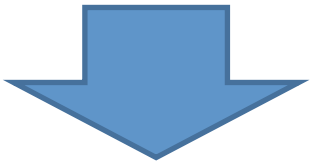
Development of the extraction kicker at Kyushu University

Takashi Matsunaga (Kyushu Univ.)

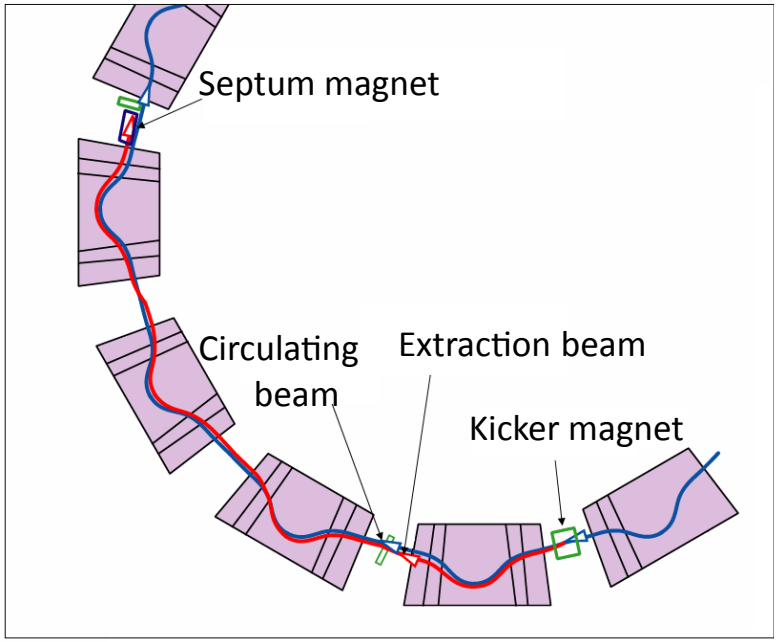
Introduction

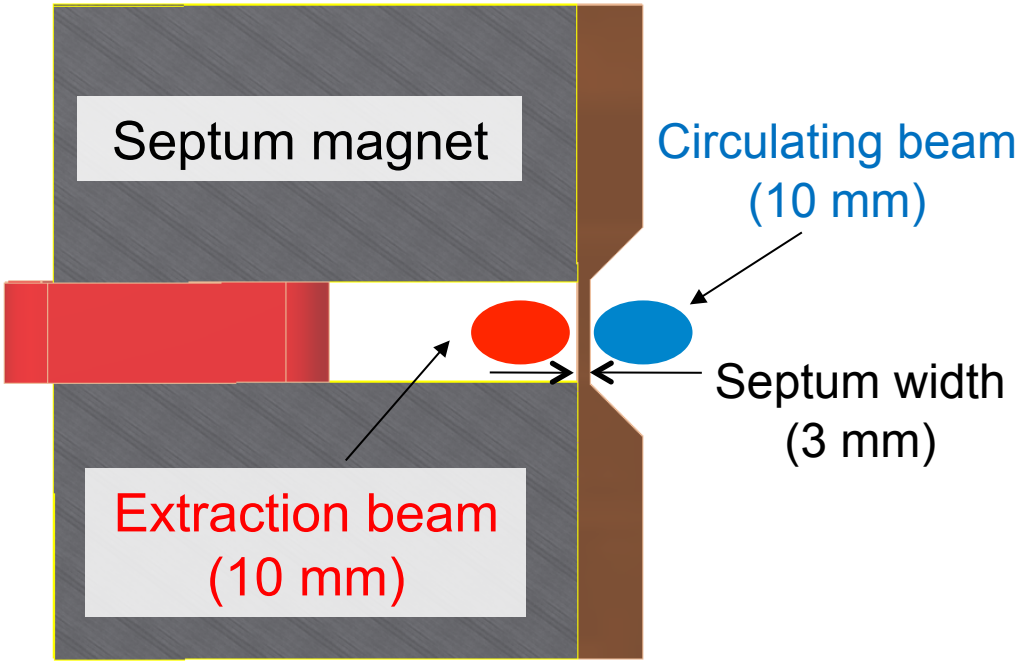
In case of 150-MeV FFAG accelerator,
10% of the extraction beam was lost
at the septum magnet at KEK.

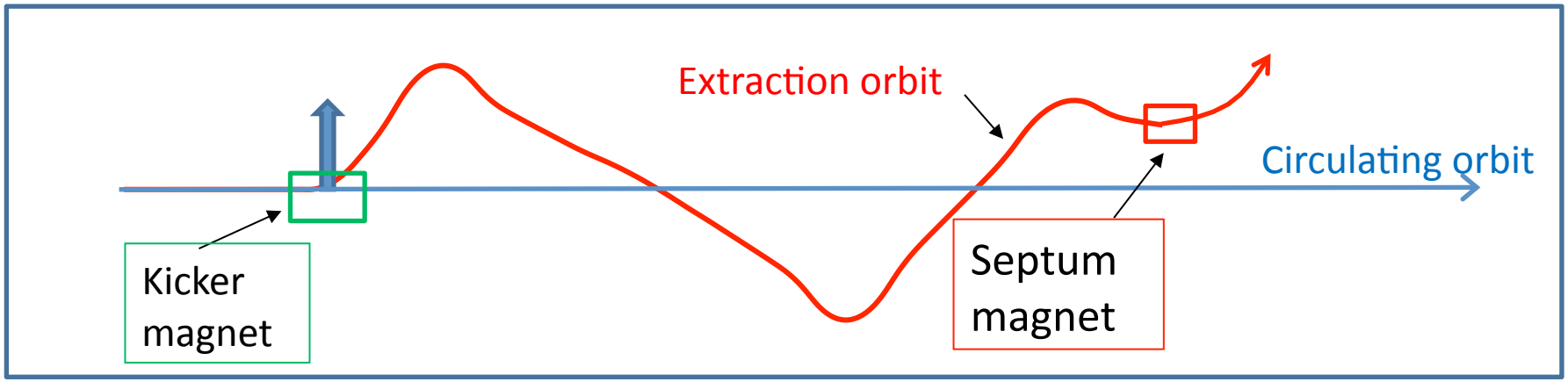


It is important to reduce the beam loss
in order to utilize the FFAG accelerator
for various applications at Kyushu University.

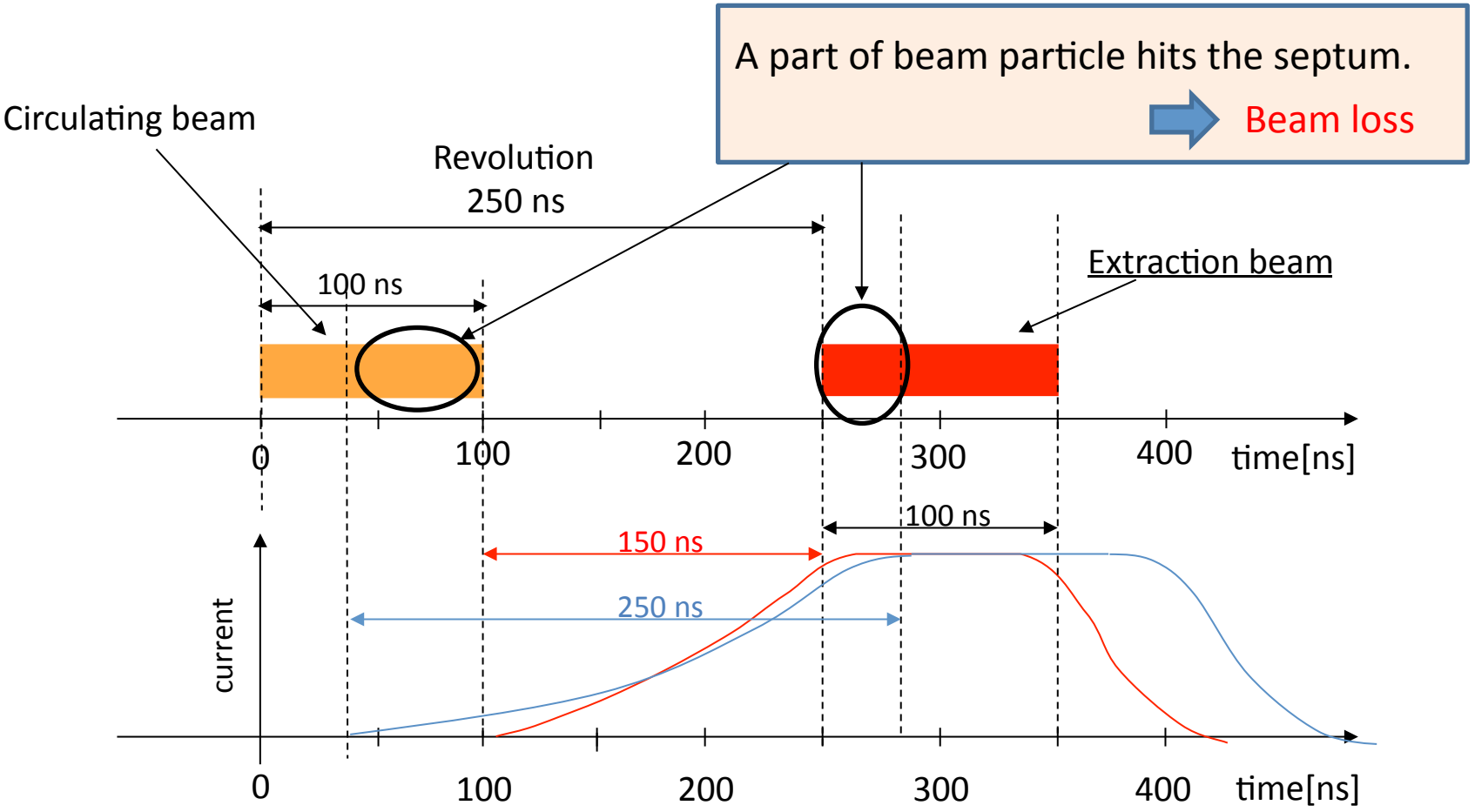
Beam extraction system of 150 MeV FFAG







Requirements for the kicker magnet



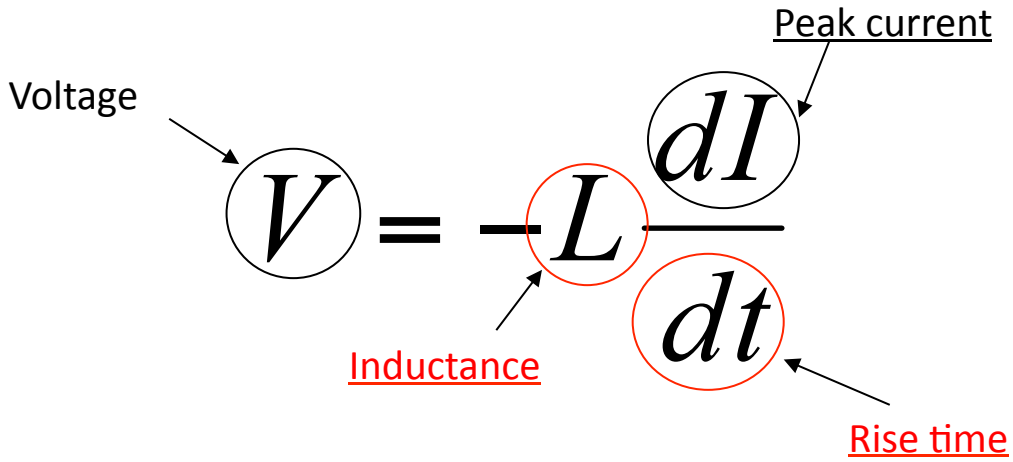
- Rise time is required less than 150 ns.
- Flat top is required more than 100 ns.

Purpose of study

Development of the kicker with fast rise time in order to increase extraction efficiency

Principle of rise time and inductance

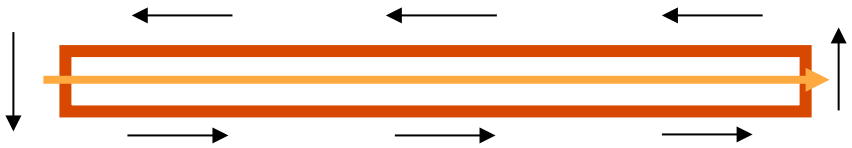
This is equation of self-induced electromotive force.



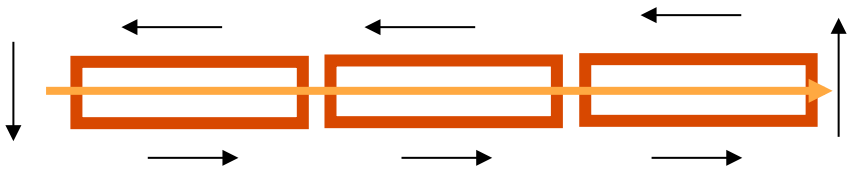
Smaller inductance realizes faster rise time.

New type of kicker magnet

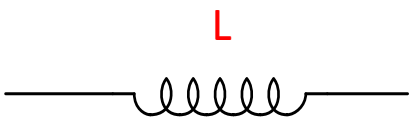
To reduce the inductance of the kicker, coil is divided into 3 parts.



present Kicker (1700A)

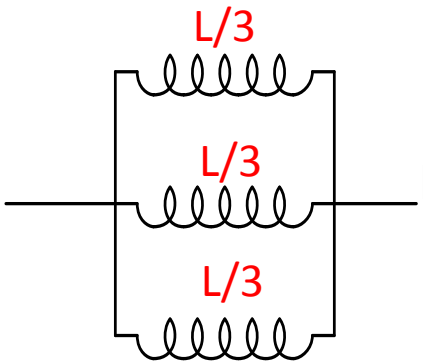


New type of Kicker (1700A x 3 = 5100A)



Measured inductance:
6.5 μH

1/9



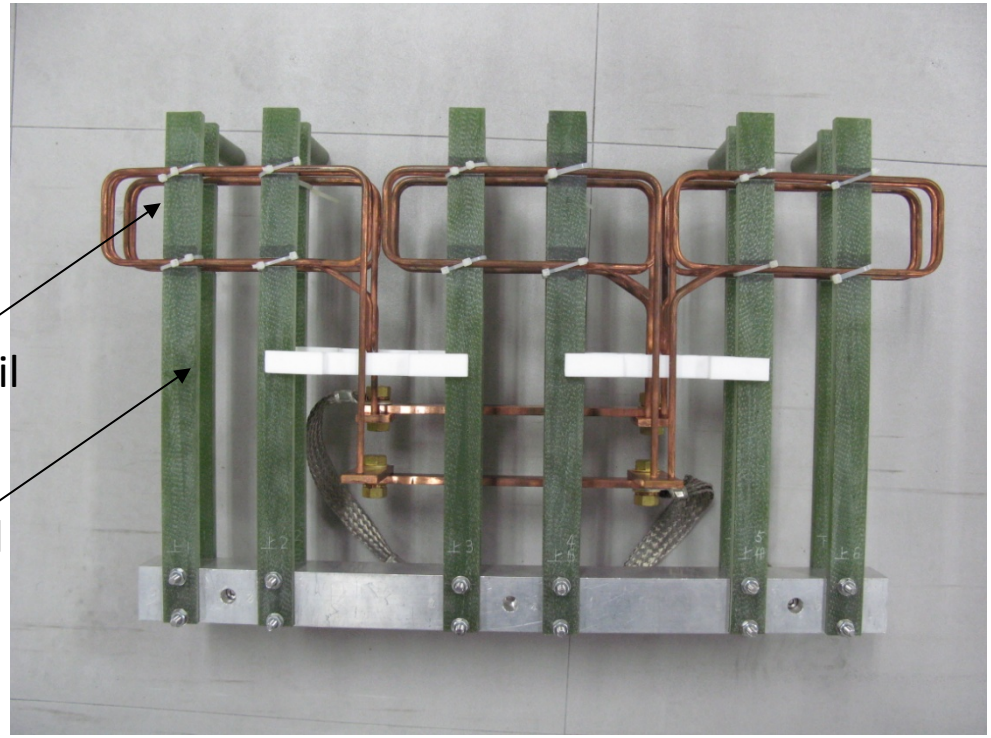
Estimated inductance:
0.72 μH

In case that the current is 5100 A, the voltage is 40 kV,
and the rise time is less than 150 ns,

The inductance is required to be less than 1.0 μH.

