Towards Diffraction Limited Storage Ring Based Light Sources

Liu Lin
Brazilian Synchrotron Light Laboratory - LNLS
Towards Diffraction Limited Storage Ring Based Light Sources

Highlights from Sirius, the Brazilian Light Source Project

Liu Lin
Brazilian Synchrotron Light Laboratory - LNLS
The new generation of Storage Ring Light Sources

High brightness and coherence
- Low emittance
- Phase-space matching

Sirius, the Brazilian Light Source Project
- Lattice design highlights: low beta sections
- Light source & beamline integration: improved solution for CARNAÚBA beamline

Conclusion
The new generation of storage rings

Adapted from R. Bartollini

\[ \epsilon_0 \propto \frac{\gamma^2}{N_B^3} \]
The new generation of storage rings

Adapted from R. Bartollini

emittance scaling

\[ \epsilon_0 \propto \frac{\gamma^2}{N_B^3} \]
The new generation of storage rings

Adapted from R. Bartollini
Some new storage rings and upgrade plans

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Planned machines are at different planning stages.
Storage ring spectral brilliance (brightness)

1st Generation
parasitic operation in colliders, bending magnets

2nd Generation
dedicated sources from bending magnets, high flux

3rd Generation
DBA, TBA lattices with straight sections for wigglers and undulators, high brilliance

4th Generation
emittance reduction with MBA lattices, high performance IDs, high coherent flux
Spectral brilliance and coherent fraction

- Spectral brilliance: Flux density in phase space

\[ B(\lambda) \propto \frac{F(\lambda)}{\left( \epsilon_x, e^- \otimes \epsilon_r(\lambda) \right) \left( \epsilon_y, e^- \otimes \epsilon_r(\lambda) \right)} \]
Spectral brilliance and coherent fraction

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Photon flux [photons/s/0.1% bw]
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electron beam emittance
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Photon flux \([\text{photons/s/0.1\% bw}]\)

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- Electron beam emittance
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Photon flux \([\text{photons/s/0.1\% bw}]\)

- Electron beam emittance
- Photon limiting emittance

\[ \epsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{4\pi} \quad \text{for Gaussian beam} \]
\[ \epsilon_r = \sigma_r \sigma_{r'} \approx \frac{\lambda}{2\pi} \quad \text{for undulator beam} \]
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- **Photon flux** [photons/s/0.1% bw]

- **Electron beam emittance**

- **Photon limiting emittance**

- **Coherent fraction for undulator radiation**

\[ f_{coh} = \frac{(\lambda/2\pi)^2}{\left( \epsilon_{x,e^-} \otimes \epsilon_r(\lambda) \right) \left( \epsilon_{y,e^-} \otimes \epsilon_r(\lambda) \right)} \]

\[ \epsilon_r = \sigma_r \sigma' = \frac{\lambda}{4\pi} \]

for Gaussian beam

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for undulator beam
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- **Diffraction limited storage ring**

\[ \epsilon_{x,y} \approx \epsilon_r(\lambda) = \frac{\lambda}{2\pi} \]

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  - Electron beam emittance
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- **Diffraction limited storage ring**
  \[ \epsilon_{x,y} \approx \epsilon_r(\lambda) = \frac{\lambda}{2\pi} \]
  - Diffraction limit for 2 keV: \( \epsilon_{x,y} \approx 100 \text{ pm.rad} \)
  - Diffraction limit for 10 keV: \( \epsilon_{x,y} \approx 20 \text{ pm.rad} \)
Achieving low emittance with MBA

\[ \epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\int H(s) h(s)^3 ds}{\int h(s)^2 ds} \]
Achieving low emittance with MBA

\[ \epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\int \mathcal{H}(s) h(s)^3 ds}{\int h(s)^2 ds} \]
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\[ \epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\int H(s) h(s)^3 ds}{\int h(s)^2 ds} \]

damping partition

curvature function

\[ h(s) = \frac{1}{\rho(s)} \]
\[ \epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\int \mathcal{H}(s) h(s)^3 \, ds}{\int h(s)^2 \, ds} \]

dispersion’s betatron amplitude
\[ \mathcal{H} = \frac{\eta^2 + (\alpha \eta + \beta \eta')^2}{\beta} \]

curvature function
\[ h(s) = \frac{1}{\rho(s)} \]

\( \eta \): dispersion function
\( \beta, \alpha \): Twiss functions
Emittance depends on optics at places where radiation is emitted (dipoles).
Achieving low emittance with MBA

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Dispersion’s betatron amplitude
\[ \mathcal{H} = \frac{\eta^2 + (\alpha \eta + \beta \eta')^2}{\beta} \]

Emittance depends on optics at places where radiation is emitted (dipoles).

