The Proposal of Accelerator Based Light Sources for TAC Project

O. Mete
Ankara University
Physics Engineering Department
FEL and Linac Research Group, Ph.D Student
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Nagele
Voronov
Sfakianakis
Alonso Alvarez
De Roo
Kuwahara
Wohlmuth
Sfyrla
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2005

Contents

- TAC Project in Brief
- IR FEL Facility
- TAC SASE FEL
- TAC Synchrotron Source

TAC Project in Brief

The studies on the design and the user potantial of accelerator based light sources in Turkey have been made by our research group under the feasibility project named as **"Particle Accelerators: What should be done in Turkey?"**

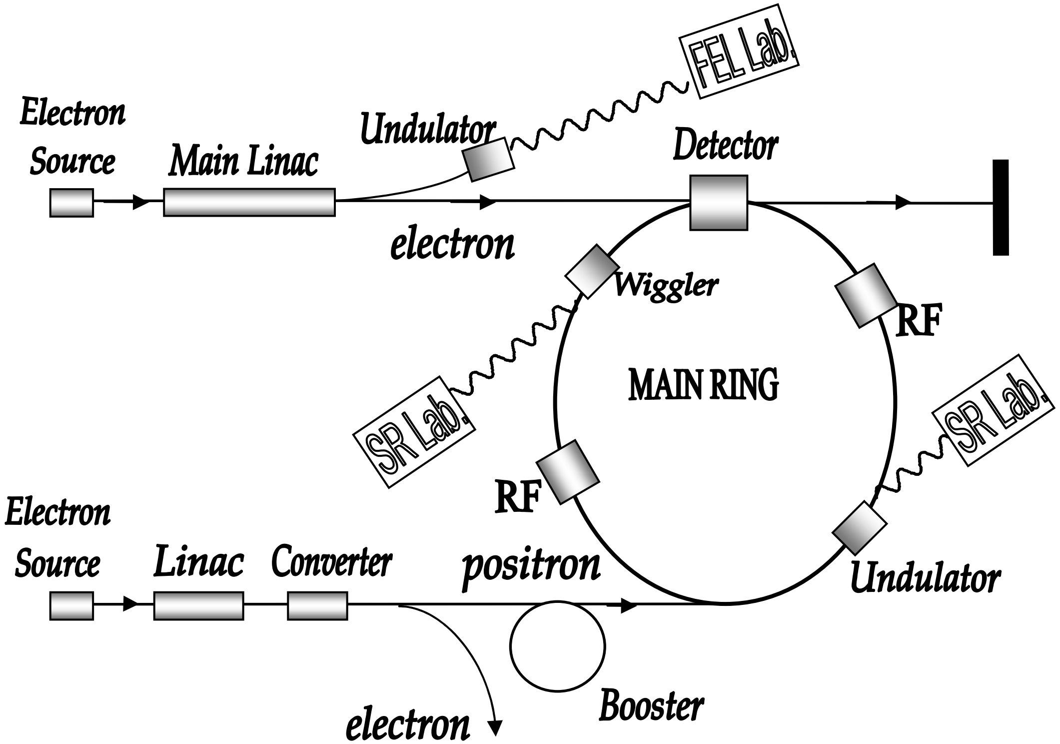
Then the research for accelerator technologies and designs dedicated to TAC (Turkish Accelerator Centre) project proceeded with several works.
http://bilge.science.ankara.edu.tr

Eventually in 2006, the project has been enlarged including 9 other universities in Turkey under the coordination of Ankara University.

TAC Project in Brief

Approximately 10 years ago, a linac-ring type charm-tau factory and a synchrotron light source were proposed as a regional project for research on elementary particle physics and applied sciences.

Starting from 2002, the conceptual design study of the TAC project has been started with a relatively enlarged group (with the DPT support).
The TAC CDR has been completed in 2006.

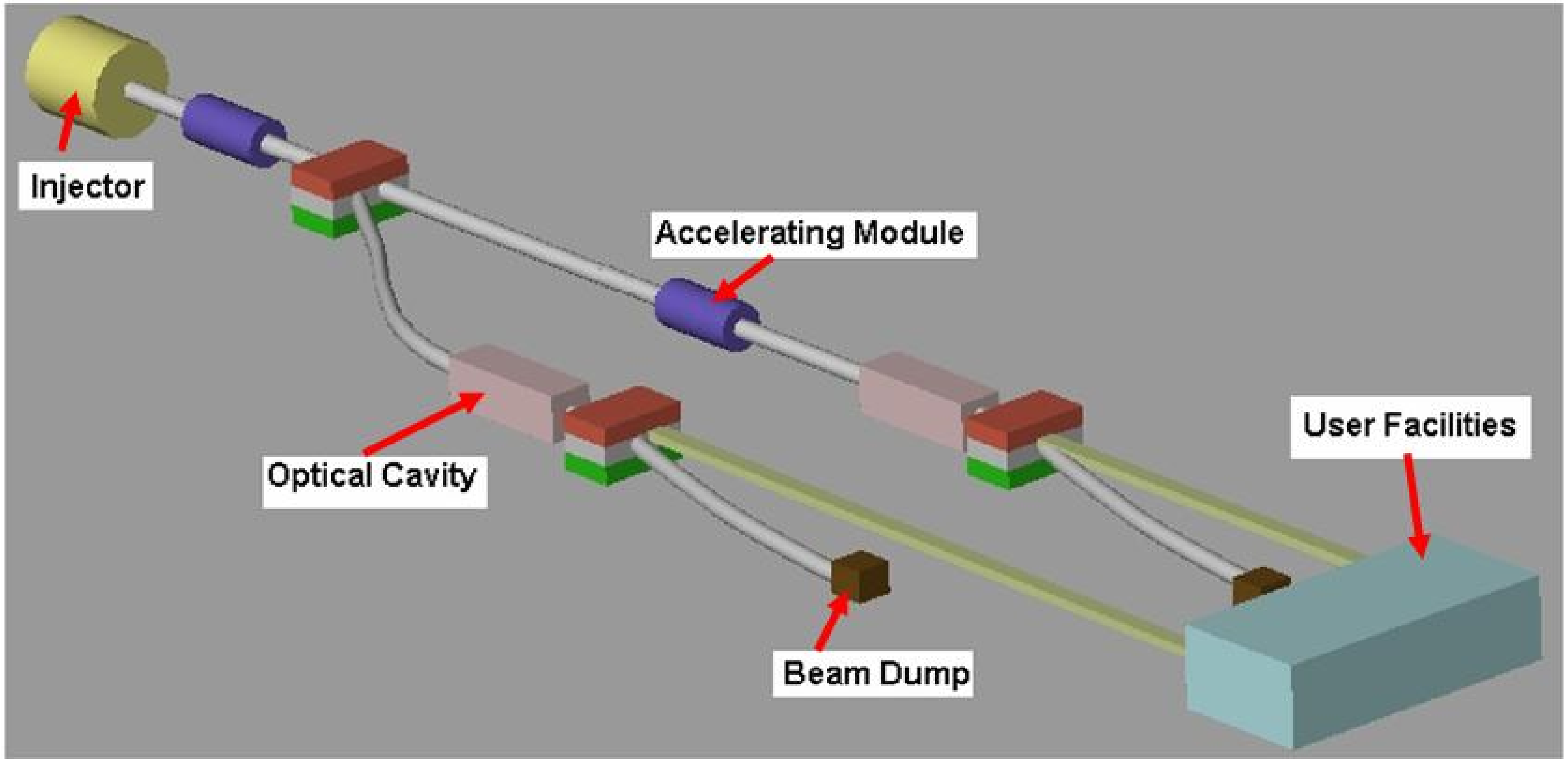


Currently TAC project includes:

- A Linac-ring type charm factory
- Free electron laser based on electron linac
- GeV scale positron accelerator
- TAC IR FEL Facility.

The Radiation Sources in TAC Project

An IR FEL as the First Facility



The Schedule of TAC Project

2006:

- **The Technical design study**

2007:

- **Infrastructure of TAC IR FEL Facility**

2008:

- **Installation of the IR FEL linac**

2009:

- **Installation of the IR FEL and beam lines with the experimental stations**
- **TAC technical design report will be completed.**

2010:

- **Commissioning of TAC IR FEL**
- **Governmental decision on approval of TAC project**

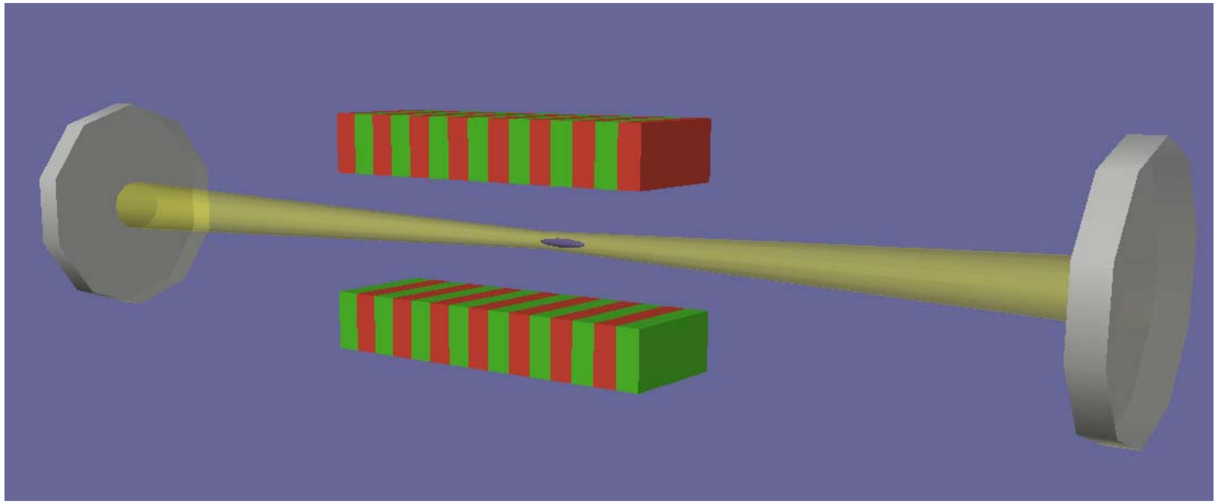
2015:

- **Particle (charm) factory and (synchrotron + SASE FEL) light source part of TAC project will be completed.**

2017:

- **Proton accelerator and experimental stations will be completed.**

FEL Oscillator

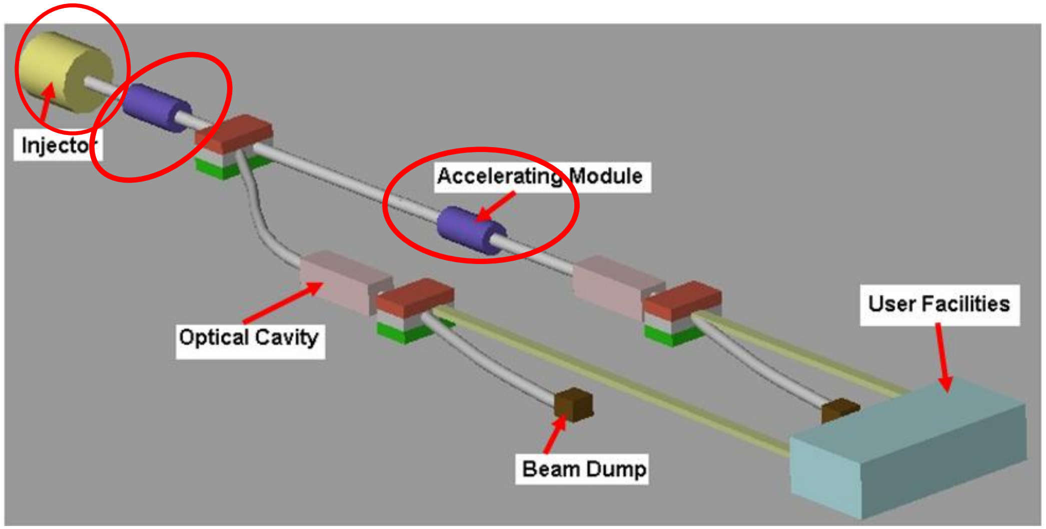


- In an FEL oscillator the radiation that is obtained from the undulator is trapped between two mirrors.