Development of kicker(1)

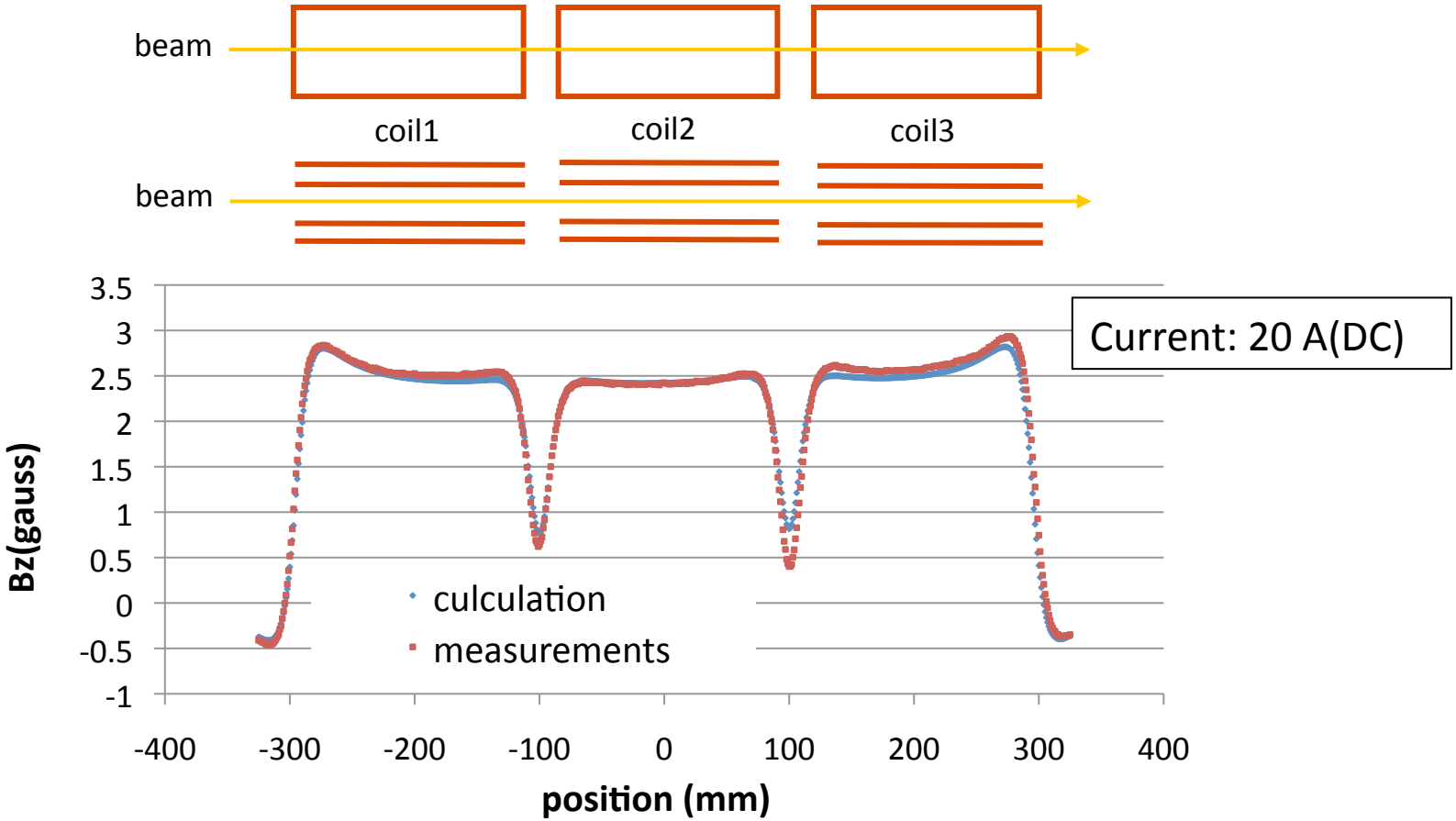
This is the kicker developed at Kyushu University.



- The three divided air core coil is connected in parallel.
- Each coil is supported by FRP board.

Measured inductance is 0.95 μH.

Development of kicker(1)



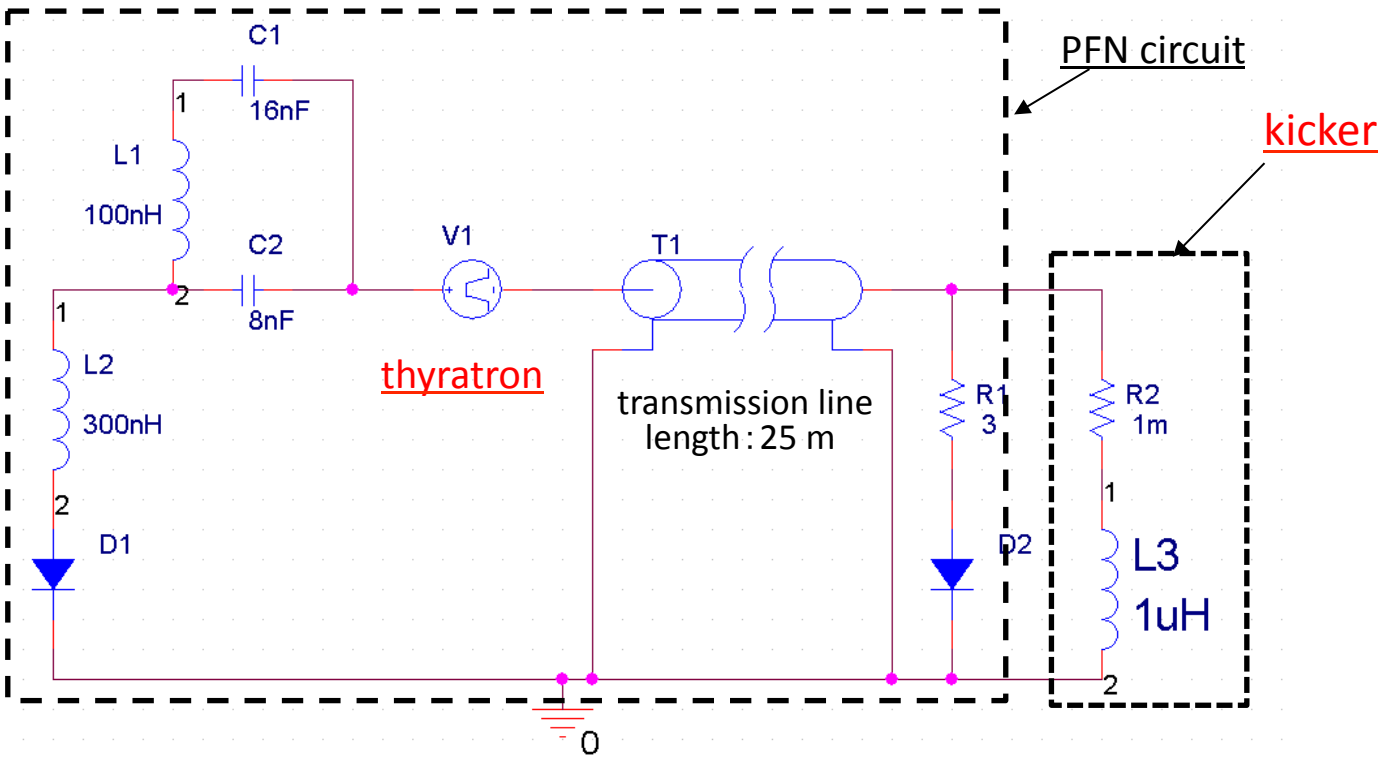
Measured magnetic field of the kicker agrees with the calculation.

Development of Power source(1)

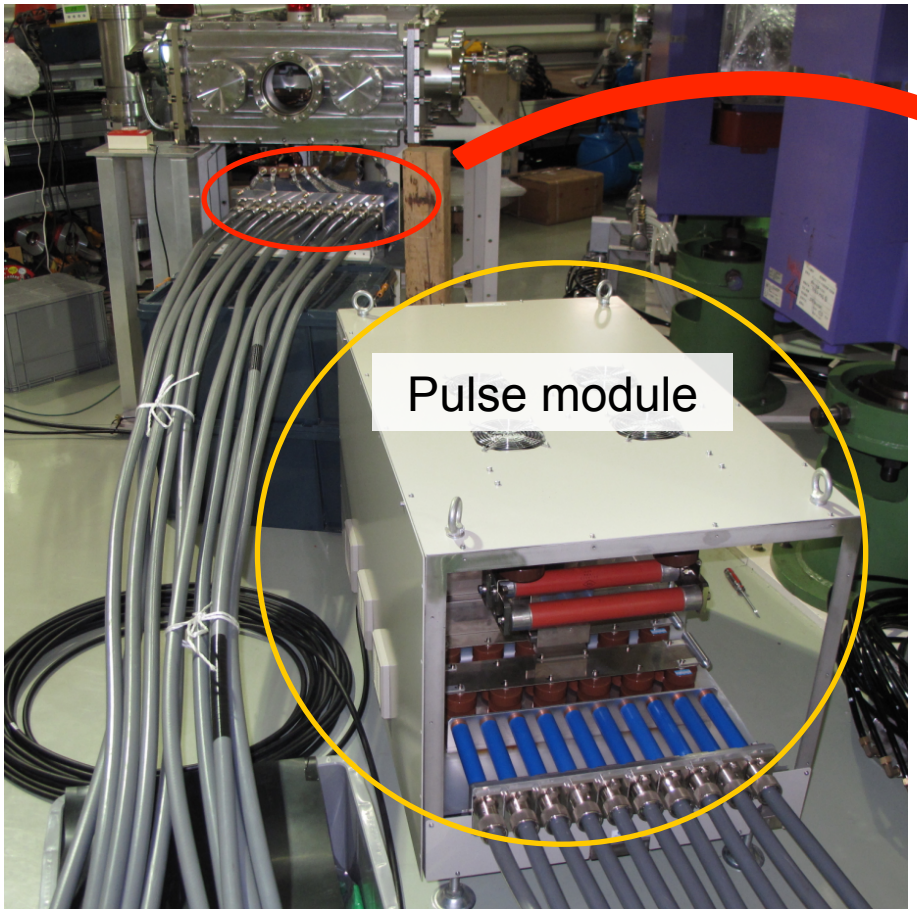
Requirements for power source

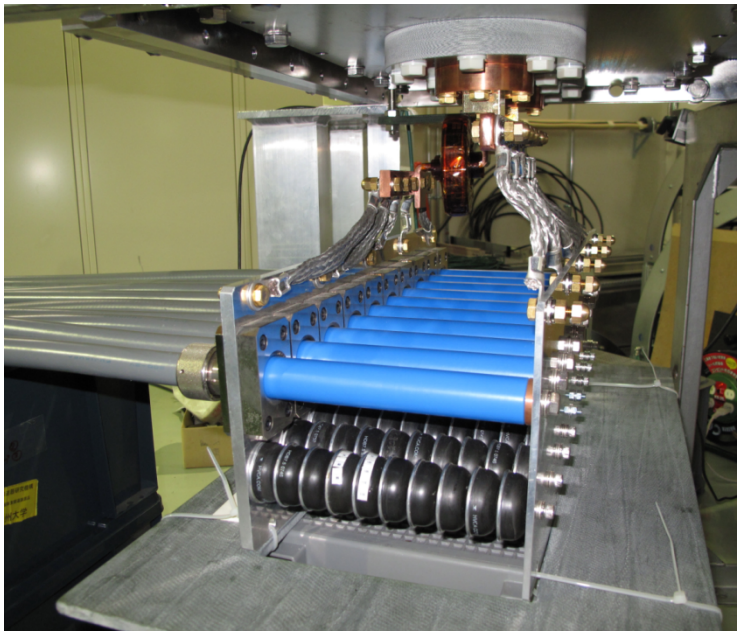
- Peak current : 5100 A
- Maximum voltage : 40 kV
- Rise time : 150 ns
- Flat top : 100 ns

- The power source consists of PFN circuit and thyratron.



Development of Power source(2)



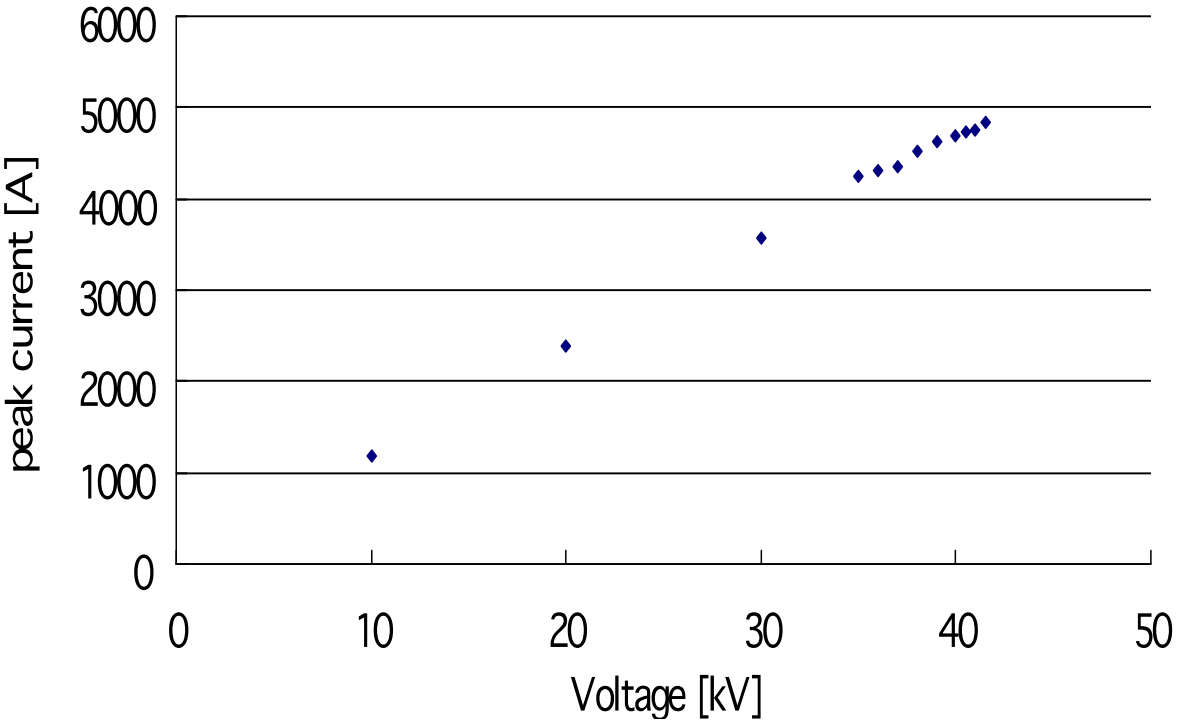


This is diodes for rectification circuit

This set up increases the inductance of the kicker by 0.15 μH

Power test(1)

