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Non-Relativistic Ion Beam Diagnostics

Chris Richard

Budker Seminar

12-2-18

Outline

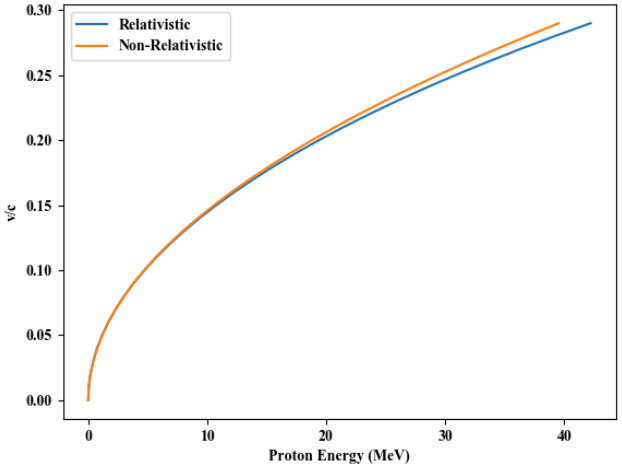
- Goals
- Low energy beams
- Transverse tails
- 200 Ω kicker energy sensitivity
- Summary

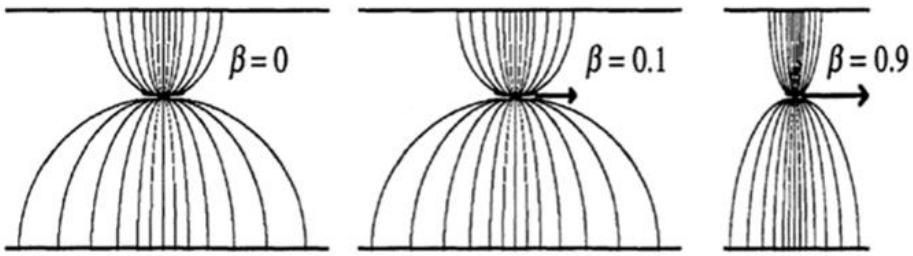
- 3rd year graduate student at Michigan State University
  - Thesis Advisor: Steve Lidia
  - Thesis topic: Non-relativistic ion beam diagnostics
- Working at Fermilab for 1 year as part of Accelerator Science and Engineering Traineeship
  - Started: January 8th
  - Fermilab mentor: Alexander Shemyakin

- Goals for time at Fermilab
  - Familiarize with beam instrumentation
  - Gain experience with experimental studies
  - Work will be part of thesis

Non-Relativistic Beams

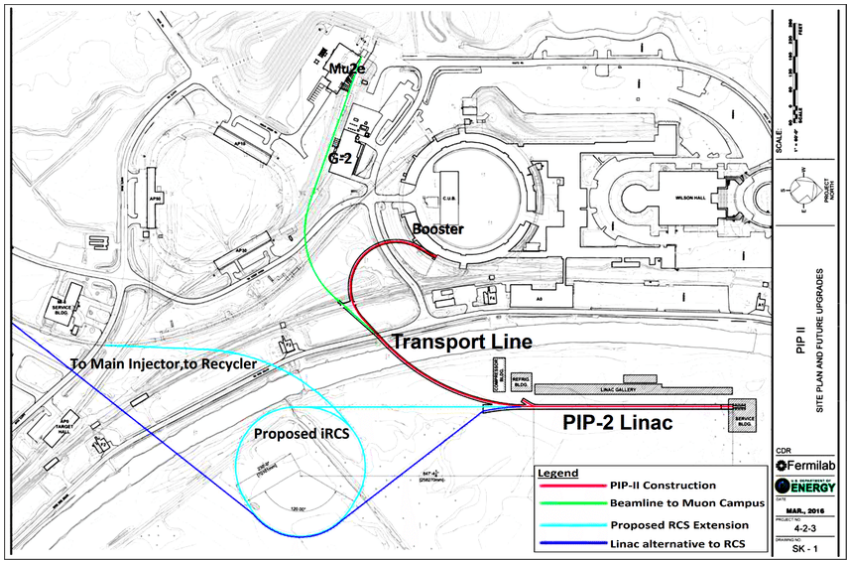
- Velocity is energy dependent
  - Use to describe region of interest, ß<~0.1
- Non-flat electromagnetic fields
  - No direct match between fields at pipe walls and longitudinal profile
- Large angles and low rigidity
  - Can steer the beam with lower fields Allows for Allison scanner to be used

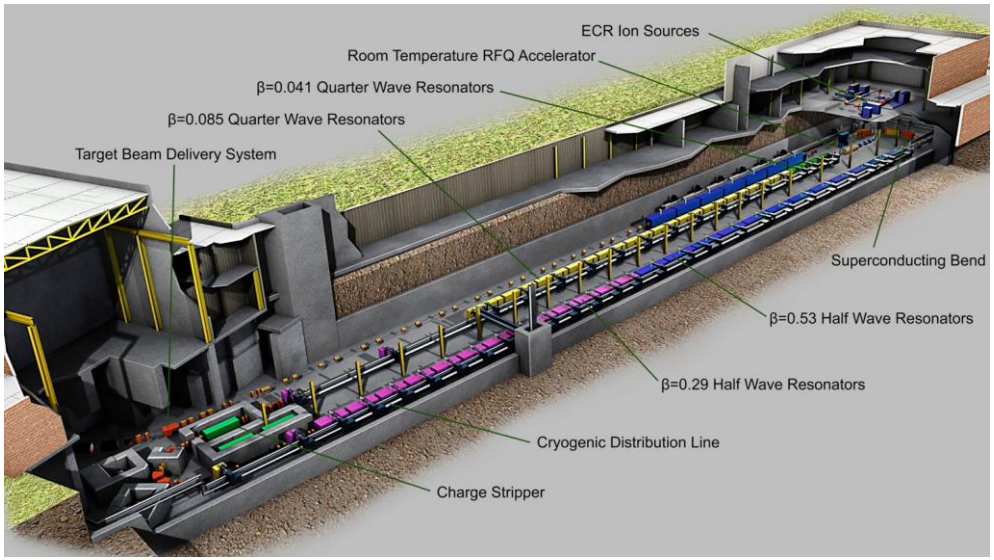




Why Come to Fermilab

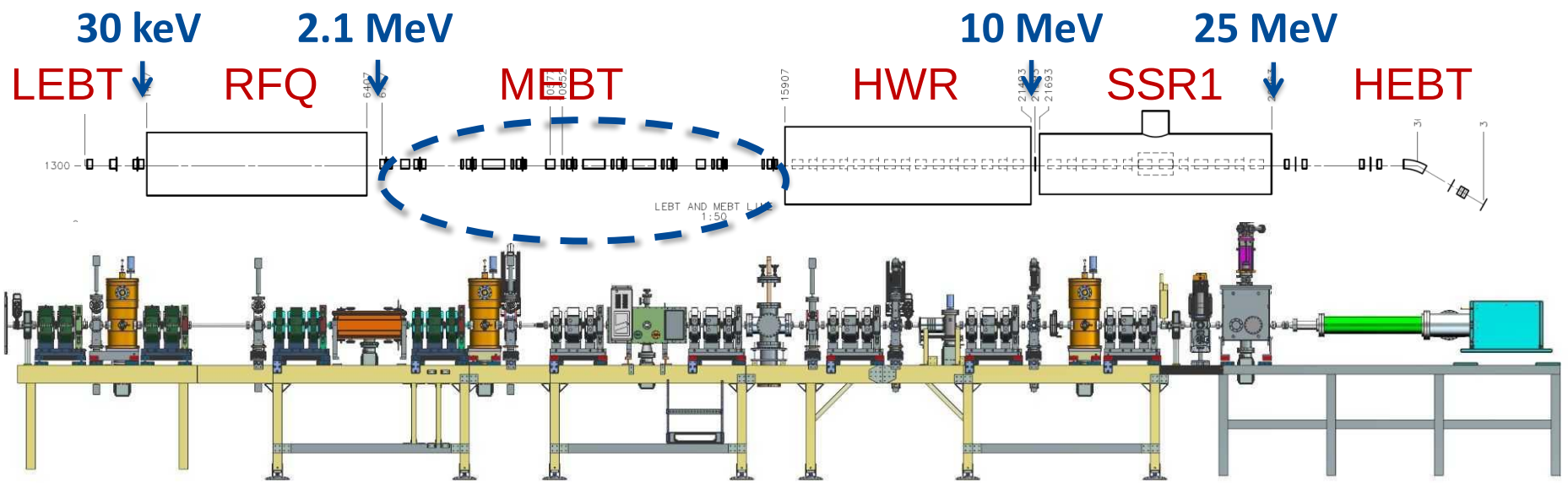
- PIP2
  - 800 MeV H- linac
- MEBT
  - 2.1 MeV/u, ß=0.06, [Bρ]=0.21 T-m
- FRIB
  - 200 MeV/u heavy ion linac
- MEBT
  - 0.5 MeV/u, ß=0.03, [Bρ]=0.11*A/q T-m





