Next Generation Synchrotron Radiation Source

A Novel Type of Undulator

Gopal Shenoy

Advanced Photon Source,

Argonne National Laboratory, Argonne, IL 60439

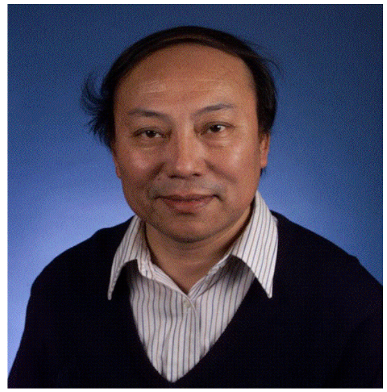
Insertion Device Workshop

Advanced Photon Source

December 5, 2002

Collaborators

John Lewellen



Deming Shu

Novosibirsk

Nikolai Vinokurov

Reference: G.K.Shenoy. J. Lewellen, D. Shu, and N. Vinokurov

Journal of Synchrotron Radiation

(to be published)

Topics to be Covered

1. *Undulator Equation*
2. *The New Concept*
3. *Expected Performance of the New Concept*
   - On High Energy Storage Ring (APS)
   - On Medium Energy Storage Ring (DIAMOND)
4. *New and Unique Capabilities*
5. *Accelerator Related Challenges*
6. *Mechanical Design Considerations*
7. *Summary*

Undulator Equation

The x-ray energy of the n^{th} harmonic of radiation, E_n, produced along the axis of the undulator is given by

$$E_n\,(\mathrm{keV}) = 0.95\,E^2\,(\mathrm{GeV})\,n\,/\,[\lambda_u(\mathrm{cm})\,(1 + K^2/2)] \qquad (1)$$

where

$$K = 0.934\,\lambda_u(\mathrm{cm})\,B_y(\mathrm{T})\,, \qquad (2)$$

where B_y is the peak value of the periodic magnetic field in the y direction.

What Options Remain for Improved Undulator Performance?

- Low X-ray Energies
  - ➡ Large K leads to broad tunability
    - ➡ Increased total power
- High X-ray Energies
  - ➡ Short periods leads to limited tunability
- Brilliance
  - ➡ Longer Undulators
    Increased Stored Current
    - ➡ Increased total power

Option for Next Generation UndulatorSources!

Variable Undulator Period

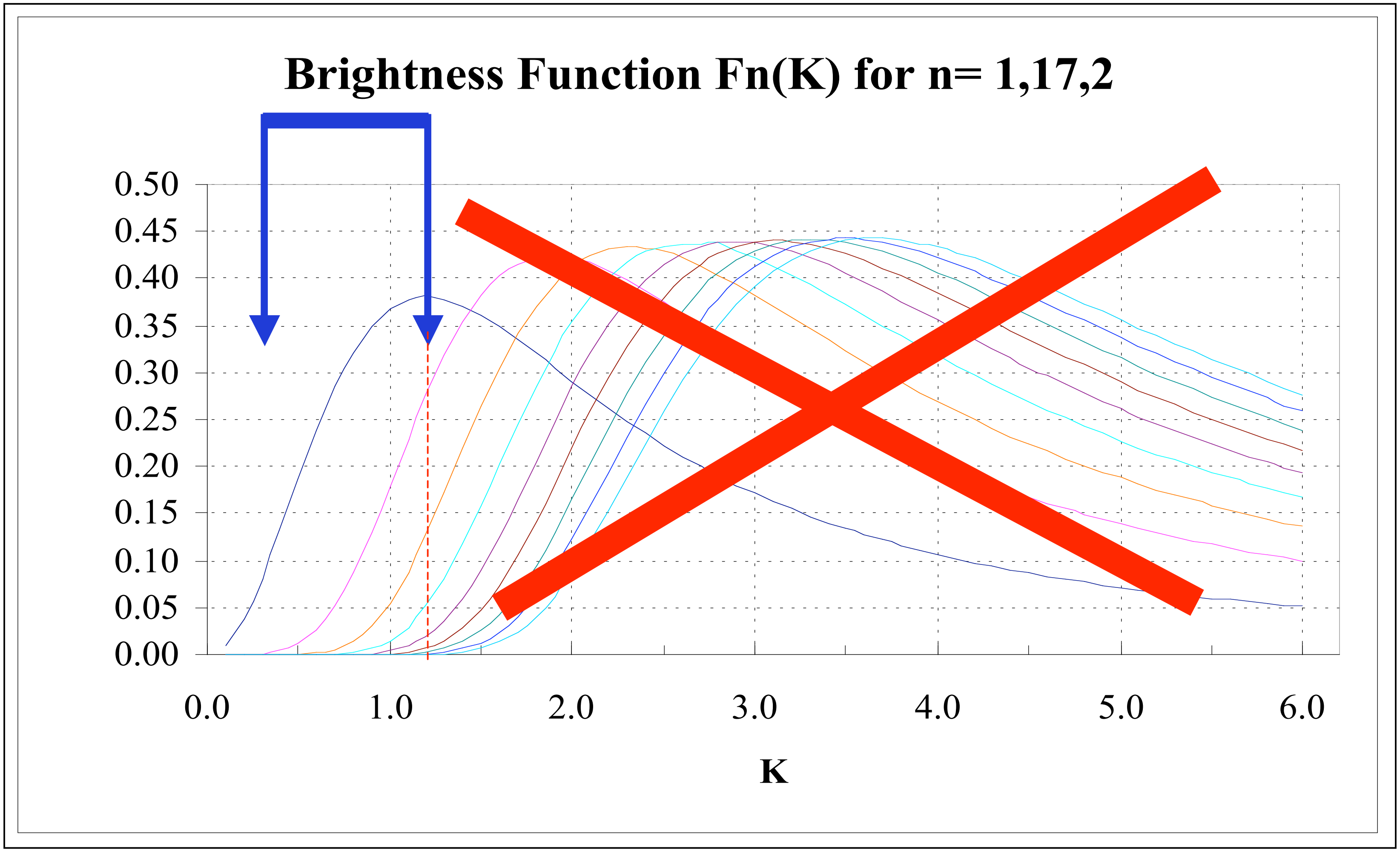
$$E_n\,(keV) = 0.95\,E^2\,(GeV)\,n\,/\,[\lambda_u(cm)\,(1 + K^2/2)] \qquad (1)$$

where $$K = 0.934\,\lambda_u(cm)\,B_y(T)\,, \qquad (2)$$

where B_y is the peak value of the periodic magnetic field in the y direction.

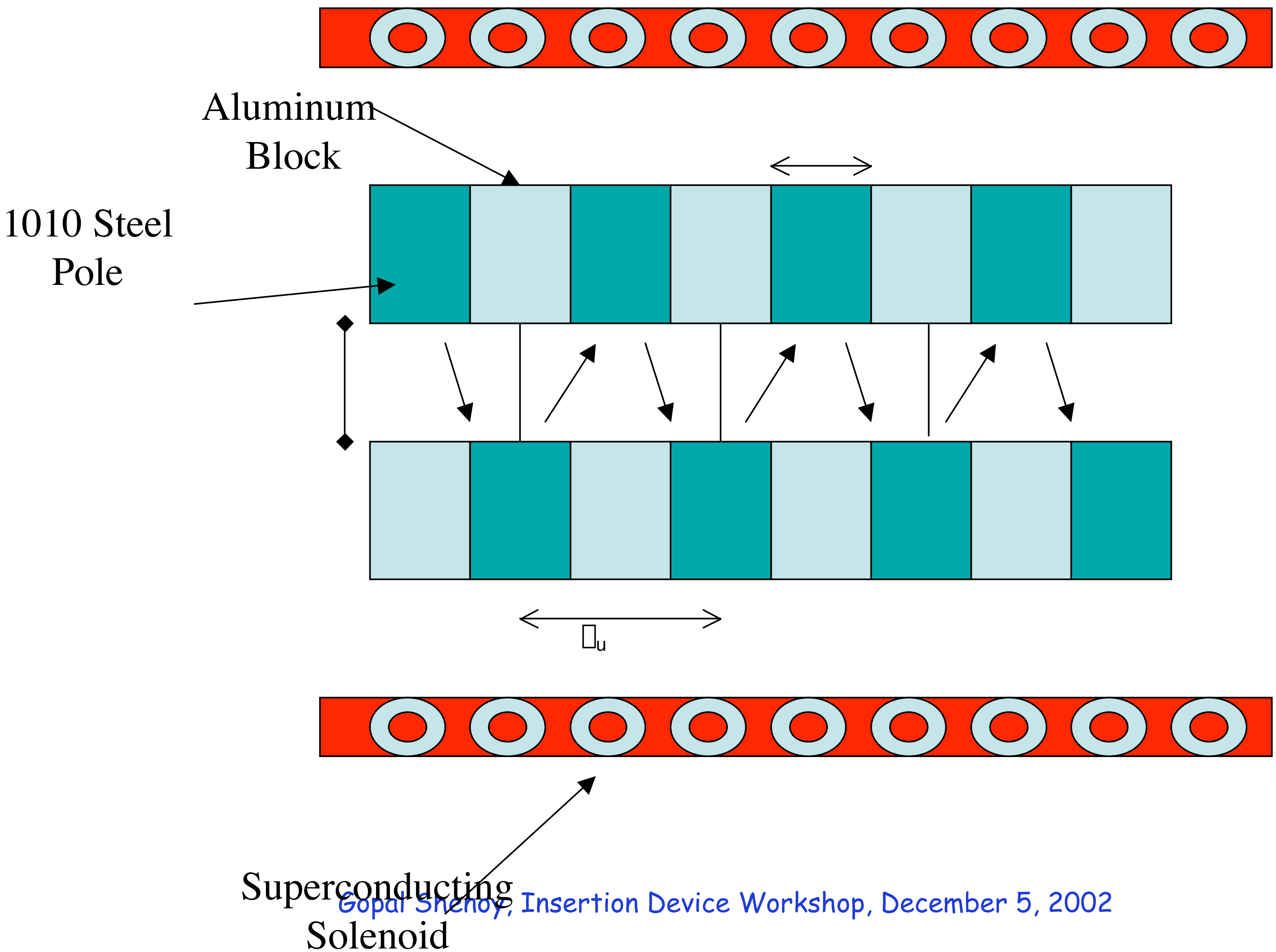
Photon Brilliance

[dn/dt/d□ /(d□/□)] = 1.21 X 10^{14} I(A) E^2 (GeV^2) N^2 F_n (K)

