Development of RF Undulator-Based Insertion Devices for Storage Rings and Free Electron lasers

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Klystron Shop Group (Andrew Haase et. al.)
Why RF Undulator?

- Many desirable features
  - Fast dynamic control of
    - Polarization
    - Wavelength
    - K
  - Large aperture (cm vs mm for static undulator)
  - No issue with permanent magnet damage by radiation
  - Economic considerations
  - Potential use as LCLS “After Burner”
  - Dynamic undulator for storage ring
Available Resource – NLCTA

- 3 x RF stations
  - 2 x pulse compressors (240ns - 300MW max), driven each by 2 x 50MW X-band klystrons
  - 1 x pulse compressors (400ns - 300MW /200ns - 500MW variable), driven by 2 x 50MW X-band klystrons.
- 1 x Injector: 65MeV, ~0.3 nC / bunch

* In the accelerator housing:
  - 2 x 2.5m slots for structures
* Shielding Enclosure:
  - suitable up to 1 GeV
* For operation:
  - Can run 24/7 using automated controls

(Gain = 3.1)
TW RF Undulator in Circular Guide

- Research initiated by Claudio Pellegrini* at UCLA
- Undulator $K$ parameter of 1 requires > 1 GW
- $K = 0.5$ of some interest
  - power level achievable 250 MW
  - surface fields (80 MV/m) would limit pulse length to < 200 ns
- Substantial enhancement of $K$ parameter can be obtained with resonant structures

Effect of Power Losses

\[ \Delta a/a \]

\[ \Delta \lambda/\lambda \]
Tuning the Undulator Profile Through LLRF System

Because the e-beam and the em wave are traveling in opposite directions one can tailor the rf pulse to compensate for errors in the waveguide and also to taper the undulator field.

Waveguide Undulator

\[ e^- \]

\[ \text{RF} \]

\[ \text{Time} \]

\[ \text{RF Power} \]
Waveguide High Gradient Studies: Maximum breakdown electric fields for different geometries and materials

Initial Design point $K \approx 0.4$

Low magnetic field

High magnetic field

Gold

Copper

Stainless steel
**HE$_{11}$ Mode in Corrugated Guide**

- Inspired by our work on a previous LDRD project which involved corrugated feed horns for CMB applications
- Lowest order mode (HE$_{11}$) is a combination of primarily TE$_{11}$ and TM$_{11}$ modes
- Magnetic field is extremely low on waveguide walls – attenuation can be less than that of smooth wall cylindrical TE$_{01}$ mode
- Field configuration ideal for beam interaction
Comparison Between $\text{TE}_{1n}$ and $\text{HE}_{1n}$ Modes

Frequency $= 11.424$ GHz, $K = 1$, Length $= 1$ m, Material: Copper

For $\text{TE}_{1n}$ modes the undulator is a simple circular waveguide.

For $\text{HE}_{1n}$ modes the undulator is a corrugated circular waveguide with following parameters:

- Slot Depth $= 0.335 \lambda$
- Slot Thickness $= \lambda/16$
- Corrugation Period $= 0.45 \lambda$

![Graph showing Power Losses vs. Undulator Inner Radius in Free Space Wavelength Units.](image1)

![Graph showing Stored Energy vs. Undulator Inner Radius in Free Space Wavelength Units.](image2)
Hybrid Mode Fields

Electric Field

Radial Field

Axial Field

Azimuthal Field

Magnetic Field
HE\textsubscript{1n} Modes Scaling Laws

For an undulator made of copper at room temperature:

\[ \lambda_u \approx \frac{\lambda}{2} \]

\[ \text{Power:} \quad P(MW) \approx K^2 J_1^2(x) \left( \frac{0.727141 a^2}{\lambda_u^{5/2}} + \frac{0.0673433 L x^2}{a \sqrt{\lambda_u}} \right) \]

\[ \text{Stored Energy:} \quad U(\text{Jouls}) \approx \frac{71.5 a^2 K^2 L J_1^2(x)}{\lambda_u^2} \]

\[ \text{Quality Factor:} \quad Q \approx \frac{1.17 \times 10^8 a^3 L}{128 \pi^2 a^3 + 117 L x^2 \lambda_u^2} \sqrt{\frac{1}{\lambda_u}} \]

