Acknowledgement

I have drawn on material from:

E. Blucher, A. Valishev, E. Prebys, S. Nagaitsev, G. Stancari
Outline

- LBNF/DUNE & Fermilab
- FAST/IOTA
- Experimental Program
- Schedule
- Summary
DUNE Sensitivity

Mass Hierarchy Sensitivity

- Aim for $5\sigma$ measurement
  - Possible for mass hierarchy within 6 years for all $\delta_{CP}$ values
  - At best possible for CP violation within 9-11 years for only 50% of all $\delta_{CP}$ values

- Increased flux will cut down on required running time

E. Blucher, FNAL Users Meeting 2017
LBNF/DUNE Staging

- ~2026: Begin operations – 1.07 MW (80 GeV) beam, 20 kt far detector
- ~2027: 30 kt far detector
- ~2029: 40 kt far detector
- ~2032: 2.14 MW (80 GeV) beam

<table>
<thead>
<tr>
<th>Time (years)</th>
<th>Exposure (kt-MW-years)</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>171</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
</tr>
<tr>
<td>10</td>
<td>556</td>
</tr>
<tr>
<td>15</td>
<td>984</td>
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</table>

E. Blucher, FNAL Users Meeting 2017
Accelerator Upgrades

• DUNE physics program requires 900 kt-MW-yr
  – For current 40 kt design detector and recent 700 kW beam operation, ~ 32 years operations required!!!

• Can accomplish with >2 MW beam power

• Hard to do
  – Beam loss
    • Damage/destruction of accelerator at large energy
    • Activation of components at high current
    • Losses must be kept to <0.1% at high intensity
Space Charge

- Space charge has been a limiting factor on the performance of particle accelerators
  - Leads to particle loss
- Overcoming space charge is crucial for the next generation of high intensity accelerator

![Graph showing fractional beam loss and beam emittance vs booster batch intensity]
IOTA – Big Picture

- Cost effective path to multi-MW beam power must be discovered
  - *Either* reduce cost of SRF by factor of 3-4
  - *Or* increase performance of synchrotrons by 3-4
  - *(And develop targets capable of handling power)*
- IOTA presents a path toward increasing performance, and it’s cheap!
  - Conventional magnets and RF cavities
  - Standard beam pipe size and material
- IOTA will be the only dedicated ring based accelerator test facility in the US for high intensity research
Path to MW Beam Power at Fermilab

- Current accelerator complex

120 GeV RCS Main Injector

8 GeV Recycler

0.5–0.7 MW on ν target

400 MeV NC Linac

8 GeV RCS Booster
Proton Improvement Plan-II

- PIP-II with 800 MeV superconducting linac
- Achieves 1.2 MW
PIP-III Option 1

- PIP-II plus 8 GeV superconducting linac
- Still injected into Recycler

120 GeV RCS Main Injector

8 GeV SC Linac $=0.8 \rightarrow 3 \rightarrow 8$

$\geq 2.5$-MW on target
PIP-III Option 2

- PIP-II plus 8-12 GeV Rapid Cycling Synchrotron
- May not need Recycler
FAST

- Fermilab’s Accelerator Science and Technology (FAST) facility home to Integrable Optics Test Accelerator

- Purpose of FAST is to
  - Study physics of high brightness beams
  - Develop high intensity accelerators for particle physics (one of three major experimental activities toward producing multi-MW beams at Fermilab)

- FAST/IOTA will be home to 300 MeV electron beam, 2.5 MeV proton beam, and storage ring to host experiments
Integrable Optics Test Accelerator

- IOTA Experimental program highlights include:

1) Demonstrating techniques to build accelerators that are strongly nonlinear yet stable
   - Achieve large tune spreads (~0.25) without loss of dynamic aperture

2) Exploration of features of space charge dynamics in rings and effect of nonlinear integrable optics
   - Beam halo formation, space charge compensation

3) Observation of optical stochastic cooling

4) Electron cooling
   - Initial experiments with low charge electron bunches emulate single particle dynamics with negligible space charge
   - Later experiments with high charge, low energy protons emulate collective effects with space charge
IOTA Lattice