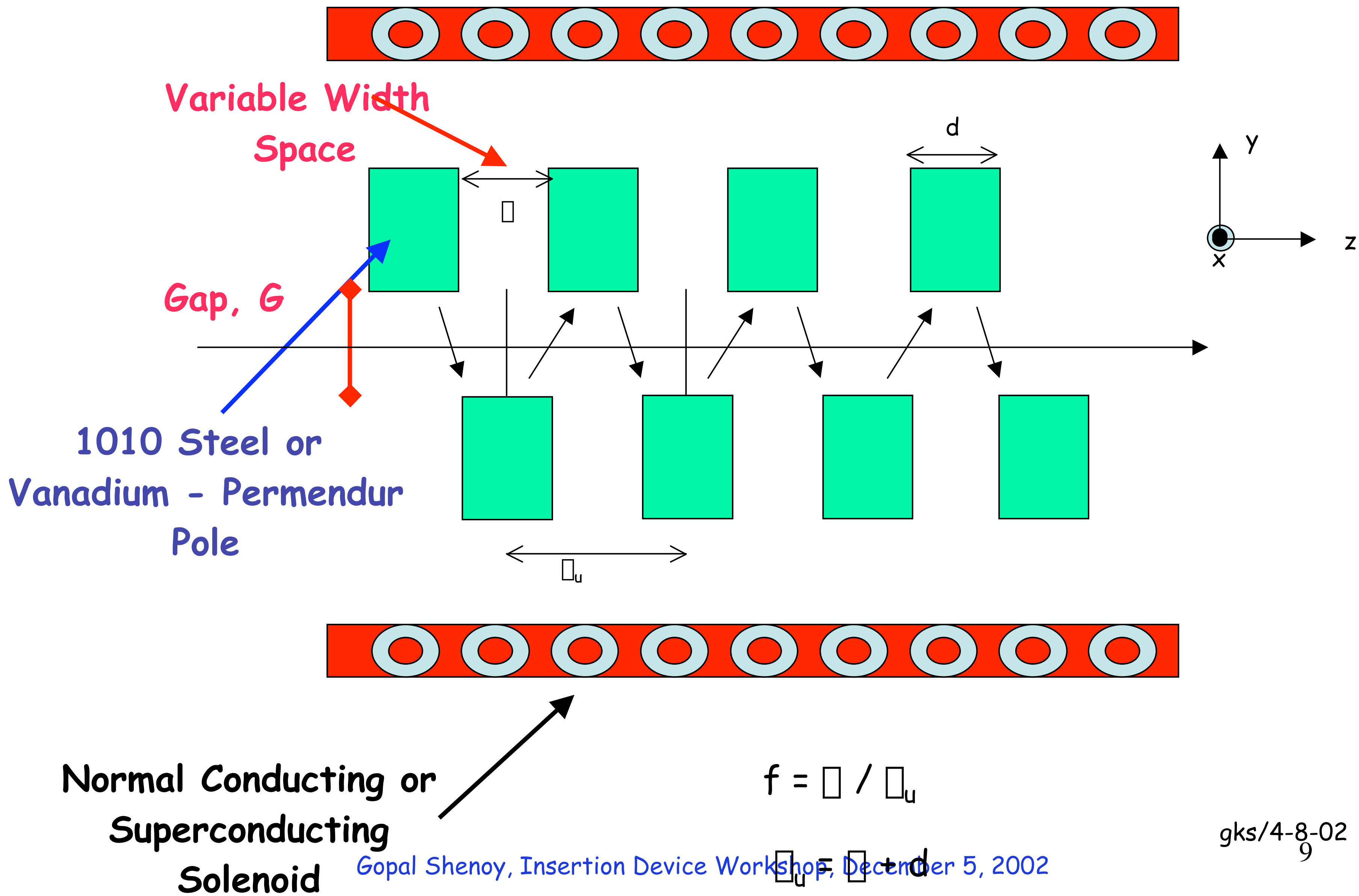


A Solenoid Driven Wiggler

A. Ho, R. H. Pantell, J. Feinstein, Y. C. Haung,
IEEE, J. Quantum Electron. 27, no. 12 (1991)



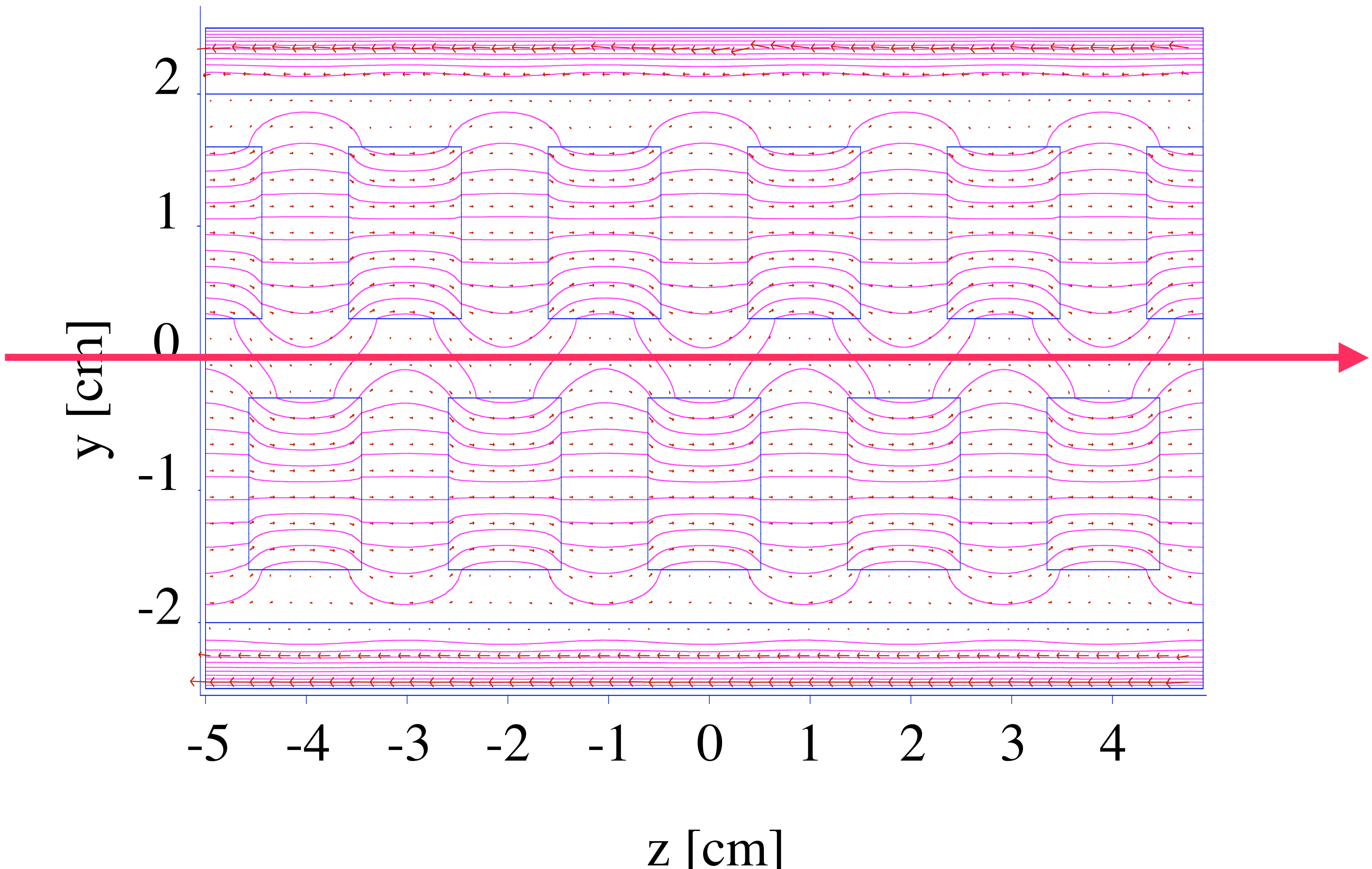
Variable-Period Undulator - A New Concept



$f = \lambda / \lambda_u$

$\lambda_u = \lambda + d$

Principle of Variable Period Undulator



Value of B_y

For small undulator period, the amplitude of the first harmonic of the magnetic field is approximated by

$$B_y = [\, 2 B_0 / \sinh (\pi g/\lambda_u)]\, (\sin \pi f)/(\pi f)$$

where g is the gap, f = □/λ_u, and B_0 is the solenoid field.

- Increasing B_o, or reducing g or □ will increase B_y
- However, the saturation magnetization of high-permeability material sets the limit on B_y
- Full analysis requires solution to Poisson equations and optimization of pole-width, d for a given value of λ_u and g.

Optimized values of f and pole width from Poisson analysis for two cases, and effective value of K (K_{eff}).

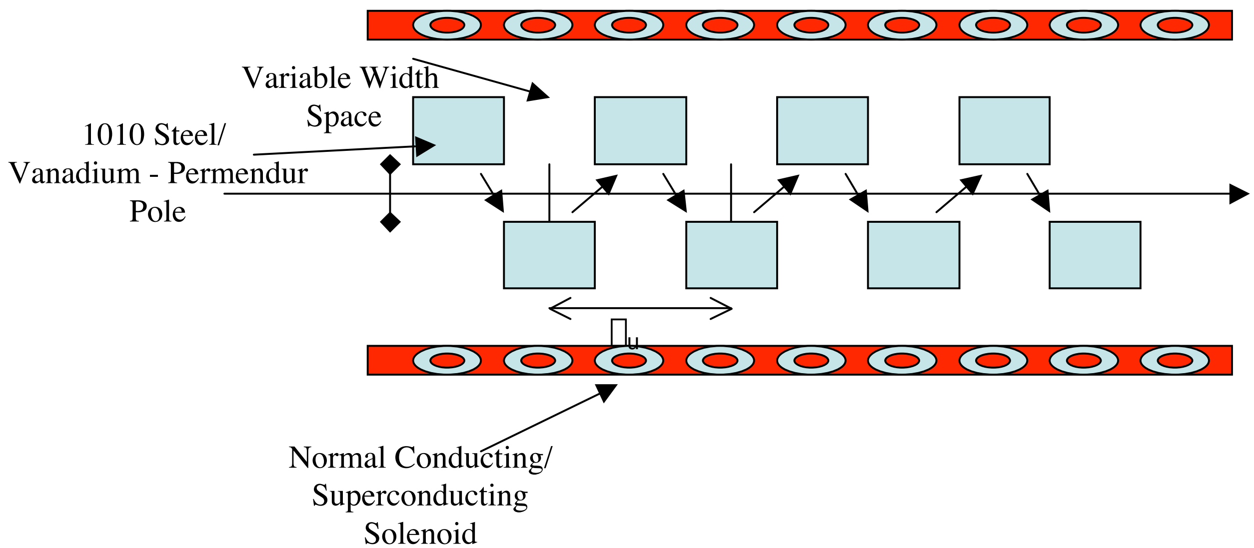
□	Minimum Period λ_u in cm*	Gap G in cm	Optimized f = □/λ_u	VariableWidth Space □ in cm	Pole-Width d in cm	K_{eff} min
I	1.3	0.5	0.615	0.53 - 1.83	0.77	0.62
II	1.5	0.6	0.564	0.37 - 1.87	1.13	0.67

□

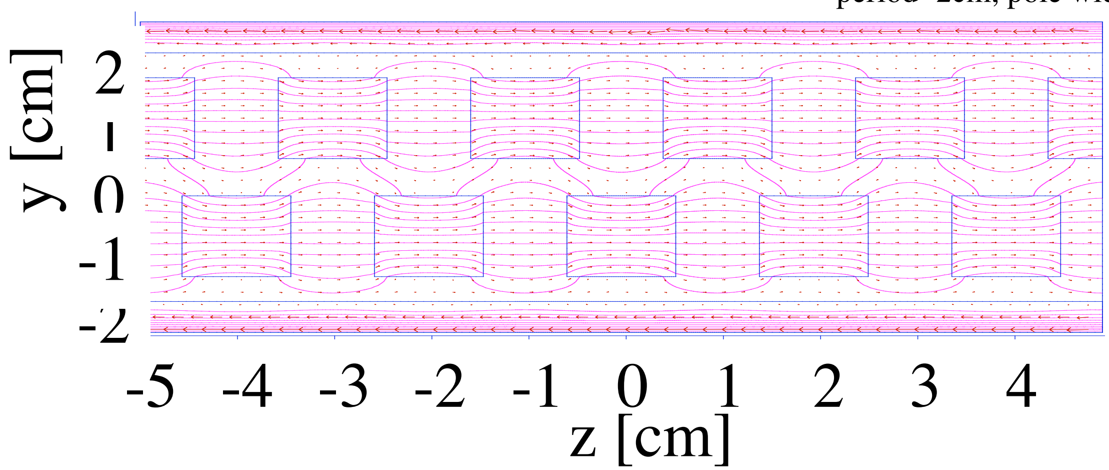
□ * Maximum value of the period is twice the minimum

