Innovative Magnet Development and Application at the National Synchrotron Light Source

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presented at

Jefferson Lab

February 20, 2002

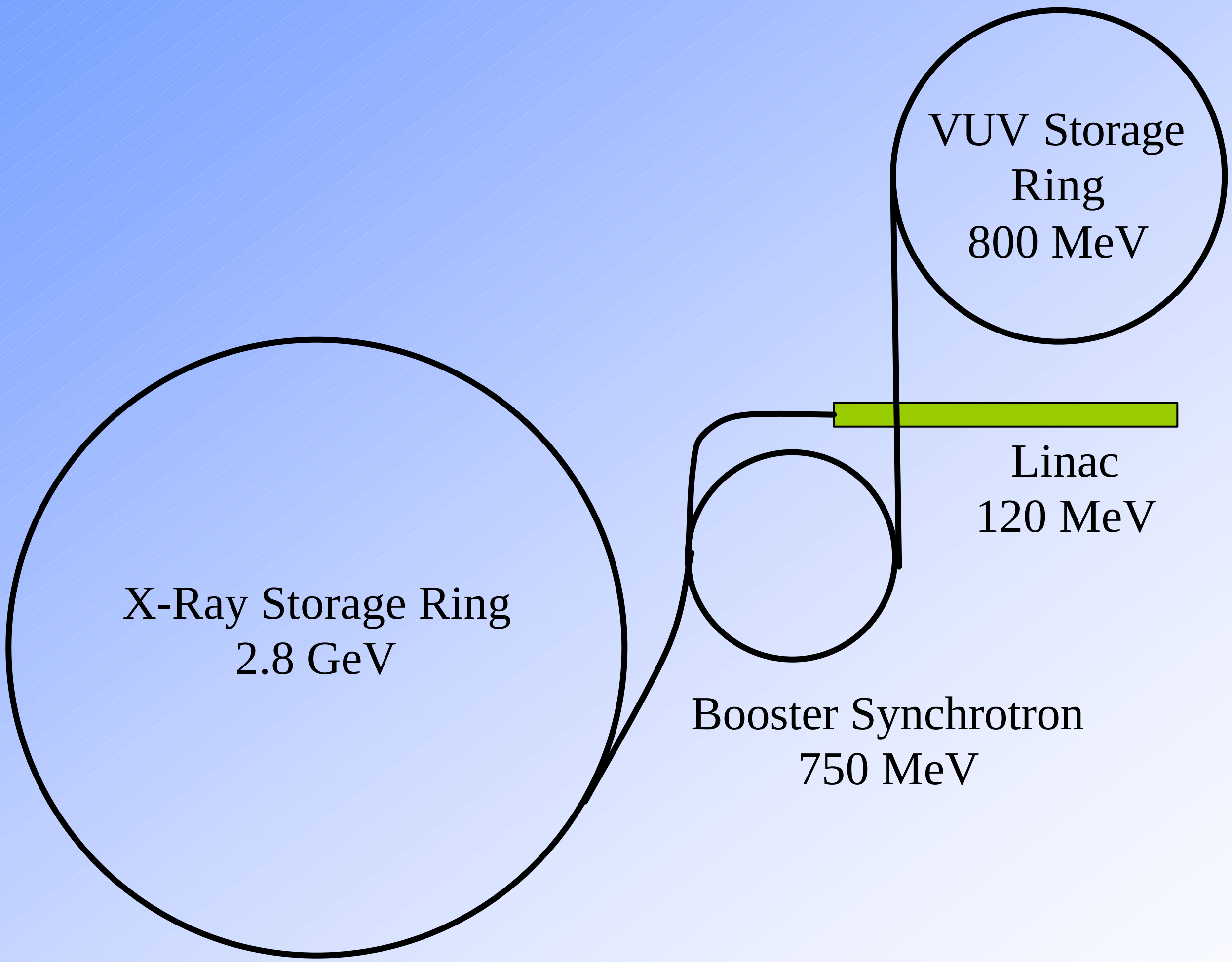
Acknowledgements

- George Rakowsky
- Don Lynch
- Sam Krinsky
- Klaus Halbach

Topics

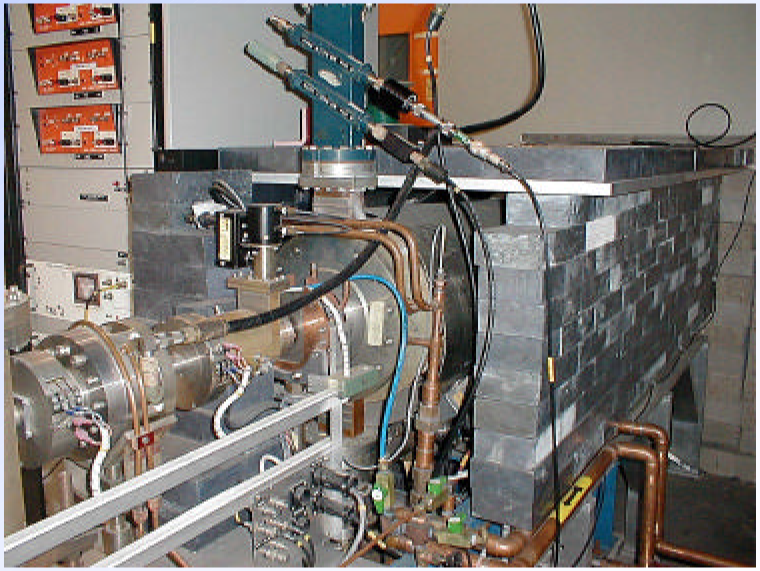
- Intro to NSLS
- Permanent Magnet Assisted Sextupole
- Superconducting Wiggler
- Hybrid In-Vacuum Undulator

NSLS Facility

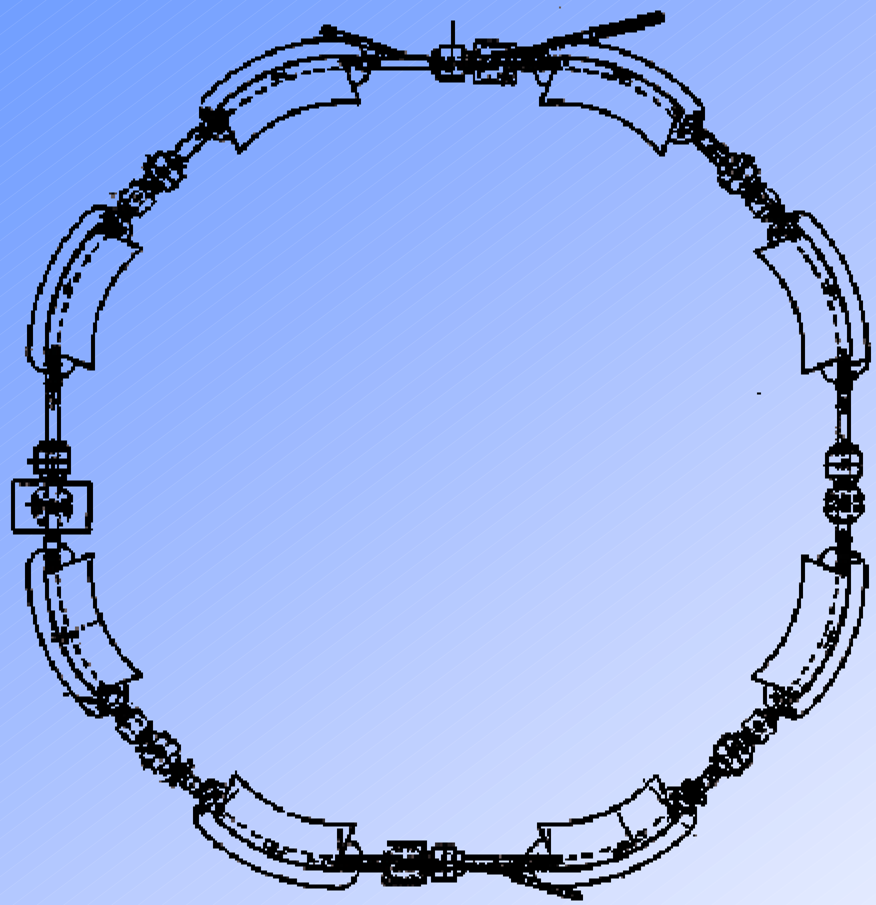


Linac

- 120 MeV
- 3 2856 MHz Sections:
  - 1- 5 m Varian
  - 2- 3 m SLAC
- 2856 MHz prebuncher
- Triode Electron Gun:
  - 1.5 A
  - 4.5 nsec pulse
  - 7 pulses, 92 nS apart



Booster



- 120-750 MeV
- 28.35 m Circumference
- 4 Superperiods
  - 2 Combined Function Dipoles (1.2 T)
  - 2 Quadrupoles
  - 1 Sextupole
- 1.91 m Bending Radius
- Nominal Tunes:

  $\nu_x = 2.42$

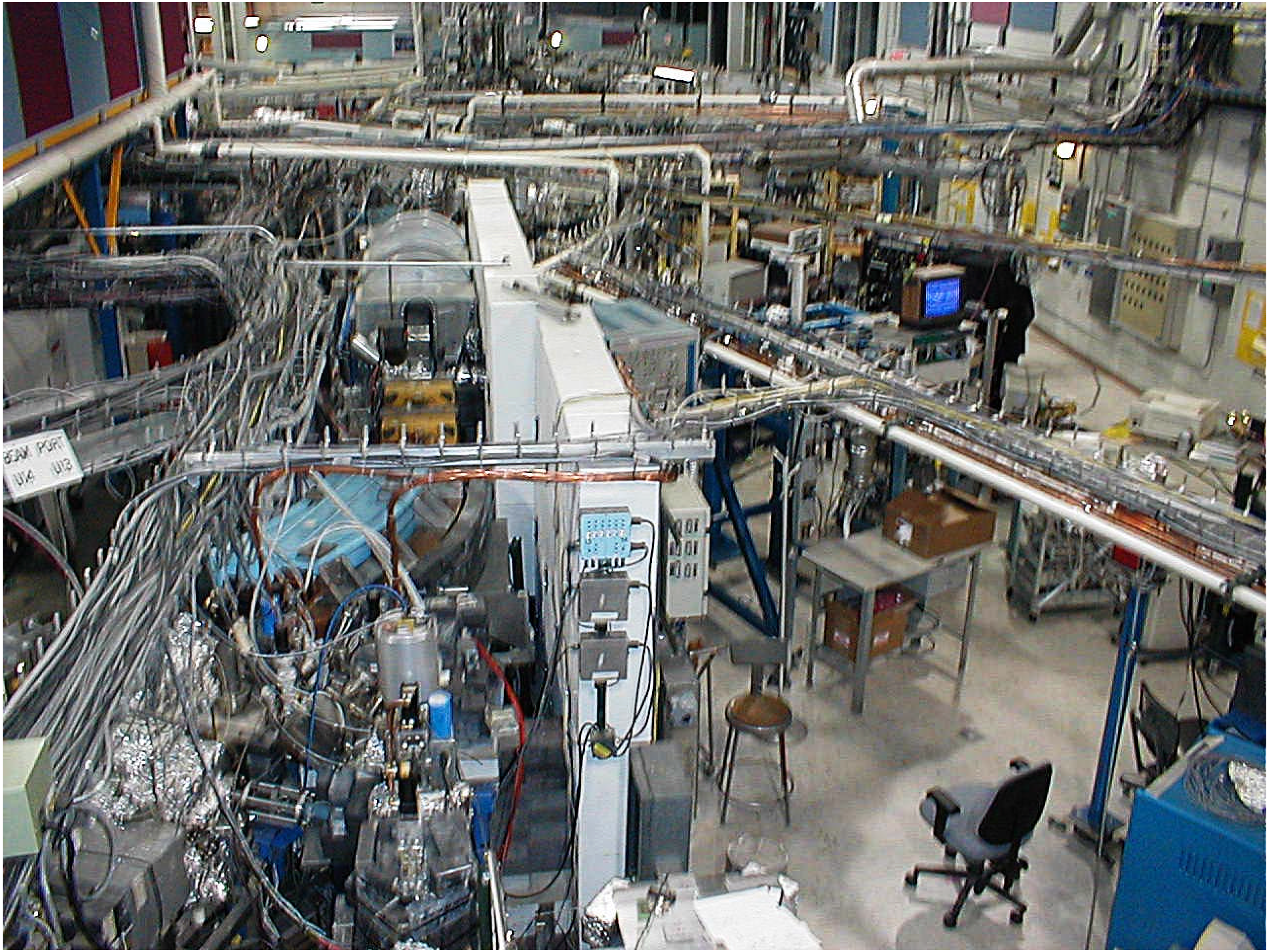
  $\nu_y = 1.37$
- 52.886 MHz RF Frequency
- 15 mA Beam Current
- 0.87 Sec cycle

nsls IR UV X

VUV Storage Ring

- Operating Energy 0.808 GeV
- Injection Energy 0.750 GeV
- Peak Current 1.0 amp
- Circumference 51.0 meters
- Number of Beam Ports on Dipoles 18
- Number of Insertion Devices 2
- Max. Length of I.D. ~ 2.25 meters
- Dipole Field 1.41 Tesla
- Lifetime @ 200 mA 590 min
- Lattice Structure(Chasman-Green) Separated Function, Quad Doublets
- Number of Superperiods 4
- Magnet Complement
  - 8 Bending (1.5 meters each)
  - 24 Quadrupole (0.3 meters each)
  - 12 Sextupole (0.2 meters each)

