Report from: “FFAG for Electron Acceleration”

Dejan Trbojevic

1. Introduction:
2. Individual reports
3. Conclusions

1. Introduction:

Application part of Electron acceleration with FFAG’s:

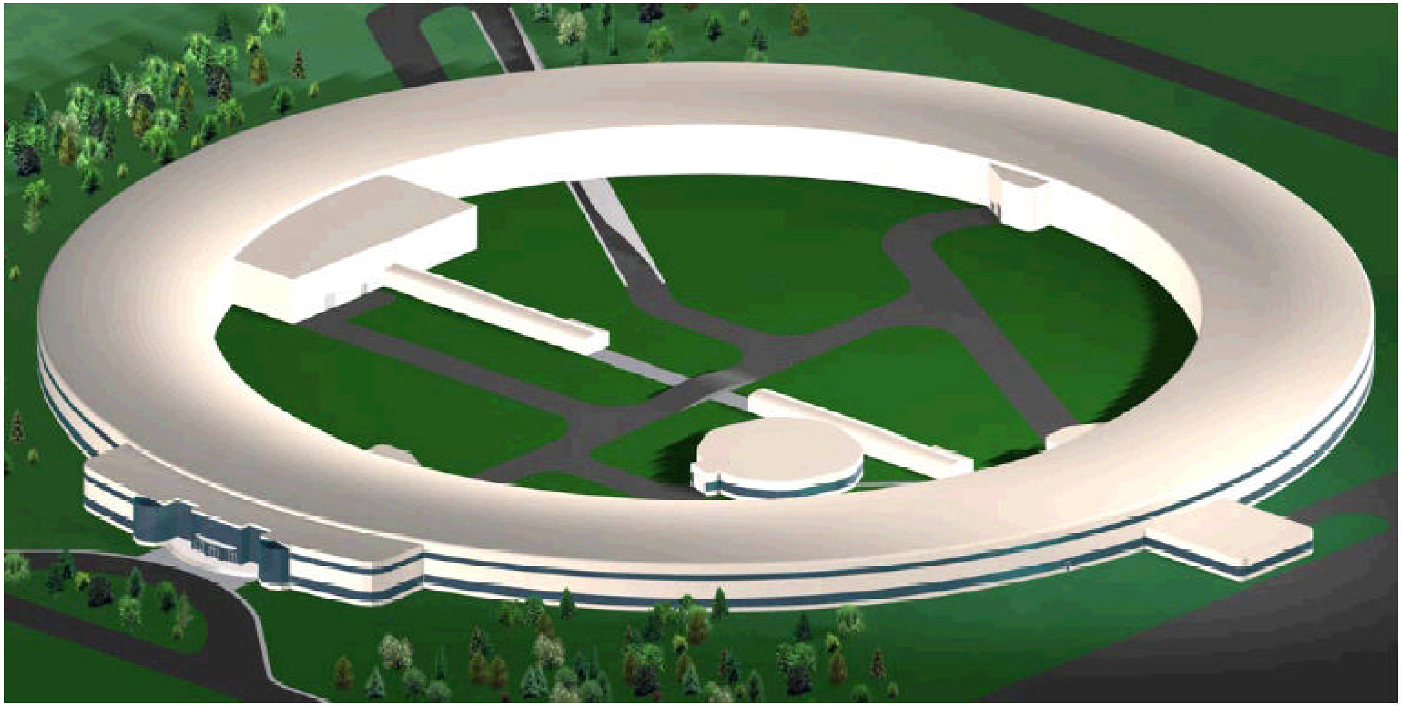
1. Wide Industrial applications
2. Light Sources
3. e-RHIC
4. Demonstration electron rings for: Proton, muon, heavy ion (RIA)

Wednesday May 17 -- FFAG for Electron Acceleration
Organizer D. Trobjevic -- Chairman T. Shaftan -- Rapporteur T. Shaftan

9:00-9:45	T. Shaftan -- Acceleration of Electrons in the NSLS2
9:45-10:30	M. Blaskiewicz -- Electron Acceleration for eRHIC in FFAG
10:30-11:00	Coffee Break
11:00-11:45	A.G. Ruggiero -- Next Generation Light Sources with FFAG
11:45-12:30	Y. Mori -- Scaling FFAG for industry electron applications
12:30-14:00	Lunch
14:00-14:45	P. Dent -- Permanent Magnets in Accelerator Design
14:45-15:30	H. Takahashi -- Quantum Aspects of Charged Beam Transport doc1 - doc2
15:30-16:00	Coffee Break

Could the FFAG's compete with the bosster synchtrotrons?

Acceleration of Electrons in the NSLS-II



T. Shaftan for the NSLS-II team

My colleagues: R. Heese, I. Pinayev, D. Raparia. J. Rose

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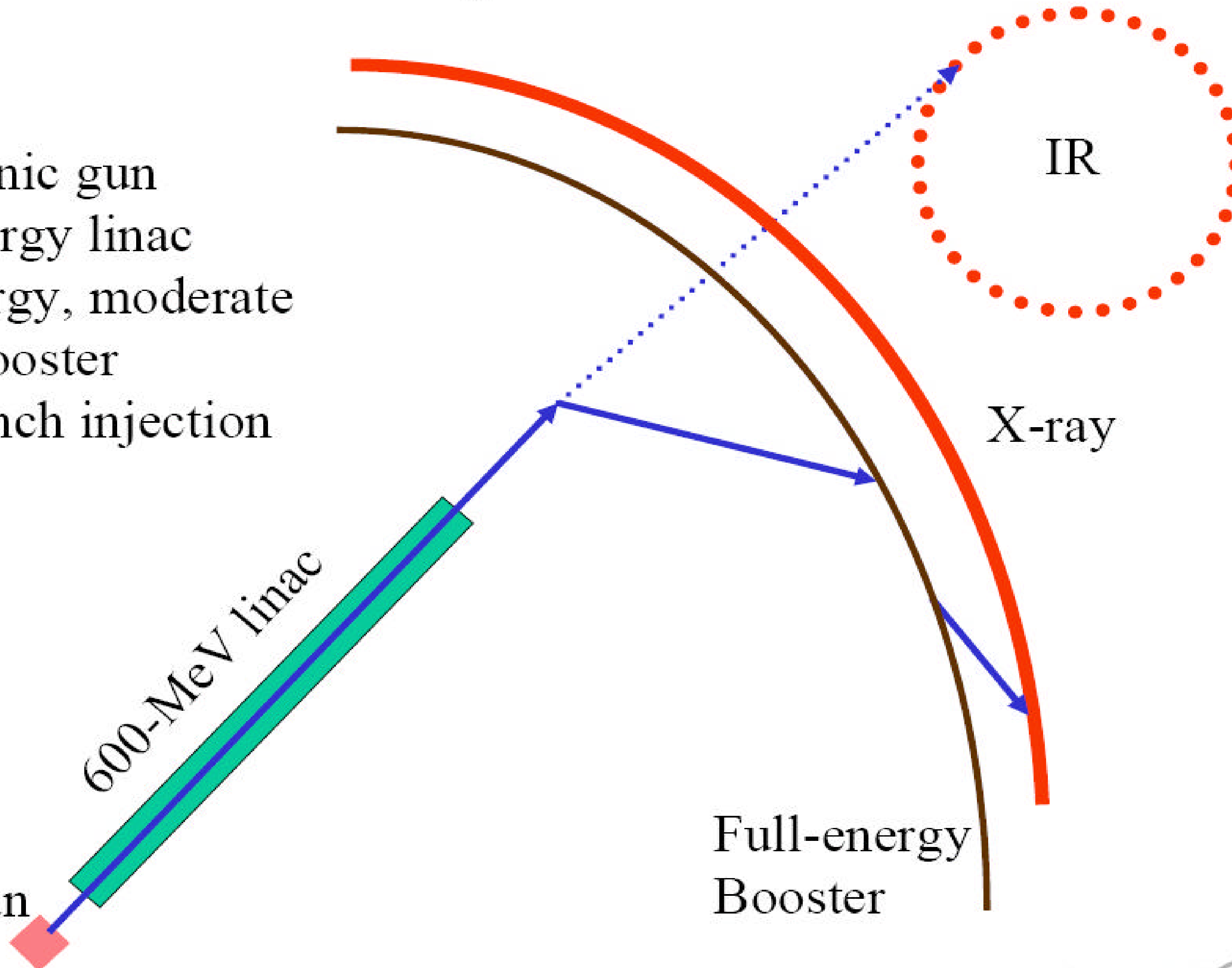
NSLS-II injection scenario

- Thermionic gun
- Low-energy linac
- Full-energy, moderate rep-rate booster
- Multi-bunch injection



NSLS-II injection parameters

Parameter	X-ray ring
Energy, GeV	3
Circulating current, A	0.5
Circumference, m	936
Revolution period, μs	3.12
RF frequency, MHz (wavelength, m)	500 (0.6)
Circulating charge, μC	1.56
Total number of buckets	1560
Number of filled buckets	$1560 \cdot {}^{4}/_{5} \approx 1280$
Charge per bucket, nC	1.22
Current per bucket, mA	0.39
Lifetime, min	~180
Interval between top-off cycles, min	1
Current variation between top-off cycles, %	0.55%
Current variation between top-off cycles, mA	2.7
Charge variation between top-off cycles, nC	8.6
Damping time, ms	75

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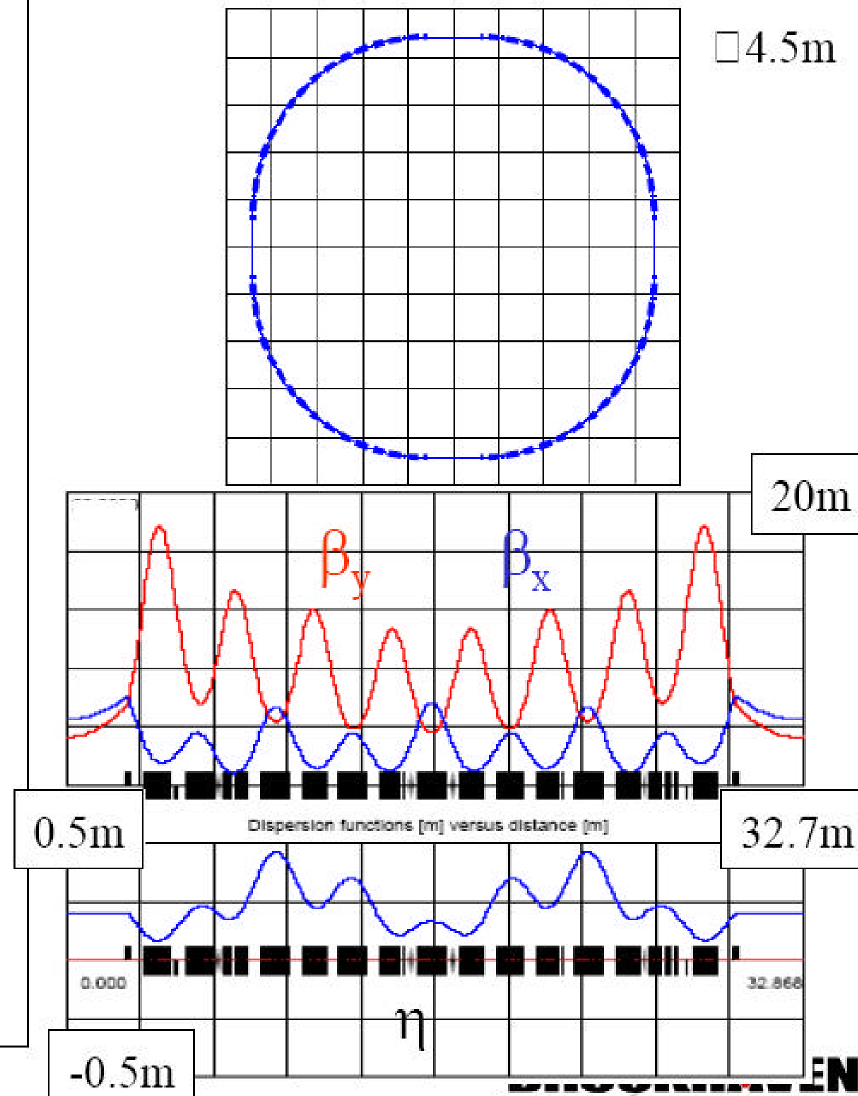
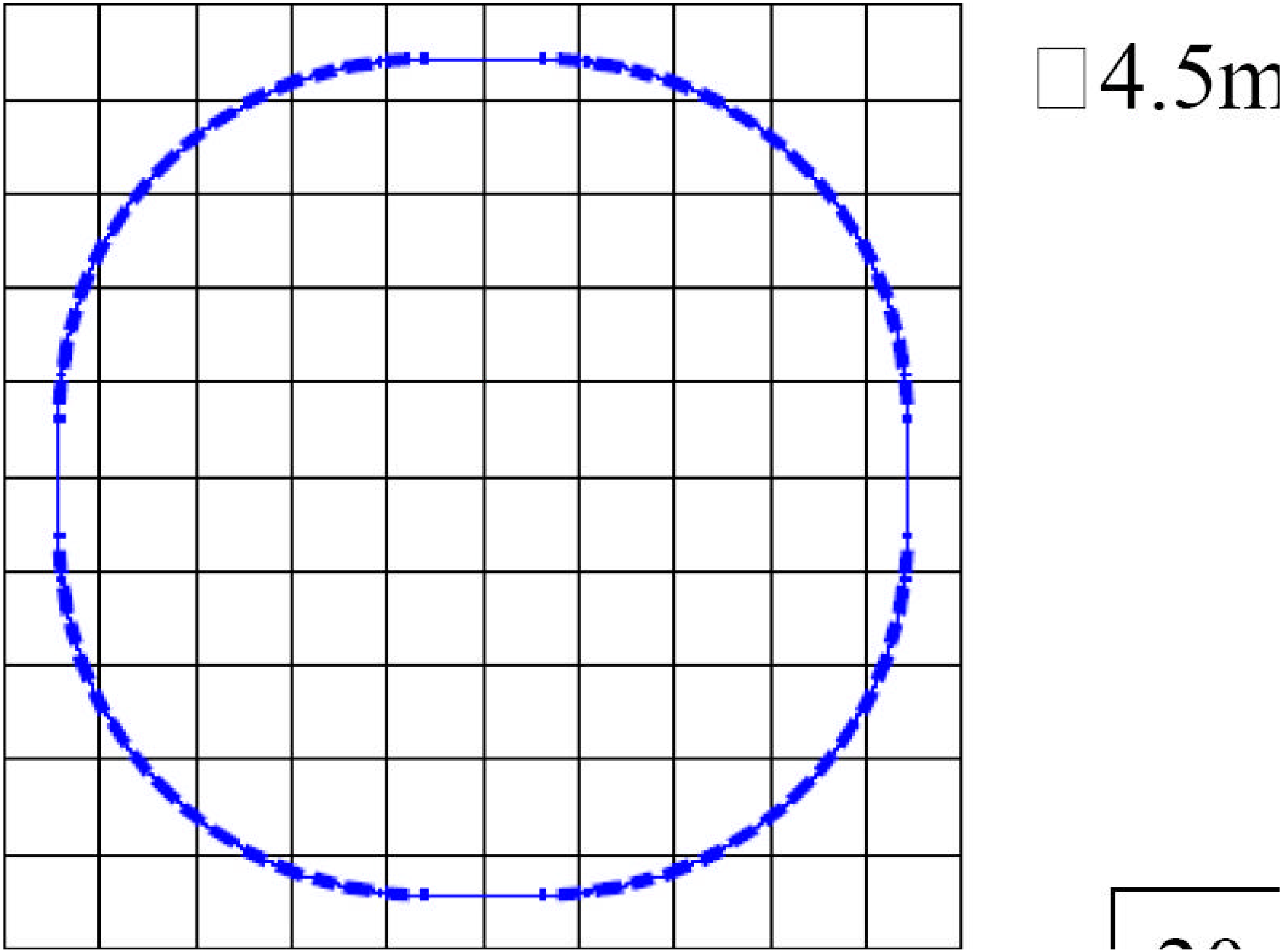
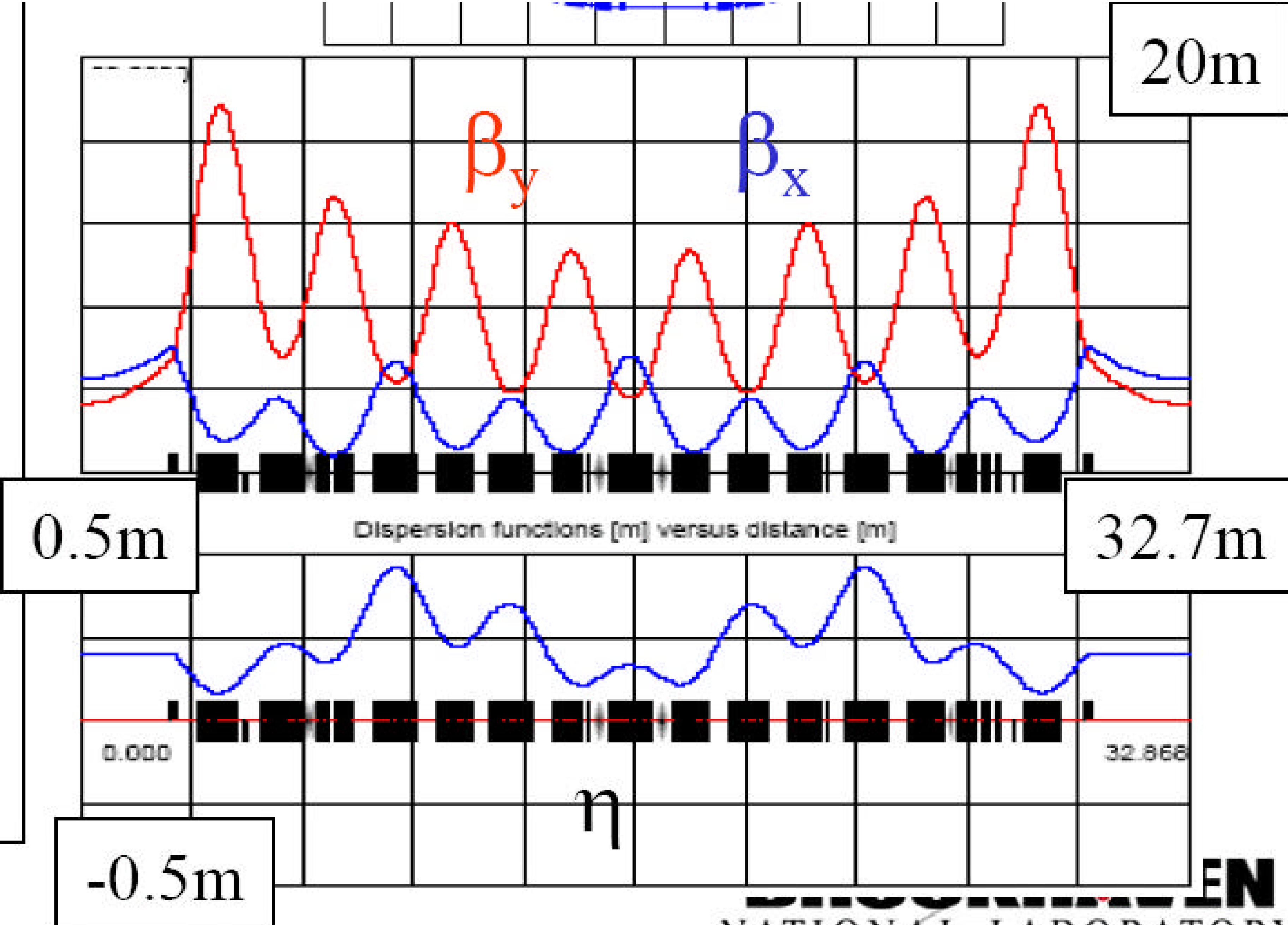
ASP booster (Danfysik)

