Impedance Optimization of Small Gap Chambers for the High Single Bunch Current Operation at the APS

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Impact of ID Chamber Impedance at the APS

- The single bunch current is limited by the vertical impedances in the ring.
- The vertical impedance is dominated by the ID chambers
  - 68% of total ring impedance (23x8mmE, 1x5mmE, 8x7.5mmR)
  - 34% by Geometric impedance
  - 34% by Resistive wall impedance
- We like to keep 16 mA in the single bunch for the hybrid mode
  - High chromaticity in x and y plane is required to store 16 mA in the single bunch.
  - If the impedance increases, we need to increase the chromaticity to keep 16 mA. However, the sextupole strengths are limited.

- Prior to the MBA lattice based APS Upgrade, we had considered replacing the 8-mm gap chambers with 7.3-mm gap chambers
  - It will increase the impedance significantly.
  - Can we do it without giving up 16-mA operation?
  - If possible, what engineering design change we need to make?
Motivation and Significance of 16-mA Operational Mode

<table>
<thead>
<tr>
<th></th>
<th>Energy (GeV)</th>
<th>Size (m)</th>
<th>Total Current (mA)</th>
<th>Bunch Current (mA)</th>
<th>Bunch Charge (nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESRFa</td>
<td>6</td>
<td>844.4</td>
<td>200</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>APSb</td>
<td>7</td>
<td>1104</td>
<td>102</td>
<td>16</td>
<td>59</td>
</tr>
<tr>
<td>Spring8c</td>
<td>8</td>
<td>1436</td>
<td>100</td>
<td>5~</td>
<td>24~</td>
</tr>
</tbody>
</table>

- The timing-mode users are very strong in the APS.
- The high-flux users have strong demands on the small gap chambers.
- So we have to optimize the small gap chambers to reduce the impedance to meet the both demands. This became the motivation of impedance optimization for the small gap ID chambers.

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a [http://www.esrf.eu/Accelerators/Operation/Modes](http://www.esrf.eu/Accelerators/Operation/Modes)
Impedance Effect on the Single Bunch Current

- The single bunch current is limited by the vertical impedances in the ring.

(Experiment by Chae, Emery, Yao)
Impedance Effect on the Single Bunch Current

- Shows the single bunch current as function of impedance in the current APS ring. Zt=1 is nominal APS.
- Can predict the current with the hypothetical increase and decrease of impedance in the APS-U
ID Chamber Optimization

- **ID Extrusion Chamber**
  - Gap
  - Width
  - Profile: Ellipse vs. Racetrack

- **APS-to-ID Chamber Transition**
  - Linear taper
  - Nonlinear taper

- **APS Extrusion Chamber**
  - Width
  - Height
  - New taper
ID Chamber Gap

- $k_y \propto \frac{1}{Gap^\alpha}$
- $\alpha = 2.1 \sim 2.4$ for Gap = [4mm, 14mm]
  - Depends on ID width, transition length, beam offset

\[
\log k_y = 16.0718 - 2.30208 \times \log \text{Gap}
\]

\[
\log \log k_y = 16.068 - 2.31972 \times \log \text{Gap}
\]
ID Chamber Width

- APS regular chamber has half width $w=42$ mm $\Rightarrow$ Fixed
- APS undulator chamber has half width $w=18$mm $\Rightarrow$ Vary

• Smaller chamber width requires small beta-$x$ for a good injection efficiency
ID Chamber Profile: Superellipse

- Also called Lamé curve
- $n < 2$: hypoellipse
- $n = 2$: ellipse
- $n > 2$: hyperellipse

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1$$
ID Chamber Profile: Superellipse (2)

- Studied various ways of reducing the taper impedance
ID Chamber Profile: Superellipse (3)

7.5mm ID Chamber: Superellipse  n=5-9

APS Extrusion: Superellipse n=2

- Profile data provided by B. Stillwell (AES-MED)

Advanced Photon Source Upgrade (APS-U) project
ID Chamber Profile: Superellipse (4)

7.5mm ID Chamber: Superellipse  n=5-9

- Profile data provided by B. Stillwell (AES-MED)
Transition

Typical Long Straight Section – Schematic

- Symmetric Transition
- Asymmetric Transition
- Nonlinear Transition
- Segmented Transition
Symmetric Transition