Chosen pole piece material is 1010 Steel

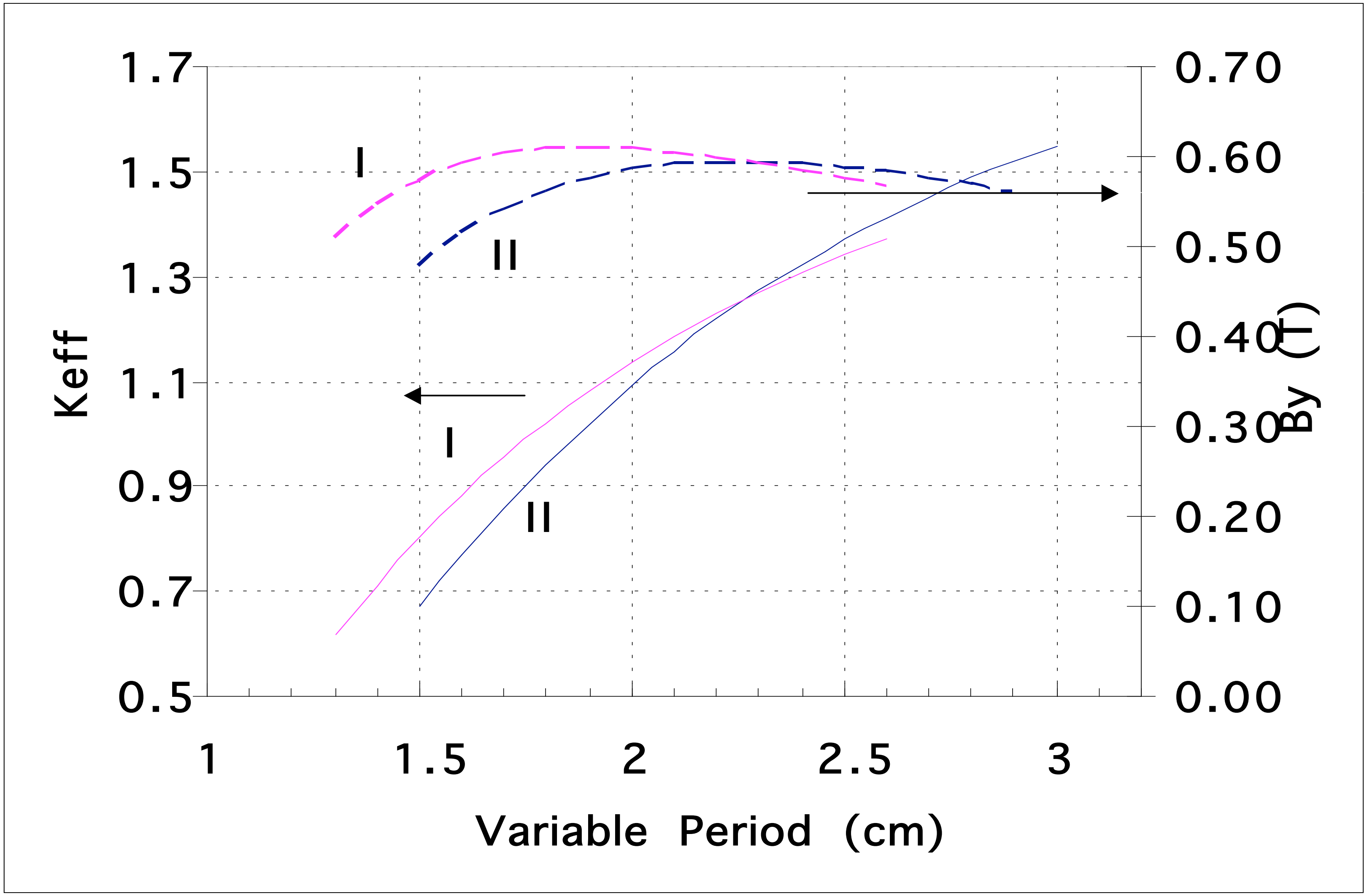
Magnetic Analysis



period=2cm, pole width=1.13cm, gap=0.6cm



Demonstration of Performance
Undulator I (Minimum Period = 1.3 cm, Gap = 0.5 cm)
Undulator II (Minimum Period = 1.5 cm, Gap = 0.6 cm)



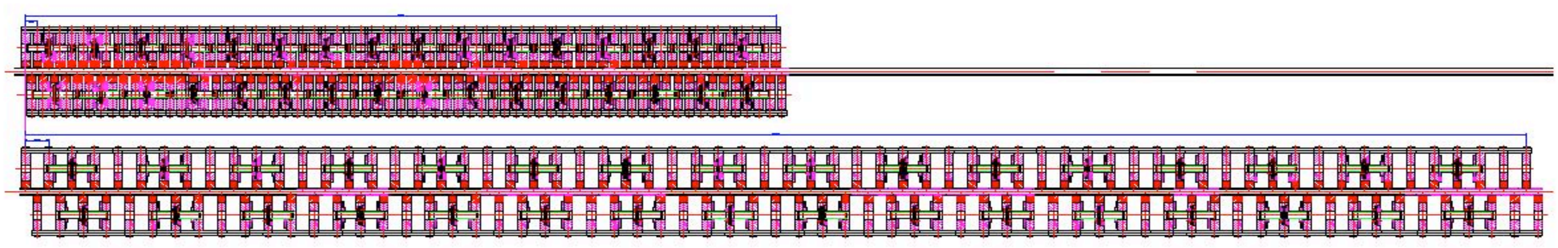
Electron beam properties used in the calculations to demonstrate the performance through period variation with in a single undulator.

Properties	Medium Energy [a]	High Energy [b]
Energy (GeV)	3.0	7.0
Current (mA)	300	100
Beam Size, σ_x (mm)	91.4	254
Beam Divergence, σ'_x(mrad)	25.7	15.6
Beam Size, σ_y (mm)	7.0	12
Beam Divergence, σ'_y(mrad)	2.8	3.0
Electron Energy Spread (10^{-3})	1.0	1.0
Minimum Undulator Period (cm)	1.3	1.5
Number of Undulator Periods	80	70
Period Increase Factor	2.0	2.0
Approximate Solenoid Length(m)	2.2	2.2
Maximum Solenoid Field (T)	1.3	1.3

aa..Taken from DIAMOND design. b. Current APS operational parameters.

