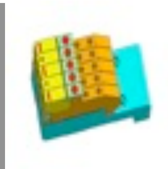
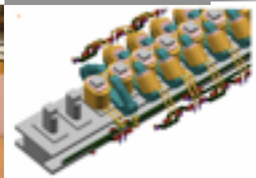




About APPLE II Operation

Thomas Schmidt
Paul Scherrer Institut
Switzerland

New Frontiers in Insertion Devices
ELETTRA
20/21, November 2006

Content

APPLE II at SLS

Operating of the standard APPLE II

Operating of the fixed gap APPLE II

Advanced operation of APPLE II

APPLE II at SLS started in close collaboration with BESSY

UE56 twin undulator

UE54 works on extreme high harmonics: energy range 200eV-8keV

(up to 28th harmonic)

Increasing user demand on LinRot

LinRot is a true 2-dim problem (Circ is just a single line in gap-shift room)

Need for an automated setting

Wish for 0-180 rotation: 4 shift axes

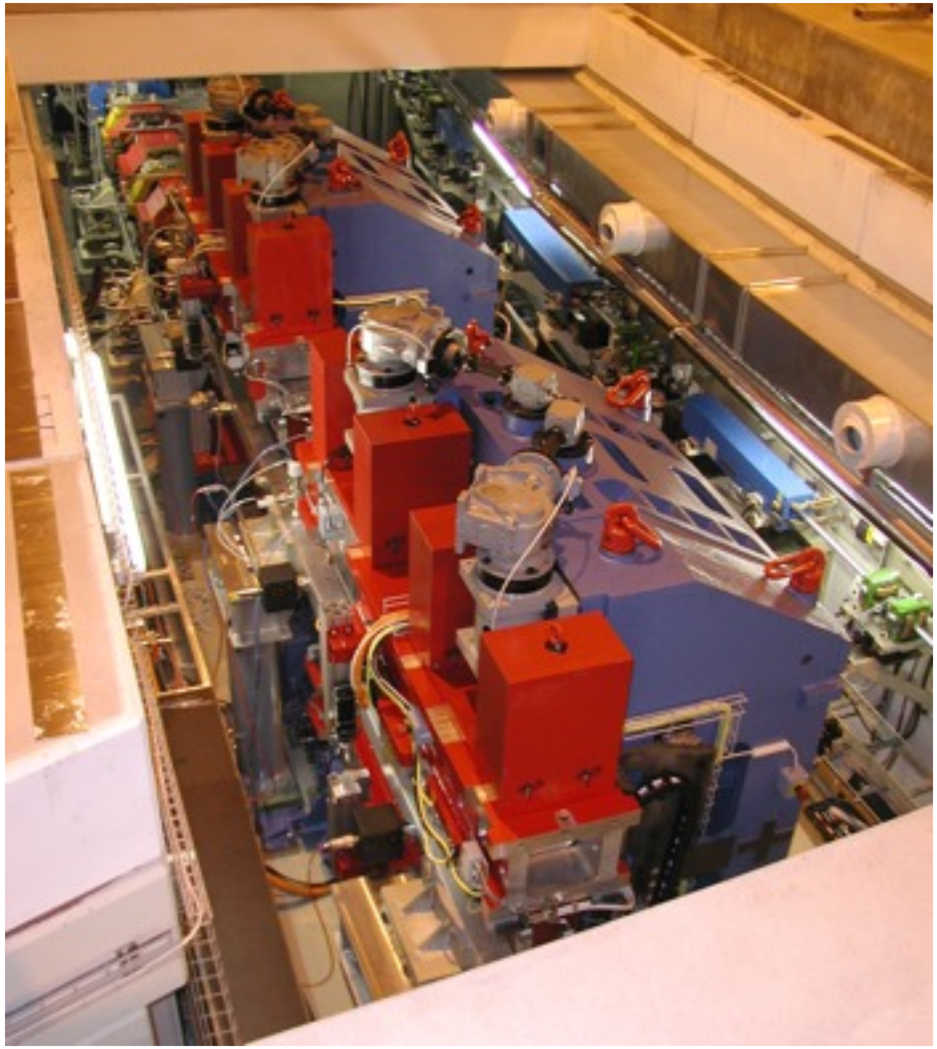
Plan to use adjustable phase concept

UE44 fixed gap undulator (installed Nov. 2006)

Automated setting of phase and energy shift

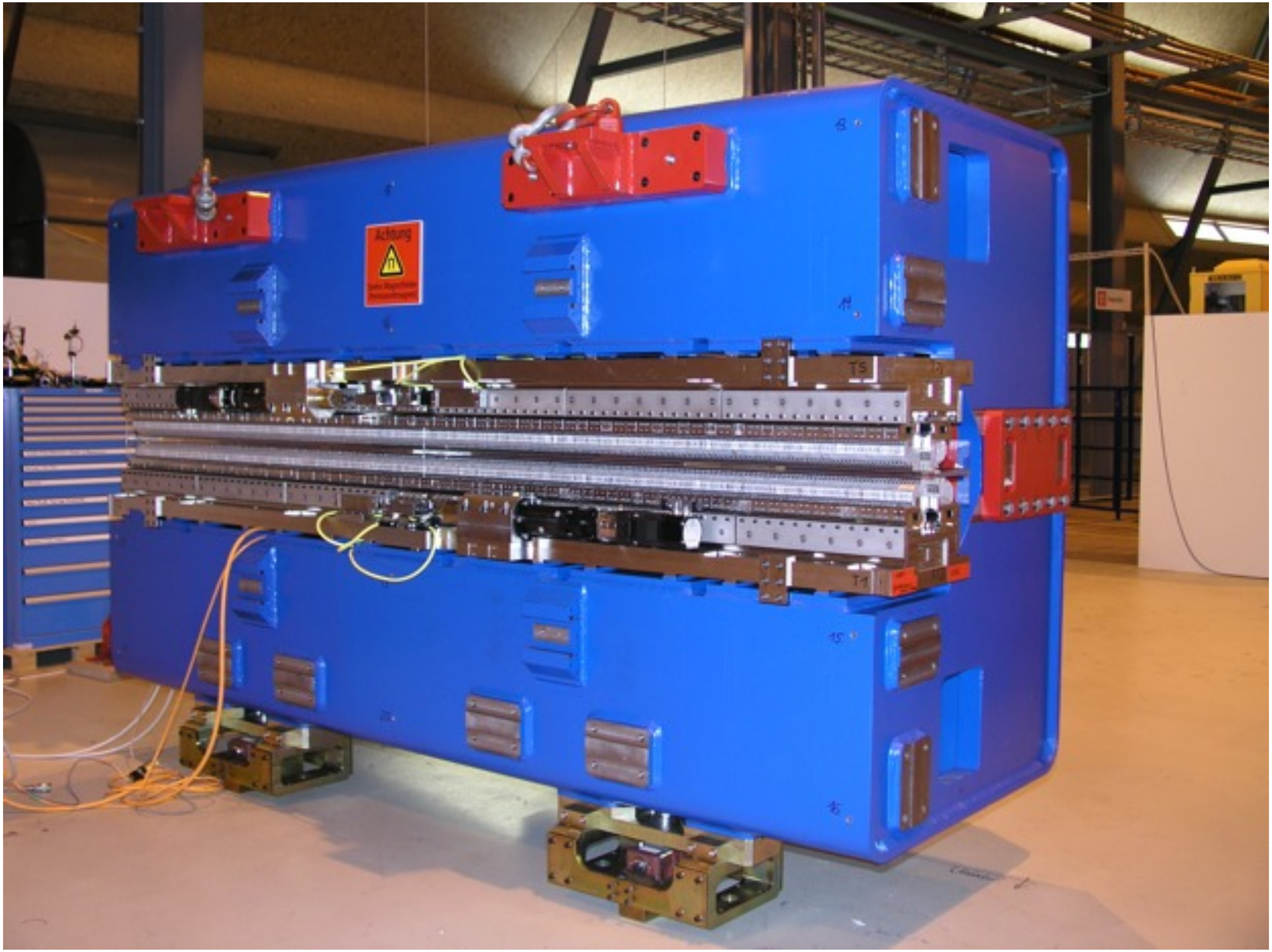
UE56 Twin Undulator

built after design of BESSY with strong support from J.Bahrdt



Modes: circular, elliptical, linear 0 – 90 deg

UE44 fixed gap APPLE II



ID	gap [mm]	Bz/Bx [T]	Kz/Kx	N	Harm	Energy [keV]	Type
Soft x-ray:							
UE56	16	0.83/0.6	4.4/3.2	2x32	1-5	0.09–2	twin APPLE II
UE54	16	0.79/0.54	4.0/2.7	32	3-30	0.2–8	APPLE II
UE44	11.4	0.86/0.65	3.5/2.7	75	1-5	0.3-2	fixed gap APPLE II
UE212	20	0.4/0.1	7.9/2.0	2x19	1-7	0.008–0.6	quasi-periodic ELM
Hard x-ray:							
U24	6	0.93	2.0	65	3-11	5-12	NdFeB (32EH)
U19	5	0.86	1.5	95	3-13	5-18	Sm_2Co_{17} (Recoma 28)
U19 (2x)	5	0.89	1.6	95	3-13	5-18	NdFeB (27VH)
U19	5.5	0.85	1.5	95	3-13	5-18	NdFeB (32EH)
Wiggler:							
W61	8	1.95	11.1	30		$E_c = 7.5$	wiggler
W138	12	1.83	23.6	15	1	0.0015	modulator Femto