**Double bend achromat - DBA**

- **Dispersion function**
- **Quadrupole**
- **Dipole**

**Multiple bend achromat – MBA**

- Many small dipoles to keep horizontal focus in each dipole

\( \eta \): dispersion function
\( \beta, \alpha \): Twiss functions
The Multi Bend Achromat Challenges

Courtesy: Ricardo Rodrigues
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MBA → Many short cells → Small beam emittance
The Multi Bend Achromat Challenges

Courtesy: Ricardo Rodrigues

MBA

Many short cells → Small beam emittance → High orbit stability
The Multi Bend Achromat Challenges

MBA

Many short cells → Small beam emittance → High orbit stability

- Stable magnets, girders and floor
- Stable power supplies

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

Many short cells → Small beam emittance → High orbit stability

- Stable magnets, girders and floor
- Stable power supplies
- Tight orbit correction with fast feedback, feedforward

MBA

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

Many short cells → Small beam emittance → High orbit stability

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- Tight orbit correction with fast feedback, feedforward
- Minimize beam instabilities, optimize components impedance

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

MBA
- Many short cells
- Small beam emittance
- High orbit stability

High magnetic field gradients

- Stable magnets, girders and floor
- Stable power supplies
- Tight orbit correction with fast feedback, feedforward
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The Multi Bend Achromat Challenges

MBA

Many short cells ➔ Small beam emittance ➔ High orbit stability

Very sensitive to errors

High magnetic field gradients

• Stable magnets, girders and floor
• Stable power supplies

• Tight orbit correction with fast feedback, feedforward
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The Multi Bend Achromat Challenges

Many short cells • Tight orbit correction with fast feedback, feedforward

Small beam emittance • Stable magnets, girders and floor • Stable power supplies

High orbit stability • Tight orbit correction with fast feedback, feedforward

High magnetic field gradients • Minimize beam instabilities, optimize components impedance

Very sensitive to errors

Strong non-linear beam dynamics

MBA

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

MBA

Many short cells

Small beam emittance

High orbit stability

High magnetic field gradients

Very sensitive to errors

Small clearance for injection

Low lifetime

Strong non-linear beam dynamics

• Stable magnets, girders and floor
  • Stable power supplies

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Non-linear dynamics optimization tools
New elements, octupoles

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Strong non-linear beam dynamics
The Multi Bend Achromat Challenges

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- Small beam emittance
- High orbit stability

- Stable magnets, girders and floor
- Stable power supplies

- Tight orbit correction with fast feedback, feedforward

- Minimize beam instabilities, optimize components impedance

- Non-linear dynamics optimization tools
- New elements, octupoles

- Novel injection schemes, on-axis injection, ultra-fast kickers

- High sensitive to errors
- Very sensitive to errors
- Strong non-linear beam dynamics
- Small clearance for injection
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- MBA

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

- Many short cells
  - Very sensitive to errors
  - Strong non-linear beam dynamics
  - Compact magnets
- Small beam emittance
  - Small clearance for injection
  - Low lifetime
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  - Compact magnets
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  - Combined function magnets
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- High coupling impedance
- High vacuum impedance

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

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- Small beam emittance
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- Small aperture vacuum chambers
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- Compact magnets
- High magnetic field gradients

- MBA

- Stable magnets, girders and floor
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- Special pumping, NEG coating

Courtesy: Ricardo Rodrigues
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High magnetic field gradients

Courtesy: Ricardo Rodrigues
The Multi Bend Achromat Challenges

Recent advances in accelerator technology, simulation tools, new design ideas, etc, are helping to overcome the challenges but many issues are still open and require R&D.
Other ingredients to reduce emittance