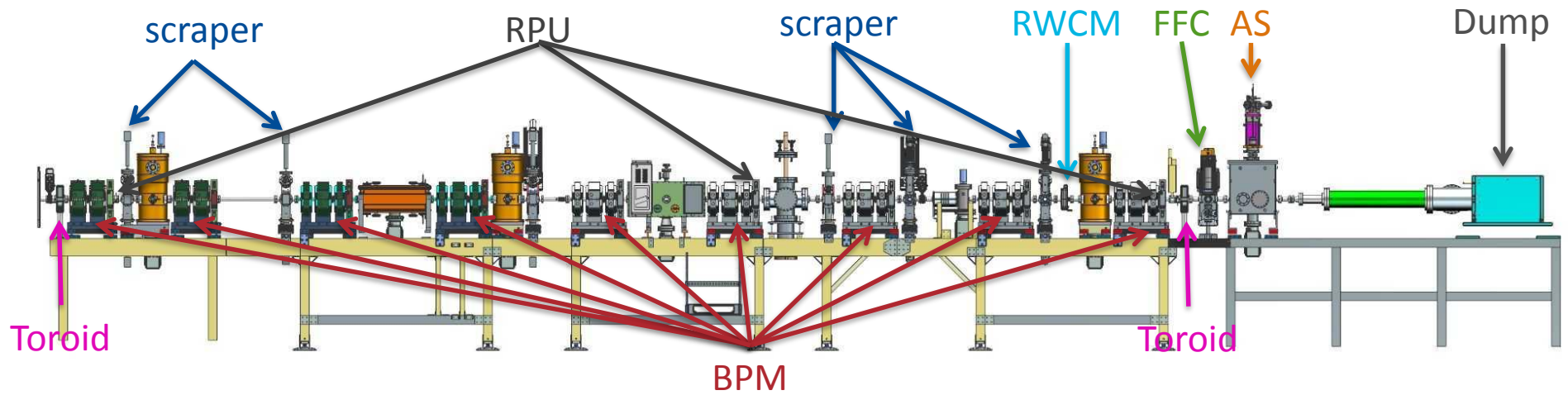
PIPII Injector Test (PIP2IT)

- Test of PIP2 front end
  - 30 keV H- source
  - 162.5 MHz RFQ
  - MEBT: 2.1 MeV, 0.2 mm-mrad
  - 5 mA nominal current



PIP2IT Diagnostics

- Position
  - Beam position monitors (BPM)
- Profile
  - Resistive wall current monitor (RWCM)
  - Fast faraday cup (FFC)
- Emittance
  - Allison Scanner (AS)
- Current
  - Ring Pick ups (RPU)
  - Beam dump
  - Scrapers
  - Toroids



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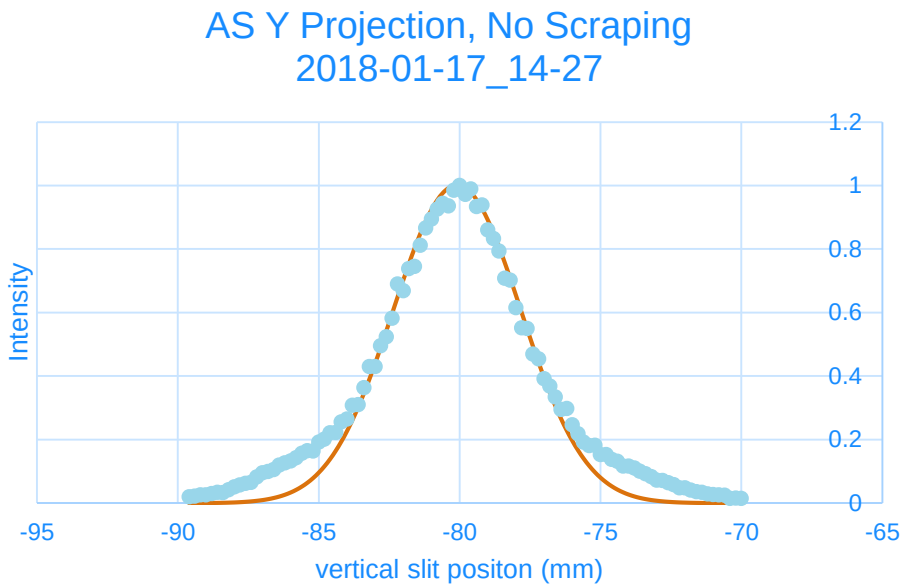
Transverse Tails

- Measured vertical phase space shows deviations even with scraped beams
- These deviations increase the beam size
  - Increased losses
  - Damage to SRF cavities
- Want to remove tails
  - First need a definition of beam tail



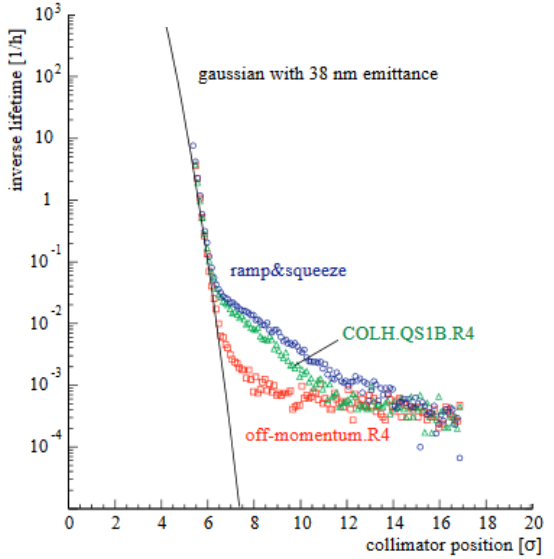
Measuring Transverse Tails

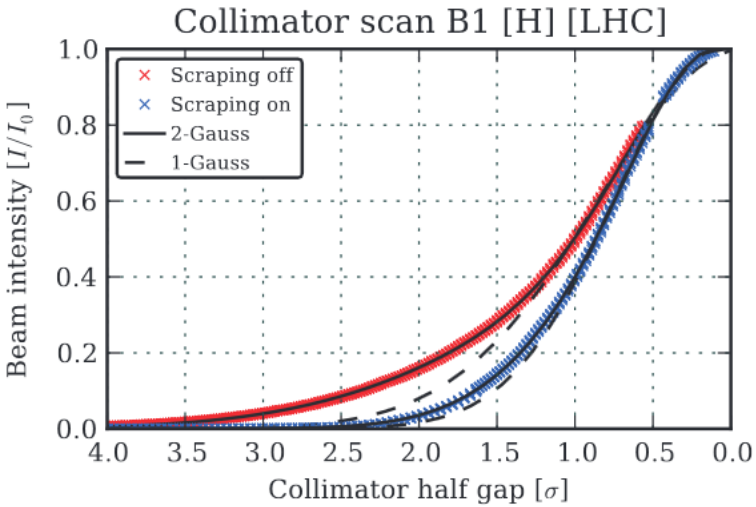
- Measure tails using beam lifetime (LEP)
  - Measure lifetime as a function collimator insertion
  - Cannot take this measurement in PIP2IT

