Proton Driver for the Demonstrator and Muon Collider

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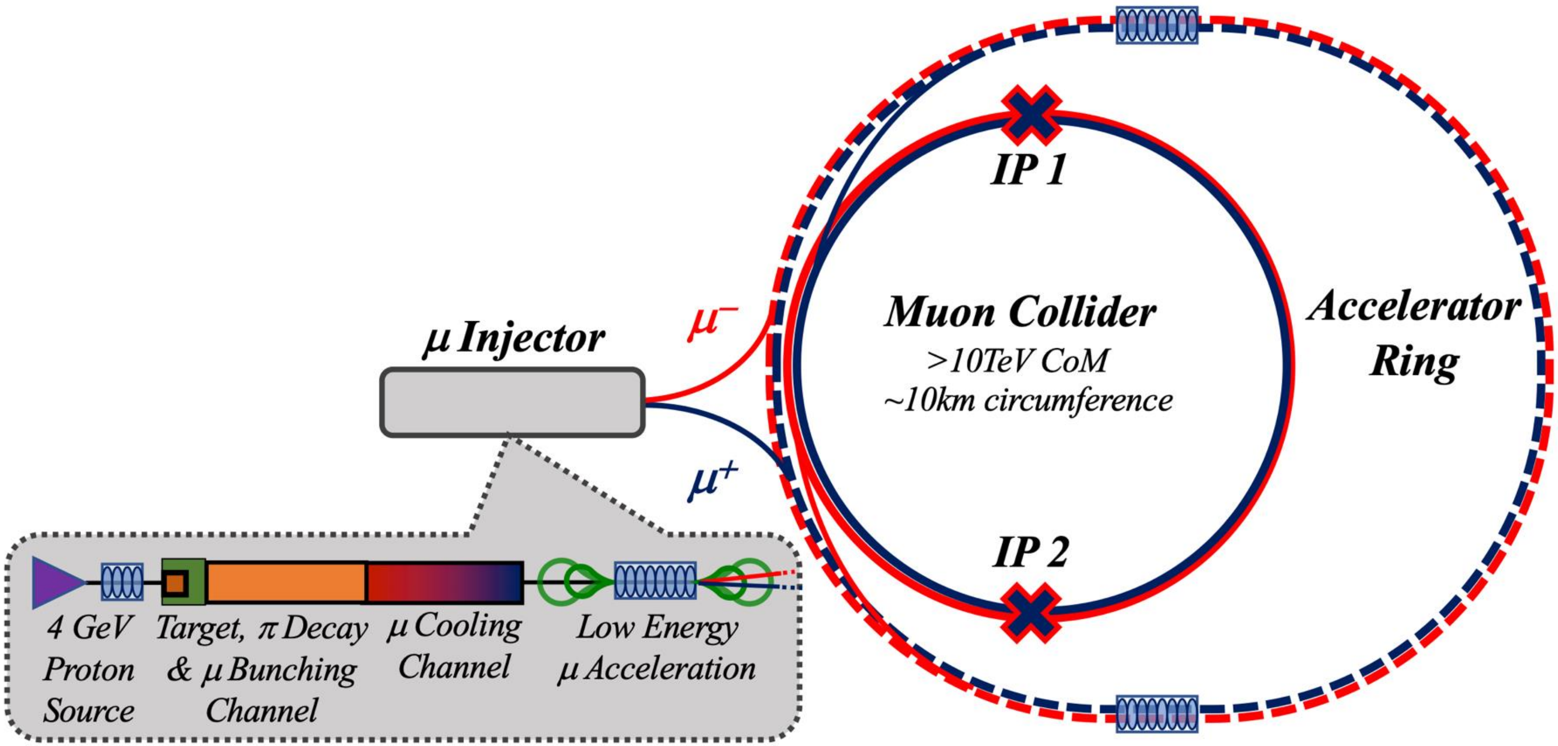
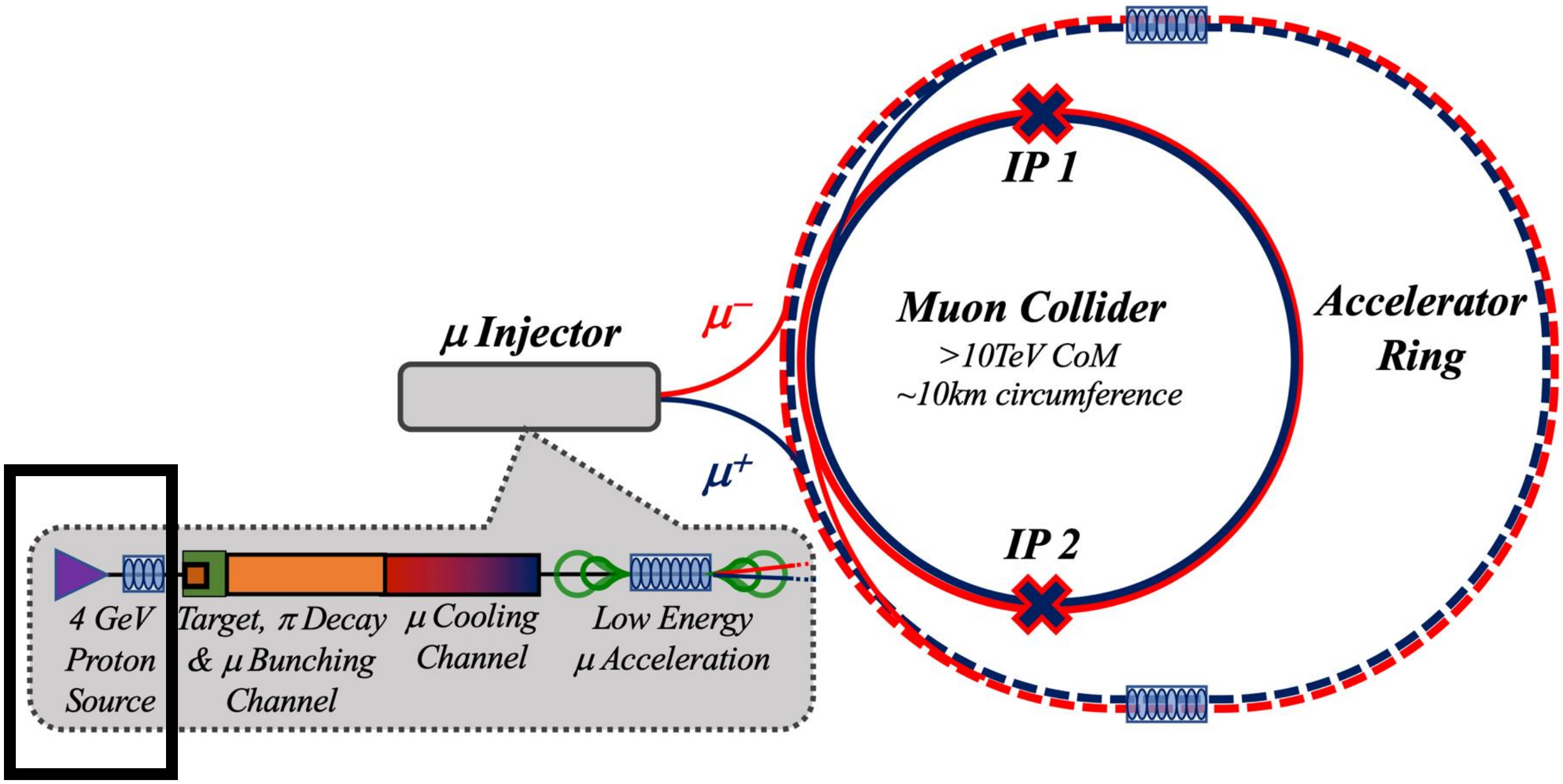
Outline

- SNS resembles IMCC proton driver concept
- SNS has unique capabilities (bunch intensity, energy flexibility, phase space painting, diagnostics)
- Feasibility of bunch compression using existing hardware
- Preliminary simulations and experiments

Overview of SNS accelerator and comparison to IMCC design



https://arxiv.org/abs/2303.08533



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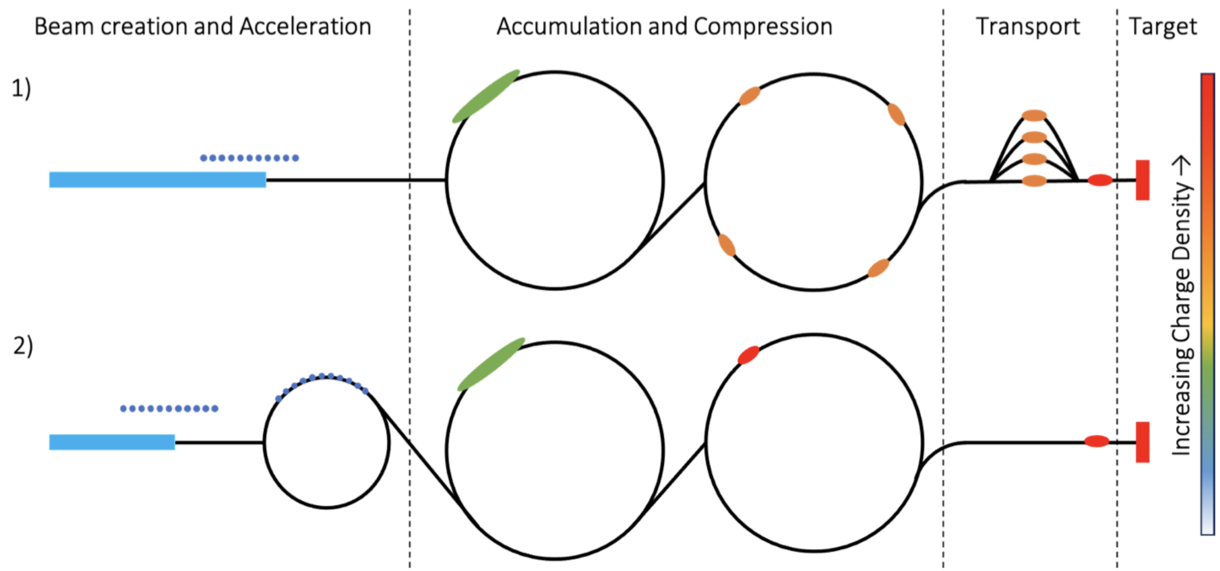
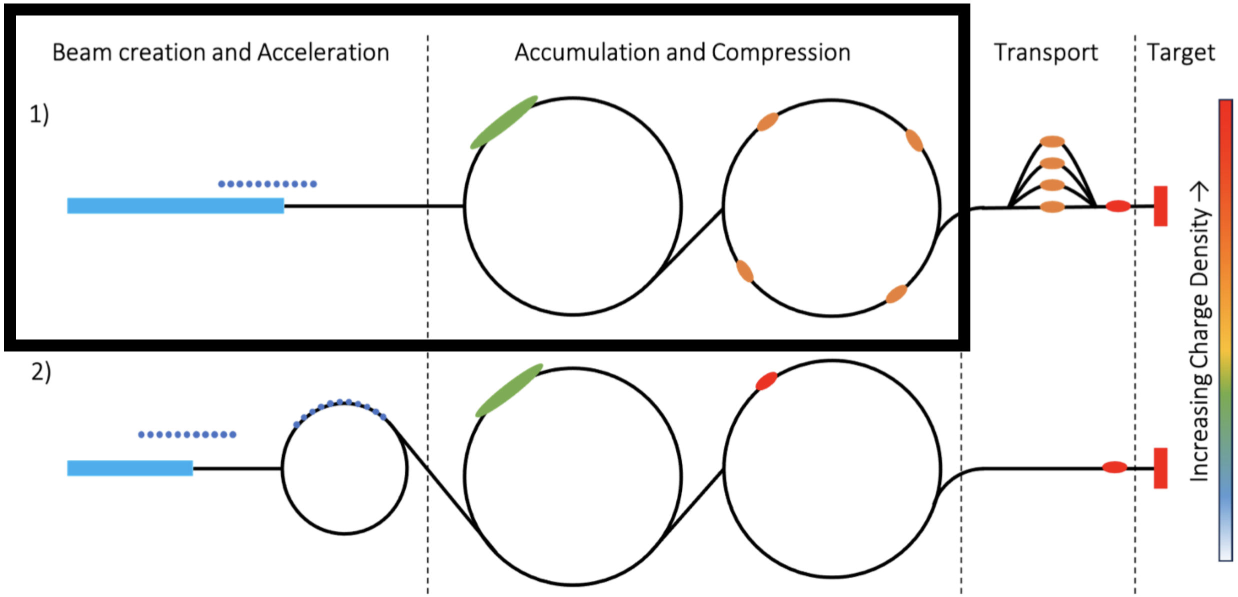


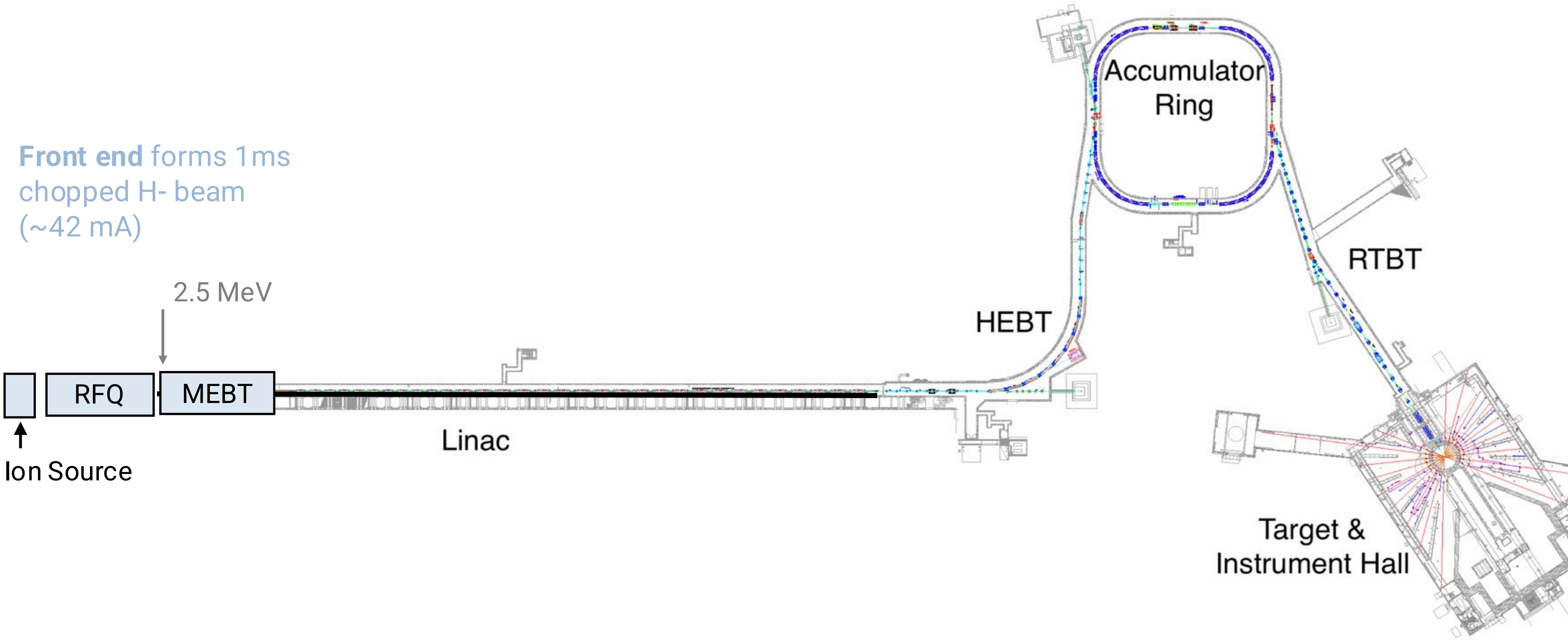
Fig. 5.1: Schematic layouts for the proton complex section. Our baseline design is the schematic 1 on the figure. The bunch density as the proton travels thought the complex is also depicted. The closer to the target the highest the bunch charge density and at the point where is collides with the target.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



2-4 MW
5-10 GeV
10 Hz
2 ns

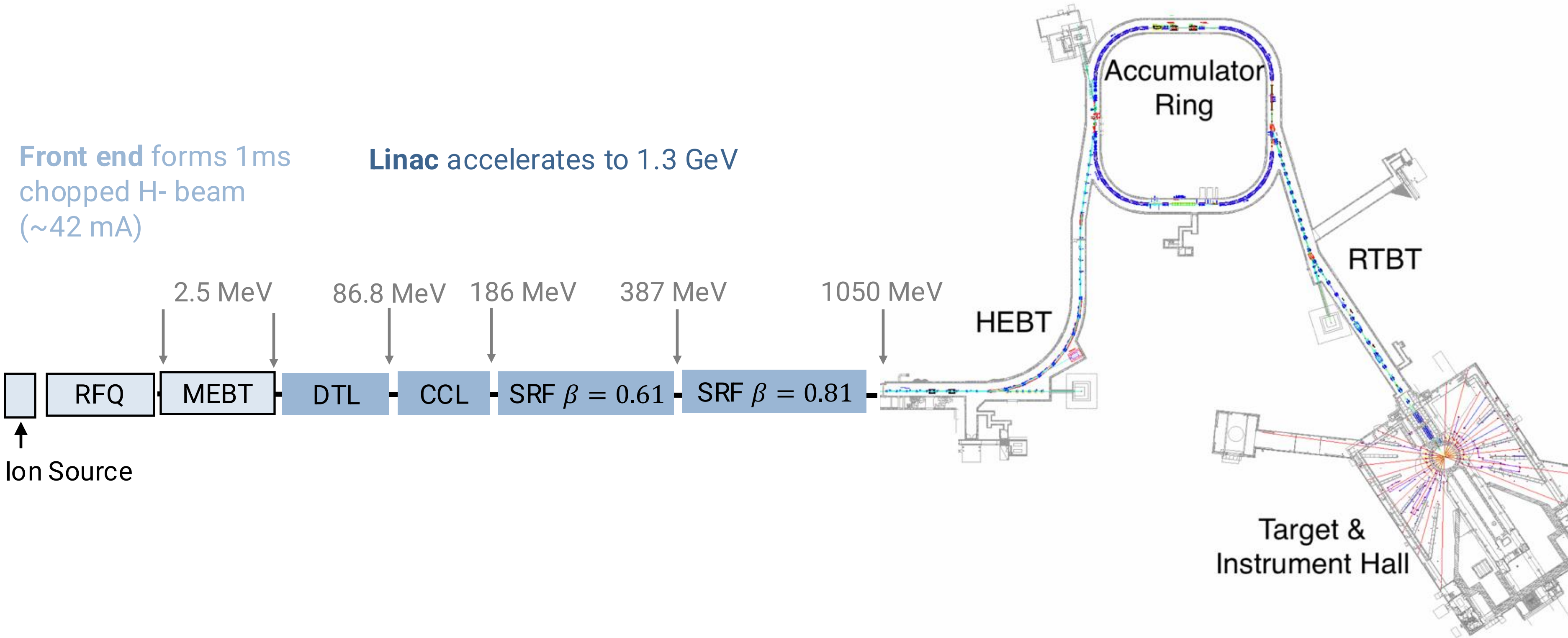
Fig. 5.1: Schematic layouts for the proton complex section. Our baseline design is the schematic 1 on the figure. The bunch density as the proton travels thought the complex is also depicted. The closer to the target the highest the bunch charge density and at the point where is collides with the target.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