Operating an APPLE II:

user interested in Energy and Polarization

Energy, Polarization = f(gap, shift)

but what's needed:

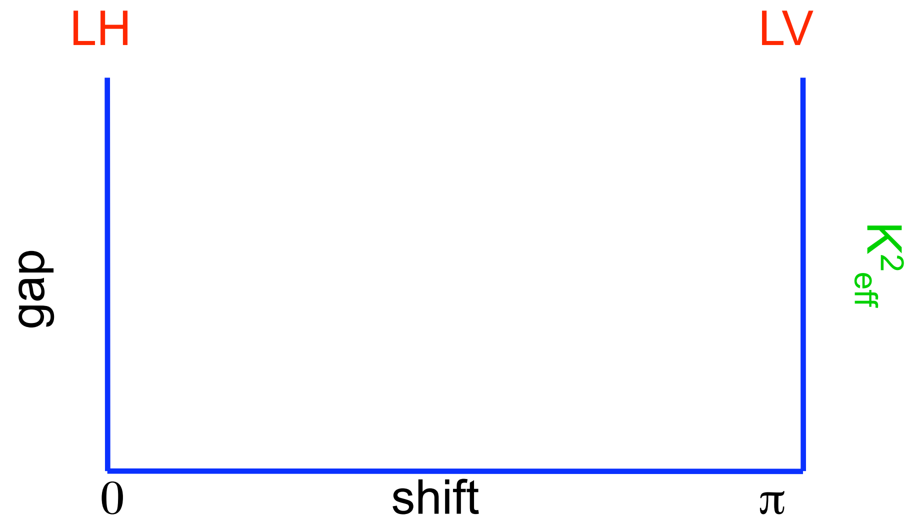
Gap, Shift = f(Energy, Polarization),

including energy shift due to emittance and aperture

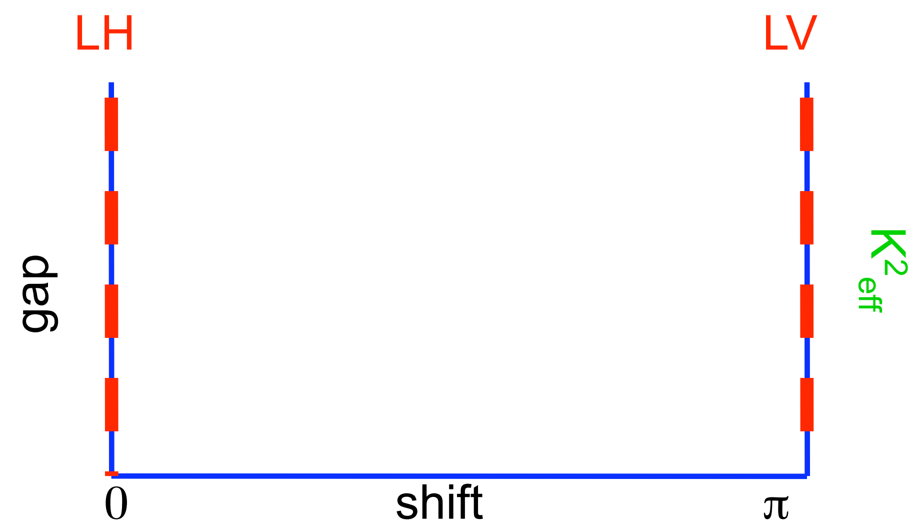
⇩

Semianalytical Model

Operation of standard APPLE II

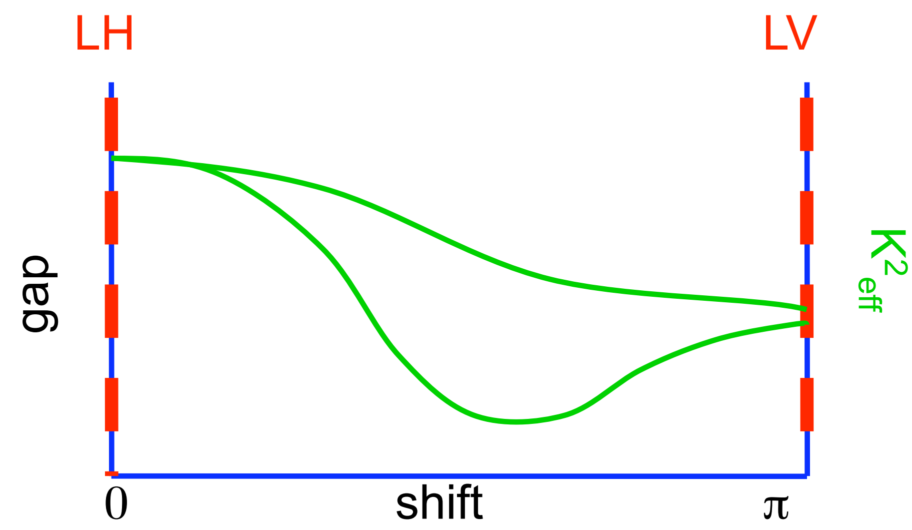


Operation of standard APPLE II



1st Fit energy to gap at the beamline at known polarizations: LH and LV

Operation of standard APPLE II



1st Fit energy to gap at the beamline at known polarizations: LH and LV

2nd use analytical model for shift dependence

Gap dependence

Fit to measured energies vs gap at LH and LV

Model ppm $$B = a \times \exp(-\pi \, g/\lambda_U)$$

Fit to measured energies vs gap at LH and LV

Model ppm

$$B = a \times \exp(-\pi\, g/\lambda_U) \quad \longrightarrow \quad B_z / B_x = const$$

(the expression $B = a \times \exp(-\pi\, g/\lambda_U)$ is crossed out on the page)

Gap dependence

Fit to measured energies vs gap at LH and LV

Model ppm

$$B = a \times \exp(-\pi\, g/\lambda_U) \quad \longrightarrow \quad B_z/B_x = const$$

hybrid

$$B = a \times \exp(-b\, g/\lambda_U + c\, g^2/\lambda_U{}^2) \quad ✓$$

Gap dependence

Fit to measured energies vs gap at LH and LV

Model ppm ~~$B = a \times \exp(-\pi\, g/\lambda_U)$~~ → $B_z / B_x = const$

hybrid $B = a \times \exp(-b\, g/\lambda_U + c\, g^2/\lambda_U{}^2)$ ✓

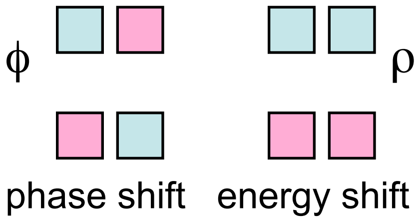
⇓

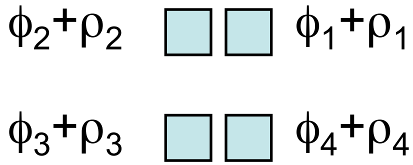
$$E = \frac{C}{1 + \frac{K^2}{2}} \qquad C = 1.24 \times 10^{-6} \times 2\gamma^2/\lambda_U$$

$$E_{LH} = \frac{A_0}{1 + A_1 \exp(g(A_2 + A_3 g))} \qquad K_{z0}^2 = A_1 \times \exp(g(A_2 + A_3 g))$$

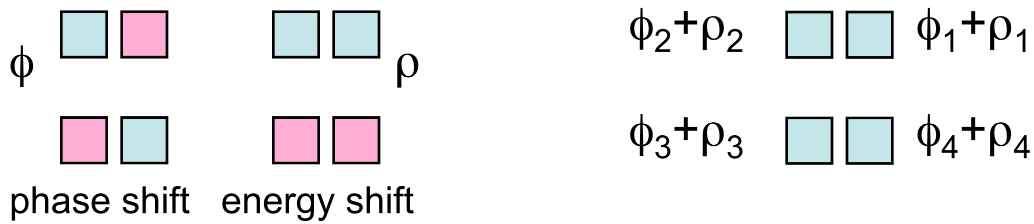
$$E_{LV} = \frac{B_0}{1 + B_1 \exp(g(B_2 + B_3 g))} \qquad K_{x0}^2 = B_1 \times \exp(g(B_2 + B_3 g))$$

Shift variation



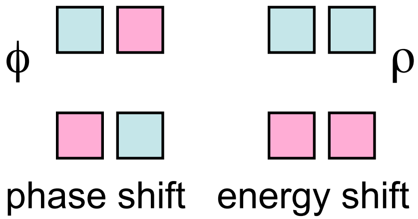


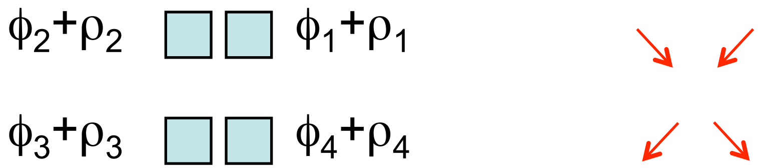
Shift variation



$$K_z(s) = K_{zi}\left[\cos(ks+\phi_1+\rho_1)+\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)+\cos(ks+\phi_4+\rho_4)\right]$$
$$K_x(s) = K_{xi}\left[\cos(ks+\phi_1+\rho_1)-\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)-\cos(ks+\phi_4+\rho_4)\right]$$

