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Possible bunch compression experiments at the SNS

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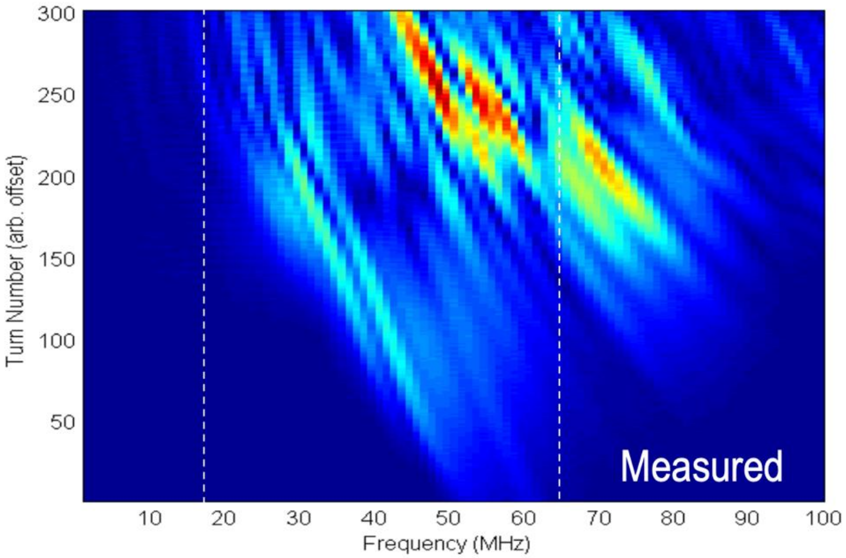
WP3 Proton Complex Meeting

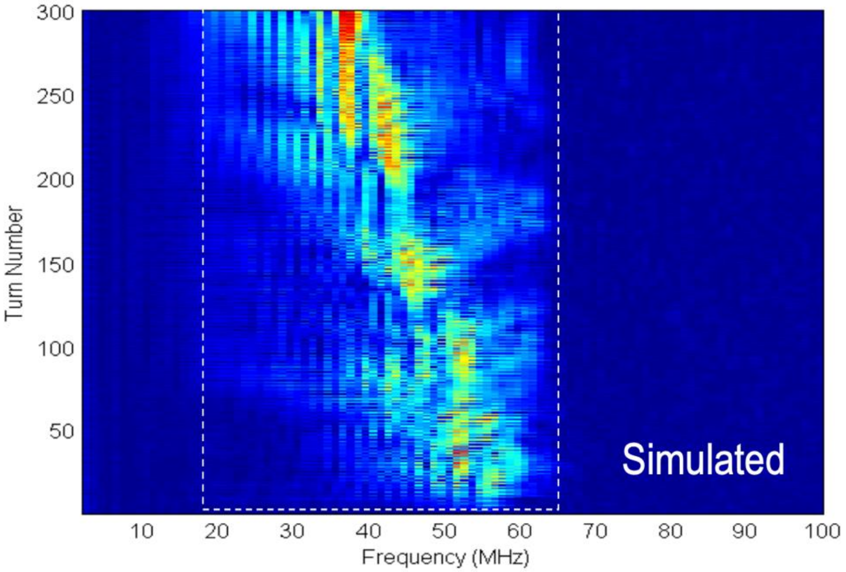
January 31, 2025

Motivation #1: Experimentally study collective effects at high charge density

- Space charge, halo formation, wake fields, electron cloud
- Mitigation techniques (phase space painting)

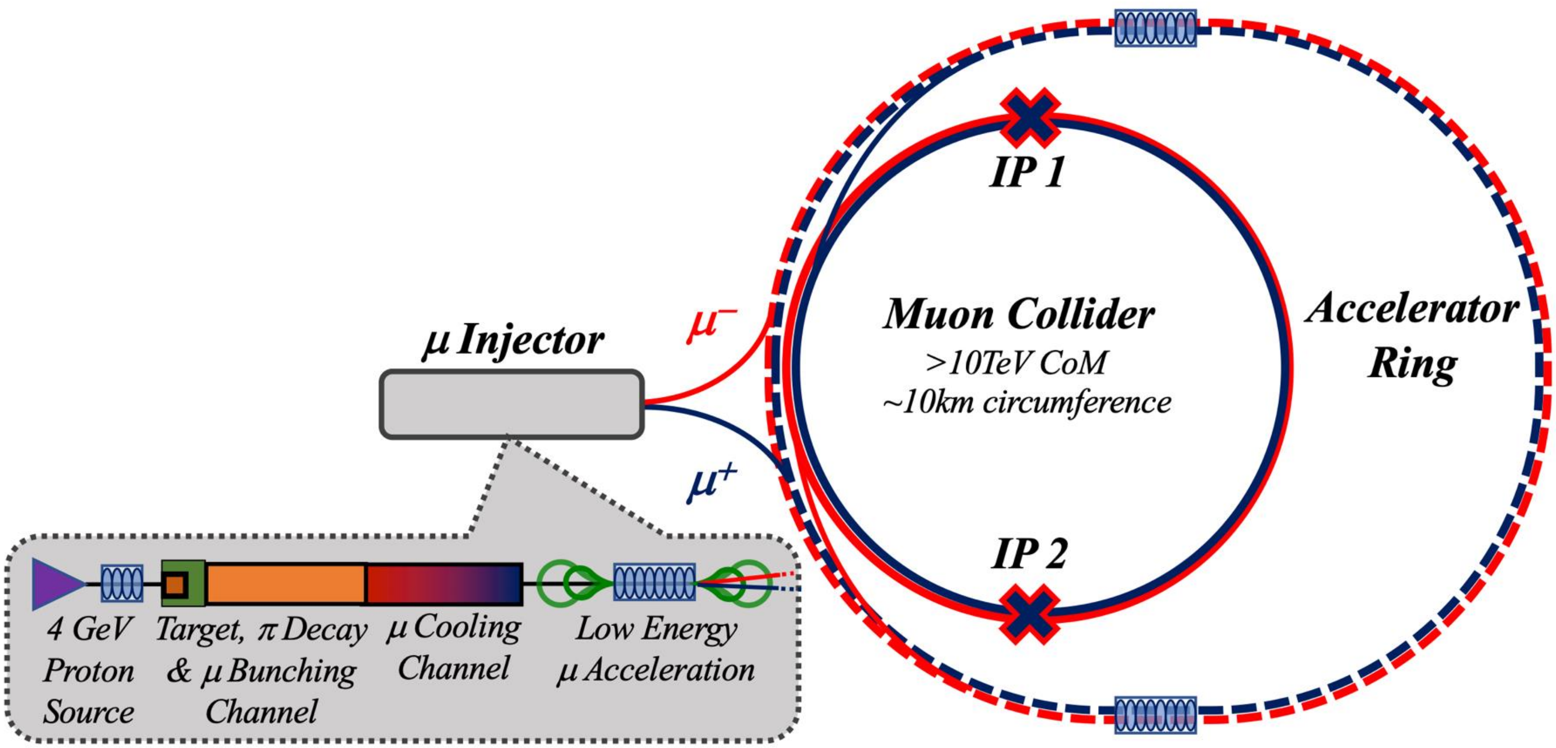
Motivation #2: Benchmark simulation codes





Cousineau et al., ECLOUD 2007

Motivation #3: Contribute to muon collider R&D



https://arxiv.org/abs/2303.08533

Motivation #3: Contribute to muon collider R&D

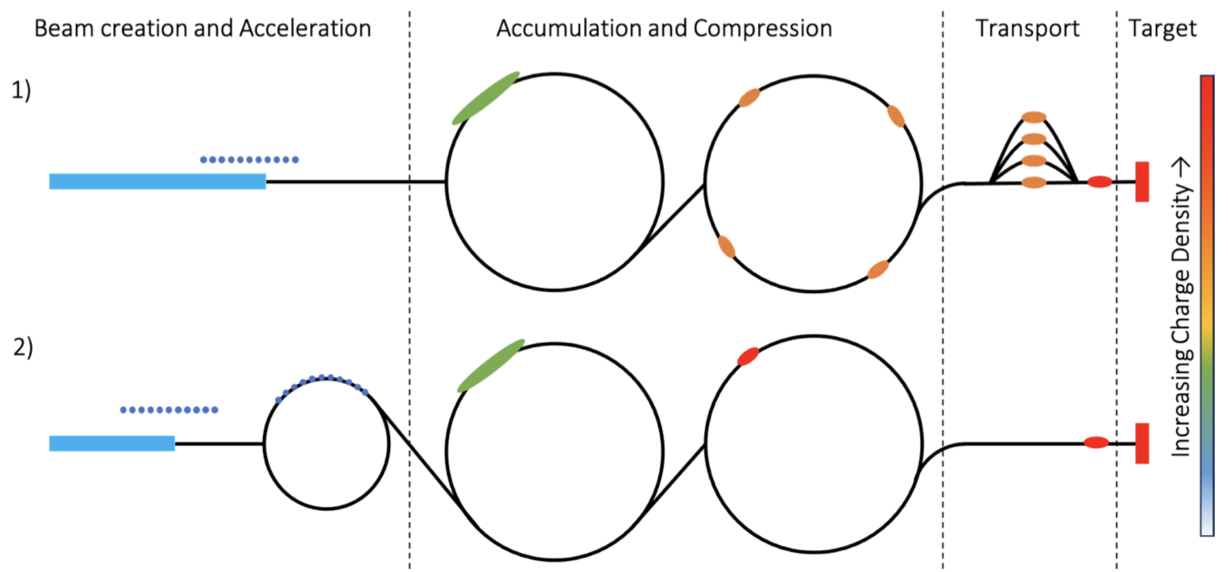
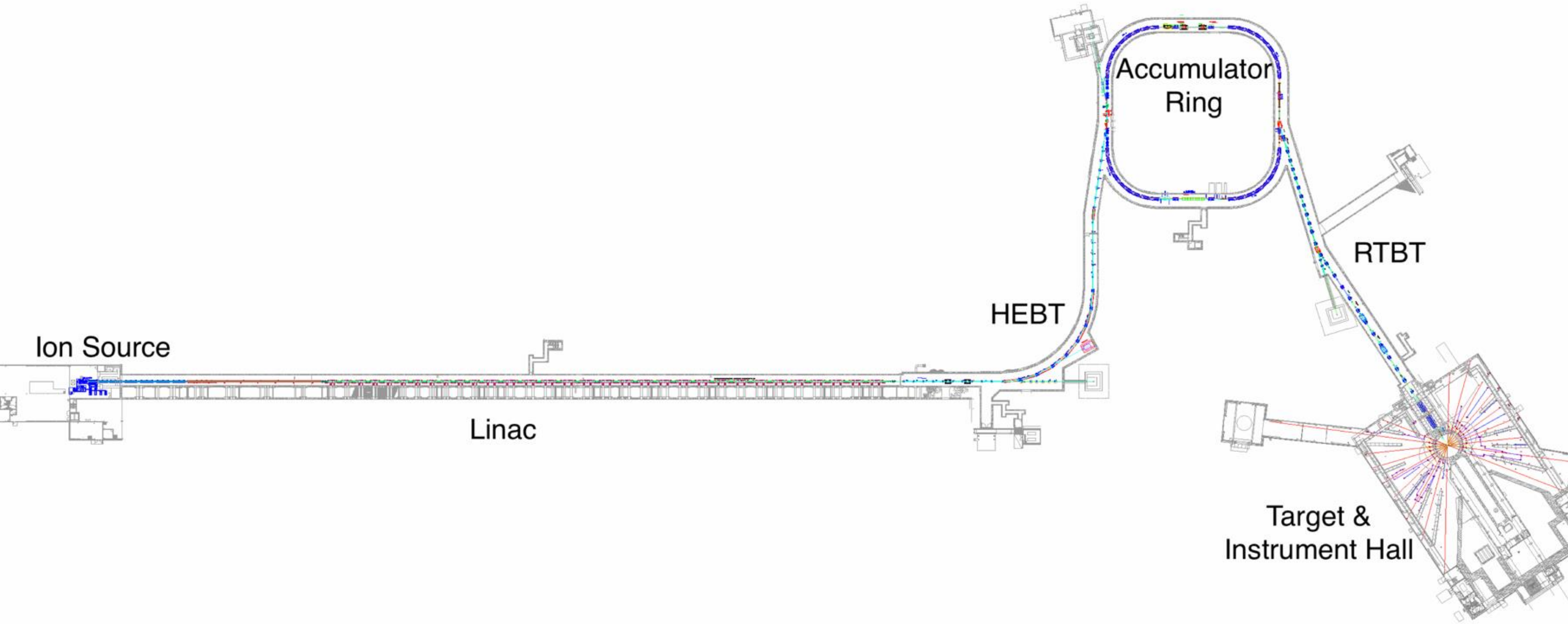
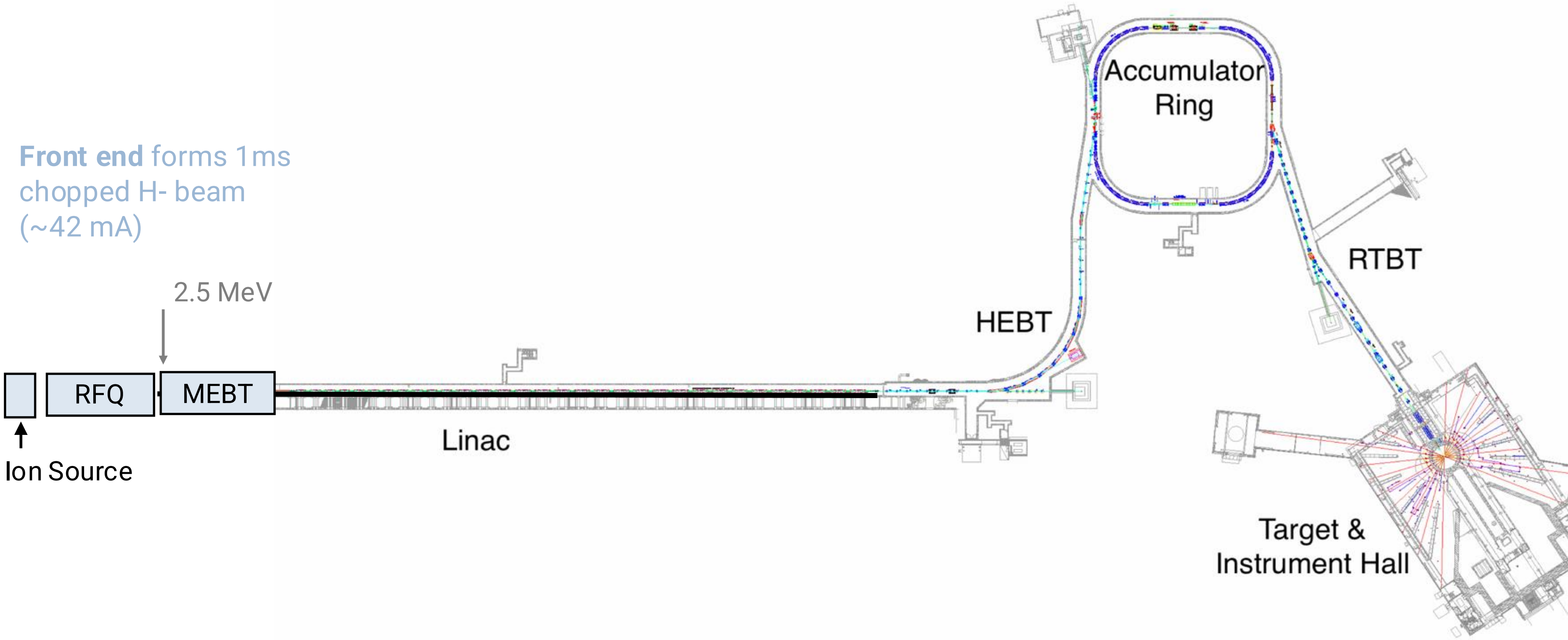


Fig. 5.1: Schematic layouts for the proton complex section. Our baseline design is the schematic 1 on the figure. The bunch density as the proton travels thought the complex is also depicted. The closer to the target the highest the bunch charge density and at the point where is collides with the target. To reach high densities is one the the main challenges in the design of the part of the muon collider.