- The radiation interacts with the electron beam in its each round trip in the cavity.

TAC IR FEL FACILITY

RF Photo Injector



Superconducting Acceletor Modules

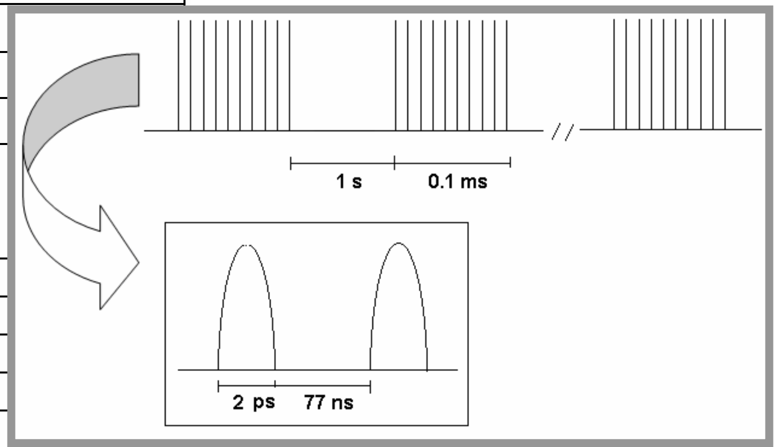
(2 or 3 9-cell cavities considering an achievable gradient of 15 MV/m)

Electron Beam Parameters

Energy (MeV)	15-60
Bunch Charge (pC)	50
Bunch Repetition Rate (MHz)	13
Average Beam Current (mA)	2.5

Electron Beam Temporal Structure

Macro Pulse Duration (ms)	0.1
Macro Pulse Period (s)	1
Machine Cycle (%)	0.01
Number of micro bunches	1299
Micro Bunch Duration (ps)	2
Micro Pulse Seperation (ns)	77



Undulator for IR FEL

Halbach formula for the peak field

$$\hat{B} = a \exp\left(b\frac{g}{\lambda_0} + c\left(\frac{g}{\lambda_0}\right)^2\right) \qquad (1)$$

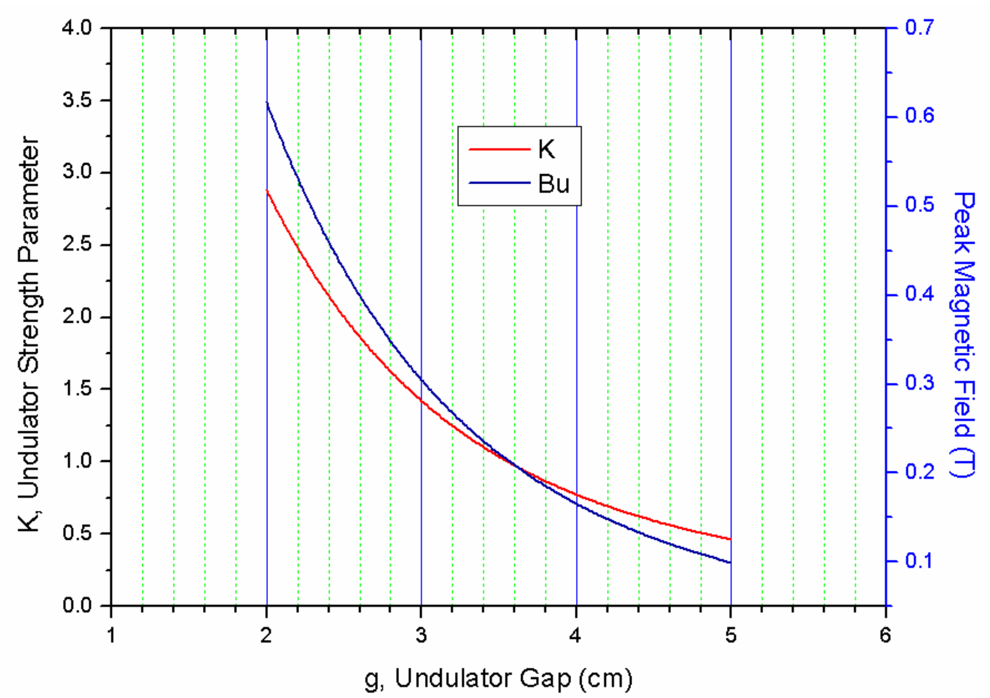
where both $\hat{B}$ and a are expressed in units of Tesla and b and c are dimensionless. The results

Case	Description	a	b	c	Gap Range
A	PPM Planar Vertical Field	2.076	-3.24	0	$0.1 < g/\lambda_0 < 1$
B	PPM Planar Horizontal Field	2.400	-5.69	1.46	$0.1 < g/\lambda_0 < 1$
C	PPM Helical Field	1.614	-4.67	0.620	$0.1 < g/\lambda_0 < 1$
D	Hybrid with Vanadium Permendur	3.694	-5.068	1.520	$0.1 < g/\lambda_0 < 1$
E	Hybrid with Iron	3.381	-4.730	1.198	$0.1 < g/\lambda_0 < 1$
F	Superconducting Planar, Gap = 12 mm	12.42	-4.79	0.385	$12mm < \lambda_0 < 48mm$
G	Superconducting Planar, Gap = 8 mm	11.73	-5.52	0.856	$8mm < \lambda_0 < 32mm$
H	Electro-magnet Planar Gap = 12 mm	1.807	-14.30	20.316	$40mm < \lambda_0 < 200mm$

Table 1: Fit coefficient a,b and c defining the peak field as a function of the ratio of gap over period as defined in Eq.(1).

Undulator for IR FEL

- With respect to the Halbach formula, with a period length of 5 cm, K and B values for the gap values between 2 and 5:



$$0.1 < \frac{g}{\lambda_u} < 1$$

$$0.3 < \frac{g}{\lambda_u} < 1$$

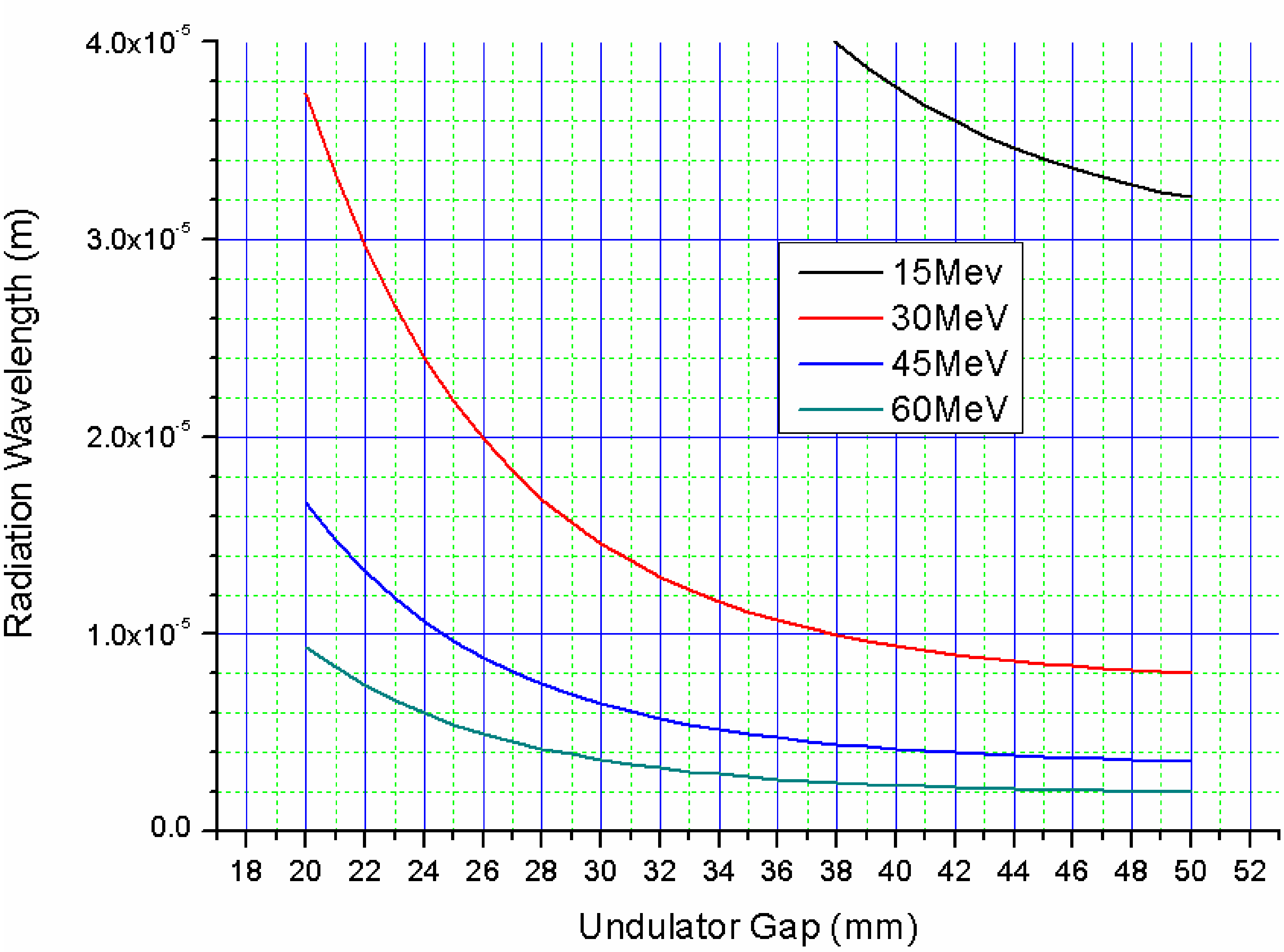
$$K \rightarrow 2.88 - 0.46$$

$$B_u \rightarrow 0.62 - 0.09$$

- The minimum value of the gap has been chosen as 2 cm in order to leave enough space for diagnostics tools and the vacuum chamber inside the undulator.

