Theoretical and Preliminary Experimental Research on A Mini Bremsstrahlung X-ray Source (MBXS)

Gu Xiaofeng

BFEL Lab, IHEP

Outline:

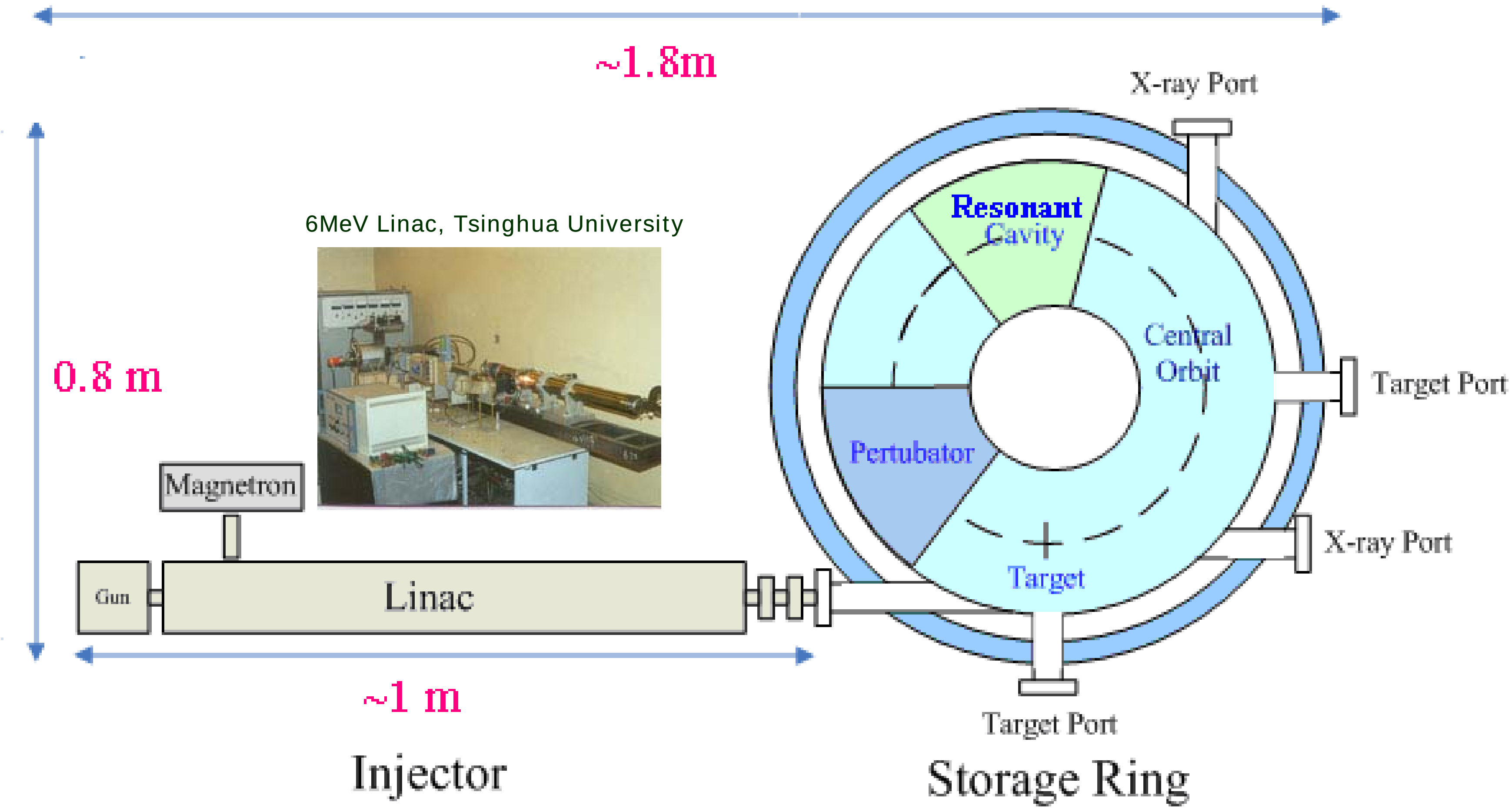
1、Introduction to the MBXS

2、Physical design

3、Preliminary Experiments

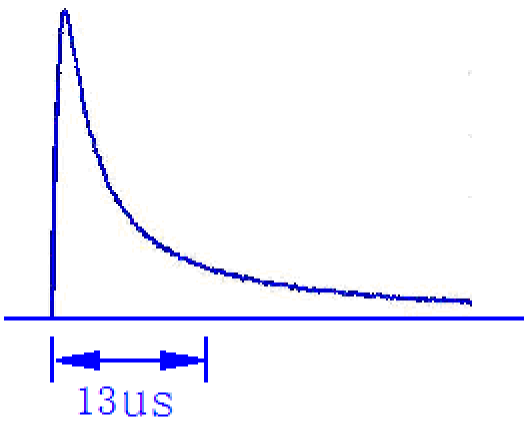
4、The Upgrade of the BFEL Facility

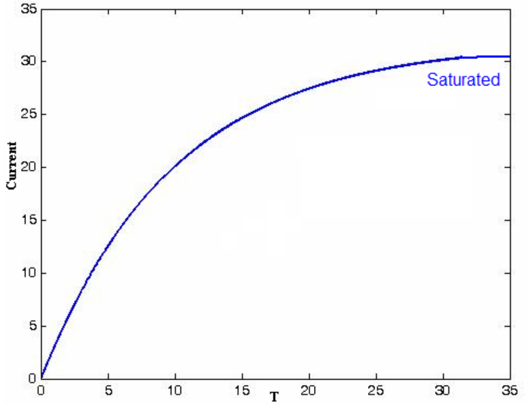
A 、Introduction to the MBXS



The Parameters of the Storage Ring and Injector

Storage Ring	Electron Energy	6MeV
	Orbit Radius	15.54cm
	Average Current	~0.11A
	Size (H×W)	~0.3m×0.8m
	Beam lifetimes	~10us
	SR Energy Loss	$7.6\times10^{-7}\,keV$
	Circulating Periods	3.27ns
	Circulating Frequency	306.25MHz
	Center Field	$B_o = 0.134$ T
Injector	Accelerator type	Linac
	Injector Size	~1 meter
	Electron Energy	6MeV
	RF Frequency	2.45GHz
	Repetition Periods	2.5ms (400Hz)
	Pulse Width	3us
	Average Current	100mA
	Inject efficiency	30%
	Beam Size	2mm

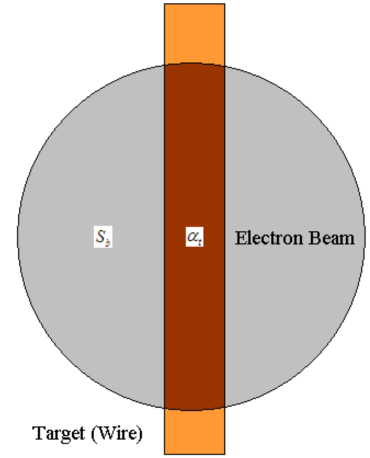




The Parameters of the X-ray source

Material	tungsten
Mechanism	Bremsstrahlung
Angle	85mrad
X-ray Spot Size	~10um （wire）
Spectrum	**1keV~6MeV（White）**
Brilliance	1×10^{8} Photons /s/mrad^2/mm^2/0.1%BW
Energy loss (By SR)	$7.6\times10^{-7}\,keV$
Energy loss (By Brem.)	34keV（10um）
Target particle density	$6.32\times10^{28}/m^3$
Cross Section (Br.)	$1.22\times10^{-27}m^2$
Beam Loss Rate by Br.	$1.73\times10^{4}/s$
Beam Loss Rate by scat.	$8.51\times10^{4}/s$
Photon Num./(electron) (14~30keV)	~ 0.0027
Photon number/（electron mrad^2）	1.31×10^{-6}
Photon number/（s mm^2 mrad^2）	$\sim 2.2\times10^{10}$

Brilliance of the MBXS



The Collided volume

$$V_t = \chi_t \alpha_t$$

The Number of Atom

$$N_t = n_t \cdot V_t = n_t \cdot \chi_t \alpha_t$$

L.I.Schiff cross-section

$$d\sigma_k = \frac{2Z^2 r_0^2}{137} \frac{dk}{k} \left\{ \left[1 + \left(\frac{E}{E_0} \right)^2 - \frac{2}{3} \frac{E}{E_0} \right] \left(\ln M(0) + 1 - \frac{2}{b} \tan^{-1} b \right) + \frac{E}{E_0} \left[\frac{2}{b^2} \ln\left(1+b^2\right) + \frac{4\left(2-b^2\right)}{3b^3} \tan^{-1} b - \frac{8}{3b^2} + \frac{2}{9} \right] \right\}$$

Total cross-section

$$\sigma_{total} = d\sigma_k \cdot N_t = d\sigma_k \cdot n_t \chi_t \alpha_t$$

Probability

$$P = \frac{\sigma_{total}}{\alpha_t} = d\sigma_k n_t \chi_t$$

Quantum Electrodynamics
Coulomb correction
Screened

Thin target approximation

Electron number

$$N_e = \frac{I\Delta t}{e} \cdot \frac{\alpha_t}{S_b}$$

Total photon number

$$N_{br} = P \cdot N_e = P \cdot \frac{I\Delta t}{e} \cdot \frac{\alpha_t}{S_b}$$

The brilliance

$$B = \frac{2Z^2 \cdot r_o^2}{137} \frac{n_t \cdot \chi_t \cdot I}{e \cdot S_b \cdot \Omega} \bullet \frac{dk}{k} \{[1+(\frac{E}{E_o})^2 - \frac{2E}{3E_o}][\ln M(0) + 1 - \frac{2}{b}\tan^{-1} b] + \frac{E}{E_o}[\frac{2}{b^2}\ln(1+b^2) + \frac{4(2-b^2)}{3b^2}\tan^{-1} b - \frac{8}{3b^2} + \frac{2}{9}]\}$$

Target Parameters

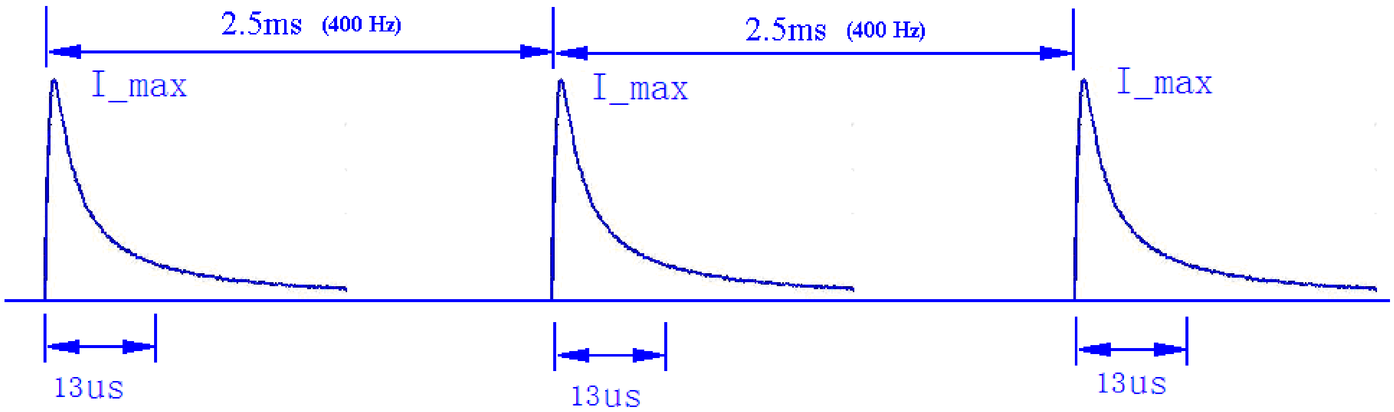
Cross-section	α_t	Density	ρ
Thickness	χ_t	Avogardo constant	N_a
Atom density	$n_t = \frac{N_a \bullet \rho}{A}$	Atomic weight	A

10^{12} photons/s/mrad^2/mm^2/0.1%BW ?