Overview of the SNS accelerator

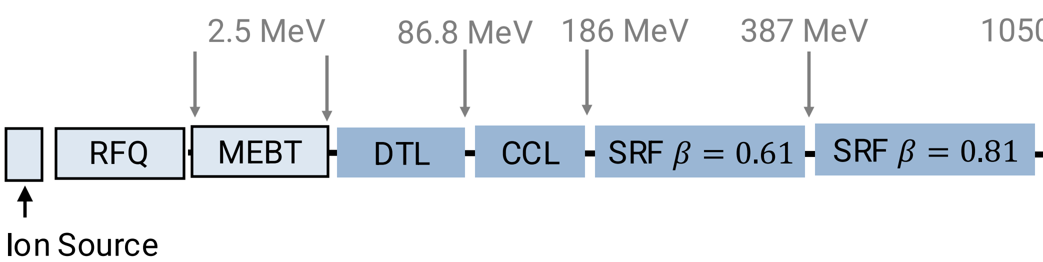

Accumulator
Ring
RTBT
HEBT
Ion Source
Linac
Target &
Instrument Hall

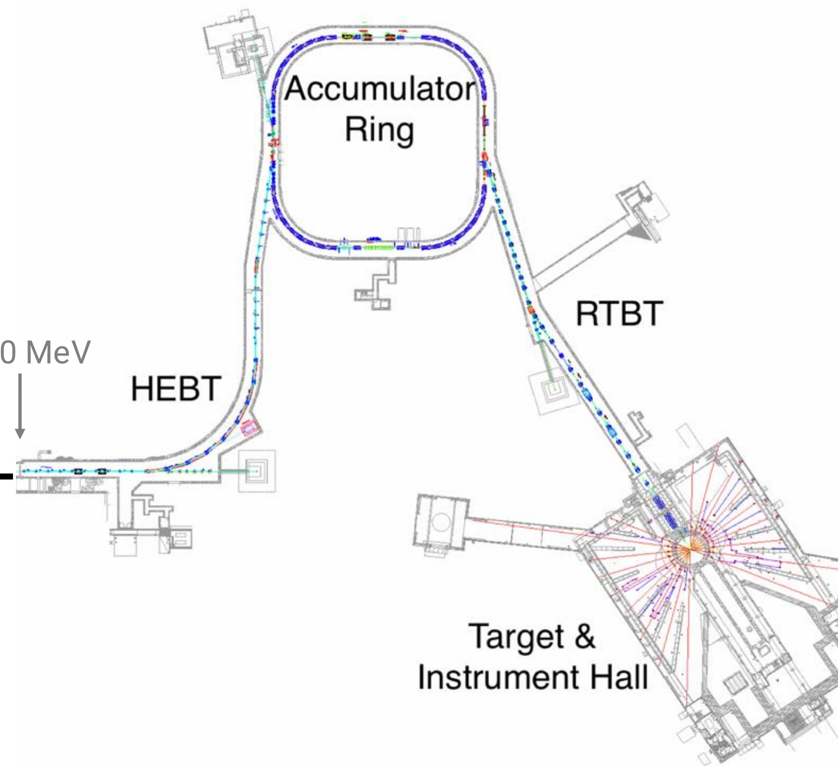
Front end forms 1ms chopped H- beam (~42 mA)



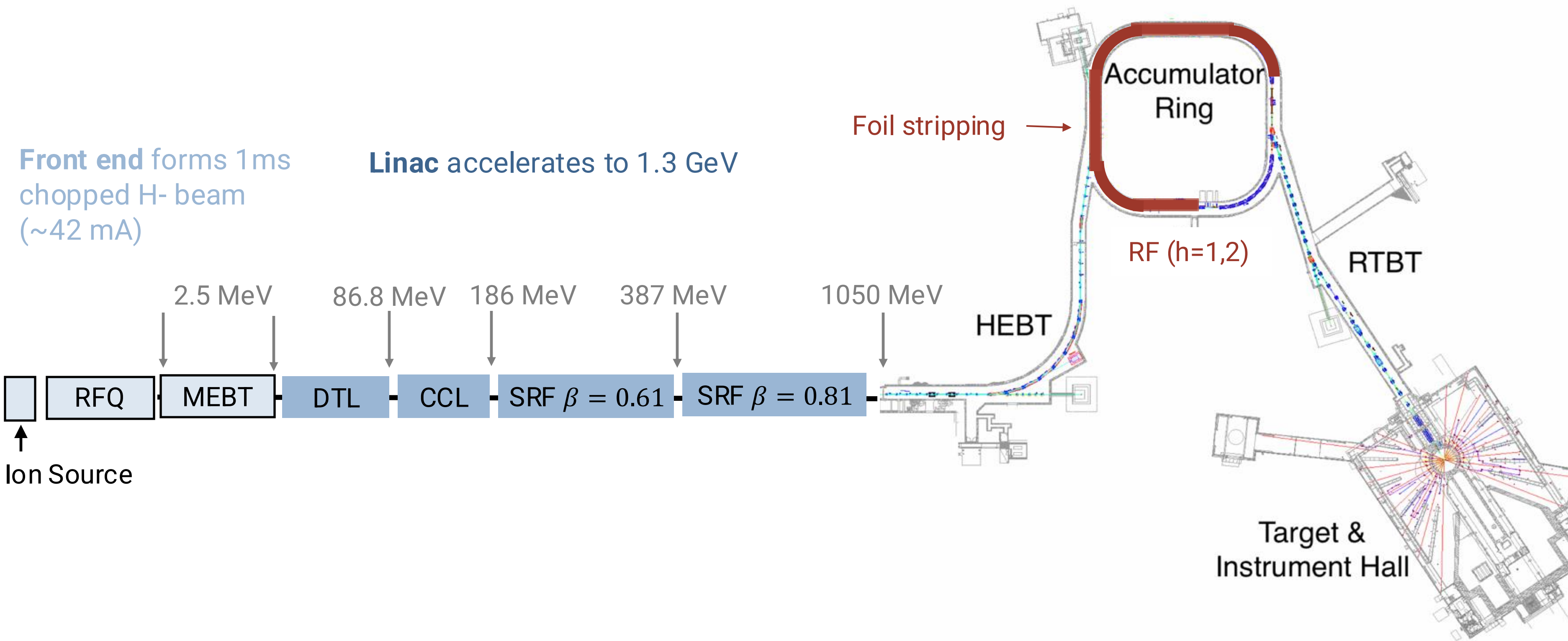
Front end forms 1ms chopped H- beam (~42 mA)

Linac accelerates to 1.3 GeV





Accumulator ring compresses 1 ms pulse to 700 ns



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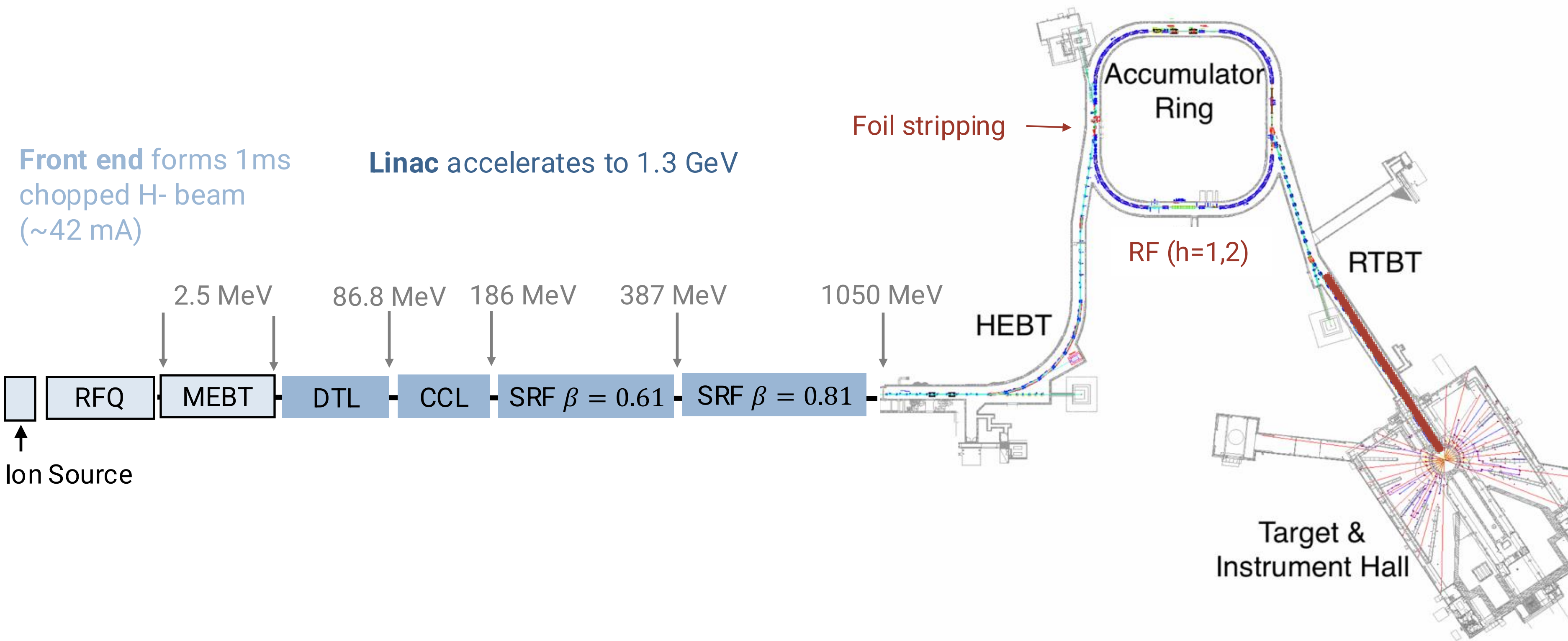
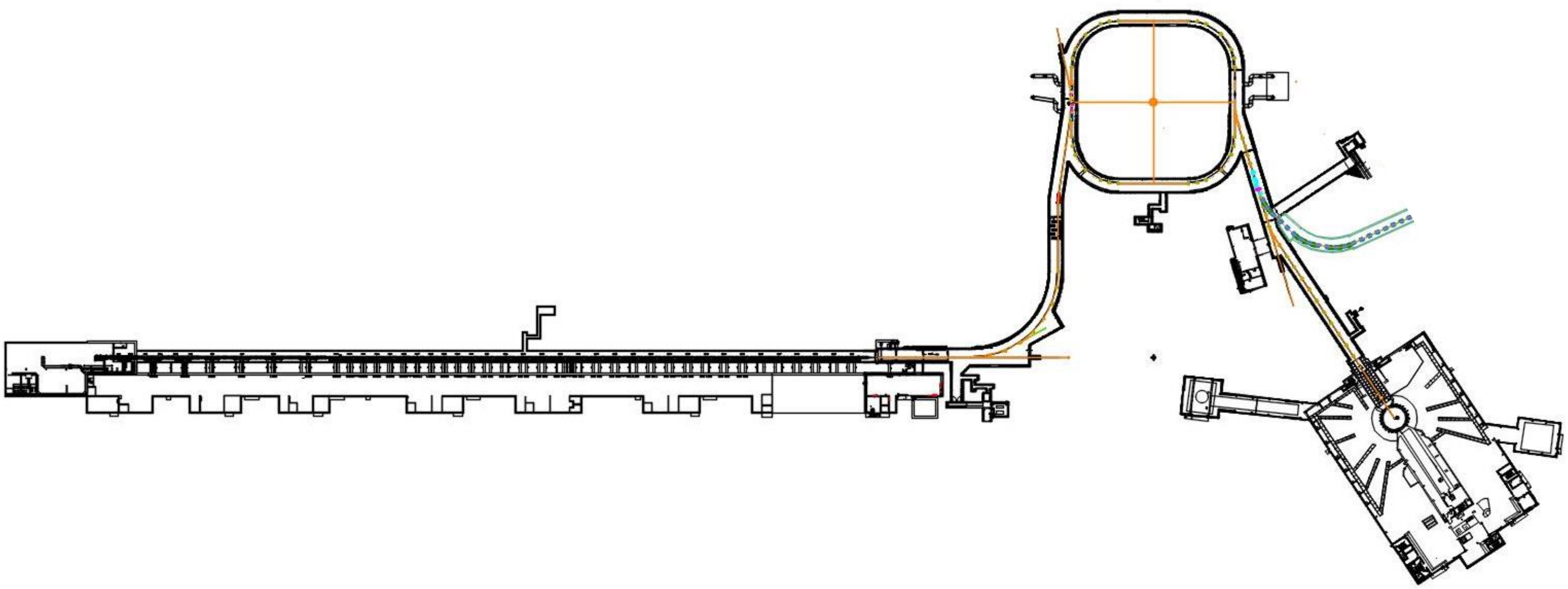


