

Development of Scaling e-FFAG in Japan

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Activities for e-FFAG in Japan

■ Design studies

■ FFAG03, Tsukuba

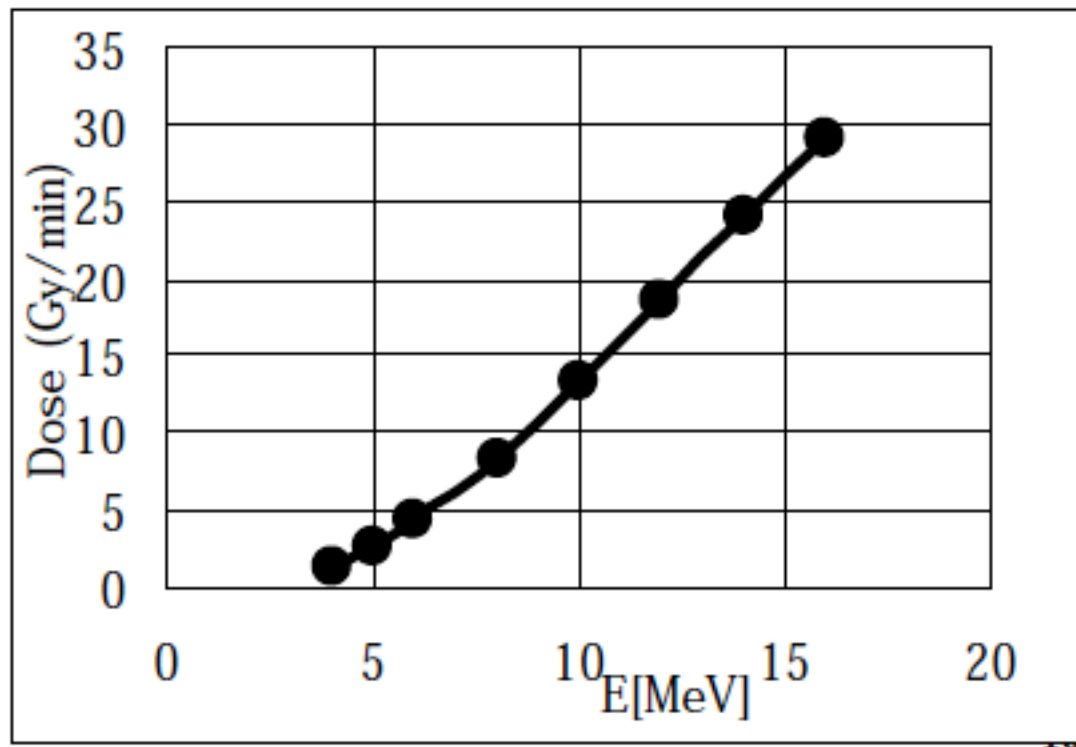
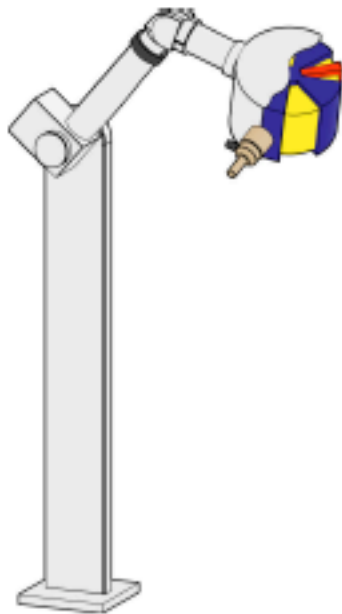
- LAPTOP ACCELERATOR 50-250keV ← by H.Tanaka(Mitsubishi Ele.)
- WG2: 50-500keV e-FFAG ← Summary by T.BaBa

■ FFAG04, Tsukuba

- WG3: 100keV-10MeV e-FFAG ← Summary by Y.Yuasa

Application of LAPTOP Accelerator

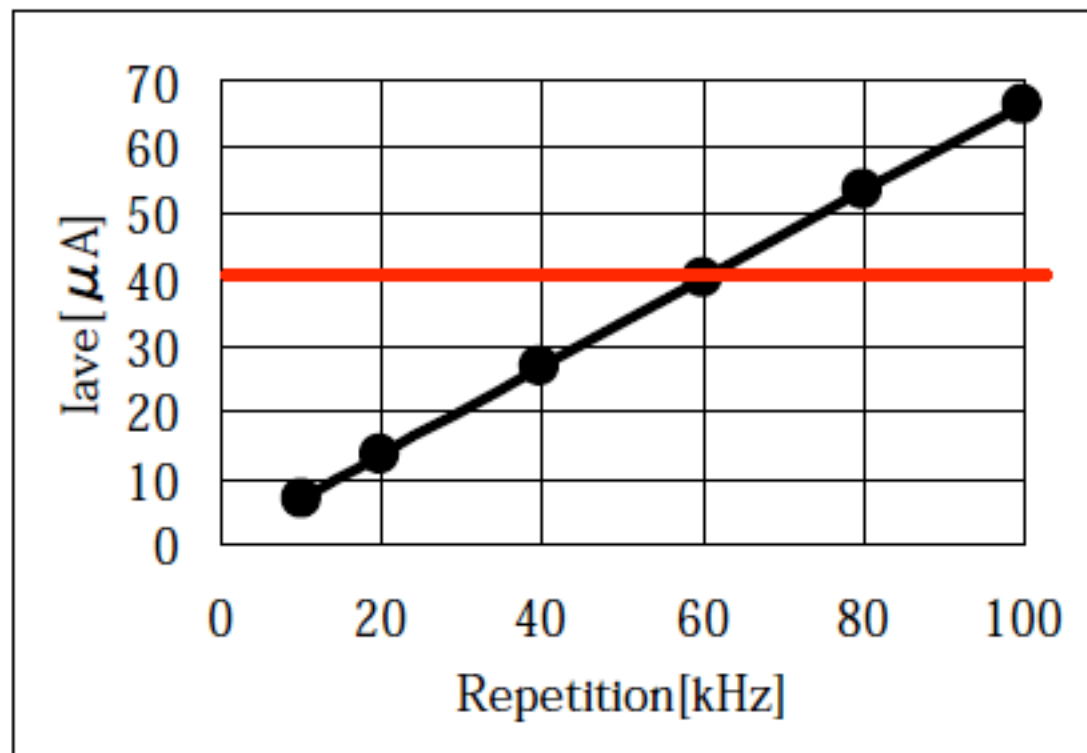
- X-rays irradiation
- X-rays radiation therapy
- X-rays CT





Average beam current of a conventional Betatron

- from old papers
- Normalized orbit radius and beam energy: $r=0.1\text{m}$, $E=6\text{MeV}$



Average beam current v.s. repetition



Basic parameters

Proto-type Machine

Injection Energy	50 [keV]
Acceleration Energy	6 [MeV]
Injection Radius	0.1 [m]
Extraction Radius	0.125[m]
K value	2~3
Magnet	Spiral Sector Magnet
Repetition	1 [kHz]
Duty	2 [%]
Energy after injection	50~250[keV]

