## OSC Progress

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## Test of OSC in Fermilab

- IOTA - a dual purpose small electron ring
- Integrable optics
- OSC
- ~6 m straight is devoted to OSC



## OSC in IOTA

- Chicane for beam separation
- Optical amplifier \& light focusing

- Collider type optics is required to maximize cooling range for $x$-plane
- Rectangular dipoles
- Center quad (QD) introduces non-zero $M_{51}$ \& $M_{52}=>\perp$ cooling


Optics functions for half OSC straight (starting from center)

## OSC in IOTA

- Stable configuration
- No changes for more than year
- Major parameters
- $100 \mathrm{MeV}(\gamma \approx 200)$ electrons
- Basic wave length - $2.2 \mu \mathrm{~m}$
- 7 period undulators
- Two modes of operation
- Passive - Optical telescope with suppression of depth of field
- Active - $\sim 10 \mathrm{~dB}$ optical amplifier
- We plan OSC demonstration
- with large number of particles
- and single electron
- quantum mechanics and electrodynamics
$\Rightarrow$ Wave-function localization
$\Rightarrow$ Two photon radiation
$\Rightarrow$...


## Basics of OSC: Damping Rates

- Linearized longitudinal kick in pickup wiggler

$$
\begin{aligned}
\frac{\delta p}{p}= & k \xi_{0} \Delta s=k \xi_{0}\left(M_{51} x_{1}+M_{52} \theta_{x_{1}}+M_{56} \frac{\Delta p}{p}\right) \\
& \xrightarrow[\text { in the absence of }]{\text { betron motion }}
\end{aligned} k_{0}\left(M_{51} D_{x}+M_{52} D_{x}^{\prime}+M_{56}\right) \frac{\Delta p}{p} .
$$

- Partial slip factor (pickup-to-kicker) describes a longitudinal particle displacement in the course of synchrotron motion

$$
\tilde{M}_{56}=M_{51} D_{1}+M_{52} D_{1}^{\prime}+M_{56}
$$

- Cooling rates (per turn)

$$
\begin{aligned}
& \lambda_{x}=\frac{k \xi_{0}}{2}\left(M_{56}-\tilde{M}_{56}\right) \\
& \lambda_{s}=\frac{k \xi_{0}}{2} \tilde{M}_{56}
\end{aligned}
$$

$$
\lambda_{x}+\lambda_{s}=\frac{k \xi_{0}}{2} M_{56}
$$

## Basics of OSC: Cooling Range

- Cooling force depends on $\Delta s$ nonlinearly

$$
\frac{\delta p}{p}=k \xi_{0} \Delta s \Rightarrow \frac{\delta p}{p}=\xi_{0} \sin (k \delta s)
$$

where $k \delta s=a_{x} \sin \left(\psi_{x}\right)+a_{p} \sin \left(\psi_{p}\right)$ and $a_{x} \& a_{p}$ are the amplitudes of longitudinal displacements in cooling chicane due to $\perp$ and $L$ motions measured in units of laser phase

- Averaging yields the form-factors

- for damping rates

$$
\begin{aligned}
& \lambda_{s, x}\left(a_{x}, a_{p}\right)=F_{s, x}\left(a_{x}, a_{p}\right) \lambda_{s, x} \\
& F_{x}\left(a_{x}, a_{p}\right)=\frac{2}{a_{x}} \mathrm{~J}_{0}\left(a_{p}\right) \mathrm{J}_{1}\left(a_{x}\right) \\
& F_{p}\left(a_{x}, a_{p}\right)=\frac{2}{a_{p}} \mathrm{~J}_{0}\left(a_{x}\right) \mathrm{J}_{1}\left(a_{p}\right)
\end{aligned}
$$

- Damping requires both lengthening amplitudes ( $a_{x}$ and $a_{p}$ ) to be smaller than $\mu_{0} \approx 2.405$



## Basics of OSC: Non-linearity of Longitudinal Motion

- Major non-linear contribution comes from particle angles

$$
\Delta s=M_{51} x_{1}+M_{52} \theta_{x_{1}}+M_{56} \frac{\Delta p}{p}+\frac{1}{2} \int_{s_{1}}^{s}\left(\theta_{x}^{2}+\theta_{y}^{2}\right) d s+\ldots
$$

- It is large and has to be compensated
- X-plane makes much larger contribution due to small $\beta_{x}{ }^{*}$
- Correction of path length non-
 linearity is achieved by two pairs of sextupoles located between dipoles of each dipole pair of the chicane
- Very strong sextupoles: $\mathrm{SdL}_{y}=-7.5 \mathrm{kG} / \mathrm{cm}_{1} \mathrm{SdL}_{x}=1.37 \mathrm{kG} / \mathrm{cm}$. It results in a considerable limitation on the dynamic aperture.