- Injection for electrons or protons
- Experiments fit in long straight sections
  - One or two nonlinear inserts
  - Nonlinear electron lens
  - Space charge compensation
  - Optical stochastic cooling
- RF cavity provides proton bunches and replaces electron energy lost to synchrotron radiation
IOTA 3D
# Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electrons</th>
<th>Protons</th>
<th>Units</th>
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<tr>
<td>Circumference</td>
<td>40</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Revolution period</td>
<td>0.133</td>
<td>1.83</td>
<td>μs</td>
</tr>
<tr>
<td>Experimental straight sections</td>
<td>4 (3)</td>
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<tr>
<td>Kinetic energy</td>
<td>150</td>
<td>2.5</td>
<td>MeV</td>
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<tr>
<td>Vacuum</td>
<td>300</td>
<td>6</td>
<td>$10^{-10}$ torr</td>
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<tr>
<td>Beam lifetime (time)</td>
<td>30</td>
<td>5</td>
<td>min</td>
</tr>
<tr>
<td>Beam lifetime (turns)</td>
<td>13.5</td>
<td>0.169</td>
<td>$10^9$ rev</td>
</tr>
<tr>
<td>Beam current</td>
<td>2.4</td>
<td>8</td>
<td>mA</td>
</tr>
<tr>
<td>Number of particles</td>
<td>2</td>
<td>90</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Beam size, x, y</td>
<td>0.6, 0.4</td>
<td>6, 4</td>
<td>mm</td>
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<tr>
<td>Bunch length</td>
<td>0.0108</td>
<td>1.7</td>
<td>m</td>
</tr>
<tr>
<td>Bunching frequency</td>
<td>Single bunch</td>
<td>2.18</td>
<td>MHz</td>
</tr>
<tr>
<td>Space charge tune shift (unbunched, bunched)</td>
<td>0</td>
<td>-0.5, -1.2</td>
<td></td>
</tr>
</tbody>
</table>
IOTA Experimental Program
Integrable Optics History

- Search for stable solutions that are strongly nonlinear
  - Orlov (1963)
  - McMillan (1967) – 1D solution
  - Perevedentsev & Danilov (1990) – generalization of McMillan case to 2D, required non-Laplacian potentials
    - VEPP-2000 at BINP demonstrated record beam-beam tune shift of ~0.25 in 2013 using round colliding beams with 1 invariant
  - Chow & Cary (1994)
  - Danilov & Nagaitsev (2010) – Solution for nonlinear lattice with two invariants of motion possible with Laplacian potential (special magnets), PRSTAB 13, 084002
    - To be experimentally verified in IOTA
Perturbed Hamiltonian

• For a perturbed Hamiltonian system

\[ H = h(J_1, J_2) + \epsilon q(J_1, J_2, \theta_1, \theta_2) \]

h, q are analytic functions and \( \epsilon \) is a small perturbation

• Under special conditions on h, the system remains stable for exponentially long time
  – Functions h satisfying this condition “steep” functions

• One steep function (Hamiltonian) being implemented in IOTA
  1) Drift of length L with \( \beta_x = \beta_y \)
  2) Optics insert, T, with transfer matrix that of thin axially symmetric lens

Danilov & Nagaitsev, PRAB 13, 2010
Nonlinear Integrable Optics (IO)

- Nonlinearities with zero resonance strength are called “integrable” = having a sufficient number of conserved quantities (i.e. integrals of motion)
- 2-D system, such as transverse focusing, requires two integrals of motion
- Possible to construct nonlinear dynamic system with two integrals of motion by introducing additional transverse magnetic field along drift
  - Potential satisfies Laplace equation → can be implemented with conventional electromagnet
- First integral of motion: time independent Hamiltonian (for time independent choice of potential)
- Second integral of motion is quadratic function of momenta

\[
H = \frac{p_x^2 + p_y^2}{2} + \frac{x^2 + y^2}{2} + \beta(\psi) V \left( x \sqrt{\beta(\psi)}, y \sqrt{\beta(\psi)}, s(\psi) \right)
\]

\[
I = \left( x p_x - y p_y \right)^2 + c^2 p_x^2 + \frac{2 c^2 t \xi \eta}{\xi^2 - \eta^2} \left( \eta \sqrt{\xi^2 - 1} \cosh \left( \frac{\xi}{\eta} \right)^{-1} + \xi \sqrt{\eta^2 - 1} \left( \frac{\pi}{2} + \cosh \left( \frac{\eta}{\xi} \right)^{-1} \right) \right)
\]

\[
\xi = \frac{\sqrt{(x+c)^2 + y^2} + \sqrt{(x-c)^2 + y^2}}{2c} \quad \eta = \frac{\sqrt{(x+c)^2 + y^2} - \sqrt{(x-c)^2 + y^2}}{2c} \quad t, c \text{ arb. const.}
\]
Nonlinear Magnet

