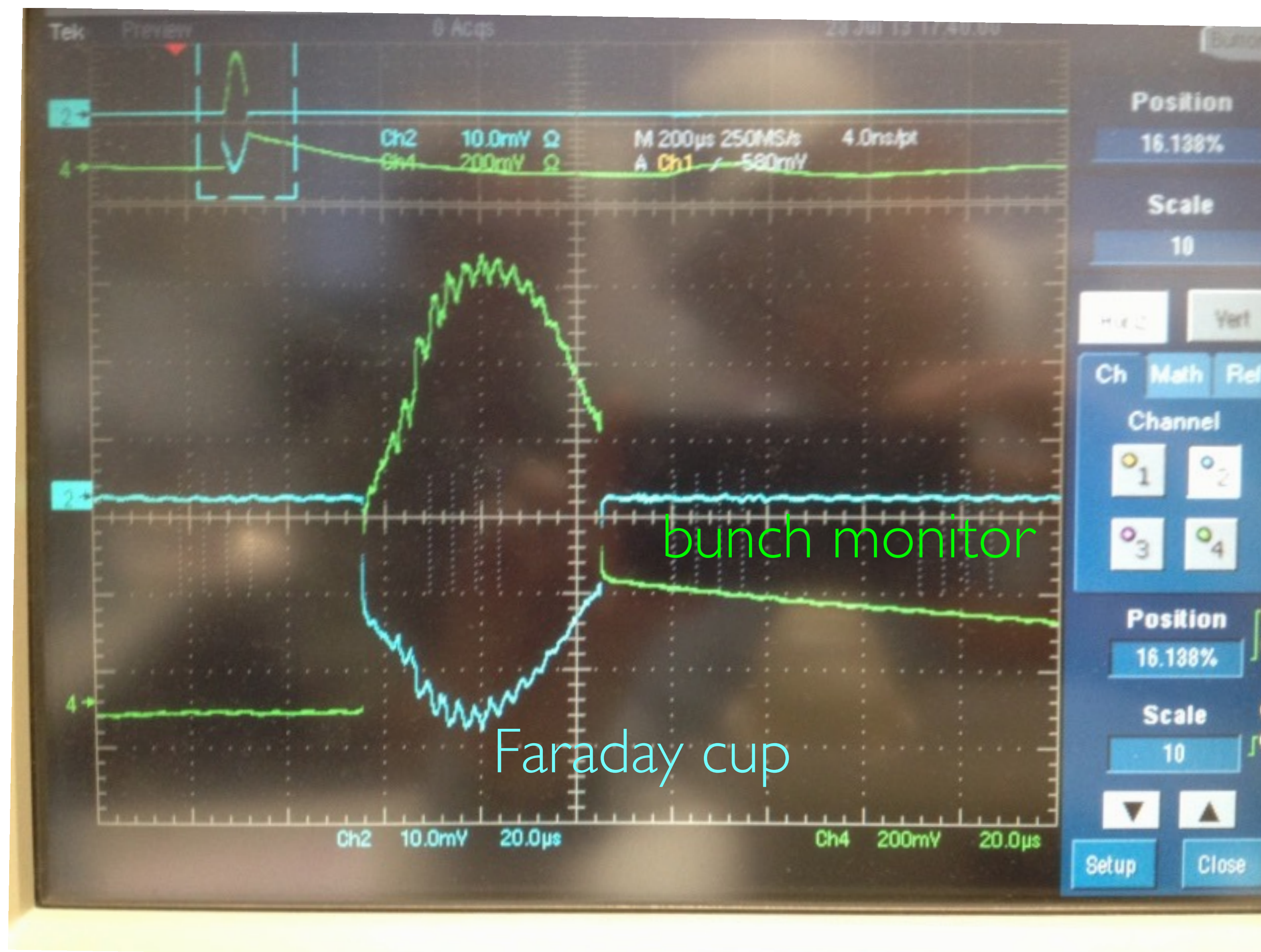
Faraday cup

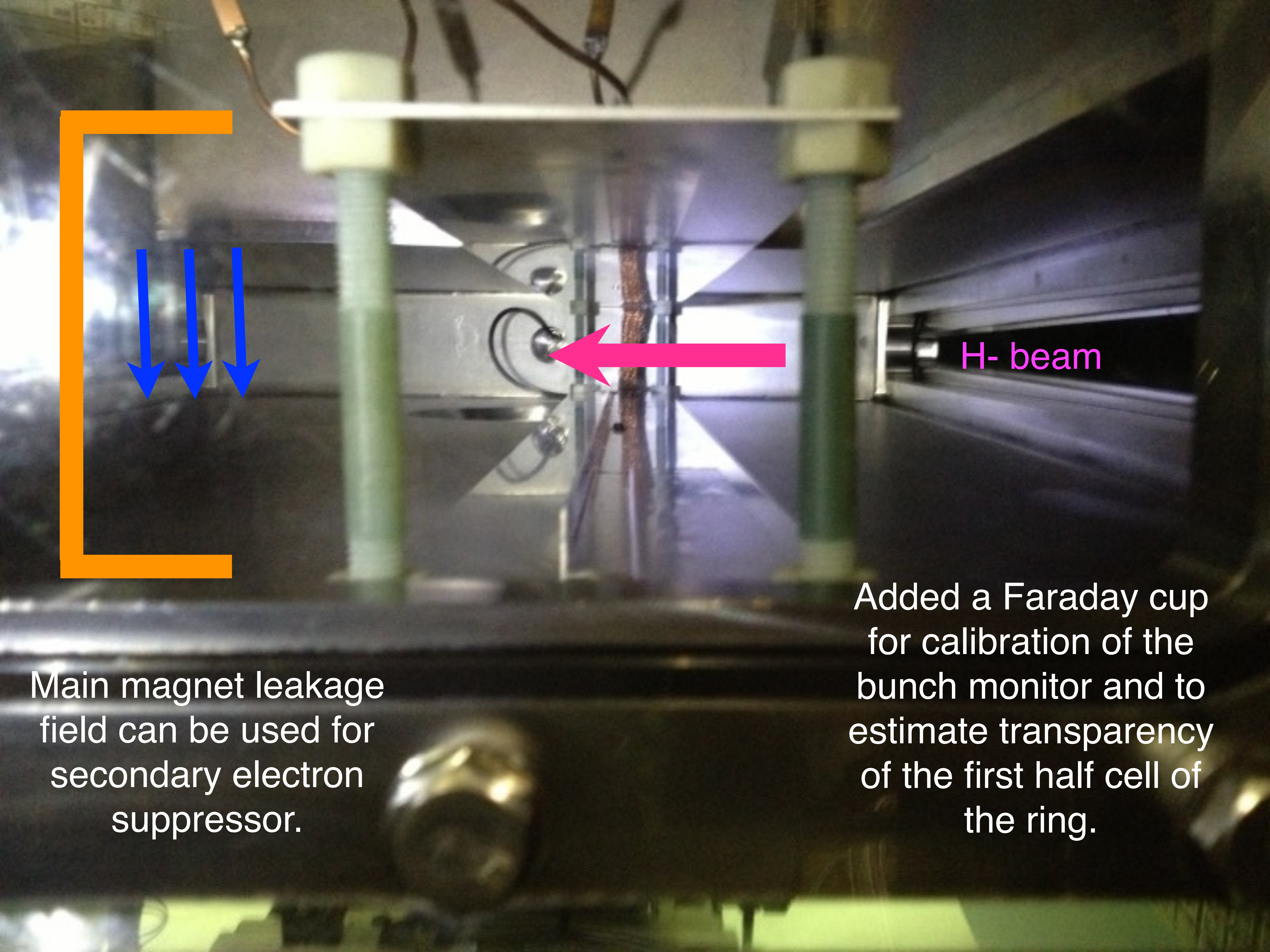


Long tailed decay in bunch monitor signal seems to be back scatter of the secondary electron (suppression is not perfect)
→ RC constant
R = 1MΩ (input impedance of the amp)
C = 171pF

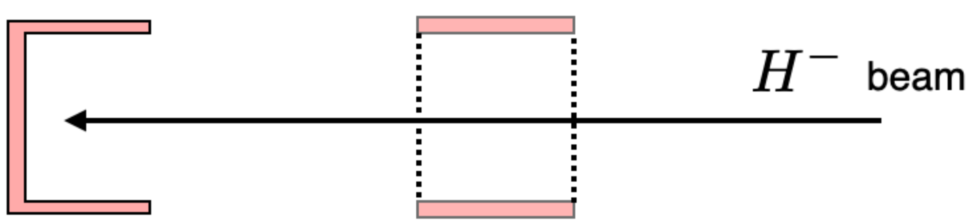
faraday cup signal is read thru 50Ω at 20Hz rep. rate

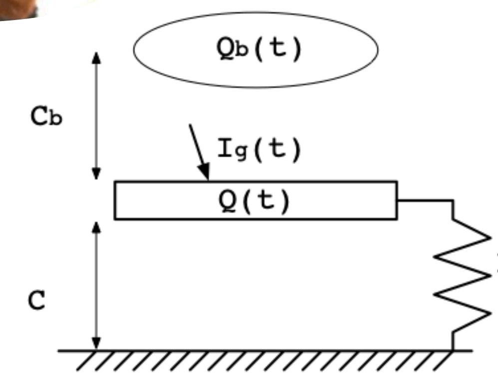
$$I_{\rm av} = \frac{\int V_{\rm FC} dt}{50} \times 20$$

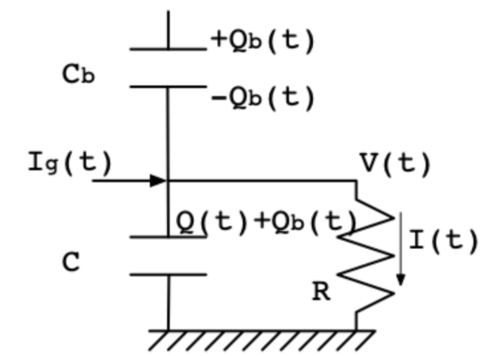



H- beam
Main magnet leakage field can be used for secondary electron suppressor.
Added a Faraday cup for calibration of the bunch monitor and to estimate transparency of the first half cell of the ring.

Full Aperture Beam Monitor (FAB)

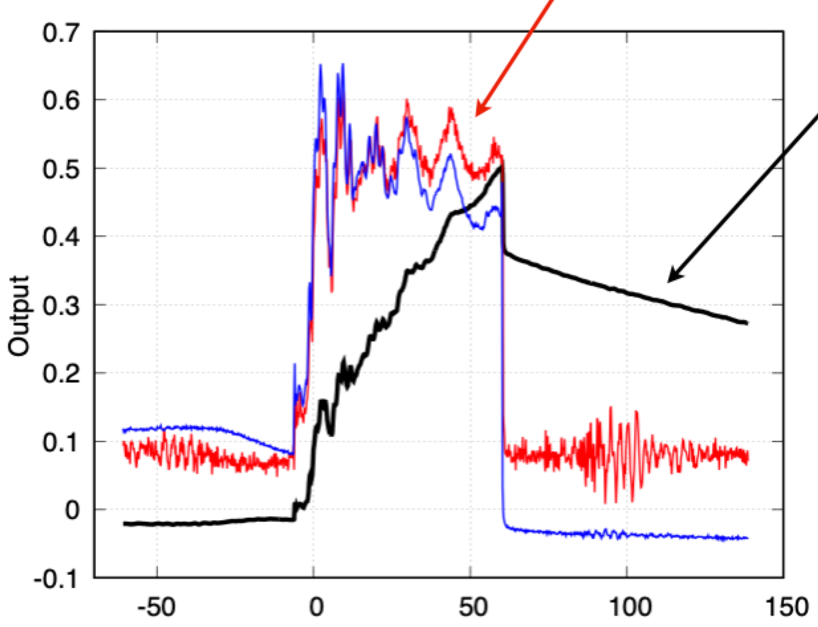






Destructive current monitor (FC)
(temporally installed in the ring)

Newly installed Beam monitor (FAB)

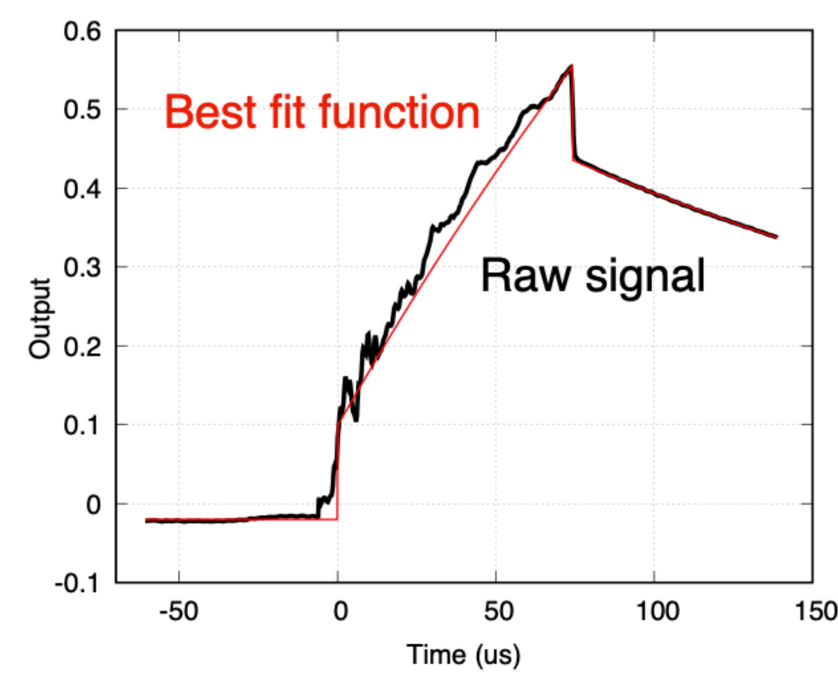


$$GR \times \left[\quad I_g - \left(I_g - \frac{Q_b}{\tau} \right) \exp\left(-\frac{t}{\tau} \right) \right] \qquad (0 < t < T)$$

$$GR \times \left[\left(e^{T/\tau} - 1 \right) \left(I_g - \frac{Q_b}{\tau} \right) \exp\left(-\frac{t}{\tau} \right) \right] \qquad (T < t)$$

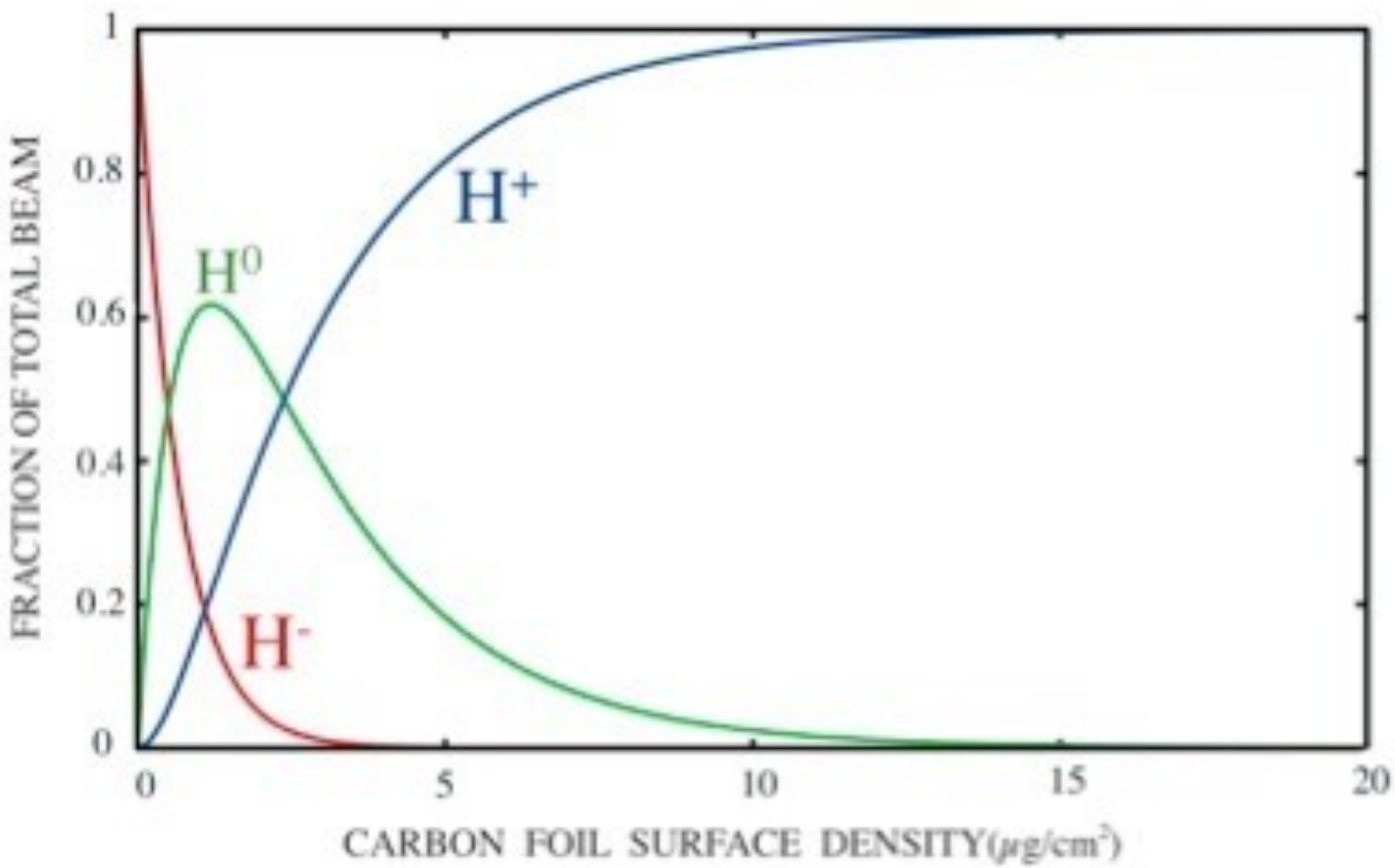
$$G = \frac{46\ dB}{2}, \quad R = 1\ M\Omega, \quad \tau = 265\ \mu s,$$