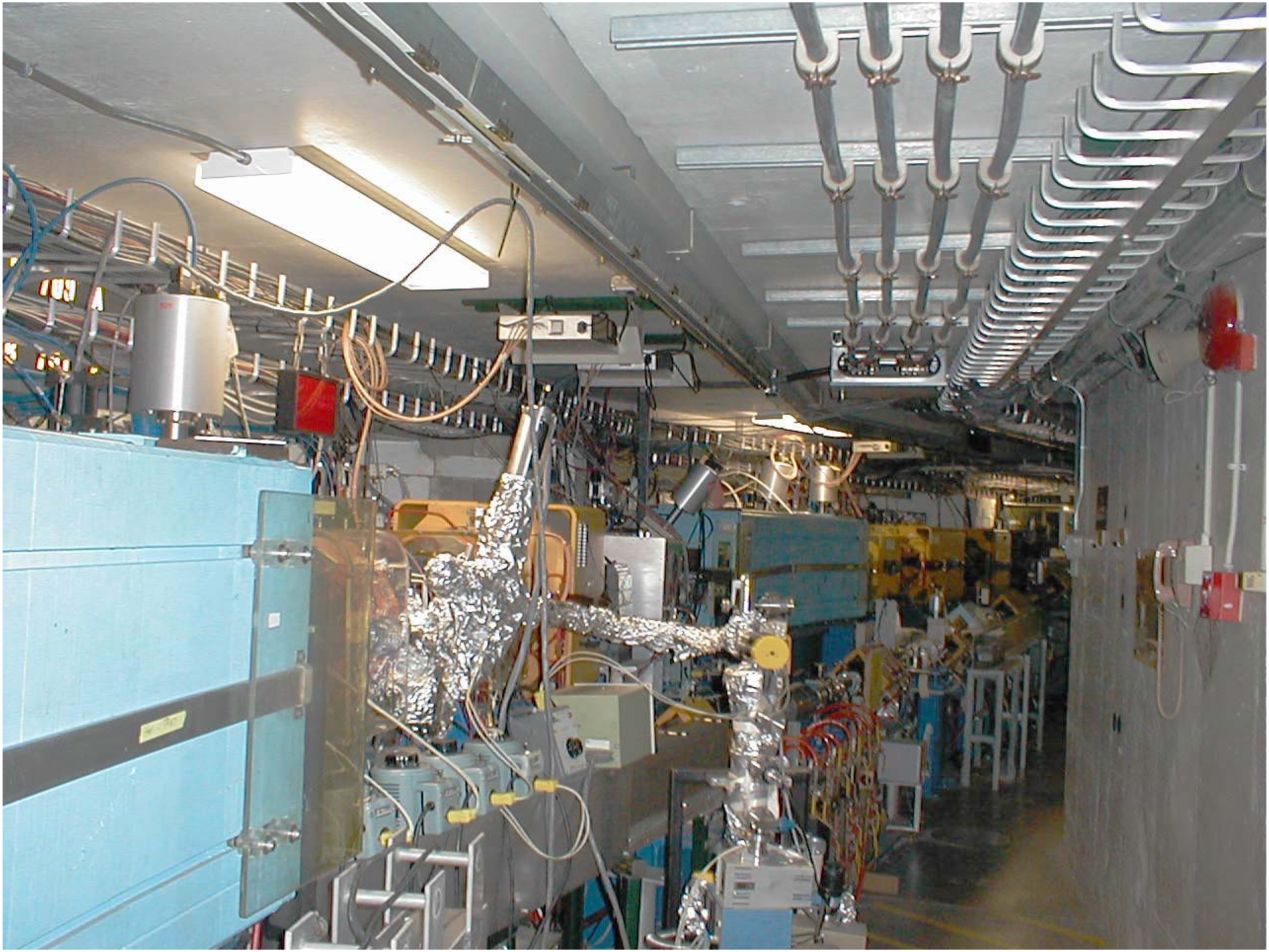
- Nom. Tunes (x , y) 3.14, 1.26
- RF Frequency 52.886 MHz
- Radiated Power 20.4 kW/A
- RF Peak Voltage 80 KV
- Design RF Power 50 KW
- 4^{th} Harmonic RF System
- Synchrotron Tune 0.0018
- Bunch Length (2σ) 9.7 cm
  (36 cm with 4^{th} harmonic system)
- RF Harmonic 9
- Typical Number of Bunches 7
- H Emittance 1.62×10^{-7} m-rad
- V Emittance 3.5×10^{-10} m-rad
- Power per Horizontal Milliradian (1A) 3.2 Watts


BEAM PORT
U14 U13

X-Ray Storage Ring

- Operating Energy 2.800 GeV
- Injection Energy 0.750 GeV
- Peak Current 350 mA
- Circumference 170.1 meters
- Number of Beam Ports on Dipoles 30
- Number of Insertion Devices 5
- Max. Length of I.D. ~ 4.5 meters
- Dipole Field 1.36 Tesla
- Touschek Lifetime (250 mA) >22 hr
- Lattice Structure(Chasman-Green) Separated Function, Quad Triplets
- Number of Superperiods 8
- Magnet Complement
  - 16 Bending (2.7 meters each)
  - 40 Quadrupoles (0.45 meters each)
  - 16 Quadrupoles (0.80 meters each)
  - 32 Sextupole (0.2 meters each)

- Nom. Tunes (x , y) 3.8, 5.7
- RF Frequency 52.886 MHz
- Radiated Power 198 kW (0.25A)
- RF Peak Voltage 1120 KV
- Design RF Power 450 KW
- Synchrotron Tune 0.003
- Bunch Length (2s) 10.5 cm
- RF Harmonic 30
- Typical Number of Bunches 25
- H Emittance 4.6×10^{-8} m-rad
- V Emittance 7.8×10^{-11} m-rad
- Power per Horizontal Milliradian (250 mA) 32 Watts
- Critical Energy 7.1 KeV



Permanent Magnet Enhanced Sextupole

- Motivation
  - X-Ray Ring low emittance lattice
  - Stronger sextupoles required
  - Existing sextupoles highly saturated
  - Sextupoles designed for 1/2 current required

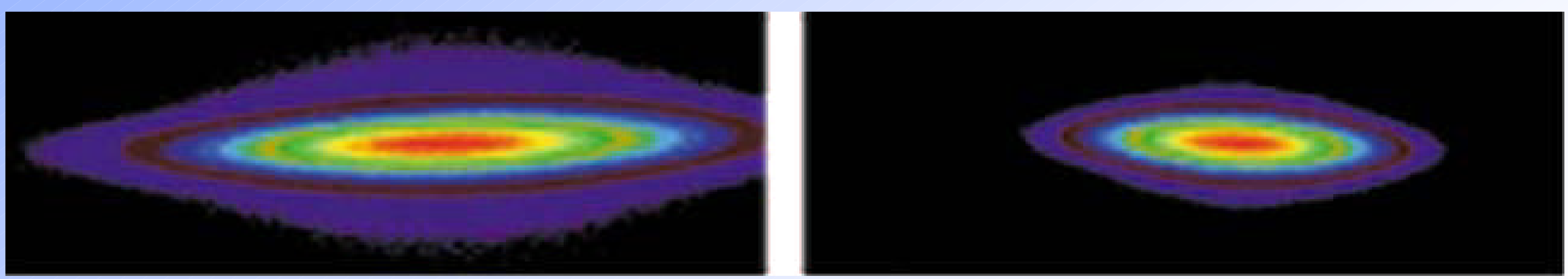
X-Ray Ring Lattices

Original Lattice

- ε_x = 90 nm-rad
- ε_y = 0.1 nm-rad
- ν_x = 9.14
- ν_y = 6.20
- $\eta = 0$ in long straights

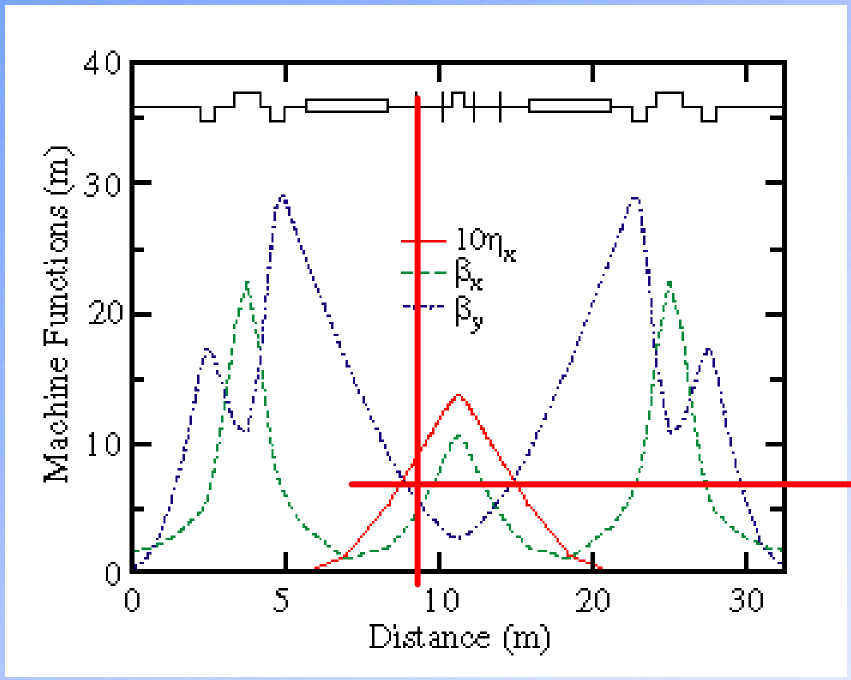
Low Emittance Lattice

- ε_x = 46 nm-rad
- ε_y = 0.08 nm-rad
- ν_x = 9.83
- ν_y = 5.71
- $\eta > 0$ in long straights

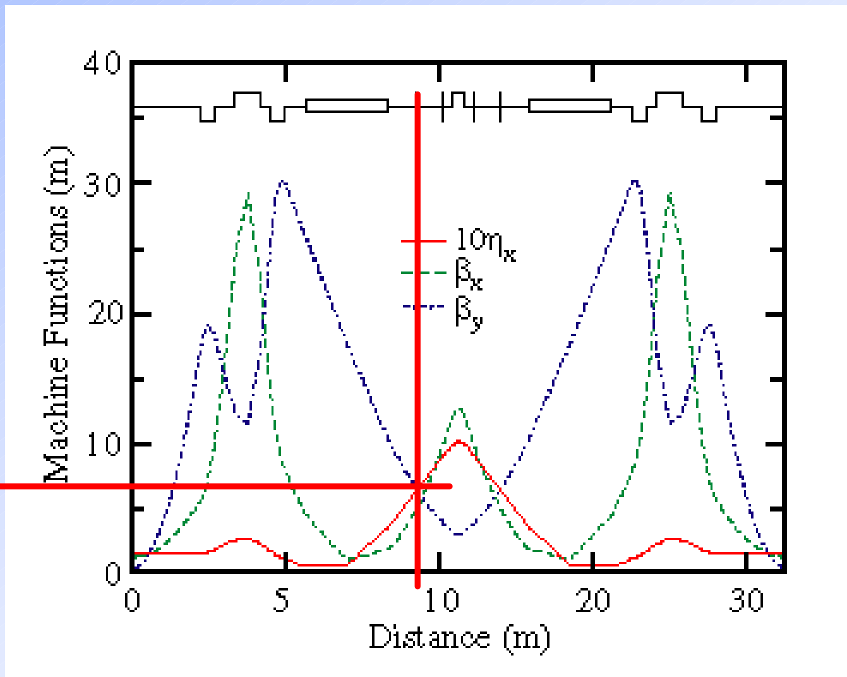


Lattice Plots

High Emittance Lattice



Low Emittance Lattice



Sextupole Effectiveness

- Sextupole contribution $\propto \beta(s)M(s)\eta(s)$
- $\beta_y(s)$ nearly unchanged at sextupoles
- $\eta(s)$ smaller in low emittance lattice
- M(s) must be bigger

BUT

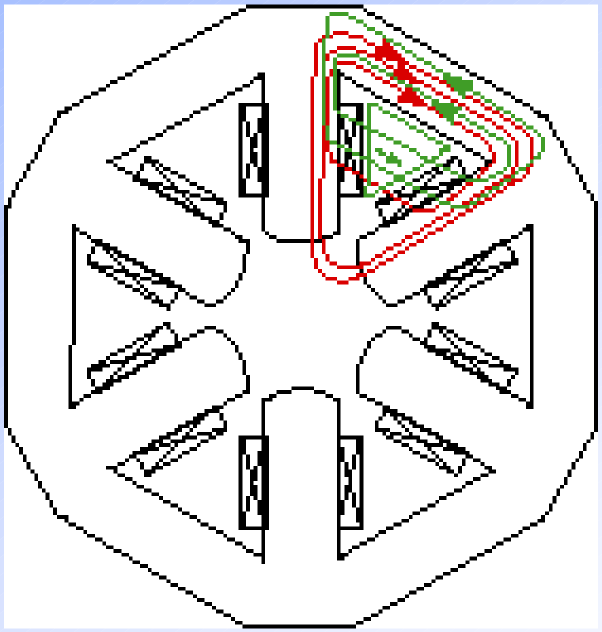
- At 800 A (maximum sextupole current)
  can only get chromaticity = 0

Alternatives

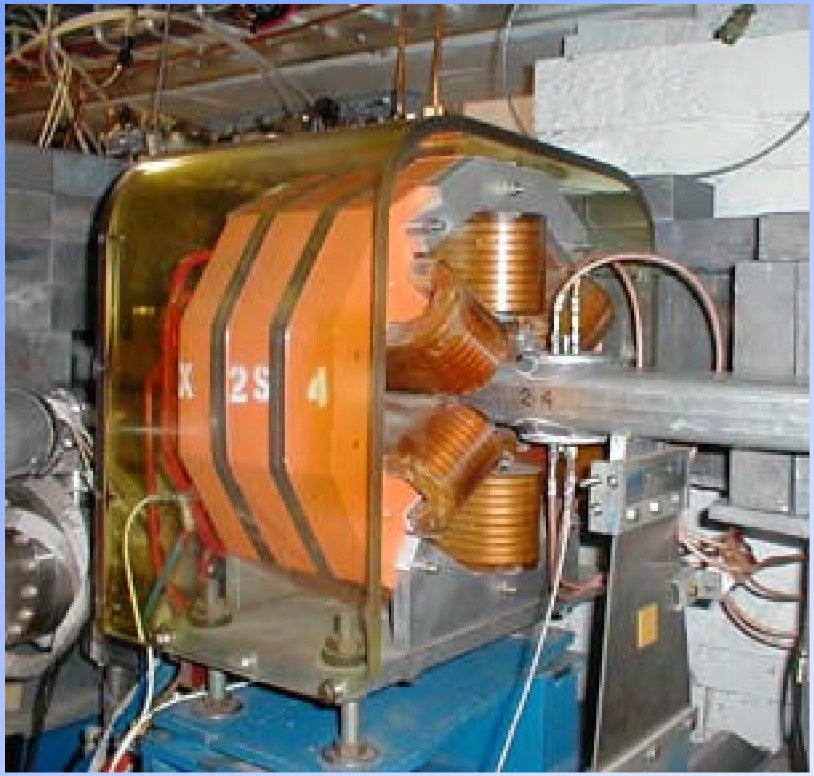
- Increase current
  - Already running at over twice design current
- Replace sextupoles
  - Expensive
- Modify sextupoles