- Increase damping partition number $J_x$ by adding transverse field gradient in dipoles.

$$J_x = 1 - \frac{\int (1 - 2n)\eta |h(s)^3| ds}{\int h(s)^2 ds}$$
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• Increase damping partition number $J_x$ by adding transverse field gradient in dipoles.

\[ J_x = 1 - \frac{\int (1 - 2n) \eta |h(s)^3| ds}{\int h(s)^2 ds} \]

• Longitudinal dipole gradient

\[ \epsilon_x \propto \int H(s) h(s)^3 ds \]

  – Curvature function $h(s) = 1/\rho(s)$
  – To keep product small: compensate variation in $H(s)$ with variation in $h(s)$
  – Radiate more (high curvature) where $H(s)$ is small.
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- Achromatic cells and low field dipoles to enhance emittance reduction with Insertion Devices.
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• Achromatic cells and low field dipoles to enhance emittance reduction with Insertion Devices.

• Different dipole lengths, shorter dipoles at cell ends, where $\eta = \eta' = 0$. 
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- Increase damping with Damping Wigglers $\rightarrow$ energy spread increases.
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- Different dipole lengths, shorter dipoles at cell ends, where $\eta = \eta' = 0$.

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- Anti-bends (SLS). Disentangle dispersion $\eta$ and beta function $\beta_x$. 
Diffraction Limit: low emittance is not all!

Phase space matching

Electron beam and radiation phase-space

matched

mismatched

photon limiting emittance

electron beam emittance

actual radiation emittance

Matching condition

$$\beta_e = \frac{\sigma_e}{\sigma_e'} = \frac{\sigma_r}{\sigma_r'}$$
Diffraction Limit: low emittance is not all!
Phase space matching

Electron beam and radiation phase-space
mismatched  matched

photon limiting emittance

Electron beam and radiation phase-space
mismatched  matched

photon limiting emittance

Matching condition
\[
\beta_e = \frac{\sigma_e}{\sigma'_e} = \frac{\sigma_r}{\sigma'_r}
\]

Highest brilliance from undulator of length L is achieved when

\[
\beta_{x,y}^{opt} \approx \frac{L}{\pi}
\]

\[
\beta_{x,y}^{opt} \sim 1 - 2m
\]


IV. CONCLUSIONS

In this paper we have described three different coherent mode representations of partially coherent undulator radiation. We began with the well-known Gaussian-Schell decomposition in terms of Gauss-Hermite modes, which is valid provided the electron beam emittance is much larger than the natural radiation emittance \( \lambda/4\pi \). In this largely incoherent case the specifics of the single-electron undulator field are unimportant. We then refined our analysis to include the situation when the electron beam emittance \( \varepsilon_x \) in one direction is arbitrary, and found that the modes along \( y \) are determined by solving a matrix
Diffraction Limit: low emittance is not all!
Phase space matching

Highest brilliance from undulator of length $L$ is achieved when

$$\beta_{x,y}^{opt} \approx \frac{L}{\pi}$$

$$\beta_{x,y}^{opt} \sim 1 - 2m$$


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Figure 8(a) shows that the coherence is maximized when $\beta_x \approx L_u/\pi$ (or $\hat{\beta}_x \approx 1$), which indicates that the “natural” Rayleigh range of undulator radiation $Z_R \approx \beta_x \approx L_u/\pi$. Unfortunately, it is nearly impossible for lattice designers to make the beta functions in both $x$ and $y$ be simultaneously that small, and typically $\beta_x > 3L_u/\pi$. More careful inspection shows that the width of the angular

090702-14
SINGLE PHOTON’S "PHASE SPACE" (900 eV)
(Wigner Distribution Function)
from single electron

Courtesy: Harry Westfahl Jr.
SINGLE PHOTON’S “PHASE SPACE” (900 eV)
(Wigner Distribution Function)
from single electron

ELECTRONS PHASE SPACE
(HORIZONTAL)

AVERAGE PHOTON’S “PHASE SPACE”
(Wigner Distribution Function=Brilliance)