$$I_p = \frac{\ell}{\tau v} Q_b = 45\ \mu A, \quad I_g = 10\ nA$$

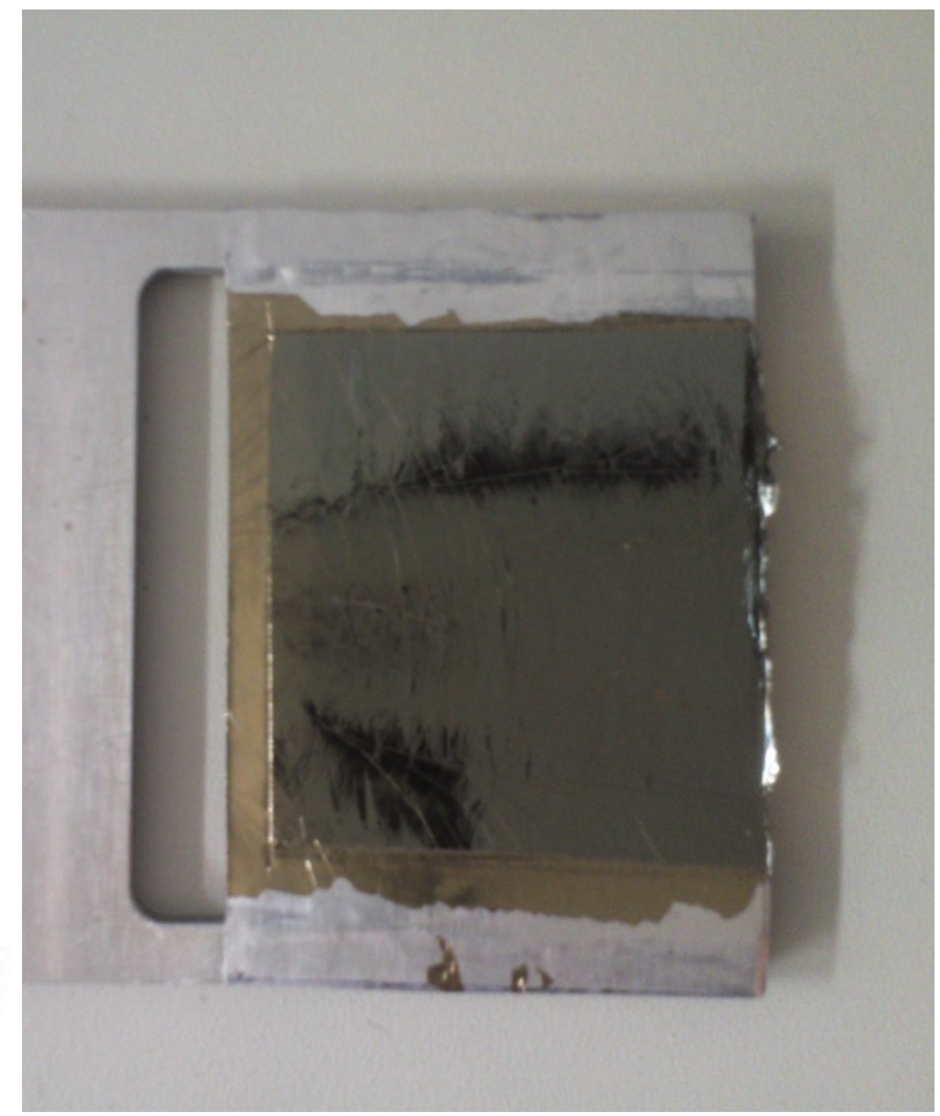


injection study

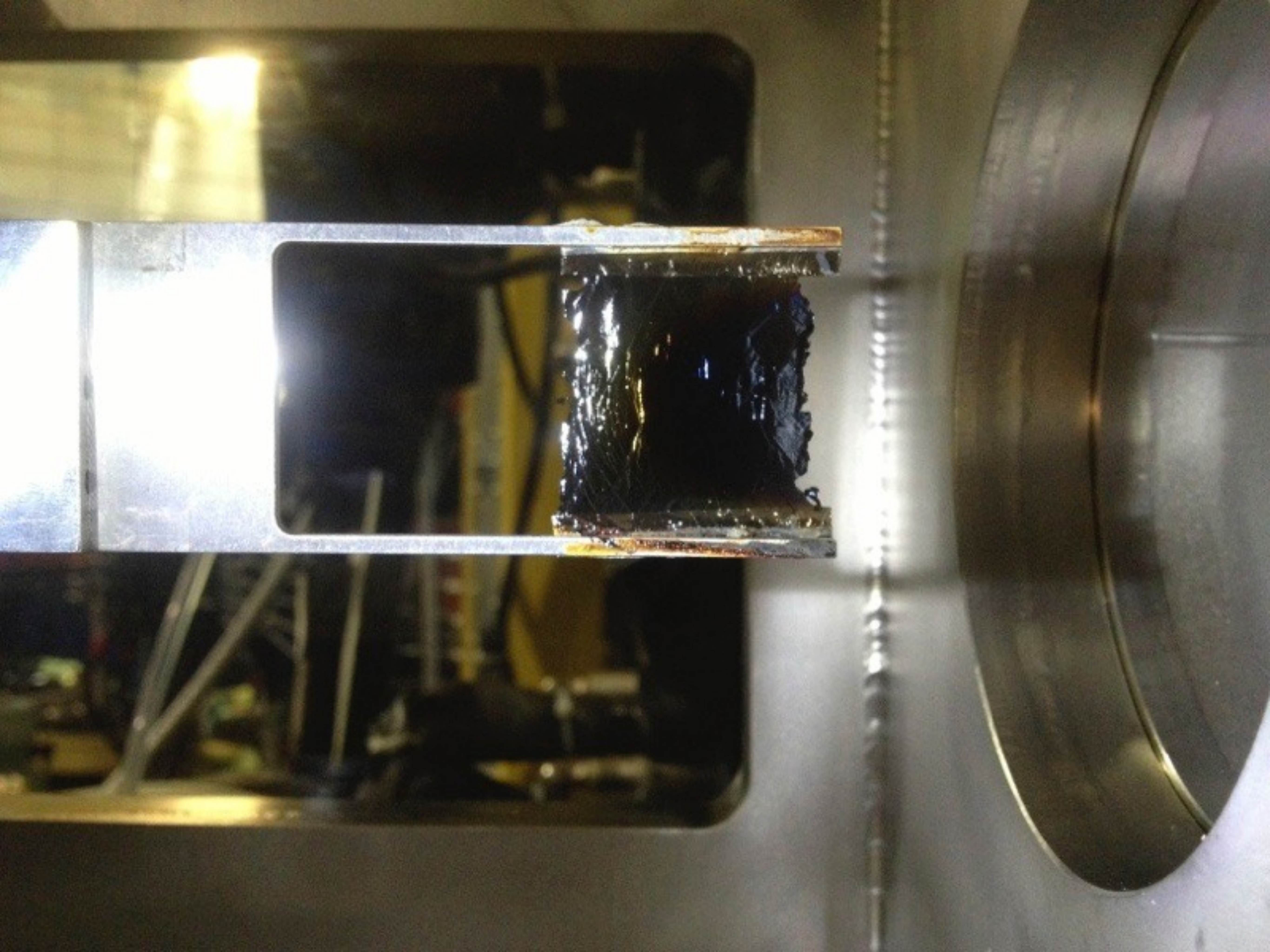
charge exchange efficiency vs foil thickness



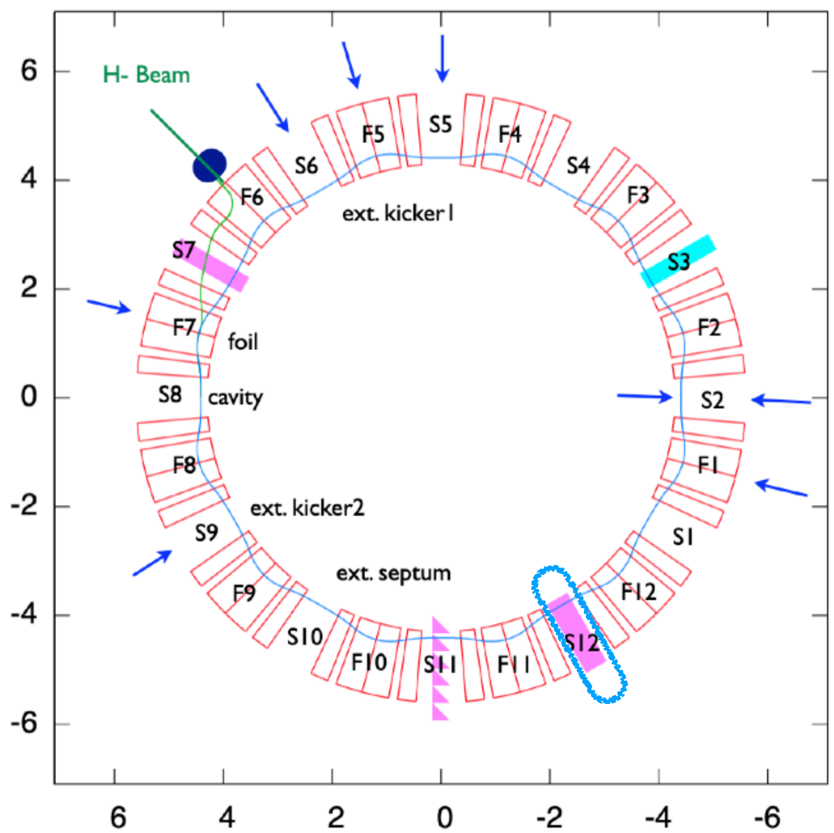
brand-new foil
20 ug/cm2

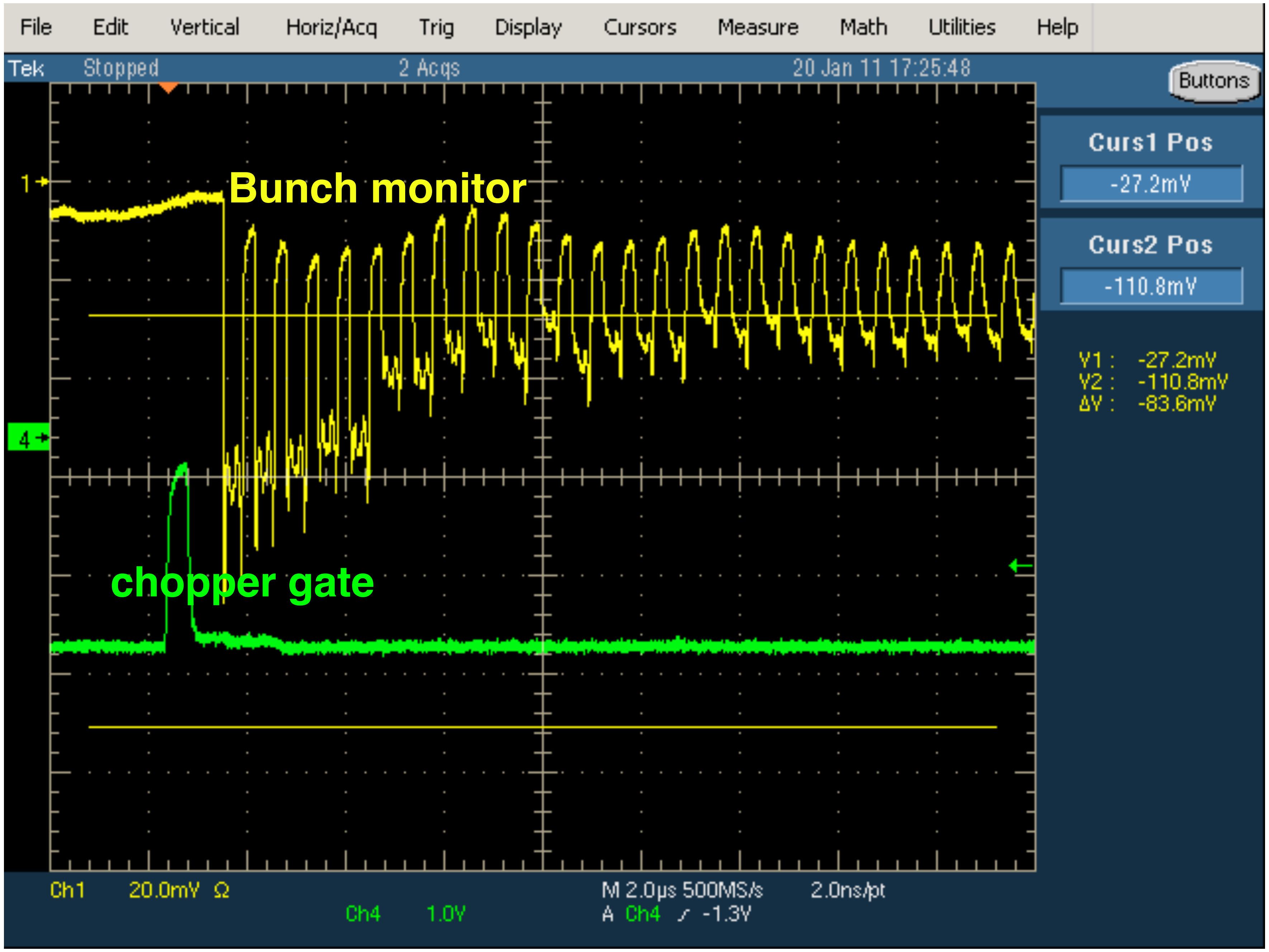


1.5 years later…



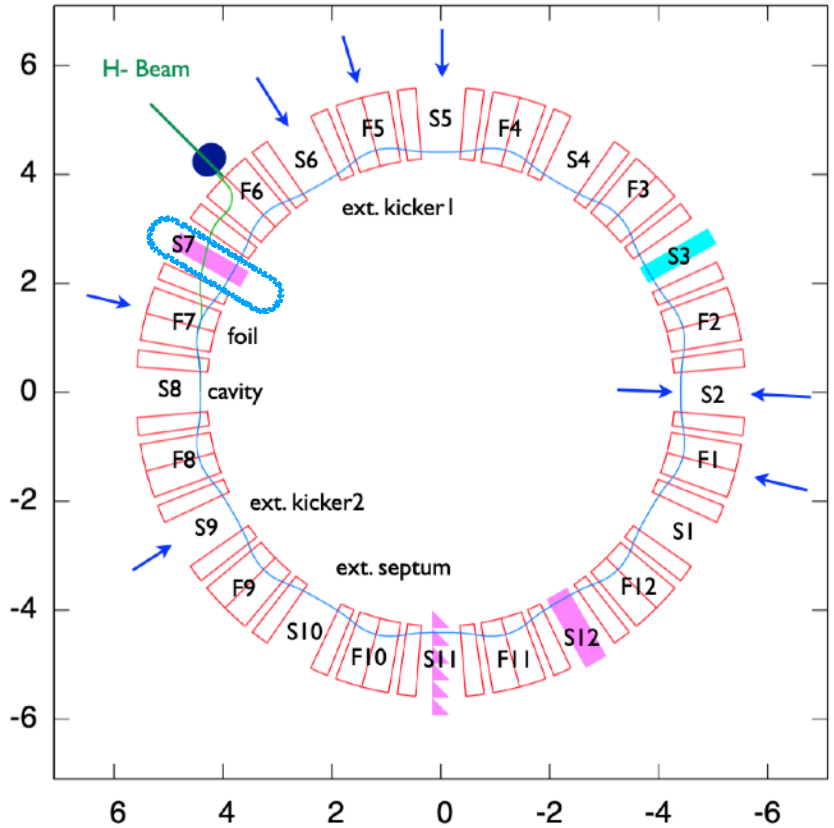
Bunch monitor signal at the injection

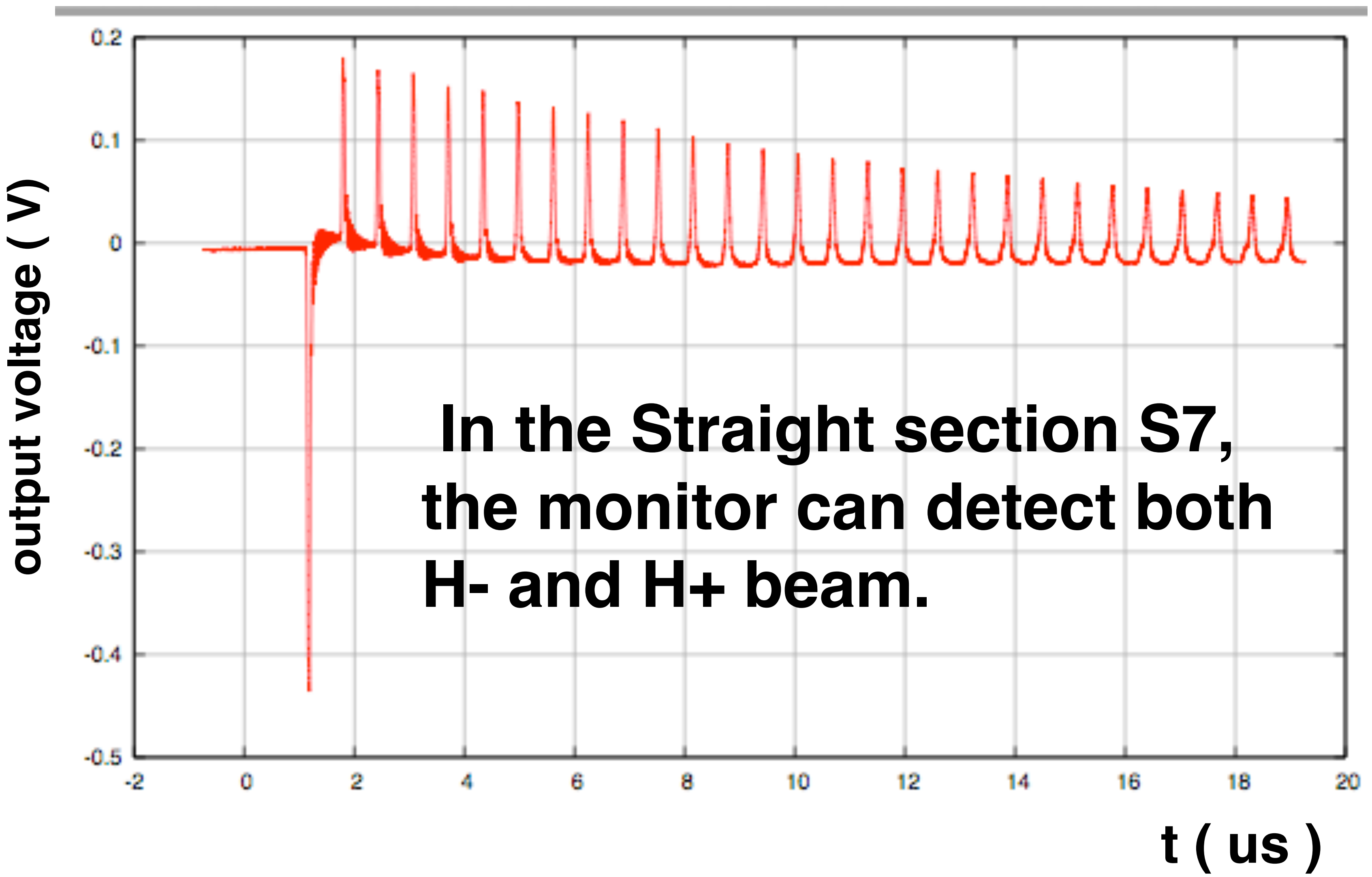




200 ns pulse shaped by the beam chopper
no rf voltage
injected beam is decreased under 30 % within first 10 turns after the injection

Beam signal from the bunch monitor





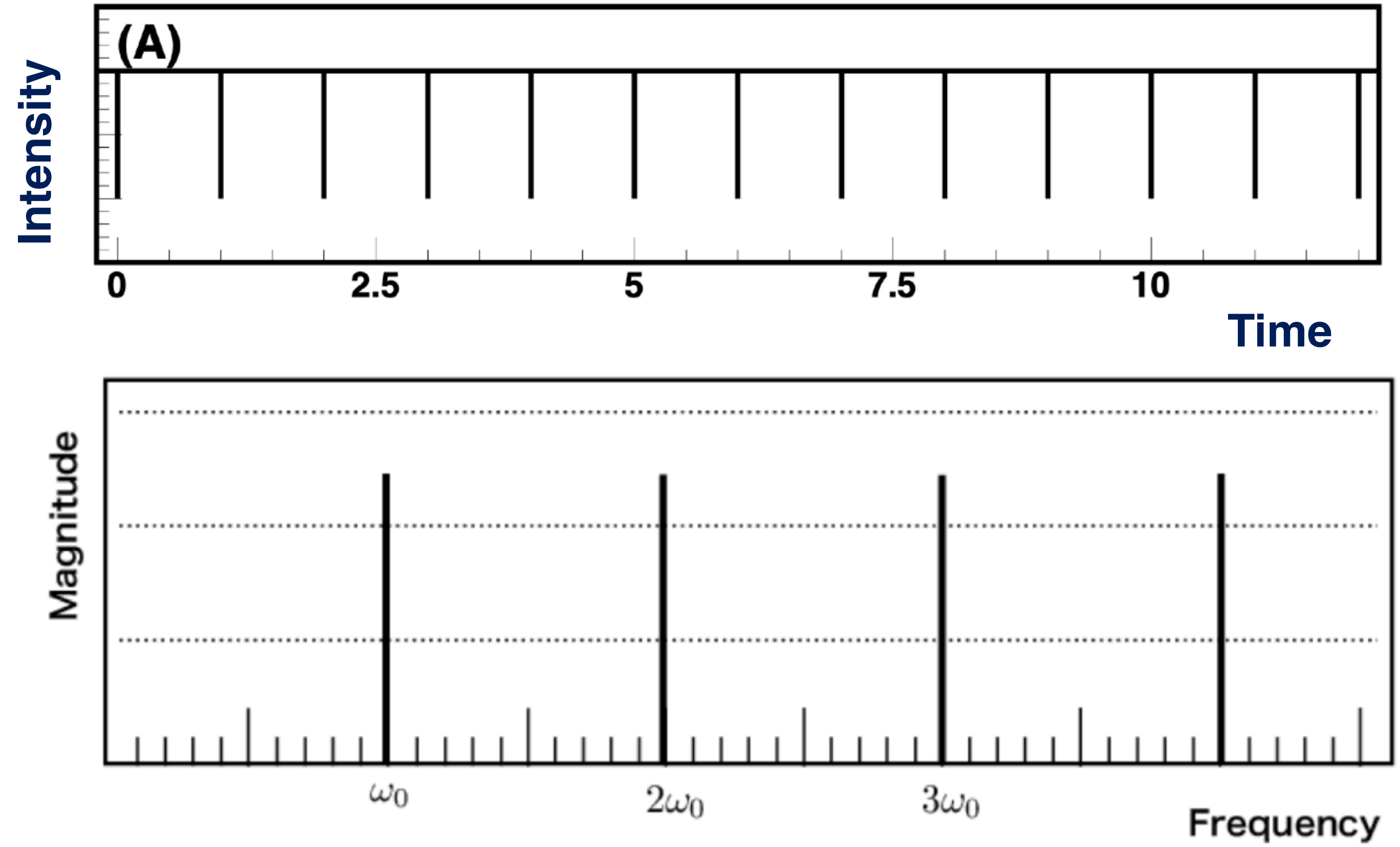
In the Straight section S7, the monitor can detect both H- and H+ beam.