    I. Reichel, *et al., Proc PAC97,* p. 1819-1821

- Double Gaussian Fit (LHC)
  - For symmetric beam profile, compare double gaussian fit to single gaussian fit
  - In PIP2IT, difficultly fitting gaussians to scraped beam

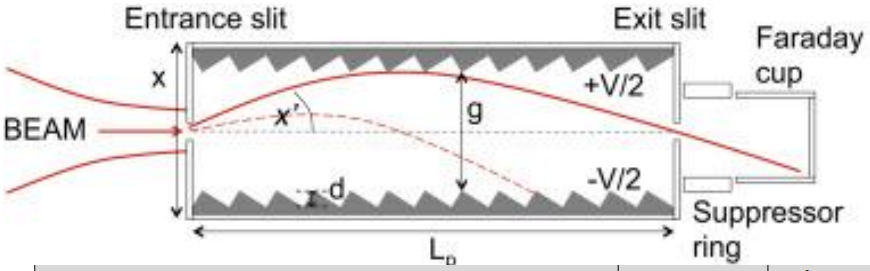
    L. Drosdal *et al. Proc. IPAC13*, p. 957-959





Measuring Beam Profile in PIP2IT

- Method 1: insert a scraper and measuring current at dump
  - Accurate to a few percent
- Method 2: Allison Scanner at end of MEBT
  - Vertical profile measured by varying entrance slip position
  - Voltage between plates bends the beam slice
  - Intensity of particles that are bent to the exit slit is measured with faraday cup
  - Convert voltage to angle

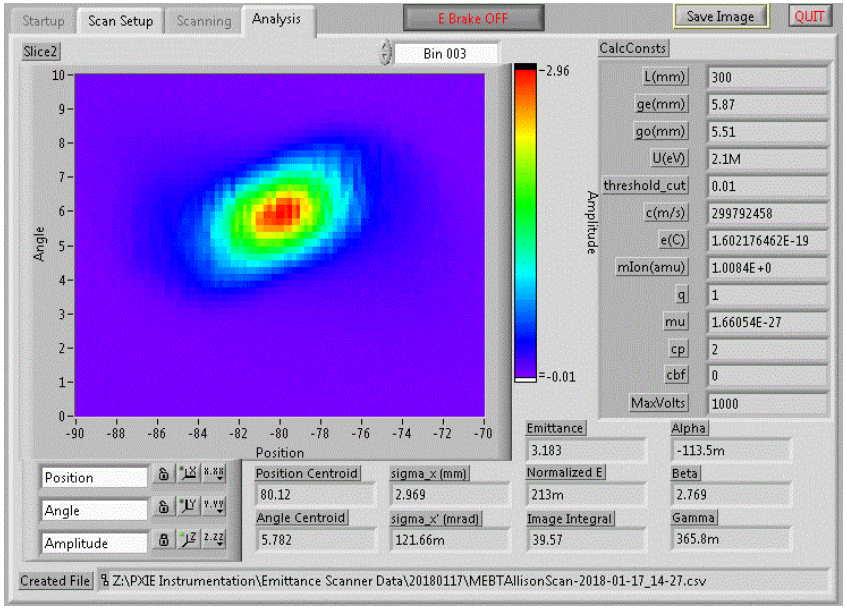


Parameter	Unit	Value
Motion and positioning		
Vertical range of measurement positions with respect to the beam line axis	mm	± 15
Absolute accuracy of vertical position of the sensor	mm	≤ 1
Reproducibility of vertical position	mm	≤ 0.1
Resolution of vertical position	mm	≤ 0.025
Sensor horizontal alignment with respect to beam line axis	mm	≤ 1
Sensor yaw alignment with respect to beam line axis	mR	10
MAES module pitch adjustment range	mR	± 35
MAES module pitch adjustment resolution	mR	1
MAES module pitch angle stability thru measurement region	mR	0.2
Scanner dimensions		
Scanner slit-to-slit distance	mm	320
HV deflector plate length	mm	300
Minimum HV deflector plate width	mm	> 40
Gap between teeth on HV plates	mm	5.5 ±0.2*
Angle of the teeth surface on HV plates	degree	> 2
Teeth depth	mm	≤ 0.5
Front slit gap	mm	0.2
Rear slit gap	mm	0.2
Front slit/Rear slit/HV plates axial alignment	mm	< 0.2
Electric		
HV amplitude on each plate	kV	-1 to +1
Time Slice Resolution	µS	1

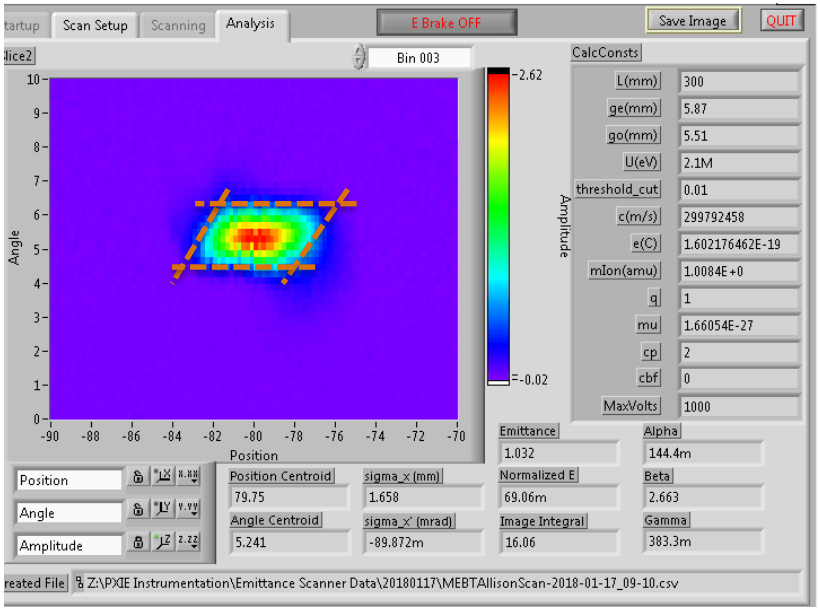
Allison Scanner Phase Portraits

- Scan slit position and voltage and measure intensity of each point
- Convert voltage to angle
- Generate y-y' phase portrait of the beam

Unscraped Beam



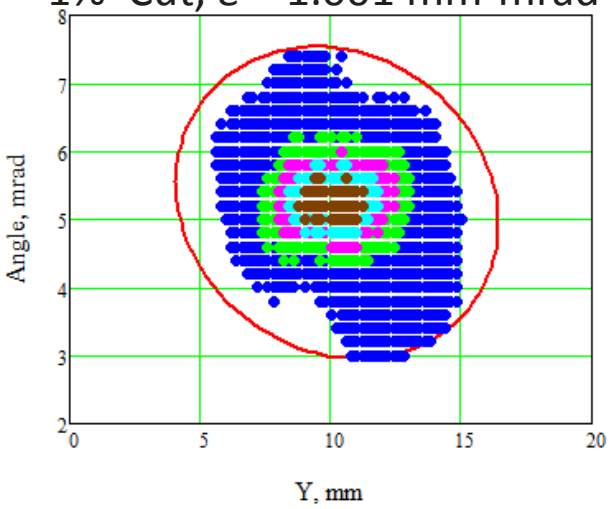
Scraped Beam

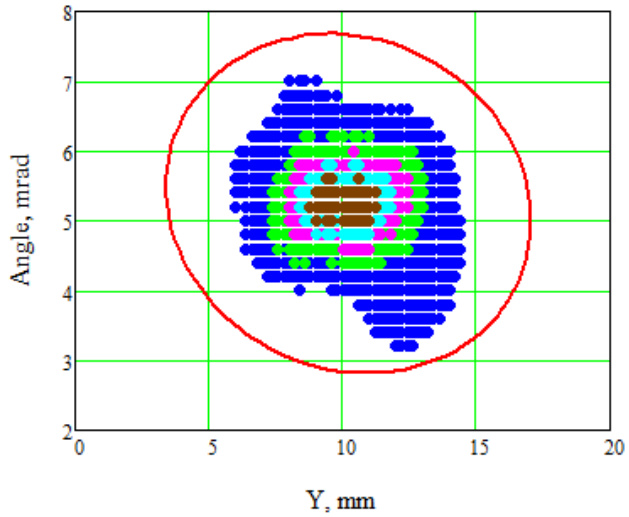


Cleaning Phase Portraits

- Current method:
  - Subtract mean noise
  - Set to zero all points below 1% of maximum intensity
  - Calculate RMS Twiss parameters
- Issue: 1% is arbitrary choice
  - If cut isn't large enough, noise will effect data
  - If cut is too large, will lose information about tails