- Energy: 0.1→3 GeV
- Rep. Rate: 1 Hz
- Circumference: 130 m
- RF frequency: 500 MHz
- Emittance: 30 nm rad
- Radiation loss: 743 keV/turn
- Beam current: >5 mA
- Magnet power: 240 kW



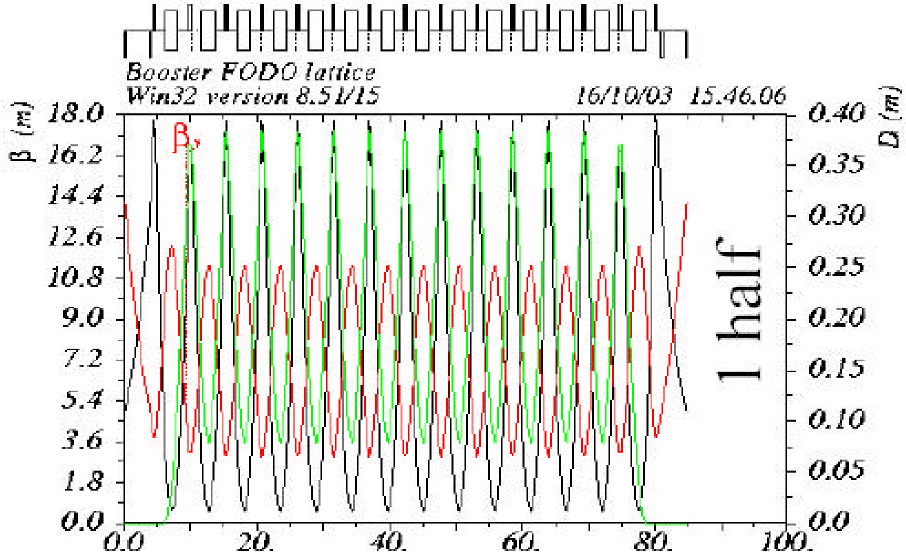

4.5m

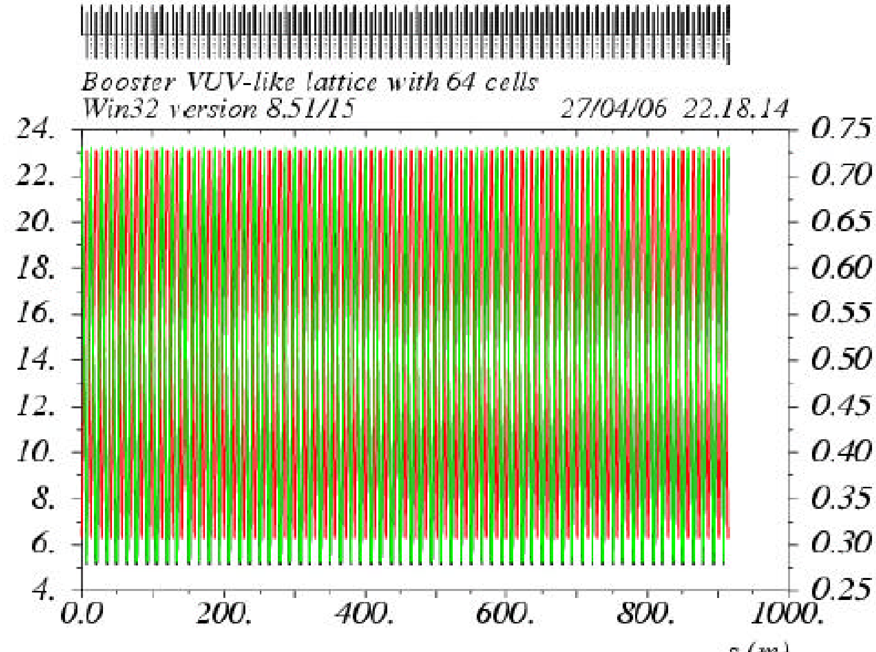


20m
β_y
β_x
0.5m
Dispersion functions [m] versus distance [m]
32.7m
0.000
32.868
η
-0.5m

Full-energy booster

- Compact booster
  - 24-cell TME lattice with 4 dispersion suppressors
  - Two 10-m straights for RF and injection and for extraction
  - Single dipole power supply
  - Requires building of NSLS X-ray ring size
- "Same-tunnel" booster
  - Same circumference as the main ring
  - 64-cell TME, 10 m between dipoles
  - Require additional families of quadrupoles and sextupoles
  - 8 "small" dipole power supplies
  - Requires rearrangement of the lattice for optimization





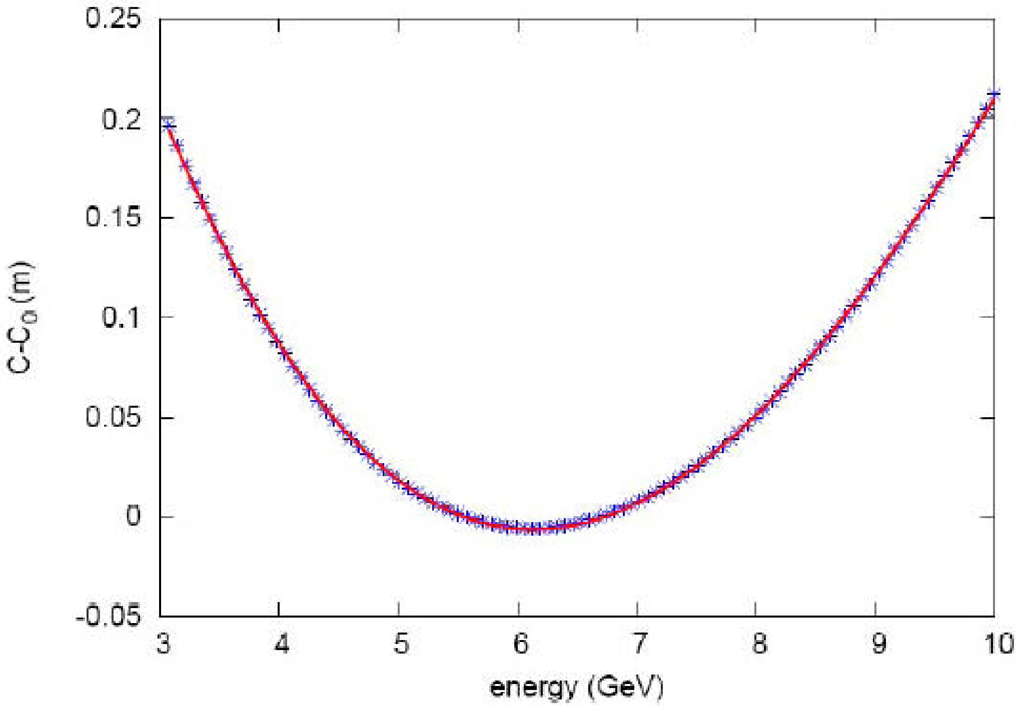
Booster comparison

Parameter @ 3.6 GeV & 1Hz	"Compact" booster	"Same tunnel" booster
Dipole	13.8°, 1.0 T, 2.9m, 15cm, 2.5cm, 10 turns, 2.5e^3 mm^2, 4.8 mΩ, 10 mH	5.625°, 0.8 T, 1.5m, 15cm, 2.5cm, 12 turns, 165mm^2, 4.6 mΩ, 7.5 mH
Total peak power	Active 120 kW Reactive 525 kW	Active 8 x 16 kW Reactive 8 x 52 kW
Voltage x Current from PS	650V x 1.0 kA	8 x 100V x 680A
Booster current in top-off	13 mA	2.8 mA
SR losses	1.25 MeV/turn, 16 kW	1 MeV/turn, 2.8 kW
Cavity Voltage, RF acceptance	2MV, 0.9%	2MV, 0.9%

NSLS II Tunnel

FFAG for eRHIC

The goal is to design a rapid cycling accelerator for 3 to 10 GeV. Dejan Trbojevic designed a lattice with a nominal circumference C=1277m. The variation in circumference with electron energy is



Installed Voltage

At 10 GeV an electron radiates 12.9 MeV per turn.

The reverse bends are important. For a circular path with C=1277m, an electron loses 4.3 MeV per turn.

Take an installed voltage of 20 MV/turn.

Use 2, 701 MHz cavities being designed for the e-cooling ERL.

Taking 10^{11} electrons per bunch and a bunching frequency of 28.1 MHz , the DC electron beam current is 0.49 Amperes.

