FFAG加速器ビーム増強
現状と今度の展開

京大炉におけるビーム利用のための次期中性子源検討 2

2014.1.17

京大原子炉　石　禎浩
森　義治
上杉智教
栗山靖敏
阪本雅昭

目次

1.FFAGの特徴

2.FFAG加速器システム開発の経緯

3.現在の利用状況

4.ビームスタディー結果

5.ビーム増強

6.FFAG加速器の今後の展開（加速器中性子源）

7.まとめ

FFAG: Fixed Field Alternating Gradient

- 固定磁場（時間変化しない）

サイクロトロン的であるが、軌道の広がりは小さい

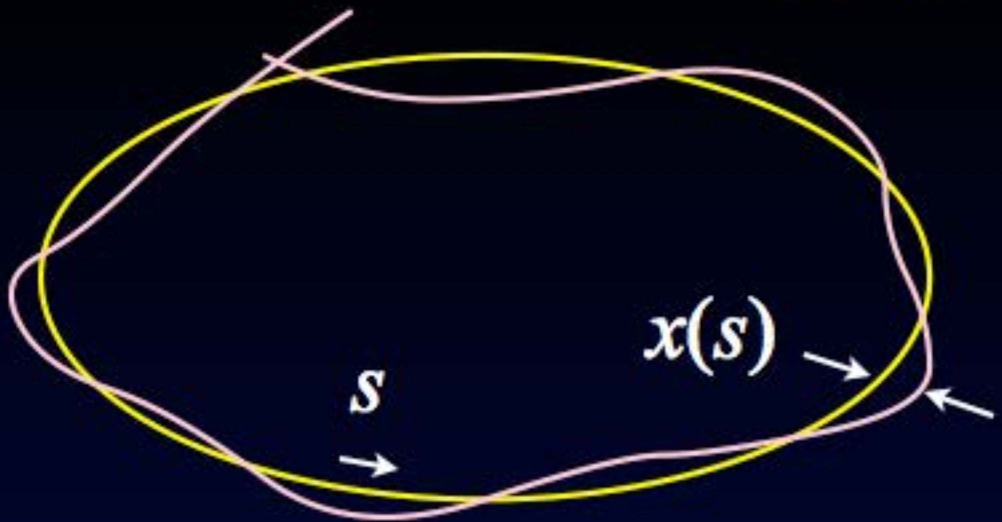
$$B(r) = B(r_0)\left(\frac{r}{r_0}\right)^k$$

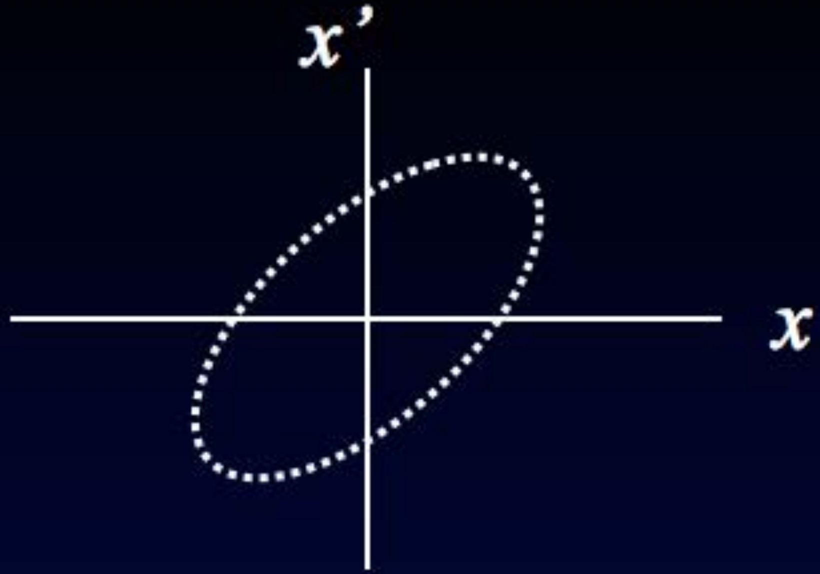
  - 速い加速が可能
    - 磁場と*RF*の同期が不要
  - 高繰り返しが可能
    - 一度に加速する粒子数を減らす事が可能
    - 空間電荷効果やその他の不安定性を軽減
- 交互勾配ー強収束 (6D-focusing i.e. x, px, y, py, s, ps)

シンクロトロン的

  - コンパクトサイズの電磁石
  - 高エネルギーでの収束が安定
  - さまざまな RF gymnasticsが可能
    - *Bunching, Stacking etc.*

ベータトロン振動





$$x'' + K_x(s)x = 0$$

$$y'' + K_y(s)y = 0$$

Hill's equation

$$x(s) = \sqrt{\epsilon_x \beta_x(s)} \cos\left(\psi_x(s) + \delta_x\right)$$

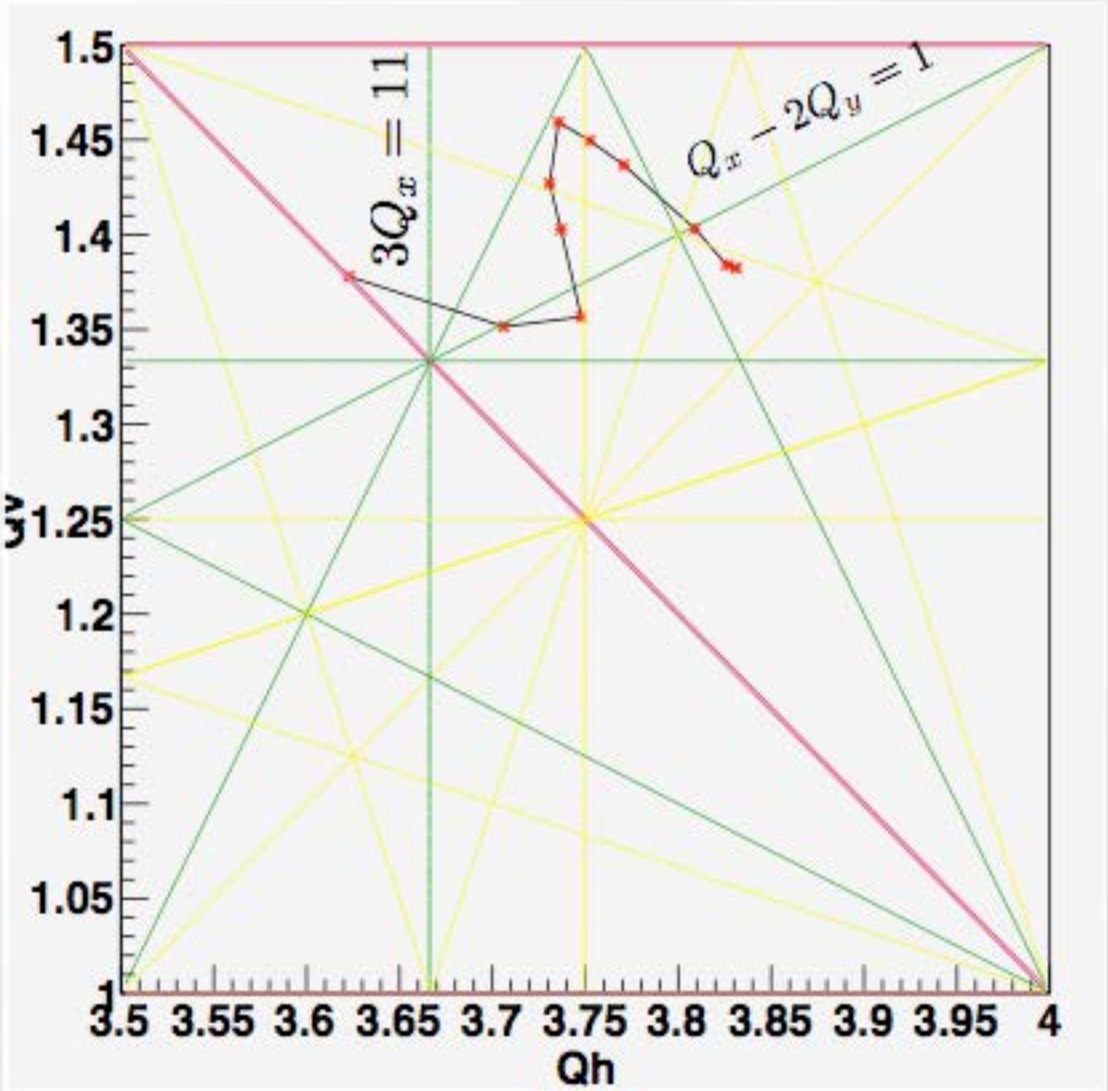
$$y(s) = \sqrt{\epsilon_y \beta_y(s)} \cos\left(\psi_y(s) + \delta_y\right)$$

$$\Delta\psi(s_1 \rightarrow s_2) = \int_{s_1}^{s_2} \frac{1}{\beta(s)} ds$$

$$\nu_{x,y} = \frac{1}{2\pi} \oint \frac{1}{\beta_{x,y}(s)} ds$$

$$l\nu_x + m\nu_y = n$$

横方向（ベータトロン振動）の共鳴によるロスを低減する



$$lQ_h + mQ_v = n$$

$|l| + |m|$ 共鳴の次数

n ハーモーニクス

リングの対称性を上げる

→COD*補正

共鳴線通過時間を短くする→

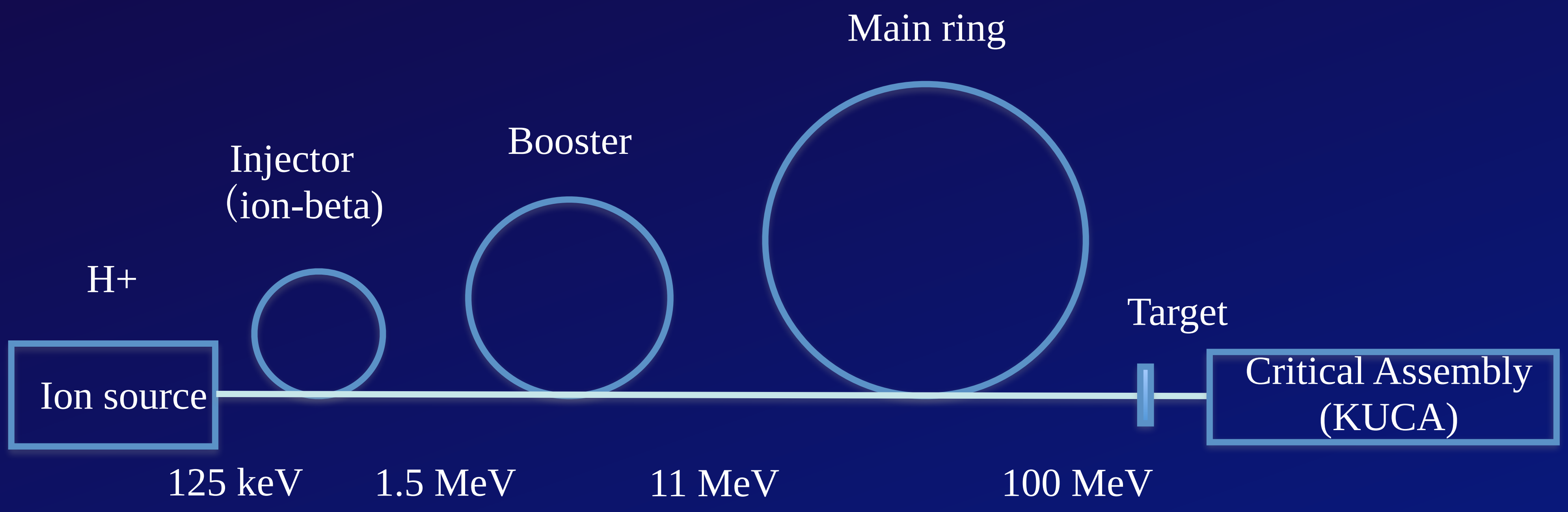
加速時間の短縮

（加速電圧強化が必要）

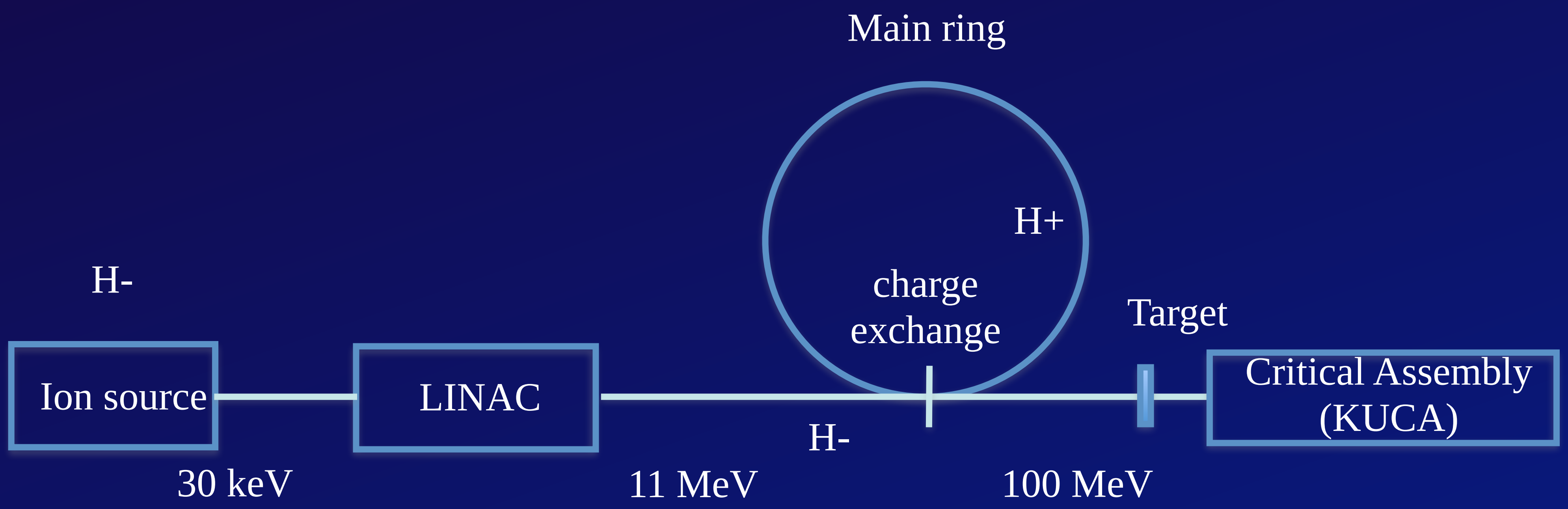
おまけ（繰り返しが上がる）

*COD (Closed Orbit Distortion)

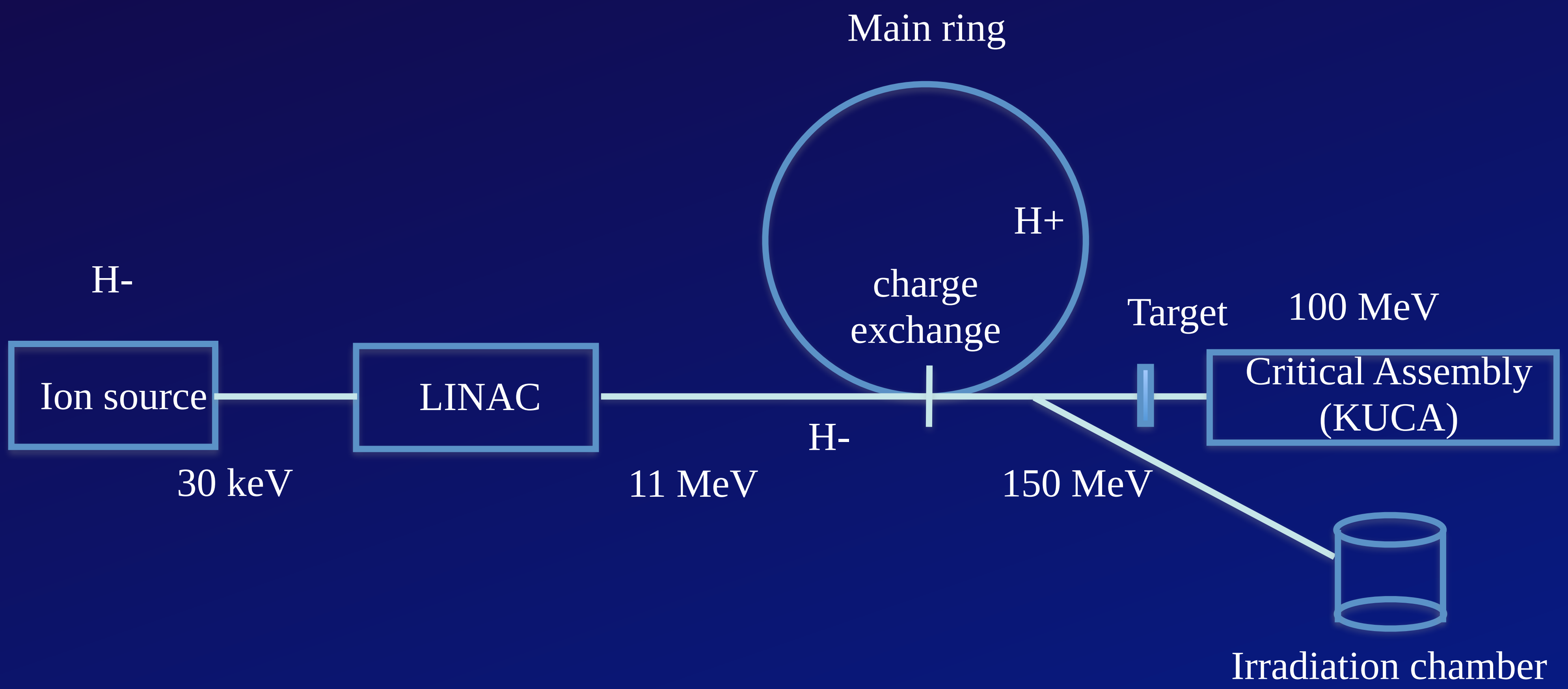
FFAG – KUCA ADS system
schematic diagram (original) 2008 - 2010



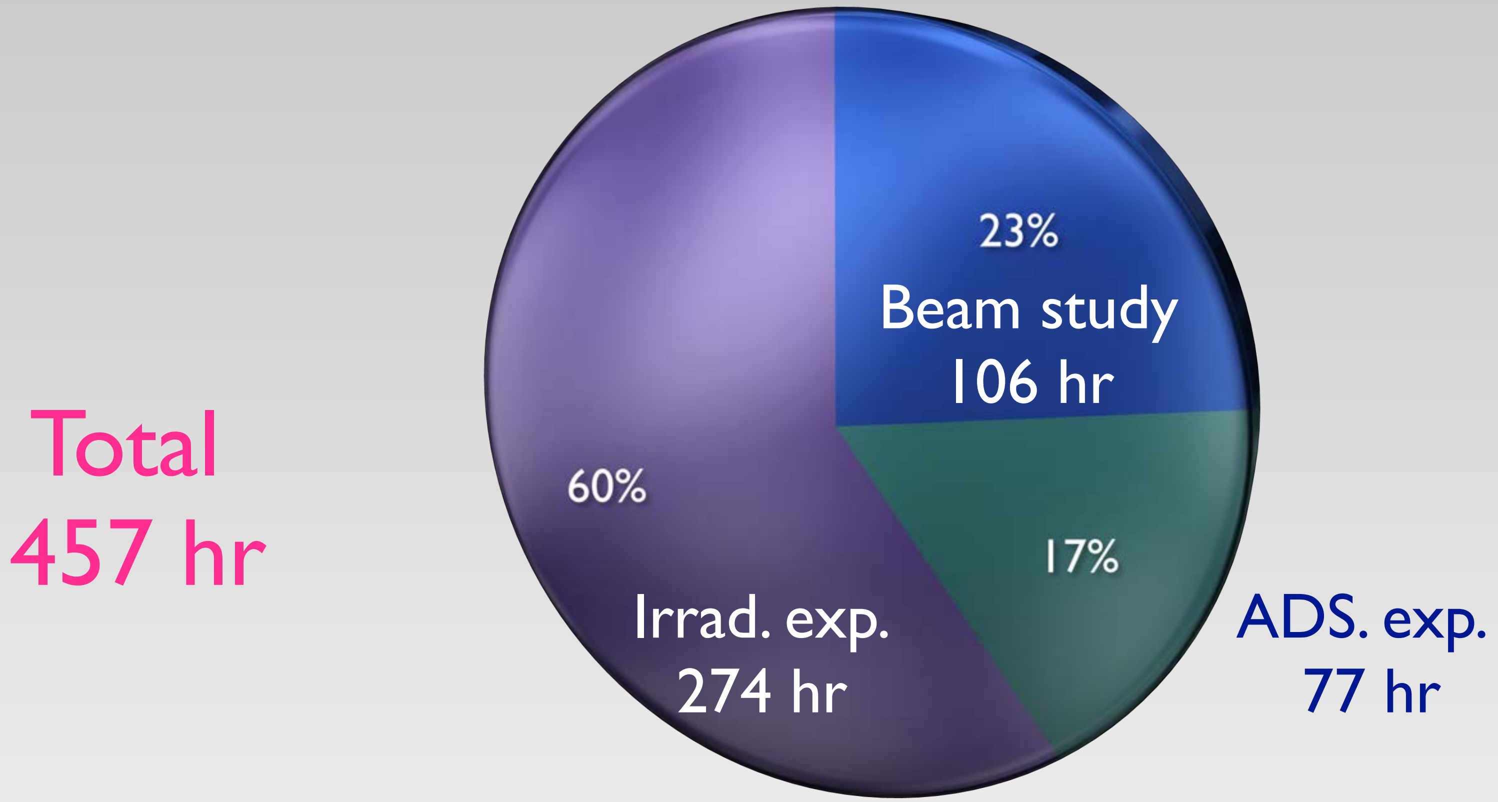
FFAG – KUCA ADS system schematic diagram (upgraded) from 2011



FFAG – KUCA ADS system schematic diagram (upgraded) from 2012



Summary of Machine Time (FY 2012)