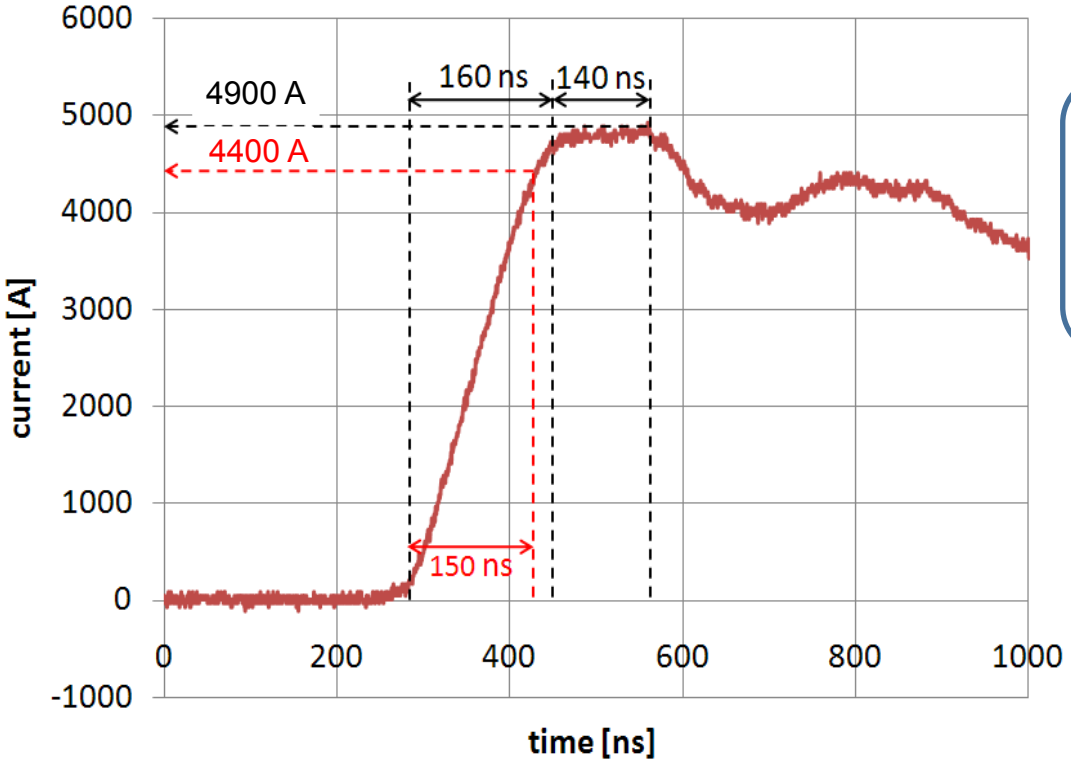
This graph shows the relation the peak current of the kicker to the voltage of the power supply.



The power source operated from 10 kV to around 40 kV

Power test (2)

this graph shows current waveform of the power test.



Experiment condition

Kicker : 0.95 μH
Additional inductance :0.15 μH
Voltage : 41.5 kV(pulse)

Result

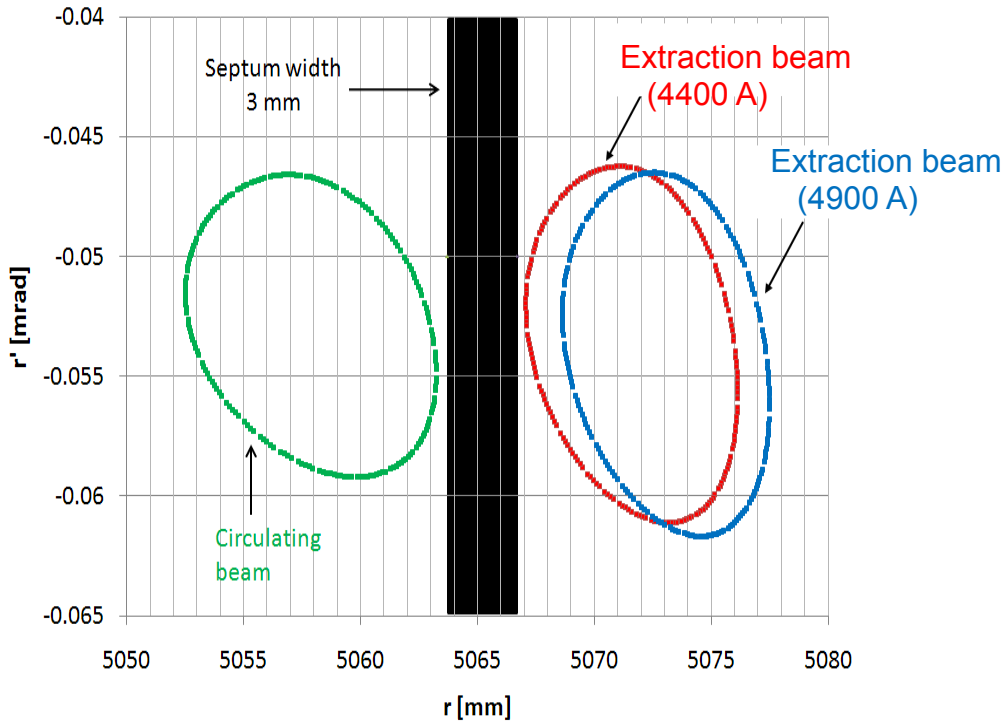
Rise time(5-96%):160 ns
Flat top(more than 96%):140 ns
Peak current:4900 A

Peak current and rise time don't meet the requirements,
because the total inductance exceeds more than 1.0 μH

→ Is there any beam loss in this case?

Simulation of the beam extraction

The extraction beam kicked when the current of the kicker is from 4400 A to 4900 A.



The extraction beam doesn't hit the septum,
but the distance between the extraction beam(4400 A) and the septum is very short.

It is important to reduce the additional inductance

Summary

Purpose of study

Development of the kicker with fast rise time
in order to increase extraction efficiency

We designed a new type of the kicker

- The kicker coil was divided three part of coil

The new kicker was developed

- Inductance of the developed kicker is 0.95 μH

The power source for the kicker was developed

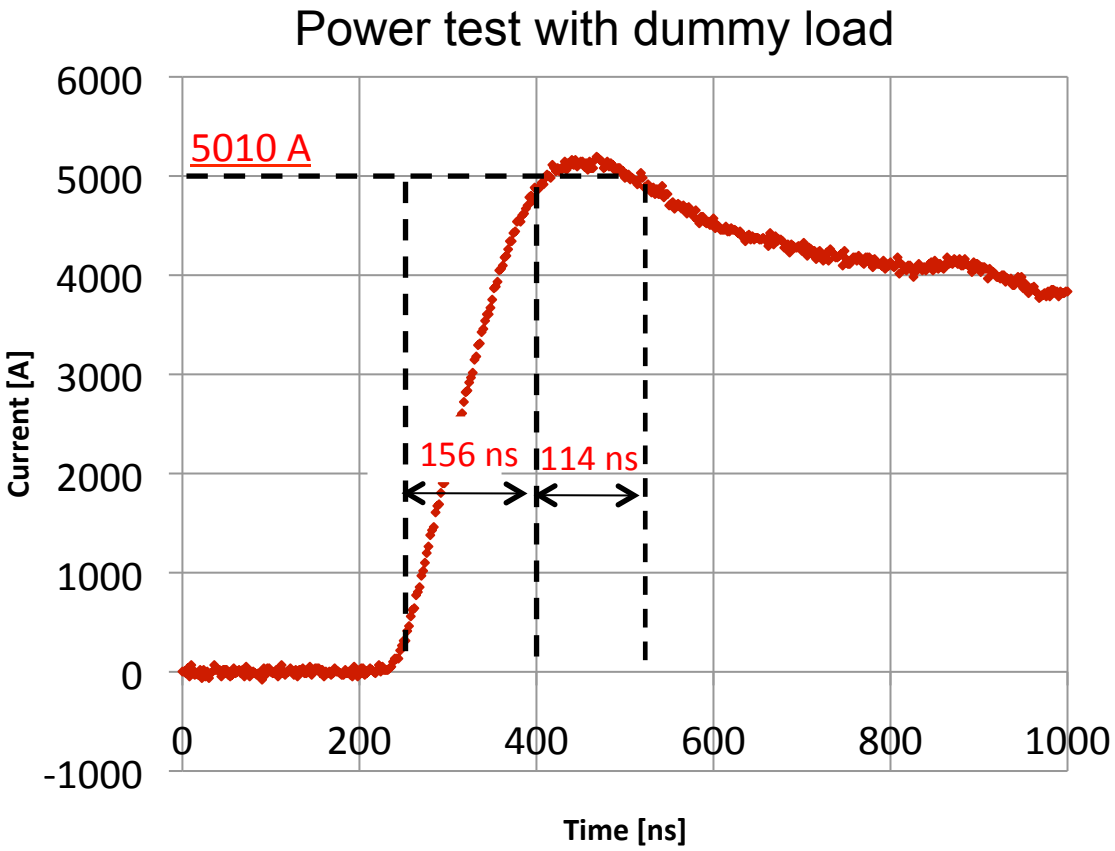
- Rise time of kicker current is 160 ns,
  and flat top is 140 ns.

The extraction beam doesn't hit the septum.

But it is necessary to reduce the additional inductance.

Thank you for listening to my presentation

Power test(1)

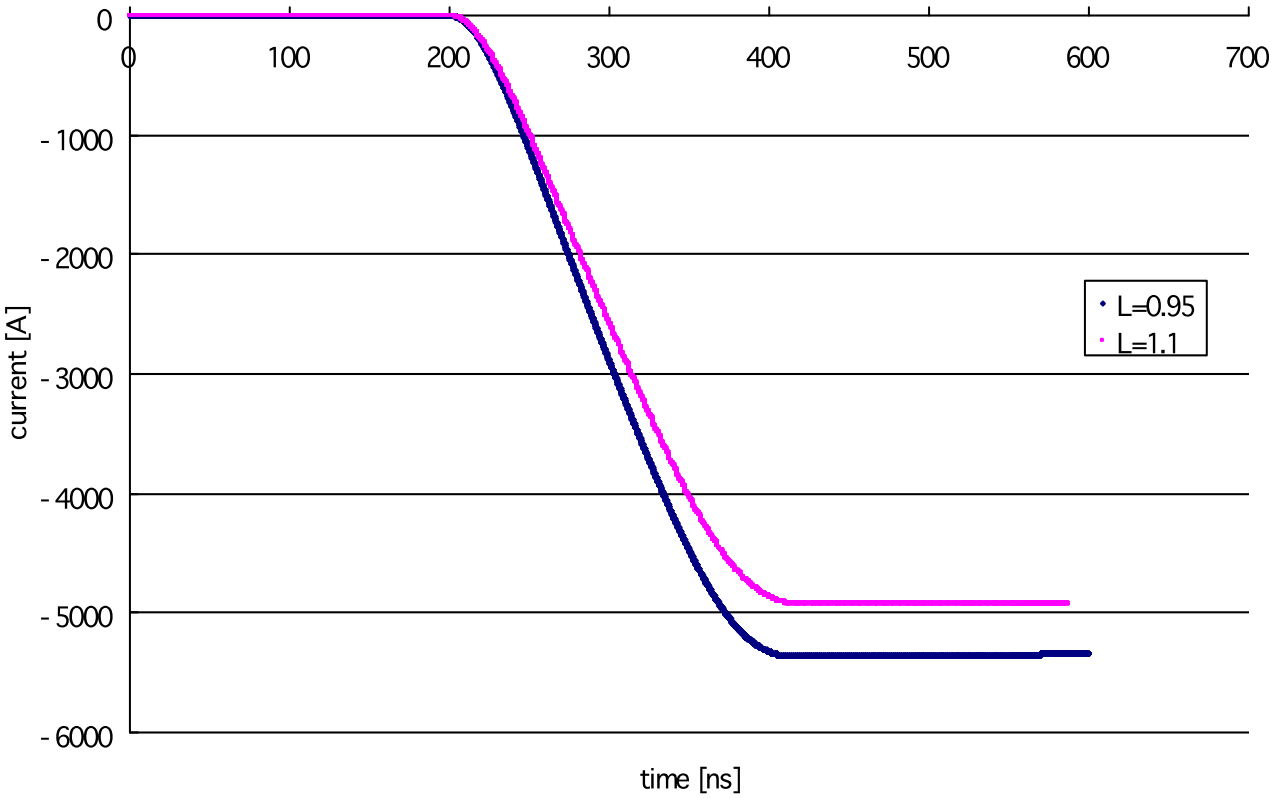


Experiment condition

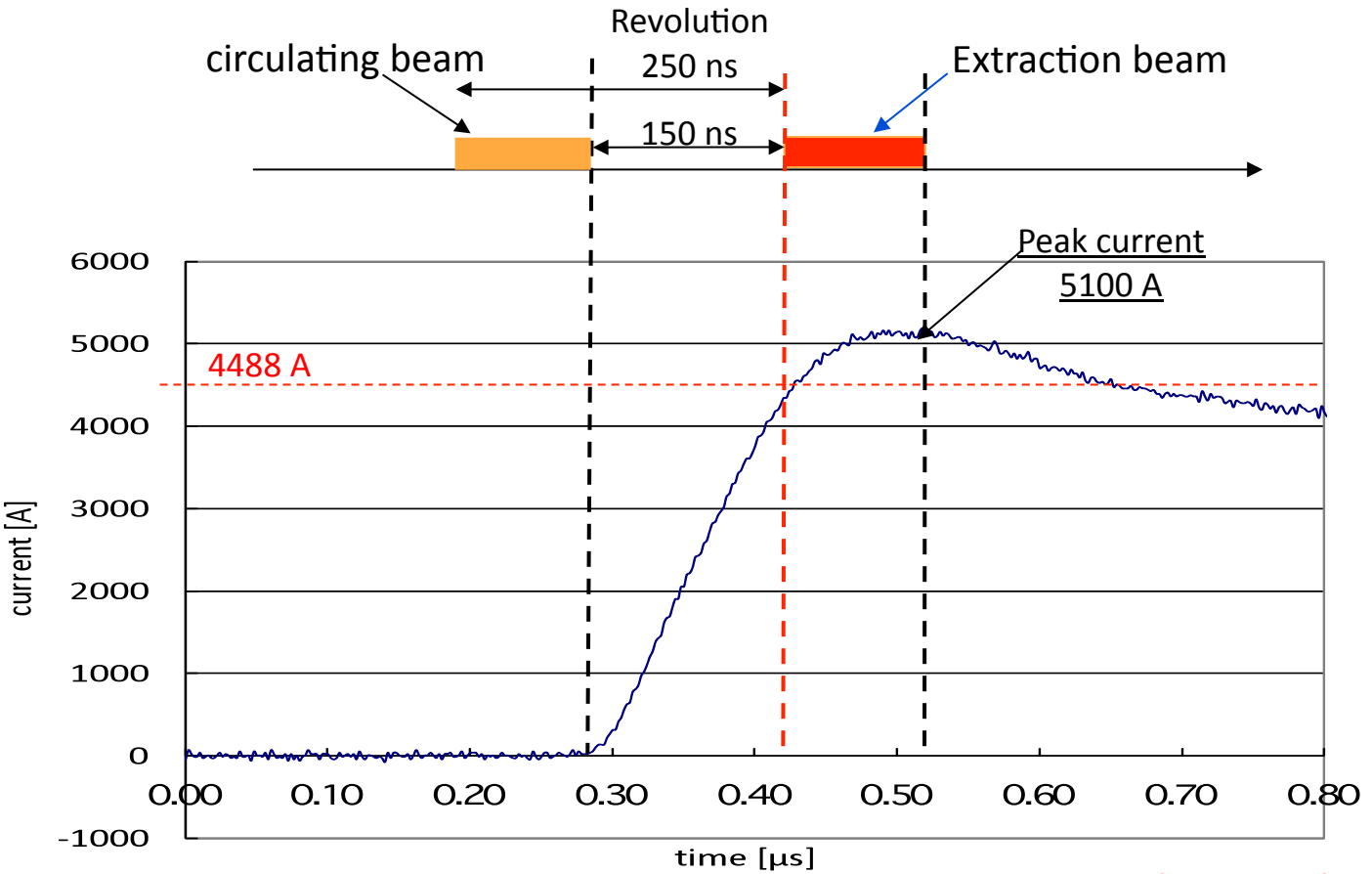
Dummy load: 1 μH
Voltage : 42 kV(pulse)