File
Edit
Vertical
Horiz/Acq
Trig
Display
Cursors
Measure
Math
Utilities
Help
Tek
Stopped
10 Acqs
20 Jan 11 18:45:02
Buttons
Curs1 Pos
-410.0mV
Curs2 Pos
400.0mV
Bunch monitor
synchrotron motion
RF monitor
Ch1 200mV
Ch3 500mV Ω
Ch4 1.0V
File
Edit
Vertical
Horiz/Acq
Trig
Display
Cursors
Measure
Math
Utilities
Help
Tek
Stopped
10 Acqs
20 Jan 11 18:35:38
Buttons
Curs1 Pos
-340.0mV
Curs2 Pos
350.0mV
V1 : -340.0mV
V2 : 350.0mV
ΔV : 690.0mV
Bunch monitor
RF monitor
Ch1 200mV 5.0µs
Ch3 500mV 5.0µs
Ch4 1.0V 5.0µs

Betatron tune

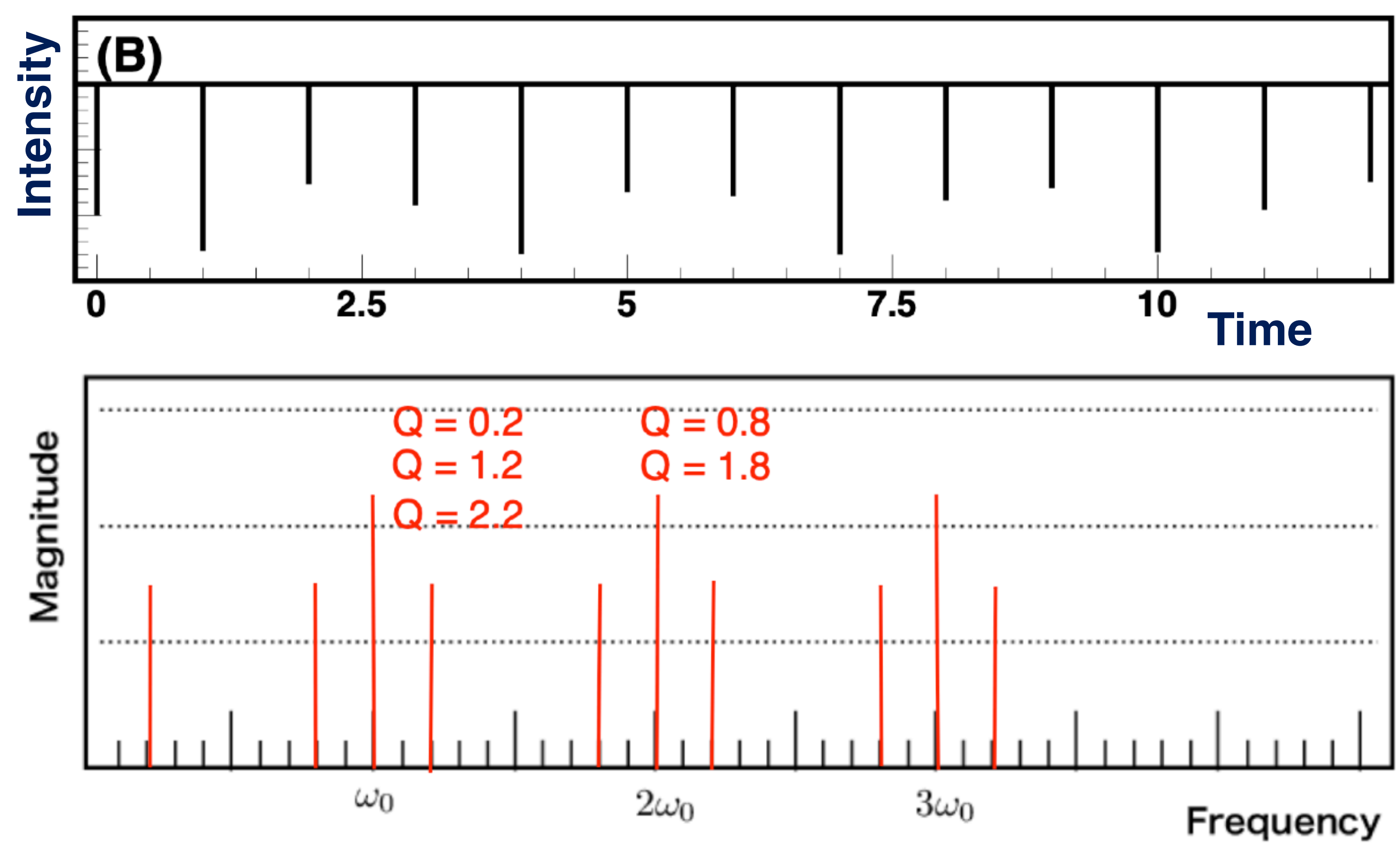
no coherent betatron oscillation

Periodic delta function

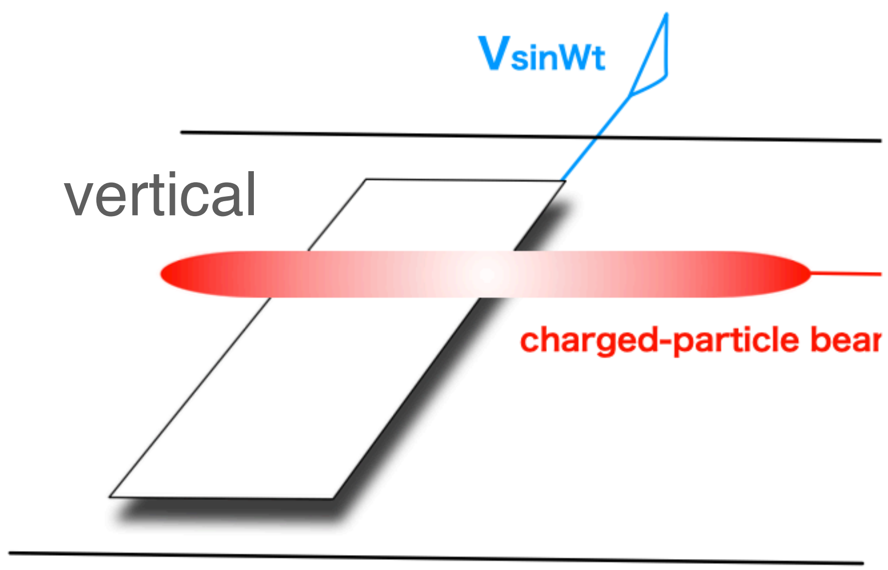


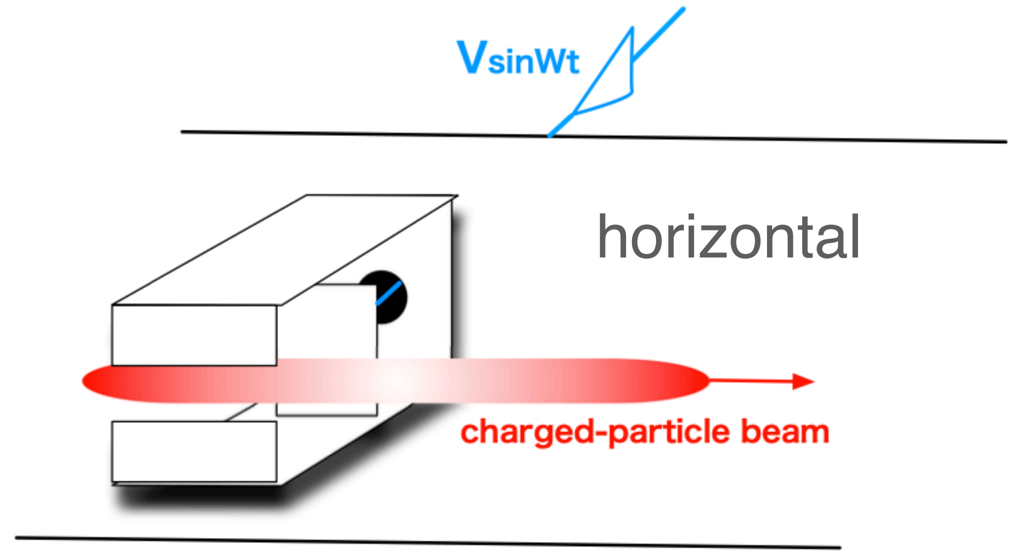
coherent betatron oscillation as an amplitude modulation