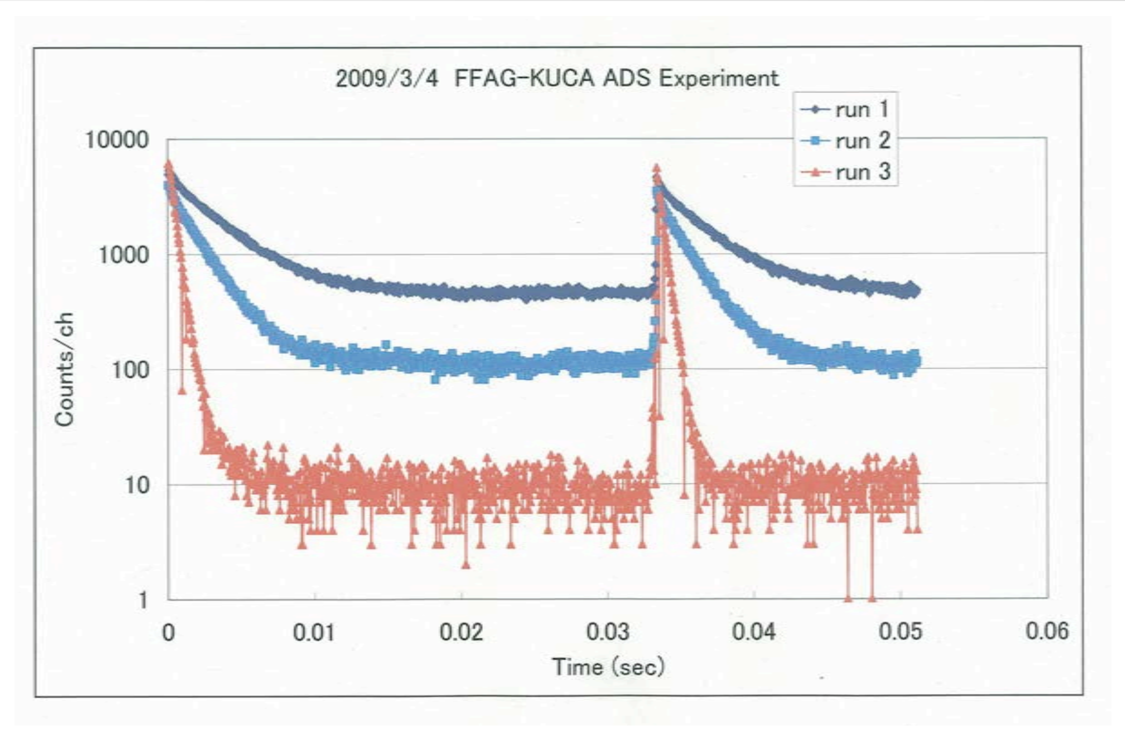
	unit	May. - Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Beam Study	hr	77	21	5	3	0	0	0
ADS Exp.	hr	0	0	28	0	49	0	0
Irrad. Exp.	hr	0	9	0	14	24	73	153
Ext. Energy	MeV	100/150	150	100	150	100	150	150

KURRI FFAGのユーザー

- KUCAでのADS 実験 100MeV / 1nA
- 材料照射・放射化学 150MeV / 1nA (~10nA max)
- BNCT基礎研究のための生物ハイブリッド照射 100MeV / 1nAを計画中

KUCAでのADS実験

動特性測定



Require ultra low intensity (but quite stable) beams to avoid piling up of neutron counting. e.g. 5pA - 10pA 1/1000 ordinary intensity

放射化を用いた中性子スペクトル測定

Two-layer target study (^{235}U-core) - 2013

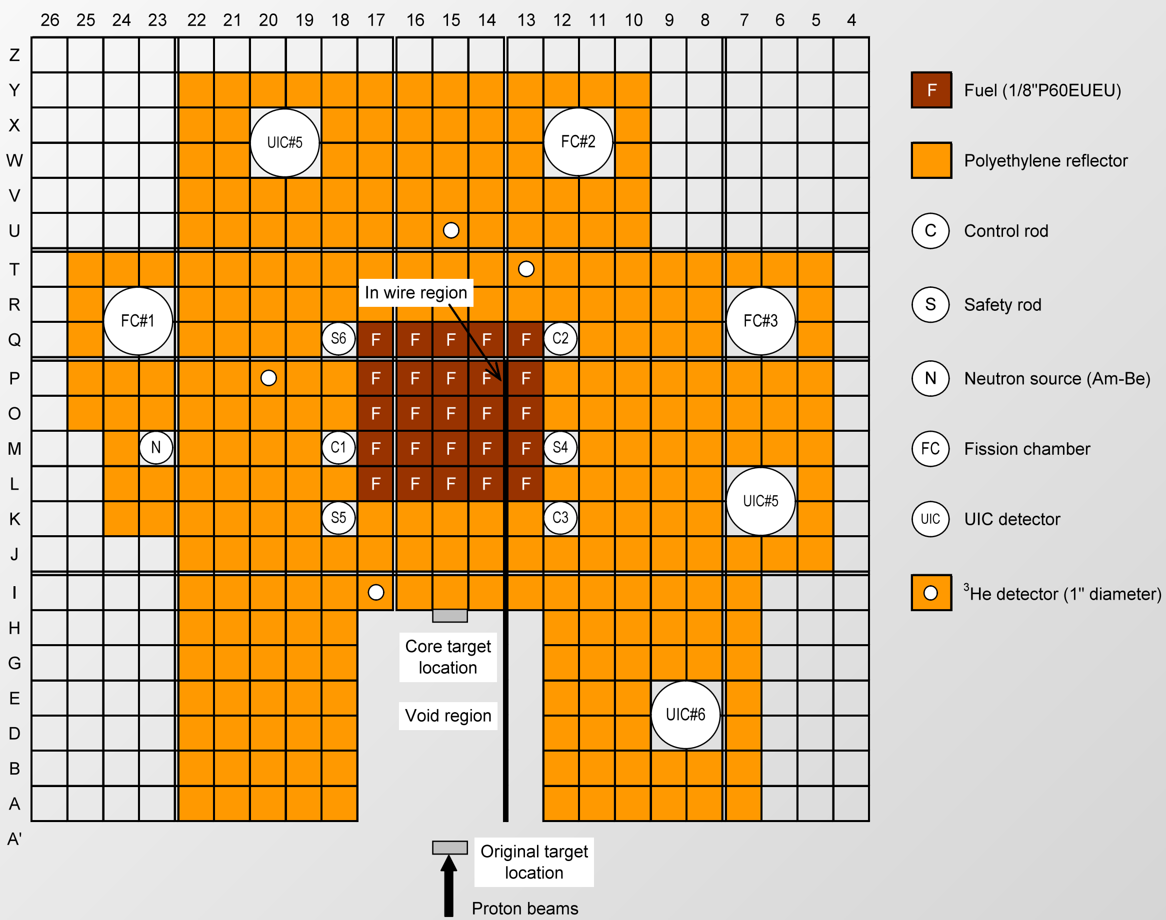


Fig. Core configuration of ^{235}U-loaded cores (100 MeV protons)

(Protons: 100 MeV, 0.5 nA, 100 ns, 20 Hz)

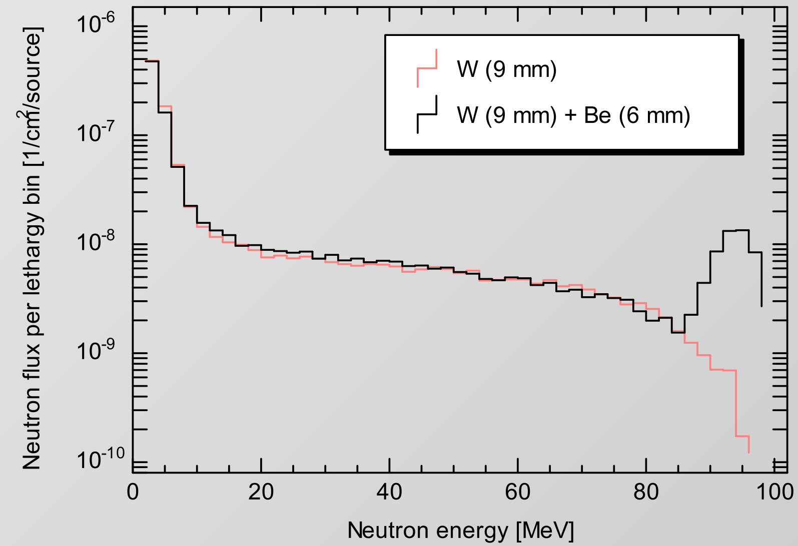


Fig. Neutron spectra (W vs. W+Be)

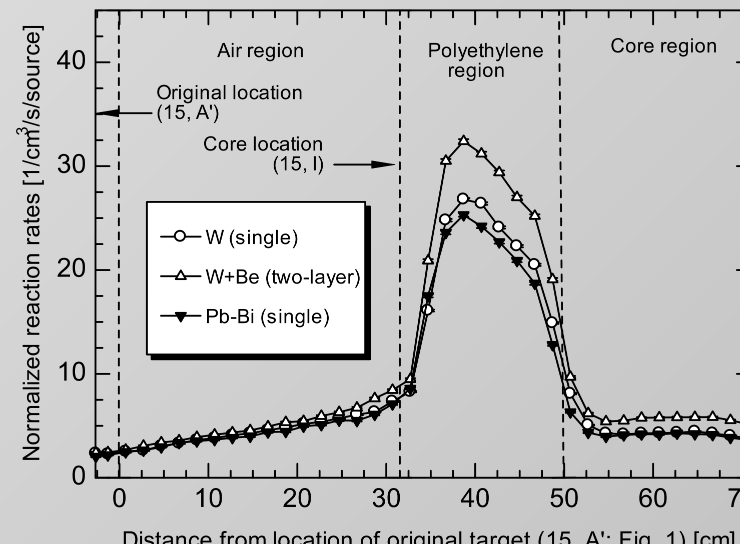
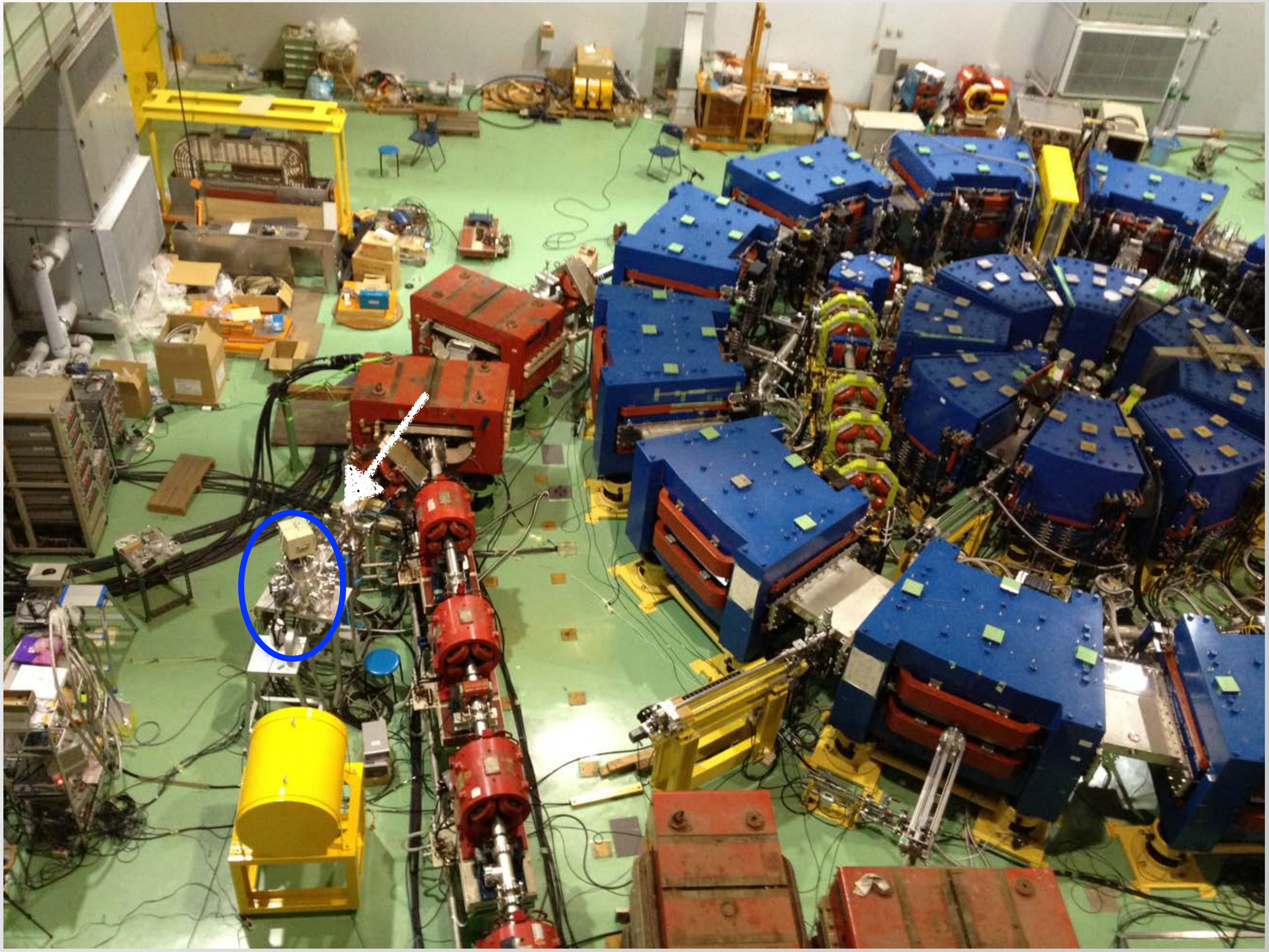


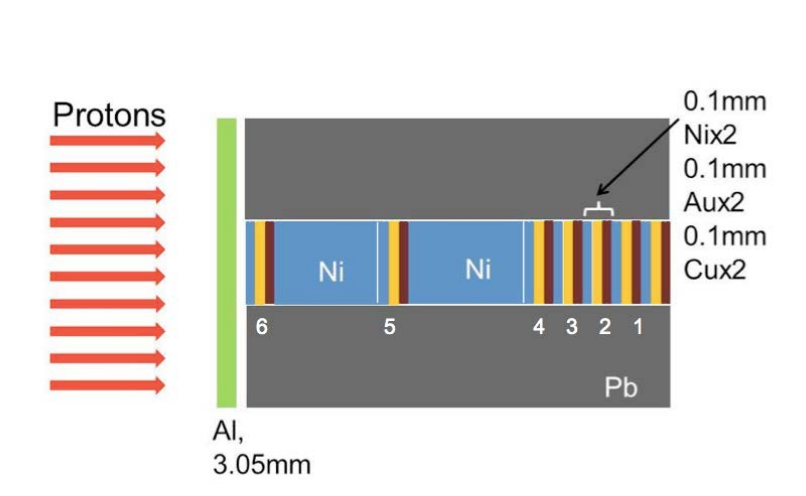
Fig. In reaction rates (W, W+Be and Pb-Bi)

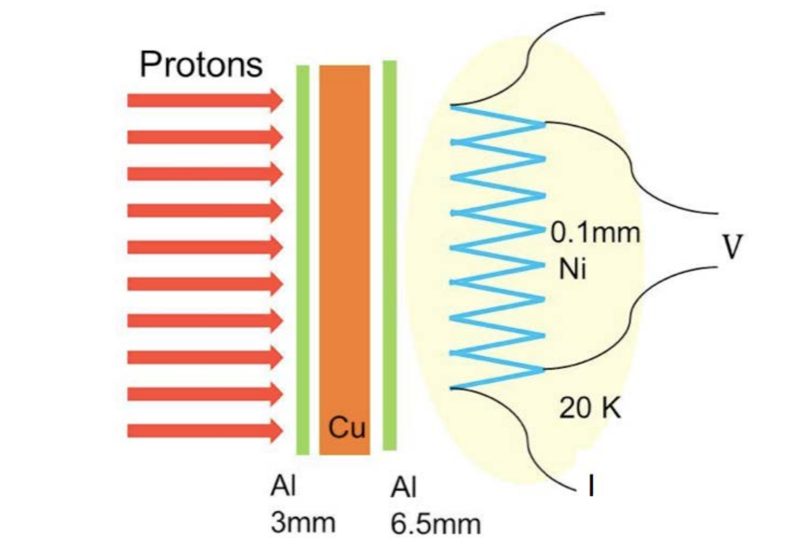
1 - 2時間ビームトリップが許されない

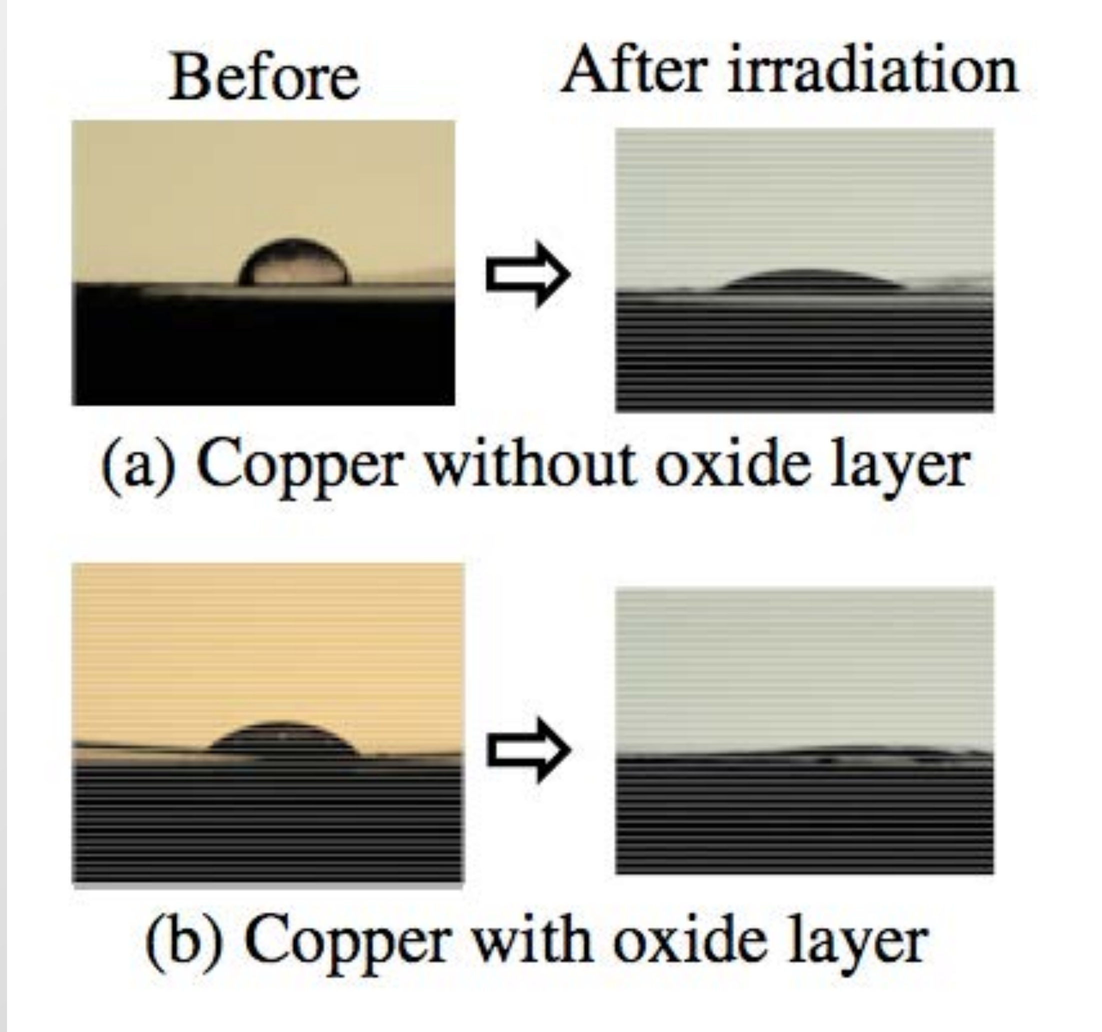
Beam Line and Chamber for Irradiation Experiments