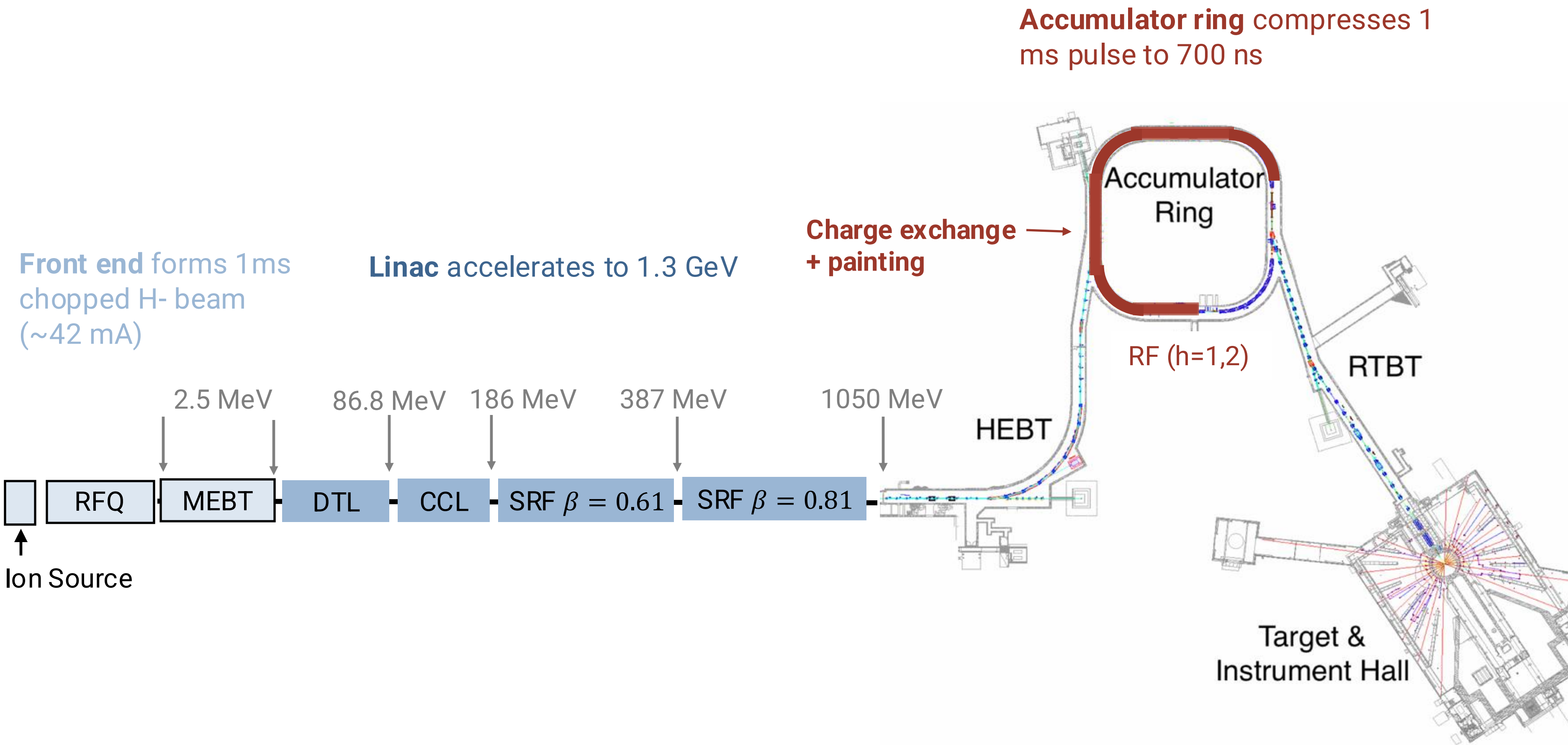
Front end forms 1ms chopped H- beam (~42 mA)



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

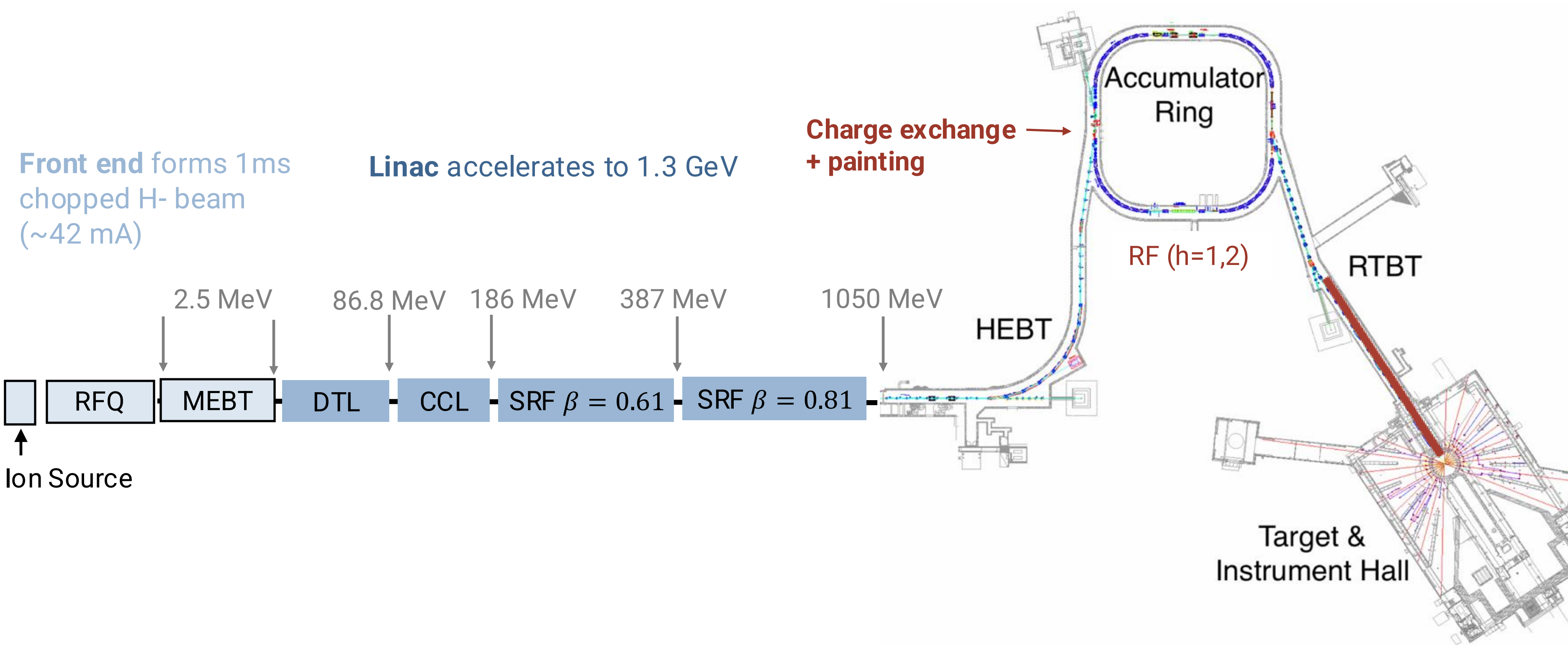
Linac accelerates to 1.3 GeV





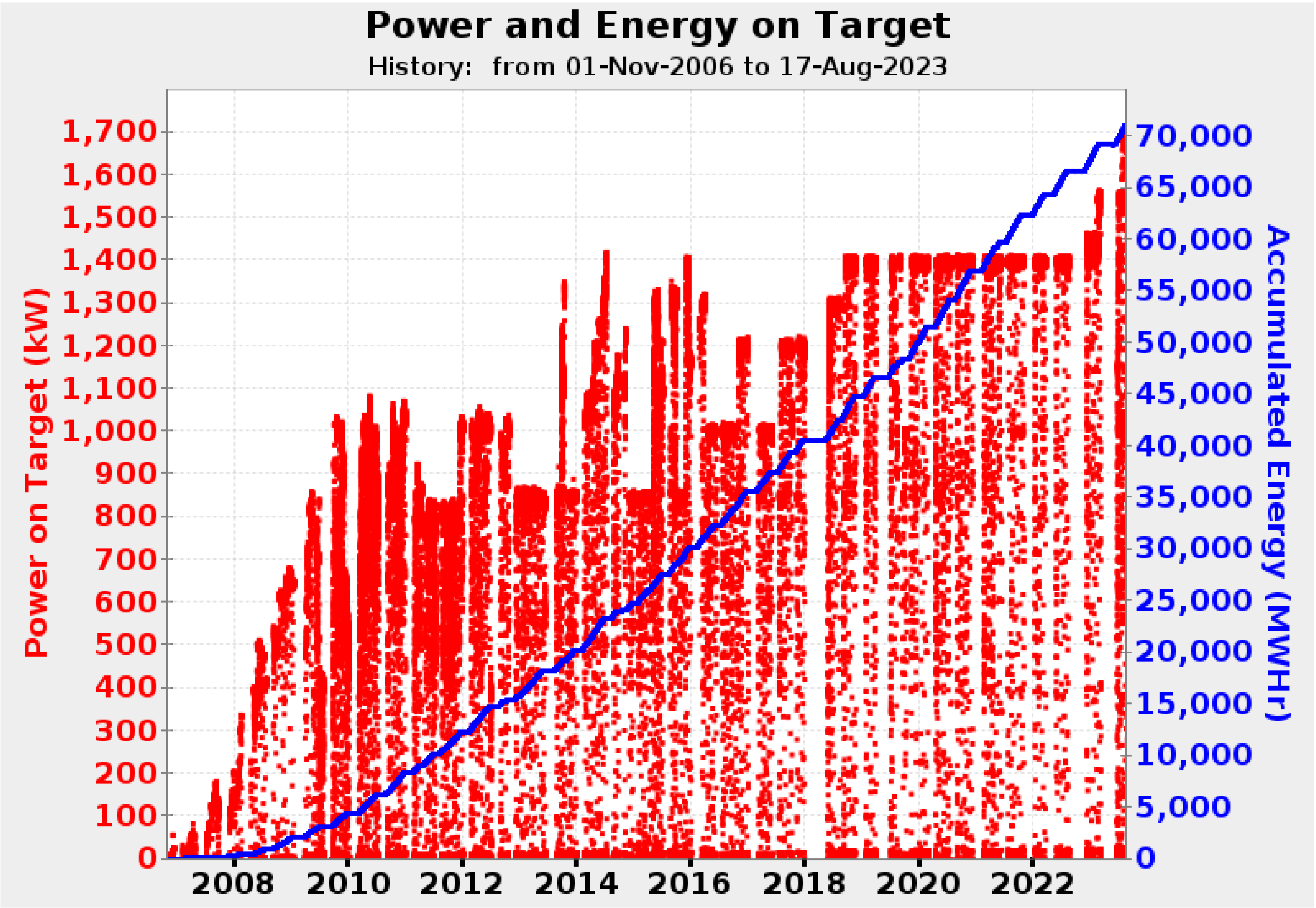
Accumulator ring compresses 1 ms pulse to 700 ns
Accumulator Ring
Charge exchange + painting
Front end forms 1ms chopped H- beam (~42 mA)
Linac accelerates to 1.3 GeV
RF (h=1,2)
RTBT
HEBT
2.5 MeV
86.8 MeV
186 MeV
387 MeV
1050 MeV
RFQ
MEBT
DTL
CCL
SRF $\beta = 0.61$
SRF $\beta = 0.81$
Ion Source
Target & Instrument Hall

Accumulator ring compresses 1 ms pulse to 700 ns

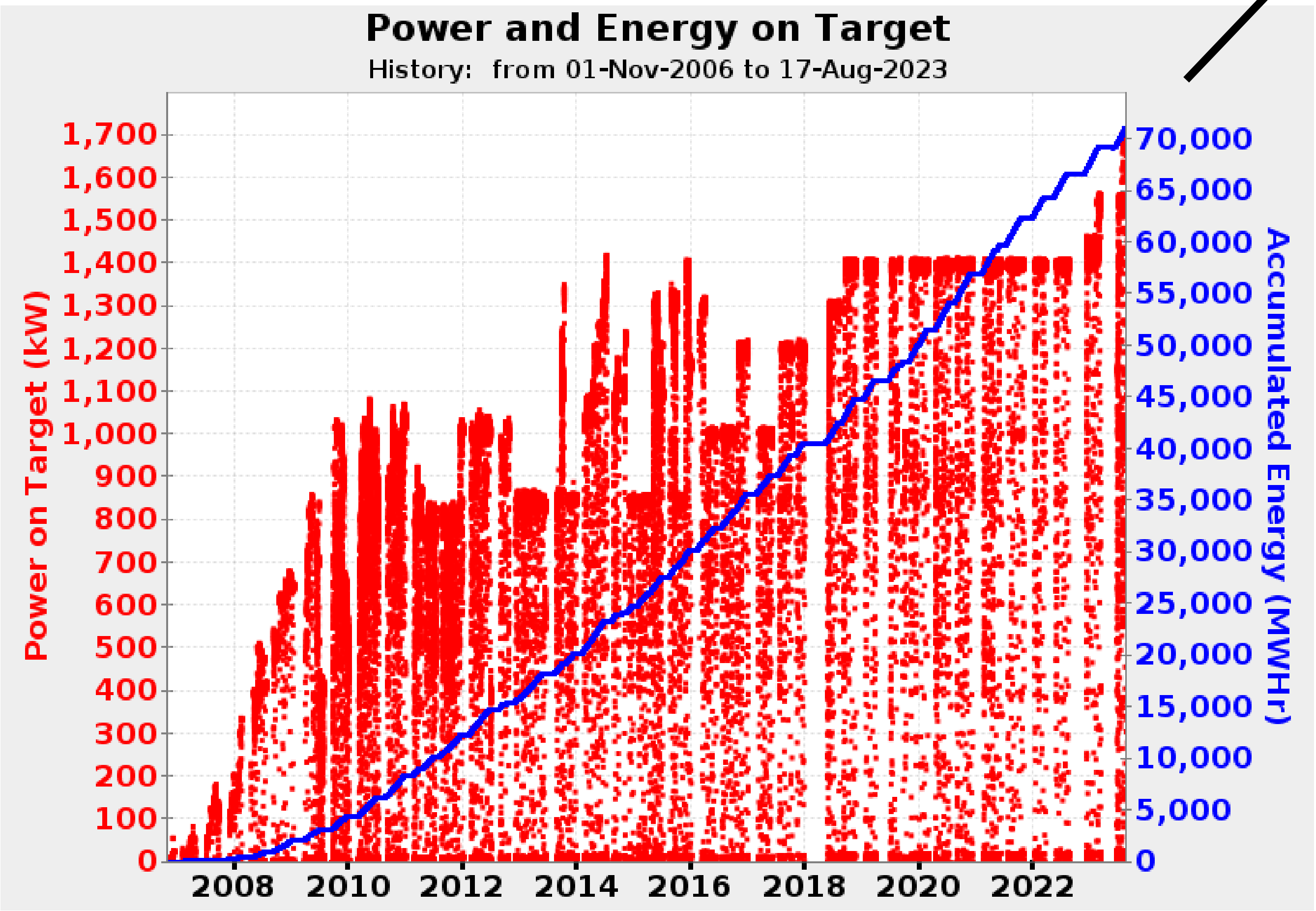


1.8 MW @ 60 Hz

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

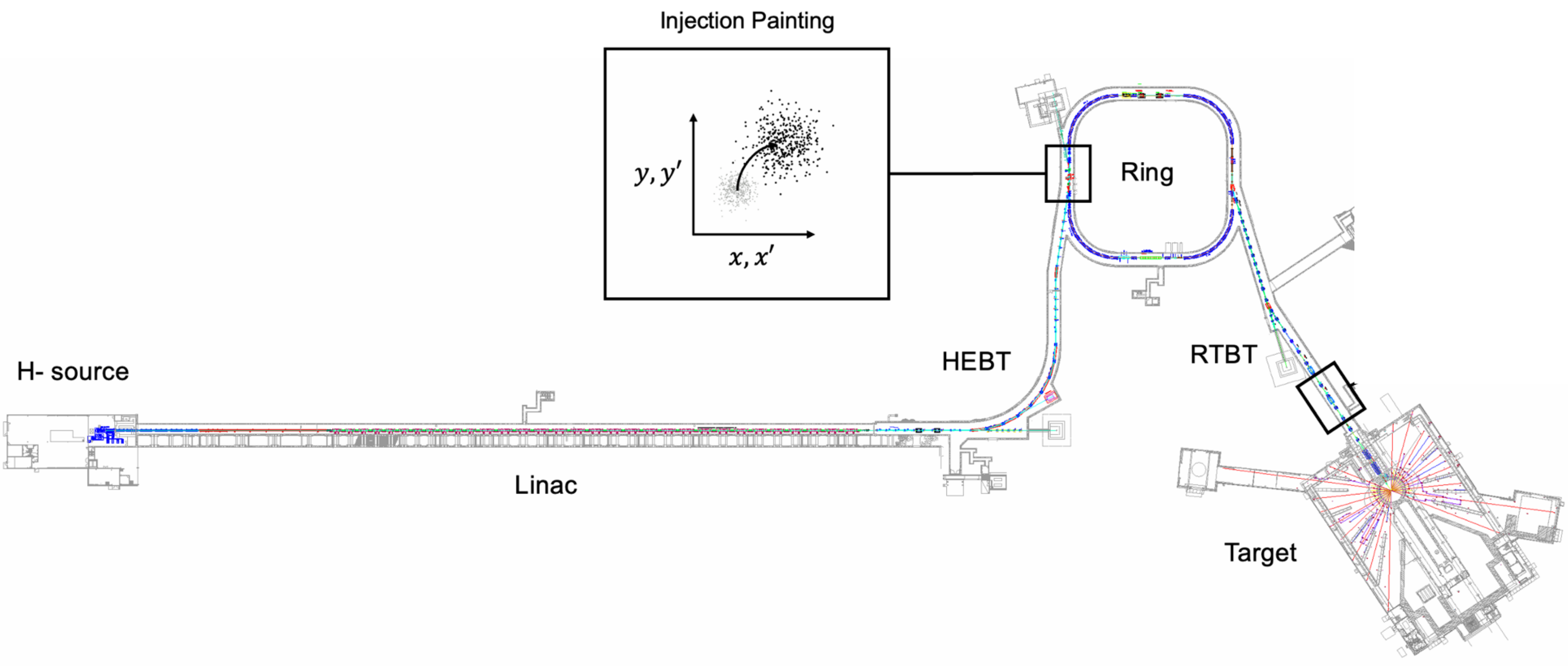

Power and Energy on Target
History: from 01-Nov-2006 to 17-Aug-2023
Power on Target (kW)
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
2008
2010
2012
2014
2016
2018
2020
2022
Accumulated Energy (MWHr)
70,000
65,000
60,000
55,000
50,000
45,000
40,000
35,000
30,000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

