Muon Collider Proton Driver R&D Design

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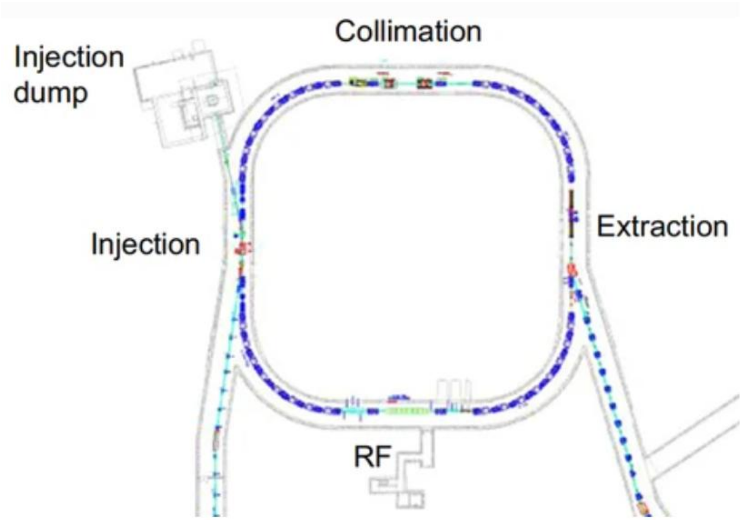
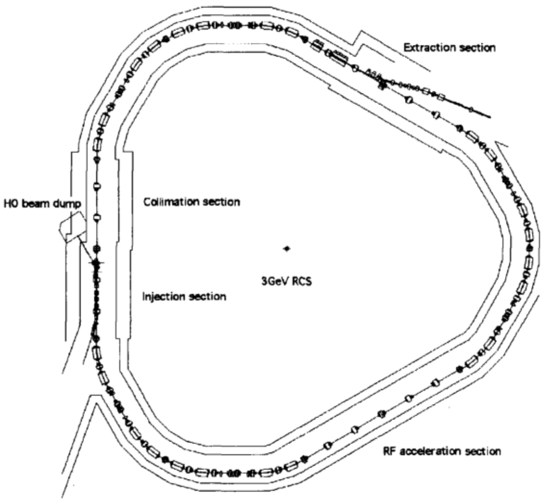
Seminar Series for the
National Lab Muon Accelerator Study Group
November 11th 2025

Existing Proton Machines (~2007)





1) Oak Ridge SNS
Neutron Spallation Source
1.0 GeV AR, ~1.4MW
1.3-GeV AR, -> 2.8MW

2) J-PARC RCS
Meson/Muon Production
0.2-3 GeV RCS, ~0.5MW
0.4-3 GeV RCS, -> 1.4MW

Both MW-class facilities that serve as a model for proton driver…
Except we need 2-4MW, 5-12 GeV, 1-3ns pulses (from ~us).

Proton Driver as Muon Collider R&D Topic

Candidly, proton driver design is not biggest factor for technical risk, muon collider performance, or overall cost.

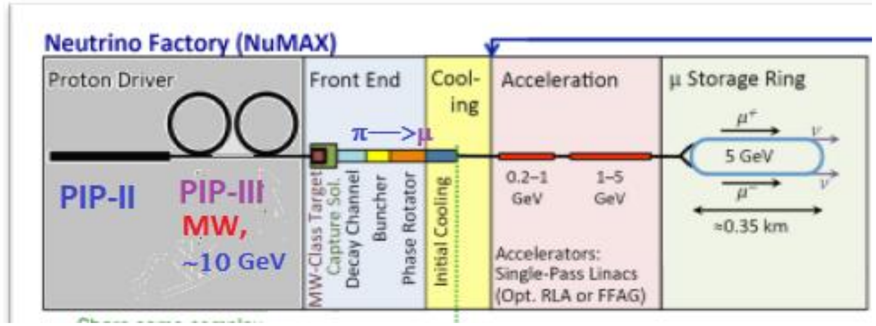
- Closest to existing technology and operational experiences.

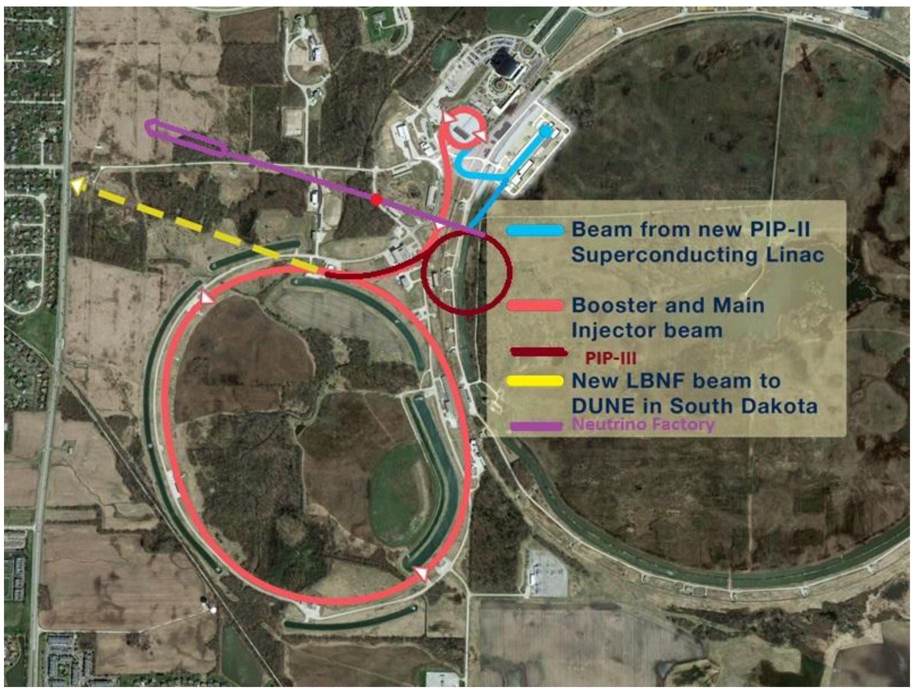
So why study proton driver as a muon collider R&D topic?

- We are still working towards a self-consistent baseline scenario.
- Any technical risk that we can offload from the muon-side onto the proton driver would be highly cost-effective.
- Proton driver is chronologically first by virtue of being upstream. For the hypothetical Gantt chart of building a Muon Collider, it needs the highest level of technical readiness.
- Proton drivers present opportunities for HEP staging.

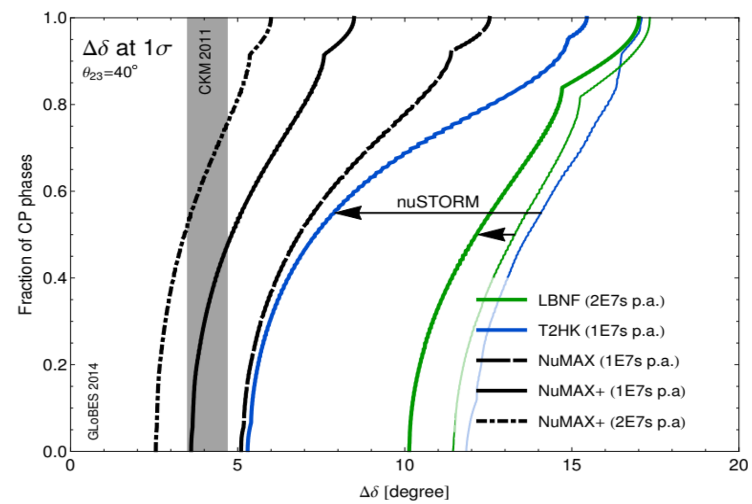
Possible Proton Driver HEP Staging

1) Built Proton Driver
2) Built separate muon ring for neutrino program.
3) Continue MC construction.

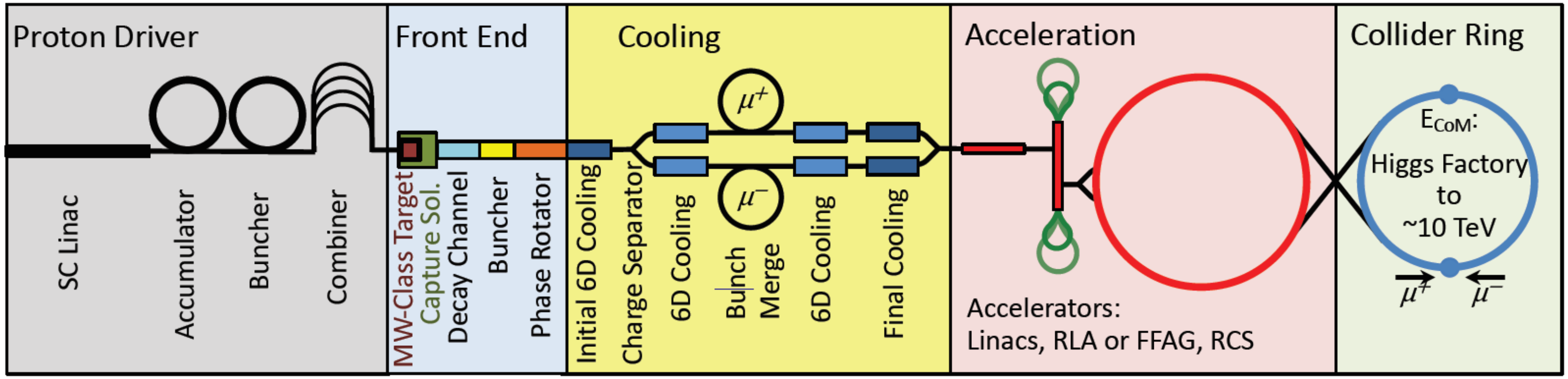




Vastly improves δ_{CP} resolution.
Unitarity tests of PMNS matrix.