150 MeV陽子ビームラインに設置された照射チェンバー。冷凍機と引っぱり試験機が装備され陽子ビーム照射中での測定が可能。

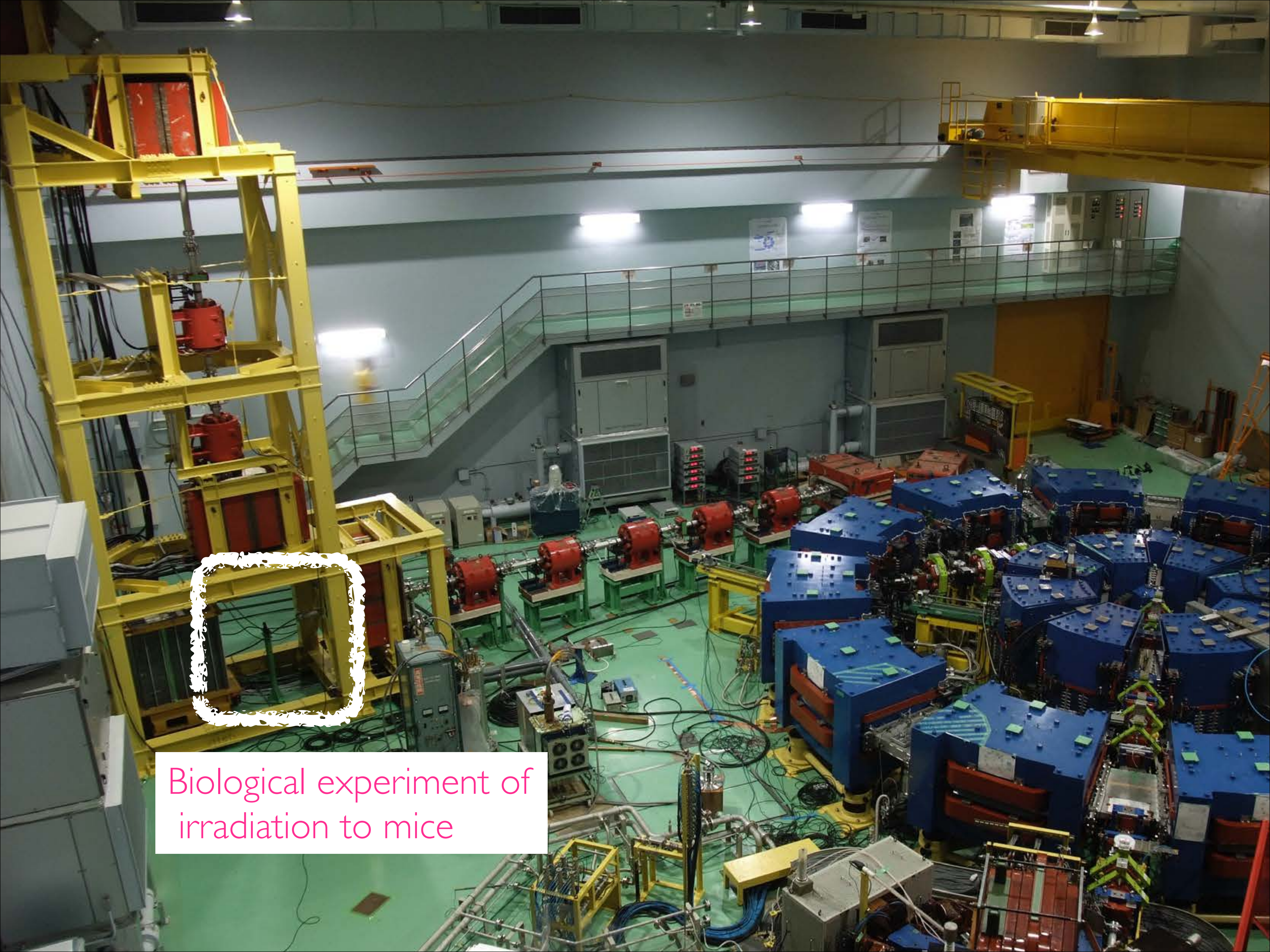




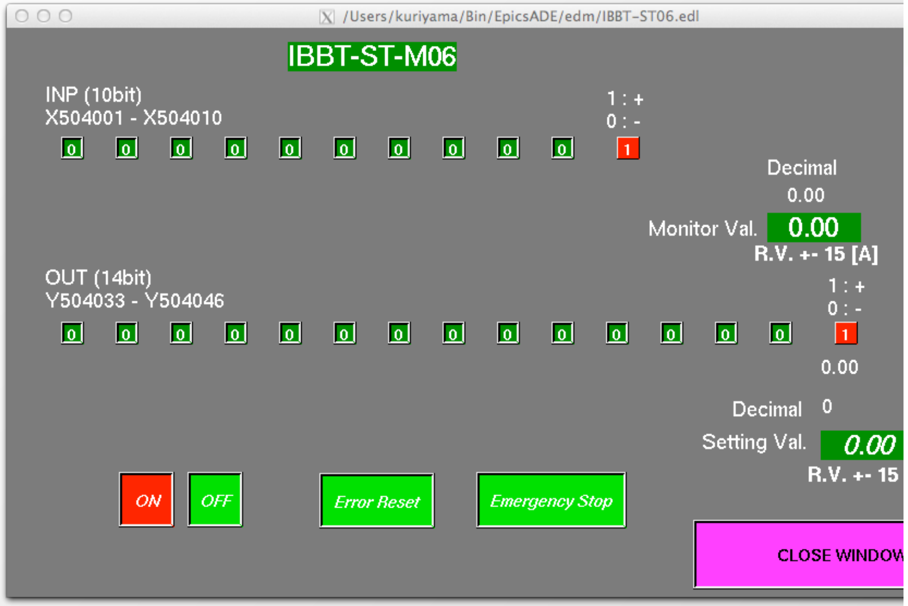


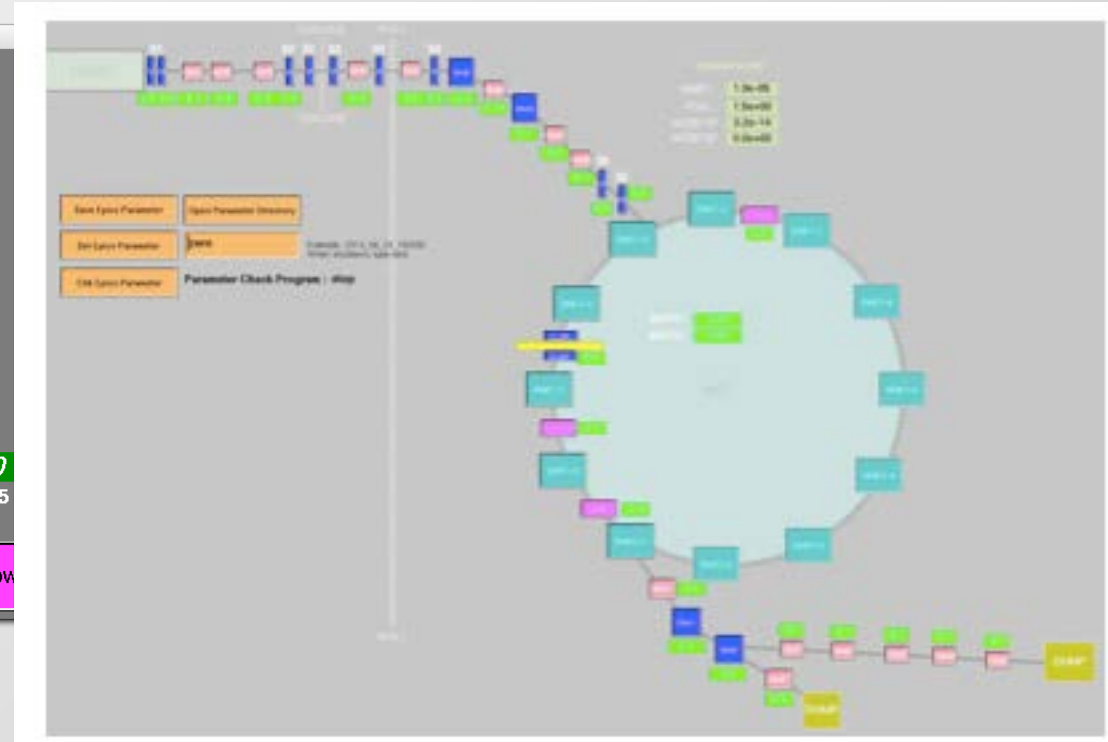
陽電子寿命測定、電気抵抗測定において格子欠陥の生成分布に計算との違いがみられた。電気抵抗測定の追実験により確認を実施中。

100 MeV陽子ビームの照射（240nA-h）により表面ぬれ性の改善 がみられた.

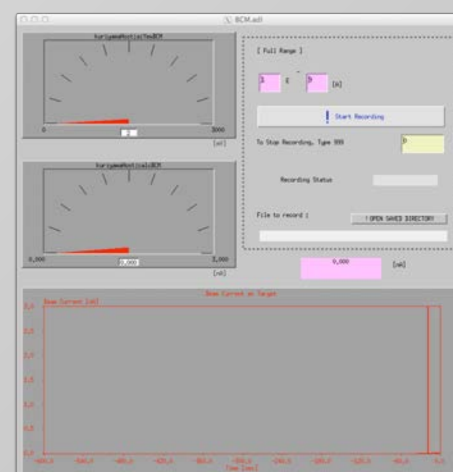

Biological experiment of
irradiation to mice

Upgrade of control system

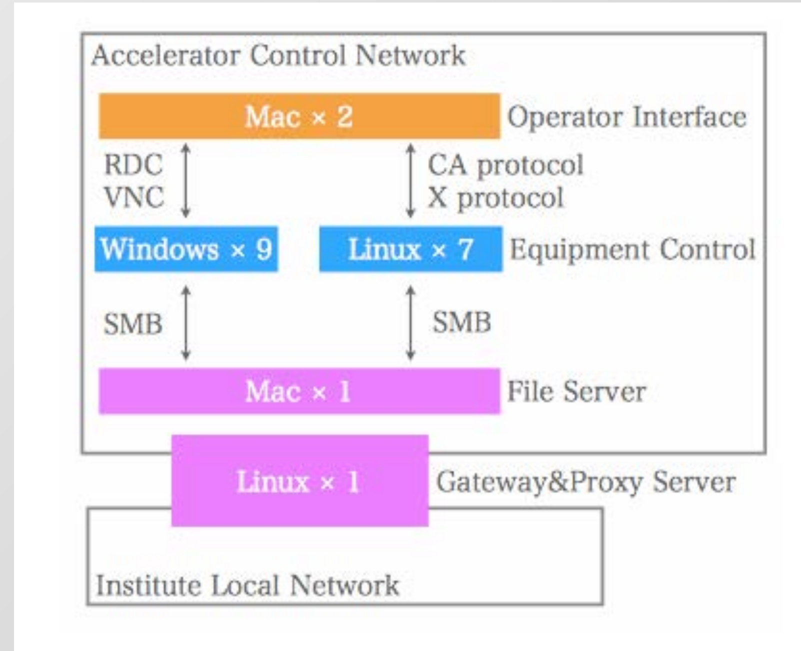




The control system of FFAG accelerator at KURRI has been upgraded with EPICS under collaboration with the KEK accelerator control group. Some parts of the system are using LabView on Windows XP, but they are going to be replaced by EPICS based program for more reliable and secure system.



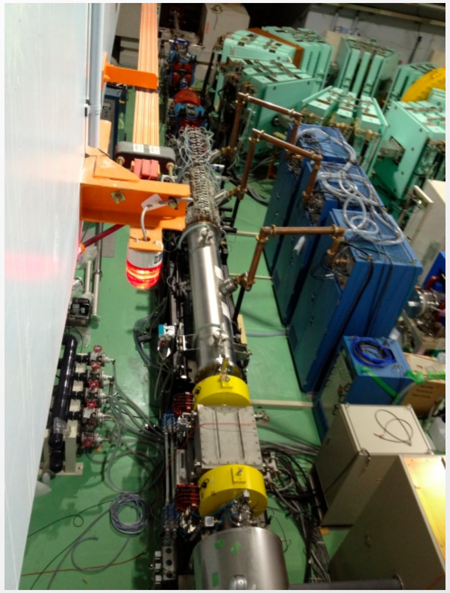
View of Control Room

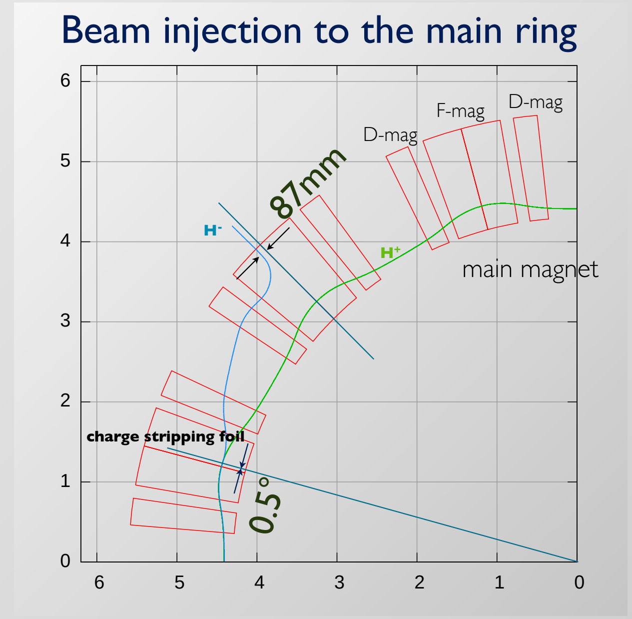


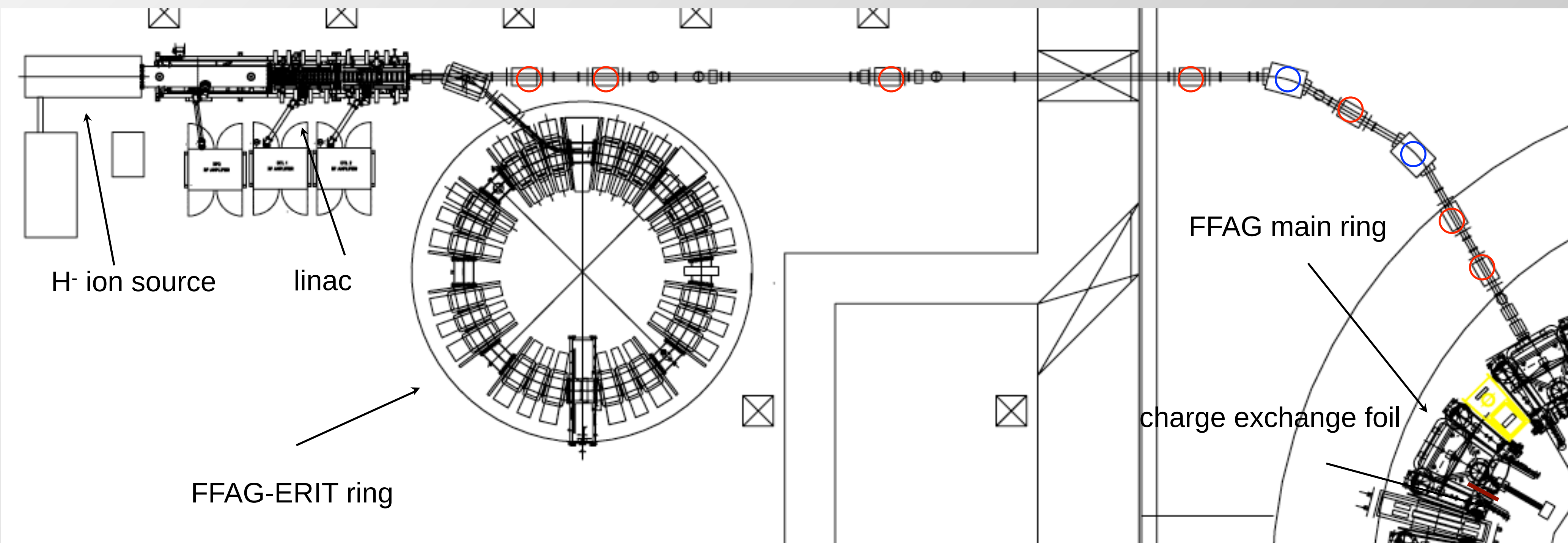
The FFAG accelerator control room. Only one person can operate whole system. There are two Macs link to Windows and LINUX PCs which command PLCs to control accelerator devices.

Beam diagnostics system upgrade

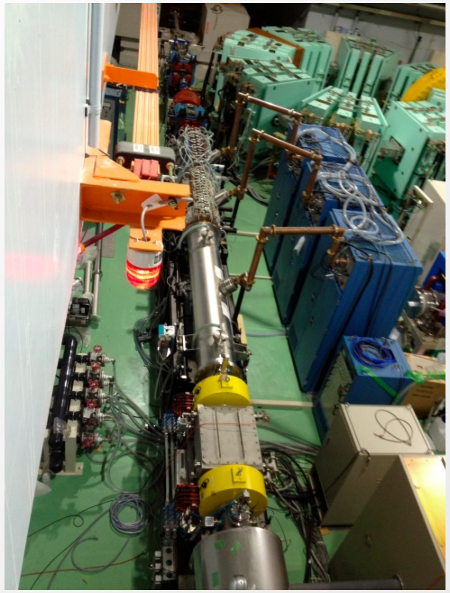
H- injection

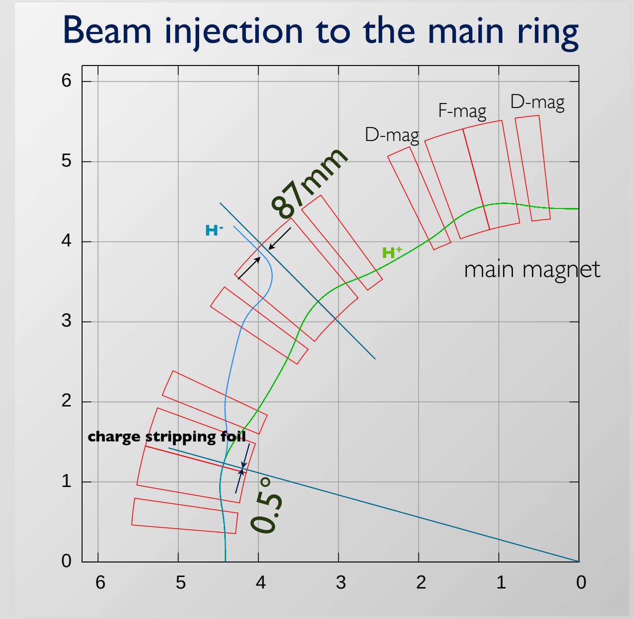



Beam injection to the main ring
D-mag
F-mag
D-mag
87mm
H-
H+
main magnet
charge stripping foil
0.5°
6
5
4
3
2
1
0

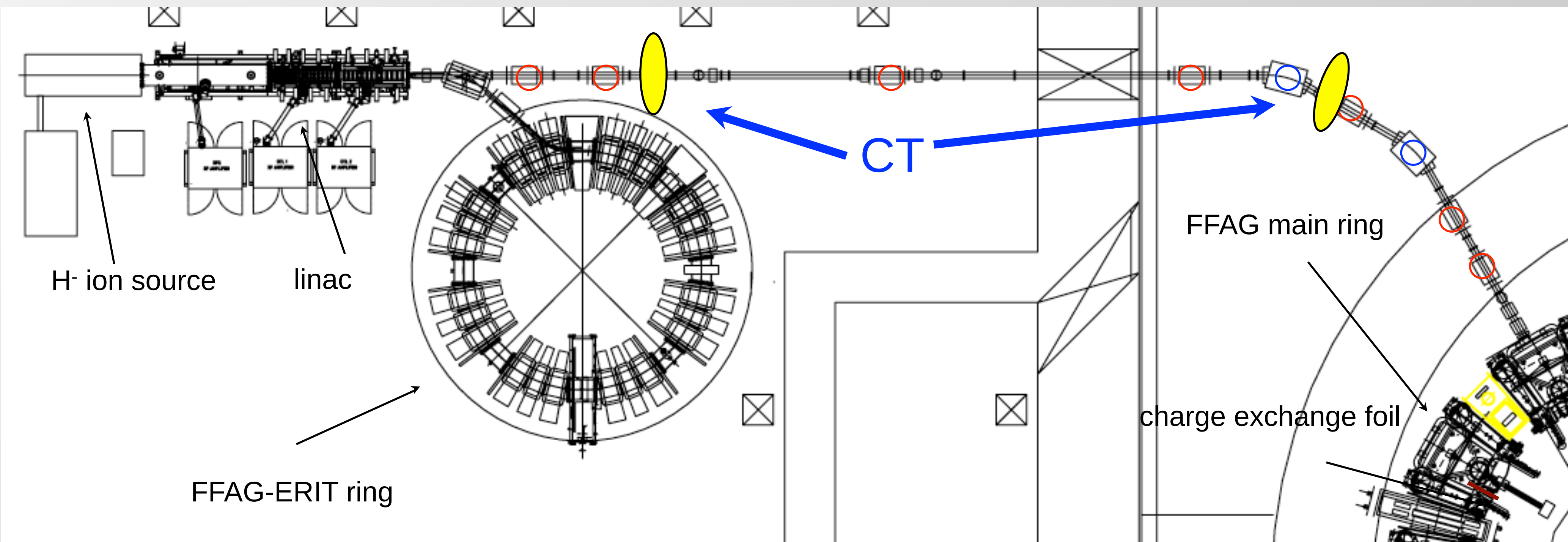

H- ion source
linac
FFAG-ERIT ring
FFAG main ring
charge exchange foil

H- injection



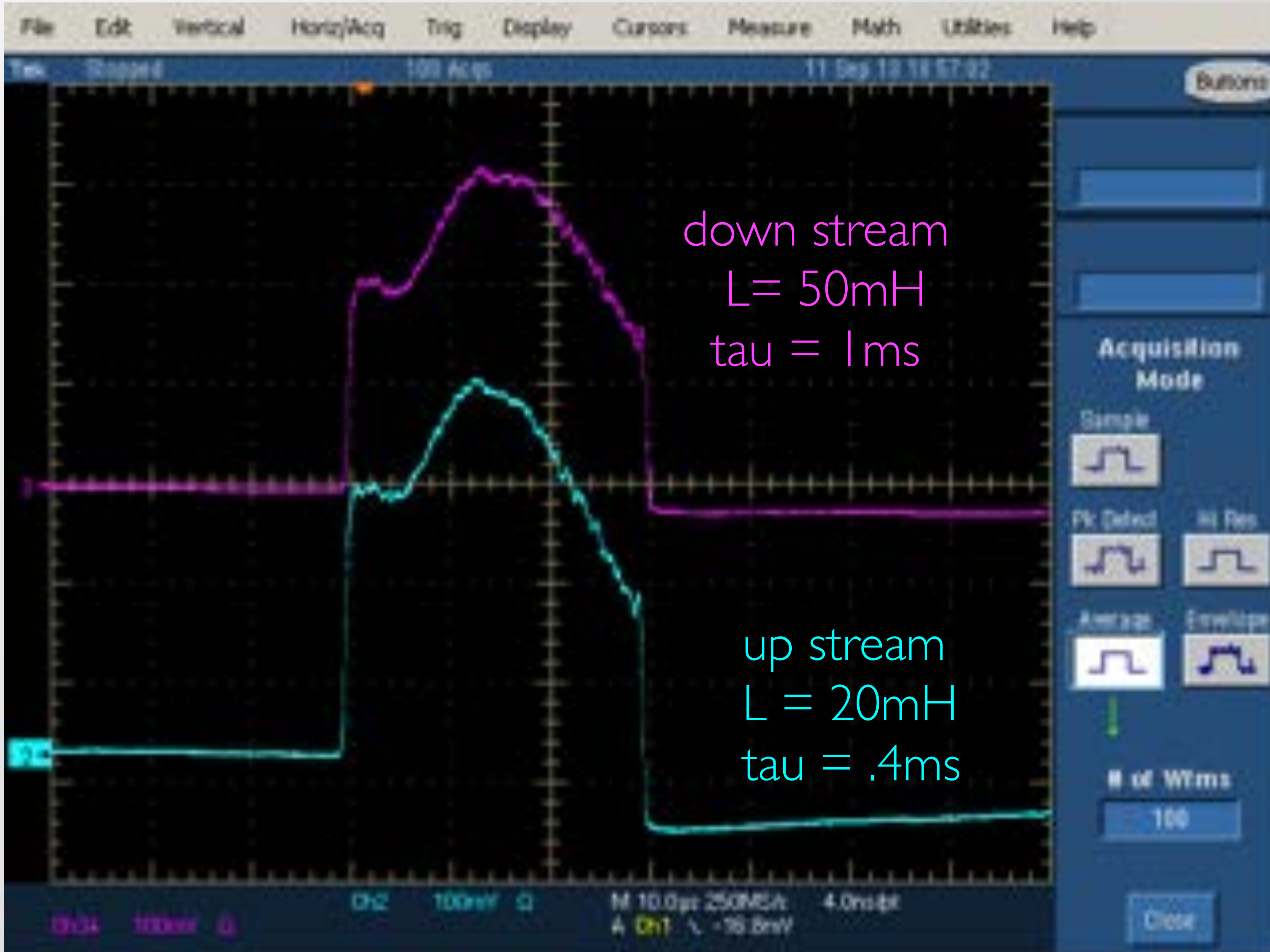


Beam injection to the main ring
D-mag
F-mag
D-mag
87mm
H-
H+
main magnet
charge stripping foil
0.5°
6
5
4
3
2
1
0
6
5
4
3
2
1
0