This translates to 6.3 MW of radiation power at 10 GeV, which sets the scale for the RF power supplies. The ideal cavity impedance based on radiation requirements is then

$$R_{sh} = \frac{V}{I_{beam} \sin \varphi_s} = 30 M\Omega = 200\Omega \times Q,$$

$$Q = 1.5 \times 10^5$$

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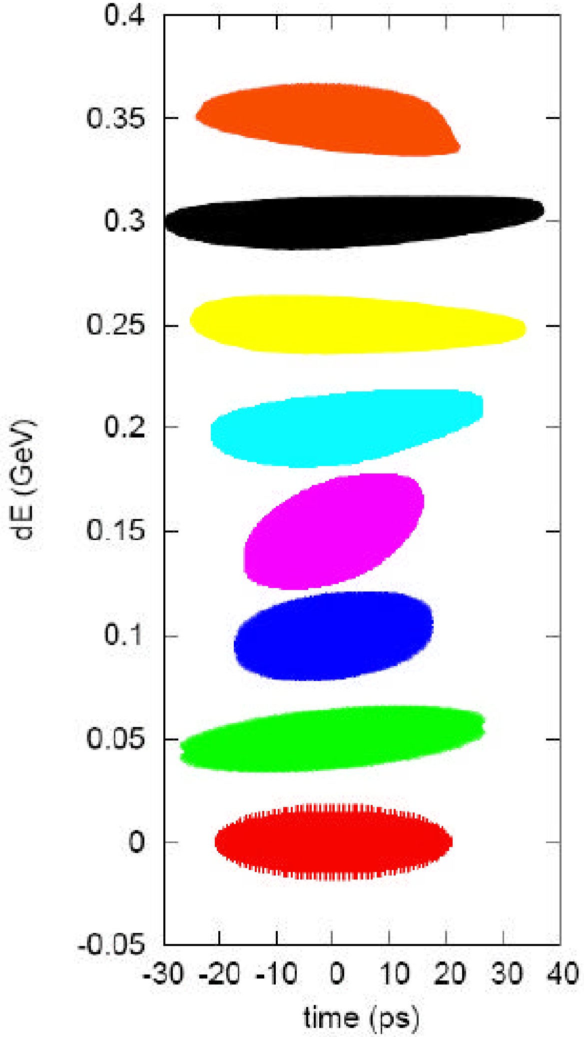
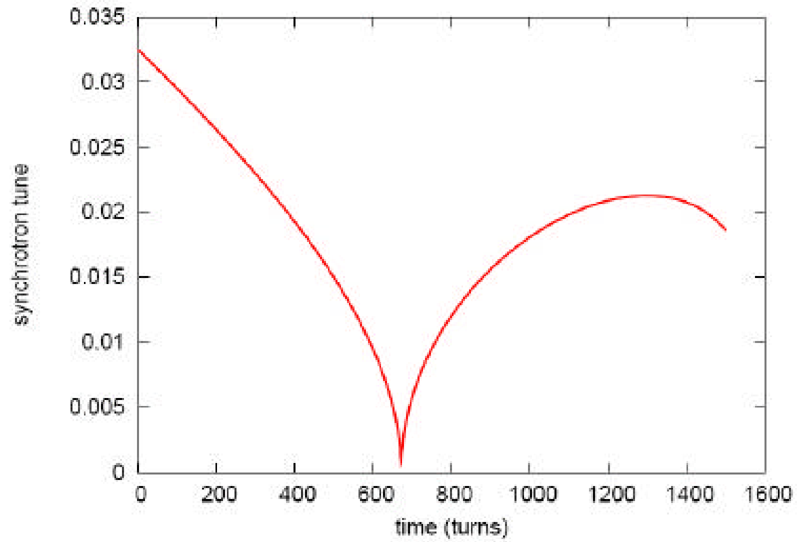
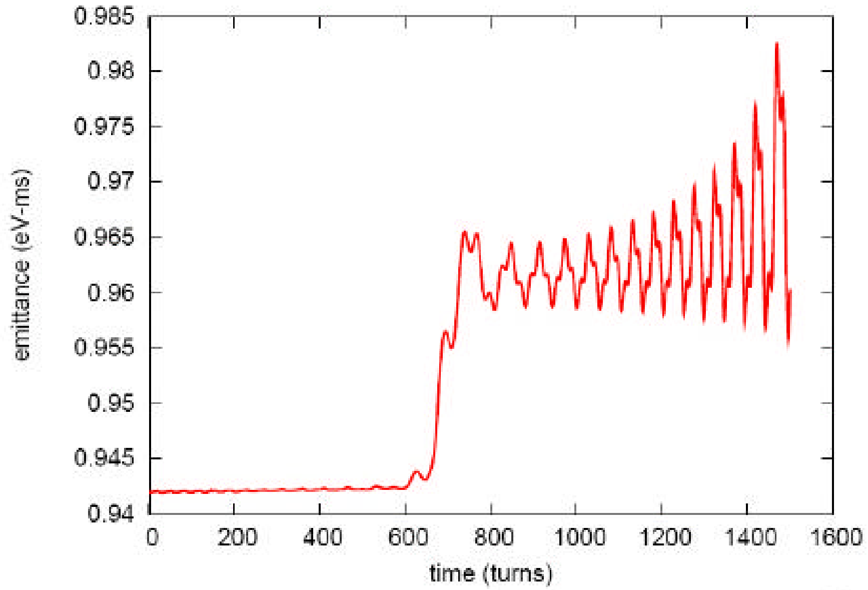
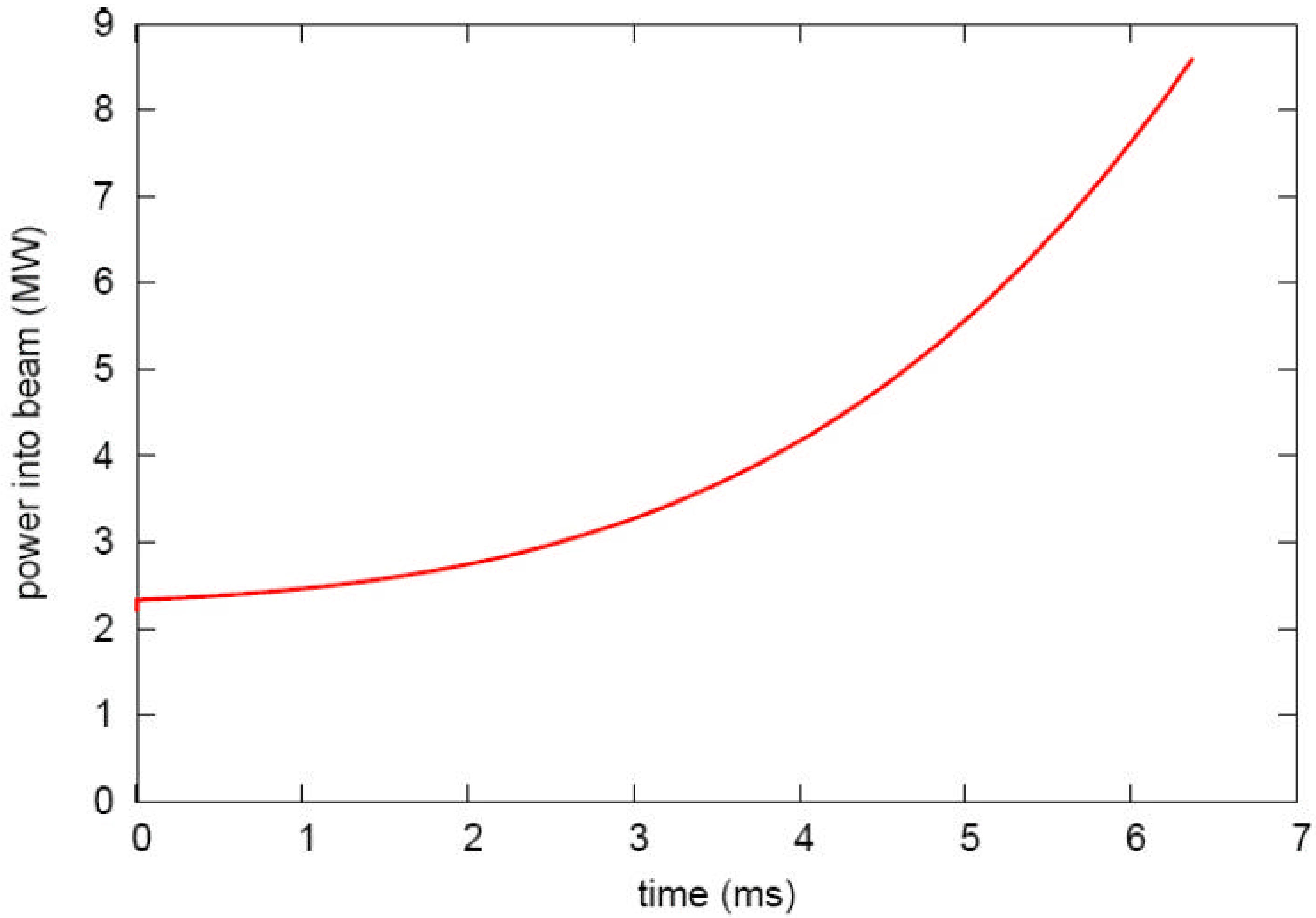
Simulations







power budget with constant dE/dt



Development of Scaling e-FFAG in Japan

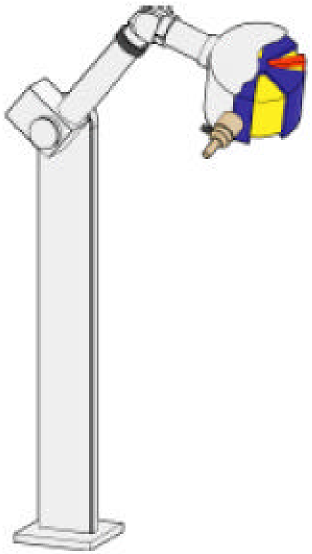
Yoshiharu Mori
Research Reactor Institute, Kyoto University

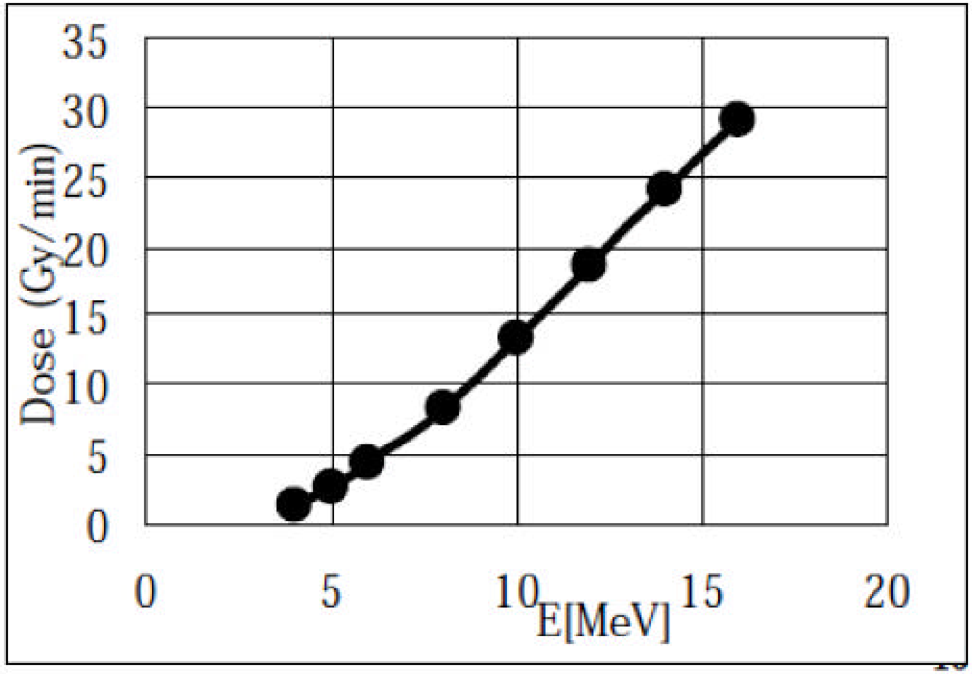
Activities for e-FFAG in Japan

- 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





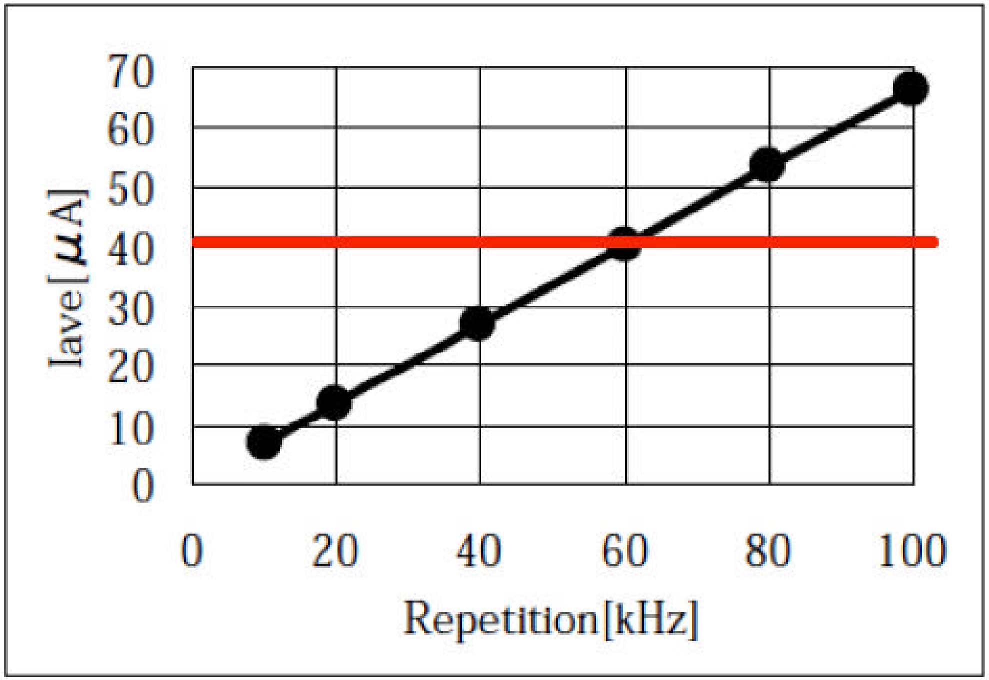
Basic parameters

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]

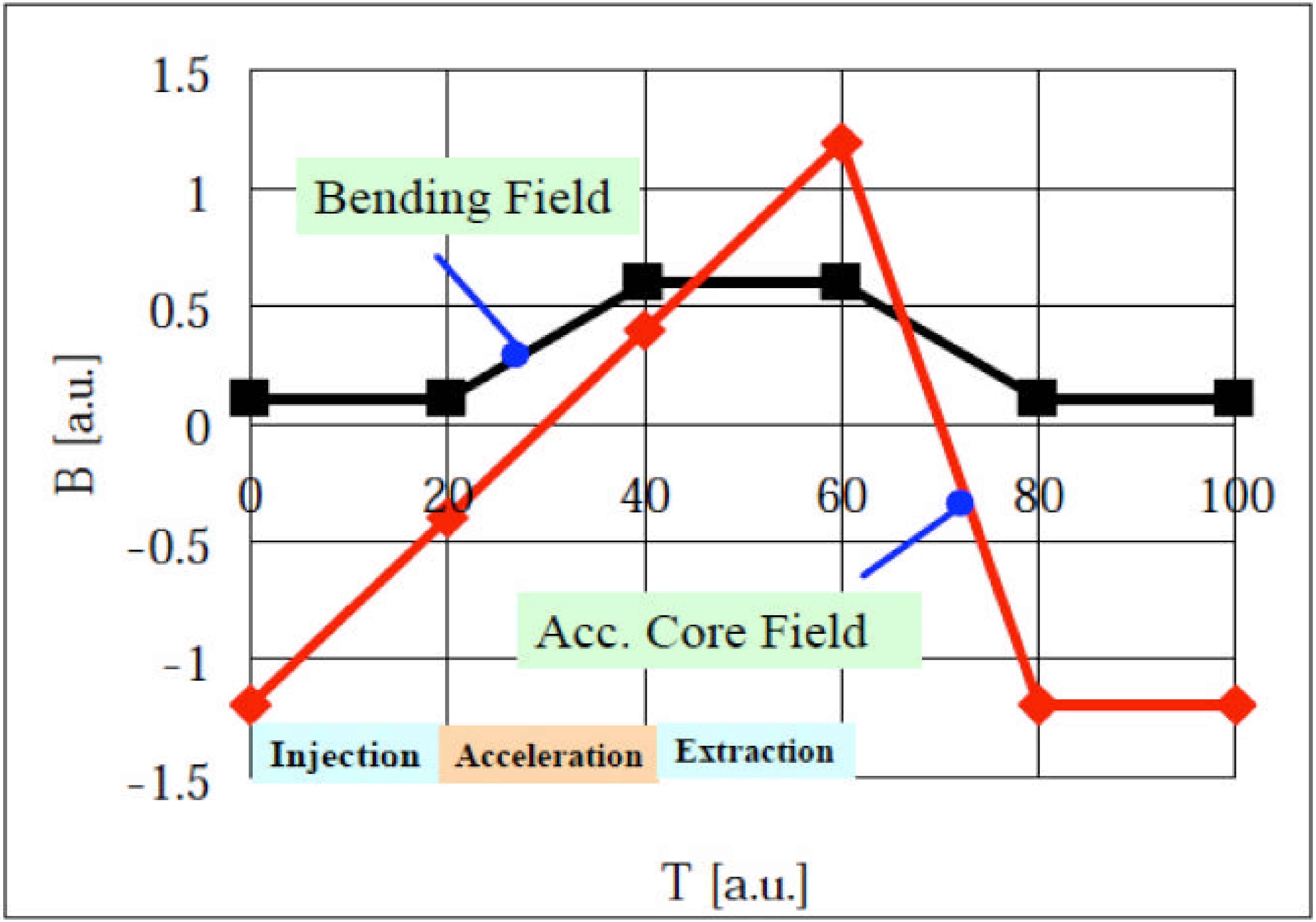
Average beam current of a conventional Betatron