\[ \text{Filling Time:} \quad t_f(\mu s) \approx \frac{124208 a^3 L \sqrt{\lambda_u}}{128 \pi^2 a^3 + 117 L x^2 \lambda_u^2} \]

\[ \text{Peak Surface E Field:} \quad E_s (\text{MV} / \text{m}) \approx \frac{1.02 K x J_1(x)}{a} \]

\[ \text{Peak Surface B Field:} \quad B_s (\text{mT}) \approx \frac{3.4 K x J_1(x)}{a} \]

\[ x \rightarrow \{2.40483, 5.52008, 8.65373, 11.7915\} \text{ for } HE_{11}, HE_{12}, HE_{13}, HE_{14} \text{ modes} \]
**HE$_{1n}$ Modes Scaling Laws**

For an undulator made of copper at room temperature:

\[ \lambda_u \approx \frac{\lambda}{2} \]

**Optimal Radius**: \[ a(m) \approx 0.23 \lambda^{2/3} \sqrt[3]{L} x^{2/3} \]

**Minimum Power**: \[ P(MW) \approx \frac{0.28 K^2 L^{2/3} x^{4/3} J_1^2(x)}{\lambda_u^{7/6}} \]

**Stored Energy**: \[ U(Jouls) \approx \frac{9.22 K^2 L^{5/3} x^{4/3} J_1(x)^2}{\lambda_u^{2/3}} \]

**Quality Factor**: \[ Q \approx \frac{30867L}{\sqrt[3]{\lambda_u}} \]

**Filling Time**: \[ t_f(\mu s) \approx 32.8L \sqrt{\lambda_u} \]

**Peak Surface E Field**: \[ E_s(MV/m) \approx \frac{1.02 K x J_1(x)}{a} \]

**Peak Surface B Field**: \[ B_s(mT) \approx \frac{3.4 K x J_1(x)}{a} \]

\[ x \to \{2.40483, 5.52008, 8.65373, 11.7915\} \text{ for } \text{HE}_{11}, \text{HE}_{12}, \text{HE}_{13}, \text{HE}_{14} \text{ modes} \]
Undulator Design

Undulator Mechanical Structure

Electric Field Distribution

Simulated Electric Field
Simulated Magnetic Field, $cB$
Two coupling ports $90^\circ$ apart to excite two polarizations independently.

**Undulator Coupler Design**

- Corrugation Period = 0.4254 $\lambda$
- Inner Radius = 0.75 $\lambda$
- Outer radius = 1.01293 $\lambda$
- Corrugation Thickness = $\lambda/16$
- Number of periods = 98

**Electric Field Distribution**

- $\lambda$ = 2.6242296 cm
- Undulator Wavelength = 1.39306 cm
- Power required (for linearly polarized, $K=1$) = 48.8 MW
- $Q_0$ = 94,000
Transverse Beam Distribution

Simulated Bunch Drift for $K = 0.7$

- At entrance
- At exit

- $120$ MeV
- $60$ MeV
# Field Integrals

\[ M = 2 \frac{\Lambda + \beta}{(1 + \Lambda)} \]

\[ N = 4\pi \frac{1 - \beta^2}{(1 + \Lambda)} \]

\[
I_1(z) = \left[ M f(z) e^{i2\pi z} + N \int g(z) e^{i2\pi z} \, dz \right]
\]

\[
I_2(z) = \int I_1(z) \, dz
\]

\[
\dot{x} + i\dot{y} = \frac{K}{\gamma} e^{i2\pi t_0} I_1(z)
\]

\[
x + iy = \frac{K}{\gamma} e^{i2\pi t_0} I_2(z)
\]
Drift in $\rho$-$z$

K = 0.707; Energy: 119.6 MeV

Symplectic Integration
Field Integrals

$\rho$ (mm)

z (cm)

