SYNCHROTRON RADIATION SOURCES

PAST, PRESENT AND FUTURE

OUTLINE

History

Maxwell Formulation

Spontaneous Emission
    Dipole - Circular orbit
    Undulator - Undulated orbit

Beam-Radiation Interaction
    Low Gain - FEL
    High Gain - SASE

Future Directions

HISTORY

1873 Maxwell Formulation

1887 Hertz radiation experiment

1898 Lienard-Wiechert, Retarded potential

1900 Lienard, Derived the Synchrotron Radiation

1946 Blewett, Shrinkage of Synchrotron orbit
(1947) Observation on GE 70 MeV Synchrotron

1949 Schwinger, Complete evaluation of radiation from circular orbit

1951 Motz, Undulator proposed

1968 1st storage ring for research (240 MeV TANTALUS)

1980 Halbach, Permanent magnet undulator

1985 Mushrooming of Undulator storage-ring sources

Coherent Emission

1982 High Gain: SASE

1995-2000 Prove of principle

2008 LCLS
(1.5Å, 350 MW)

1971 Low Gain: FEL (Madey)

2006 JLAB IR+UV FEL

MAXWELL FORMULATION

Liénard-Wiechert potentials for point charge

$$\begin{cases} \vec{A} = \left(\dfrac{1}{\kappa}\dfrac{e\vec{\beta}}{R}\right)_{ret} \\[2ex] \phi = \left(\dfrac{1}{\kappa}\dfrac{e}{R}\right)_{ret} \end{cases}$$

$\vec{R} = R\hat{n}$ = vector from e to field point

$\kappa = (1-\vec{\beta}\cdot\hat{n})$ = direction factor

ret = retarded time $t_r = t - \frac{R}{c}$

Field vectors

$$\begin{cases} \vec{B} = \hat{n}\times\vec{E} \\[2ex] \vec{E} = e\underset{\substack{\uparrow \\ \text{Coulomb term} \\ \left(\substack{\text{velocity} \\ \text{longitudinal} \\ \text{near}}\right)}}{\left(\dfrac{\hat{n}-\vec{\beta}}{\gamma^2\kappa^3R^2}\right)_{ret}} + \dfrac{e}{c}\underset{\substack{\uparrow \\ \text{Radiation term} \\ \left(\substack{\text{acceleration} \\ \text{transverse} \\ \text{far} \to \infty}\right)}}{\left(\dfrac{\hat{n}\times\left[(\hat{n}-\vec{\beta})\times\dot{\vec{\beta}}\right]}{\kappa^3R}\right)_{ret}} \end{cases}$$

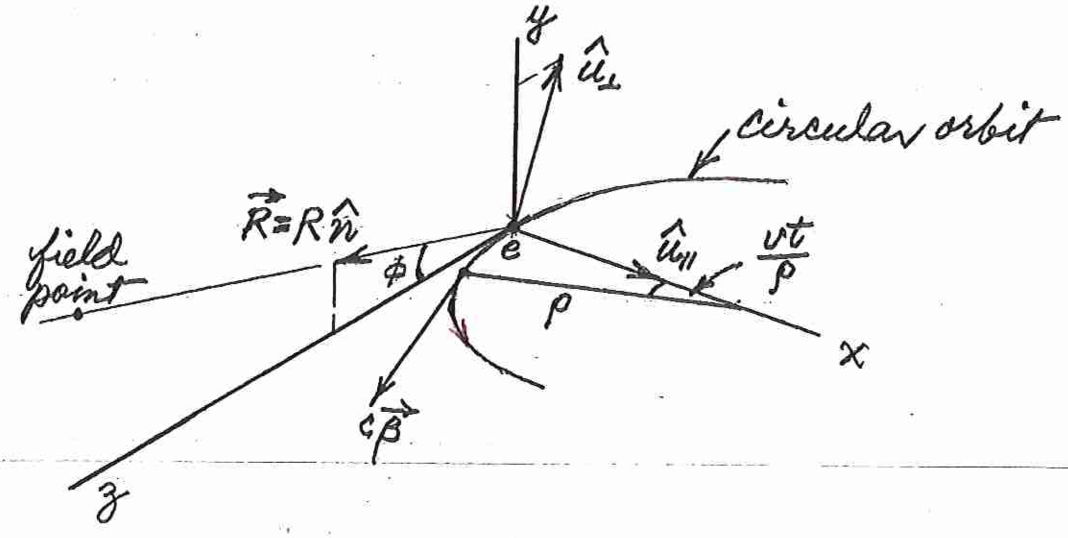
Total power radiated (Spontaneous emission)

$$P = \frac{2}{3}\frac{e^2}{c}\left|\dot{\vec{\beta}}\right|^2 = \frac{2}{3}\frac{e^2}{c}\gamma^2\left(\dot{\vec{\beta}}_{\parallel}^{\,2} + \gamma^2\dot{\vec{\beta}}_{\perp}^{\,2}\right)$$

$\dot{\vec{\beta}}_{\perp}$ more effective

$\propto \gamma^4$ small m (electron) more effective

SPONTANEOUS EMISSION: CIRCULAR ORBIT



$$\frac{d^2U}{d\omega\, d\Omega}(\omega,\phi) = \frac{3e^2\gamma^2}{4\pi^2 c}\left(\frac{\omega}{\omega_c}\right)^2(1+\gamma^2\phi^2)^2\left[K_{\frac{2}{3}}^2(\xi) + \frac{\gamma^2\phi^2}{1+\gamma^2\phi^2}K_{\frac{1}{3}}^2(\xi)\right]$$

$$\begin{cases} \phi \text{ scales as } \frac{1}{\gamma} \\ \omega \text{ scales as } \omega_c \equiv \frac{3}{2}\frac{c}{\rho}\gamma^3 = \text{critical frequency} \\ \xi = \frac{1}{2}\frac{\omega}{\omega_c}(1+\gamma^2\phi^2)^{\frac{3}{2}} \end{cases}$$

$$\frac{dU}{d\omega} = \frac{8\pi}{9}\frac{e^2}{c}\gamma S\left(\frac{\omega}{\omega_c}\right)$$

$$U = \frac{8\pi}{9}\frac{e^2}{c}\gamma$$

Define Brightness (Brilliance)

$$B = \frac{\text{photon flux}}{\frac{\delta\omega}{\omega}\,\delta a\,\delta\Omega} = \frac{\text{photon flux}}{\frac{\delta\omega}{\omega}\,\delta\epsilon_x\,\delta\epsilon_y} \qquad \left[\text{units } \frac{\text{Photons/s}}{10^{-3}(\mu m r)^2}\right]$$

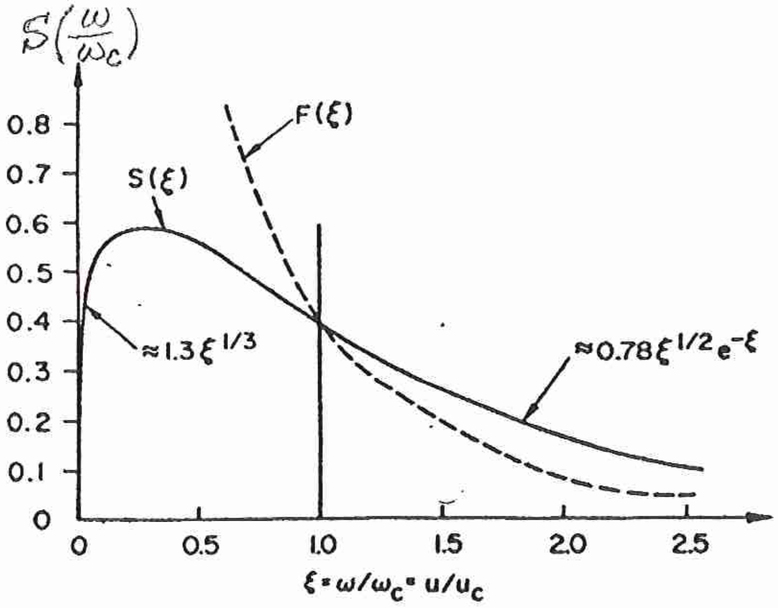


FIG. 42--Normalized power spectrum S and photon number spectrum F of synchrotron radiation.

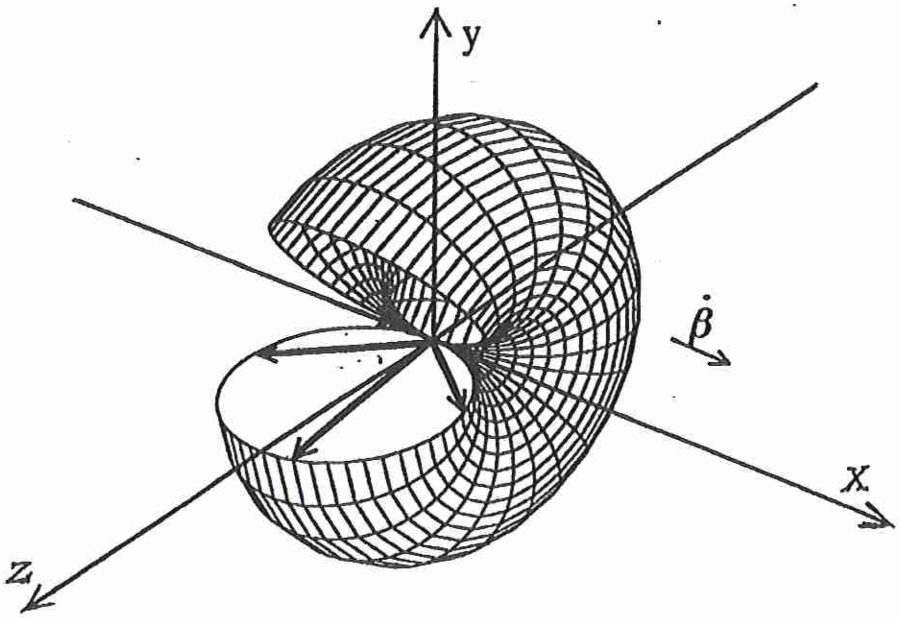


Fig. 7.2. Radiation pattern in the particle frame of reference or for nonrelativistic particle in the laboratory system

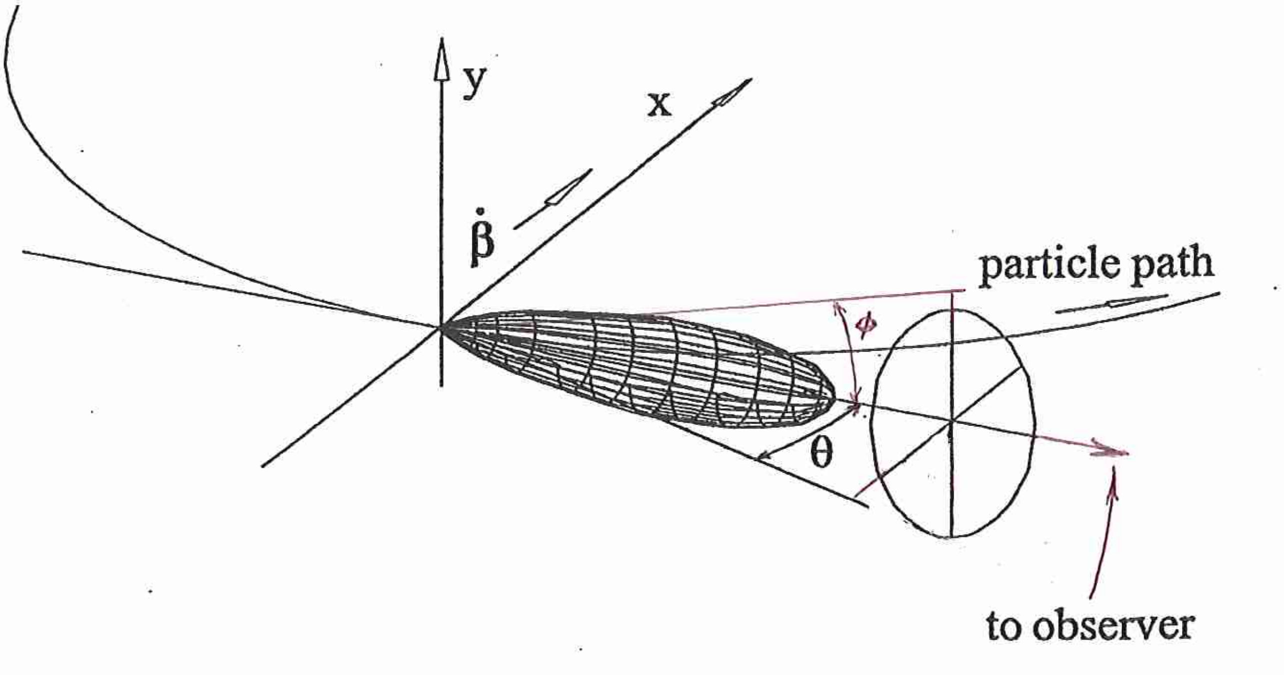


Fig. 7.3. Radiation geometry in the laboratory frame of reference for highly relativistic particles