2.8 MW

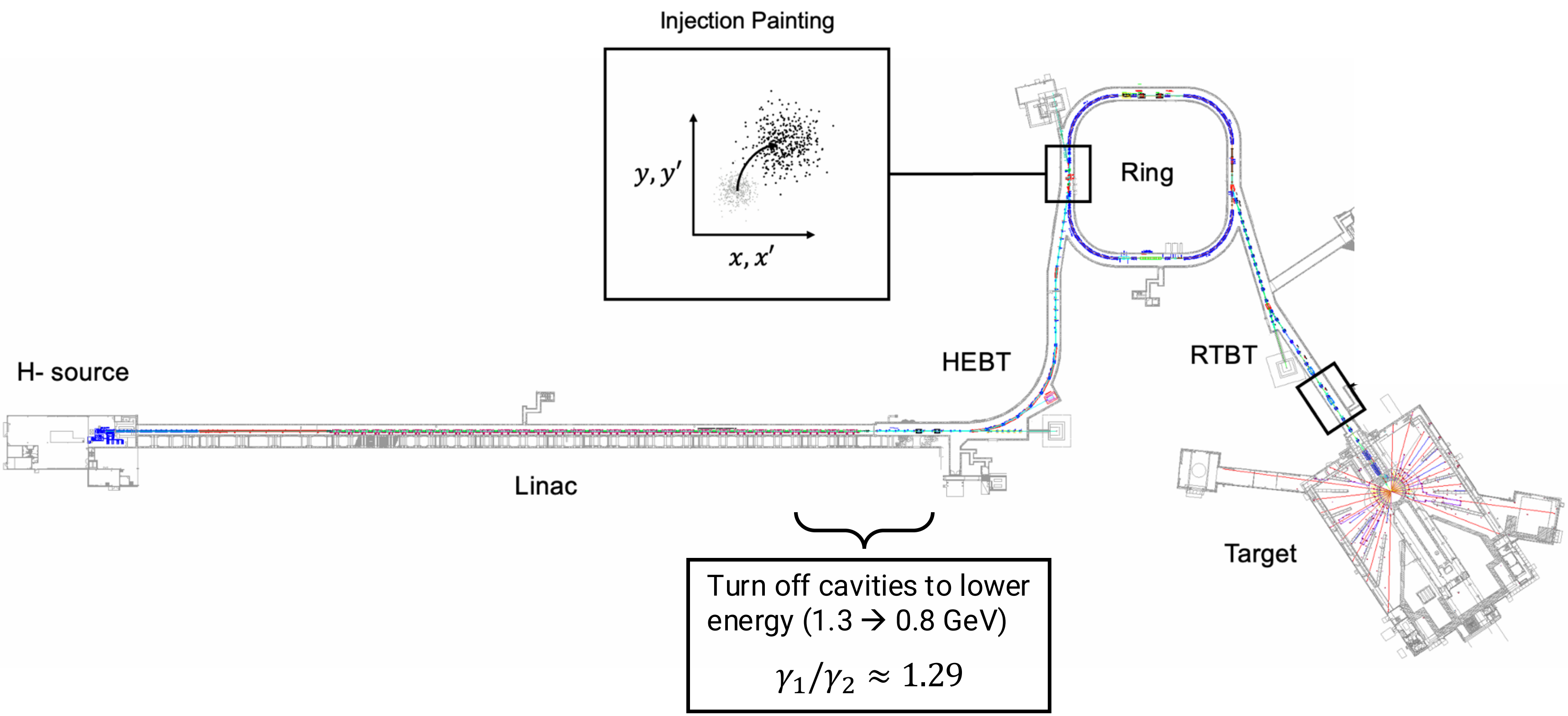


Power and Energy on Target
History: from 01-Nov-2006 to 17-Aug-2023
Power on Target (kW)
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Accumulated Energy (MWHr)
70,000
65,000
60,000
55,000
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
2008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

Collective effects can be amplified using phase space painting



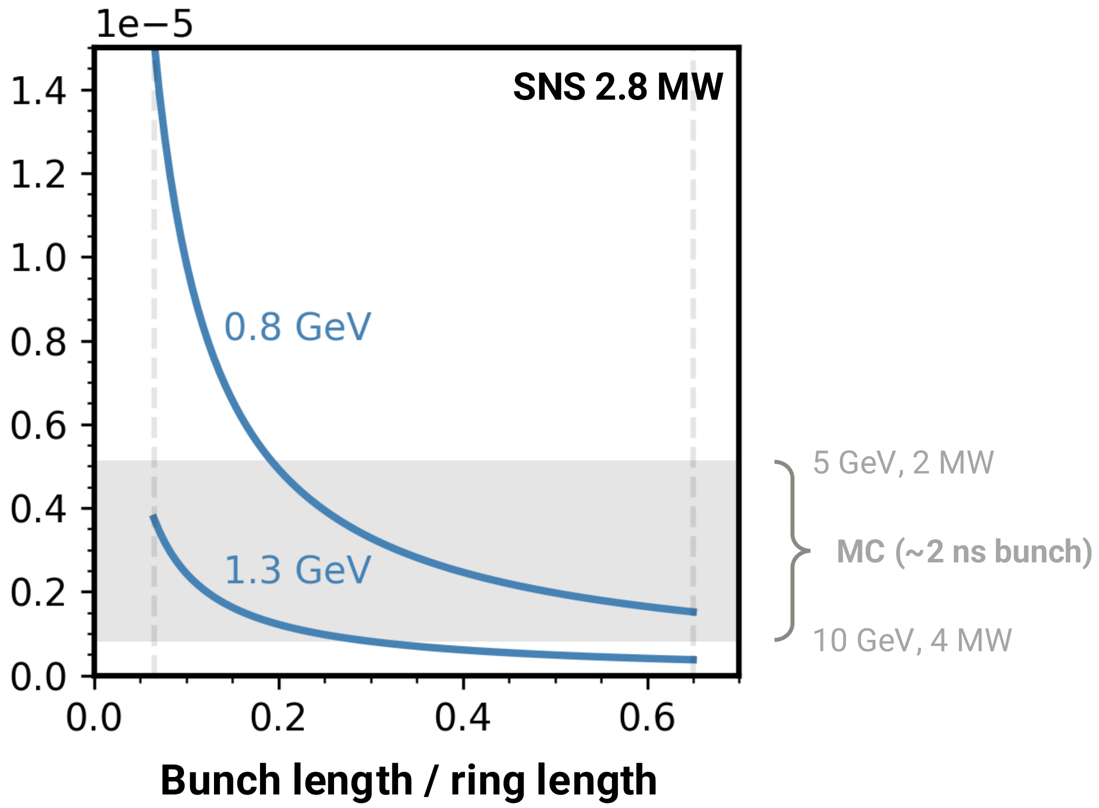
Collective effects can be amplified using phase space painting and beam energy reduction



With strong compression, SNS could probe MC space charge regime

Space charge

$$Q \sim \frac{\lambda}{\beta^2 \gamma^3}$$

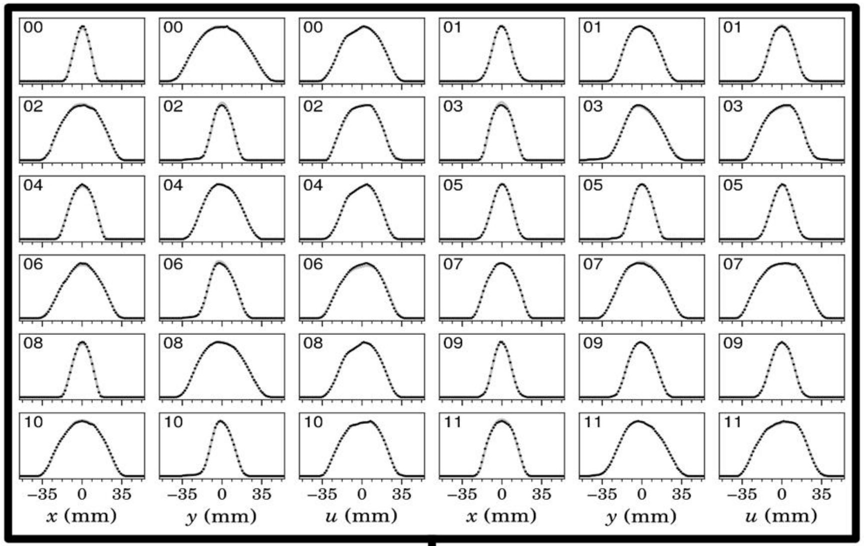


Diagnostics available to measure turn-by-turn particle distribution

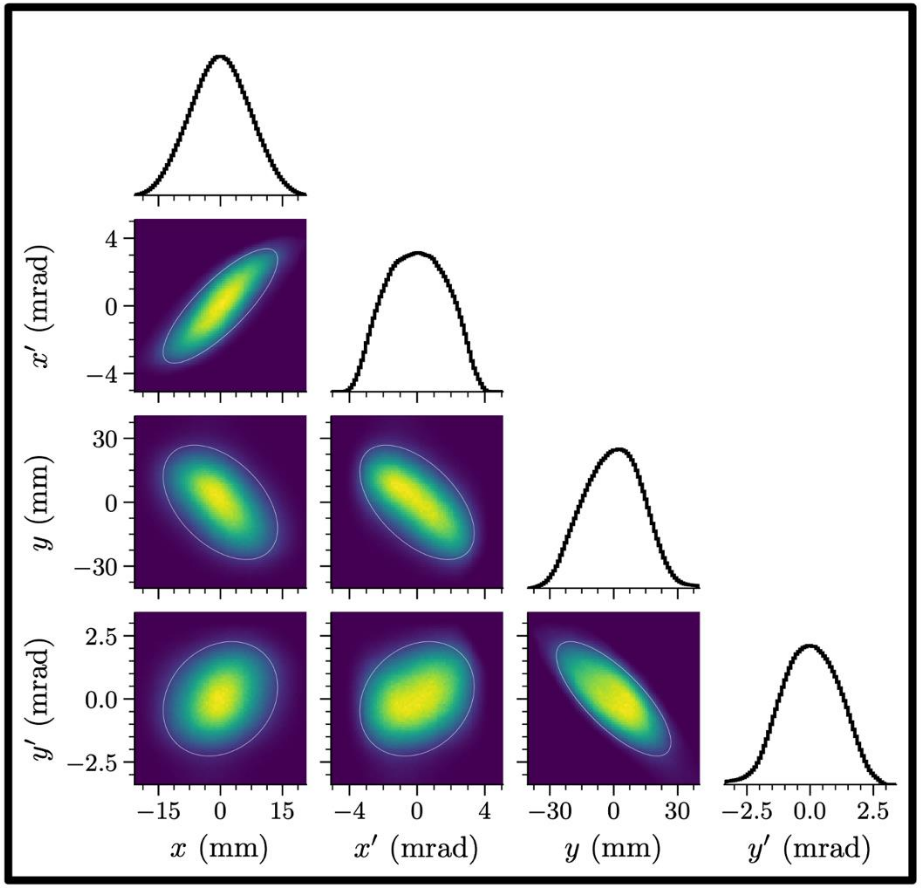
Diagnostic	Measured Quantity	Operational?	Speed
Ring instability monitor (RIM)	$FFT\{\ \bar{x}(z,t), \bar{y}(z,t)\ \}$	Yes	Instant
Beam position monitors (BPM)	$\{\bar{x}(t), \bar{y}(t)\}$	Yes	Instant
Beam current monitor (BCM)	$\rho(z,t)$	Yes	Instant
Wire scanners (WS)	$\{\rho(x\ ), \rho(y), \rho(x-y)\}$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