SNS today

650 ns pulse

1.55×10^{14} protons

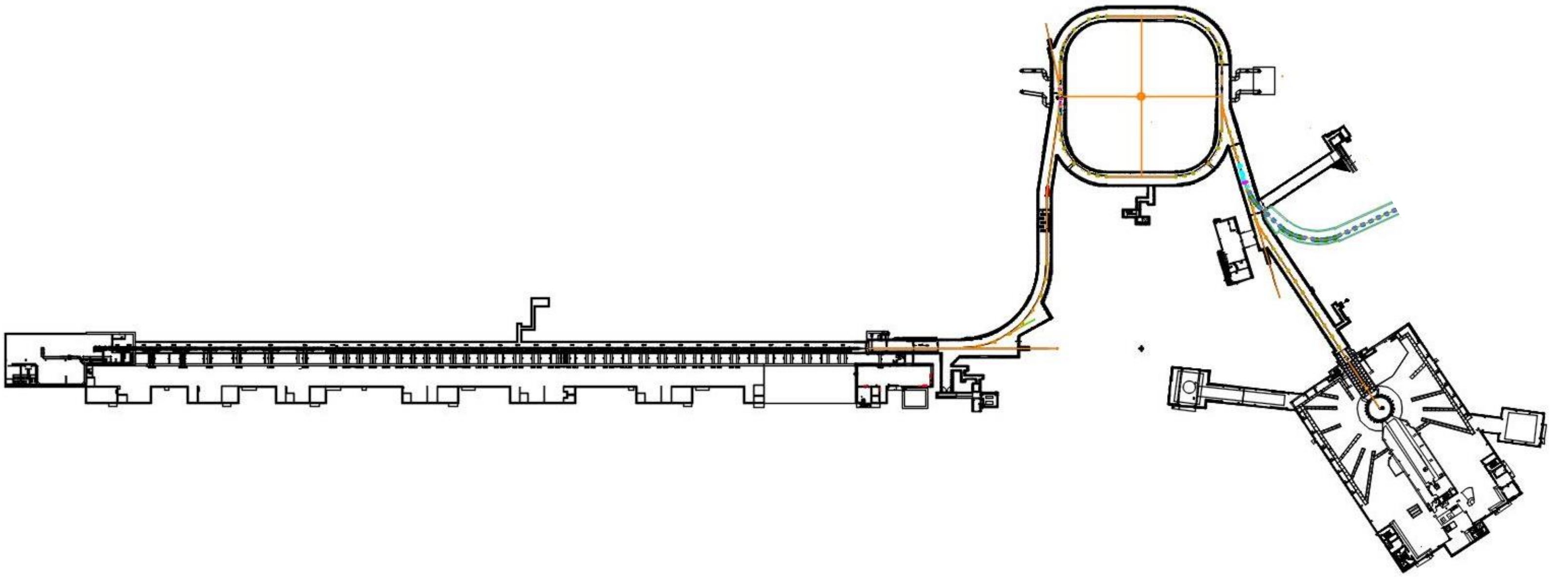


1.7 MW @ 60 Hz

SNS in a couple years (slow power ramp-up)

650 ns pulse

2.25×10^{14} protons



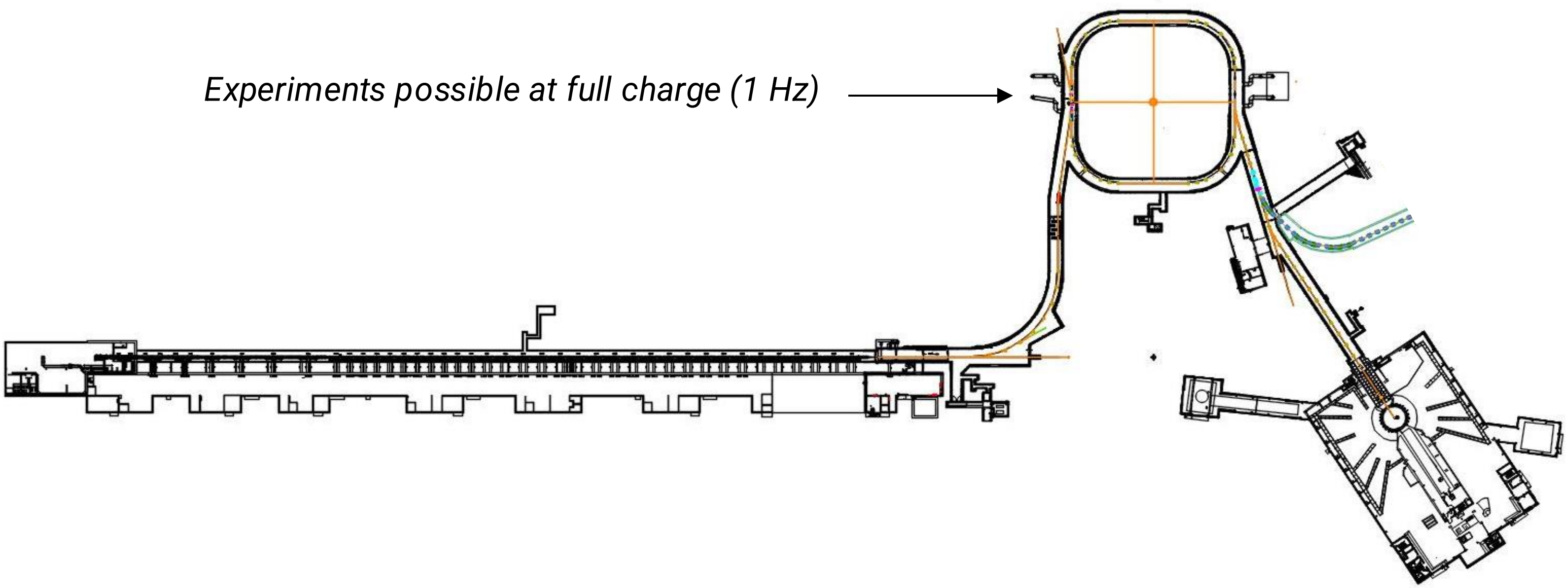
2.8 MW @ 60 Hz (capable)
2.0 MW @ 60 Hz (target limit)

SNS in a couple years (slow power ramp-up)

650 ns pulse

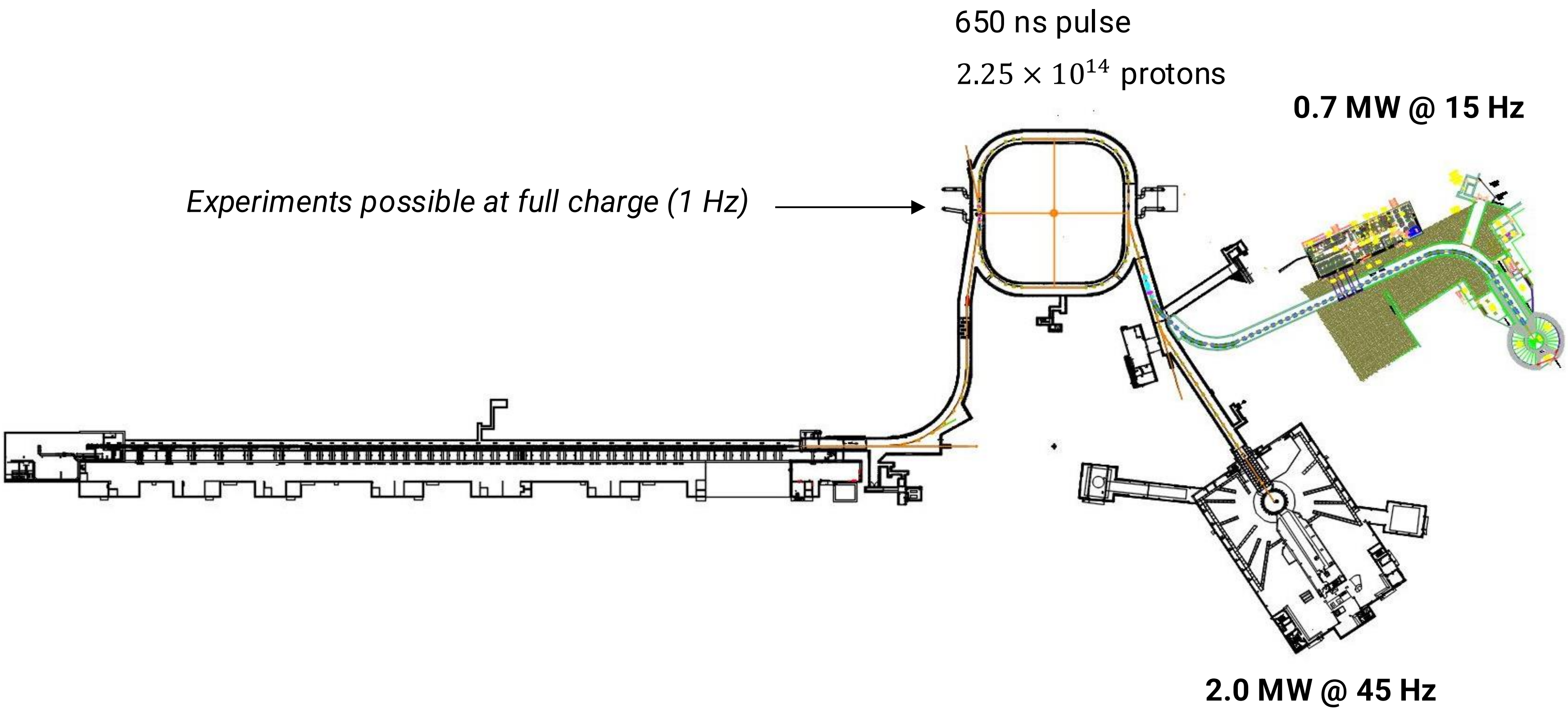
2.25×10^{14} protons

Experiments possible at full charge (1 Hz)

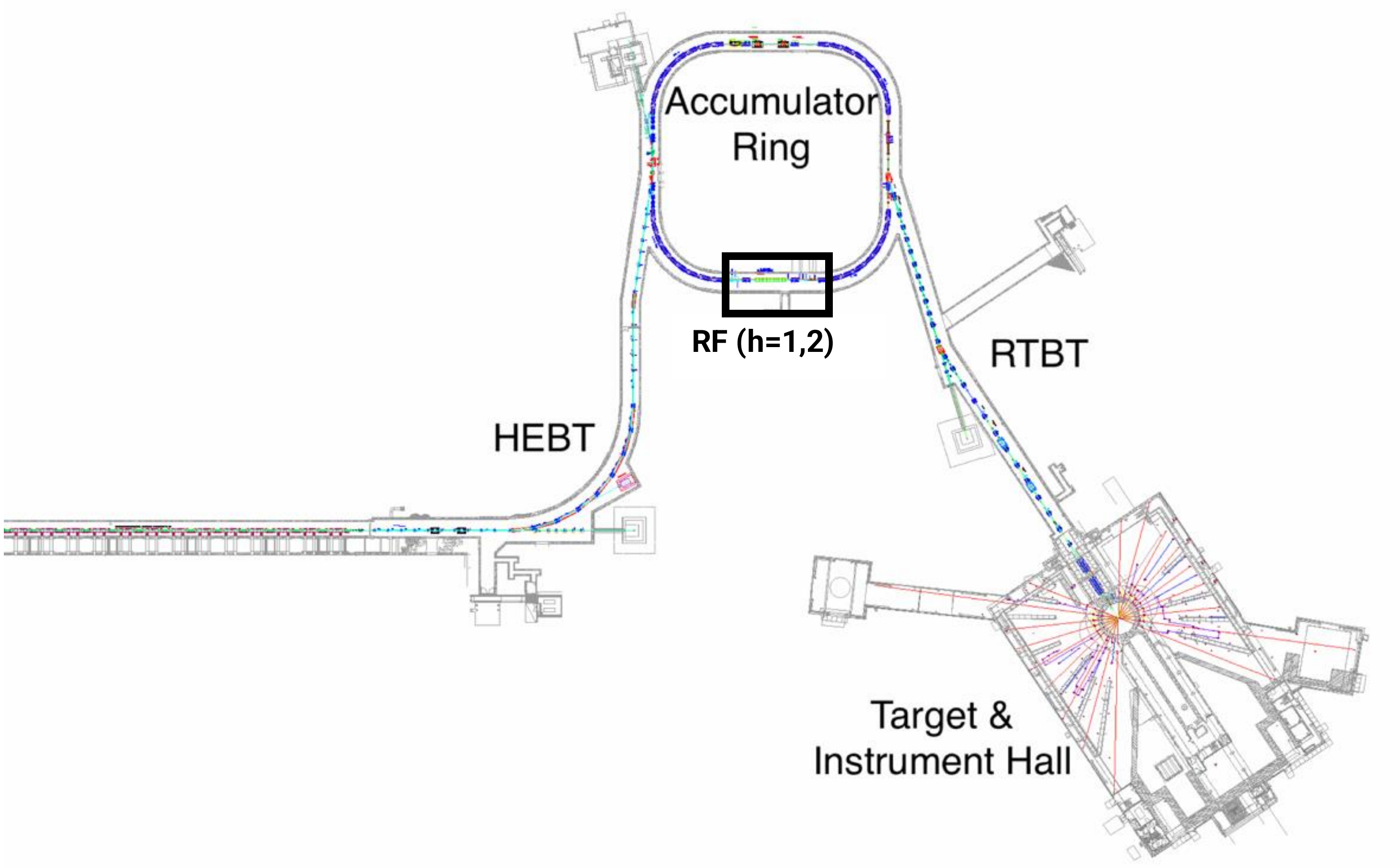


2.8 MW @ 60 Hz (capable)
2.0 MW @ 60 Hz (target limit)

SNS in 10-15 years (Second Target Station)