Result

Rise time(5-96%):156 ns
Flat top(more than 96%):114 ns
Peak current:5010 A


0
0
100
200
300
400
500
600
700
- 1000
- 2000
- 3000
- 4000
- 5000
- 6000
current [A]
time [ns]
L=0.95
L=1.1

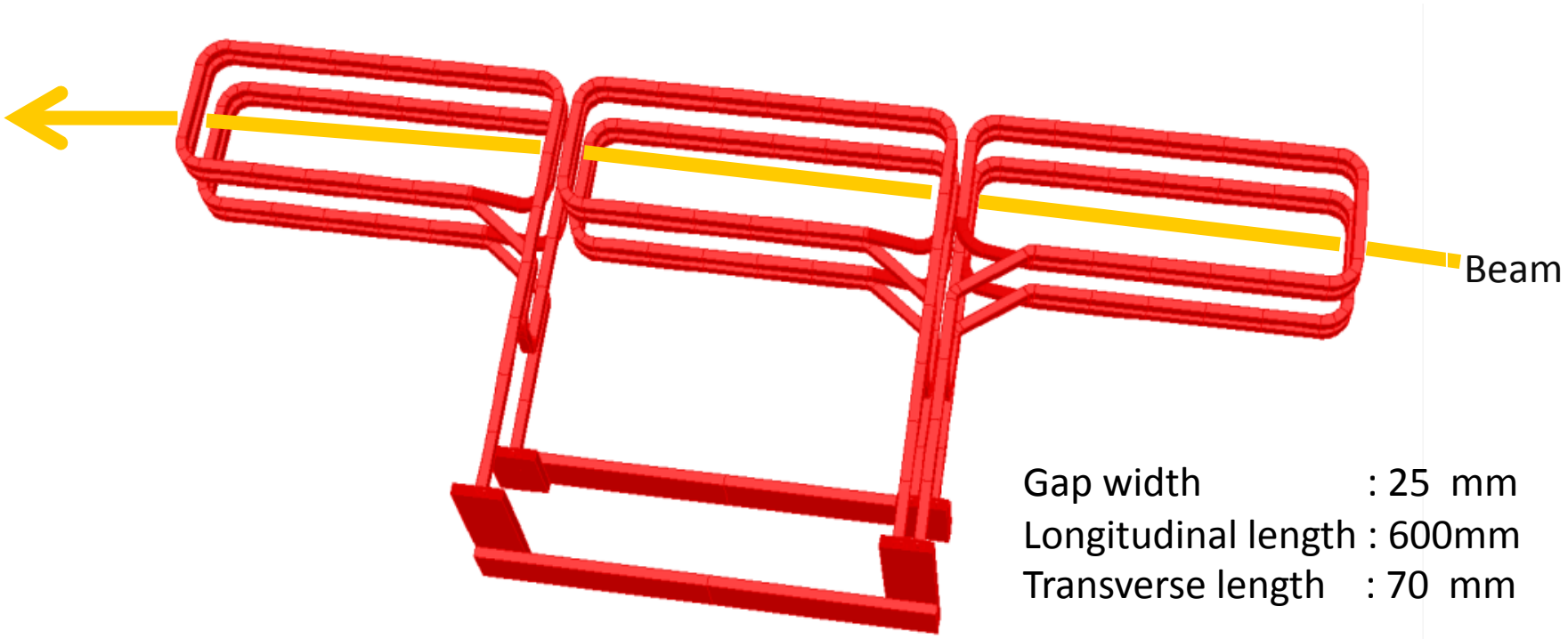
Simulation of the beam extraction(1)



Voltage 39 kV

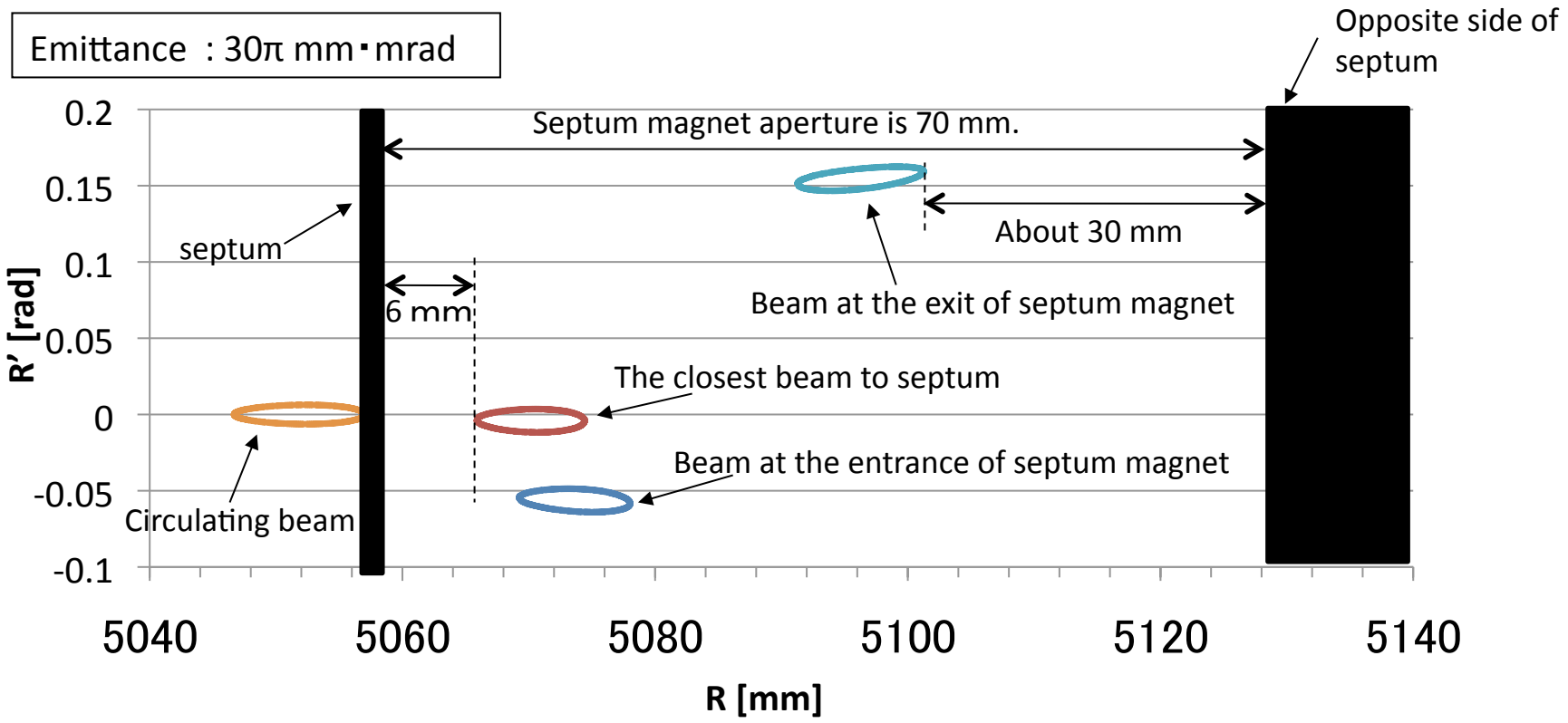
- The extraction beam is kicked when peak current is from 4488 A to 5100 A.

Tracking simulation with Opera-3D



Simulation of the beam extraction

the extraction beam at septum magnet



The extraction beam is not lost at the septum magnet.

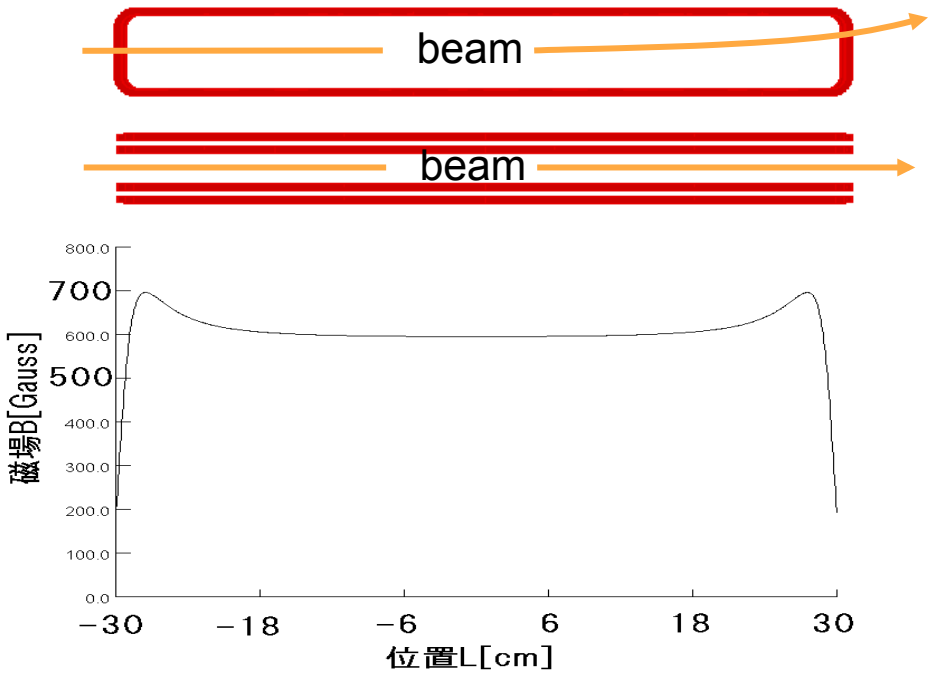
資料①

☆磁場計算

電流量・・・各コイルあたり1700A

1700A

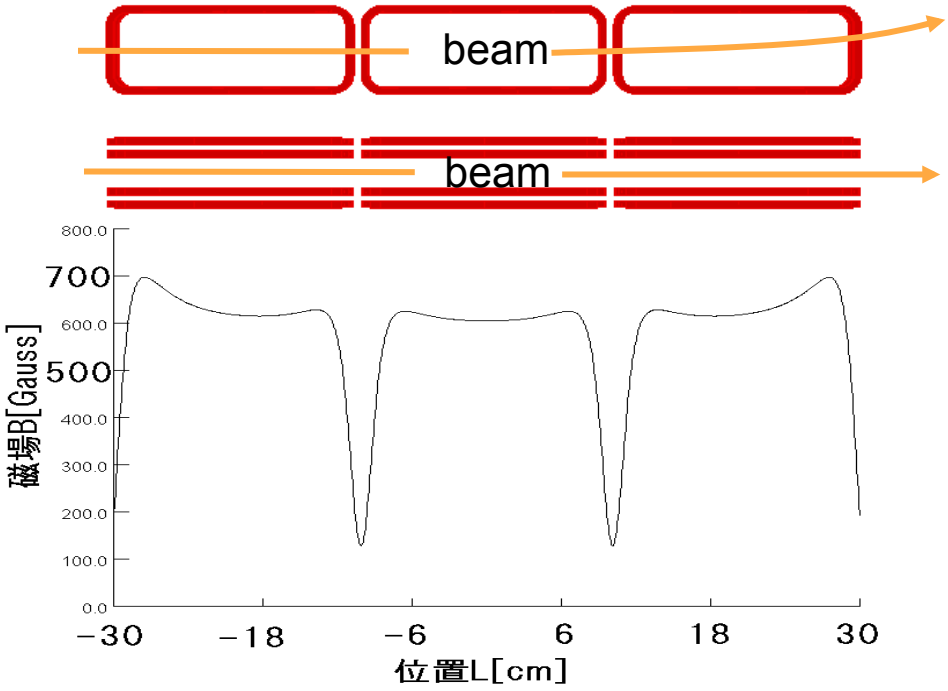
○従来のキッカー電磁石



$\int B \cdot dL$ →0.0355 [T・m]

5100A

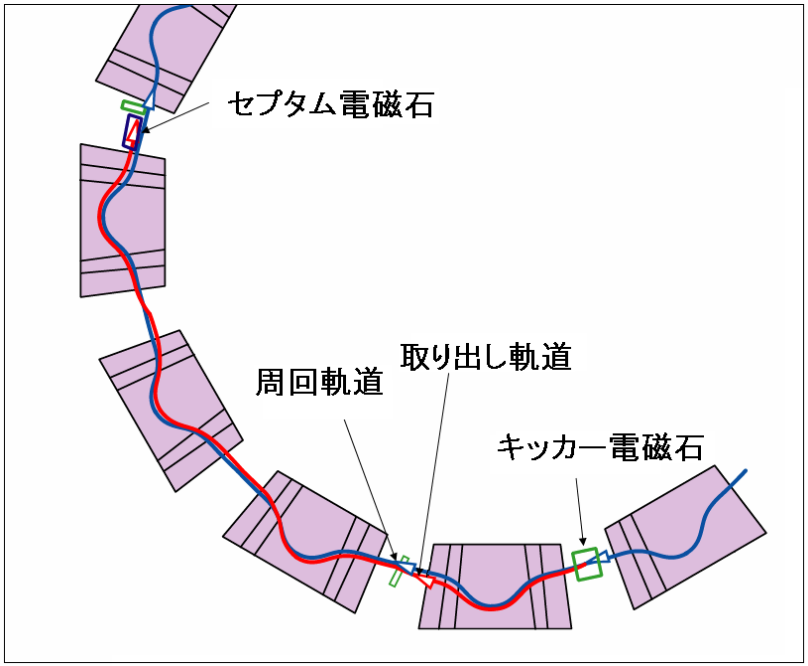
○改良したキッカー電磁石

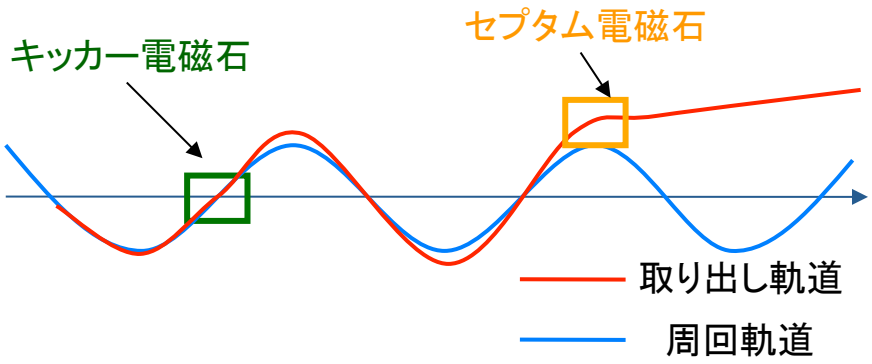


$\int B \cdot dL$ → 0.0346 [T・m]