$y$ (mm)

x (mm)
Calculations from cold test data @ 20 °C with air:
Resonance Frequency \( (f_0) = 11.419 \text{ GHz} \) (11.424 under vacuum @12.1 °C)
\( \beta = 1.53 \), \( Q_0 = (1+ \beta) \) \( Q_{\text{total}} = 91,000 \) (Simulations 94,000)
Comparison between Simulations and Cold Test Data
Measured Filling Profile the Structure

\[ E_{\text{emitted}} = \sqrt{P_{\text{emitted}}} = \sqrt{\frac{2 \pi f_0 U \beta_{\text{coupling}}}{Q_0}} \propto K \]
Undulator Operation

\begin{figure}
\centering
\includegraphics[width=\textwidth]{undulator_operation.png}
\caption{Graph showing the power and intensity of incident and reflected waves over time.}
\end{figure}
Far Field @ 69 MeV

Electric field polarization vector
Far Field @ 69 MeV

Electric field polarization vector
RF Undulator Radiation Spectrum (Beam Energy: 53.7 MeV, K = 0.67)

- with regular beam (x3)
- with ~800nm microbunched beam

Intensity (relative) vs. Wavelength (nm)
Date of measurements: July 18, 2012 (The idea of these measurements was initiated by Erik Hemsing)
Far Field @ 74.8 MeV

Without seed

With 800 nm seed
Spectrum shift as a function of K

Spectrum of Radiation for various values of K

Normalized Intensity

wavelength (nm)

K=0.25
K=0.35
K=0.45
K=0.55
K=0.67
K=0.70
K=0.72
Fitting the Measured Spectrum

Spectrum for $K = 0.65 \, @ \, 69 \, \text{MeV}$

- Blue line: obtained from spectrometer
- Green line: calculated theoretically

(normalized intensity vs. wavelength (nm))
Raw Measurements

- measured from spectrum
- calculated from K assuming 71.3 MeV beam

Graph: 
- Y-axis: Radiation wavelength (nm)
- X-axis: K (calculated from RF measurements)
Measurements of the undulator K parameter

Beam Energy: 70 MeV

Calculated from Measured Spectrum Data

Calculated from RF Power Measurements

<table>
<thead>
<tr>
<th>Radiation Wavelength (nm)</th>
<th>Calculated from RF Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td></td>
</tr>
<tr>
<td>380</td>
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<td>400</td>
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<tr>
<td>480</td>
<td></td>
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<tr>
<td>500</td>
<td></td>
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</tbody>
</table>

K - 0.96 x Value Calculated from RF Measurements
Stn0 m20
Polarization Plate Rotate
Sensitivity to input frequency shift

Spectrum for Various Frequency Shifts (K = 0.6, Beam Energy = 69 MeV)
Beam Shift

Max drift (measured) = 1.52 ± 0.03 mm (assuming 0.094 ± 0.002 mm/pixel)
Max drift (calculated) = 1.27 mm

K = 0.6 69 MeV

Measured
Sinusoidal Fit

Drift (mm)

RF Phase (degrees)
An HE₁₁ Undulator as an After Burner for LCLS

\[ a = 7.848 \text{cm} \]
\[ \lambda u = 5.55169 \text{cm} \]
\[ B_p = 310 \text{ mTesla} \]
\[ K = 2.48 \]
\[ V_g/c = 0.83 \]
\[ V_p = 1.12 \]

Total Power = 46 MW

Filling Time = 7.5427

Stored Energy = 346 Jouls

Peak Electric Field at Guide Wall = 40 MV/m

Energy Supplied by One 5045 Klystron is 228 Joules
Status of the development:

- A novel concept for using the balanced hybrid mode in corrugated waveguide to create ultra-high filed in the center of the waveguide with relatively small surface fields have been developed.
- The scaling laws for this device have been developed.
- The phase conjugate end mirrors have been developed.
- The single particle dynamics and the end field profile required to minimize both integrated transverse momentum kick and total transverse displacement have been studied and implemented in the design.
- A prototype at designed with 1.4 cm undulator wavelength is under construction to test the concepts. The undulator is expected to have a K parameter of ~1 with possibility of switching the polarization by controlling the phases of the RF source.
- Initial test for this undulator with beams is scheduled on June 18 at NLCTA at SLAC.
- The THz structure is being designed mechanically.
- The THz source at University of Maryland have been tested up to 80 KW recently with a pulse length of 7 µS.