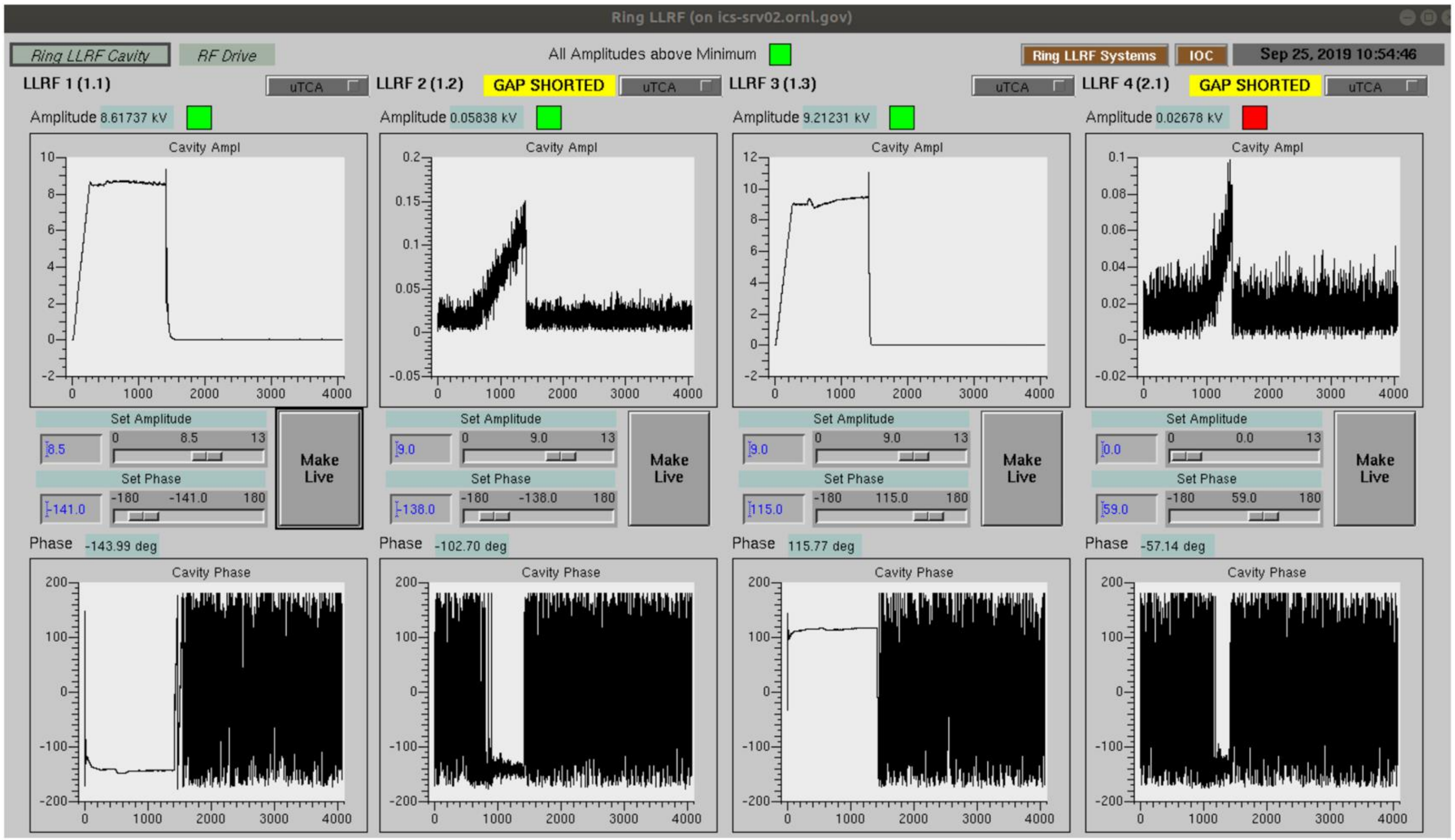


SNS ring has four RF cavities (h=1, h=2)



Only two cavities are used in production

Primary Operations Ring LLRF EPICS screen (1.0 MW beam, 9/25/2019):



Dual-harmonic waveforms reduce peak density

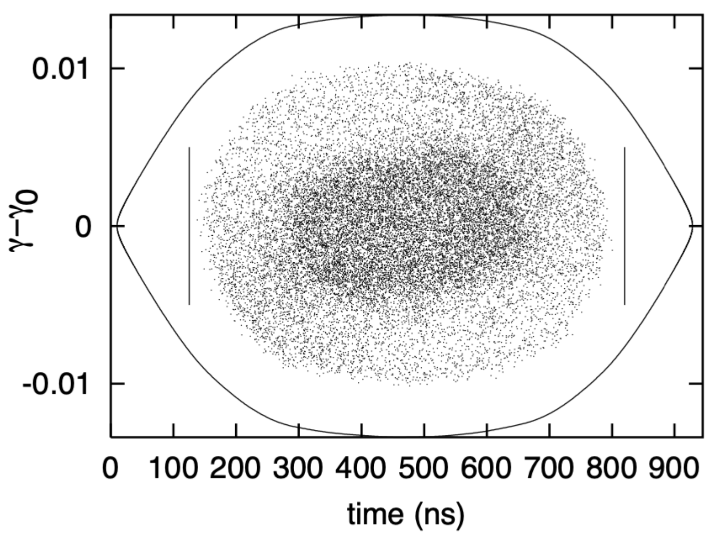


Figure 3: Phase space distribution and bucket at extraction for nominal design.

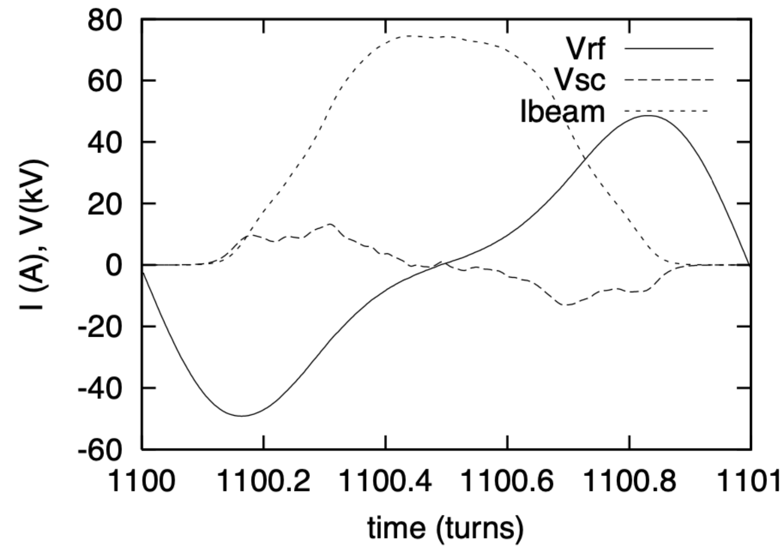
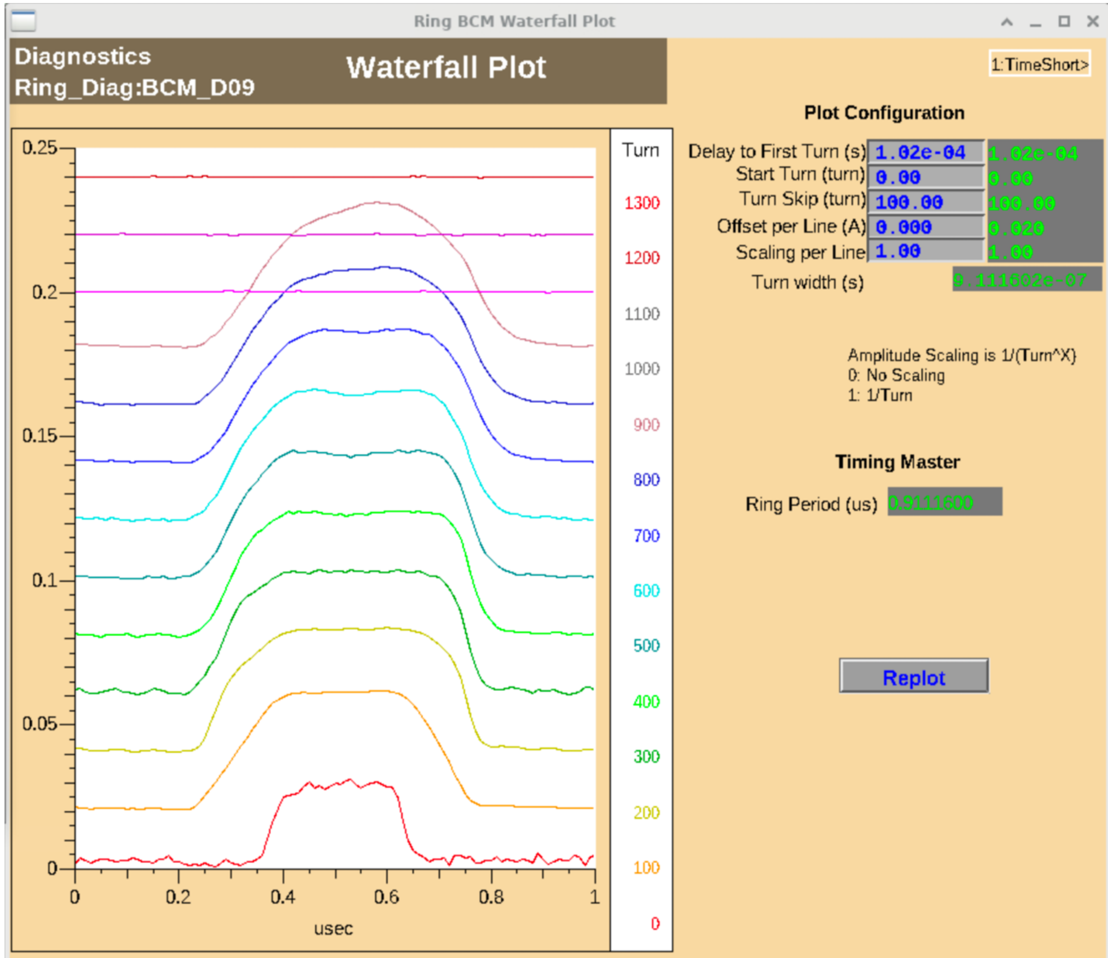


Figure 4: Currents and voltages at extraction for nominal design. The binned current, convolved with a 50ns smoothing pulse, is shown.


Ring BCM Waterfall Plot
Diagnostics
Ring_Diag:BCM_D09
Waterfall Plot
1:TimeShort>
Plot Configuration
Delay to First Turn (s) 1.02e-04 1.02e-04
Start Turn (turn) 0.00 0.00
Turn Skip (turn) 100.00 100.00
Offset per Line (A) 0.000 0.020
Scaling per Line 1.00 1.00
Turn width (s) 9.111602e-07
Amplitude Scaling is 1/(Turn^X)
0: No Scaling
1: 1/Turn
Timing Master
Ring Period (us) 0.9111600
Replot
Turn
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
usec

Could we compress the bunch in the SNS accumulator ring?

We do not have a separate compressor ring

- Stage 1: accumulation (~1000 turns)
- Stage 2: storage + compression (h=1 cavity)
- Cavity waveforms must change immediately after accumulation

Goal during **storage**: ramp h=1 cavity to maximum voltage as fast as possible

- Maximum voltage ~20 kV using two cavities
- Voltage ramp duration ~200 turns
- Synchrotron period ~ 2000 turns at 1.3 GeV

Goal during **accumulation**: minimize energy spread and maintain extraction gap

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- Option 1: production waveforms

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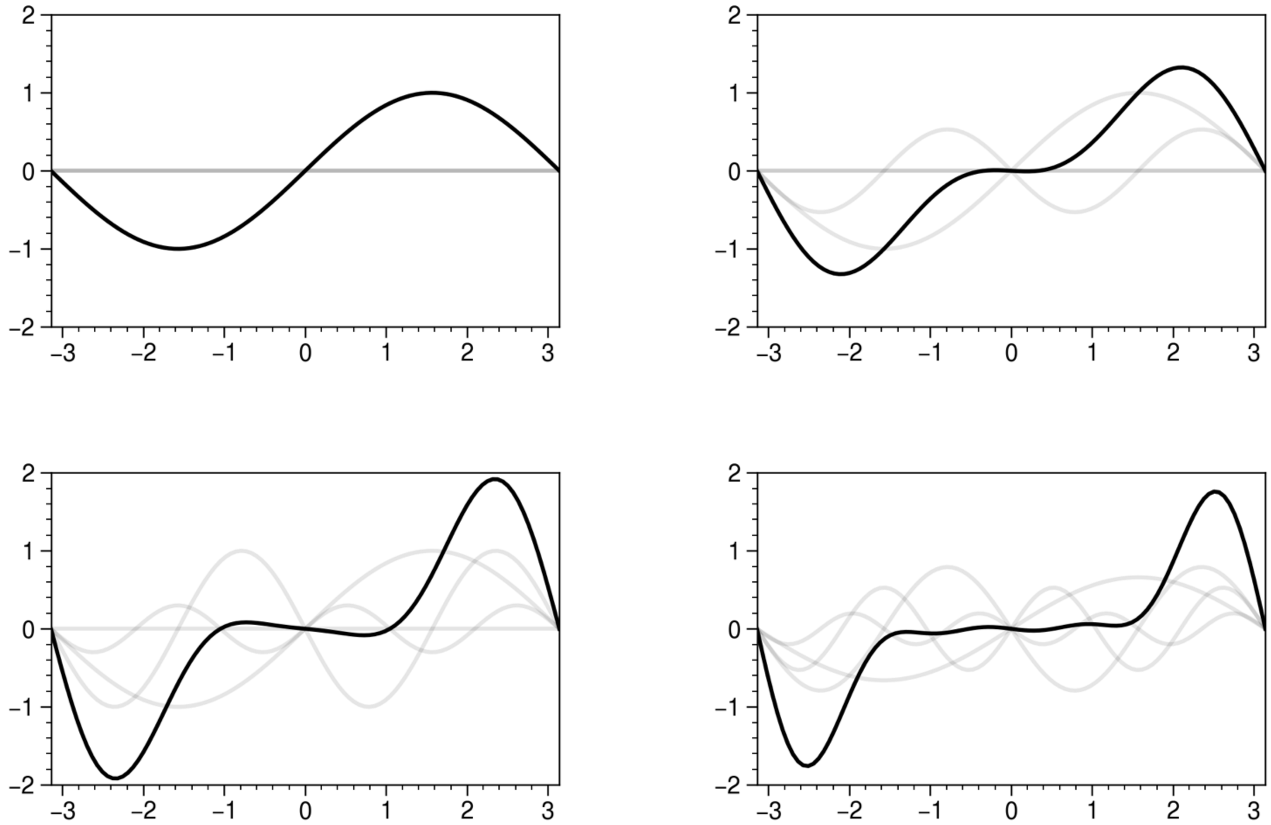
- Option 2: use additional harmonics to approximate barrier waveform (square well)

