μCATALYST 08/10/2026 Updates

Rosalyn Beckwith – Northeastern University

Brookhaven National Lab

Advised by Dr Stephen Brooks | Professor Toyoko Orimoto

Bunching Methods

Project focuses on modeling longitudinal beam dynamics in the AGS to study how RF systems compress a proton bunch to a target of 2ns RMS before extraction

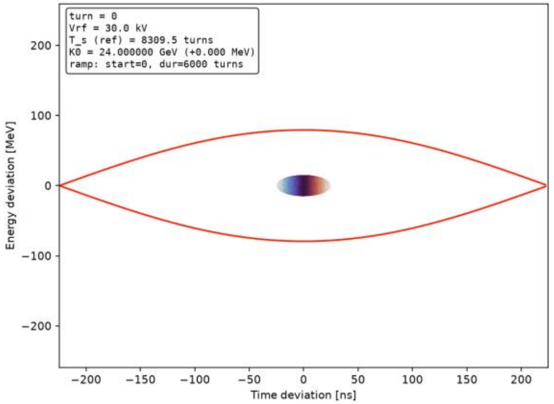
Git: https://github.com/rbeckwith1/bnl-beam-simulation

AGS parameters:

- Momentum Compaction: ~ 0.014
- Harmonic number: h = 6
- Maximum Voltage: 320 kV
- Emittance: 1.35 eV*ns (updated value)

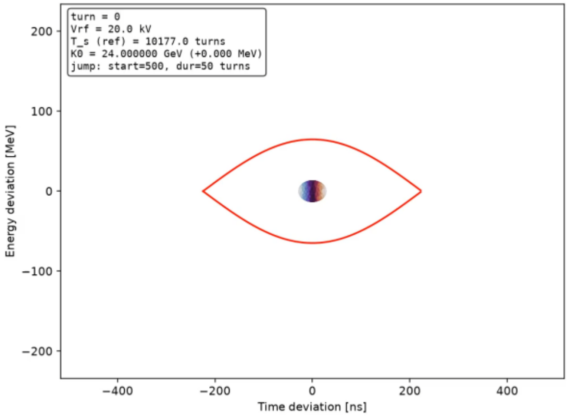
Simulations using general reference values:

Min Bunch Length:
5.952 ns



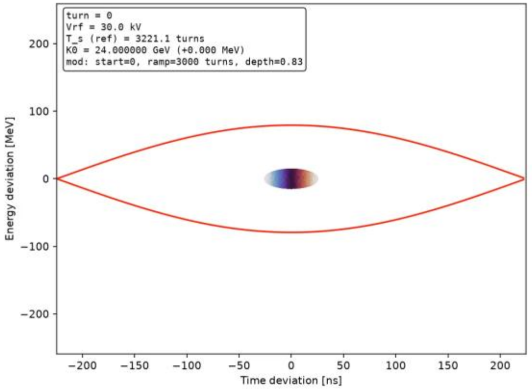
Adiabatic

Min Bunch Length:
3.593 ns



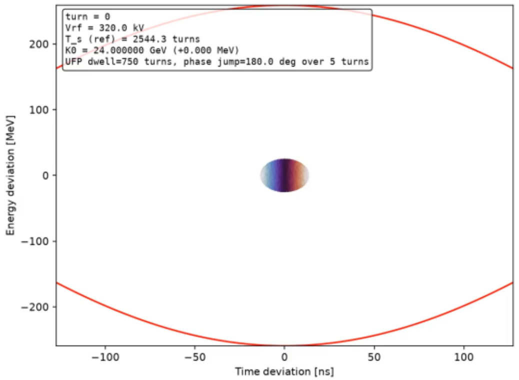
Non-Adiabatic

Min Bunch Length:
2.140 ns



Quad Pumping

Min Bunch Length:
3.052 ns



Unstable Fixed-Point

Optimization

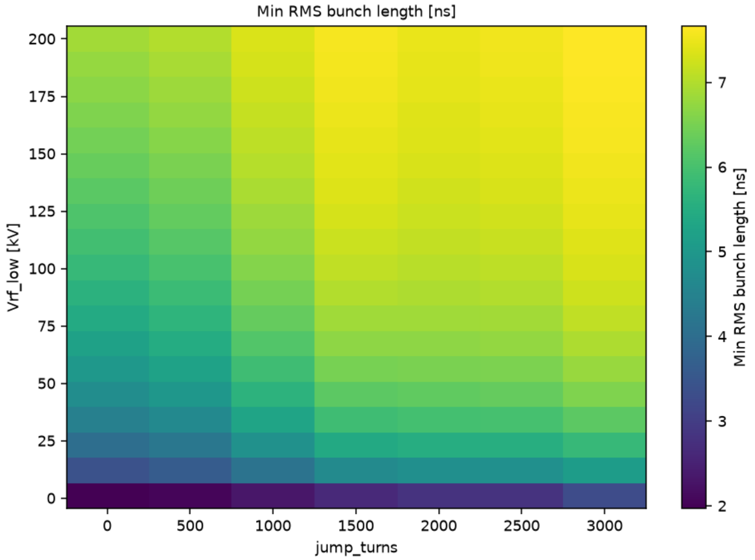
Optimized the non-adiabatic, quad pumping, and unstable fixed point methods

Re-ran optimizations with the updated longitudinal emittance: only the non-adiabatic method achieved < 2 ns RMS

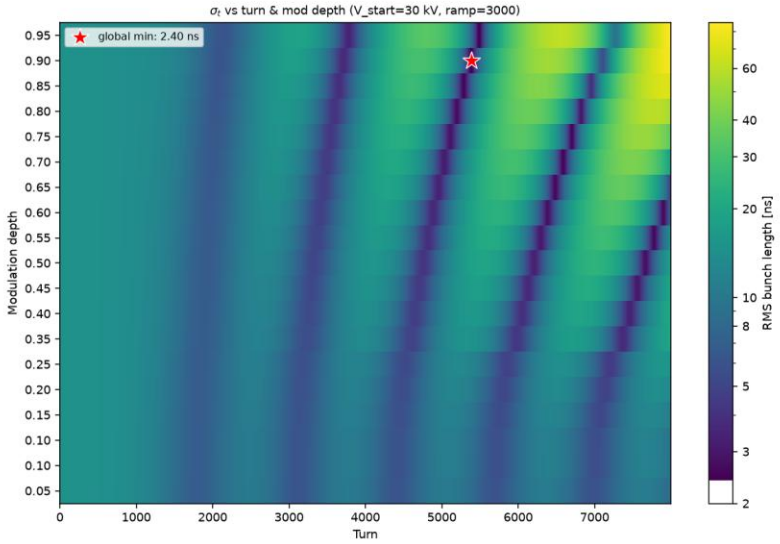
feasibility of the required RF voltage/phase changes has not yet been established

Minimum of each method:

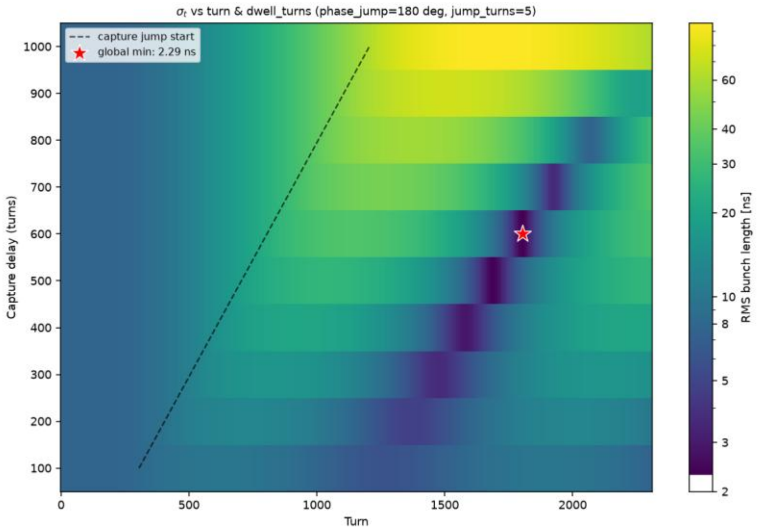
- Non adiabatic: 1.97 ns RMS
- Quad pumping: 2.40 ns RMS
- Unstable fixed-point: 2.29 ns RMS