1% Cut, ε = 1.001 mm-mrad





3% Cut, ε = 0.955 mm-mrad

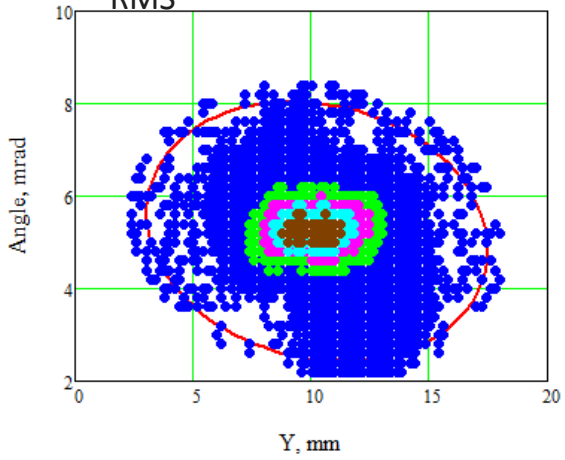
Beam with scraping, AS:
2018-01-17 14:27

Improvement to Phase Portrait Cleaning

- Possible method:
  - Subtract mean noise
  - Set to zero all points below $N_{noise}*\sigma_{noise}$
  - Remove all points outside of $N_{rms}*\varepsilon_{rms}$
  - Remove all points with no non-zero neighbors
- Calculate N_{noise} to remove most of noise pixels

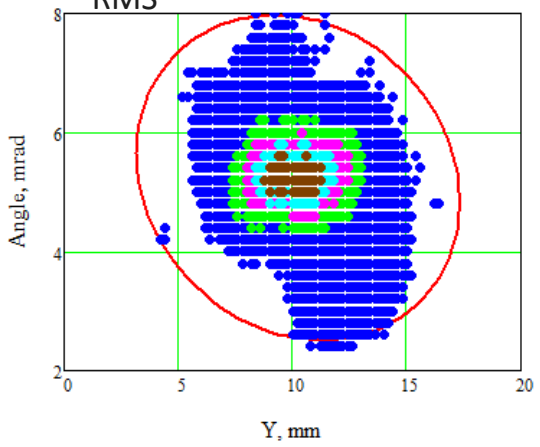
N_{noise} = 1, N_{rms} = 9

ε_{RMS}=1.113 mm-mrad



N_{noise} = 4, N_{rms} = 9

ε_{RMS}=1.061 mm-mrad



Beam with scraping,
AS: 2018-01-17 14:27

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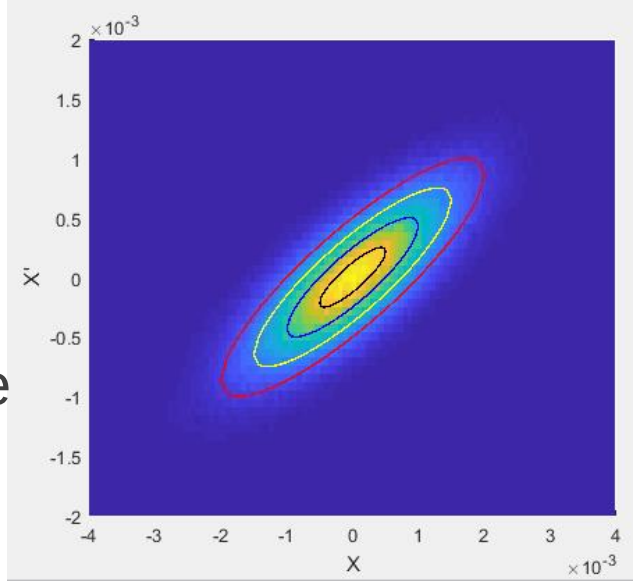
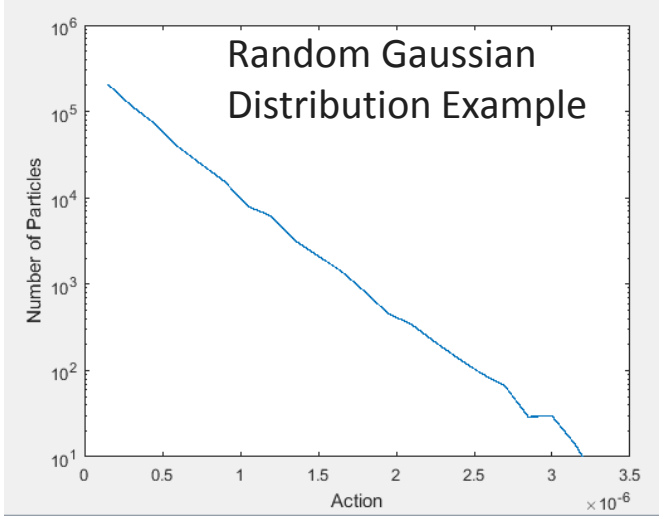
Action

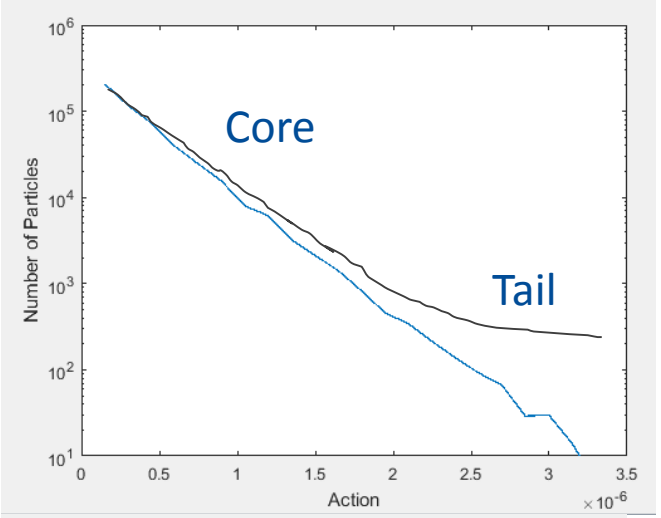
- Challenging to analyze tails from phase portraits
  - No clear distinction between core and tail
  - Tails may propagate differently than core
- Possible alternative: Action, angle
  - $J = \frac{1}{2}\left(\gamma x^2 + 2\alpha x x' + \beta x'^2\right)$
    α,ß,ɣ twiss parameters;
    x,x’ particle position and angle
  - Action of a particle is constant under linear optics
  - For gaussian beam, number of particles with given action is linear in semilog space