Undulator Parameters

Type	Hybrid
Undulator Period	50 mm
Gap Range	20-50 mm



4.0x10-5
3.0x10-5
2.0x10-5
1.0x10-5
0.0
Radiation Wavelength (m)
18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Undulator Gap (mm)
15Mev
30MeV
45MeV
60MeV

Flux for FEL Oscillator

$$F_n(K)=\begin{cases}\xi=\frac{1}{2}\frac{K^2}{1+K^2}\rightarrow for\_helical\_undulators\\ \xi=\frac{1}{4}\frac{K^2}{1+K^2/2}\rightarrow for\_planner\_undulators\\ \xi n^2\left[J_{(n-1)/2}(n\xi)-J_{(n+1)/2}(n\xi)\right]^2\end{cases}$$

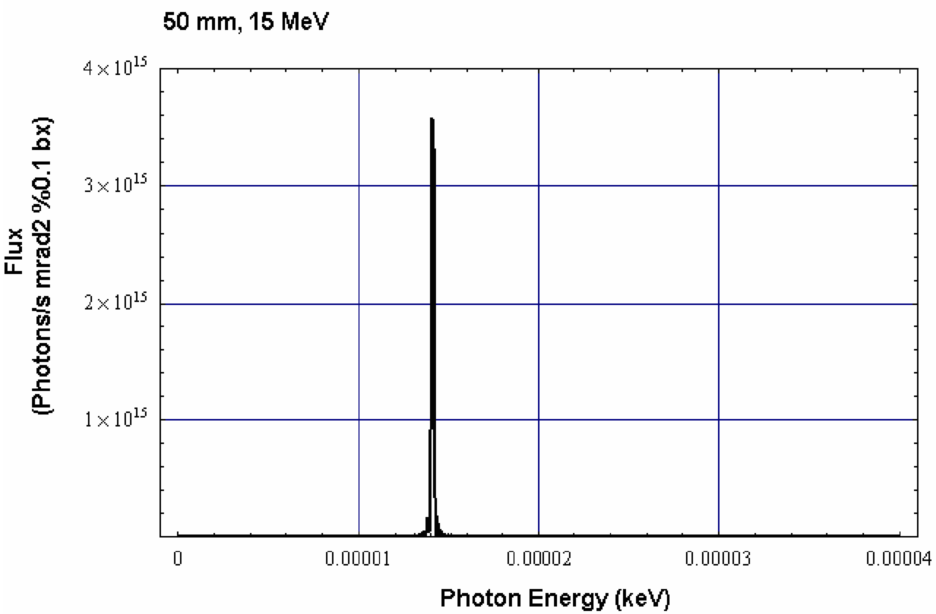
$$\left.\frac{d^2F_n}{d\omega d\Omega}\right|_{\theta=0}=1.74\times10^{14}N^2E^2[GeV]I[A]F_n(K)f(n\nu_n)$$

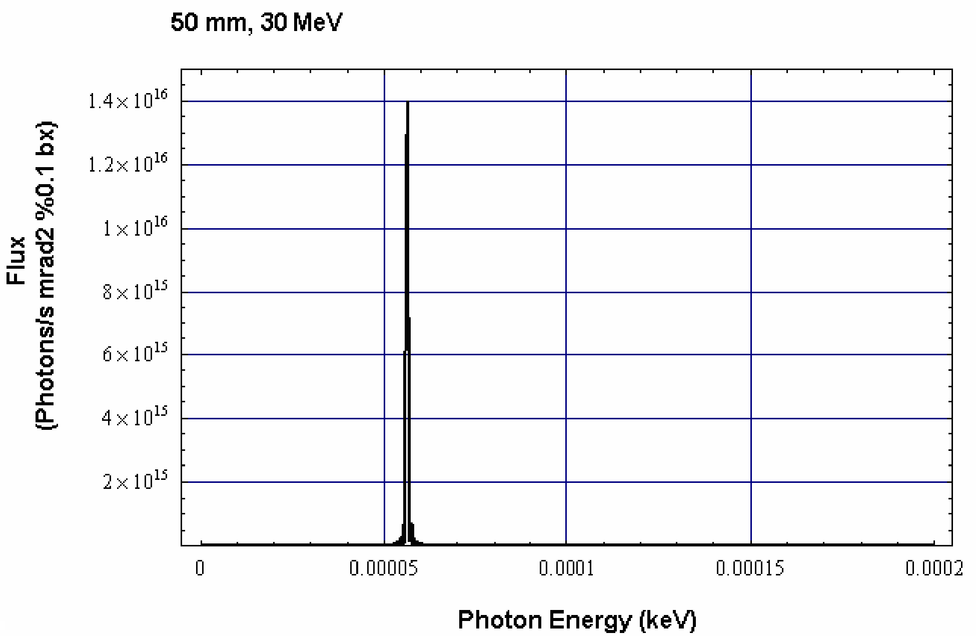
$$f(\nu)=\left(\frac{\sin\nu/2}{\nu/2}\right)^2$$

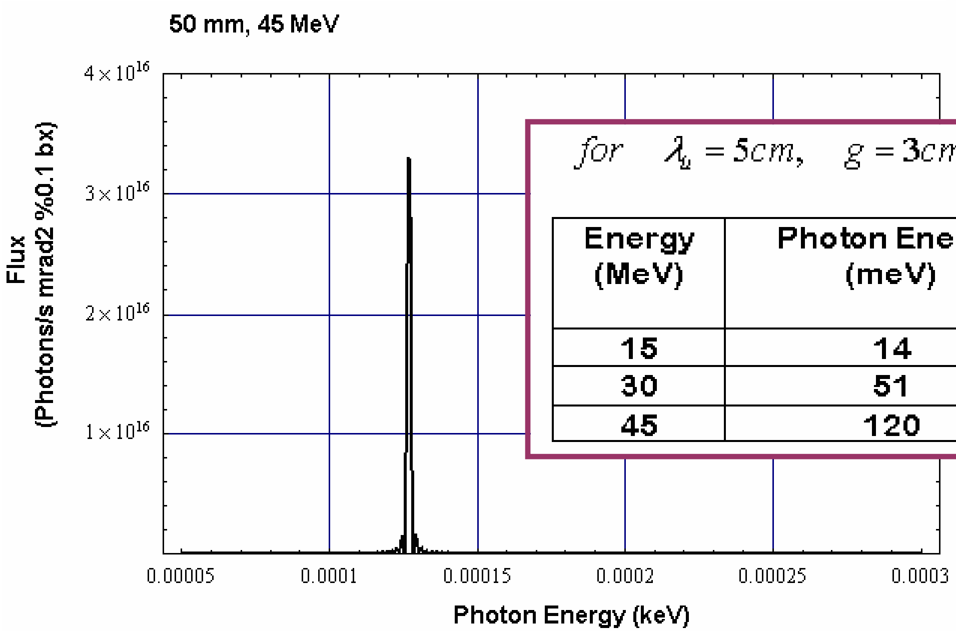
$$\varepsilon_n=n\varepsilon=\frac{0.947n[E(GeV)]^2}{\lambda_u(cm)(1+K^2/2)}$$

$$\nu=2\pi N\frac{\varepsilon_n-\varepsilon}{\varepsilon_n}$$

Flux for FEL Oscillator







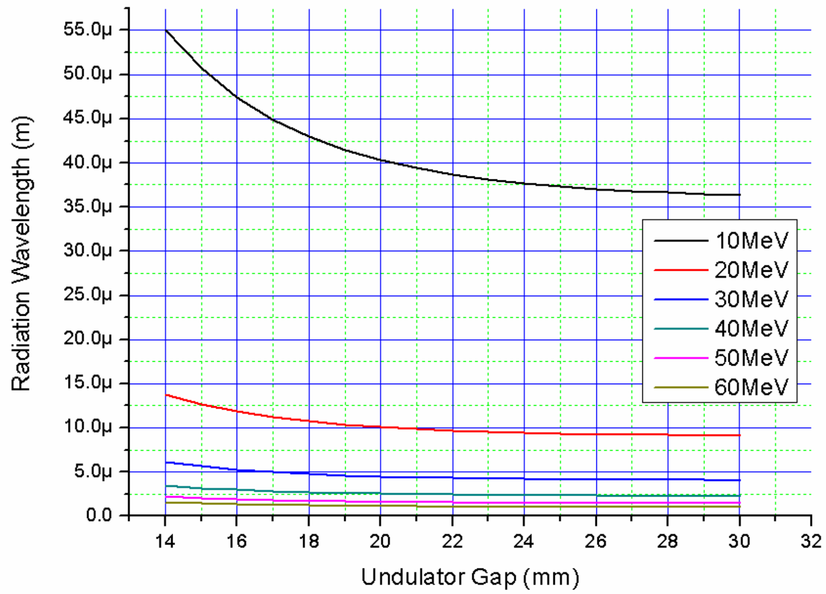
for $\lambda_u = 5cm, \quad g = 3cm$

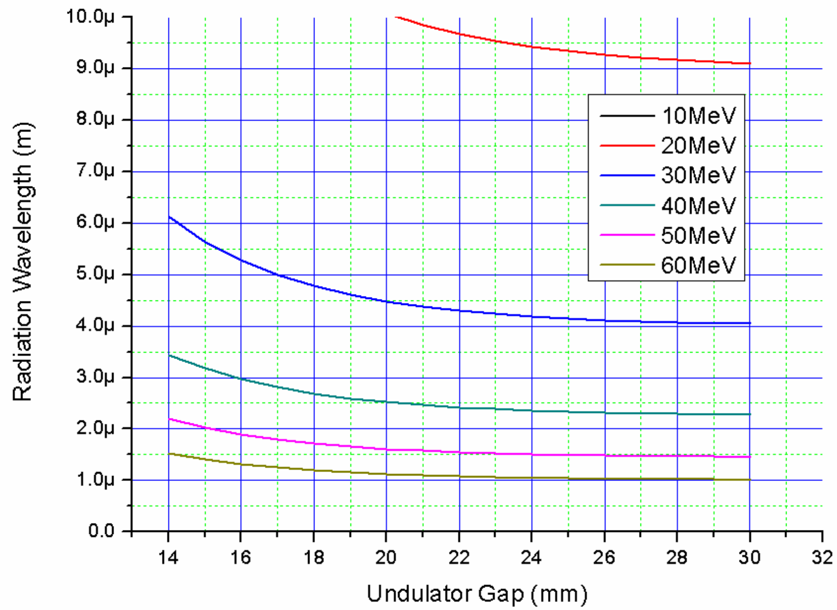
Energy (MeV)	Photon Energy (meV)	Pulse Energy (μJ)	Flux (Photons/s mrad^2 mm^2 %0.1bw)
15	14	0.034	3.8E15
30	51	0.14	1.4E16
45	120	0.3	3.3E16