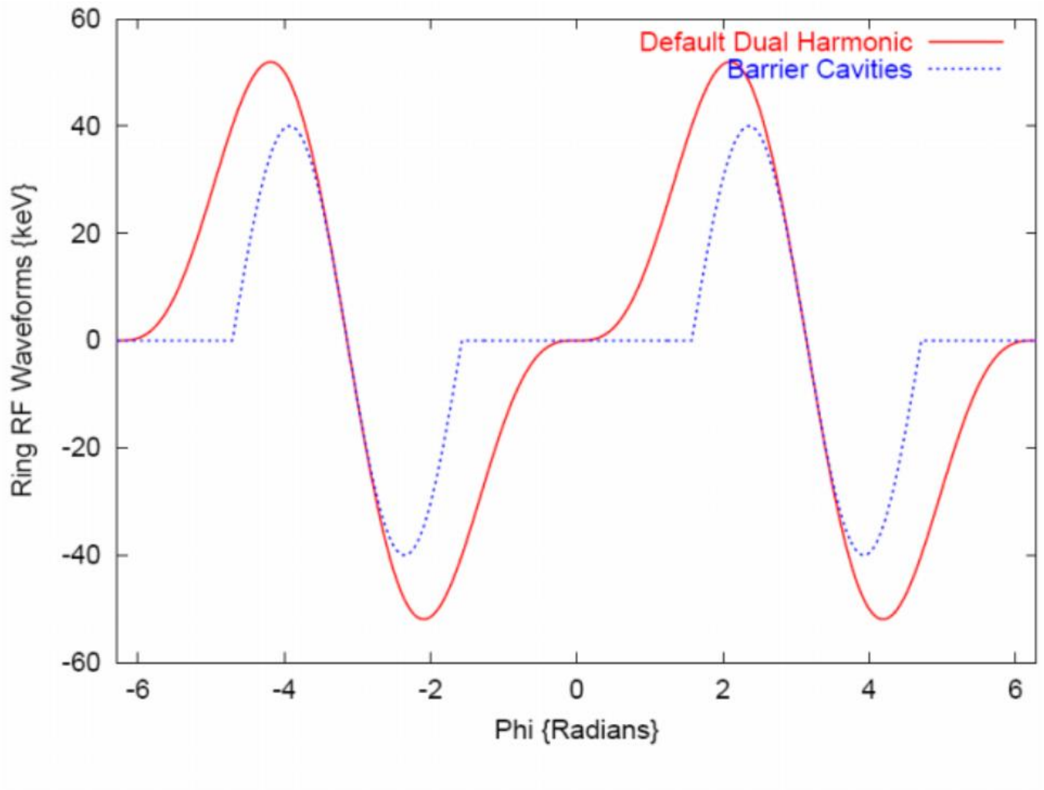
Goal during **accumulation**: minimize energy spread and maintain extraction gap

- Option 1: production waveforms
- Option 2: use additional harmonics to approximate barrier waveform (square well)
- Option 3: turn off cavities

We've never tried operating cavities at higher harmonics — should be possible

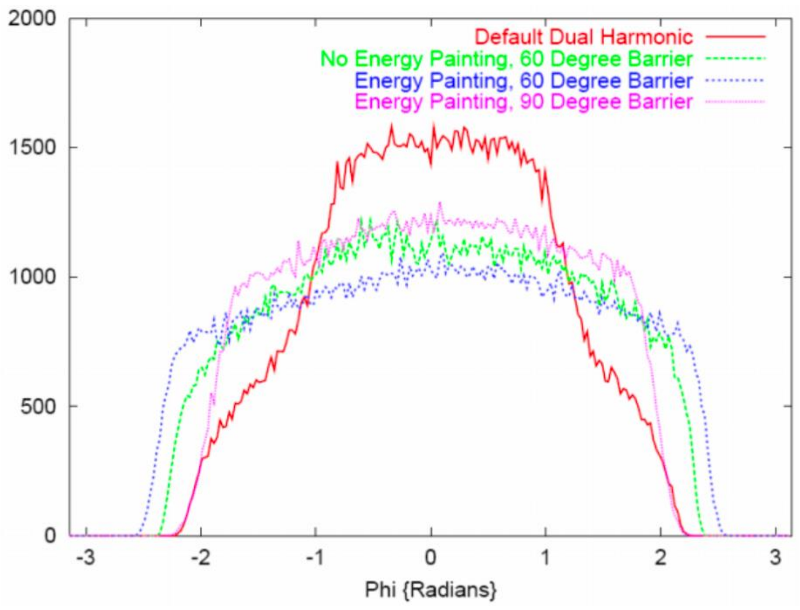


Old simulations show influence of barrier waveforms on longitudinal distribution

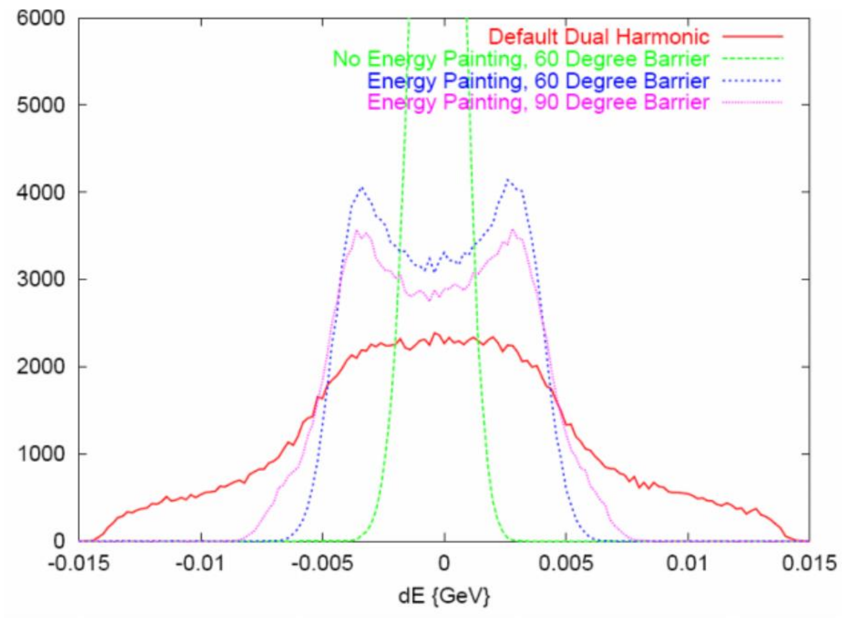


Old simulations show influence of barrier waveforms on longitudinal distribution

$\rho(\phi)$



$\rho(E)$



Holmes et al., HB 2006

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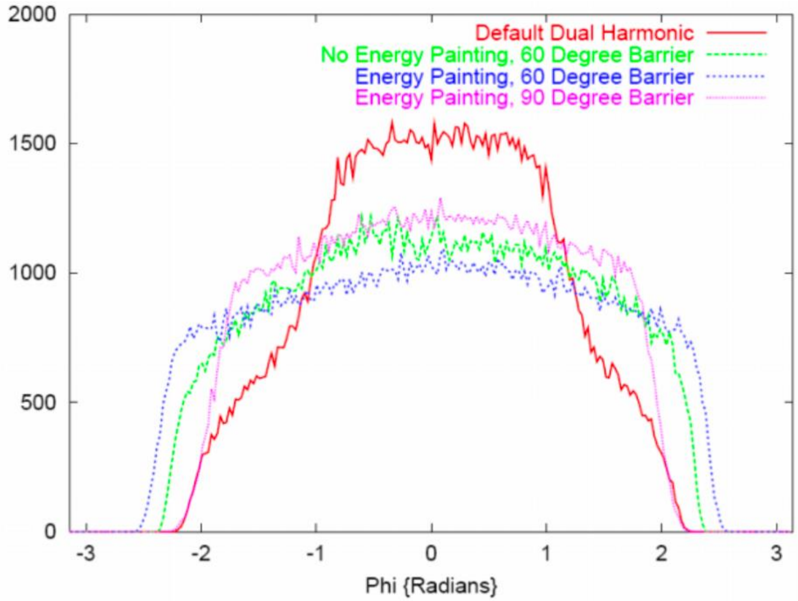
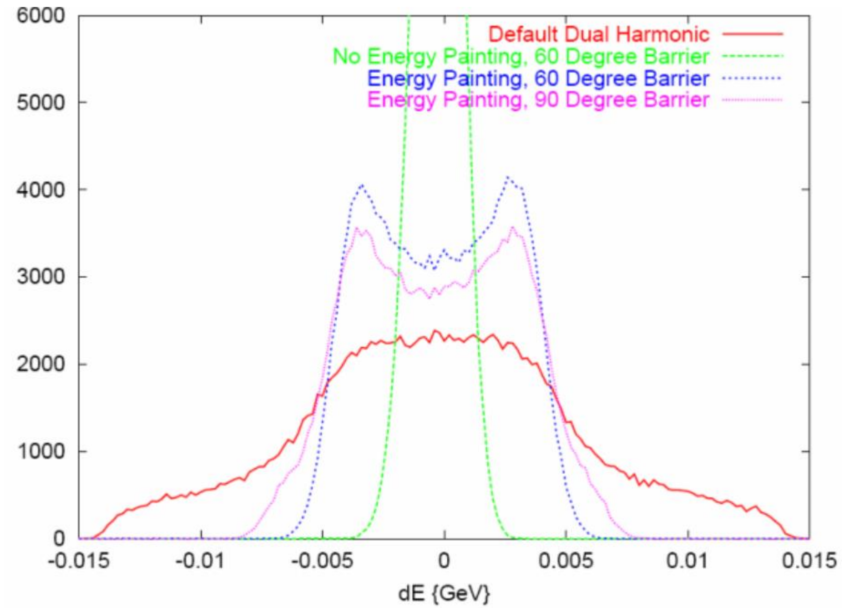
$\rho(\phi)$



$\rho(E)$



$\sqrt{\langle E^2 \rangle} \approx 1$ [MeV]

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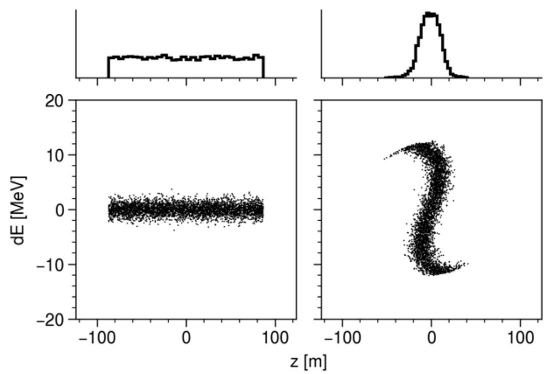
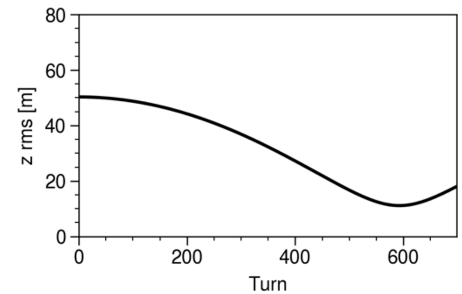
Holmes et al., HB 2006

ΔE =1 [MeV]

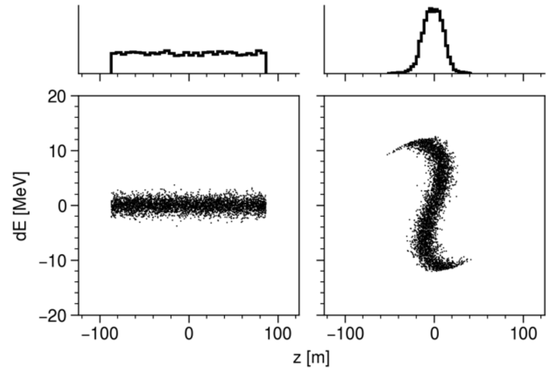


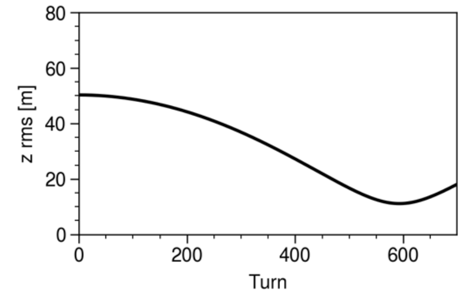
dE [MeV]
20
10
0
−10
−20
−100
0
100
−100
0
100
z [m]



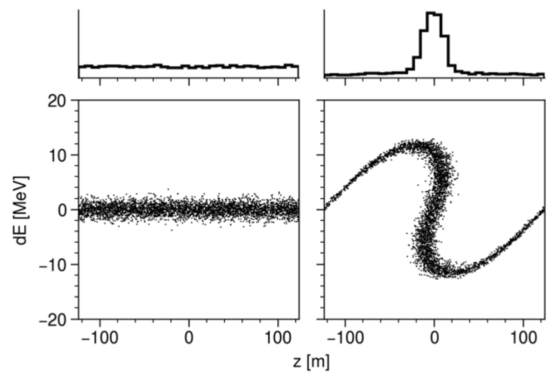
z rms [m]
80
60
40
20
0
0
200
400
600
Turn