- from old papers
- Normalized orbit radius and beam energy: r=0.1m, E=6MeV



Average beam current v.s. repetition

Acceleration Scenario

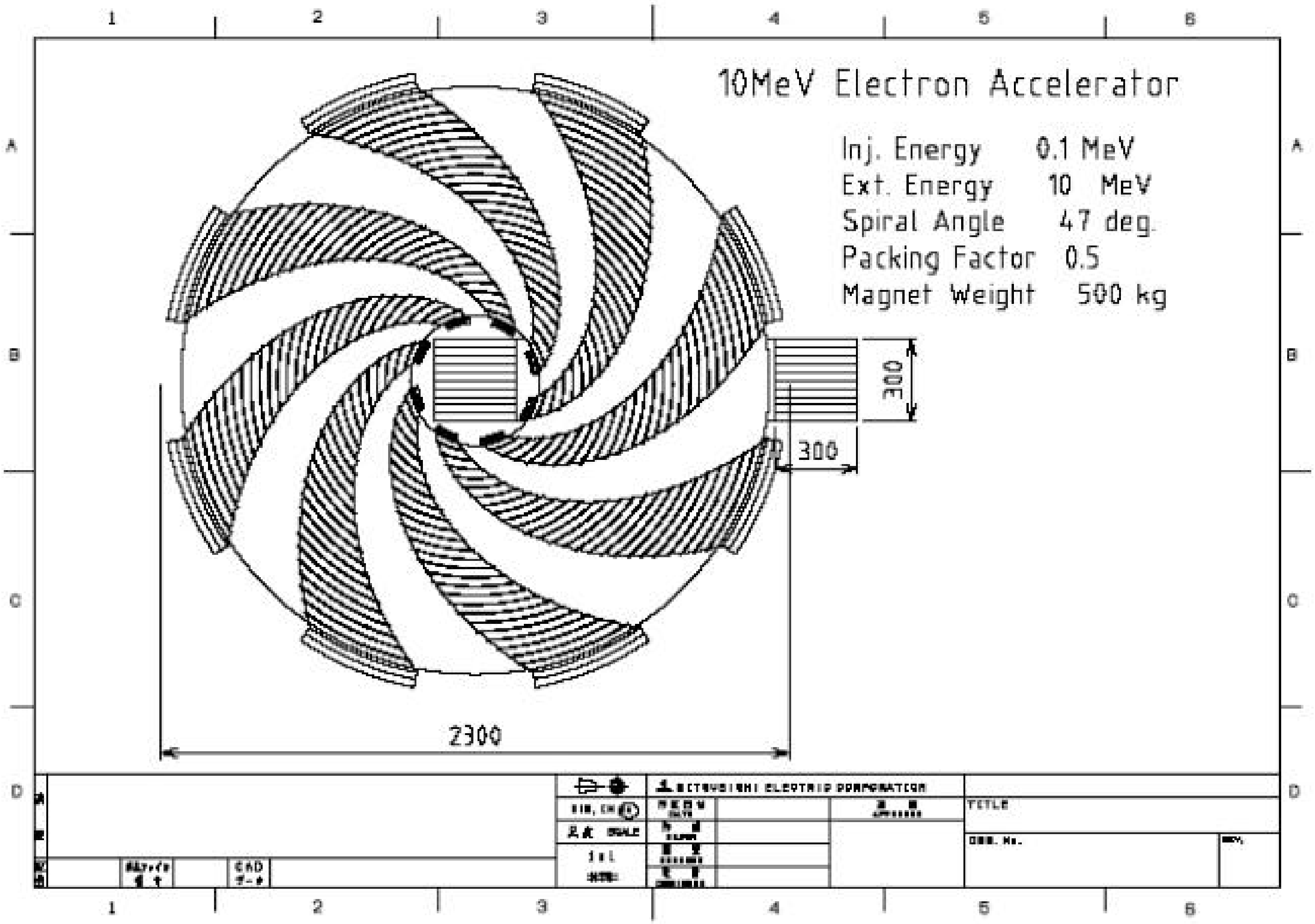


e-FFAG 10MeV (FFAG04)

- 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



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

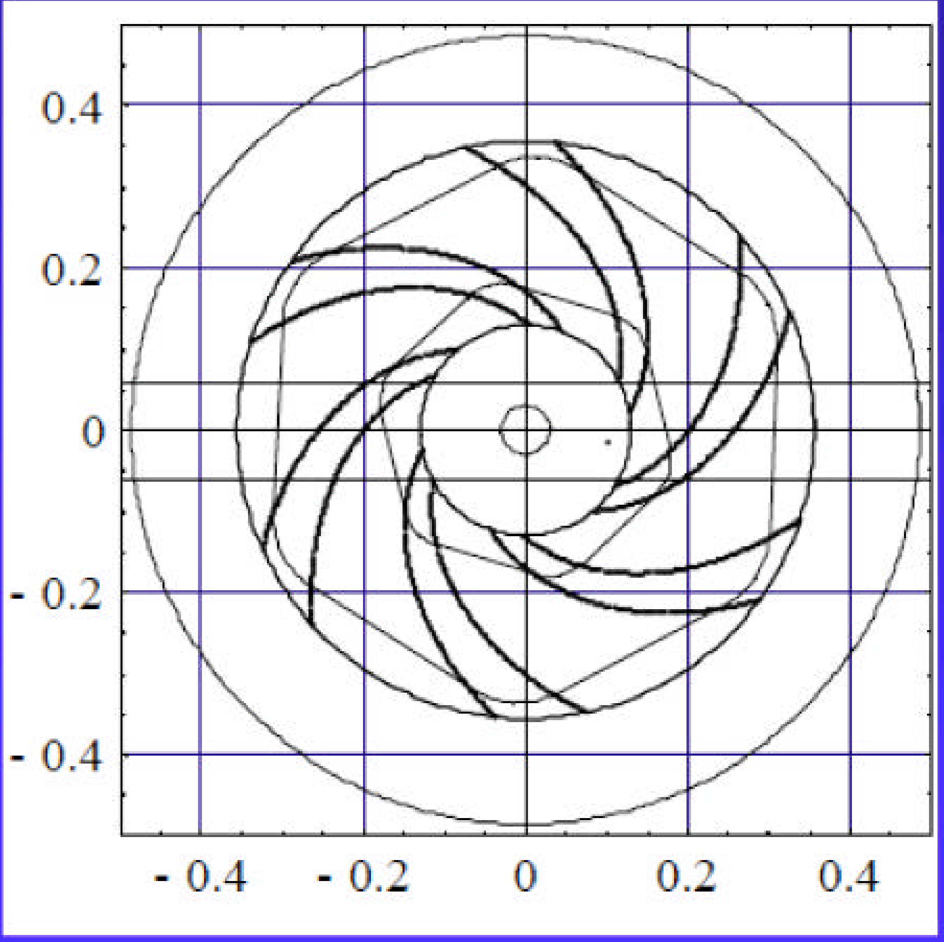
Machine (system) constraints	
- circumference	1.5m
- initial/running cost(acc.)	20M¥
- power consumption	20kW
- operation	0

Lattice

Case2: Without Clamp

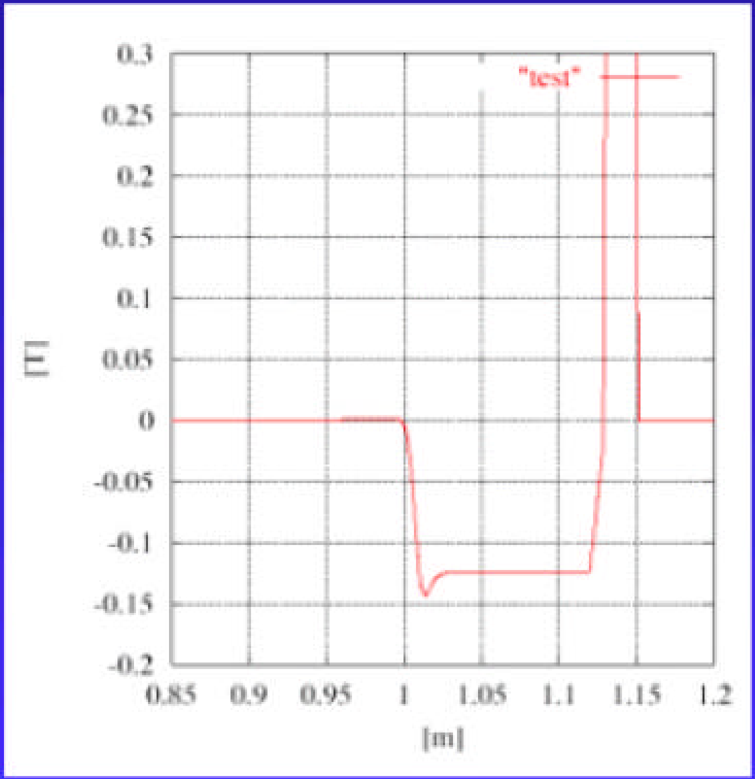
Nsect	6
K value	1.2
Spiral Angle	52 [Degree]
Injection Radius	0.18 [m]
Extraction Radius	0.33[m]
Packing Factor	0.30
Full Gap	26[mm]
Fint	0.45
Repetition	20 [kHz]
Energy Gain	800 [V/turn]
Turn Separation	0.64 [mm/Inj]
Bin/Bout	143/293 [Gauss]