The formula becomes less reliable as:

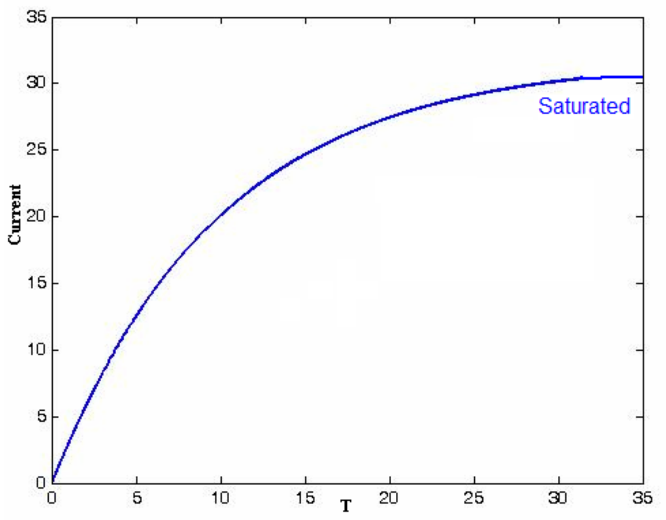
- The photon energy approaches the high frequency;
- The atomic number of the target increases;
- The initial electron energy decreases.

Beam Current



$$\overline{I} = R_i \cdot \varepsilon_i \Delta_t I_0 f_{RF} \cdot \tau \cdot (1 - e^{-t/\tau})$$

10^8 photons/s/mrad^2/mm^2/0.1%BW



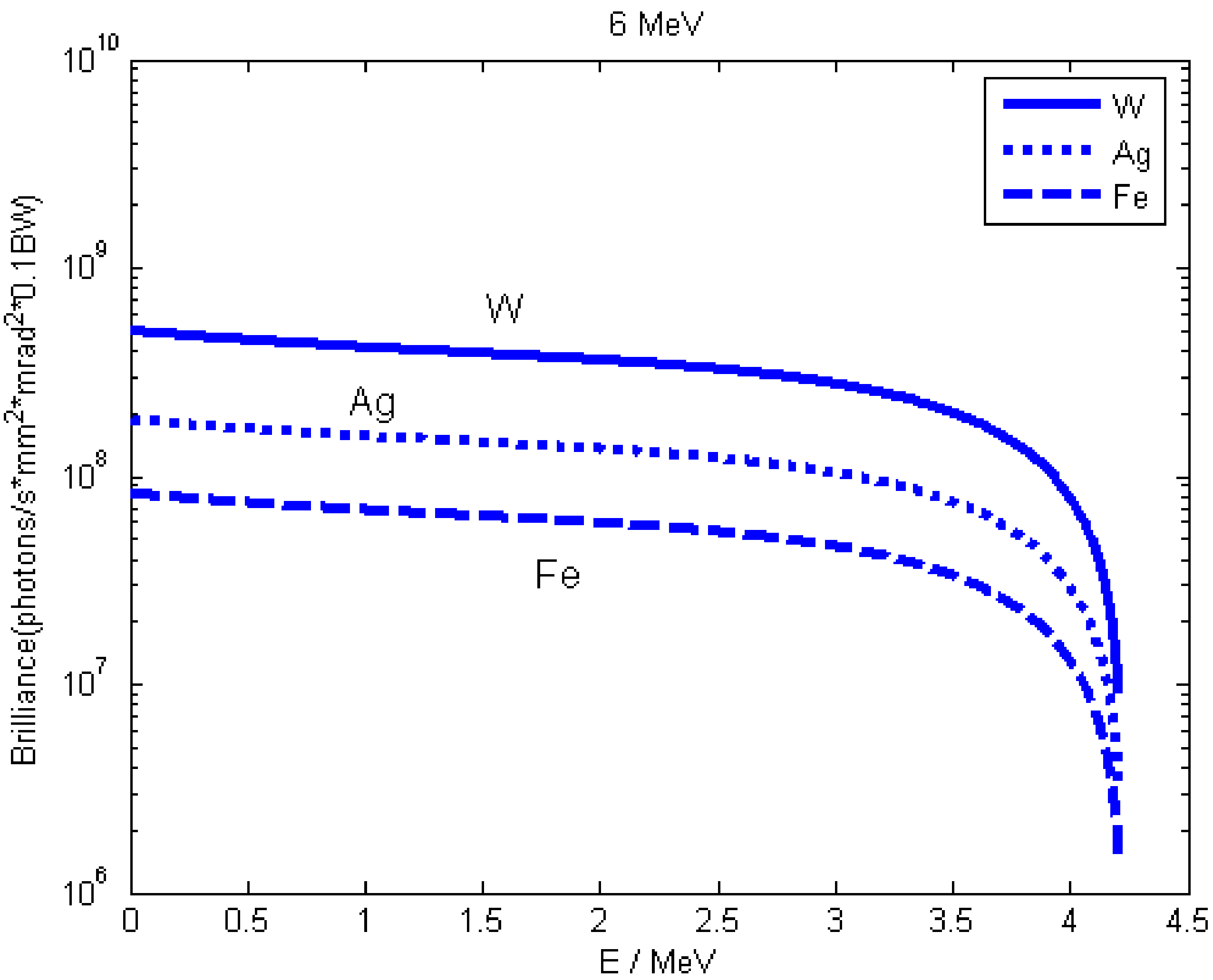
$$\frac{dI}{dt} = R_i \varepsilon_i I_0 \Delta_t f_{RF} - \mu I - \eta I^2$$

$$\frac{dI}{dt} = 0, \eta = 0$$

$$I = R_i \varepsilon_i I_0 \Delta_t f_{RF} / \mu$$

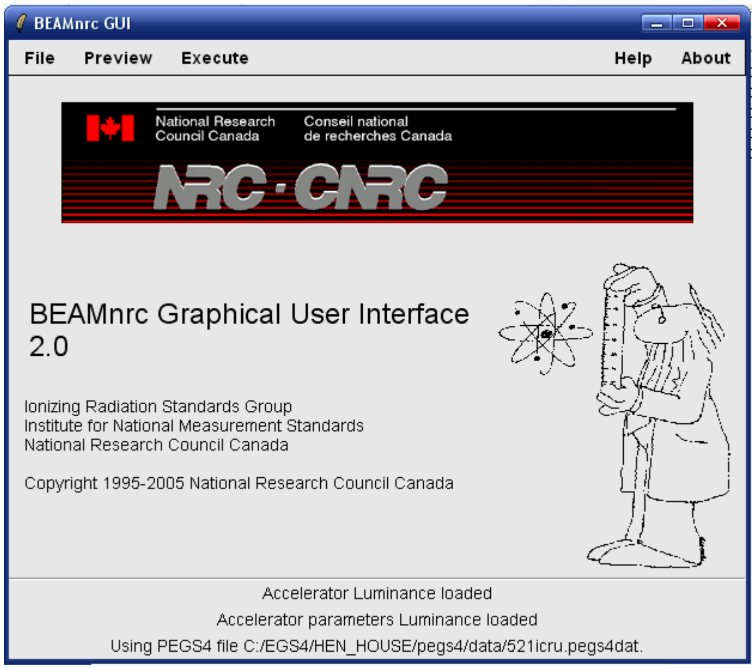
10^{12} photons/s/mrad^2/mm^2/0.1%BW

Examples



6 MeV
10^10
10^9
10^8
10^7
10^6
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
E / MeV
Brilliance(photons/s*mm^2*mrad^2*0.1BW)
W
Ag
Fe
W
Ag
Fe

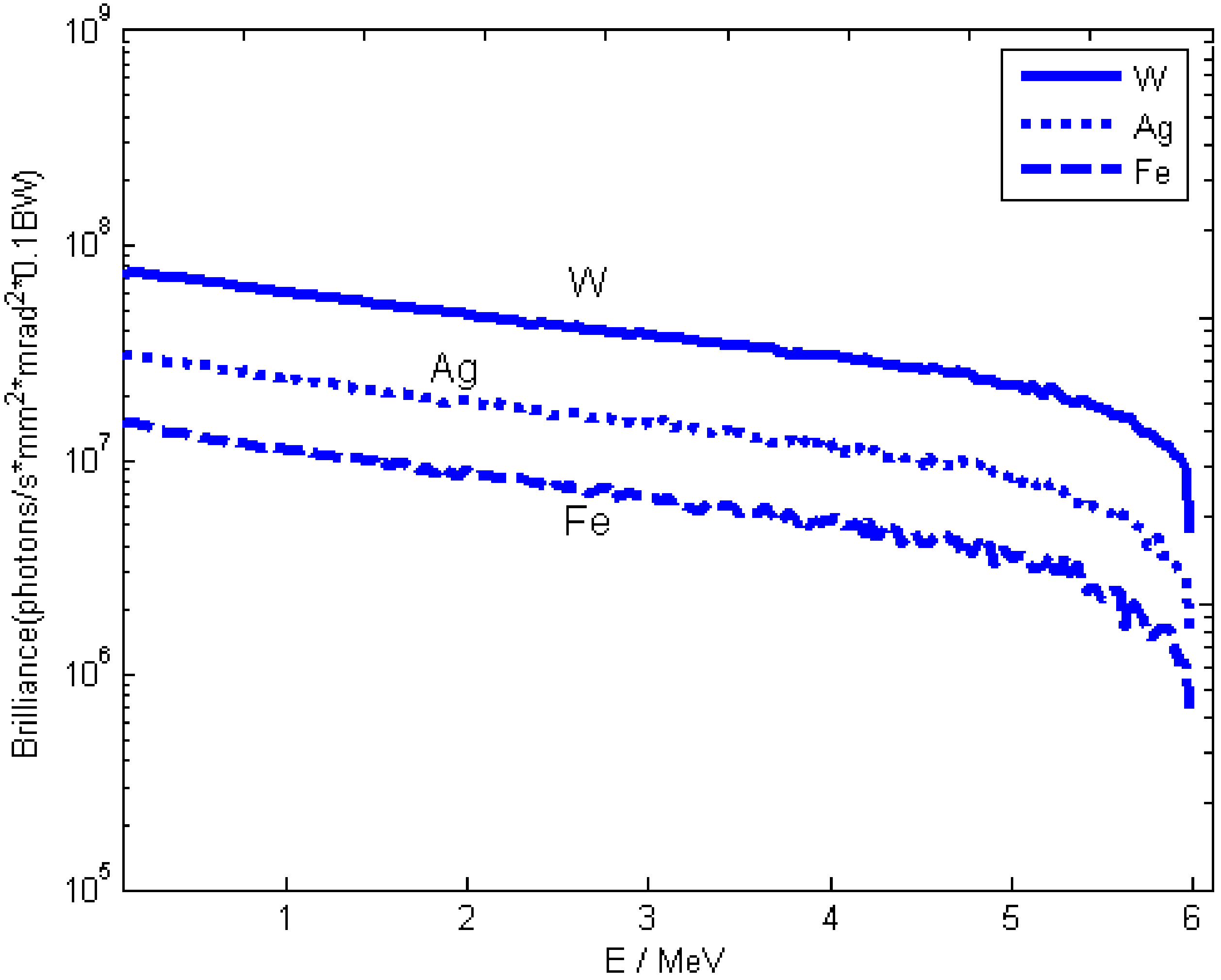
Beamnrc (EGS4)



Preference	6MeV	27.39MeV、27.77MeV
Boundary Crossing Algorithm	EXACT	PRESTA-I
Electron-Step	PRESTA-II	PRESTA-I
Spin Effects	ON	ON
Brems Angular Sampling	KM	Simple
Brems Cross Section	NIST	NIST
Bound Compton Scatting	ON	ON
Pair angular Sampling	KM	KM
Photo Electron Angular Sampling	ON	ON
Rayleigh Scatting	OFF	OFF
Atomic Relaxations	ON	OFF

$$Y_{plot} = \frac{N_{pbin}}{N_{INC} \cdot S \cdot \dfrac{E_{\max} - E_{Min}}{N_{bin}}}$$

Examples (By EGS4)



Summary:

- Physical process:
  Bremsstrahlung
- Electrons:
  Can be re-used;
- Brilliance :
  10^8 photons/s/mrad^2/mm^2/0.1%BW.
- Advantage:
  Simple (injector and storage ring)
  Small (1.8m × 0.8m)
  Low price (About 200,000 Euro)
- Used:
  Small Labs, hospitals or factories.