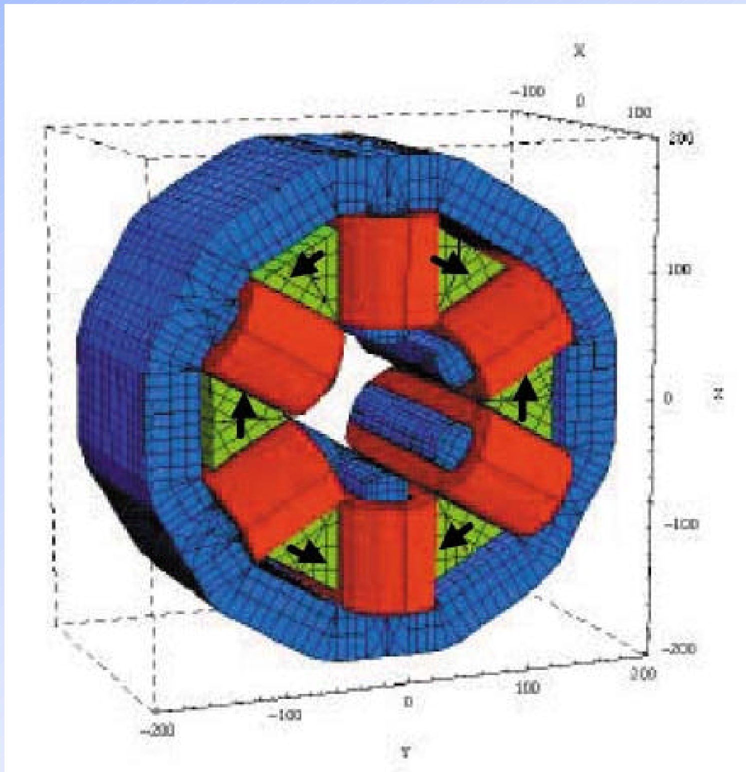
P M Enhanced Electromagnet

- Proposed by Halbach, Proc. 7th FEL Conf. (1985)
- Excitation of pole comes from electromagnet coil
- Permanent magnet cancels flux in iron



Sextupole



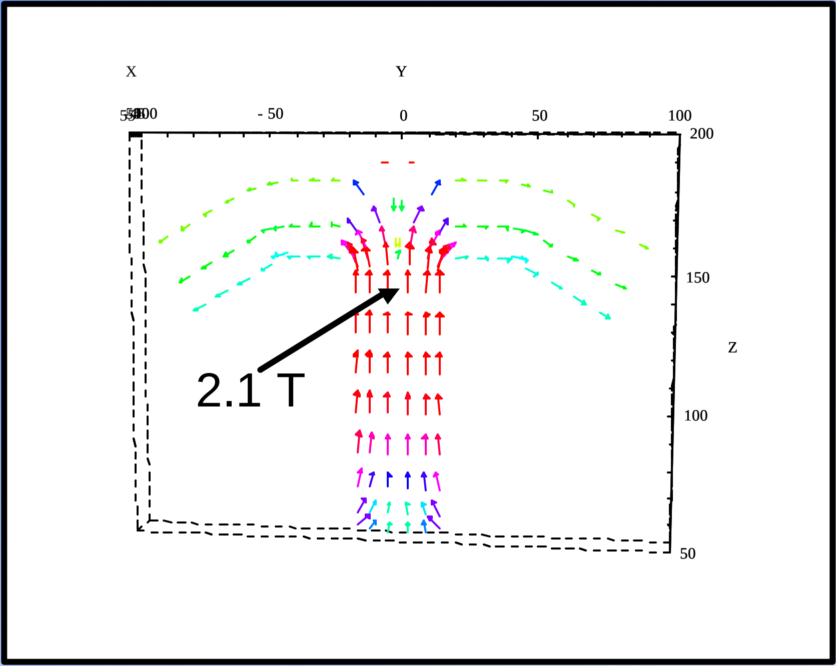


Sextupole Parameters

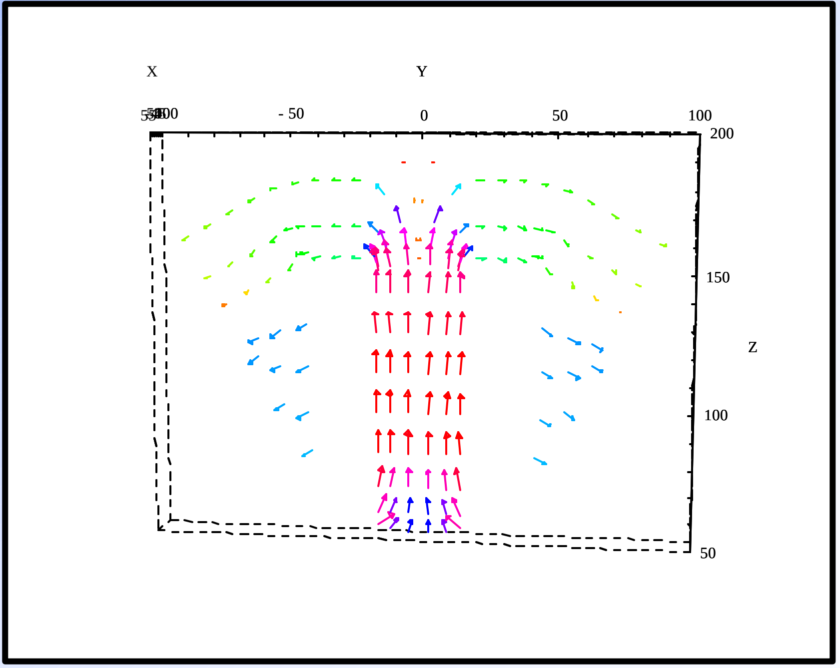
■ Aperture Radius	5 cm
■ Magnetic Length	20 cm
■ Turns Per Pole	18
■ Maximum Current	800 A
■ Pole Tip Field (800 A)	0.65 T