Periodic delta function with side bands

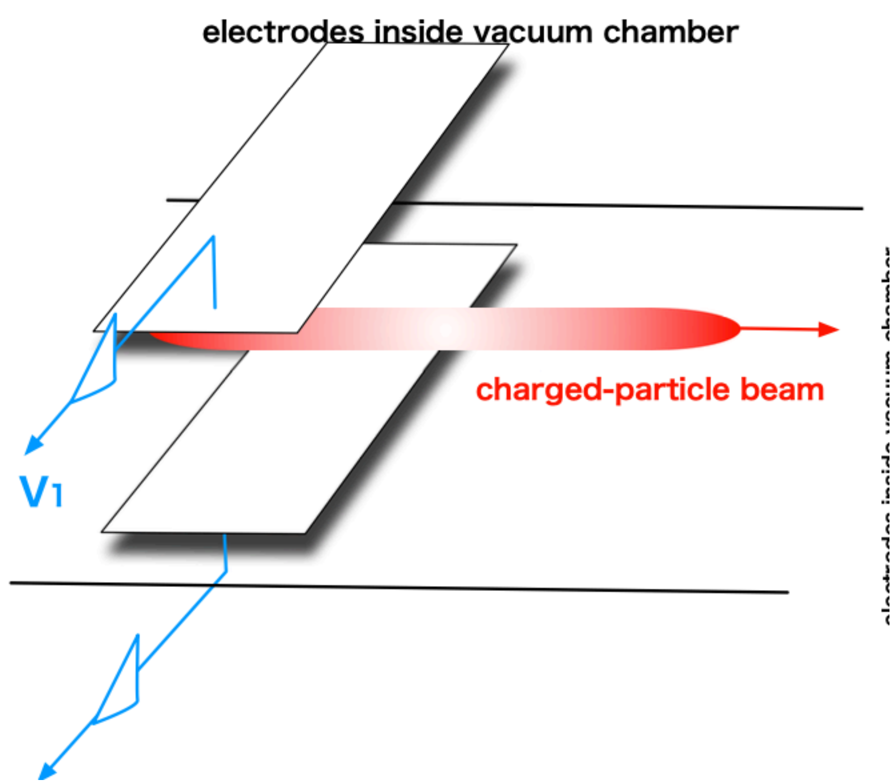


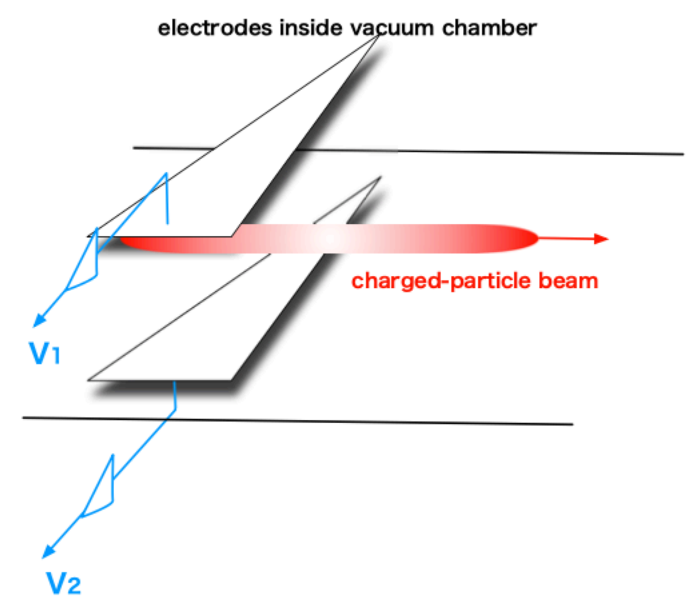
1. Excite coherent oscillations



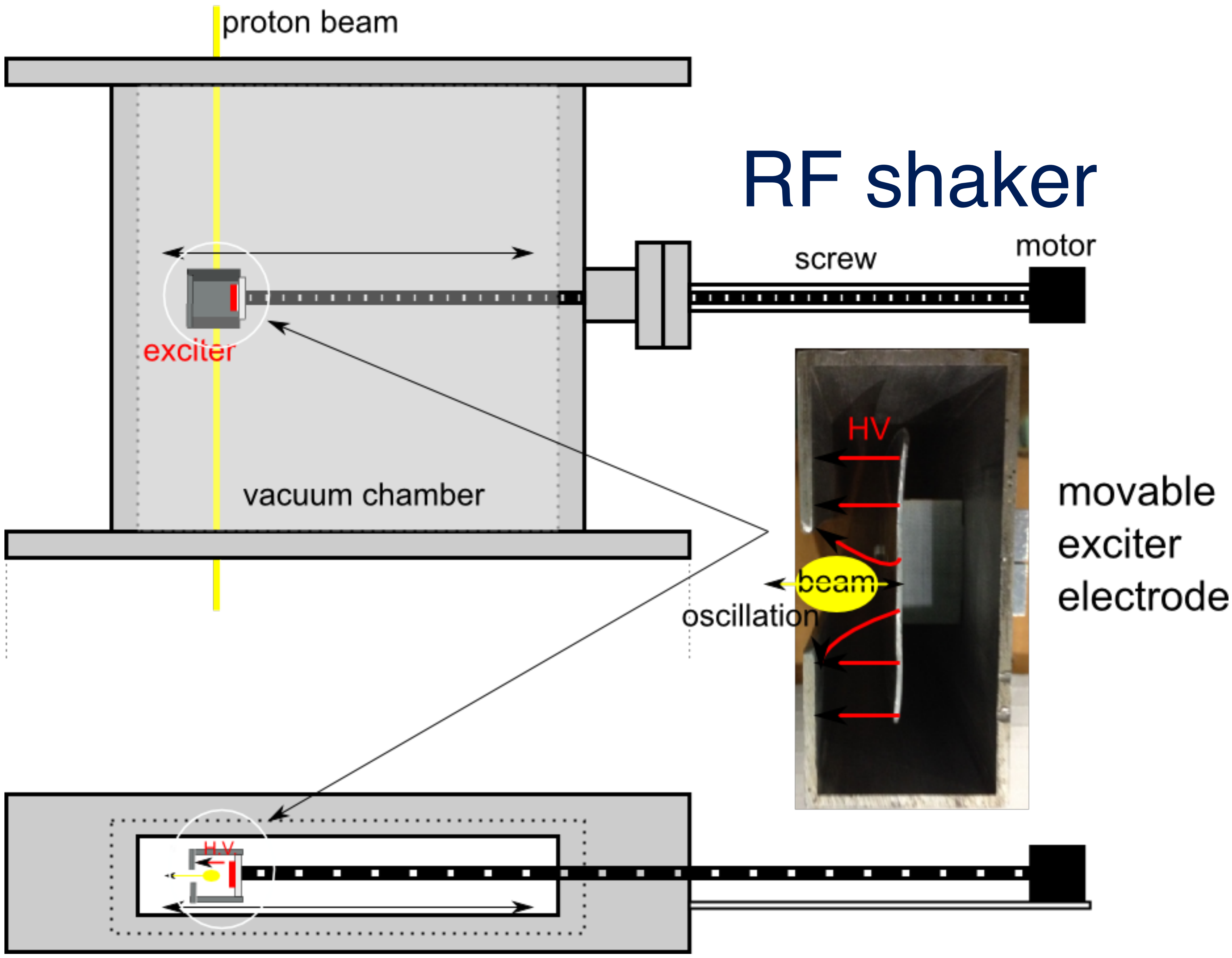


2. Detect coherent oscillations

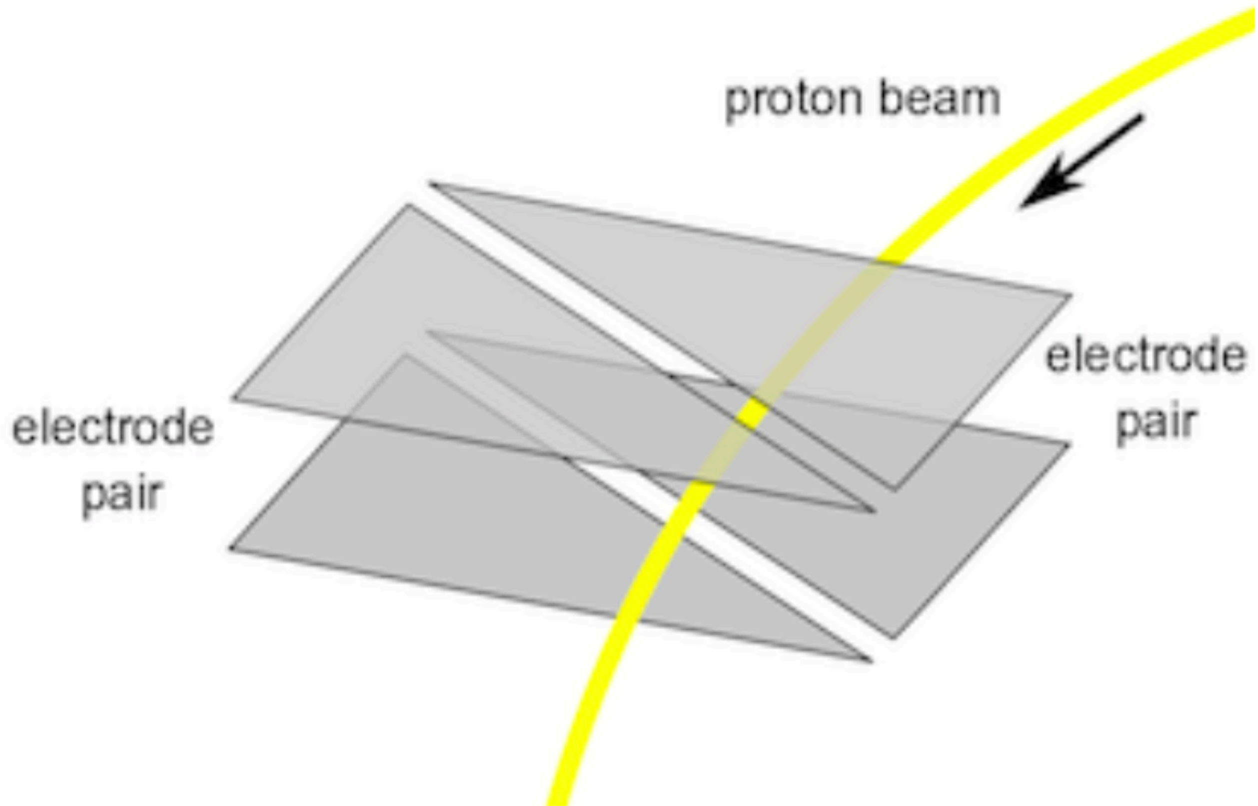




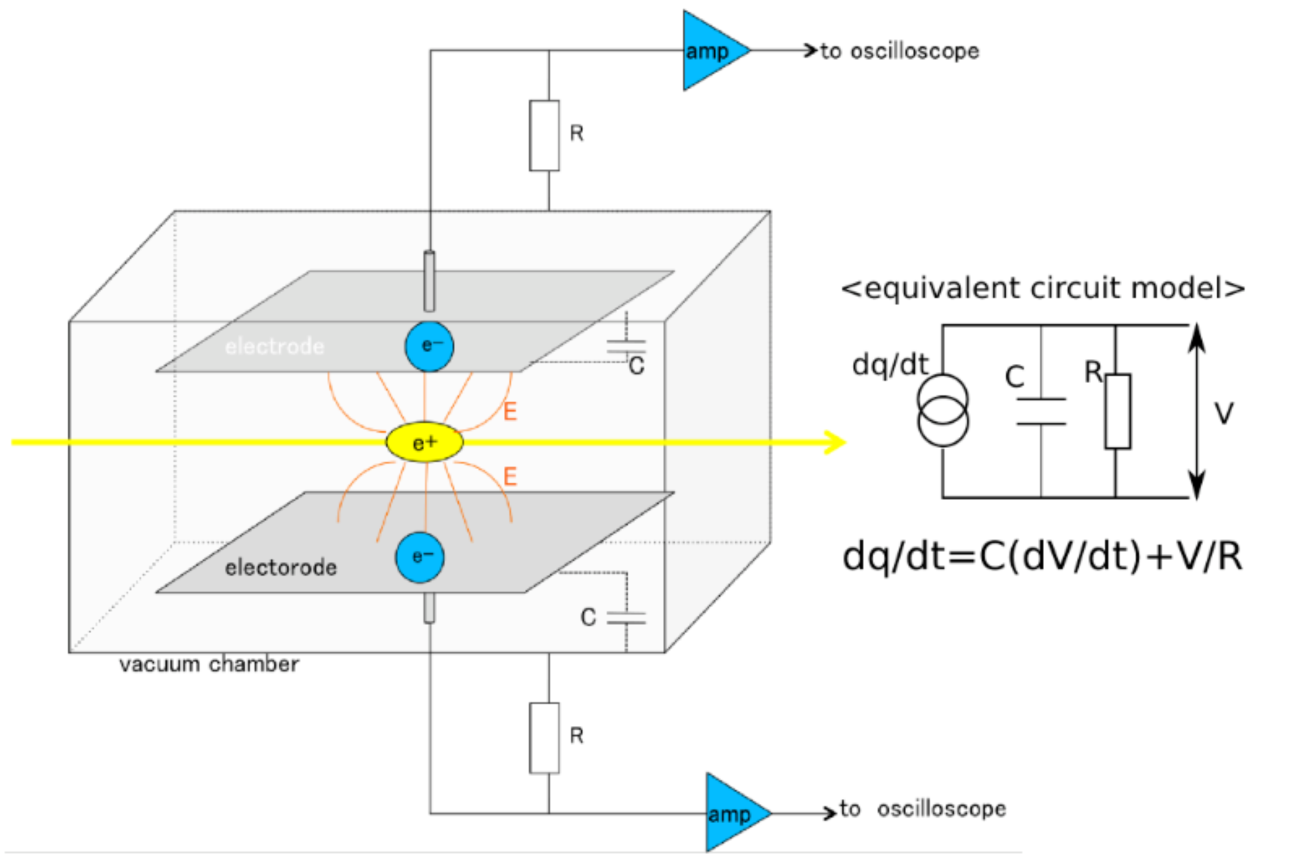
horizontal excitation

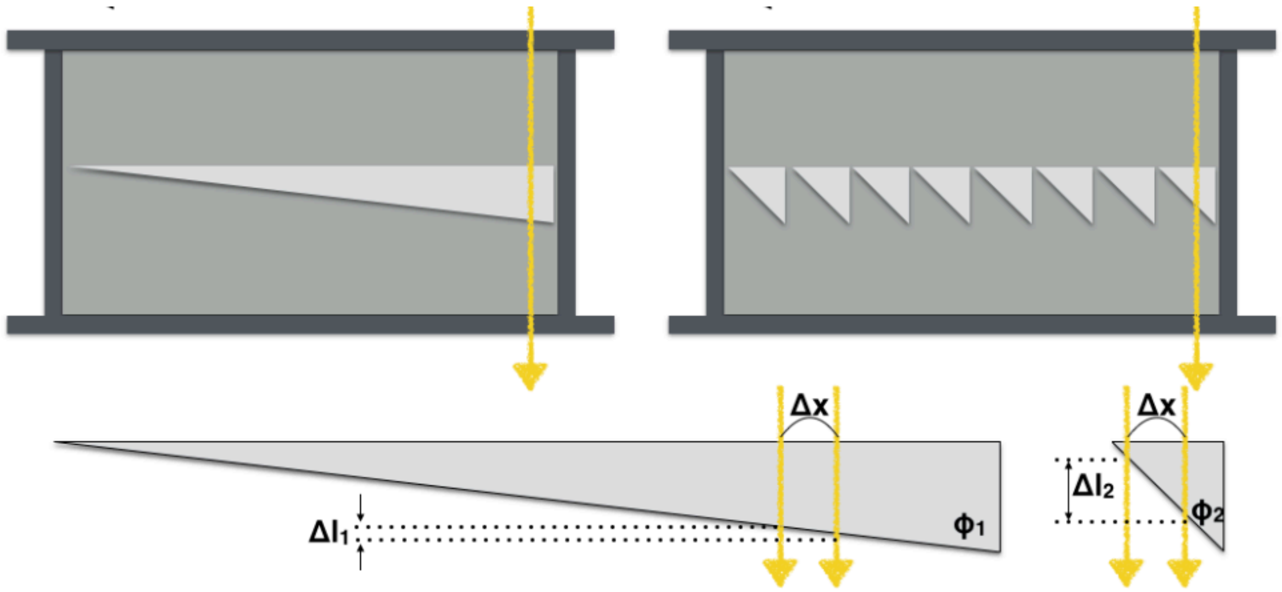


horizontal detection



vertical detection





$$\frac{\Delta x}{\Delta l} = \tan\phi$$

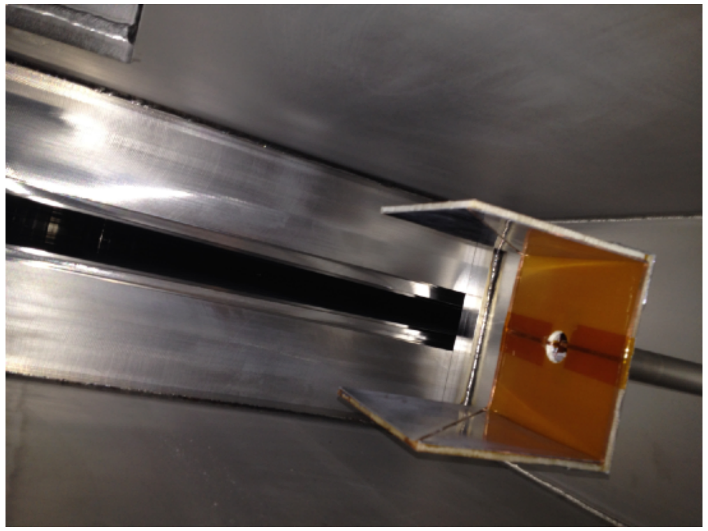
$$\Delta V \propto \frac{\Delta x}{\tan\phi}$$