1D measurements constrain 2D/4D phase space density of accumulated bunch

1D measurements



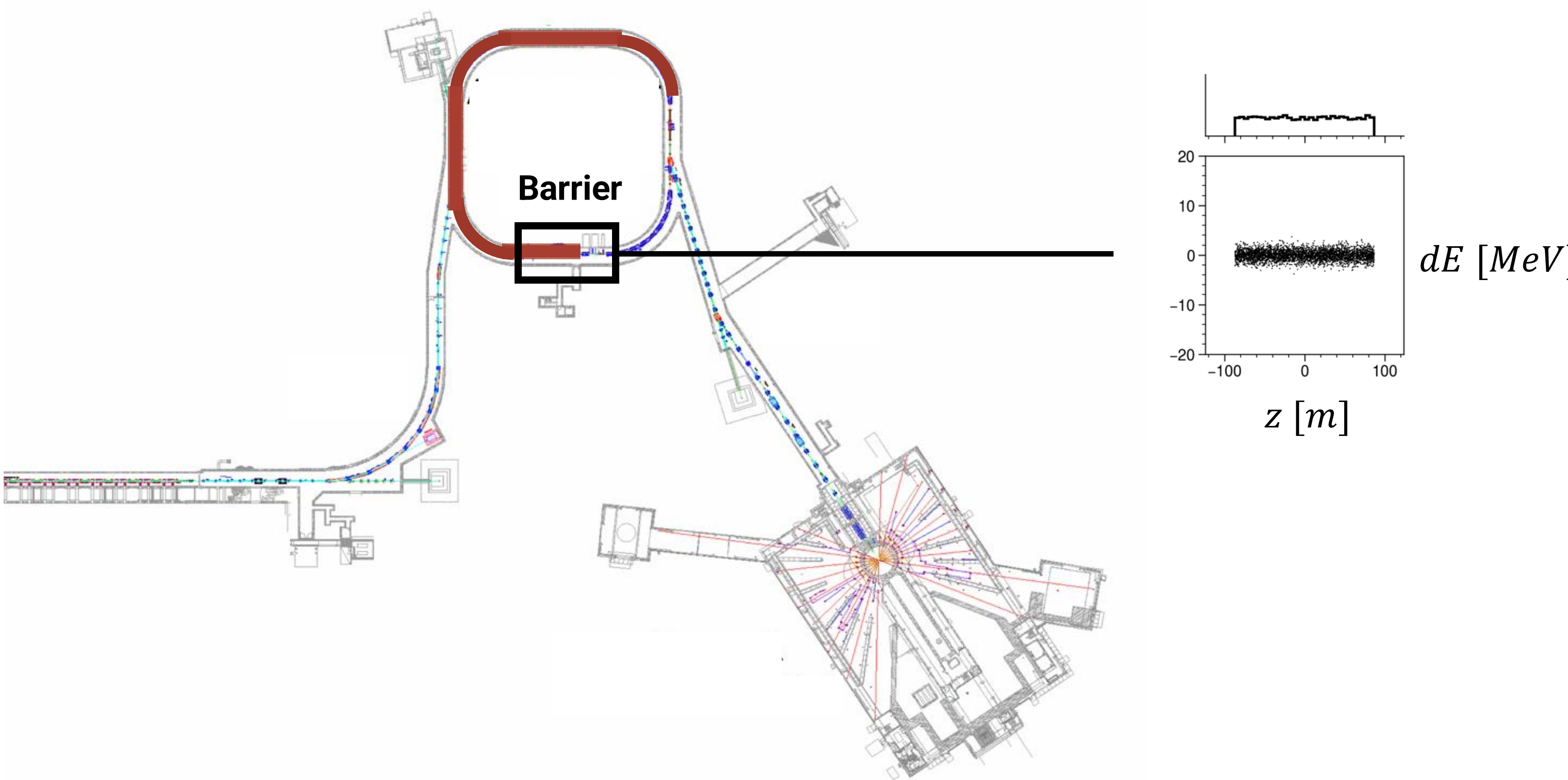
4D phase space distribution



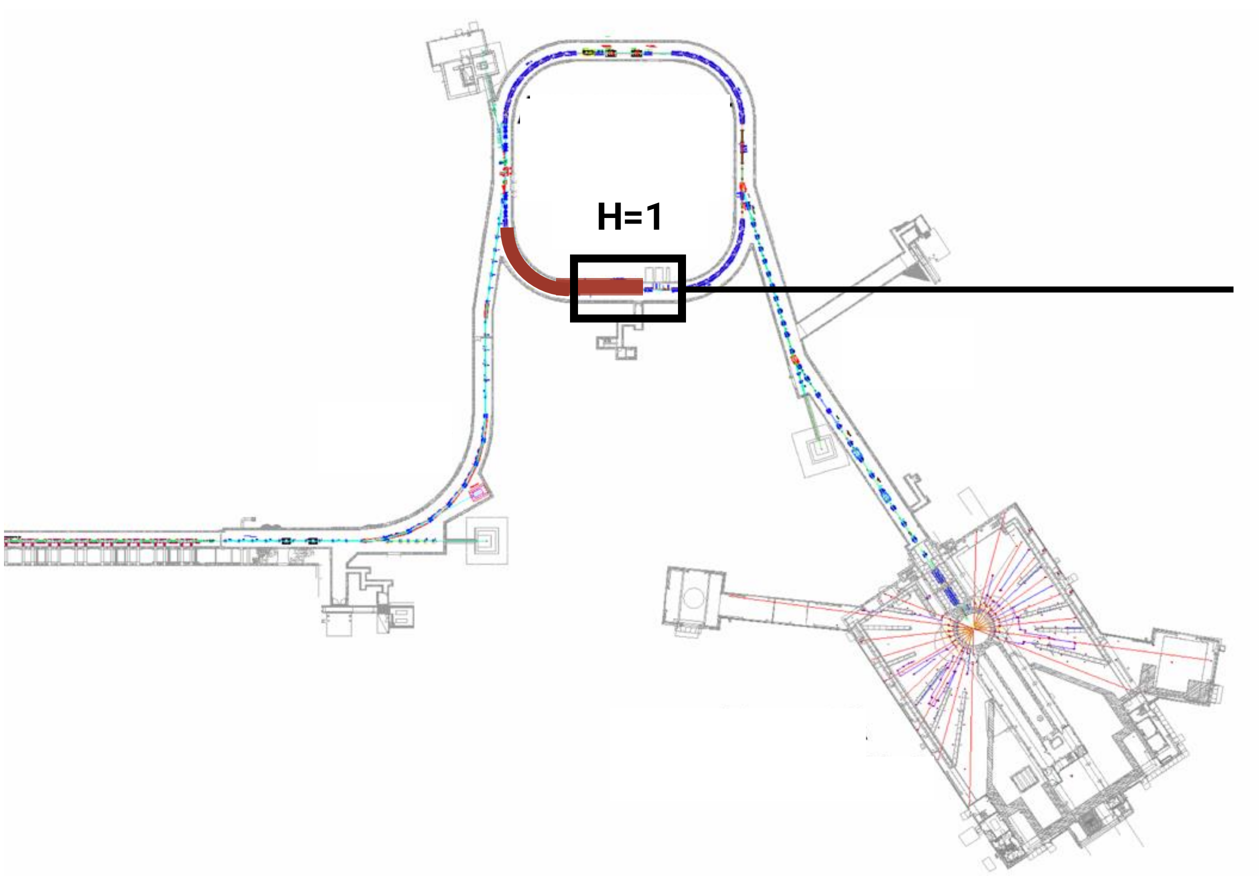
Phys. Rev. Accel. Beams **27**, 122802 (2024)

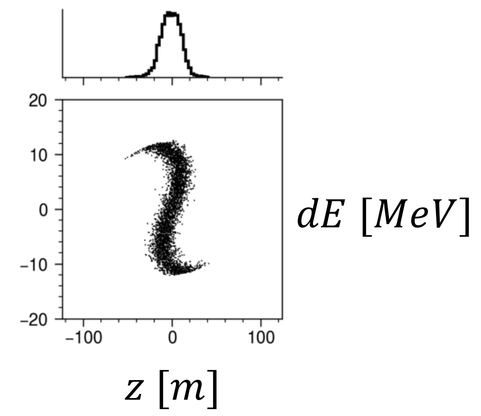
Feasibility of bunch compression at SNS

Goal 1: Accumulate with *barrier* waveform

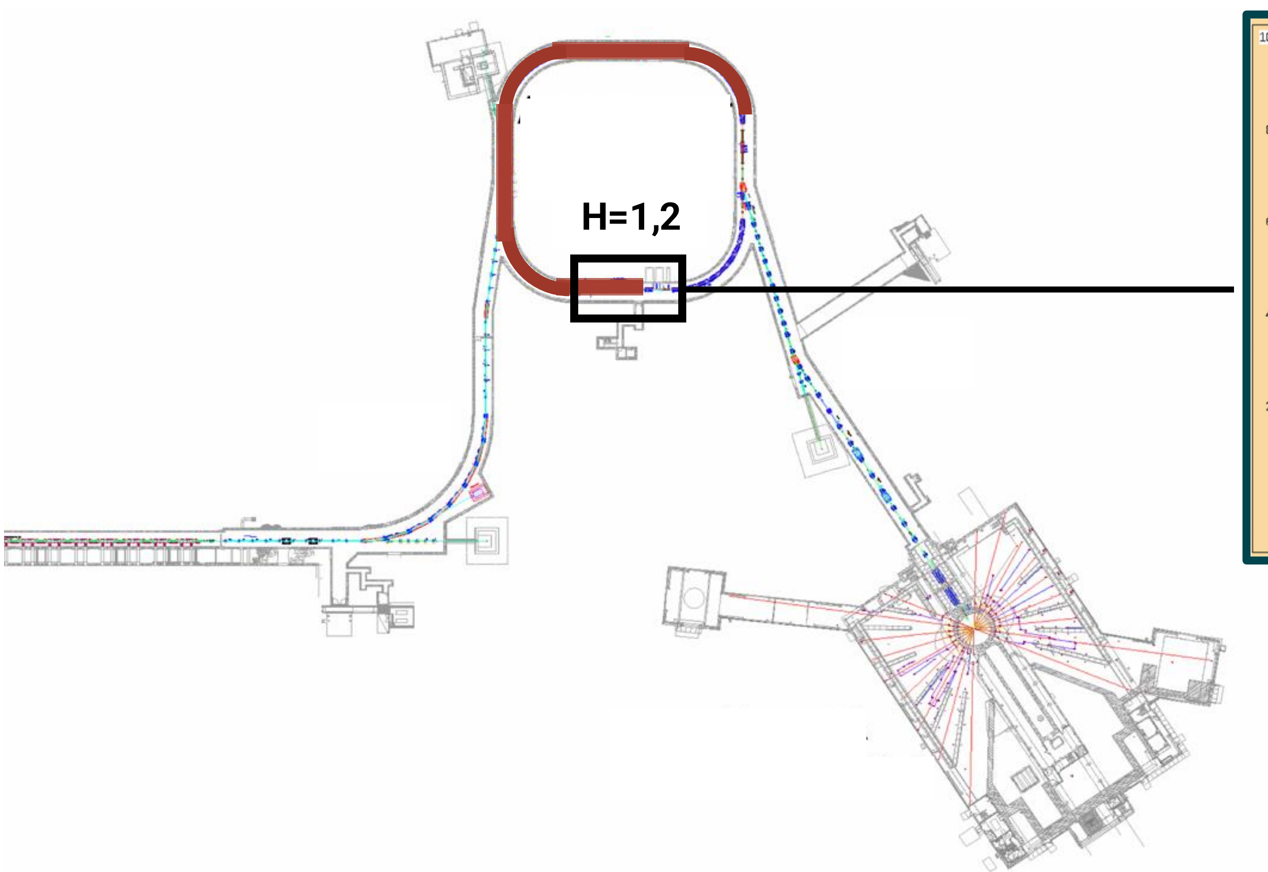


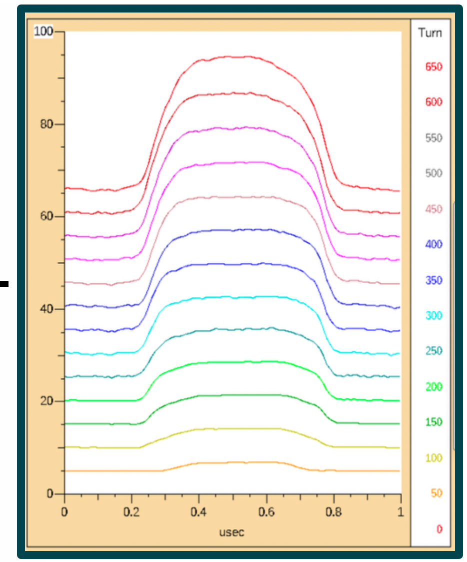
Goal 2: Compress with *single-harmonic* waveform





SNS uses dual-harmonic RF to maintain extraction gap and reduce peak density



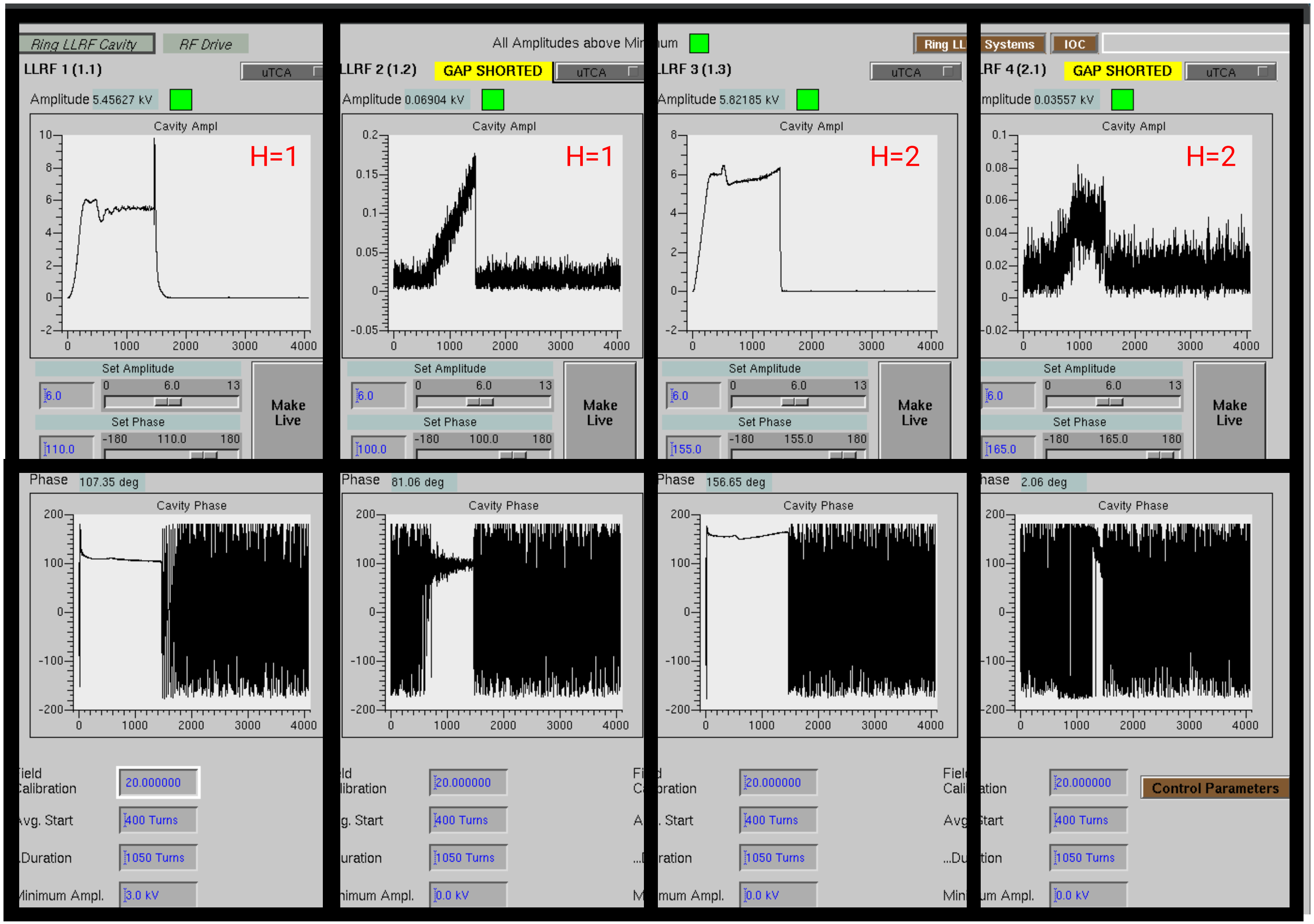


2/4 cavities used during production (6/13 kV)

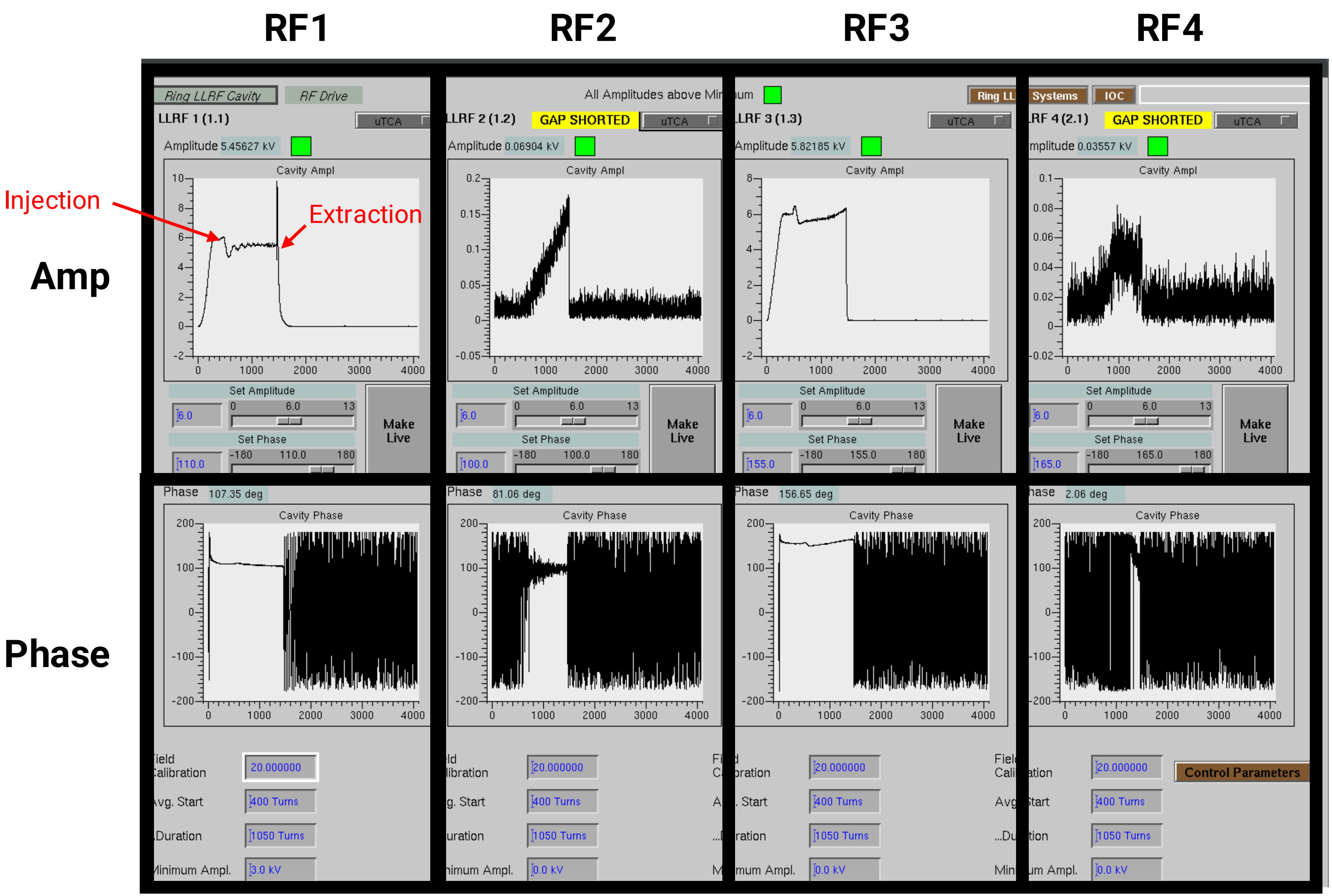
RF1 **RF2** **RF3** **RF4**

Amp

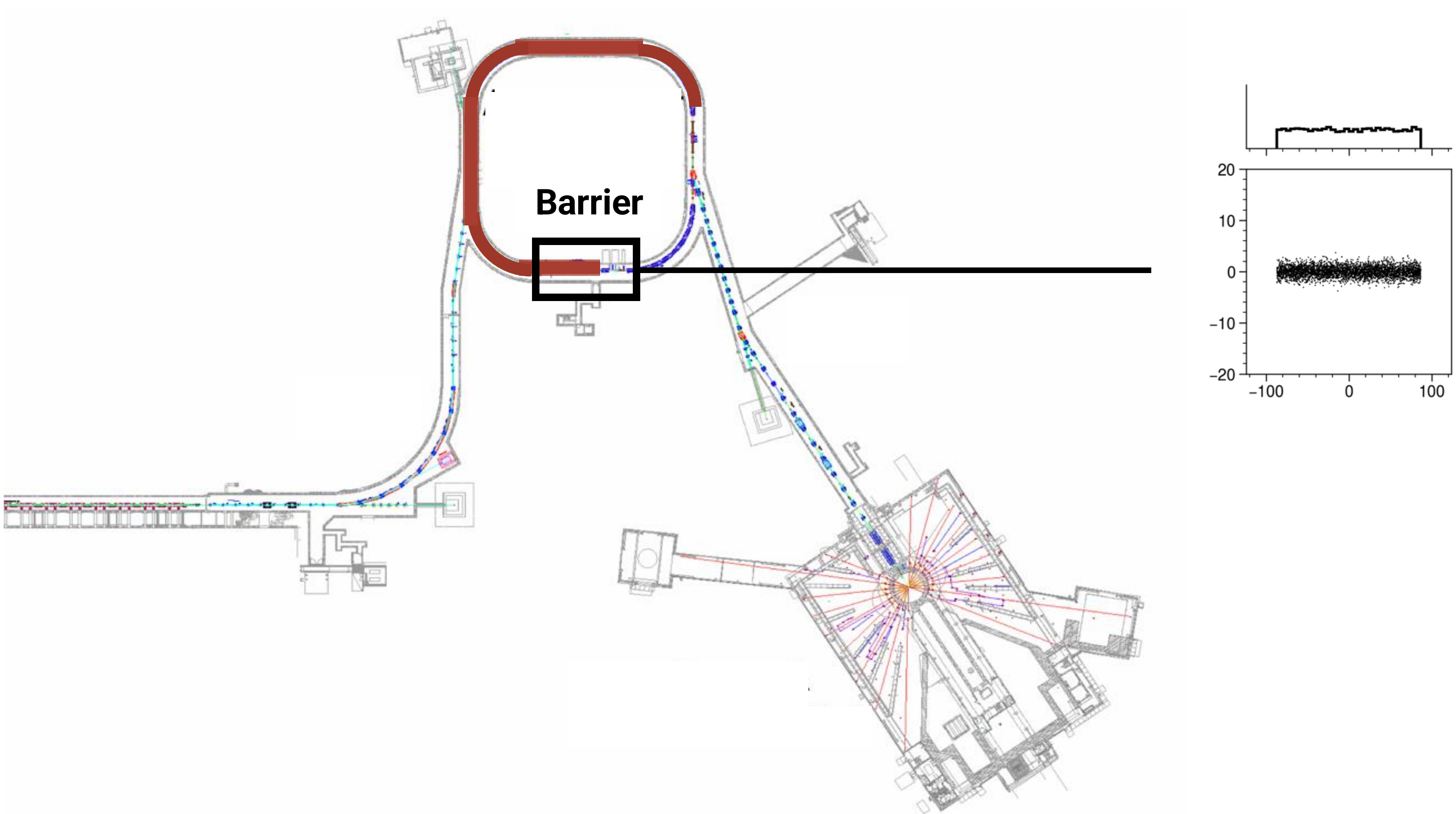
Phase



Feedback system modifies phases/amplitudes



Question 1: Can we approximate barrier waveforms during accumulation?