Field in Iron

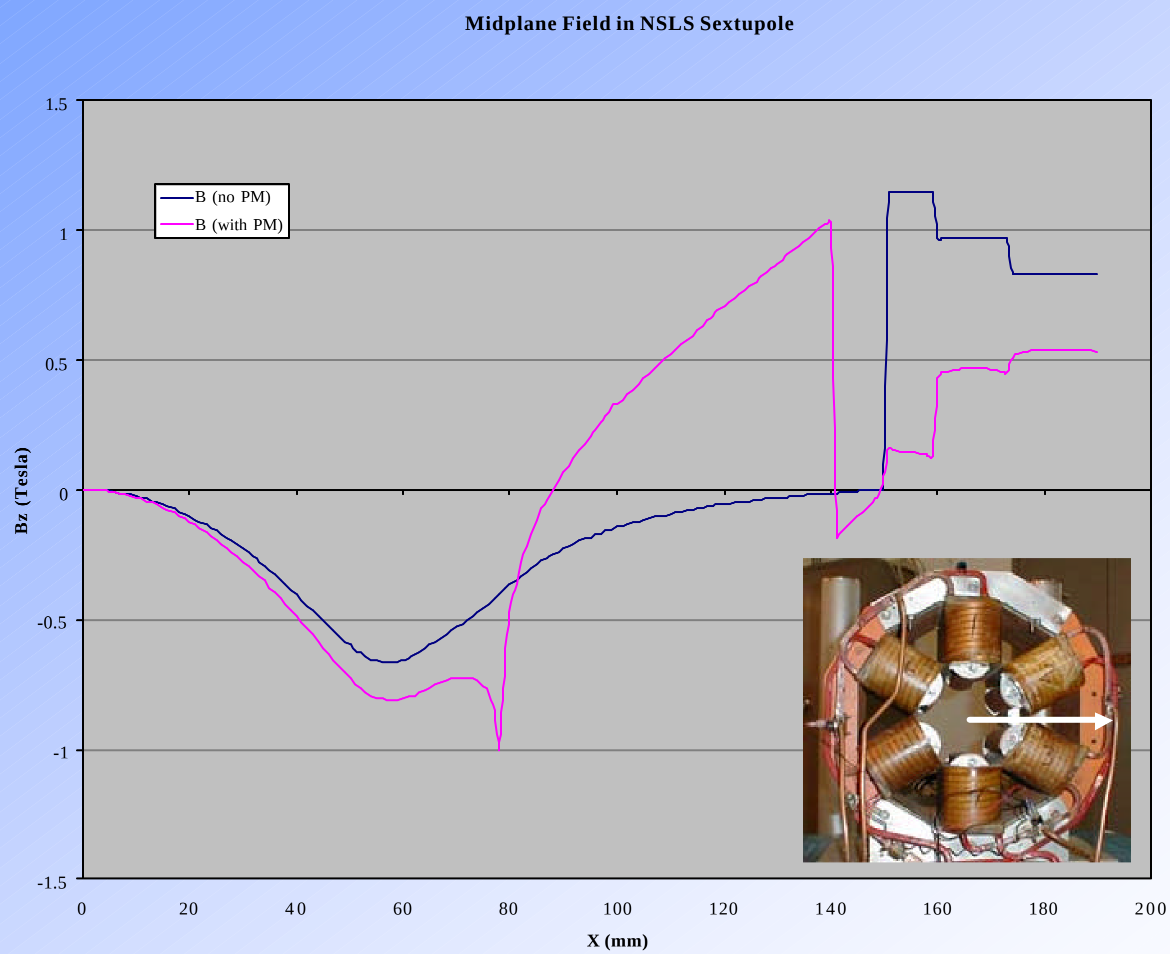
Without Permanent Magnet

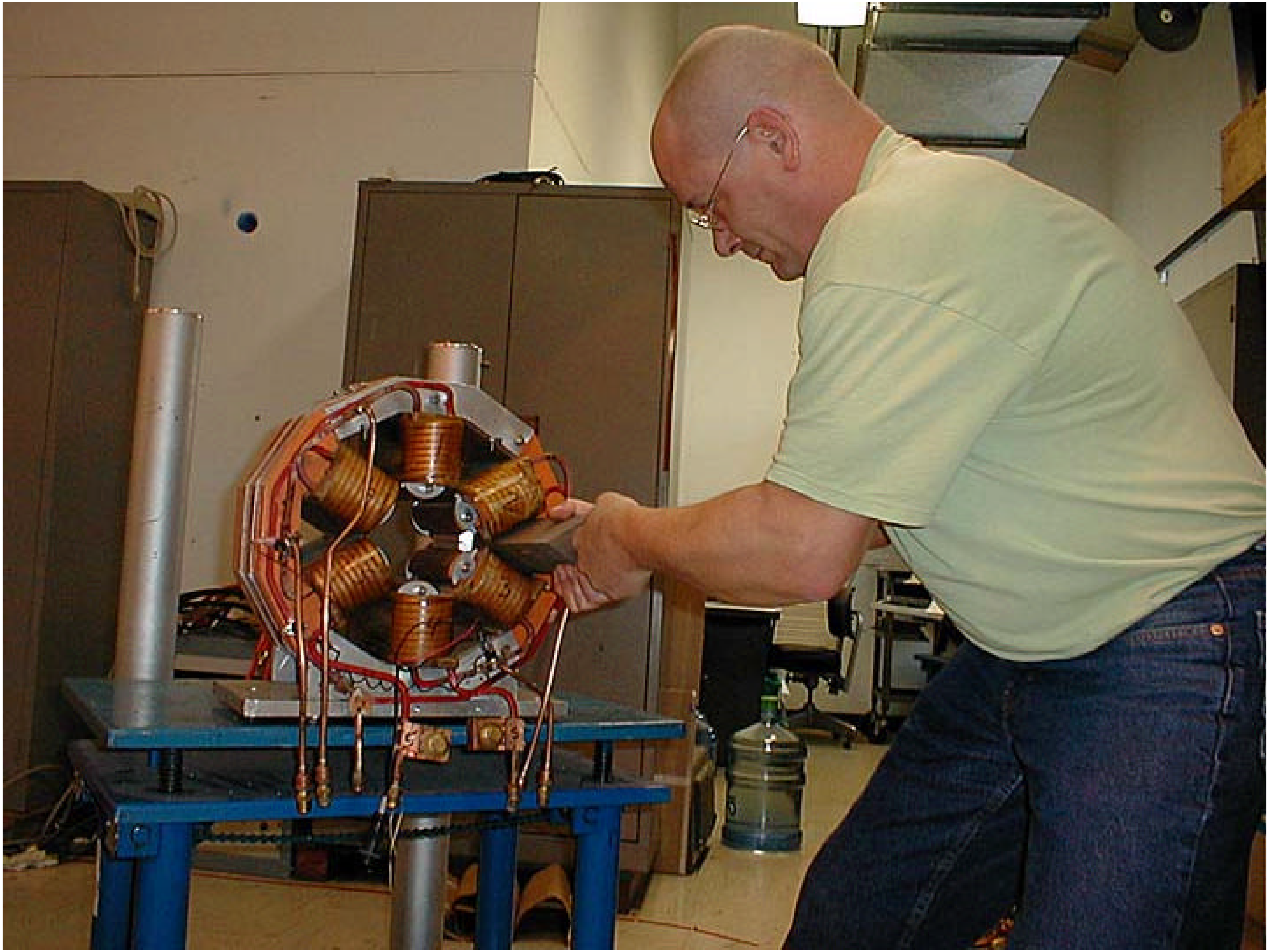


With Permanent Magnet

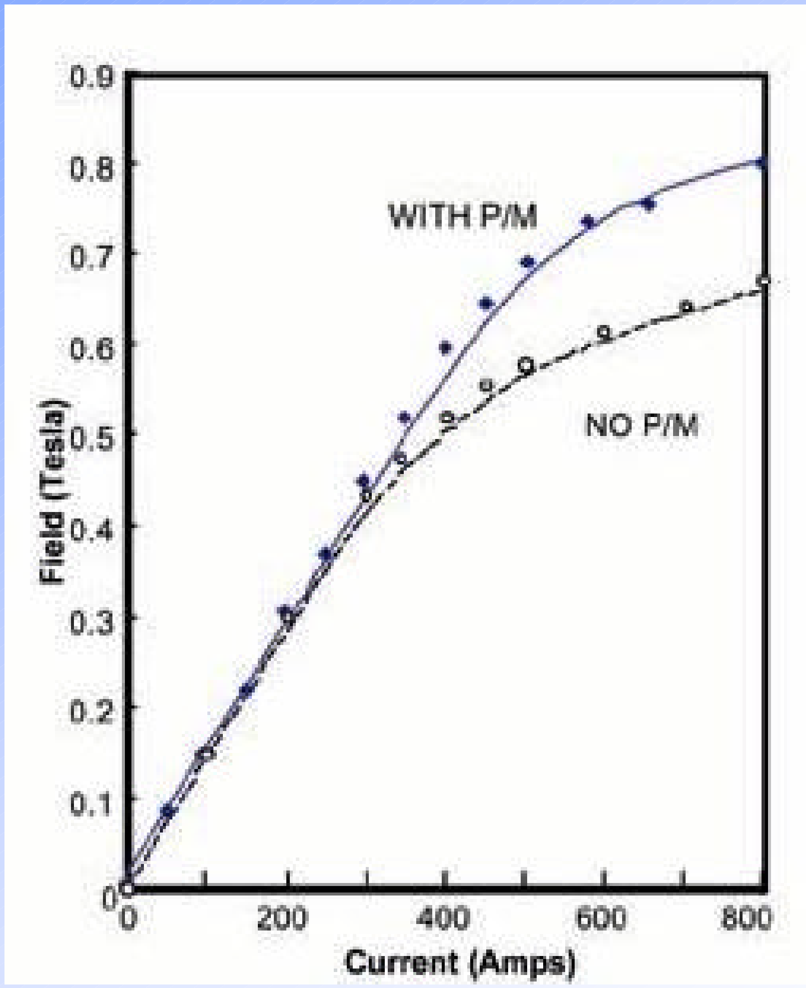


Field in Midplane





Field vs. Current



Superconducting Wiggler

- Replace existing 5 pole, 4.7 T wiggler
- Three operating modes
  - 11 Poles, 3.0 T (+2 half-strength poles at ends)
  - 5 Poles, 4.7 T
  - 1 Pole , 5.5 T
- Extremely low heat leakage
  - 0.35 l/hr liquid helium use
  - No refrigerators, filled from dewar
  - High T_C leads in neck BAD MISTAKE

Wiggler Characteristics

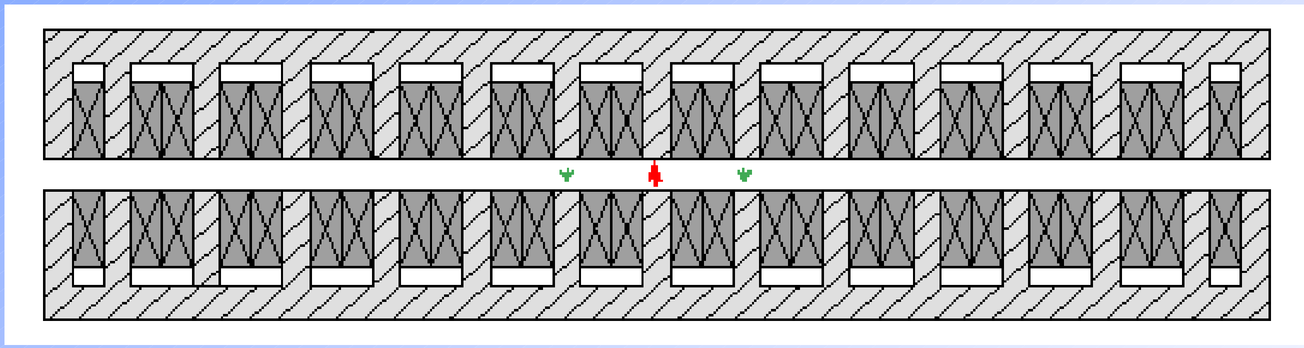
Period	17.16 cm
Number of Poles	13
Maximum Field	5.5 T
Horizontal Beam Aperture	5.95 cm
Vertical Beam Aperture	1.95 cm
Good Field Region	±5 mm

Allowed Field Errors

	OPERATION	RAMPING
Dipole (?$B_y$dz)	1.00 G-m	5.00 G-m
Skew Dipole (?$B_x$dz)	1.00 G-m	1.00 G-m
Quadrupole	110.00 G	110.00 G
Skew Quadrupole	150.00 G	150.00 G
Sextupole	29.00 KG/m	29.00 KG/m
Skew Sextupole	10.00 KG/m	10.00 KG/m
??$B_y d^2 z$	2.00 G-m^2	5.00 G-m^2

Wiggler Operating Modes

Wavelength Shifter



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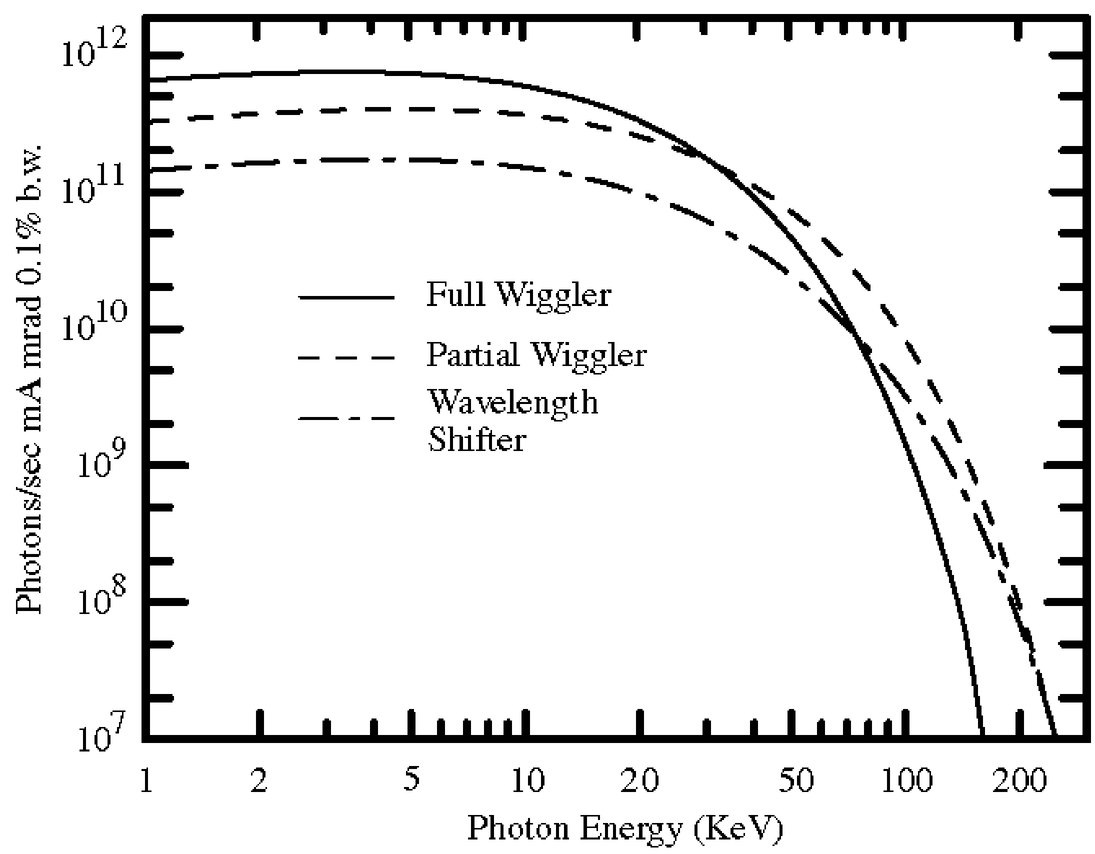
Synchrotron Radiation Spectrum



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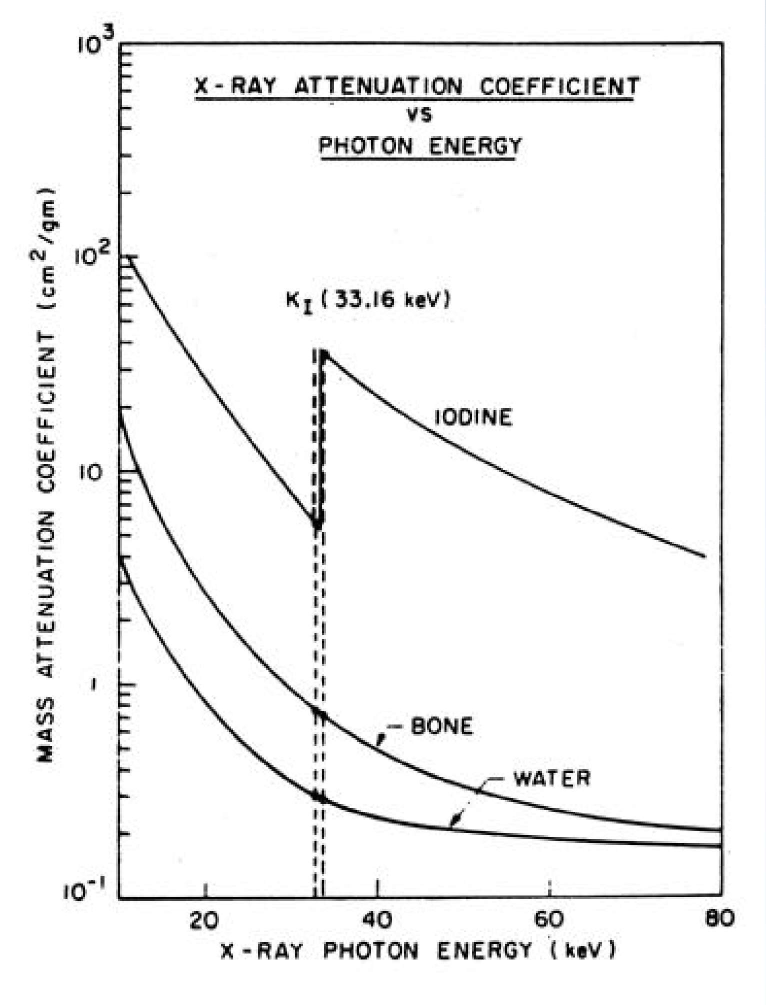
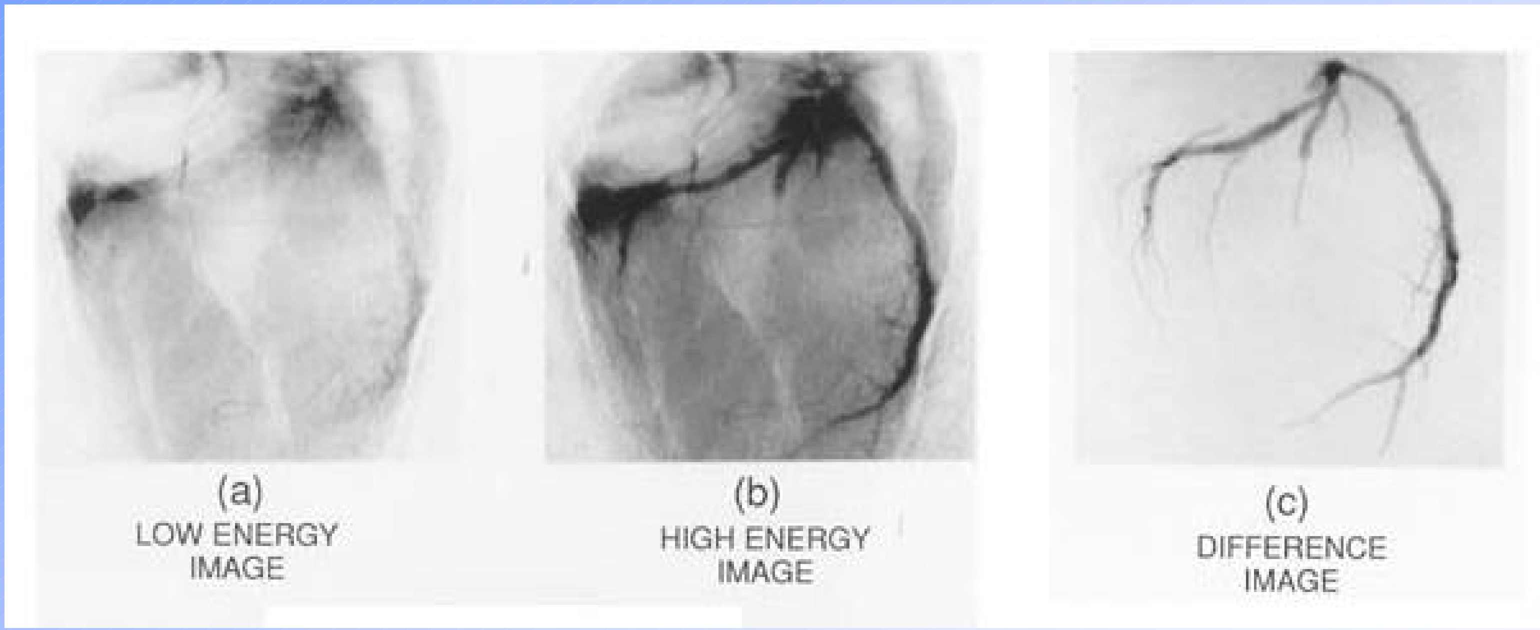
Why 33 KeV?