Acceleration scheme

■ Injection: Continuous Injection

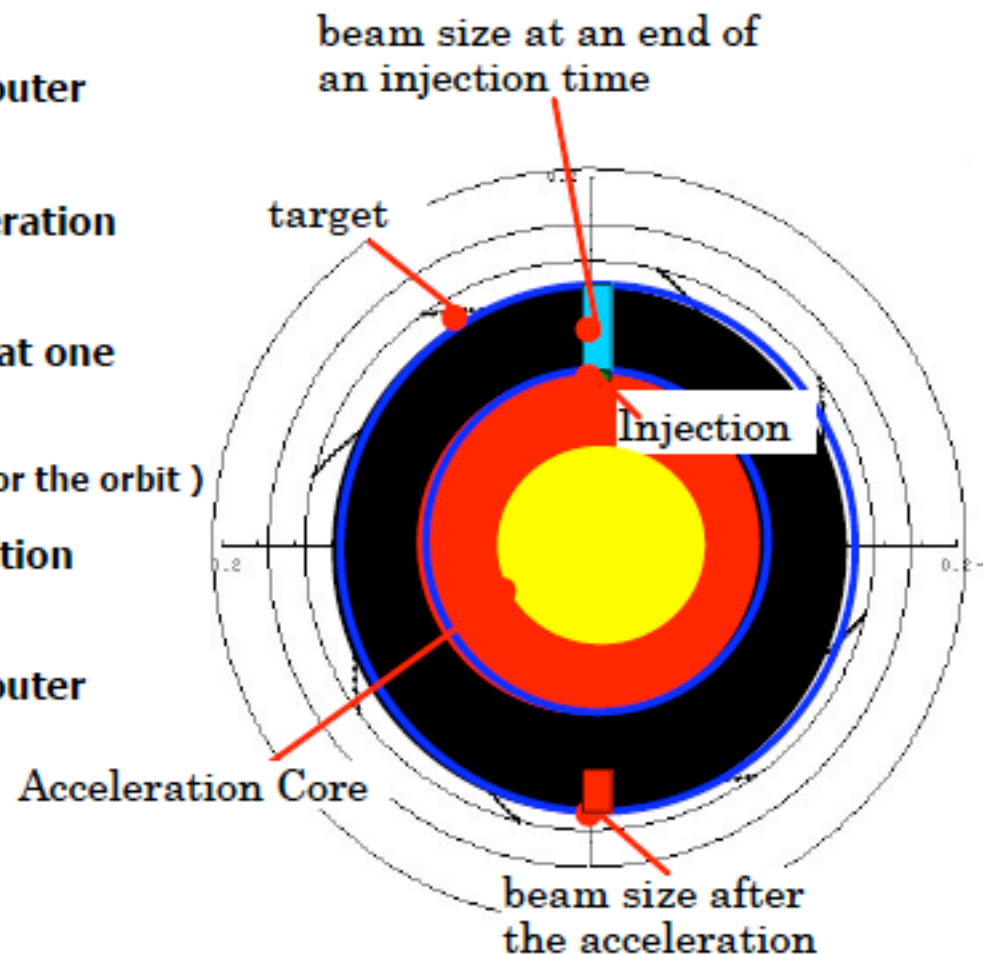
- ⌘ Bending Field: constant
- ⌘ Acceleration orbit: move to outer radius

■ Acceleration: Betatron Acceleration

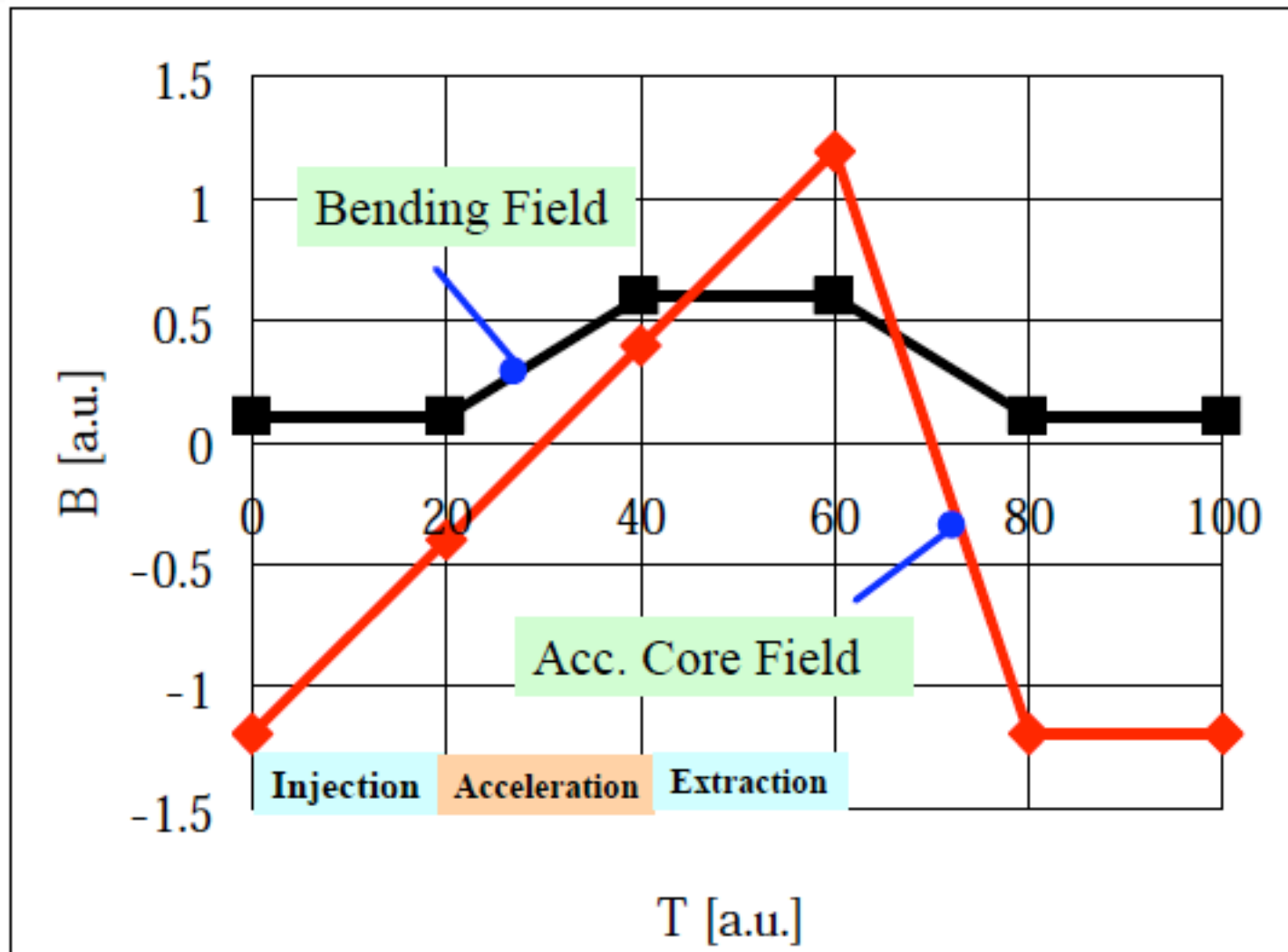
- ⌘ Bending Field: change
- ⌘ Acceleration orbit: constant at one orbit
- ⌘ $2\Delta B(\text{on one orbit}) = \Delta B$ (interior the orbit)

■ Extraction: Continuous Extraction

- ⌘ Bending Field: constant
- ⌘ Acceleration orbit: move to outer radius



Acceleration Scenario



50-500keV e-FFAG (FFAG03)

Goal of beam specs and machine constraints of electron FFAG accelerator for industrial irradiation

Beam specifications

- Injection energy	50keV
- Extraction beam energy	500keV
- Initial current from electron gun	100mA
- beam current	20mA
- Lattice type	spiral
- repetition rate	50(60)Hz
- pulse width/emittance/ $\Delta p/p$	NA