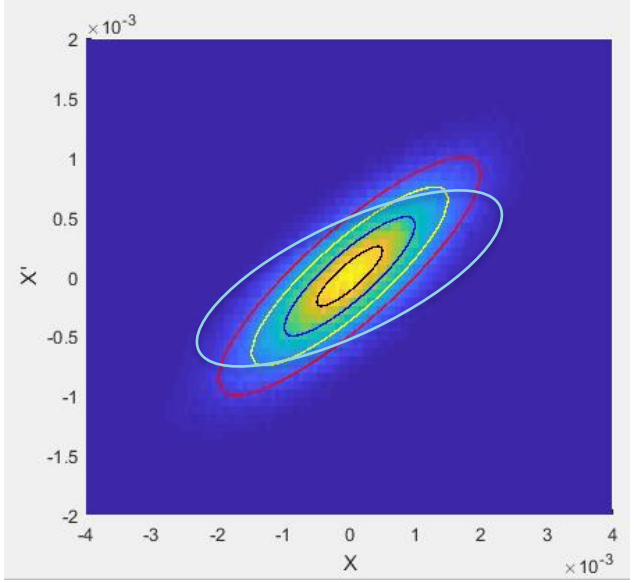




Action with Beam Tails

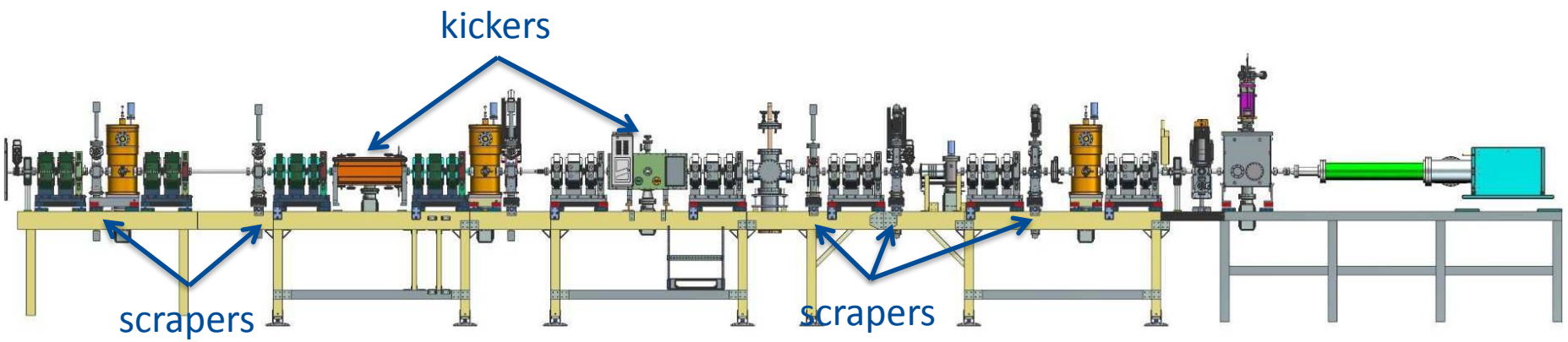
- Linear portion of action describes core, non-linear describes tails
  - Use scrapers to remove particles in the tail region
- Requires twiss parameters to describe beam core
  - RMS twiss parameters well defined, but will include tails
  - Tails will skew RMS Twiss parameters
  - Choice of how to cut out tails may affect action





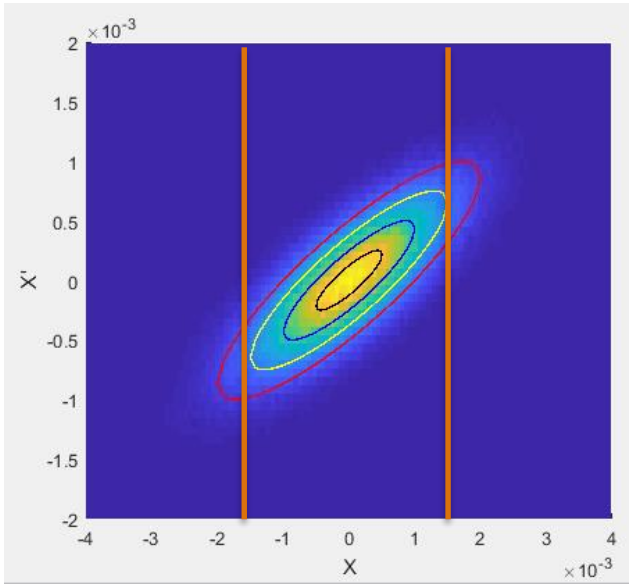
Tail Formation

- Transverse tail formation in PIP2IT
  - RFQ – due to non-linear effects
  - Kickers – due to rising and falling edge of kicking pulse
  - Space charge
  - Non-linear fields – field deviations of 1% at 80% of the pipe aperture
- Tails removed using scrapers at 4 locations



Tail Removal

- Removal of tail by removing of all particles with large action
- Performed with two sets of scrapers 90 degrees apart
  - First scraper removes particles with large offset, but not all with large action
  - After 90 degrees phase advance, particles with initially large action and smaller orbit now have large offset and can be scraped



Studies for Next PIP2IT Run

- Developing tool to quantify tails
  - Allows us to study formation and growth
- Possible studies in up coming run (Feb 19-Apr 12)
  - How do tails grow after scrapers?
  - How does space charge effect tail growth?
  - How much of an effect do the kickers have on tail formation
  - Study efficiency of scrapers for removing tails
  - Study size of tails we expect to inject into SRF

Outline

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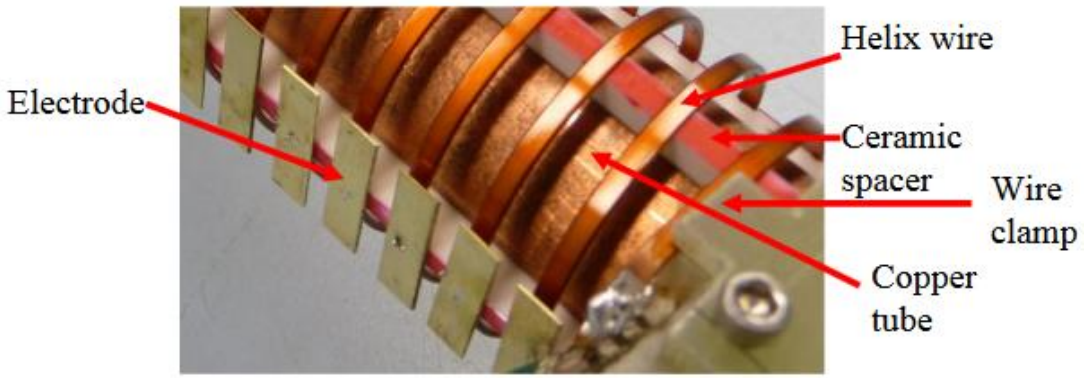
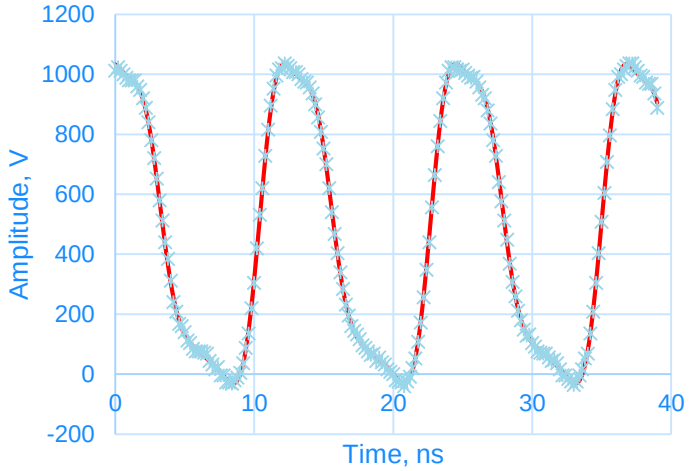
- Low energy beams
- Transverse tails
- 200 Ω kicker energy sensitivity
- Summary