資料②

☆取り出し





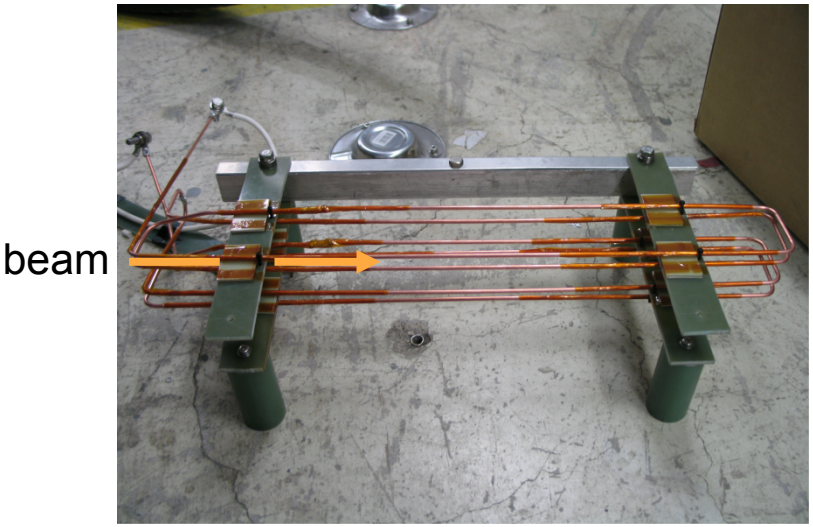
ビーム取り出し効率

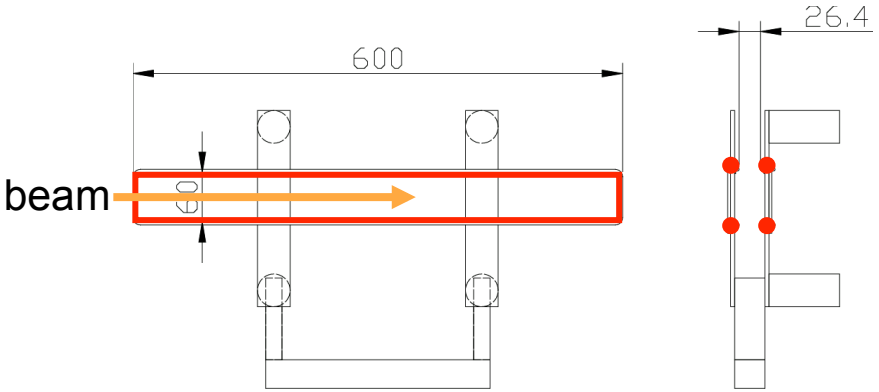
ビームの移動量（キッカー電磁石） ＆ セプタム厚（セプタム電磁石）

によって決定される

資料③

☆従来のキッカー電磁石





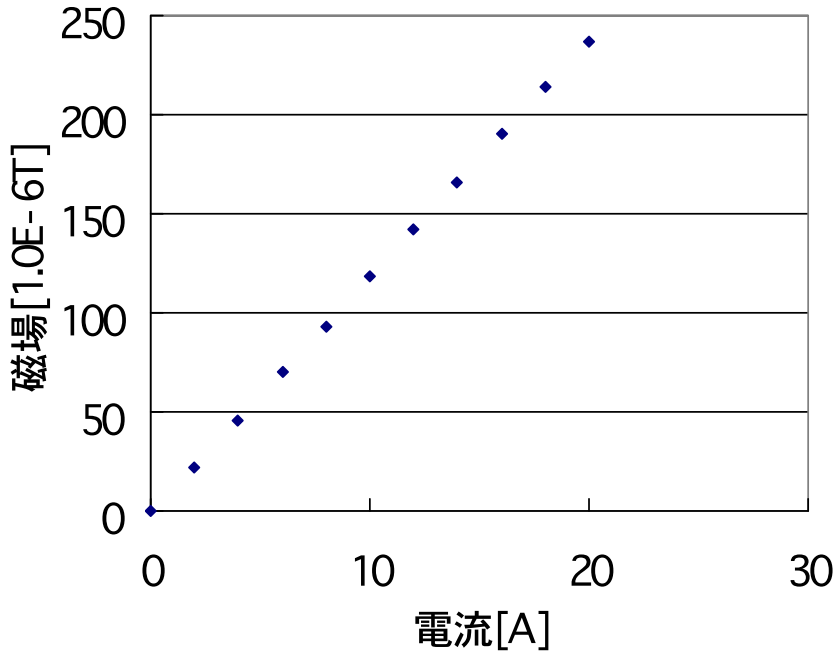
・励起磁場は最適化されている
・電流の立ち上がり時間は約250ns

→ 取り出し効率は90%・・・

資料④

☆予備実験①（磁場の電流に対する線形性）

点Aにおける磁場の電流変化に対する挙動を確認



☆予備実験②（磁場の揺らぎ）

点Aにおける20Aの電流での磁場を20回測定

237~238[1.0E-6T]

資料⑤

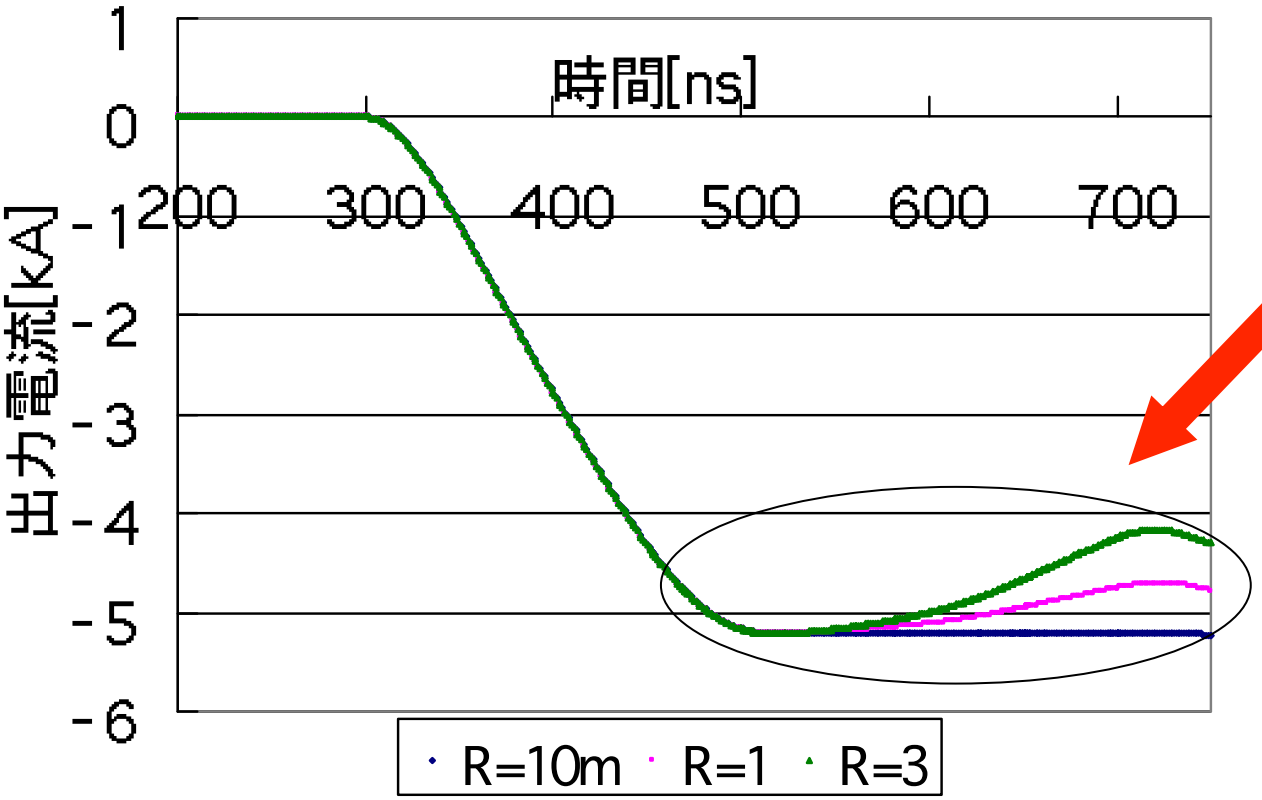
☆150MeVFFAG加速器の加速パラメータ

電磁石	**Radial Sector型（DFD-triplet)**
セル数	**12**
k値	**7.62**
ビームエネルギー	**12～150MeV（10～125MeV)**
平均半径	**4.47～5.20m**
ベータトロンチューン	水平方向；**3.69～3.80**
	垂直方向：**1.14～1.30**
最大磁場	**F磁極：1.63T/D磁極：0.78T**
周回周波数	**1.55～4.56MH z**
繰り返し	**100Hz/Cavity**