## Compensation of Non Linear Sample Lengthening



## IOTA Optics

Main Parameters of IOTA storage ring for OSC

| Circumference | 40 m |
| :--- | :---: |
| Nominal beam energy | 100 MeV |
| Bending field | 4.8 kG |
| SR rms $\times$ emittance, $\varepsilon_{x S R}\left(\varepsilon_{y}=0\right)$ | 2.6 nm |
| Rms momentum spread, $\sigma_{p}$ | $1.06 \cdot 10^{-4}$ |
| SR damping times (ampl.), $\tau_{x} / \tau_{y} / \tau_{s}$ | $1.7 / 2 / 1.1 \mathrm{~s}$ |

Main parameters of cooling chicane

| Delay in the chicane, $\Delta s$ | 2 mm |
| :--- | :---: |
| Horizontal beam offset, $h$ | 35.1 mm |
| $M_{56}$ | 3.91 mm |
| $D^{*} / \beta^{*}$ | $48 \mathrm{~cm} / 12 \mathrm{~cm}$ |
| Cooling rates ratio, $\left(\lambda_{x}=\lambda_{y}\right) / \lambda_{s}$ | 0.58 |
| Cooling ranges (before $O S C), n_{\sigma x}=n_{\sigma y} / n_{\sigma s}$ | $14 / 4.4$ |
| Dipole: magnetic field *length | $2.5 \mathrm{kG} * 8 \mathrm{~cm}$ |
| Strength of central quad, $G d L$ | 0.45 kG |

- Energy is reduced $150 \rightarrow 100 \mathrm{MeV}$ to reduce $\varepsilon, \sigma_{p}$ and length of undulator period
- Operation on coupling resonance $Q_{x} / Q_{y}=5.42 / 3.42$ reduces horizontal emittance and introduces vertical damping
- Small $\beta^{*}$ is required to minimize sample lengthening due betatron motion


## IOTA Optics (2)

A. Romanov


## Challenges of the OSC Chicane Design

Structure of the half of the OSC region (from OSC center to the end of undulator)


- Very tight space allocations for all elements
- Because of small allocated space and small wave length of radiation
- Very strong sextupoles
- Larger distance between sextupoles increases DA => shorter sextupoles
- E.-M. radiation (2.2-3.1 $\mu \mathrm{m}, \lambda_{\max } / \lambda_{\min } \sim 1.4$ ) should come through magnets


## OSC Chicane Dipoles (A. Romanov)

- Relatively small B ( 2.5 kG ) => coils can be partially hidden in the core
- Magnetic shields at the ends to reduce interference with nearby elements
- 3D optimization of magnet geometry nearly complete
- Light passage
- Inner dipoles - outside poles
- Outer dipoles inside poles

Major parameters

| Gap | 16 mm |
| :--- | :--- |
| Max. beam size diameter (10 $\sigma)$ | 12 mm |
| Magnetic field | 2.5 kG |
| Magnetic length | 8 cm |



## OSC Chicane Sextupoles

- Light divergence: $\theta_{\max }=4 \mathrm{mrad}\left(\theta_{\max } \gamma=0.8\right)$
- Aperture larger than $\mathrm{R}=2.5 \mathrm{~cm}$ is required if sextupoles are identical
- Making sextupoles different greatly reduces aperture requirements


## Major parameters of sextupoles

|  | Inner | Outer |
| :--- | :---: | :---: |
| Length, cm | $10 ?$ | 10 |
| Inscribed radius, cm | 0.65 | 2.1 |
| Gradient, kG/cm |  |  |
| Field at pole tip, kG | -0.75 | 1.37 |

- 3D design is nearly complete
- Making vacuum chamber integrated with sextupoles would enable further reduction of the sextupole apertures

Light passage through both sextupoles


Light passage through outer sextupole


Light passage through inner sextupole


## OSC Chicane Sextupoles (2)

(A. Romanov)



Inner sextupole ( $\mathrm{B}_{\text {iron }}<2 \mathrm{kG}$ )

| Inner diameter | 0.65 cm |
| :--- | :--- |
| Maximum gradient $\left(\mathrm{d}^{2} \mathrm{~B} / \mathrm{dr}^{2}\right)$ | $1.1 \mathrm{kG} / \mathrm{cm}^{2}$ |
| Coil current | 40 A |
| Current density | $1 \mathrm{~A} / \mathrm{mm}^{2}$ |

Outer sextupole ( $\mathrm{B}_{\text {iron }}<15 \mathrm{kG}$ )

| Inner diameter | 2.1 cm |
| :--- | :--- |
| Maximum gradient $\left(\mathrm{d}^{2} \mathrm{~B} / \mathrm{dr}^{2}\right)$ | $1.8 \mathrm{kG} / \mathrm{cm}^{2}$ |
| Coil current | 2200 A |
| Current density | $2 \mathrm{~A} / \mathrm{mm}^{2}$ |