200 Ohm Kicker

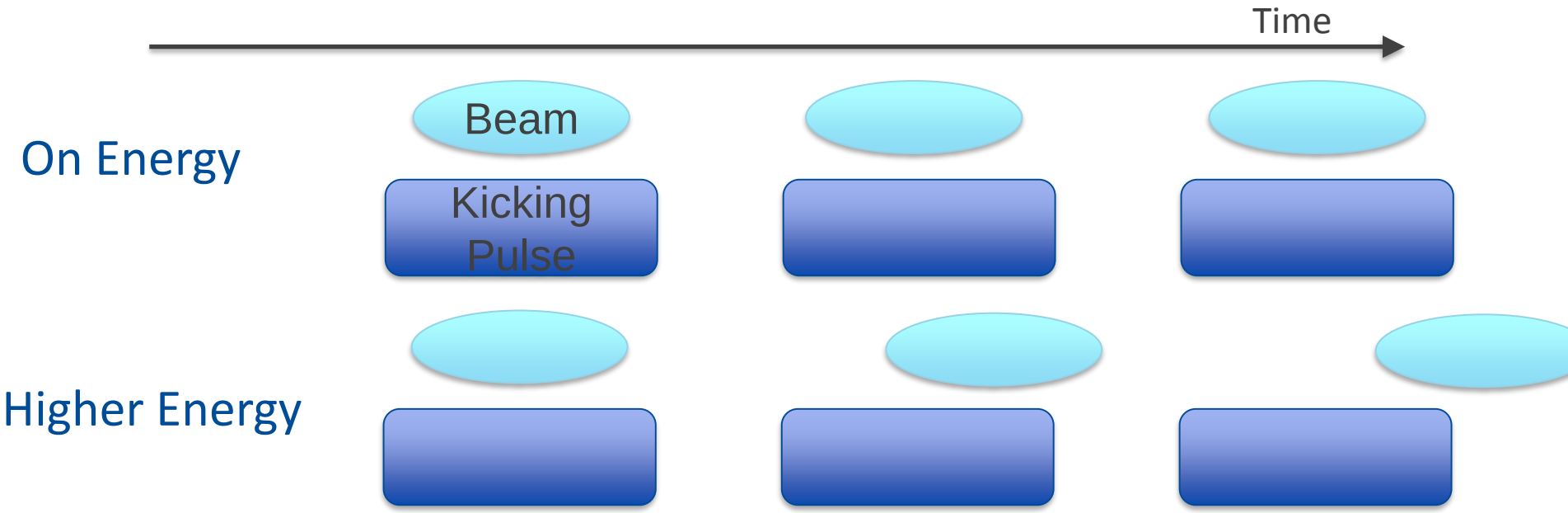
- PIP requires arbitrary kicked bunch pattern by removing bunches from 162.5 MHz bunch train
  - Requires fast kicking
  - Extinction ~10^-4
- Kick single bunch by slowing down kicking pulse with helix
  - Pulse travels with fixed velocity matching the beam velocity
- Beam: 20.1mm/ns, ToF across kicker = 24.8ns, typical RMS bunch length = 0.2ns





Off Energy Kicking

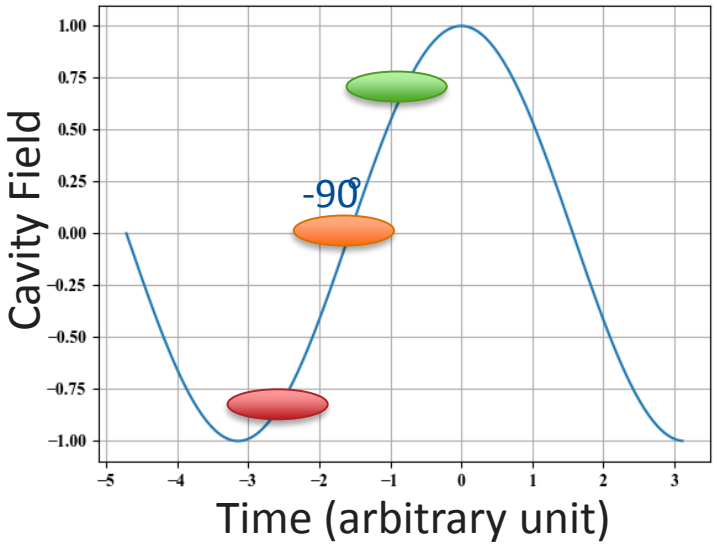
- If beam travels with different velocity than the kicking pulse it will slip past
  - The slip causes a reduction in kicking
- How much of an effect does beam energy have on kicking efficiency?

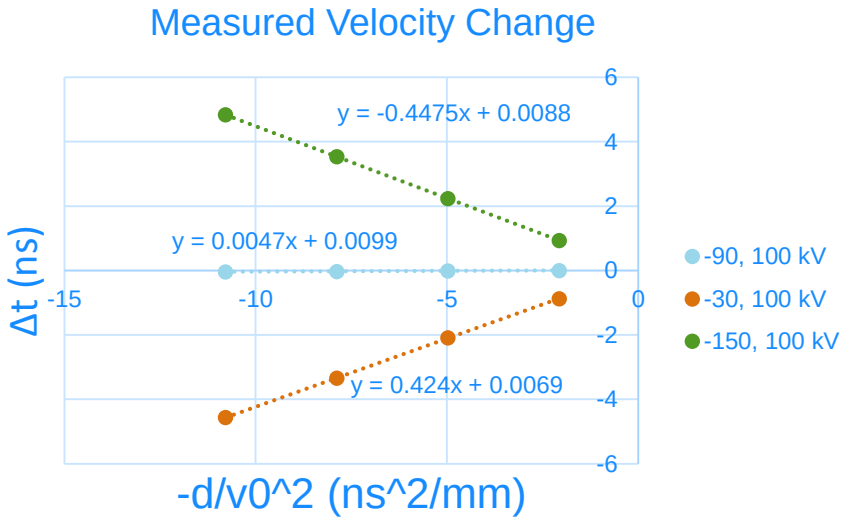


Changing beam energy

- Vary buncher cavity phase
  - Define -90° as max focus, no acceleration
- Energy change calculated with BPMs
  - Use change in BPM phase to calculate change in time of flight
  - Can only measure relative changes