Question 1: Can we approximate barrier waveforms during accumulation?

Idea 1: Turn off cavities

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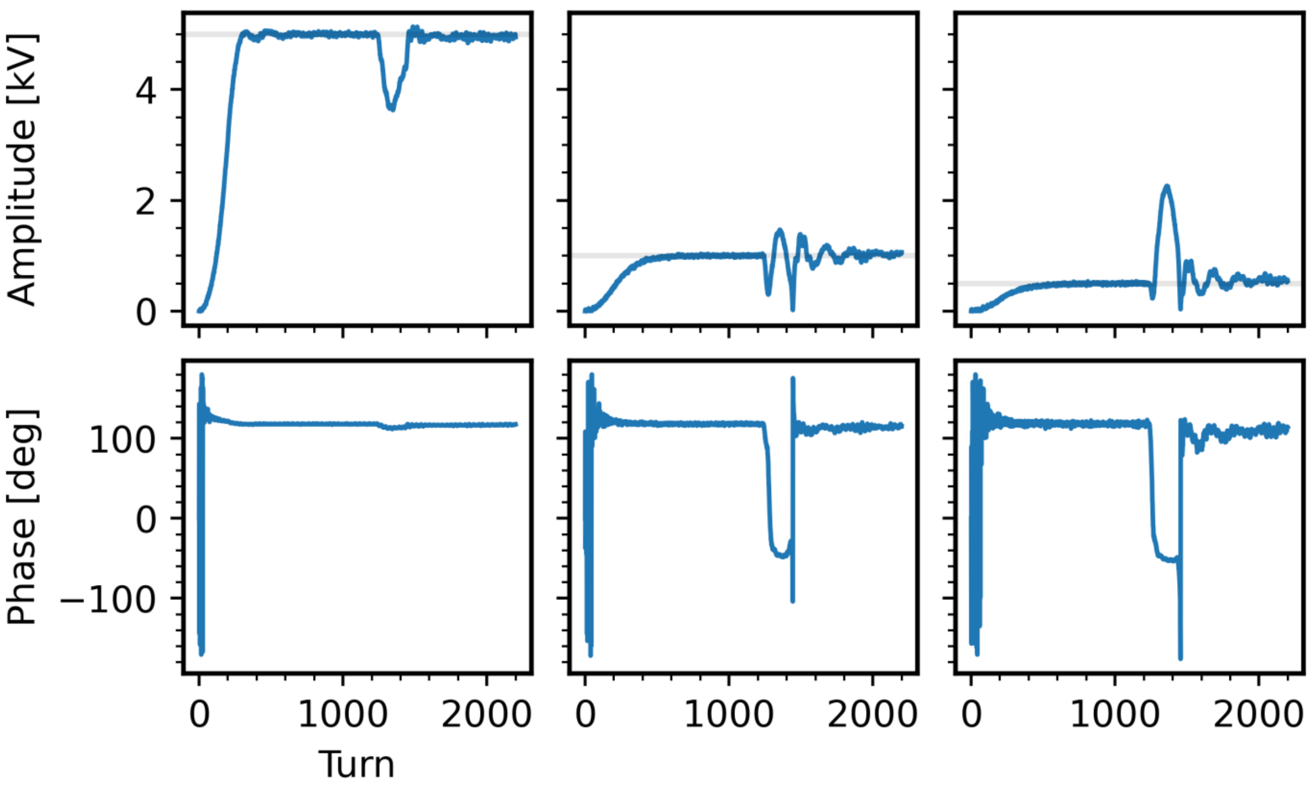
Idea 1: Turn off cavities

Idea 2: Force zero net voltage using RF feedback system


Amplitude [kV]
4
2
0
Phase [deg]
100
0
−100
0
1000
2000
0
1000
2000
0
1000
2000
Turn

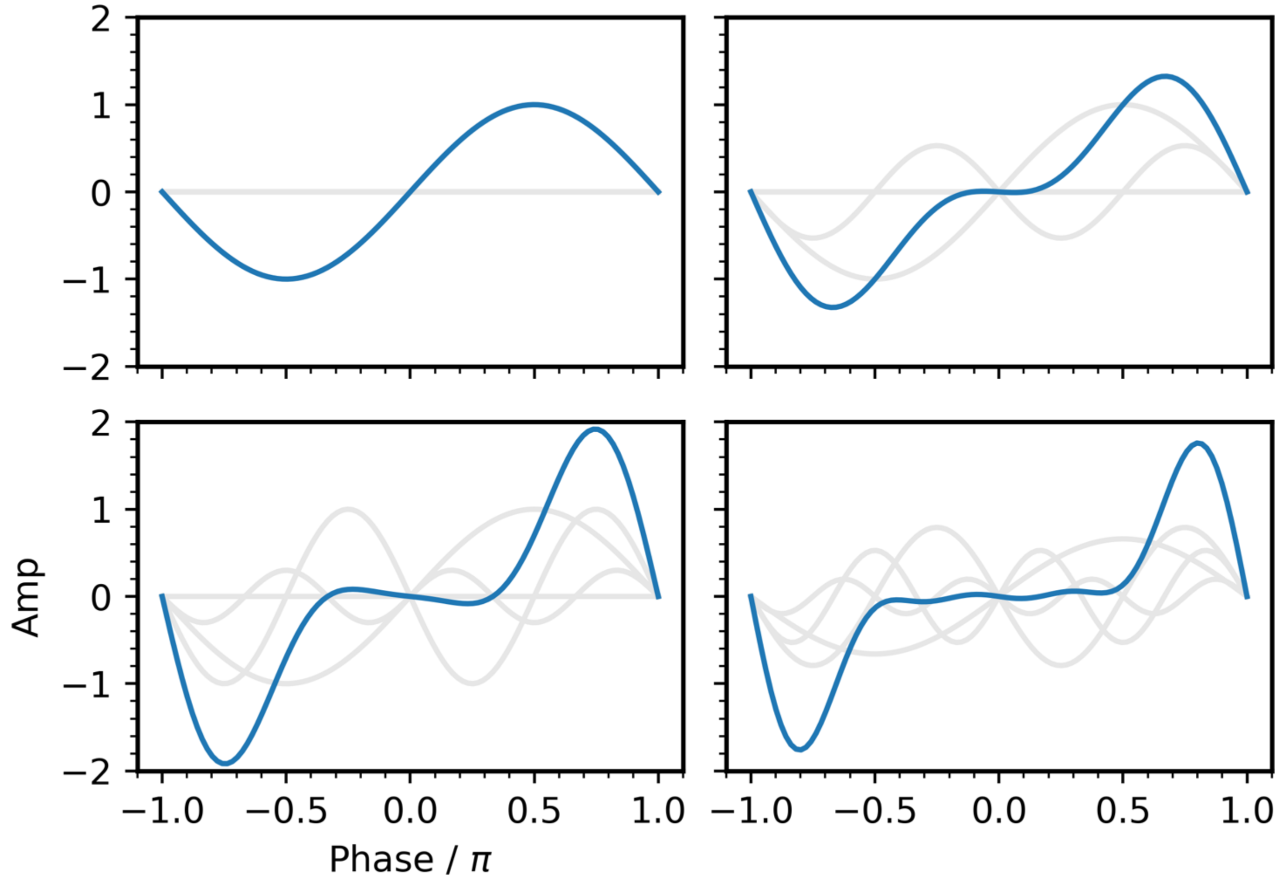
Question 1: Can we approximate barrier waveforms during accumulation?

Idea 1: Turn off cavities

Idea 2: Force zero net voltage using RF feedback system

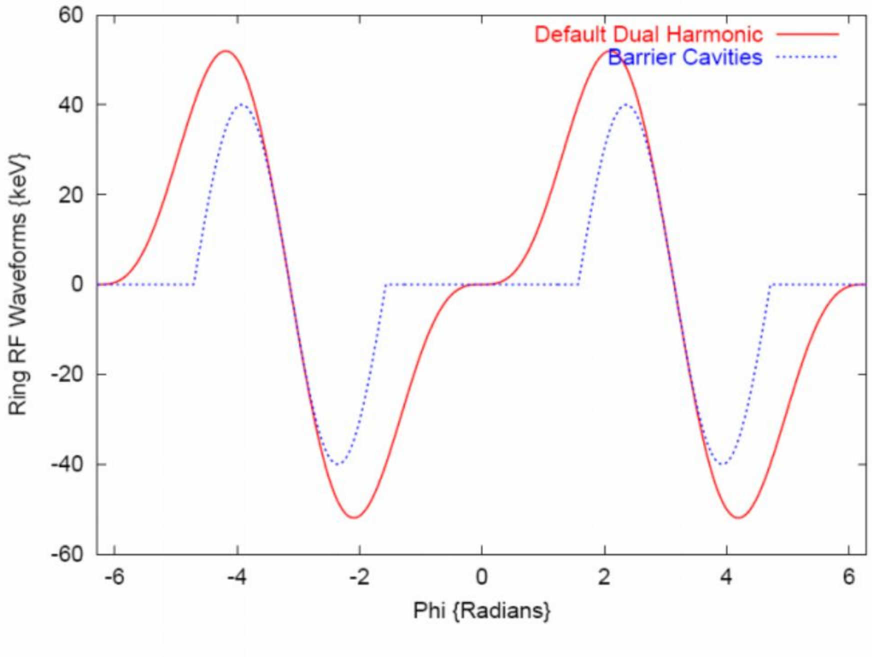
Idea 3: Approximate barrier waveforms using additional harmonics

Four harmonics are enough for ~flat waveforms

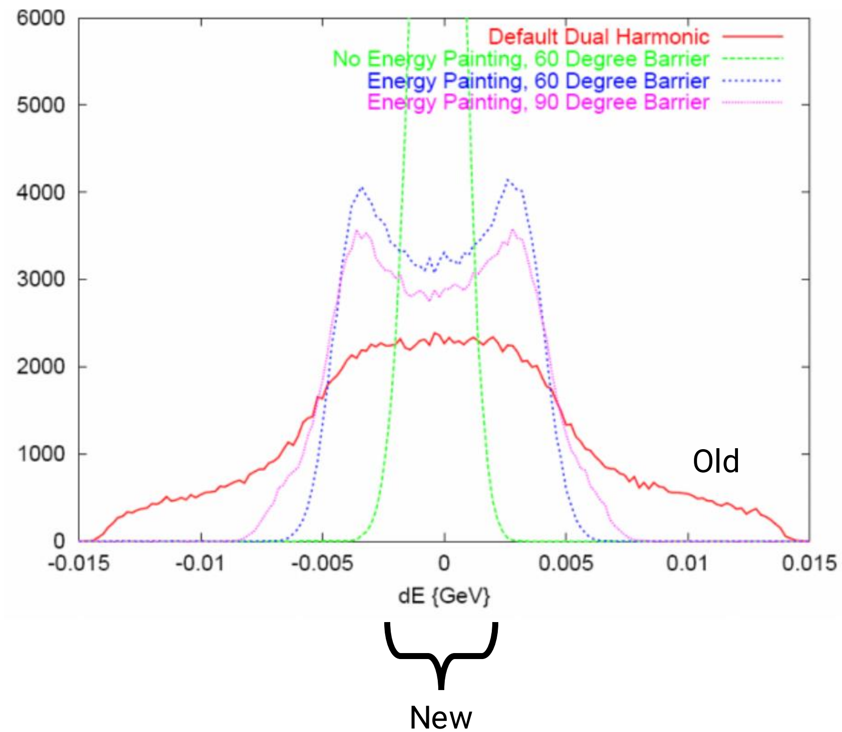


Old simulations show influence of barrier waveforms on longitudinal distribution

Waveforms



Energy distribution



Holmes et al., HB 2006

Unclear if higher harmonics are possible with existing hardware

- Unsuccessful initial attempt to reach h=3 with custom waveform generator and tuning current.
- Reaching h>2 may require new ferrite rings.

Question 1: Can we approximate barrier waveforms during accumulation?

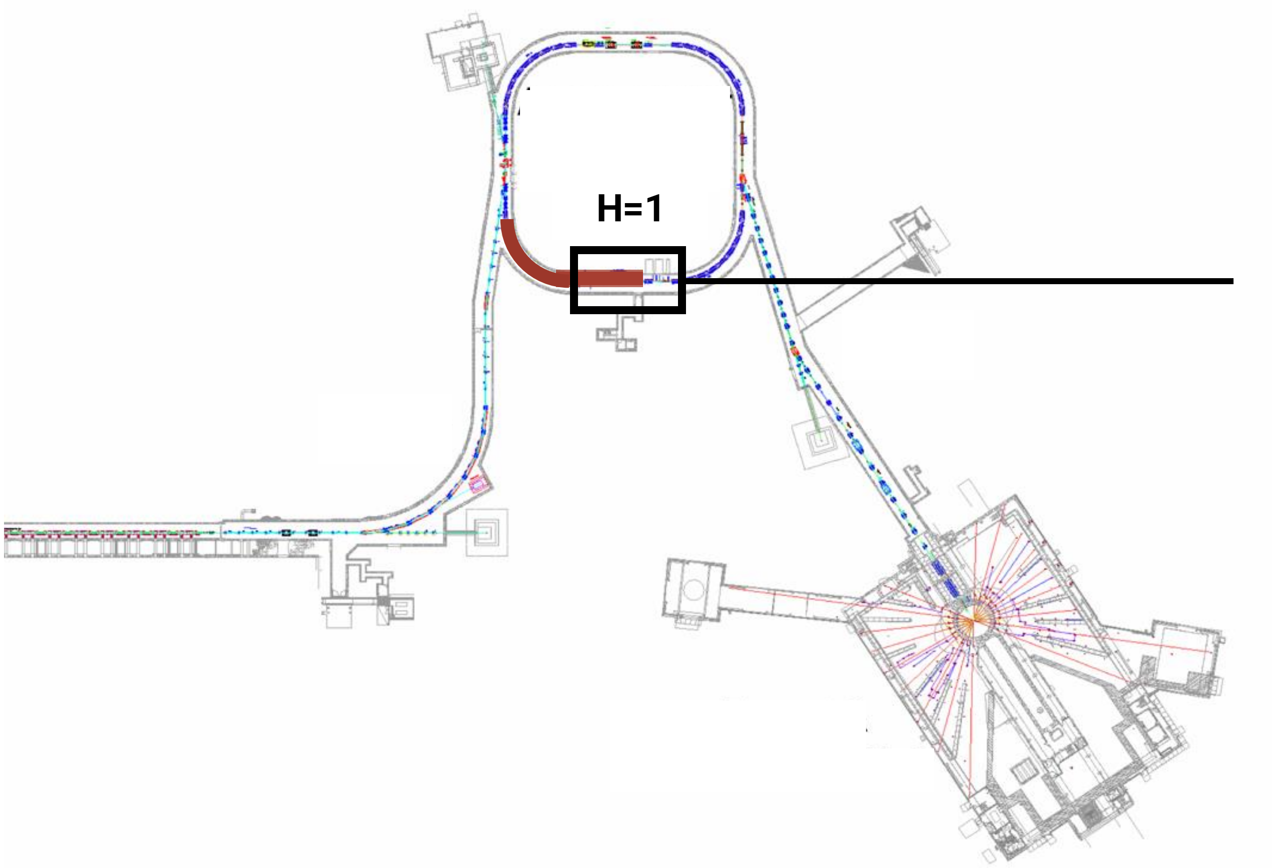
Idea 1: Turn off cavities

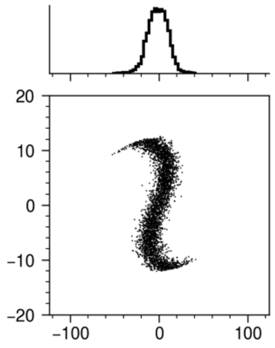
Idea 2: Force zero net voltage using RF feedback system

Idea 3: Approximate barrier waveforms using additional harmonics

Idea 4: Install new barrier cavities [$$$]

Question 2: Can we compress the bunch?