- We need to discuss a possibility of shortening the inner sextupoles


## OSC Quads and Undulators

- The design of OSC quads and undulators does not represent a significant challenge
- Center quad
$L=6 \mathrm{~cm}, G=0.2 \mathrm{kG} / \mathrm{cm}, 2 a=16 \mathrm{~mm}, B_{\text {tip }}=0.16 \mathrm{kG}, I_{\text {pole }}=55 \mathrm{~A}$
- Four outer quads
$L=10 \mathrm{~cm}, G=1 \mathrm{kG} / \mathrm{cm}, 2 a=25 \mathrm{~mm}, B_{\text {tip }}=1.25 \mathrm{kG}, I_{\text {pole }}=800 \mathrm{~A}$
- Undulator
$L=77.5 \mathrm{~cm}, 7$ poles, period $=11.1 \mathrm{~cm}$, gap $=25 \mathrm{~mm}$,
$\mathrm{B}_{\text {max }}=1.5 \mathrm{kG}$, $\mathrm{I}_{\text {pole }}=1.5 \mathrm{kA}$
- The design initiation
- For quads it will be determined by availability of resources
- For undulators we expect ANL help/expertise


## Focusing of Beam Radiation in the Passive Scheme

- Three lens system with complete suppression of depth of field

$$
\left(\begin{array}{cc}
1 & L_{1} \\
0 & 1
\end{array}\right) \cdot\left(\begin{array}{cc}
1 & 0 \\
-\frac{1}{F_{1}} & 1
\end{array}\right) \cdot\left(\begin{array}{ll}
1 & L_{2} \\
0 & 1
\end{array}\right) \cdot\left(\begin{array}{cc}
1 & 0 \\
-\frac{1}{F_{2}} & 1
\end{array}\right) \cdot\left(\begin{array}{cc}
1 & L_{2} \\
0 & 1
\end{array}\right) \cdot\left(\begin{array}{cc}
1 & 0 \\
-\frac{1}{F_{1}} & 1
\end{array}\right) \cdot\left(\begin{array}{ll}
1 & L_{1} \\
0 & 1
\end{array}\right)=p \cdot\left(\begin{array}{ll}
1 & 0 \\
0 & 1
\end{array}\right)
$$



- Outer lenses are located just outside of inner dipole
- 29 mm beam-to-beam distance

$$
\begin{array}{ll}
\mathrm{L}_{4}:=\mathrm{L}_{\text {tot }}-\mathrm{L}_{2}=143 \mathrm{~cm} & \mathrm{~F}_{2}:=\mathrm{L}_{2}=32 \mathrm{~cm} \\
\mathrm{~L}_{\text {tot }}=175 \mathrm{~cm} & \mathrm{~F}_{2}=-4.613 \mathrm{~cm}
\end{array}
$$

(out of 35.1 mm in the center quad)


## Optical Telescope

- An accuracy and stability of $\perp$ \& \| alignment is determined by the diffraction size of e.-m. radiation in the pickup: $\rho_{\max }=\lambda_{L \gamma} \approx 430 \mu \mathrm{~m}$
- Lenses are mounted on the optical girder and their $\perp$ and || locations are adjusted and finally set in the lab
- The optical girder, as a whole, is aligned relative to the IOTA ring
- Requirements to the initial lens positioning inside telescope
- Transverse $<70 \mu \mathrm{~m}$
$\Rightarrow$ Corresponds to the focal point displacement of 0.5 mm (amplification ~7)
- Longitudinal < 0.5 mm
$\Rightarrow$ Corresponds to the spot size increase of $\sim 40 \mu \mathrm{~m}\left(\sim \rho_{\max } / 10\right)$
- Requirements to the long-term lens stability inside telescope
- Transverse < $6 \mu \mathrm{~m}\left(\sim \rho_{\max } / 10\right)$
- Longitudinal < 0.2 mm (not a problem)




## Optical Telescope (2)

- The optical girder is mounted inside vacuum chamber and is supported at two points (near ends) to prevent its bending by forces induced by atmospheric pressure
- The girder can be Ti or Al pipe (large ratio E/ $) \quad \Delta x=\frac{2 \cdot \mathrm{p} \cdot \mathrm{g}}{\mathrm{E} \cdot \mathrm{R}^{2}} \cdot \frac{5 \cdot \mathrm{~L}_{2}{ }^{4}}{24}$
- radius $\geq 25 \mathrm{~mm}$ is required (sagitta <2.6 $\mu \mathrm{m}$ )

$$
\Delta x=\frac{2 \cdot \rho \cdot \mathrm{~g}}{\mathrm{E} \cdot \mathrm{R}^{2}} \cdot \frac{5 \cdot \mathrm{~L}_{2}{ }^{4}}{24}
$$

Two tilted plates with variable and equal angles regulate delay of the E.-M. radiation pulse (up to $\pm 20 \mu \mathrm{~m}$ )

- Tilt angle near Brewster angle minimizes reflections
- Material and a necessity of antireflection coating require additional insight



## Optical Lenses

- Lenses are manufactured from barium fluoride ( $\mathrm{BaF}_{2}$ )
- Material with very small $2^{\text {nd }}$ order dispersion
- Antireflection coating should also protect from humidity damage
- Total thickness of the lenses (at axis) is determined by required delay of 2 mm
$\Rightarrow h_{\text {total }}=4.245 \mathrm{~mm}$ (Out of this value 1 mm is reserved for delay adjustment)

|  | inner | outer |
| :--- | :---: | :---: |
| Focal distance, mm | -46.13 | 320 |
| Thickness at center, mm | 0.76 | 1.24 |
| Radius of lens, mm | 5 | 10 |