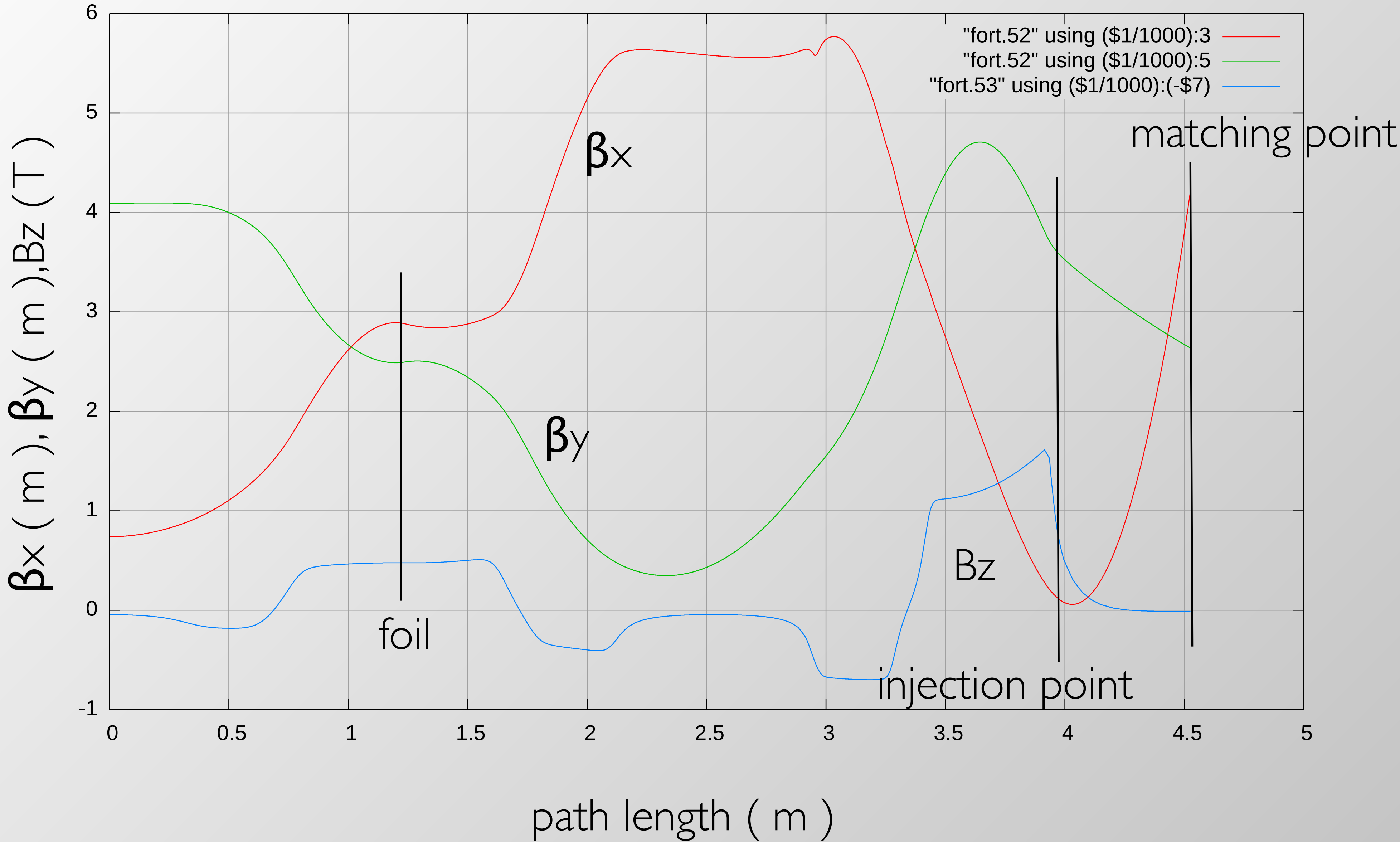


CT
H- ion source
linac
FFAG main ring
charge exchange foil
FFAG-ERIT ring

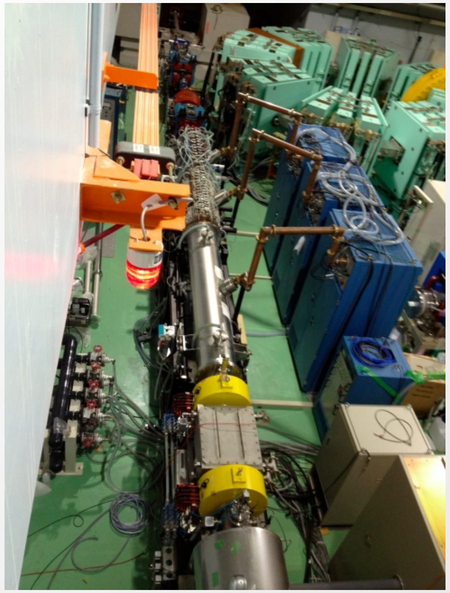
CTs installed in vacuum

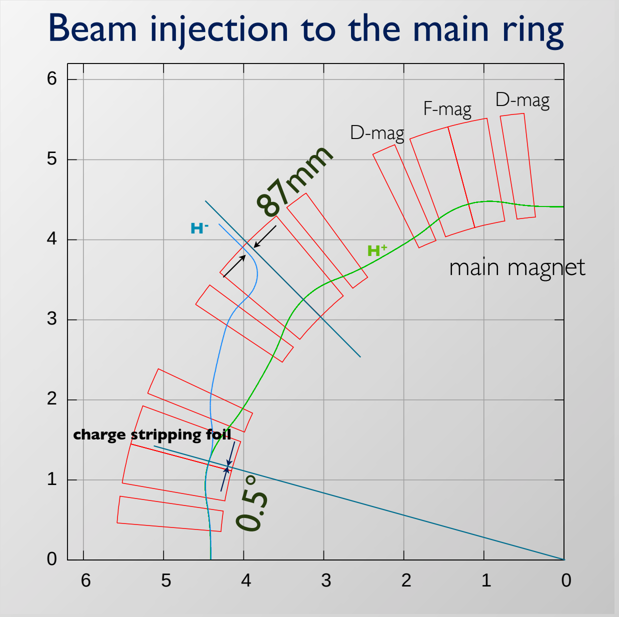


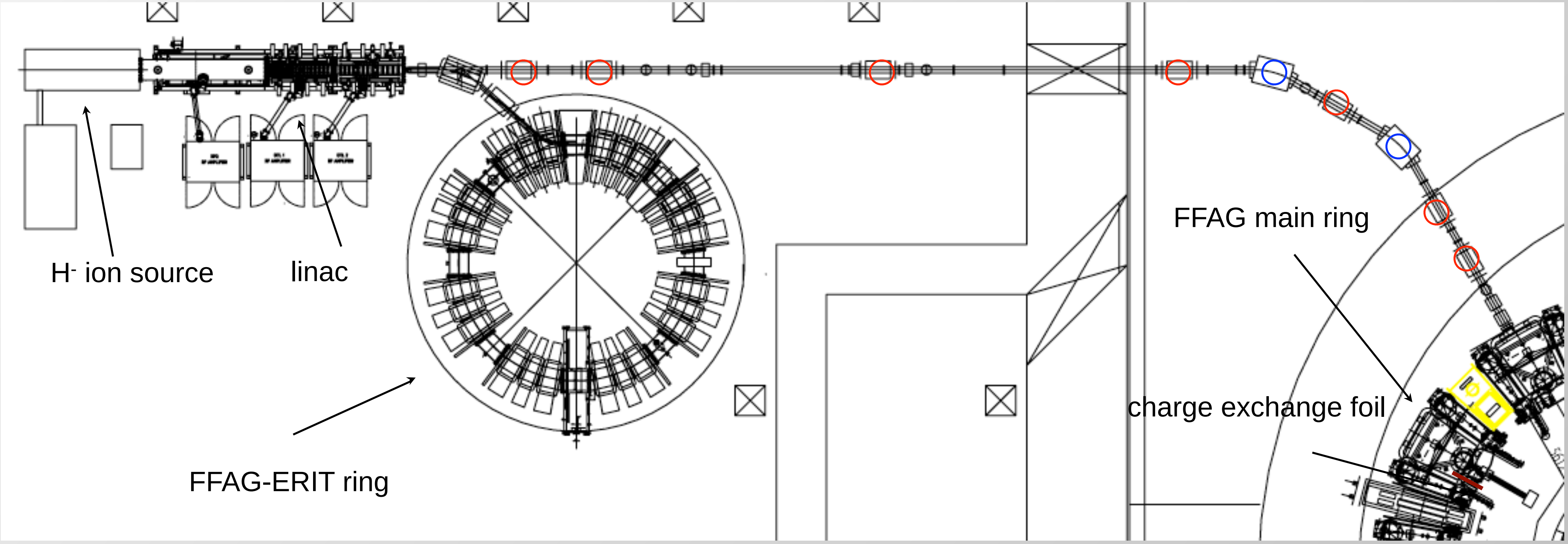
Beta functions calculated from backward tracking in the main ring



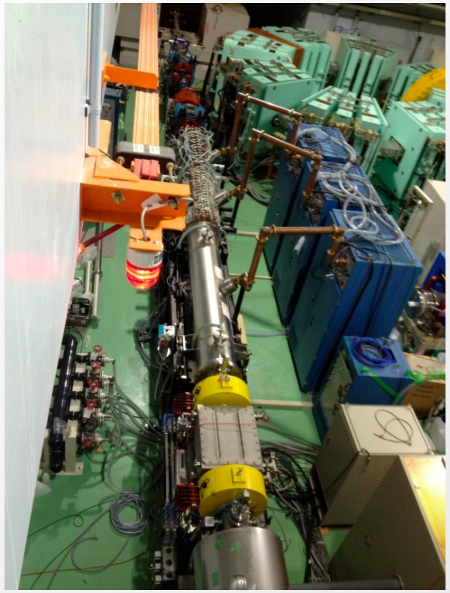
H- injection

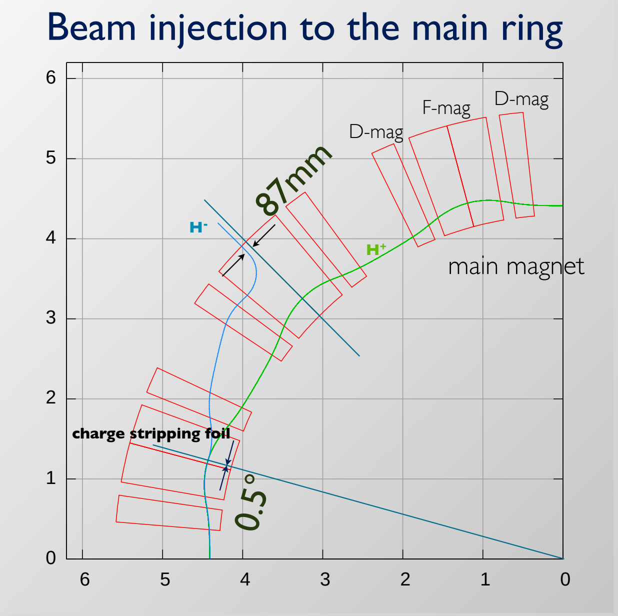



Beam injection to the main ring
D-mag
F-mag
D-mag
87mm
H-
H+
main magnet
charge stripping foil
0.5°
6
5
4
3
2
1
0
6
5
4
3
2
1
0

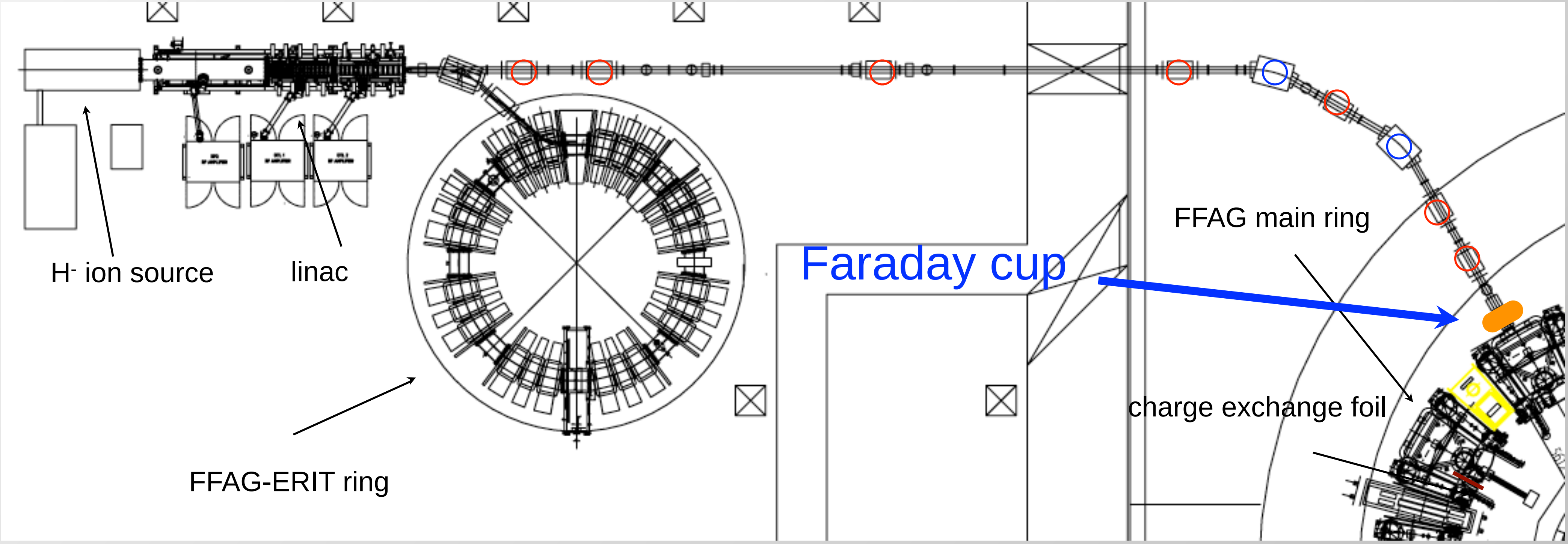

H- ion source
linac
FFAG-ERIT ring
FFAG main ring
charge exchange foil

H- injection

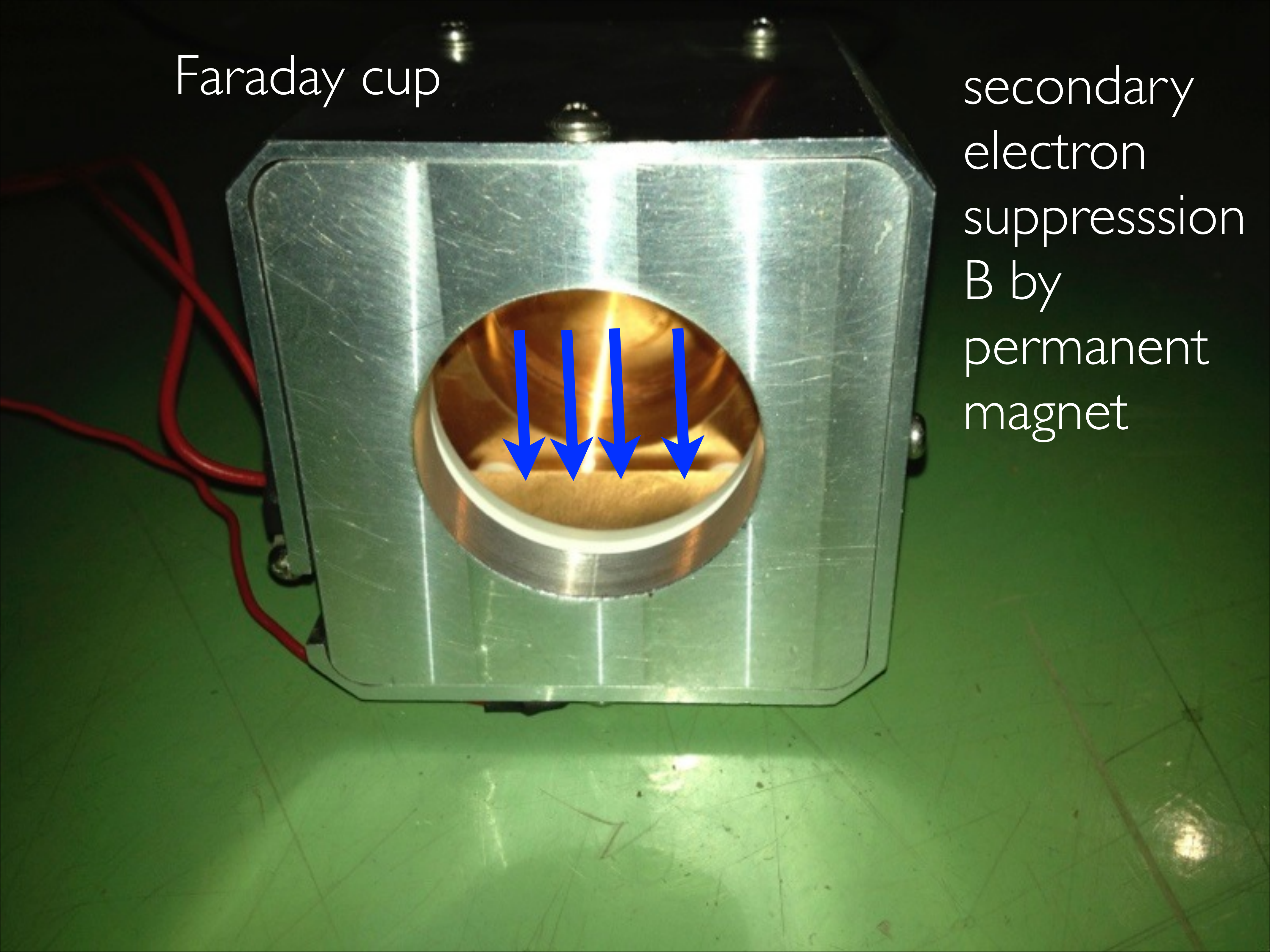




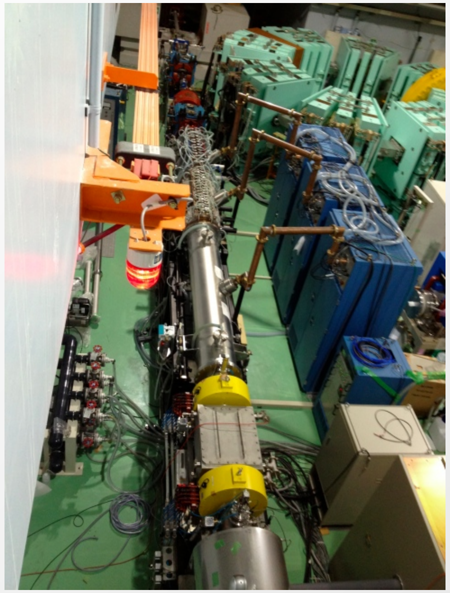
Beam injection to the main ring
D-mag
F-mag
D-mag
87mm
H-
H+
main magnet
charge stripping foil
0.5°