Parameters for 221 micron undulator (corresponding to the available 680 GHz source; with pulse compression few MW could be achieved using this source)

\[ P(MW) \approx \frac{0.24K^2L^{2/3}}{\lambda_u^{7/6}} \]

900 kW for K=0.03, 10 MW for K=0.1 (5.5 T)

\[ t_{\text{filling}}(\mu s) = 32.8L\sqrt{\lambda_u} \]

48 ns filling time

\[ a(m) = 0.41\lambda_u^{2/3}\sqrt[3]{L} \]

1.4 mm diameter aperture
Resonant Ring Configuration

- A closed ring with length $n\lambda g$
- Tune by adjusting ring length
- Considerable development for relevant components (miter bend, couplers) has been done (ITER transmission lines)
200 micron Wavelength Undulator

We have explored three possible designs:

- **Dielectric tube or dielectric slab guiding structure**
  - Simple to design, and build.
  - The source is the 5 micron laser being developed for the accelerator structure.
  - The electromagnetic wave co-propagates with the electron beam to stretch the undulator wavelength to 200 microns.
  - Forces due to electric and magnetic fields tend to cancel each other, hence, the surface and bulk fields are high in comparison to the net equivalent deflecting field.
  - The field is guided within the volume of the dielectric and the beam interacts with the evanescent field, thus forcing the undulator aperture to be close to one wavelength.

- **Bragg reflector type structure**
  - More complicated to design and build.
  - The source is the 5 micron laser being developed for the accelerator structure.
  - The electromagnetic wave co-propagates with the electron beam to stretch the undulator wavelength to 200 microns.
  - Forces due to electric and magnetic fields tend to cancel each other, hence, the surface and bulk fields are high in comparison to the net equivalent deflecting field.
  - The field is guided within the vacuum region surrounded by the Bragg guiding structure. The beam interacts with the bulk of the field, thus allowing the undulator aperture to be large compared to the wavelength.

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June 27, 2012
Metallic structure driven by a THz source

- Very complicated to design, but easier to build.
- The source is a THz high power source. Compact pulsed Gyrotrons have been recently developed at 680 GHz at University of Maryland. Size is comparable to lasers. Other sources are under development.
- The electromagnetic wave counter propagates with the electron beam thus reducing the undulator wavelength by a factor of two from the THz radiation wavelength.
- Forces due to electric and magnetic fields add to each other, hence, the surface and bulk fields are small in comparison the net equivalent deflecting field. Potentially this approach will produce the highest possible K parameter at 200 micron wavelength.
- The filed is guided within the vacuum region surrounded by a metallic corrugated structure. the beam interacts with the bulk of the field, thus allowing the undulator aperture to be extremely large compared to the wavelength.
General expressions for a monochromatic circularly symmetric Field

\[
\begin{align*}
E_z &= \frac{2 \sqrt{2} x \sqrt{2} \hat{\lambda}_u - 1 \sin(\phi) J_1 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right)}{x + 1} \\
\hat{H}_z &= \frac{2 \sqrt{2} \hat{\lambda}_u - 1 \cos(\phi) J_1 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right)}{x Z + Z} \\
\hat{E}_r &= \frac{i \hat{\lambda}_u \sin(\phi) \left( J_1 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right) - \pi \hat{\lambda}_u \sqrt{2} \hat{\lambda}_u - 1 \left( J_0 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) - J_2 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right)}{\sqrt{2} \hat{\lambda}_u - 1} \\
\hat{E}_\phi &= \frac{i \hat{\lambda}_u \cos(\phi) \left( J_1 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right) - \pi \hat{\lambda}_u \sqrt{2} \hat{\lambda}_u - 1 \left( J_0 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) + J_2 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right)}{\sqrt{2} \hat{\lambda}_u - 1} \\
\hat{H}_r &= \frac{i \hat{\lambda}_u \cos(\phi) \left( J_1 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right) - \pi \hat{\lambda}_u \sqrt{2} \hat{\lambda}_u - 1 \left( J_0 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) - J_2 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right)}{\sqrt{2} \hat{\lambda}_u - 1} \\
\hat{H}_\phi &= \frac{i \hat{\lambda}_u \sin(\phi) \left( -\pi \hat{\lambda}_u \sqrt{2} \hat{\lambda}_u - 1 \left( J_0 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) + \pi \hat{\lambda}_u \sqrt{2} \hat{\lambda}_u - 1 \left( J_2 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right) \right) + (\hat{\lambda}_u - 1) J_1 \left( \frac{2 \pi \sqrt{2} \hat{\lambda}_u - 1}{\hat{\lambda}_u} \right) \right)}{\pi \hat{\lambda}_u \sqrt{2} \hat{\lambda}_u - 1} \\
\hat{E}_r - \hat{Z} \hat{H}_\phi \bigg|_{r \to 0} &= 1
\end{align*}
\]
The philosophy of the design is to write down the profile of the electromagnetic fields required and then “dress it with materials to guide it”

