Innovative Magnet Development and Application at the National Synchrotron Light Source

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Acknowledgements

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

- Intro to NSLS
- Permanent Magnet Assisted Sextupole
- Superconducting Wiggler
- Hybrid In-Vacuum Undulator
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
**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
- **4th Harmonic RF System**
- **Synchrotron Tune**: 0.0018
- **Bunch Length (2σ)**: 9.7 cm
  - (36 cm with 4th harmonic system)
- **RF Harmonic**: 9
- **Typical Number of Bunches**: 7
- **H Emittance**: \(1.62 \times 10^{-7}\) m-rad
- **V Emittance**: \(3.5 \times 10^{-10}\) m-rad
- **Power per Horizontal Milliradian**: (1A) 3.2 Watts

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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 x 10^-8 m-rad
- V Emittance 7.8 x 10^-11 m-rad
- Power per Horizontal Milliradian (250 mA) 32 Watts
- Critical Energy 7.1 KeV

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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
- $\varepsilon_x = 90$ nm-rad
- $\varepsilon_y = 0.1$ nm-rad
- $\nu_x = 9.14$
- $\nu_y = 6.20$
- $\eta = 0$ in long straights

Low Emittance Lattice
- $\varepsilon_x = 46$ nm-rad
- $\varepsilon_y = 0.08$ nm-rad
- $\nu_x = 9.83$
- $\nu_y = 5.71$
- $\eta > 0$ 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. 7\textsuperscript{th} 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

2.1 T
Field vs. Current

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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

<table>
<thead>
<tr>
<th></th>
<th>OPERATION</th>
<th>RAMPING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole ($\mathcal{B}_y dz$)</td>
<td>1.00 G-m</td>
<td>5.00 G-m</td>
</tr>
<tr>
<td>Skew Dipole ($\mathcal{B}_x dz$)</td>
<td>1.00 G-m</td>
<td>1.00 G-m</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>110.00 G</td>
<td>110.00 G</td>
</tr>
<tr>
<td>Skew Quadrupole</td>
<td>150.00 G</td>
<td>150.00 G</td>
</tr>
<tr>
<td>Sextupole</td>
<td>29.00 KG/m</td>
<td>29.00 KG/m</td>
</tr>
<tr>
<td>Skew Sextupole</td>
<td>10.00 KG/m</td>
<td>10.00 KG/m</td>
</tr>
<tr>
<td>$\mathcal{B}_y d^2z$</td>
<td>2.00 G-m²</td>
<td>5.00 G-m²</td>
</tr>
</tbody>
</table>

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Wiggler Operating Modes

Wavelength Shifter
Synchrotron Radiation Spectrum

![Graph showing synchrotron radiation spectrum with photon energy on the x-axis and photons/sec mA mrad 0.1% b.w. on the y-axis. Three lines represent different conditions: Full Wiggler, Partial Wiggler, and Wavelength Shifter.](image-url)
Why 33 KeV?
Digital Subtraction Angiography

Excised pig heart with iodine contrast agent injected into coronary arteries
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
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 ⇒
Short radiation wavelength ⇒
Short undulator period ⇒
Small gap
Pure Permanent Magnet Undulator
Prototype Small Gap Undulator
Reduces $\beta_{v,\text{min}}$ from 32 to 16 cm
Reduces minimum gap from 3.3 to 2 mm
Mini-Quadrupole

Dimensions in cm

13 Amps
172 Turns
Undulator + Quadrupoles
<table>
<thead>
<tr>
<th></th>
<th>PSGU</th>
<th>IVUN</th>
<th>MGU</th>
<th>(mini-β)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period $\lambda_u$</td>
<td>16 mm</td>
<td>11 mm</td>
<td>12.5 mm</td>
<td></td>
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<tr>
<td>Magnet Gap</td>
<td>6 mm</td>
<td>3.3 mm</td>
<td>3.3 mm</td>
<td>(2.0 mm)</td>
</tr>
<tr>
<td>Peak Field $B_u$</td>
<td>0.62 T</td>
<td>0.68 T</td>
<td>1.0 T</td>
<td>(1.66 T)</td>
</tr>
<tr>
<td>$K_{max}$</td>
<td>0.93</td>
<td>0.70</td>
<td>1.17</td>
<td>(1.94)</td>
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<tr>
<td>Fund. Energy</td>
<td>3.2 Kev</td>
<td>5.4 KeV</td>
<td>3.5 KeV</td>
<td>(1.76 KeV)</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>2.8 GeV</td>
<td>2.8 GeV</td>
<td>2.8 GeV</td>
<td></td>
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</table>
MGU Spectrum

![Graph showing photon energy distribution with annotations for n=1, n=2, n=3, n=4, n=5, gap = 3.3 mm, K = 1.17.](image)

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MGU-13 Mapping

After Adjusting Taper by 0.14 mm. Gap - 3.3 mm

Byavg
MGU-13: 1st Integral of By
After adjusting taper by 0.14 mm; Gap = 3.3 mm
MGU Second Integral

MGU-13: 2nd Integral of By
After adjusting taper by 0.14 mm; Gap = 3.3 mm

[Graph showing the 2nd Integral of By with Z (mm) on the x-axis and values ranging from -0.6 to 0.6 on the y-axis.]
**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