Non-Adiabatic



Quad Pumping



Unstable Fixed-Point

Longitudinal Stability

- Current assumed emittance does not achieve the **<2 ns RMS** compression target.
- Investigating whether **lower longitudinal emittance** can enable further compression while maintaining beam stability.
- Using the **Keil–Schnell–Boussard criterion** to estimate the longitudinal impedance threshold throughout compression

momentum spread

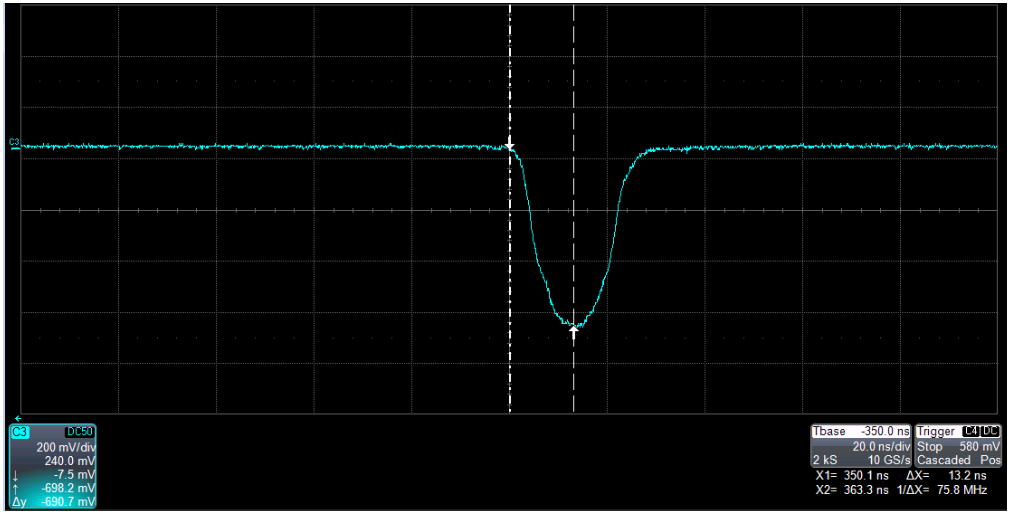
$$\left(Z/h\right)_{th} = 2\pi\beta E\eta F\,\frac{(\Delta P/p)^2}{I_{pk}} \qquad \text{vs.} \qquad \text{AGS Impedance} = 10\,\Omega$$

impedance threshold

- Currently verifying calculation and against given code
- Next: scan initial emittance to determine how far emittance can be reduced while maintaining stability margin

Refining Initial Bunch Distribution

- Initial simulations assumed a uniformly filled elliptical distribution
- AGS oscilloscope traces of the longitudinal bunch profile, I(t)
- Currently extracting quantitative I(t) data from the oscilloscope images



```
C3          DC50
   200 mV/div
     240.0 mV
↓     -7.5 mV
↑   -698.2 mV
Δy  -690.7 mV

Tbase   -350.0 ns   Trigger  C4 DC
       20.0 ns/div  Stop     580 mV
2 kS     10 GS/s    Cascaded    Pos
X1=  350.1 ns     ΔX=     13.2 ns
X2=  363.3 ns   1/ΔX=     75.8 MHz
```

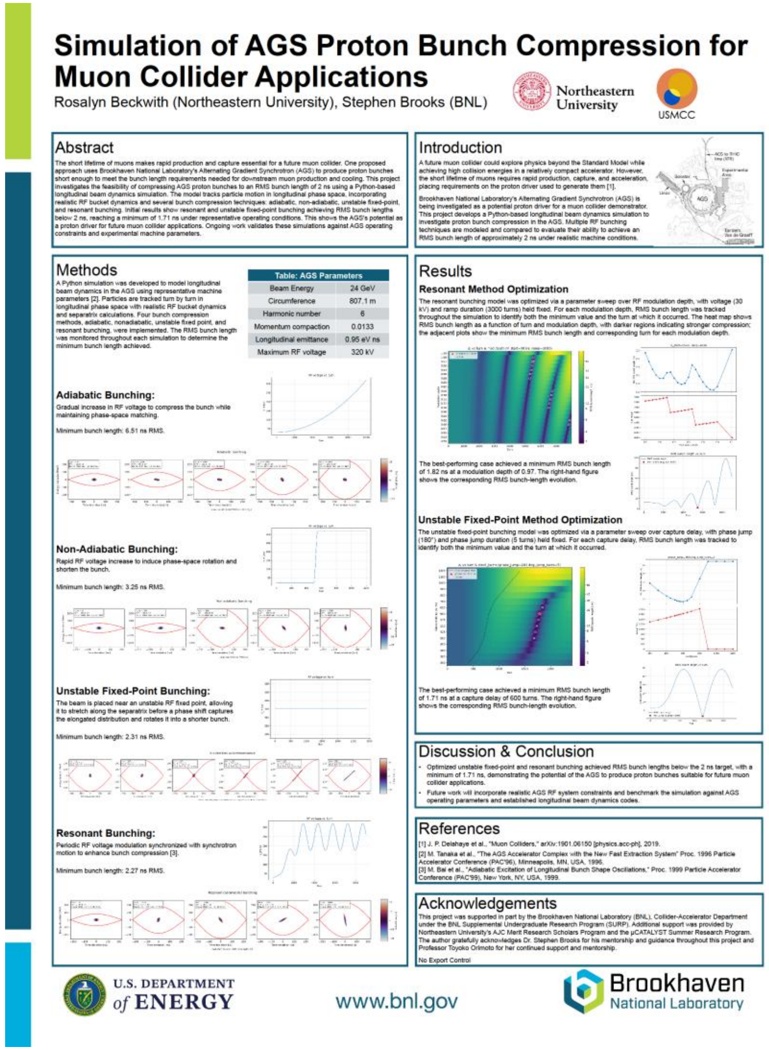
$$I(t) = I_0 \left[1 - (t/T)^2\right]^J$$