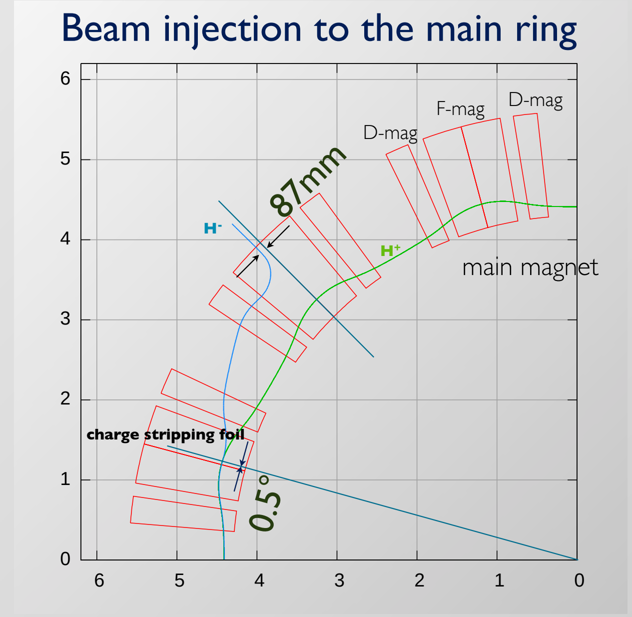


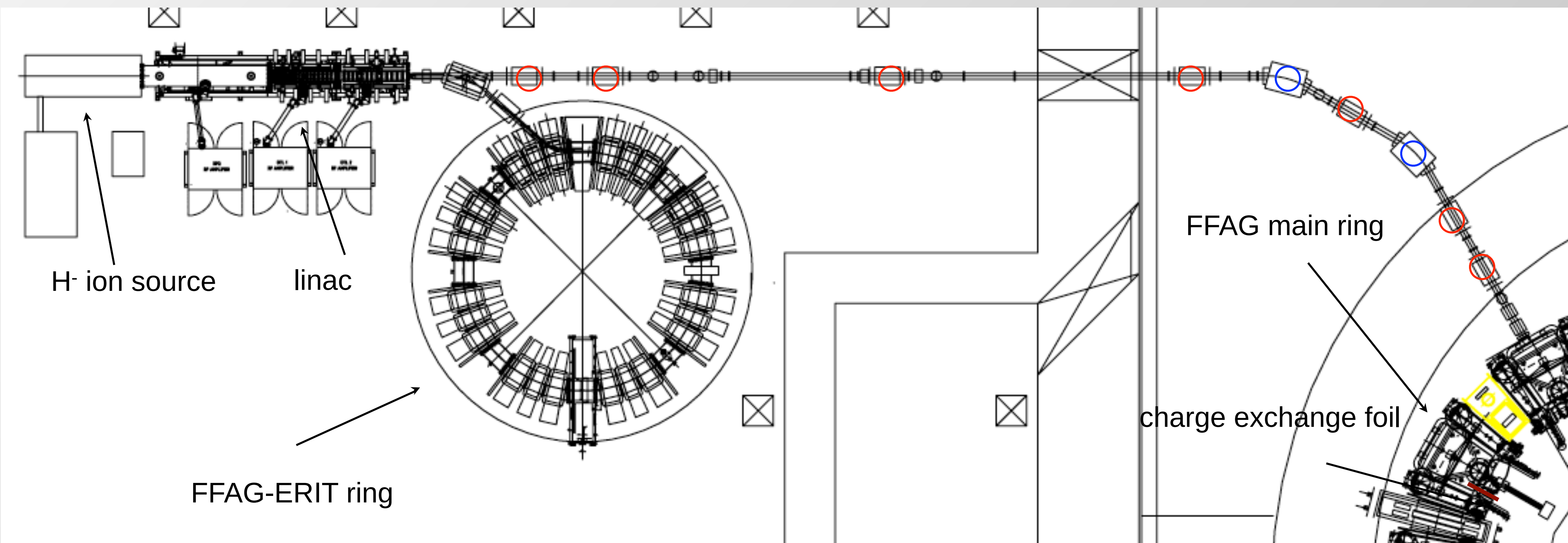
H- ion source
linac
FFAG-ERIT ring
Faraday cup
FFAG main ring
charge exchange foil


Faraday cup
secondary
electron
suppresssion
B by
permanent
magnet

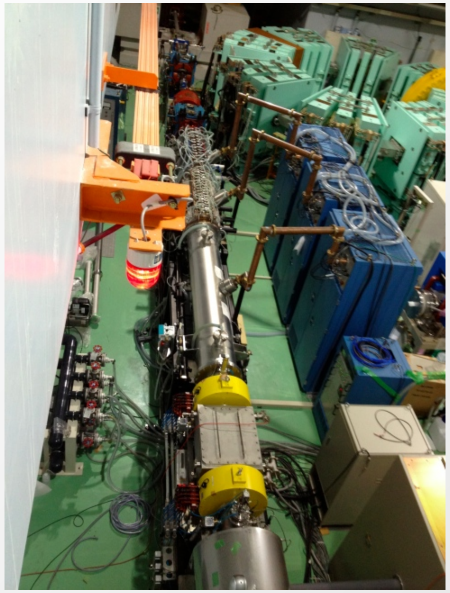
H- injection

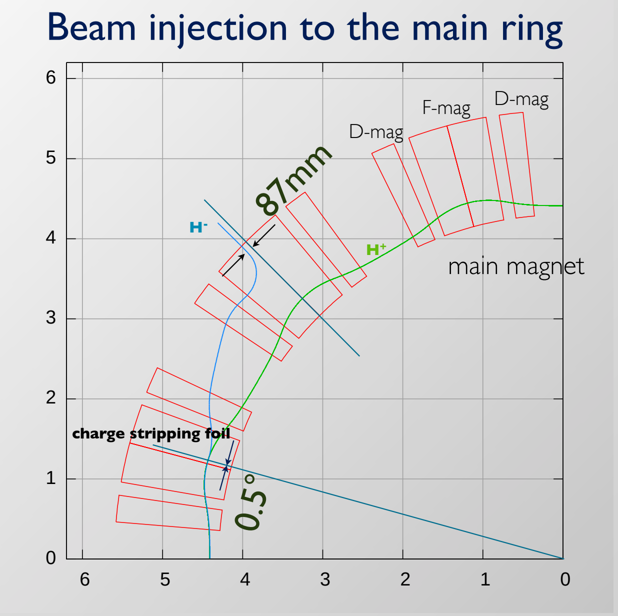



Beam injection to the main ring
D-mag
F-mag
D-mag
87mm
H-
H+
main magnet
charge stripping foil
0.5°
6
5
4
3
2
1
0

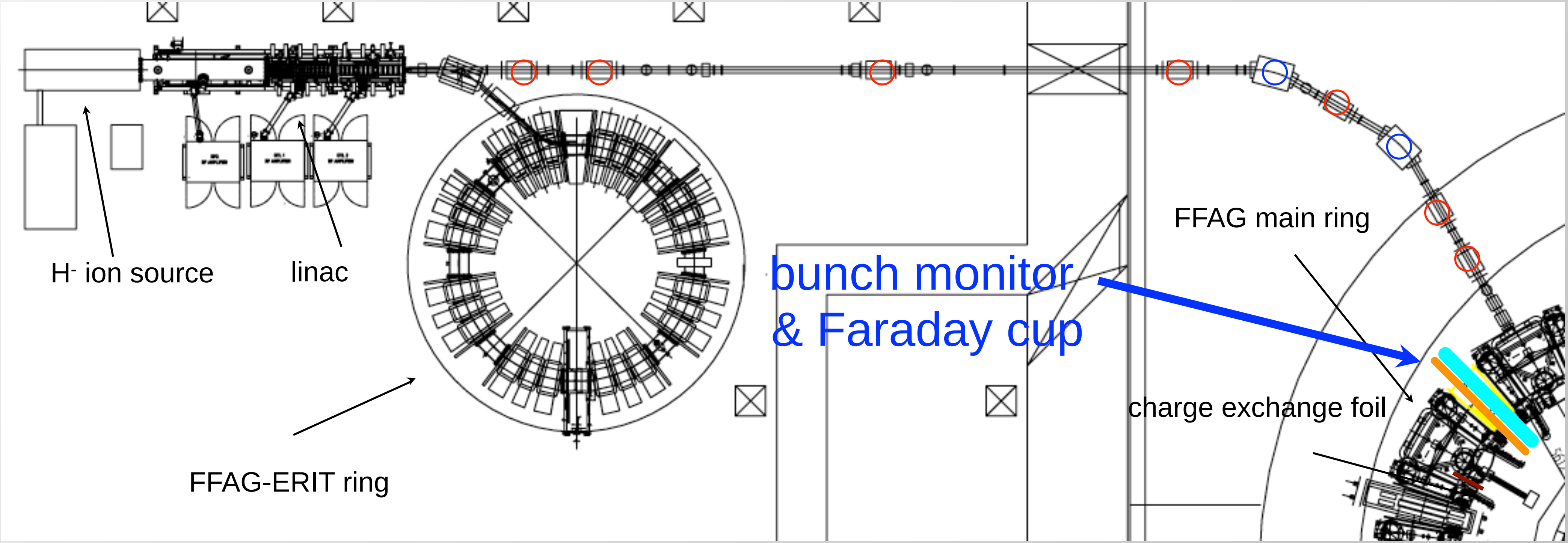

H- ion source
linac
FFAG-ERIT ring
FFAG main ring
charge exchange foil

H- injection

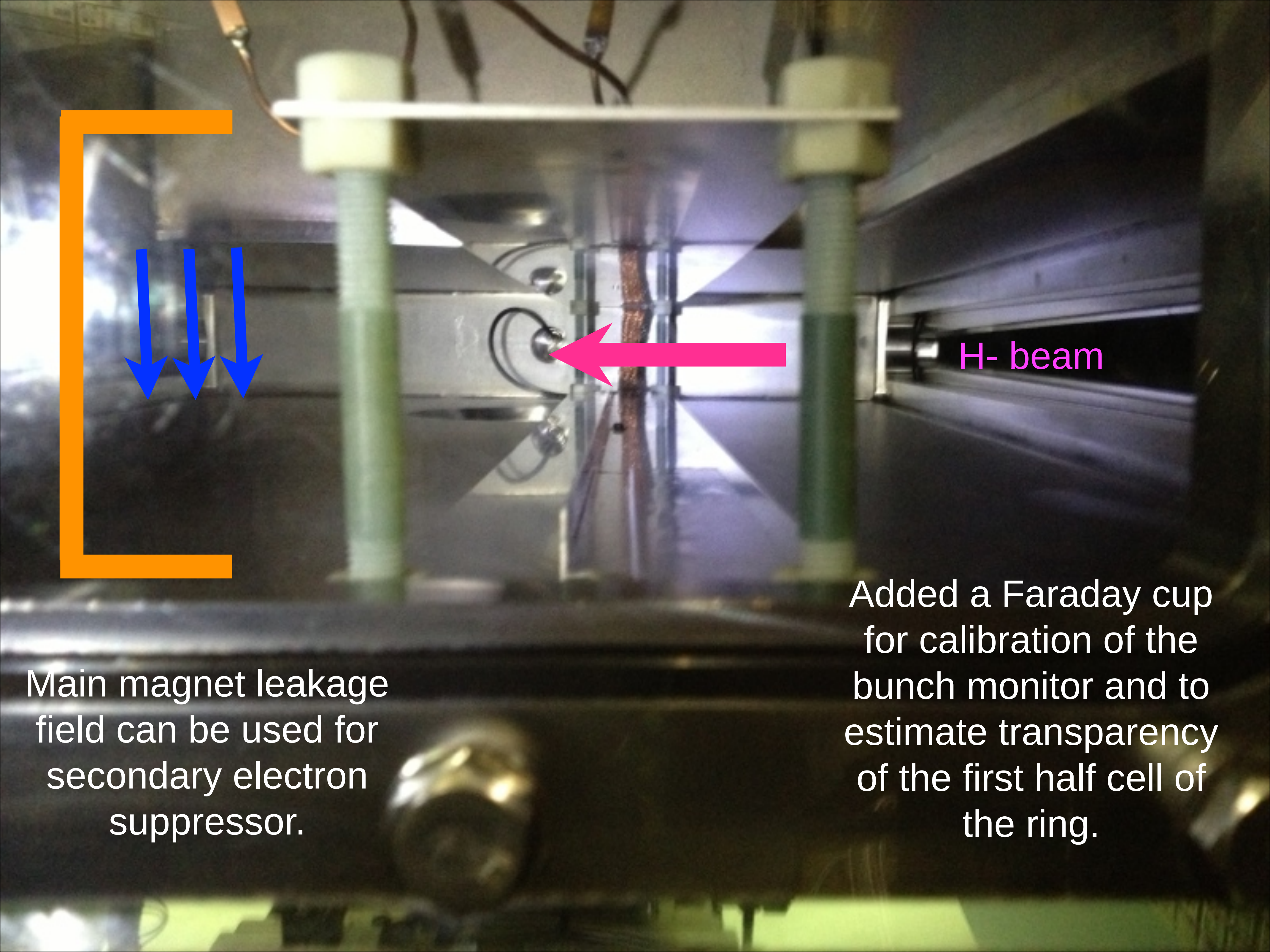




Beam injection to the main ring
D-mag
F-mag
D-mag
87mm
main magnet
charge stripping foil
0.5°



H- ion source
linac
FFAG-ERIT ring
bunch monitor
& Faraday cup
FFAG main ring
charge exchange foil


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.

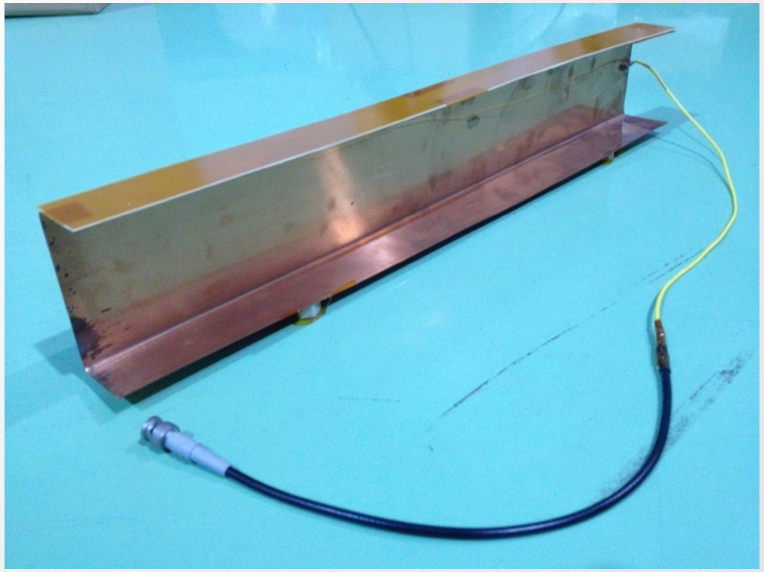
Faraday cup

Long tailed decay in bunch monitor signal seems to be back scatter of the secondary electron (suppression is not perfect)

→ RC constant

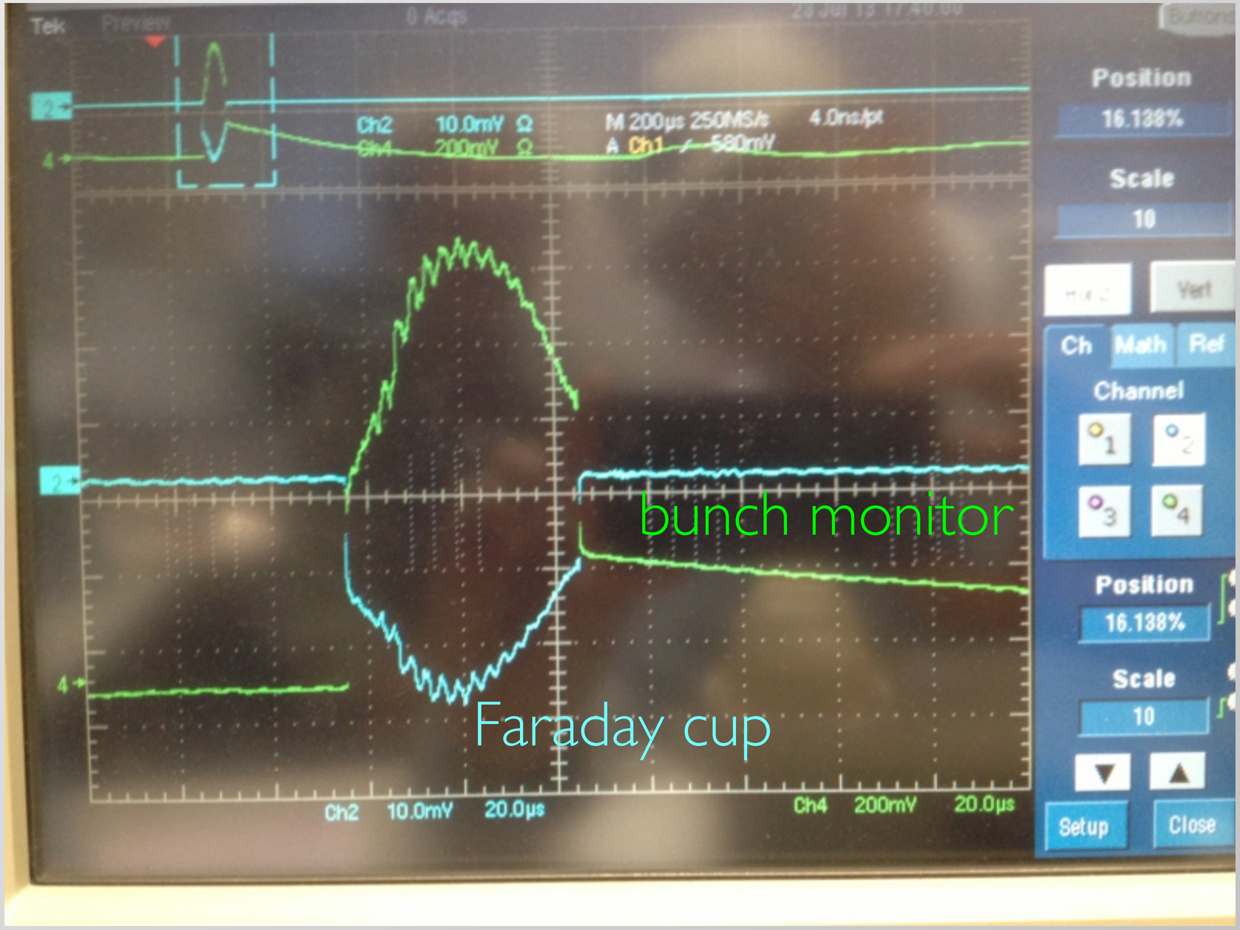
R = 1MΩ (input impedance of the amp)

C = 171pF



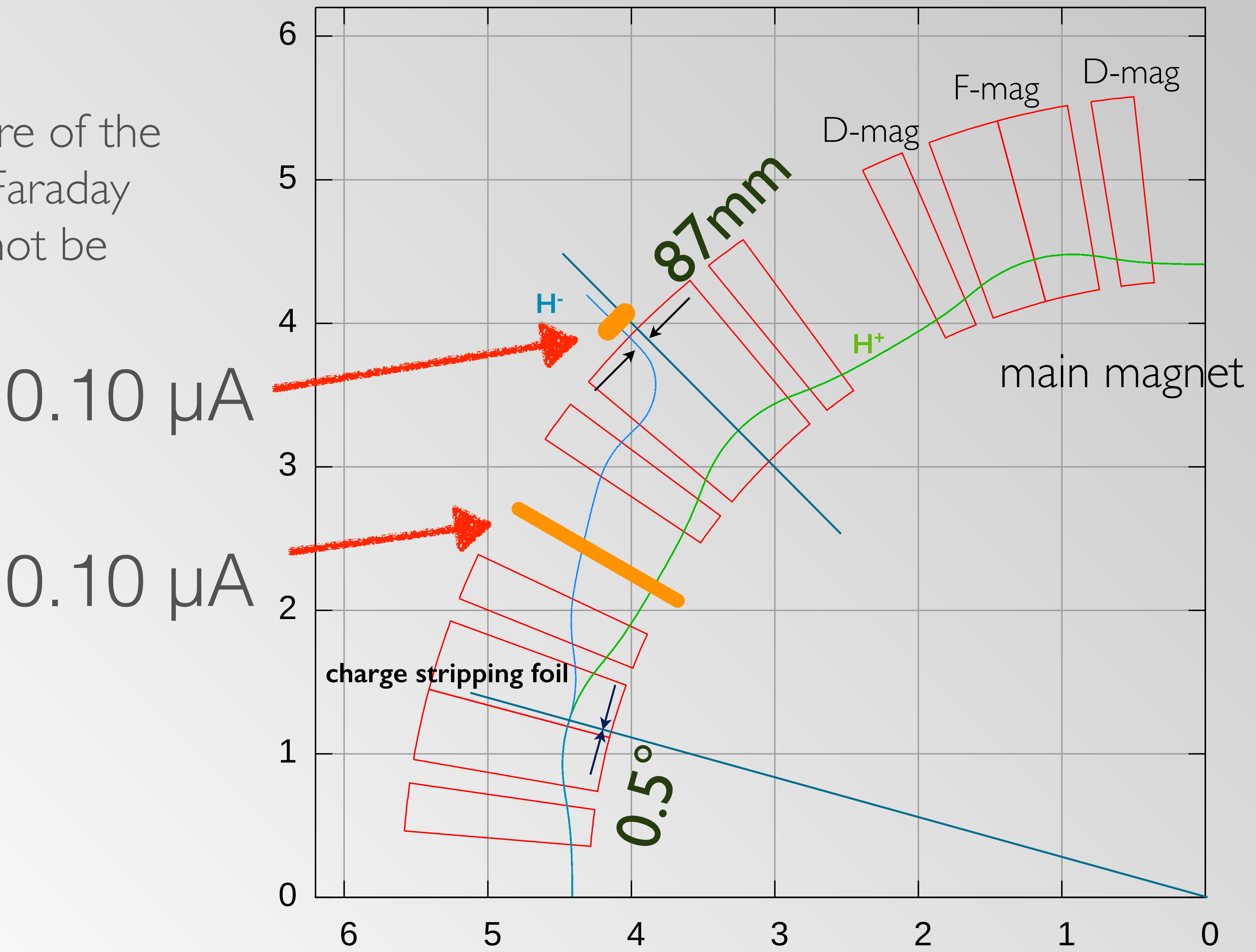
faraday cup signal is read thru 50Ω at 20Hz rep. rate