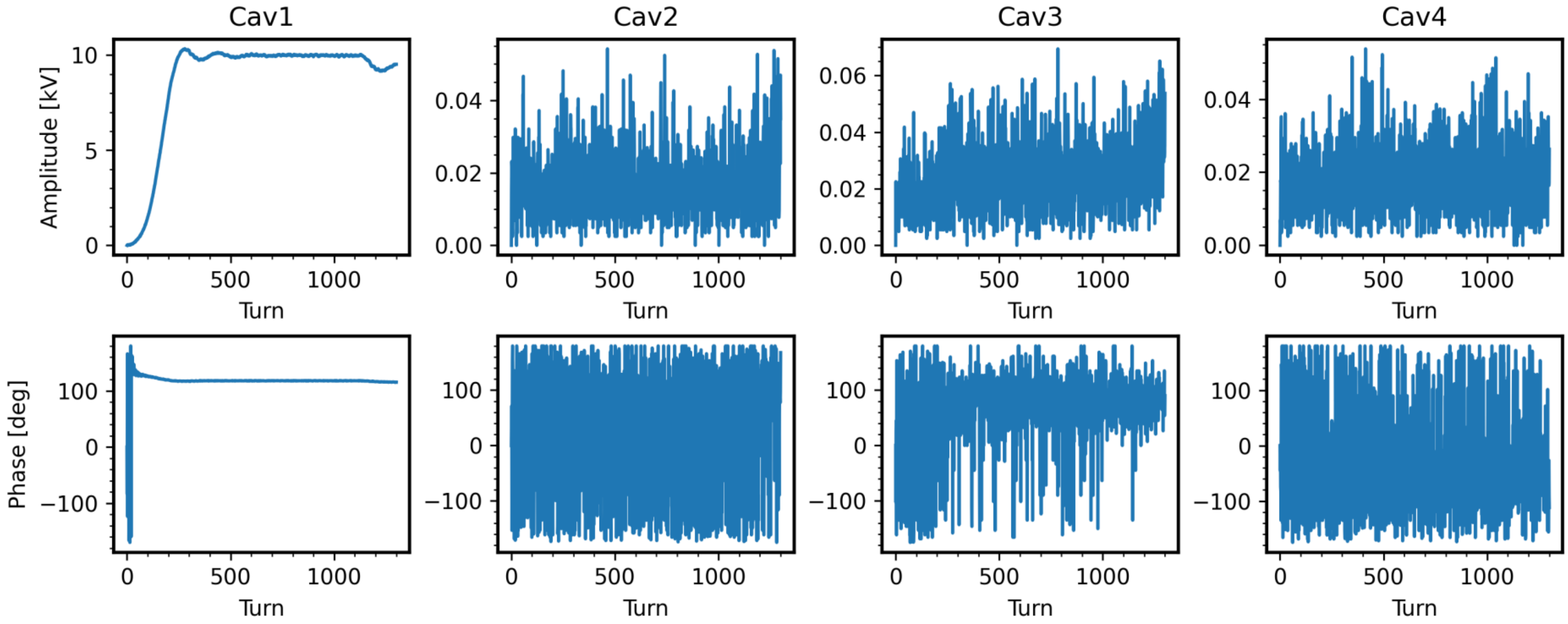


Question 2: Can we compress the bunch?

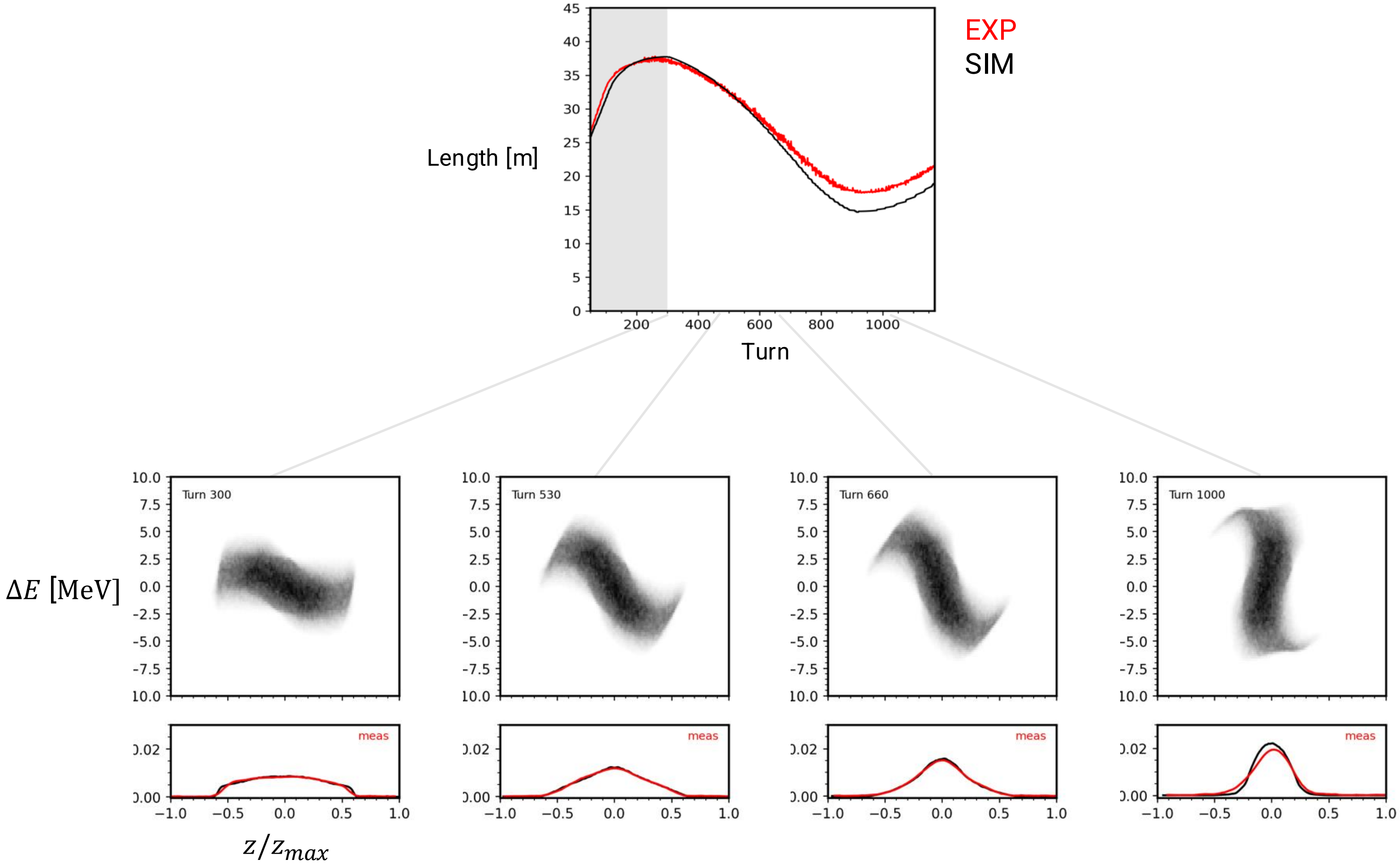
- Max voltage ~ 20 kV (with 2 cavities).
- Synchrotron period ~ 2000 turns (at 1.3 GeV)
- New custom waveform generator should allow switching waveforms mid-cycle.
- Limited storage time — try to extend.
- Optimal RF settings accounting for collective effects?

Initial experiment and simulation benchmarking

Initial experiment injected 300 turns into 10-kV RF voltage (closed loop)

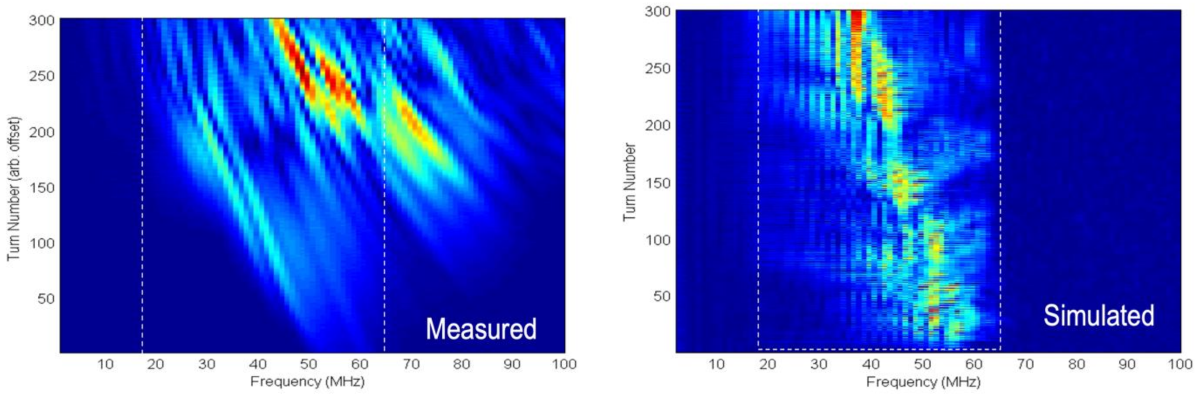


1D simulation shows reasonable agreement with initial experiment



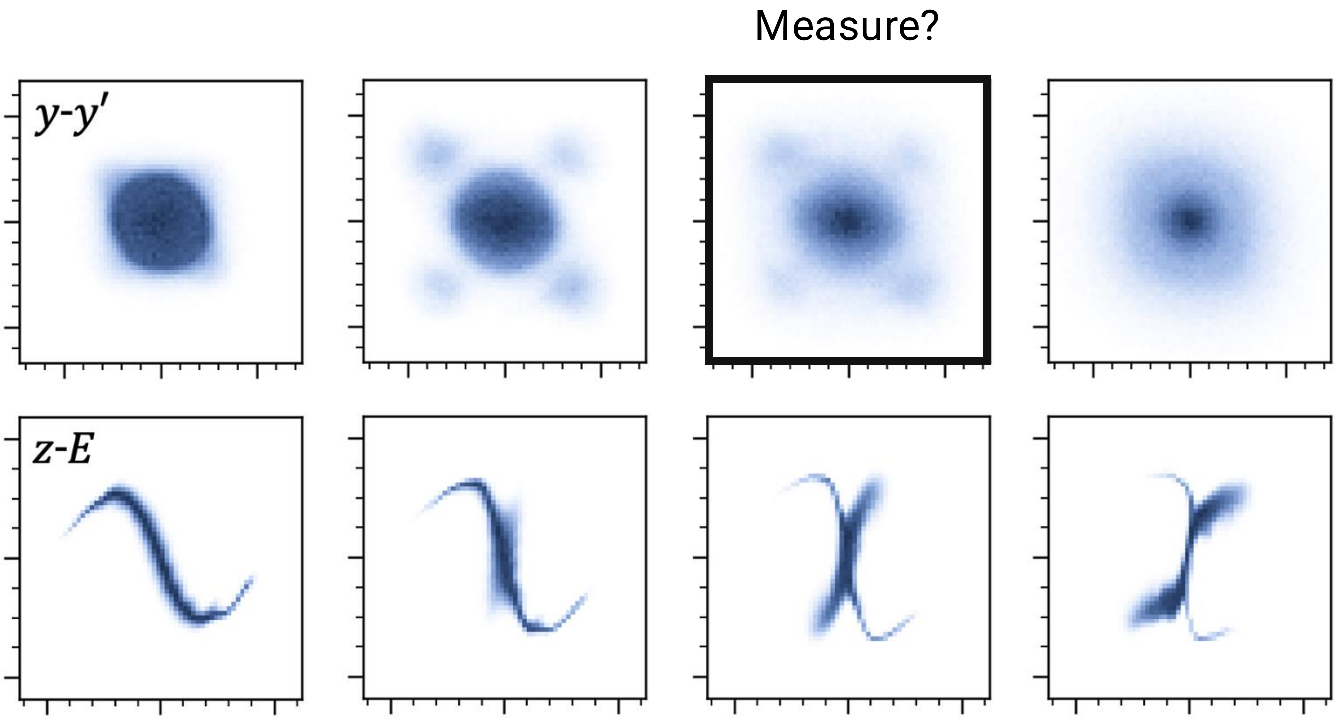
Future modeling/benchmarking considerations

- Codes: (PyORBIT, ImpactX, Xsuite)
- Space charge solver (3D/2.5D/2D/1D)
- Wake fields, beam-cavity interaction, feedback system
- Electron cloud



Cousineau et al., ECLOUD 2007

Are nonlinear space charge forces resolved properly?

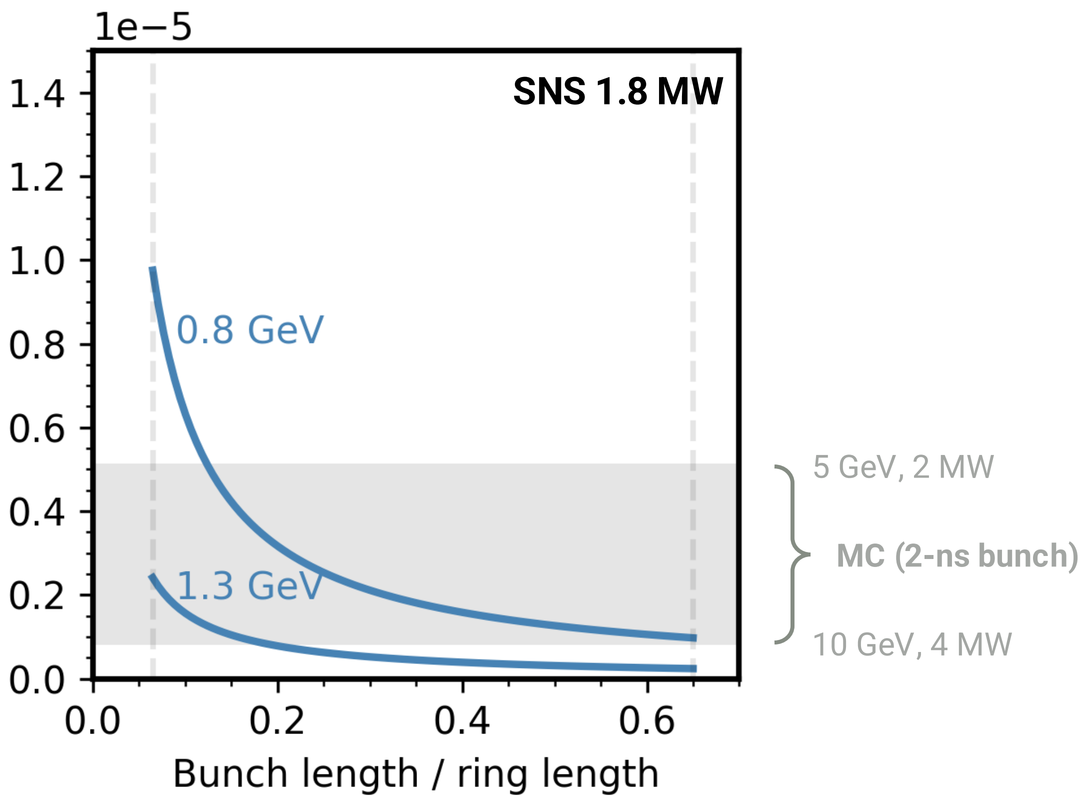


Conclusion

- Bunch compression experiments ongoing at SNS.
- Success may depend on RF engineering/hardware upgrades.
- Interested to collaborate with other facilities
- Future work: explore limits of current setup and develop simulation benchmarks.
- *Acknowledgements*: Chip Piller, Amith Narayan, Nick Evans, Wim Blokland, Inci Karaaslan, Sarah Cousineau

With strong compression, SNS could probe MC space charge regime

$$Q \sim \frac{\lambda}{\beta^2 \gamma^3}$$



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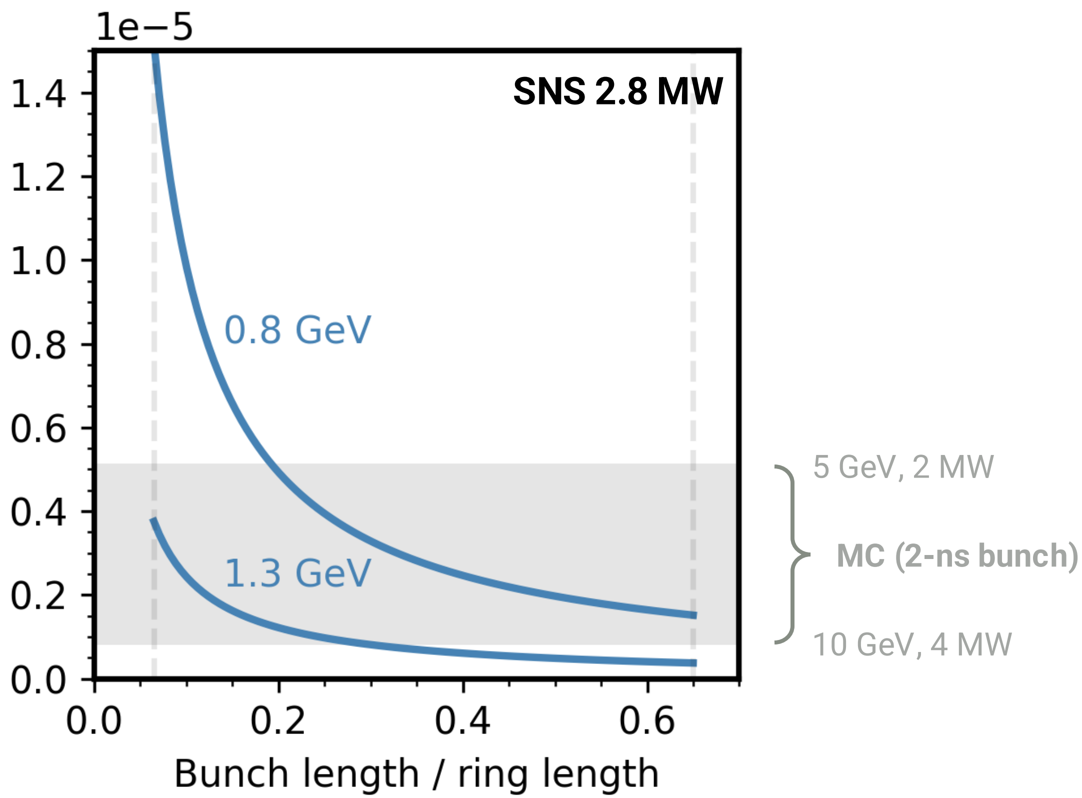
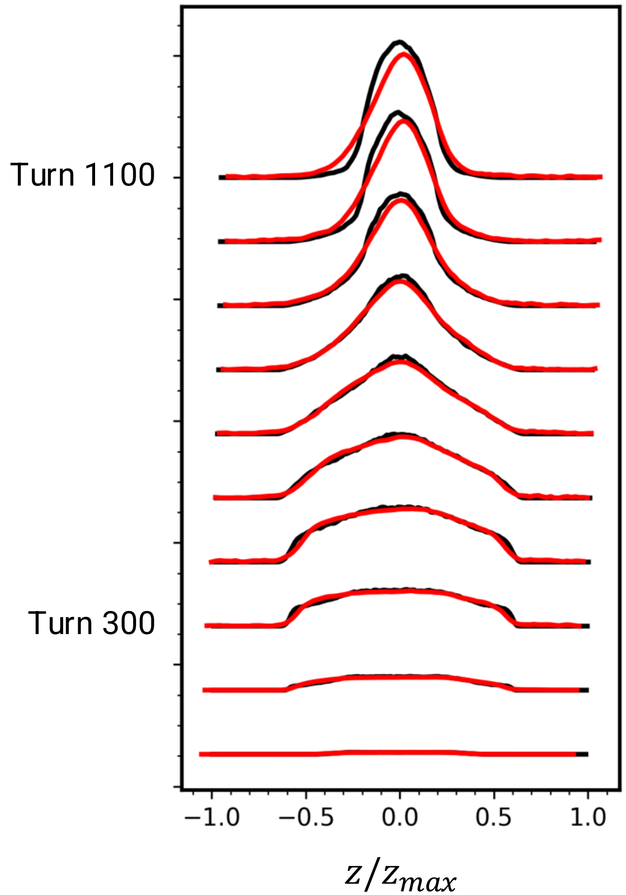
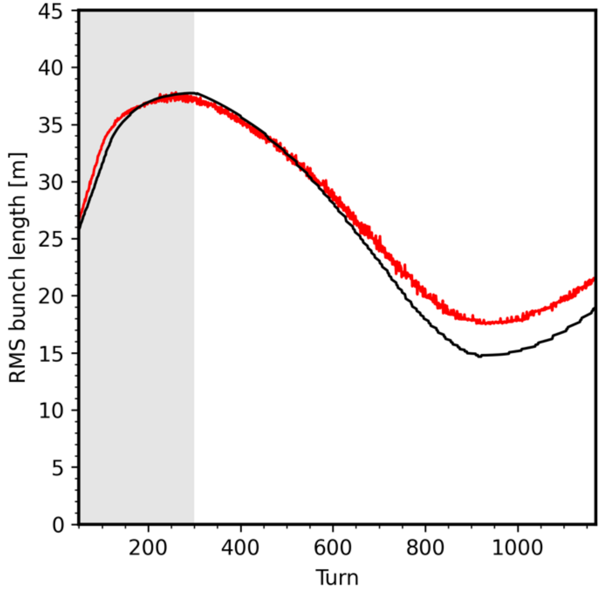