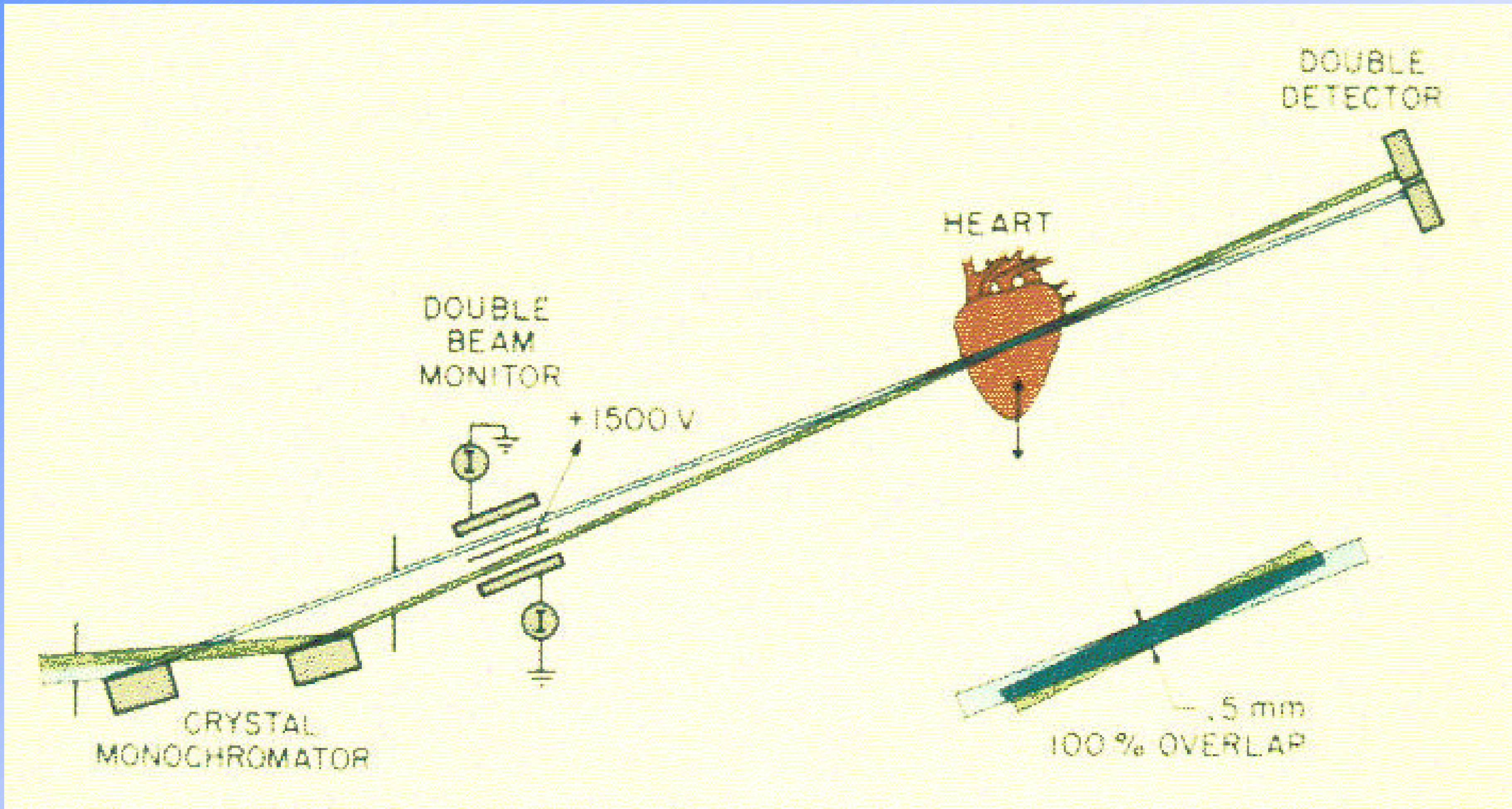

X-RAY ATTENUATION COEFFICIENT
VS
PHOTON ENERGY
K_I (33.16 keV)
IODINE
BONE
WATER
MASS ATTENUATION COEFFICIENT (cm^2/gm)
X-RAY PHOTON ENERGY (keV)
10^3
10^2
10
1
10^{-1}
20
40
60
80

Digital Subtraction Angiography

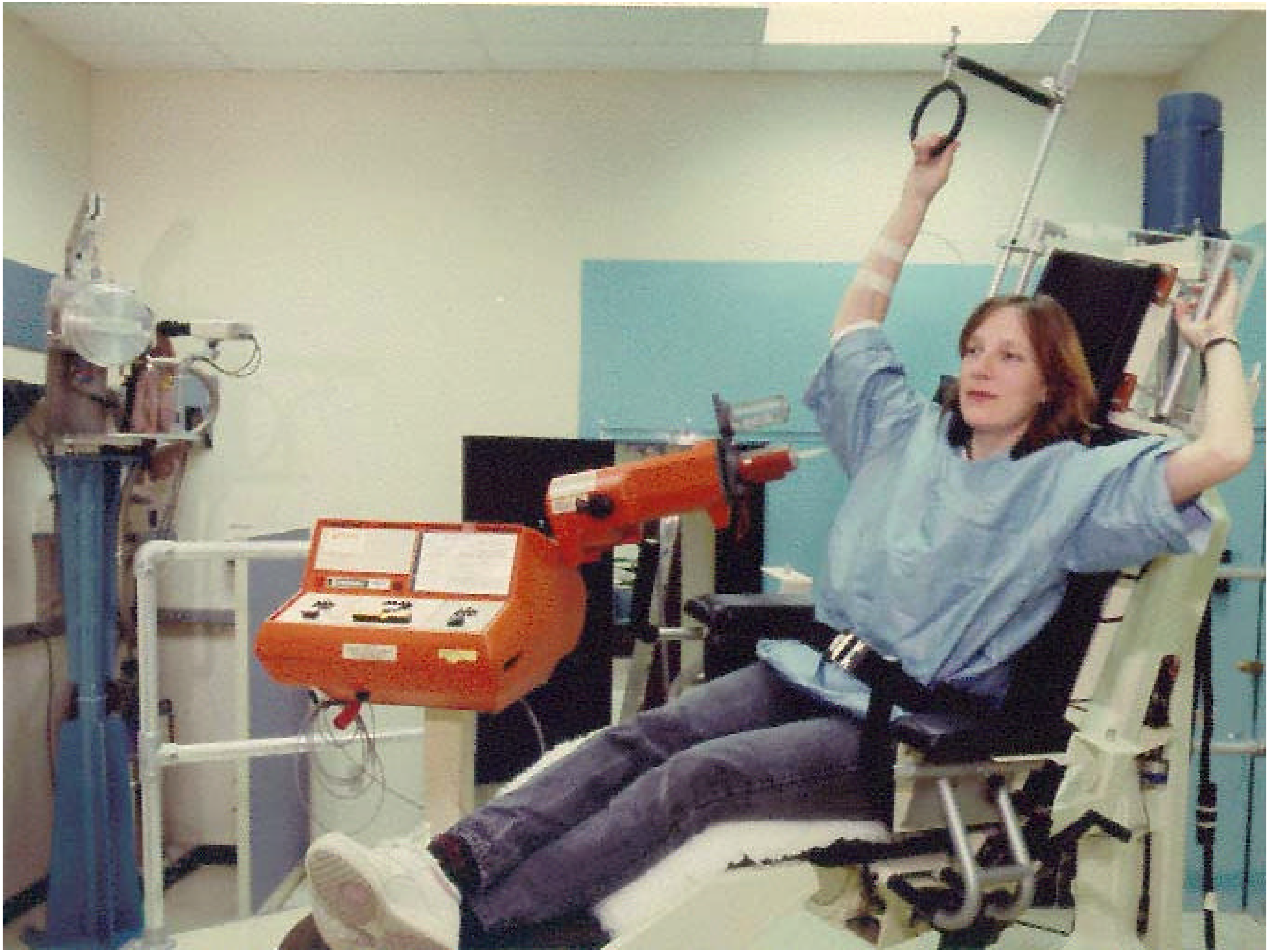


Excised pig heart with iodine contrast agent injected into coronary arteries

Imaging



DOUBLE
DETECTOR
HEART
DOUBLE
BEAM
MONITOR
+1500 V
CRYSTAL
MONOCHROMATOR
.5 mm
100 % OVERLAP



Wiggler Construction

- Extremely low carbon Remko B iron
  - Minimizes residual magnetization
- NbTi Wire
  - 1:1 Nb:Ti ratio
- Coils divided radially into two sections:
  - Minimizes current in high field region near pole
  - Inner coil wire: 1 mm dia., 285 A/mm
  - Outer coil wire: 0.7 mm dia., 485 A/mm
  - Maximum current 295 A
- Stored Energy 170 KJ

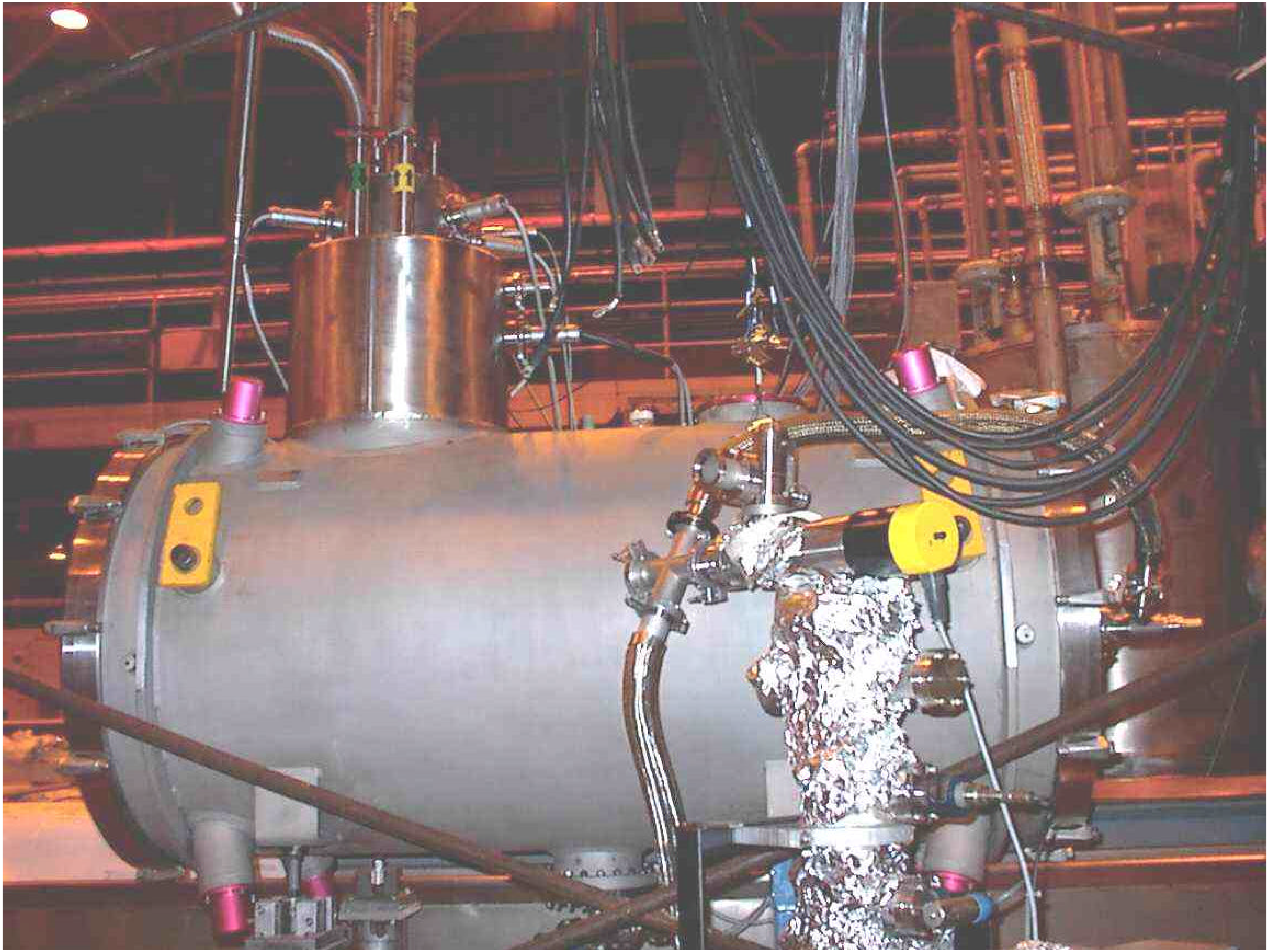
Cryostat

- Warm bore-cold iron
- 4.5 K He bath
- Insulated bore tube
- Heaters to keep beam pipe above freezing
- 20K shield cooled by He boil-off
- 80K liquid nitrogen cooled shield
- High T_C leads in LN_2 pot

Electrical Characteristics

- Ramping rate (1.1 T to max) 1.14 T/min
- Voltage during ramp 16.5 V

- Passive quench protection
  - Diode-resistor networks across coils in cryostat
  - Power can safely stay on during quench



Status

- Wiggler constructed by Oxford Instruments, field mapped
- Delivered to BNL, Spring 1998
- Vacuum leak discovered, returned to Oxford
- Repaired at Oxford
- Delivered to BNL, Fall 1999
- High T_C lead exploded when powered
- Returned to Oxford
  - They believe lead may have been damaged in transit
  - Bad mechanical design, high stress on brittle lead
- Delivery expected Spring 2002