Undulator for IR FEL

Forschungszentrum Rossendorf, ELBE
U27

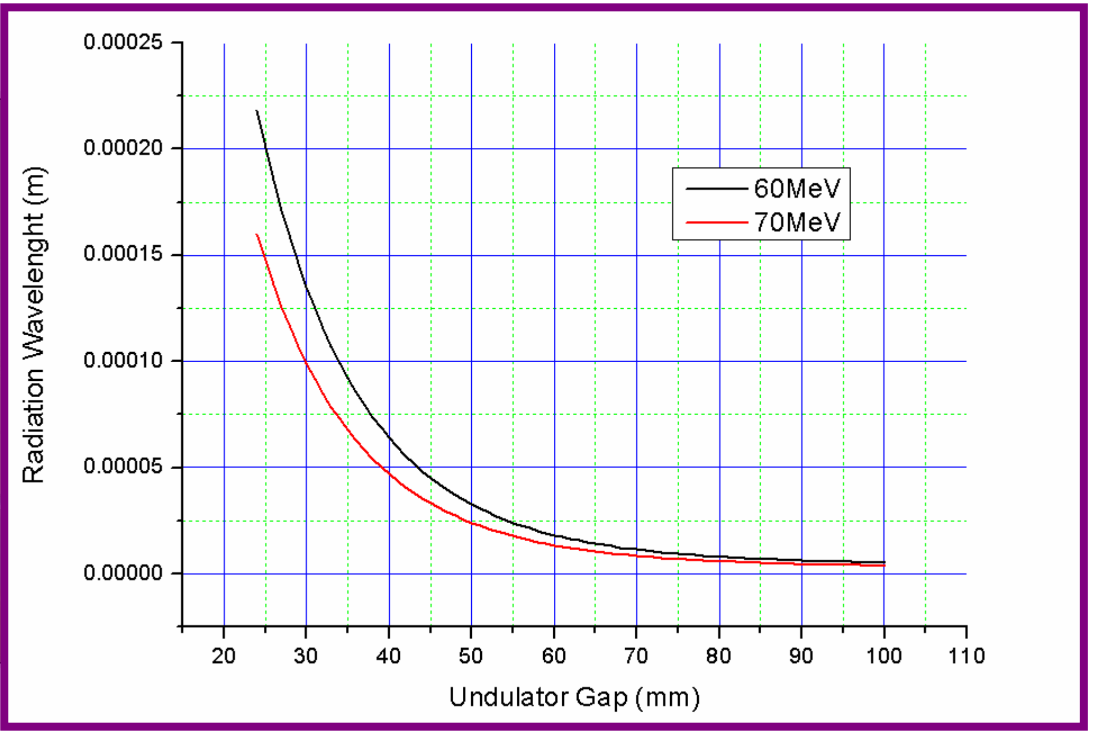
Period length	2.73 cm
Number of periods	2x34=68
Maximum undulator parameter	0.68





Undulator for IR FEL

Forschungszentrum Rossendorf, ELBE
U100



Perod length	10 cm
Number of periods	38
Minimum gap	24 mm
Maximum undulator parameter K_{rms}	2.7

Brightness for FEL Oscillator

Brigthness $B = \frac{F}{4\pi^2\sigma_x\sigma_z\sigma'_x\sigma'_z} = \frac{F}{4\pi^2\varepsilon_x\varepsilon_z} = foton/s/mm^2/mrad^2/\%0.1bg$

Electron beam divergence

$$\sigma'_{x,z} = \sqrt{\varepsilon_{x,z}\beta_{x,z}}$$

In practical units...

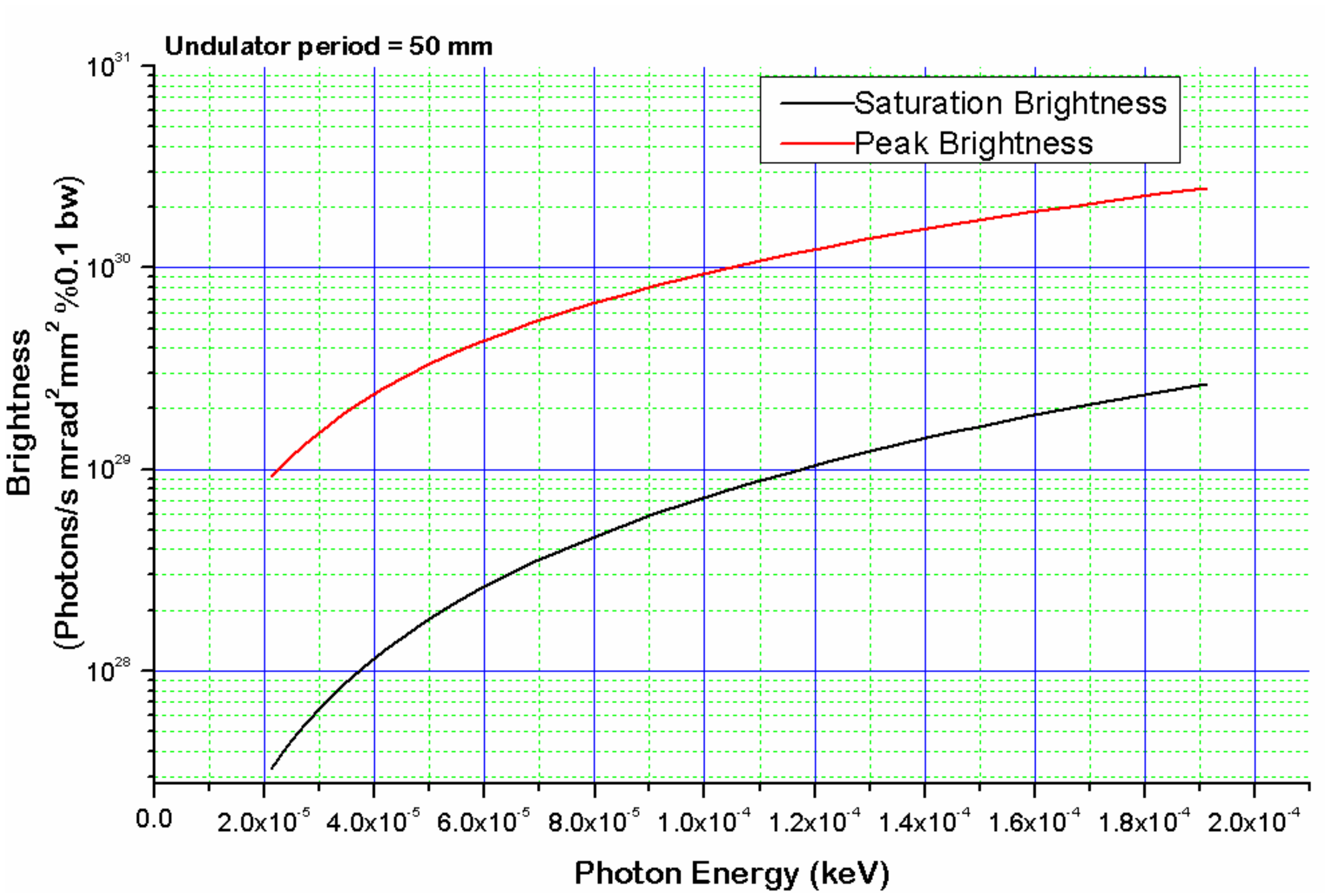
Saturation Brigthness $B_S \cong 3.977\times10^{42}\left(\frac{E[GeV]}{N}\right)^4 \frac{\sigma_z[mm]}{(\lambda_u[cm][Kf_b(K)])^2}$

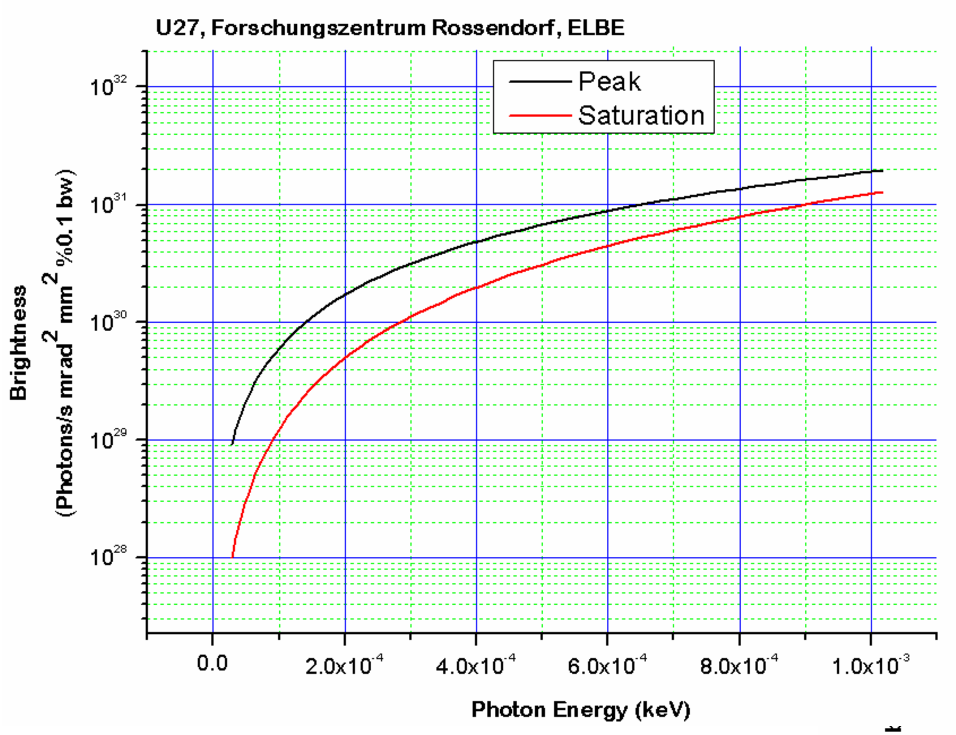
$$\sigma_{x,z} = \sqrt{\varepsilon_{x,z}\beta_{x,z}}$$