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

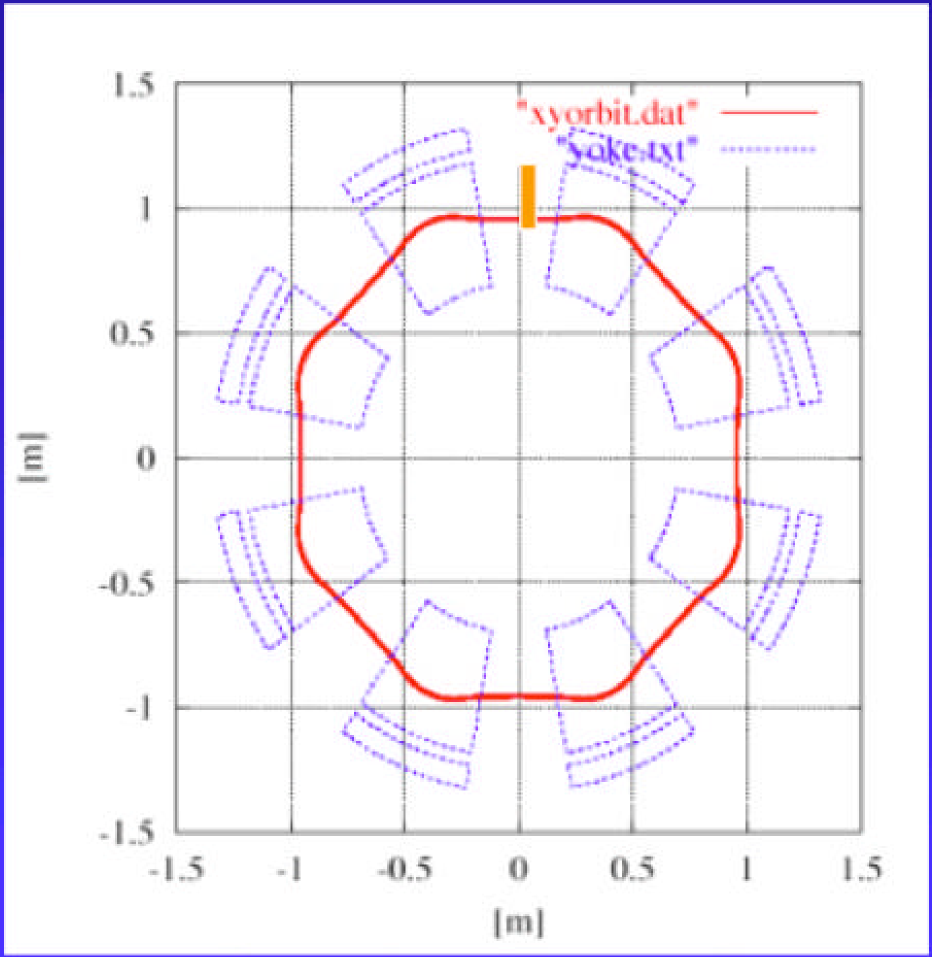


Tracking simulation

At 1.00m
Energy: 500keV
RF voltage: 60V



Magnetic flux density at the medium plane



Configuration of extraction system

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

Permanent Magnet Diploes and Quadrupoles for FFAGs

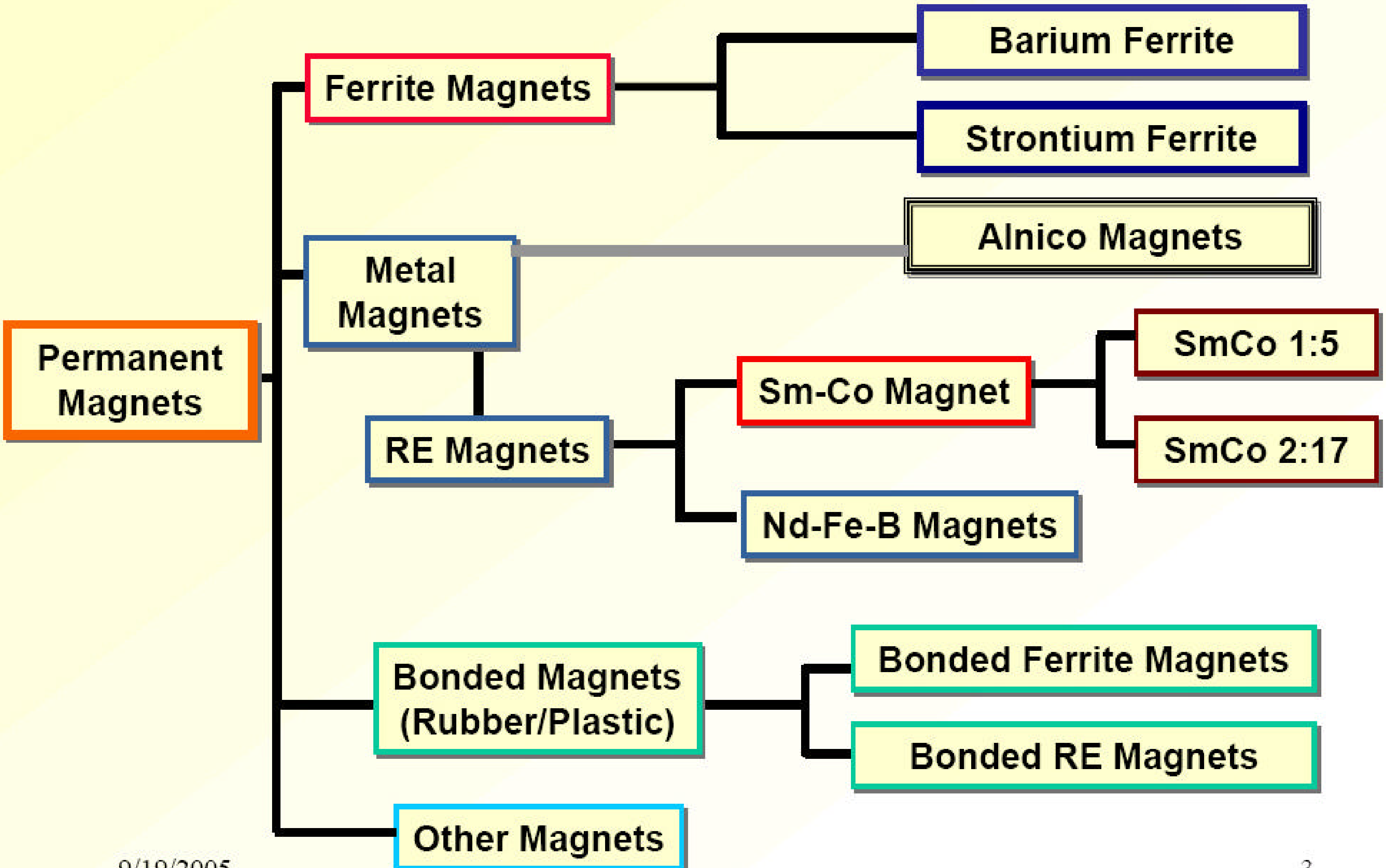
Jinfang Liu and Peter Dent

Electron Energy Corporation

924 Links Ave, Landisville PA 17538

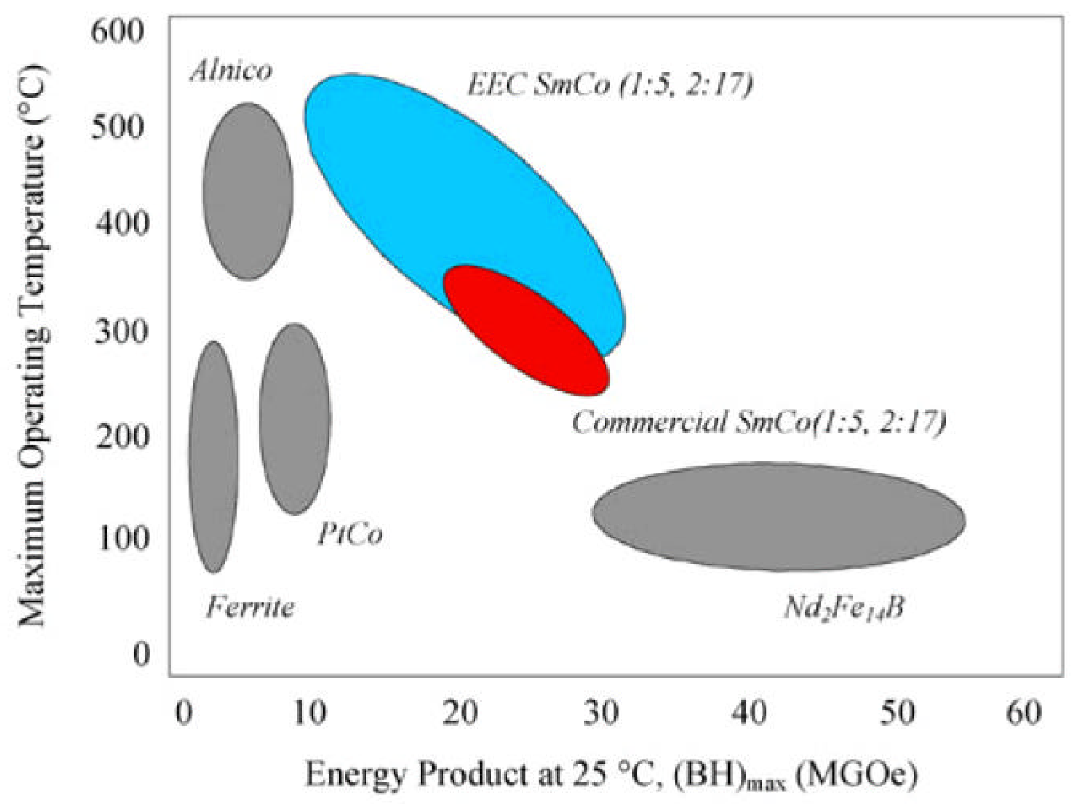
Phone: 717-898-2294 Fax: 717-898-0660

Types of Commercial magnets



$(BH)_{max}$ versus Maximum Operating Temperature

Overview



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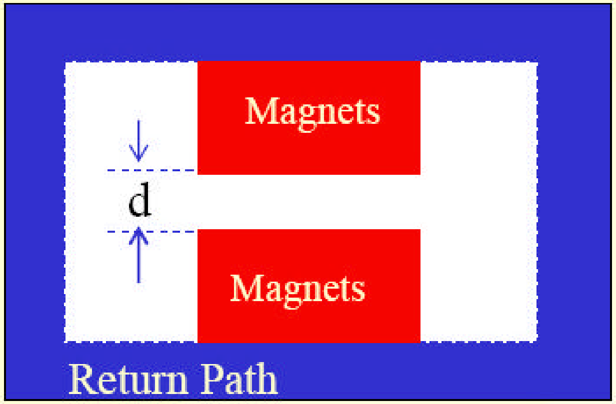
Permanent magnets --- properties comparison

Typical magnetic properties, in terms of energy product, of selected commercial magnets:

- ✓Sintered Nd-Fe-B magnets: up to 50 MGOe
- ✓Sintered Sm-Co magnets: up to 32 MGOe
- ✓Isotropic bonded Nd-Fe-B magnets: up to 10 MGOe
- ✓Sintered ceramic magnets: up to 4 MGOe
- ✓Cast Alnico magnets: up to 9 MGOe

Permanent Magnet Dipoles

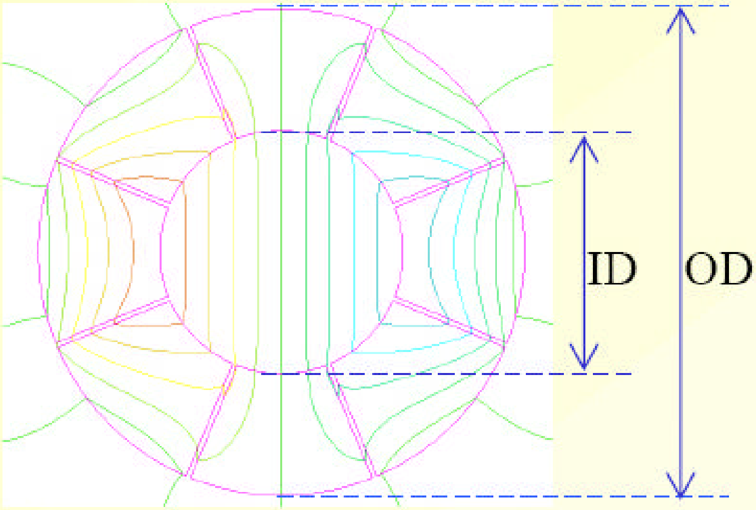


$$B_g = \frac{B_m A_m}{k_1 A_g}$$

A_m =Magnet area perpendicular to the direction of magnetization;
B_m =Flux density of the magnet corresponding to the operating point of the demagnetization curve;
B_g =Flux density desired in the air gap;
A_g =Cross section area of the air gap perpendicular to the flux lines.

The Air Gap Flux Density Is A Lot Lower Than The B_r Of The Permanent Magnets

Permanent Magnet Dipoles



Halbach PM Dipole Structures:

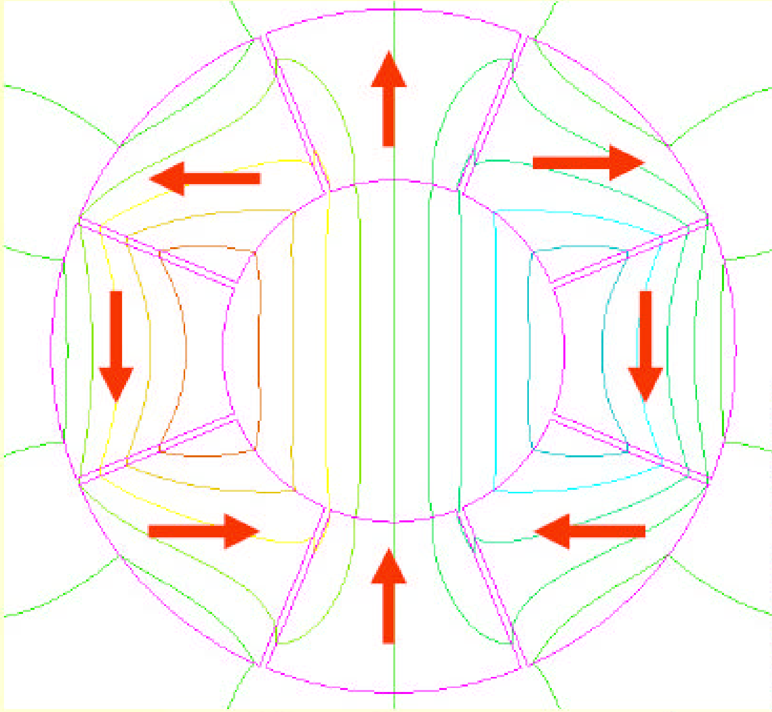
$$B_g = B_r \ln(OD/ID)$$

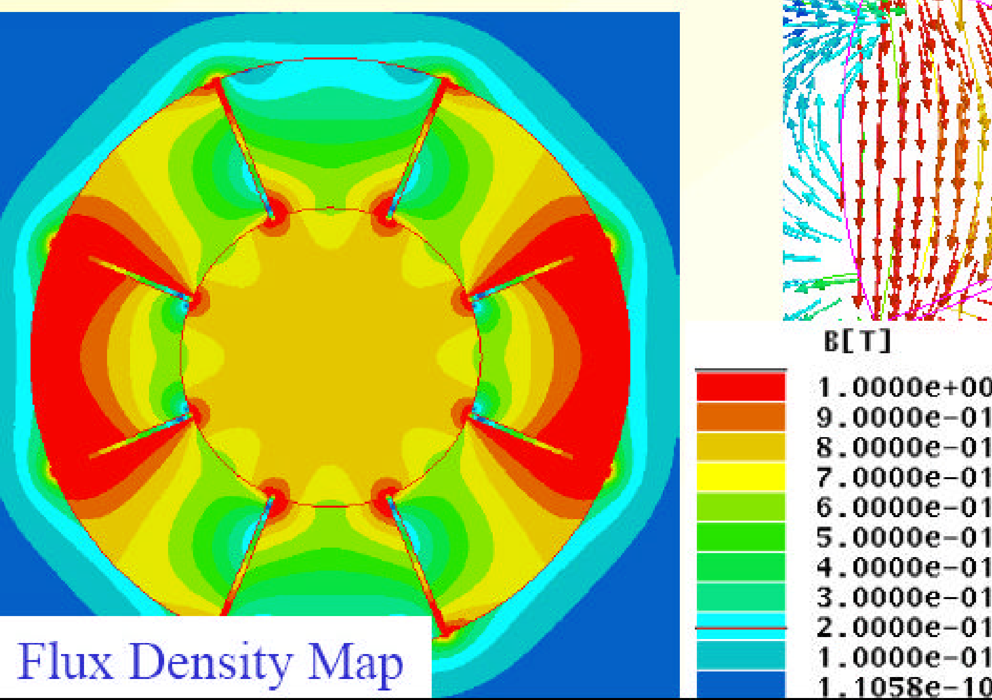
There is no upper limit for air gap flux density in Halbach dipole structures according to above equation. But in reality it would be limited by:

(1) The realistic size

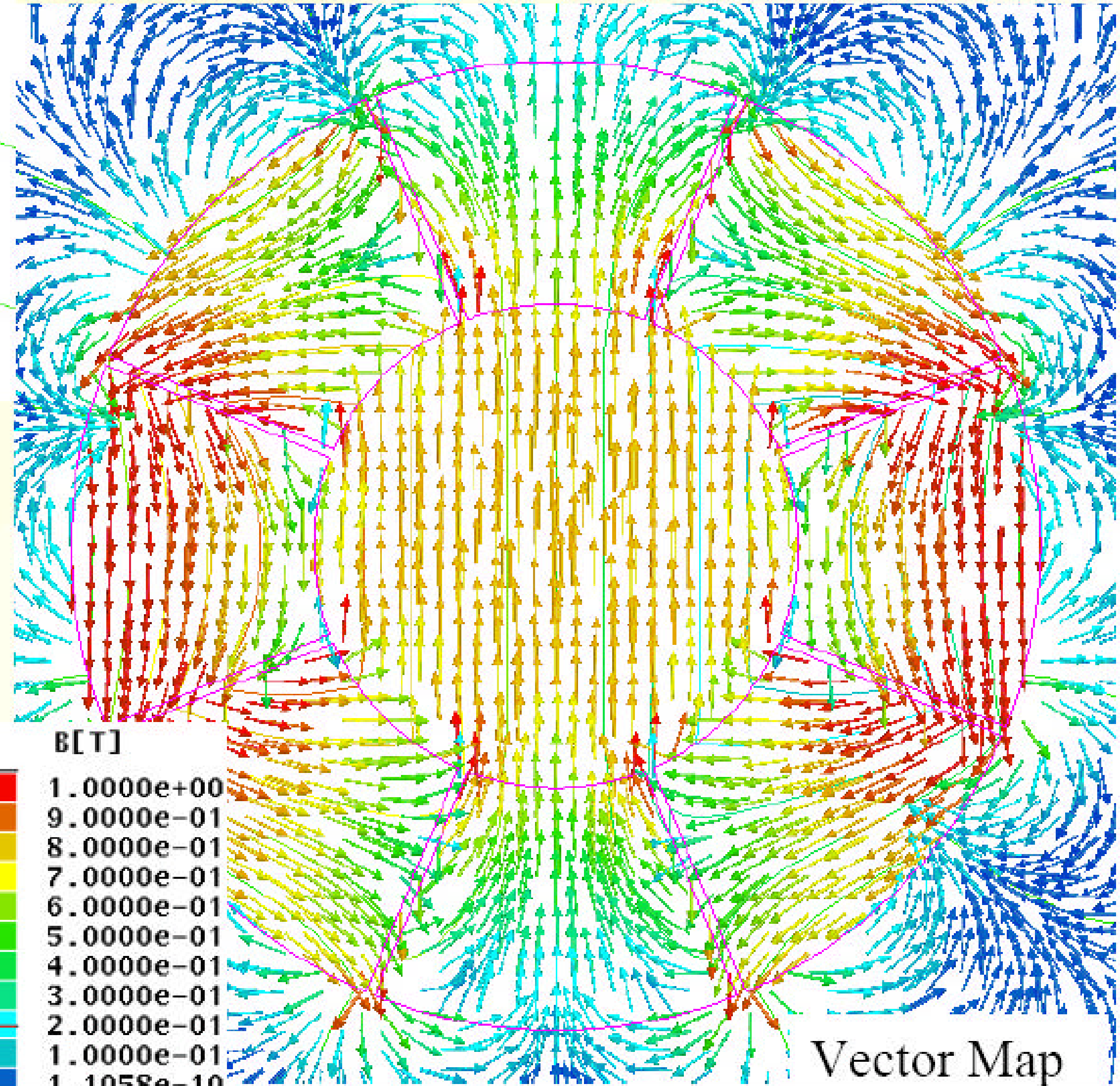
(2) The demagnetization effect

Halbach Dipole Example





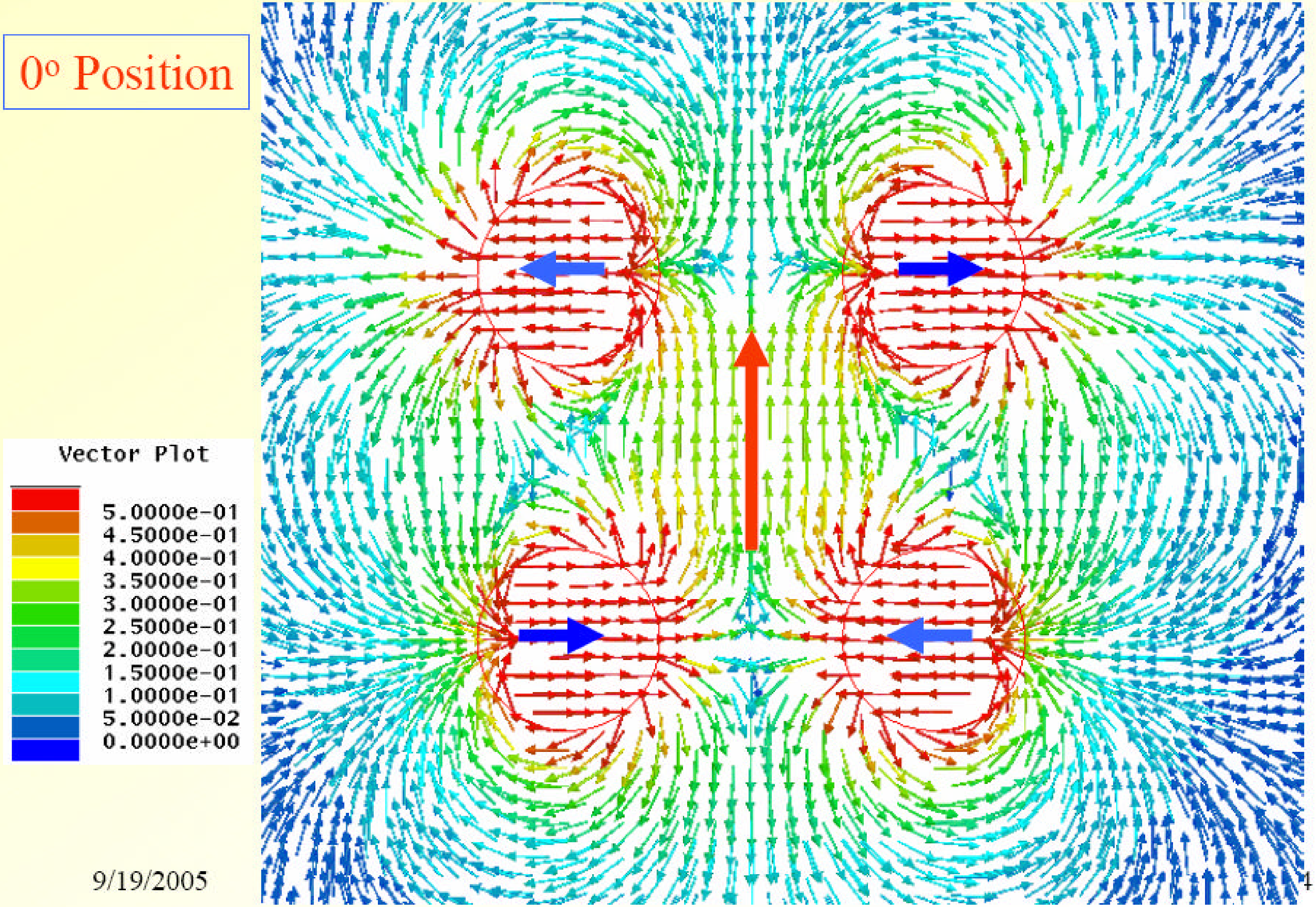
Flux Density Map



Vector Map

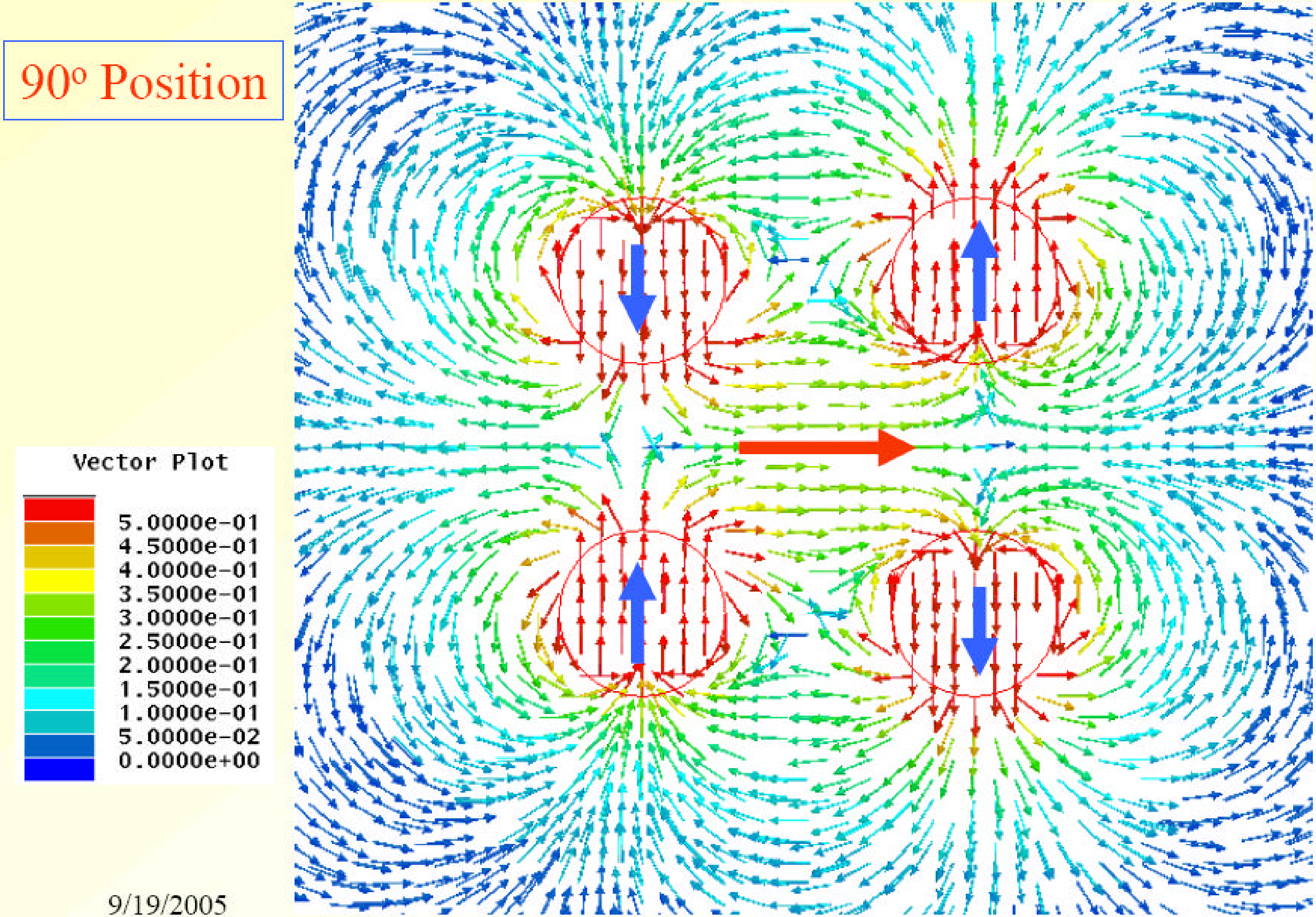
Magnetic Mangles

0º Position

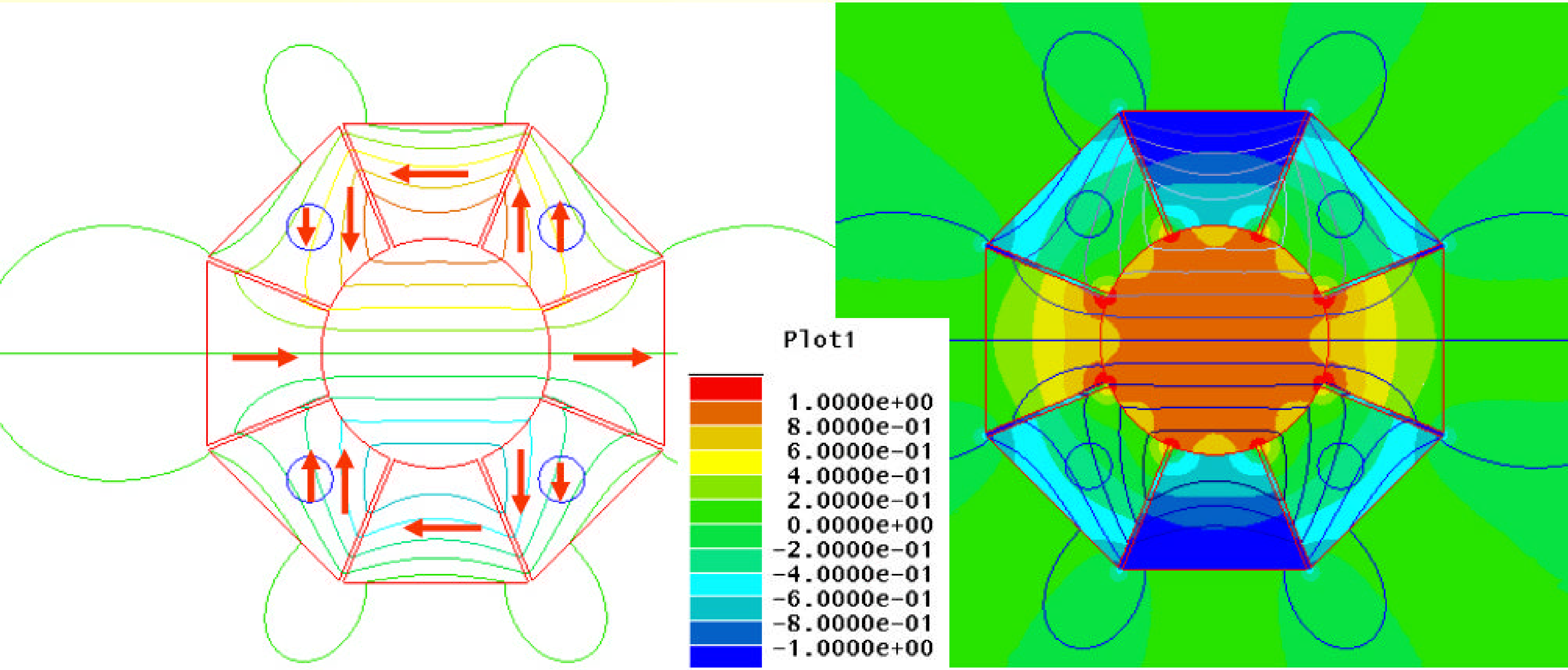


Magnetic Mangles

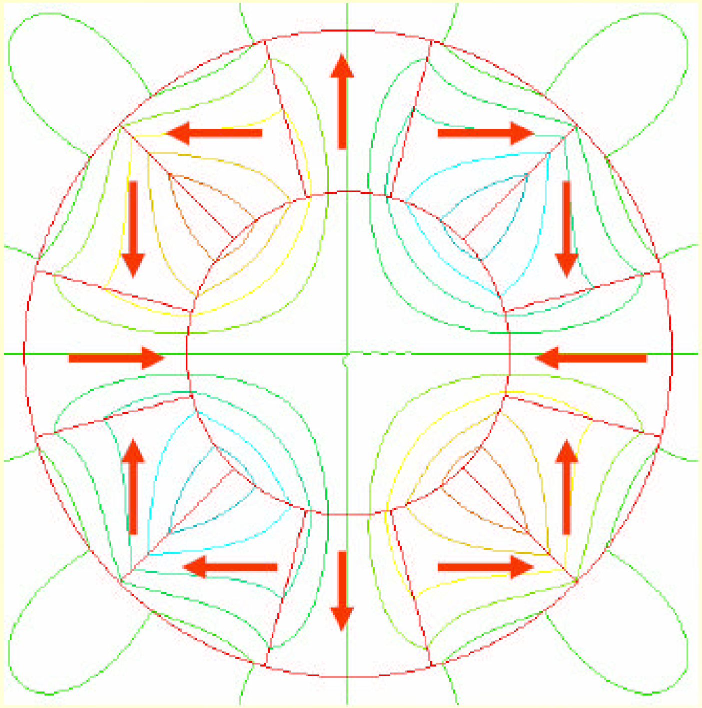
90º Position

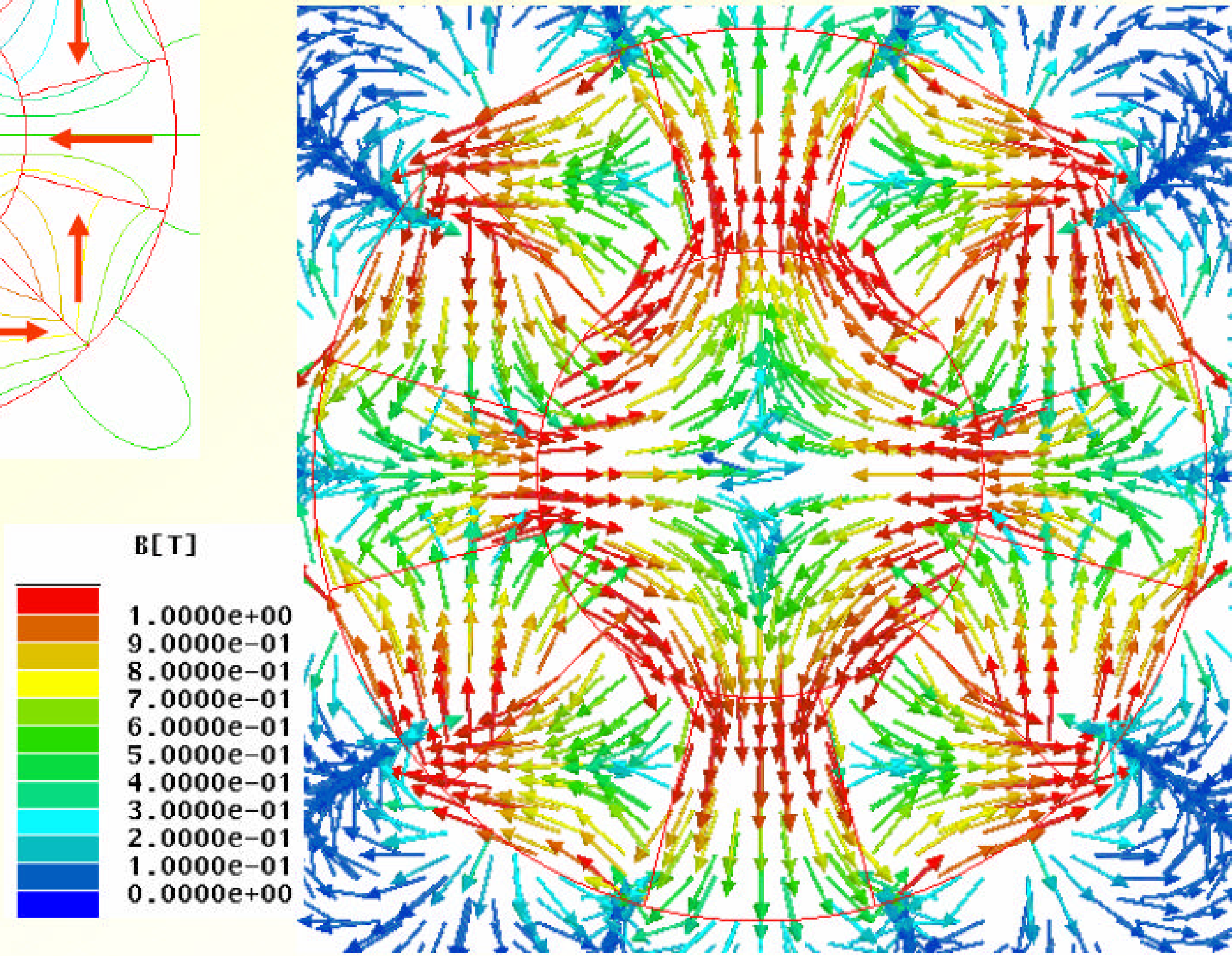


Combination of magnetic mangles and Habach structures can make the air gap flux density adjustable to some degree

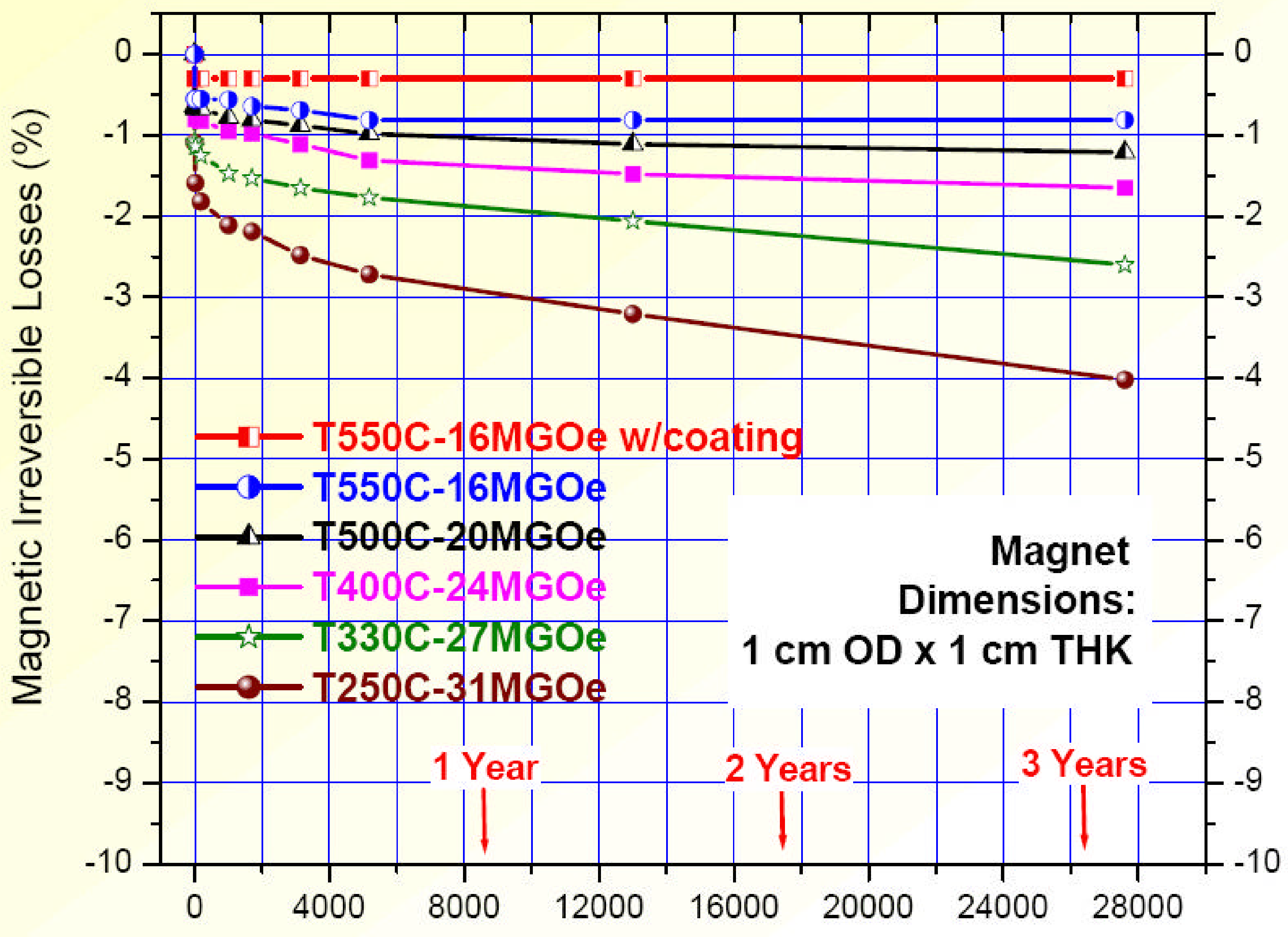


A Example of Halbach PM Quadrupole





Long-term Thermal Stability of SmCo Magnets at 300°C in Air



Summary

✓Permanent magnet dipoles and quadrupoles can have high air gap flux density if designed with Halbach principles.

✓Innovative designs can make the air gap flux density adjustable.

✓Permanent magnet selection might include trade-offs between cost and performance.