Small Gap Undulators

Radiation wavelength $\lambda_o = (\lambda_u/2\gamma^2)(1+K^2/2)$

$K = 0.934\ B_u[T]\ \lambda_u[cm]$

peak field $B_u \propto \exp[-\pi G / \lambda_u]$

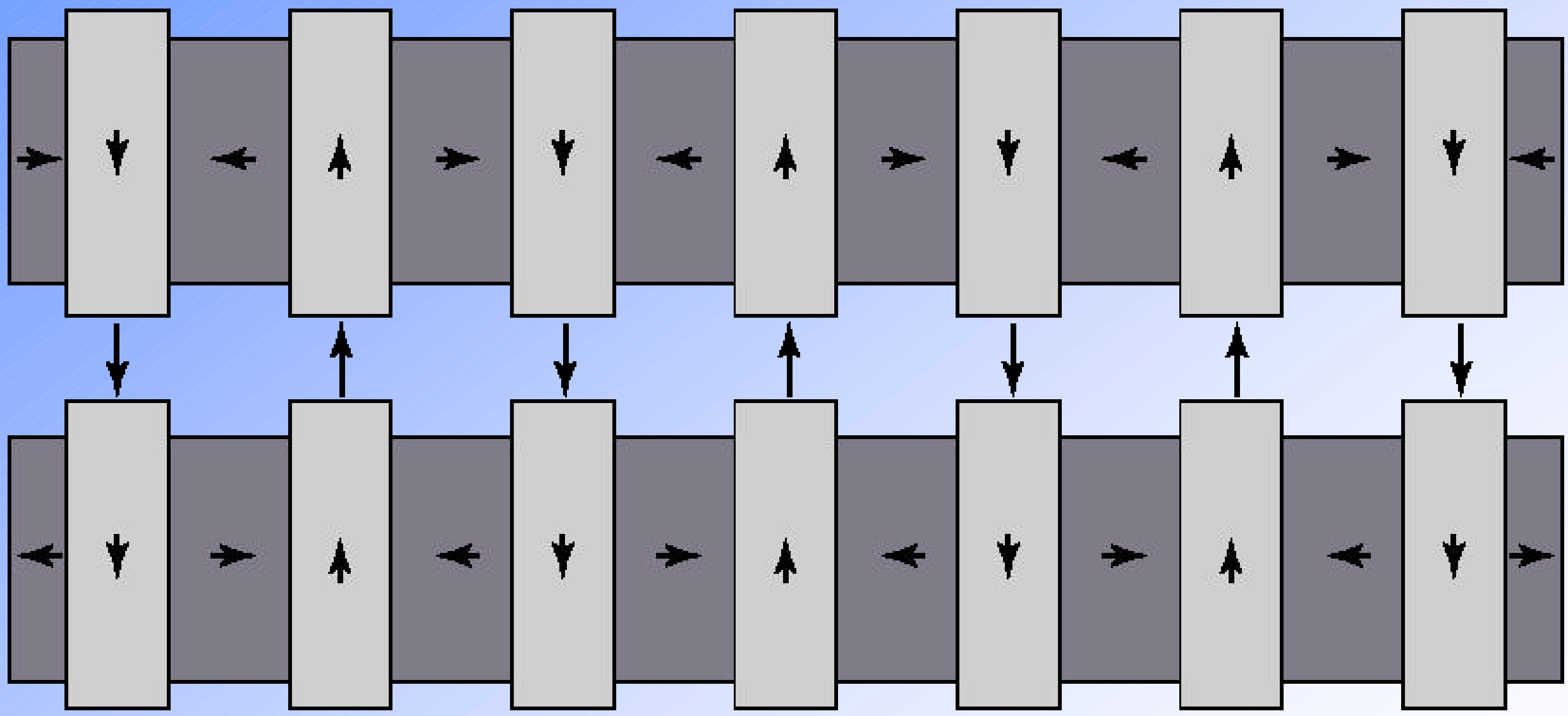
High photon energy $\Rightarrow$

Short radiation wavelength $\Rightarrow$

Short undulator period $\Rightarrow$

Small gap

Hybrid Undulator



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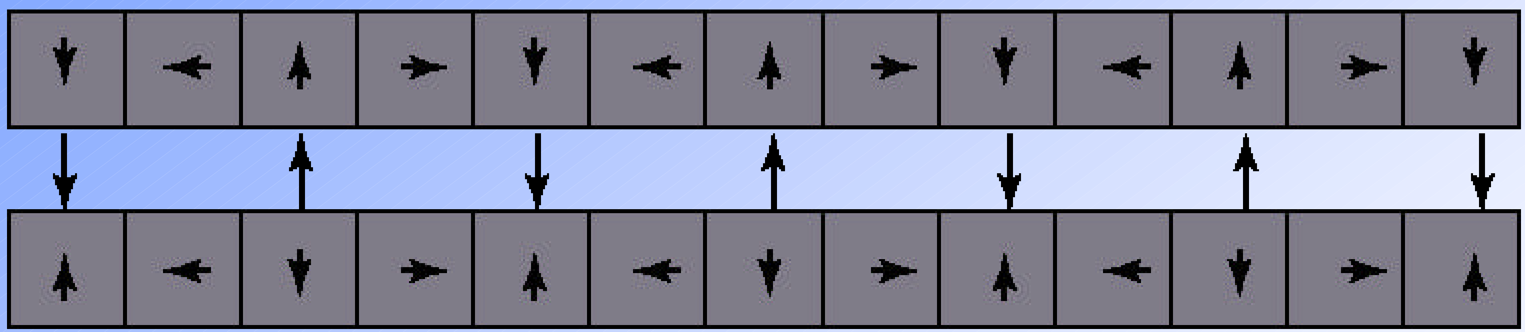
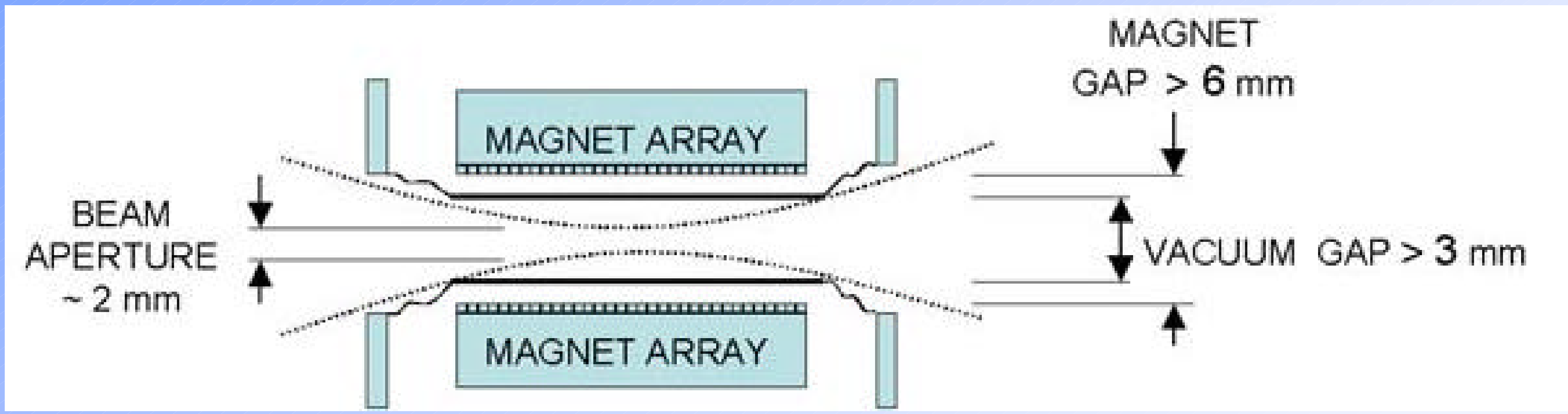
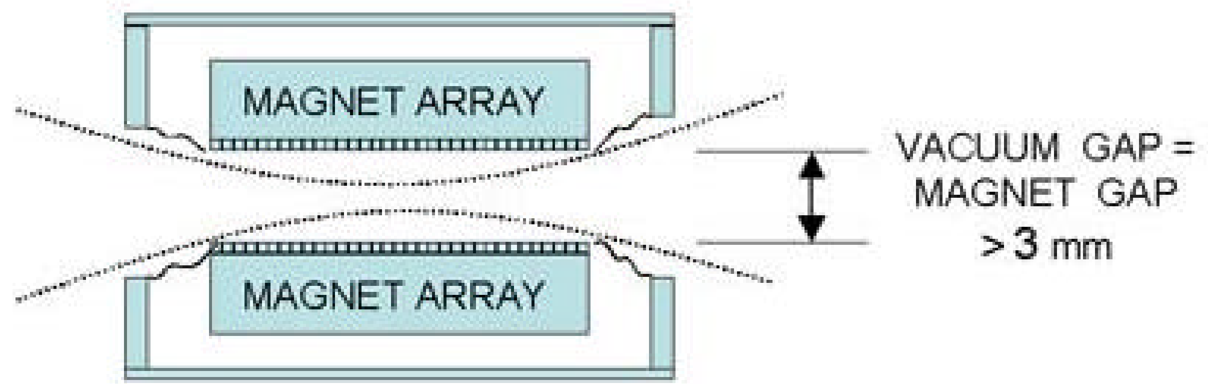
Pure Permanent Magnet Undulator



