## Northern Illinois <br> University

## Measurements with the Danilov-Nagaitsev Magnet (NIO)

S. Szustkowski, N. Kuklev, A. Romanov, A. Valishev

06/16/2020

## Outline

- Quick run down of Danilov-Nagaitsev Nonlinear Magnet
- Tune Measurements
- Amplitude Dependent Tune Maps
- Vertical Amplitude Dependent Tune Shifts
- M2L Sync-Light Measurements
- Outlook and Conclusion


## Nonlinear Magnet

Start with a linear focusing accelerator with equal horizontal and vertical optics.

- The linear optics can be built with standard optics, but must have a $\mathrm{n}-\pi$ phase advance,"T-insert"
- Drift region $L$, matched beta function ( $\mathrm{L}=1.8 \mathrm{~m}$ in IOTA)

$$
\begin{aligned}
& H_{N}=\frac{\left(p_{x N}^{2}+p_{y N}^{2}\right)}{2}+\frac{x_{N}^{2}+y_{N}^{2}}{2}+U\left(x_{N}, y_{N}, \psi\right) \\
& U(x, y)=\frac{f(\xi)+g(\eta)}{\xi^{2}+\eta^{2}}, \quad \begin{array}{l}
f_{2}(\xi)=\xi \sqrt{\xi^{2}-1}[d+t \operatorname{acosh}(\xi)] \\
g_{2}(\eta)=\eta \sqrt{1-\eta^{2}}[b+t \operatorname{acos}(\eta)]
\end{array}
\end{aligned}
$$

$$
\xi=\frac{\sqrt{(x+c)^{2}+y^{2}}+\sqrt{(x-c)^{2}+y^{2}}}{2 c} \quad \eta=\frac{\sqrt{(x+c)^{2}+y^{2}}-\sqrt{(x-c)^{2}+y^{2}}}{2 c}
$$



To have lowest multipole expansion term to be a quadrapole: $d=0, b=-\frac{\pi}{2} t$, $t$ is then the nonlinear potential strength
V. Danilov and S. Nagaitsev, Phys. Rev. ST-AB 13, 084002 (2010)


## Tune Measurements

- Nonlinear Magnet t -strengths of $\mathrm{t}=0.218,0.42,0.48$
- Calculated tunes via FFT ( $\mathrm{N}=512$ turns)
- Summed FFT Amplitudes from 20 BPM's
- Vertical Amplitude Dependent Tune Shift
- Percentage Beam Loss from BPM Intensity Signal
- Moving Average of 10 turns from 20 BPM's


## Small－Amplitude Map

NIU



 ニーー－ $0.3 \rightarrow|><|<|$ $Q y=0.190 \pm 0.001$
0.0



Theoretical： $\mathrm{Qx}=0.422, \mathrm{Qy}=0.042$
Measured Run 2： $\mathrm{Qx}=0.418 \pm 0.002$ $Q y=0.041 \pm 0.001$

Qx

## Amplitude Dependent Tune Map, $\mathbf{t = 0 . 2 2}$



Vertical:
Small Amplitude: Qy=0.225
Theoretical Maximum: $\Delta Q y=0.028$
Measured Run 1: $\Delta Q y=0.0245 \pm 0.0018$
Measured Run 2: $\Delta Q y=0.0312 \pm 0.0067$

## Horizontal:

Small Amplitude: $\mathrm{Qx}=0.359$
Theoretical Maximum: $\Delta \mathrm{Qx}=0.026$
Measured Run 1: $\Delta Q x=0.0334 \pm 0.0018$
Measured Run 2: $\Delta Q x=0.0234 \pm 0.0020$

## Vertical Amplitude Dependent Tune Shift, $\mathbf{t = 0 . 2 2}$

(a)

(b)

(a)


Loss from Horizontal Kicks


## Amplitude Dependent Tune Map, $\mathbf{t = 0 . 4 3}$



## Vertical:

Small Amplitude: $\mathrm{Qy}=0.12$
Theoretical Maximum: $\Delta Q y=0.085$
Measured Run 1: $\Delta Q y=0.0530 \pm 0.0018$
Measured Run 2: $\Delta Q y=0.0524 \pm 0.0013$