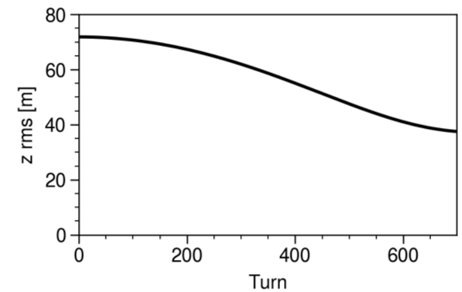
ΔE =1 [MeV]



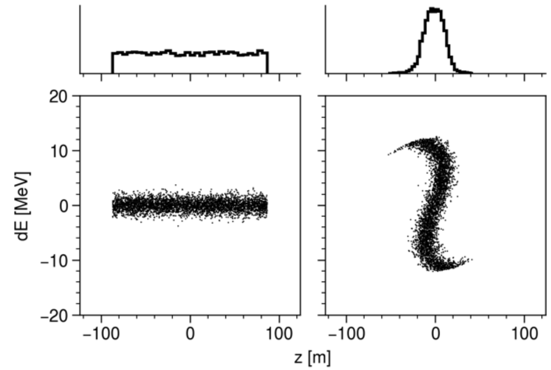


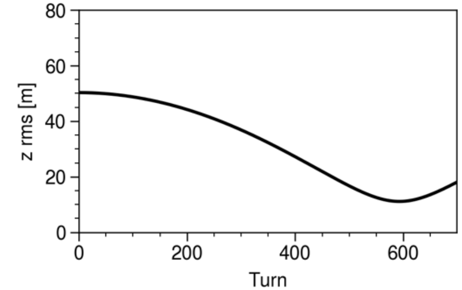
ΔE =1 [MeV]
Unbunched



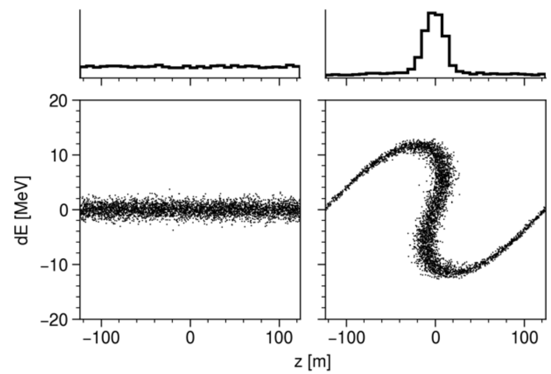


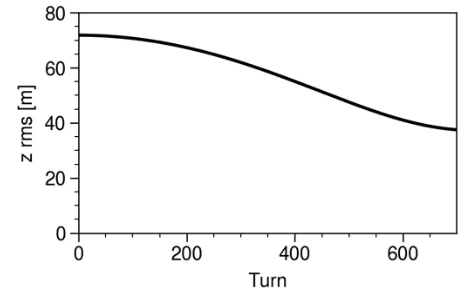
ΔE =1 [MeV]



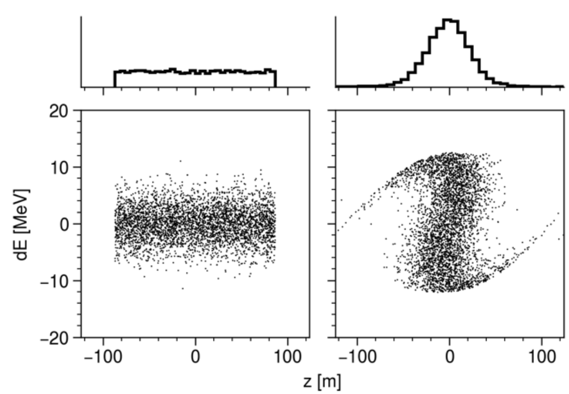


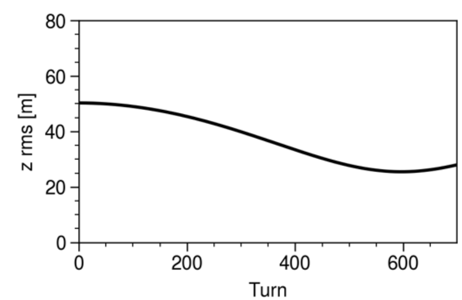
ΔE =1 [MeV]
Unbunched





ΔE =3 [MeV]





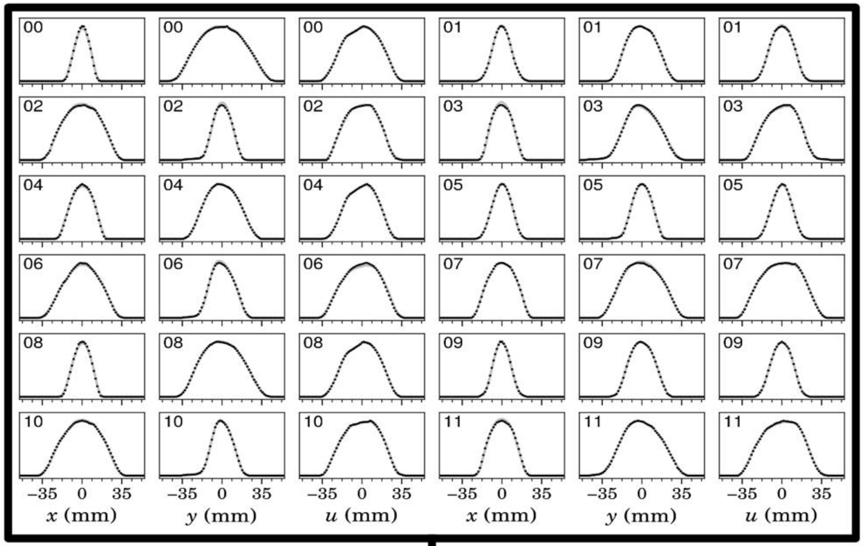
Diagnostics and simulation benchmarking

Diagnostics are available to measure turn-by-turn phase space distribution

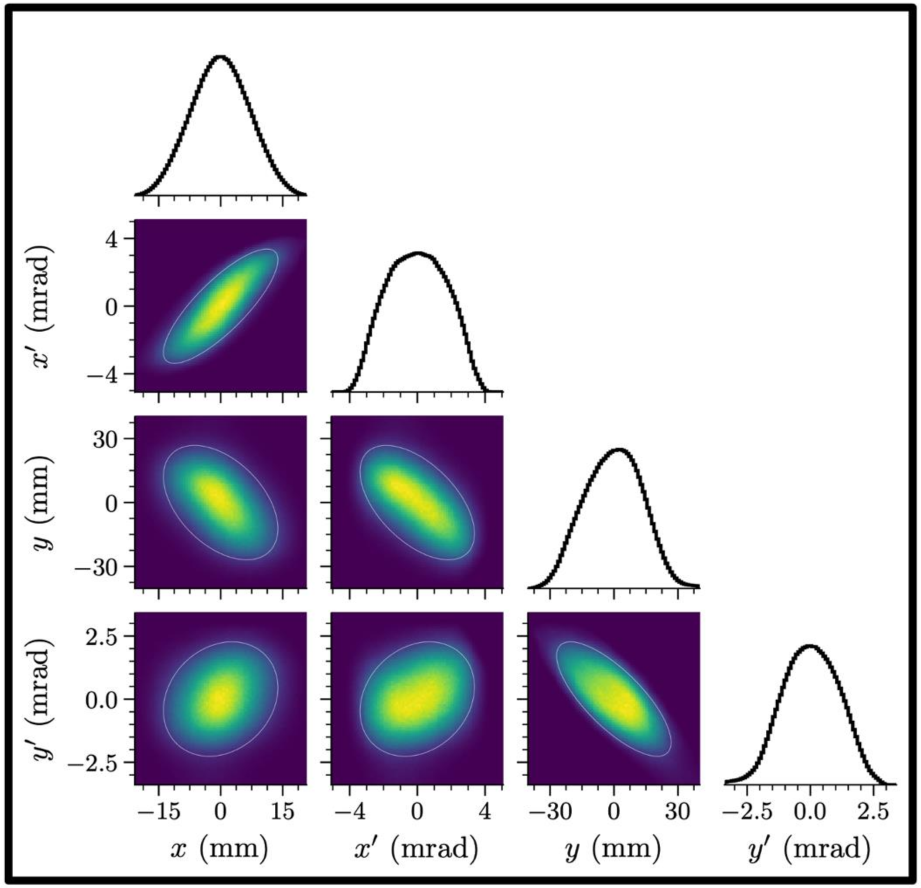
Diagnostic	Measured Quantity	Operational?	Speed
Ring instability monitor (RIM)	$FFT\{\bar{x}(z,t), \bar{y}(z,t)\}$	Yes	Instant
Beam position monitors (BPM)	$\{\bar{x}(t), \bar{y}(t)\}$	Yes	Instant
Beam current monitor (BCM)	$\rho(z,t)$	Yes	Instant
Wire scanners (WS)	$\{\rho(x), \rho(y), \rho(u)\}$	Yes	5-15 mins
Electron scanner (ES)	$\{\rho(x,z,t), \rho(y,z,t)\}$	No	Instant

Wire scanners constrain 2D/4D phase space density of extracted bunch

1D measurements



4D phase space distribution

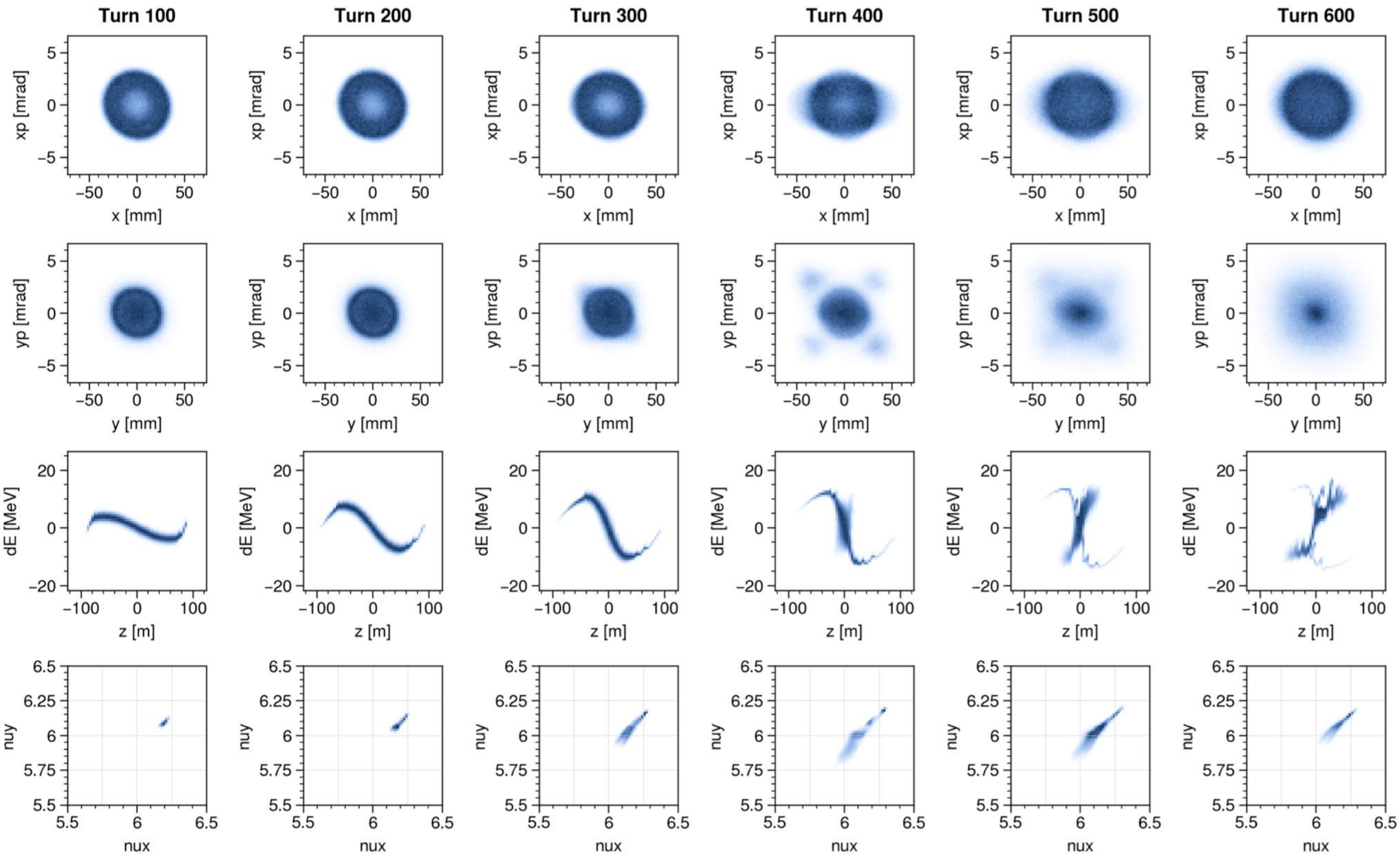


Hoover, Phys. Rev. Accel. Beams **27**, 122802 (2024)

Potential to test modeling assumptions against turn-by-turn data

- Multiple codes: PyORBIT, Impact-X, X-Suite (PyORBIT-X??)
- Space charge during compression (3D slice-by-slice?)
- Wake fields — beam-cavity interaction
- Electron cloud