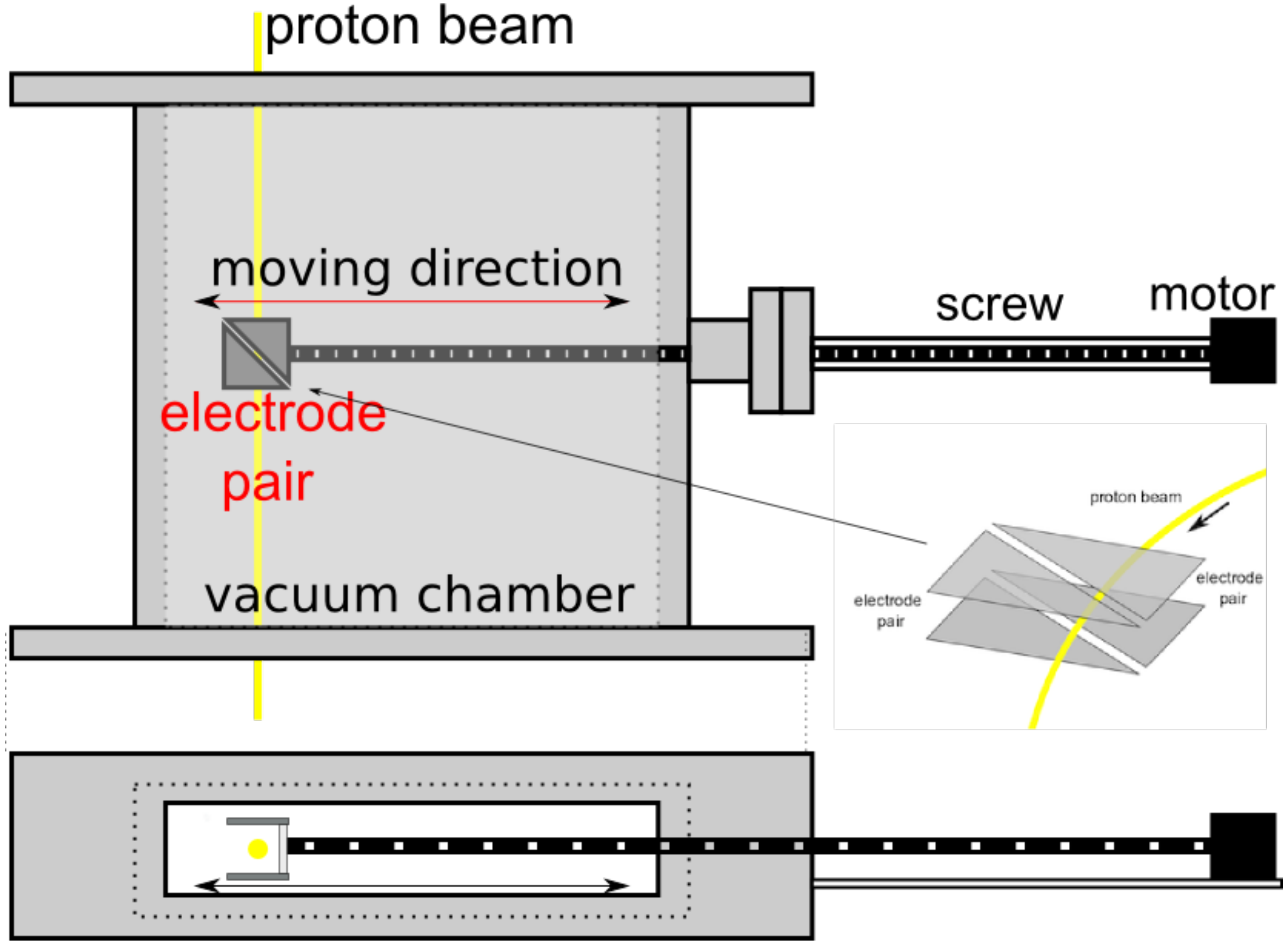
smaller ϕ : better resolution

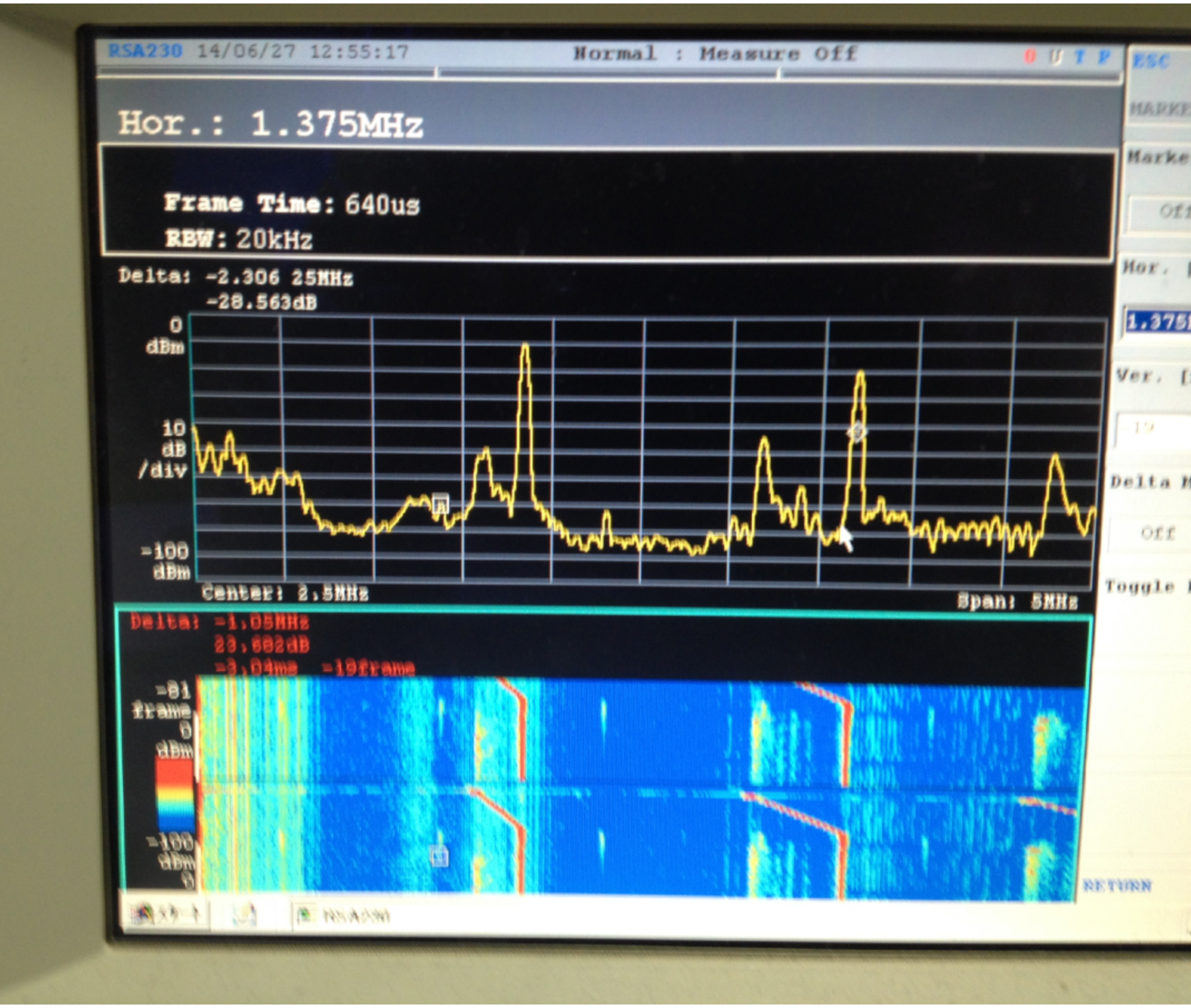
new horizontal detection system

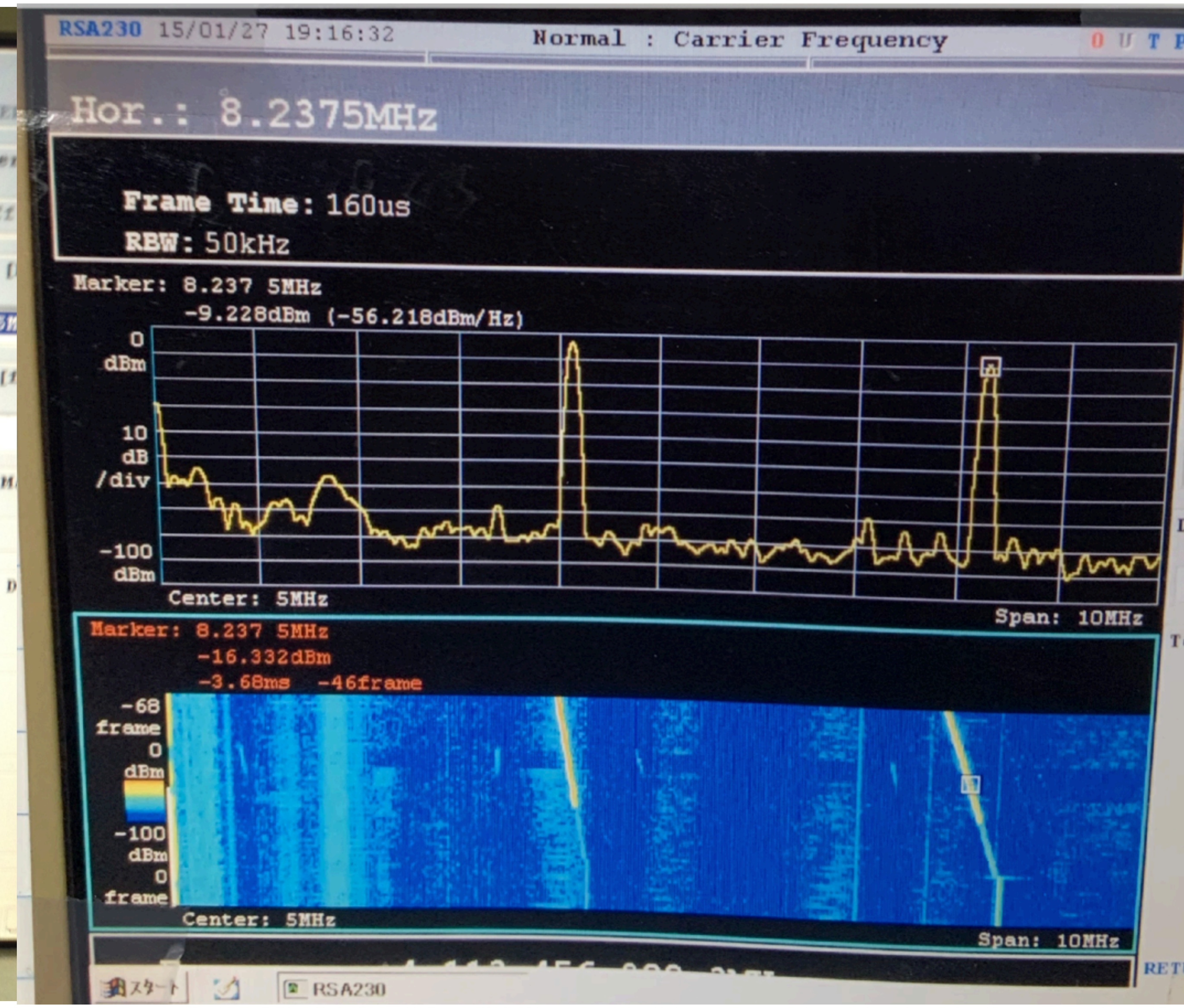
many amps and cables needed

single read out system

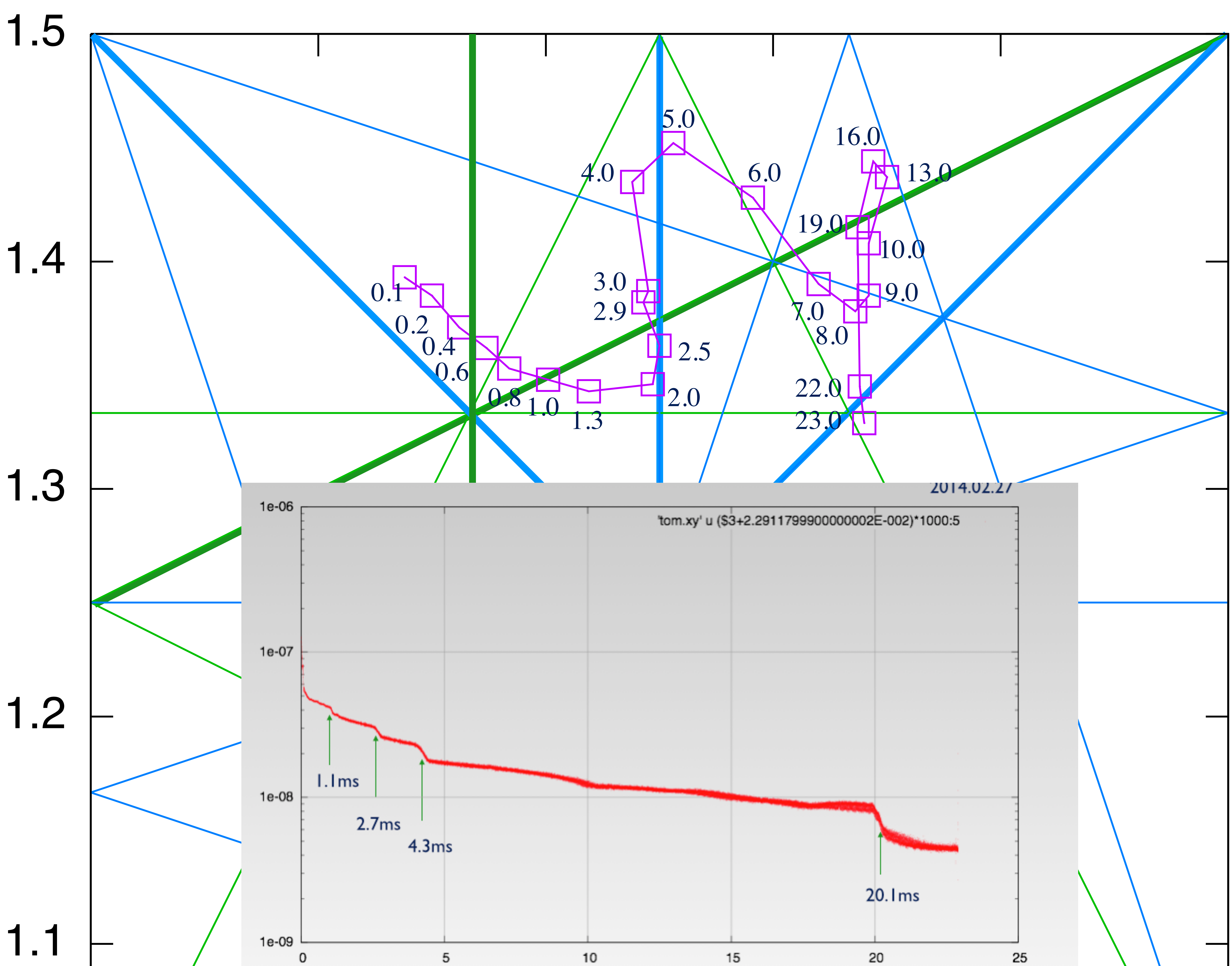








Real time spectrum analyzer

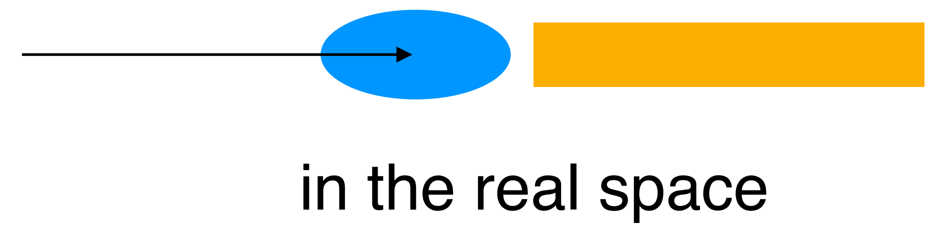

1.5
1.4
1.3
1.2
1.1
0.1
0.2
0.4
0.6
0.8
1.0
1.3
2.0
2.5
2.9
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
13.0
16.0
19.0
22.0
23.0
2014.02.27
'tom.xy' u ($3+2.2911799900000002E-002)*1000:5
1e-06
1e-07
1e-08
1e-09
0
5
10
15
20
25
1.1ms
2.7ms
4.3ms
20.1ms

Measurement of beam position using a movable prove

1. Flat top method
2. Acceleration method

1.Flat top method

The beam is accelerated up to e.g. 25 MeV
Circulating at the flat top by fixing the rf frequency
Insert the radial probe from the outside



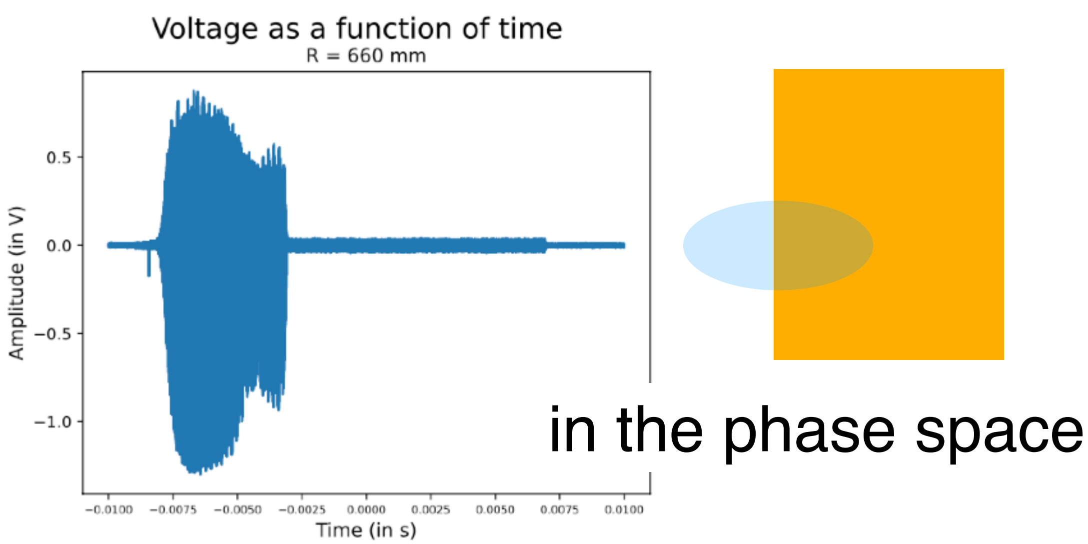


Figure 20: Fully inserted - 25 MeV

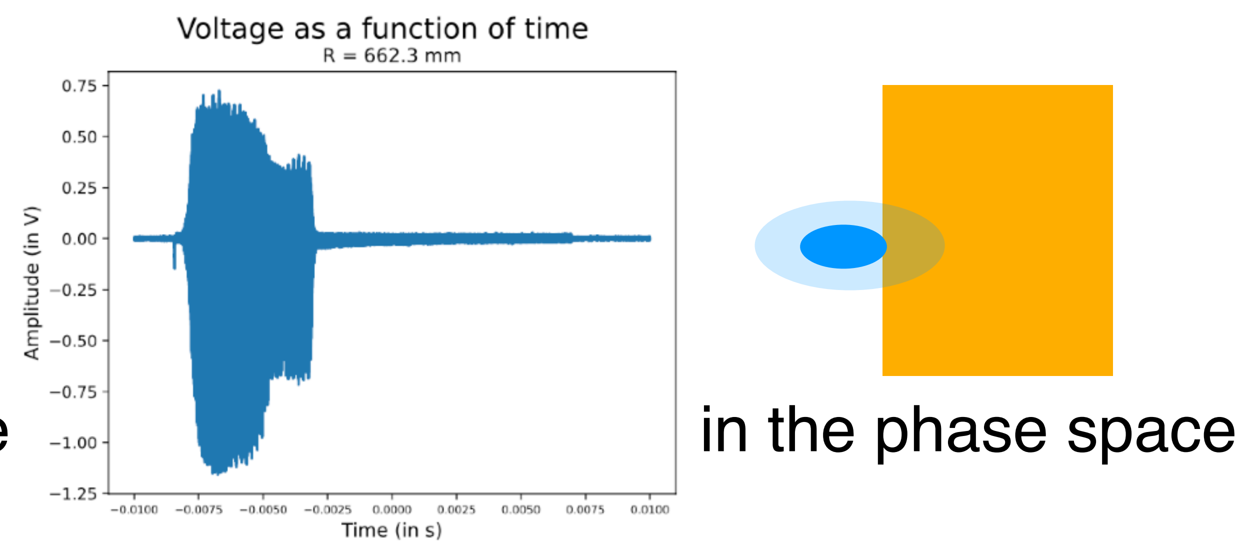


Figure 21: Three quarter inserted - 25 MeV

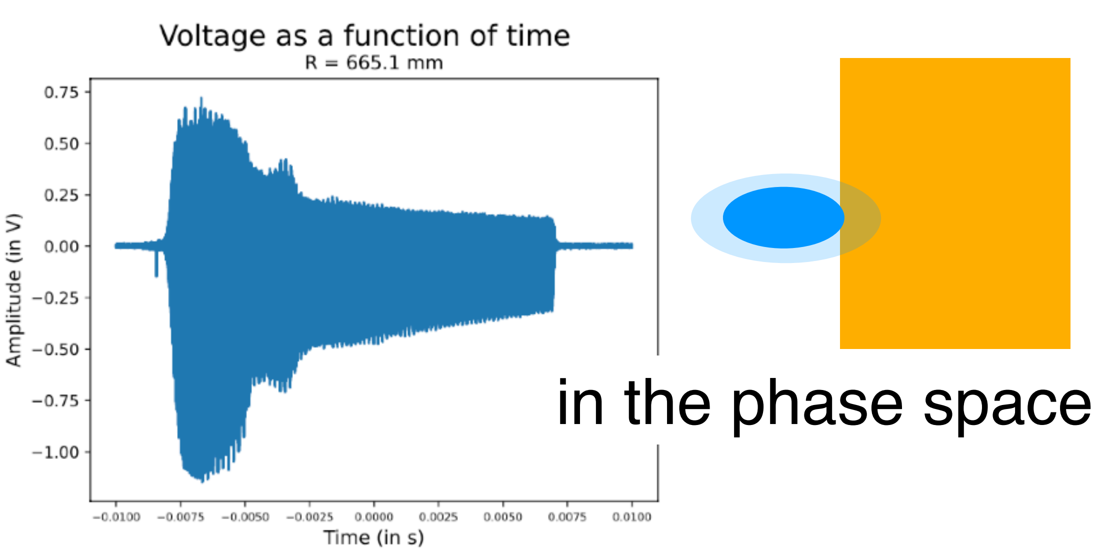


Figure 22: One quarter inserted - 25 MeV

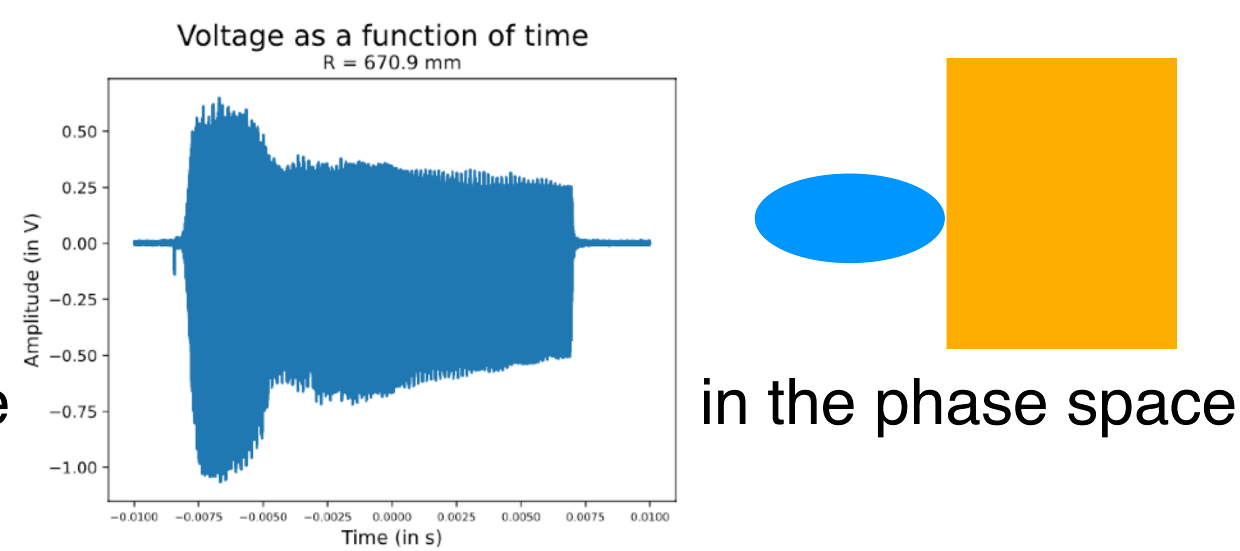
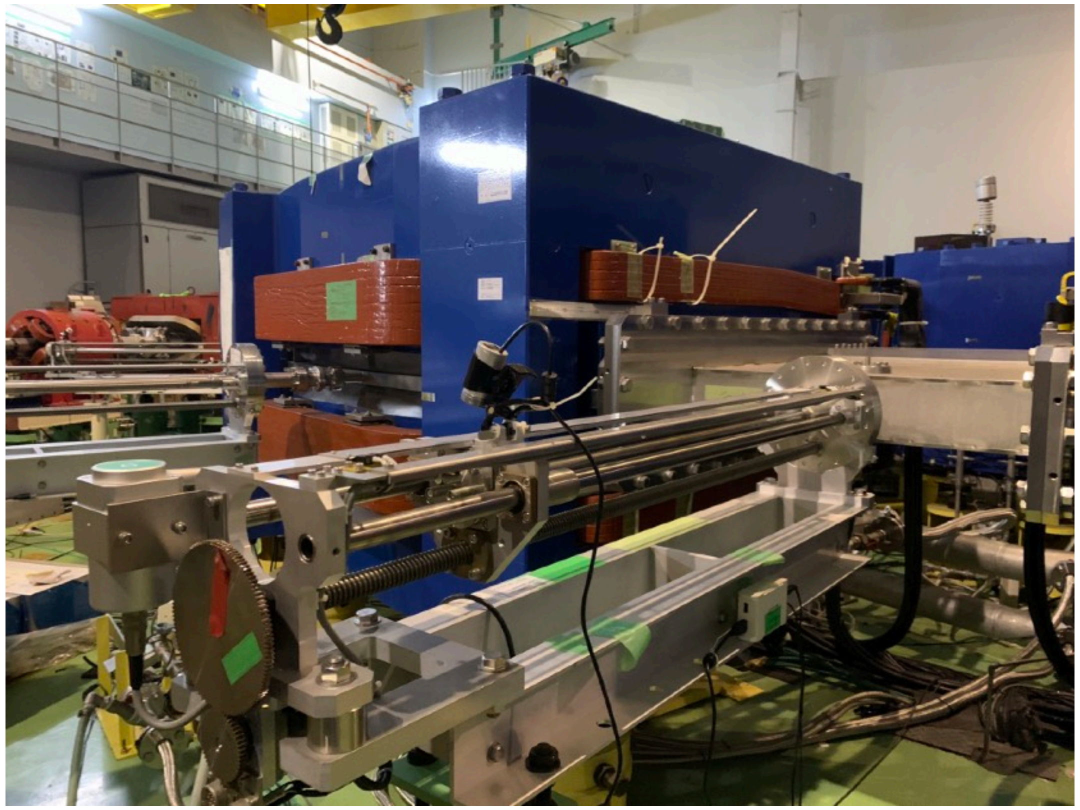
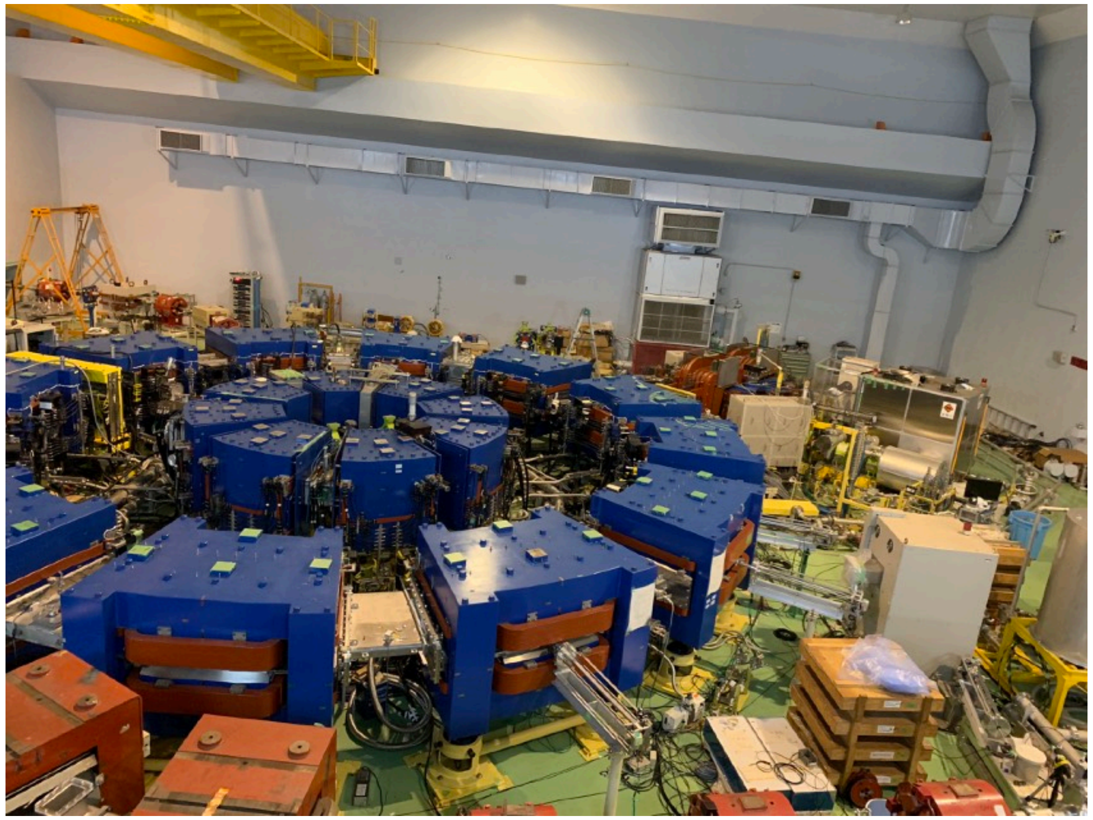
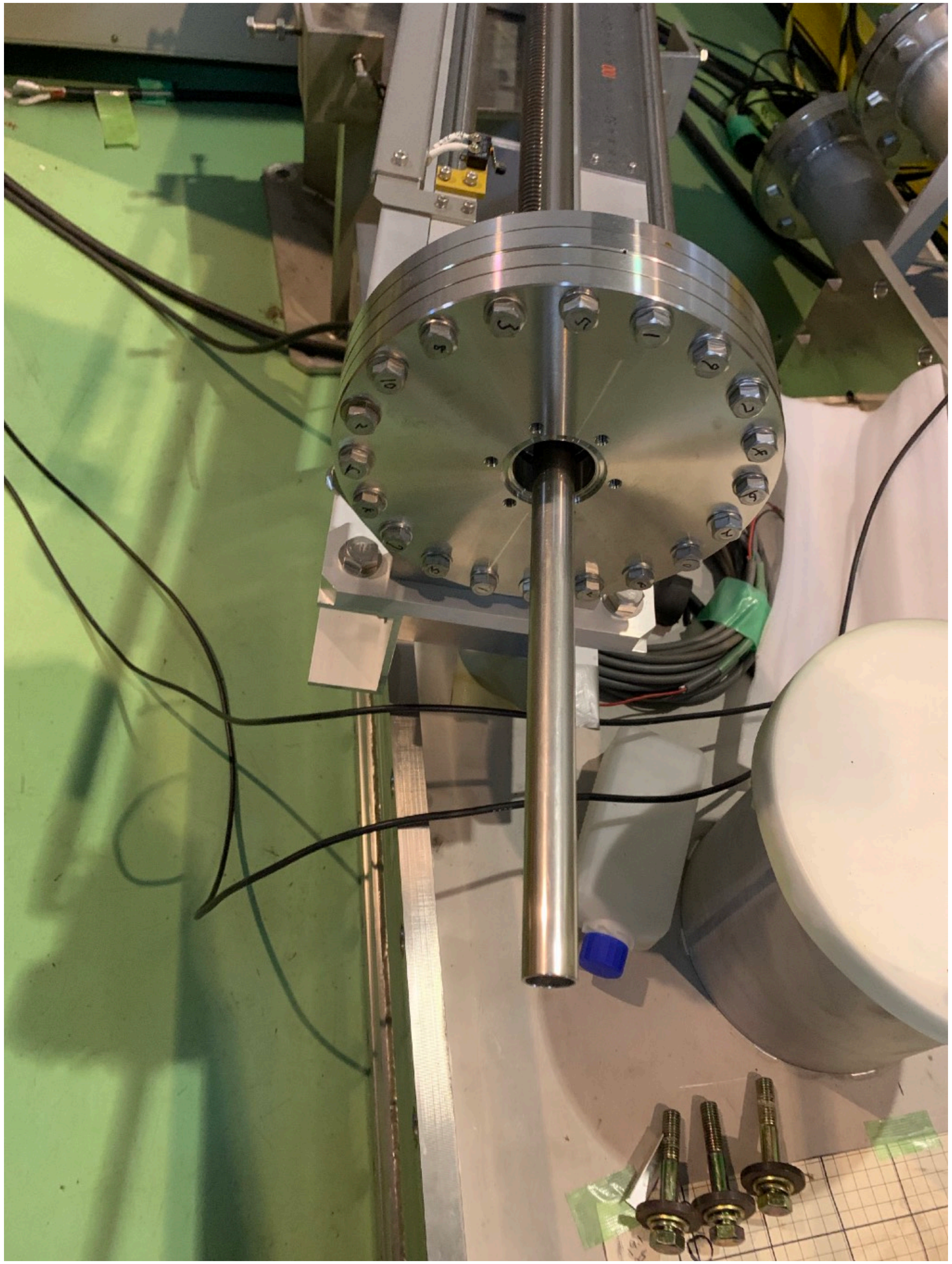