Machine (system) constraints

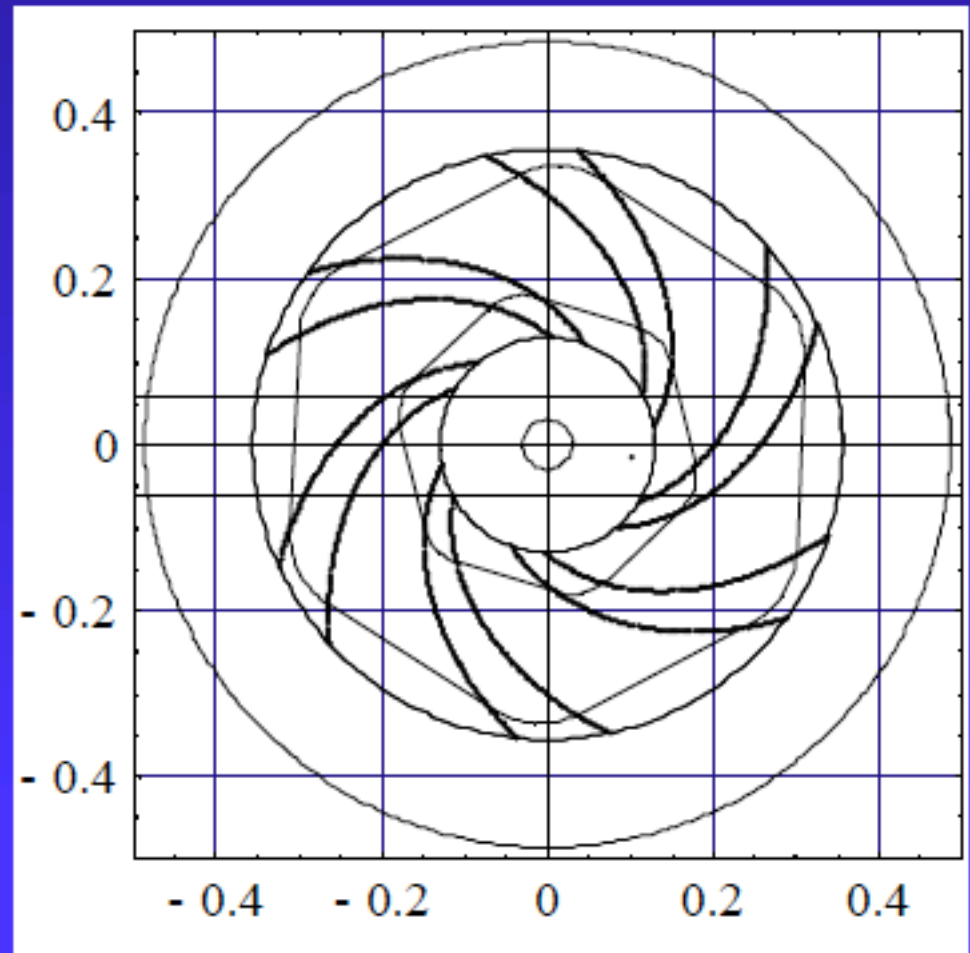
- circumference	1.5m
- initial/running cost(acc.)	20M¥
- power consumption	20kW
- operation	0

Lattice

Case2: Without Clamp

Nsect	6
K value	1.2
Spiral Angle	52 [Degree]
Injection Radius	0.18 [m]
Extraction Radius	0.33[m]
Packing Factor	0.30
Full Gap	26[mm]
Fint	0.45
Repetition	20 [kHz]
Energy Gain	800 [V/turn]
Turn Separation	0.64 [mm/Inj]
Bin/Bout	143/293 [Gauss]

Nux,Nuy	2.24, 1.11
Phase Advance(degree)	134.1, 66.7
Betax,betay (max)	0.63, 0.46



Core for acceleration (betatron acceleration)



Material	FINEMET
V _{gap}	800 [V]
Frequency	20 [kHz]
Duty	20 [%]
ΔB	1.76 [T]
Core Loss	~ 10 [kW]
Cross section	9 x 10 [cm]
Weight	60 [kg]
Cost	1 [M¥]

Magnet

Calculation result using main coil only

Field 130.0 - 276.7 gauss

Magnet size

420 mm x 150 mm

Height 110 mm

Weight 15 kg/1set

Main coil 320 A (2coil)

Width 10 mm

Height 20 mm

Current density

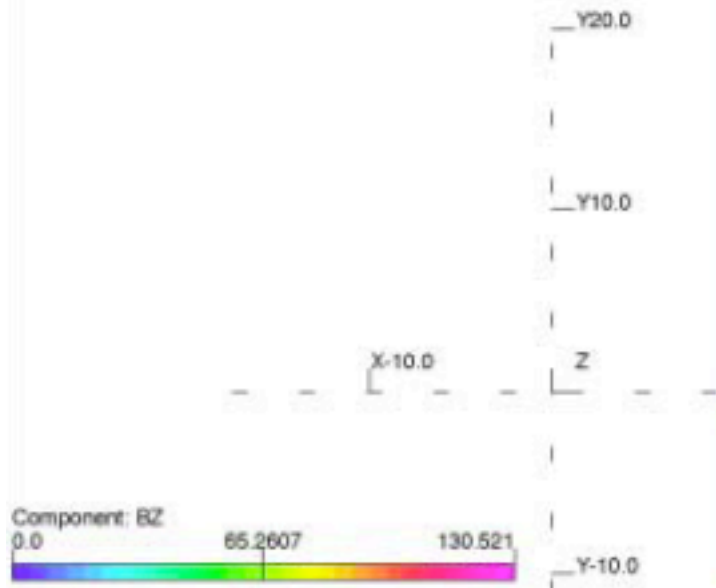
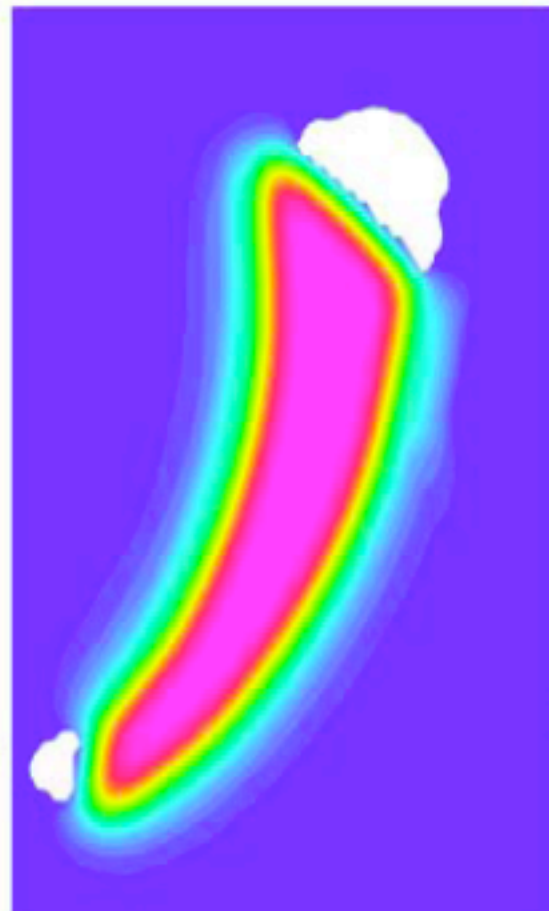
0.8 A/mm²