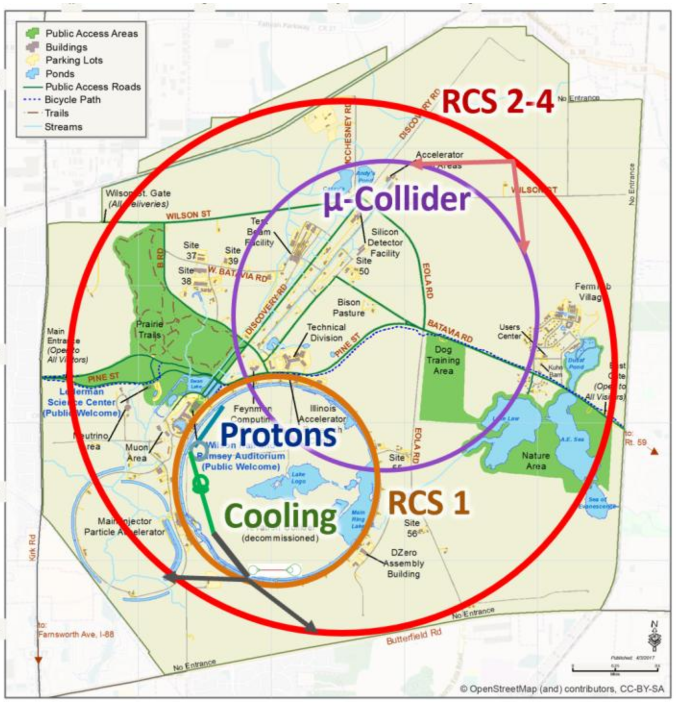
Proton Driver on the MAP



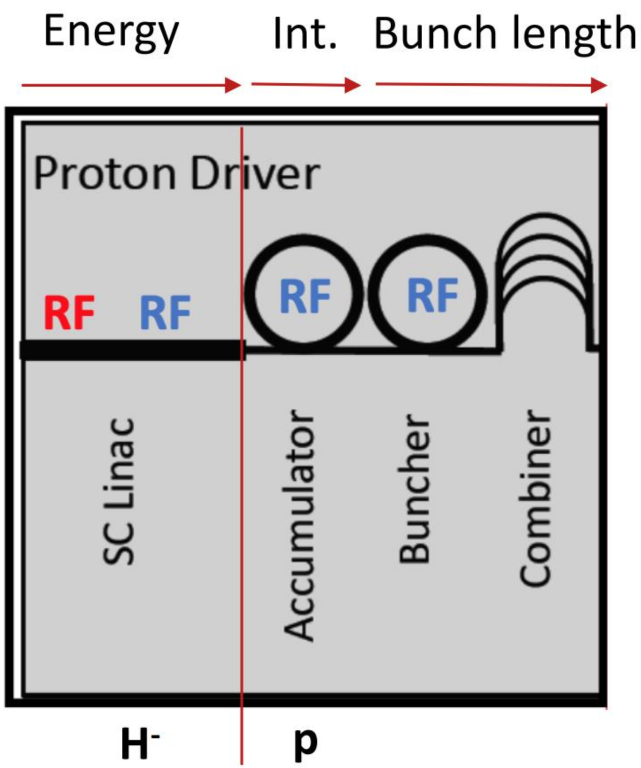
The **Proton Driver** determines the proton energy, pulse intensity, beam power, spot size on target, bunch length on target for muon production stage.

There in turn feed in the x, y, and t phase-space of the initial cooling stage, muon rate, and pulse repetition rate.

By the end, just luminosity and rep. rate.



Proton Driver Overview



H- Linac, accelerates up to 5-12 GeV

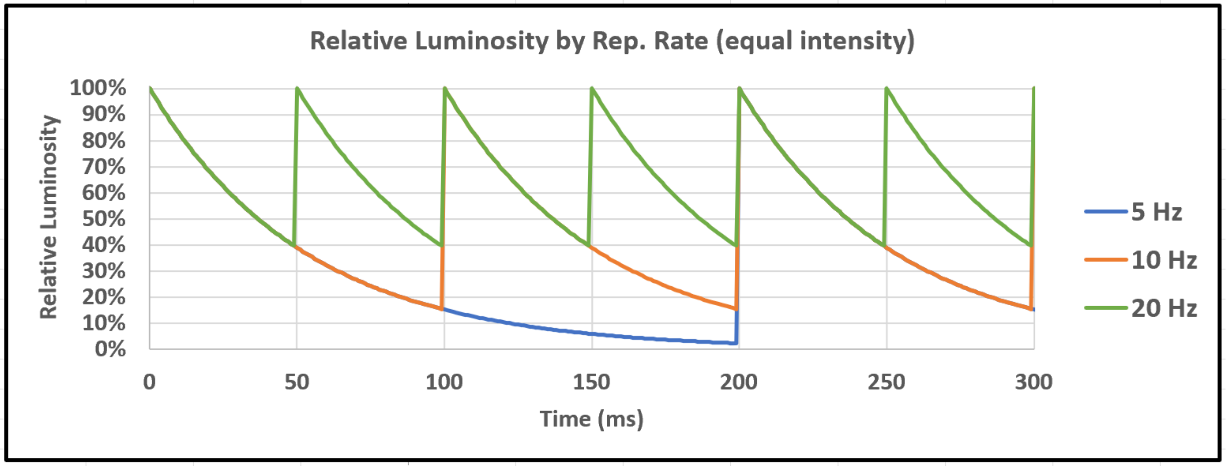
Accumulation Ring (AR), collects H^- ~3e14 particles and paint into stable bunches.

Compressor Ring (CR), performs bunch rotation to extract 1-3ns bunches.

Combiner, ensures that all (typically 1-6) bunches converge on the target simultaneously.

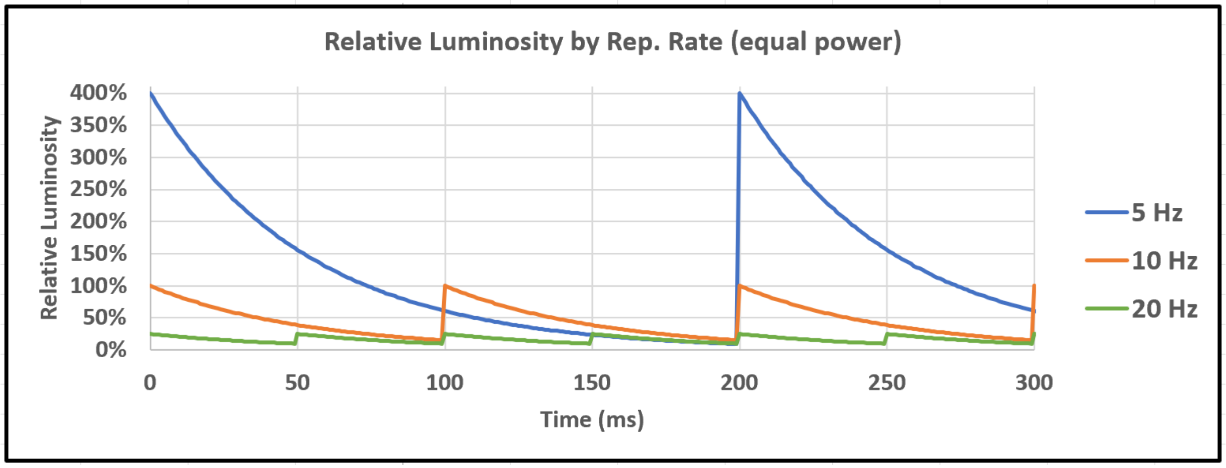
Muon Collider Proton Driver Parameters

Rep Rate 5-10 Hz: At 5 TeV beams, muon decay time is 0.1s in the lab frame. Luminosity depends on bunch intensity squared (neglecting beam quality losses).



Higher rep rates are better, given the same number of particles per pulse.

Above 20 Hz, diminishing returns for luminosity.



However, lower rep rates are better for a fixed beam power, because each pulse is more intense.

10 Hz may be a good balance of considerations.

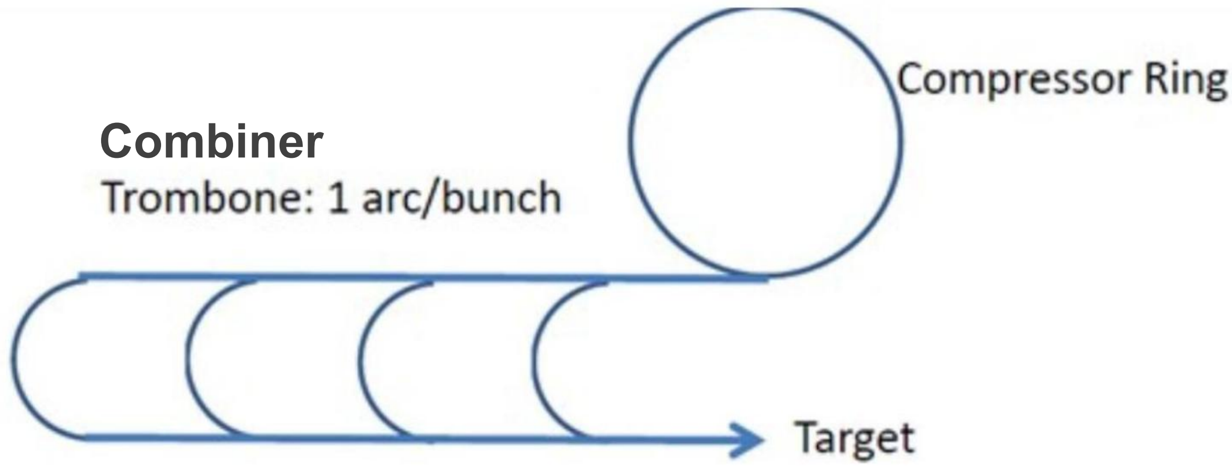
Muon Collider Proton Driver Parameters

Beam Energy 5-12 GeV: Muon yield per kW on target is relatively flat from 5-10 GeV, smaller beyond that. Using **Fermilab 8 GeV** is a reasonable choice.

Bunch Length 1-3 ns: The time structure of the proton beam gets largely passed on to the pion/muon beam produced for the target, so **1-3ns** bunch length alleviates the 6D cooling requirements as much as possible.

Proton Beam Power 1-4 MW: To achieve overall luminosity goals (20e34 $cm^{-2}s^{-1}$). At 8-GeV and 10 Hz, the corresponding proton pulse is 80-320e12 protons.