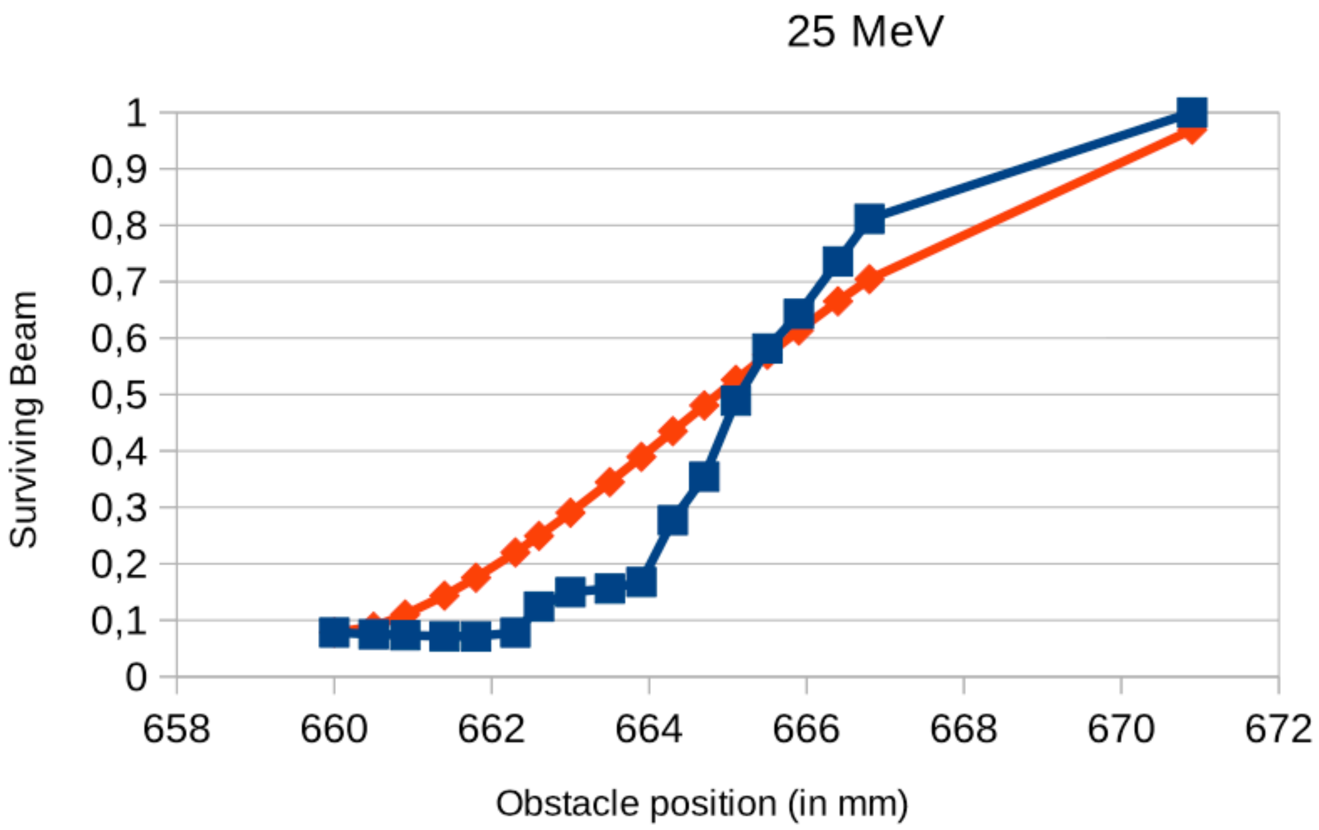
Figure 23: Removed - 25 MeV



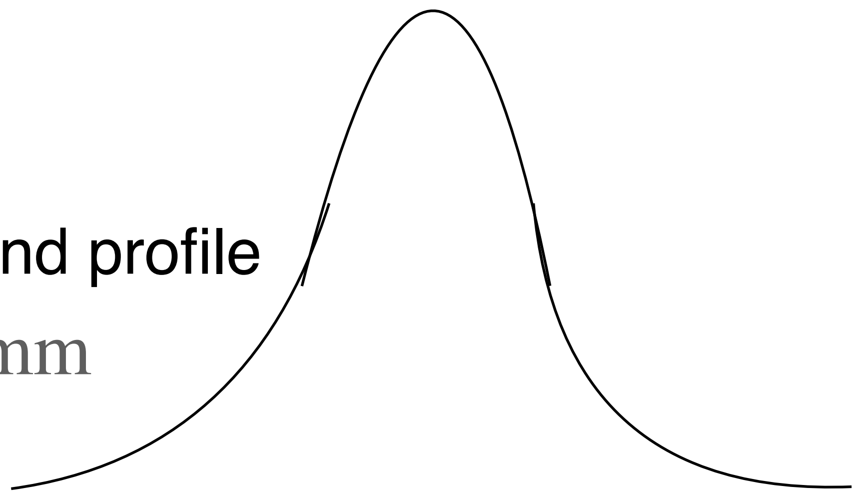




Surviving Beam	
Position in mm	**Surviving beam ξ**
660	7,83 %
662.6	12.41 %
663.5	15.60 %
664.3	27.71 %
665.1	48.89 %
665.9	64.30 %
666.8	81.15 %
670.9	100 %



differentiation of blue curve



obtain beam position and profile

$\sigma = 5$ mm

2.Acceleration method

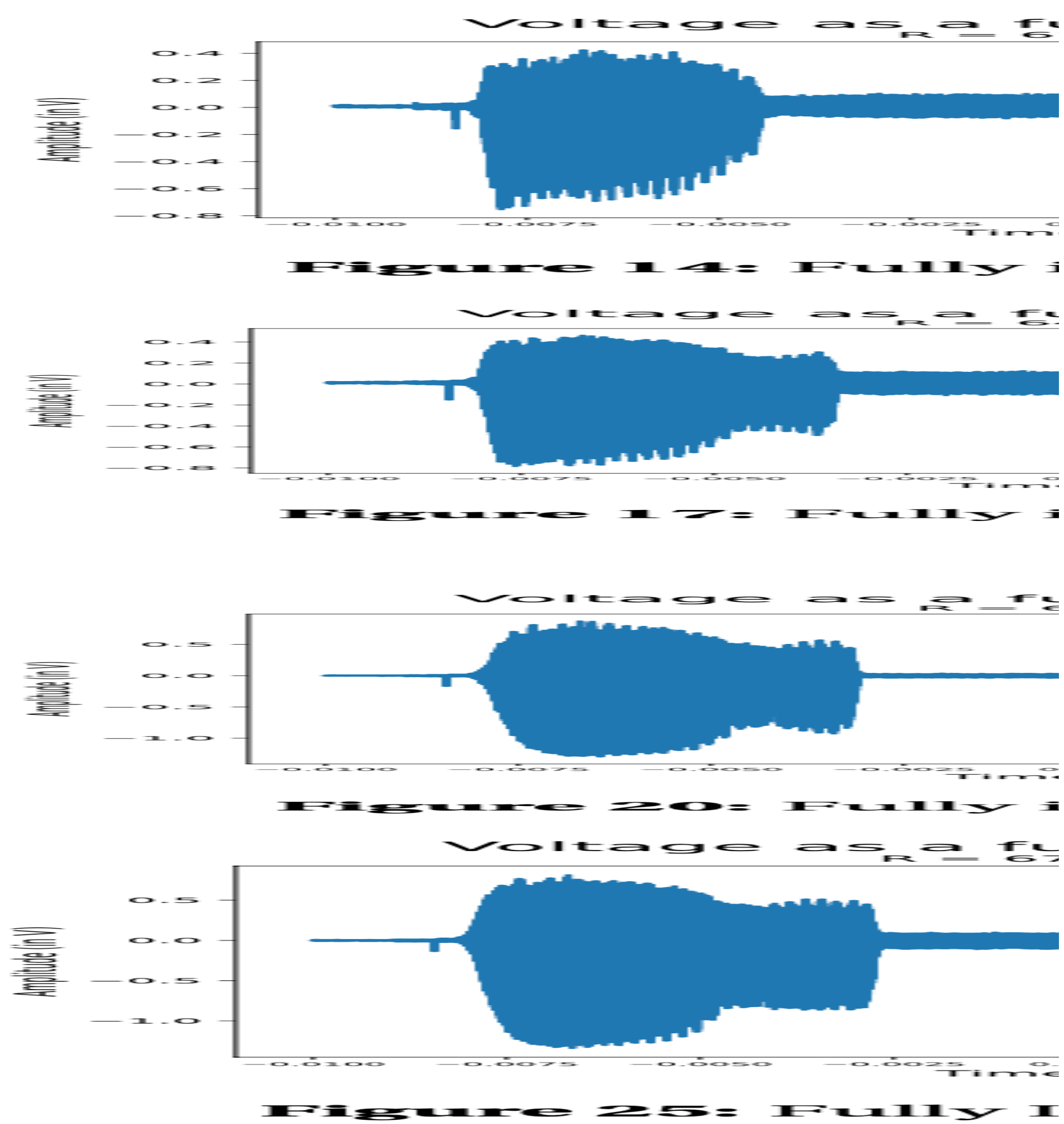
The beam is accelerated up to the final energy

Changing the probe position, measure the beam loss timing

It tells the momentum compaction $\alpha(r)$ and flattens of the k

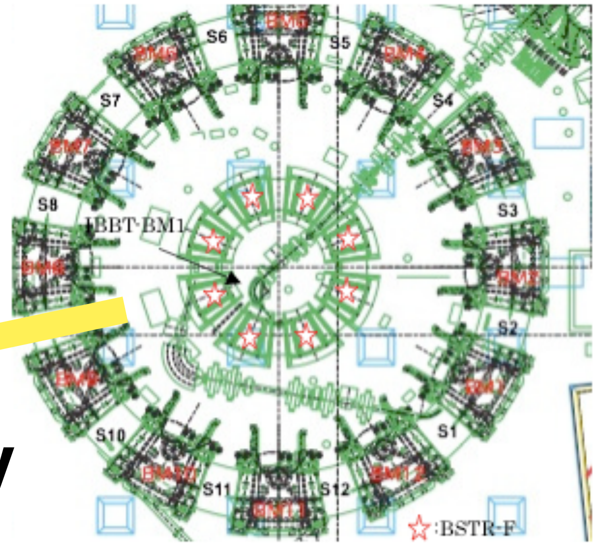
$$\frac{p}{p_0} = \left(\frac{r}{r_0}\right)^{k+1}$$