Elliptical Profile ; J controlls distribution shape

ex: uniform ellipse: $J = 1/2$

Fitting the measured profile with elliptical distributions of varying shape parameter J

BNL Summer Program Poster Symposium



Simulation of AGS Proton Bunch Compression for Muon Collider Applications

Rosalyn Beckwith (Northeastern University), Stephen Brooks (BNL)

Abstract

The short lifetime of muons makes rapid production and capture essential for a future muon collider. One proposed approach uses Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS) to produce proton bunches short enough to meet the bunch length requirements needed for downstream muon production and cooling. This project investigates the feasibility of compressing AGS proton bunches to an RMS bunch length of 2 ns using a Python-based longitudinal beam dynamics simulation. The model tracks particle motion in longitudinal phase space, incorporating realistic RF bucket dynamics and several bunch compression techniques: adiabatic, non-adiabatic, unstable fixed-point, and resonant bunching. Initial results show resonant and unstable fixed-point bunching achieving RMS bunch lengths below 2 ns, reaching a minimum of 1.71 ns under representative operating conditions. This shows the AGS's potential as a proton driver for future muon collider applications. Ongoing work validates these simulations against AGS operating constraints and experimental machine parameters.

Introduction

A future muon collider could explore physics beyond the Standard Model while achieving high collision energies in a relatively compact accelerator. However, the short lifetime of muons requires rapid production, capture, and acceleration, placing requirements on the proton driver used to generate them [1].

Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS) is being investigated as a potential proton driver for a muon collider demonstrator. This project develops a Python-based longitudinal beam dynamics simulation to investigate proton bunch compression in the AGS. Multiple RF bunching techniques are modeled and compared to evaluate their ability to achieve an RMS bunch length of approximately 2 ns under realistic machine conditions.

Methods

A Python simulation was developed to model longitudinal beam dynamics in the AGS using representative machine parameters [2]. Particles are tracked turn by turn in longitudinal phase space with realistic RF bucket dynamics and separatrix calculations. Four bunch compression methods, adiabatic, nonadiabatic, unstable fixed point, and resonant bunching, were implemented. The RMS bunch length was monitored throughout each simulation to determine the minimum bunch length achieved.

Table: AGS Parameters	
Beam Energy	24 GeV
Circumference	807.1 m
Harmonic number	6
Momentum compaction	0.0133
Longitudinal emittance	0.95 eV ns
Maximum RF voltage	320 kV

Adiabatic Bunching:

Gradual increase in RF voltage to compress the bunch while maintaining phase-space matching.

Minimum bunch length: 6.51 ns RMS.

Non-Adiabatic Bunching:

Rapid RF voltage increase to induce phase-space rotation and shorten the bunch.

Minimum bunch length: 3.25 ns RMS.

Unstable Fixed-Point Bunching:

The beam is placed near an unstable RF fixed point, allowing it to stretch along the separatrix before a phase shift captures the elongated distribution and rotates it into a shorter bunch.

Minimum bunch length: 2.31 ns RMS.

Resonant Bunching:

Periodic RF voltage modulation synchronized with synchrotron motion to enhance bunch compression [3].

Minimum bunch length: 2.27 ns RMS.

Results

Resonant Method Optimization

The resonant bunching model was optimized via a parameter sweep over RF modulation depth, with voltage (30 kV) and ramp duration (3000 turns) held fixed. For each modulation depth, RMS bunch length was tracked throughout the simulation to identify both the minimum value and the turn at which it occurred. The heat map shows RMS bunch length as a function of turn and modulation depth, with darker regions indicating stronger compression; the adjacent plots show the minimum RMS bunch length and corresponding turn for each modulation depth.