B 、Physical design

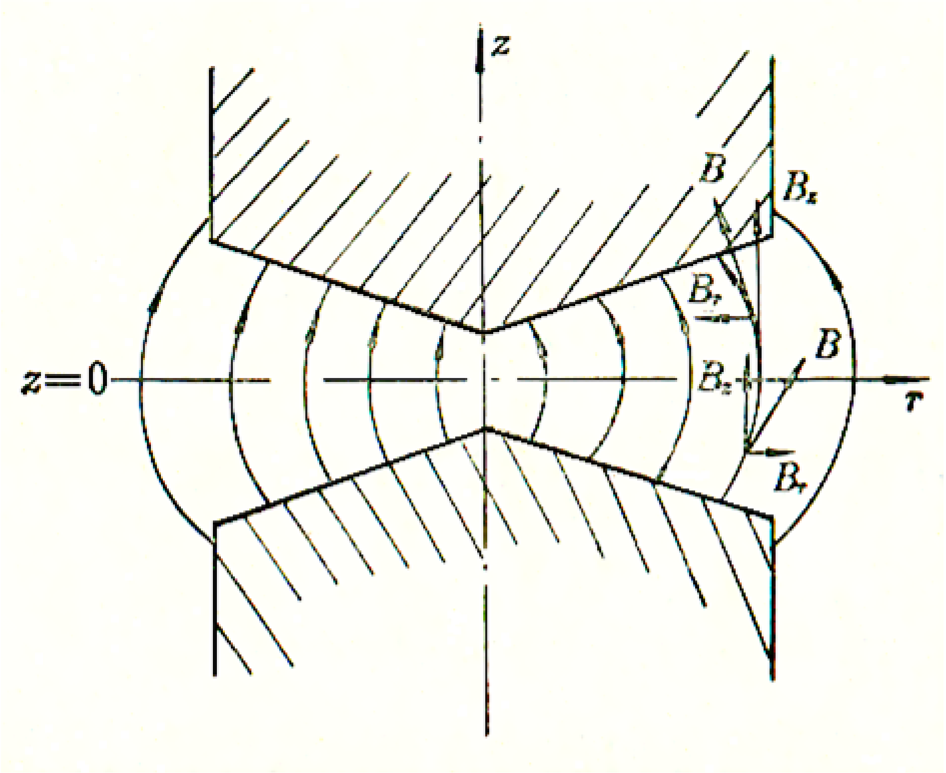
1、The Storage Ring

2、Perturbator

3、Resonant Cavity

The Storage Ring

a piece of cylinder weak focus magnet



magnetic field distribution

$$B_z = \frac{C}{r^n}$$

$$n = -\frac{r}{B}\frac{\partial B}{\partial r}$$ magnetic field index

Storage ring physics

$$\begin{cases} \beta_x = \dfrac{r_c}{\sqrt{1-n}} \\ \beta_z = \dfrac{r_c}{\sqrt{n}} \\ \alpha_r = 0 \\ \alpha_z = 0 \\ \gamma_x = \dfrac{\sqrt{1-n}}{r_c} \\ \gamma_z = \dfrac{\sqrt{n}}{r_c} \end{cases}$$

Twiss Parameters

$$\begin{cases} \xi_r = -\dfrac{\sqrt{1-n}}{2} \\ \xi_z = -\dfrac{\sqrt{n}}{2} \end{cases}$$

Nature Chromaticity

$$\eta_r = \frac{r_c}{1-n}$$

Dispersion Functions

Tune

$$\begin{cases} \nu_z = \sqrt{n} \\ \nu_x = \sqrt{1-n} \end{cases} \rightarrow 0 < n < 1$$

$$\begin{cases} J_x = \dfrac{n}{1-n} \\ J_z = 1 \\ J_\varepsilon = \dfrac{3-4n}{1-n} \end{cases} \rightarrow 0 < n < 0.75 \rightarrow 0.5 < n < 0.75$$

Attenuation distribution number

$$\begin{cases} U_z = \dfrac{1}{2} m\varpi^2 n z_m^2 \\ U_x = \dfrac{1}{2} m\varpi^2 (1-n) x_m^2 \end{cases} \rightarrow 0.5 < n$$

The Mini Storage Ring Parameters

Field Index	$n = 0.72$	**Orbit Radius**	$r = 15.54\text{cm}$
Energy	$E = 6MeV$	**Center Field**	$B_o = 0.134$ T
Periods	$T_o = 3.27$ ns	**Circulating Frequency**	$f_o = 306.25$ MHz
Beam size	$\sigma_x = 168.85\times10^{-7} m$	**Nature Chromaticity**	$\xi_x = -0.26$
	$\sigma_z = 1.87\times10^{-7} m$		$\xi_z = -0.42$
Twiss	$\beta_x = 0.29m$	**Damping Time**	$\tau_x = 891.12s$
	$\beta_z = 0.18m$		$\tau_z = 2291.44s$
	$\alpha_x = 0$		$\tau_\varepsilon = 5346.7s$
	$\alpha_z = 0$	**Dispersion Function**	$\eta_r = 0.56m$
	$\gamma_x = 3.40m^{-1}$	**SR Energy Loss**	$U_o = 7.38\times10^{-7} keV$
	$\gamma_z = 5.46m^{-1}$	**Tune**	$\nu_x = 0.529$
Beam Time	$t = 9.77us$		$\nu_z = 0.8485$

Designed by formulas

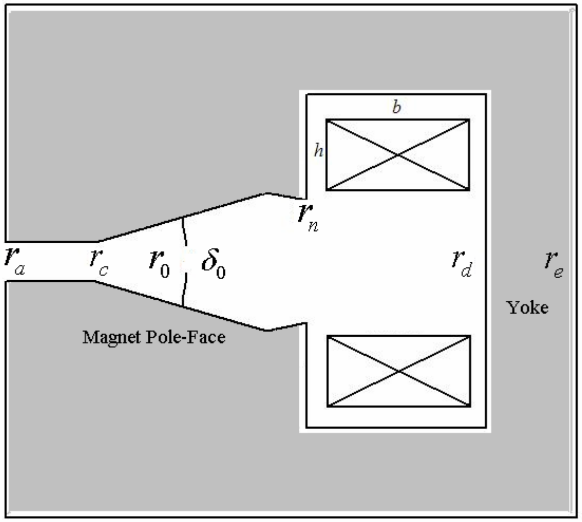
$$\delta_0 = 2b_0\sqrt{\frac{1-n}{n}}$$

$$b_0 = r_0 - r_c$$

$$\delta_x = \delta_o \left(\frac{r_x}{r_o}\right)^n$$

$$\begin{cases} H = H_{0m}\left(\frac{r_0}{r}\right)^n \\ \lambda_0 H_{0m} = \lambda_x H_{xm} \end{cases}$$

$$\begin{cases} \lambda_0 \approx \delta_0 \\ \lambda_x \approx \delta_x \end{cases}$$



$$\begin{cases} X = 0.26\delta_n \\ Y = 0.1\delta_n \end{cases}$$

$$NI_{air} = \frac{B_0\delta_0}{2\mu_o}$$

$$h \times b = \frac{F_n}{2\sqrt{2}\cdot J}$$

$$b \geq (1.5 \sim 2)\delta_0$$

$$F_n = 0.88 H_{0m}\delta_0$$

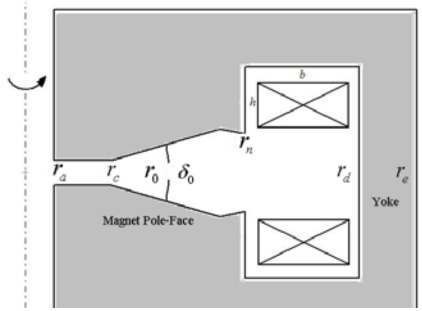
$$B_z = \frac{C}{r^n}$$

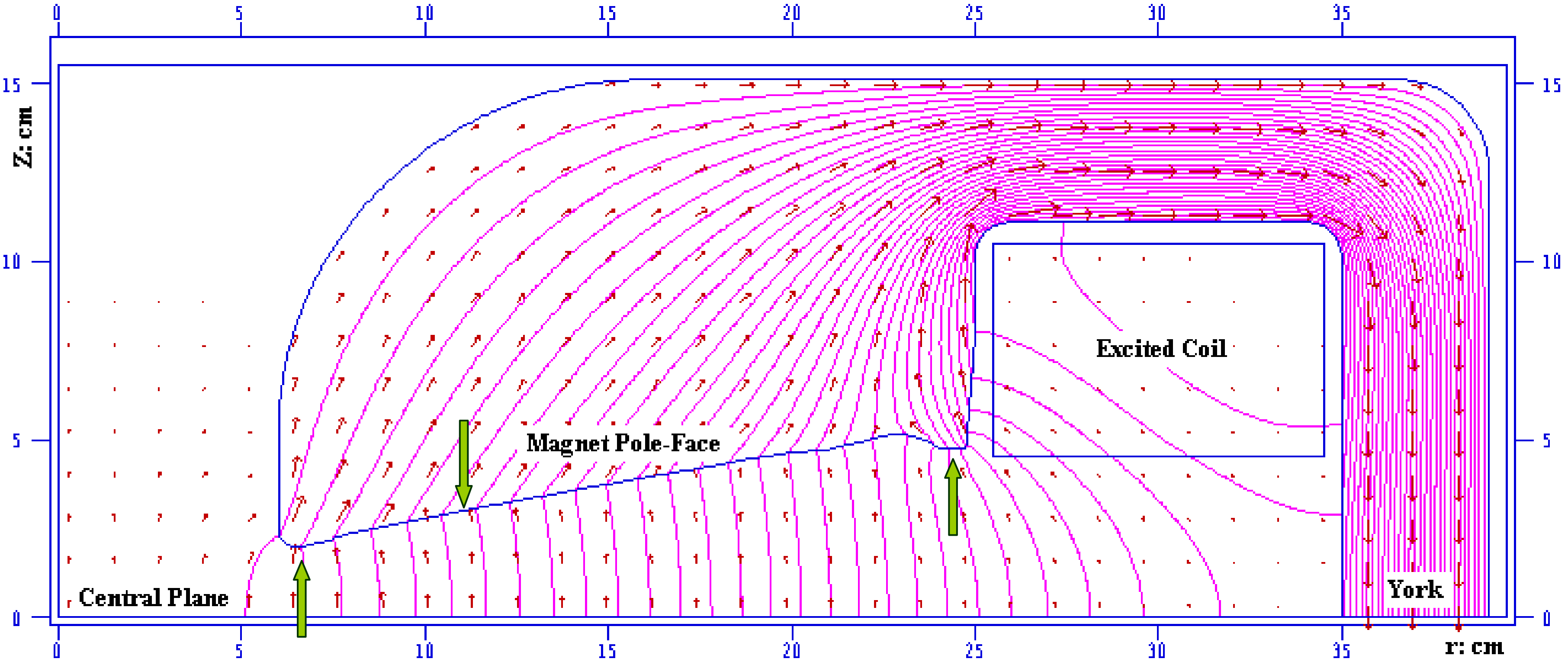
$$n = -\frac{r}{B}\frac{\partial B}{\partial r}$$

Designed by formulas

Inner Radius r_a	3cm	**Height of Coil Area** h	6cm
Pole-face Outer Radius r_n	23cm	**Width of Coil Area** b	12m
Orbit Radius r_0	15.54cm	**Pole-face Distance** δ_0	7.48cm
r_d	35cm	**Ampere Turn**	4300AT
Outer Radius r_e	41cm	**Current Density**	0.4A/mm^2
Pole-face Inner Radius r_c	9cm	**Height**	34cm
Orbit Magnet Field B_0	0.134T		

