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# Design of high intensity proton rings

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*Upgrading Existing High Power Proton Linacs*
*8-9 November 2016 at ESS Lund*

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- A bit more details
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# Introduction: back of the envelope calculations

# SNS Accumulator Ring Design Parameters

**Design Parameters**

Circumference: 250 m

Energy: 1 GeV

Intensity: 1.5e14 ppp

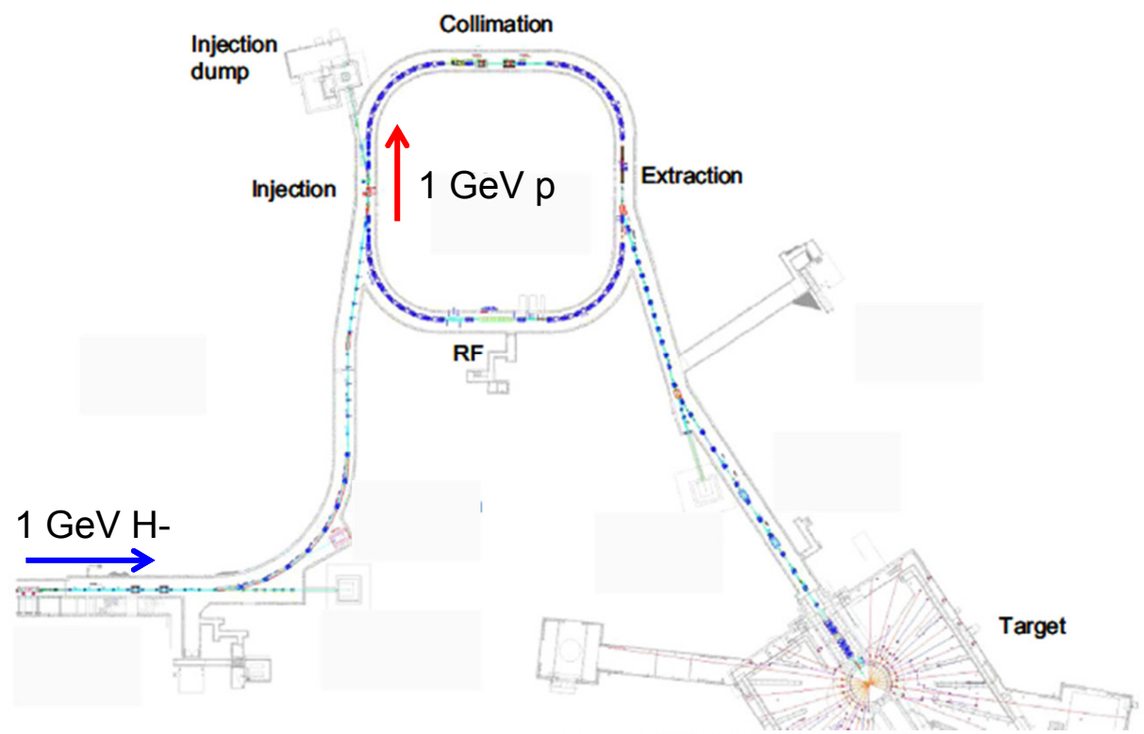
# bunches: 1

Bunch length: 700 ns

Accumulation Time: 1 ms

Repetition Rate: 60 Hz

= Beam Power: 1.4 MW



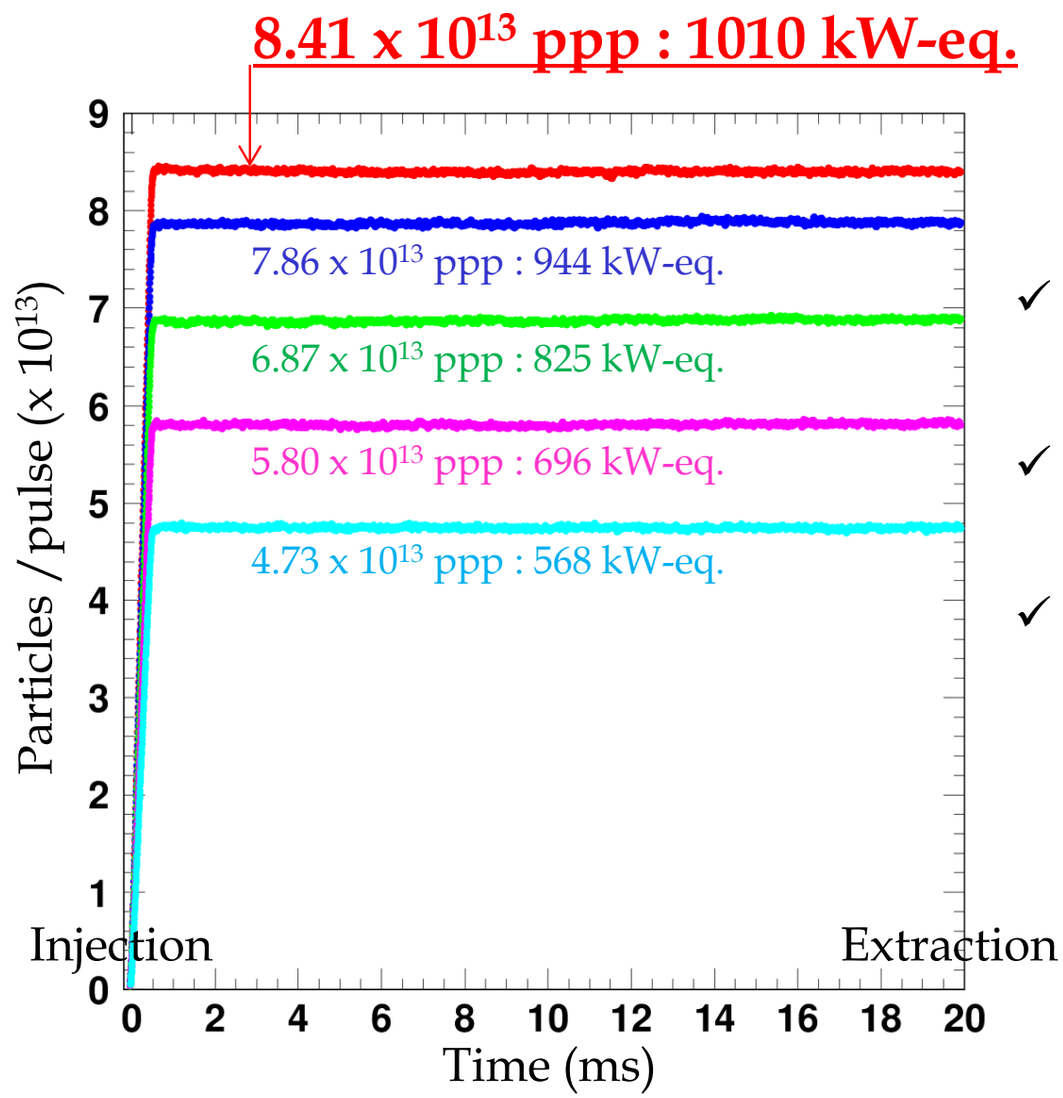

**The design of the ring was focused on beam loss control.**

It has been in operation for 10 years.

*It has performed beautifully.*

# Achievement of the 1-MW beam acceleration

Circulating beam intensity over the 20 ms from injection to extraction measured by CT