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



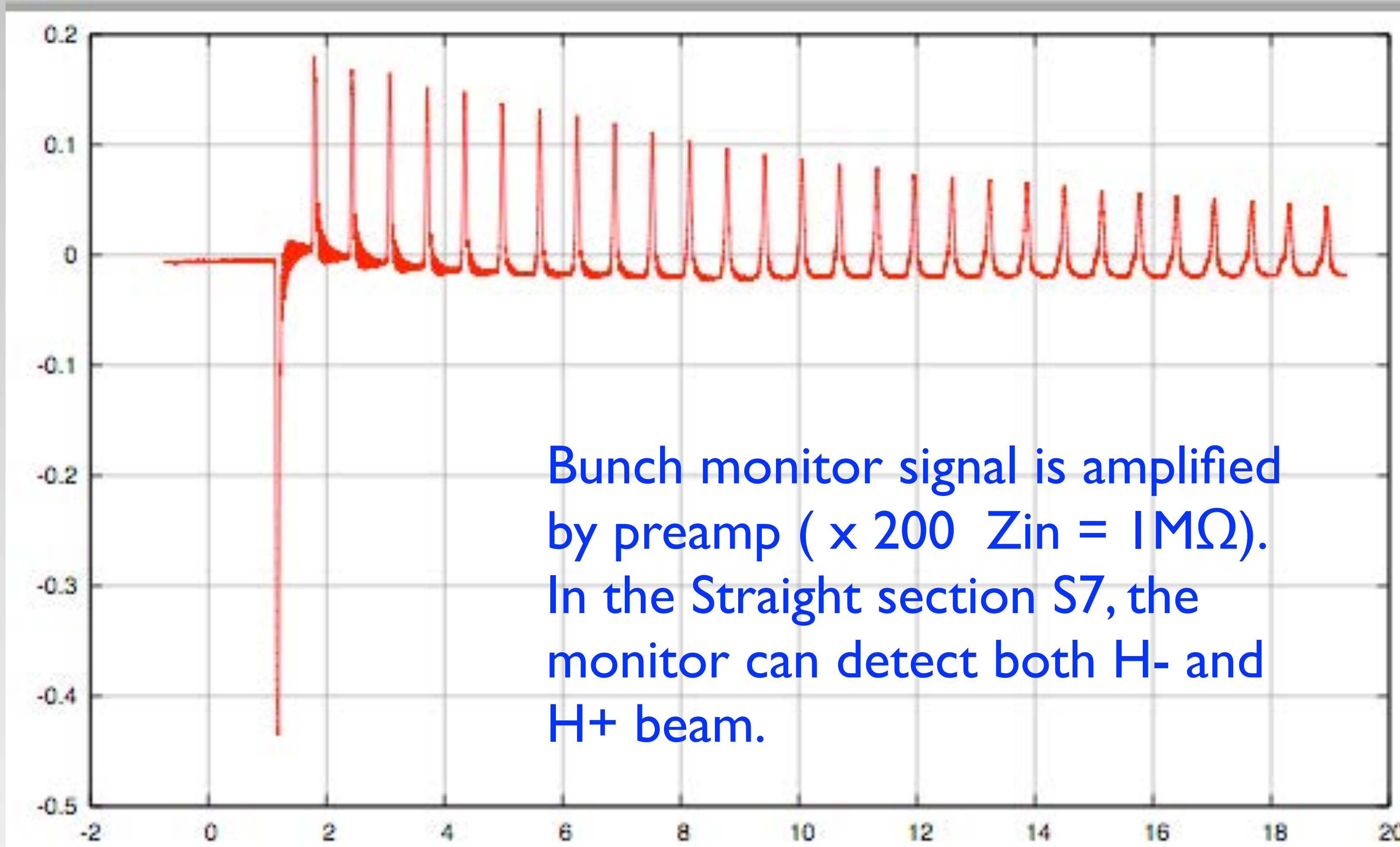
Beam injection to the main ring

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



Results from beam studies in this summer

Injection Studies in ADSR-FFAG Ring



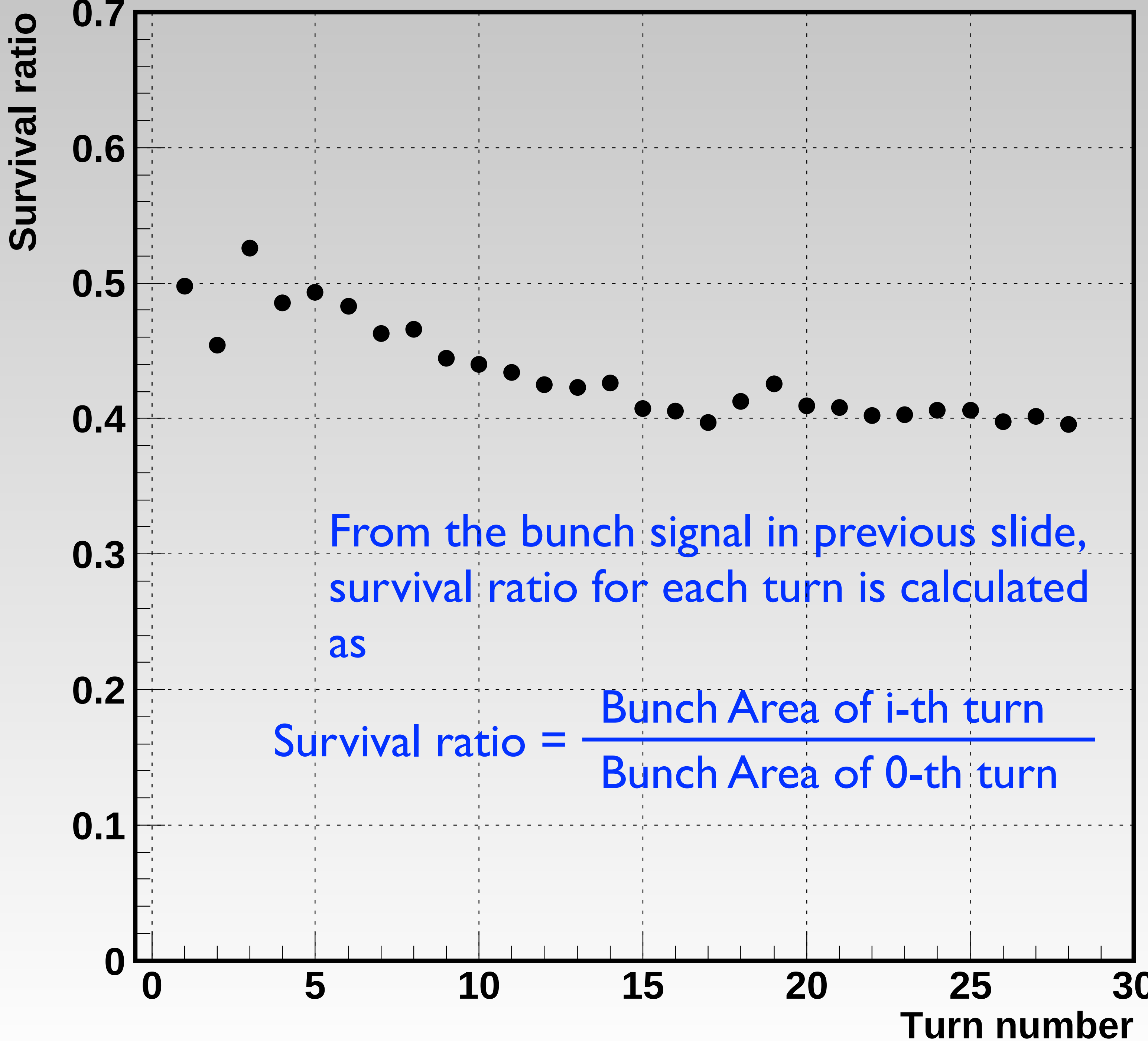
output voltage (V)

t (us)

Bunch monitor signal is amplified by preamp (x 200 Zin = 1MΩ). In the Straight section S7, the monitor can detect both H- and H+ beam.

Beam signal from the bunch monitor

Survival ratio vs turn number

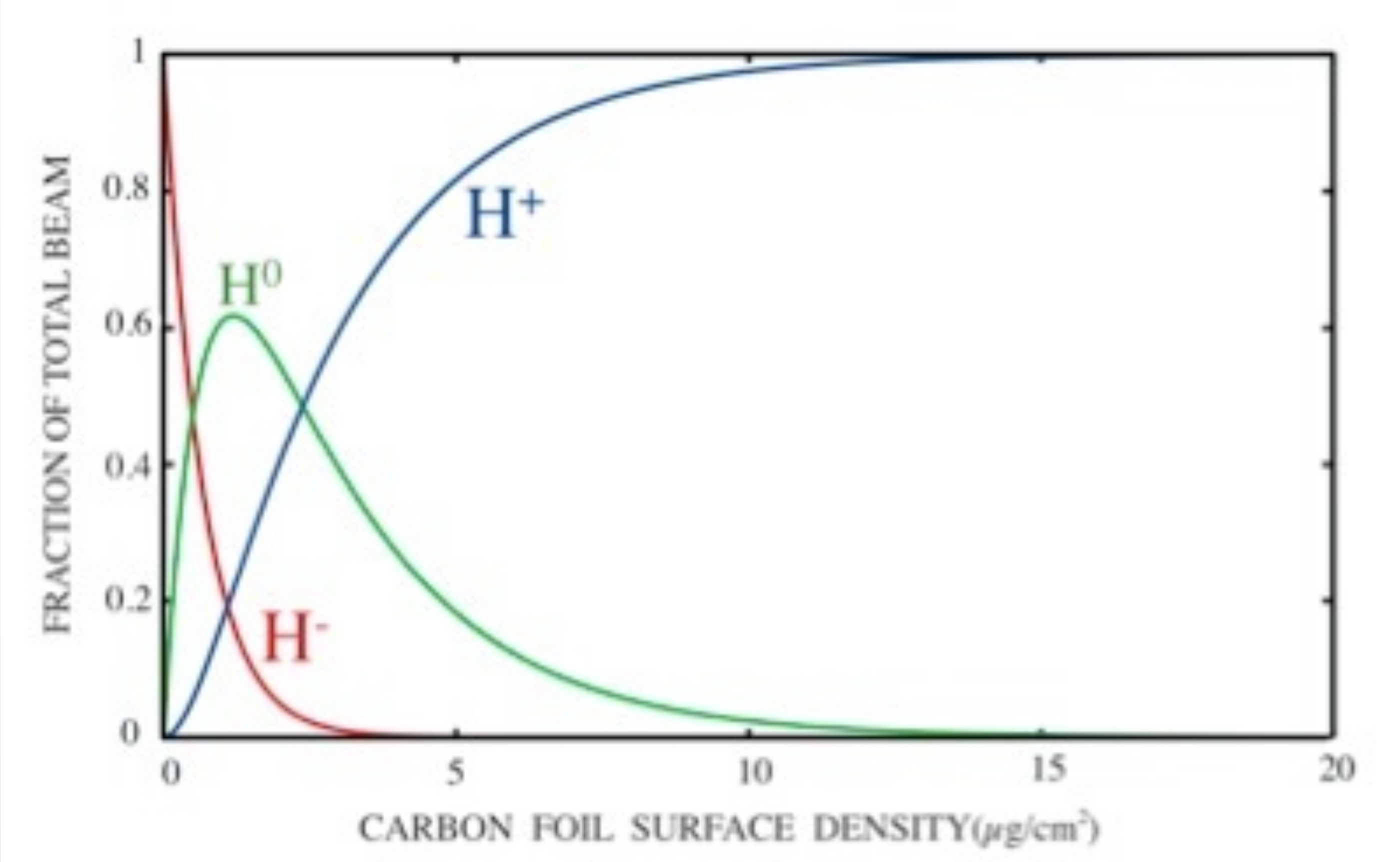


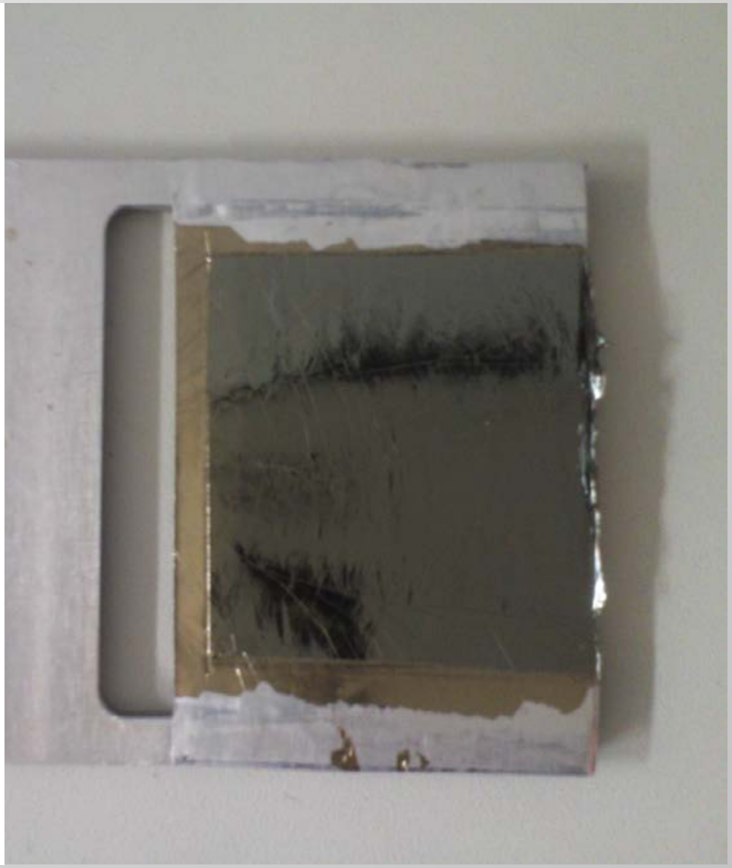
From the bunch signal in previous slide, survival ratio for each turn is calculated as

$$\text{Survival ratio} = \frac{\text{Bunch Area of i-th turn}}{\text{Bunch Area of 0-th turn}}$$

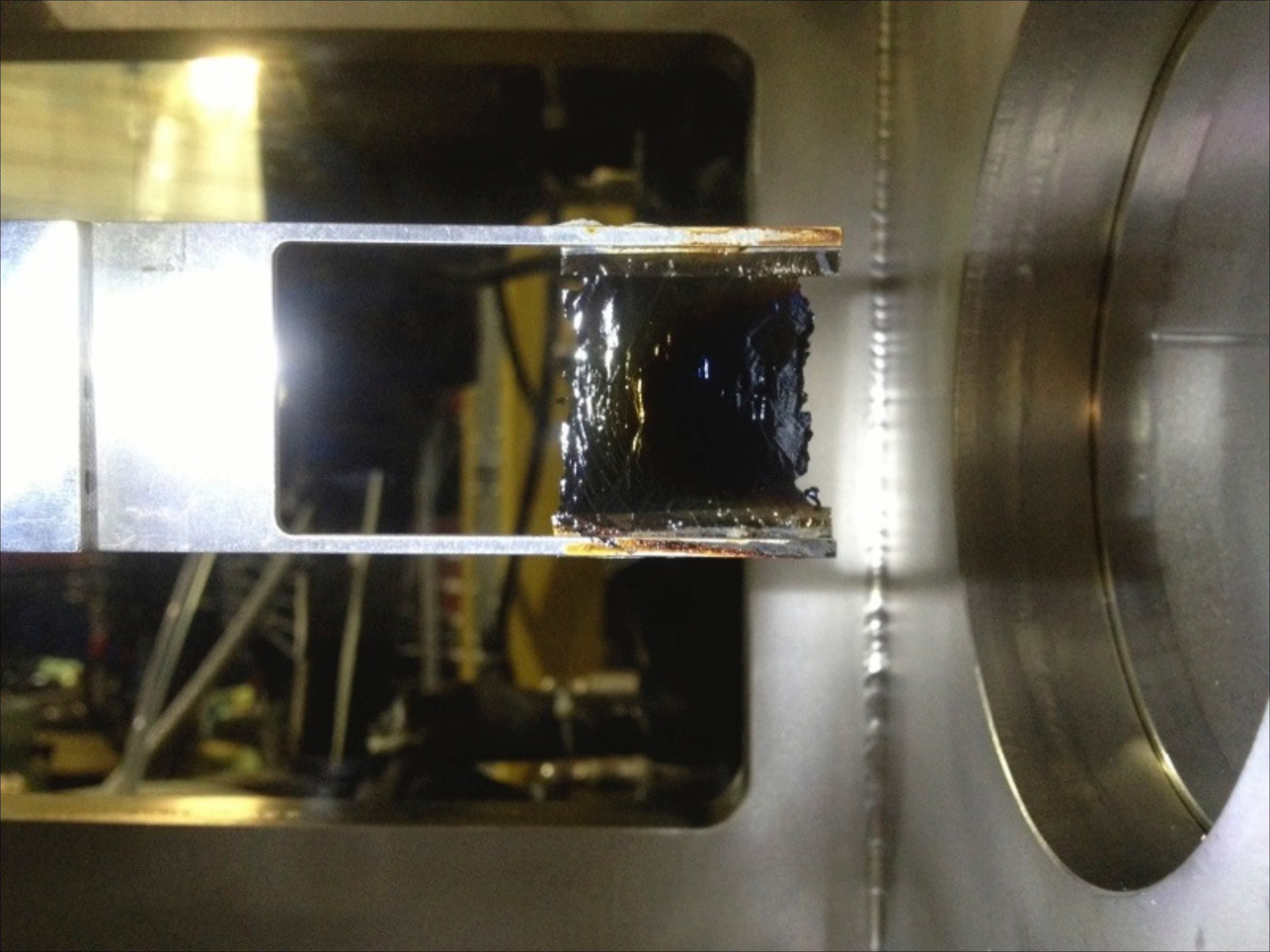
Emittance growth due to the multiple scattering by charge stripping foil

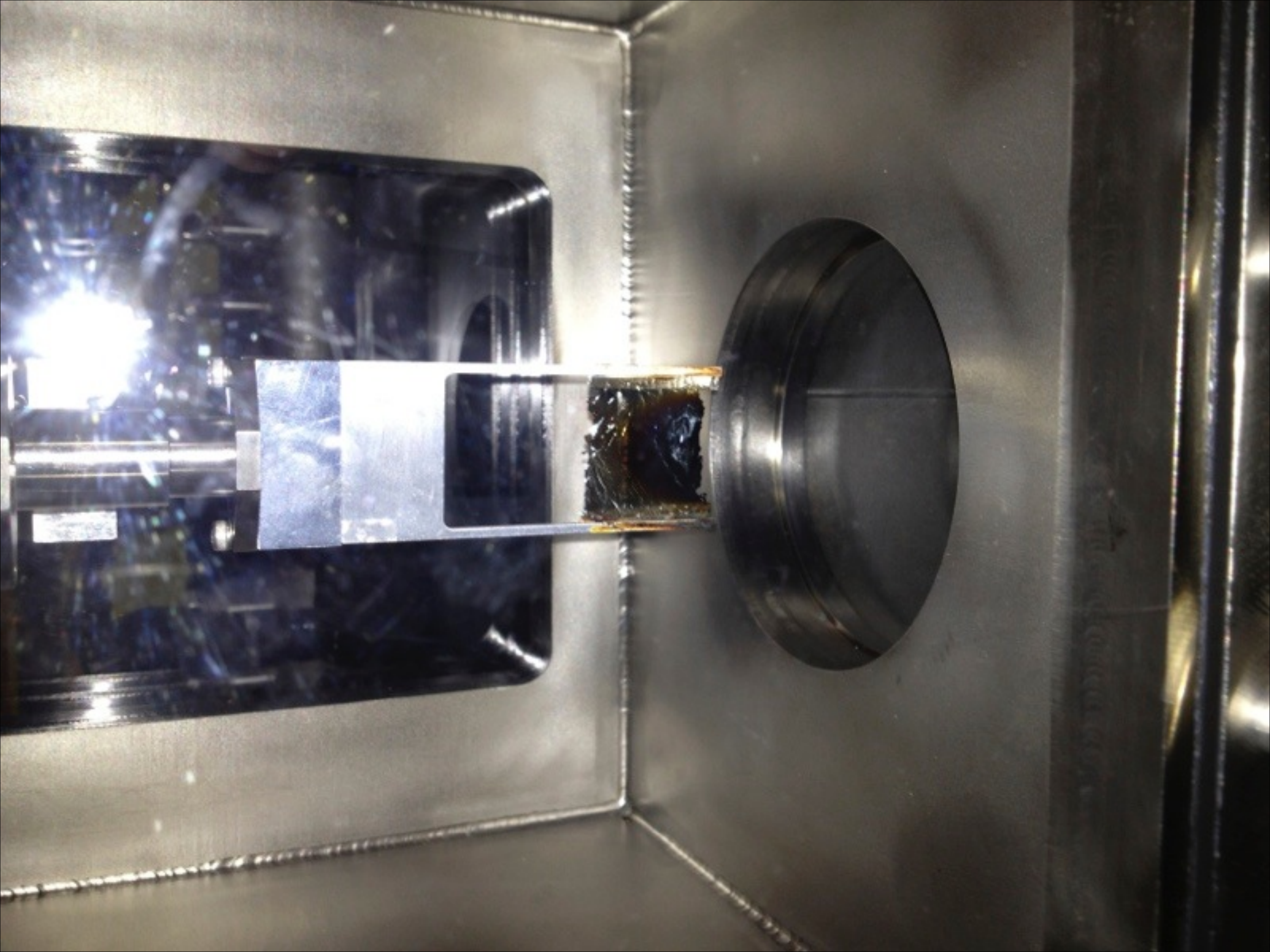
brand-new foil
20 ug/cm2





after 1.5 years...