However, split among four bunches sent to combiner, **20-80e12 protons/bunch.**



Linac & H- Injection

Linac Macropulse Structure

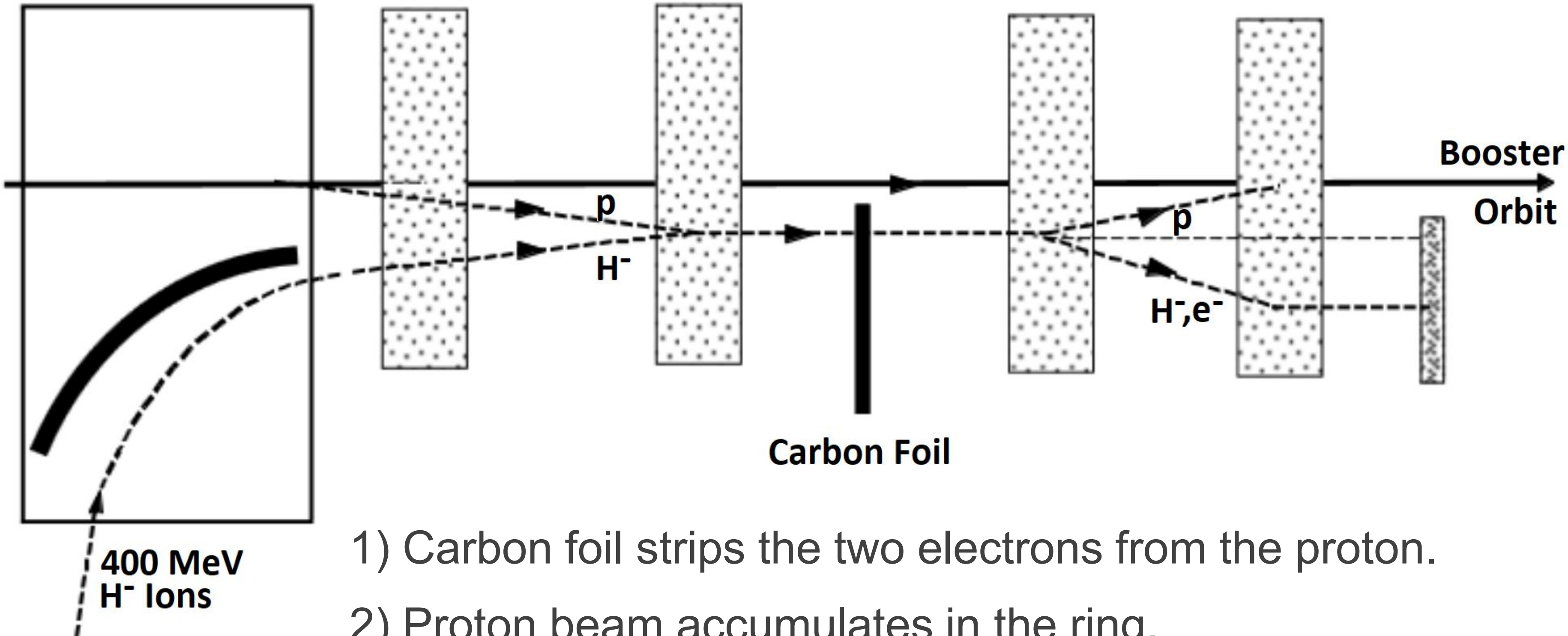
For a pulsed linac klystrons are used for RF sources and for a continuously operating linac solid state amplifiers are used.

Pulsed power is much more affordable and much closer to what the linac needs to deliver 160-320e12 every 5-20 Hz.

Recent FNAL ACE design exercise for an 8-GeV Linac

- Injector chain begins with PIP-II linac with a beam current upgrade.
- **10 Hz x 5 mA x 2 ms x 8 GeV = 0.8 MW**
- 1.3 GHz ILC style cavity, LCLS-II style cryomodule, E-XFEL style klystron RF power sources 1.5-2ms.
- Use higher linac current of **6-25mA**, that becomes **1-4 MW.**
- Might be better to let PIP-II serve 2mA CW users, and build new injector.

Charge Exchange Injection



1) Carbon foil strips the two electrons from the proton.

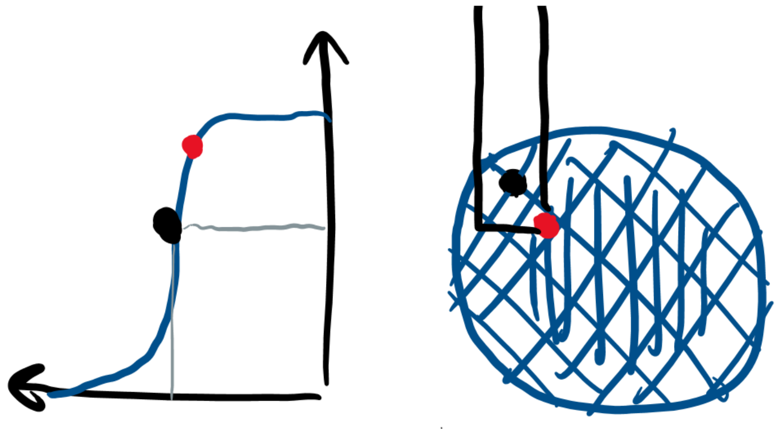
2) Proton beam accumulates in the ring.

3) Unstripped H- ions are sent to an absorber.

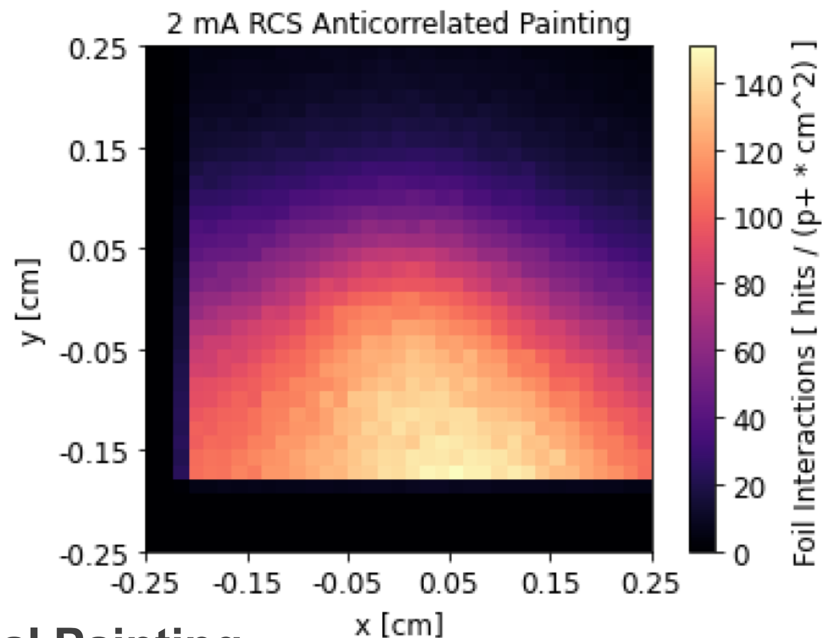
Linac current is concentrated 100s to 1000s times over!

Longitudinal & Transverse Painting

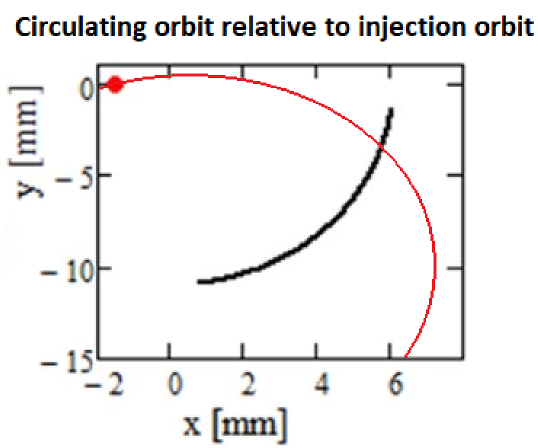
Beam Distribution during Injection



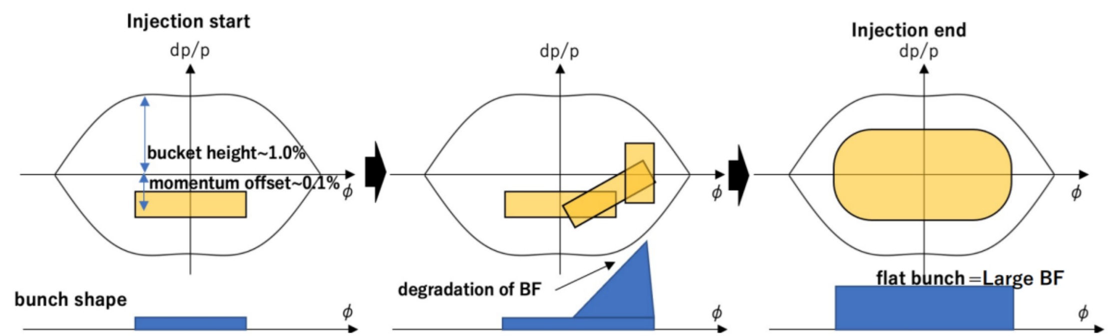
Foil Interaction Distribution



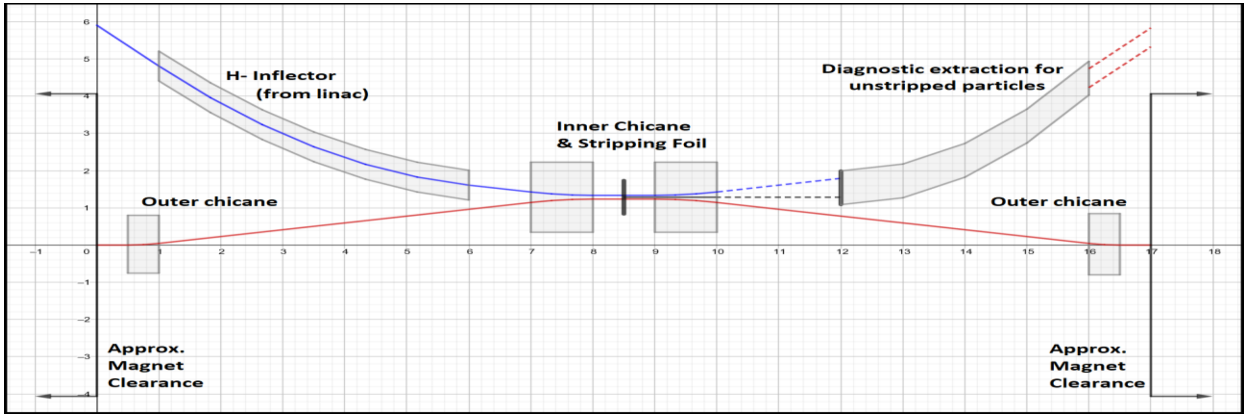
Anti-correlated Painting Injection



Longitudinal Painting



H- Injection Foil Challenges



Long Injection Chicane to avoid early H- stripping, worse with energy.

Extraction to absorber, to remove unstripped H-/H0 particles

Foil Failure due to beam heating, Foil failure at 2000-2300 K

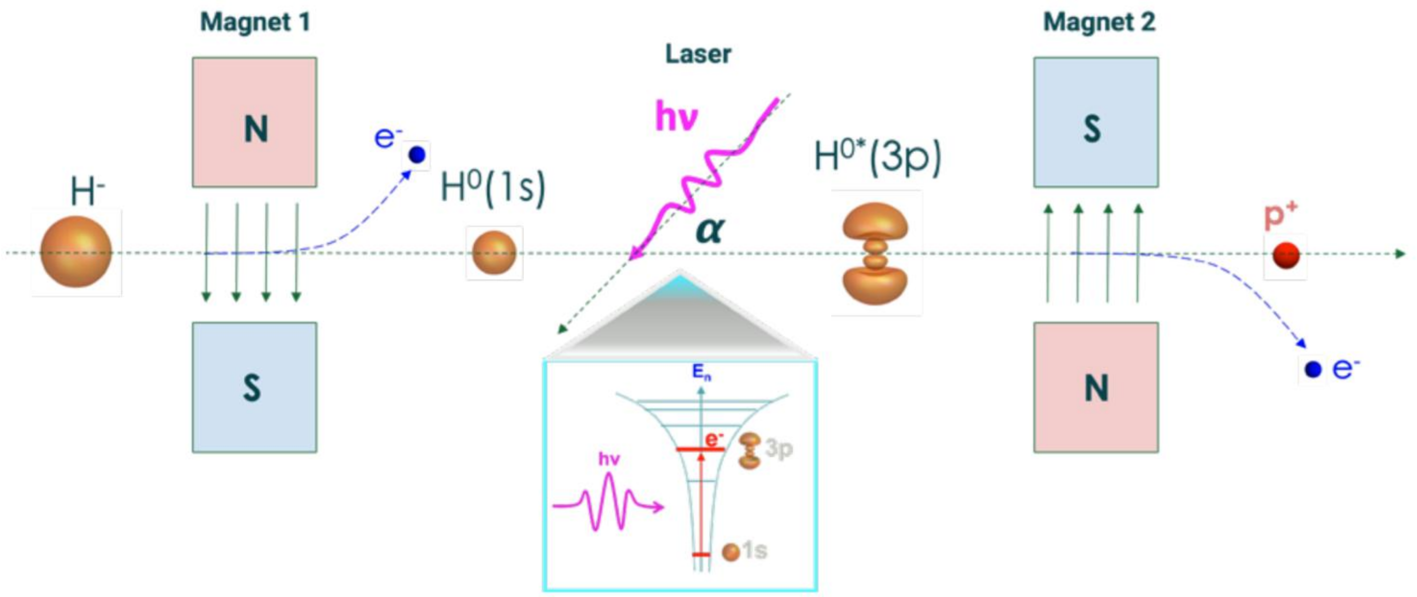
Circulating Proton Beam Scatters off Injection Foil, hard to absorb

At GeV-scale energy helps, but at higher energy it hurts.
- Proton scattering persists, absorbing particles is much are harder.