There is rather a limited set of fields that
— satisfy Maxwell’s equations,
— have a dipole like field and
— have net deflection as they propagate with the beam

The field configurations shown in the figures are theoretically the best possible field profiles; i.e., profiles that gives the highest possible deflecting field with minimum surface field.

Typically the relative group velocity is related to the undulator wavelength by:

$$v_g / c = \frac{\lambda_u / \lambda_0 - 1}{\lambda_u / \lambda_0}$$
Optimization for a forward interaction RF undulator with small aperture

\[ \frac{E_s}{E_d} \approx \frac{\pi^2 \frac{\lambda_u}{\lambda} - 1}{\frac{a}{\lambda}} \frac{a}{\lambda} \]

\[ \frac{\lambda_u}{\lambda} = (\infty, 20, 10, 5) \]
Overmoded optimization for a forward interaction RF undulator

Limiting the aperture to 10 wavelengths

Limiting the aperture to 8 wavelengths
Design example of a planer undulator with an undulator wavelength of 100 micrometer.
Design example of a planer undulator with an undulator wavelength of 50 micrometer.
Stretching the laser wavelength using either dielectric slab or Bragg guiding structure undulator (Continued)

- Status of the design for dielectric structures that stretches the excitation wavelength:
  - we have exhaustively considered all possible field profiles and created the scaling laws governing each type of structure.
  - It clear that ultimately we have to use a Bragg guiding structure.
  - We are now exploring practical implementation of both types of structures
    - Slab structure have the potential of an easy implementation which might allow us to conduct experiments in the near future with a K parameters, at best approaching 0.01 (0.5 T) with a rather narrow beam aperture.
    - while the Bragg structure have the potential of producing K values ~0.05 (2.7 T) with a large beam aperture

<table>
<thead>
<tr>
<th>Gap</th>
<th>Thickness</th>
<th>Width</th>
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<tbody>
<tr>
<td>~7.5µm</td>
<td>~0.5µm</td>
<td>~40µm</td>
</tr>
<tr>
<td>~500µm</td>
<td>Silicon</td>
<td>SiO₂</td>
</tr>
</tbody>
</table>

Wafer #1
Wafer #2

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June 27, 2012
Key feature

- SiO$_2$: 1.444um, 0.754 um
- Si: >50um

Diagram showing layers of SiO$_2$ and Si with specified thicknesses.
Step 15

- Dicing
- HF wet etch
Mask #2 (front side spacer)

- On front side of the wafer
- Structure to create 16um high channel
Schedule

• Fabrication and validation of structure with photomasks (Aug 22\textsuperscript{nd})
• Measure refractive index of deposited single layer film at 10.6\textmu m. (Aug 17\textsuperscript{th})
• Fabrication of undulator (Sept 14\textsuperscript{th})
Status of Optical Undulator

• Stratified coating and masks have been generated
• Measurements at 10.6 microns will be performed soon (an OPA at SLAC will be available in two weeks, we hope to do the measurements at UCLA before that)
• We hope that the structure will be available in about 3-4 weeks for testing at BNL(ATF)
Superconducting Undulator (1 % duty cycle)

Undulator wavelength ~ 1cm imply operating frequency of ~16 GHz. The undulator test done to date was at 11.4 GHz with undulator wave length of 1.393 cm. Reducing it to 1 cm should be straight forward.

- One could decrease the filling time by decreasing the external Q.
- The peak power would increase, of course.
- At a filling time of 1 ms, the peak power required is 50kW/m.
- At CW the peak power required is 500 watts/m.
The Future

- More precision measurements at NLCTA
- After Burner for LCLS
- Short Wavelength Undulator at 10mm for ILC
- Short Wavelength Undulator at 5mm for NGLS
- Superconducting undulators