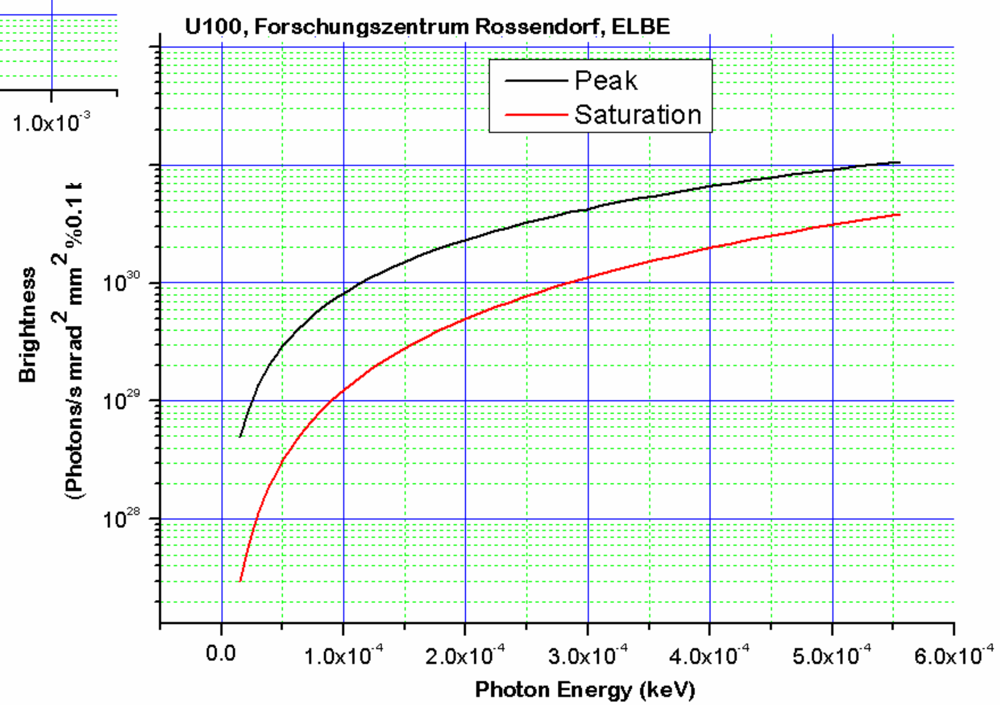
Electron beam transverse dimensions

Peak Brigthness $B_p \cong 6.4\times10^{37}\frac{\hat{I}[A]}{N}\frac{E[GeV]^3}{\lambda_u[cm]L_c[cm]}\frac{\sigma_z[mm]}{1+\frac{K^2}{2}}$

Brightness for FEL Oscillator




U27, Forschungszentrum Rossendorf, ELBE
Peak
Saturation
Brightness
(Photons/s mrad2 mm2 %0.1 bw)
Photon Energy (keV)


U100, Forschungszentrum Rossendorf, ELBE
Peak
Saturation
Brightness
(Photons/s mrad2 mm2 %0.1 b
Photon Energy (keV)

Cavity for IR FEL

✓ Mirrors have to be considered !

• Determination of the radius for each mirror

• Radiation spot sizes on mirrors and in the undulator

• Radiation waist is a limit for minimum applicable undulator gap

$$2\omega_0 < g$$

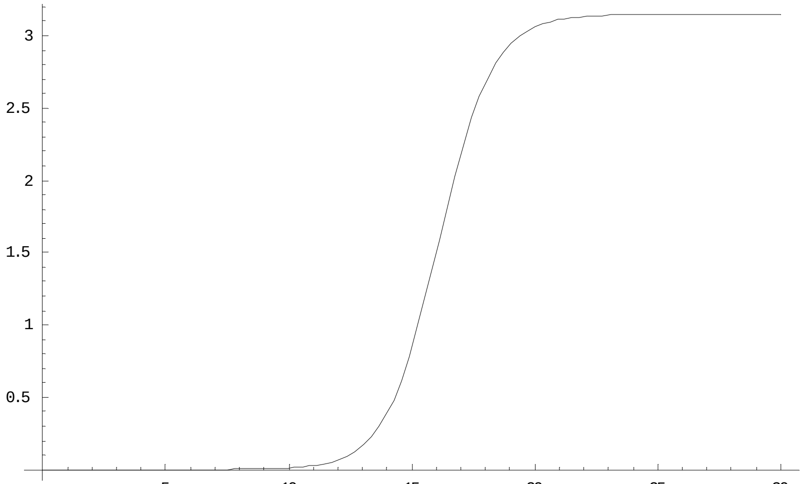
Radiation Power for IR FEL

Electron Beam Energy (MeV)	Rad. Power (MW) (Period 50 mm)
15	0.98
30	1.97
45	2.96

$$XR = X0 * \frac{((1-\eta) * (1+G))^{R}}{1 + \frac{X0}{XE} * (((1-\eta) * (1+G))^{R} - 1)}$$

intracavity equilirium power intensity

intra-cavity losses



Semi-Analytical Gain Model

- An FEL oscillator operates in low gain regime where the paramount parameter is low gain parameter given as,

$$g_0 = \frac{16\pi}{\gamma}\lambda[m]\lambda_u[m]N^3\frac{J\left[A/m^2\right]}{I_0[A]}\xi f_b(\xi)^2$$

Bessel factor $f_b = J_0(\xi) - J_1(\xi)$ $\qquad \xi = \frac{1}{4}\frac{K^2}{1+K^2/2}$

- Other parameters can affect the gain and must be taken into account when calculating it.

→ $\mu_c = \frac{\Delta}{\sigma_z}$ $\quad \Delta = N\lambda$ Slippage effect **(velocity difference between photon and electron beam)**

→ $\mu_\varepsilon = 4N\sigma_\varepsilon$ Inhomogenious broadening effects **(energy spread)**

→ $\theta = \frac{4\delta L}{g_0\Delta}$ $\quad \theta_s = 0.456$ Cavity length detuning parameter