SPONTANEOUS EMISSION: UNDULATED ORBIT

Kinematics

$$\theta_{max} = \frac{eB_u ƛ_u}{mc\gamma} \equiv \frac{K}{\gamma} \qquad K \equiv \frac{eB_u ƛ_u}{mc} = \text{Deflection Parameter}$$

$$= (93.37\ T^{-1} m^{-1}) B_u \lambda_u$$

$$\left(\text{rms radiation angle} = \frac{1}{\gamma}\right)$$

For undulator $\theta_{max} < \frac{1}{\gamma}$ or $K < 1$ $(< 3 \text{ OK})$

Radiation Wavelength

$$\lambda = \lambda_u \underbrace{(1-\beta)}_{\substack{\text{Doppler}\\ \text{shift}}} \underbrace{\left(1+\frac{K^2}{2}\right)}_{\substack{\text{Undulations}\\ \text{about } z\text{-axis}}} \cong \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \quad \text{and harmonics}$$

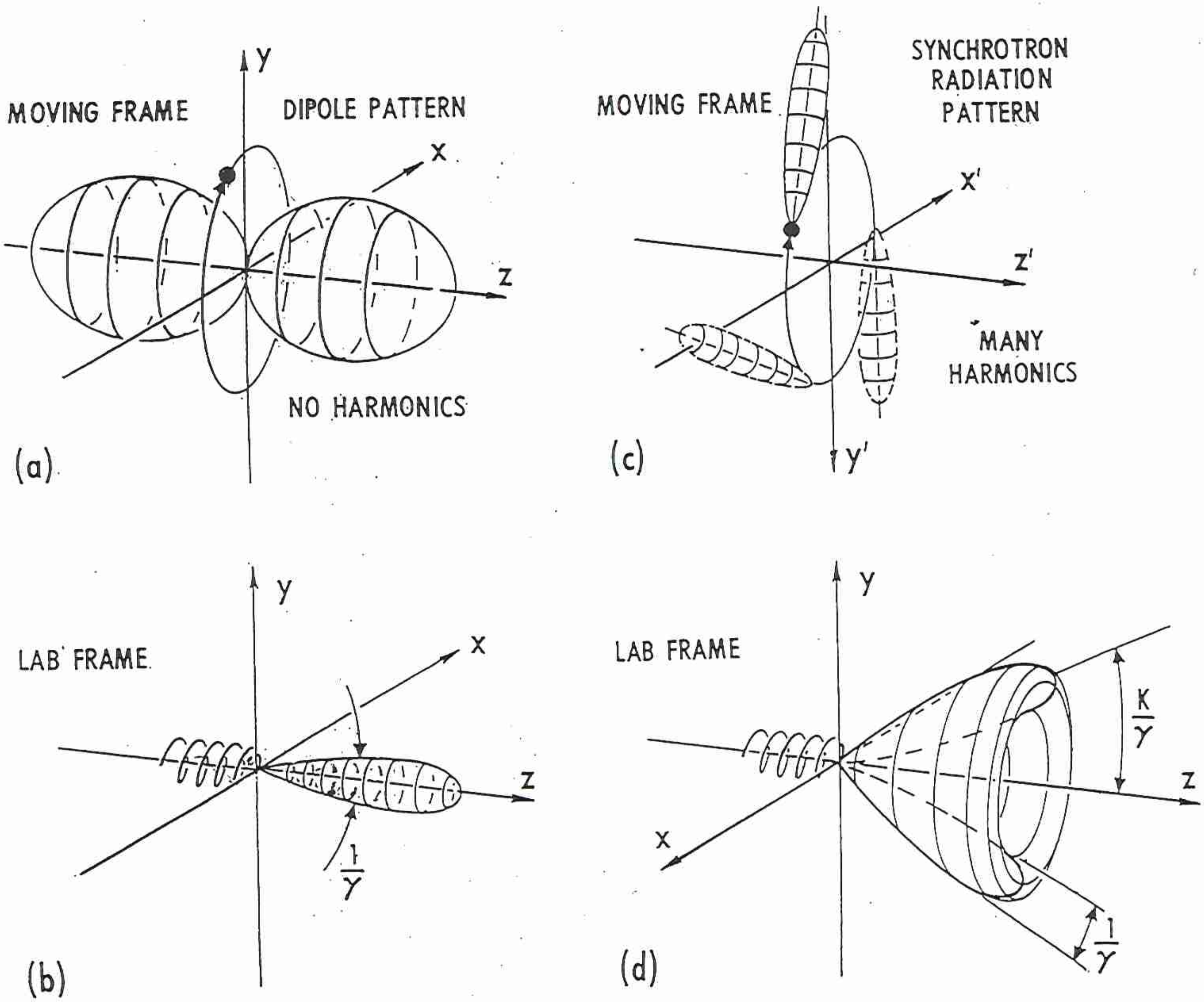
For permanent magnet (Nd-Fe-B) APS undulator A

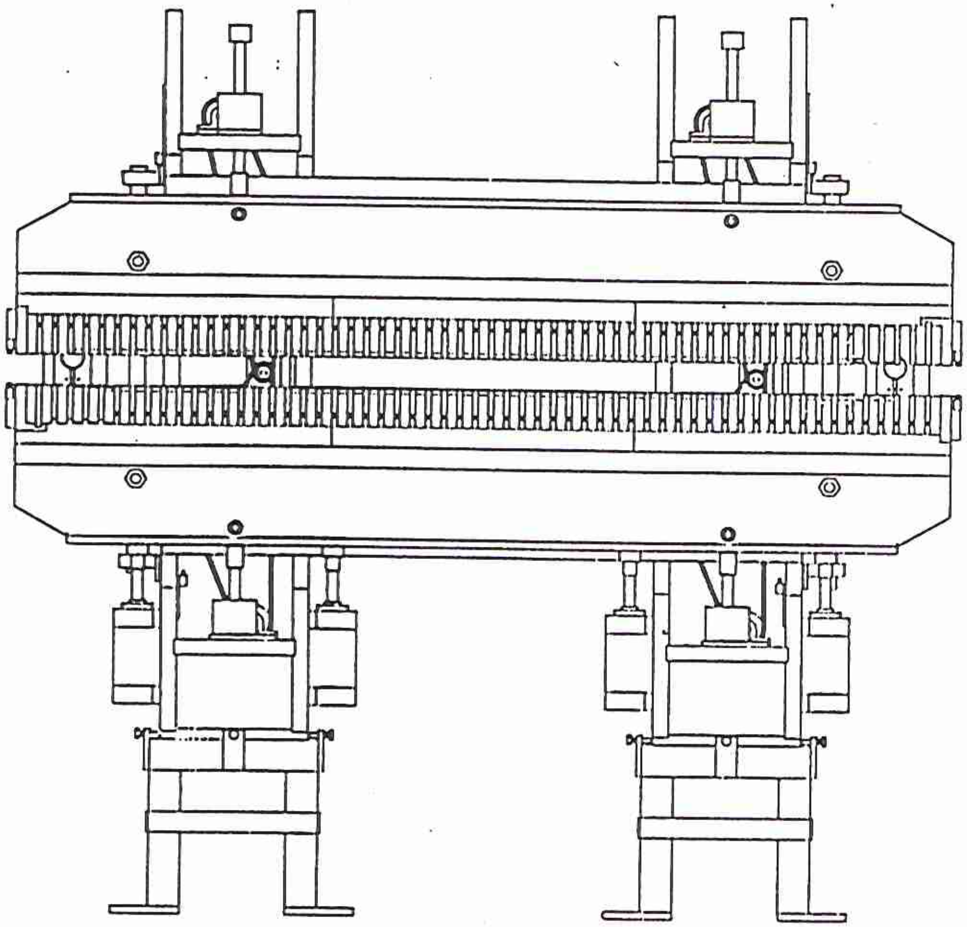
$\lambda_u = 0.033$ m, $K = 2.6$

$E_e = 7.0$ GeV $(\gamma = 13700)$

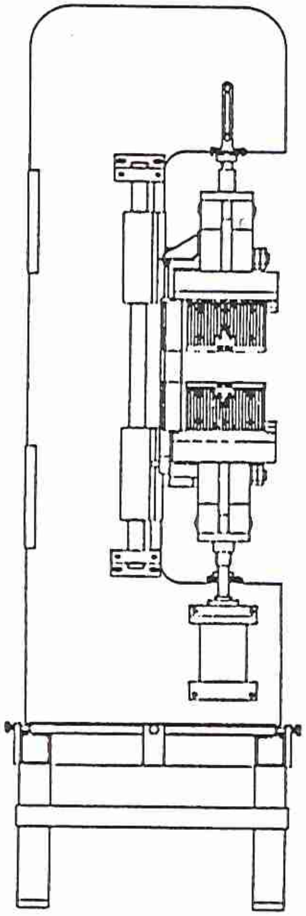
we get

$\lambda = 3.85$ Å and harmonics

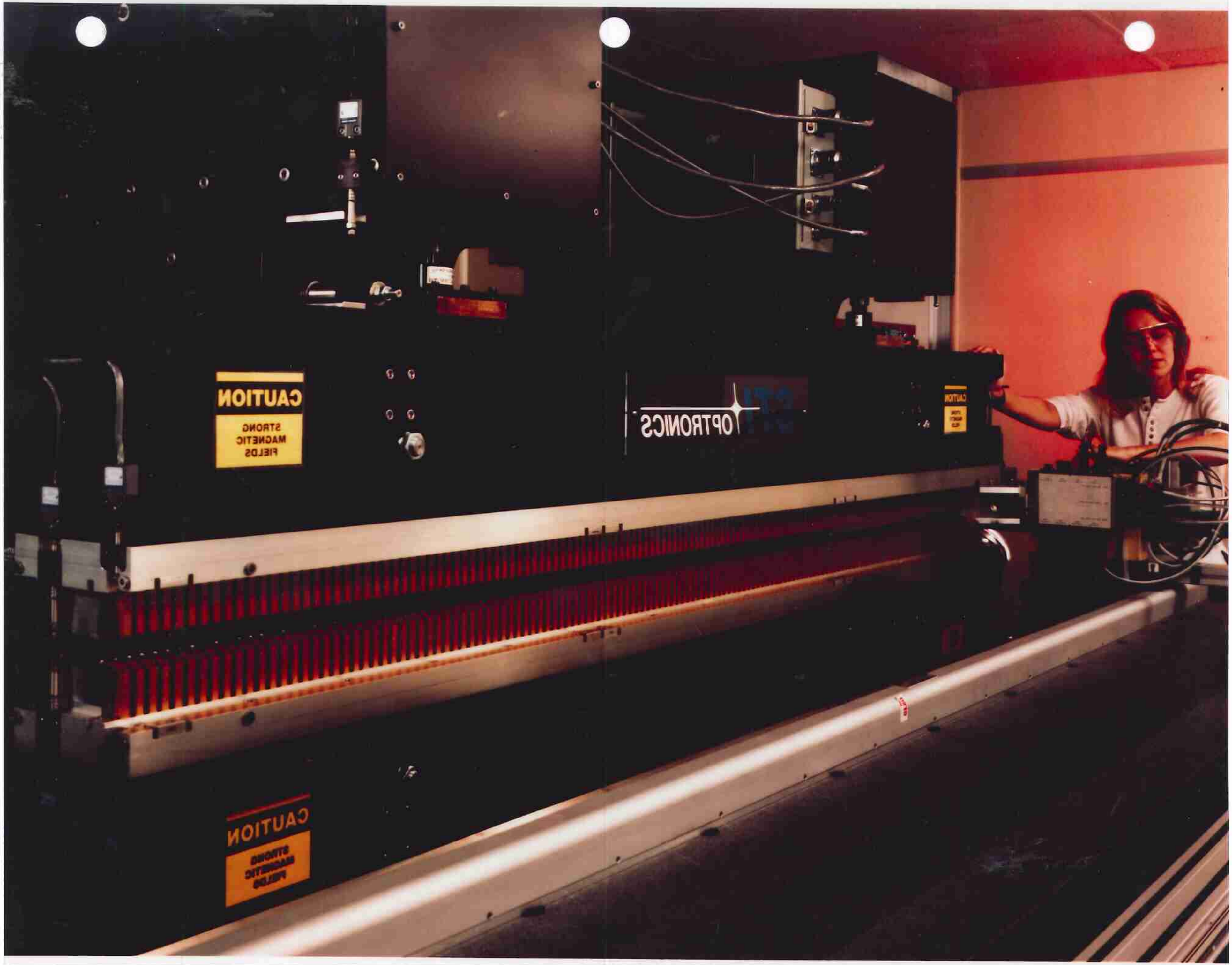

MOVING FRAME
DIPOLE PATTERN
y
x
z
NO HARMONICS
(a)
MOVING FRAME
SYNCHROTRON RADIATION PATTERN
x'
z'
y'
MANY HARMONICS
(c)
LAB FRAME
y
x
z
$\frac{1}{\gamma}$
(b)
LAB FRAME
y
x
z
$\frac{K}{\gamma}$
$\frac{1}{\gamma}$
(d)