Surface coil Total

341 A (2coil)

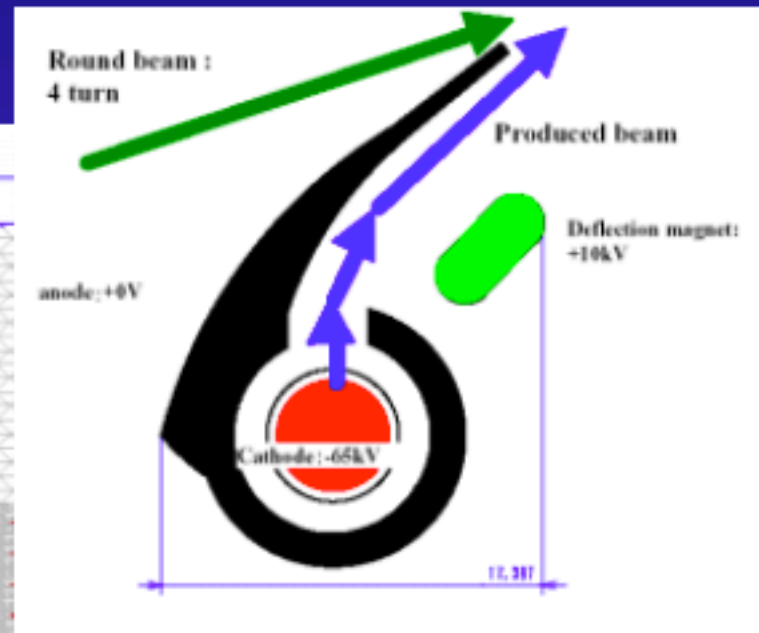
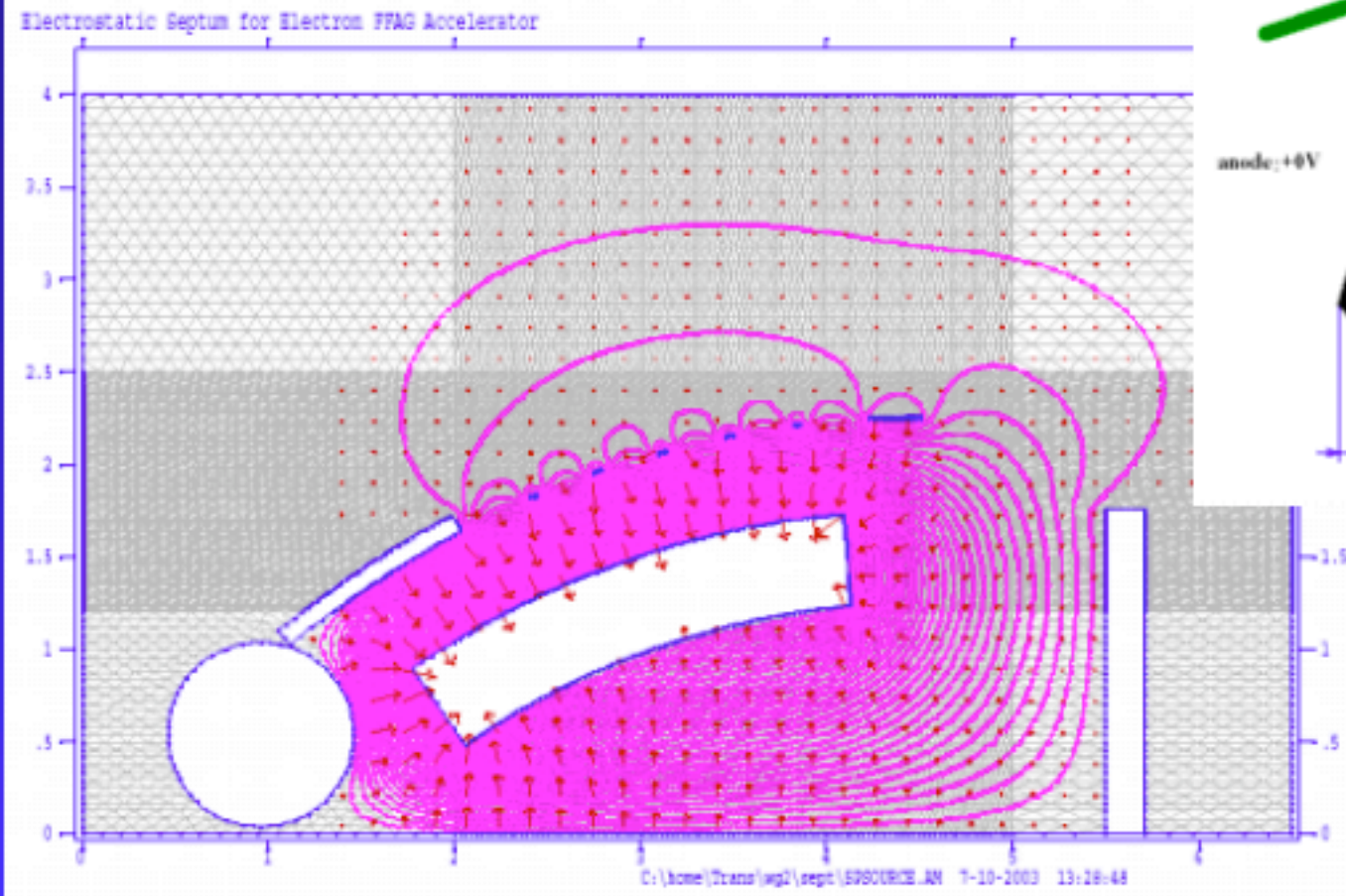
Distribution(radial)

2273 A/m (2coil)



Injection scheme

electrostatic wire septum



Field $\sim 2\text{kV/mm}$
 $\rho \quad 50\text{mm}$
Bending angle 45deg
Wire $0.1\text{mm } \phi$

Turn separation $\sim 3\text{mm}@4\text{turn}$

Beam collide with wire slightly.