- Hamiltonian time independence requires nonlinear potential must continuously change along length of nonlinear section

- Potential dependent on strength parameter, $t$, and geometric parameter, $c$

- Continuously varying potential approximated by 18 thin magnets

- IOTA nonlinear insert 1.8 m long, $c$ varies from 8-14 mm, horizontal beam pipe aperture 12-21 mm
Tune Spread

- Simulations with single and multi particle tracking codes done to determine achievable tune spread in machine built using such magnets
  - Imperfections taken into consideration (no space charge)
- Tune footprint shows achievable vertical tune spread exceeding 1 using four nonlinear elements (cells)
- In IOTA, only 1 cell tested (0.25 max.)
IO with Nonlinear Electron Lens

- In IOTA, electron beam generated by thermionic cathode, confined and transported by axial magnetic fields, finally steered into collector

- As nonlinear element, provide tunable transverse kick dependent on betatron amplitude

- Two applications of electron lenses for nonlinear integrable optics
  - McMillan type thin radial kick, $\Delta \nu \sim \beta_{x,y} k_e / 4\pi$
  - Thick axially symmetric kick, $\Delta \nu \sim L / (2\pi \beta_{x,y})$

$k_e$ = focusing strength
Frequency maps: conventional vs. nonlinear integrable

**Example of conventional machine**
with nonlinearity (beam-beam force)

- Tune space
  - \( Q_y \) vs \( Q_x \)
  - Tune spread = 0.03

- Amplitude space
  - \( A_y \) vs \( A_x \)

Resonance overlap, restricted dynamic aperture

**IOTA with nonlinear electron lens**
in 0.7-m solenoid, \( k_e = 0.6 \text{ /m} \) (1 A)

- Tune space
  - \( Q_y \) vs \( Q_x \)
  - Tune spread = 0.16

- Amplitude space
  - \( A_y \) vs \( A_x \)

Tune spread of \( \sim 0.2 \) is achievable
No chaotic motion or particle loss
SCC with Electron Column

- Proton beam ionizes gas within the interaction region
- Plasma electrons are confined with solenoidal magnetic field and electrodes
- Gas density, magnetic field and electric field strength tuned to create appropriate electron distribution
  - Match transverse profile to that of beam
- As opposed to SCC with electron lens, electron column does not require external source of electrons or transport system
Optical Stochastic Cooling

• Stochastic cooling rate determined by signal acquisition
  – Traditionally 1 – 10 GHz
  – Operating in the optical range (~100 THz) allows increase of cooling bandwidth by orders of magnitude

• Beam send through undulator and emits radiation (pickup)
  – OSC only works for relativistic particles due to frequency of emitted light

• Radiation amplified in optical amplifier and used to kick same bunch in second undulator (kicker)

• Chicane allows for simultaneous arrival of beam and amplified radiation
Electron Cooling of Protons in IOTA

- Extends range of beam emittances (brightness) for SCC experiments
- Provides beam diagnostics downstream of electron lens through spontaneous recombination
- *Allows the question of whether limitations on electron cooling from space charge tune spreads and instabilities are alleviated by nonlinear integrable optics to be investigated*
- Cooling rates of about 20 ms are expected, leading to reduction of transverse emittance and increase in space charge tune shift by about a factor of 10

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy</td>
<td>2.5</td>
<td>MeV</td>
</tr>
<tr>
<td>β (relativistic)</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>Number of particles</td>
<td>5x10^9</td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>0.44</td>
<td>mA</td>
</tr>
<tr>
<td>Normalized RMS emittance</td>
<td>0.3 → 0.03</td>
<td>μm</td>
</tr>
<tr>
<td>RMS beam size at cooler</td>
<td>4 → 1.3</td>
<td>mm</td>
</tr>
<tr>
<td>Relative momentum spread</td>
<td>5x10^-4</td>
<td></td>
</tr>
<tr>
<td>Space charge tune shift</td>
<td>-0.028 → -0.28</td>
<td></td>
</tr>
<tr>
<td>Transverse temperature (avg.)</td>
<td>5 → 0.5</td>
<td>eV</td>
</tr>
<tr>
<td>Longitudinal temperature</td>
<td>0.6</td>
<td>eV</td>
</tr>
</tbody>
</table>
Schedule

- Commissioning of 300 MeV electron beamline imminent
  - ~2 month experimental program planned
- IOTA installation begun, expected completion of ring summer 2018
- Electron experiments 2018-2019
- Proton experiments 2019-2020
Outlook