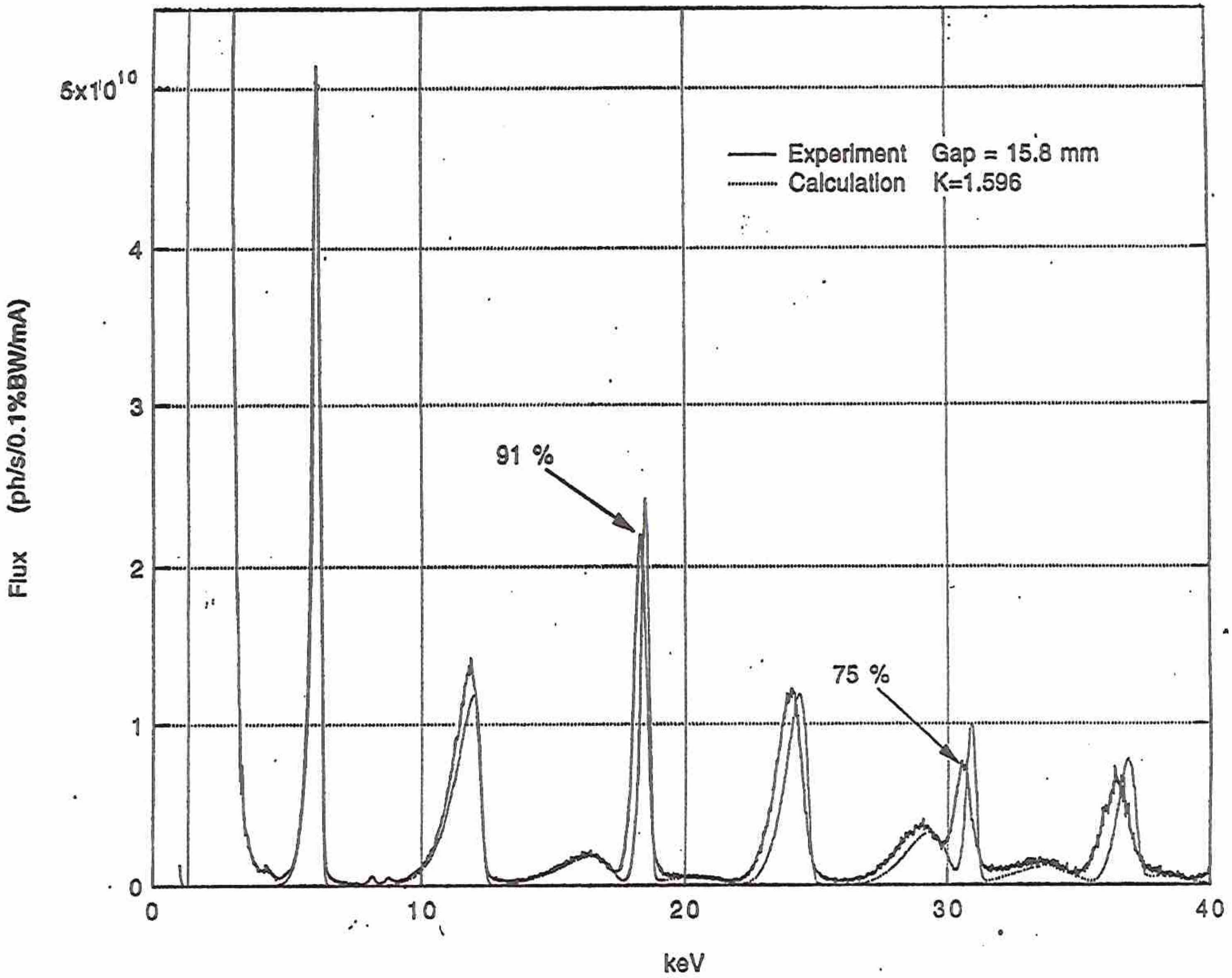
SIDE



END


CAUTION
STRONG MAGNETIC FIELDS
STI OPTRONICS
CAUTION
STRONG MAGNETIC FIELDS


CAUTION
CAUTION
CAUTION
CAUTION
CAUTION


5x10^10
4
3
2
1
0
Flux (ph/s/0.1%BW/mA)
0
10
20
30
40
keV
Experiment Gap = 15.8 mm
Calculation K=1.596
91 %
75 %

Spectral and Angular Distribution

(P.F. Alferov, Yu A. Bashmakov & E.G. Bessonov
Sov. Phys - Tech Phys. 18, 1336, 1974)

$$\frac{d^2U}{d\omega\, d\Omega}(\omega; \theta, \phi) = \frac{4e^2}{c} h^2 N_u^2 \bar{\gamma}^2 \left(g_x^2 + g_y^2\right) W(\nu)$$

where

$$g_x = \left[L_\nu(p,q) - \frac{\sin \pi\nu}{\pi\nu}\right]\bar{\gamma}\sin\theta\cos\phi + Q\left[L_{\nu+1}(p,q) + L_{\nu-1}(p,q)\right]$$

$$g_y = \left[L_\nu(p,q) - \frac{\sin \pi\nu}{\pi\nu}\right]\bar{\gamma}\sin\theta\sin\phi$$

$$L_\nu(p,q) = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\alpha\, e^{i\nu\alpha} e^{i(p\sin\alpha + q\sin 2\alpha)}$$

$$W(\nu) = \left(\frac{\sin \pi N_u \nu}{N_u \sin \pi\nu}\right)^2$$

$$\nu = \frac{\omega}{\omega_1}\left(1 + \bar{\gamma}^2\theta^2\right) \qquad \omega_1 = \omega_u \frac{2\gamma^2}{1 + K^2/2}$$

$$p = \frac{\omega}{\bar{\omega}}\frac{K}{\gamma}\sin\theta\cos\phi \qquad Q^2 = \frac{K^2/4}{1 + K^2/2}$$

$$q = \frac{\omega}{\bar{\omega}}\frac{1}{8\bar{\beta}}\frac{K^2}{\gamma^2}\cos\theta \qquad \omega = h\omega_1 + \delta\omega = \omega_h + \delta\omega$$

$$\bar{\beta} = (\beta_z)_{rms} = 1 - \frac{1 + K^2/2}{2\gamma^2} \qquad \bar{\omega} = \frac{\bar{\beta}}{2\bar{\gamma}^2}\omega_1$$

$$\bar{\gamma} = \frac{1}{\sqrt{1 - \bar{\beta}^2}} = \frac{\gamma}{\sqrt{1 + K^2/2}}$$

Radiation Energy

Each harmonic h

$$U_h = \frac{4\pi e^2}{c} N_u Q^2 \hbar\omega_1 [J,J]_h^2 \qquad Q \equiv \frac{K^2/4}{1+K^2/2}$$

$$[J,J]_h \equiv J_{\frac{h-1}{2}}(hQ^2) - J_{\frac{h+1}{2}}(hQ^2)$$

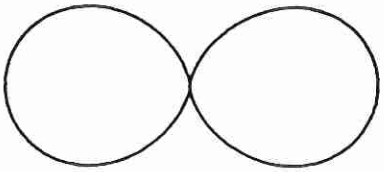
Total

$$U = \sum_h U_h = \frac{4\pi^2}{3} e^2 \gamma^2 \frac{N_u K^2}{\lambda_u} = \left(7.26\times 10^{11} \frac{m}{GeV}\right) E_e^2 \frac{N_u K^2}{\lambda_u}$$

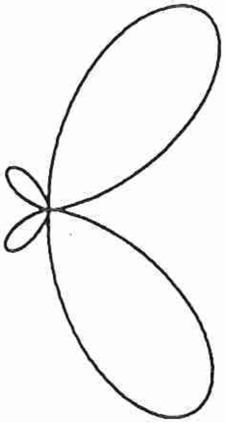
Example: APS-UA variable gap g_u

g_u (mm)	15.8	10.5	8.0
K	1.6	2.6	3.1
$\lambda(\text{Å})_{7GeV}$	2.0	3.9	5.1
U (keV)	19.9	52.5	74.6