- The radiation wave length depends on angle $\Rightarrow$ Lens shape correction for the outer lenses
- $\sim 11 \mu \mathrm{~m}$ correction at $r=10 \mathrm{~mm}$
- ~2.5 $\mu \mathrm{m}$ correction at the light beam radius ( 7.3 mm )
- Errors of focal lens $<3 \%$ can be compensated by lens displacement at the initial tuning in the lab





## First Order Dispersion Effects in Optical Lenses

- The first order dispersion, $\mathrm{d} n / \mathrm{d} \lambda$, results in $1.5 \%$ difference between phase and group velocities in the lens material
- It is accounted in the total lens thickness
- Significant separation of radiation of the first and higher harmonics
- Higher harmonics do not interact resonantly in kicker and have little effect on cooling (make negligible diffusion)



Overlap of radiation for the second and third harmonics of undulator radiation

- Dependence of focusing strength on the wave length (1-st order chromaticity) results in a few percent reduction of cooling rates (if uncompensated


## Second Order Dispersion Effects in Optical Lenses




The second order dispersion, $d^{2} n / d \lambda^{2}$, results in lengthening of the light packet and, consequently, $6 \%$ loss of cooling rates

## Single Pass Optical Amplifier for OSC at IOTA

- Demonstration of OSC with optical amplifier is important part of the experimental program
- Should follow the passive OSC
- Major problem is obtaining large gain with quite short optical delay ( 2 mm )


## Basic Characteristics

- Cr:ZnSe solid state lasing gain medium.
- Bandwidth FWHM 2.2-2.9 $\mu \mathrm{m}$.
- 1 mm thickness ( $\sim 1.44 \mathrm{~mm}$ delay)
- CW pumping at $1.908 \mu \mathrm{~m}$ with $\sim 100 \mathrm{~kW} / \mathrm{cm}^{2}$

Matt Andorf and Philippe Piot


- High power (105 W) commercially available Thulium pump
- Gain
- Combination of short crystal length, small signal intensity and depleted ground state gives rise to exponential signal growth through the crystal.
- Total gain in power, G=5


## Single Pass Optical Amplifier for OSC at IOTA (2)

- Radiation is modified in 3 ways while passing through the amplifier
- Group Velocity Dispersion from the host medium lengthens the pulse
- Gain narrowing (pulse broadening) from finite amplifier bandwidth
- Phase distortions from amplification.
- Lengthening through GVD has largest effect
- Amplifier is expected to increases cooling rates by about factor of 2



## Requirements to Beam Position \& Optics Stability Beam Optics Sensitivity to Errors in Magnets

- Sextupoles are located at larger beta-function than the betafunction in the OSC chicane center and have larger effect on optics
- Feeddown of quad focusing from sextupoles has to be below GdL~30 G
$\Rightarrow$ Required beam position stability in sextupoles is <20 $\mu \mathrm{m}$
■ Optics measurements will correct for this feeddown focusing
- Magnetic field of OSC chicane dipoles has to be within $2 \cdot 10^{-4}$ in the good field region of $2 a=8 \mathrm{~mm}$

Effect of focusing due to feeddown in sextupoles on the ratio of cooling rates


Effect of focusing due to feeddown in sextupoles on the cooling range


## Other Comments

- Good knowledge of beam optics is required
$\Rightarrow$ Accurate optics measurements
- Beta-function control $<10 \%$
- Dispersion control $<10 \mathrm{~cm}$ ( $<7 \%$ from maximum $D$ )
- Beam intensities in the OSC experiments are quite low and therefore the beam based beam position stabilization is unfeasible
$\Rightarrow$ Mechanical stability of the ring and an accuracy of power supplies have to
be sufficiently good to keep uncontrolled beam motion within $\pm 10 \mu \mathrm{~m}$
- There is no readily available photo-detectors capable to register single photon in the range of [2.2-3] $\mu \mathrm{m}$
- Some beam tuning and studies can be done at $2^{\text {nd }}$ and $3^{\text {rd }}$ harmonics which radiation is much easier to observe
- Note that the dispersion in the lens material separates in time the radiations from pickup and kicker undulators
- No interference at $2^{\text {nd }}$ and $3^{\text {rd }}$ harmonics
- Geometrical parameters for the beam and light optics are expected to be adjusted with advance of mechanical design
- It will not have significant effect on parameters of OSC cooling


## Conclusions

- We are at transition from a conceptual design of the experiment to a conceptual design of sub-systems
- Conceptual design of chicane magnets (D, Q, S) A. Romanov
- Conceptual design of Optical Amplifier, M. Andorf
- Some advances in optical instrumentation, J. Ruan
- We are ready to initiate mechanical design of the OSC region
- The pace of progress will depend on available resources
- A formal document - Conceptual Design Report - still needs to be written
- Insufficient resources and priority
$\Rightarrow$ Very little progress in the last year
- We began discussion of OSC instrumentation and tuning procedures
- No show stoppers so far
- Time of beam arrival to IOTA is approaching fast
- It is time put more resources onto the OSC