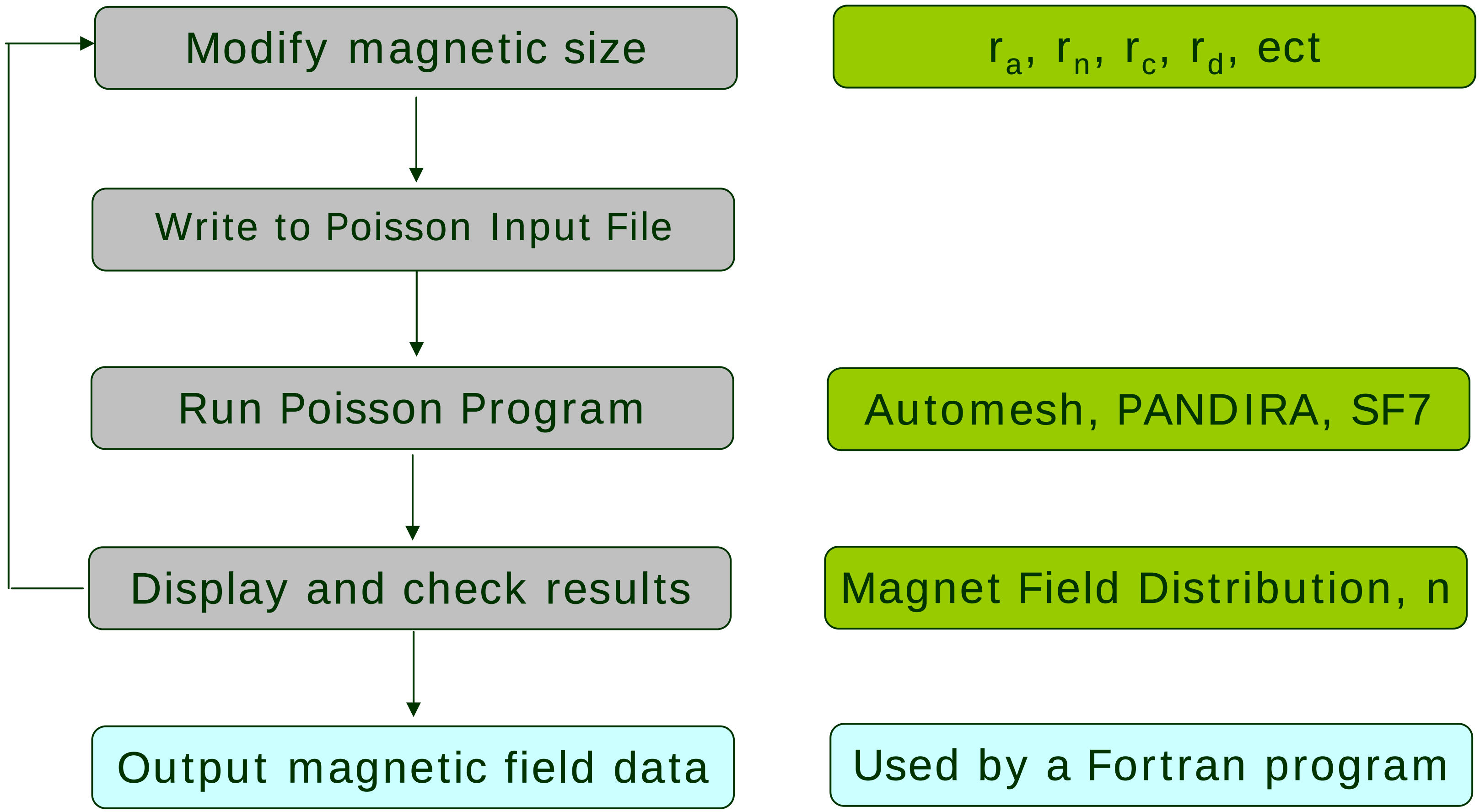
Optimized by Poission Superfish



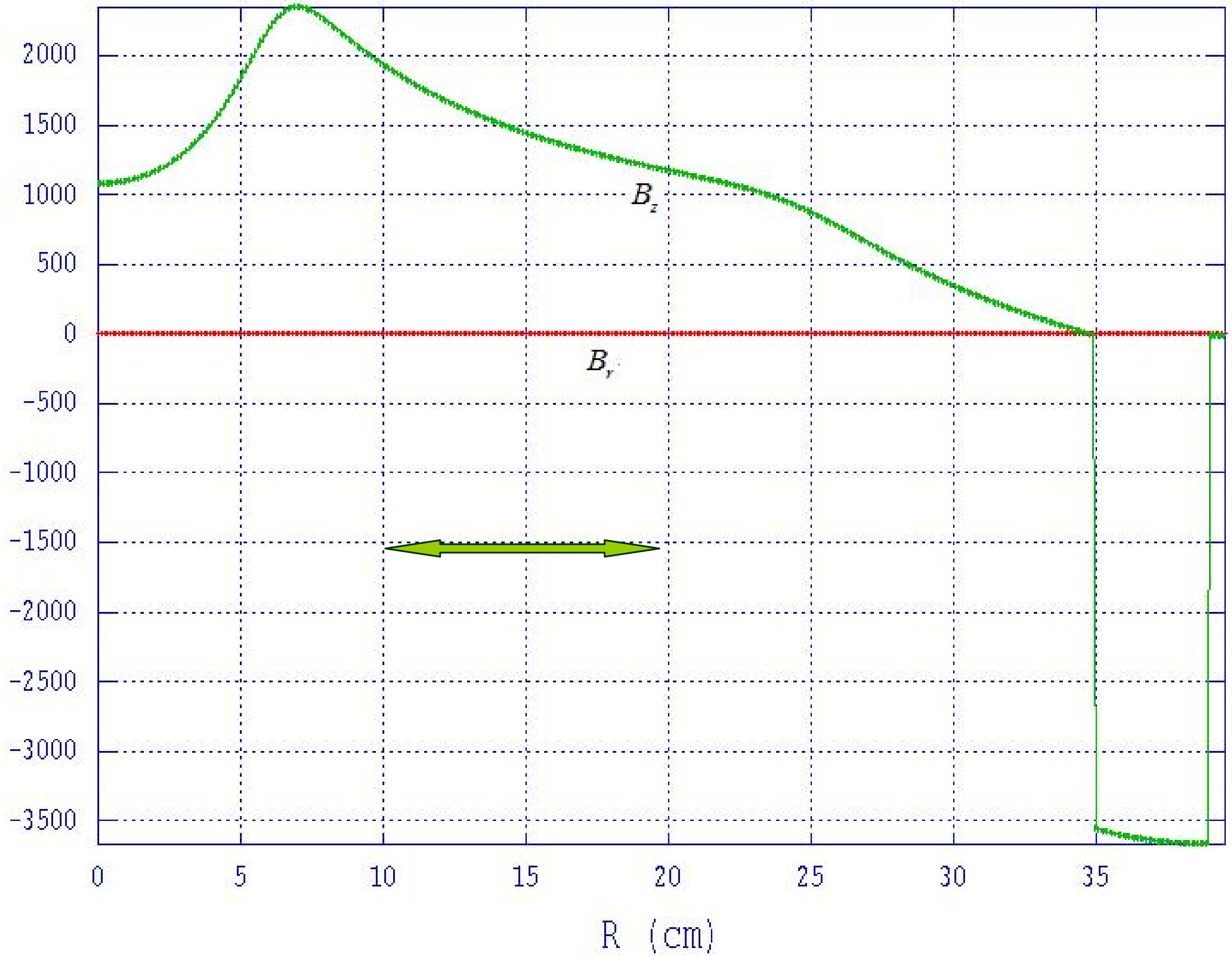


A matlab program

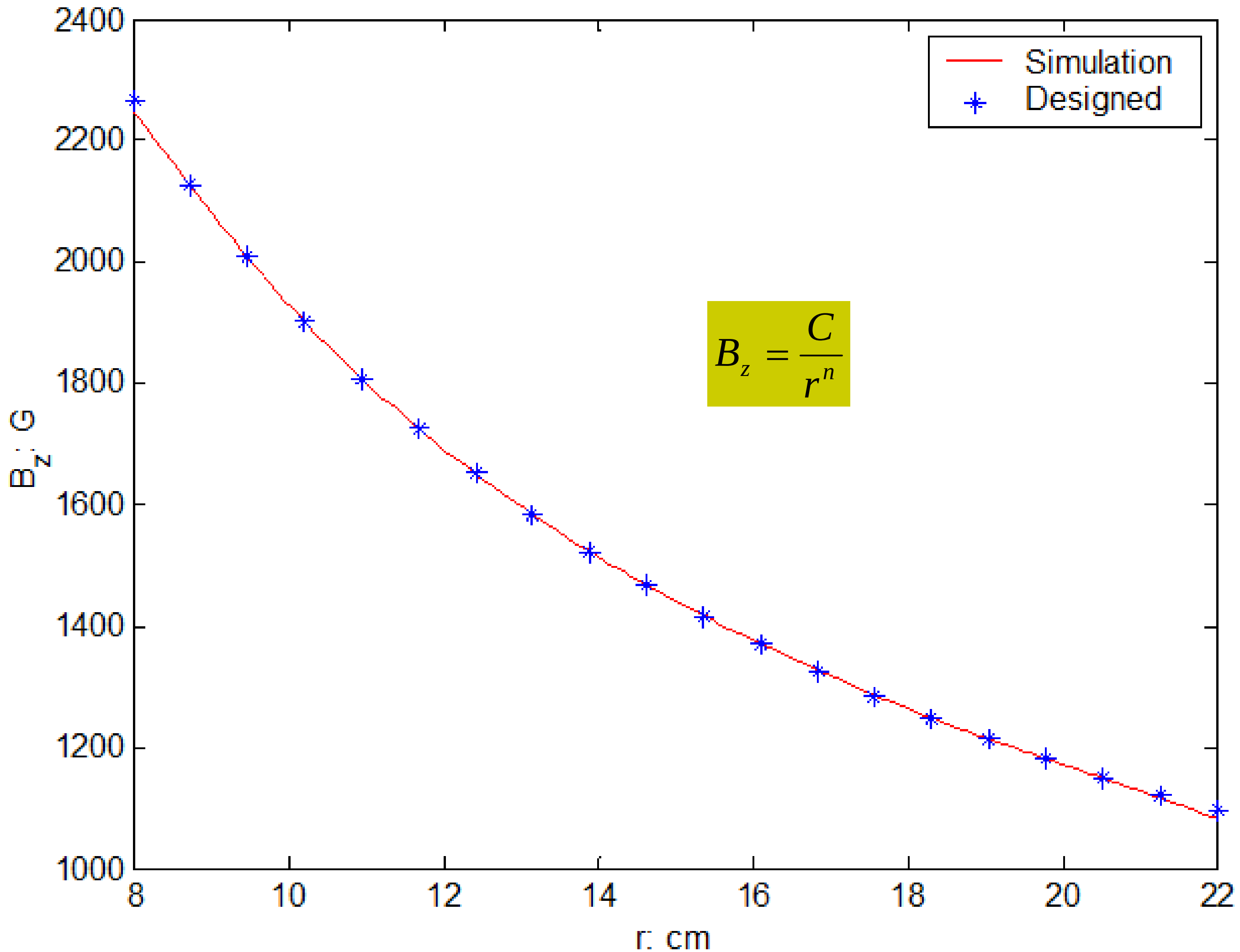
Flow Chart



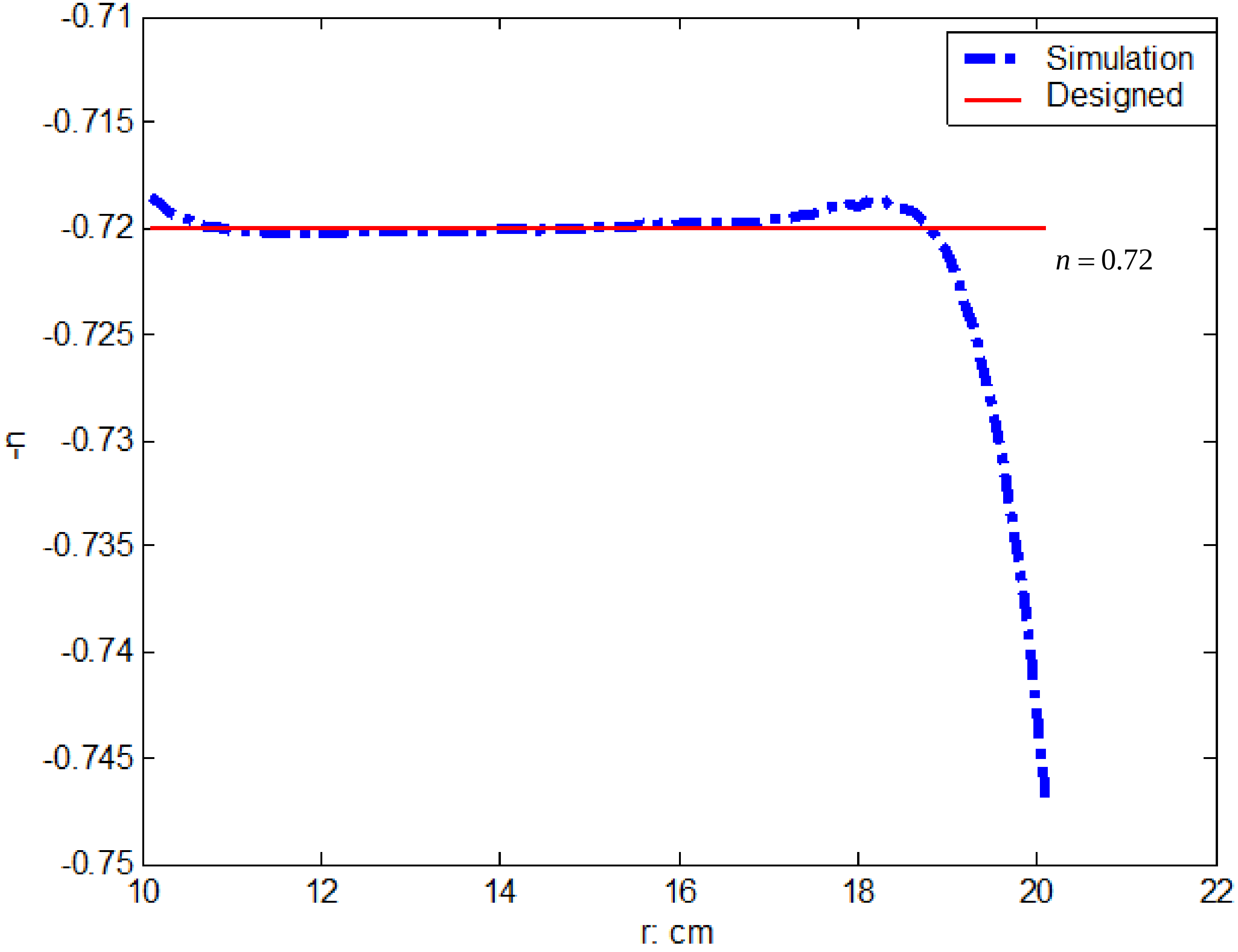
Magnetic Field Distribution



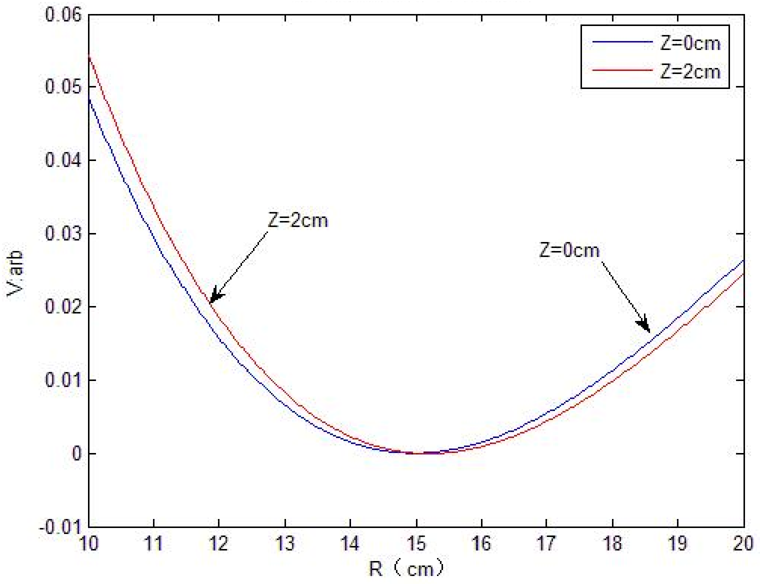
Magnetic Field Distribution

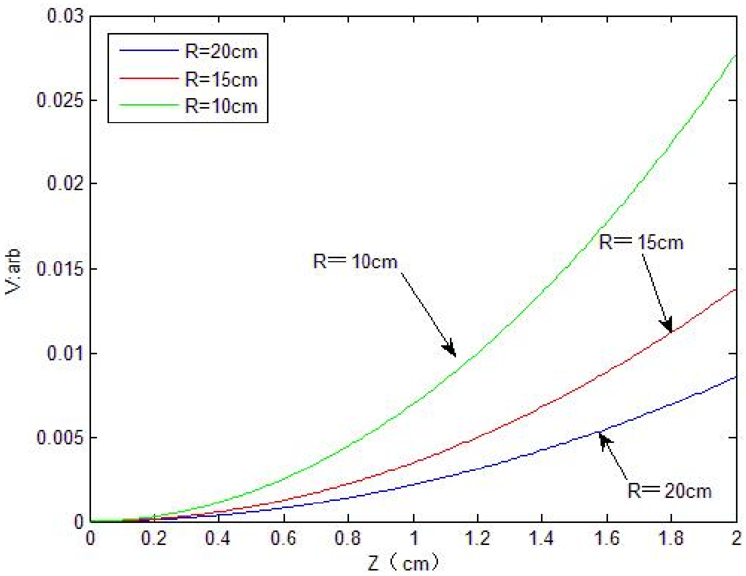


Magnetic field Index



Potential-well in Radial and Axial direction