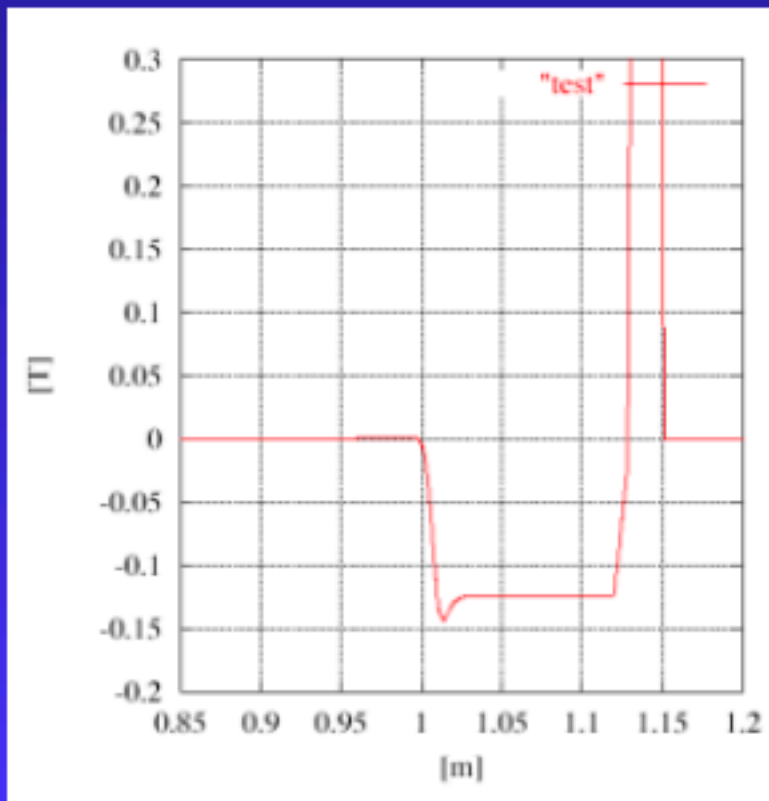


Tracking simulation

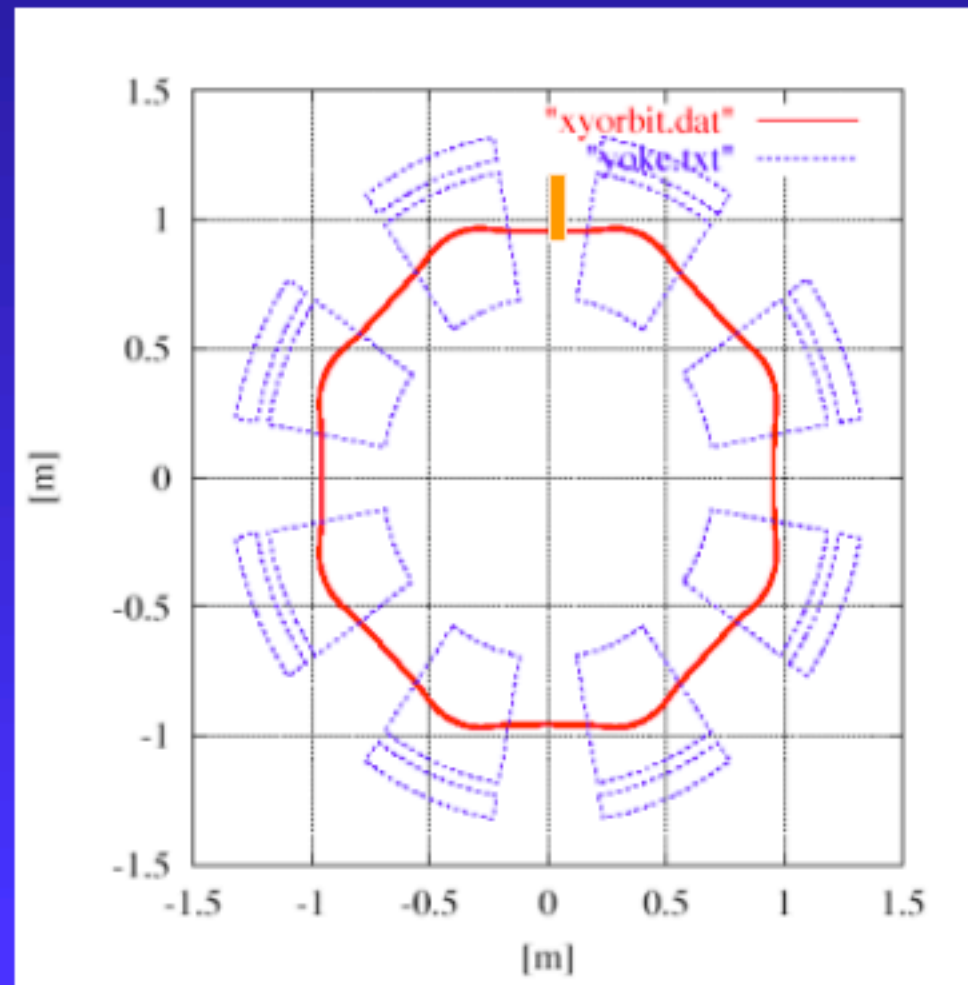
At 1.00m

Energy: 500keV

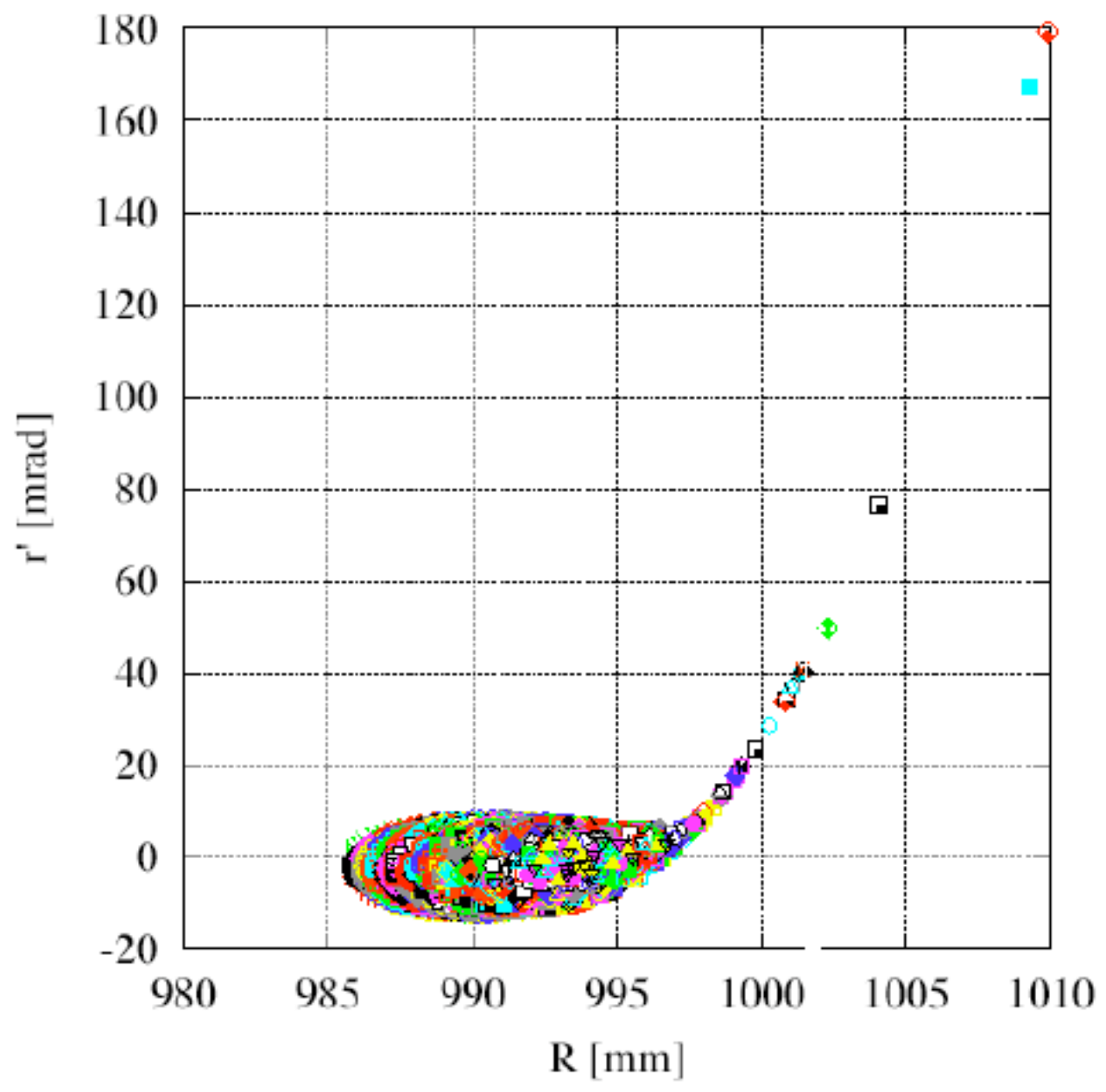
RF voltage: 60V



Magnetic flux density at the medium plane



Configuration of extraction system



Results of beam specs and machine constraints for electron FFAG accelerator

Beam specifications

- Injection energy	50keV	⇒ 50keV
- Extraction beam energy	500keV	⇒ 500keV
- Initial current from electron gun	100mA	⇒ (100mA)
- beam current	20mA	⇒ 20mA
- Lattice type	spiral	⇒ spiral
- repetition rate	50(60)Hz	⇒ 20kHz
- pulse width/emittance/ $\Delta p/p$	NA	