Laser Stripping injection for H- Injection

Is foil stripping even feasible for a 4MW proton driver AR?

In laser-assisted charge-exchange (LACE), H- is Lorentz-stripped to H0, H0 excited with a laser, and then H0* stripped to proton with a second magnet.



If laser stripping efficiency is 95%, 200 kW is being directed to a beam dump!

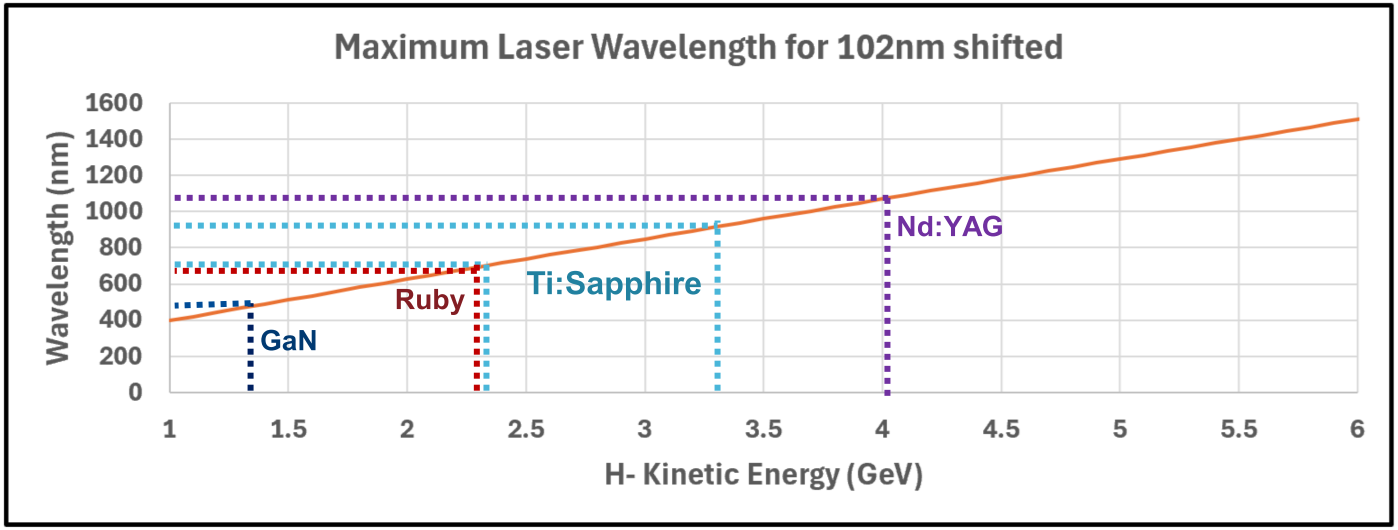
This technology is being developed at SNS and J-PARC

Energy Dependence on H- Laser Stripping injection

Laser wavelength is Doppler-boosted to target Lyman series

n=1 -> n=3, λ_0 **= 102 nm** line.

$$\lambda_{laser}/\gamma_0(1+\beta_0\cos\theta)=\lambda_0$$



Changing the angle, any shorter wavelength laser can still be used at higher energies.

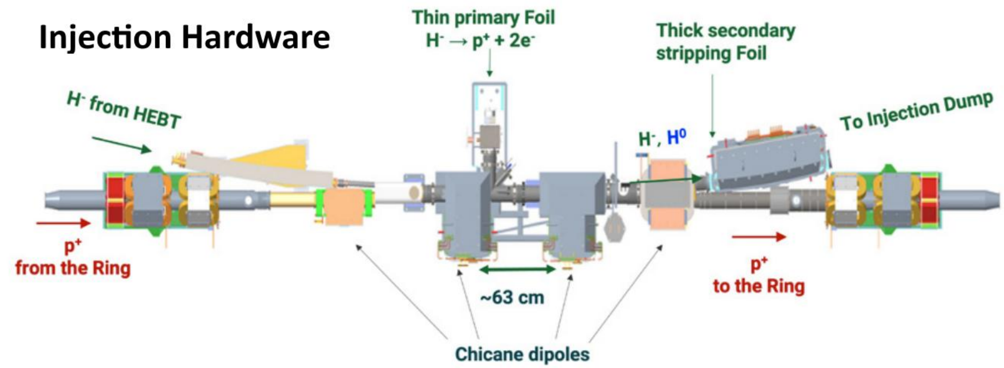
Above ~4 GeV, essentially the full range of laser technology and optics.

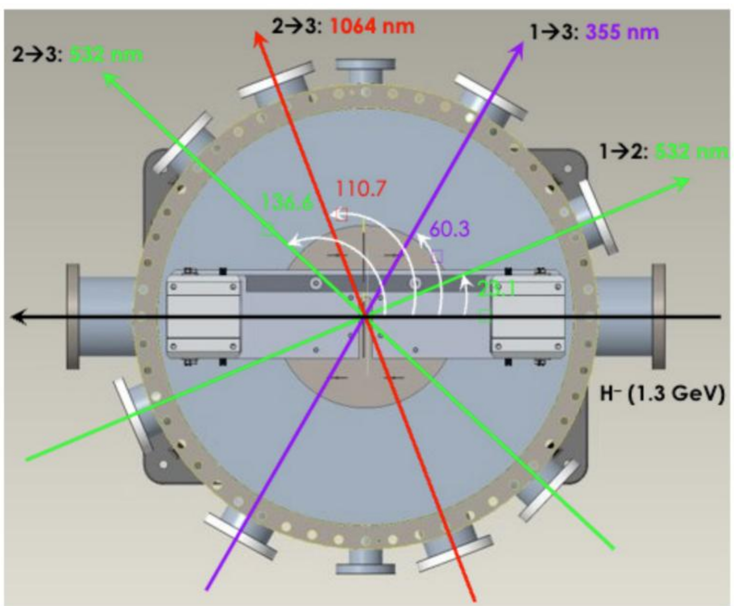
Status of LACE R&D at ORNL SNS

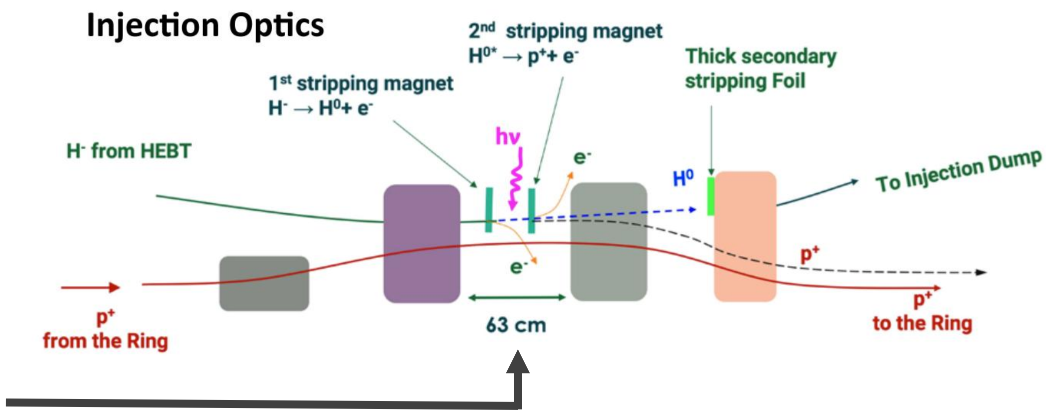
Commisioning 1.3 GeV H- beam.

New laser chamber at injection.

Laser system at 355 nm to excite directly to 3p, or in two steps with Green+IR.







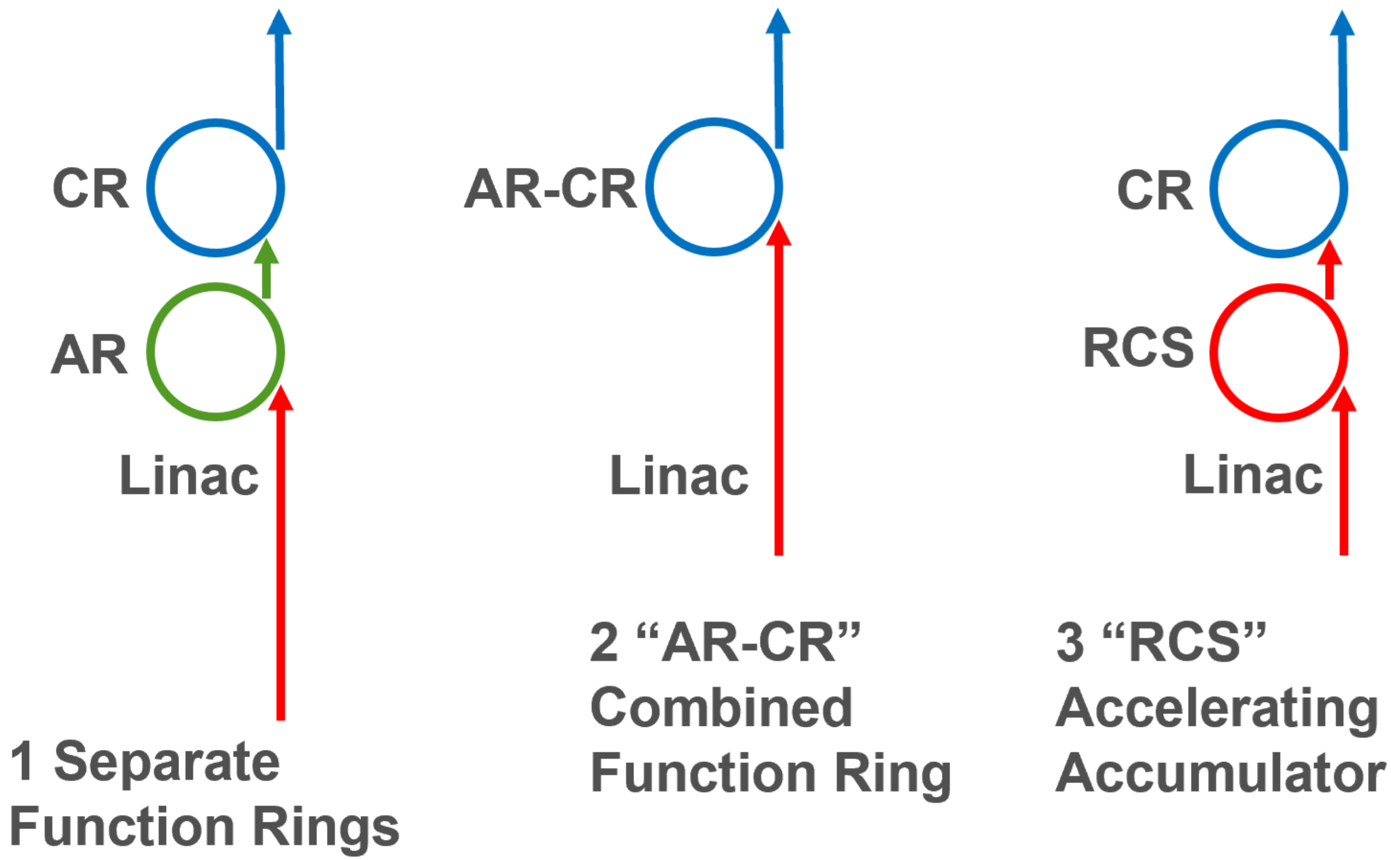
Cousineau 2017 (1, 2) & **Gorlov 2019** (here)