- ✓ RCS successfully achieved the 1-MW beam acceleration in January 10, 2015.
- ✓ There was no significant beam loss even for the 1-MW beam.
- ✓ But, at this stage, there still remained slight un-localized beam loss ($<10^{-3}$) in the high dispersion area.

# Space charge tune shift

| | J-PARC 0.18 | J-PARC 0.40 | SNS 1.0 | SNS 1.3 | **ESS 2.0** |
|---|---|---|---|---|---|
| beam power MW | 0.4 | 1.0 | 1.4 | 2.8 | **5.0** |
| energy GeV | 0.18 | 0.40 | 1.0 | 1.3 | **2.0** |
| repetition Hz | 25 | 25 | 60 | 60 | **14** |
| ppb | $3.33 \times 10^{13}$ | $8.33 \times 10^{13}$ | $1.5 \times 10^{14}$ | $2.5 \times 10^{14}$ | **$1.1 \times 10^{15}$** |
| collimator acceptance | 200 pi | 200 pi | 300 pi | 300 pi | **300 pi** |
| $b^2g^3$ | 0.5011 | 1.4755 | 6.750 | 11.190 | **27.58** |
| $B_f$, $F$ | 0.40, 2 | 0.40, 2 | 0.25, 2 | 0.25, 2 | **0.40, 2** |
| $\triangle Q$ | -0.41 | -0.35 | -0.15 | -0.15 | **-0.16** |