## Backup slides

## Beam Parameters and Beam Lifetime

| RF voltage, VRF | 30 V |
| :---: | :---: |
| Harmonic number | 4 |
| RF frequency | 30 MHz |
| SR loses per turn | 13.2 eV |
| Momentum compaction | -0.0165 |
| Bucket height, $\Delta \mathrm{p} /\left.\mathrm{p}\right\|_{\max }$ | $1.08 \cdot 10^{-3}(10 \sigma)$ |
| Synchrotron tune | $4.8 \cdot 10^{-5}(360 \mathrm{~Hz})$ |
| Bunch length set by SR | 21 cm |
| Particles per bunch, $\mathrm{N}_{e}$ | $1-10^{7}$ |
| Geom. acceptance with OSC insert | $1 \mu \mathrm{~m}$ |
| Dynamic acceptance | $0.25 \mu \mathrm{~m}\left(10 \sigma\right.$ for $\left.\varepsilon_{x S R}\right)$ |
| Touschek lifetime @ $\mathrm{N}_{e}=2 \cdot 10^{5}$ | 1.46 hour |
| Effective vacuum ( $\mathrm{H}_{2}$ ) | 2.10-10 Torr |
| Vacuum lifetime | 1.9 hour |
| $\left(\mathrm{d} \varepsilon_{x, y} / \mathrm{d} \dagger\right)_{\text {gas }} /\left(\mathrm{d} \varepsilon_{x} / \mathrm{d} \dagger\right)_{\text {SR }}$ | 0.027/0.034 |
| $\left.\left(\mathrm{d} \varepsilon_{x} / \mathrm{d} t\right)_{\text {IBS }} / \mathrm{d} \varepsilon_{x} / \mathrm{d} t\right)_{\text {SR }} @ \mathrm{~N}_{e}=2 \cdot 10^{5}$ | 0.39 |
| $\left(\mathrm{d} \sigma_{\mathrm{p}}{ }^{2} / \mathrm{dt}\right)_{\text {IBS }} /\left(\mathrm{d} \sigma_{\mathrm{p}}{ }^{2} / \mathrm{dt}\right)_{\text {SR }} @ \mathrm{~N}_{e}=2 \cdot 10^{5}$ | 0.46 |

## OSC Limitations on IOTA Optics

- In the first approximation the orbit offset in the chicane ( $h$ ), the path lengthening ( $\delta s$ ) and the
 defocusing strength of chicane quad ( $\Phi$ ) together with dispersion

$$
M_{56} \approx 2 \Delta s
$$ and beta-function in the chicane

$$
\begin{aligned}
& \tilde{M}_{56} \approx 2 \Delta s-\Phi D^{*} h, \\
& \lambda_{x} / \lambda_{s} \approx \Phi D^{*} h /\left(2 \Delta s-\Phi D^{*} h\right), \\
& n_{\sigma p} \approx \mu_{0} /\left(\left(2 \Delta s-\Phi D^{*} h\right) k \sigma_{p}\right), \\
& n_{\sigma x} \approx \mu_{0} /\left(2 k h \Phi \sqrt{\varepsilon \beta^{*}}\right),
\end{aligned}
$$ center ( $D^{*}, \beta^{*}$ ) and determine the $\lambda_{x} / \lambda_{s} \approx \Phi D^{*} h /\left(2 \Delta s-\Phi D^{*} h\right)$, entire cooling dynamics

- $\delta \boldsymbol{s}$ is set by delay in the amplifier

$$
\Rightarrow M_{56}
$$

- $\Phi D^{*} h$ is determined by the ratio of decrements => for known $\varepsilon$ we obtain the dispersion invariant $\left(A^{*}\right)$

$$
\Rightarrow \Phi D^{*} h \approx \frac{\mu_{0}}{2 k n_{\sigma x}} \sqrt{\frac{A^{*}}{\varepsilon}}, A^{*} \equiv \frac{D^{* 2}}{\beta^{*}}
$$

- An average value of $A$ in dipoles determines the equilibrium emittance. $A^{*}$ is large and $A$ needs to be reduced fast to get an acceptable value of the emittance ( $\varepsilon$ )


## Parameters of Chicane Optics



## Dependence of Cooling Efficiency on Undulator Parameter




- With increase of Ku a particle motion in undulator becomes comparable to the size of the focused radiation
- It reduces cooling efficiency
- An increase of $K \cup$ also increases undulator magnetic field and, consequently, the equilibrium emittance and undulator focusing
- Chosen undulator parameter $\mathrm{K}=1.038$ corresponds to the 7 period undulator with $\mathrm{B}_{0}=1 \mathrm{kG}$. It results in a moderate increase of equilibrium emittance of $\sim 5 \%$.