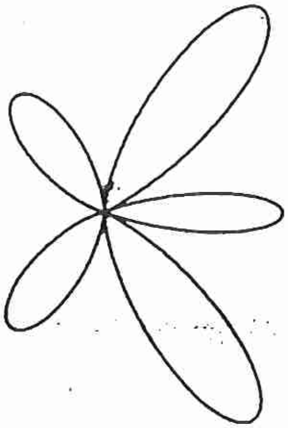
Moving Frame Radiation Patterns



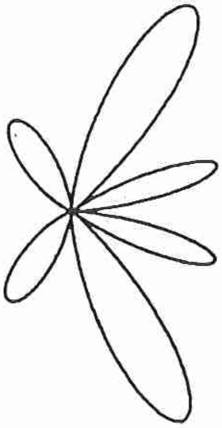
Fundamental



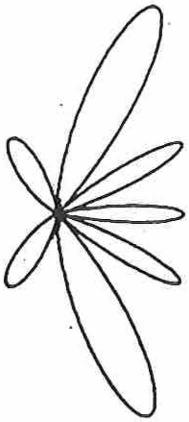
Second harmonic



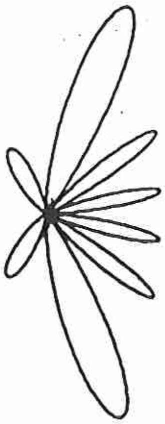
Third harmonic



Fourth harmonic



fifth harmonic



Sixth harmonic

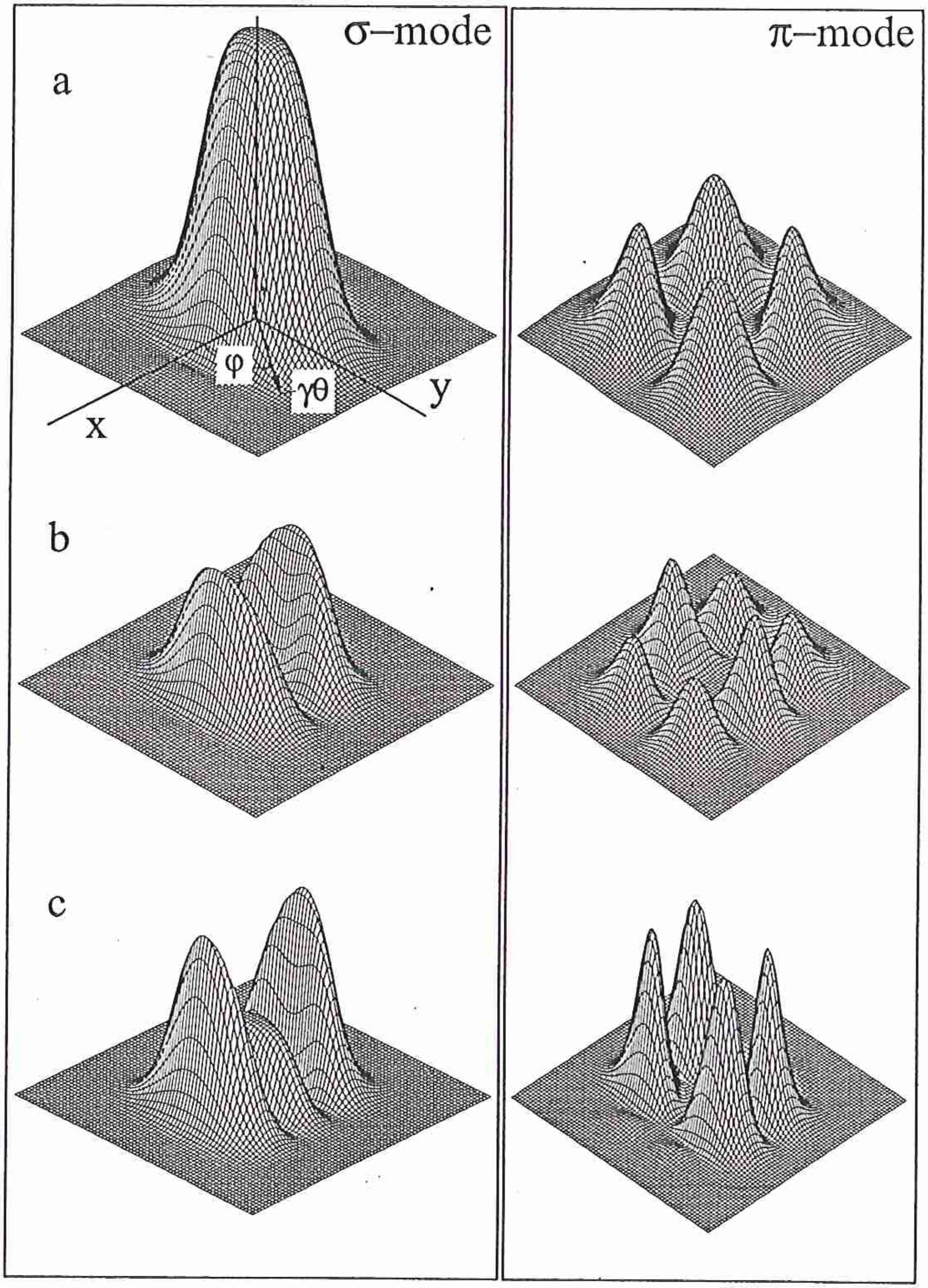
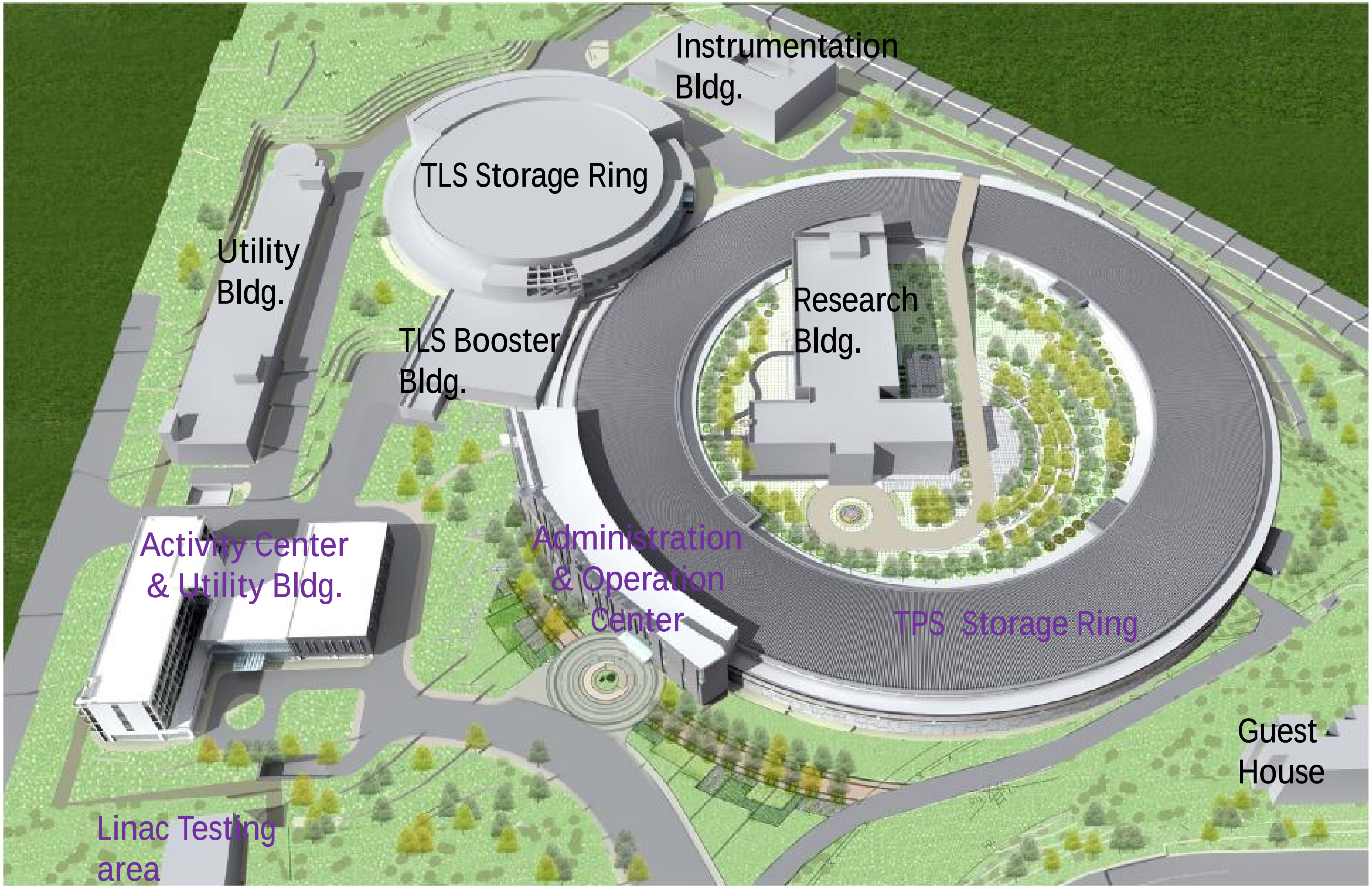


Fig. 11.5. Radiation distribution for the first three harmonics $k = 1, 2, 3$. Distributions on the left are for σ-mode polarization and those on the right for π-mode polarization

NSRRC Top Overview after TPS



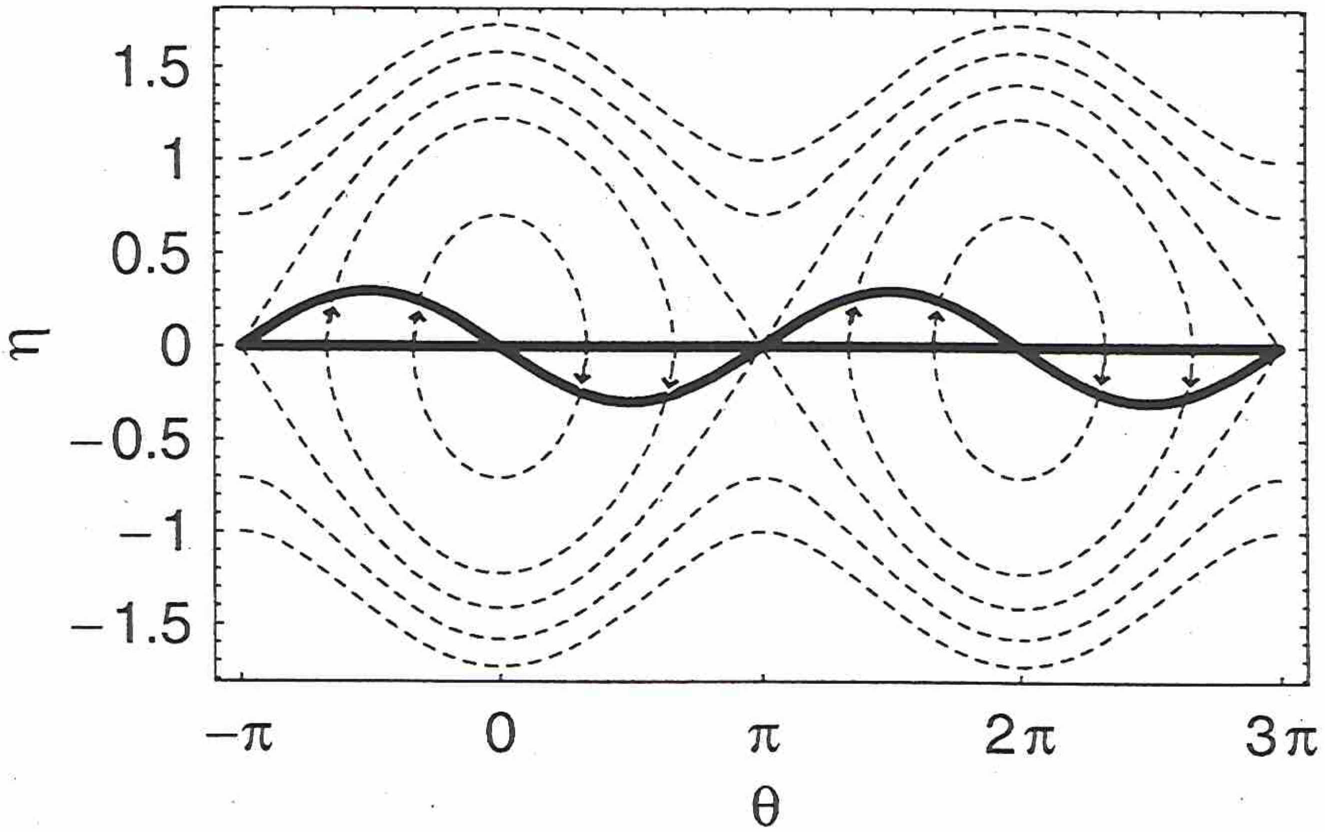
Beam-Radiation Interaction: Low Gain (FEL)

The spontaneously emitted radiation from circular or undulated orbit is incoherent. To get coherent emission we need beam-radiation interaction as in a Laser

The motion of the electrons acted on by the (coherent) external radiation field is that of a circular pendulum and is shown by the next phase diagram. At Low Gain:

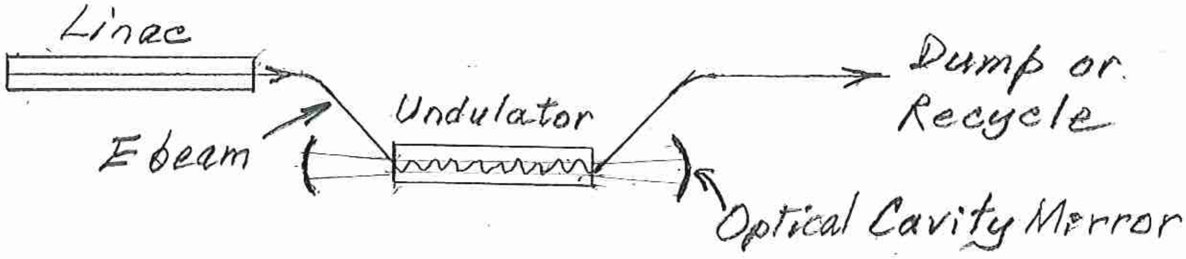
- If the beam has exactly the "resonant" energy ($\eta = 0$) to satisfy $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$ the net energy gain from the radiation is zero.
- If the beam is at a higher energy than resonant ($\eta > 0$) it emits energy to amplify the radiation coherently.
- At slightly lower energy than "resonant" the beam absorbs energy from the radiation and gets accelerated (rf accelerating cavity in accelerator)

The undulated ebeam acts exactly like a lasing material.