Shift variation

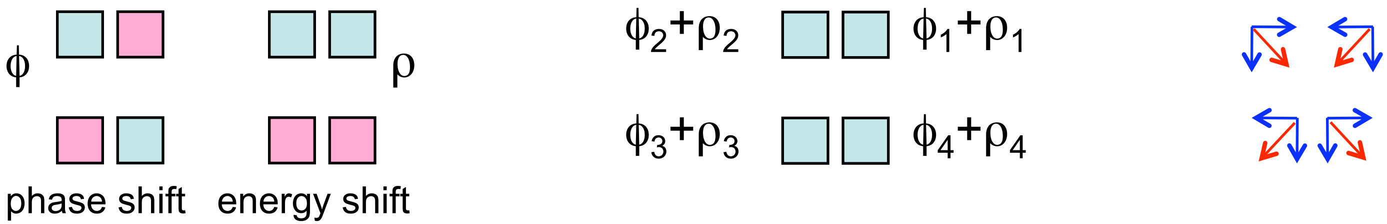




$$K_z(s) = K_{zi}\left[\cos(ks+\phi_1+\rho_1)+\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)+\cos(ks+\phi_4+\rho_4)\right]$$

$$K_x(s) = K_{xi}\left[\cos(ks+\phi_1+\rho_1)-\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)-\cos(ks+\phi_4+\rho_4)\right]$$

Shift variation



$$K_z(s) = K_{zi}\left[\cos(ks+\phi_1+\rho_1)+\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)+\cos(ks+\phi_4+\rho_4)\right]$$

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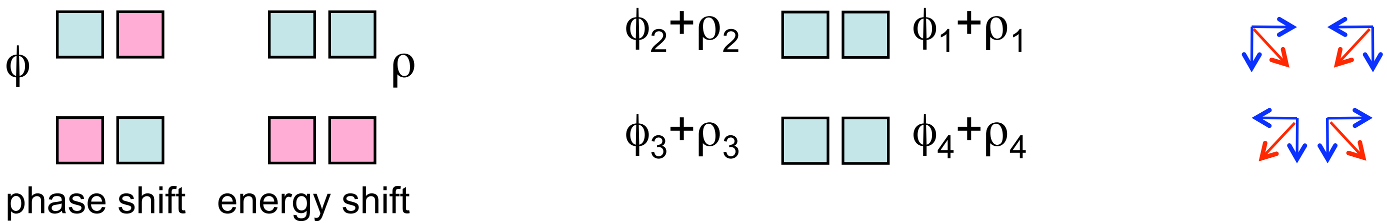
Shift variation



$$K_z(s) = K_{zi}\left[\cos(ks+\phi_1+\rho_1)+\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)+\cos(ks+\phi_4+\rho_4)\right]$$

$$K_x(s) = K_{xi}\left[\cos(ks+\phi_1+\rho_1)-\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)-\cos(ks+\phi_4+\rho_4)\right]$$

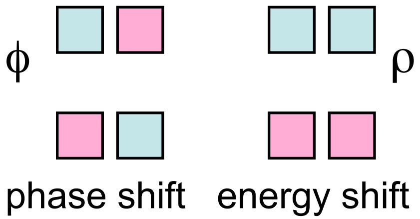
Shift of maxima:

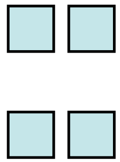
$$K_z = s_0 + \frac{\phi}{2} + \frac{\rho}{2} \qquad K_z = s_0 + \frac{\rho}{2}$$

$$K_x = s_0 + \frac{\phi}{2} + \frac{\rho}{2} + \frac{\lambda_U}{4} \qquad K_x = s_0 + \frac{\rho}{2}$$

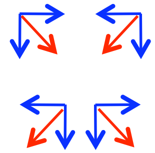
circular — linear

Shift variation



$\phi_2+\rho_2$  $\phi_1+\rho_1$

$\phi_3+\rho_3$ $\phi_4+\rho_4$



$$K_z(s) = K_{zi}\left[\cos(ks+\phi_1+\rho_1)+\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)+\cos(ks+\phi_4+\rho_4)\right]$$
$$K_x(s) = K_{xi}\left[\cos(ks+\phi_1+\rho_1)-\cos(ks+\phi_2+\rho_2)+\cos(ks+\phi_3+\rho_3)-\cos(ks+\phi_4+\rho_4)\right]$$

Shift of maxima:

circular	linear
$K_z = s_0 + \frac{\phi}{2} + \frac{\rho}{2}$	$K_z = s_0 + \frac{\rho}{2}$
$K_x = s_0 + \frac{\phi}{2} + \frac{\rho}{2} + \frac{\lambda_U}{4}$	$K_x = s_0 + \frac{\rho}{2}$

Link to angle and energy:

$$\tan\alpha = K_z / K_x$$

$$E = \frac{C'}{1+\frac{K_{eff}^2}{2}}, \quad K_{eff}^2 = K_z^2 + K_x^2, \quad C' = A_0\cos^2\phi + B_0\sin^2\phi$$

limes for K_{eff} ® 0, including red shift

Discussion of red shift

Red shift due to:

aperture	const.
electron emittance	const.
diffraction	energy dependent for lower energies

Example UE56:

theoretical limes

from fits at LH and LV

covers all components of red shift

Discussion of red shift

Red shift due to:

aperture	const.
electron emittance	const.
diffraction	energy dependent for lower energies

Example UE56:

$$C = 1.24 \times 10^{-6} \times 2\gamma^2 / \lambda_U \qquad E = 2.411 GeV, \lambda_U = 56.3 mm$$

$$C = 980.5 eV$$

theoretical limes

$$A_0 = 963.3 eV$$

$$B_0 = 965.1 eV$$

from fits at LH and LV

$$C' = A_0 \cos^2\phi + B_0 \sin^2\phi$$

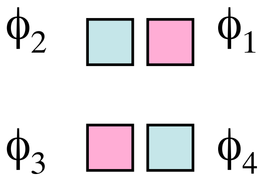
$$K_{z0}^2 = A_1 \times \exp(g(A_2 + A_3 g))$$

$$K_{x0}^2 = B_1 \times \exp(g(B_2 + B_3 g))$$

covers all components of red shift

APPLE II with two shift axes

Circular

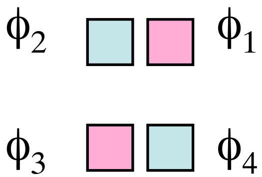


Linear

APPLE II with two shift axes

Circular $\phi_1 = \phi_3 = \phi$

$$K_z(s) = K_{zi}\left(2\cos(ks+\phi) + 2\cos ks\right)$$
$$K_x(s) = K_{xi}\left(2\cos(ks+\phi) - 2\cos ks\right)$$



$$\Downarrow$$

$$\cos x + \cos y = 2\cos\frac{x+y}{2}\cos\frac{x-y}{2}$$
$$\cos x - \cos y = -2\sin\frac{x+y}{2}\sin\frac{x-y}{2}$$

$$K_z = K_{z0}\cos\tfrac{\phi}{2} \qquad K_x = -K_{x0}\sin\tfrac{\phi}{2}$$

Linear $\phi_3 = -\phi_1$

$$K_z(s) = K_{zi}\left(\cos(ks+\phi) + \cos(ks-\phi) + 2\cos ks\right)$$
$$K_x(s) = K_{xi}\left(\cos(ks+\phi) + \cos(ks-\phi) - 2\cos ks\right)$$

$$K_z = K_{z0}\cos^2\tfrac{\phi}{2} \qquad K_x = -K_{x0}\sin^2\tfrac{\phi}{2}$$

APPLE II with two shift axes

Circular

Linear

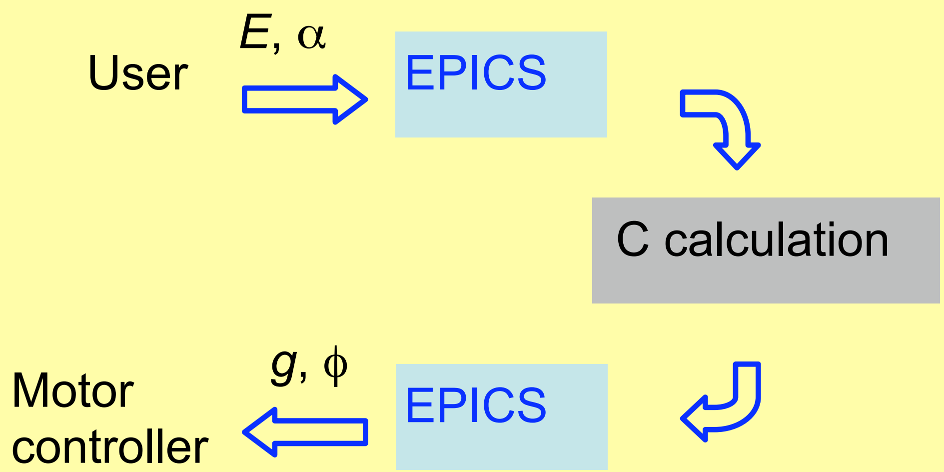
Implementation:

Fit measured *E* vs *g* @ LH and LV

Calculate gap and shift by

Numerical solution of *E* = f(*g*)

Calculate ϕ



APPLE II with two shift axes

Circular	Linear
$\phi = 2\arctan R_h \frac{K_{z0}}{K_{x0}}, \quad R_h = 1(0.8,0.6)$	$\phi = 2\arctan \sqrt{\frac{1}{\tan\alpha}\frac{K_{z0}}{K_{x0}}}$
$E = \frac{C'}{1+0.5\left(K_{zo}^2\cos^2\frac{\phi}{2} + K_{x0}^2\sin^2\frac{\phi}{2}\right)}$	$E = \frac{C'}{1+0.5\left(K_{zo}^2\cos^4\frac{\phi}{2} + K_{x0}^2\sin^4\frac{\phi}{2}\right)}$

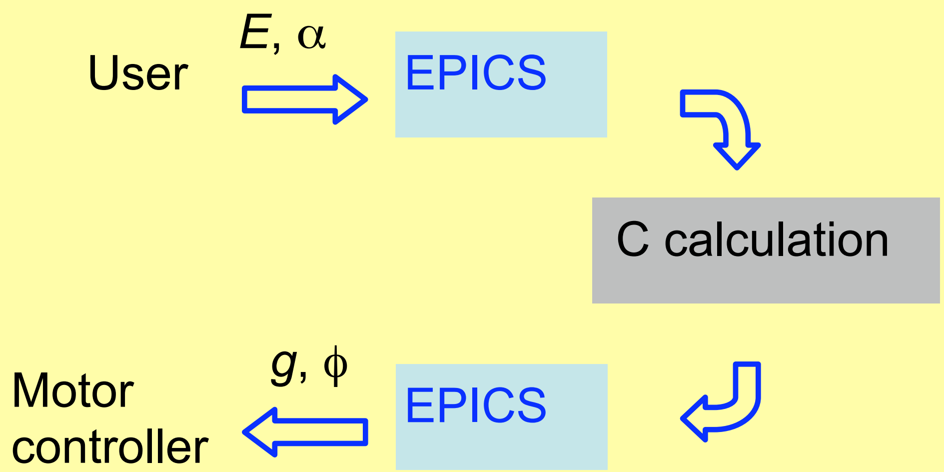
Implementation:

Fit measured *E* vs *g* @ LH and LV

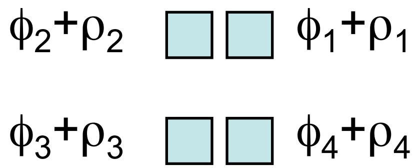
Calculate gap and shift by

Numerical solution of *E* = f(*g*)

Calculate ϕ



Fixed gap: 4 shift axes



Circular

C' from E vs ρ

analytic

Fixed gap: 4 shift axes

$\phi_2+\rho_2$ $\phi_1+\rho_1$

$\phi_3+\rho_3$ $\phi_4+\rho_4$

Circular $\phi_3 = \phi_1 = \phi, \quad \rho_1 = \rho_2 = \rho$

$$K_z(s) = K_{zi}\left(\cos(ks+\phi+\rho) + \cos(ks+\rho) + \cos(ks+\phi) + \cos ks\right)$$

$$K_x(s) = K_{xi}\left(\cos(ks+\phi+\rho) - \cos(ks+\rho) + \cos(ks+\phi) - \cos ks\right)$$

$$K_z(s) = K_{z0}\cos\tfrac{\phi}{2}\cos\tfrac{\rho}{2}\cos\tfrac{2ks+\phi+\rho}{2} \qquad K_z = K_{z0}\cos\tfrac{\phi}{2}\cos\tfrac{\rho}{2}$$

$$K_x(s) = -K_{x0}\sin\tfrac{\phi}{2}\cos\tfrac{\rho}{2}\sin\tfrac{2ks+\phi+\rho}{2} \qquad K_x = K_{x0}\sin\tfrac{\phi}{2}\cos\tfrac{\rho}{2}$$

$$\phi = 2\arctan R_h \frac{K_{z0}}{K_{x0}}$$

$$E = \frac{C'}{1+0.5\cos^2\frac{\rho}{2}\left(K_{z0}^2\cos^2\frac{\phi}{2} + K_{x0}^2\sin^2\frac{\phi}{2}\right)}$$

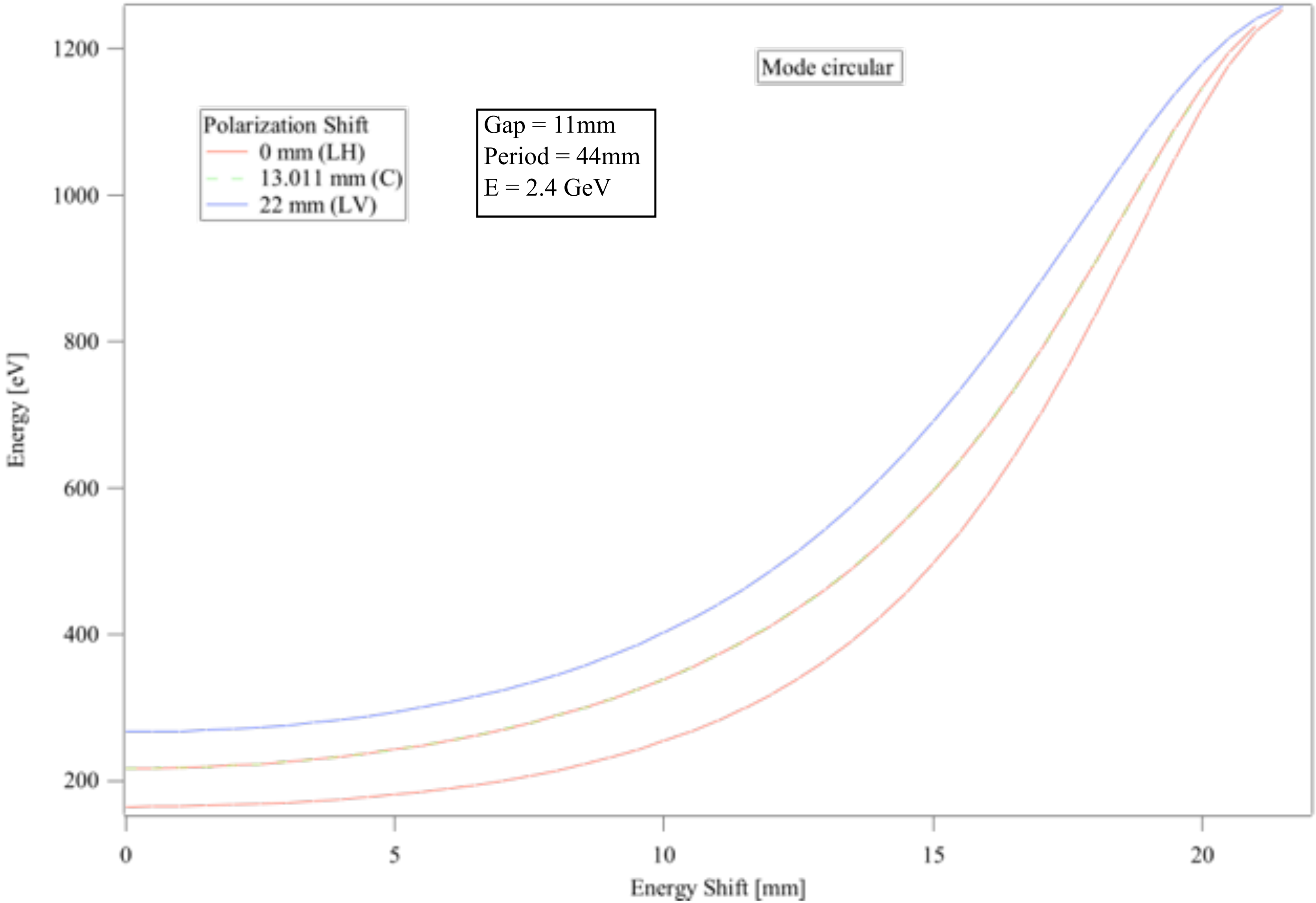
$$\rho = 2\arccos\sqrt{2\left(\frac{C'}{E}-1\right)\frac{1}{K_{z0}^2\cos^2\frac{\phi}{2} + K_{x0}^2\sin^2\frac{\phi}{2}}}$$