- Constraint: $L = L_1 + L_2$ is fixed
- $L_1 = L_2$, $\beta_1 = \beta_2$

$$L_1, \beta_1 \quad \quad \quad \quad \quad \quad \quad \quad \quad L_2, \beta_2$$

$$T_1 \quad \quad \quad \quad \quad \quad \quad \quad \quad T_2$$

$$\begin{align*}
K_{yNorm} & = 0.302077 + 12.7971x - 24.982x^2 \\
\end{align*}$$
Asymmetric Transition

- Constraint: \( L = L_1 + L_2 \) is fixed
- \( L_1 \neq L_2, \beta_1 = \beta_2 \)

\[ L_1, \beta_1 \quad \text{T1} \quad L_2, \beta_2 \quad \text{T2} \]

\[ L(\text{Transition}) = L_1(\text{In}) + L_2(\text{Out}) \]

\[ L_1 = L_2 \] makes the minimum \( K_y \)

\[ Ky_{\text{norm}} \]

\[ Ky \text{ (V/nC/mm)} \]

\[ L(\text{mm}) \]

\[ L(\text{In}) \]

Advanced Photon Source Upgrade (APS-U) project
Asymmetric Transition (2)

- SPX Chamber: $L_1=50\text{cm}$, $L_2=20\text{cm}$, $\beta_1=8\text{m}$, $\beta_2=4\text{m}$
- Optimize: $\beta_1*K_y_1 + \beta_2*K_y_2$

SPX Chamber Condition for the APS-Upgrade

Minimum
Nonlinear Transition

Impedance Formula for constant width chamber*

\[
Z_{y,\text{rect}} = j \frac{Z_0 w}{4} \int_{-\infty}^{\infty} dz \frac{h'(z)^2}{h(z)^3}
\]

- Optimize \( w \) ➞ narrow horizontal aperture
- Optimize linear \( h'(z) \) ➞ long taper
- Optimize \( h(z) \) ➞ nonlinear taper

* G. Stupakov, Geometrical Wake of a Smooth Flat Collimator, SLAC-PUB-7167, 1996
Nonlinear Transition (2)

- Optimum profile found by B. Podobedov and I. Zagorodonov*

\[ h(z) = \frac{h_{\text{min}}}{\left(1 + \left(\beta^{-1/2} - 1\right)\frac{z}{L}\right)^2}, \quad \beta \equiv \frac{h_{\text{max}}}{h_{\text{min}}} \]

\[
\frac{Z_{y}^{\text{optimum}}}{Z_{y}^{\text{linear}}} = \frac{8\beta}{(1 + \beta)^2\left(1 + \sqrt{\beta}\right)^2}
\]

APS Chamber
- h_{\text{max}}=21 \text{ mm}, \; h_{\text{min}}=4 \text{ mm}
- Ratio=5/8

Nonlinear Transition (3)

Material boundaries
1. ID Chamber
   - Gap
   - Width
   - Profile

2. Transition
   - Length
   - Symmetric
   - Asymmetric
   - Nonlinear Taper

3. APS Chamber
   - Width
   - New Taper
Advanced Photon Source Upgrade (APS-U) project
APS Chamber Width

- APS undulator chamber has half width \( w = 18\text{mm} \) ➔ **Fixed**
- APS regular chamber has half width \( w = 42\text{mm} \) ➔ **Vary**

Very interesting, But not practical
New Taper
New Taper Optimization

Horizontal Plane: Width effect

W=42mm

a=Vary

W=18mm

Vertical Plane: b vs. slope

H=21mm

b=Vary

H=4mm
New Taper Optimization: fixed a

- H = 21 mm
- b = Vary
- H = 4 mm

Normalized by $K_y$ ($a = 42$ mm, $b = 21$ mm)
New Taper Optimization: fixed b

- As “a” decreases, $Ky$ also decreases
- As “a” decrease, rf heat load increases
- **We determined that a=b=17 mm**
Aperture: $a=42\text{mm}, \; b=21\text{mm}$
ID Chamber with New Transition - Wakefield