Latest reports: IPAC25 & NAPAC25

Fermilab

Accumulator Ring & Compressor Ring

Architecture



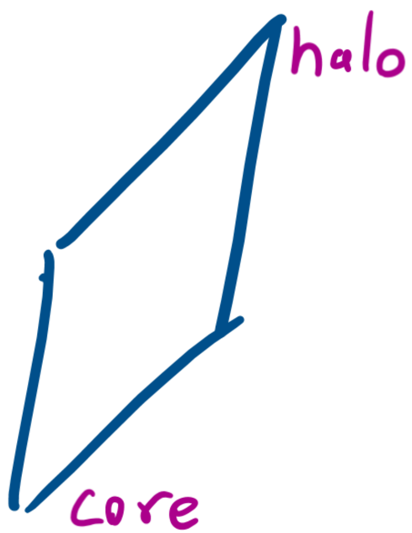
Can the CR accumulate without losing compression performance?
Can the AR accelerate without losing accumulation performance?
For now keep the rings separate when in reality they may be the same…

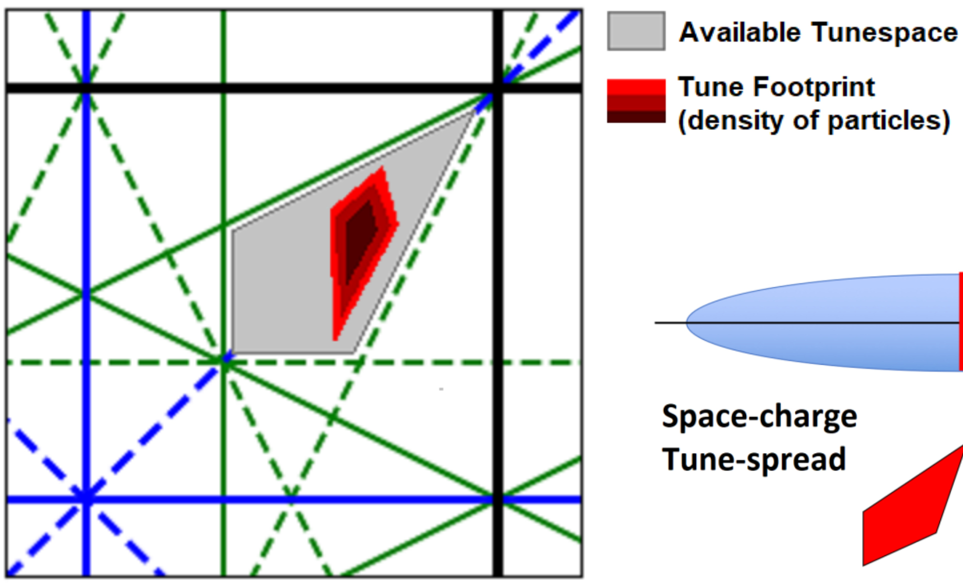
Space-charge Limit

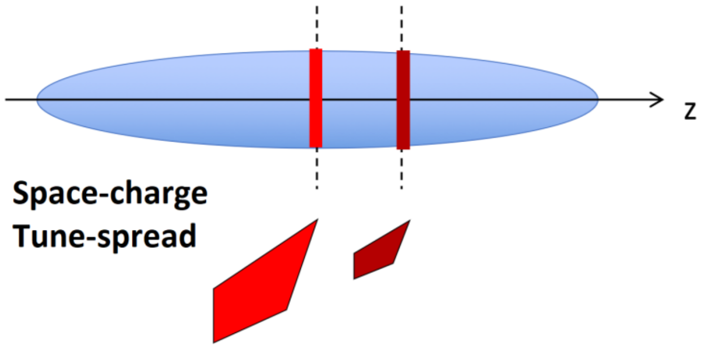
Laslett Spacecharge Tuneshift parameter:

$$\Delta Q_{SC} = \frac{N r_p}{2\pi \epsilon_n \beta_0 \gamma^2} B_f F < \sim 0.2$$

- Number of particles
- Bunching factor (inverse to bunch length)
- Form factor (deviation from round gaussian)
- Transverse emittance (prop to beam-size squared)
- Relativistic β,γ factors







Space-charge Limit

Laslett Spacecharge Tuneshift parameter:

$$Q_{SC} = \frac{N r_p}{4\pi \epsilon_n \beta_0 \gamma^2} B_f F < \sim 0.2$$

- Number of particles (N)
- Bunching factor (inverse to bunch length) (B_f)
- Form factor (deviation from round gaussian) (F)
- Transverse emittance (prop to beam-size squared) (ϵ_n)
- Relativistic β,γ factors (β_0, γ)

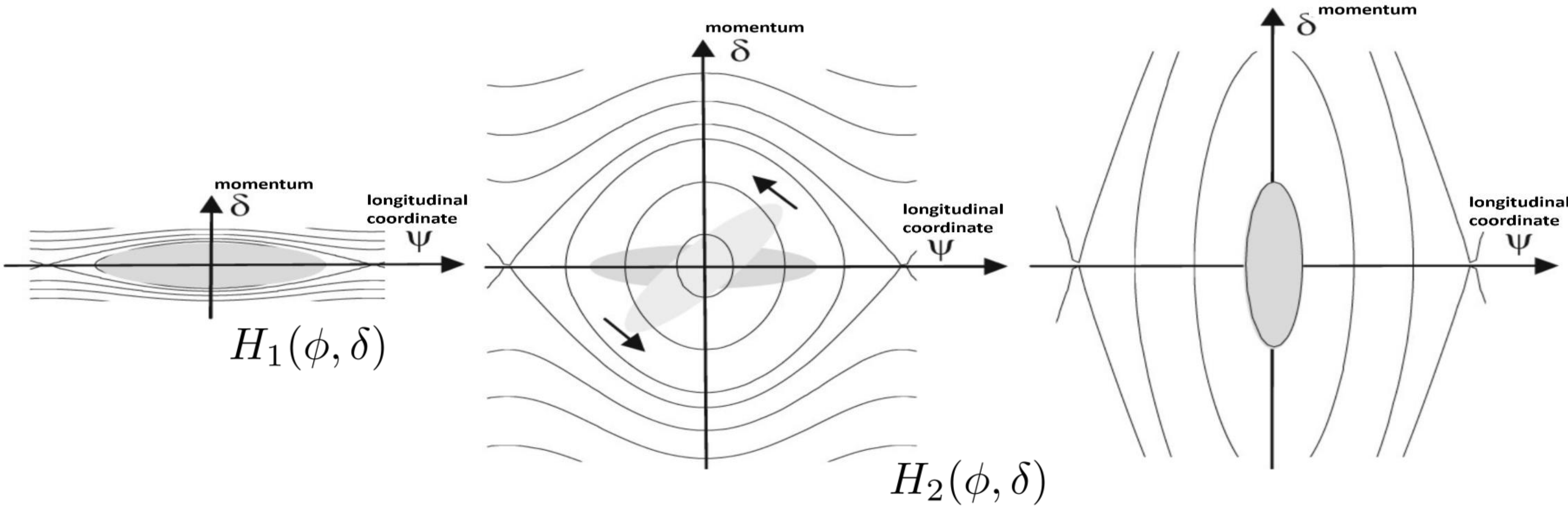
Bunching factor B_f means that the smaller the bunch length the more intense the space-charge force! Going from 2us to 2ns a major challenge

However also scales with γ^2 , so accumulating at 5-10 GeV instead of at 0.4-1 GeV helps counterbalance.

Increasing emittance ε_N is effective, but not cost-free for AR/CR design. Furthermore, we can't support an arbitrarily large spot size or divergence on muon production target.

More compact ARs and CRs are more effective, but can we use superconducting magnets in a messy charge-dominated ring?