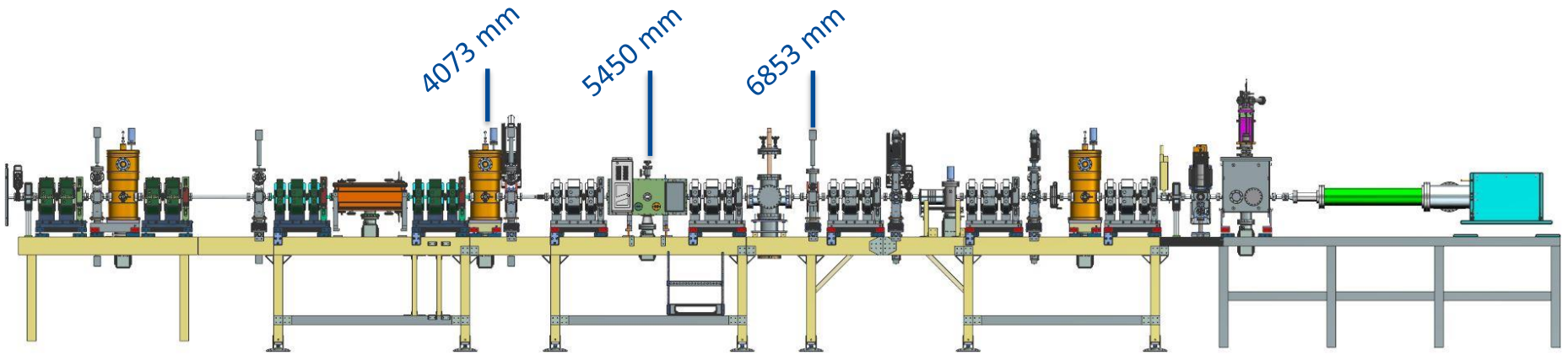
$$\Delta t = -\Delta v \frac{d}{v^2}$$





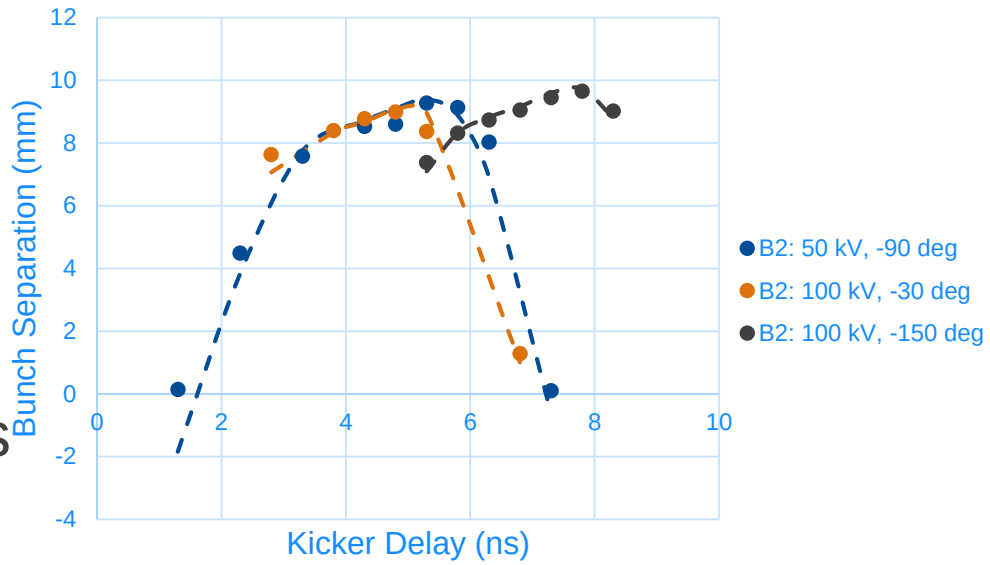
200 Ohm Kicker Test

- Procedure, 1/17/2018 AM Shift
  - Used three buncher cavity phase setting to vary beam energy
    - -150̊ 100 kV, -90̊ 50 kV, -30̊ 100 kV
    - Change voltage to keep bunch length constant
  - Kick every other bunch with 200 Ω kicker
  - Measure bunch separation with scraper



Bunch Separation Fitting

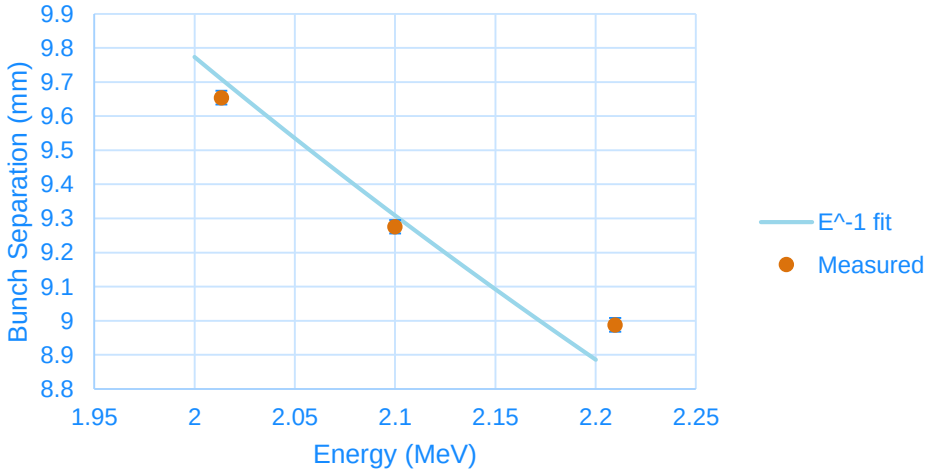
- Adjust delay of kicker pulse to maximize bunch separation
- Fit bunch separation to kicker waveform
- Expected max separations to be approximately evenly spaced



Phase (deg)	Energy (MeV)	ToF to Kicker calc (ns)	ToF Difference from -90	Measured difference
-90	2.100	68.51		
-30	2.187	67.40	-1.11	-0.5
-150	2.013	70.26	1.75	2.5

Energy Sensitivity

- Decreasing bunch separation with energy
- Simple no-slip model: bunch travels through a constant electric field
  - $kick \approx \frac{qVd}{4E}$, q:charge, V=voltage, d= plate separation, E=beam energy
- Preliminary conclusion: Kicking pulse is long enough compared to bunch length to ignore slip



Summary

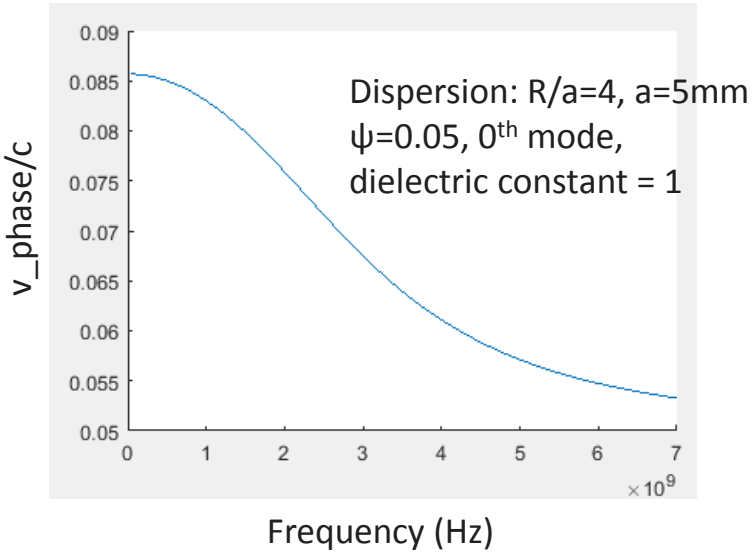
- Work at Fermilab to familiarize with beam instrumentation
  - Experimental portion of thesis on low energy beams
- Studies while at Fermilab
  - Primary study: Investigate transverse tails
    - Clean Allison scanner images
    - Develop action language of describing beam tails
    - Measure tail removal and formation
  - Characterize the sensitivity of the kickers to energy changes
    - Off velocity effects appear to be small
    - Perform study on 50 Ohm kicker

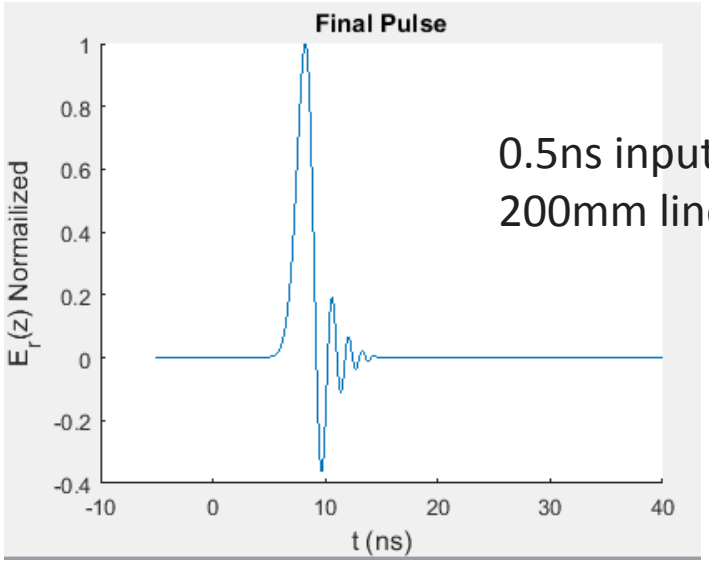
Estimate Ph.D Timeline

- 2018: Experimental studies at Fermilab
- 2019: Finish research at Michigan State
  - Finishing work stated at MSU
  - Wrapping up studies done at Fermilab
- 2020: Writing an defending thesis

Helical Pulse Line for BPM Calibration

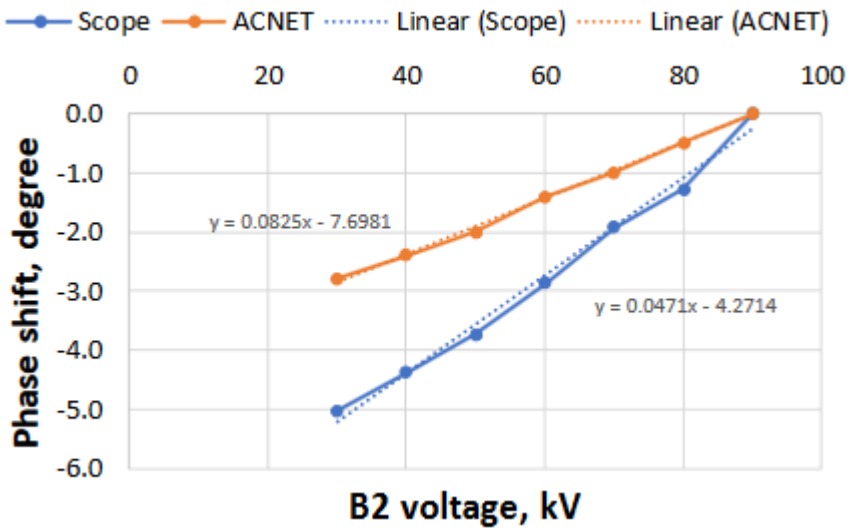
- Calibrate for low energy effects in BPMs by propagating pulse at beam velocity
- Low pulse velocities achieved using helical line
- Issue: dispersion creates dramatic signal deformation
- Issue: effects wrapping helix around dielectric core