Machine (system) constraints

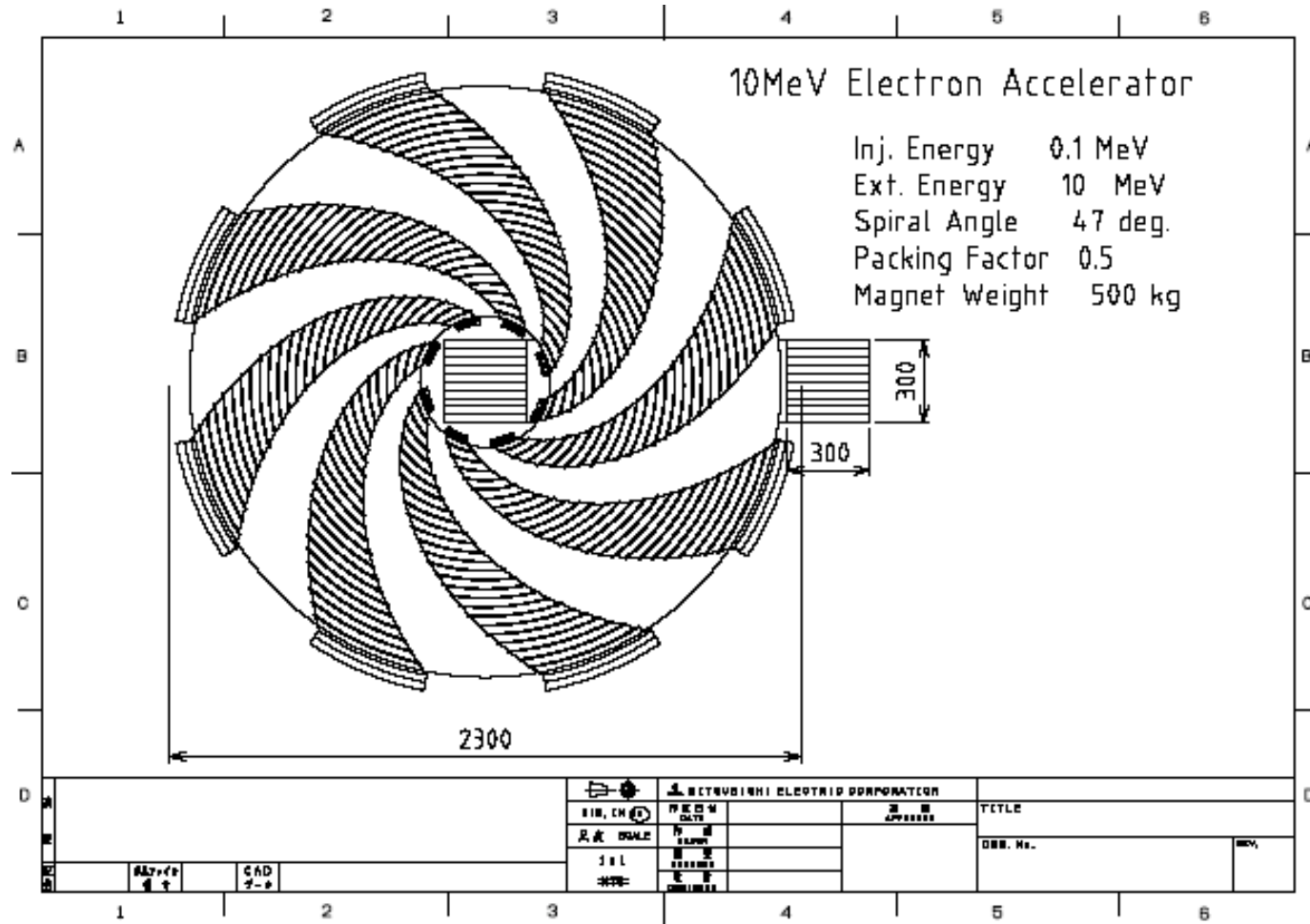
- circumference	1.5m	⇒ 1.6m
- weight		⇒ \sim 200kg
- initial/running cost(acc.)	20M¥	⇒ (20M¥)
- power consumption	20kW	⇒ \sim 20kW
- operation	0	⇒ (0)

e-FFAG 10MeV (FFAG04)

- Requirements for 10MeV, 200kW eFFAG
 - Energy 100keV-10MeV
 - Average/Peak current 20mA/100mA
 - Duty 20%
 - Outer diameter <3m
 - Power consumption <500kW
 - Weight <11 ton
 - Cost <¥500M

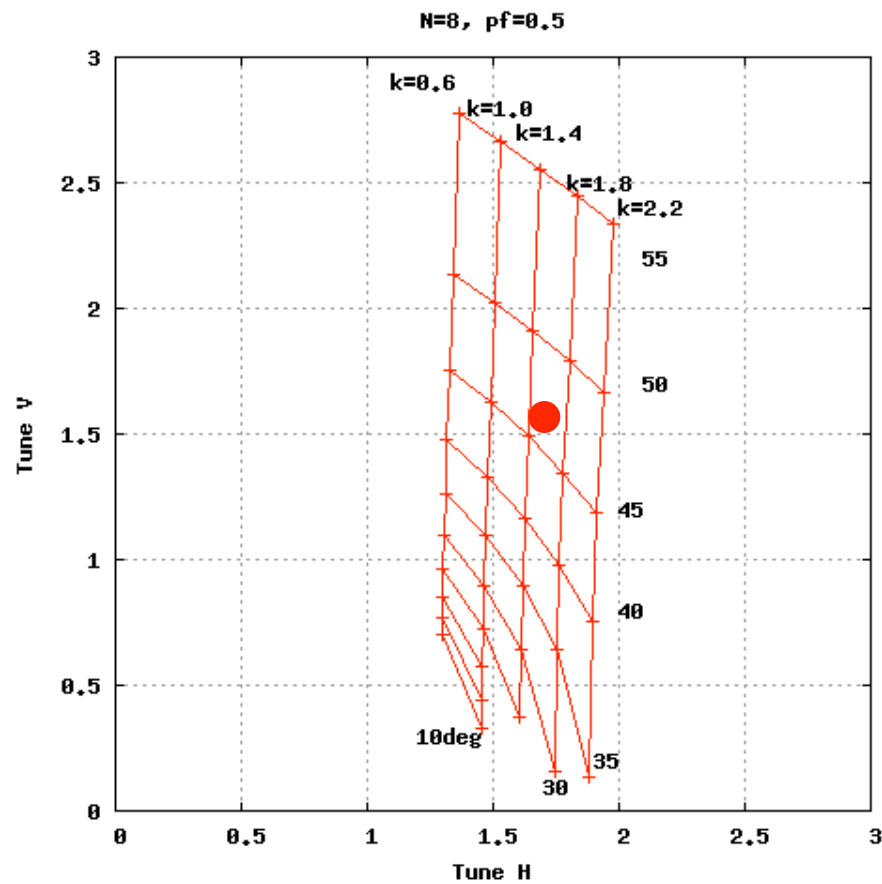
View in Goal

- Based on FFAG03 design



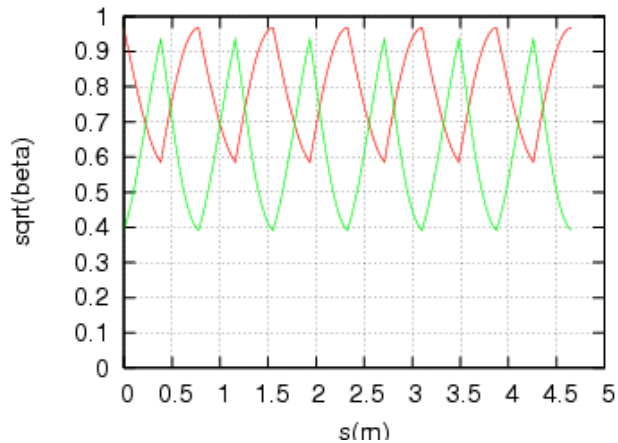
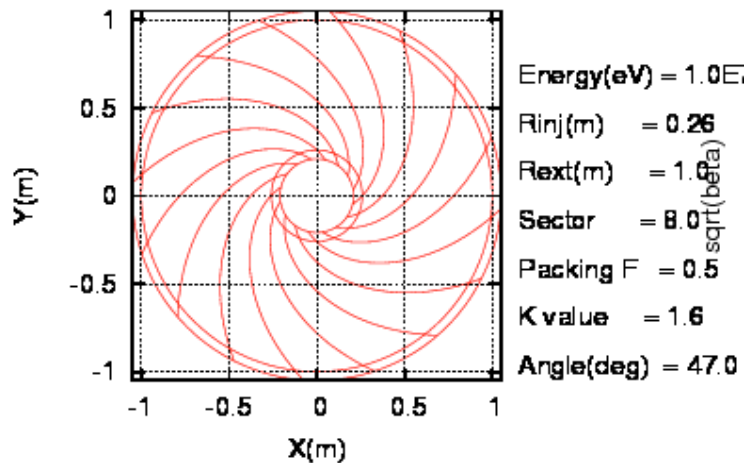
Optics