Full Scale View of the Variable Period Undulator

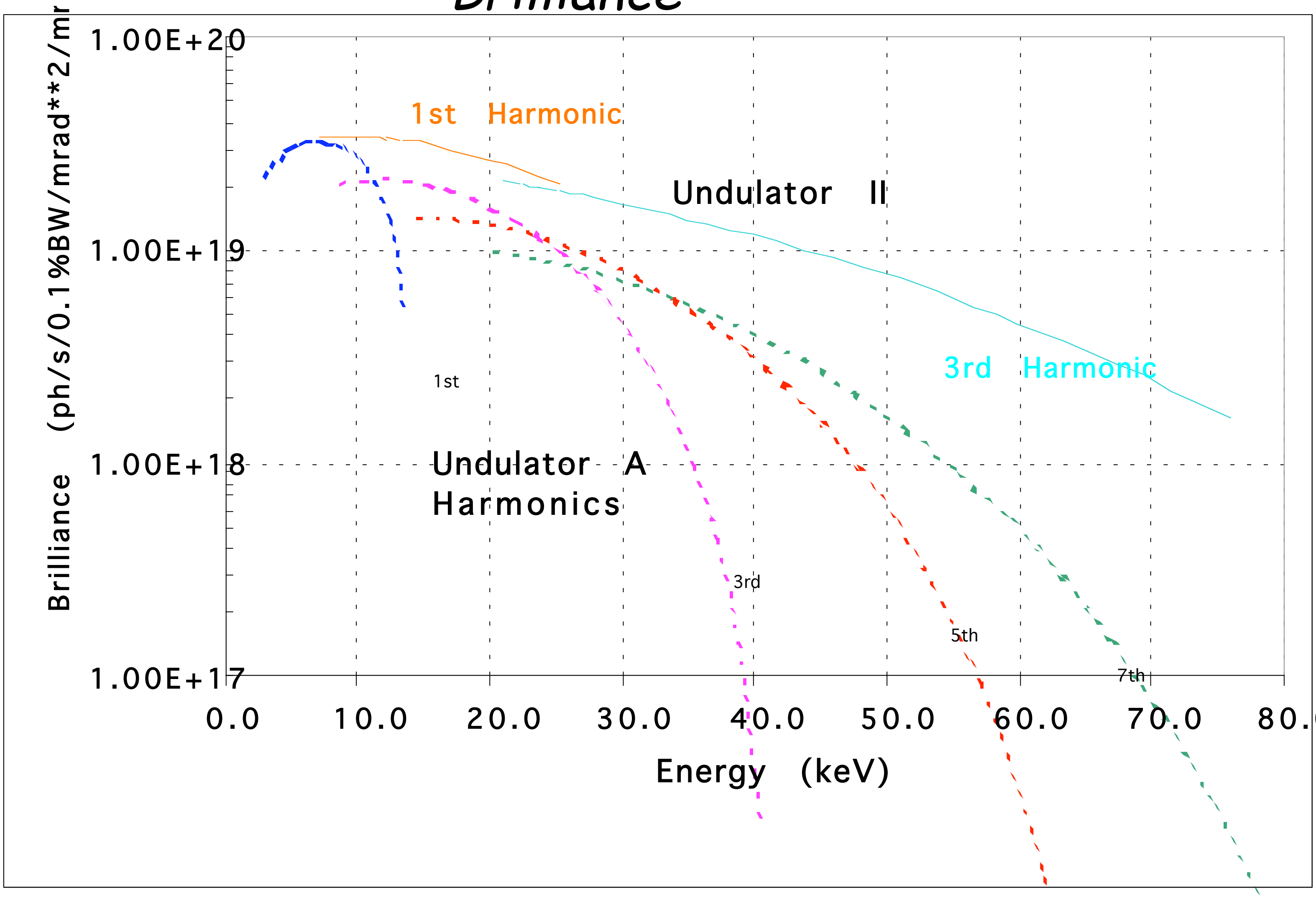
λ_u = 1.5 cm, N = 78, L = 1.2 m

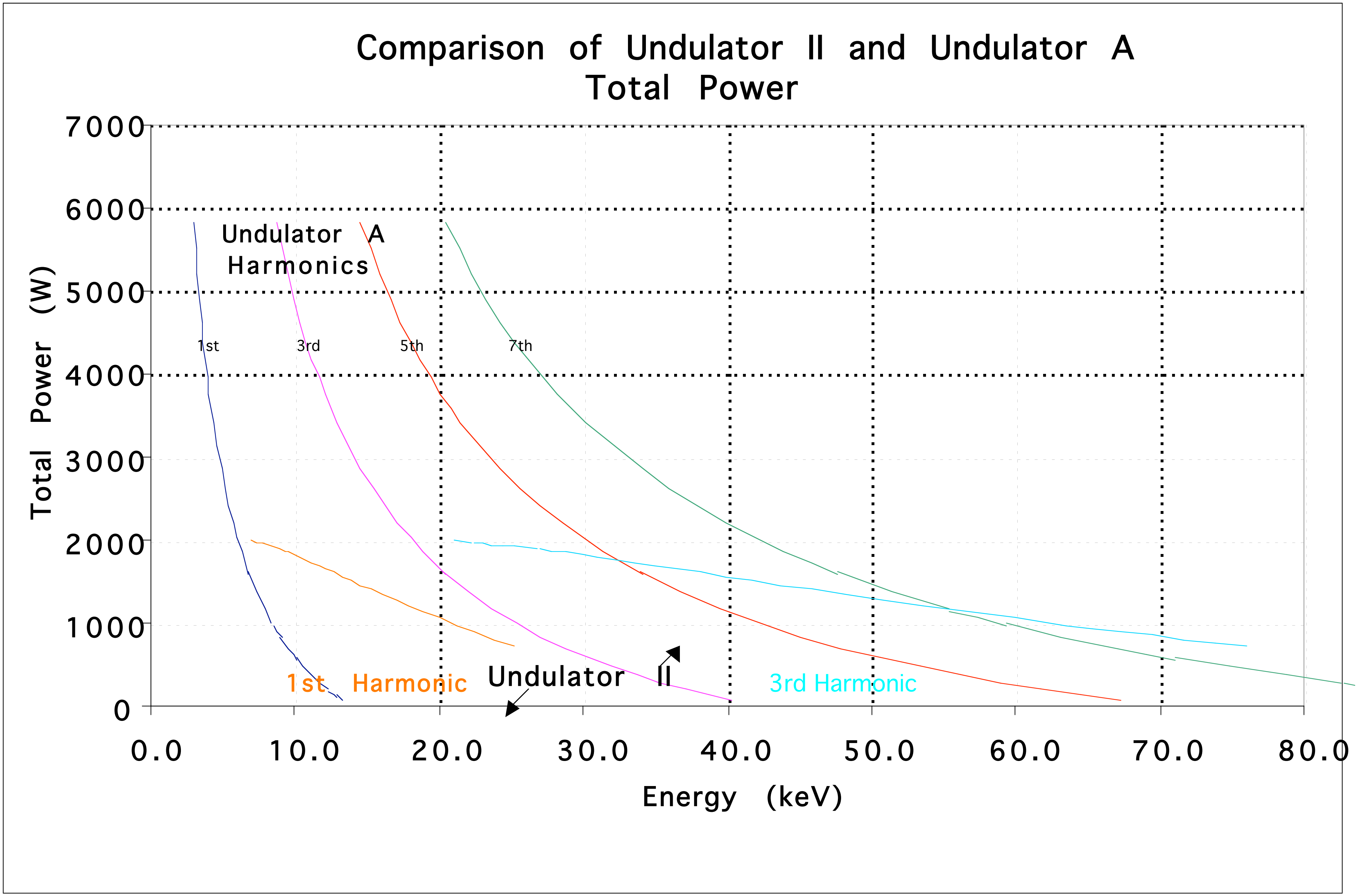


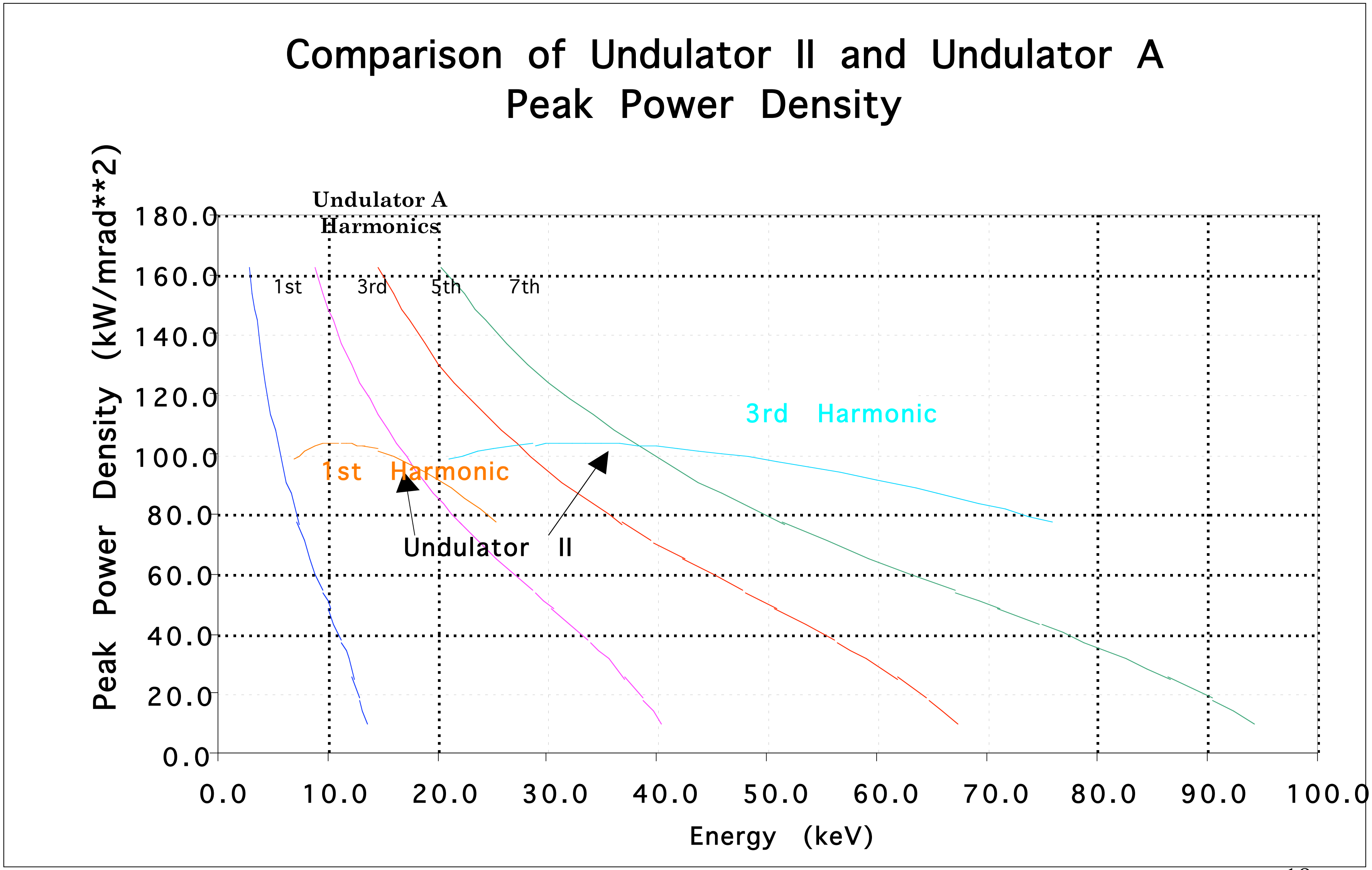
λ_u = 3.0 cm, N = 78, L = 2.4 m

Solenoid Length ~ 2.45 m, B_o = 1.2 T

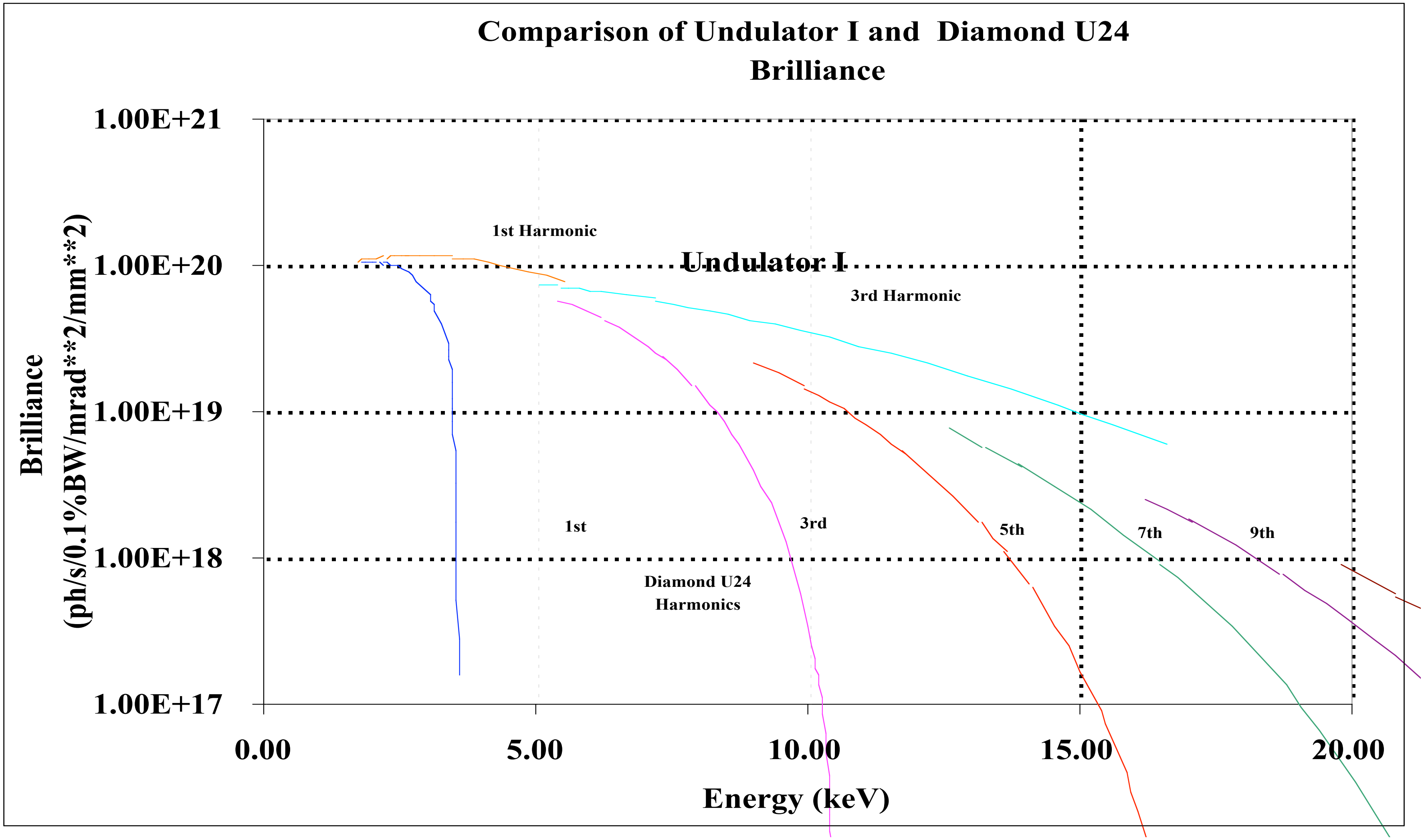
Comparison of Undulator II and Undulator A Brilliance




Comparison of Undulator II and Undulator A
Total Power
Total Power (W)
Energy (keV)
7000
6000
5000
4000
3000
2000
1000
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Undulator A
Harmonics
1st
3rd
5th
7th
1st Harmonic
Undulator II
3rd Harmonic