1.5
1
0.5
0
−0.5
−1
−1.5
η
−π
0
π
2π
3π
θ

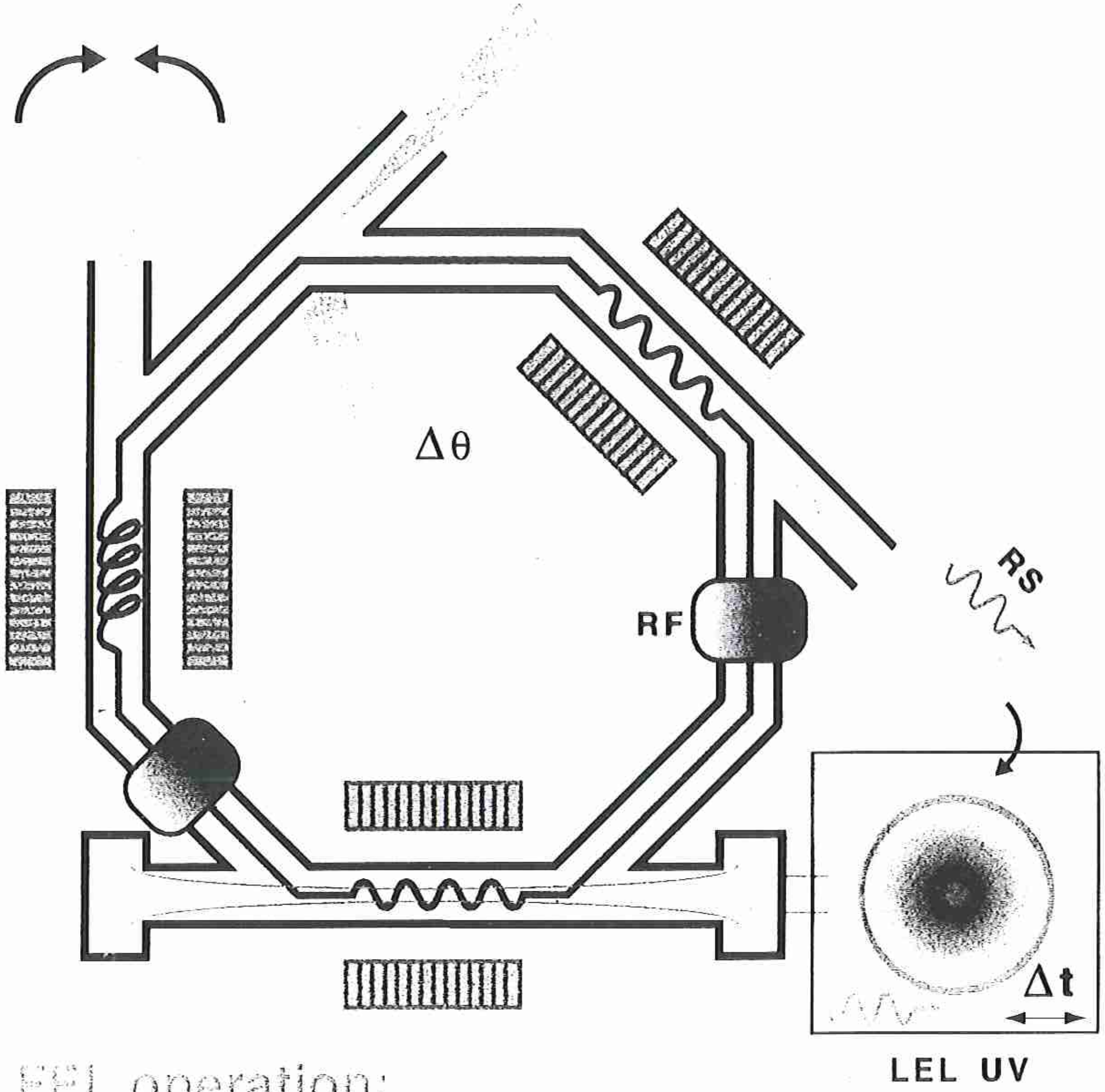
An FEL then looks like



In fact, the radiation travels along and interacts with the ebeam ($\beta \cong 1$) anyway. There is, in principle, no need for the cavity. But the length is too long

The worlds most powerful cw IR-FEL is at the Jefferson Laboratory (1.6 μm, 14 kW)

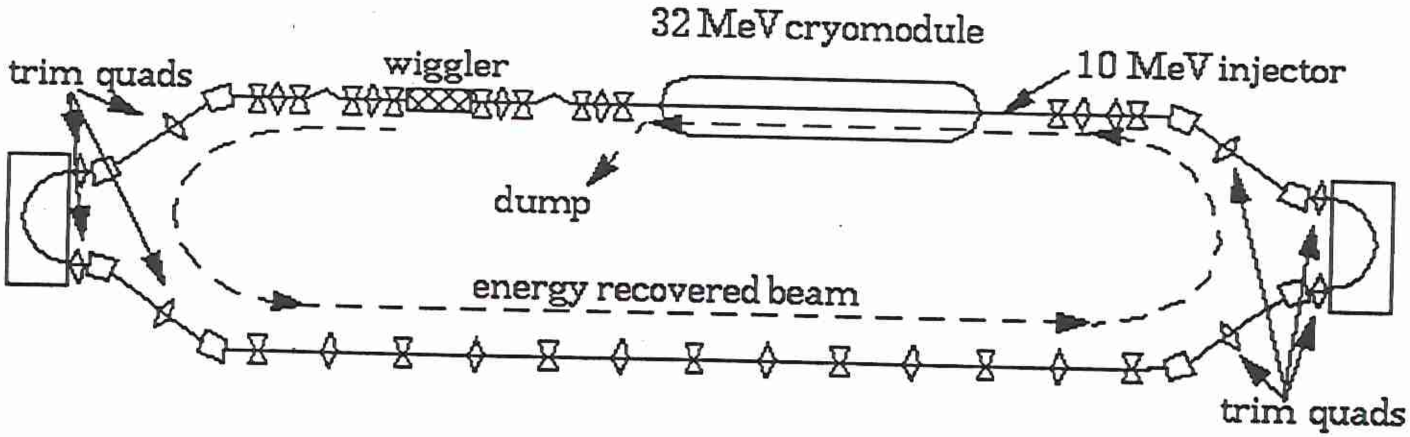
THE SUPER-ACO STORAGE RING

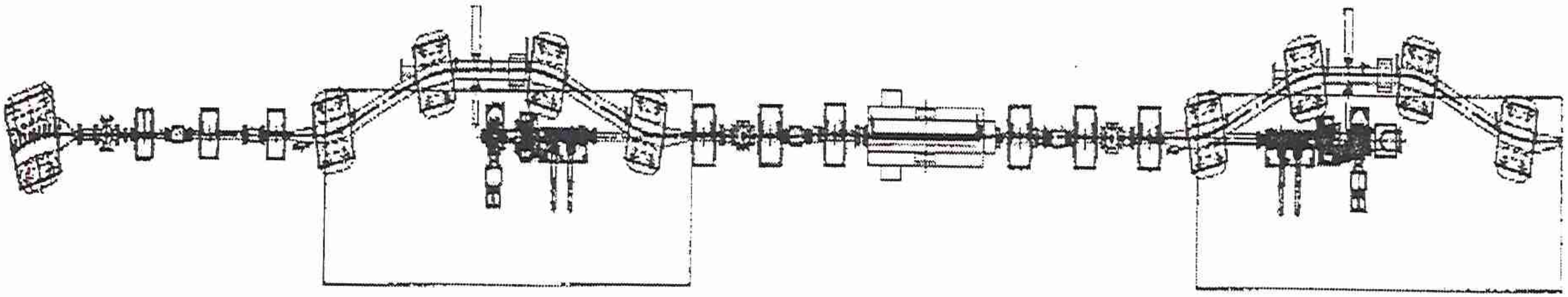


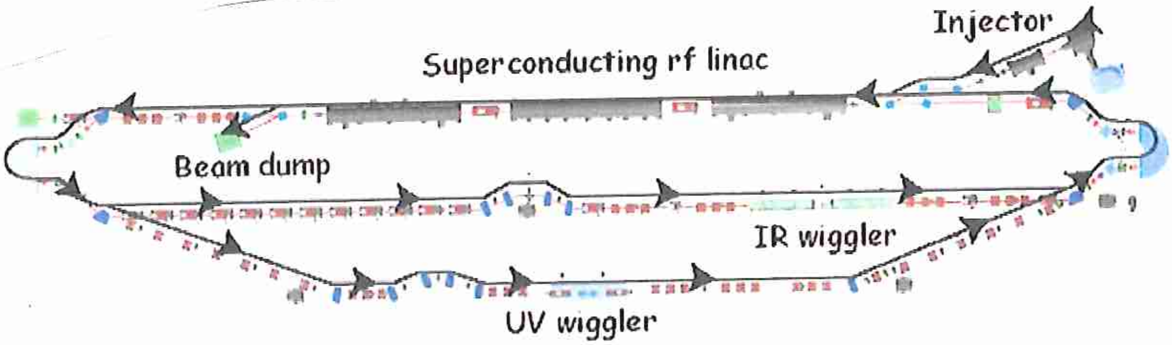
for FEL operation:

- E = 0.8 GeV   40 nm rad,   2 bunches
- I = 2x60 mA
- σ_l = 90 - 300 ps RMS (30-100 ps, harm. cavity)
- feedback on modes of coh synchrotron oscillations
- $\sigma_x = \sigma_z$ = 300 µm
- lasing duration : 10 h-3 h
- Mode of operation compatible with the VUV community using the temporal structure

Conceptual Layout of IR FEL Driver







A schematic of the FEL is shown above.

Jefferson Lab FEL Output Light Parameters

	IR Branch	UV Branch
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser energy / pulse (microJoulesJ)	100 - 300	25
Laser power (kW)	> 10	> 1
Repetition Rate (cw operation, MHz)	4.7 - 75	4.7 - 75

Jefferson Lab FEL Electron Beam Parameters

Energy (MeV)	80-200	200
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50%	0.13%
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

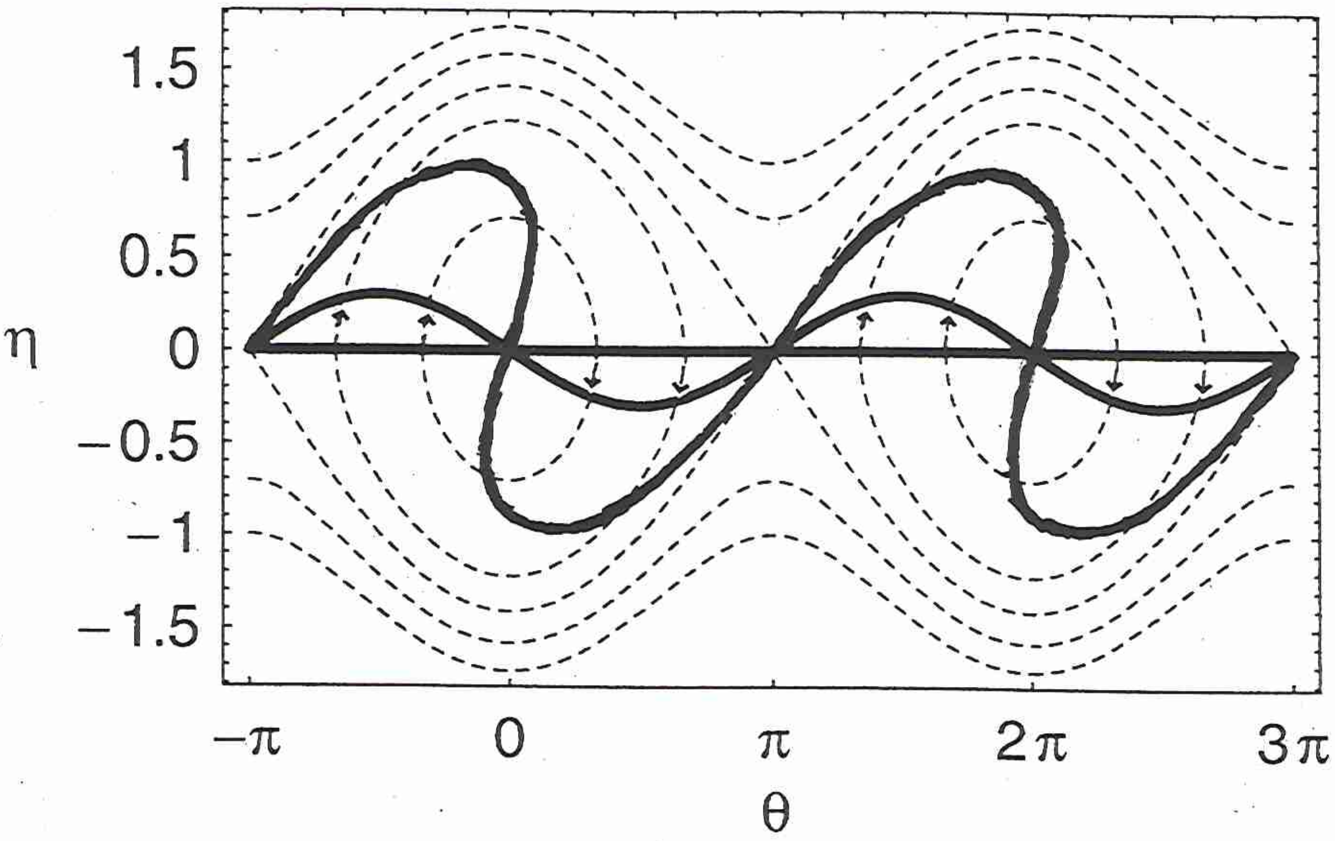
Jefferson Lab (Broadband) THz Beamline Parameters