Superfish →

$$F_z = \frac{e^2}{m}(H_{z0} r_0) H_r$$

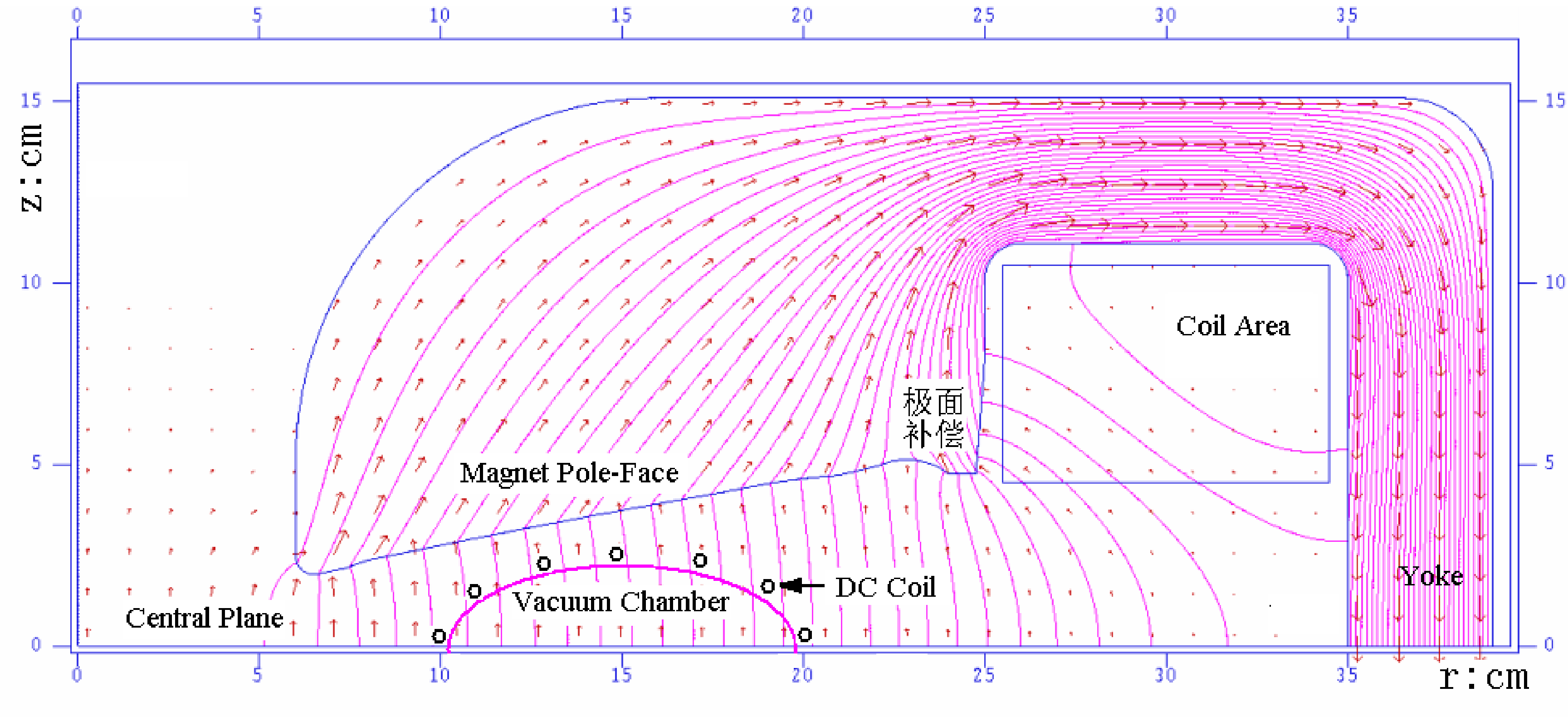
$$F_r = \frac{e^2}{m}(H_{z0} r_0)(H_z - H_{z0}\frac{r_0}{r})$$

$$H_r = -\frac{1}{r}\int_0^z nH_z dz$$

→

$$\begin{cases} V_m(r, z = c) = -\int_{r_0}^{r} F_r dr \\ V_m(z, r = c) = -\int_0^z F_z dz \end{cases}$$

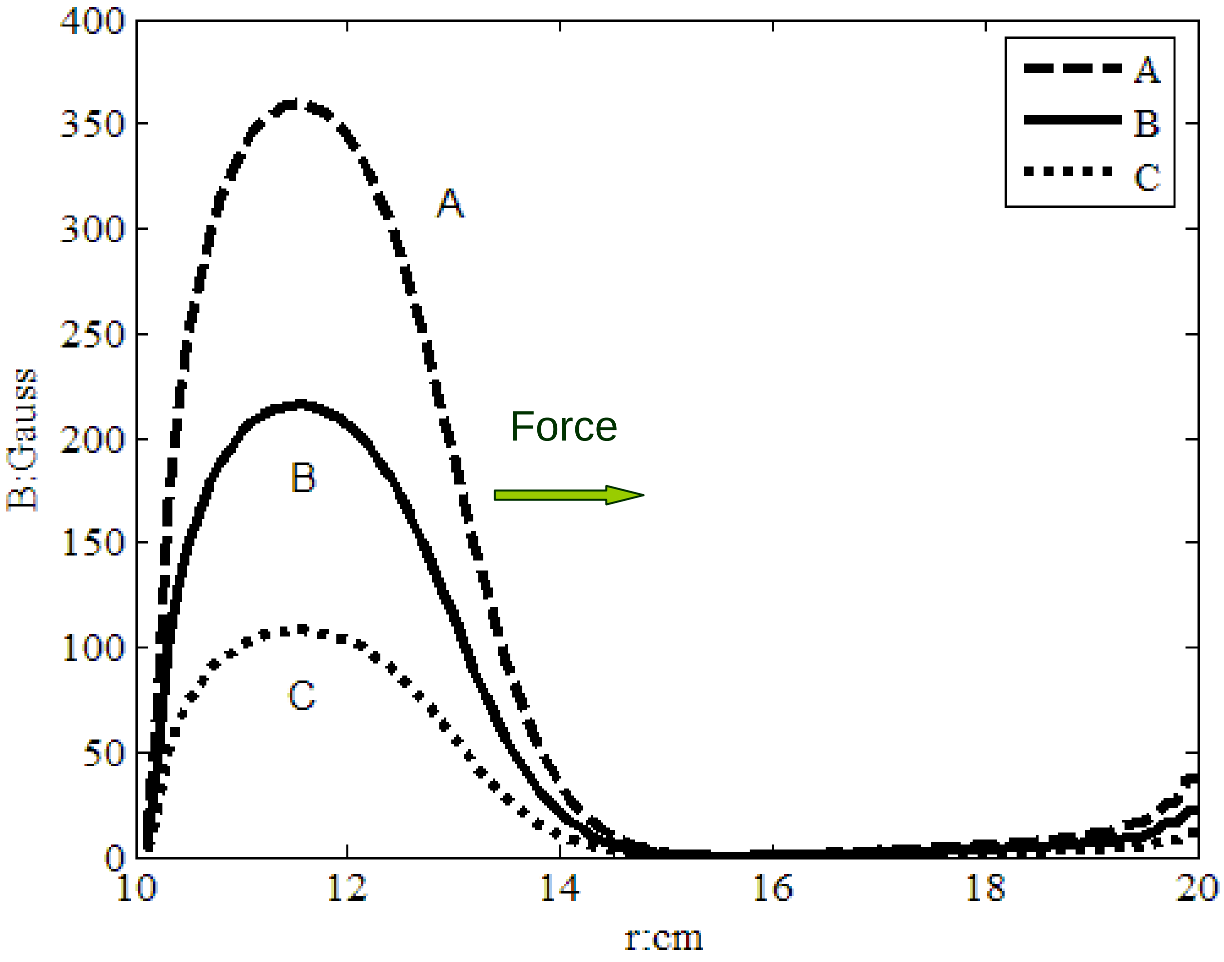
Perturbator



1、It's just several windings!

2、It only works during beam injection.