- IOTA offers a diverse physics program aimed at increasing beam intensity for future proton rings 3-5x
  - Demonstration of nonlinear, stable systems with tune shifts ~0.25
  - Investigate space charge dynamics in rings

- Techniques investigated in IOTA should prove invaluable for meeting the physics requirements of DUNE in a reasonable amount of time

- IOTA presents an excellent opportunity for training young accelerator scientists
Thank you for your attention!
Backup Slides
Neutrinos

- Weakly interacting
- Have mass (< 1 eV)
- Flavor eigenstates related to mass eigenstates through Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
  - Neutrinos oscillate
    \[
    \begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
    \end{pmatrix} =
    \begin{pmatrix}
    c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\
    -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\
    s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13}
    \end{pmatrix}
    \begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
    \end{pmatrix}
    \]
    \(c_y \equiv \cos \theta_y, \ s_y \equiv \sin \theta_y\)

- Probability of observing conversion between two flavor eigenstates
  \[
  P_{\nu_i \rightarrow \nu_j} = \sin^2(2\theta) \sin \left( \frac{\left((m_2^2 - m_1^2)c^3\right)}{4\hbar E} z \right)^2
  \]
  (two neutrino species)

- \(m_3\) either larger or smaller than \(m_1\) & \(m_2\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>Units</th>
<th>Acc. (%)</th>
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<tr>
<td>(\sin^2\theta_{12})</td>
<td>0.297</td>
<td></td>
<td>5.8</td>
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<tr>
<td>(\sin^2\theta_{13})</td>
<td>0.0214</td>
<td></td>
<td>4.7</td>
</tr>
<tr>
<td>(\sin^2\theta_{23})</td>
<td>0.437</td>
<td></td>
<td>9.0</td>
</tr>
<tr>
<td>(\delta m^2)</td>
<td>7.37x10^{-5}</td>
<td>eV^2</td>
<td>2.4</td>
</tr>
<tr>
<td>(</td>
<td>\Delta m^2</td>
<td>)</td>
<td>2.5x10^{-3}</td>
</tr>
<tr>
<td>(\delta)</td>
<td>1.35</td>
<td>(\pi)</td>
<td></td>
</tr>
</tbody>
</table>

\(\delta m^2 = m_2^2 - m_1^2\)
\(|\Delta m^2| = m_3^2 - (m_1^2 + m_2^2)/2\)

IOTA Beta Functions

- 1 Nonlinear insert
- Same for electrons and protons

A. Romanov, IOTA Collaboration Meeting June '17
Other Machines

- What about machines such as the Spallation Neutron Source (SNS) or Japan Proton Accelerator Research Complex (J-PARC)?
  - Achieve MW beam power and 0.25 tune spread
  - Costly:
    - Large aperture ceramic beam pipe at J-PARC
    - Phase space “painting” possible at SNS due to large acceptance
- Integrable optics provides a method for achieving large tune spread with small acceptance/aperture (e.g. FNAL Booster, which is 1/10 that of SNS and J-PARC)
  - Significant cost reduction
Beam – Lens Interaction

- Beam experiences linear focusing strength

\[ k_e = 2\pi \frac{j_0 L (1 \pm \beta_e \beta_z)}{(B \rho) \beta_e \beta_z c^2} \]

- Tune shift for small strengths (away from half integer resonances)

\[ \Delta \nu = \frac{\beta_{x,y} k_e}{4\pi} = \frac{\beta_{x,y} j_0 L (1 \pm \beta_e \beta_z)}{2 (B \rho) \beta_e \beta_z c^2} \]

\( j_0 \) = electron current density
\( L \) = lens length
\( \beta_e \) = electron v/c
\( \beta_z \) = beam v/c
\( B \rho \) = magnetic rigidity
\( \beta_{x,y} \) = transverse beta functions
McMillan Type Thin Radial Kick

- Electron lens must have specific current density distribution
  \[ j(r) = j_0 \frac{a^4}{(r^2 + a^2)^2} \quad a = \text{effective lens radius} \]

- Circulating beam experiences nonlinear transverse kick
  \[ \theta(r) = k_e r \frac{a^2}{r^2 + a^2} \]

- Two independent invariants of motion if element is thin \((L \ll \beta_{x,y})\) and betatron phase advance near an odd multiple of \(\pi/2\)
  - Particle trajectories are regular and bounded (neglecting longitudinal effects)