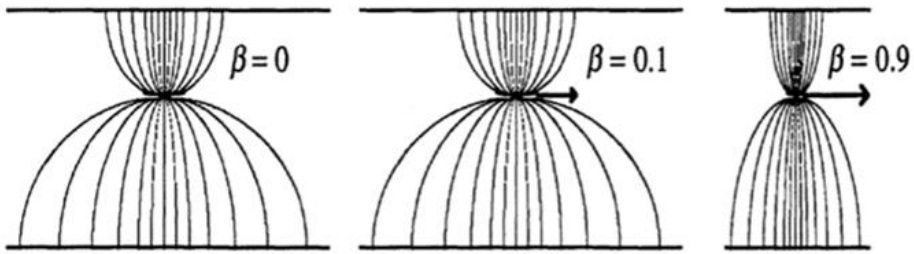


Beam Position Monitors

- Issue: digitizer at lower frequency than measured by BPM
  - Causing the phase measurements to differ from measured with scope
- Issue: Low energy beam affects measured signal
  - Different frequency spectra on opposite buttons

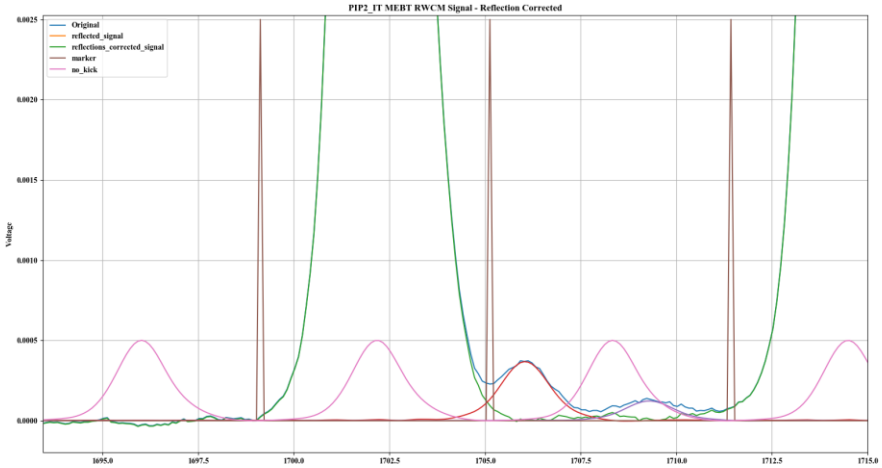


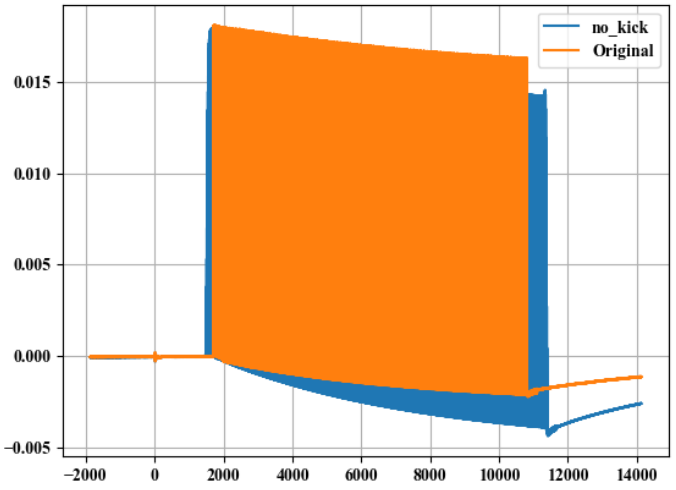
V. Scarpine, PIP2 Technical Meeting, 2018-1-16



Resistive Wall Current Monitor

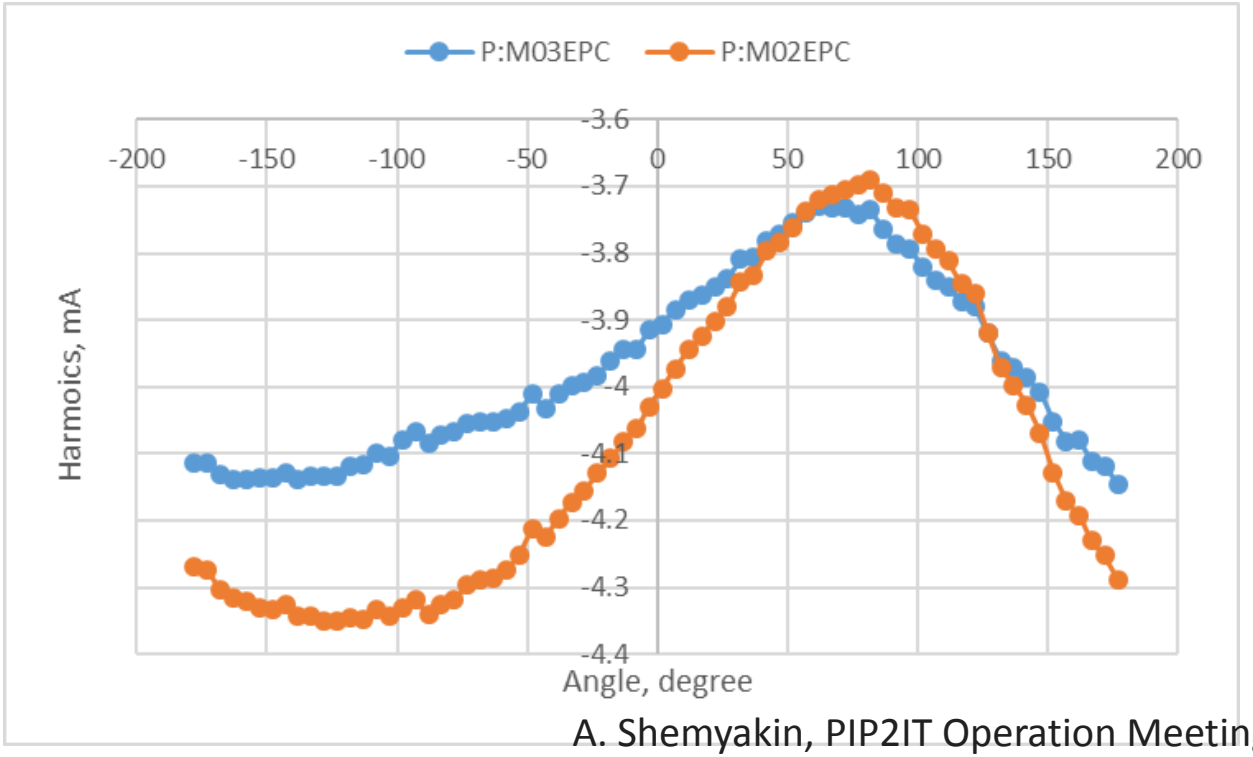
- Used to measure kicked bunch extinction
  - Required level 10^-4, measured level ~10^-3
- Issues: reflections, dispersion, non-flat fields, signal droop





Ring Pick Ups

- Cylindrical electrode, measures 1st and 3rd harmonic of 162.5MHz
- Use to measure beam current
- Signals is dependent on beam energy and bunch length



A. Shemyakin, PIP2IT Operation Meeting, 2017-4-21