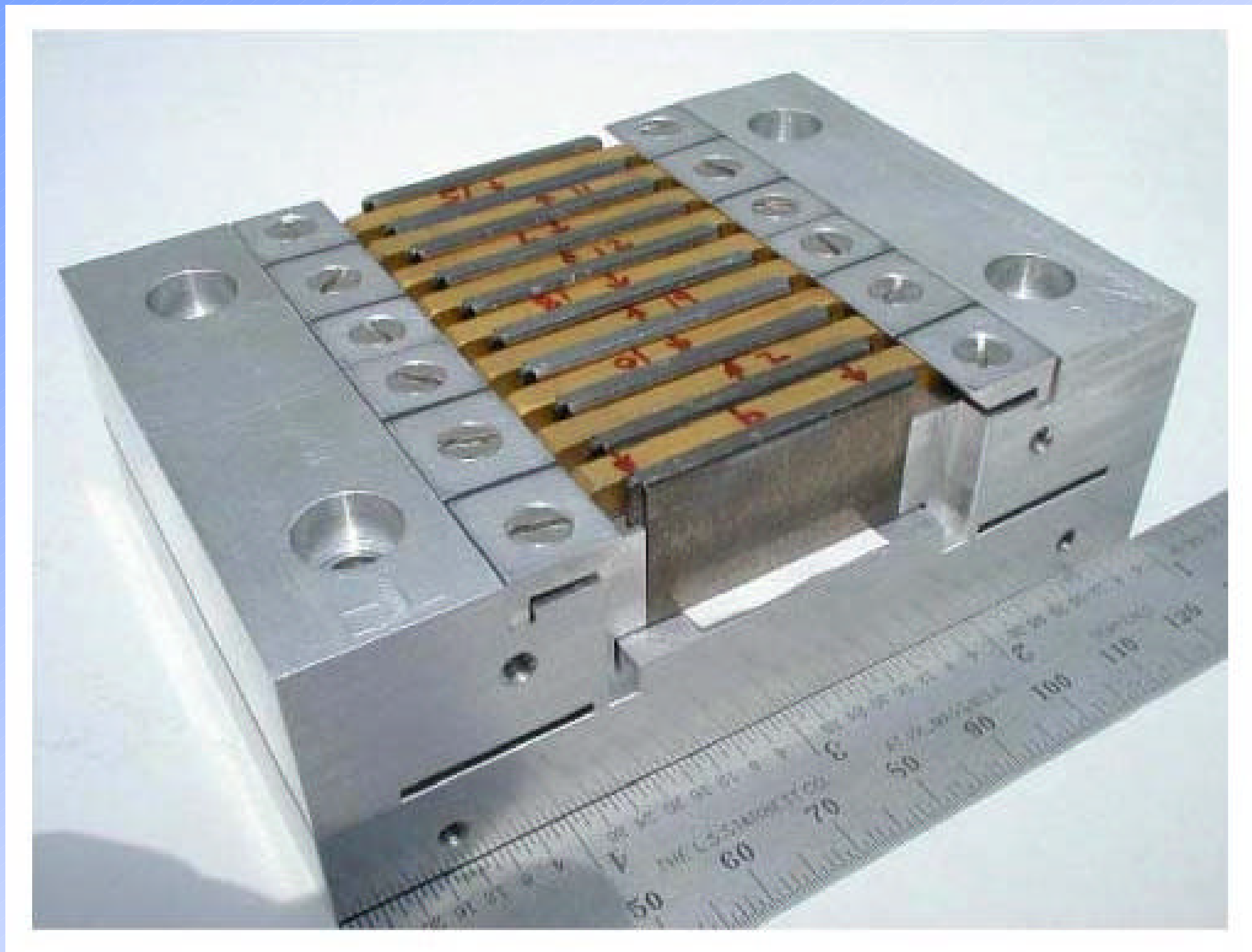
Prototype Small Gap Undulator



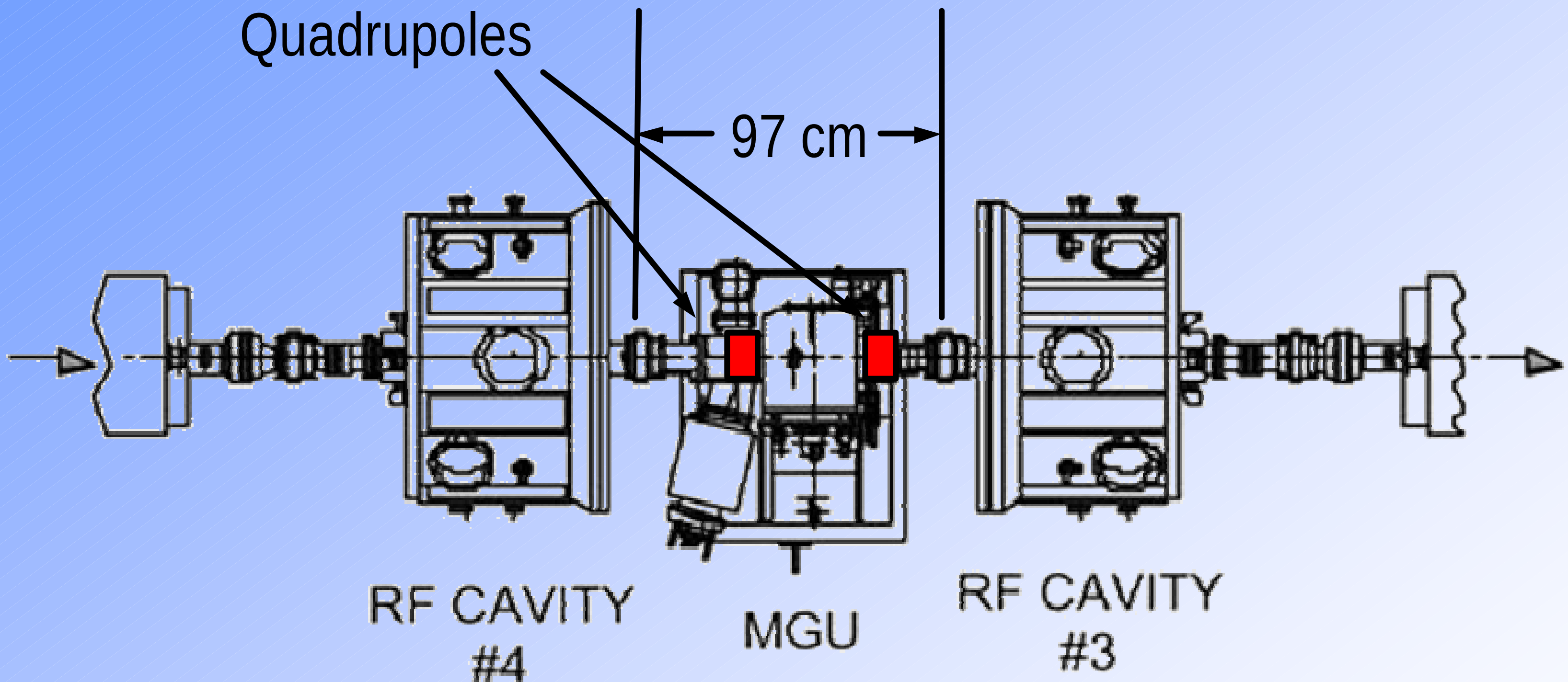
In-Vacuum Undulator



Mini-Gap Undulator



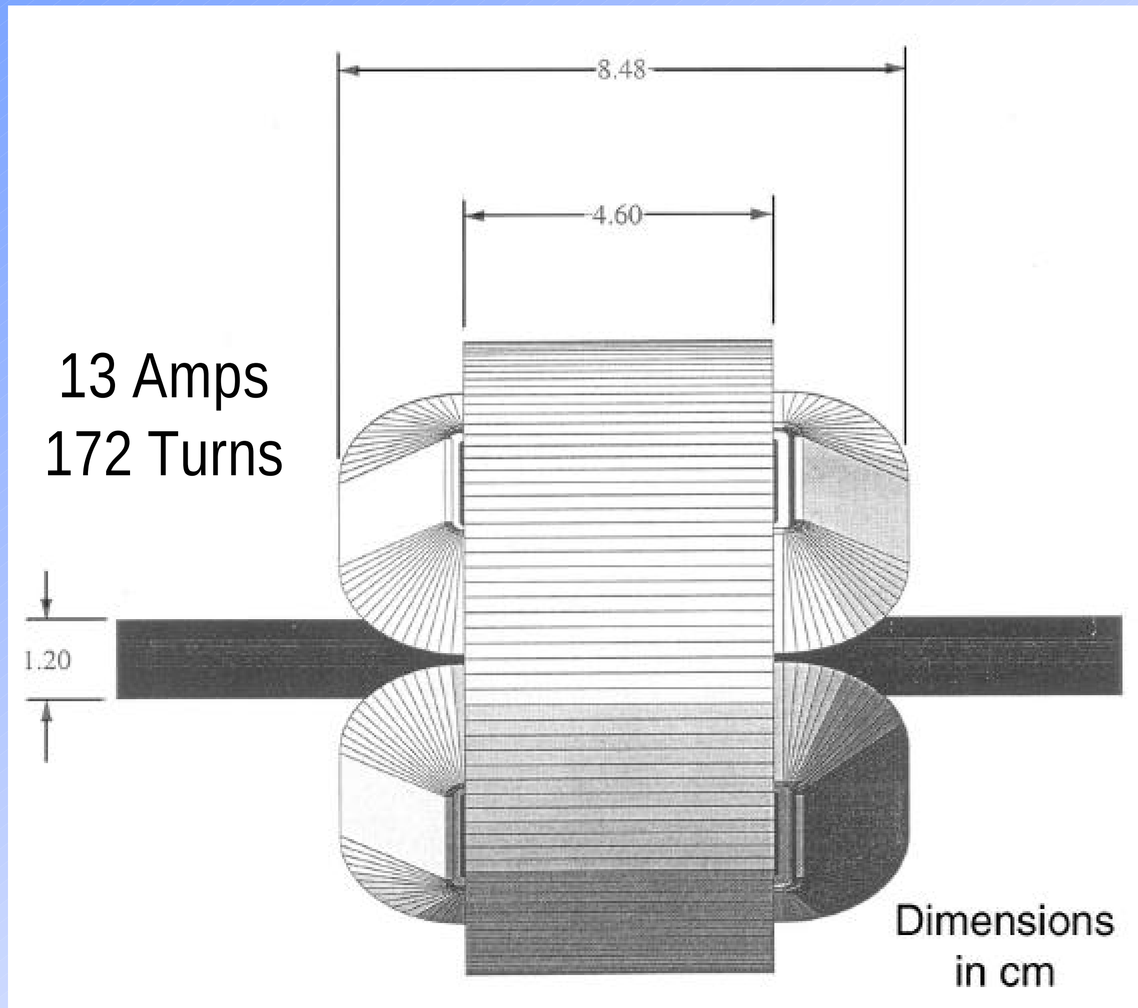
Undulator Location



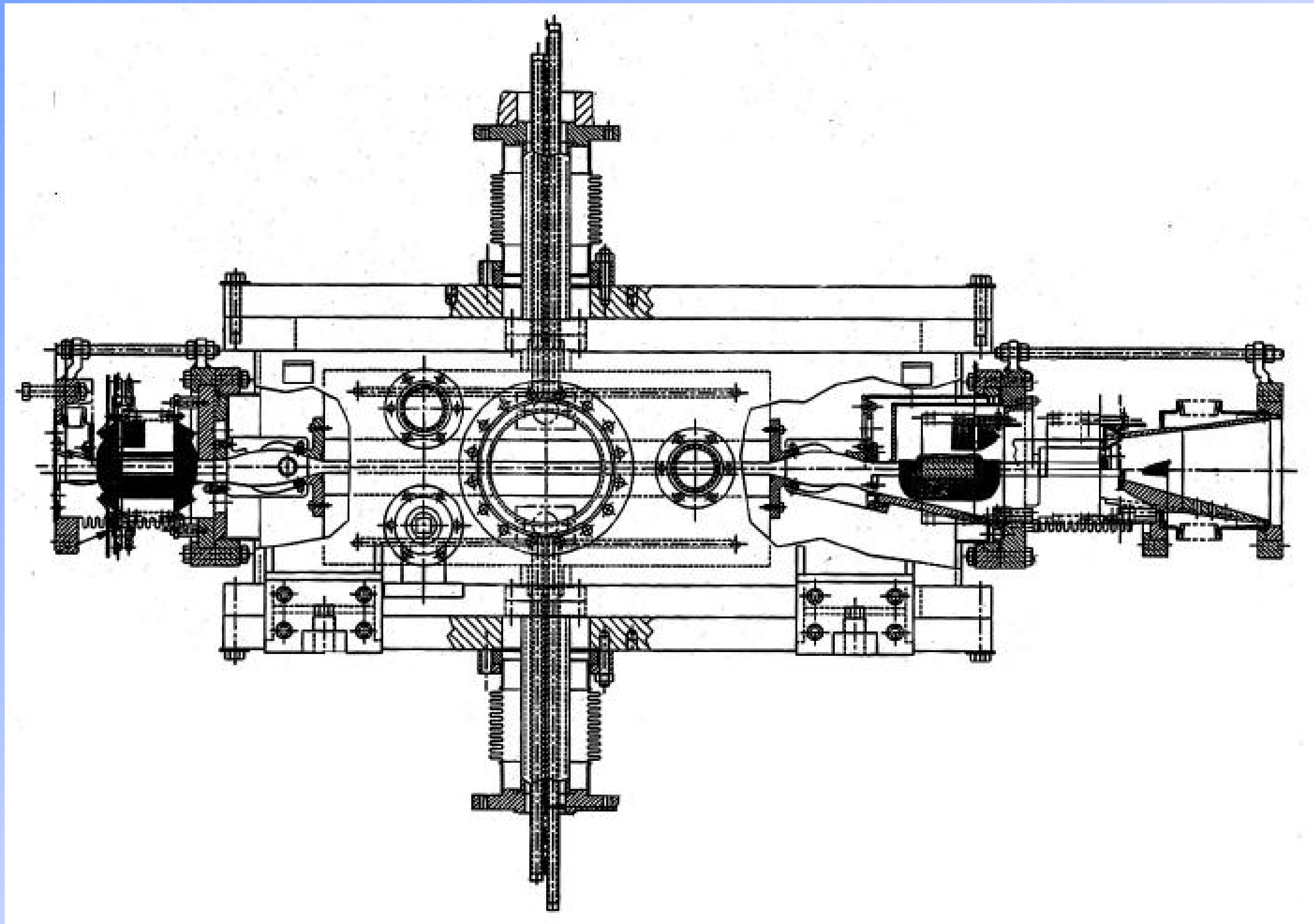
Reduces $\beta_{v,\,min}$ from 32 to 16 cm