Perturbator Magnetic Field Distribution



A Fortran electron trace program

quadratic equation

↓

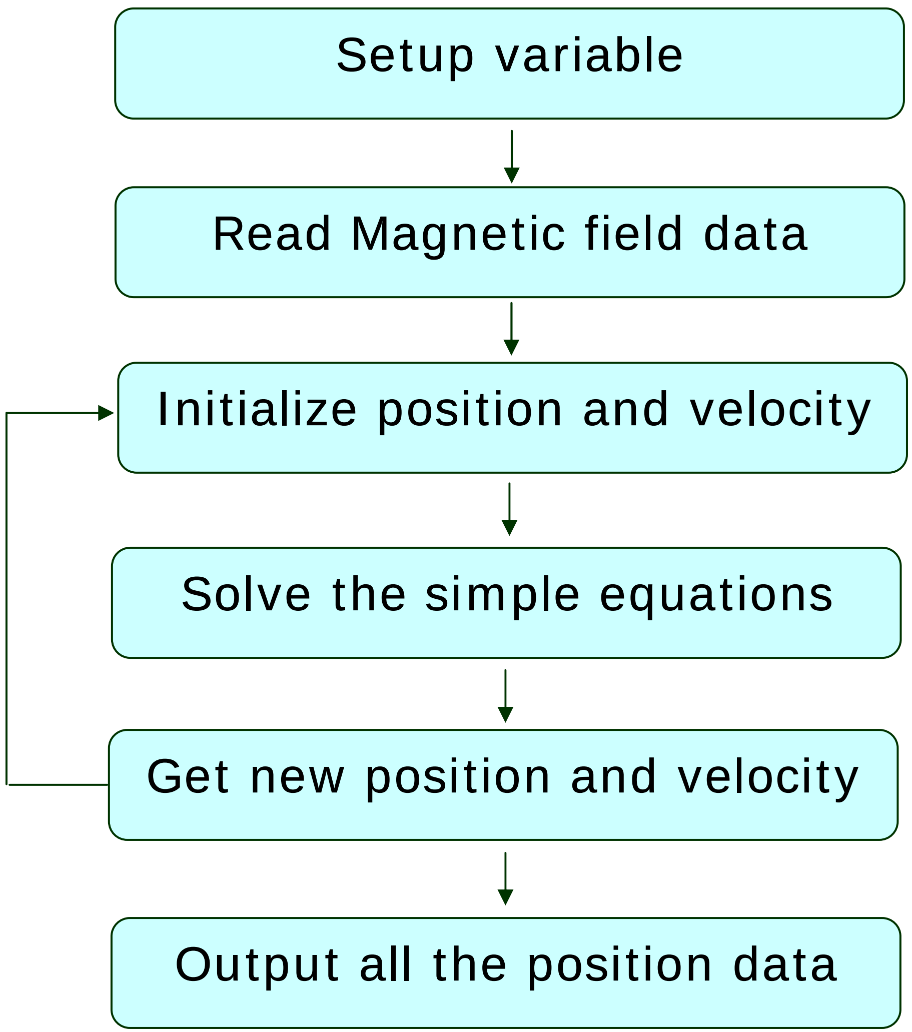
simple equation

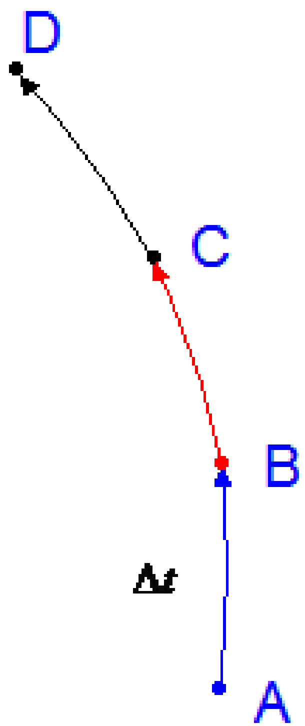
$$\begin{cases} \dfrac{d}{dt}\left(m\dfrac{dr}{dt}\right) = mr\left(\dfrac{d\theta}{dt}\right)^2 + qeB_z r\dfrac{d\theta}{dt} \\ \dfrac{1}{r}\dfrac{d}{dt}\left(mr^2\dfrac{d\theta}{dt}\right) = -qeB_z\dfrac{dr}{dt} + qeB_r\dfrac{dz}{dt} \\ \dfrac{d}{dt}\left(m\dfrac{dz}{dt}\right) = -qeB_r\dfrac{d\theta}{dt} \end{cases}$$

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_1 x_4^2 + \dfrac{qeB_z}{m} x_1 x_4 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = \dfrac{1}{x_1}\dfrac{qeB_r}{m} x_6 - \dfrac{qeB_z}{m} x_2 \dfrac{1}{x_1} - \dfrac{2x_2 x_4}{x_1} \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = -\dfrac{qeB_r}{m} x_1 x_4 \end{cases}
\qquad
\begin{cases} x_1 = r \\ x_2 = \dot{r} \\ x_3 = \theta \\ x_4 = \dot{\theta} \\ x_5 = z \\ x_6 = \dot{z} \end{cases}$$

A Fortran electron trace program

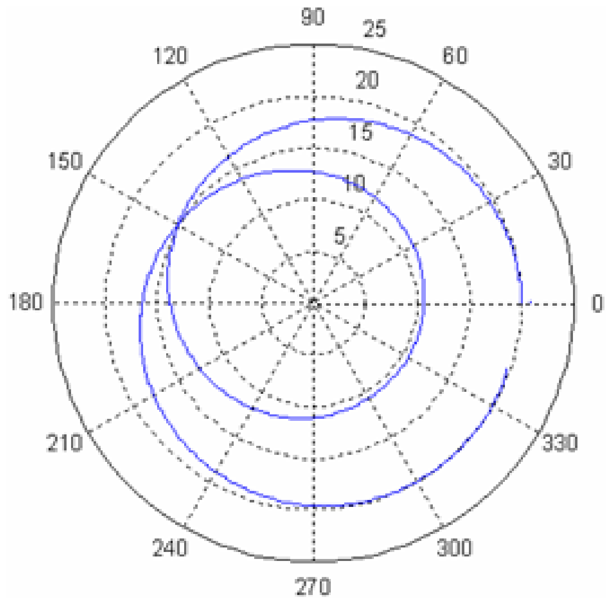
Flow Chart

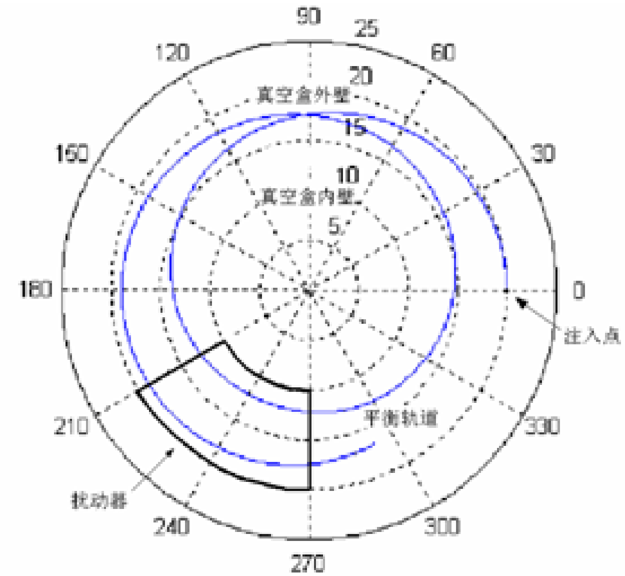




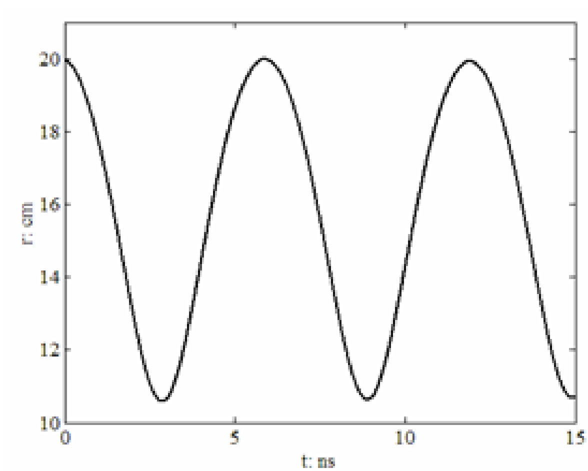
Results

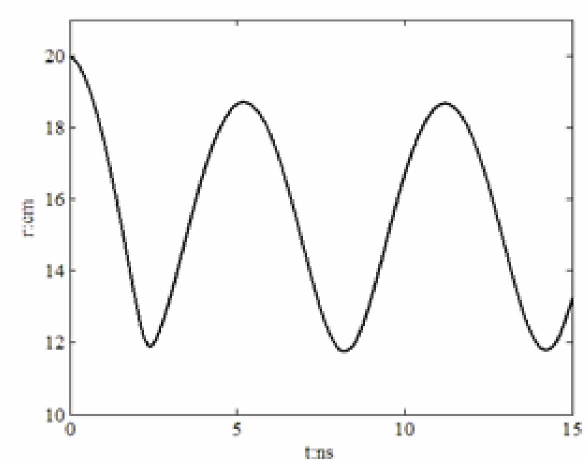
Electron Trace



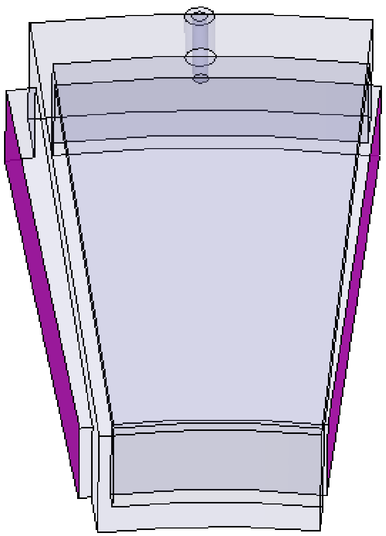


Electron Amplitude





Resonant Cavity(1/4wavelengh)

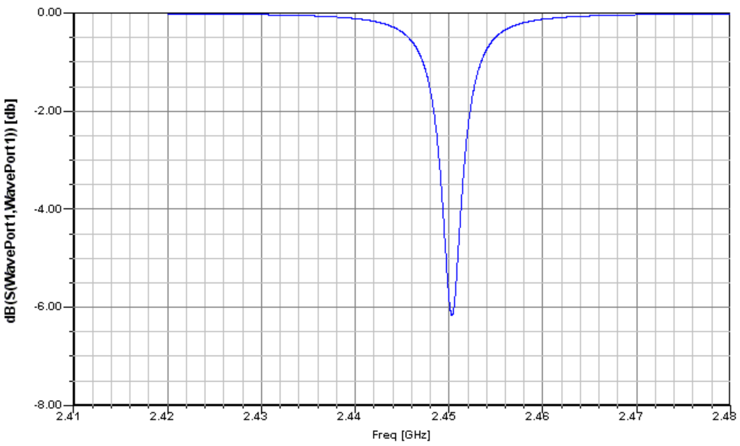


HFSS

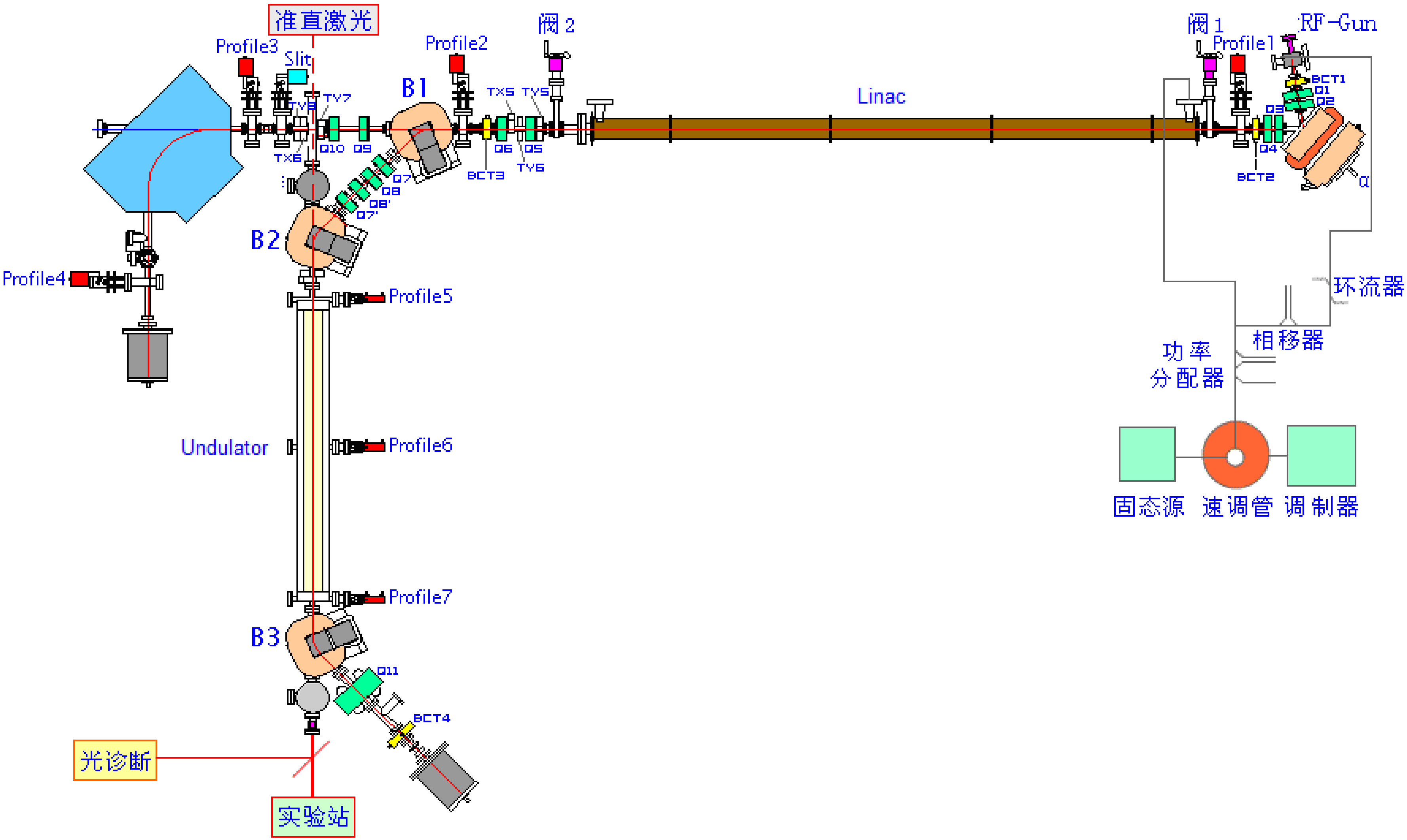
RF Parameters

Parameters	Value
Average Current	~0.11A
Energy loss/ Turn	~34keV
Beam Power Loss	3.74kW
Harmonics Number	8
RF frequency	2.45GHz
Circulating Frequency	306.25MHz
RF-voltage	120keV