$\forall\rho$

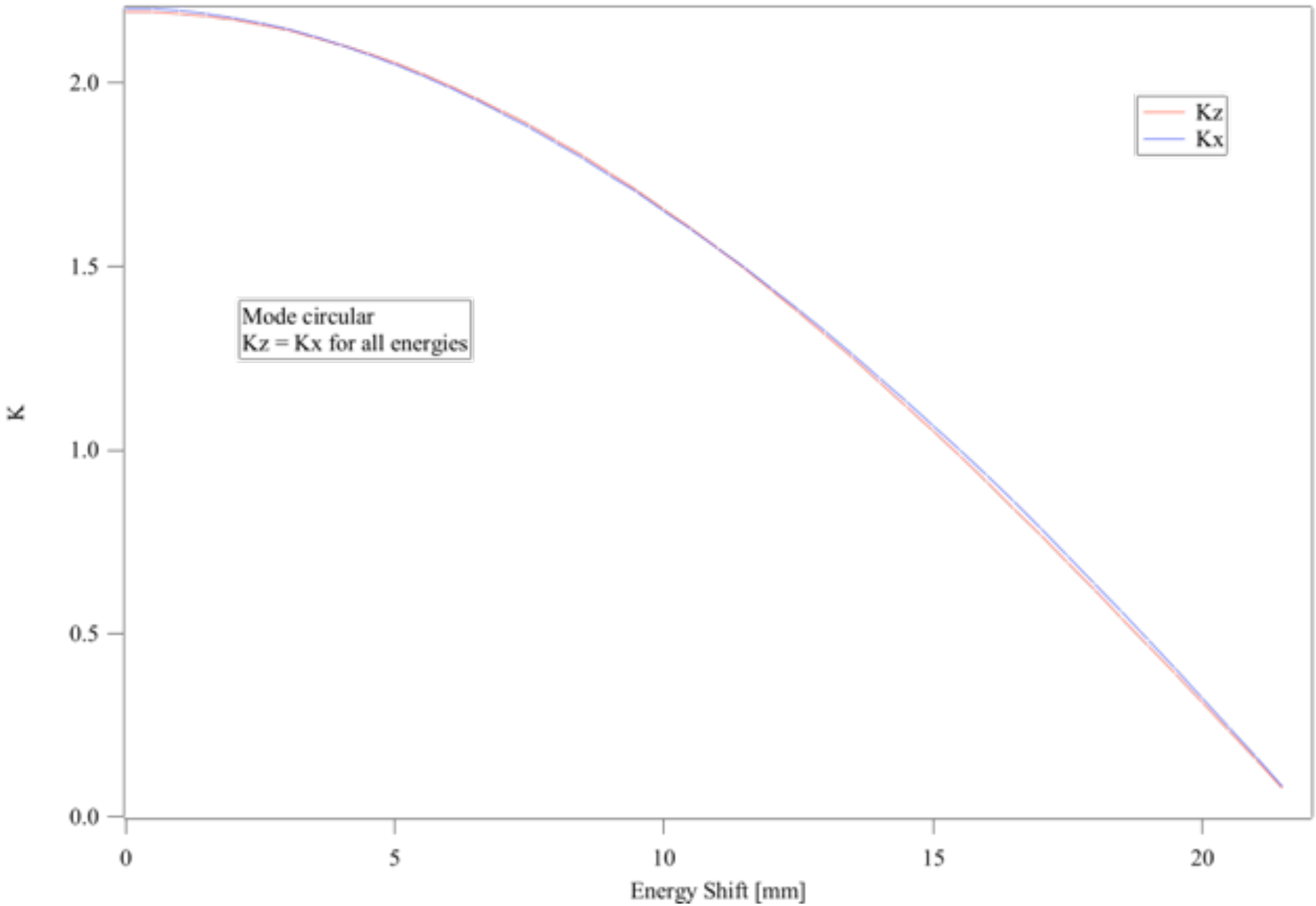
C' from E vs ρ

analytic

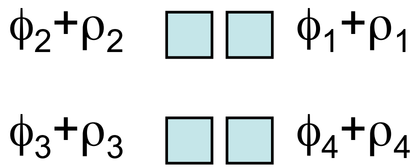
UE44: energy vs energy shift, circular mode



UE44: Kz, Kx vs energy shift, circular mode



Fixed gap: 4 shift axes



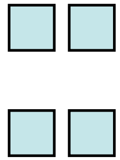
Linear

Maximum shifts by $\rho/2$

ks ® $ks - \rho/2$

Numeric solution

Fixed gap: 4 shift axes



Linear $\phi_3 = -\phi_1, \quad \rho_1 = \rho_2 = \rho$

$$K_z(s) = K_{zi}\left(\cos(ks+\phi+\rho)+\cos(ks+\rho)+\cos(ks-\phi)+\cos ks\right)$$
$$K_x(s) = K_{xi}\left(\cos(ks+\phi+\rho)-\cos(ks+\rho)+\cos(ks-\phi)-\cos ks\right)$$

$$K_z(s) = K_{z0}\cos\tfrac{\phi}{2}\cos\tfrac{\phi+\rho}{2}\cos\tfrac{2ks+\rho}{2} \qquad K_z = K_{z0}\cos\tfrac{\phi}{2}\cos\tfrac{\phi+\rho}{2}$$
$$K_x(s) = K_{x0}\sin\tfrac{\phi}{2}\cos\tfrac{\phi+\rho}{2}\sin\tfrac{2ks+\rho}{2} \qquad K_x = K_{x0}\sin\tfrac{\phi}{2}\cos\tfrac{\phi+\rho}{2}$$

Maximum shifts by ρ/2

ks ® $ks - \rho/2$

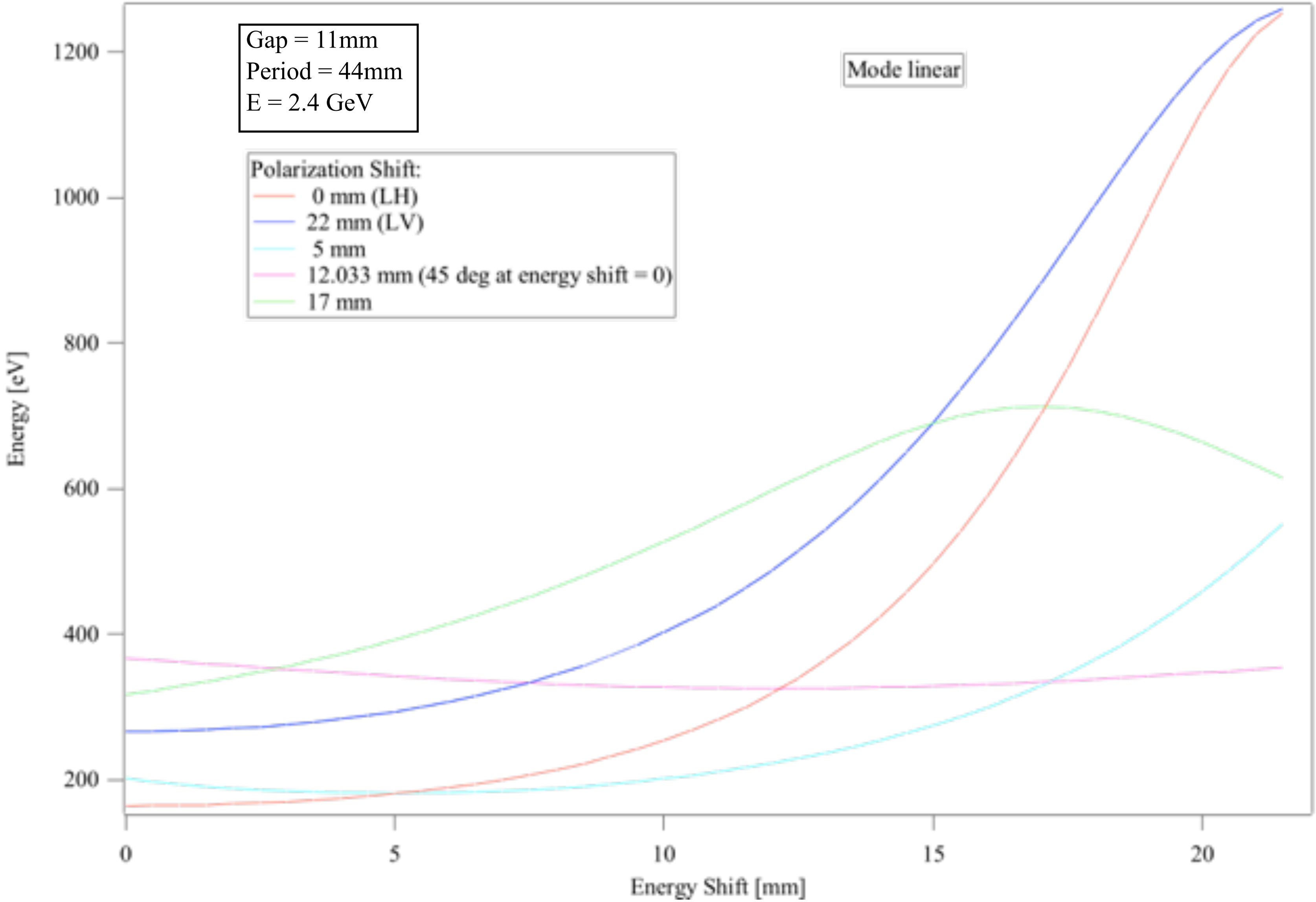
$$\tan\alpha = \frac{K_{z0}}{K_{x0}}\cot\tfrac{\phi}{2}\cot\tfrac{\phi+\rho}{2}$$

$$\rho = 2\arctan\left[\frac{K_{z0}}{K_{x0}}\cot\tfrac{\phi}{2}\cot\alpha\right]-\phi$$