$$\frac{\Delta p}{p} = \frac{1}{k+1}\frac{\Delta r}{r}$$

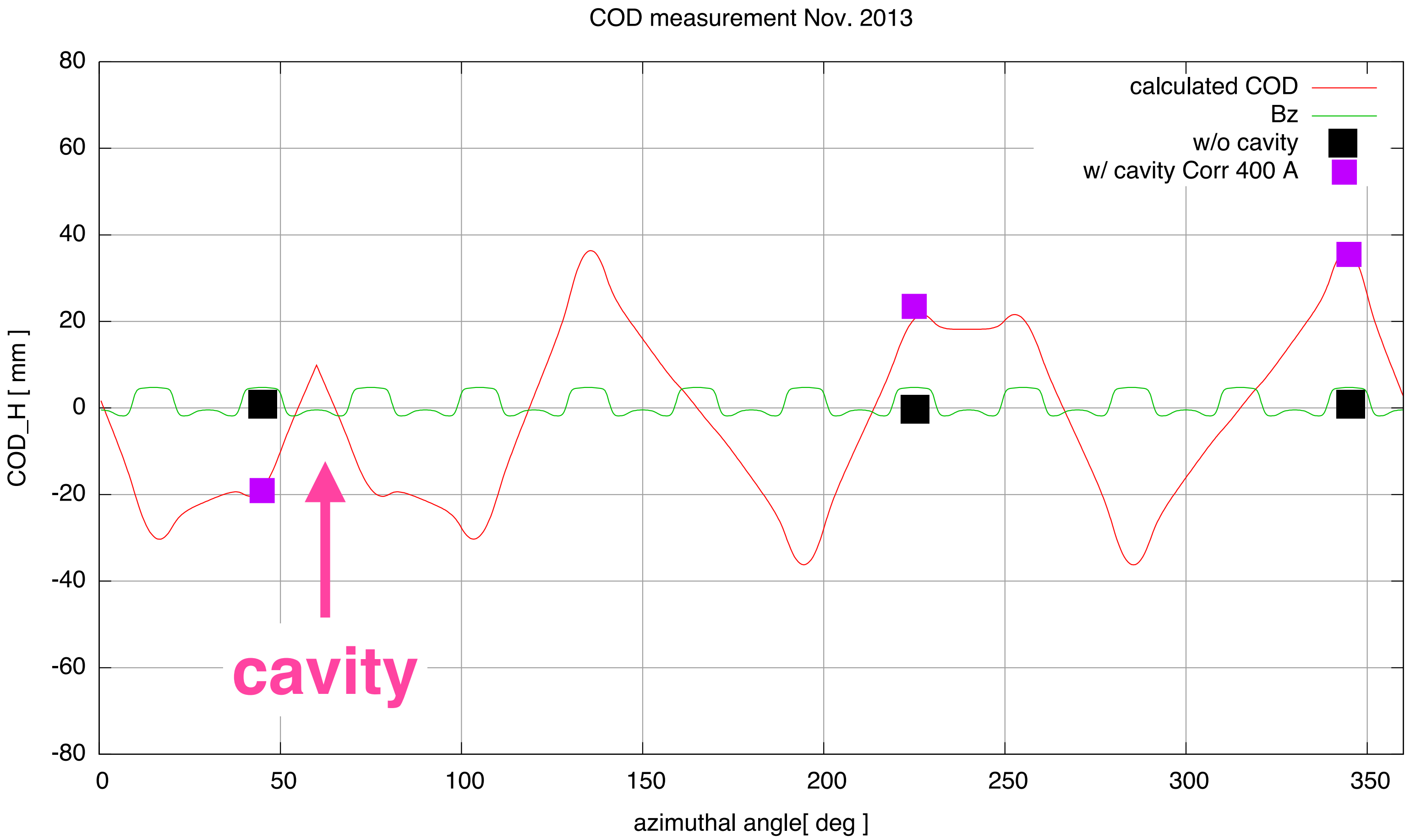


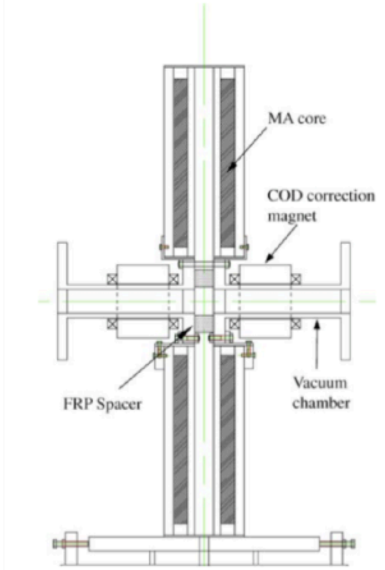
COD measurement

position measurement at the different sections gives information about the COD

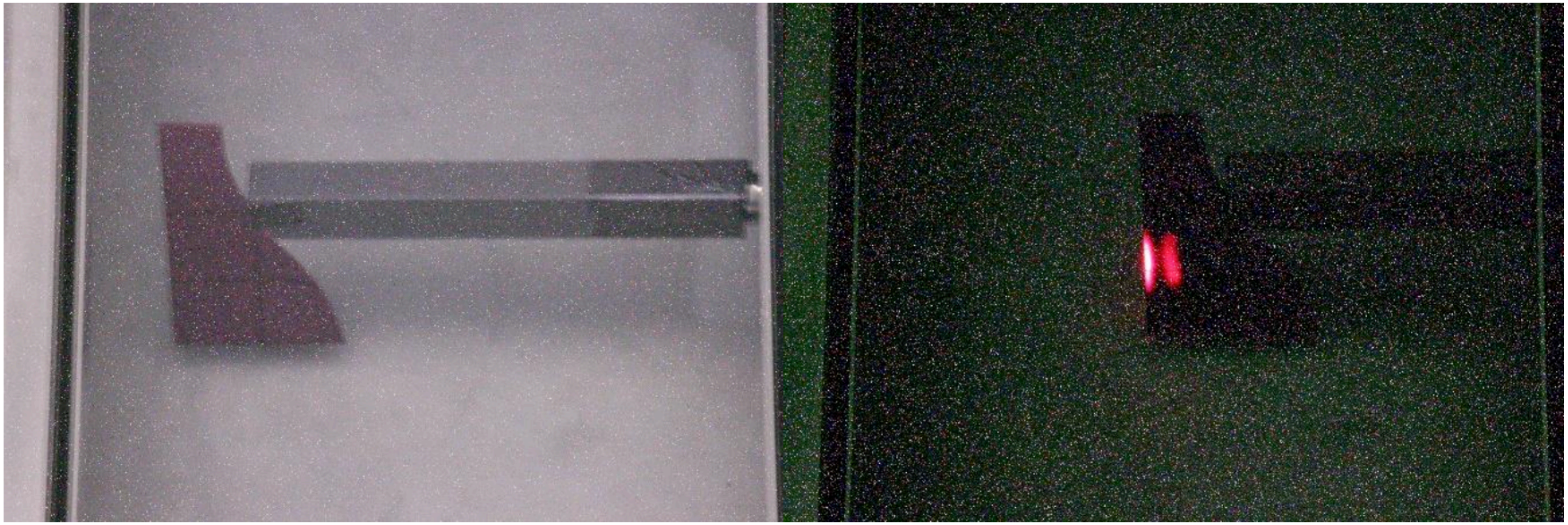


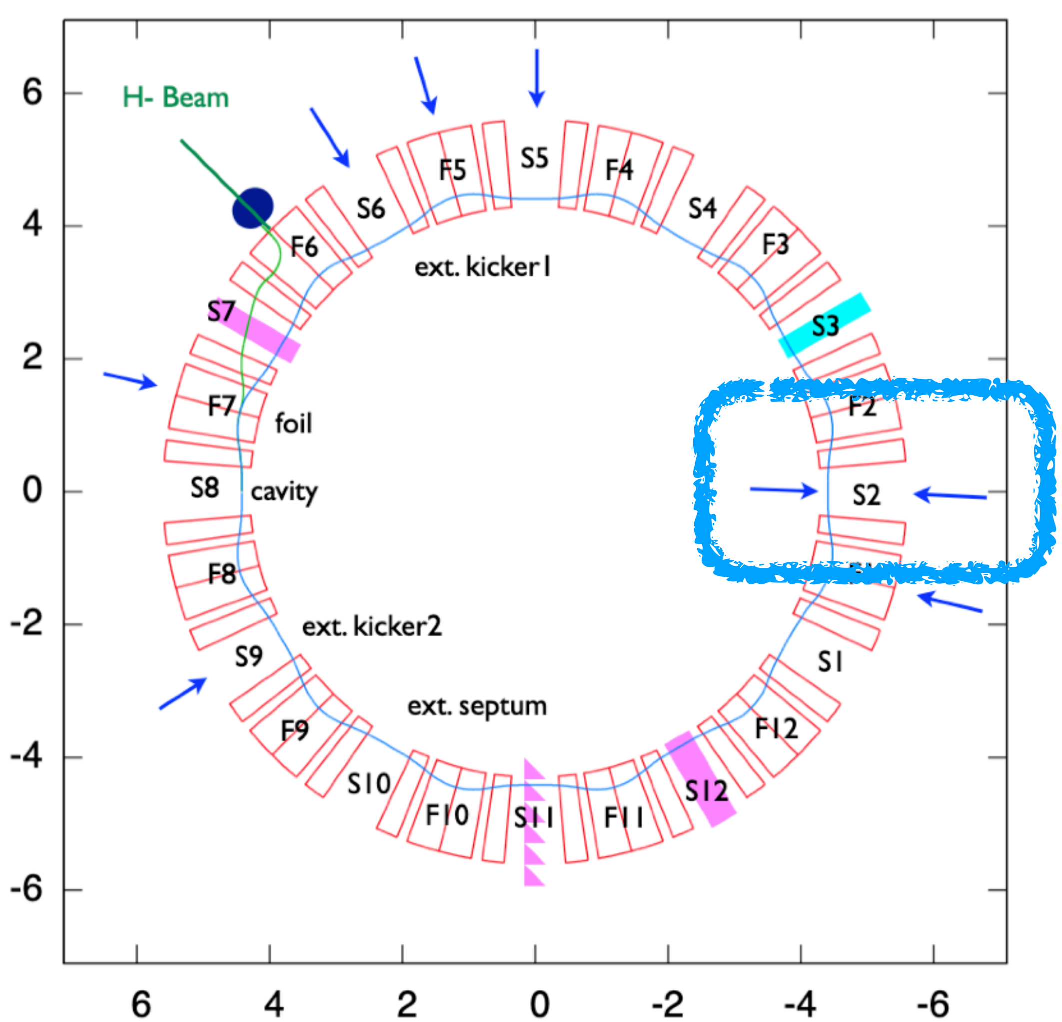
cavity



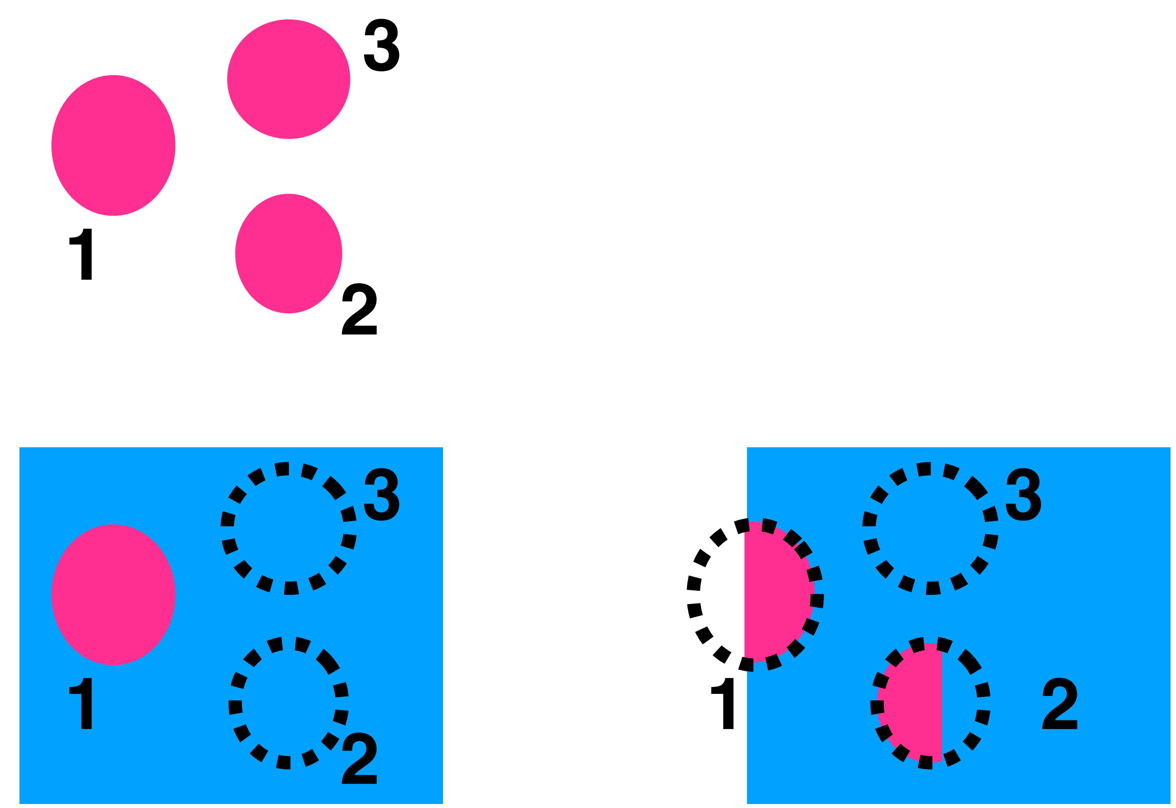


Leakage field in the straight section is absorbed by the cavity. Therefore, an apparent kick appears in the straight section.

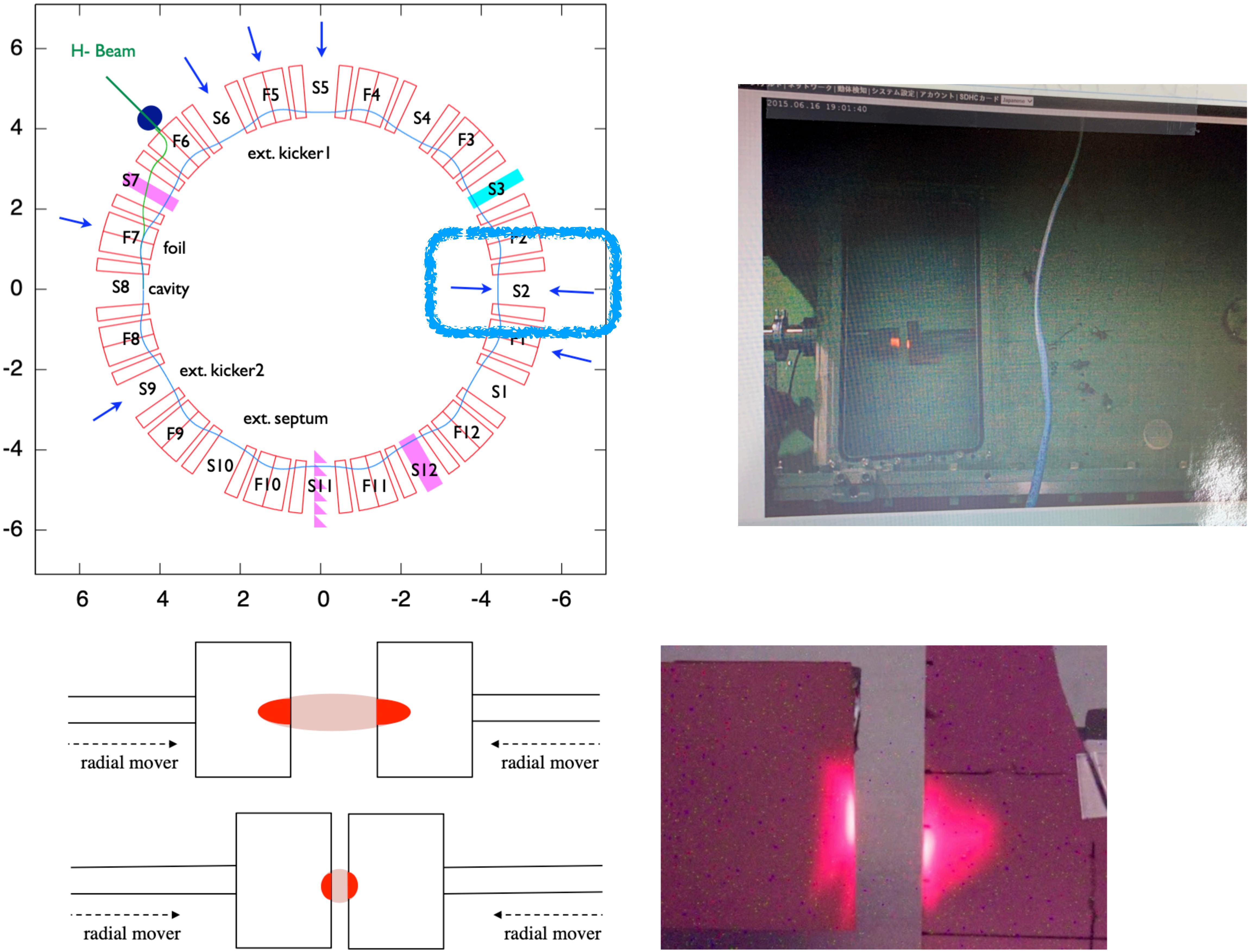



H- Beam
F5
S5
F4
S6
S4
F6
F3
ext. kicker1
S7
S3
F7
foil
F2
S8
cavity
S2
F8
ext. kicker2
S9
S1
ext. septum
F9
F12
S10
F10
S11
F11
S12
6
4
2
0
-2
-4
-6