## Cooling Rates

- Undulator period was chosen so that $\left.\lambda\right|_{\theta=0}=2.2 \mu \mathrm{~m}$
- Cooling rates were computed using earlier developped formulas(HB2012)
- Optical system bandwidth of $\sim 40 \%$ is limited by telescope acceptance $\lambda=[2.2-3.1] \mu \mathrm{m}$


## Main parameters of OSC

| Undulator parameter, K | 1.038 |
| :--- | :---: |
| Undulator period | 11.063 cm |
| Radiation wavelength at zero angle | $2.2 \mu \mathrm{~m}$ |
| Number of periods, $m$ | 7 |
| Total undulator length, $L_{w}$ | 0.774 m |
| Length from OA to undulator center | 1.75 m |
| Telescope aperture, $2 a$ | 14 mm |
| OSC damp. rates $(x=y / s)$ | $5.8 / 10 \mathrm{~s}^{-1}$ |

- Effective bandwidth of SC system is determined by number of undulator periods and dispersion in the lens: $1 / n_{\text {per }}$
- Higher harmonics of SR radiation, if present, introduce small additional diffusion ( $1 / n_{\text {poles }}$ ) and reduce effective bandwidth
- 4 mrad angular acceptance of optical system (aperture $a=7 \mathrm{~mm}$ )
- Undulator parameter $K \approx 1$ is close to the optimal for chosen bandwidth and aperture $\left(\theta_{\max } \gamma=0.8\right)$


## Effect of Beams Overlap on Cooling Rates

- There are 2 possible solutions for three lens telescope (1) With positive identity matrix
(2) With negative identity matrix
- The second choice is preferred for two reasons
- Smaller focusing chromaticity
- Transfer matrices for particles are close to the negative identity matrix. It mostly compensates separation of light and particles due to betatron motion

- Particle motion in undulators have to be also accounted


Kicker


## Sensitivity of OSC parameters to Optics Variations

- Sensitivity of cooling range to optics variations does not represent significant problems
- It requires
- beta-function control <10\%


Dependence of cooling range and ratio of cooling rated on the beta-function and dispersion at the beginning of OSC

## Basics of OSC - Correction of the Depth of Field

- It was implied above that the radiation coming out of the pickup undulator is focused
 on the particle during its trip through the kicker undulator
- It can be achieved with lens located at infinity

$$
\frac{1}{2 F+\Delta s}+\frac{1}{2 F-\Delta s}=\frac{1}{F} \rightarrow \frac{1}{F-\Delta s^{2} / 4 F}=\frac{1}{F} \xrightarrow{F \rightarrow \infty} \frac{1}{F}=\frac{1}{F}
$$

- but this arrangement cannot be used in practice
- A 3-lens telescope can address the problem within limited space
$\left[\begin{array}{ll}1 & L \\ 0 & 1\end{array}\right]\left[\begin{array}{cc}1 & 0 \\ -F_{1}^{-1} & 1\end{array}\right]\left[\begin{array}{cc}1 & L_{1} \\ 0 & 1\end{array}\right]\left[\begin{array}{cc}1 & 0 \\ -F_{2}^{-1} & 1\end{array}\right]\left[\begin{array}{cc}1 & L_{1} \\ 0 & 1\end{array}\right]\left[\begin{array}{cc}1 & 0 \\ -F_{1}^{-1} & 1\end{array}\right]\left[\begin{array}{ll}1 & L \\ 0 & 1\end{array}\right]=\left[\begin{array}{cc}-1 & 0 \\ 0 & -1\end{array}\right]$



## Choice of Optical Lens Material

Table for different material ( $2.2 \mu \mathrm{~m}$ )

| material | n |  | $\mathrm{dn} / \mathrm{d} \lambda(\mu \mathrm{m}-1)$ | $\mathrm{GVD}(\mathrm{fs} 2 / \mathrm{mm})$ | $\mathrm{D}(\mathrm{ps} / \mathrm{nm} * \mathrm{~km})$ | absorption(cm-1) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| BK7_schott | 1.4913 | -0.016528 | -148.08 | 57.64105785 | 0.18079 |  |
| S-BSL7(OHARA) | 1.4911 | -0.016 | -139.26 | 54.20781818 | $\mathrm{n} / \mathrm{a}$ |  |
| E-BK7(HIKARI) | 1.4922 | -0.01494 | -106.97 | 41.63873554 | $\mathrm{n} / \mathrm{a}$ |  |
| N-BAF10(schott) | 1.6373 | -0.016366 | -126.97 | 49.4238595 | 0.116 |  |
| E-BAF10(HIKARI) | 1.6377 | -0.015435 | -94.243 | 36.6846719 | $\mathrm{n} / \mathrm{a}$ |  |
| N-BAK1(schott) | 1.5473 | -0.013673 | -110.57 | 43.04005785 | 0.10246 |  |
| N-FK51A(schott) | 1.4707 | -0.0090109 | -69.45 | 27.03384298 | 0.055554 |  |
| N-LASF9(schott) | 1.8028 | -0.017 | -92.8 | 36.12297521 | 0.1037 |  |
| N-SF5(schott) | 1.6316 | -0.017728 | -110.38 | 42.96609917 | 0.14267 |  |
| N-SF10(schott) | 1.6821 | -0.01758 | -103.7 | 40.36586777 | 0.08 |  |
| N-SF11(schott) | 1.7318 | -0.018 | -103.34 | 40.22573554 | 0.109 |  |
| Fused Silica | 1.435 | -0.016 | -149.53 | 58.20547934 | $\mathrm{n} / \mathrm{a}$ |  |
| Calcium Fluoride | 1.4229 | -0.0054083 | -33.439 | 13.01633802 | Good transmission |  |
| Barium Fluoride | 1.4641 | -0.0032188 | -9.7405 | 3.79155 | Good tran smission |  |
| Cesium Fluoride | 1.4687 | -0.00196 | 1.2522 | -0.487426612 | $\mathrm{n} / \mathrm{a}$ |  |
| Potassium Fluoride | 1.3553 | -0.00253 | -10.8 | 4.203966942 | $\mathrm{n} / \mathrm{a}$ |  |
| Lead Fluoride | 1.7286 | -0.0062161 | 21.853 | -8.506415702 | $\mathrm{n} / \mathrm{a}$ |  |
| Magnesium Fluoride | 1.3754 | -0.0096468 | -42.47 | 16.53171074 | $\mathrm{n} / \mathrm{a}$ |  |
| Zinc Selenide | 2.44 | -0.01114 | 250.31 | -97.43471901 | $\mathrm{n} / \mathrm{a}$ |  |