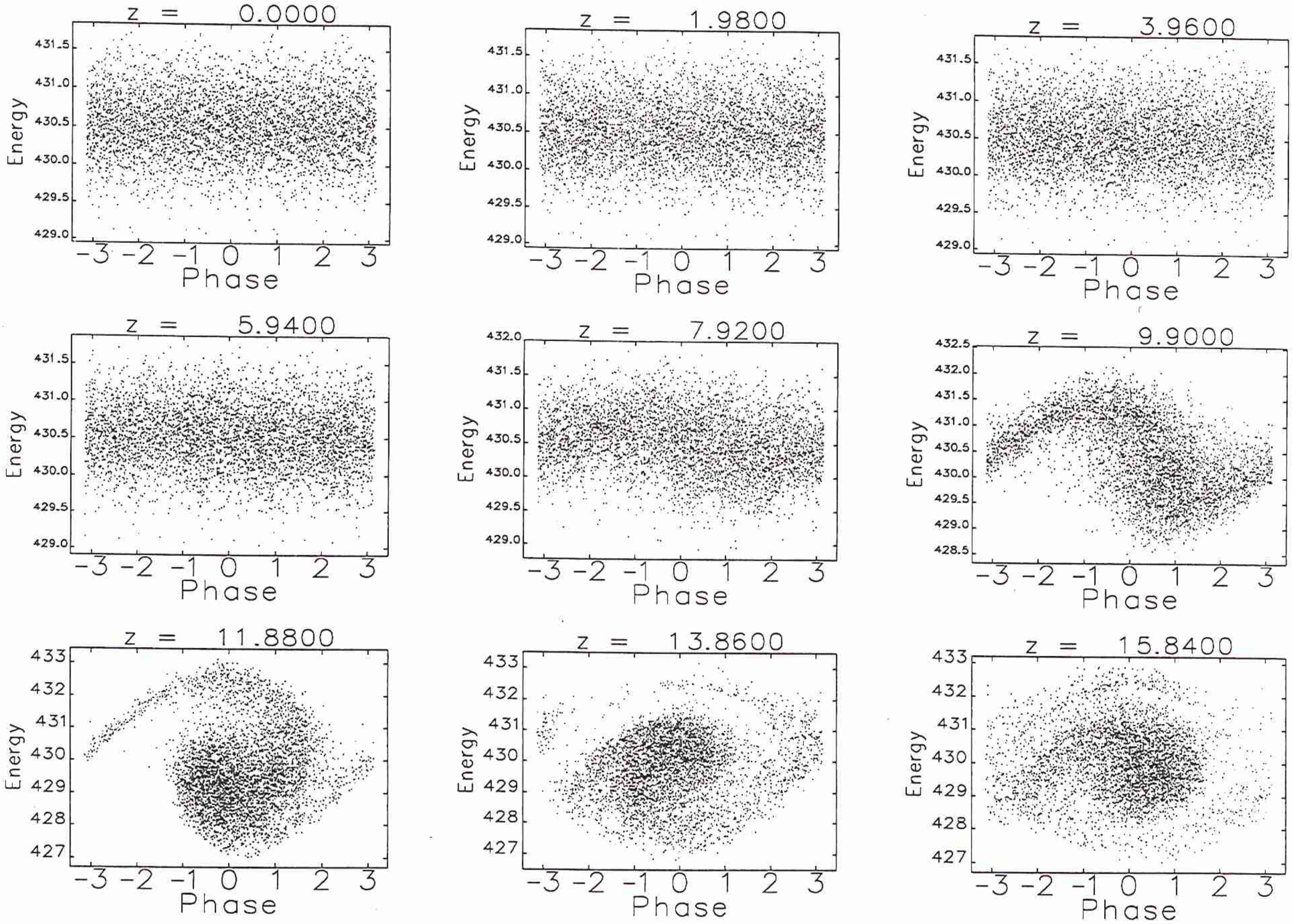
Wavelength Range (THz)	0.1 - 10
Pulse Length (ps)	0.2 - 2
Energy / pulse (microJoules)	2
Repetition Rate	1 Hz - 75 MHz
Total Power (watts)	150

Beam-Radiation Interaction: High Gain (SASE)

At High Gain, radiation acts back and bunches the beam at the same radiation phase in each wavelength. See next drawing.

This increases the coherence of the spontaneous emission and increases the radiation intensity by a factor of N_C = Number of Coherent electrons, which can be $10^7 - 10^{10}$! Since the radiation travels along with and interacts continually with the ebeam, the action grows exponentially and no cavity is necessary to store the radiation. This process was given the whimsical name of "Superradiant" by the early authors. It is now known as the Self-Amplified Spontaneous Emission (SASE). The device is generally called SASE-FEL. We shall abbreviate it as "SASER".


1.5
1
0.5
0
−0.5
−1
−1.5
η
−π
0
π
2π
3π
θ


z = 0.0000
z = 1.9800
z = 3.9600
z = 5.9400
z = 7.9200
z = 9.9000
z = 11.8800
z = 13.8600
z = 15.8400
Energy
Phase
429.0
429.5
430.0
430.5
431.0
431.5
432.0
432.5
428.5
427
428
429
430
431
432
433
-3 -2 -1 0 1 2 3

Simple 1-D Treatment

All quantities are functions of t and z only. For the j^{th} electron the equations are

$$\begin{cases} \dot{\theta}_j = c k_u \left(1 - \dfrac{\gamma_r^2}{\gamma_j^2}\right) + \left(\begin{matrix}\text{radiation} \\ \text{induced term}\end{matrix}\right) & \left[\begin{matrix}\text{phase slip} \\ \text{when } \gamma_j \neq \gamma_r\end{matrix}\right] \\ \dot{\gamma}_j = -\dfrac{eK}{2mc}\left(a \dfrac{e^{i\theta_j}}{\gamma_j} + \text{c.c.}\right) & \left[\begin{matrix}\text{energy gain} \\ \text{from radiation}\end{matrix}\right] \\ \dot{a} = 2\pi e c n K \left\langle \dfrac{e^{-i\theta_j}}{\gamma_j} \right\rangle_j & \left[\begin{matrix}\text{radiation vector potential} \\ \text{induced by beam}\end{matrix}\right] \end{cases}$$

where

(θ_j, γ_j) are the phase space coordinates of the j^{th} electron

a = Complex amplitude of the vector potential

n = Density of the ebeam

The first 2 equations give the phase-motion (spherical pendulum) of the j^{th} electron under the influence of the radiation field. The 3rd equation give the EM field induced by the ebeam. These equations are scaled, linearized and averaged to give the collective motion of the beam and the radiation.

The results are:

① Threshold for exponential gain

$\frac{\gamma - \gamma_r}{\gamma_r} \lesssim 7\rho$ gives required ebeam energy & spread

② Gain length

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\,\rho} \qquad \rho \equiv \frac{1}{2\gamma}\left[n r_e \pi \left(\bar{\lambda}_u K [J,J]\right)^2\right]^{\frac{1}{3}}$$

= Pierce parameter

③ Bandwidth of radiation

$\left(\frac{\Delta\omega}{\omega}\right)^2 \sim \frac{\rho}{N_u}$ limits the energy spread of the beam

④ Coherence length & electron number

$$L_c = \frac{\lambda}{3^{3/4}}\sqrt{\frac{N_u}{\rho}} \quad \left(= \sqrt{2\pi}\,\frac{c}{\Delta\omega}\right)$$

$N_c = n a L_c$ a = cross-sectional area of beam

⑤ Saturation radiation power

$P_s \cong \rho P_b$ P_b = ebeam power

⑥ Saturation length

$$L_S = L_G \ln\frac{P_s}{P_0} \qquad P_0 = P_{seed} + P_{noise}$$

Discussions

① All operating parameters are better for larger ρ. Thus, we need high ebeam current and low emittances.

② One generally uses a photocathode rf gun as esource. A great deal of R&D is now devoted to improving the gun for SASER.

③ Good operation depends on a good "seed". This is another current R&D concentration.

④ After use the ebeam still retains most of its power and can be recirculated through the linac to recycle the power. This operation has been demonstrated successfully at JLAB but has yet to be applied.

⑤ 3D SASE operation must be solved by computer simulation. Some popular programs are:

GINGER - W. M. Fawley (LBNL)

GENESIS - S. Reiche (SLAC)

TDA - T. M. Tran (BNL), J. S. Wurtele (LBNL)

MEDUSA - H. P. Freund (SAIC), B. Levush (NRL)

Their results compare well with one another and with measurements.

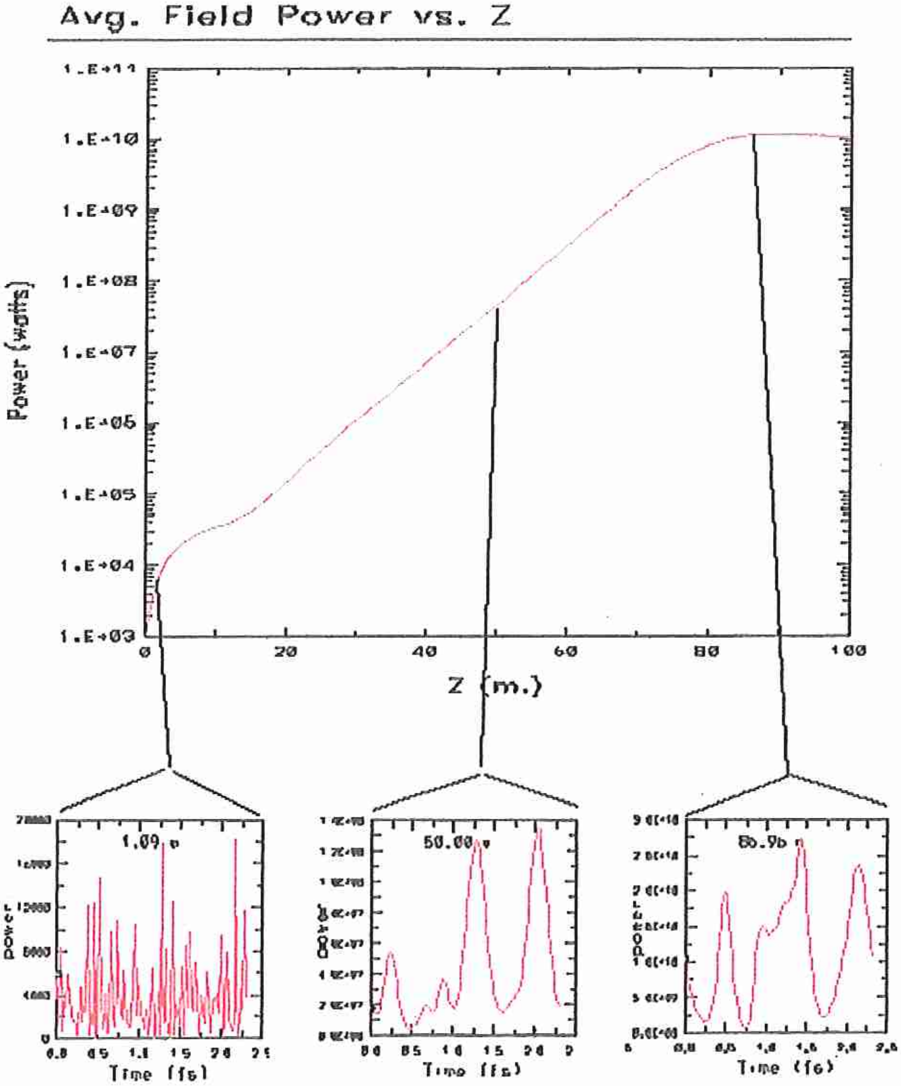
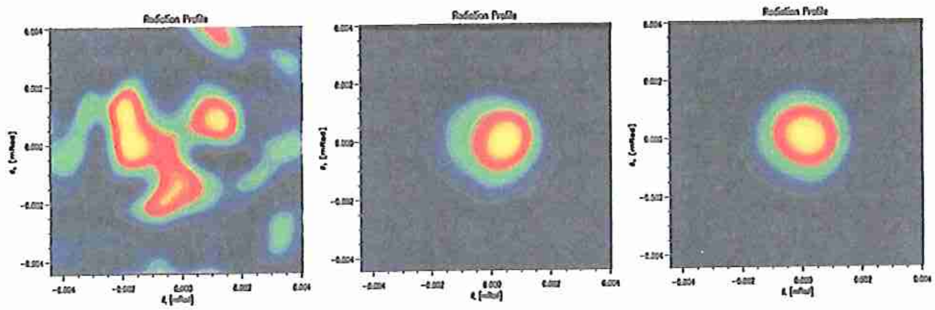


FIGURE 2. Evolution of the LCLS radiation power and the temporal coherence (courtesy of H.-D. Nuhn, SLAC).