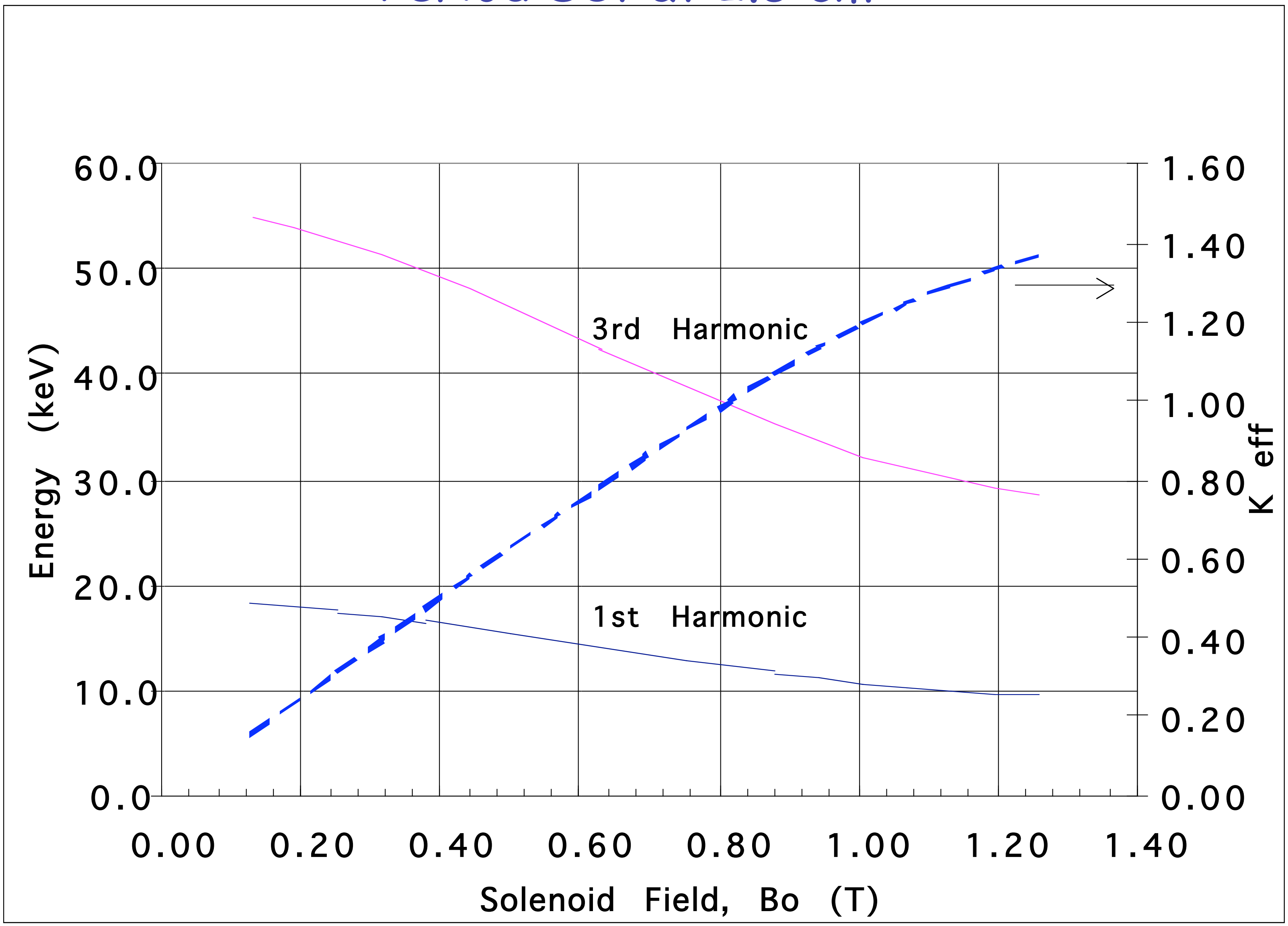


Comparison of Undulator II and Undulator A
Peak Power Density
Undulator A
Harmonics
1st
3rd
5th
7th
3rd Harmonic
1st Harmonic
Undulator II
Peak Power Density (kW/mrad**2)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
Energy (keV)



Comparison of Undulator I and Diamond U24
Brilliance
1.00E+21
1.00E+20
1.00E+19
1.00E+18
1.00E+17
Brilliance
(ph/s/0.1%BW/mrad**2/mm**2)
1st Harmonic
Undulator I
3rd Harmonic
1st
3rd
5th
7th
9th
Diamond U24
Harmonics
0.00
5.00
10.00
15.00
20.00
Energy (keV)

Tunability of Undulator II through Solenoid Field Variation
Period Set at 2.5 cm



Constant K Operation

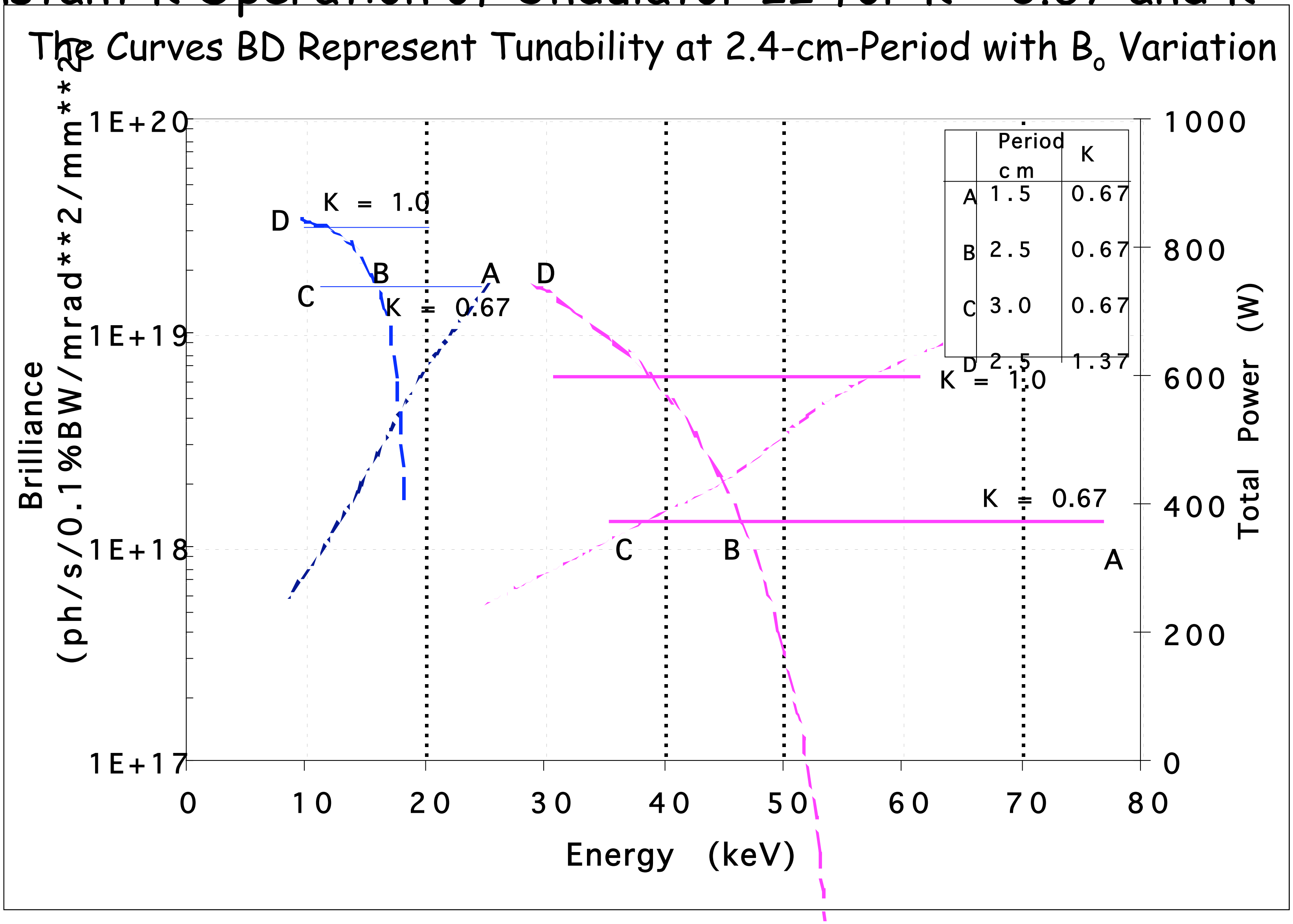
. Results in Constant Flux (and Brilliance at High X-ray Energies) at all X-ray Energies

. Value of K can be a Constant by Adjustment of Solenoid Field when Period is Changed

. A True Use of the Top Up Operation of the Storage Ring by Keeping the Brilliance Constant at all X-ray Energies

Currently impossible!

Constant K Operation of Undulator II for K = 0.67 and K = 1.0



Constant Power Operation

$$P_T = 0.633 \times 10^{-3}\, E^2 (GeV^2)\, I\,(A)\, N\, \lambda_u\, B_y^2$$

P_T at All X-ray Energies is a Constant if

$$\lambda_u\, B_y^2 = Constant$$

Constant Power Load on FE and Optics at All X-ray Energies when Operated in the Top-Up Mode.

Currently Impossible!

Unique Capabilities and Advantages

- Device:
  - Ambient or UHV Environment
  - No Radiation Degradation
- Modulating X-ray Energies / Switching Between X-ray Energies
  - Spectroscopies
  - Anomalous Scattering and MAD
  - Effective Undulator Tapering

All Through Manipulation of Solenoid Field, B_o

- Higher Current Operation of Storage Rings with Existing Heat Load Solutions

Unique Capabilities and Advantages (continued)

Variable Period Undulators for Tunable SASE FELs Or as After Burners.

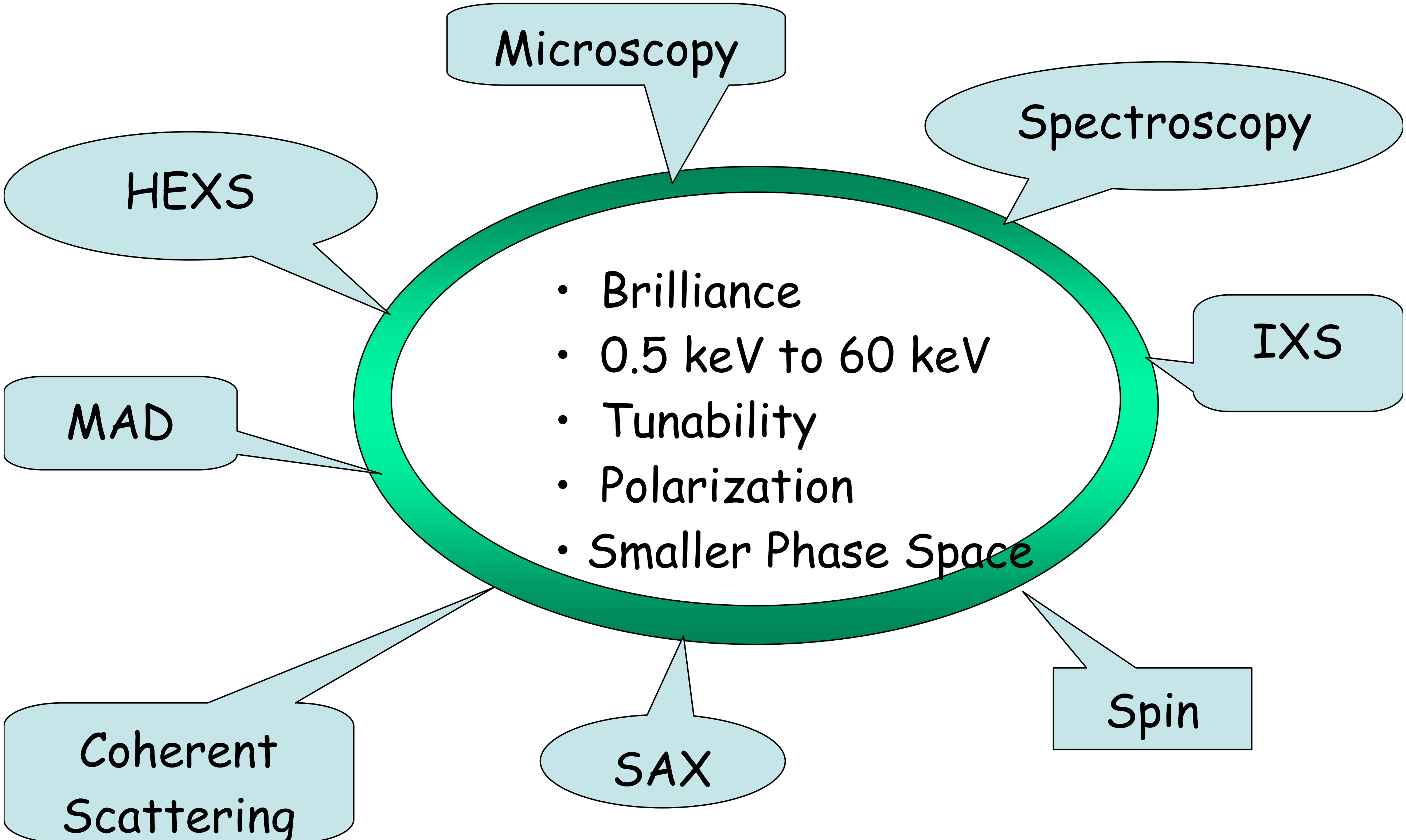
Possible New Geometries of Poles to Modify X-ray Properties.
E.g., Polarization

Optimized Power Load Design to Suite the Needs of the Experiment

Why is this undulator unique?