Fourth-order resonance driven by multipoles in space charge potential



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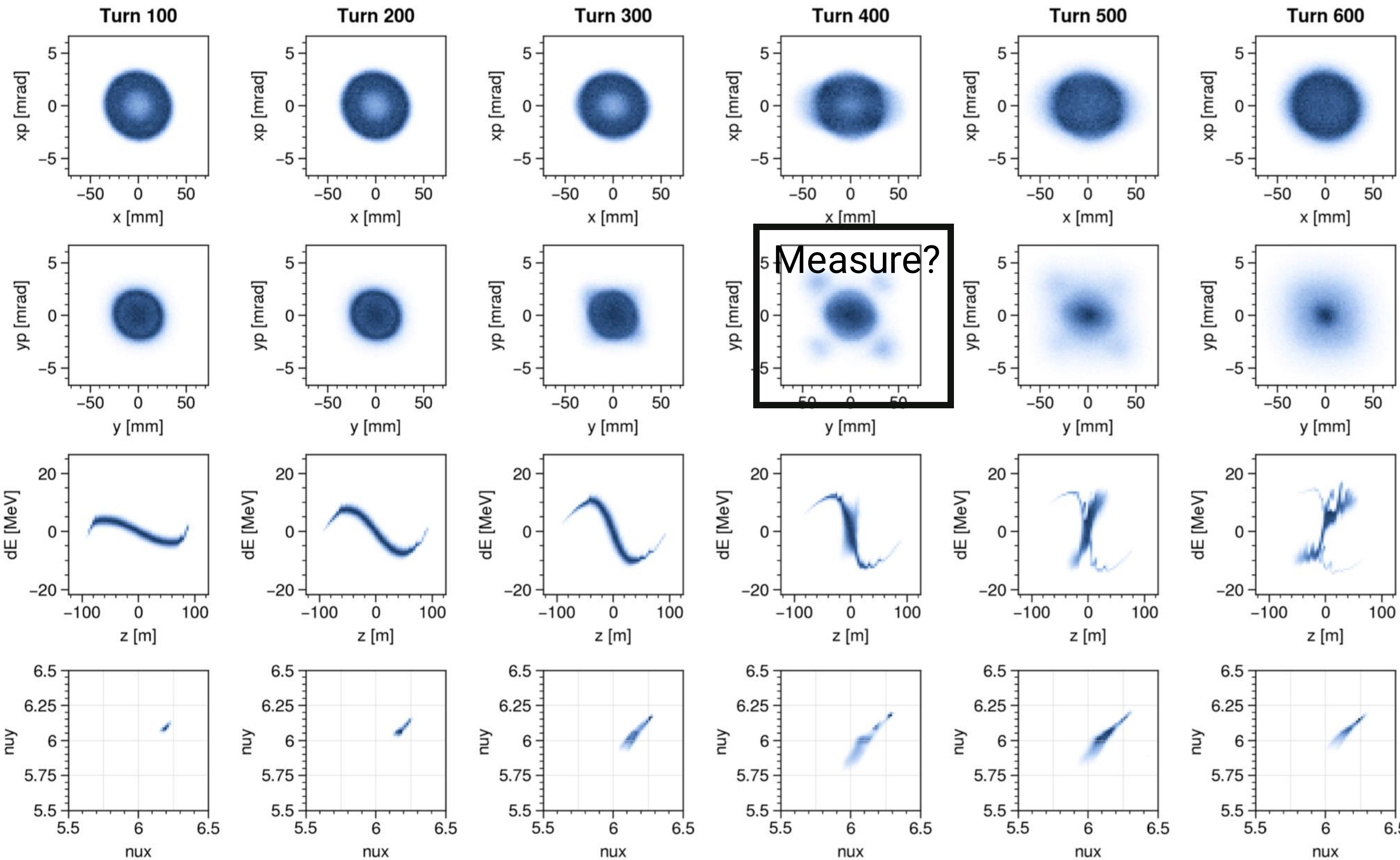
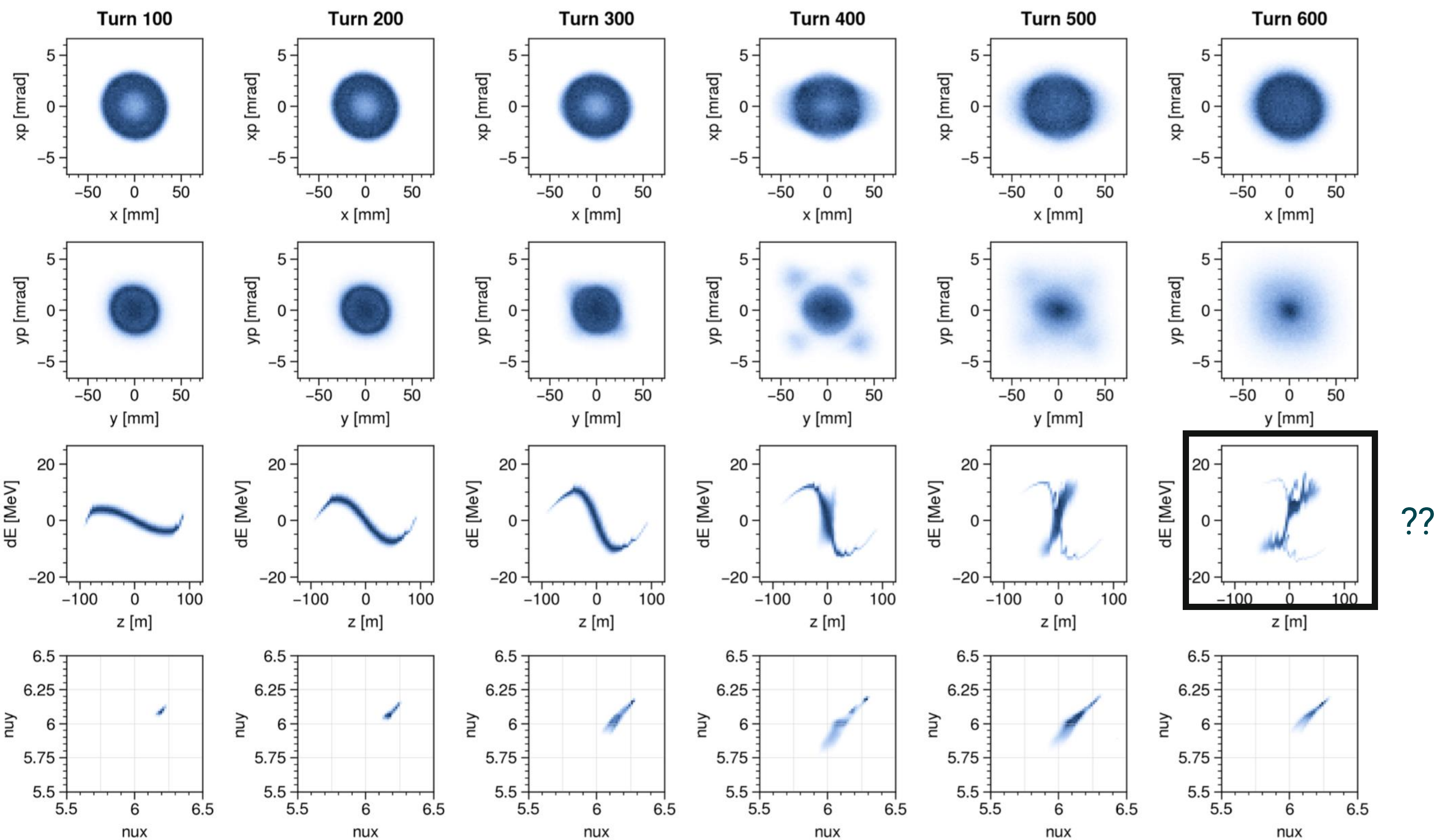
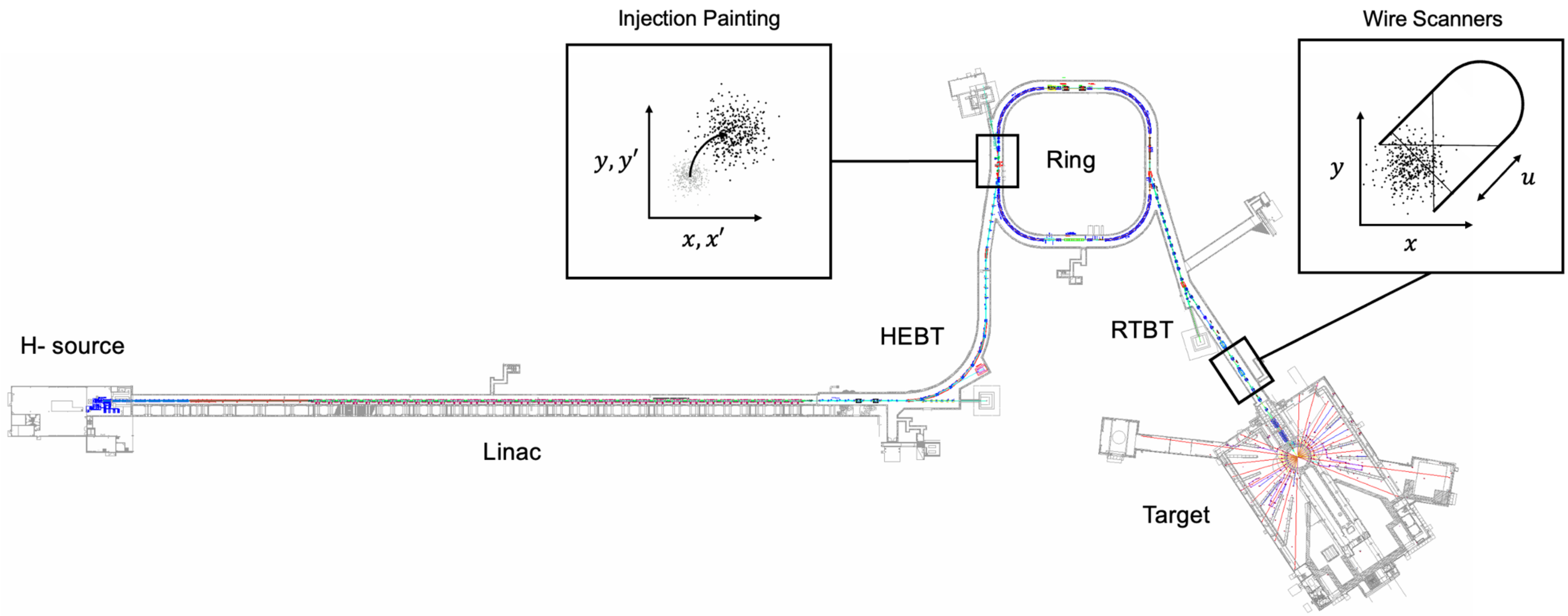


Artificial noise from longitudinal space charge solver



Can amplify collective effects via phase space painting and energy modulation

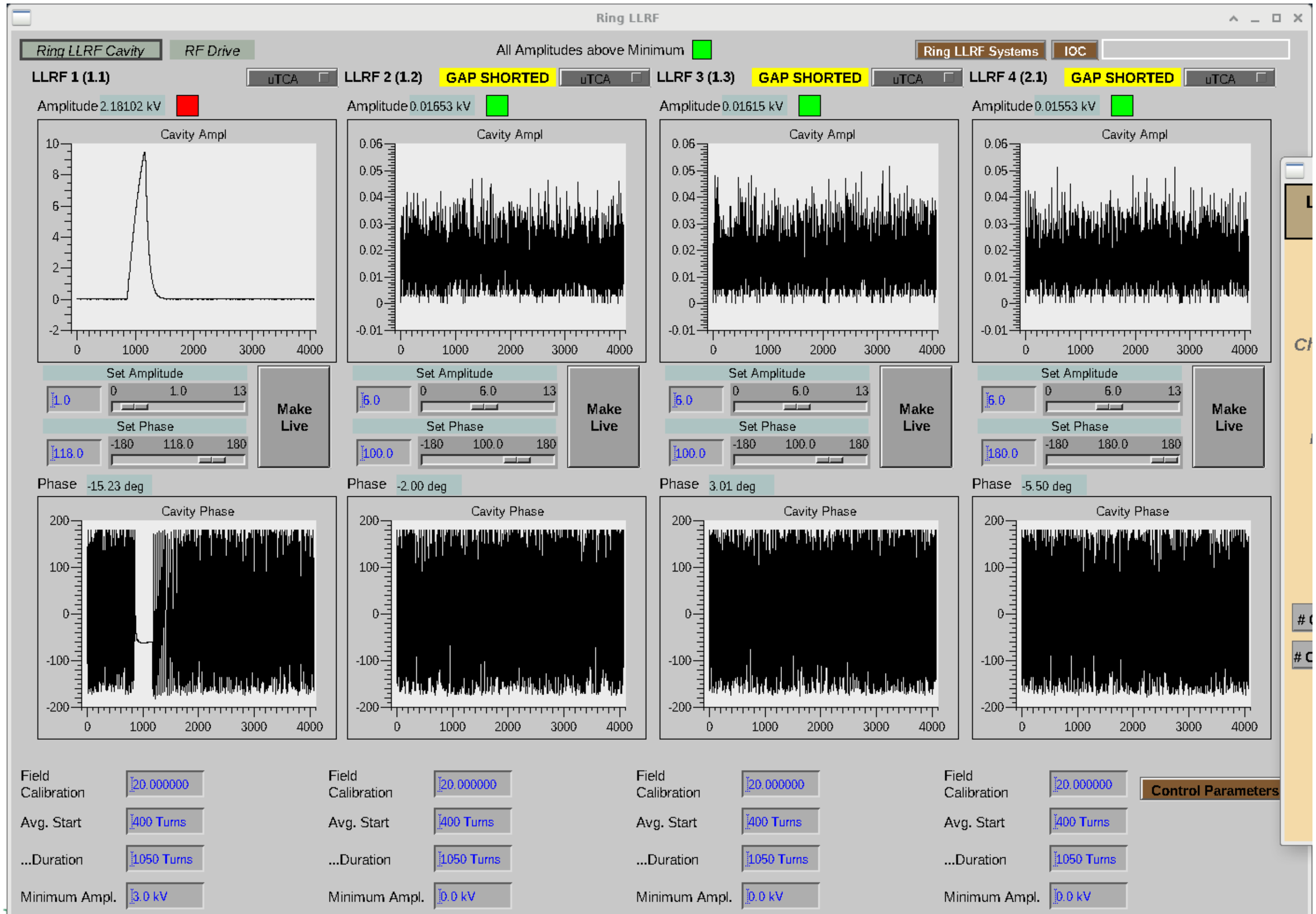


First experiment

RF system is limited right now

- We **cannot** switch waveforms mid-cycle.
- We **can** ramp the h=1 cavity drive amplitude on a delay (ramp starts after accumulation).
- We **cannot** unshort the cavity mid-cycle. So there will be beam-induced voltage during accumulation.