Semi-Analytical Gain Model

$$\mu_c = \frac{\Delta}{\sigma_z} \qquad \Delta = N\lambda$$

Slippage effect

$$\mu_\varepsilon = 4N\sigma_\varepsilon$$

Inhomogenious broadening effects

$$\theta = \frac{4\delta L}{g_0 \Delta} \qquad \theta_s = 0.456$$

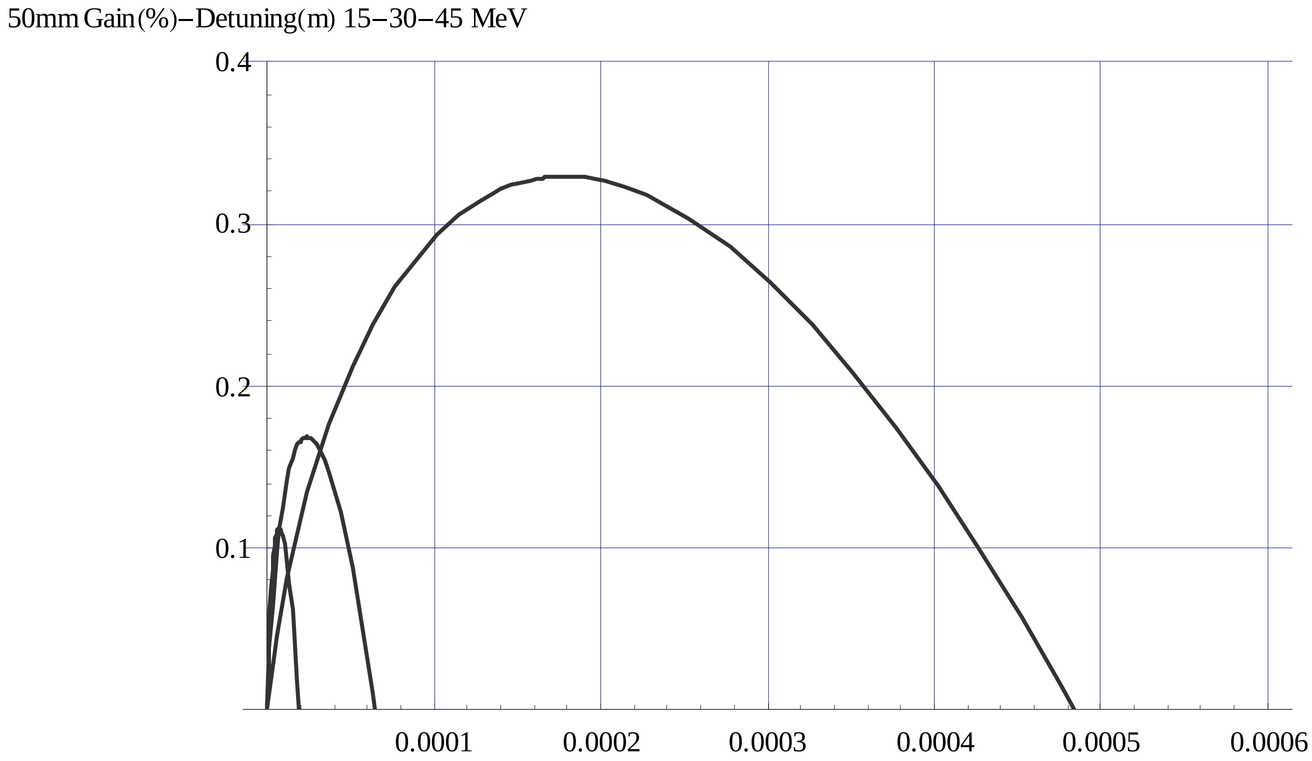
Cavity length detuning parameter

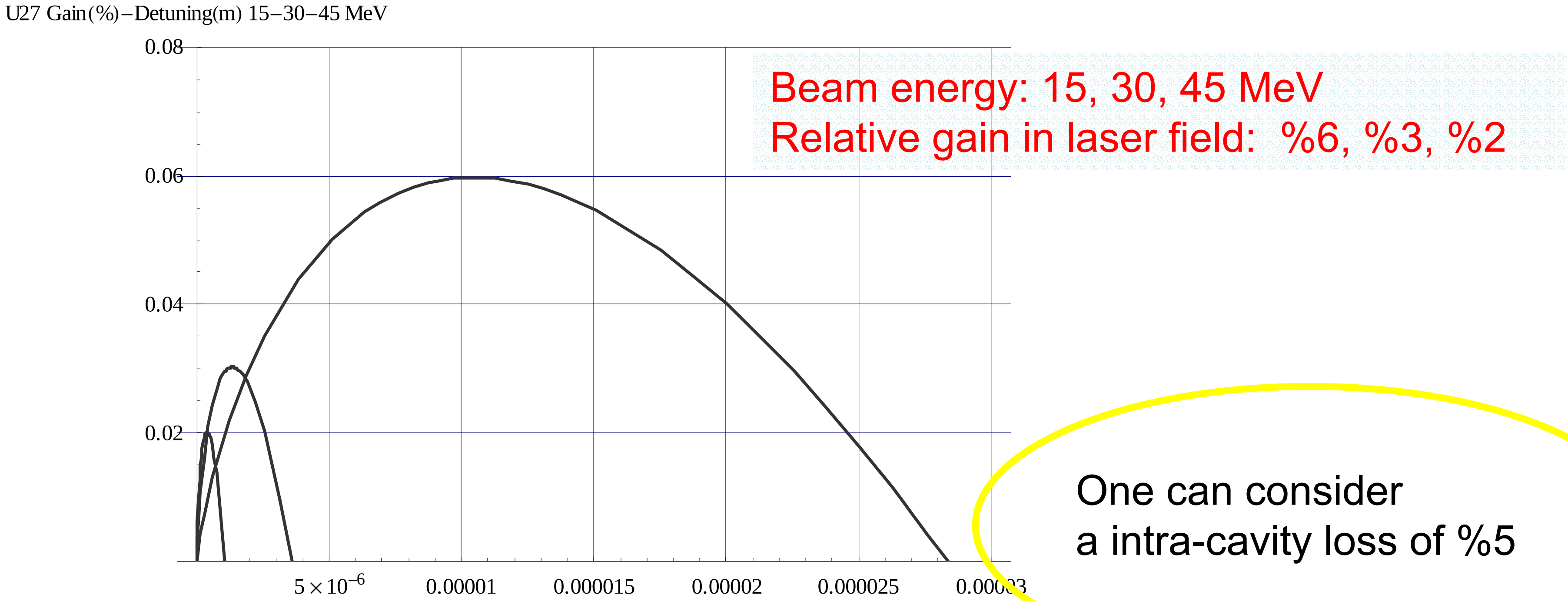
$$\gamma(\mu_c, \mu_\varepsilon) = (1 + \frac{1}{3}\mu_c)(1 + 1.7\mu_\varepsilon)$$

$$G = -\phi(g_0)\frac{\theta}{\theta_s}\left(\ln\left(\frac{\theta}{\theta_s}\gamma(\mu_c, \mu_\varepsilon)\right) - 1\right)$$

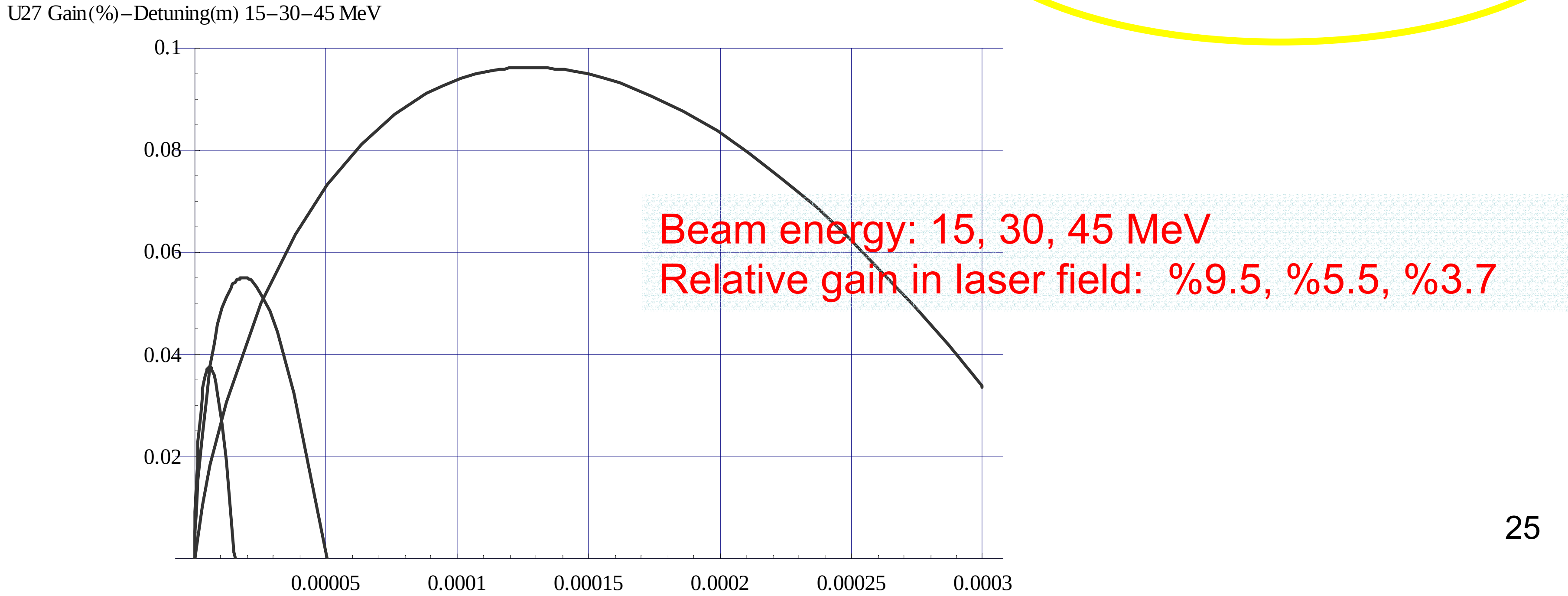
$$\phi(g_0) = 0.85 g_0 + 0.19 g_0^2$$

Beam energy: 15, 30, 45 MeV
Relative gain in laser field: %33, %17, %11



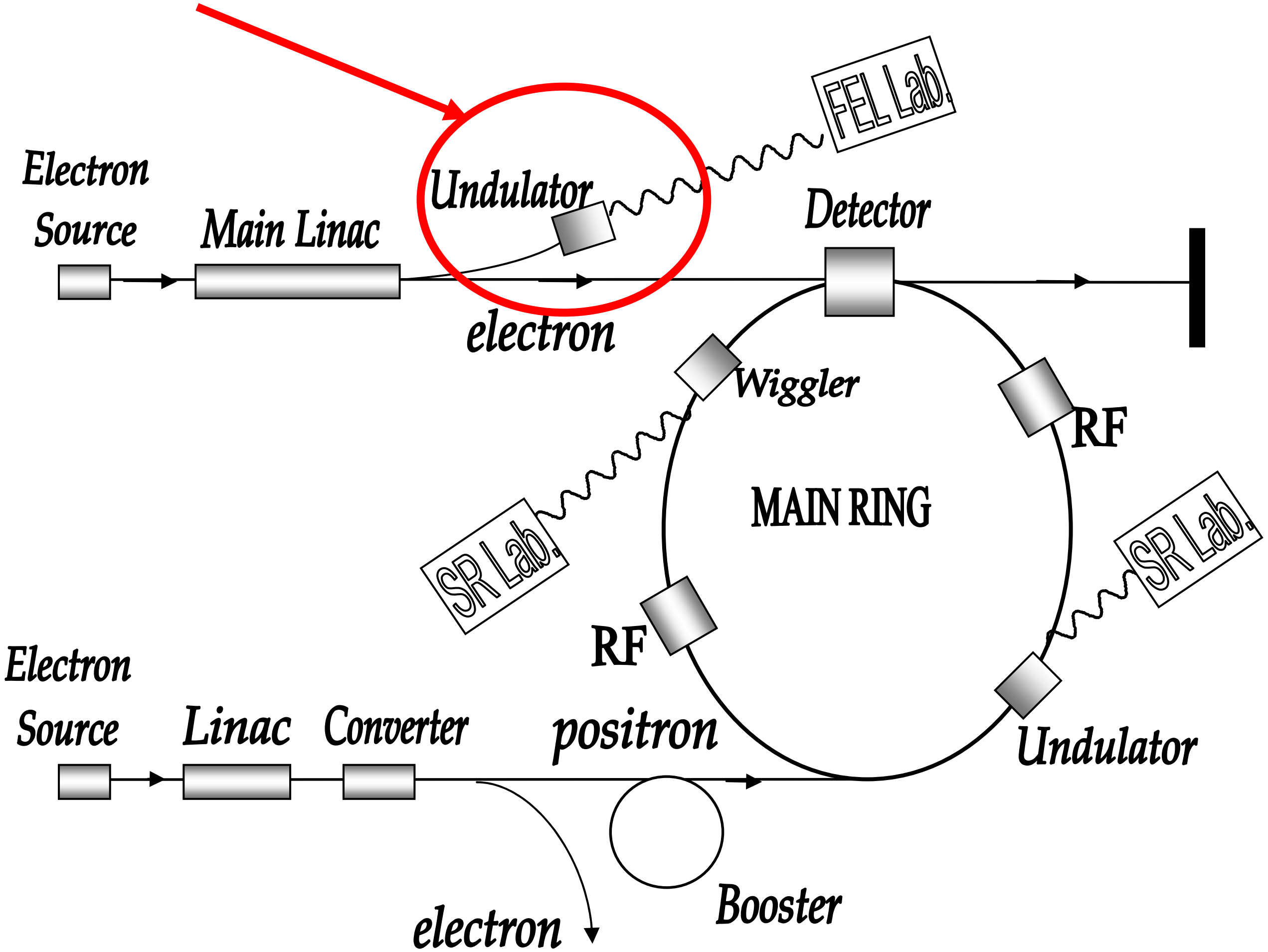


One can consider
a intra-cavity loss of %5



TAC SASE FEL

SASE FEL from electron beam with energy of 130 MeV



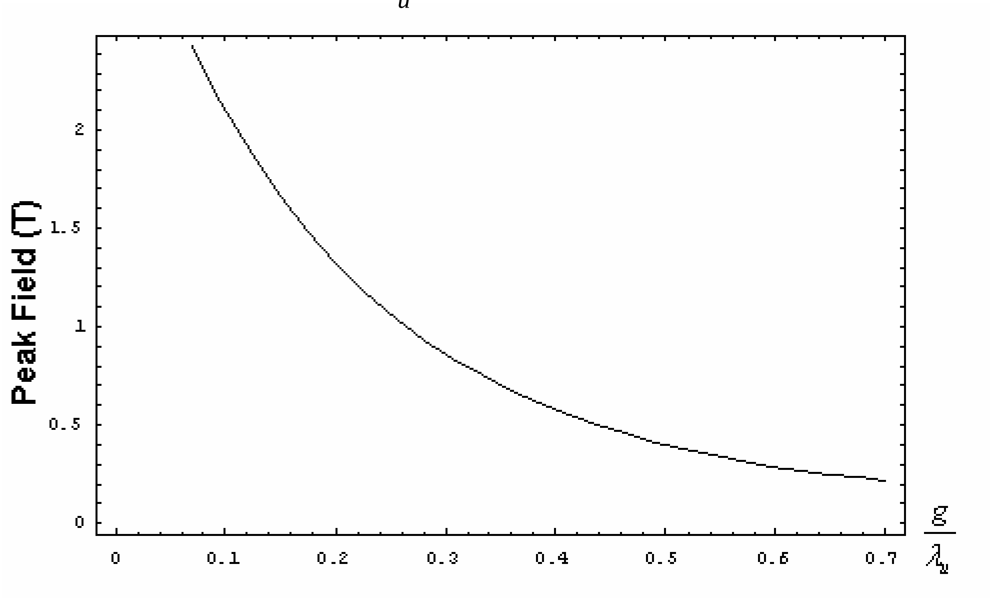
TAC SASE FEL

A NbFeB hybrid undulator has been considered for the SASE FEL.