β_x = 1.5 m
WDF(0,0) = 10^{21}

β_x = 9 m
WDF(0,0) = 5 \times 10^{20}

Courtesy: Harry Westfahl Jr.
Sirius, the Brazilian Light Source Project

First beam 2018 – Open in 2019

Budget
- Accelerators 100 M US$
- 13 beamlines 140 M US$
- Building 213 M US$
- Human Res 57 M US$
- Total 510 M US$

Schedule
- Jan.2015 start of building construction
- Oct.2017 start of machine installation
- Jul.2018 start of SR commissioning
- Sep.2018 phase 1 operation (20mA, NCC)
- Feb.2019 phase 2 operation (100mA, SCC)
City of Campinas (population: 1,100,000)

UVX
- 1.37 GeV
- 100 nm.rad
- 18 beamlines
- Over 1200 users/yr

200 employees
80 students & trainees

40,000 students

40,000 students

CTBE

LNLS

LNNano
Sirius main parameters

**Storage Ring**
- Beam energy: 3.0 GeV
- Circumference: 518.4 m
- Lattice: 20 x 5BA
- Hor. emittance (bare lat.): 0.25 nm.rad
- Hor. emittance (with IDs): → 0.15 nm.rad
- Betatron tunes (H/V): 49.11 / 14.17
- Natural chrom. (H/V): -119.0 / -81.2
- rms energy spread: 0.85 x 10^{-3}
- Energy loss/turn (dipoles): 473 keV
- Dam. times (H/V/L) [ms]: 16.9 / 22.0 / 12.9
- Nominal current, top up: 350 mA

**BOOSTER**
- E = 3 GeV
- Emittance @ 3 GeV: 3.5 nm.rad
- Circumference: 496.8 m
- Lattice: 50 Bend
- Cycling frequency: 2 Hz

**LINAC**
- E = 150 MeV
The Sirius 5BA magnet lattice

- Quadrupole doublet
- Dipole $B=0.58$ T
- Superbend $B=3.2$ T, $\theta=1.4^\circ$
- Dipole $B=0.58$ T
- Quadrupole triplet
The Sirius 5BA magnet lattice

- 20 - 5BA arcs and 2 types of straight sections for insertion devices:
  - 5 high $\beta_x$ straight sections of 7.0 m – matching with quad doublets.
  - 15 low $\beta_x$ straight sections of 6.0 m – matching with quad triplets.
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  - sharp peak field of $B_p = 3.2$ T in the center → critical photon energy of $e_c = 19.2$ keV
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• Low field (0.58 T) EM and PM dipoles with transverse field gradient (7.8 T/m)
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- Different lengths for B1 and B2 (but same unit block)
- NEG coated copper beam pipe \( \varnothing = 24 \) mm (internal)
Superbends (no wigglers allowed)

Permanent magnet (NdFeB)

High field insert (3.2 T) superbend
- 19 keV critical energy at peak
- Hard X-rays produced only at beamline exit
- Total energy loss/turn from dipoles = 473 keV
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Sirius optics

- 5-fold symmetric optics with 5 high and 15 low $\beta$ sections.
- Achromatic cells.
- At low $\beta$ sections
  - $\beta_x \approx \beta_y \approx 1.5$ m
  - Optimized electron and photon beam phase-space matching for undulators.

- At superbend
  - Strong focusing of dispersion and $\beta_x$ functions
  - Beam size: 9.6 $\times$ 3.6 $\mu$m$^2$
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### High β SS
\[
\sigma [\mu\text{m}^2] = 66 \times 3.0 \\
\sigma'[\mu\text{rad}^2] = 3.7 \times 0.8
\]

### Low β SS
\[
\sigma [\mu\text{m}^2] = 18 \times 2.0 \\
\sigma'[\mu\text{rad}^2] = 13 \times 1.2
\]
New low $\beta_x$ operation mode

Symmetry=10
New low $\beta_x$ operation mode

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New low $\beta_x$ operation mode

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New low $\beta_x$ operation mode

Symmetry 5: $5 \text{ high } \beta_x + 15 \text{ low } \beta_x$
Low $\beta$ optics: phase-space matching