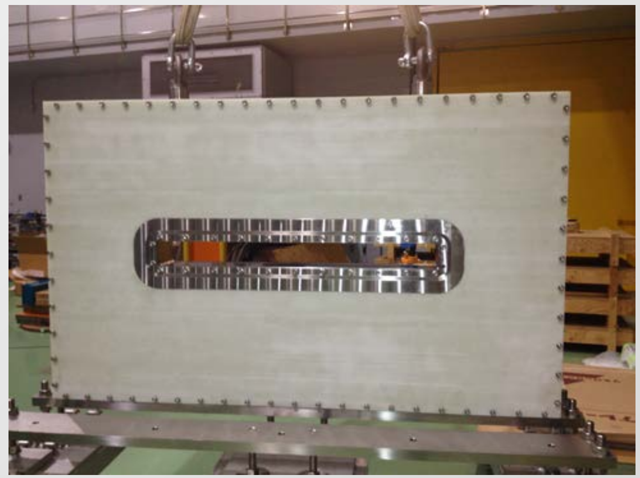




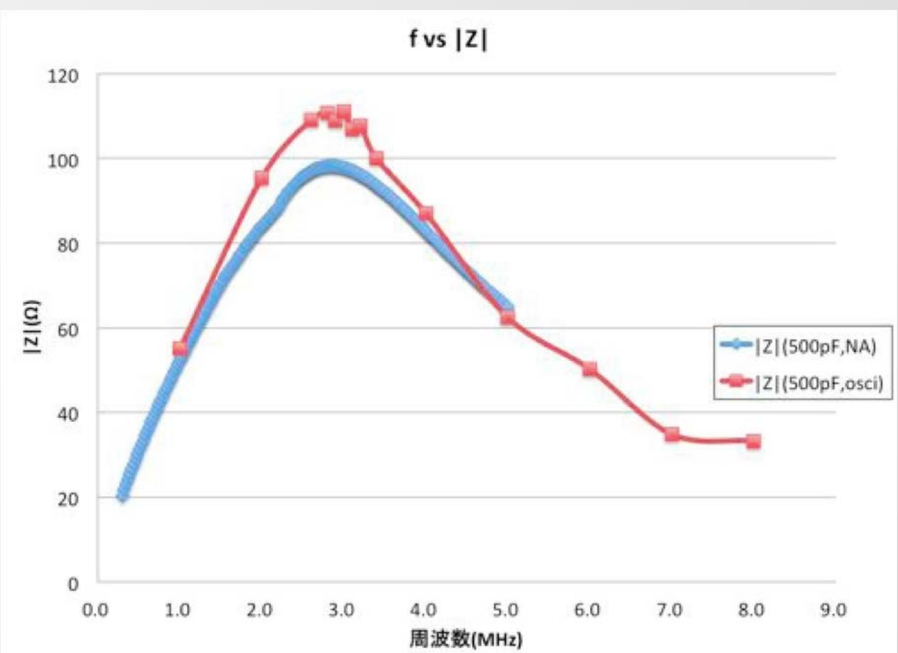
ビーム増強の手段

- 加速電圧の増強（空洞台数：1台→2台）
  - 捕獲・加速効率アップ
  - 繰り返し（ 20Hz → 100 - 200 Hz)アップ
  - 共鳴によるビームロスの低減
- 極薄フォイルの開発（ 20ug/mm^2 → 10ug/mm^2)
  - ビームとフォイルの衝突によるエミッタンス増大を抑制
  - アニール等による強度アップ
- COD補正（ビーム診断系・補正電源追加）
  - アパーチャーの拡大
  - 共鳴によるビームロスの低減
- ライナックエネルギー増強
  - 空間電荷効果の緩和

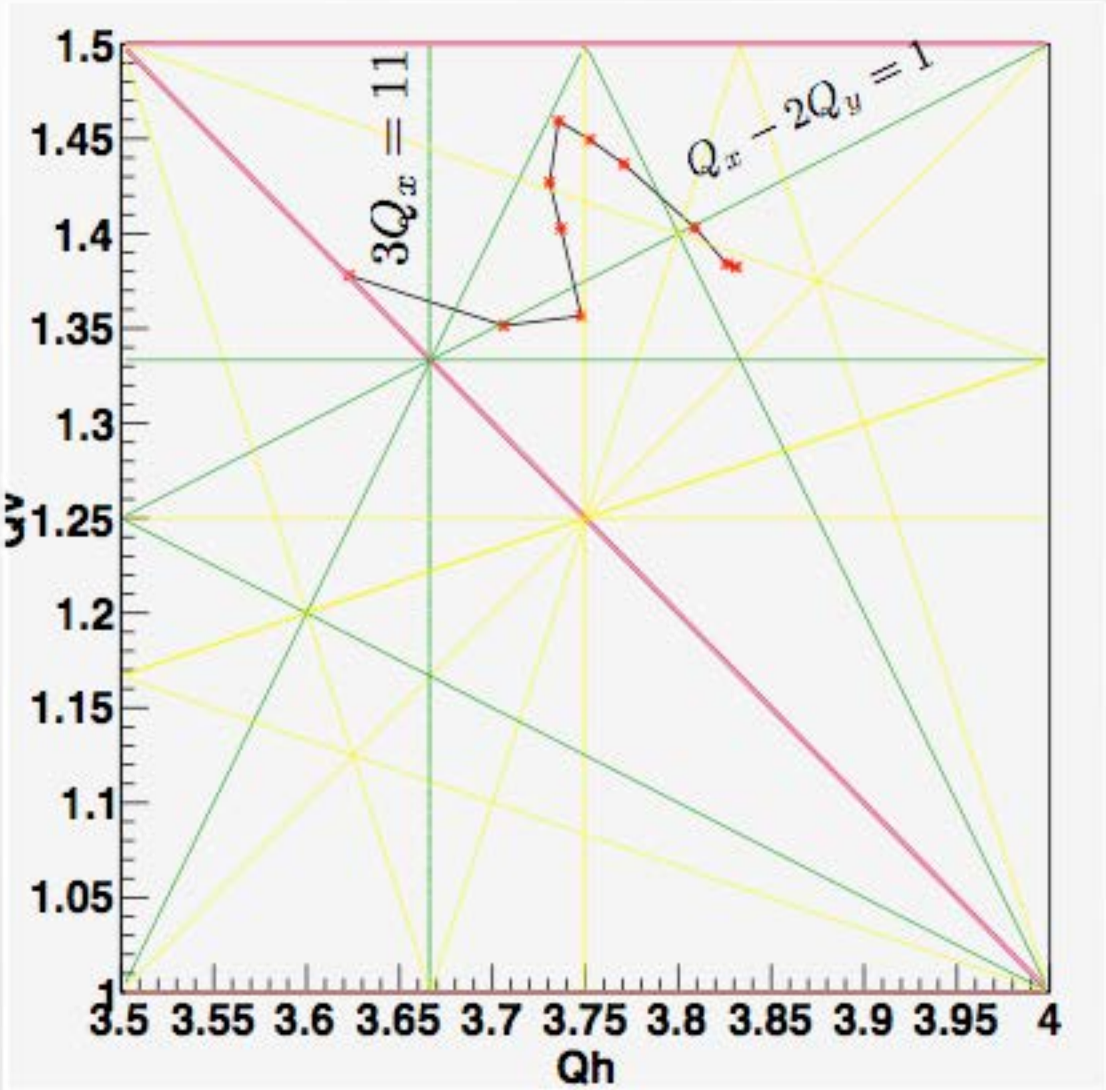
PETAL CORE CAVITY



1. New installation of another rf cavity to obtain higher accelerating voltage. (4kV → 2 x 4 kV)
2. Reuse of damaged circular core for wide aperture cavities.
3. A low-power measurements has been done.
4. With this new cavity, rep. rate 100 Hz can be accomplished.



横方向（ベータトロン振動）の共鳴によるロスを低減する



$$lQ_h + mQ_v = n$$

$|l| + |m|$ 共鳴の次数

n ハーモニクス

リングの対称性を上げる

→COD*補正

共鳴線通過時間を短くする→

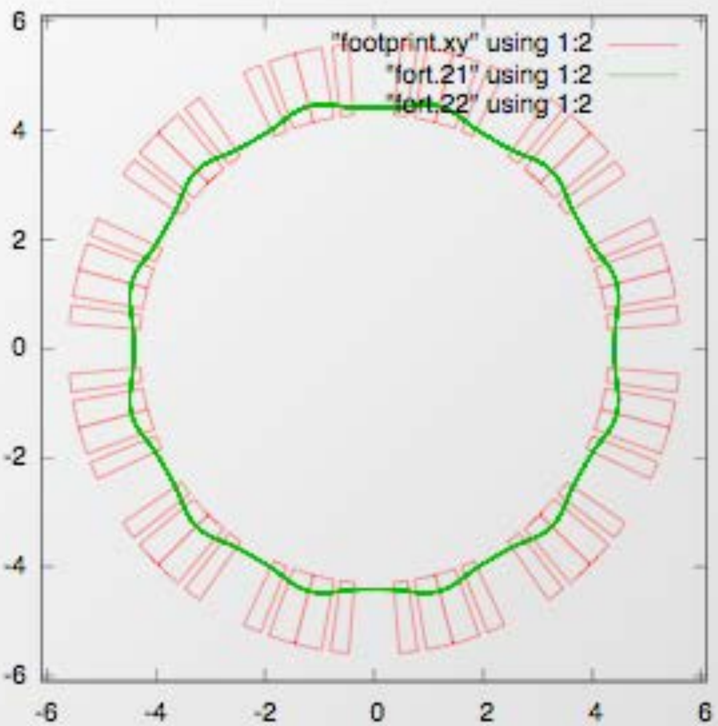
加速時間の短縮

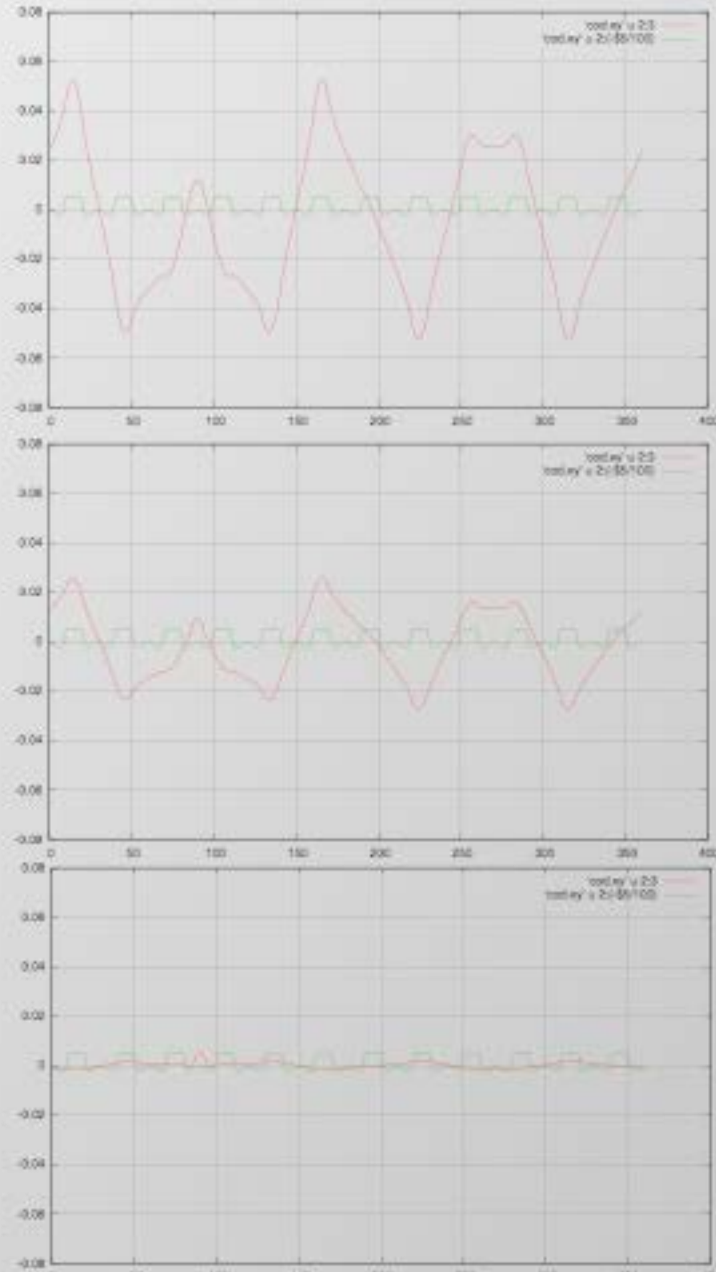
（加速電圧強化が必要）

おまけ（繰り返しが上がる）

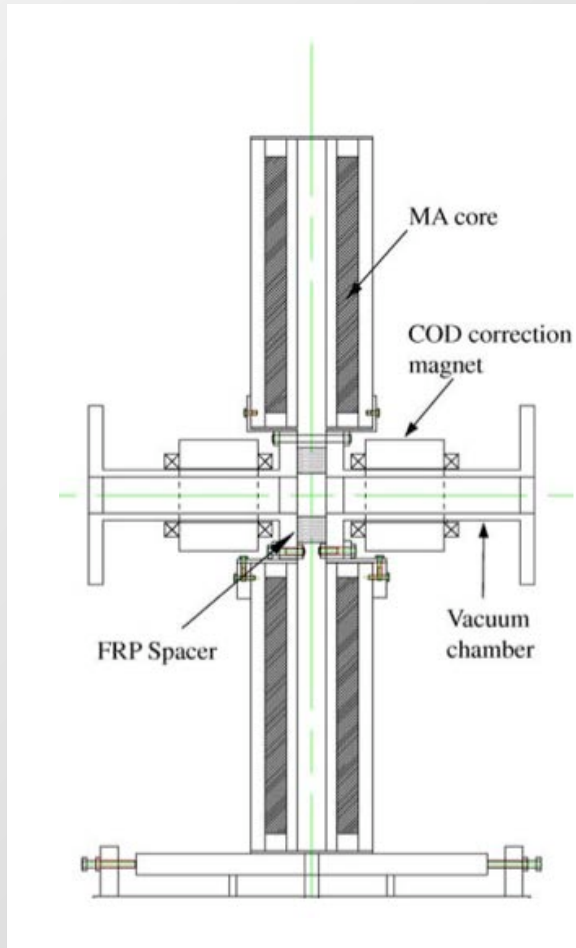
*COD (Closed Orbit Distortion)

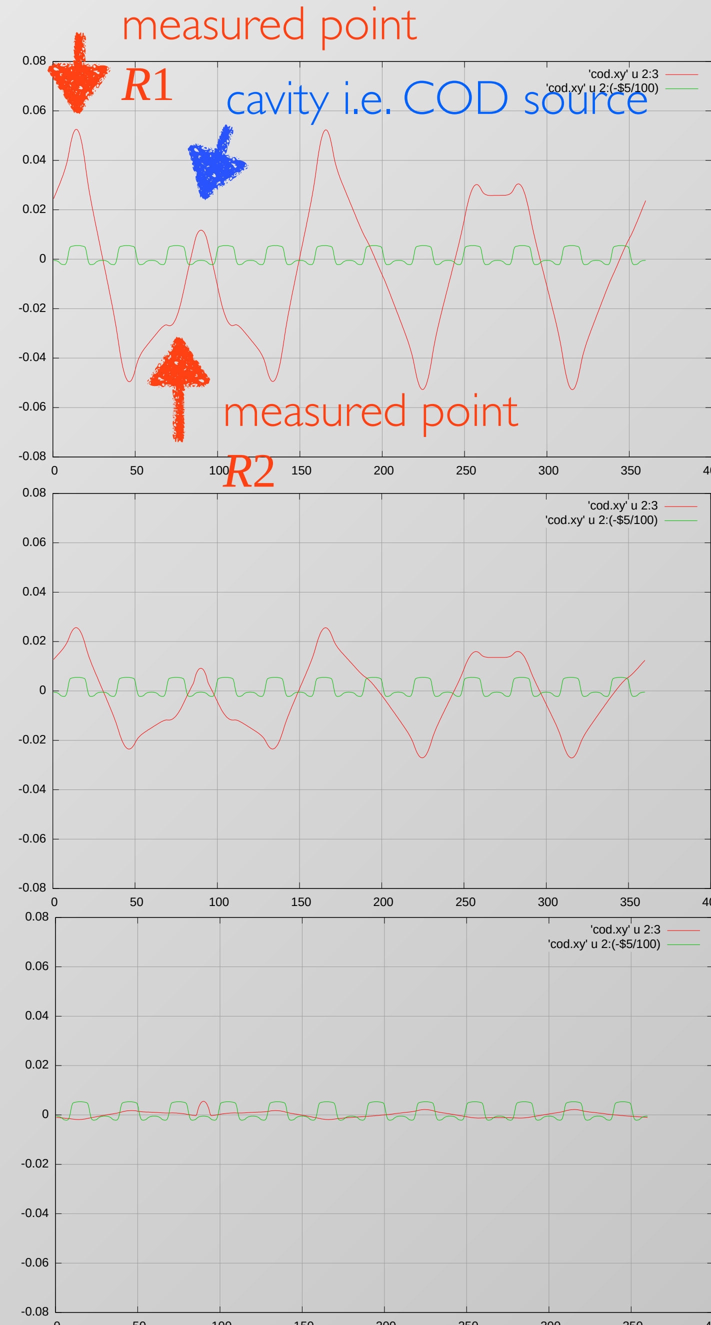
COD補正


"footprint.xy" using 1:2
"fort.21" using 1:2
"fort.22" using 1:2
6
4
2
0
-2
-4
-6
-6
-4
-2
0
2
4
6



COD correction by the correction dipoles





空間電荷効果によるチューンシフト

$$\Delta\nu_{y,\mathrm{inc}} = -\frac{N r_0 R}{\pi \nu_y \beta^2 \gamma}\left(\beta^2 \frac{\epsilon_1}{h^2} + \beta^2 \frac{\epsilon_2}{g^2} + \frac{F/B}{\gamma^2 b(a+b)} \right)$$

$$= -2.25 \times 10^{-5}\ \mathrm{m}^{-2} \times (4.\ \mathrm{m}^2 + 3.\ \mathrm{m}^2 + 14004.\ \mathrm{m}^2)$$

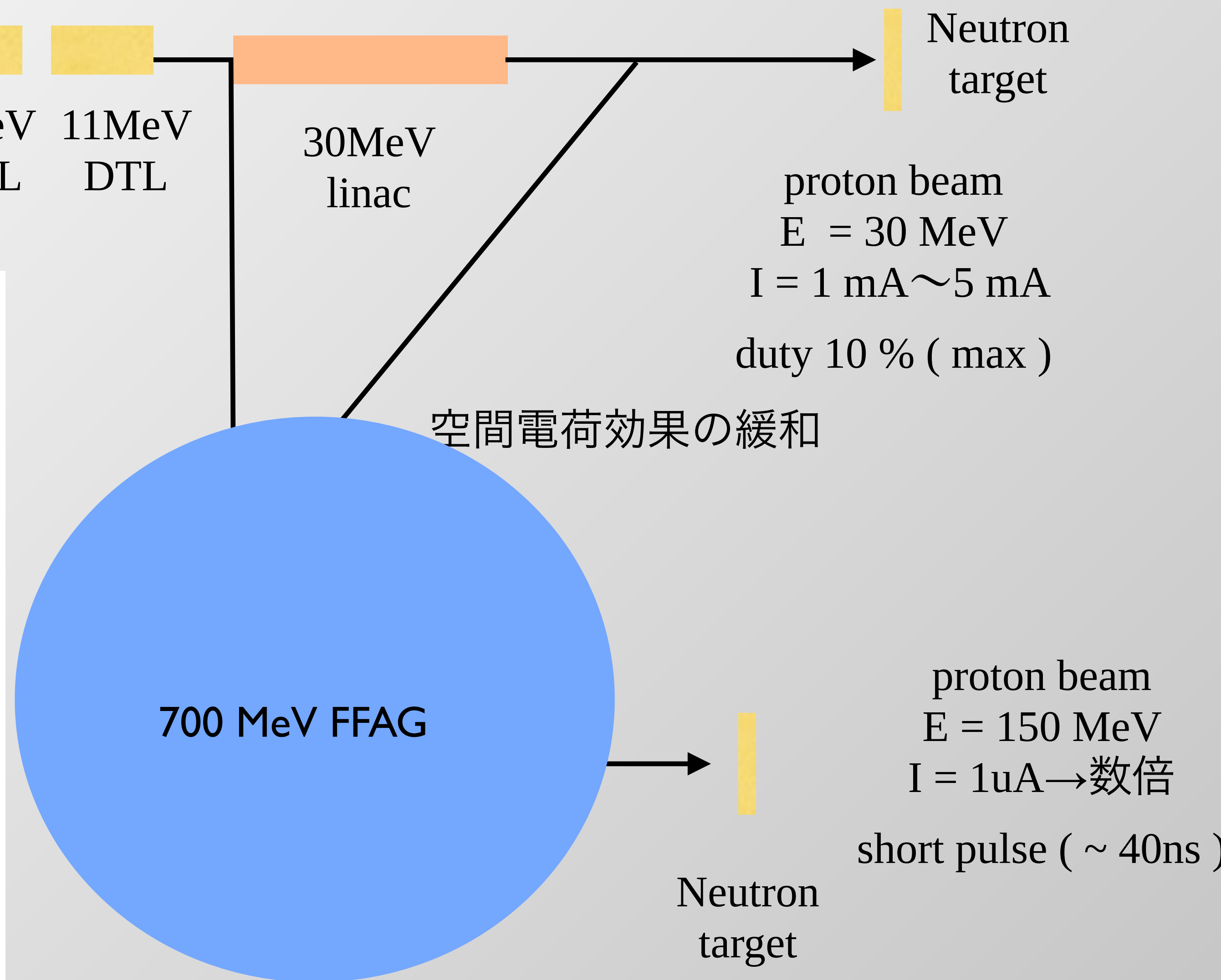
$$= -0.315$$

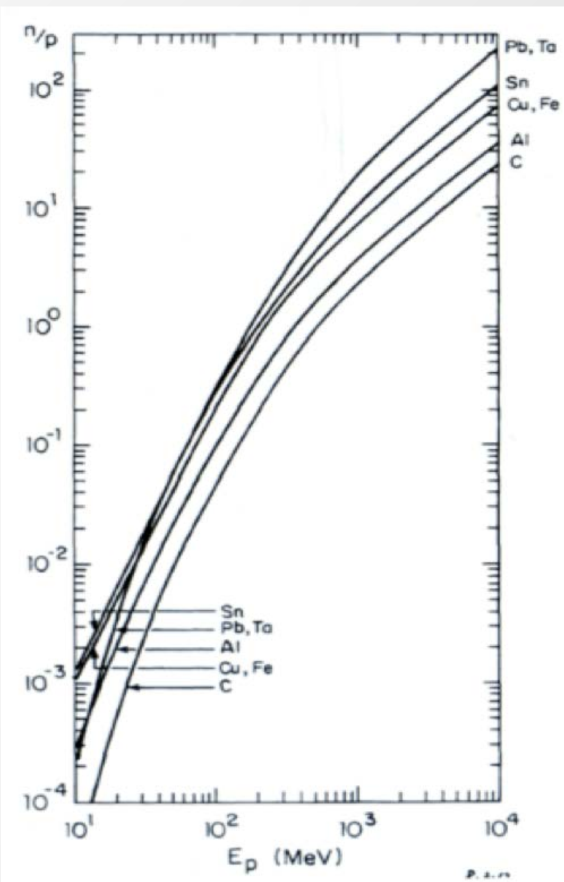
N	3.125×10^{11} /ring	（仮に）1 μA-20 Hz 相当
r_0	1.53×10^{-18} m	陽子
R_0	4.54 m	入射軌道平均半径
β, γ	0.147, 1.011	11 MeV
ν_x, ν_y	(3.7,1.4)	入射エネルギーで
(a, b)	(20,15) mm	
B_f	1/5	
F	1.5	
h	32.5 mm	真空チェンバーギャップ/2
g	37.9 mm	磁極ギャップ/2

運転繰り返し：100 ~ 200 Hz

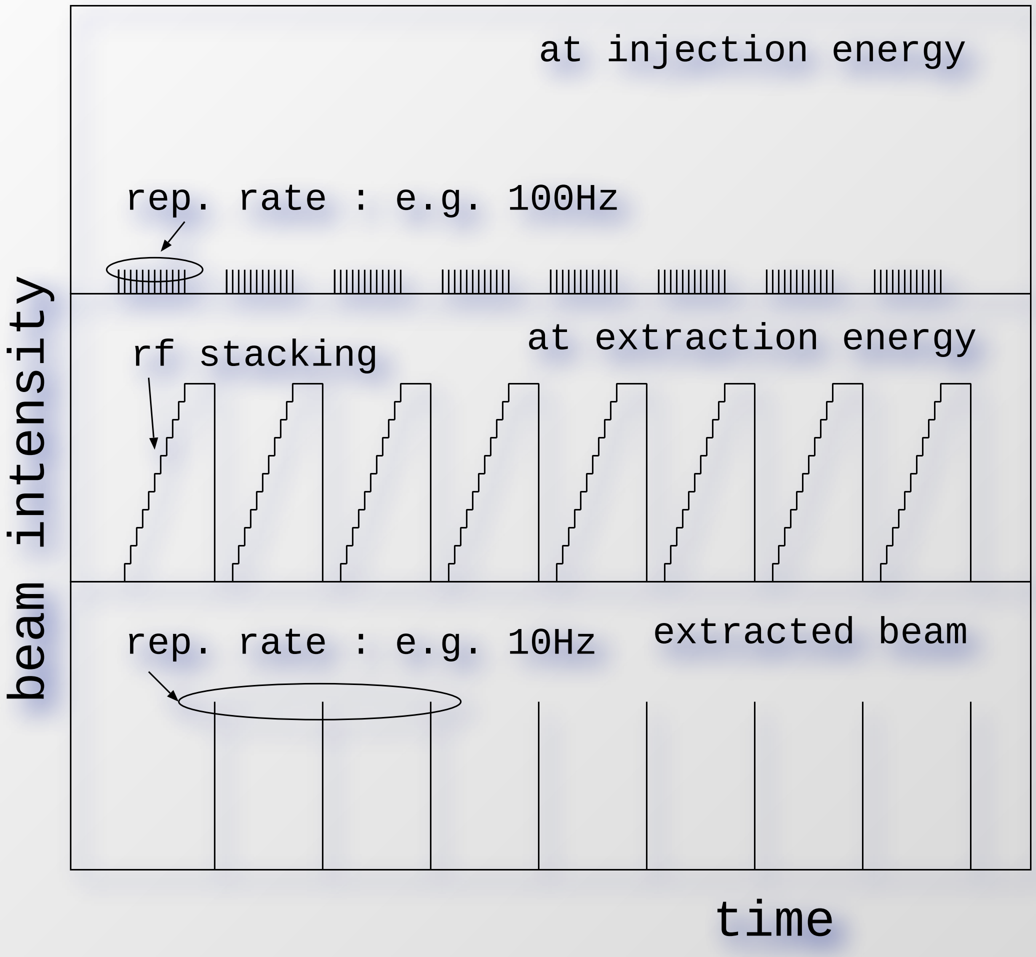
平均ビーム強度：5uA

加速器中性子源案（Linacベース）





RF stacking at the extraction energy



Some users desire low spill rate (~10 Hz) for the experiments e.g. neutron radiography using TOF which needs to get rid of contamination from the pulse of different timing.