## Simulations with SRW (Synchrotron radiation workshop)

Jinhao Ruan and Matt Andorf

- SRW has an accurate model for SR and accounts for diffraction in the lenses and dispersion in their material
- Particle interaction with e.-m. wave is accounted separately
- Both transverse and longitudinal particle displacements are accounted
- Good coincidence with previously derived analytical formulas
- Simulations were helpful to understand details of interaction



Light pulse at front,center and back of kicker. Left with no dispersion, right with dispersion.
Note a particle would move from left to right relative to light pulse with the way time field is plotted.

## Simulations with SRW (continue)




## Green-no dispersion. Blue-dispersion

The effect of dispersion is light from front of pickup is not as focused as light from center/back.
Results in roughly 10\% descrease in maximum kick.

## Simulations with SRW (continue)




Energy loss estimate with different number of undulator periods. Total undulator length is fixed to about 75 cm .

- Reduction of Cooling force with $\mathrm{K}_{\mathrm{u}}$ is related to separation of radiation and particle due to motions in pickup and kicker undulators


## Single Pass Optical Amplifier for OSC at IOTA

Matt Andorf and Philippe Piot

## Basic Characteristics

- $\mathrm{Cr}: \mathrm{ZnSe}$ solid state lasing gain medium.
- Bandwidth FWHM 2.2-2.9 $\mu \mathrm{m}$.
-1 mm length ( $\sim 1.44 \mathrm{~mm}$ delay).
- CW pumping at $1.93 \mu \mathrm{~m}$ with $\sim 100 \mathrm{~kW} / \mathrm{cm}^{2}$
- Pump wavelength chosen because
- High power (50-100 W) commercially available Thulium pump
- Reduction in heat deposited in crystal over shorter wavelengths
- Gain
- Combination of short crystal length, small signal intensity and depleted ground state gives rise to exponential signal growth through the crystal.
- Total gain in power, G=5




## Single Pass Optical Amplifier for OSC at IOTA (2)

- The broadband pulse is modified in 3 ways while

$$
E_{2}(\omega, z)=E_{1}(\omega) \exp \left[i\left(z \beta+\phi_{a m p}\right)\right] G^{\frac{1}{2\left(1+\Delta x^{2}\right)}}
$$ passing through the amplifier

- Group Velocity Dispersion (GVD) from the host medium lengthens the pulse and introduces energy chirp, $\beta=2 \pi n / \Lambda$
- Gain narrowing (pulse broadening) from finite amplifier bandwidth
- Phase distortions from amplification.
- Lengthening through GVD has largest effect, works to reduce field amplitude.

$$
\gamma_{12}(\tau)=\frac{\left\langle E_{1}(t) E_{2}^{*}(t+\tau)\right\rangle}{\left.\left.\left.\left[\left.\langle | E_{1}\right|^{2}\right\rangle\langle | E_{2}\right|^{2}\right\rangle\right]^{1 / 2}}
$$

- Correlation function multiplied by gain estimates total increase in kick $\gamma_{12} \sqrt{G}=2.05$
- Amplifier increases
 damping rates by a factor of 2


## Basics of OSC - Radiation from Undulator



## Basics of OSC - Radiation Focusing to Kicker Undulator

- Modified Kirchhoff formula

$$
\begin{aligned}
E(r)= & \frac{\omega}{2 \pi i c} \int_{S} \frac{E\left(r^{\prime}\right)}{\left|r-r^{\prime}\right|} \mathrm{e}^{i \omega\left|r-r^{\prime}\right|} d s^{\prime} \\
& \Rightarrow \quad E(r)=\frac{1}{2 \pi i c} \int_{S} \frac{\omega\left(r^{\prime}\right) E\left(r^{\prime}\right)}{\left|r-r^{\prime}\right|} \mathrm{e}^{i \omega\left|r-r^{\prime}\right|} d s^{\prime}
\end{aligned}
$$