資料⑥

☆回路シミュレーション

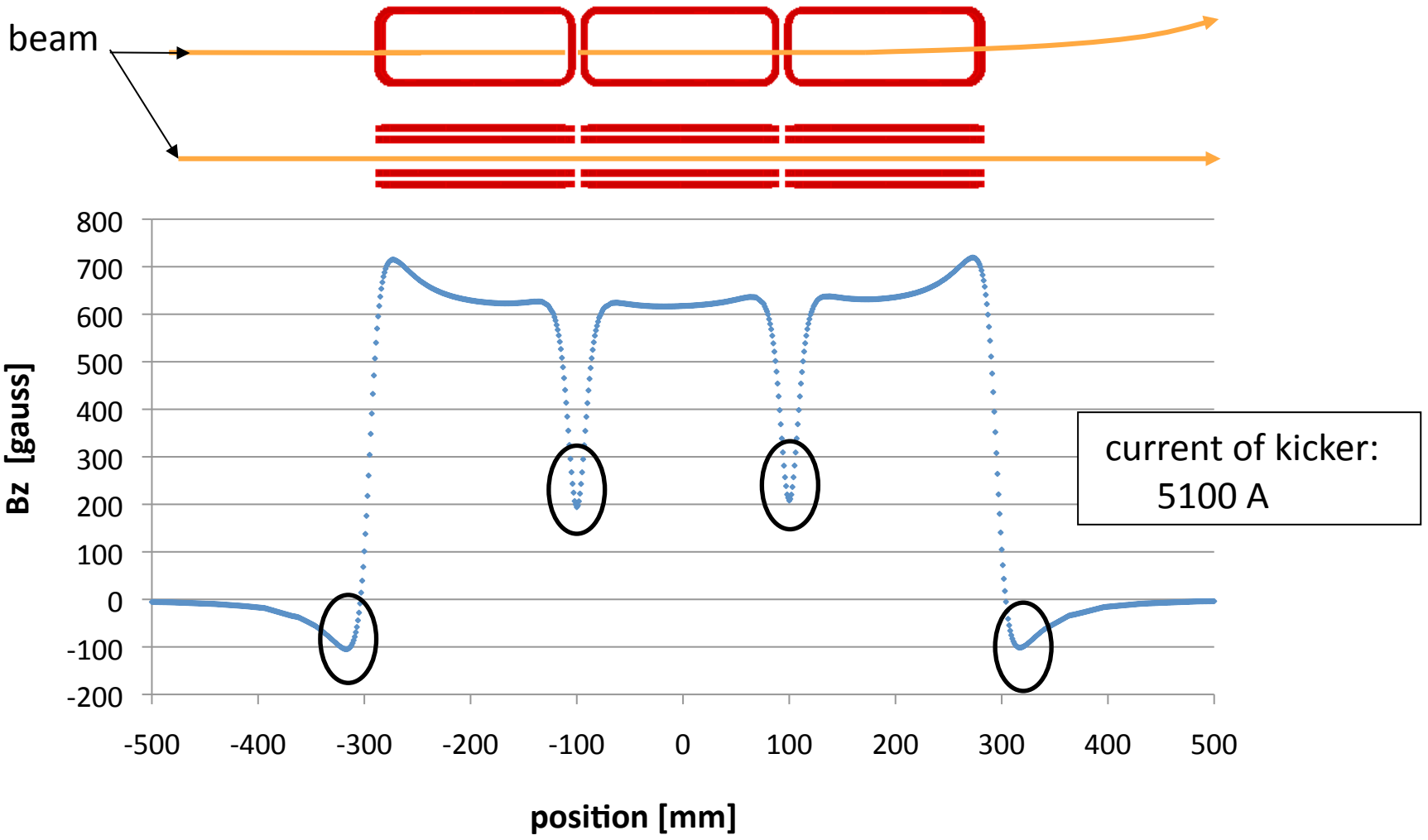
ダイオードの直列抵抗Rを変化させて出力電流波形を比較



波形のなまりは
直列抵抗によって
発生している

試験結果と比較すると
直列抵抗が数Ωである
ことがわかる

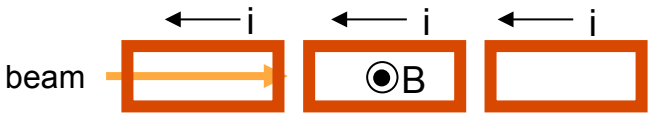
Calculation of magnetic field



資料⑦

i　新型キッカー電磁石の形状の検討

3つの小型コイルを用いたキッカー電磁石で
電流の立ち上がり時間を150 ns以下に出来る
インダクタンスは・・・



○コイルの自己誘導起電力の式

1700/coil（BL積の要請から）→5100A

40 kV（真空の放電限界）

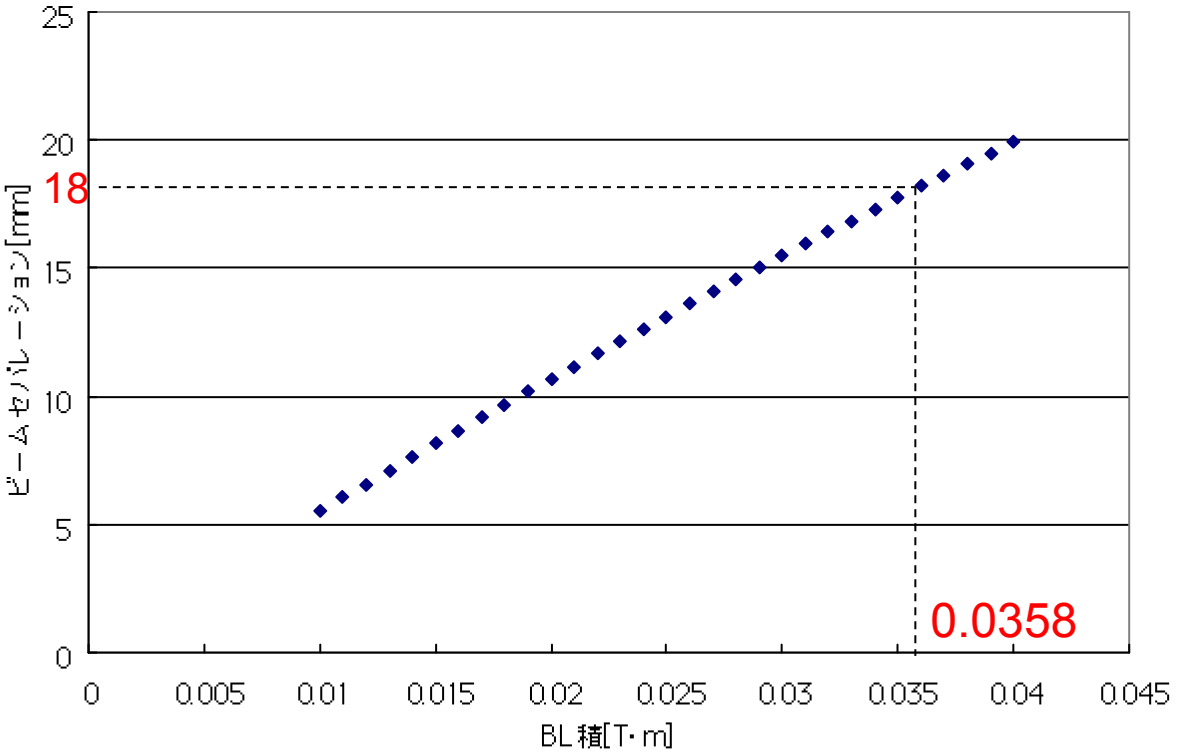
$$V = -L\frac{dI}{dt}$$

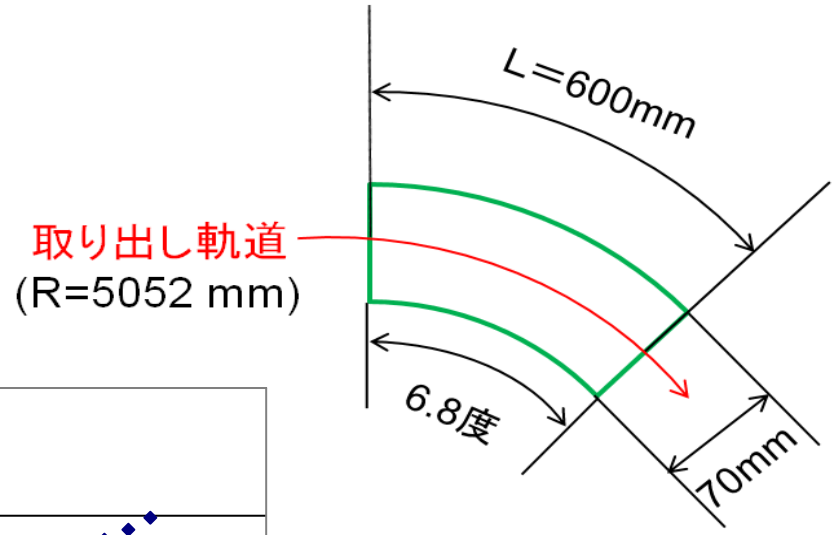
インダクタンス　1 μH

150 ns（目標とする電流の立ち上がり時間）

資料⑧

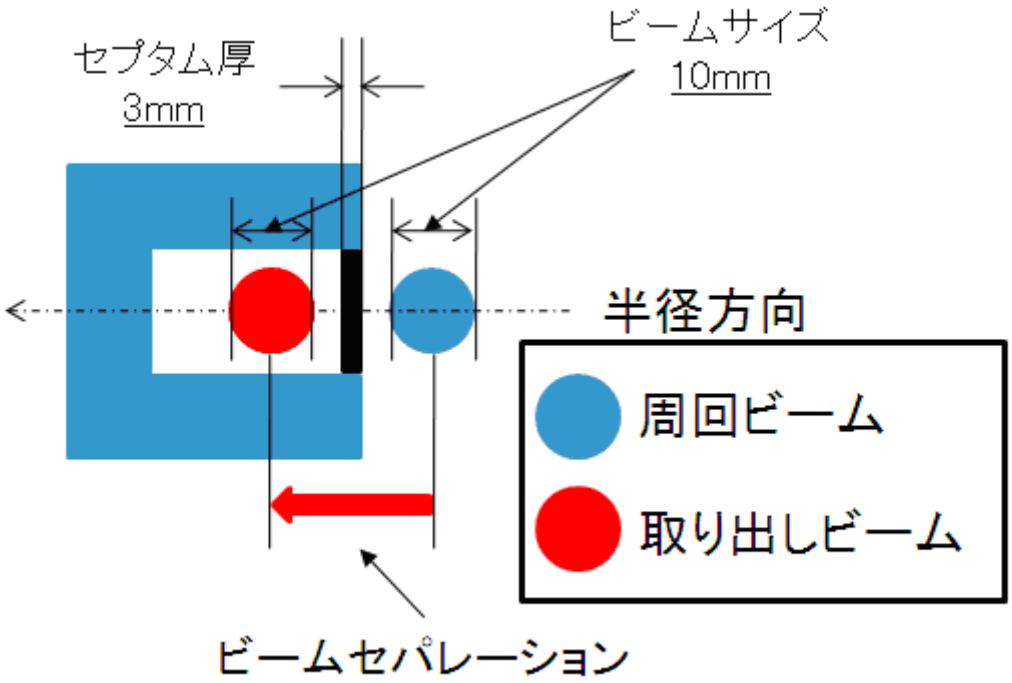
☆BL積とビームセパレーションの関係





資料⑨

☆ビームセパレーション

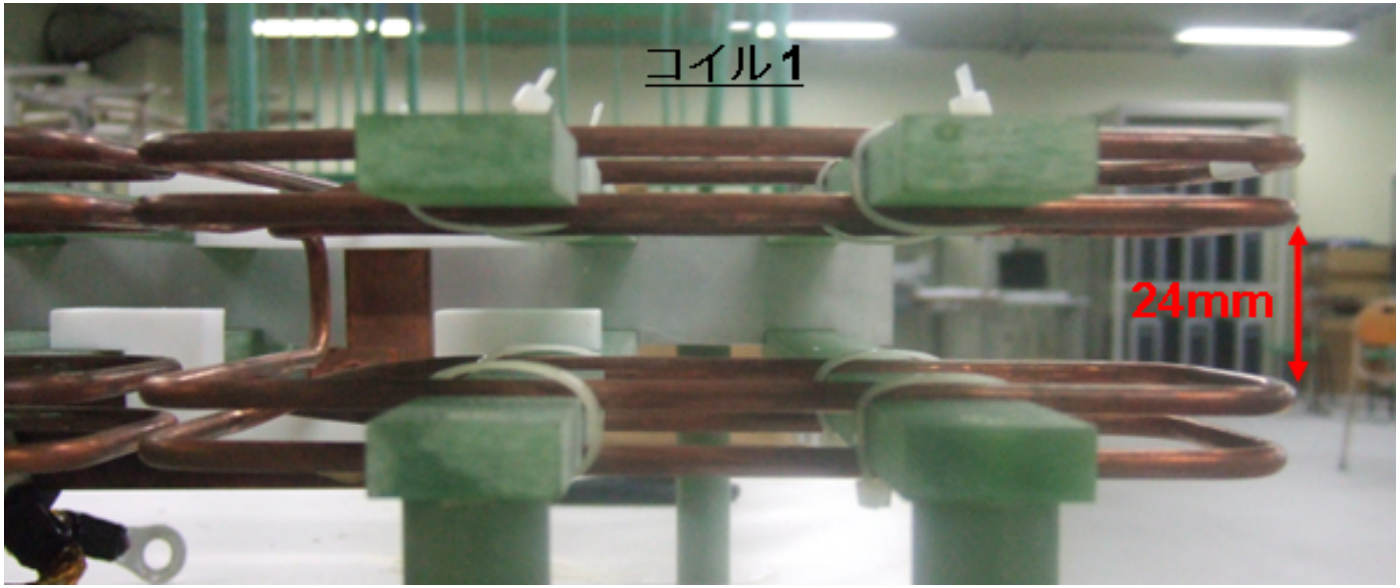


最低限13mm必要
＋
ビームサイズの半分5mmを安全ファクタ

ビームセパレーションの目標値
18mm

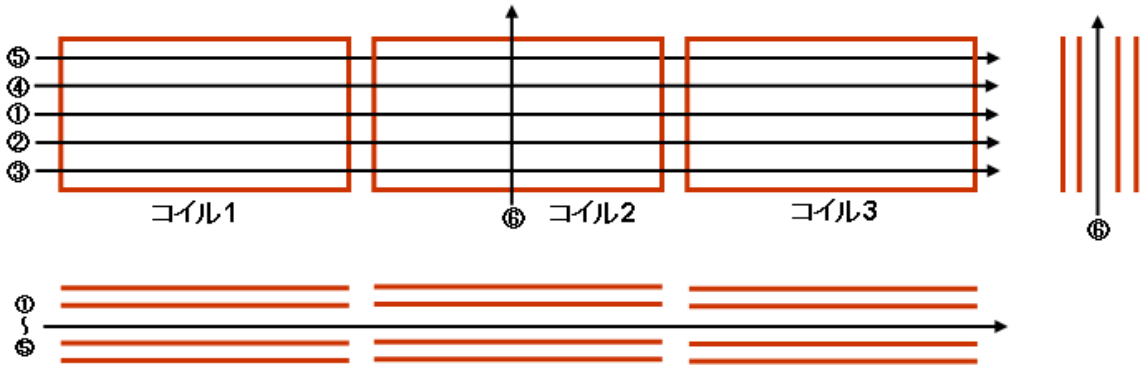
資料⑩

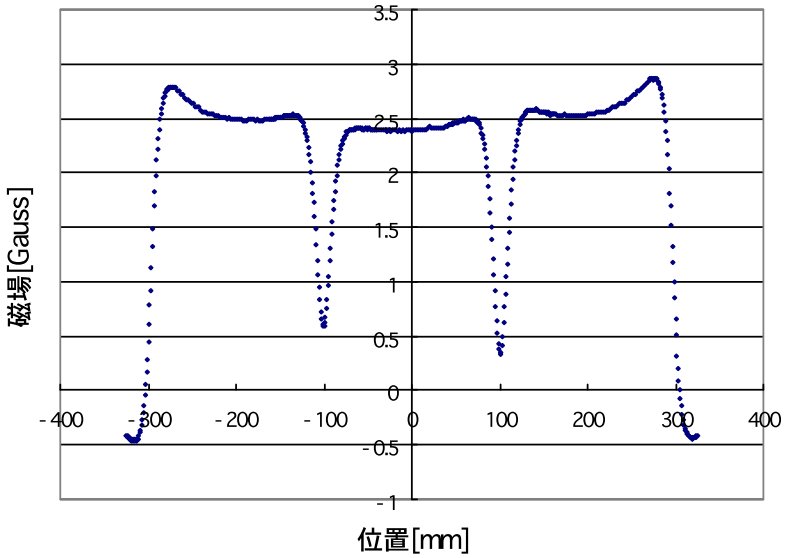
☆キッカー電磁石の側面図



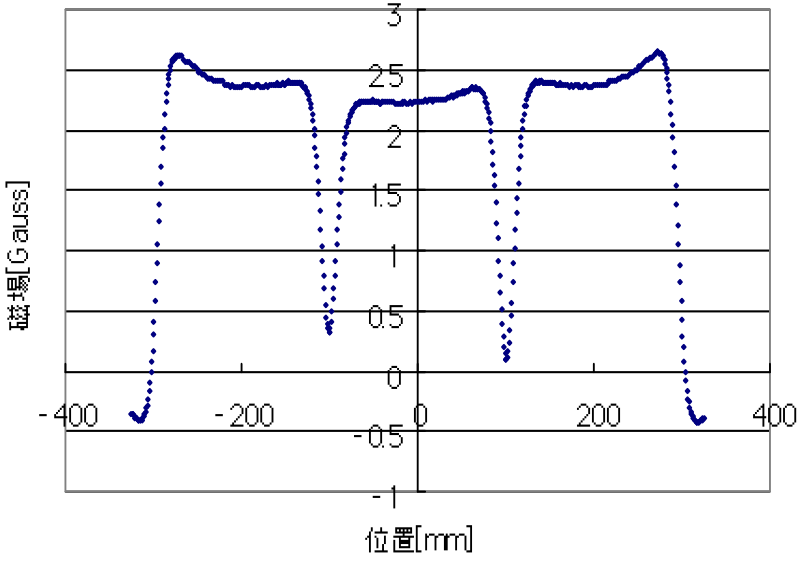
資料⑪

☆直流電流での磁場測定結果





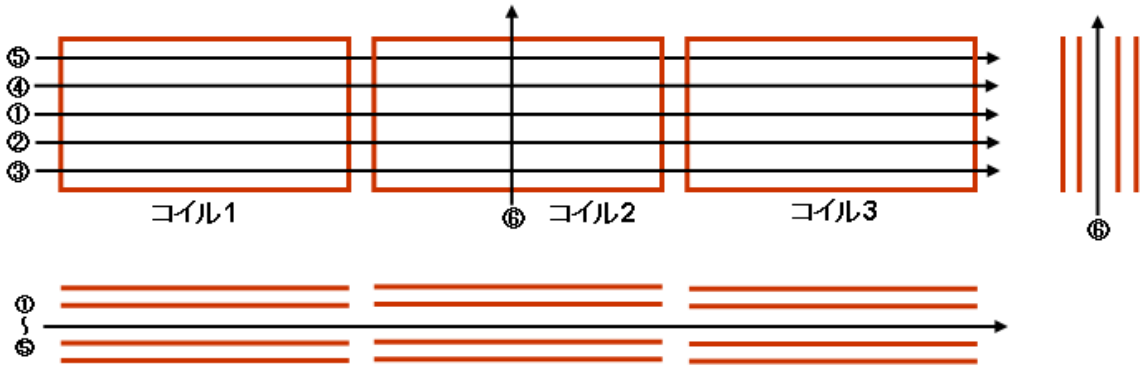
②の磁場分布・・・BL積99.4%

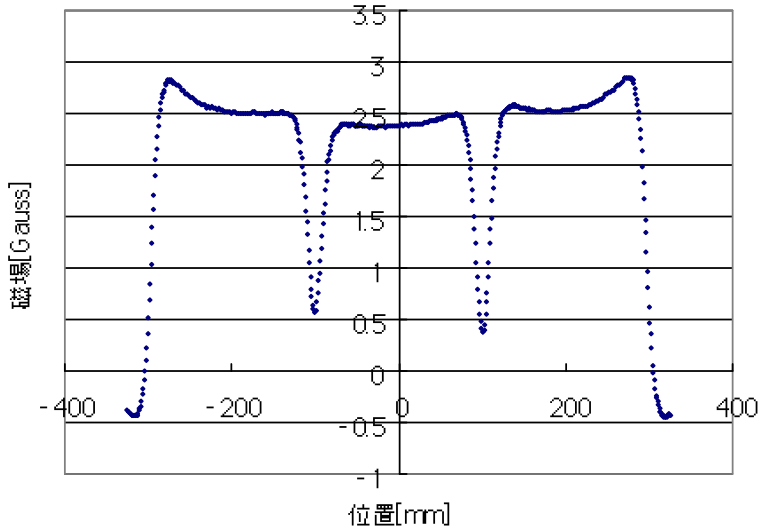


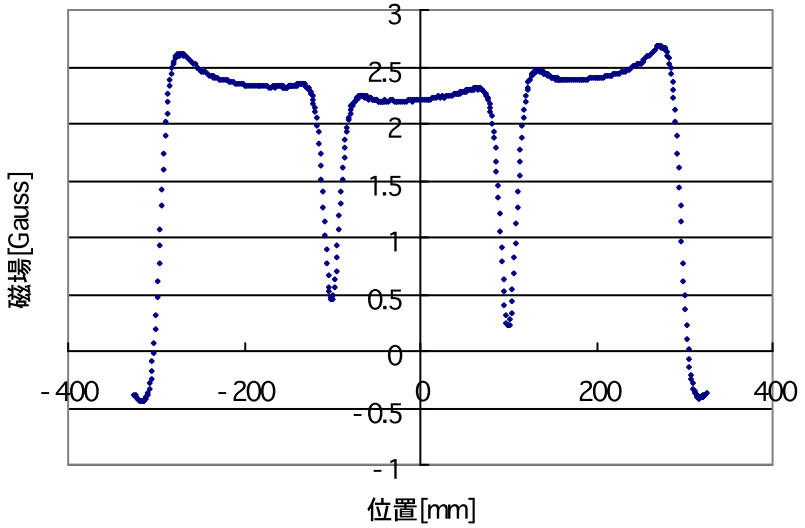
③の磁場分布・・・BL積100.7%

資料⑫

☆直流電流での磁場測定結果