It can be operated with K = 0.5 ~ 1.5 .
Net result is the following:

- Broad Tunability with a Single Device
- Low Power Loads Allowing Higher Stored Current Operation
- Two Independent Controls in Defining Radiation Properties: Period and Solenoid Field (No Gap Variation)
- Potential for ERLs and Tunable FEL Applications


Microscopy
Spectroscopy
HEXS
IXS
MAD
• Brilliance
• 0.5 keV to 60 keV
• Tunability
• Polarization
• Smaller Phase Space
Coherent Scattering
SAX
Spin

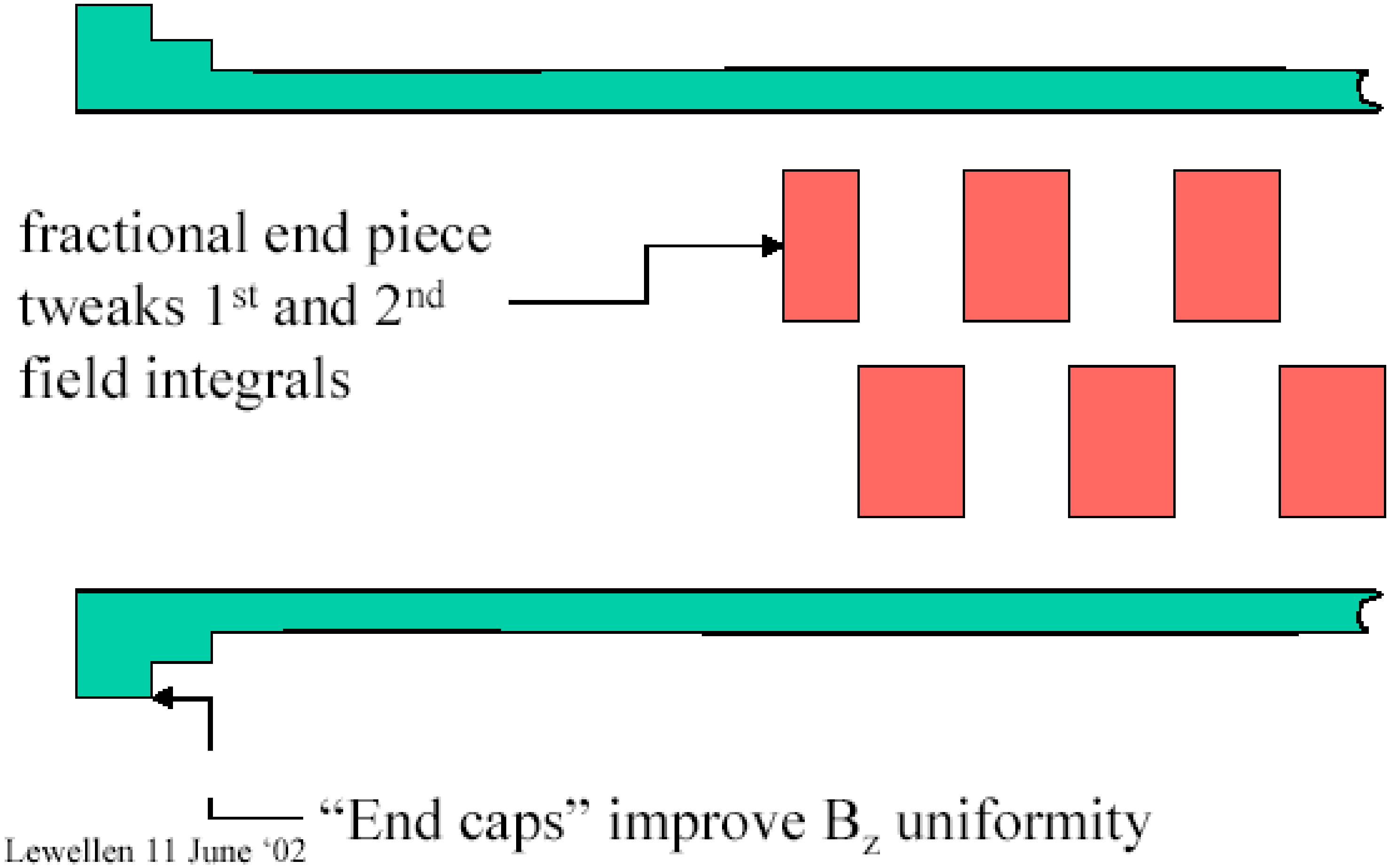
Accelerator Related Challenges - But No Show Stoppers

- *Storage ring operation with small aperture straight sections (5mm); top-up relives stored-beam life-time degradation*

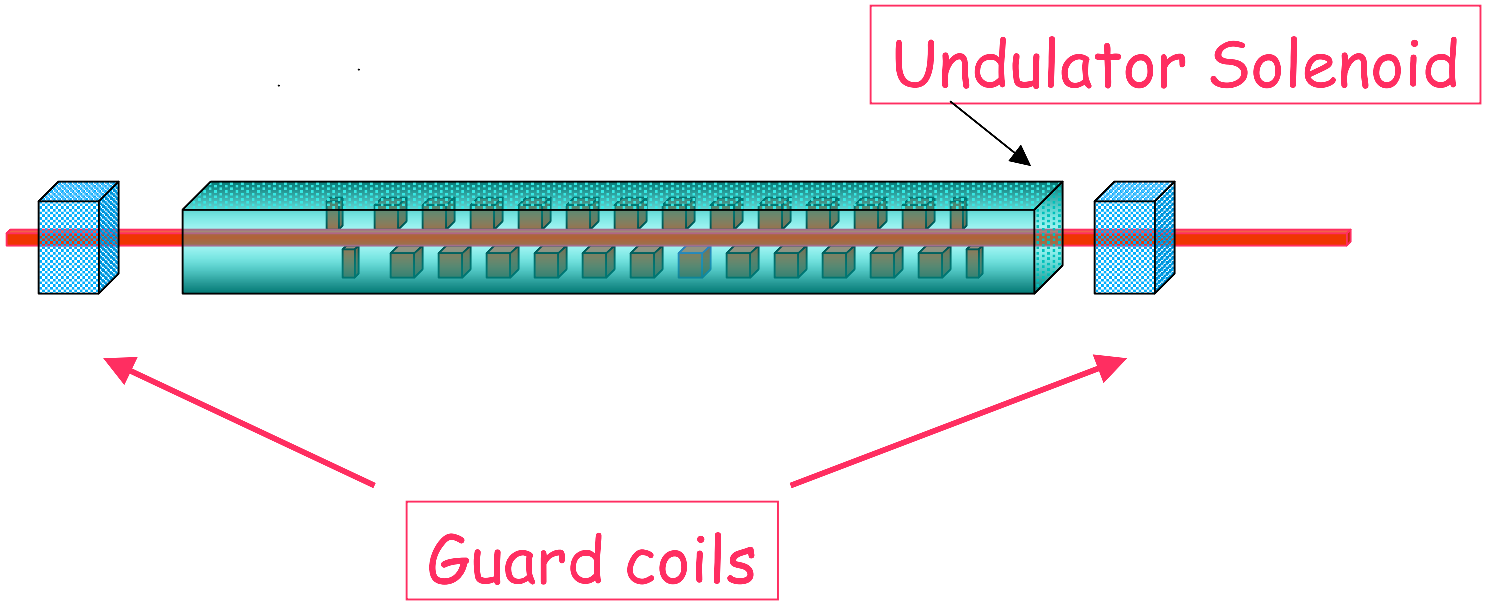
- *End correction for the solenoid and the undulator*

- *Longitudinal solenoid field - x-y coupling*
  - *Adding 'guard' solenoids at either ends of the device*
  - *Most likely superconducting coils to conserve straight section space*

End Correction Scheme for the Solenoid And The Undulator



Compensation Scheme for Electron Beam Rotation Due to x-y Coupling from Longitudinal Field



Guard coils are possibly superconducting to conserve straight-section space

Phase Errors

Governing Factors:

- Peak Field Fluctuation
- Period Fluctuation
- Field Shape Fluctuation

Example: APS - 3.3 cm period, B = 0.71T, K=2.2

1 degree phase error is introduced by:

- Either 0.2% RMS Peak Field Fluctuation
- Or about 40μ Period Fluctuation

Preliminary study shows that the above requirements can be met in the new device, especially since only the first two odd-harmonics are of importance

Mechanical Design Considerations for Variable Period Undulator

- Driving Mechanism for Variable Period Undulator
- Supporting and Guiding Structure for Variable Period Undulator