Snap Bunch Rotation in Phase-Space



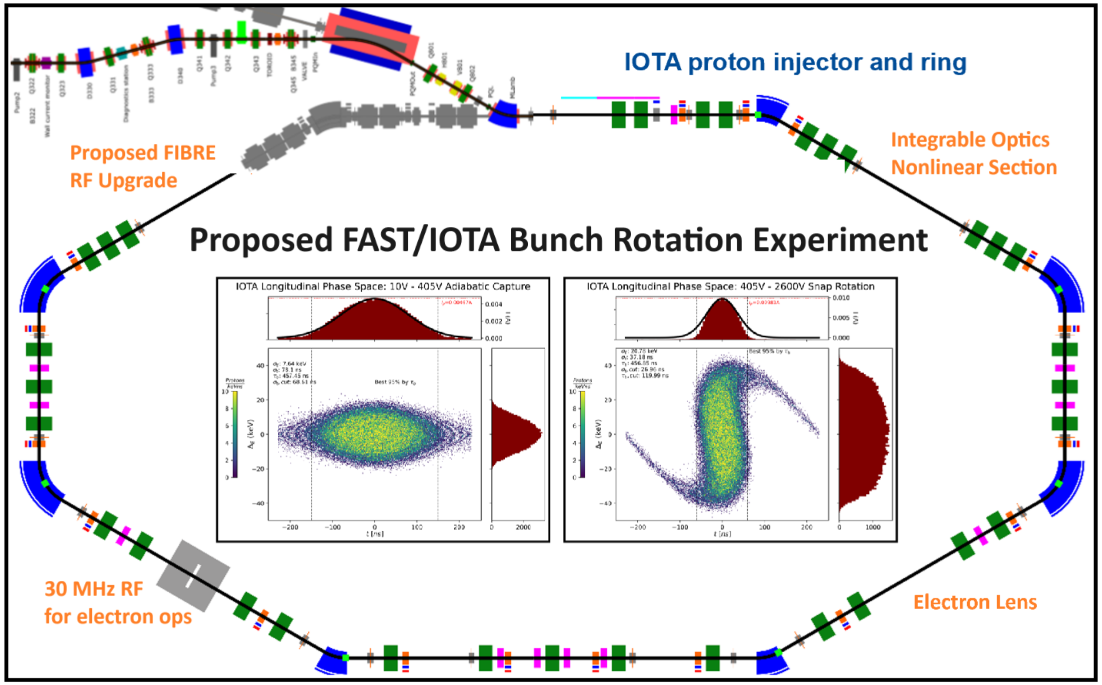
1) Start with as low as momentum spread beam as possible.
2) Jump up the voltage as high as possible as quickly as possible.
3) Particles follow new phase-space contours to rotate 1/4 synch period.

$$\text{This achieves } \sigma_{\delta,f} = \left(\frac{V_2}{V_1}\right)^{1/2} \sigma_{\delta,i}, \quad \text{versus adiabatic changes } \sigma_{\delta,f} = \left(\frac{V_2}{V_1}\right)^{1/4} \sigma_{\delta,i},$$

Only the particles near the center full rotate, RF flattening may help.

There are also resonant schemes (modulate voltage at 1/2 synch period).

Bunch Rotation & Strong Space-charge (R&D)



Proposed **FAST/IOTA Bunch Rotation Experiment (FIBRE)**

- Space-charge R&D is a primary purpose of IOTA.

- Optimize bunch rotation in an extreme space-charge environment.

- Just needs a ~10 kV ~2.2 MHz RF cavity.

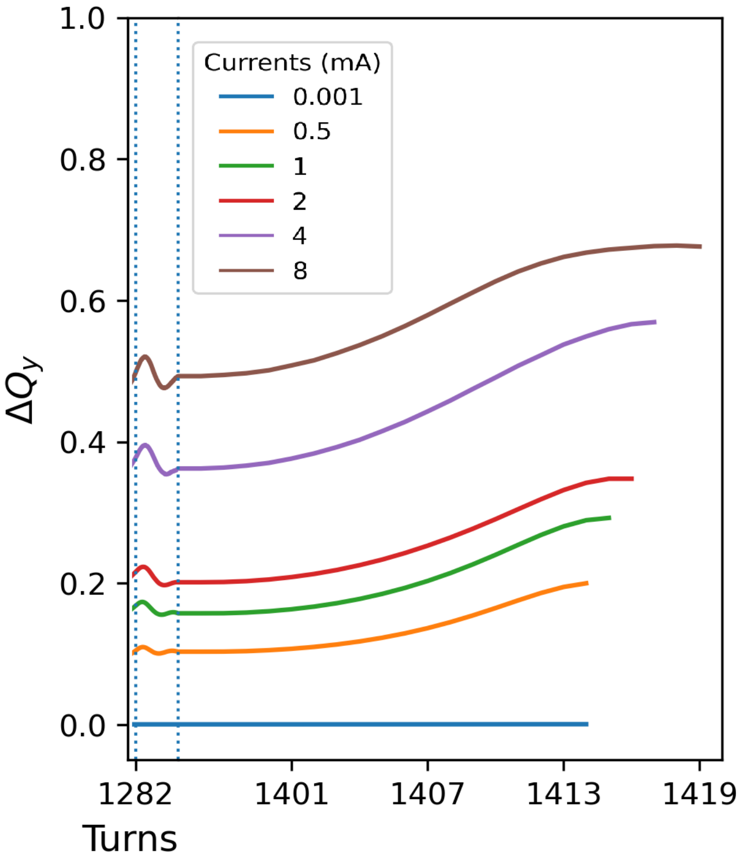
Upcoming publication from Ben Simons (NIU) for FAST/IOTA, NAPAC paper

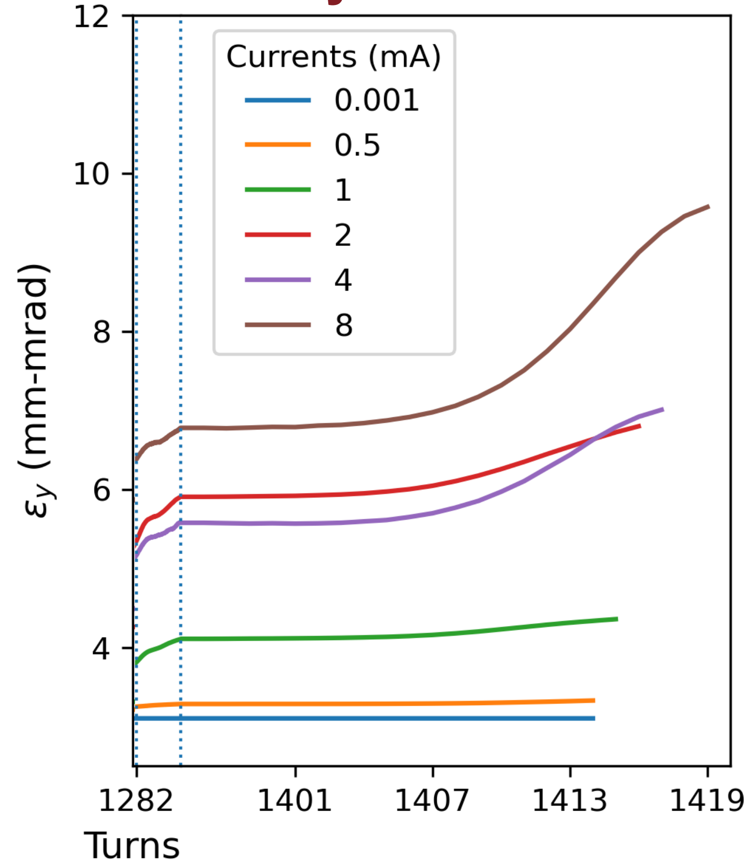
Other facility options … ORNL SNS, RAL ISIS, FNAL Booster, GSI SIS…

- They have the RF, MW beams, new HEP application for BES facility.

Bunch Rotation & Strong Space-charge (Simulation)

Preliminary Results! Simons 2025





Can push the Laslett parameter into extreme values with manageable impact on transverse emittances. Rotation occurs in tens of us!

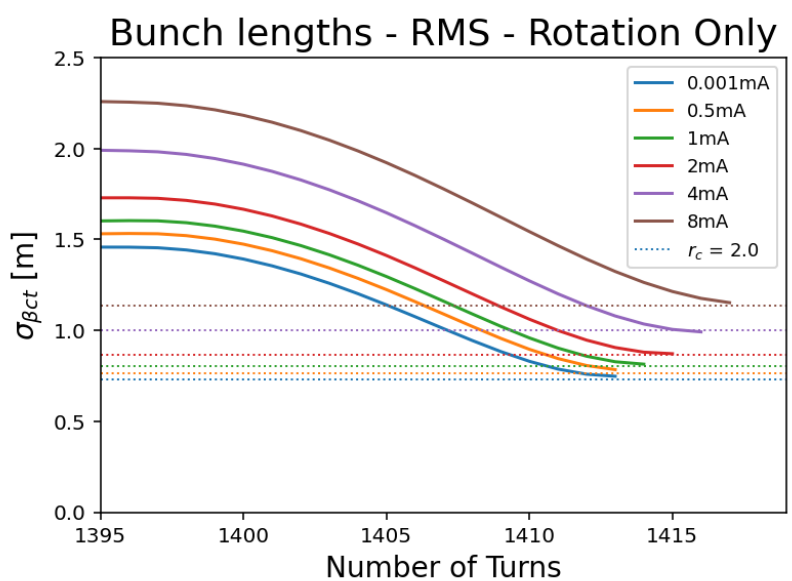
Fermilab

Bunch Rotation & Longitudinal SC

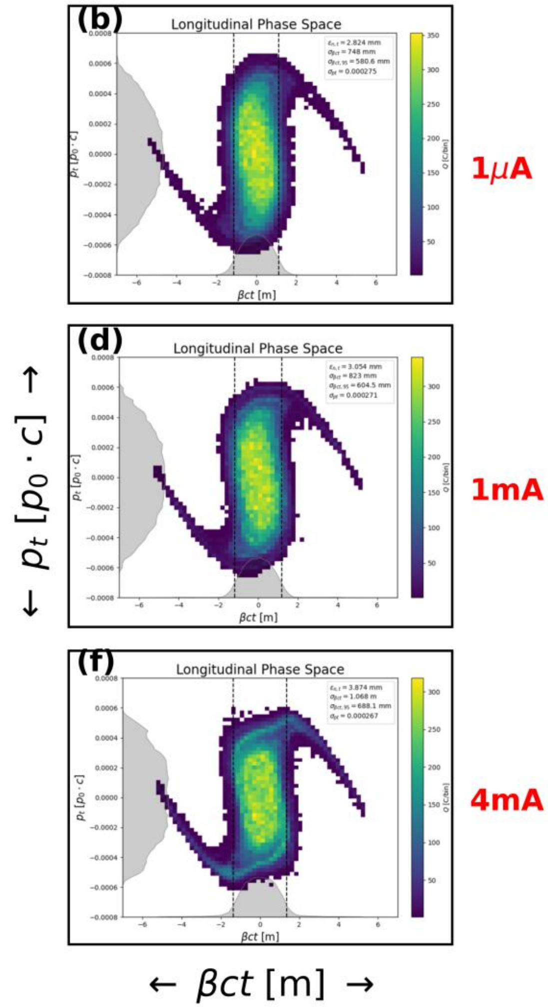
Effective Longitudinal Focusing/defocusing

$$\left.\frac{\text{Sp-ch force}}{\text{Rf force}}\right|_{\text{critical}} = \frac{eN_b|Z/n|_{\text{spch}}}{\sqrt{2\pi}h\omega_0^2\sigma_\tau^3 V_{\text{rf}}}$$

$$V_{eff} \approx -h\left(\frac{L_{RF}}{\sqrt{2\pi}\sigma}\right)^3 \frac{qk_e}{c} I_0 \frac{g}{\beta_0\gamma_0^2}$$