✓SmCo magnets are far superior to NdFeB magnets with respect to radiation resistance.

Contact Information

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FFAG for next Light Source

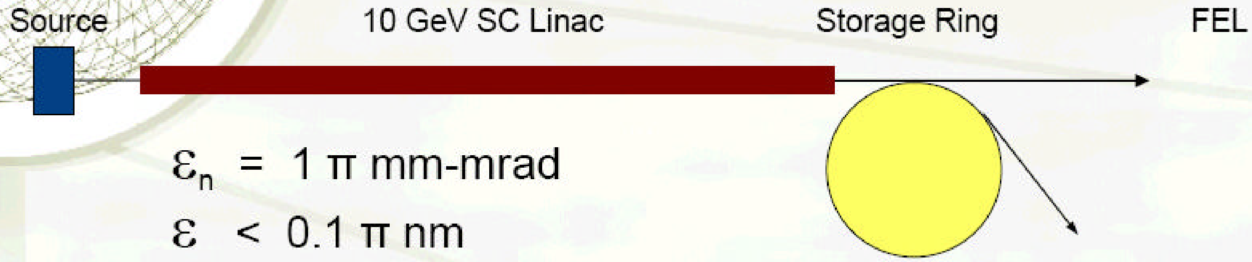
Alessandro G. Ruggiero

Semi-Annual FFAG-2006 Workshop

May 15 - 19, 2006

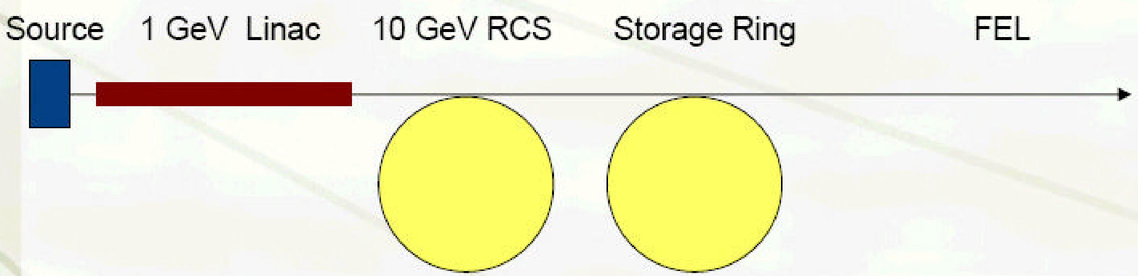
Components: 10 mA - 8 GeV

Brilliance --> Source + Lattice Properties



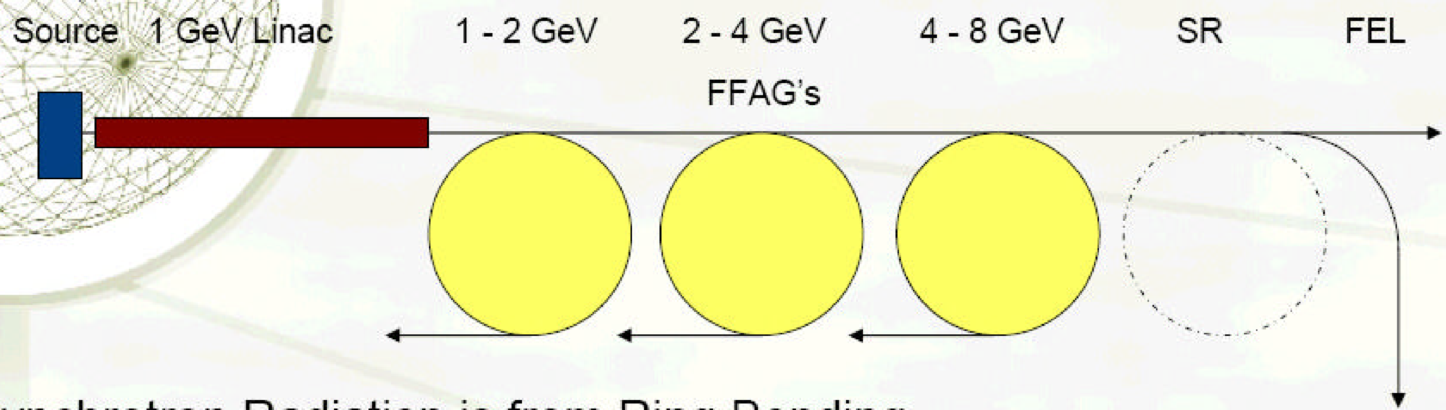
$\varepsilon_n = 1\,\pi$ mm-mrad

$\varepsilon < 0.1\,\pi$ nm



Damping Time + Quantum Fluctuation

FFAG Rings for Acceleration and Storage



Synchrotron Radiation is from Ring Bending.

Beam Brilliance is determined originally by the Source

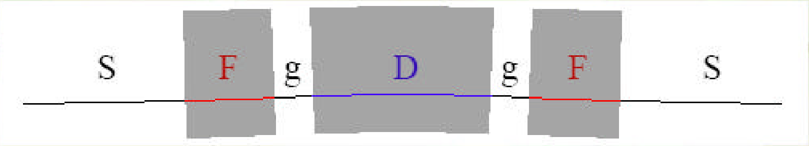
The Ring Lattice can only decrease the Brilliance

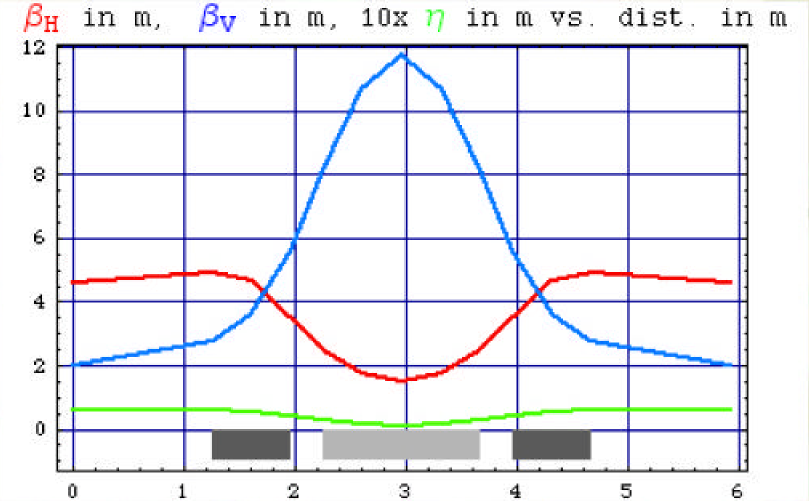
Quantum Fluctuation makes the Brilliance even smaller.

The goal is to minimize acceleration and storage time so that the Beam spends in FFAG's a period of time smaller than the Damping Time.