phase space

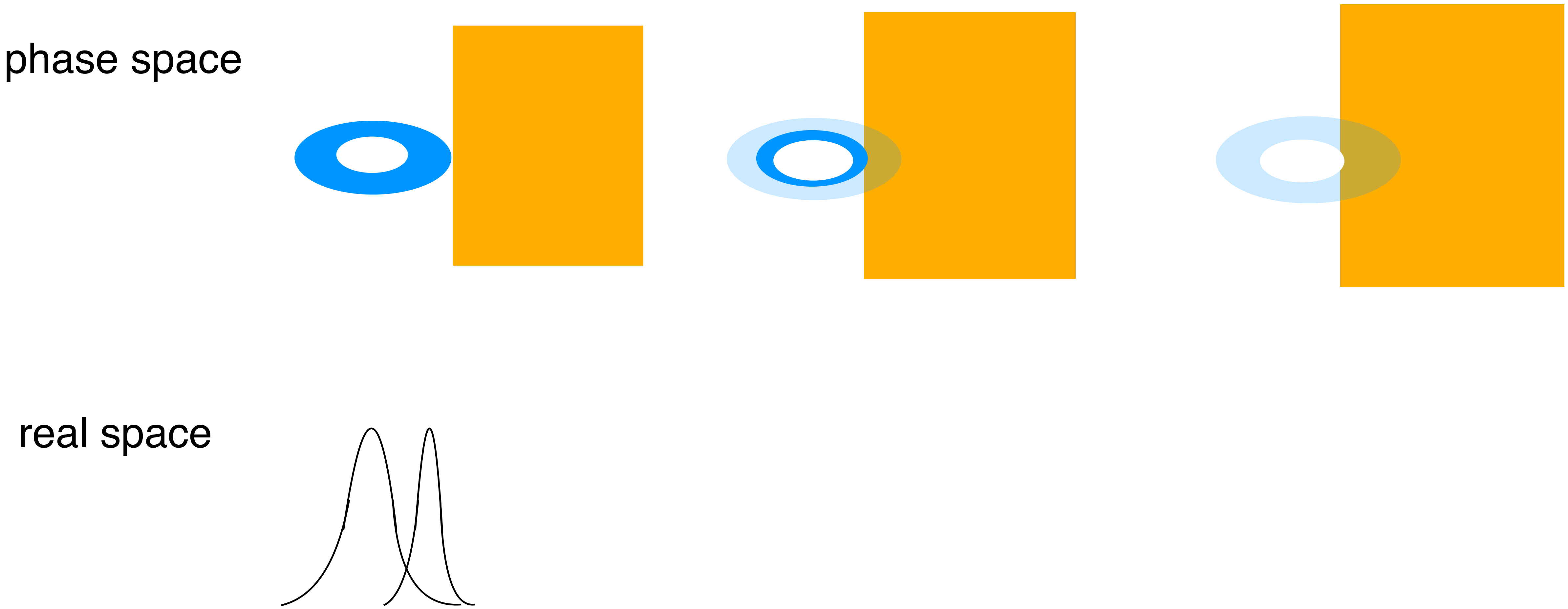

1
2
3
1
2
3
1
2
3

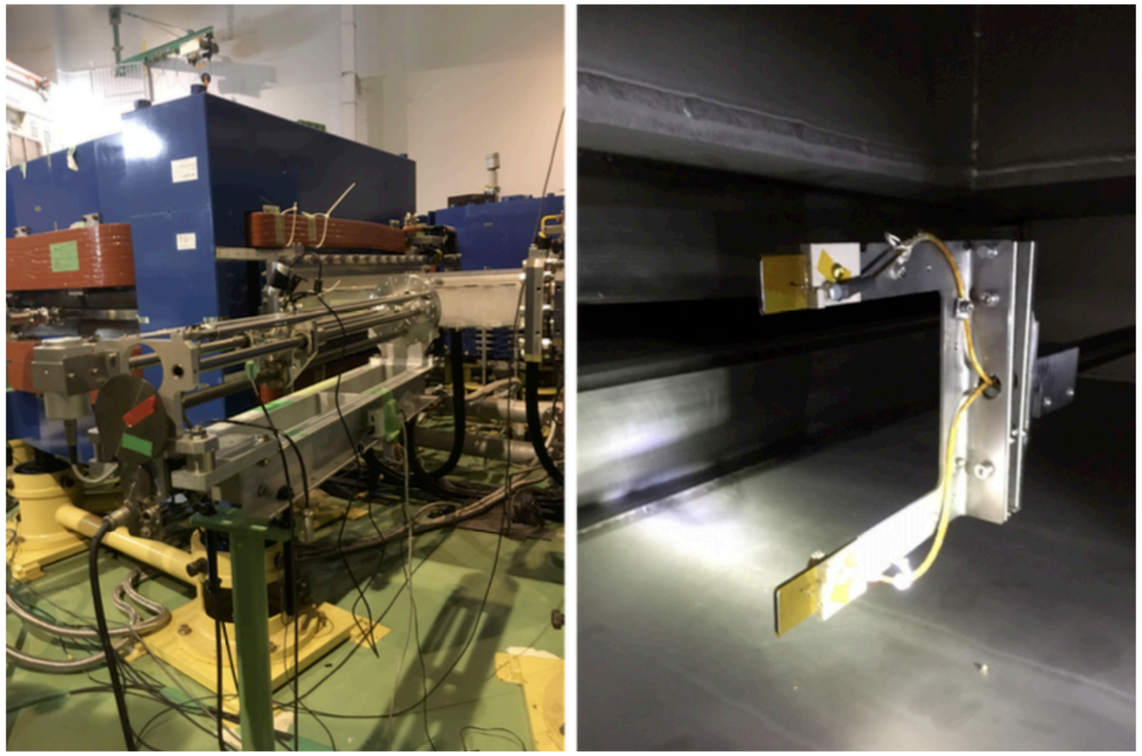
Beam profile

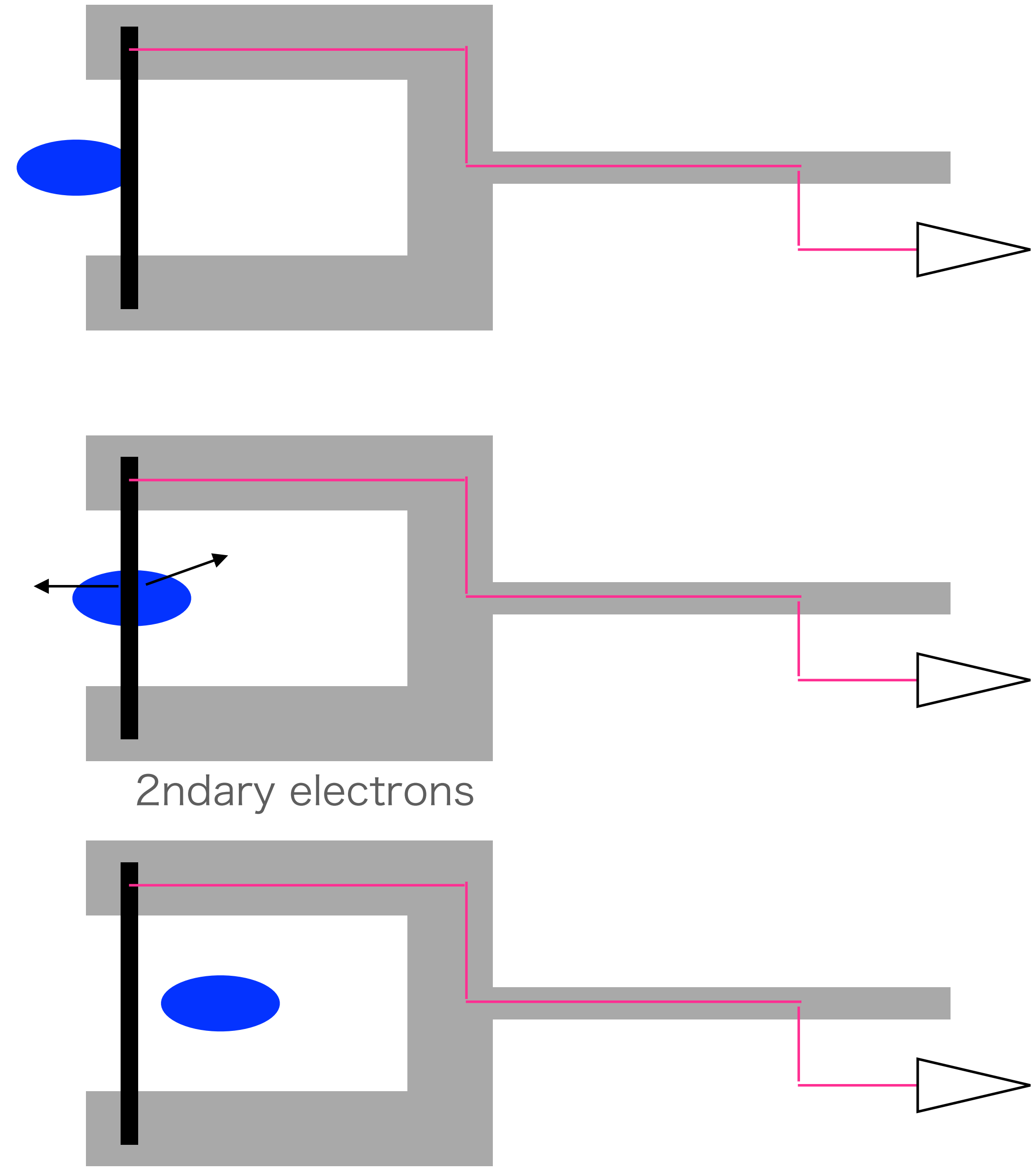

H- Beam
S5
F5
F4
S6
S4
F6
F3
ext. kicker1
S7
S3
F2
F7
foil
S2
S8
cavity
F1
F8
ext. kicker2
S1
S9
ext. septum
F9
F12
S10
F10
S11
F11
S12
6
4
2
0
-2
-4
-6
2015.06.16 19:01:40
radial mover
radial mover
radial mover
radial mover

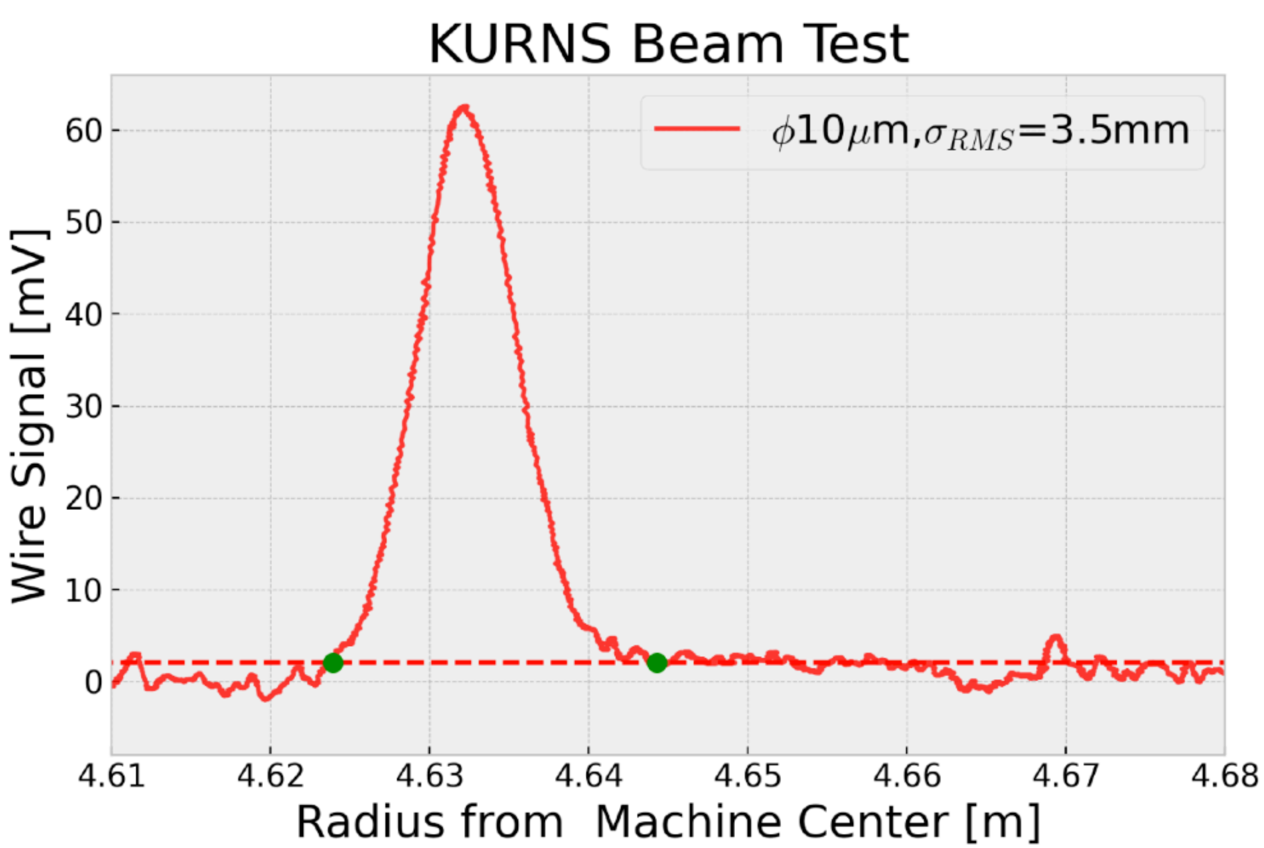
(a) (b)

For a hollow beam, beam profile in the real space cannot be reconstructed by using radial probe intercepting method







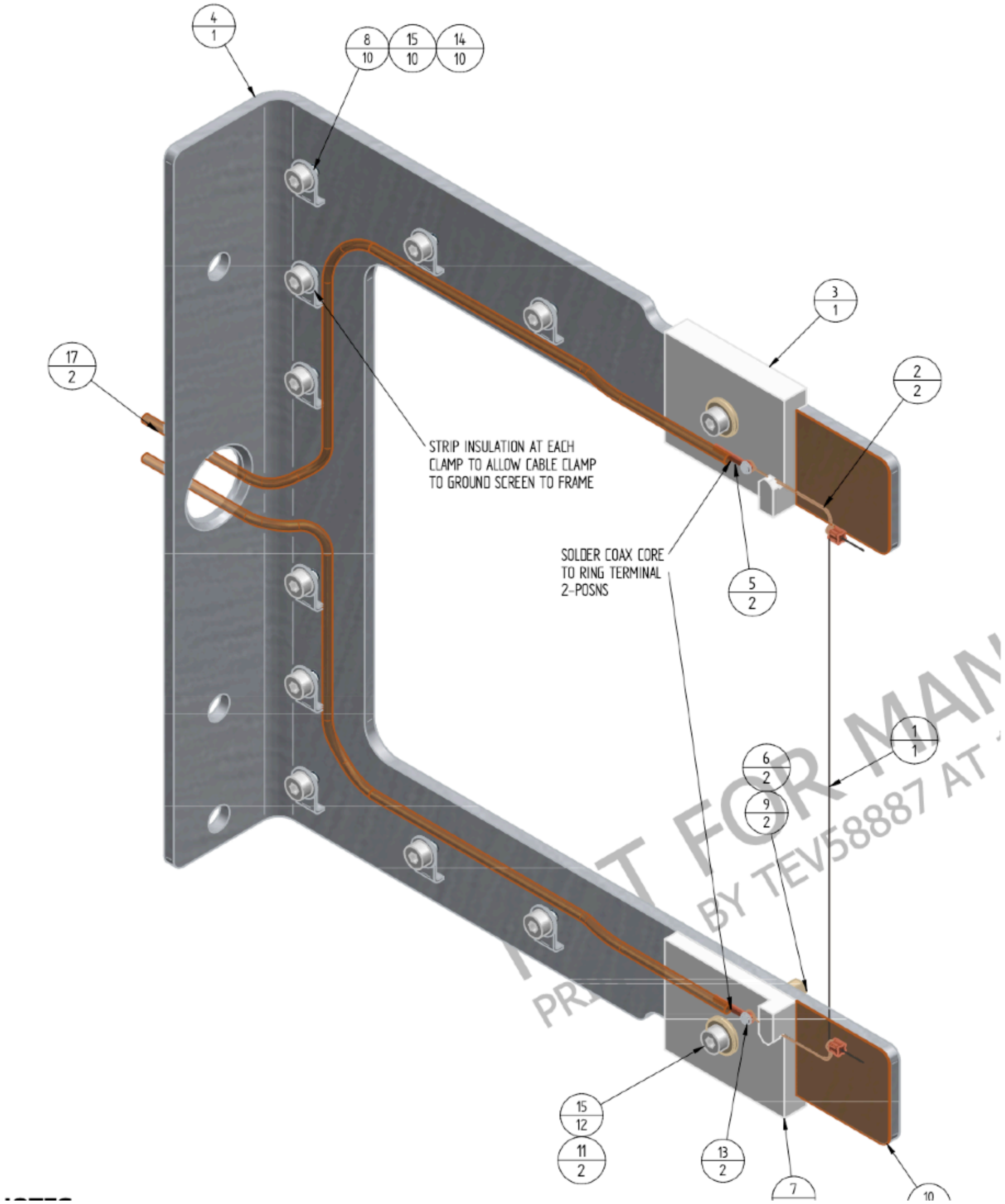


wire is fixed

beam moves as turn separation of 64.2 um

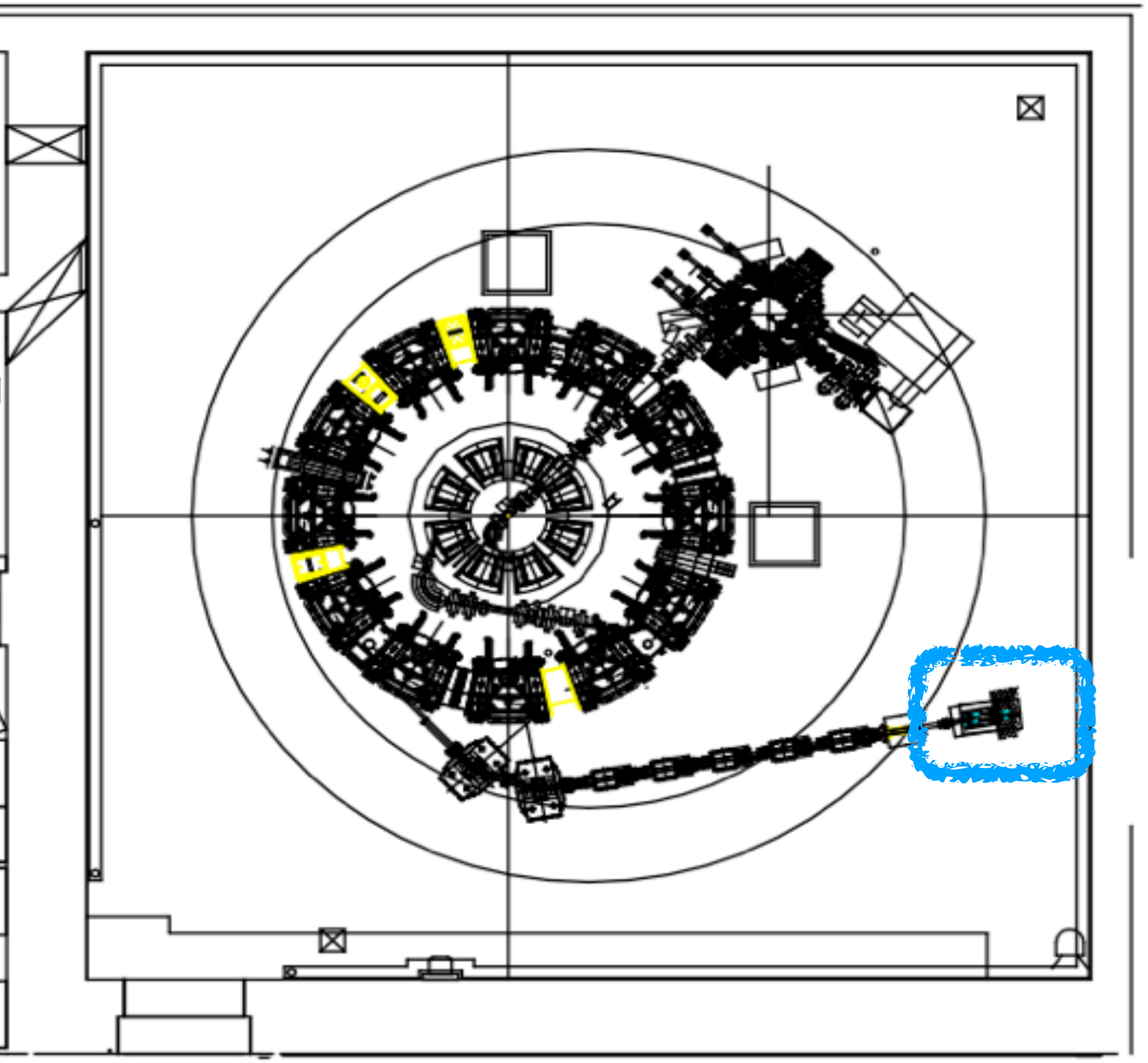
wire diameter 10 um

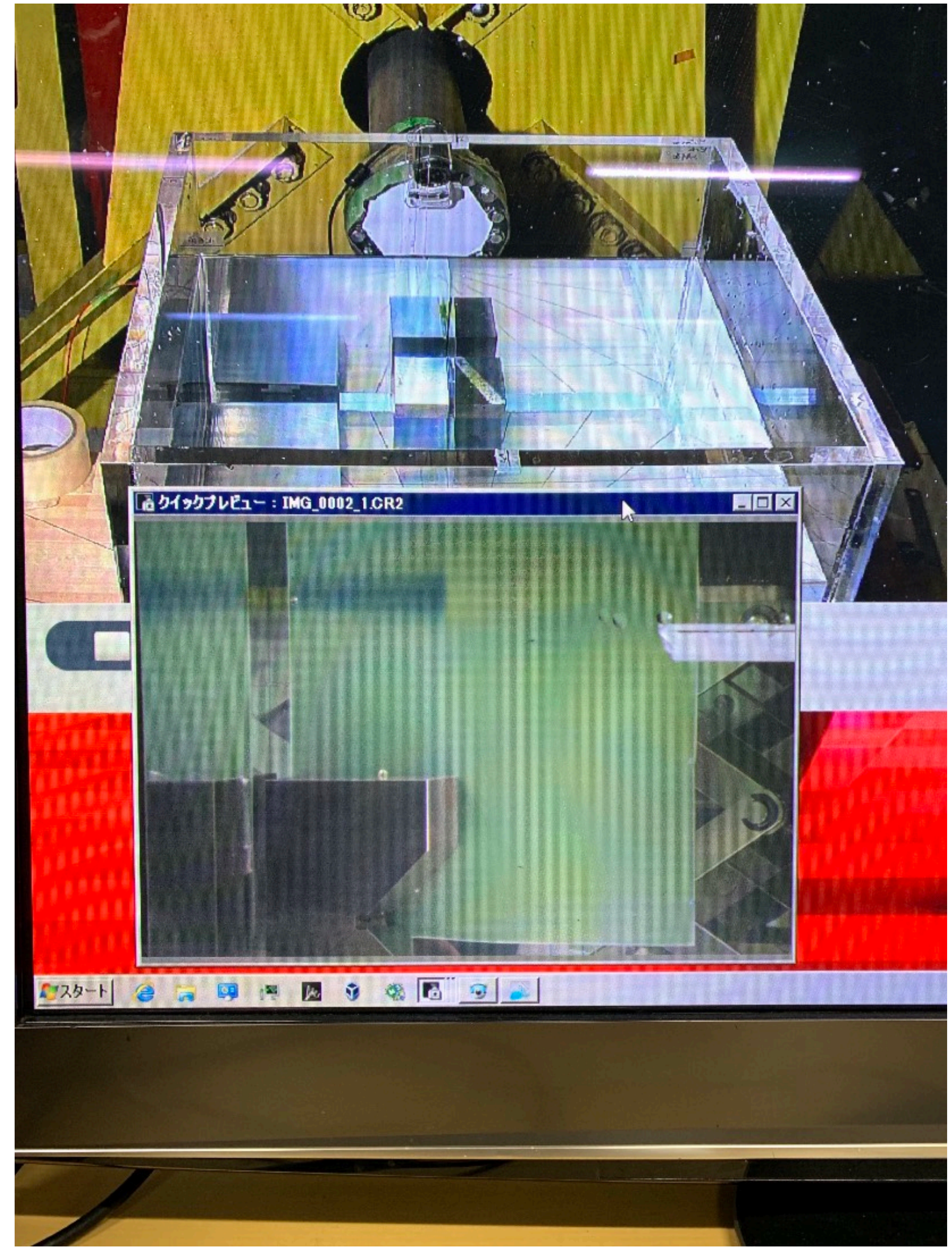
turn separation >> wire diameter



STRIP INSULATION AT EACH
CLAMP TO ALLOW CABLE CLAMP
TO GROUND SCREEN TO FRAME
SOLDER COAX CORE
TO RING TERMINAL
2-POSNS
4/1
8/10
15/10
14/10
3/1
2/2
17/2
5/2
1/1
6/2
9/2
15/12
11/2
13/2
7
10

Extracted beam





Direct observation of a Bragg curve using a gafchromic film at the medical irradiation experiments collaborated with Hokkaido Univ.