Reduces minimum gap from 3.3 to 2 mm

Mini-Quadrupole



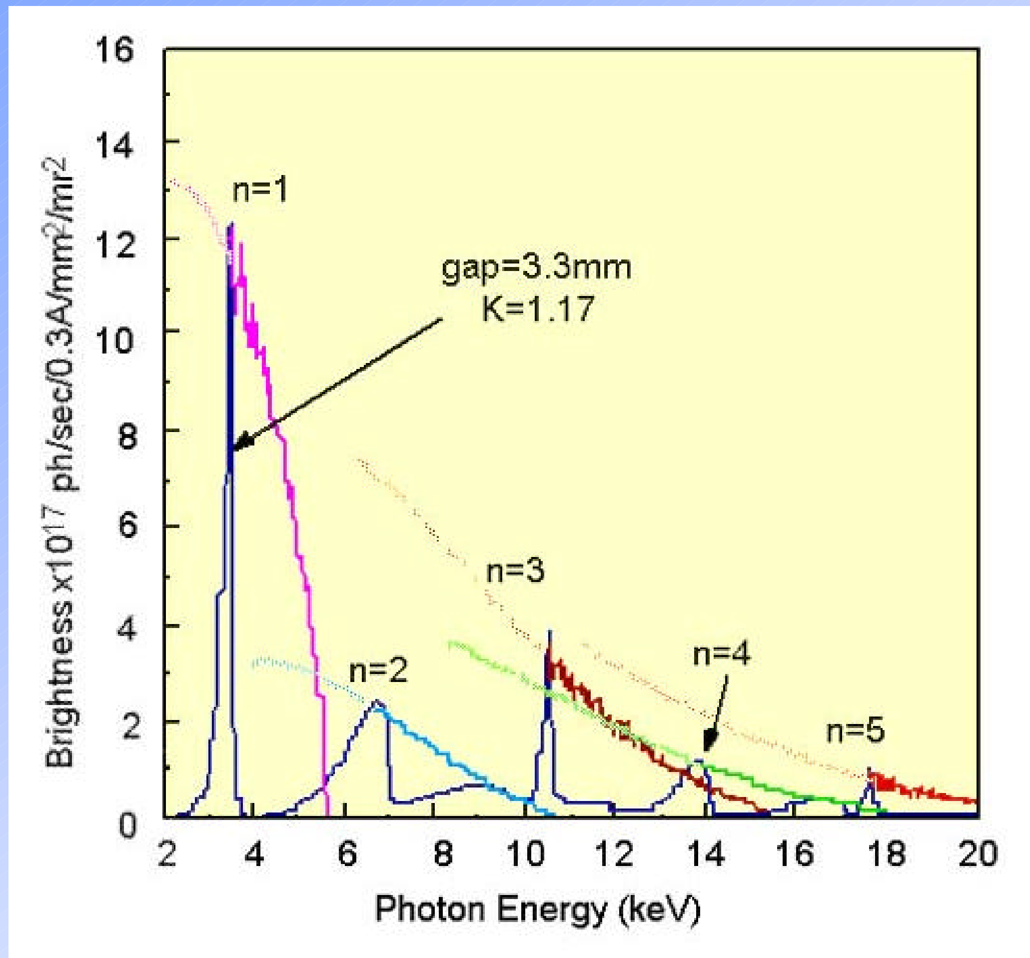
Undulator + Quadrupoles

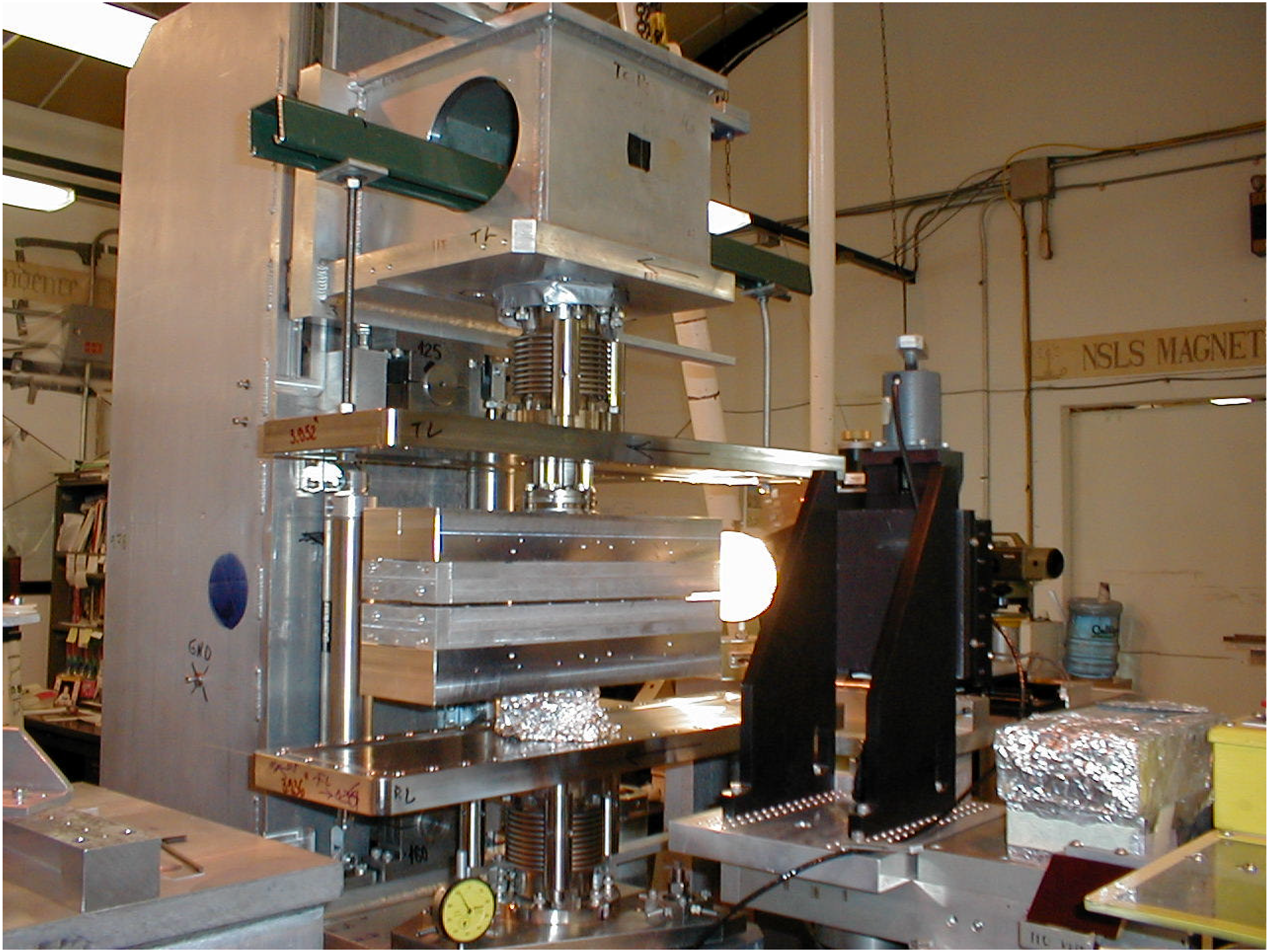


Small Gap Undulator Parameters

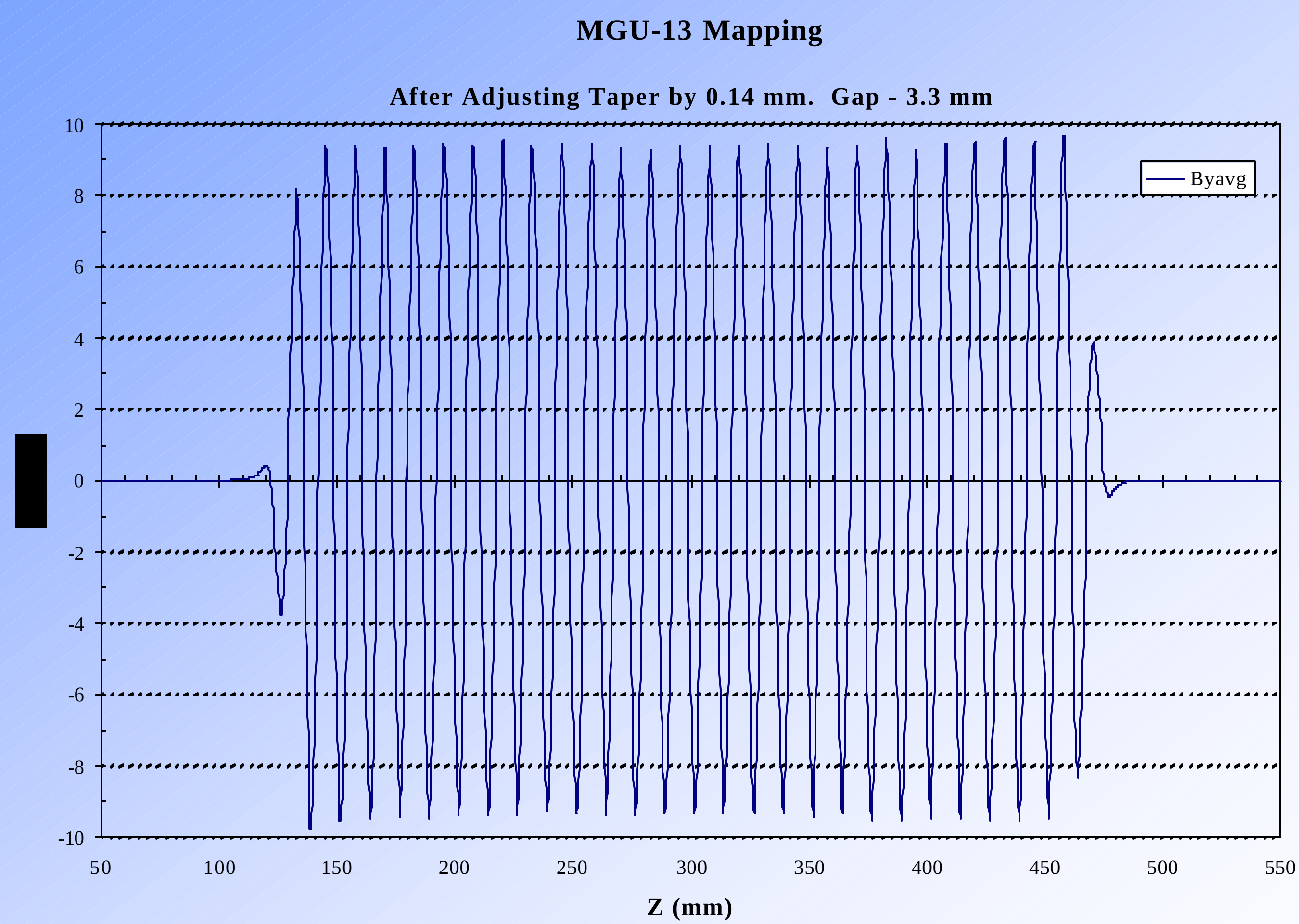
	PSGU	IVUN	MGU	(mini-β)
Period λ_u	16 mm	11 mm	12.5 mm	
Magnet Gap	6 mm	3.3 mm	3.3 mm	(2.0 mm)
Peak Field B_u	0.62 T	0.68 T	1.0 T	(1.66 T)
K_{max}	0.93	0.70	1.17	(1.94)
Fund. Energy	3.2 Kev	5.4 KeV	3.5 KeV	(1.76 KeV)
Beam Energy	2.8 GeV	2.8 GeV	2.8 GeV	

MGU Spectrum

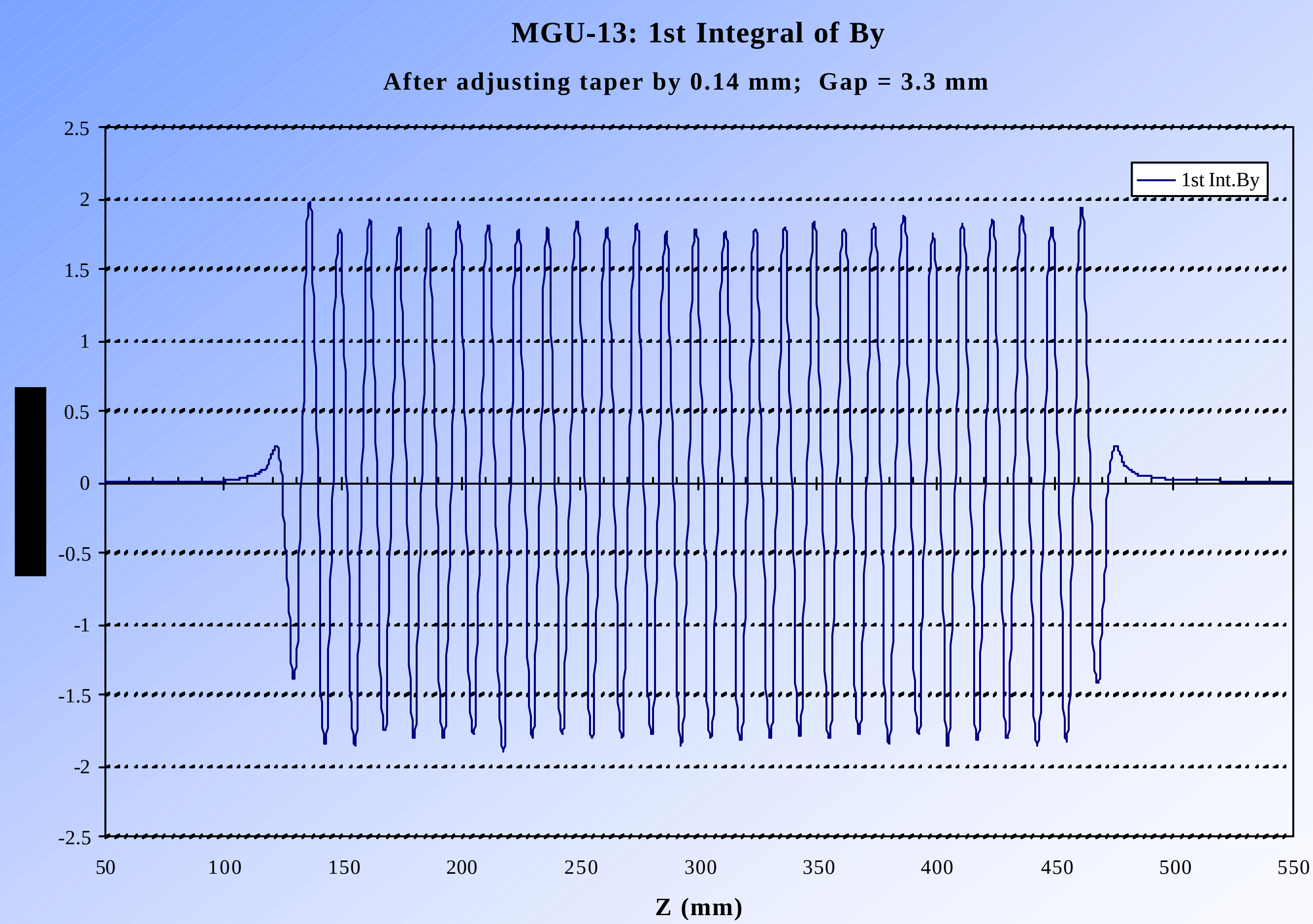



NSLS MAGNET

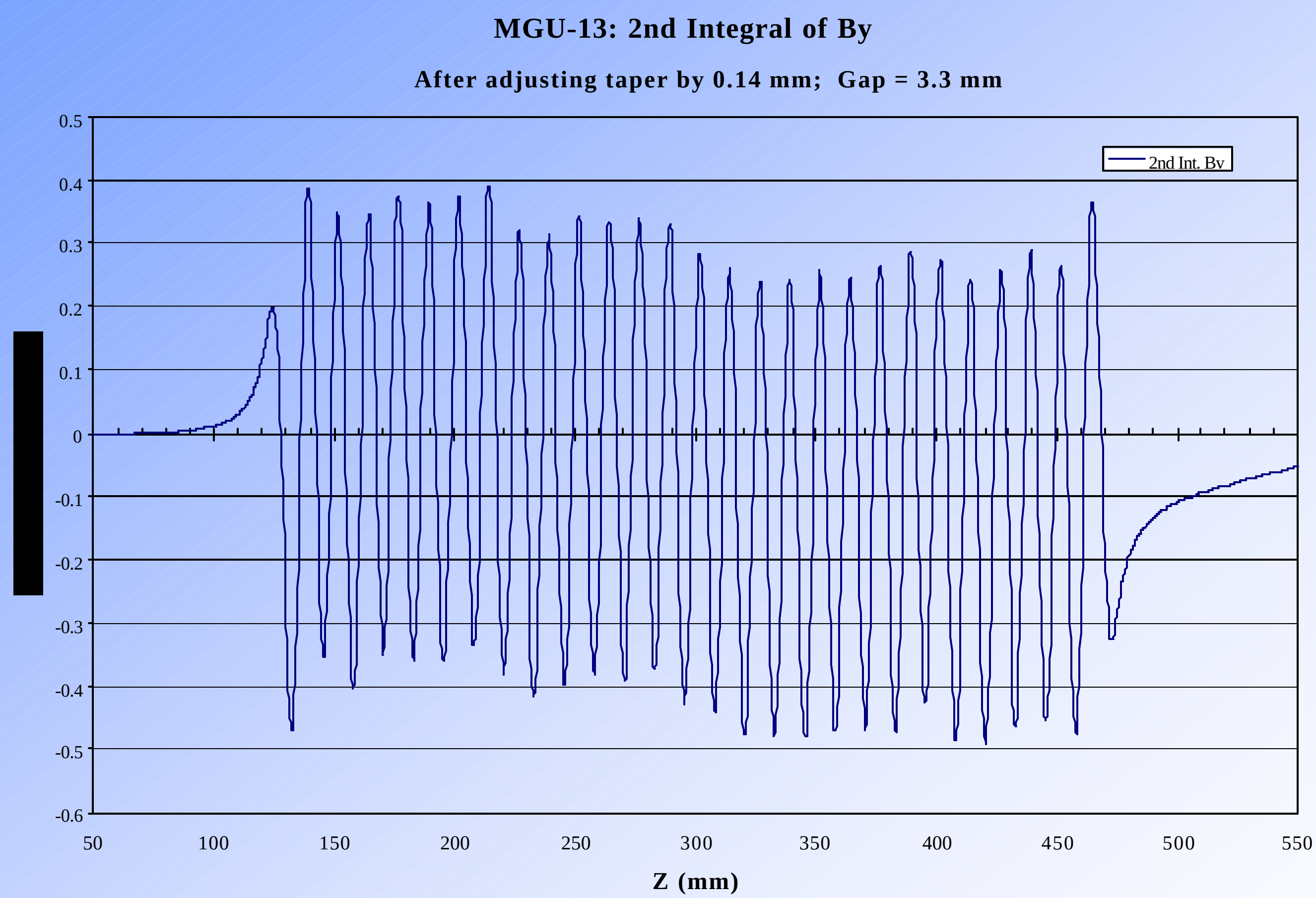
MGU Field Measurement



MGU First Integral



MGU Second Integral



Summary

- Permanent magnet assisted sextupole
  - Adding permanent magnet material can increase pole tip field by reducing saturation in iron
  - Simple method of upgrading existing magnets
- Superconducting Wiggler
  - Potentially versatile design
  - Problem with HT_c leads
- Mini-gap Undulator
  - Latest NSLS short period, in-vacuum undulator
  - Highly tunable source of hard x-rays from relatively low energy storage ring