Numerical integration of Wigner Distribution Function

Gaussian approximation of reference [H. Westfahl Jr et al, JSR, 24, 2017]
Low $\beta$ optics: phase-space matching

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Low $\beta$ optics: phase-space matching

Numerical integration of Wigner Distribution Function

Low $\beta$ optics: Beam Stay-Clear
Low $\beta$ optics: Beam Stay-Clear

- Vertical: $< 2.4 \text{ mm @ 1.2m from center}$
- Horizontal: $< 4.2 \text{ mm @ 1.2m from center}$
Low $\beta$ optics: Beam Stay-Clear

- Horizontal: $< 11.5 \text{ mm @ 1.2m from center}$
- Vertical: $< 3.0 \text{ mm @ 1.2m from center}$

- Horizontal: $< 4.2 \text{ mm @ 1.2m from center}$
- Vertical: $< 2.4 \text{ mm @ 1.2m from center}$
Low $\beta$ optics: Beam Stay-Clear

Sirius IDs will be based on Delta and APU undulators.

- $< 11.5$ mm @ 1.2m from center (horizontal)
- $< 3.0$ mm @ 1.2m from center (vertical)
- $< 4.2$ mm @ 1.2m from center (horizontal)
- $< 2.4$ mm @ 1.2m from center (vertical)
Low $\beta$ optics: Insertion Devices

- **Delta Undulators**
  - Possible for Sirius due to small Hor. BSC
  - Smoother $K$ changes
  - Horizontal, Vertical and Circular x-ray polarizations on the same energy range
  - Do not introduce strong harmful multipoles

<table>
<thead>
<tr>
<th></th>
<th>$B_0$ [T]</th>
<th>$\lambda$ [mm]</th>
<th>L [m]</th>
<th>$K_{\text{max}}$</th>
<th>Diag. gap [mm]</th>
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</thead>
<tbody>
<tr>
<td>Delta21</td>
<td>1.12</td>
<td>21</td>
<td>2.4</td>
<td>2.2</td>
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<td>Delta52</td>
<td>1.19</td>
<td>52</td>
<td>3.6</td>
<td>5.85</td>
<td>13.85</td>
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</tbody>
</table>

Effect of 14 Delta21 and 14 Delta52 on DA 7 in each polarization (H/V) distributed in low beta sections
Effect of IDs on emittance and energy spread

### Sirius Phase-1 Beamlines

<table>
<thead>
<tr>
<th>Beamline</th>
<th>ID Type</th>
<th>SS</th>
<th>$\beta_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARNAÚBA</td>
<td>Delta21</td>
<td>06</td>
<td>low</td>
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<tr>
<td>EMA</td>
<td>APU19</td>
<td>08</td>
<td>low</td>
</tr>
<tr>
<td>CATERETÊ</td>
<td>Delta21</td>
<td>07</td>
<td>low</td>
</tr>
<tr>
<td>IPÊ</td>
<td>Delta52</td>
<td>11</td>
<td>low</td>
</tr>
<tr>
<td>SABIÁ</td>
<td>Delta52</td>
<td>10</td>
<td>low</td>
</tr>
<tr>
<td>MANACÁ</td>
<td>APU20</td>
<td>09</td>
<td>high</td>
</tr>
<tr>
<td>PGM++</td>
<td>Delta52</td>
<td>12</td>
<td>low</td>
</tr>
</tbody>
</table>

### Sirius IDs

<table>
<thead>
<tr>
<th>ID Type</th>
<th>$B_0$ [T]</th>
<th>$\lambda$ [mm]</th>
<th>$L$ [m]</th>
<th>$K_{\text{max}}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Delta21</td>
<td>1.12</td>
<td>21</td>
<td>2.4</td>
<td>2.2</td>
<td>6.92</td>
</tr>
<tr>
<td>Delta52</td>
<td>1.19</td>
<td>52</td>
<td>3.6</td>
<td>5.85</td>
<td>13.85</td>
</tr>
<tr>
<td>APU19</td>
<td>1.28</td>
<td>19</td>
<td>2.4</td>
<td>2.3</td>
<td>5.0</td>
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<td>APU20</td>
<td>1.07</td>
<td>20</td>
<td>2.4</td>
<td>2.0</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Sirius: initial phase beamlines (2019-2020)