- Linear optics (hard edge)



Optics

- Parameters



Energy	0.1 – 10 (MeV)
Cell Number	8
K value	1.6
Radius	0.26 – 1.0 (m)
Packing Factor	0.5
Spiral Angle	47 (deg)
dr/dV	1mm / 1.6 kV
Magnetic Field	81 – 700 (Gauss)
Phase advance	77.3 / 71.0
Tune	1.718 / 1.577

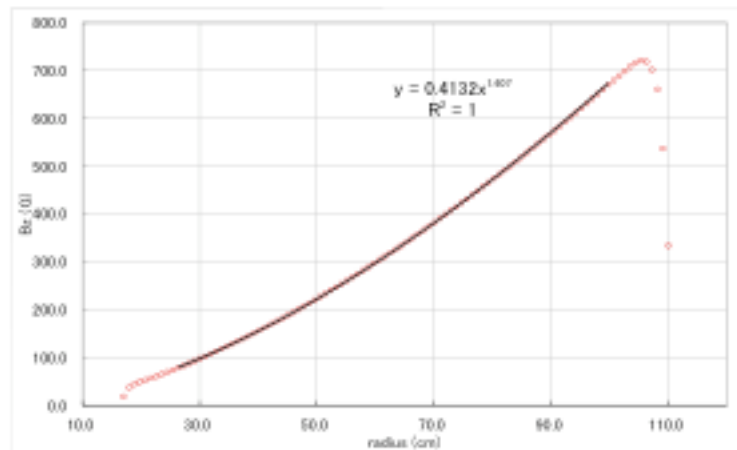
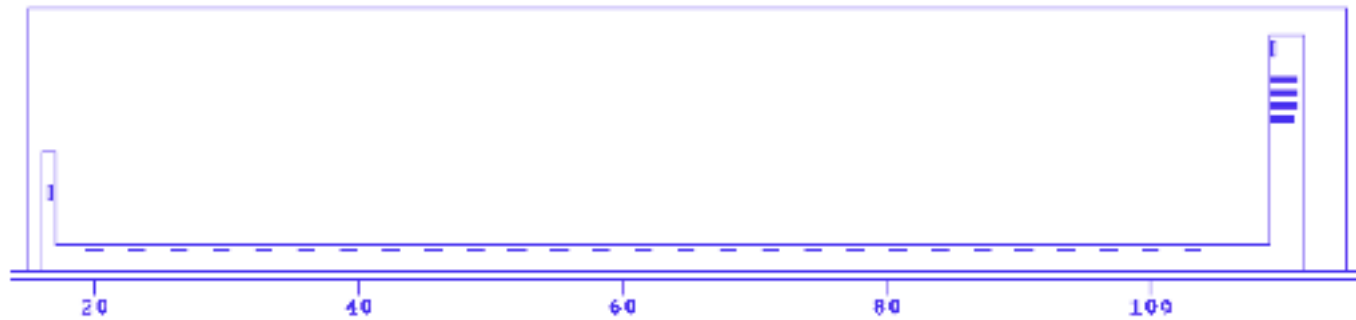
Induction acceleration

- Core design

Material	FINEMET	
Vgap	2 (kV)	Turn separation for injection
Cross Section	30*30 (cm ²)	Iner radius of accelerator
Duty	20 (%)	
dB	2 (Tesla)	Up to 10MeV : Saturation
Frequency	5 (kHz)	
Core Loss	30 (kW)	+200kW < 500kW
Weight	2 (ton)	
Cost	¥40M	

Magnet

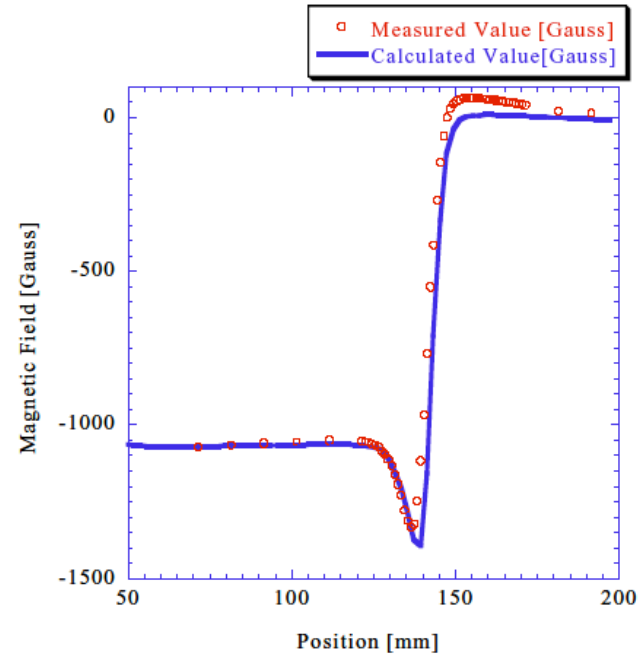
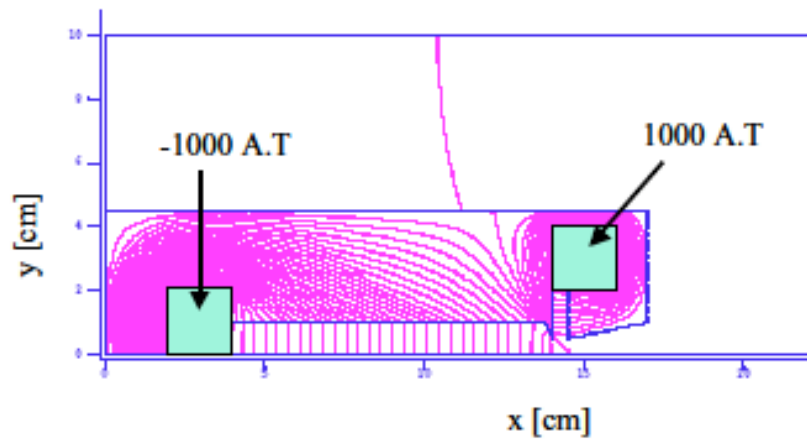
- Distributed coil model



It is $K=1.6$!