Inner Length	67mm
Outer Length	44mm
Distance	4mm
Wall Thickness	2mm
Slit Width	5mm
Cavity Frequency	2450.3 MHz
Q Value	~2500



Layout of the BFEL Facility

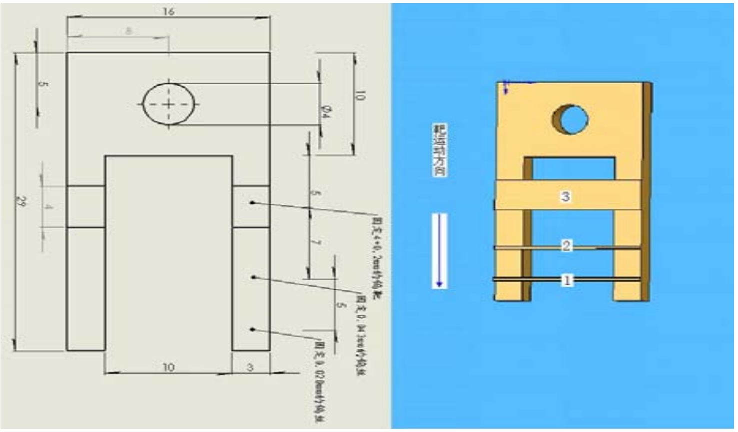


Parameters of the BFEL

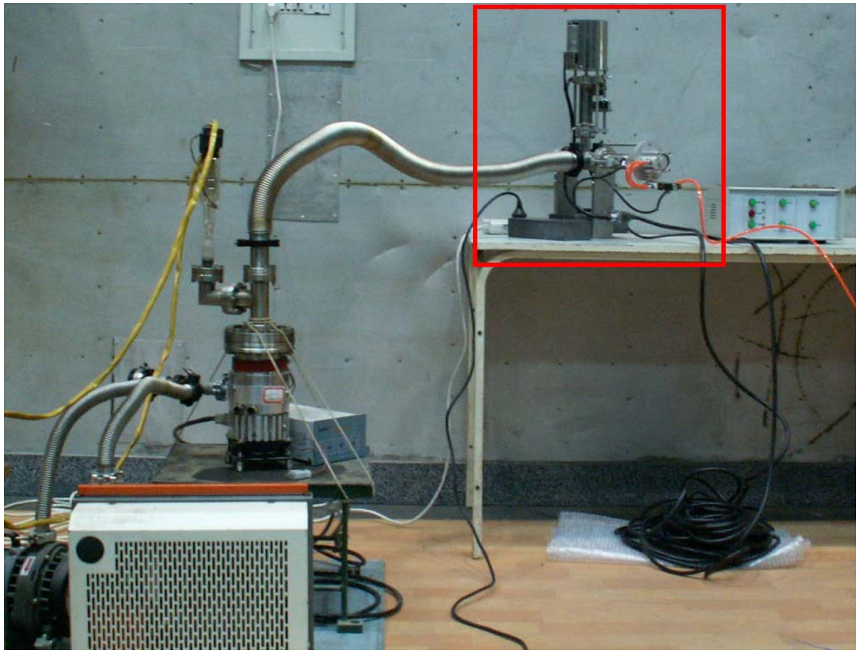
Energy	15-30MeV
Energy Spread	0.5%
Emittance	50-80 mm mrad
Macro Pulse Width	4us
Micro Pulse Width	4ps
Macro Pulse Average Current	200mA
Micro Pulse Average Current	15-20A
Repetition Rate	3.125Hz
Average Current	1.875×10^{-6}A
RF Frequency	2856MHz

New Profile &Targets

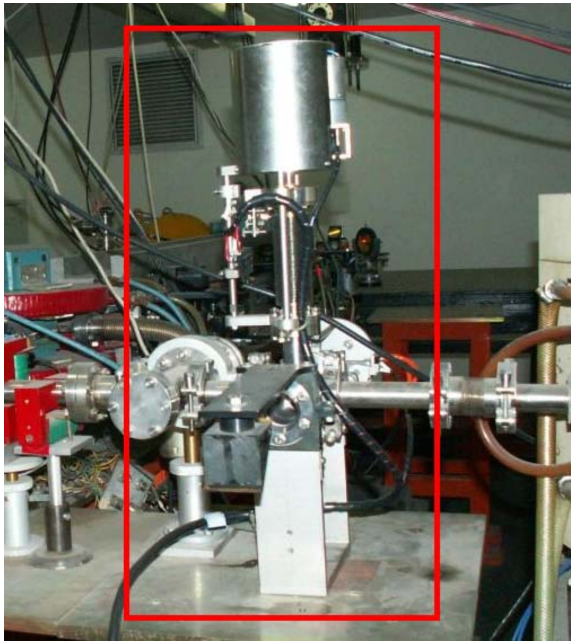
Target Num.	Size	Shape	Material
1 (Radius)	85um	Wire	Tungsten
2 (Radius)	210um	Wire	Tungsten
3 (Thickness)	120um	Foil	Tungsten



New Profile

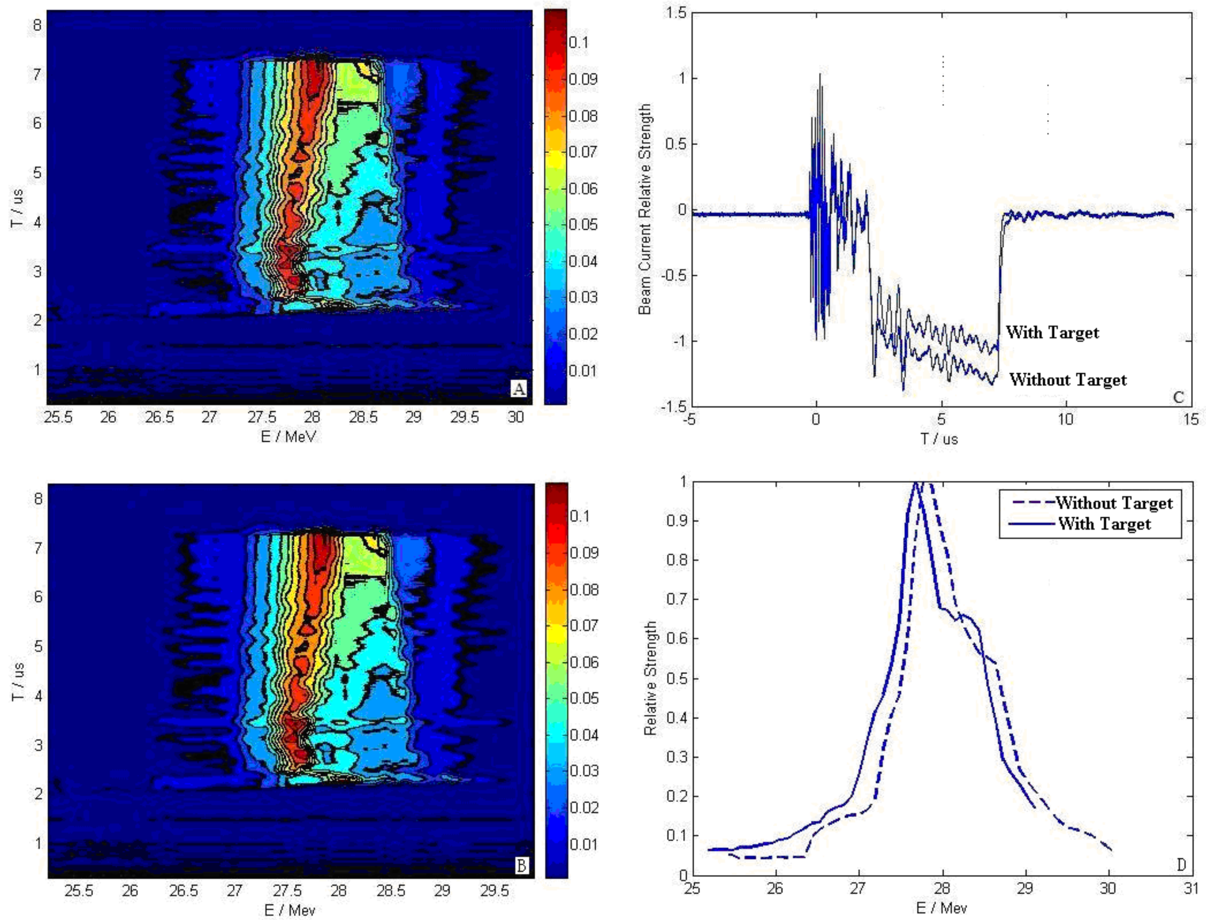


Vacuum Testing



Online Assemble

Some Results



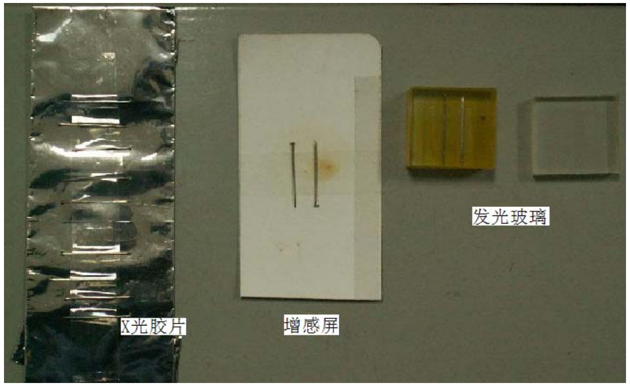
Beam current

Energy

Some Results

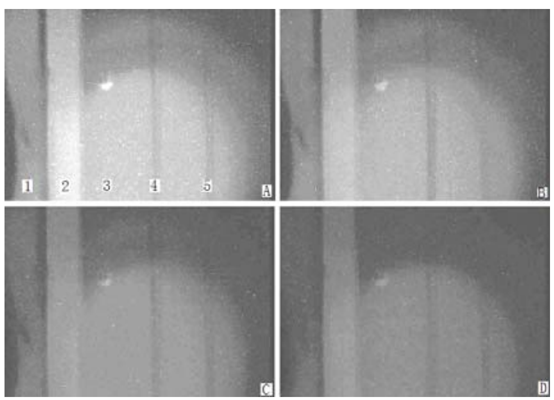
120um Tungsten Foil		Without Target	With Target	Changed
Experiment	Energy MeV	27.77	27.67	0.4%
	Energy Spread	4.04%	4.23%	1.9%
	Electron Loss	—	—	25%
Simulation(EGS4)	Energy MeV	27.77	27.57	0.7%
	Energy Spread	0	0.2%	—
Analytical calculations	Energy MeV	27.77	26.835	3.4%
	Energy Spread	—	—	—
	BCT1	BCT2	BCT3	—
Beam Current	662mA	143mA	140mA	—