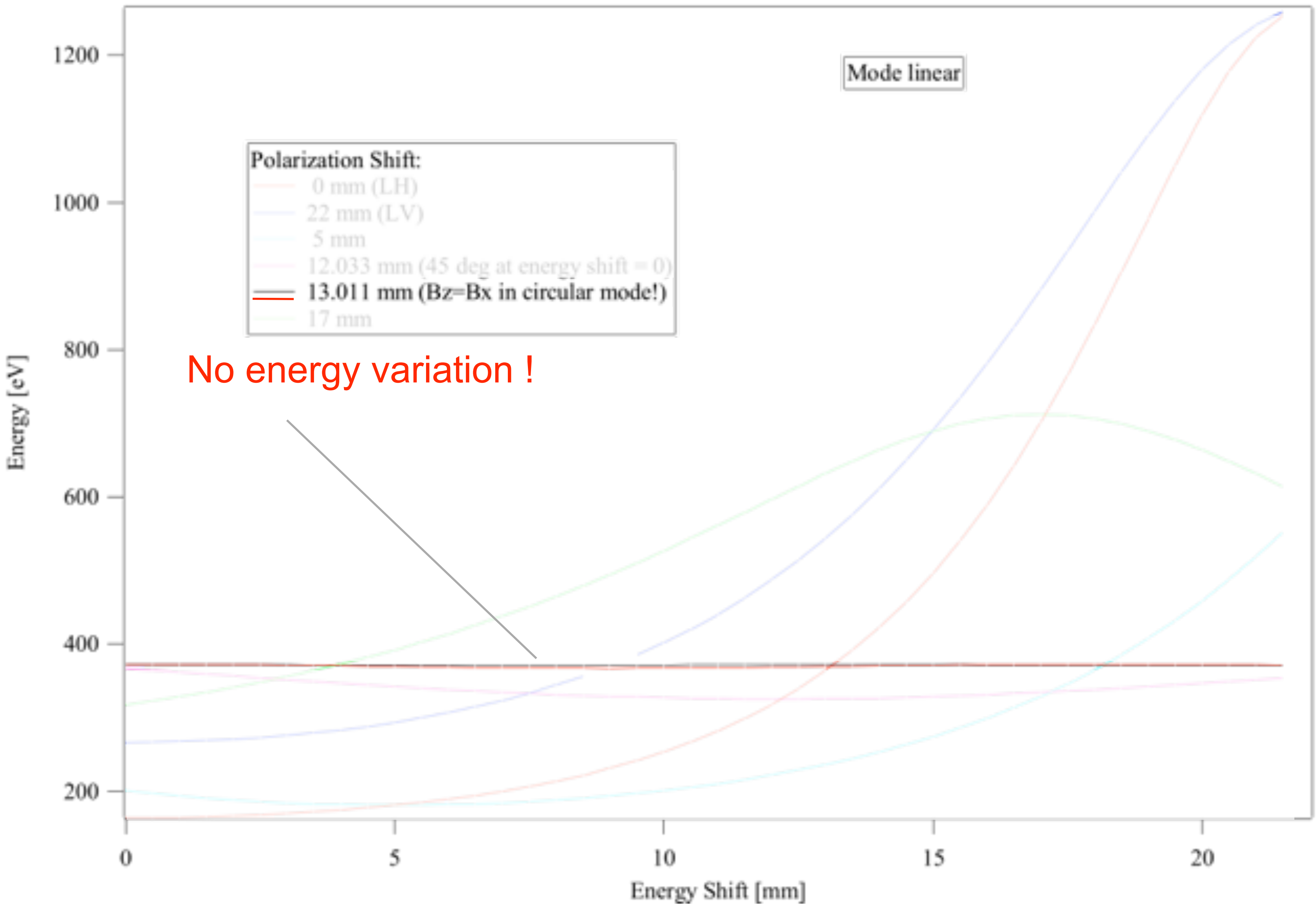
$$E = \frac{C'}{1+0.5(K_{z0}^2\cos^2\frac{\phi}{2}\cos^2\frac{\phi+\rho}{2}+K_{x0}^2\sin^2\frac{\phi}{2}\sin^2\frac{\phi+\rho}{2})}$$

Numeric solution

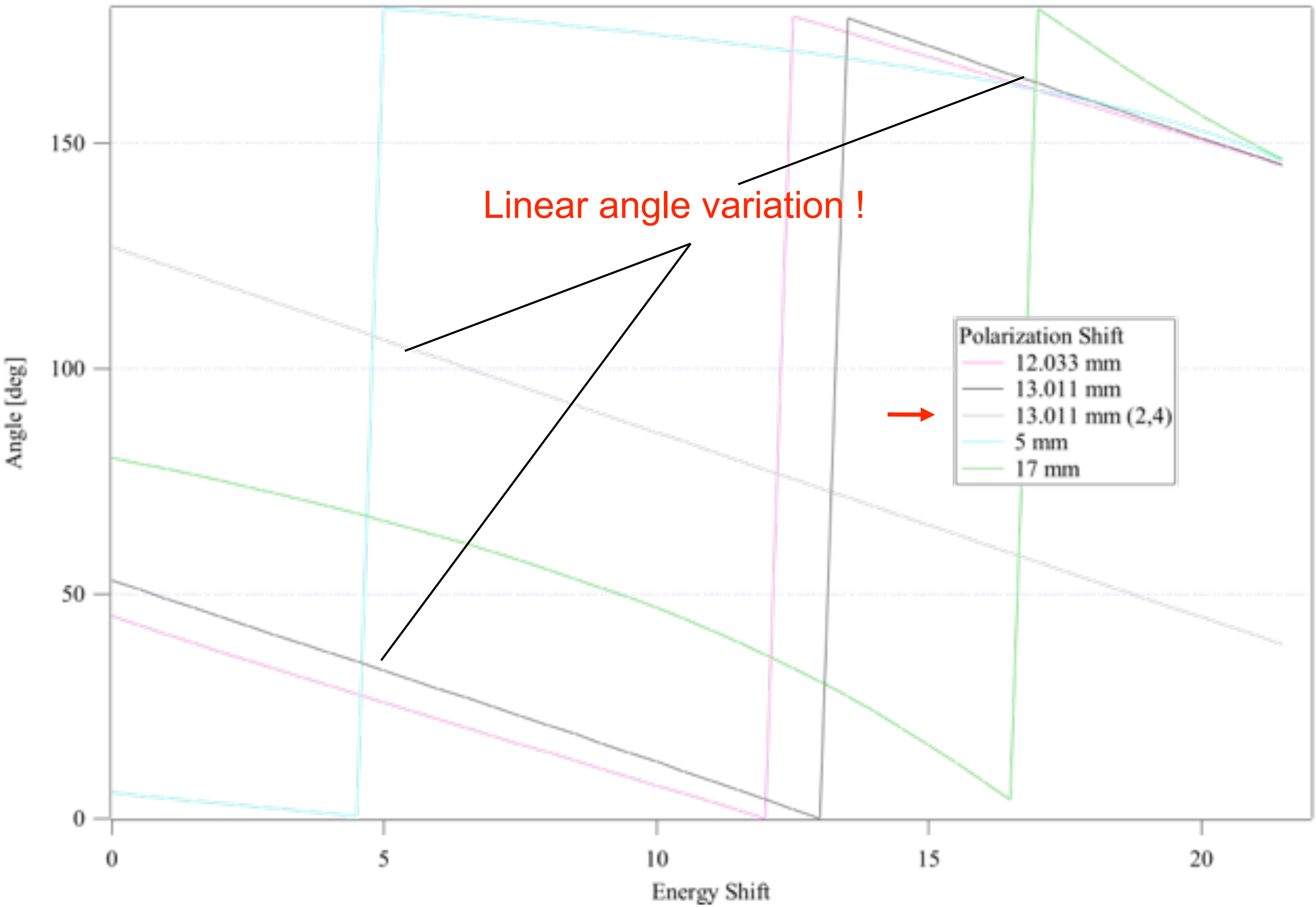
UE44: energy vs energy shift, linear mode



UE44: energy vs energy shift, linear mode



UE44: energy vs energy shift, linear mode



Symmetry Phase

No energy variation with energy shift:

Linear angle variation:

Symmetry Phase

No energy variation with energy shift:

$$E \propto K_{eff}^2 = K_{z0}^2 \cos^2\tfrac{\phi}{2}\cos^2\tfrac{\phi+\rho}{2} + K_{x0}^2 \sin^2\tfrac{\phi}{2}\sin^2\tfrac{\phi+\rho}{2} \equiv const.$$

$$\frac{\partial K_{eff}^2(\phi,\rho)}{\partial\rho} = -K_{z0}^2 \cos^2\tfrac{\phi}{2}\cos\tfrac{\phi+\rho}{2}\sin\tfrac{\phi+\rho}{2} + K_{x0}^2 \sin^2\tfrac{\phi}{2}\cos\tfrac{\phi+\rho}{2}\sin\tfrac{\phi+\rho}{2} = 0$$

$$\phi = \phi_s = 2\arctan\frac{K_{z0}}{K_{x0}}$$

Linear angle variation:

$$\rho = 2\arctan\left(\tfrac{K_{z0}}{K_{x0}}\frac{1}{\tan\arctan\frac{K_{z0}}{K_{x0}}}\cot\alpha\right) - 2\arctan\tfrac{K_{z0}}{K_{x0}}$$

$$= 2\arctan(\cot\alpha) - 2\arctan\tfrac{K_{z0}}{K_{x0}}$$

$$\rho = 2\left(\pm\tfrac{\pi}{2} \mp \alpha\right) - \phi_s$$

Symmetry Phase

Full symmetry of an APPLE II at the symmetry phase:

In circular mode:

constant degree of polarization

energy setting with energy shift ρ

In linear mode:

constant energy

linear variation of polarization angle with ρ

Symmetry Phase

Full symmetry of an APPLE II at the symmetry phase:

$$\phi_s = 2\arctan\frac{K_{z0}}{K_{x0}}$$

In circular mode:

constant degree of polarization

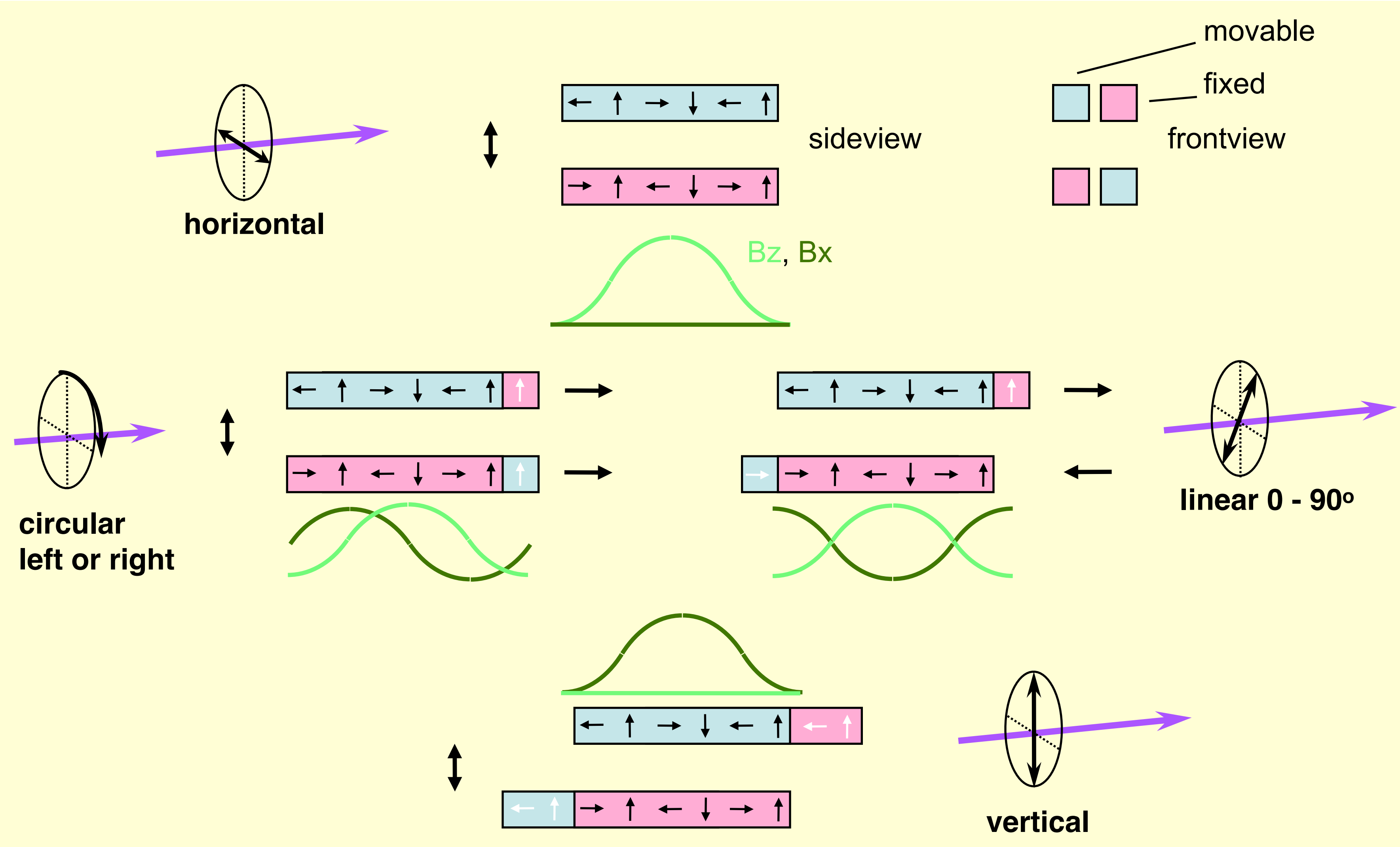
energy setting with energy shift ρ

In linear mode:

constant energy

linear variation of polarization angle with ρ

APPLE II – 4 motor

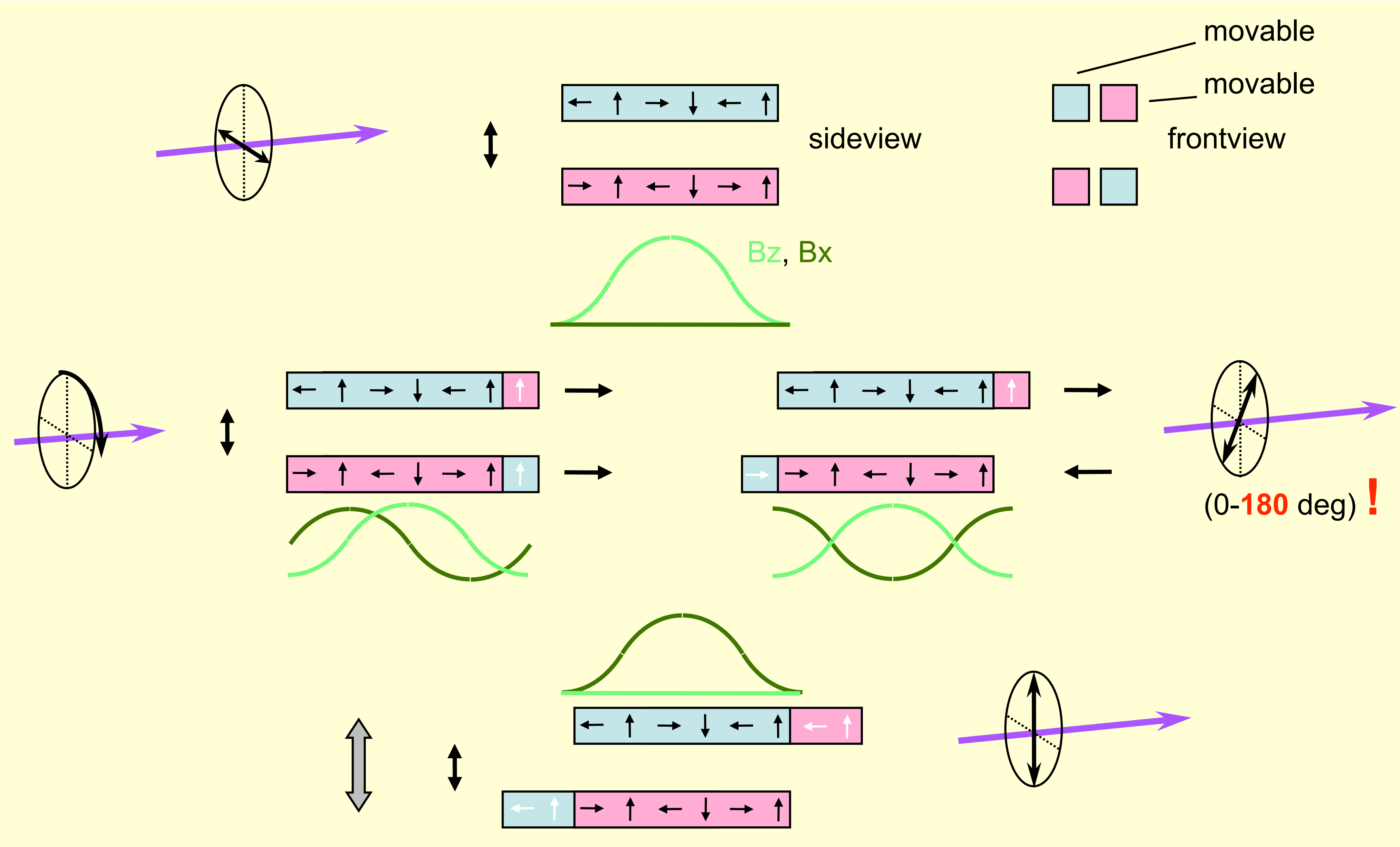


2 gap, energy

2 shift, polarization

energy, polarization = f(gap,shift)