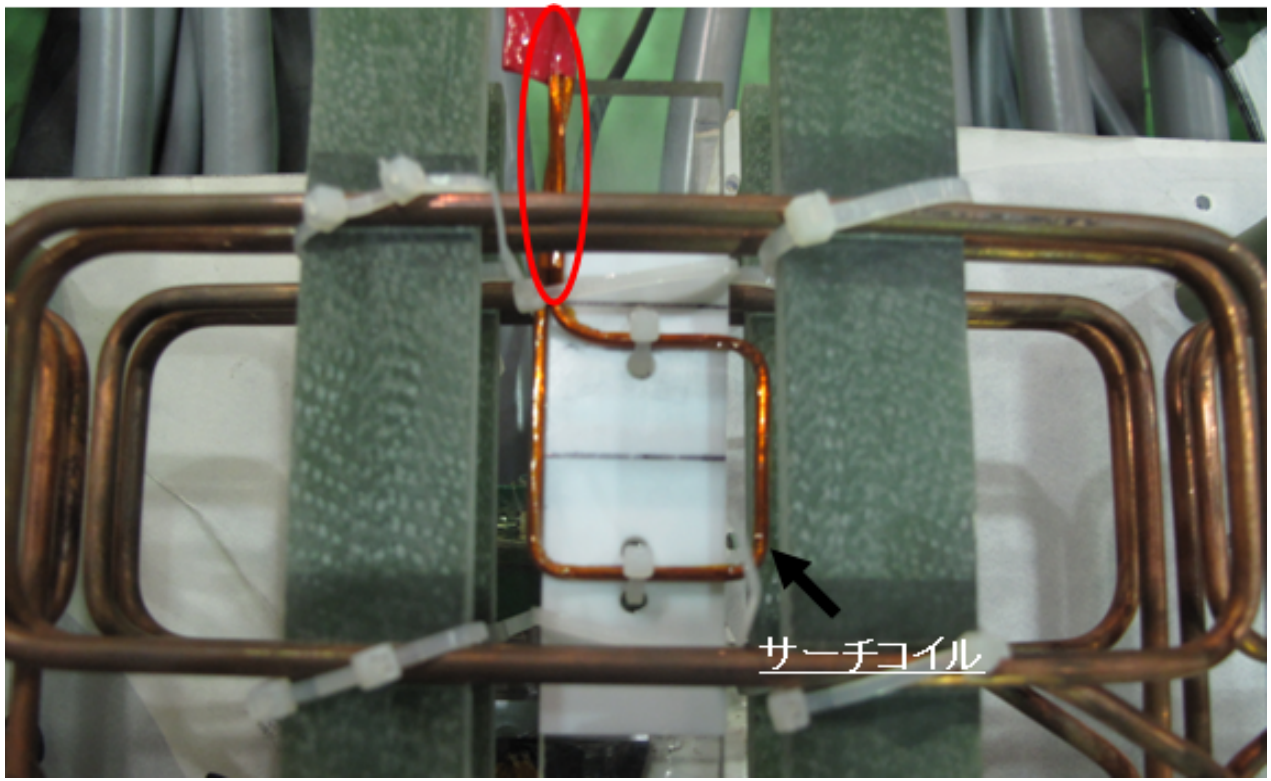


④の磁場分布・・・BL積99.5%

⑤の磁場分布・・・BL積100.8%

資料⑬

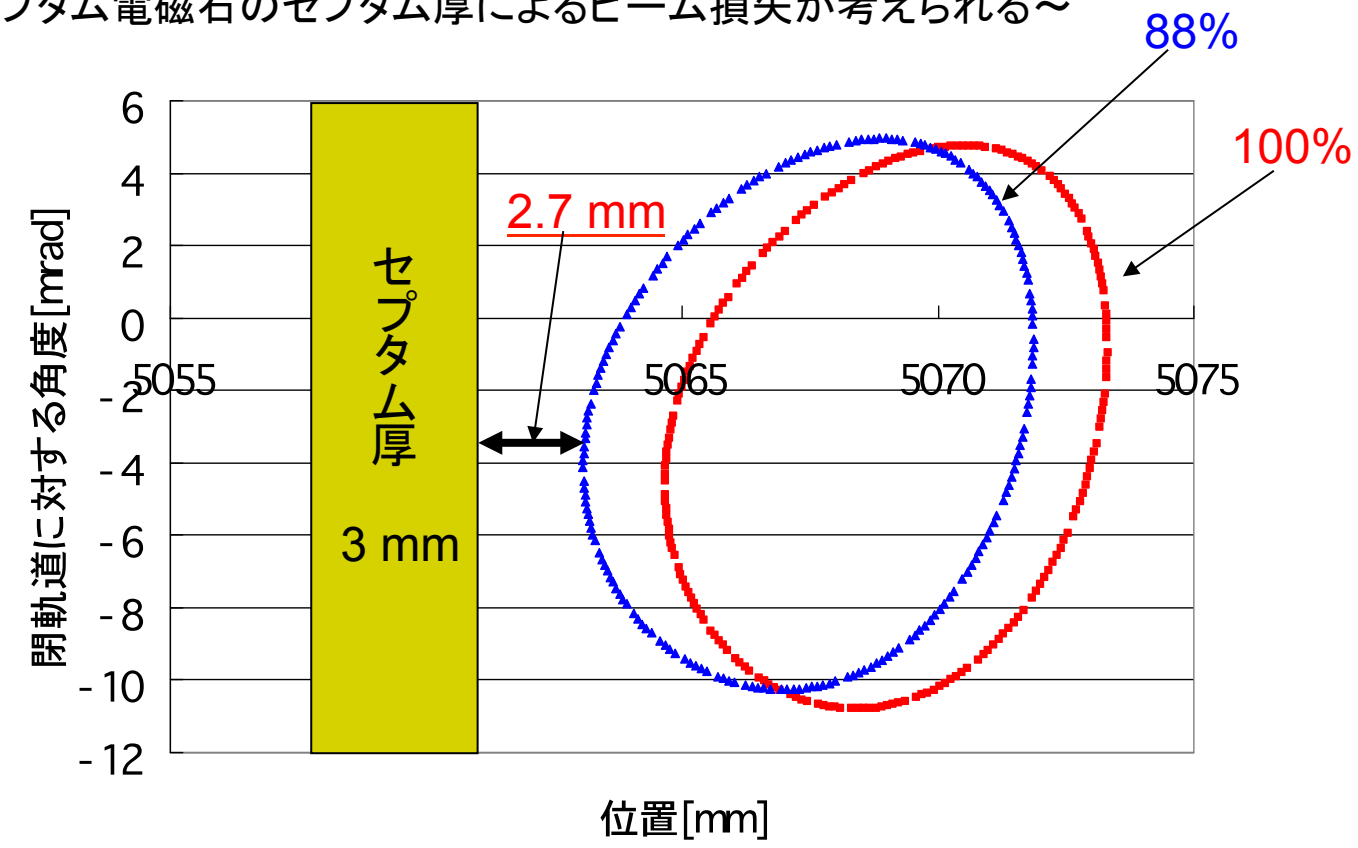
☆サーチコイル



資料⑭

☆セプタム電磁石におけるビーム損失

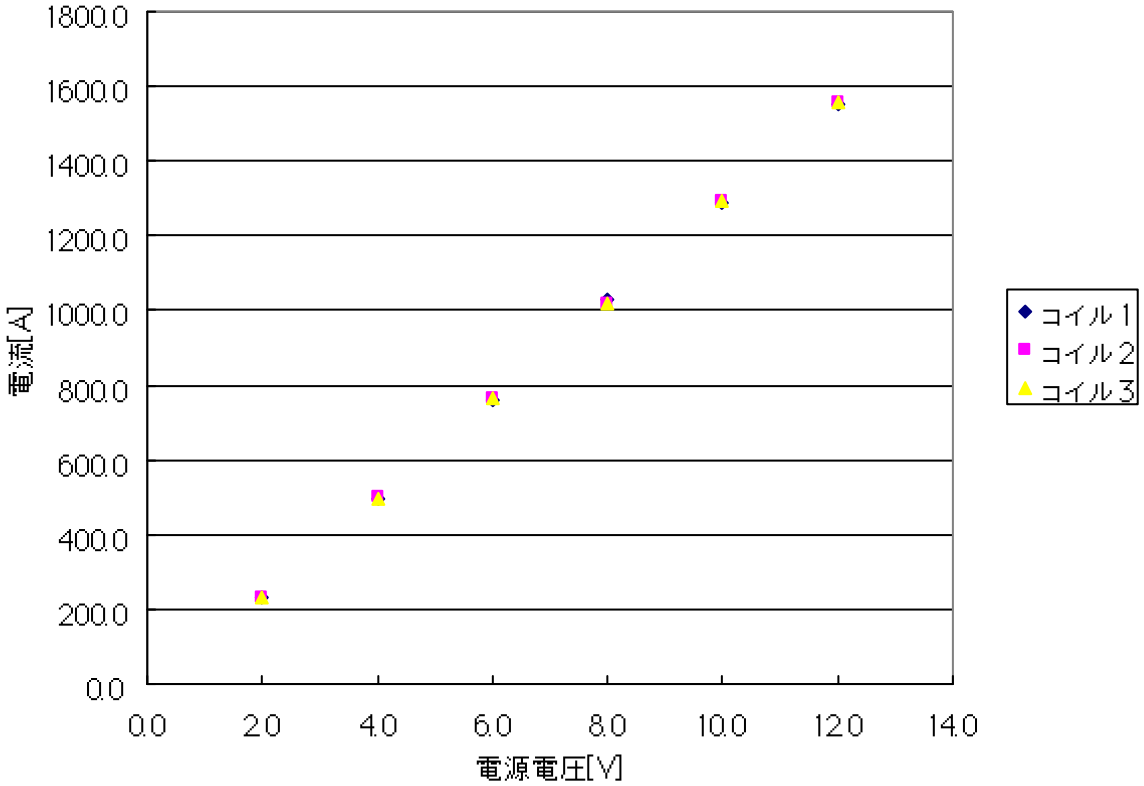
～セプタム電磁石のセプタム厚によるビーム損失が考えられる～



ビームの広がりはセプタム厚に対して2.7 mmの余裕があることが分かった
→セプタム電磁石入口でのビーム損失は発生しない

資料⑮

☆電源電圧と出力電流の関係



非常に良い線形性を示している

→近似曲線を適用し5100Aを得ることができる電源電圧を求めた

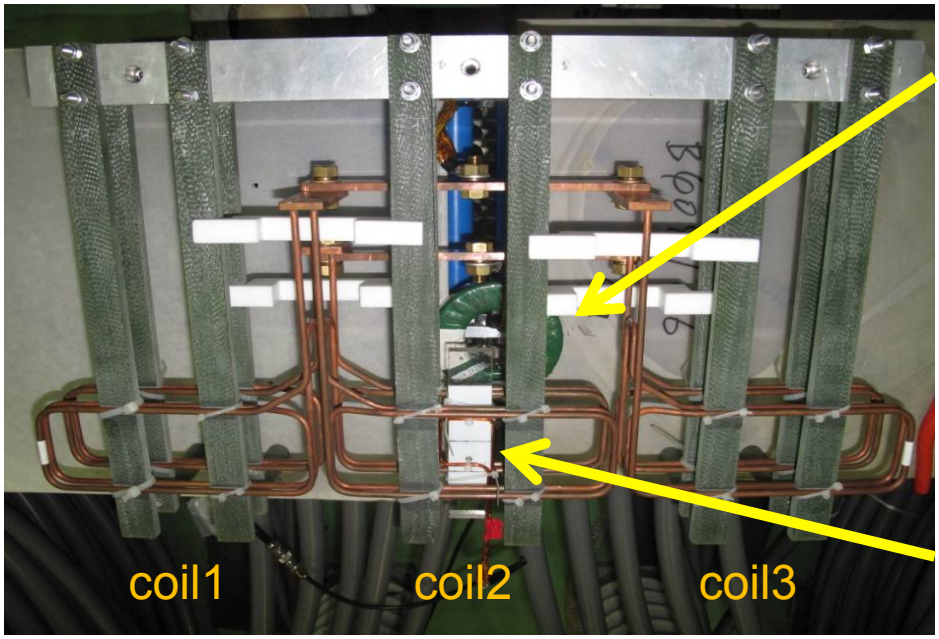
Constraint geometry of kicker

In case of 150 MeV FFAG accelerator, there is fringing field at straight section

Kicker used magnetic material causes COD

The kicker at Kyushu University need to be air core coil

Experiment input of power(2)



CT

Search coil

Experiment condition

Kicker coil :0.95 μH
Voltage : 2~12kV(pulse)

This experiment is operated in the air

coil	1	2	3
measurement/culculation	1.02	1.05	1.08

This result fulfills required magnetic field

This experiment brings out that required voltage is 39 kV in order to achieve 5100 A

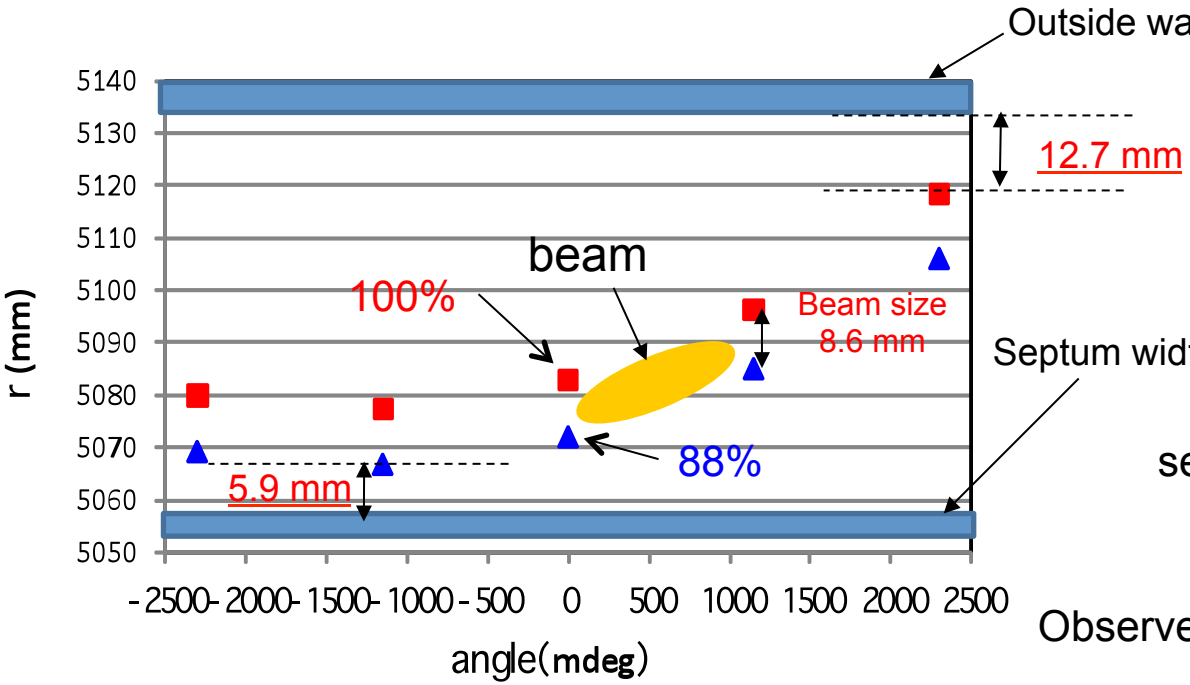
Calculation of extraction efficiency(1)