## Horizontal:

Small Amplitude: $\mathrm{Qx}=0.406$
Theoretical Maximum: $\Delta \mathrm{Qx}=0.026$
Measured Run 1: $\Delta Q x=0.0261 \pm 0.0017$
Measured Run 2: $\Delta \mathrm{Qx}=0.0300 \pm 0.0016$

## Vertical Amplitude Dependent Tune Shift, $\mathbf{t}=\mathbf{0 . 4 3}$

(a)

(b)

(a)


Loss from Horizontal Kicks


## Amplitude Dependent Tune Map, $\mathbf{t = 0 . 4 9}$



Vertical:
Small Amplitude: $\mathrm{Qy}=0.042$
Theoretical Maximum: $\Delta Q y=0.108$
Measured Run 2: $\Delta Q y=0.125 \pm 0.0016$

Horizontal:
Small Amplitude: Qx = 0.422
Theoretical Maximum: $\Delta \mathrm{Qx}=0.036$
Measured Run 2: $\Delta \mathrm{Qx}=0.028 \pm 0.0021$

Vertical Kicks only
Significant beam loss after kick.
Chromaticity was not corrected
Had to realign orbit through center of NL

## Vertical Amplitude Dependent Tune Shift, $\mathbf{t = 0 . 4 9}$



## Nonlinear Potential

## Used Mathematica to find stable fixed points.

Potential Expressed as[1]:

$$
\begin{gathered}
V\left(x_{N}, y_{N}\right)=\frac{1}{2}\left(x^{2}+y^{2}\right)-t * \mathfrak{R e}\left(\frac{z}{\sqrt{1-z^{2}}} \arcsin (z)\right), \\
z=x_{N}+i y_{N}
\end{gathered}
$$




[1] Mitchell, Ryne, and Hwang, Phys. Rev. E 100, 053308 (2019)

## Measurements from M2L

- Recorded images with 1 second exposure from synchrotron-light diagnostics
- M2L lattice parameters: $\beta_{x} \approx 3.761$ [m], $\beta_{y} \approx 0.199$ [m], $D_{x} \approx 0.094472$ [m]
- Low Intensity Beam, (survived crossing integer resonance)
- Stable at fixed points for higher t-strength
- Distance between the two stable fix points increase nonlinear with t-strength.
- Ideal lattice maximum distance $=1.445$
- $10 \%$ Error on Beta-function $=1.515$
- At $t=0.90$, nearing mechanical aperture, one of the beamlets slowly decays
- Past $t=0.90$, limit reached
- Need to further analyze synchrotron light diagnostic systematics.





## Summary and Outlook

- Run 1 Largest observed tune shift of $\Delta \mathrm{Qx}=0.0261 \pm 0.0017$ and $\Delta \mathrm{Qy}=0.0530 \pm 0.0018$ at $\mathrm{t}=0.43$
- Run 2 Largest observed tune shift of $\Delta \mathrm{Qx}=0.028 \pm 0.0021$ and $\mathbf{\Delta Q y}$ $=0.125 \pm 0.0016$ at $\mathrm{t}=0.49$
- Successfully split beam into two beamlets
- Future Run improvements,
- Correct for Resonance Drive Terms
- Systematically correct chromaticity and orbit alignment for each t-strength step


## Integrable Optics Test Accelerator

| Parameter | Value |
| :--- | :---: |
| Perimeter | 39.97 m |
| Momenta | $50-200 \mathrm{MeV} / \mathrm{c}$ |
| $p_{e-\text { beam }}$, design | $150 \mathrm{MeV} / \mathrm{c}$ |
| $p_{p-\text {-eam }}$, design | $70 \mathrm{MeV} / \mathrm{c}$ |
| Electron current | 1.2 mA |
| Proton current | 10 mA |
| RF frequency | 30 MHz |
| RF voltage | 1 kV |
| $v_{x}, v_{y}, v_{s}$ | $\left(0.3,0.3,5.7 \times 10^{-4}\right)$ |
| $\tau_{x}, \tau_{y}, \tau_{s}$ | $(2.0,0.7,0.3) \mathrm{s}$ |
| $\epsilon_{x}, \epsilon_{x, y \text { coupled }}, \mathrm{RMS}$ | $(96.3,25.3) \mathrm{nm}$ |
| $\Delta p / p$, RMS | $1.26 \times 10^{-4}$ |



## Measurements from M2L Images