Imaging Results



Two Little Pins

X-ray Port



Image

Control panel

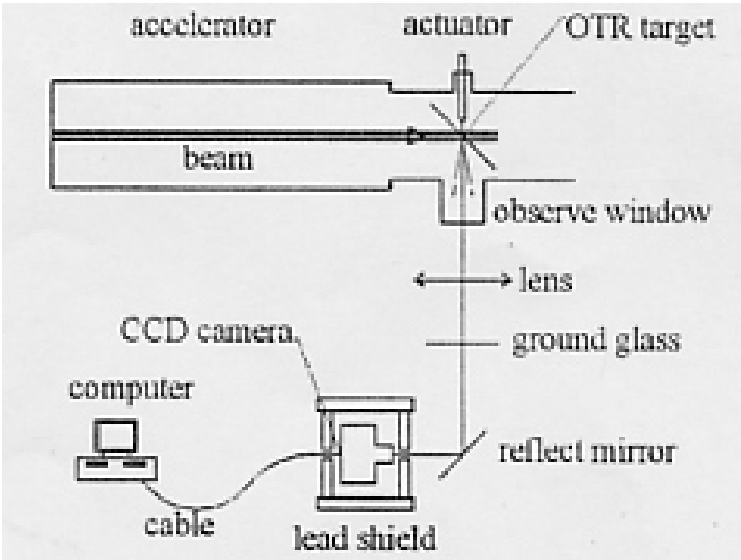
D 、The Upgrade of BFEL Facility

1、Beam Diagnoses

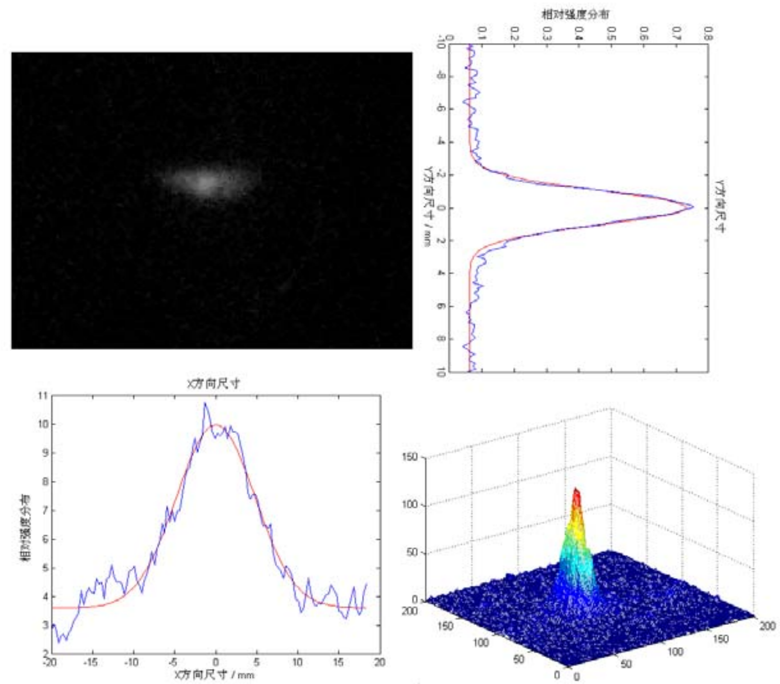
2、BFEL Commissioning

3、The First Spontaneous Radiation

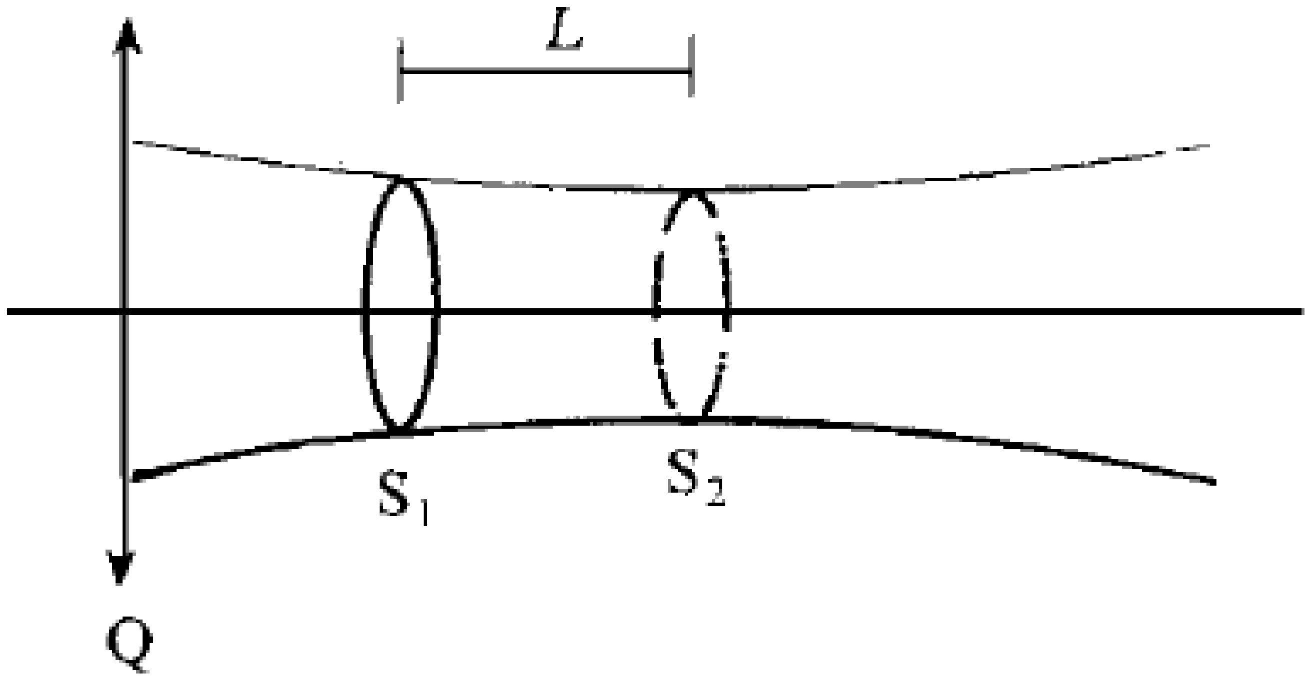
Beam size measurement



Schematic diagram of the beam size measurement



Emittance measurement



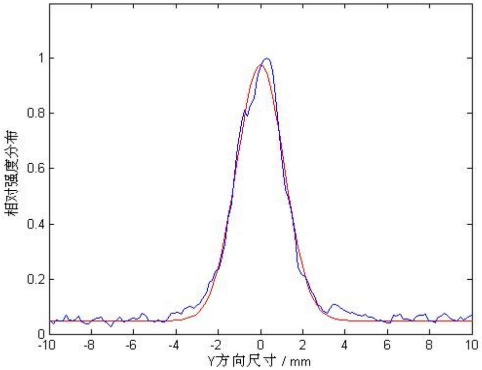
Two-screen

$$\varepsilon = \pi \cdot \gamma \cdot \frac{r_1 \cdot r_2}{L}$$

$$d\varepsilon = \pi \cdot \left(dr_1 \cdot \frac{r_2 \cdot \gamma}{L} + dr_2 \cdot \frac{r_1 \cdot \gamma}{L} + d\gamma \cdot \frac{r_1 \cdot r_2}{L} - dL \cdot \frac{r_1 \cdot r_2 \cdot \gamma}{L^2}\right)$$

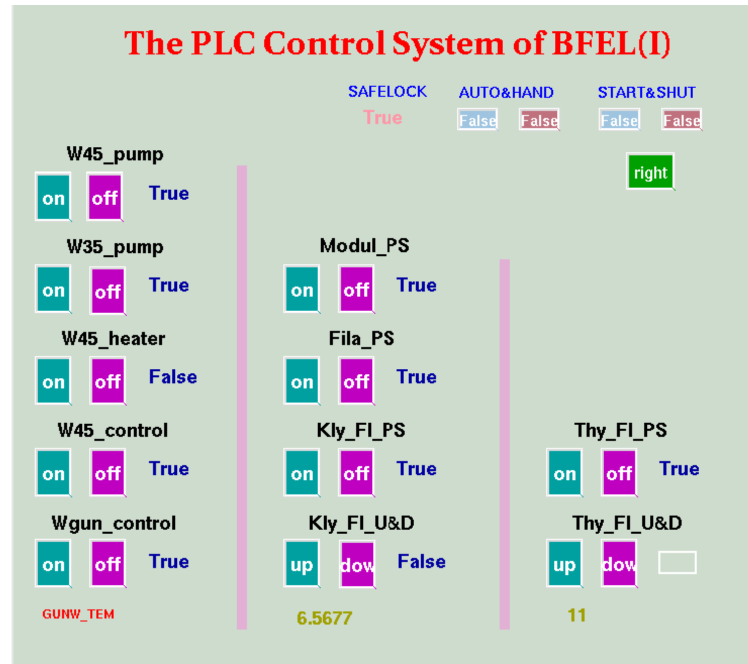
Emittance measurement

	Profile2（mm）	Profile3（mm）
RMS_1	1.15	1.02
RMS_2	1.13	1.03
RMS_3	1.13	1.03
RMS_4	1.13	1.00
RMS_5	——	1.01
RMS_6	——	1.08
RMS_7	——	1.05
$\overline{RMS}$	1.14	1.03
σ	0.01	0.03
σ'	0.03	0.02
RMS	1.14±0.04	1.03±0.05
FWHM	2.68±0.09	2.43±0.12
r	1.34±0.05	1.22±0.06

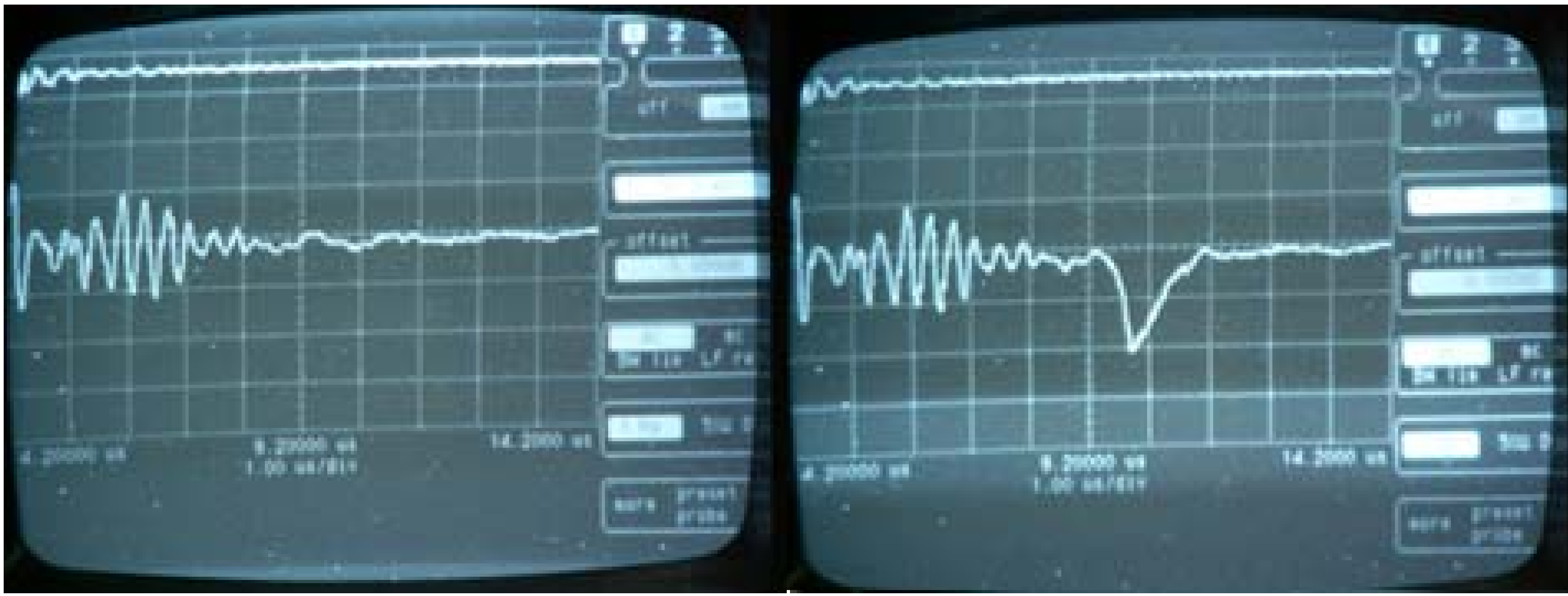


$$\varepsilon = 48.6 \pm 3.8\pi \cdot mm \cdot mrad$$

The BFEL Commissioning



The First Spontaneous Radiation



Thank You !

Gu Xiaofeng

April 2, 2008

References:

1、H.Ymada. Novel X-ray source based on a tabletop synchrotron and its unique features. Nuclear Instruments and Methods in Physics Research B 199, (2003): 509-516

2、Roderick J. Loewen. A Compact Light Source: Design and Technical Feasibility Study of a Laser-Electron Storage Ring X-Ray Source, SLAC-R-632

3、V. V. Kaplina, S. R. Uglov, O. F. Bulaev, et al. Observation of multiple passes of electrons through thin internal targets of a betatron. Nuclear Instruments and Methods in Physics Research, 2001 (B 173):3-15