Simons 2025



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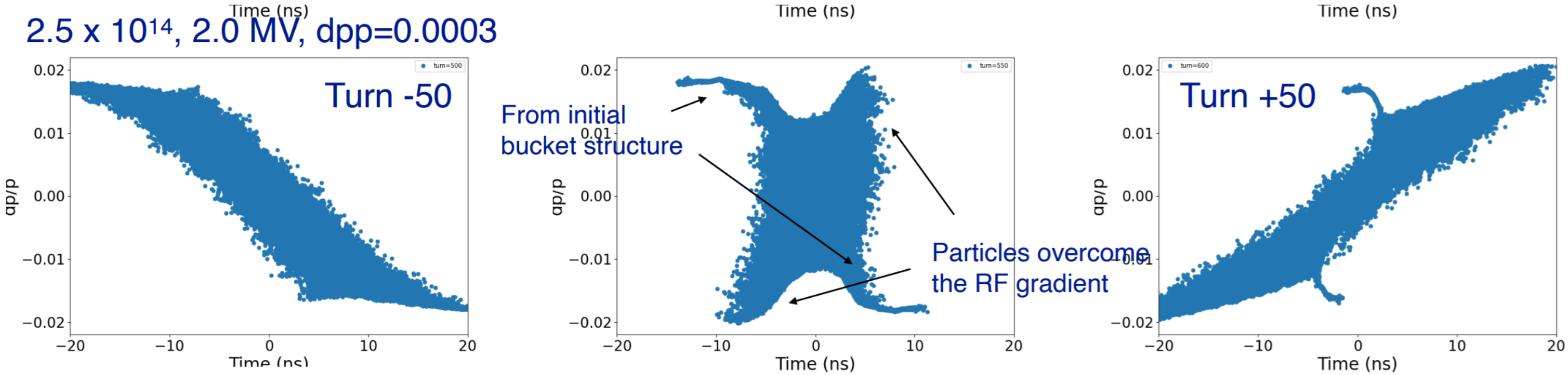
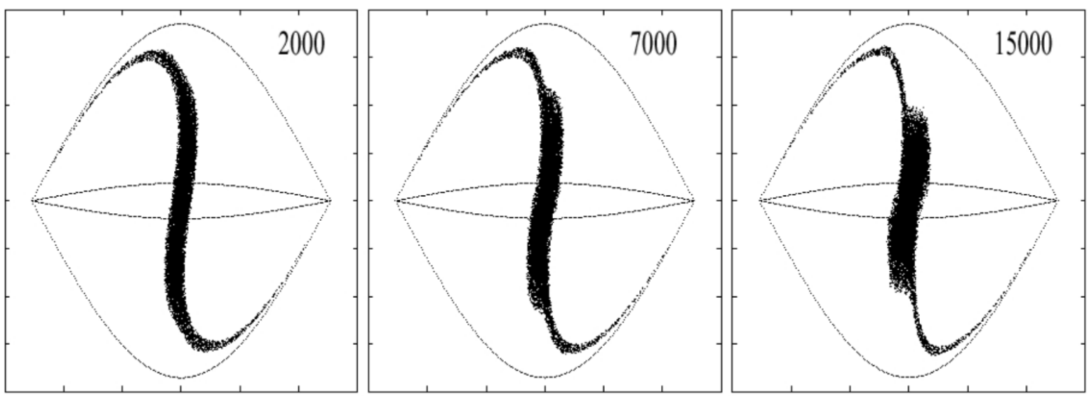
Bunch Rotation & Longitudinal SC

Shinji Machida, Proton Driver simulation 2025

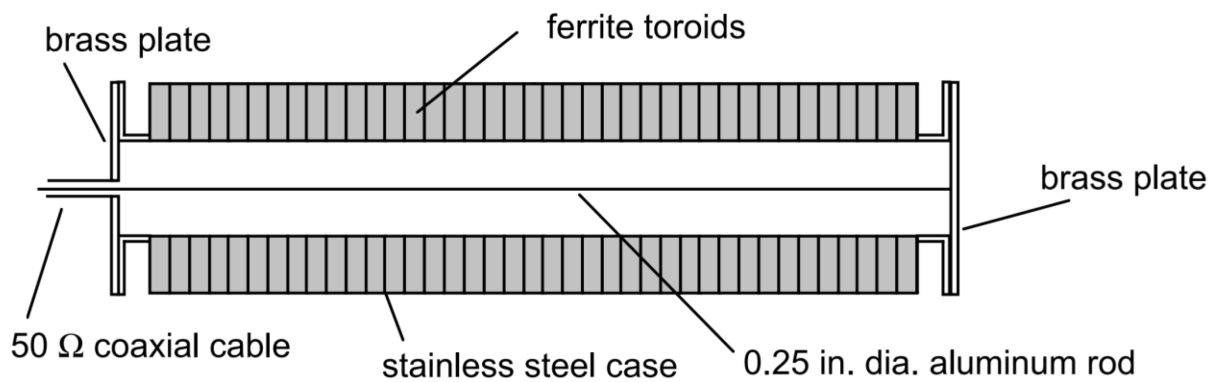


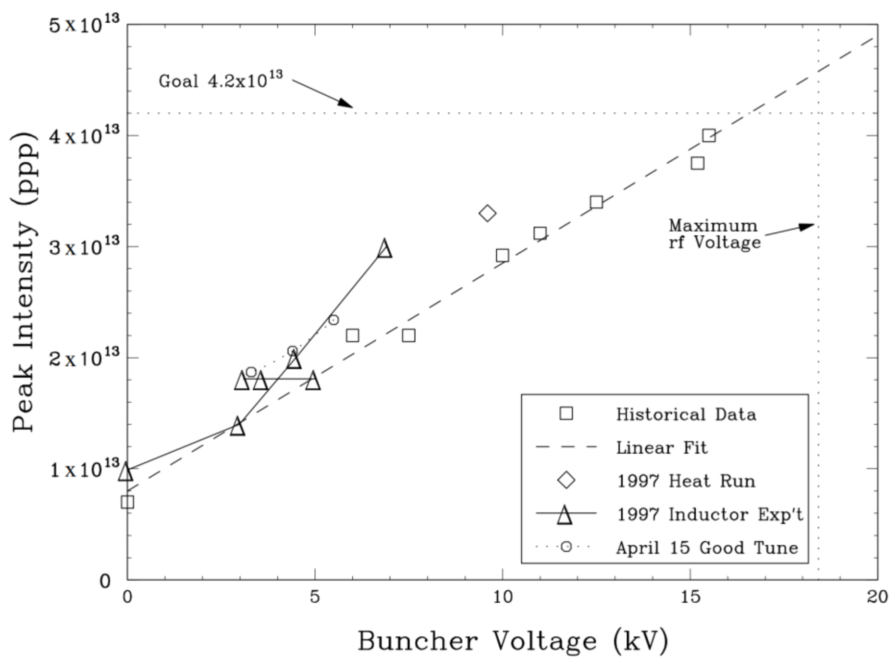
Ng Simulation of IUCF in 2001



Inductive Inserts to Compensate Long. SC

Ferrite rings to change inductive impedrance:





SC compensation demonstrated in LANL PSR in 1999!
M. Plum et al. 1999

Impedance manipulation also impact instability thresholds…

Fermilab

Bunch Rotation & Phase-slip factor

Should the phase-slip factor of the CR be large or small?

Large η
- Most extreme SC occurs briefly.
- Mode-coupling instabilities are suppressed
- Higher voltage requirements allow more extreme bunch compression, needs more RF.
- Less bunch compression means more from Linac/AR.

Small η
- Beam should be SC stable.
- Wake effects accumulate from head to tail of bunch.
- Lower voltage requirements allow more extreme bunch compression given RF power.
- More bunch compression relaxes requirements on Linac/AR.

My conclusion? We will need to keep studying both.

If the gains of larger η can be realized, it is worth it.

FNAL & CERN Scenarios

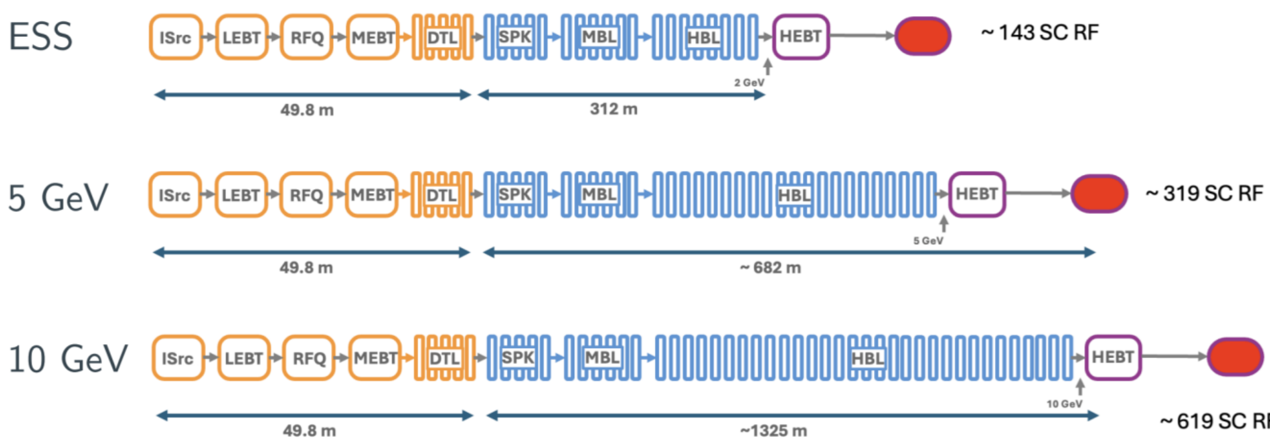
At IPAC24, FNAL & CERN proton driver scenarios have similar approach to linacs, and different CR/AR choices.

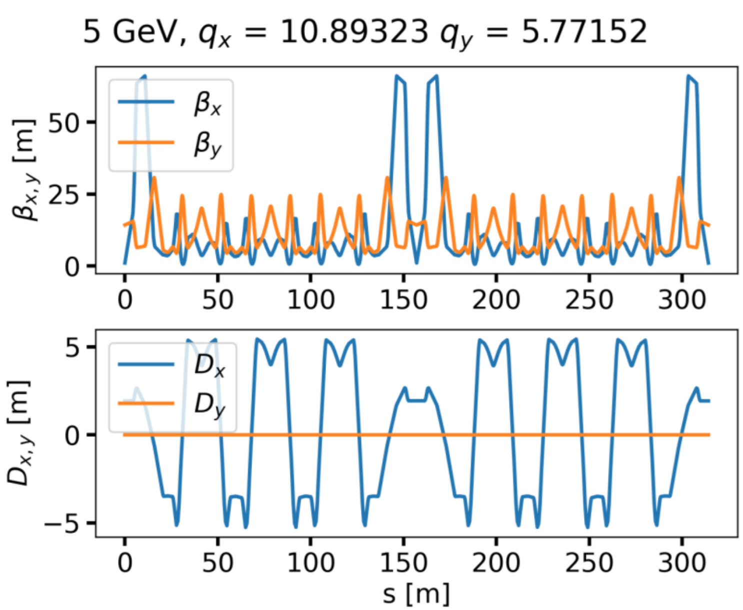
Parameter	CERN	FNAL
Energy	10 GeV	8 GeV
Rep Rate	5 Hz	10 Hz
Macro Linac Current	40 mA	25 mA
Macro Pulse Duration	2 ms	2 ms
Number of Bunches	6	4
Bunch Length in AR	120 ns	20 ns
Micro pulse Duration	720 ns	80 ns
Micro pulse Current ($1\mu s$ AR)	55 mA	310 mA
Micro pulse Duty Factor ($1\mu s$ AR)	72%	8%

In reality, either scenario could be built on any site, because the proton driver footprint is small compared to the muon collider footprint.