APPLE II – 6 motor



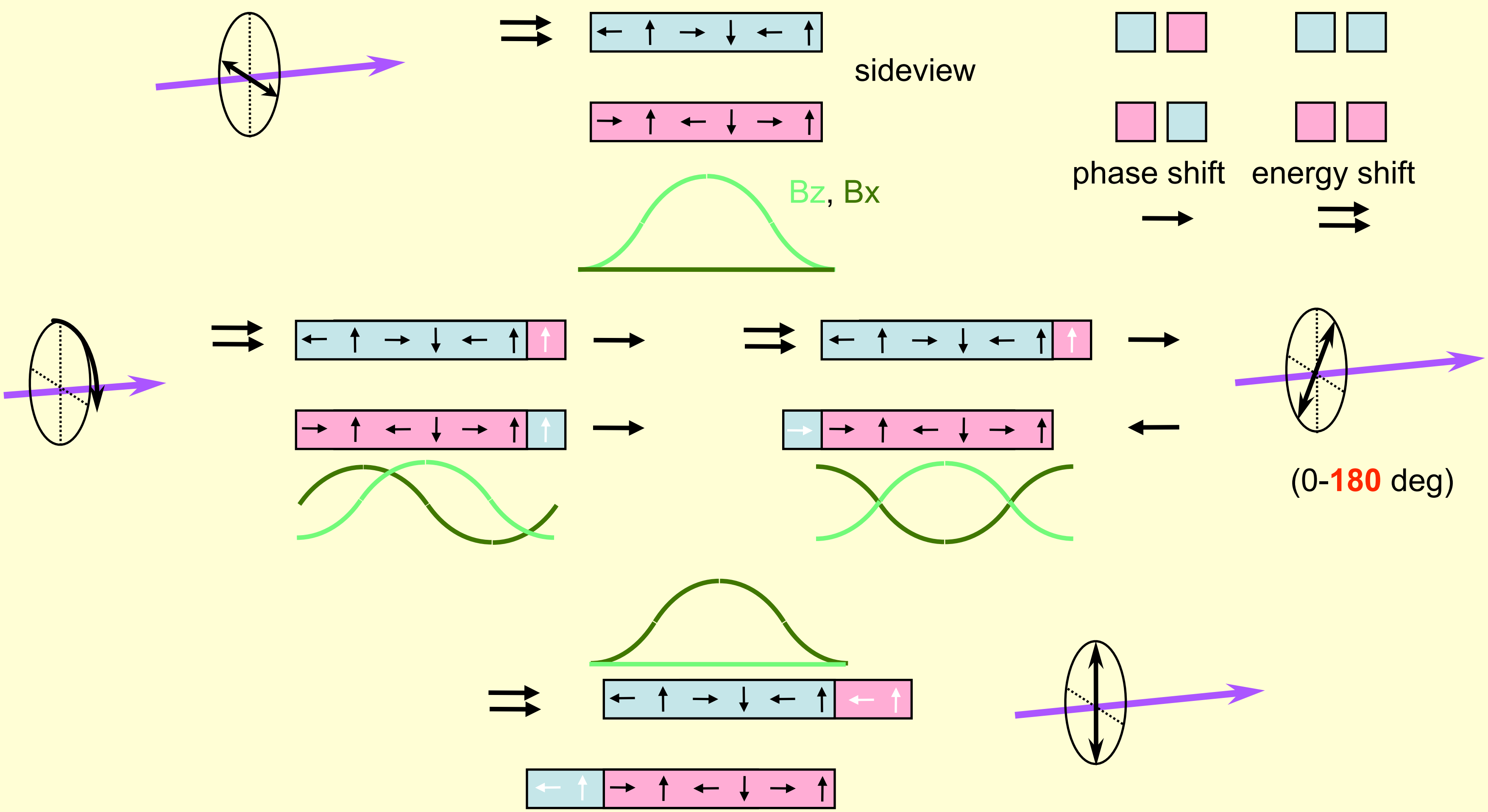
2 gap, energy

4 shift, polarization

energy, polarisation = f (gap,shift)

APPLE II – fixed gap

R. Carr, Adjustable phase undulator, NIM A306, 391 (1991)



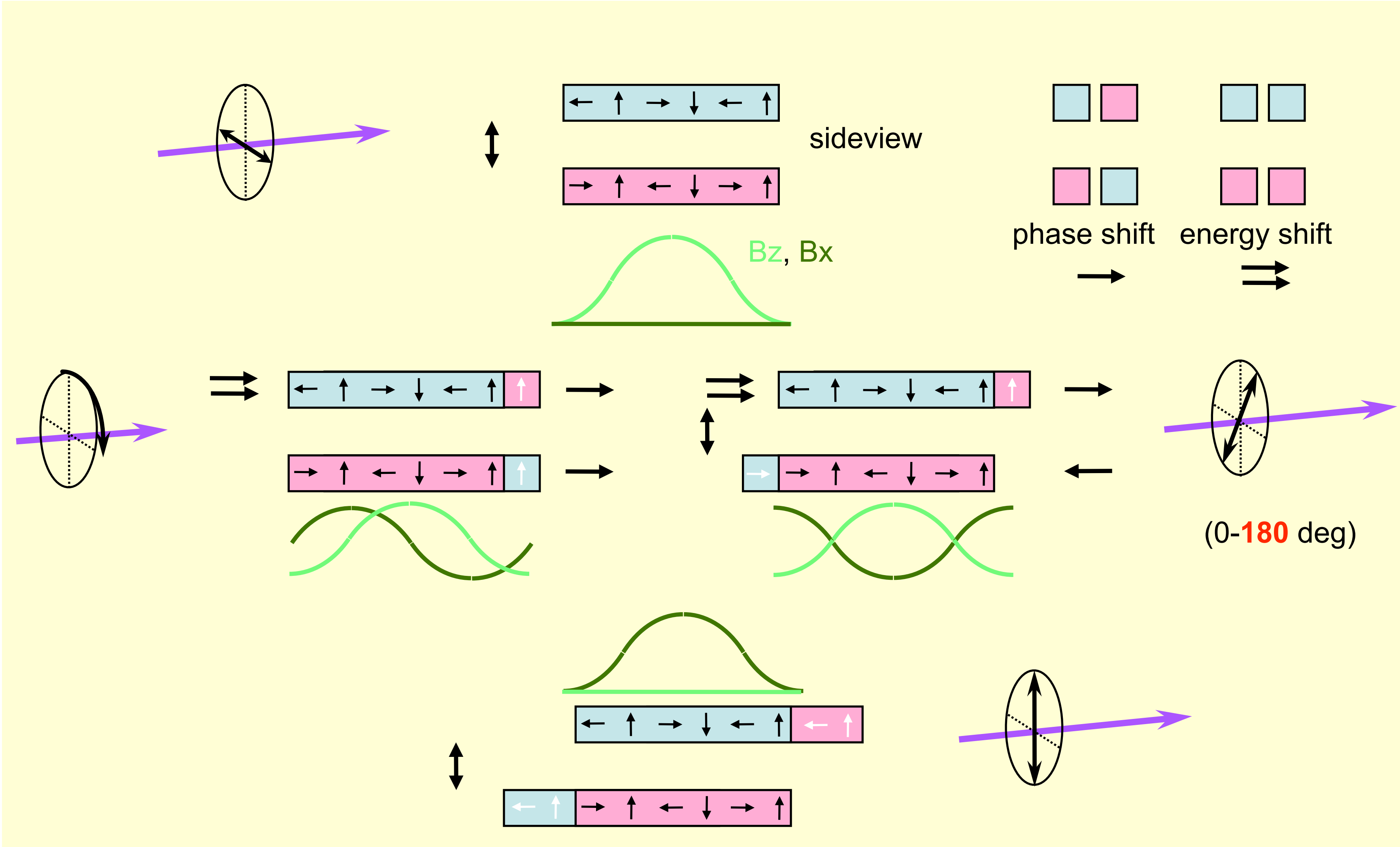
no gap drive: save costs

↔ 4 shift, polarization and energy

Circular: $E = f$ (energy shift) $|_{\textbf{phase shift}}$ **(1-dim)**

Linear: $E, \alpha = f$ (energy - and phase shift)

APPLE II – advanced 6 motor: modified operation mode



↕ 2 gap, energy

↔ 4 shift, polarization, energy

Circular: E = f (energy shift) $|_{\textbf{phase shift}}$ **(1-dim)**

Linear: α = **linear** f (energy shift) $|_{\textbf{phase shift}}$, E=f (gap)

Summary

A semianalytical Model shown for all kinds of APPLE II:

Standard APPLE II

Based on measured data at known polarization states at LH and LV

minimal commissioning effort

Automated algorithm for circular and linrot with numeric solution

Energy shift taken into account (will be implemented soon)

Fixed gap APPLE II

Analytical solution for circular

numeric solution for linrot

Options for 6 motor APPLE II

Advanced operation mode at symmetry phase (analytic, linear)

like fixed gap (use gap drive only for injection open only for injection)

like a standard APPLE II