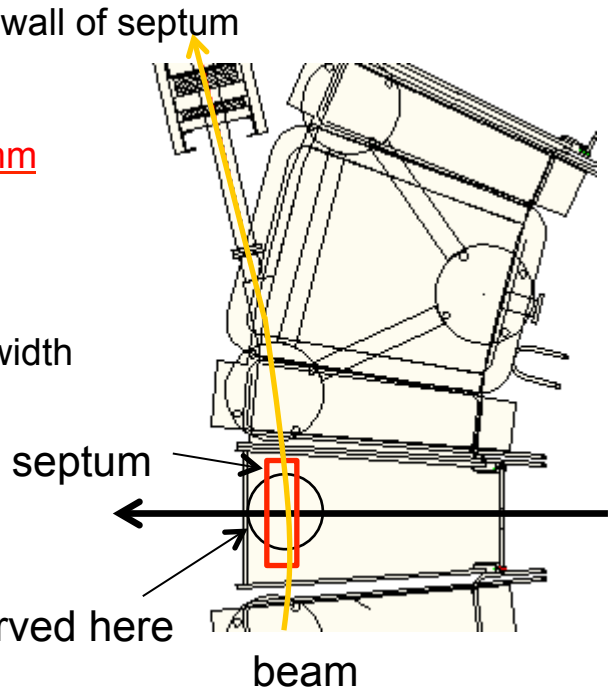
Calculation condition

Current rising time: 170 ns
Maximum current: 5100 A
Current at 150 ns: 4488 A(88%)
Incident beam emittance : 30π mm･mrad

The extraction beam is kicked
in the 88% to 100% kicker power

Calculation of extraction efficiency(2)



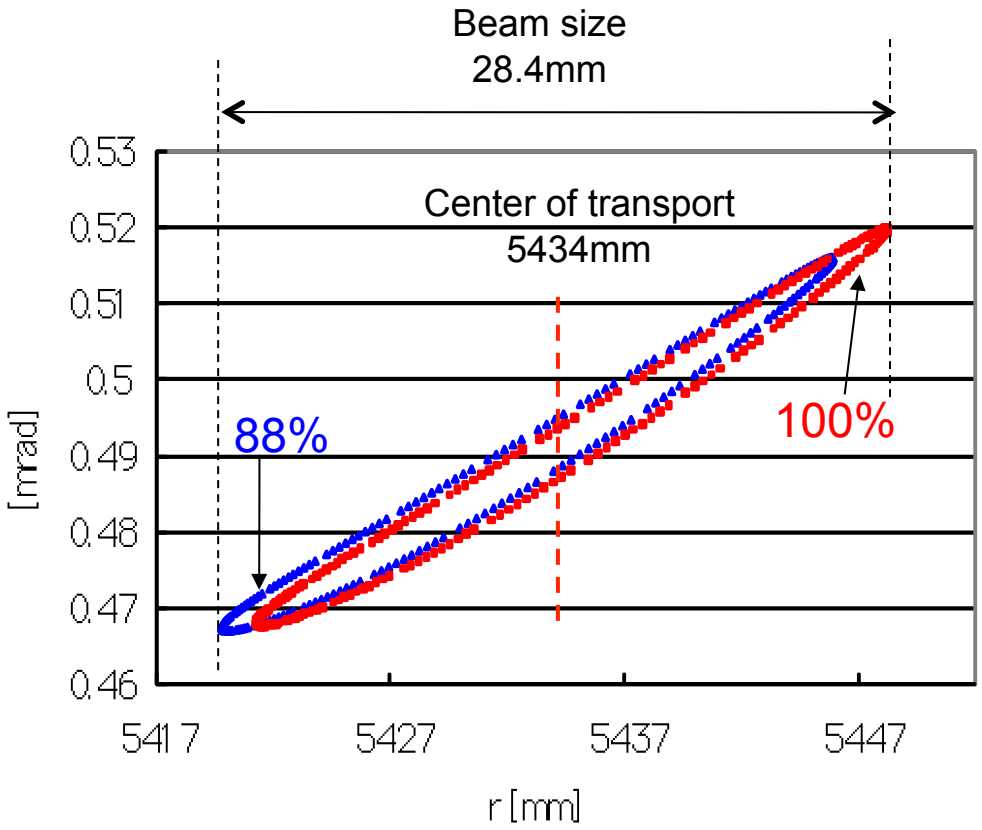


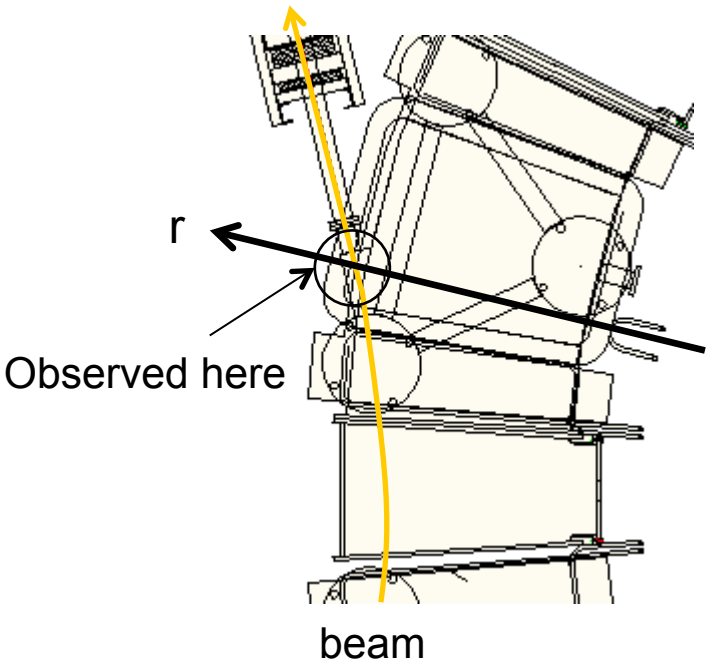
Red point is position of outside of beam kicked 100% power

Blue point is position of inside of beam kicked 88% power

There aren't beam loss at septum

Calculation of extraction efficiency(3)

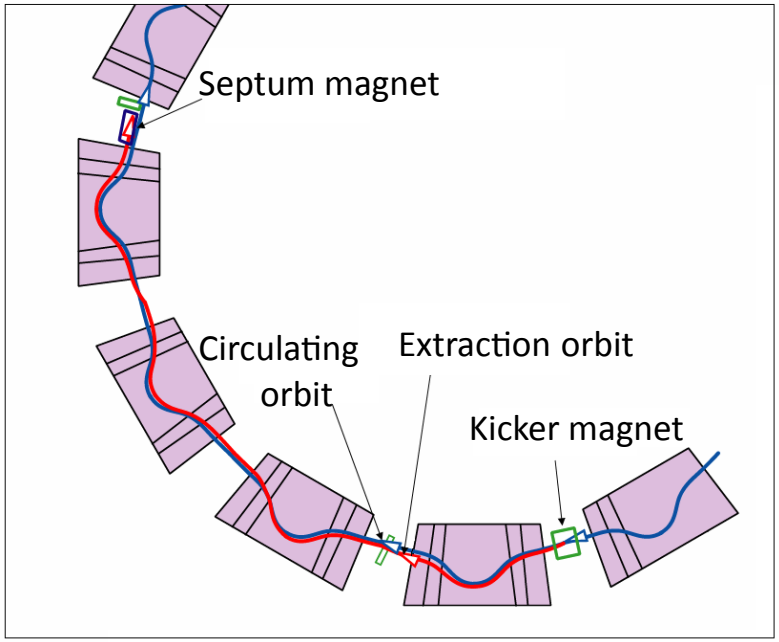


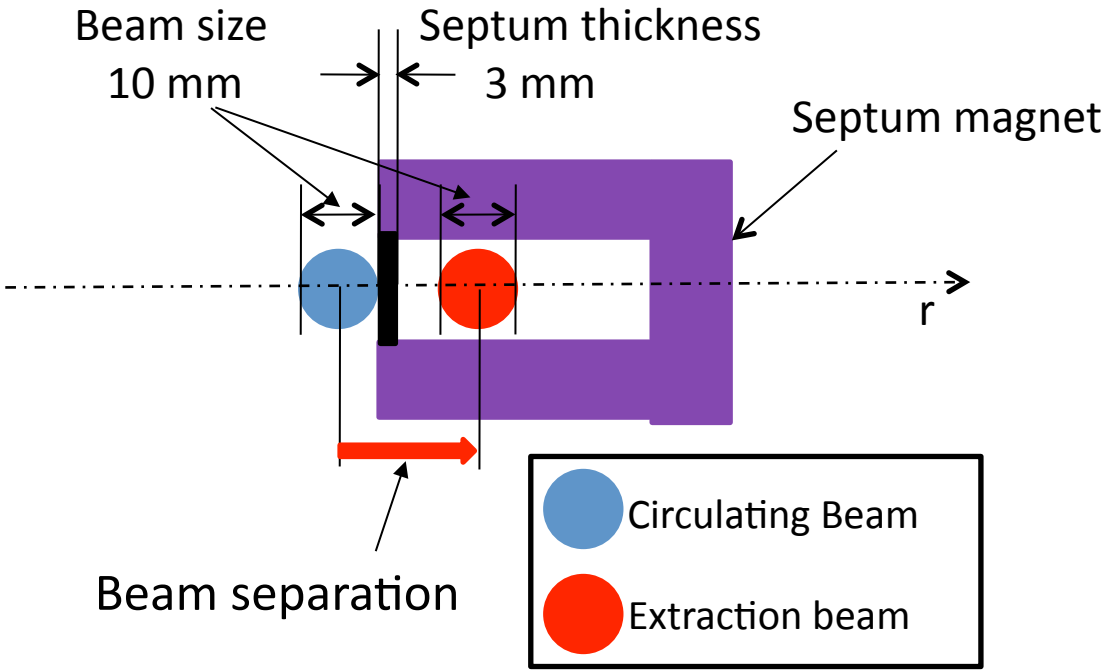


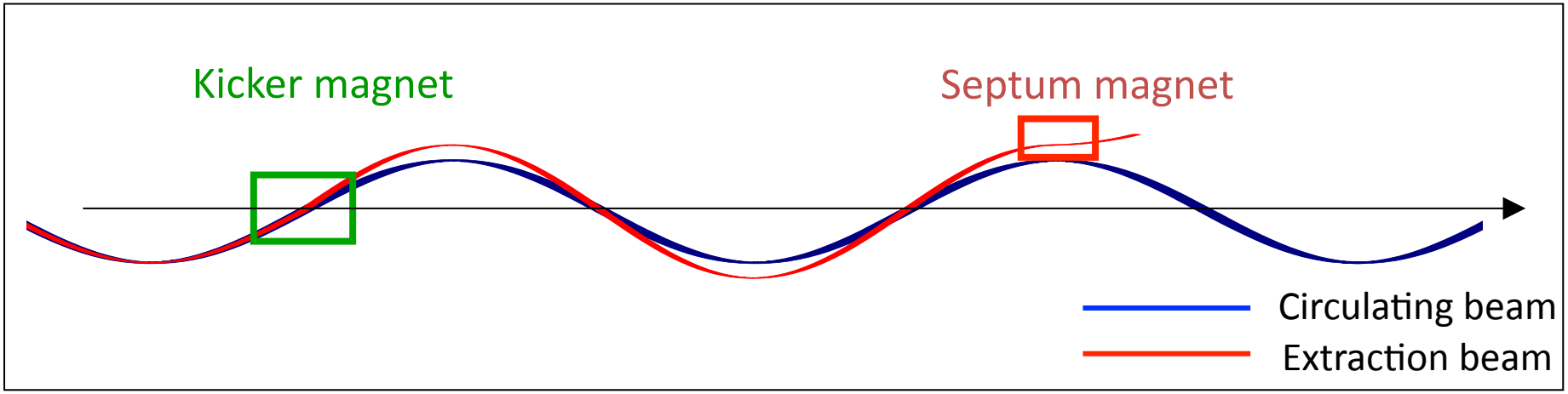
Transport aperture is 80 mm, beam size is 28.4 mm

There aren't beam loss at entrance of transport

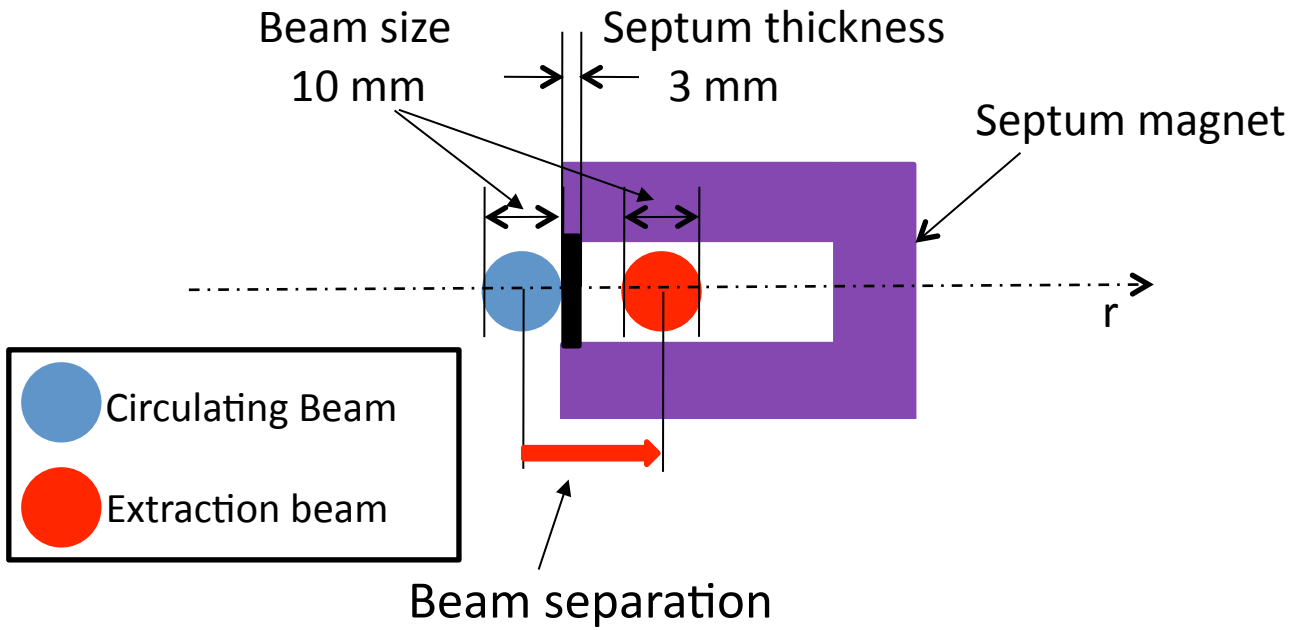
Beam extraction system of 150 MeV FFAG







Required beam separation for extraction



Beam separation is required to be more than 13 mm