$$B_{\max}(T) = a_3 \exp\left(-\left\{ \frac{g}{\lambda_u} \left(a_1 - a_2 \frac{g}{\lambda_u} \right) \right\} \right)$$

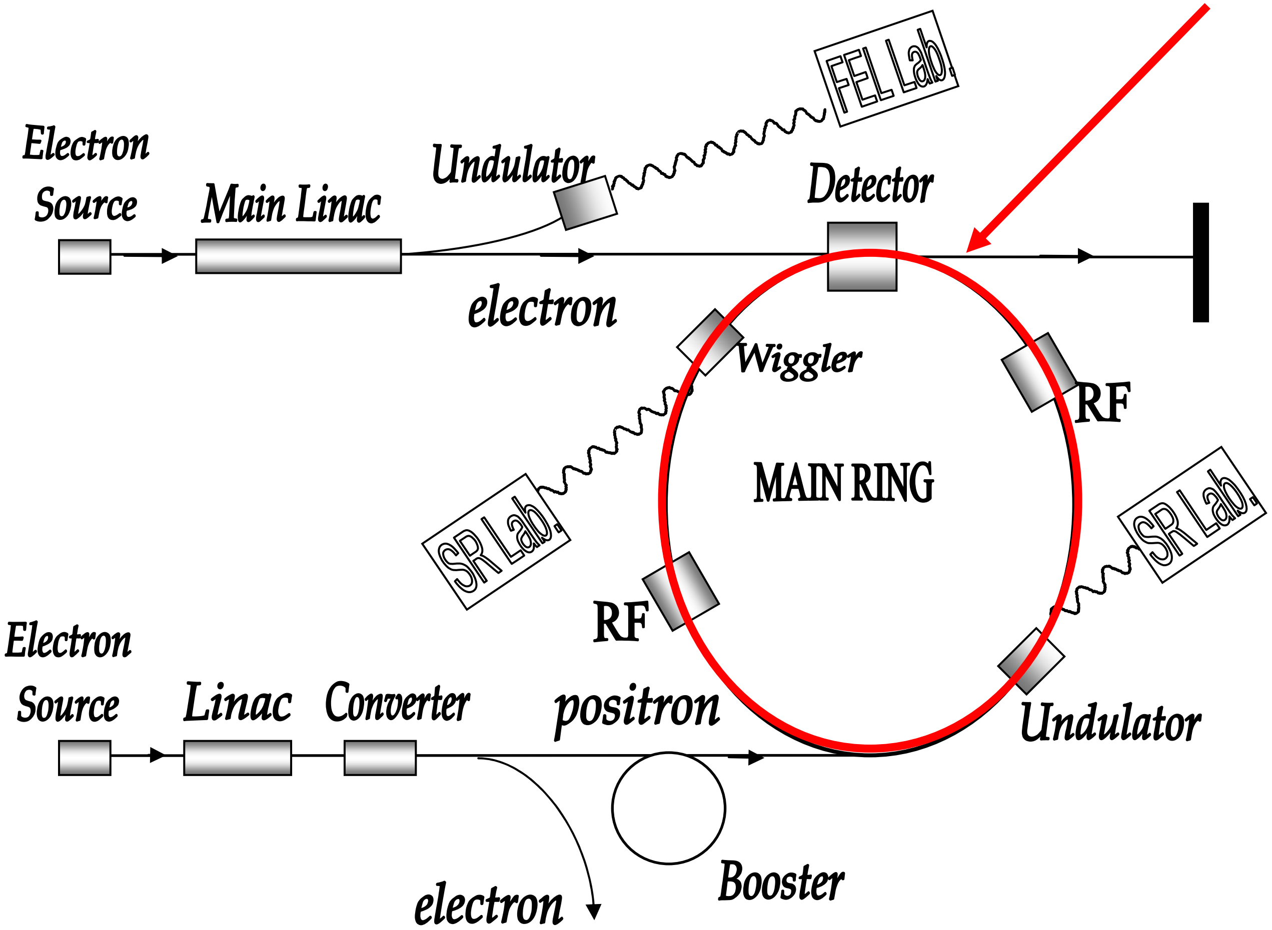
a1, a2 and a3 being the experimental costants and they have the values of 5.08, 1.54 and 3.44, respectively (Pflüger, 2000).

(between the limits of $0.07 < \frac{g}{\lambda_u} < 0.7$)



TAC Synchrotron Source

Synchrotron radiation from pozitron beam with energy of 3.56 GeV



TAC Synchrotron Source

- Indeed the ring has been proposed for a charm factory, and has a structure of DBA (double bending achromat) cell.
- The design includes 32 bending magnets, 96 focusing and defocusing quadrupoles.
- It is also proposed to have 12 magnet free regions in order to include undulator/wiggler magnets and rf cavities, 4.4 m each (Nergiz, 2004).
- Since 1 or 2 rf cavities will be used one can design at least 10 beamlines.

Energy (GeV)	3.56
Circumference (m)	264
Beam Current (mA)	216
Energy loss per turn (keV)	1163.2
Number of harmonics	442
Rf frequency (MHz)	500.25
Energy spread (%)	0.09
Emittance (nm rad)	20

(Nergiz, Z. 2004)

Some Parameters of the Magnets

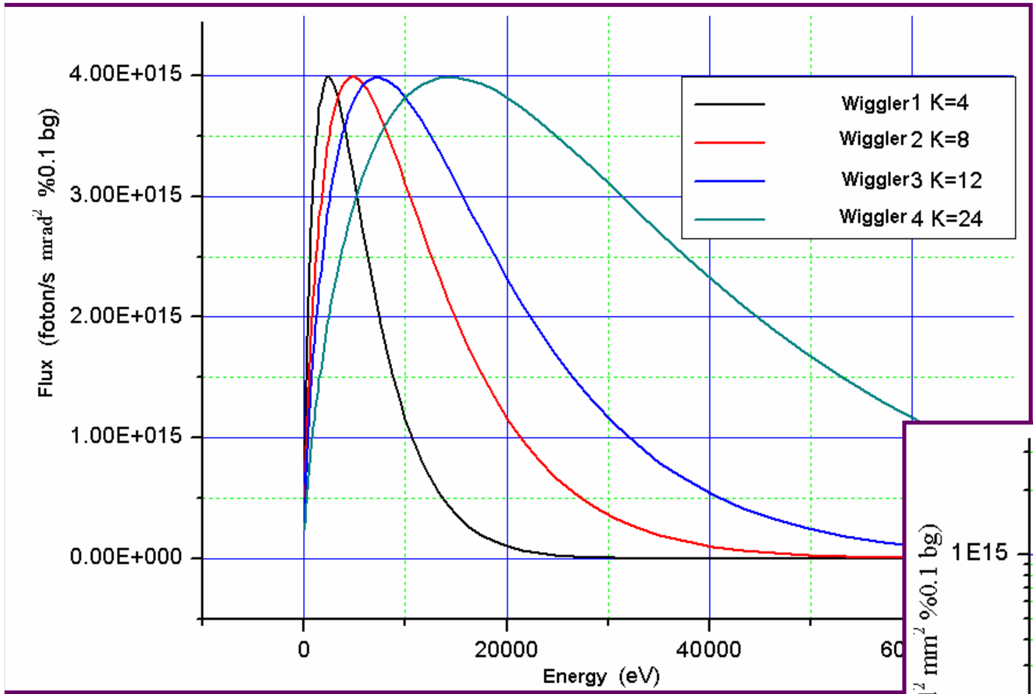
Radiation Source	Wiggler 1	Undulator 1	Undulator 2
Period Length (m)	0.10	0.08	0.04
Number of Periods	35	43	100
Magnetic field (T)	0.85	0.16	0.32
Strength Parameter, K	8	1.2	1.2
Undulator Gap (mm)	31	90	94

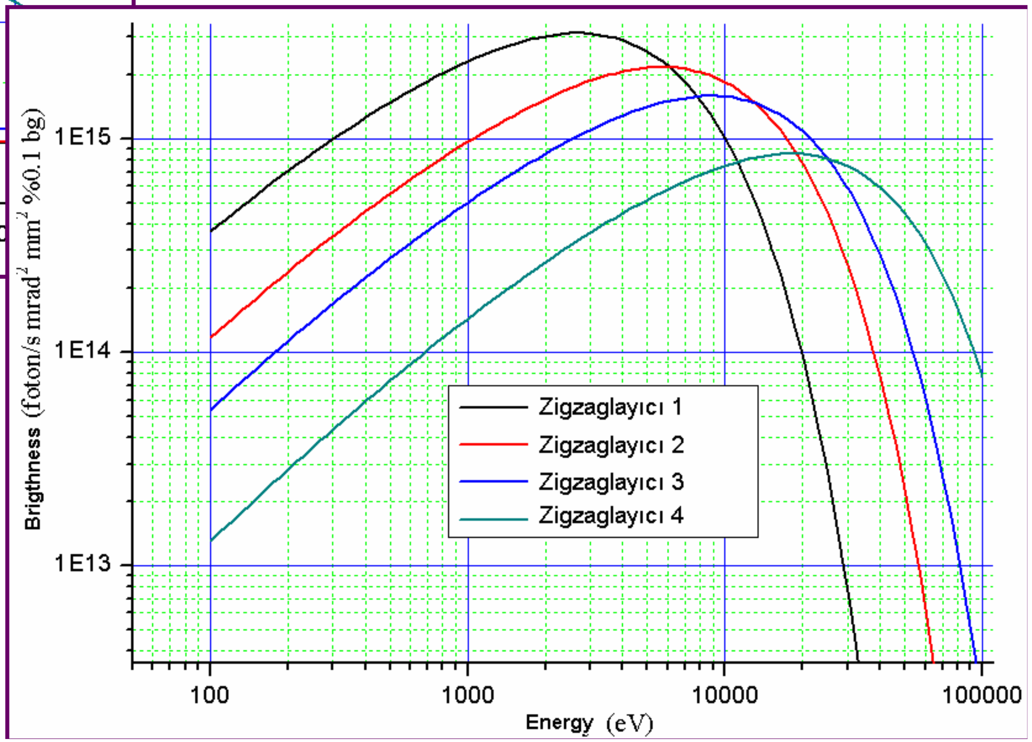
There are 4 types of wiggler magnets that are not shown here
with K values of 4, 8,12, 24 and all having the period length of 10 cm.