- Achieving and preserving desired current density profile very important

- Achievable tune spread \(\sim \beta_{x,y} k e / 4\pi\)
Axially Symmetric Thick Lens Kick

- Relies on section of ring with constant and equal beta functions
  - Achievable with solenoid axial field \( B_z = 2(B\rho)/\beta_{x,y} \)
  - Same field also confines electrons in lens

- Axially symmetric current distribution conserves Hamiltonian and longitudinal component of angular momentum as long as betatron phase advance is an integer multiple of \( \pi \)

- Achievable tune spread \( \sim L/(2\pi\beta_{x,y}) \)
  - Long solenoids and small beta functions beneficial
  - Insensitive to current density distribution (as opposed to McMillan lens)
  - Smaller achievable tune spread, but more robust than McMillan lens
Parameter Optimization

- Simulations done to determine optimal values for gas density, magnetic field, and electrode voltage

  - Electron and proton transverse profiles match well for
    - $B = 0.1 \ T$
    - $V = -5.0 \ V$
    - $P = 5 \times 10^{-4} \ \text{torr}$ (rest of ring $6 \times 10^{-10} \ \text{torr}$)

26 September, 2017

Recirculating Bunched Beam

- Simulations underway to determine effect of recirculating, bunched beam
- Below animation represents single bunch passage (100 ns) for ~ 1 μs total
- Effect of column on beam to be investigated
OSC Cooling Rates

- Particle passing through chicane receives a s position dependent correction in relative momentum
  \[ \frac{\delta p}{p} = -\xi_0 \sin (k \Delta s) \quad k = 2\pi/\lambda \]

- Particle displacement on way from pickup to kicker, relative to reference particle (0 displacement and 0 kick)
  \[ \Delta s = M_{51} x + M_{52} \theta_x + M_{56} (\Delta p/p) \]
  - \( M_{5n} \) = elements of 6x6 transfer matrix
  - \( x \) = particle coordinate
  - \( \theta_x \) = particle angle
  - \( \Delta p/p \) = relative momentum deviation in pickup

- Partial slip factor introduced so longitudinal displacement for particle without betatron oscillations and with momentum deviation \( \Delta p/p \), relative to reference particle is \( M_{\tilde{56}} \Delta p/p \)
  \[ M_{\tilde{56}} = M_{51} D_p + M_{52} D_p' + M_{56} \]
  - \( D \) = dispersion
  - \( D' \) = derivative in pickup

- Horizontal and vertical cooling rates per turn (for small amplitude oscillations)
  \[ \begin{bmatrix} \lambda_x \\ \lambda_s \end{bmatrix} = \frac{k \xi_0}{2} \begin{bmatrix} M_{56} - M_{\tilde{56}} \\ M_{\tilde{56}} \end{bmatrix} \]
OSC Parameters

- Length of OSC experiment approximately 4 m, beam delay of 2 mm
- 2.2 μm optical amplifier, operated at liquid nitrogen temperature to increase thermal conductivity and reduce thermal stress, decrease optical distortion
- Optical system has two identical lenses
  - Focuses beam radiation onto crystal
  - Focuses amplified radiation into wiggler
- OSC damping times 1/10 that of synchrotron radiation times

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>Beam Energy</td>
<td>100</td>
<td>MeV</td>
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<tr>
<td>Tunes, $Q_x$, $Q_y$</td>
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<td>Trans. RMS emittance</td>
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<td>nm</td>
</tr>
<tr>
<td>RMS momentum spread</td>
<td>$1.06 \times 10^{-4}$</td>
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</tr>
<tr>
<td>Radiation wavelength at 0 angle</td>
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<td>μm</td>
</tr>
<tr>
<td>Dipole magnetic field</td>
<td>0.25</td>
<td>T</td>
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<tr>
<td>Dipole length</td>
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<td>cm</td>
</tr>
<tr>
<td>Horizontal beam offset</td>
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<td>mm</td>
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<tr>
<td>Undulator length</td>
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<tr>
<td>Distance from undulator center to OA</td>
<td>1.65</td>
<td>m</td>
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<tr>
<td>Amplifier gain (power)</td>
<td>5</td>
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<tr>
<td>Lens focal length</td>
<td>80</td>
<td>mm</td>
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<td>SR damping times, $\tau_s$, $\tau_x$, $\tau_y$</td>
<td>1.7, 2, 1.1</td>
<td>s</td>
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<tr>
<td>OSC damping times, $\tau_s$, $\tau_x$, $\tau_y$</td>
<td>0.1, 0.17, 0.17</td>
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