FFAG rings can provide long interval pulse for users, while the machine operation itself is kept at high repetition rate by using rf stacking after acceleration[1].

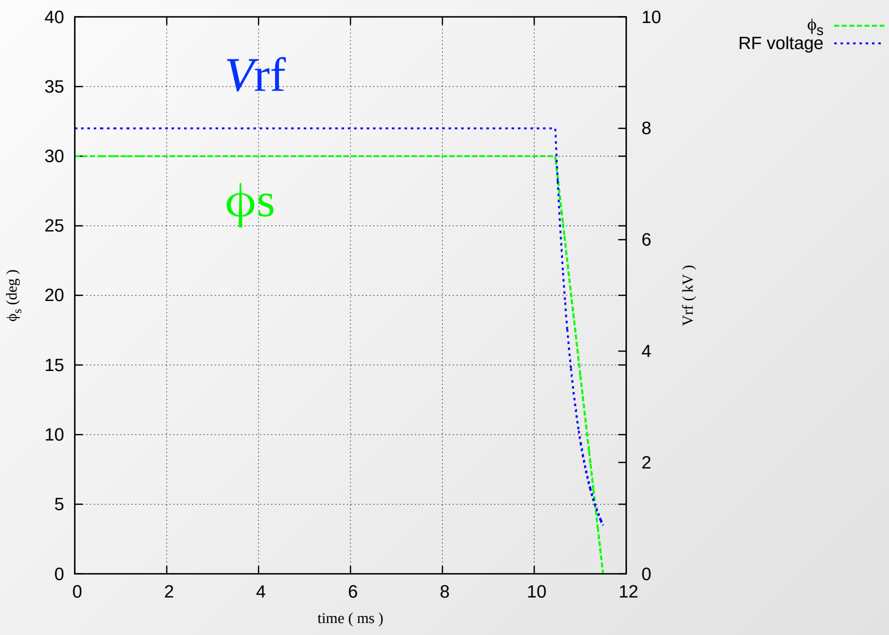
This scheme reduces space charge effects at injection energy.

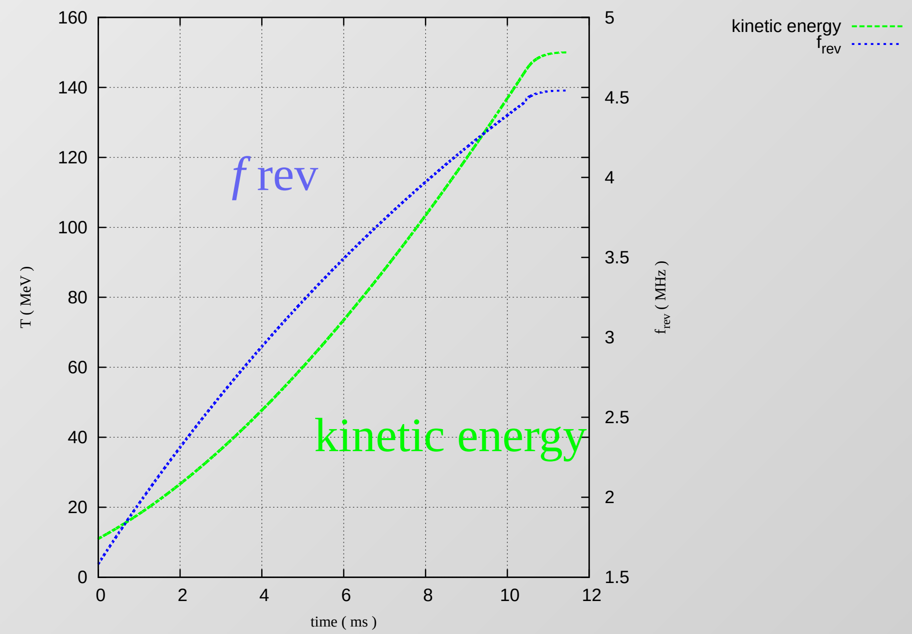
[1] S.Machida,"RFStackingatExtractionMomentum",FFAG Workshop 2003,October 13-17, 2003 at BNL, http://www.cap.bnl.gov/mumu/conf/ffag- 031013/Machida2.pdf.

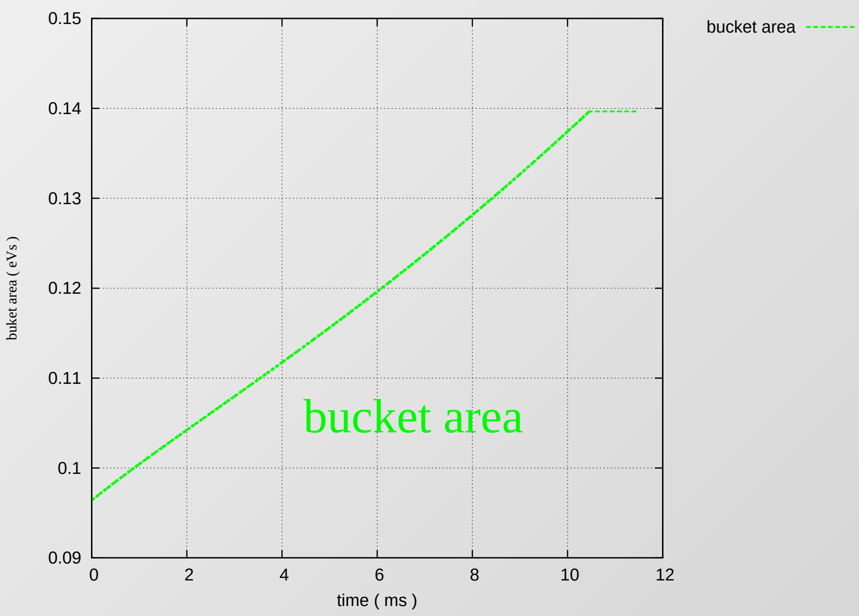
Machine parameters used in the simulation

field index k	7.7
kinetic energy T	11 - 150 [MeV]
momentum p	144 - 551 [MeV/c]
circumference C	28.8 - 33.6 [m]
momentum compaction factor α	0.115
rf voltage $V_{\rm rf}$	8 [MV]
rf frequency $f_{\rm rf}$	1.6 - 4.4 [MHz]
harmonic number h	1

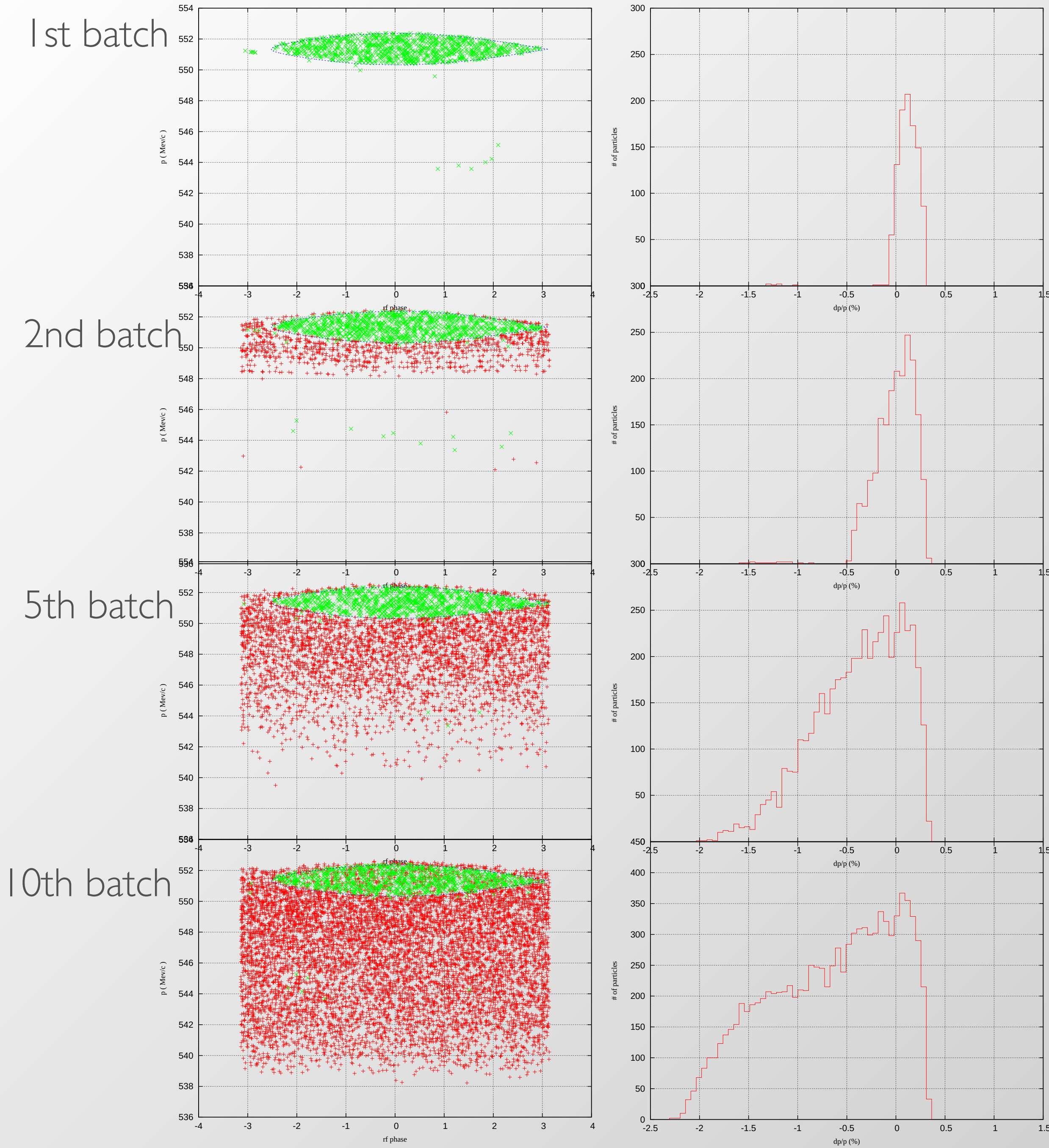
RF Scenario







In the real machine operation, we use similar scenarios in which synchronous phase **φ**s and rf voltage are fixed at 30 degree and 4 kV respectively during all the acceleration period. On the other hand, in the scenario used in this simulation study, **φ**s is dropped off linearly from 30 to zero degree when the energy of the beam is between 145 and 150 MeV for soft- landing.The rf voltage is also reduced in this region so that the bucket area is constant in order to make momentum spread small at the end of acceleration.



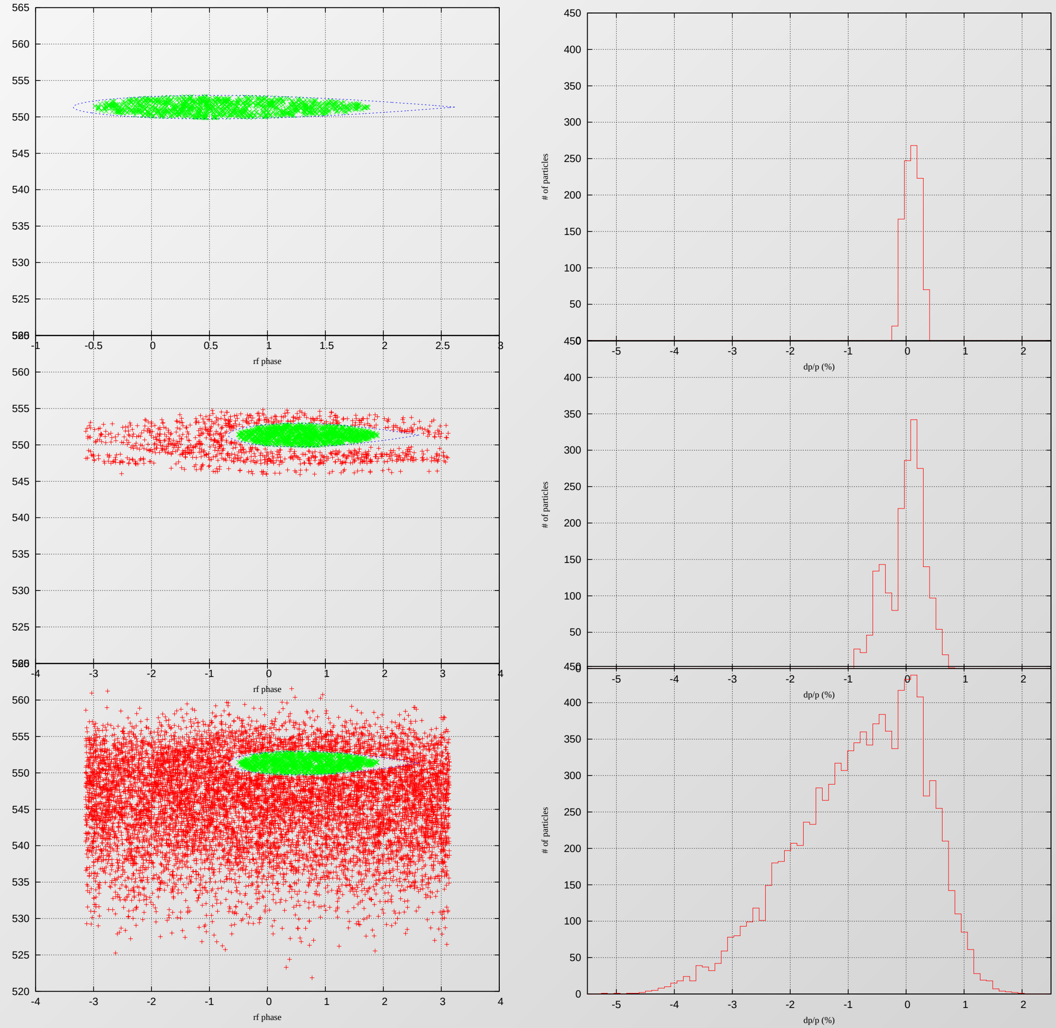
Stacking processes are simulated using 1 000 test particles for each acceleration batch.After first acceleration, full width of momentum spread is about 0.5%, the final momentum spread after 10 stacks is 2.5% of full width.

w/ soft-landing

1st batch

5th batch

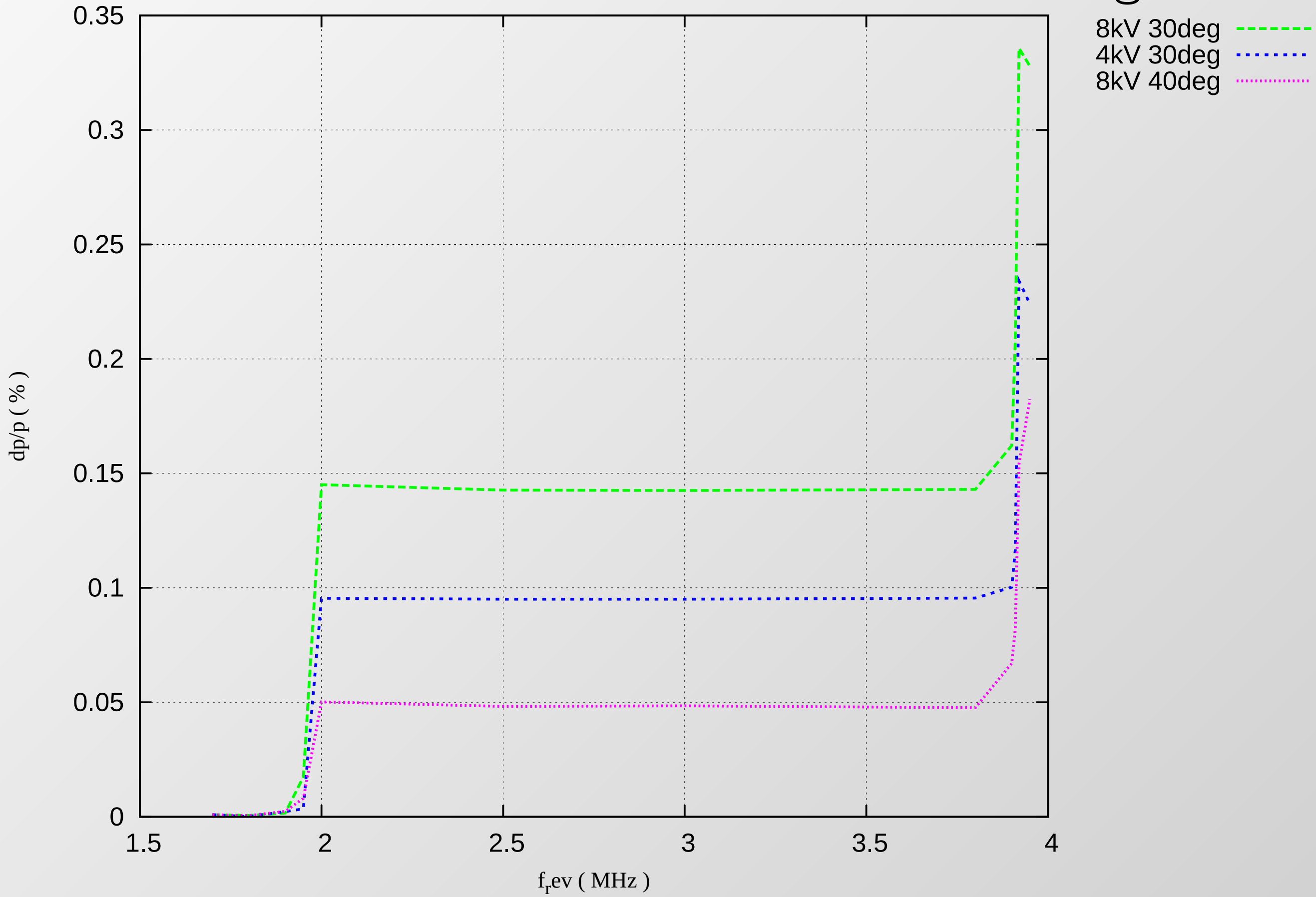
10th batch



Without soft-landing the final momentum spread after 10 stacks is 5% of full width i.e. twice as large as with soft-landing.

w/ soft-landing

Perturbation from the rf bucket to the coasting beam



Check if the acceleration bucket affects the stacked beams coasting around the extraction orbit.
Generate zero emittance test beam (100 MeV) with $\Delta p/p = 0$ and uniformly distributed in the rf phase.
Check if momentum spread is blowing up, while the accelerating bucket is coming up.
There are two steps around 2 MHz and 4 MHz in each case.
Step around 4 MHz : direct disturbance of the bucket.
Step around 2 MHz : f_drive = 1/2 f_rev(stack)
It seems that coasting beam can be affected when the accelerating bucket is passing through the frequency which is half of revolution frequency of the coasting beam.

まとめ

- 2012年度はビーム運転時間の約3/4をユーザに供給した。この期間は半年以上にわたる。
- ユーザによる成果報告が多数なさる一方、安定したビーム供給が要求されている。
- ビーム診断系および制御系の更新を継続中である。
- 先に上げた４つの方法を念頭にビーム増強を推進中である。
- 平均ビーム強度5uAをめざす。


Thank you for your attention!