Parameters	Und. 1	Und. 2	Wig. 1	Wig. 2	Wig. 3	Wig. 4
K	1.2	1.2	4	8	12	24
Wavelength (nm)	1.42	0.71	9.3	34	75	300

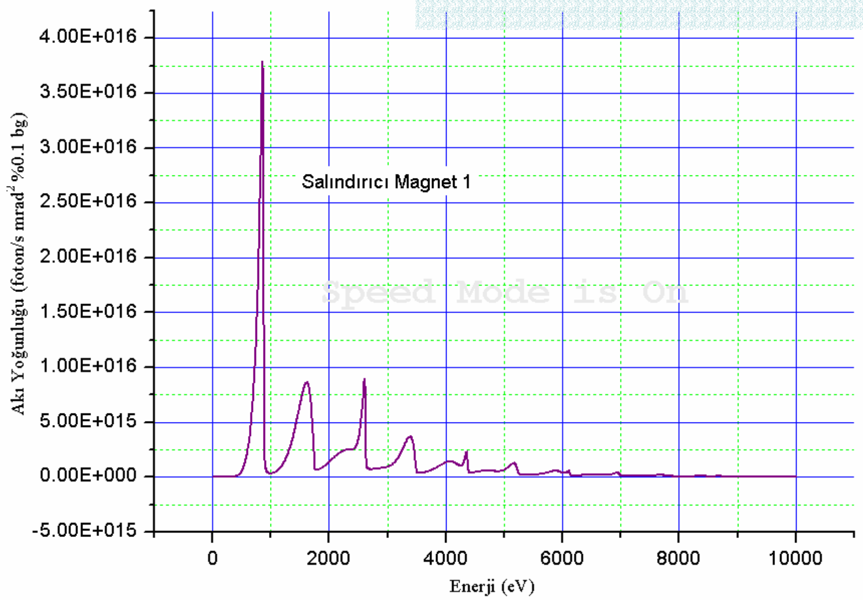
TAC Synchrotron Source

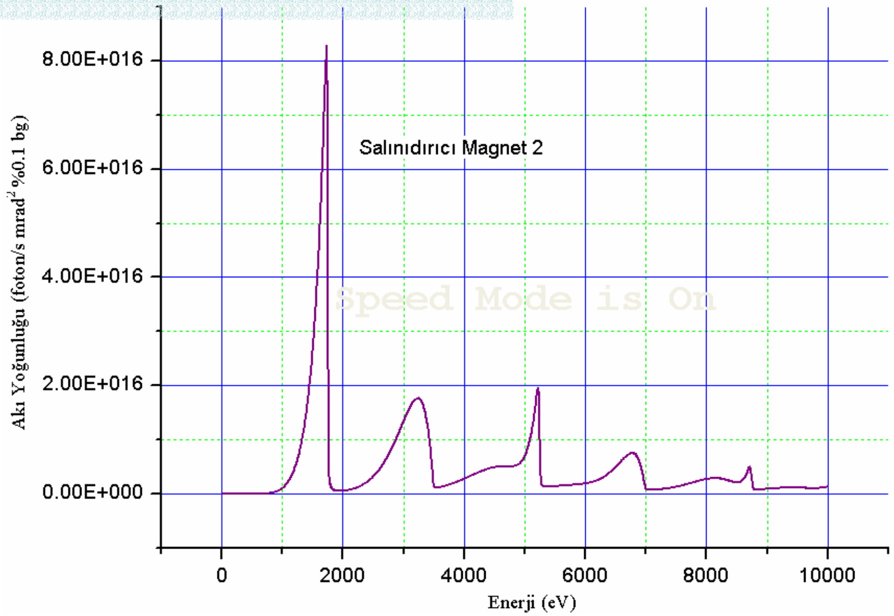
Some result of SPECTRA code.



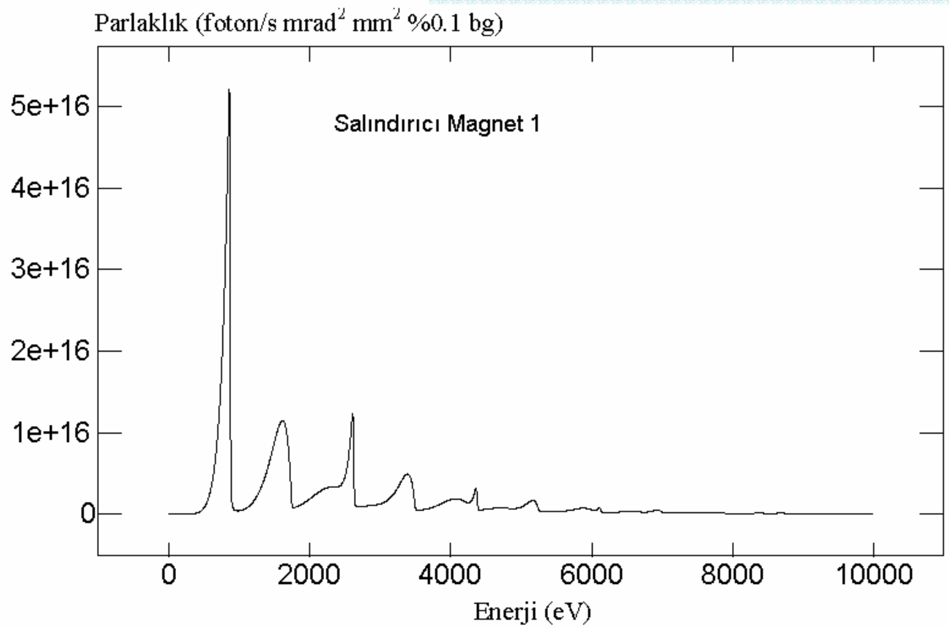


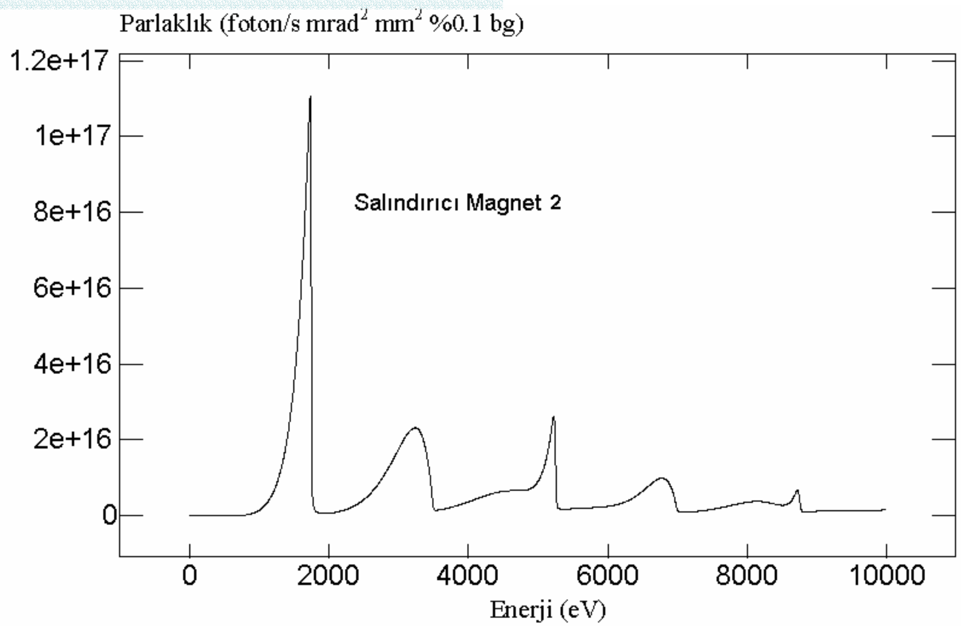
Flux



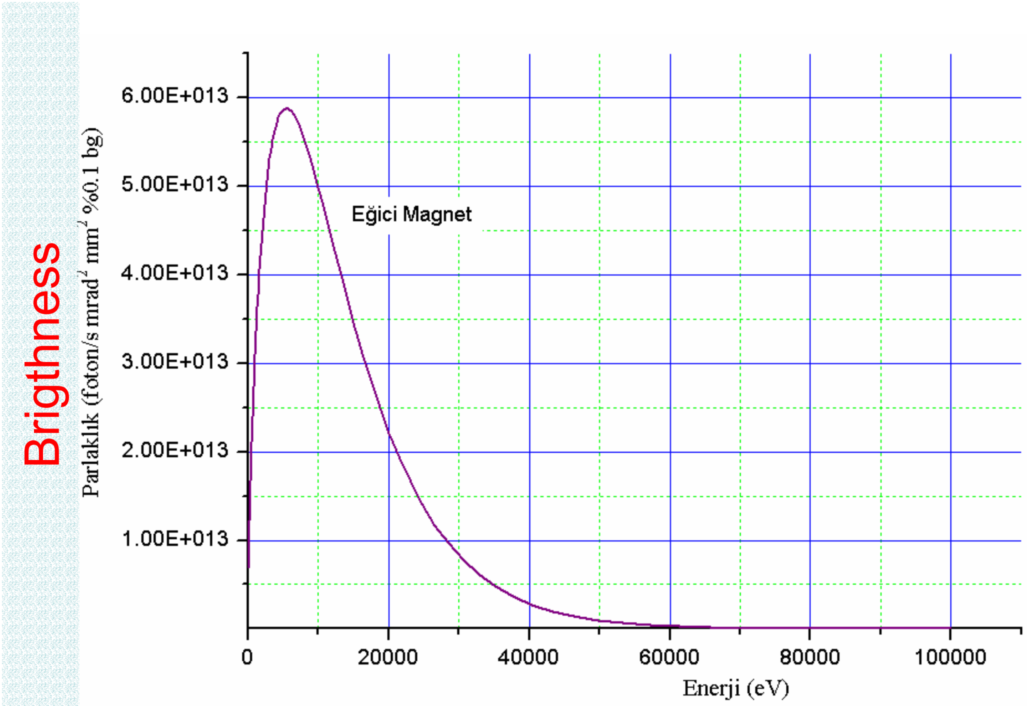


Brigthness





- The bending magnets used in the ring has a radius of 12.22 m and a magnetic field of 0.972 T .



Results and Discussion

- Three different undulators have been considered in order to propose as possible choices to use in the further design studies of IR FEL facility that will be built in Ankara.
- The possible use of obtained laser beam will be in basic and applied research areas such as biotechnology, nanotechnology, semiconductors and photo chemistry.
- The desired wavelenght range is 1-100 microns with the electron beam energy range of 15-45 MeV. (60 MeV depending on modules)
- A SASE FEL and a synchrotron source from an existing ring design were proposed as the alternative radiation sources for the project.

Further Questions on the IR FEL facility

- Using cold technology for RF gun or / and accelerator modules,
- The dimensions of the facility building including needs for radiation safety,
- Structure of beamlines and experimental stations.

Acknowledgment

Many thanks to Dr. Ulf Lehnert
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...Thank You...

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