The best-performing case achieved a minimum RMS bunch length of 1.82 ns at a modulation depth of 0.97. The right-hand figure shows the corresponding RMS bunch-length evolution.

Unstable Fixed-Point Method Optimization

The unstable fixed-point bunching model was optimized via a parameter sweep over capture delay, with phase jump (180°) and phase jump duration (5 turns) held fixed. For each capture delay, RMS bunch length was tracked to identify both the minimum value and the turn at which it occurred.

The best-performing case achieved a minimum RMS bunch length of 1.71 ns at a capture delay of 600 turns. The right-hand figure shows the corresponding RMS bunch-length evolution.

Discussion & Conclusion

- Optimized unstable fixed-point and resonant bunching achieved RMS bunch lengths below the 2 ns target, with a minimum of 1.71 ns, demonstrating the potential of the AGS to produce proton bunches suitable for future muon collider applications.
- Future work will incorporate realistic AGS RF system constraints and benchmark the simulation against AGS operating parameters and established longitudinal beam dynamics codes.

References

[1] J. P. Delahaye et al., "Muon Colliders," arXiv:1901.06150 [physics.acc-ph], 2019.
[2] M. Tanaka et al., "The AGS Accelerator Complex with the New Fast Extraction System" Proc. 1996 Particle Accelerator Conference (PAC'96), Minneapolis, MN, USA, 1996.
[3] M. Bai et al., "Adiabatic Excitation of Longitudinal Bunch Shape Oscillations," Proc. 1999 Particle Accelerator Conference (PAC'99), New York, NY, USA, 1999.

Acknowledgements

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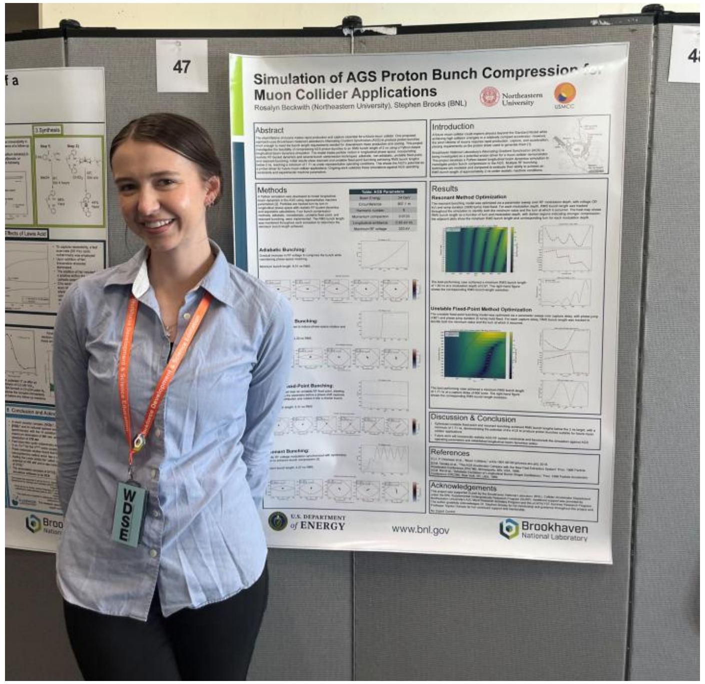

Link to Project Report:
https://drive.google.com/file/d/14FXRb1lDF5o5oW3sv7OAlRQvv5K7SZW4/view?pli=1
Link to Project Poster:
https://drive.google.com/file/d/1iv8YPeQPfn6ZX7pHeVPkT5BymNV6LiGG/view

Conclusion and Next Steps

Current Model:

- Implements four bunch-compression strategies (non-adiabatic, adiabatic, quad pumping, unstable fixed point) with turn-by-turn phase-space tracking, acceleration, and voltage-ramp control

Currently Working on:

- Evaluating microwave-instability limits to determine the minimum practical longitudinal emittance for compression
- Extracting and fitting measured AGS bunch profiles to refine the initial particle distribution

Next Steps:

- Scan longitudinal emittance to identify the best compression achievable within stability limits
- Compare compression using measured vs. idealized initial distributions
- Re-optimize compression methods incorporating realistic AGS machine constraints
- Benchmark tracking against BLonD to validate simulation accuracy