FFAG's have large Momentum and Betatron Acceptance. And are DC

FFAG Rings at Injection

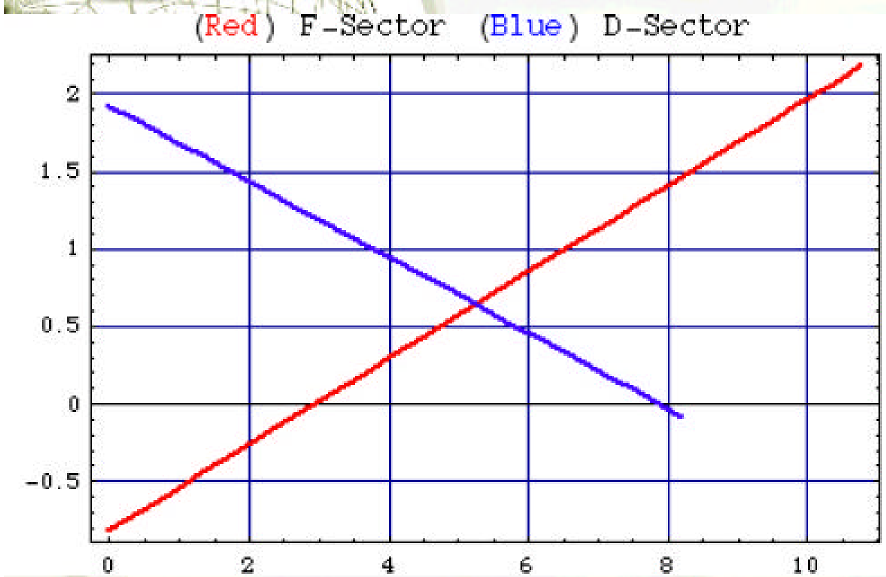


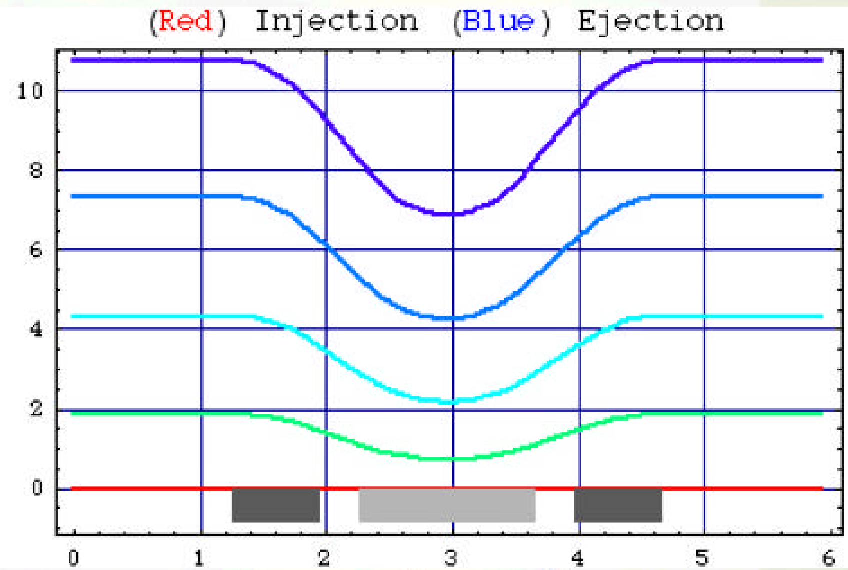


	FFAG
Circumference, m	807.091
Periodicity	136
Period Length, m	5.9345
Long Drift S, m	2.5345
Short Drift g, m	0.300
F-Sector Magnet	
Length, L_F, m	0.700
Bend Field, kG	
Gradient, kG/m	
D-Sector Magnet	
Length, L_D, m	1.400
Bend Field, kG	
Gradient, kG/m	

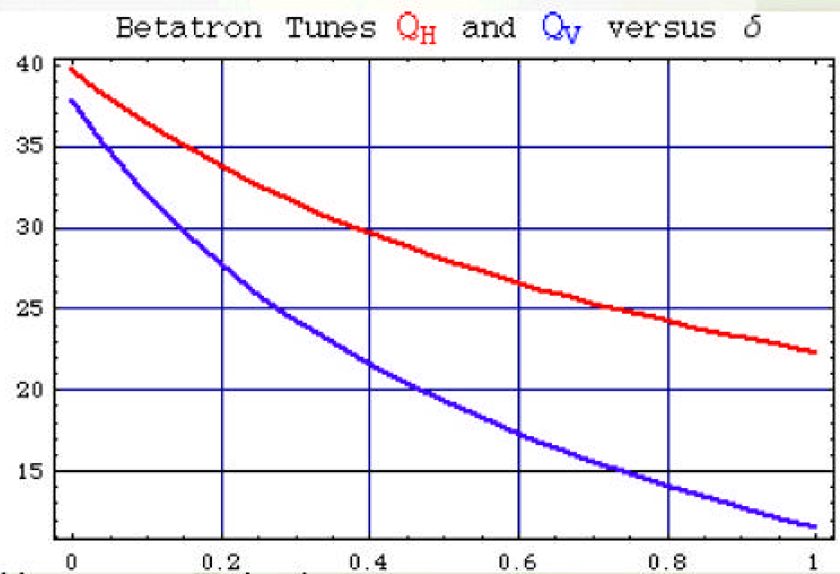
Phase Advance / Period, H / V	105º / 100º
Betatron Tunes H / V	39.76 / 37.75
Transition Energy, γ_T	-i105.5
Max β value, H / V, m	4.9 / 11.8
Max dispersion, η	6.0 cm
Chromaticity, H / V	-0.925 / 1.814

FFAG-1 1 - 2 GeV

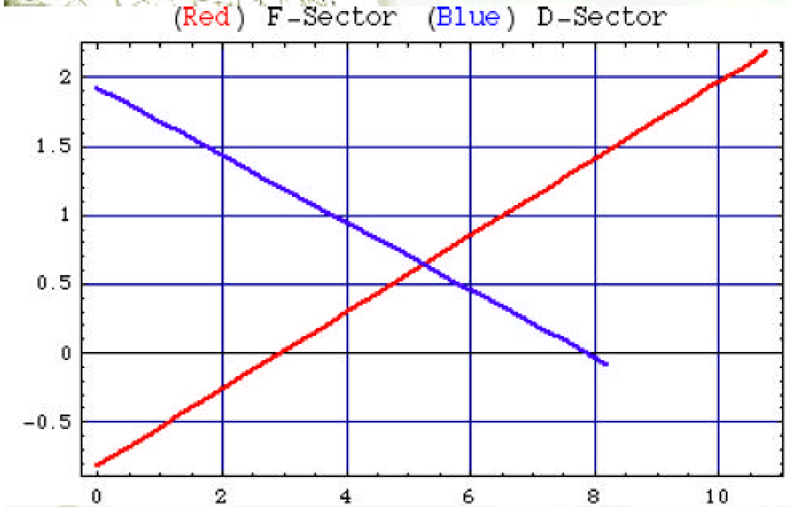


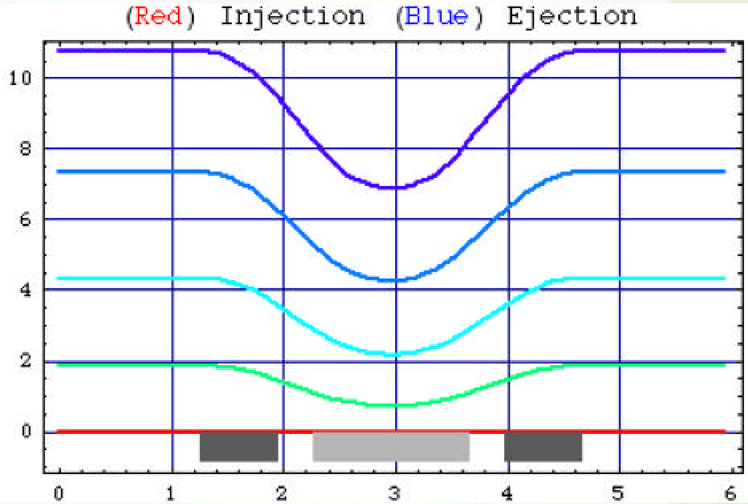


RF	201.2 MHz
h	542
Energy Gain	100 MeV/turn
Accel. Period	29.62 μs
No. of Revol.	11
Damping Time	< 55,378 μs
Energy Loss	< 0.118 MeV/turn

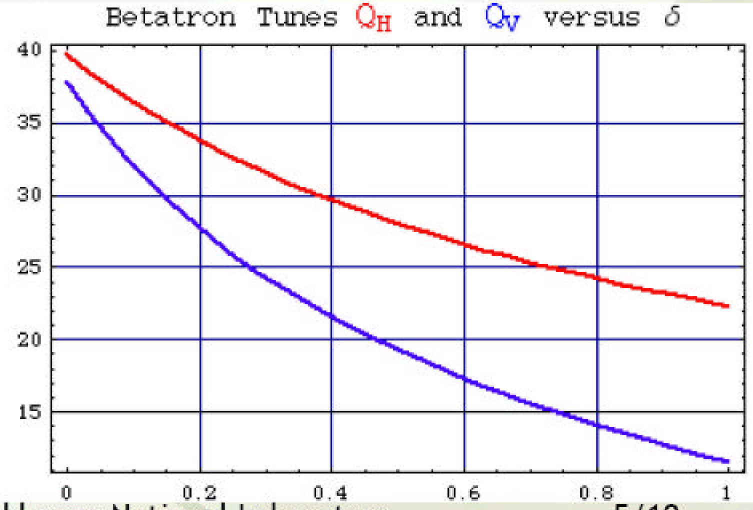


FFAG-1 1 - 2 GeV

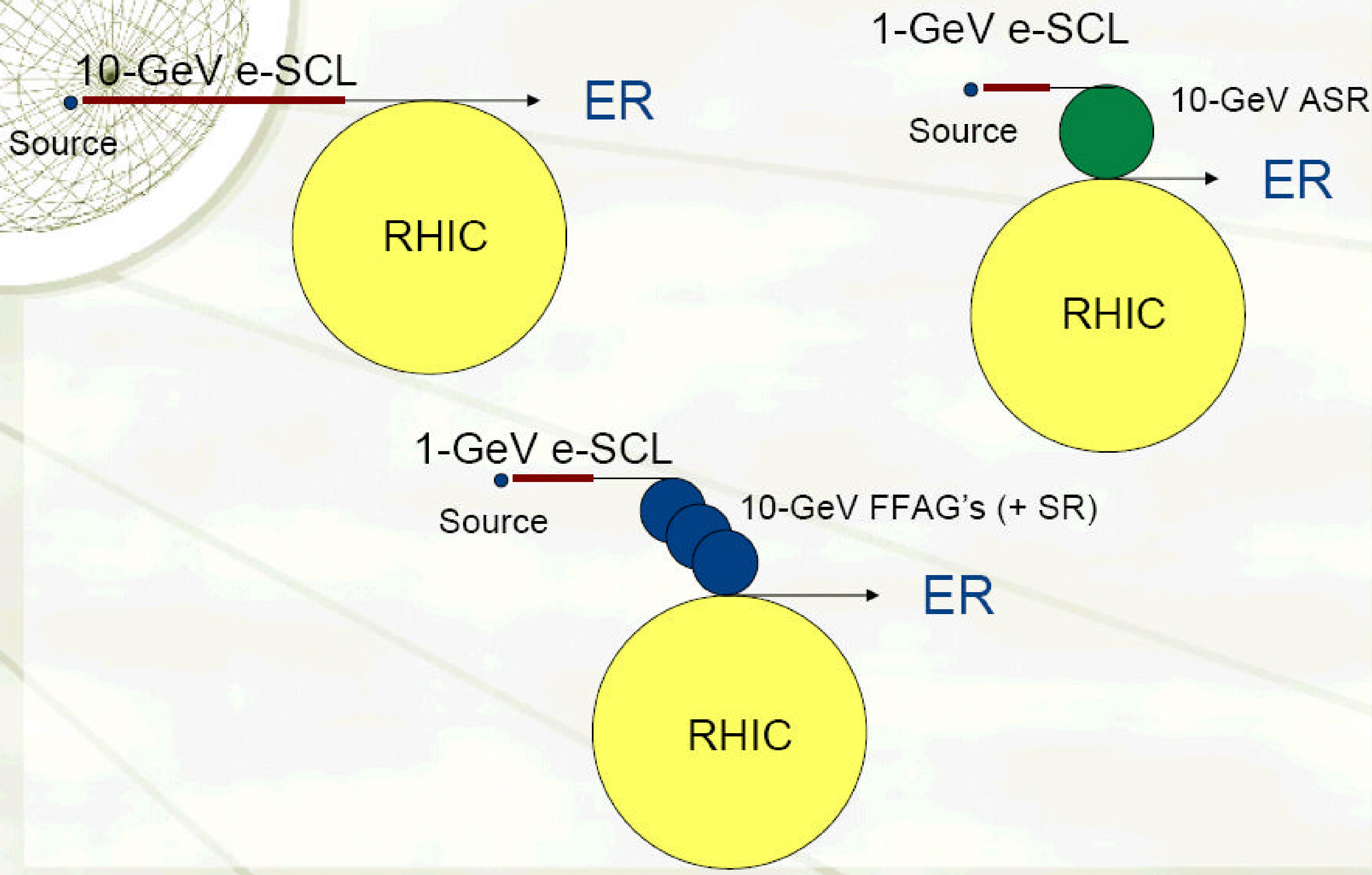




RF	201.2 MHz
h	542
Energy Gain	100 MeV/turn
Accel. Period	29.62 μs
No. of Revol.	11
Damping Time	< 55,378 μs
Energy Loss	< 0.118 MeV/turn



eRHIC: 10-GeV e x 250-GeV p or 100-GeV/u Au



Conclusions

Final Energy	8 GeV
Average Current	10 mA
Beam Power	80 MW
Power Loss during acceleration	8%

No Quantum Fluctuations

Beam Brilliance at the Source preserved

No Space Charge

No Tousheck Lifetime

FDF Triplet Lattice ideal for SR

2.5 m Drifts for RF Cavities and Insertion Devices

Very reasonable SRF system

- Quantum Aspect of charged particle beam
-
-

Hiroshi Takahashi
Brookhaven National Laboratory
FFAG-06 workshop Port Jefferson New York

May-15-19, 2006,
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- Motivation
-

ADS 10MW proton beam Mori, A.Ruggiero,

- Medical application, Proton beam for cancer treatments,
- IPP Program Budker Nuclear Physics Institute, VG, Proton, Li Resonance, Neutron production. BNCT. Neutron Flux, Radiation fields,
- Space charge Problem,
- Radiation effect in hospital.

FREE ELECTRON LASER THEORY USING TWO TIMES GREEN FUNCTION FORMALISM

HIROSHI TAKAHASHI

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$$H = \sum_i (c\,\alpha_i \cdot (p_i - eA/c) + \beta_i mc^2) + H_r + H_{ee} + H_s$$

$$H = \sum_i (c\,\alpha_i . (p_i - -eA/c) + \beta_i mc^2) + H_r + H_{ee} + H_s \quad (1.1)$$