(a) $z = 25$ m

(b) $z = 50$ m

(c) $z = 75$ m

FIGURE 3. Evolution of the LCLS transverse profiles at different z location (courtesy of S. Reiche, UCLA).

⑥ The SASERs that are in operation are:

LCLS (SLAC, USA) $\lambda = 1.5 Å$, $E_e = 13.6$ GeV
FLASH (DESY, Germany) $\lambda = 45 Å$, $E_e = 1.2$ GeV
SCSS (SPring8, Japan) $\lambda = 1.0 Å$, $E_e = 6.0$ GeV
SDUV (SSRF, China) $\lambda = 349$ nm, $E_e = 135$ MeV
(pilot for SXFEL)

⑦ The proposed full SASER projects with λ going down to 1Å are perhaps all > 5 yrs away. They are

EXFEL	Europe
JXFEL	Japan
KXFEL	Korea
SXFEL	Shanghai

Subject: Fwd: LCLS photo
From: Rick Fenner <fenner@aps.anl.gov>
Date: Tue, 08 Mar 2011 10:08:29 -0600
To: Lee Teng <teng@aps.anl.gov>

Here it is again, Lee.

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Subject:LCLS photo
Date: Mon, 07 Mar 2011 09:22:38 -0600
From: Rick Fenner <fenner@aps.anl.gov>
To: Lee Teng <teng@aps.anl.gov>

--
Richard Fenner
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lcls_firstlight_hires-7.jpg	**Content-Type:**	image/jpeg
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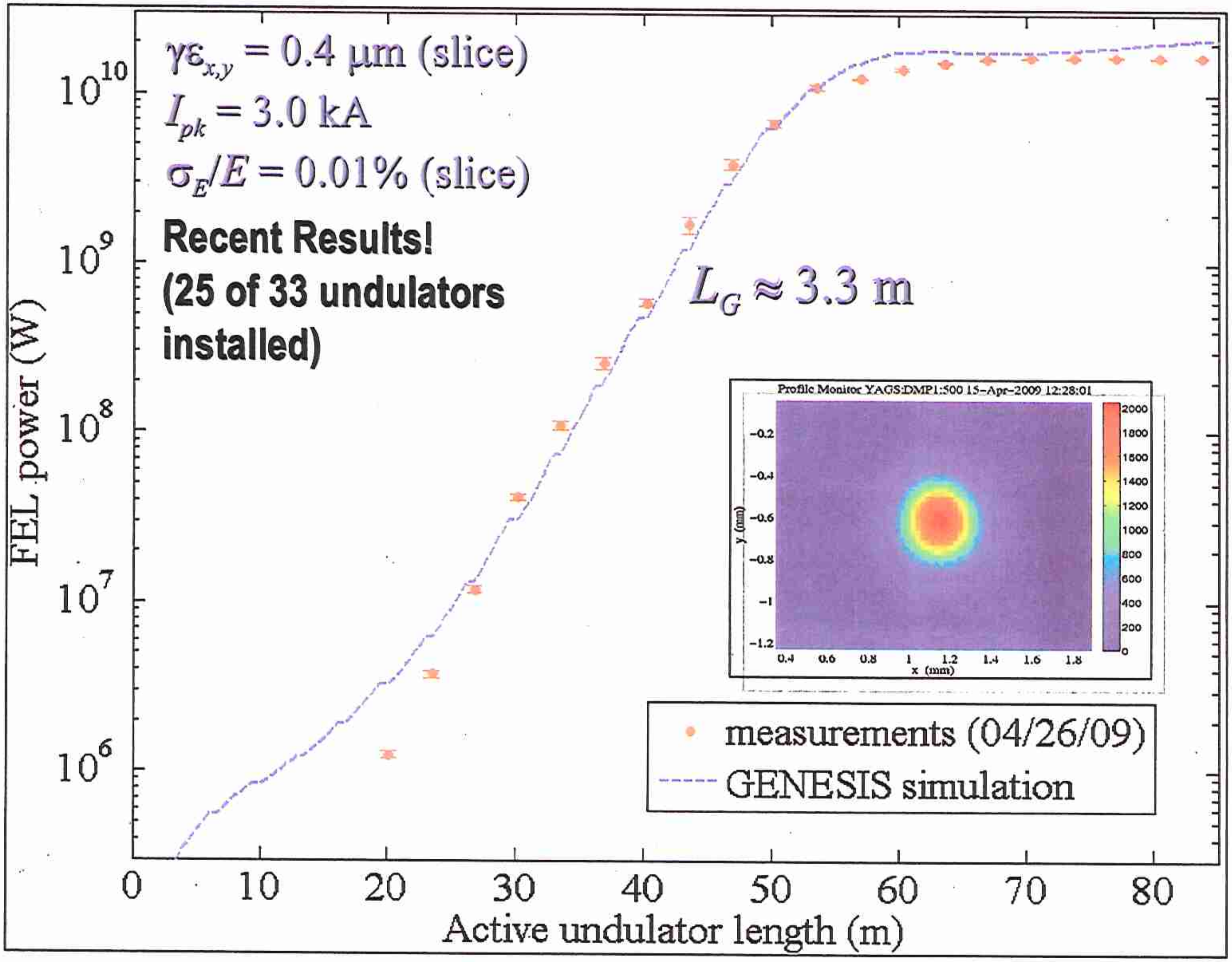
LCLS Parameters

Typical measured LCLS parameters with hard and soft x-rays. Parameters on the right side of the double-border are still in development, although already partially tested. Stability values (at bottom) are taken over a few minutes.

Oct. 8, 2009

Photon Beam Parameters	**symbol**	**hard x-rays**	**soft x-rays**	**short pulse soft**	**short pulse hard**	**unit**
Fundamental wavelength	λ_r	≥1.4	≤17	≤15	≥1.4	Å
Photon energy	□ω	2000-8700	750-2000	800-2000	2000-8700	eV
Final linac e^- energy	γmc^2	14.2	4.1	4.3	14.2	GeV
FEL 3-D gain length	L_G	3.3	1.5	~1.5	~3.3	m
Photons per pulse	N_γ	2	20	0.5	?	10^{12}
Peak brightness	B_{pk}	20	0.3	?	?	10^{32} §
Average brightness (30 Hz*)	$\langle B \rangle$	40	2	?	?	10^{20} §
Photon bandwidth	$\Delta\omega/\omega$	~0.2	~0.4	?	?	%
Bunch charge	Q	0.25	0.25	0.02	0.02	nC
Init. bunch length (rms)	σ_{z0}	0.65	0.65	0.23	0.23	mm
Final bunch length (rms)	σ_{zf}	7	20	~1	~1	μm
Final pulse duration (fwhm)	$\Delta\tau_f$	80	240	<10	<10	fs
Final peak current	I_{pk}	3.0	1.0	~3	~3	kA
Electron Beam Parameters						
Proj. emittance (injector)	$\gamma\varepsilon_{x,y}$	0.4-0.6	0.4-0.6	0.2	0.2	μm
Slice emittance (injector)	$\gamma\varepsilon^s_{x,y}$	0.4	0.4	0.15	0.15	μm
Proj. emittance (undulator)	$\gamma\varepsilon^U_{x,y}$	0.5-1.6	0.5-1.6	0.3-1.0	0.3-1.0	μm
Single bunch rep. rate	f	30*	30*	30*	30*	Hz
UV laser energy on cath.	u_l	25	25	~2	~2	μJ
UV laser diam. on cath.	$2R$	1.2	1.2	0.6	0.6	mm
e^- energy stability (rms)	$\Delta E/E$	0.04	0.07	0.1	?	%
e^- x,y stability (rms)	x/σ_x	15, 10	25, 20	?, ?	?, ?	%
e^- timing stability (rms)	Δt	50	?	?	?	fs
Peak current stab. (rms)	$\Delta I/I$	10	6	8	?	%
Charge stability (rms)	$\Delta Q/Q$	2.5	2.5	?	?	%

Undulator Gain Length Measurement at 1.5 Å



Recent Results!
(25 of 33 undulators installed)

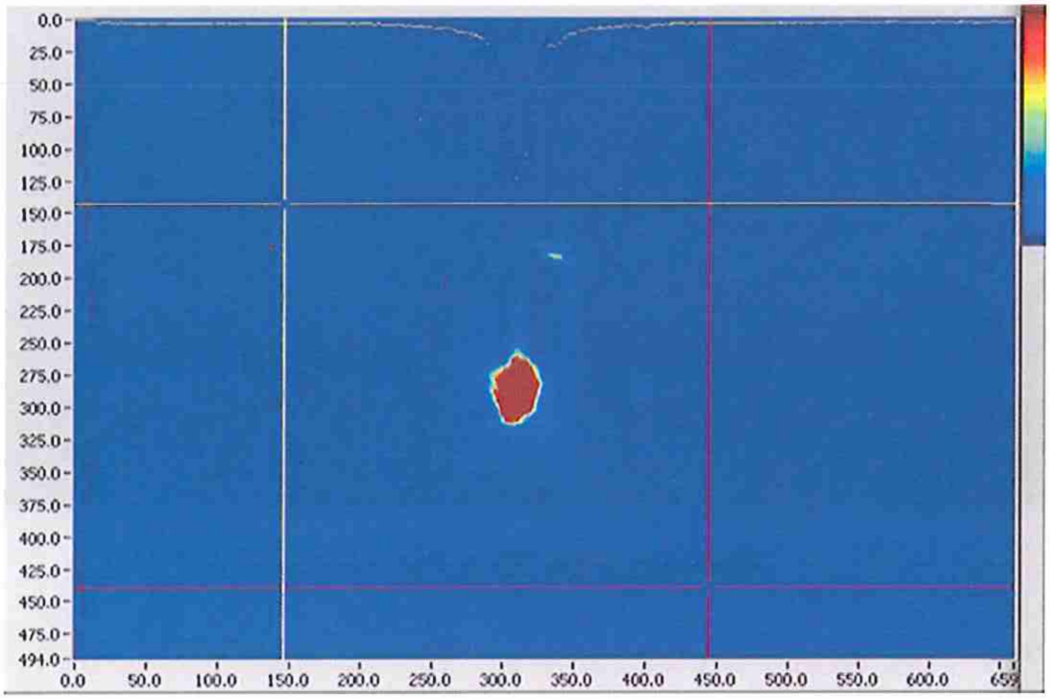
SDUV-FEL HGHG Scheme

SDUV-FEL Main Commissioning Parameters:

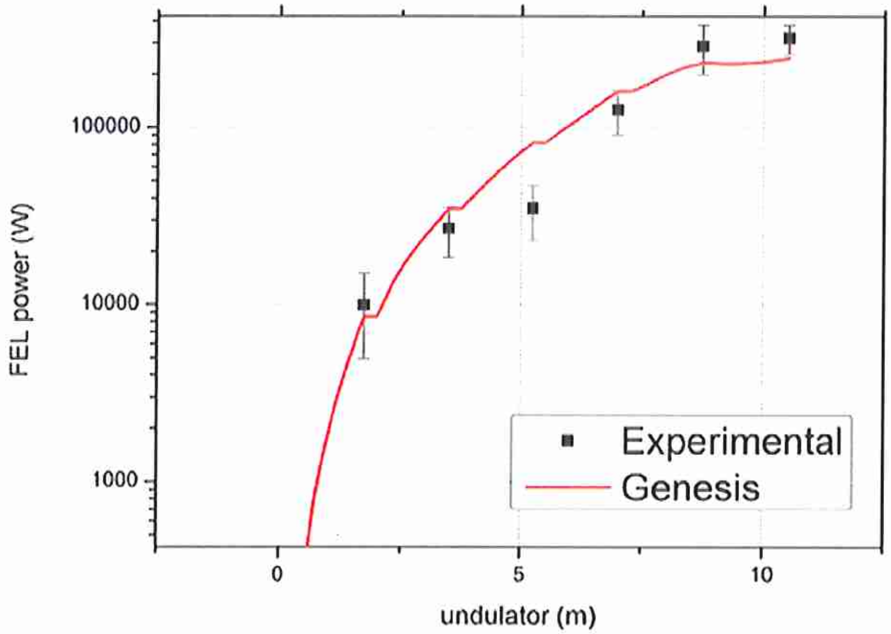
Beam Energy：135MeV
Bunch Charge: 100pC.
Normalized Emittance: ~5mm.mrad
Sliced Energy Spread: ~1e-5
Bunch Length(rms): 1~2 ps
Seed Laser Wavelength: 1047nm
Modulator: 5cmx10 periods
Radiator Undulator: 2.5cm x 60 periods x 6 sectors

Overview of the SDUV-FEL Facility

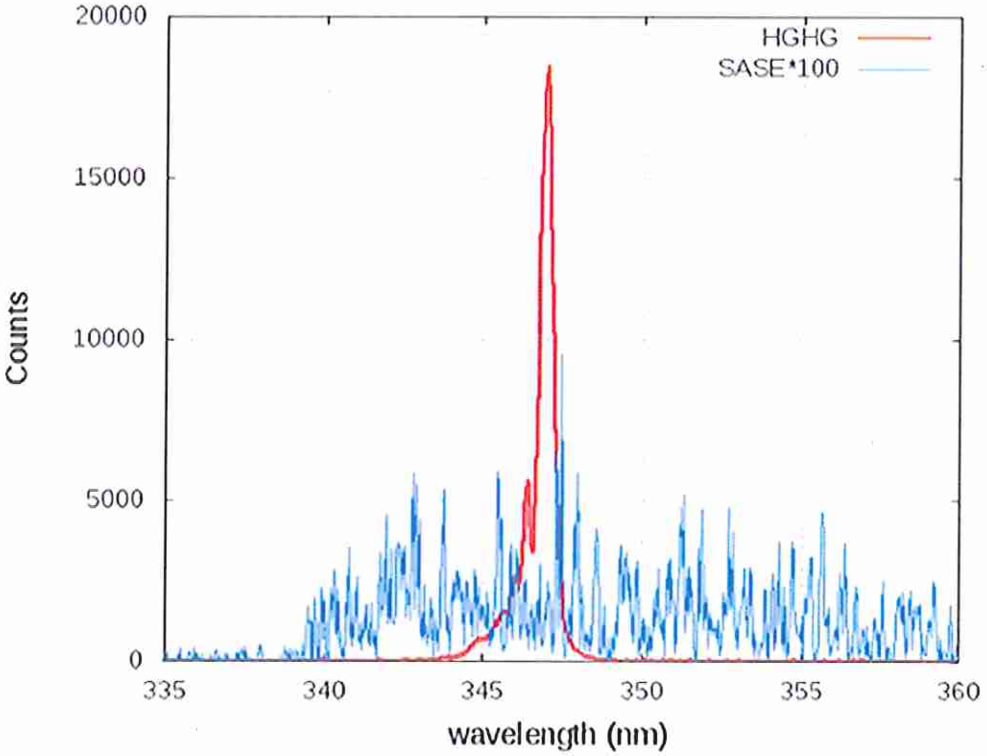
Modulator, Dispenser and Radiator Sections



HGHG-FEL Light Spot



SDUV-FEL HGHG Gain Curve



Spectrum Comparison between HGHG and SASE

FUTURE DIRECTIONS

Currently Available Performance

Brightness	$10^{20} - 10^{30}$	OK
Polarization	Adjustable	OK
Transverse Coherence	100% (diffraction limited)	OK
Longitudinal Coherence	$\sim 80\%$	OK
Frequency Tunability	Good	
Band Width	$\frac{\Delta\omega}{\omega} \sim 10^{-3}$	Fine-tune on X-ray beam
Pulse length	CW $- 10^{-15}$s	
Stability or Repeatability	Storage ring excellent SASE more operating experience	

Both accelerator and experimental people are working on x-ray beam manipulations

More urgent are economic, social, spatial desires

	NOW		DESIRE
Cost	$\$10^9$	→	$\$10^6$
Size & Operation	200m	→	10m
Construction time	10yr	→	1yr

These desires are reflected in the following work items.

Near future

Developing SASER
Perfecting seeding schemes
Multiple experiments and improving duty factor
Implement ERL

Medium future

(Lower cost and size, Better access)

High field dipole storage ring
Compton back-scatter source
Longitudinal space-charge self-bunching

Far future

Laser Plasma Linac + SASER

HIGH FIELD DIPOLE STORAGE RING

Some engineering formulas are:

$$\text{Rigidity} = B\rho(Tm) = \frac{10}{3}\, pc\,(GeV)$$

$$\text{Critical energy} = \mathcal{E}_c(eV) = 60\,\frac{[B\rho(Tm)]^3}{\rho(m)}$$

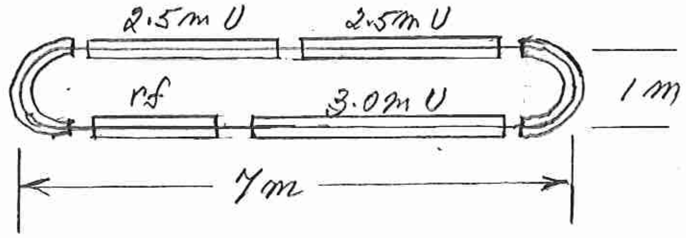
Take $B = 8\,T$ (superconducting), $\rho = 0.5\,m$ these formulas give

$E_e = 1.2$ GeV and $\mathcal{E}_c = 7.7$ keV

At harmonics 3, 5, 7 this gives

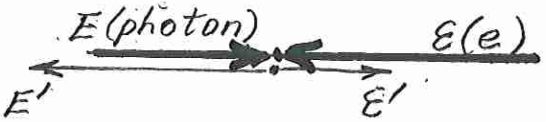
23 keV, 38.5 keV, 54 keV (OK)

We also need straight sections for rf etc.



cost ?

COMPTON BACK-SCATTER SOURCE



$$\frac{E'}{E} = \frac{1+\beta}{1-\beta+2\frac{E}{\mathcal{E}}} \approx 4\gamma^2 \quad \left(\frac{E}{\mathcal{E}} \ll 1\right) \quad \text{Doppler}$$

Take $E = 1\,\text{eV}$, $\mathcal{E} = 60\,\text{MeV}$ $(\gamma = 118.4)$ we get

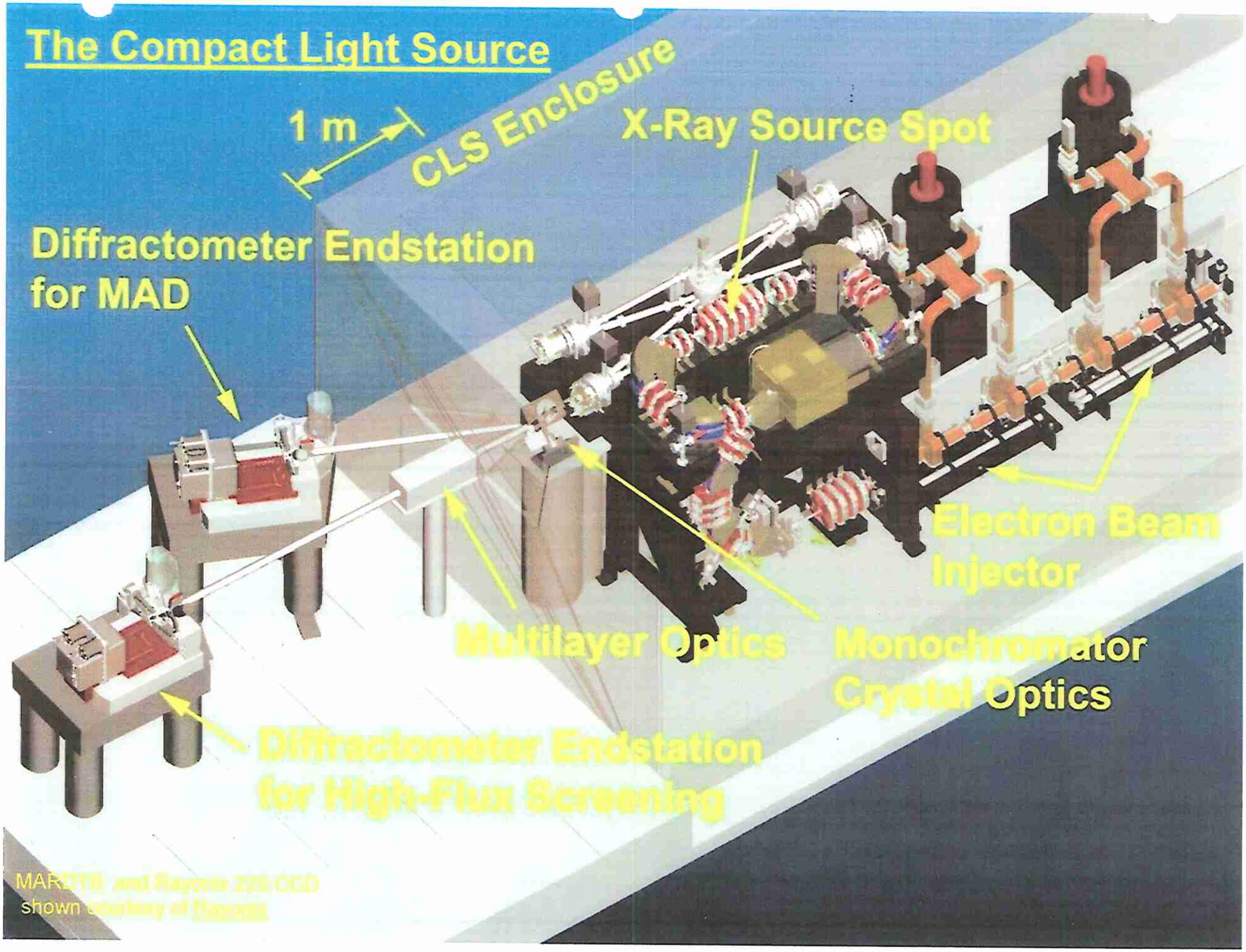
$4\gamma^2 = 56\times10^3$ or $E' = 56\,\text{keV}$ (OK)

Problem is brightness low. this is a particle scattering process with a rather low cross-section given by Klein-Nishina formula. Assuming one stores 100 mA e-beam (60 MeV) in storage ring to collide with a 10W photon beam (6.2×10^{19} photon/s) we get

Backscattered 56 keV photon flux $= 1.6\times10^{4}\,\text{s}^{-1}$

corresponding to a brightness of $\sim 1.2\times10^{6}$. A Proof of principle demonstration was built by Ron Ruth (Lynceean Tech). Asking price ~ \$10M.

The Compact Light Source



MARDTB and Rayonix 225 CCD
shown courtesy of Rayonix

Detailed View: CLS Storage Ring and Cavity