Aperture: a=17mm, b=17mm
Optimize the taper for Power & Ky (a=b=17mm)

- W=42mm
- H=21mm
- a=17mm
- b=17mm
- W=18mm
- H=4mm
ID Chamber: Full Gap=8mm (Half Width=18mm)
# Required Impedance Level (Replacing 8.0mm Ellipse by smaller gap chamber)

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>Total Impedance (zu)</th>
<th>Resistive Wall Impedance (zu)</th>
<th>Geometric Impedance (zu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.73</td>
<td>0.730</td>
<td>1.0</td>
</tr>
<tr>
<td>7.8</td>
<td>1.73</td>
<td>0.788</td>
<td>0.942</td>
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<tr>
<td>7.6</td>
<td>1.73</td>
<td>0.851</td>
<td>0.879</td>
</tr>
<tr>
<td>7.4</td>
<td>1.73</td>
<td>0.922</td>
<td>0.808</td>
</tr>
<tr>
<td>7.2</td>
<td>1.73</td>
<td>1.001</td>
<td>0.729</td>
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<tr>
<td>7.0</td>
<td>1.73</td>
<td>1.090</td>
<td>0.640</td>
</tr>
</tbody>
</table>

**Condition for 16-mA**

**Analytic Estimate**

**Required to achieve by optimization**

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Advanced Photon Source Upgrade (APS-U) project
ID Chamber: Full Gap=7.4mm (Half Width=18mm)
ID Chamber: Full Gap=7.2mm (Half Width=18mm)
Possible Replacement by Using Optimized ID Chamber

- We can replace each 8-mm gap elliptic chamber with NEW 7.3-mm gap elliptic chamber
- We can replace each 7.5-mm (Racetrack Chamber) with NEW 7.0-mm gap elliptic chamber
- We can replace 9x7.5-mm (Racetrack) and 24x8-mm gap elliptic chambers with NEW 33x7.2-mm elliptic chambers
## Acceptable Chamber Replacements with New Taper for 16-mA Operation

<table>
<thead>
<tr>
<th>5.0 (#)</th>
<th>8.0 (#)</th>
<th>7.5R (#)</th>
<th>7.4</th>
<th>7.2</th>
<th>7.0</th>
<th>Total Impe</th>
<th>Imax (mA)</th>
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<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>23</td>
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<tr>
<td>1</td>
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<td></td>
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<td>0.848</td>
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<tr>
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</tr>
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<td>1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1.034</td>
<td>20</td>
</tr>
</tbody>
</table>

2013 Run-2
NEW a=17mm
NEW a=17mm
NEW a=17mm
NEW a=17mm
NEW a=17mm
The APS Specific Engineering Recommendation for New ID Chamber

- **ID Chamber**
  - Use Elliptic Profile
  - Use Half Width 18 mm

- **Transition**
  - Use Symmetric Transition
  - Use Edge Length 50 mm
  - Use Edge Aperture 17 mm \((a=b=17\text{ mm})\)
  - Replace the pumping slot with holes
As a result at the APS

Greg Wiemerslarge, Engineer
Jason Lerch, Designer
As a result at the APS (2)

- A 5-mm gap chamber for 17-mm period undulator will be installed during the August shutdown in 2014 (G. Wiemerslarge, J. Lerch, Y. Chae).
- We will measure local impedance of two 5-mm gap chambers with new and old transition to compare each other. (V. Sajaev, Y. Chae)
- New chamber’s impedance should be < 60% of old one.
Summary

- We considered an ID vacuum chamber gap, width, and its profile as well as the taper transition for optimization.
- We found that the narrow aperture on the APS extrusion chamber side significantly reduced the impedance.
- With new chamber design principle, the 7.3-mm elliptic ID vacuum chamber can be used by replacing the existing 8.0-mm gap chamber for the 16-mA operation; the resultant undulator magnet gap will decrease from 11 mm to 10 mm.
- A 5-mm gap chamber with the new transition for short period undulator will be installed at the APS in September.
- We plan to measure the local impedances of two 5-mm gap chambers with new and old transition, respectively, located at different sectors in the ring. This will confirm the validity of design concept.