Induced voltage approaches max value after ~300 injected turns



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We didn't see any bunching :(

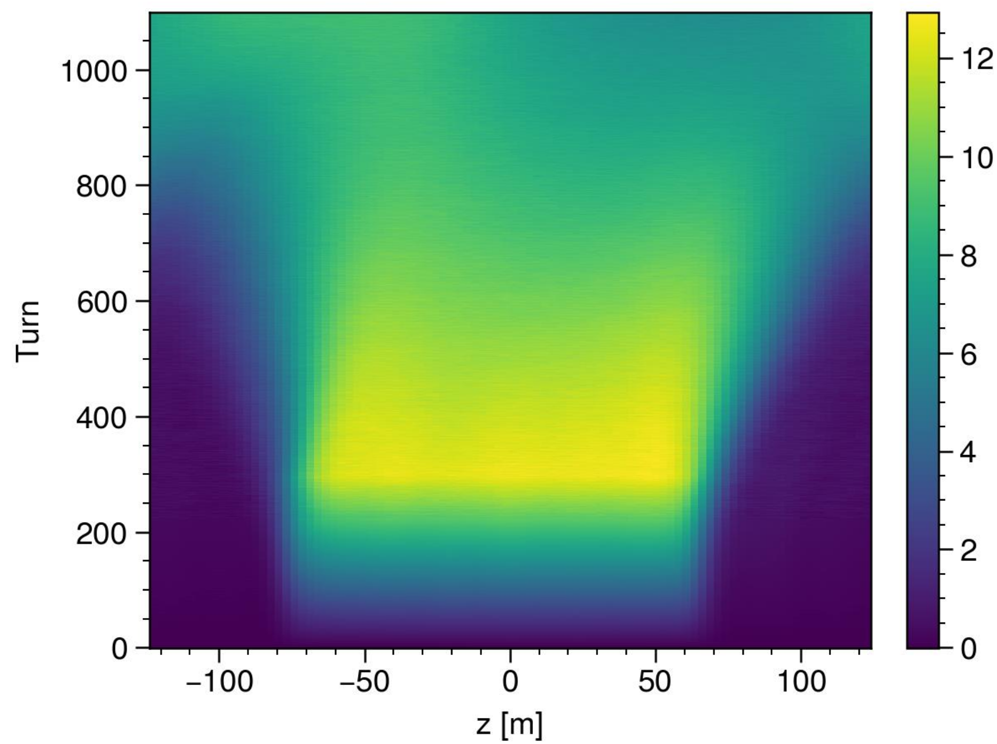
Storage

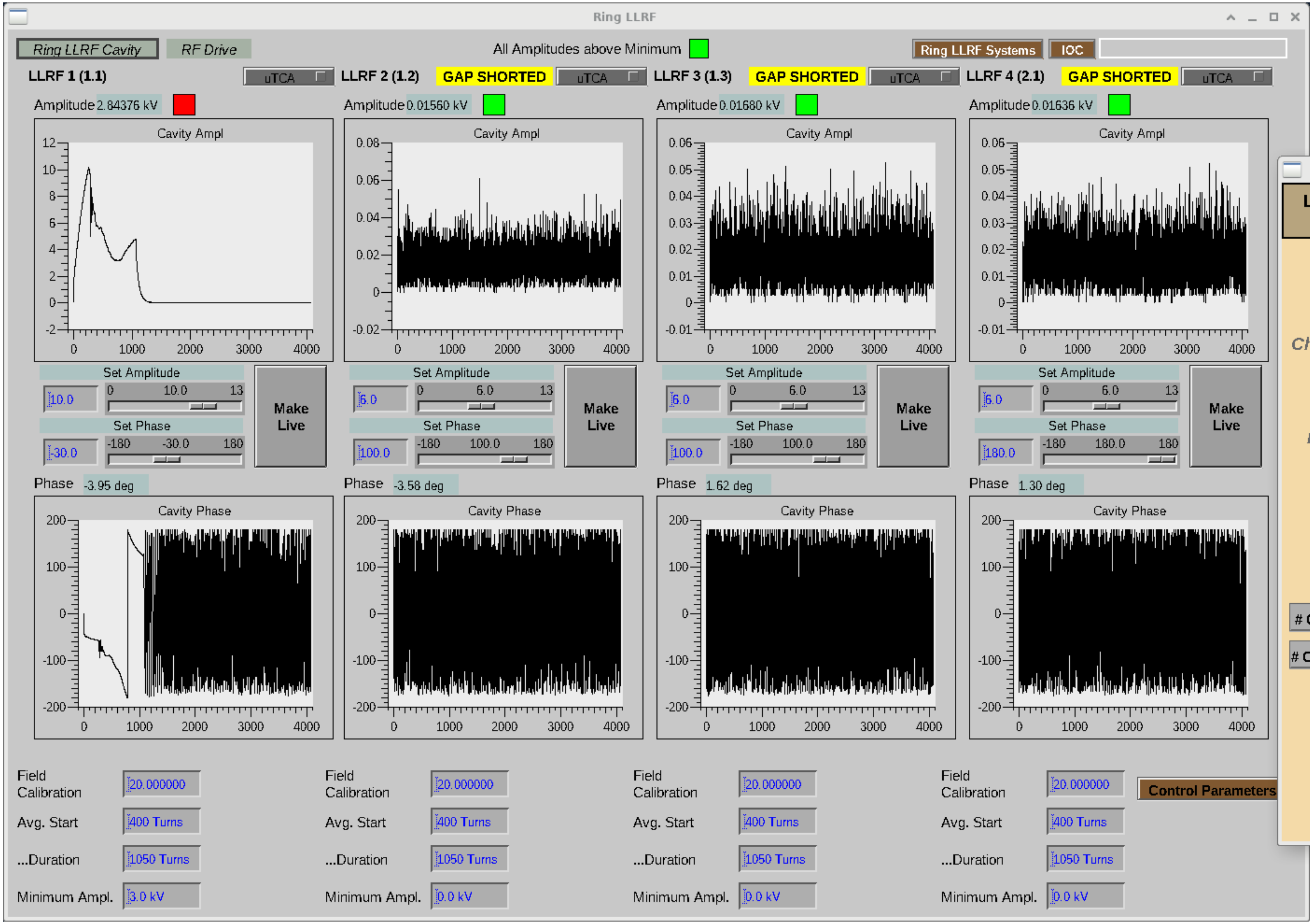
Accumulation

Constant A

Ramp A

Zero A





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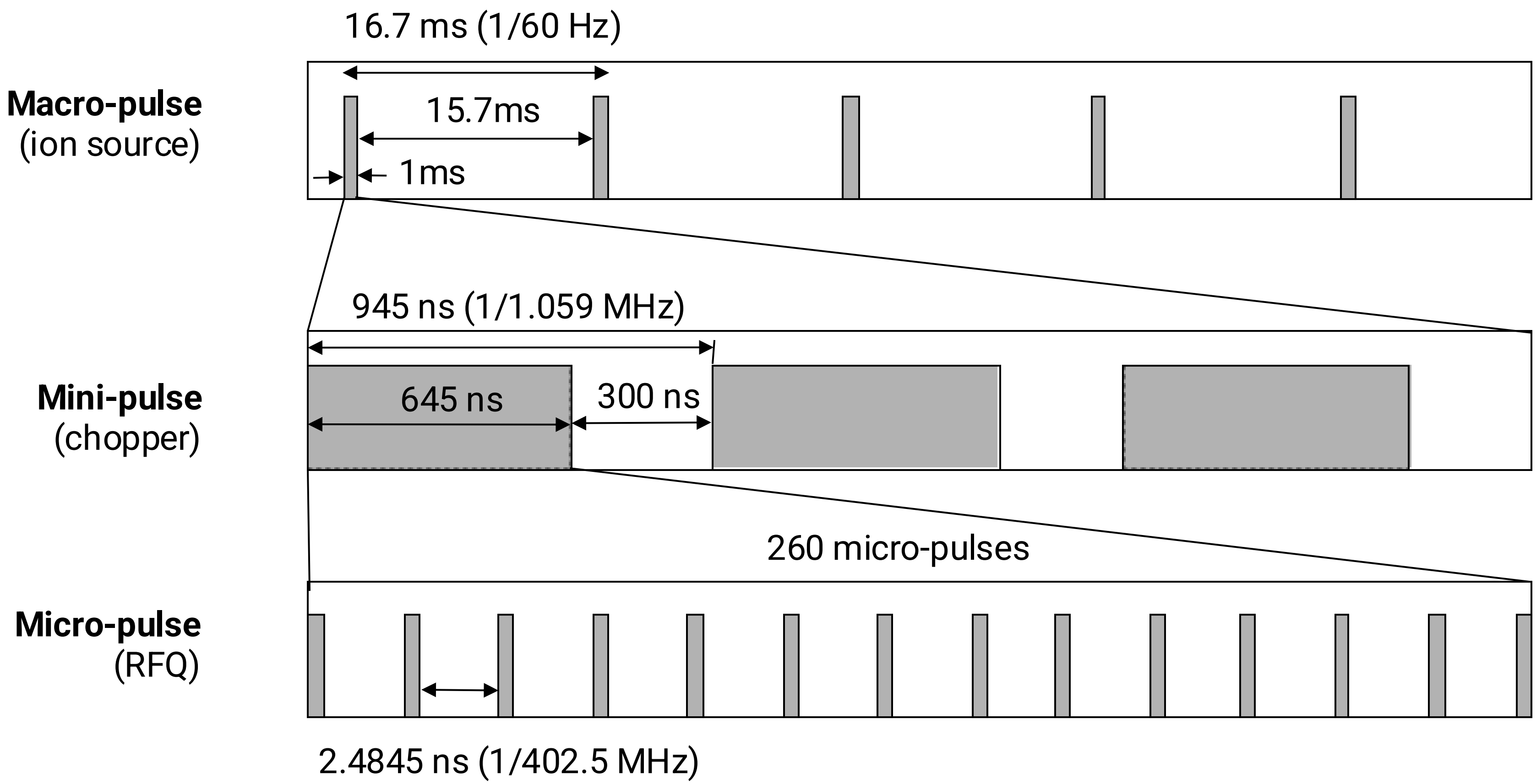
Actual RF phase was probably debunching

- RF feedback was unstable at 300 injected turns; we operated without feedback.
- Since we operated without feedback, the setpoint phase/amplitude were not equal to the actual values.
- Next time, we'll start at low intensity with feedback on.

Conclusion

- Bunch compression in the SNS could be valuable for studying collective effects
- Experiments started this month
- Success may hinge on ring RF engineering
- Thanks for listening!



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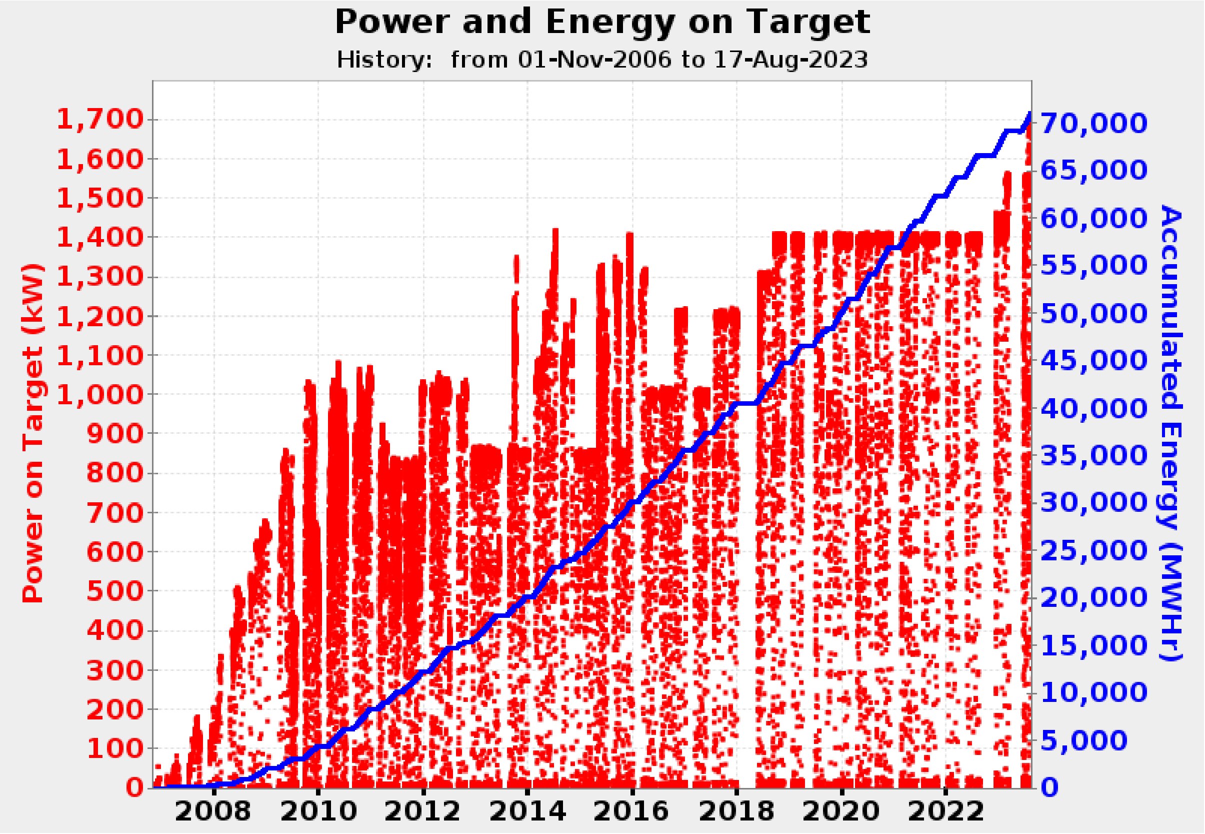
Power and Energy on Target
History: from 01-Nov-2006 to 17-Aug-2023
Power on Target (kW)
Accumulated Energy (MWHr)
0
100
200
300
400
500
600
700
800
900
1,000
1,100
1,200
1,300
1,400
1,500
1,600
1,700
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
55,000
60,000
65,000
70,000
2008
2010
2012
2014
2016
2018
2020
2022

SNS ring has four RF cavities (h=1, h=2)