**Experimental Programs**

- Tender nano-probe for spectro-ptychography
- Large FOV (30 μm) Coherent Diffraction Imaging
- Bragg CDI/XRD/XAFS under extreme conditions
- Serial micro and nano MX
- Tender x-ray RIXS
- AP-RIXS/XPS
- ARPES/PEEM
- Cone beam High Energy Tomography
- Quick-EXAFS
- 3D X-Ray Diffraction Microscopy
- High-Throughput SAXS
- Time Resolved Powder Diffraction
- nano-FTIR
• Even with future upgrades, Sirius will be competitive in the energy range of tender X-rays.

Courtesy: Harry Westfahl
• Even with future upgrades, Sirius will be competitive in the energy range of tender X-rays.

factor ~2 comes from betatron function matching

Courtesy: Harry Westfahl
Photon Flux \sim Brilliance (NA \times \delta)^2

@ LNLS today: micronutrients during brain Formation 1 mm cerebral organoids
Rafaela C. Sartore et al. (2017)

20 \mu m (@ LNLS today) \quad \rightarrow \quad 20 \text{ nm} (@ Sirius in 2019)
Combining coherent lensless X-ray imaging and fluorescence

Junjing Deng et al (2017) done at APS

green algae Chlamydomonas reinhardtii model cell for studying photosynthesis
Combining coherent lensless X-ray imaging and fluorescence

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100 nm pix

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100 nm pix 18 nm pix

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Overlay of the two measurements

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CARNAÚBA
(Coherent X-Ray Nanofocus Beamline)

@ APS today:
Acquisition time (2D):
~0.1 s/pixel & ~75 min/image
~10^4 photons/nm² at 5.2 keV

Fluorescence: ~100 nm pix  Lenseless imaging: ~18 nm pix
CARNAÚBA
(Coherent X-Ray Nanofocus Beamline)

@ APS today:
**Acquisition time (2D):**
~0.1 s/pixel & ~75 min/image
~10^4 photons/nm^2 at 5.2 keV

Sirius
50 nm pix

Fluorescence: ~100 nm pix
Lenseless imaging: ~18 nm pix
CARNAÚBA
(Coherent X-Ray Nanofocus Beamline)

@ APS today:
Acquisition time (2D):
~0.1 s/pixel & ~75 min/image
~10^4 photons/nm² at 5.2 keV

Sirius
~10^8 photons/nm² at 5.2 keV
~10 μs/pixel & ~1s/image

Fluorescence: ~100 nm pix
Lenseless imaging: ~18 nm pix

Horizontal (Hybrid method, Shi et al. 2014)
Vertical (Hybrid method, Shi et al. 2014)

50 nm pix

[Graphs and images showing data and results related to beam size, energy, and flux.]
• Scanning the source position with corrector strengths of ±400μrad can result in scanning ranges of ±400μm in each direction.
Machine & Beamline teams integration: Source scanning for ptychography


- Scanning the source position with corrector strengths of ±400μrad can result in scanning ranges of ±400μm in each direction.
- Step sizes of \( \sigma_x \) and \( \sigma_y \) result in \( \approx 40 \times 100 \) overlapping scanning points for ptychography.
Machine & Beamline teams integration: 
Source scanning for ptychography

*M. D. de Jonge et al. J. Sync. Rad. (2014)*

- Scanning the source position with corrector strengths of ±400μrad can result in scanning ranges of ±400μm in each direction.

- Step sizes of $\sigma_x$ and $\sigma_y$ result in ~ 40 x 100 overlapping scanning points for ptychography.

- Local beam bumps can be created with 4 correctors in the low beta straight section.
Conclusions

• The Synchrotron Radiation Light Source community is going through a very exciting time, with many new developments under way both in the machine and scientific application sides. Many new machines and machine upgrades are expected for next years.
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• It is important to integrate machine and beamline teams in the optimization of experiments.

• This is an open community and international cooperation is one of the most important sources for learning and advancing in this area.
Thank you!

Sirius Team – a small but highly motivated and integrated team!