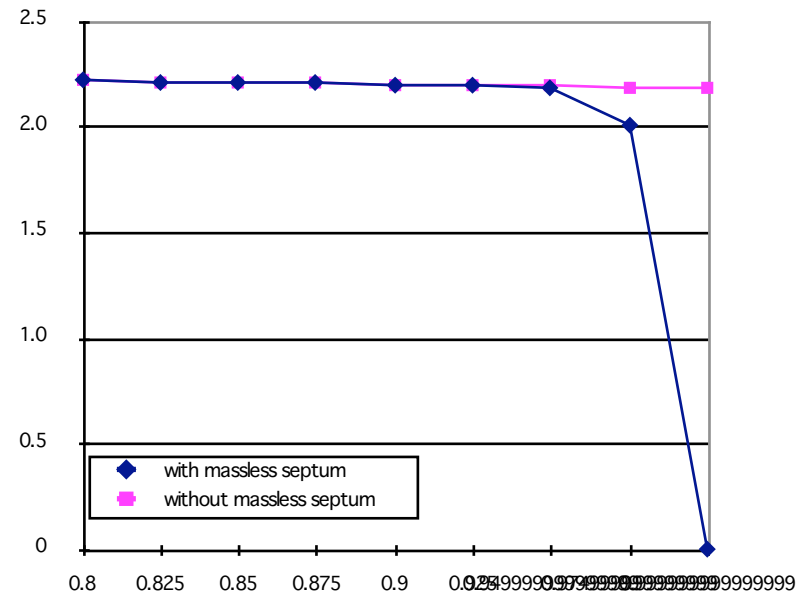
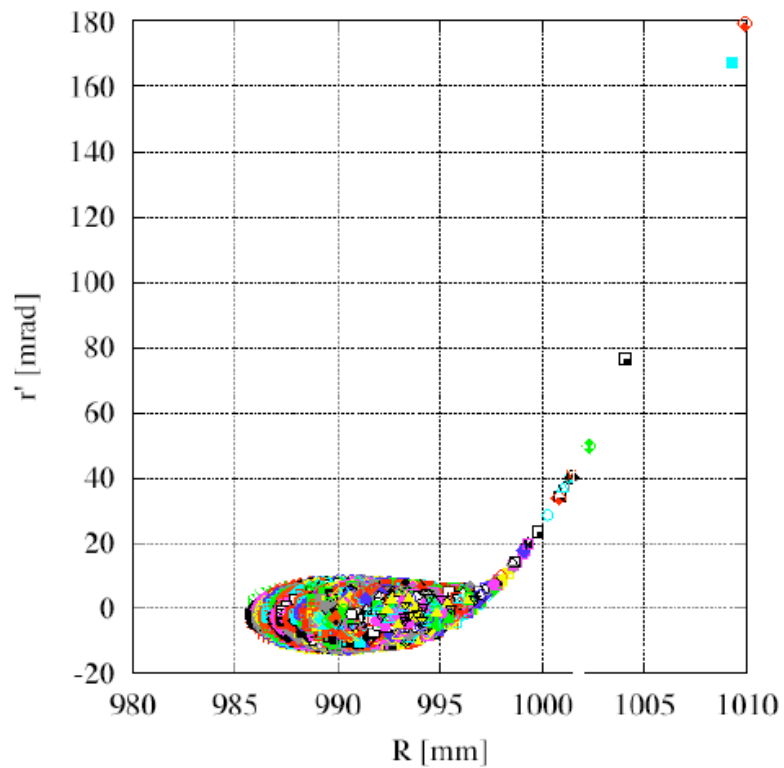
Extraction

- Massless Septum
 - FFAG03

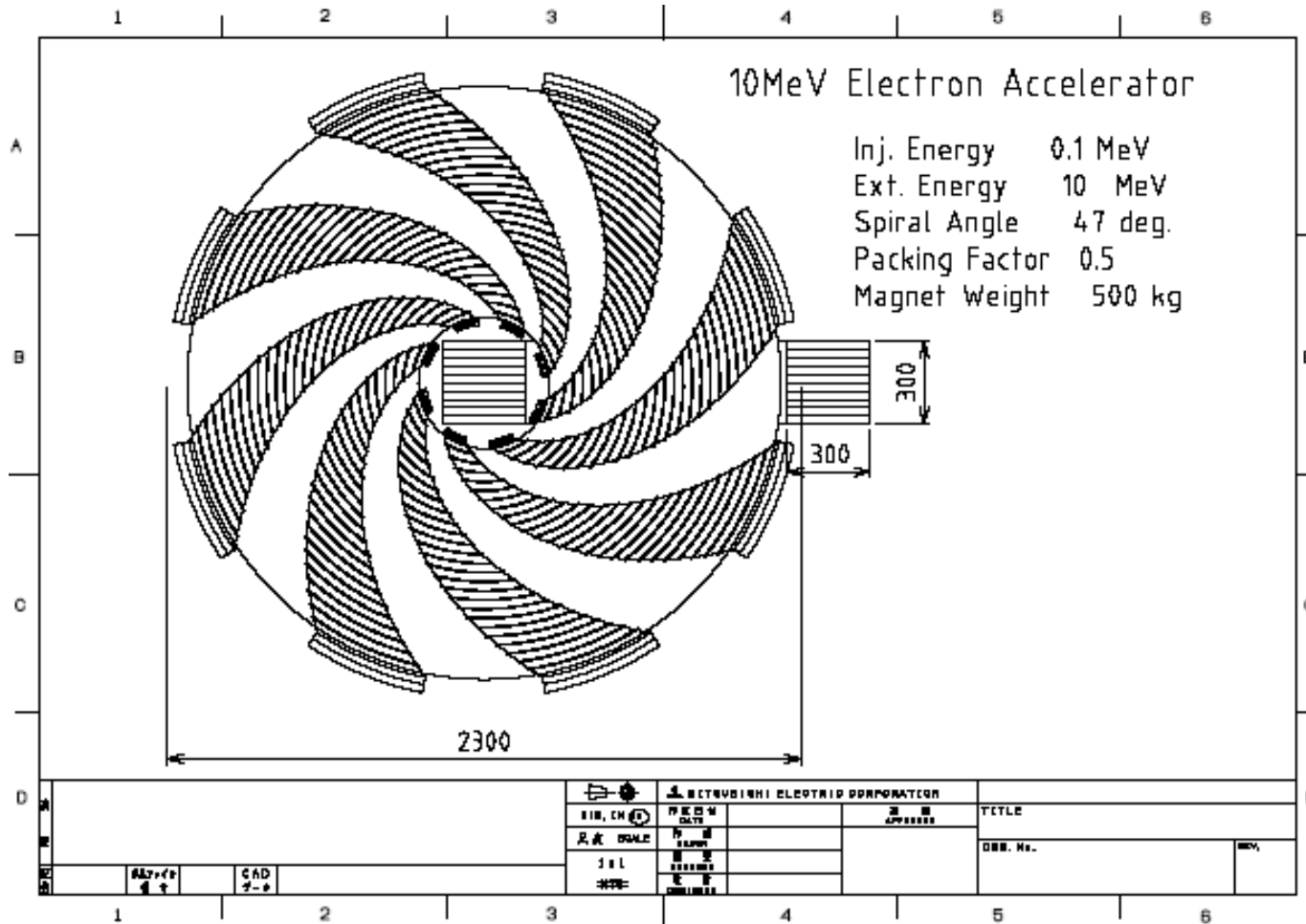


Extraction

- Massless septum
 - Resonance



View



Summary of 10MeV e-FFAG

- 10 MeV e-FFAG is promising...
- Parameters
 - Energy 100keV-10MeV
 - Outer diameter 2.3m < 3m
 - Average/Peak current 20mA / 100mA
 - Duty 20%
 - Repetition 5kHz
 - Power consumption <500kW
 - Weight 8ton < 11ton
 - Cost ¥300M < ¥500M
 - 40% cost down!!!

10MeV Electron Accelerator

Inj. Energy 0.1 MeV
Ext. Energy 10 MeV
Orbit Angle 47 deg.
Packing Factor 0.5
Magnet Weight 500 kg

株式会社 日立製作所		日立製作所 電子加速器部		TITLE	
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10MeV e-FFAG	CAD 7-*				

Summary

▣ Design studies

- 50-500keV,20mA: Scaling e-FFAG(spiral)
- 100keV-10MeV, 20mA: Scaling e-FFAG(spiral)
 - Both machines look promising!

▣ Under development

- LAPTOP ACCELERATOR(Mitsubishi Ele.)
- 50-250keV,40microA: FFAG/betatron