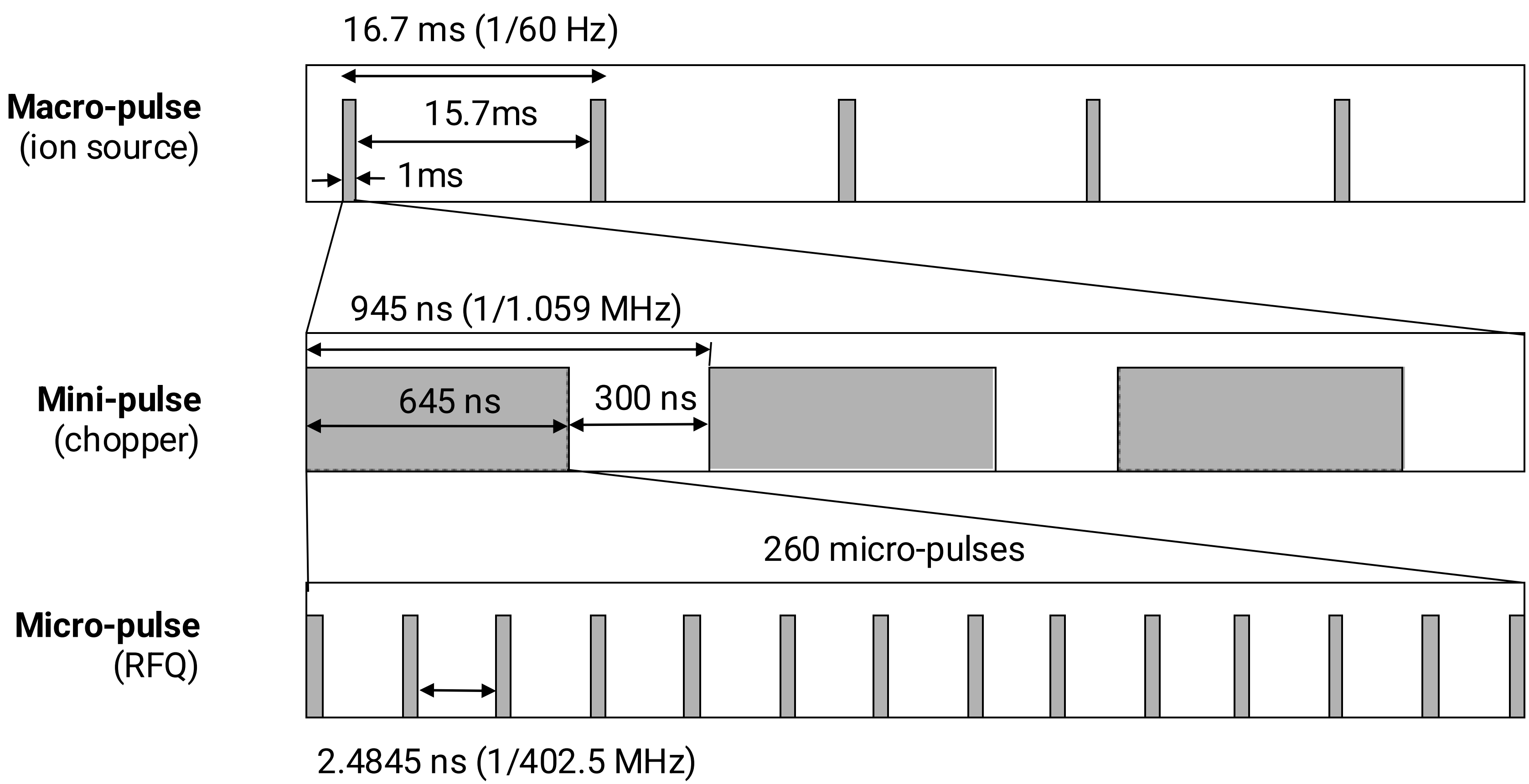
1D simulation shows reasonable agreement with initial experiment

TBT profiles



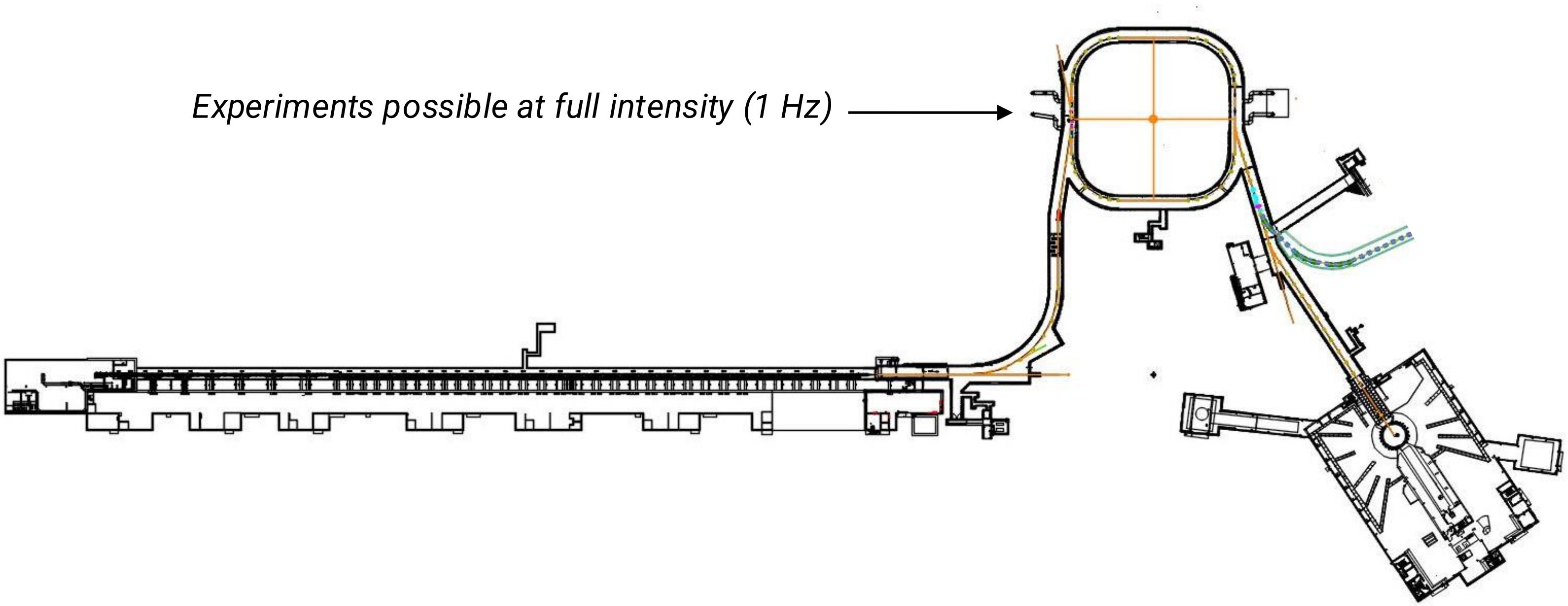
RMS length (10% thresh)




16.7 ms (1/60 Hz)
Macro-pulse
(ion source)
15.7ms
1ms
945 ns (1/1.059 MHz)
Mini-pulse
(chopper)
645 ns
300 ns
260 micro-pulses
Micro-pulse
(RFQ)
2.4845 ns (1/402.5 MHz)

SNS today: 1.55×10^{14} protons per pulse

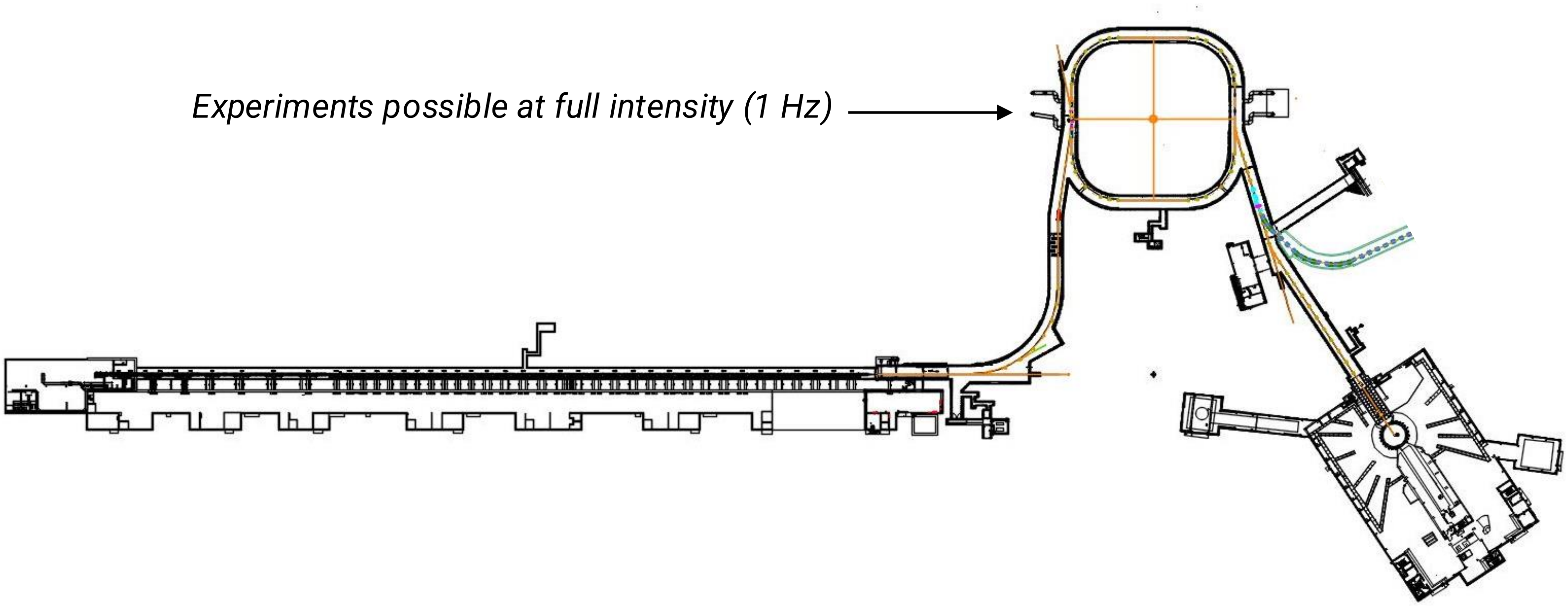
Experiments possible at full intensity (1 Hz) →



1.7 MW @ 60 Hz

SNS soon: 2.25×10^{14} protons per pulse

Experiments possible at full intensity (1 Hz)



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

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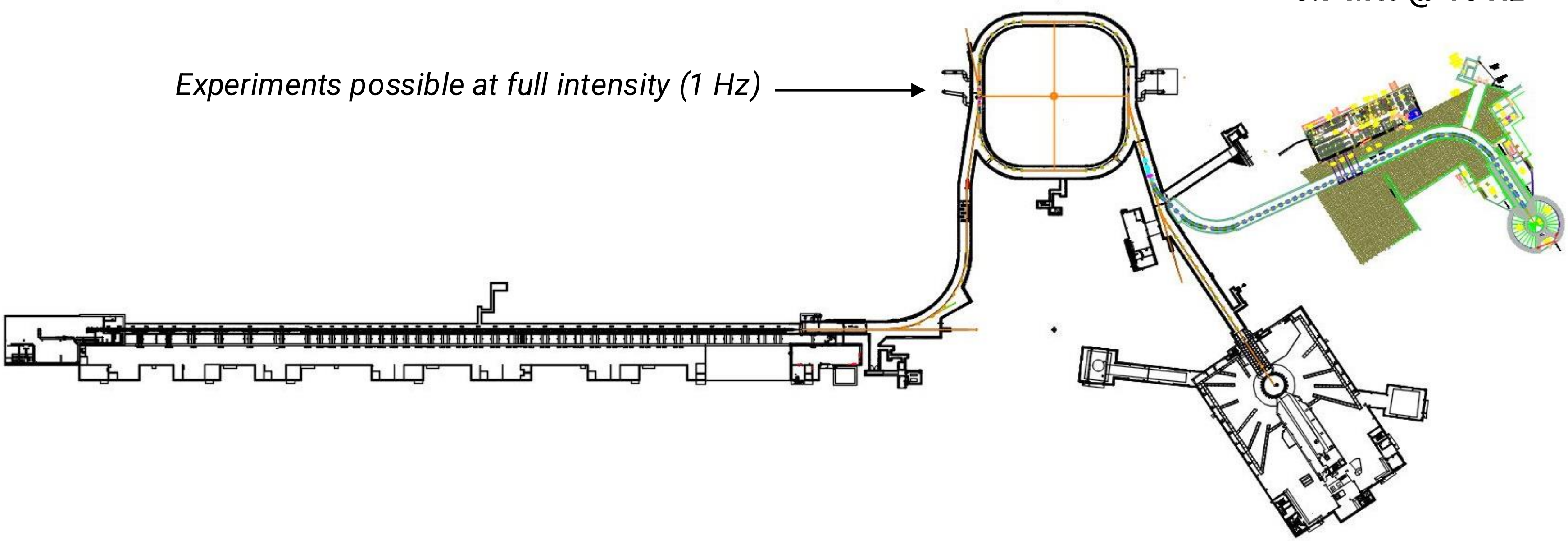
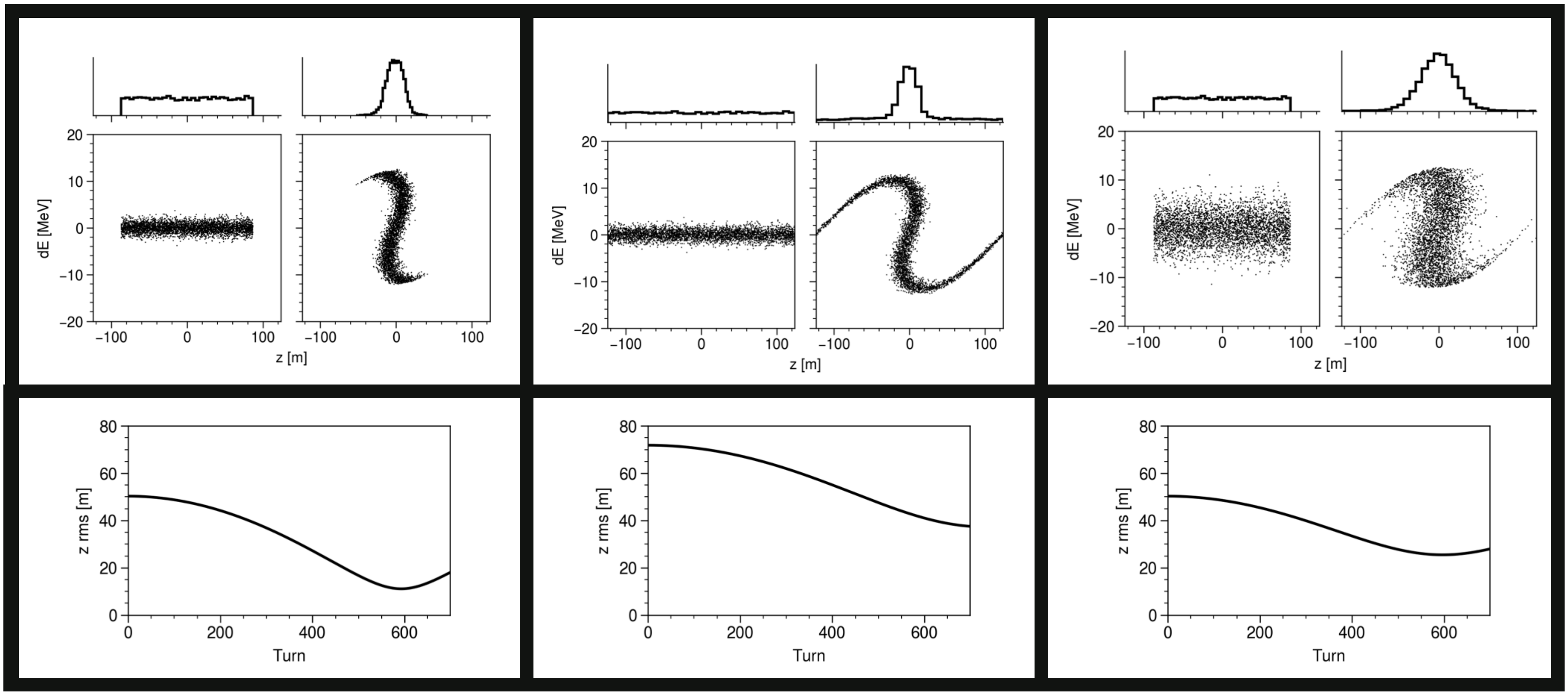
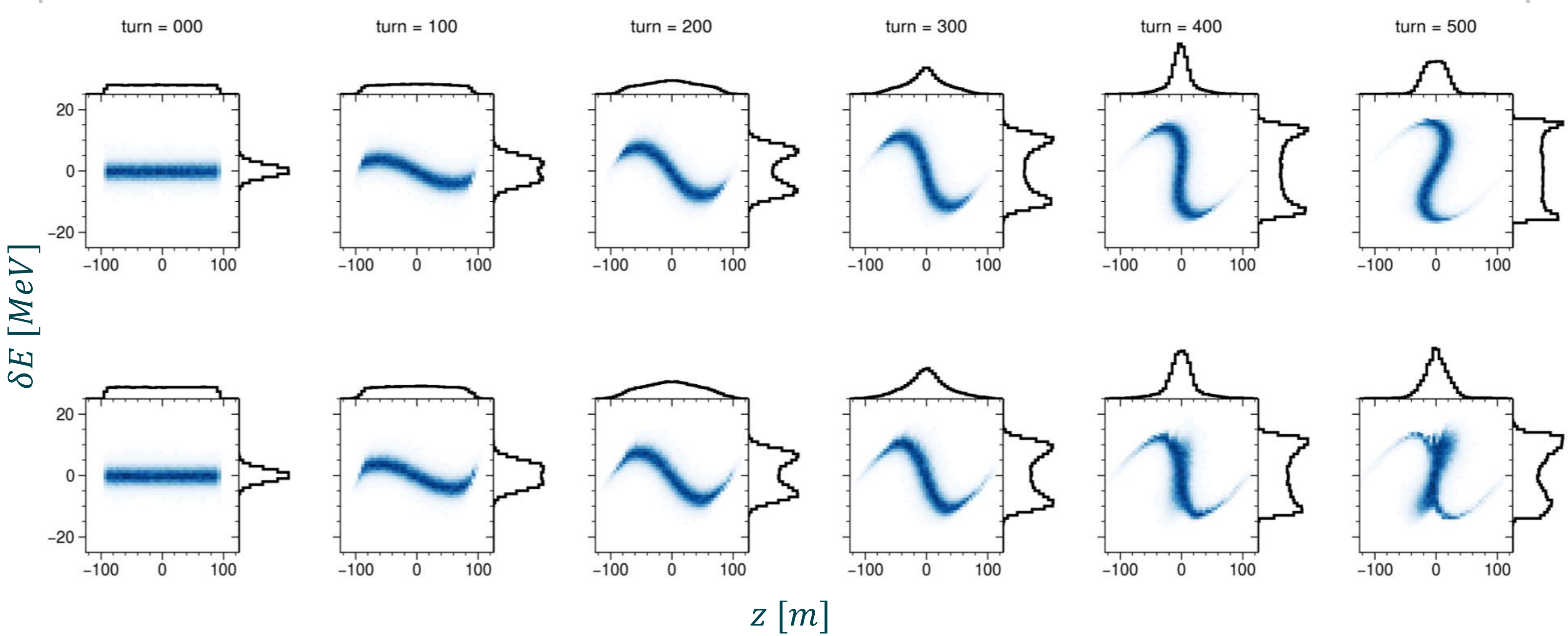
SNS in 10-15 years: Second Target Station