- Effect of higher harmonics
- Higher harmonics are normally located outside window of optical lens transparency and are absorbed in the lens material



Dependences of retarded time ( $t_{p}$ ) and Ex on time for helical undulator

- Only first harmonic is retained in the calculations presented below


## Basics of OSC - Longitudinal Kick for $K \ll 1$

- For $K \ll 1$ refocused radiation of pickup undulator has the same structure as radiation from kicker undulator. They are added coherently:


$$
\mathbf{E}=\mathbf{E}_{1}+\mathbf{E}_{2} e^{i \phi} \xrightarrow{\mathbf{E}_{1}=\mathbf{E}_{2}} 2 \cos (\phi / 2) \mathbf{E}_{1} e^{i \phi / 2}
$$

$\Rightarrow$ Energy loss after passing 2 undulators

$$
\Delta U \propto\left|E^{2}\right|=4 \cos (\phi / 2)^{2}\left|\mathbf{E}_{1}^{2}\right|=2(1+\cos \phi)\left|\mathbf{E}_{1}^{2}\right|=2\left(1+\cos \left(k M_{56} \frac{\Delta p}{p}\right)\right)\left|\mathbf{E}_{1}^{2}\right|
$$

- Large derivative of energy loss on momentum amplifies damping rates and creates a possibility to achieve damping without optical amplifier
- SR damping: $\lambda_{1-S R} \approx \frac{2 \Delta U_{S R}}{p c} f_{0}$

- OSC:

$$
\lambda_{1-O S C} \approx f_{0} \frac{2 \Delta U_{w g l}}{p c}\left(G k M_{56}\right) \xrightarrow{k M_{56}(\Delta p / p)_{\max }=\pi} f_{0} \frac{2 \Delta U_{w g l}}{p c}\left(\frac{G}{(\Delta p / p)_{\max }}\right)
$$

where $G$ - optical amplifier gain, $(\Delta p / p)_{\text {max }}$ - cooling system acceptance $\Rightarrow \lambda_{1-\text { osc }} \propto B^{2} L \propto K^{2} L$ - but cooling efficiency drops with K increase above $\sim 1$

## Basics of OSC - Longitudinal Kick for K<<1(continue)

- Radiation wavelength depends on $\theta$ as

$$
\lambda=\frac{\lambda}{2 \gamma^{2}}\left(1+\gamma^{2} \theta^{2}\right)
$$



Limitation of system bandwidth by (1) optical amplifier band or (2) subtended angle reduce damping rate

$$
\lambda_{1 / S R}=\lambda_{1 \mid-S R 0} F\left(\gamma \theta_{\mathrm{m}}\right), \quad F(x)=1-\frac{1}{\left(1+x^{2}\right)^{3}}
$$




- For narrow band: $\Delta U_{\text {wgl }}=\Delta U_{\text {wgl0 }}\left(\frac{3 \Delta \omega}{\omega}\right), \frac{3 \Delta \omega}{\omega} \ll 1$
where $\Delta U_{\text {wgl0 }}=\frac{e^{4} B^{2} \gamma^{2} L}{3 m^{2} c^{4}}\left\{\begin{array}{ll}1, & \text { Flat wiggler } \\ 2, & \text { Helical wiggler }\end{array}\right.$ the energy radiated in one undulator


## Basics of OSC - Radiation from Flat Undulator

- For arbitrary undulator parameter we have

$$
\begin{aligned}
& \Delta U_{\text {OSC_F } F}=\frac{1}{2} \frac{4 e^{4} B_{0}^{2} \gamma^{2} L}{3 m^{2} c^{4}} G F_{f}\left(K, \gamma \theta_{\max }\right) F_{u}\left(\kappa_{u}\right) \\
& F_{u}\left(\kappa_{u}\right)=\mathrm{J}_{0}\left(\kappa_{u}\right)-\mathrm{J}_{1}\left(\kappa_{u}\right), \quad \kappa_{u}=K^{2} /\left(4\left(1+K^{2} / 2\right)\right)
\end{aligned}
$$

Fitting results of numerical integration yields:

$$
F_{h}(K, \infty) \approx \frac{1}{1+1.07 K^{2}+0.11 K^{3}+0.36 K^{4}}, \quad K \equiv \gamma \theta_{e} \leq 4
$$



- Dependence of wave length on $\theta$ :
$\lambda \approx \frac{\lambda_{\text {wgl }}}{2 \gamma^{2}}\left(1+\gamma^{2}\left(\theta^{2}+\frac{\theta_{e}^{2}}{2}\right)\right)$

$$
K \equiv \gamma \theta_{e}
$$

- Flat undulator is "more effective" than the helical one
- For the same $K$ and $\lambda_{\text {wgl }}$ flat undulator generates shorter wave lengths
- For both cases of the flat and helical undulators and for fixed $B$ a decrease of $\lambda_{\text {wgI }}$ and, consequently, $\lambda$ yields kick increase
- but wavelength is limited by both beam optics and light focusing