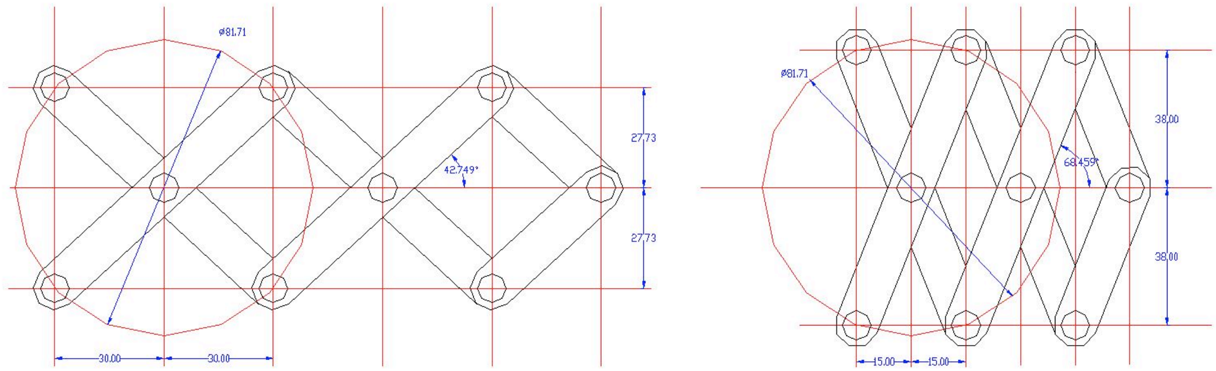
Driving Mechanism

Design Concepts

1. "Scissor or Pantograph" Design Concept

2. "Counter-Screw" Design Concept

"Scissor or Pantograph" Design Concept

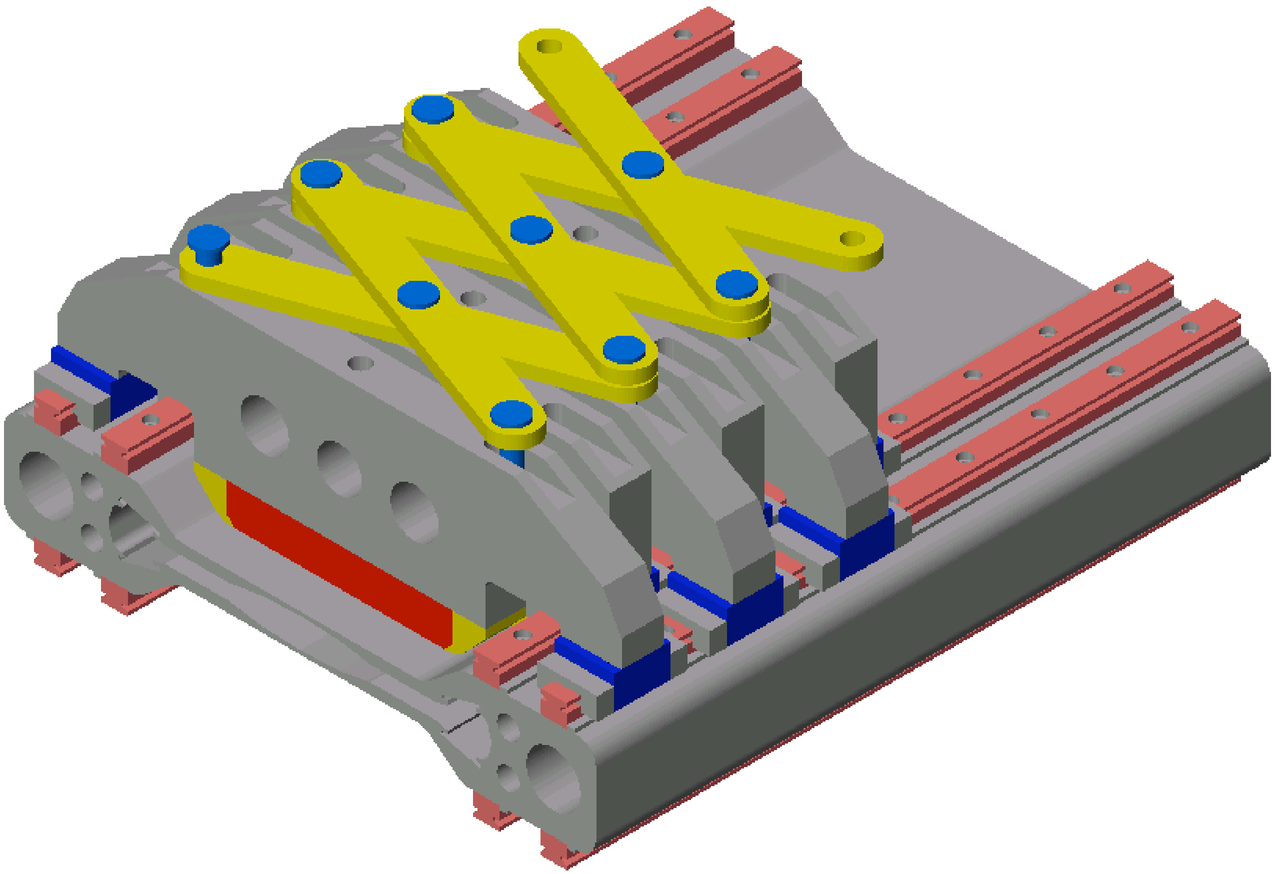


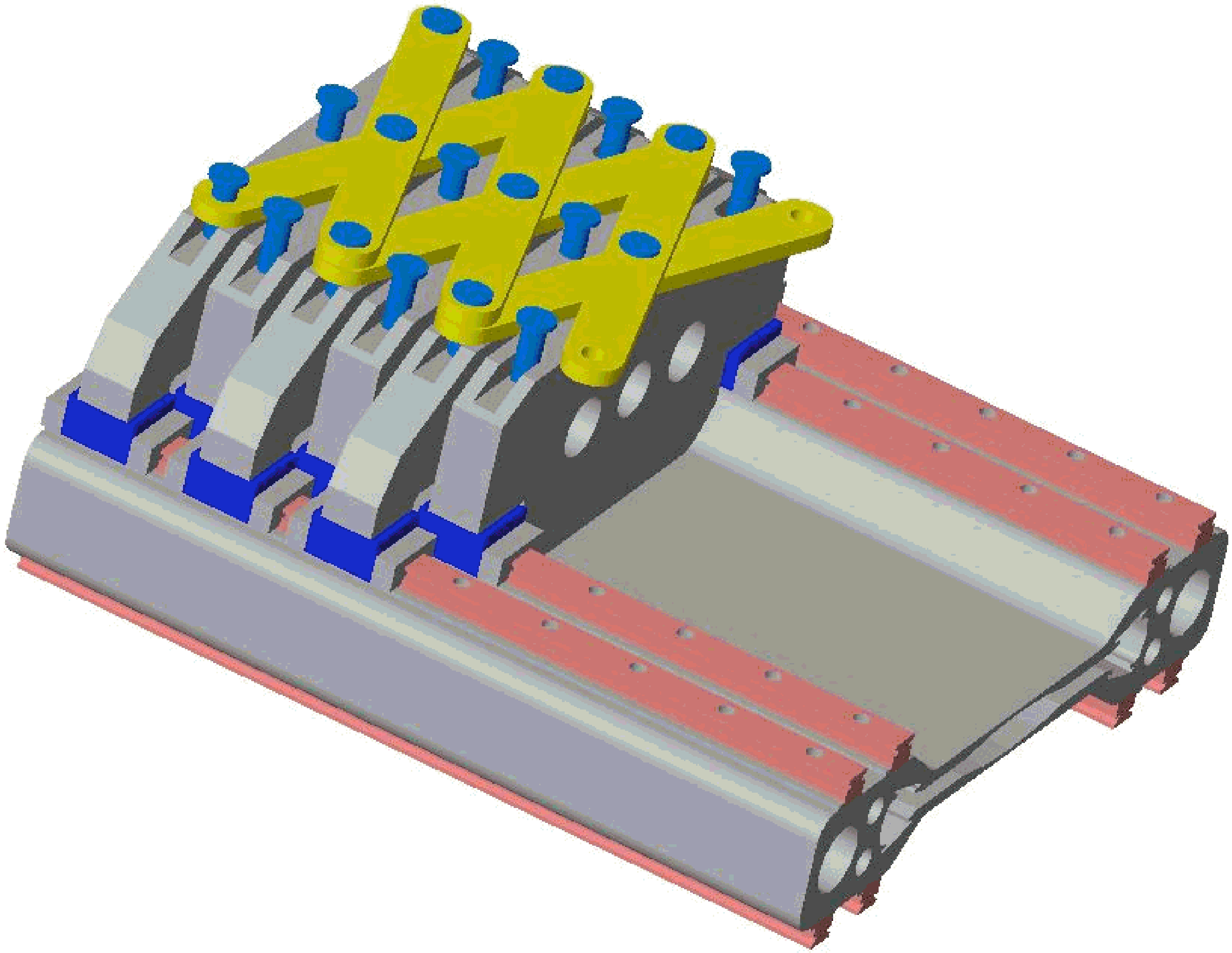
Advantage: Simple single actuator driving system,

high speed compatible

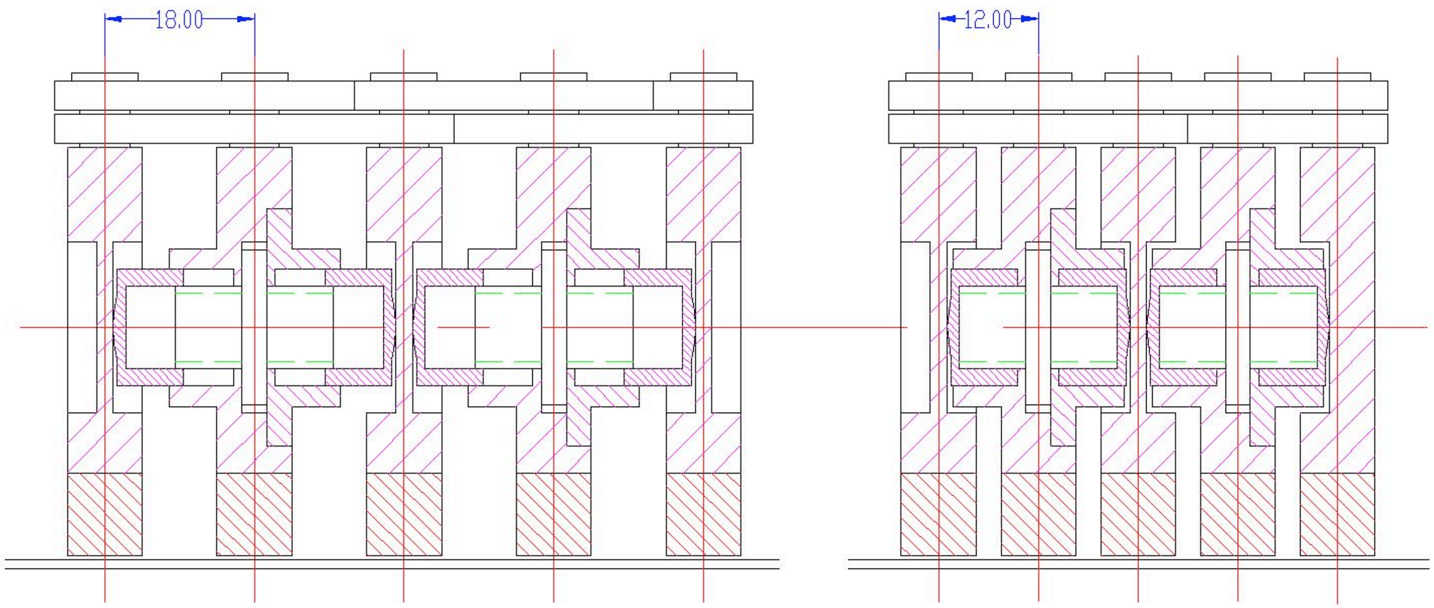
Disadvantage: Accumulated driving errors may be too large