Zero-space-charge simulation shows moderate compression for realistic energy spread



Zero charge



Full charge

Ring RF Cavity
(h1 configuration,
four 750 pF capacitors
installed per gap)

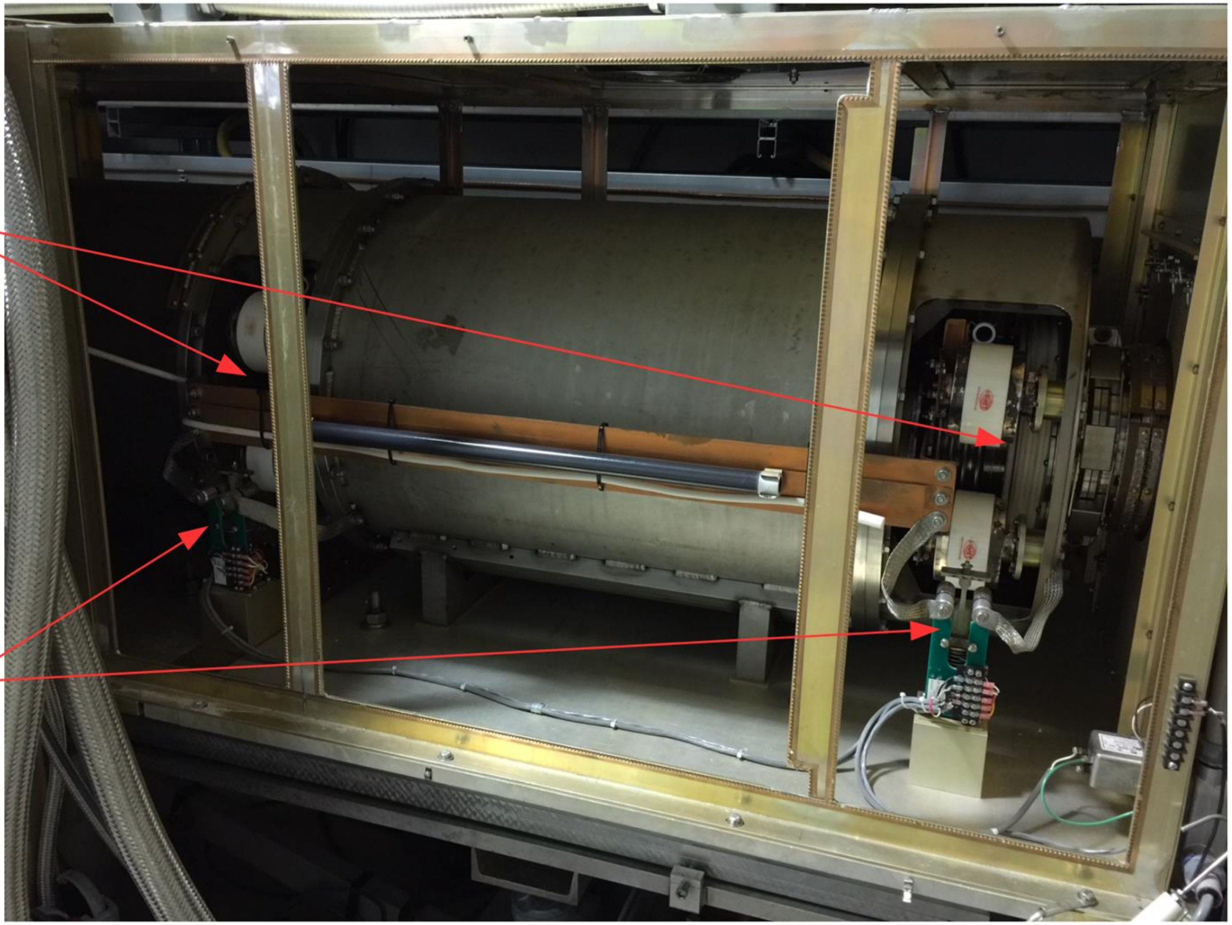
Two accelerating gaps

Two tank sections
each tank houses
21 Ferrite rings, provides
inductance for cavity

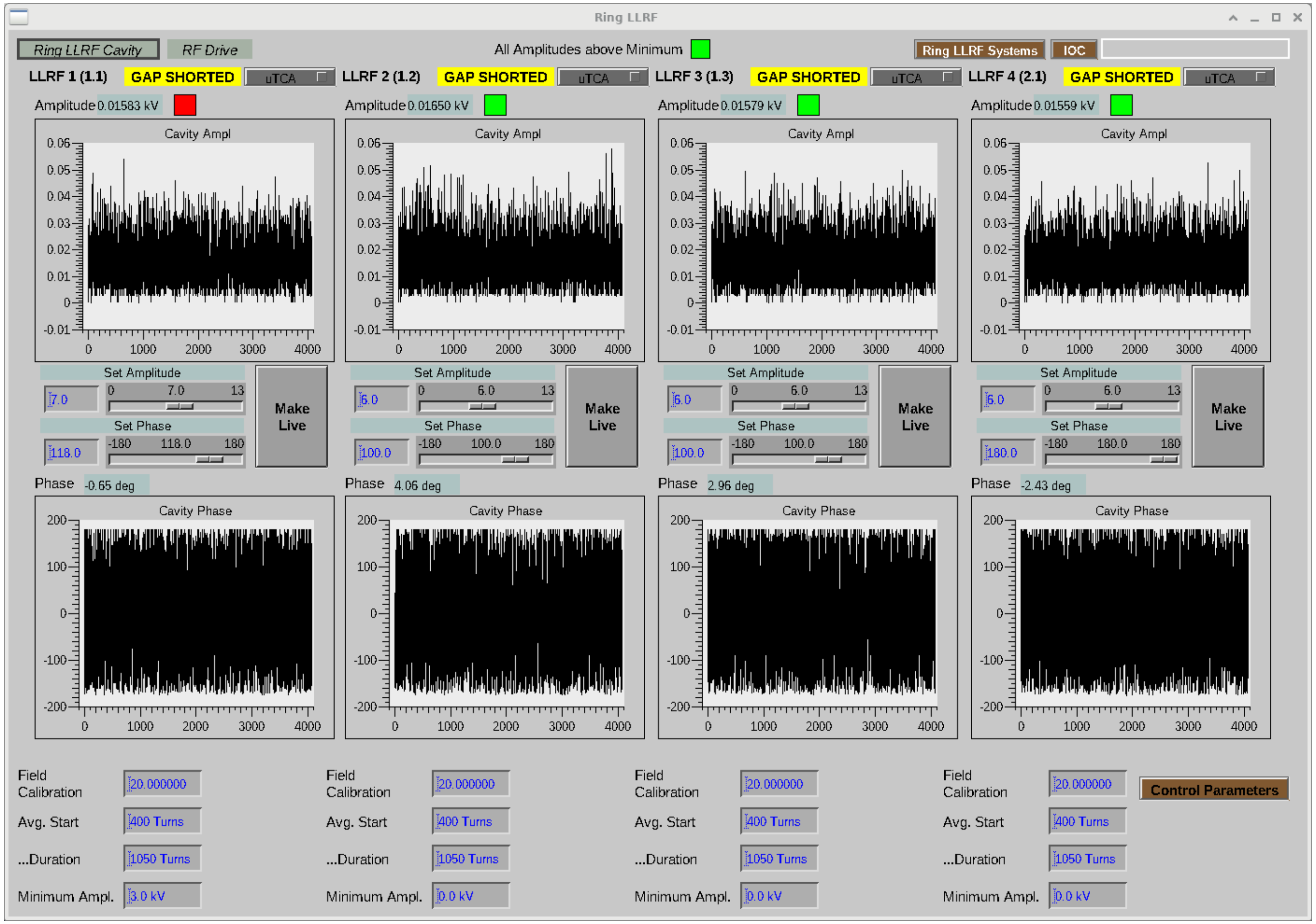
Buss bar connections

Gap short / unshort relays
(normally open)

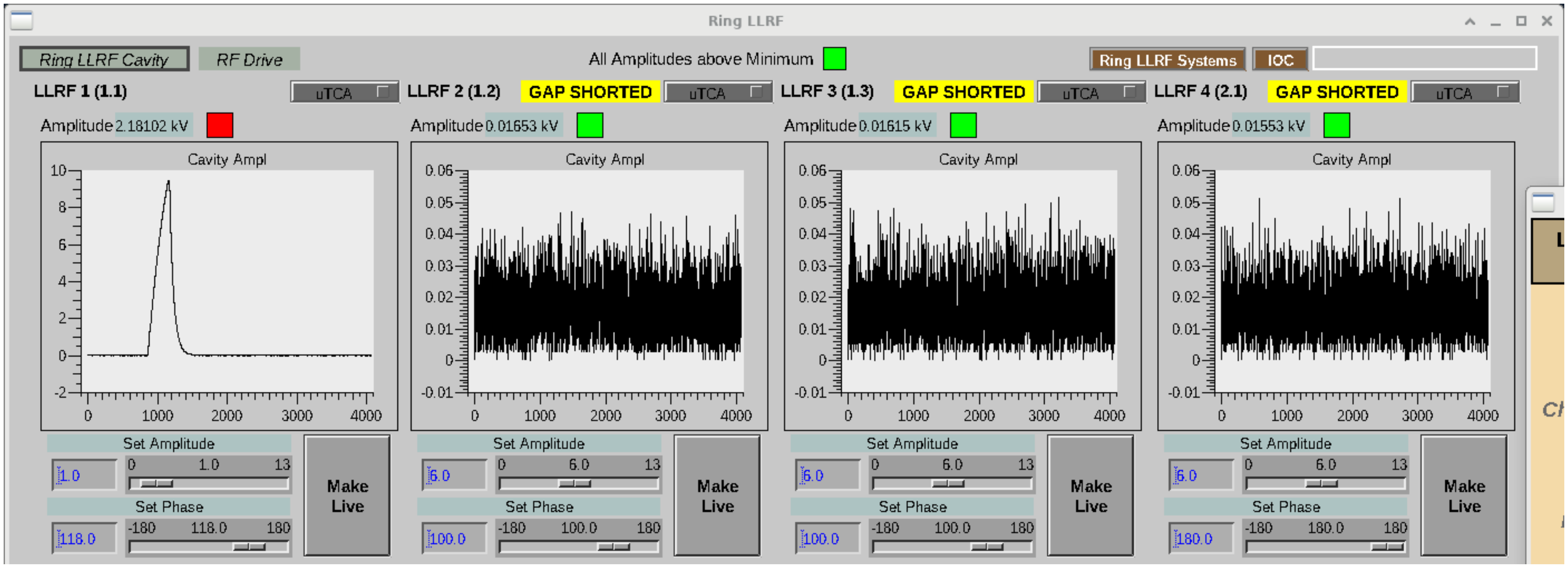
<--- beam direction right to left



Shorting cavities works, but can’t unshort after accumulation



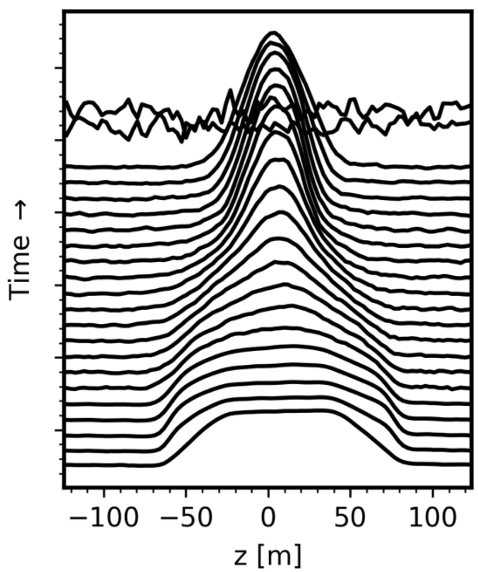
Beam-induced voltages limit beam intensity when operating cavities in open-loop



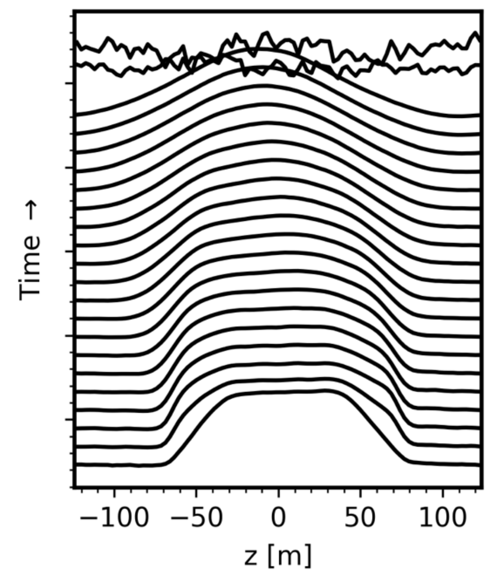
300-turn accumulation. Approaching 12 kV limit.

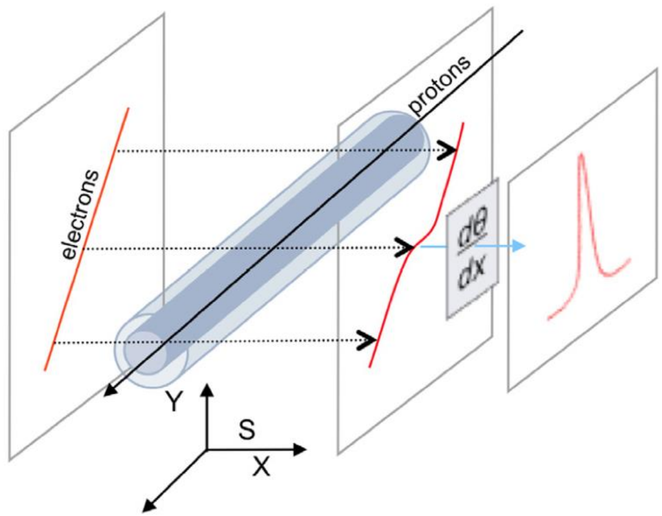
Can we use multiple cavities same frequency but different phases?

$\phi_1 = \phi_2$



$\phi_1 = \phi_2 + \pi$




protons
electrons
dθ
dx
Y
S
X