Preliminary CERN Proton Driver Design

Linac design is an extension of the ESS Linac…



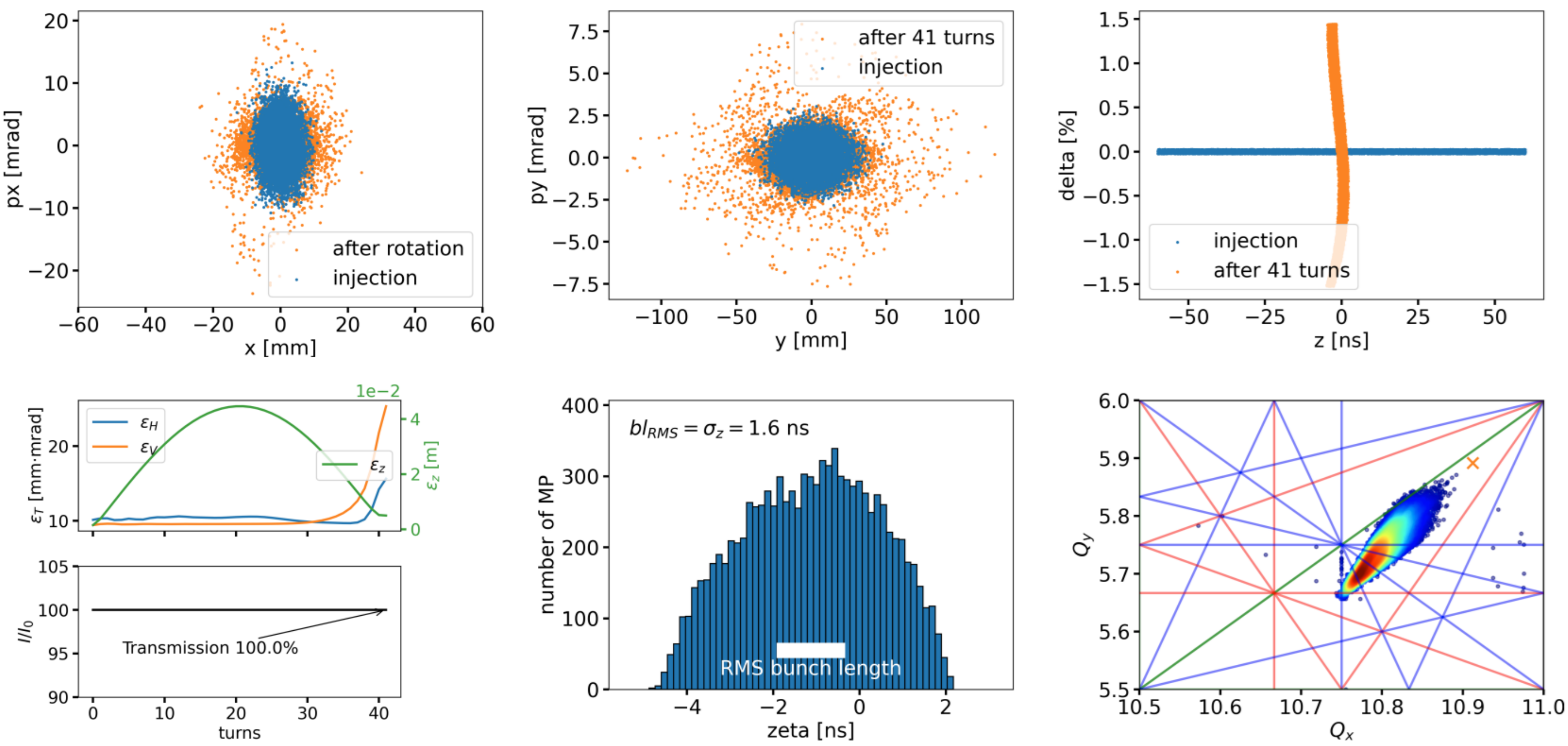


Johanesson et. al. IPAC24

CR lattice based on M. Aiba 2007

Strong phase-slip factor 0.11-0.16, but still need high voltage.

Preliminary CERN Simulations (Johanesson)



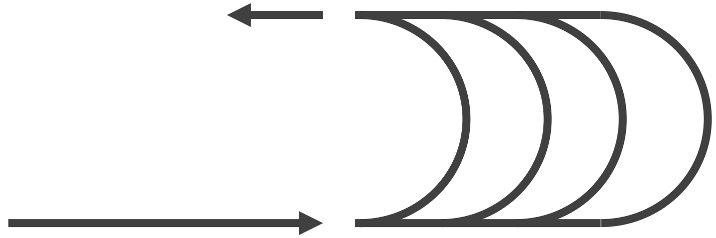
Simulation without longitudinal SC, imagine perfect compensation.

Some aspects of linac design and combiner design still ongoing…

Combiner & Target

Combiner Geometry

The combiner puts each bunch on a different path, so that the time of flights have all bunches coincide

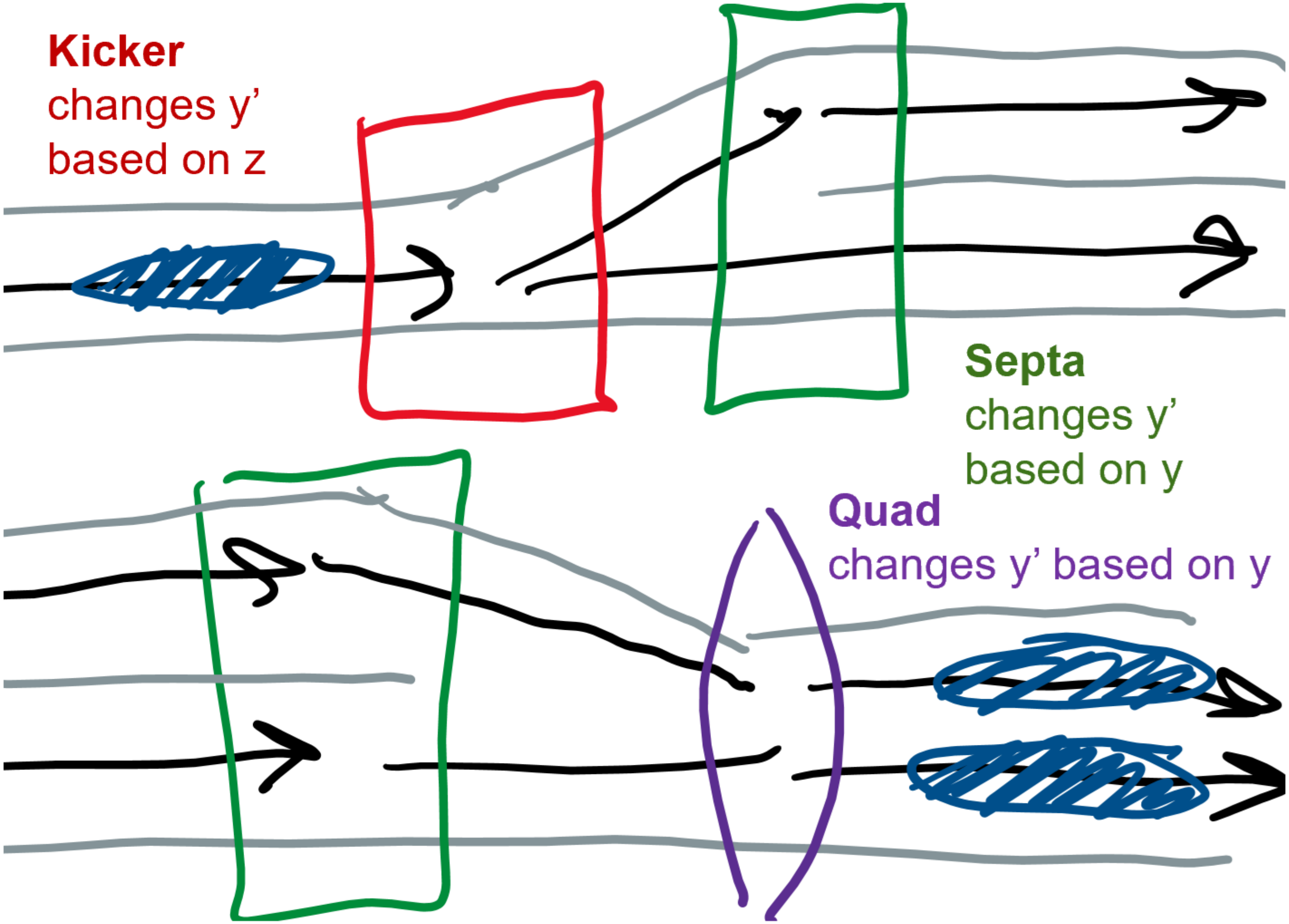


Each arc is roughly half the circumference **C/2** of the AR/CR.
Then if **N** bunches fill up roughly **f** of the circumference, then the straight sections of the combined must each by **fC/2.**
So the total length of all transfer lines is **NC/2 + fC**.

For modest numbers f =0.25, C=300m, N=4, that's 675m of accelerator.
Not much RF needed, but more than double the magnet/tunnel costs.

It will be worth if it can lower the linac or the CR/AR costs, or improve overall performance.

Combiner Transverse Optics



Impact of Multiple Bunches

You cannot use a combiner to cheat Louiville's theorem, so the implications of using more bunches is that each bunch is narrower.

What are the implication of using many bunches in a combiner?
- Technical complexity and cost of combiner line.
- Emittance growth from combining bunches.
- Transverse aperture in CR and AR smaller, lower costs.
- Smaller bunch compression factors.
- Linac beam injects into a large azimuth of AR, which means that a smaller bunch charge for the same macropulse average current.

My Conclusion? More bunches may help, but don't use any more than you have to do in order to achieve performance goals.

Summary & Questions

Summary of Top R&D Areas

1. **Laser-assisting H^- Injection** most likely a requirement.
   - Ongoing R&D at SNS & J-PARC, at more challenging beam energies.

2. **Charge-dominated bunch rotation** needs demonstration and optimization for best performance, which feeds into overall design.
   - R&D program proposed for FAST/IOTA or SNS or ISIS.
   - Currently not supported, small investment needed.
   - Can also study SC-compensating ferrite inserts.

3. **Self-consistent simulations** and end-to-end proton driver design.
   - CERN IMCC with ESS group leading the simulation effort.
   - Optimization choice of phase-slip factor in CR.
   - Optimization choice of high-charge linac vs aggressive bunch rotation vs aggressive bunch combining.
   - Optimization choice of beam energy vs muon production optimization.