Scissor Driving Mechanism





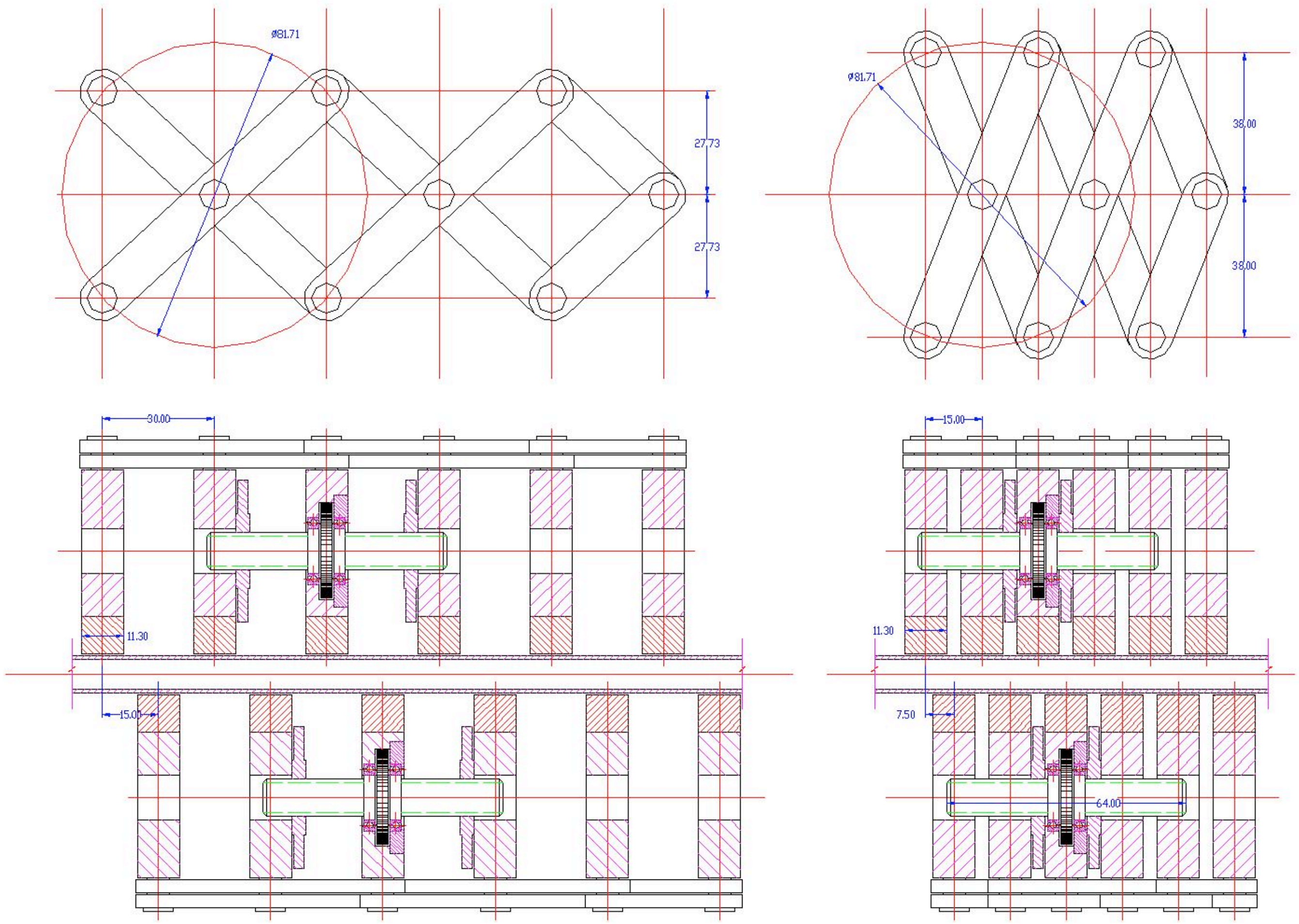
"Counter-Screw" Design Concept



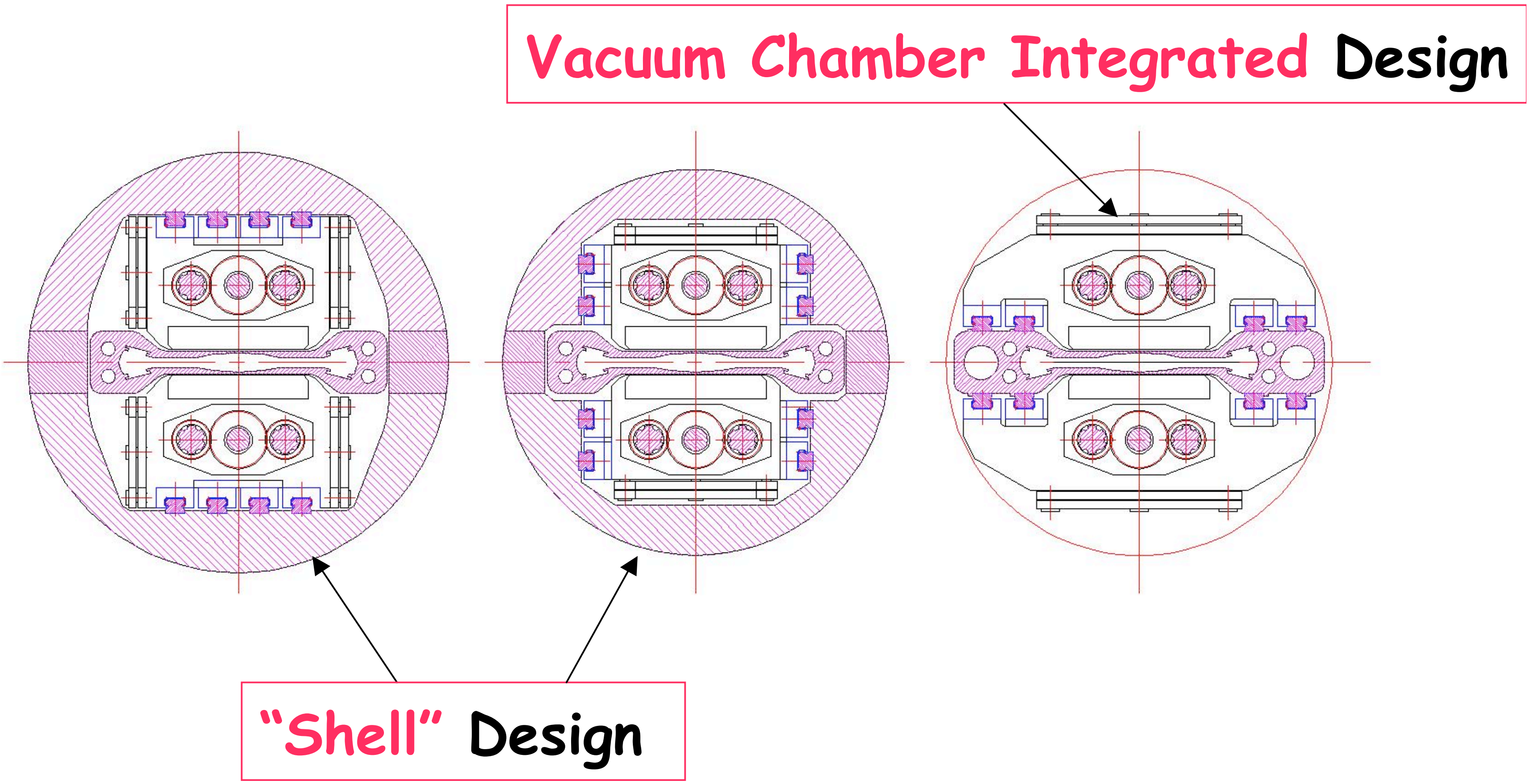
Advantage: precision driving system

Disadvantage: maximum period variable ratio is limited (< 1.5)

Combined Design Approach

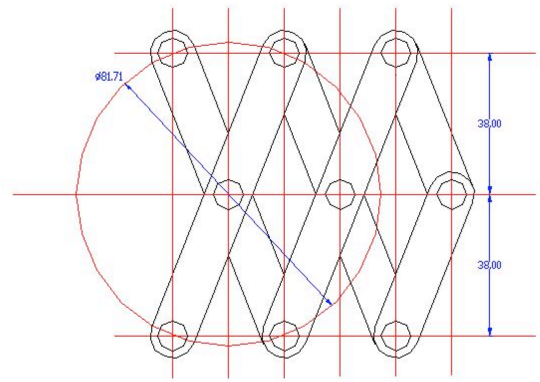


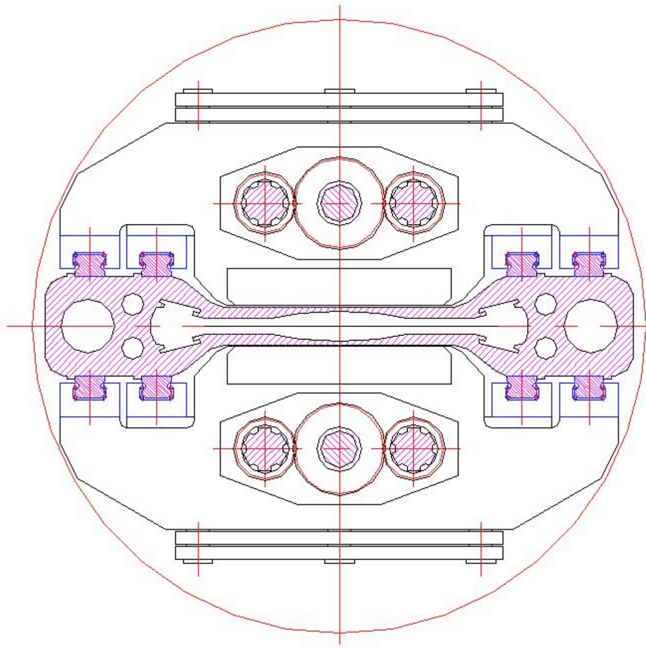
Supporting and Guiding Structure

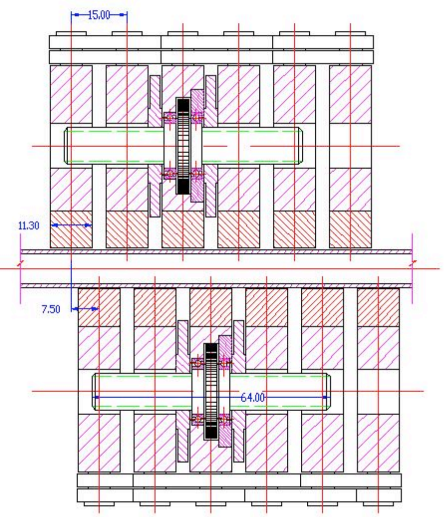


Supporting and Guiding Structure

"Shell" Design







Supporting and Guiding Structure

Design Concepts

- "Integrated with Vacuum Chamber" Design Concept

  Advantage: Compact structure, cost effective

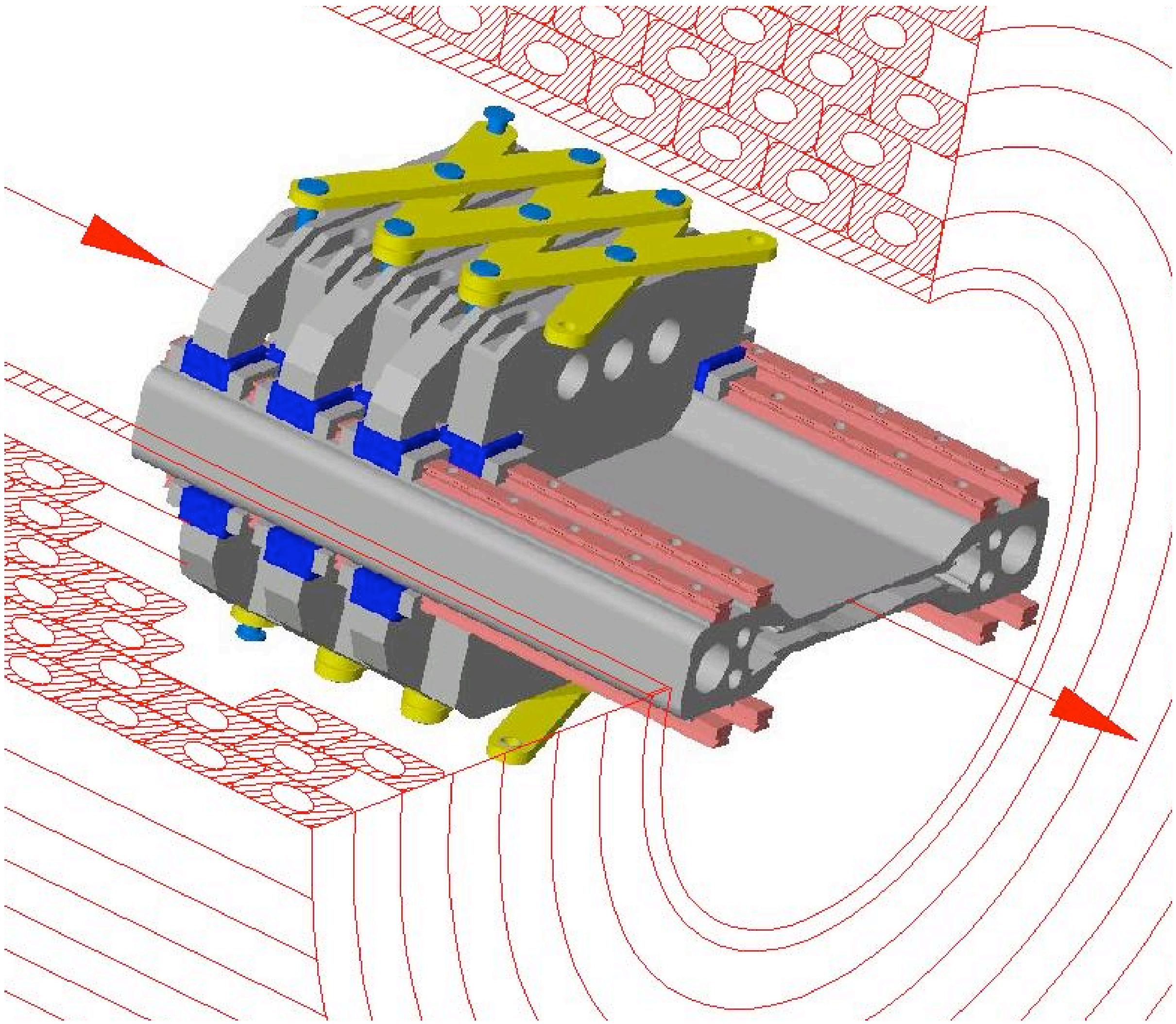
  Disadvantage: Vacuum bake-out temperature may be limited

- "Shell" Design Concept

  Advantage: Independent structure for easier maintenance

  Disadvantage: ?

Variable Period Undulator - a 3D View



Summary

- *Variable period undulator performance represents the next generation synchrotron source*

- *The device will not radiation degrade*
- *It will be useful not only for storage ring based facilities, but also for ERLs and FELs*

- More R&D, both in magnetic and mechanical design studies, is required before developing prototype devices.
  Full scale devices will follow demonstration of performance.