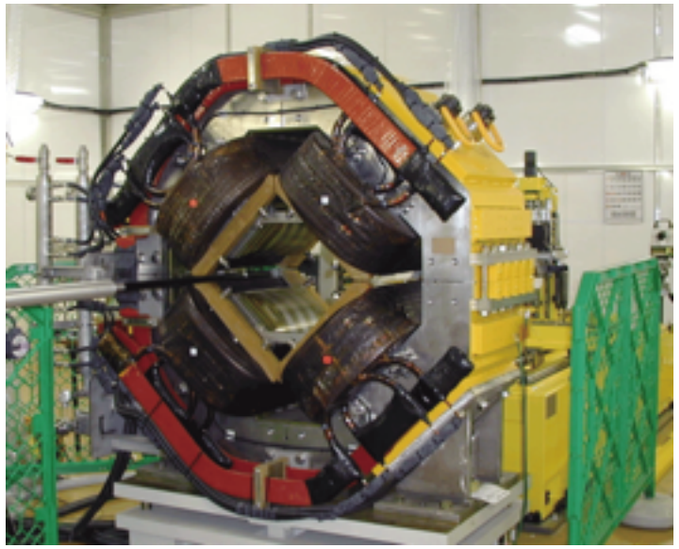
$$\Delta Q = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\epsilon_{H,V}}\frac{F}{B_f}$$

$$R = \sqrt{\beta\varepsilon}$$

# Magnet aperture

Collimator aperture (geometrical acceptance) will be 100 to 400 pi mm mrad and magnet aperture is 1.5 to 2.0 times larger.

| | beta_max = 20 m | beta_max = 25 m | beta_max = 30 m |
|---|---|---|---|
| collimator 100 - 400 pi mm mrad | R = 45 - 90 mm | 50 - 100 | 55 - 110 |
| 200 pi mm mrad | 63 | 71 | 77 |
| 400 pi mm mrad | 90 | 100 | 110 |
| 600 pi mm mrad | 110 | 122 | 134 |
| 800 pi mm mrad | 126 | 141 | 155 |



J-PARC RCS: 165 mm

SNS: 150 mm

# My first impression

Looks to me quite feasible to construct an accumulator ring with controllable beam loss.

- Circumference = 350 m (extrapolate from 1 GeV SNS of 250 m).
- In terms of optics, almost the simplest ring you can imagine can do the job.
- Magnet size should be similar to SNS. Geometrical acceptance in magnets and collimator aperture cannot be so much different.
- A gap in the ring for extraction kicker is needed. Install a LEBT/MEBT chopper and/or barrier bucket RF in the ring.

# A bit more details

# Injection

## *$1.1 \times 10^{15}$ particles with 14 Hz*

- Although it may be able to accumulate $1.1 \times 10^{15}$ particles as a single pulse, injection of **2200 turns** becomes troublesome.
  - SNS: 1000 turns, J-PARC: 350 turns.
  - Foil temperature issue if it is H- injection
  - Capture of stripped electrons if it is H- injection
  - Phase space painting if it is proton injection
- Much more comfortable if it is split into 4 pulses so that
  - 4 out of 5 in 70 Hz pulses are for neutrino with a quarter pulse length.
  - 1 out of 5 in 70 Hz pulses is for neutron with a full pulse length.

# Injection

## *$2.8 \times 10^{14}$ particles with 70 Hz*

- Total number of injection turn is now **550**.
- Space charge tune shift is -0.04 with bunching factor of 0.4.
- Acceptance/emittance ratio ~ 300, similar to the turn number.
  - Two plane proton injection is feasible.
  - With higher peak current of proton source, the number of turns can be even reduced.

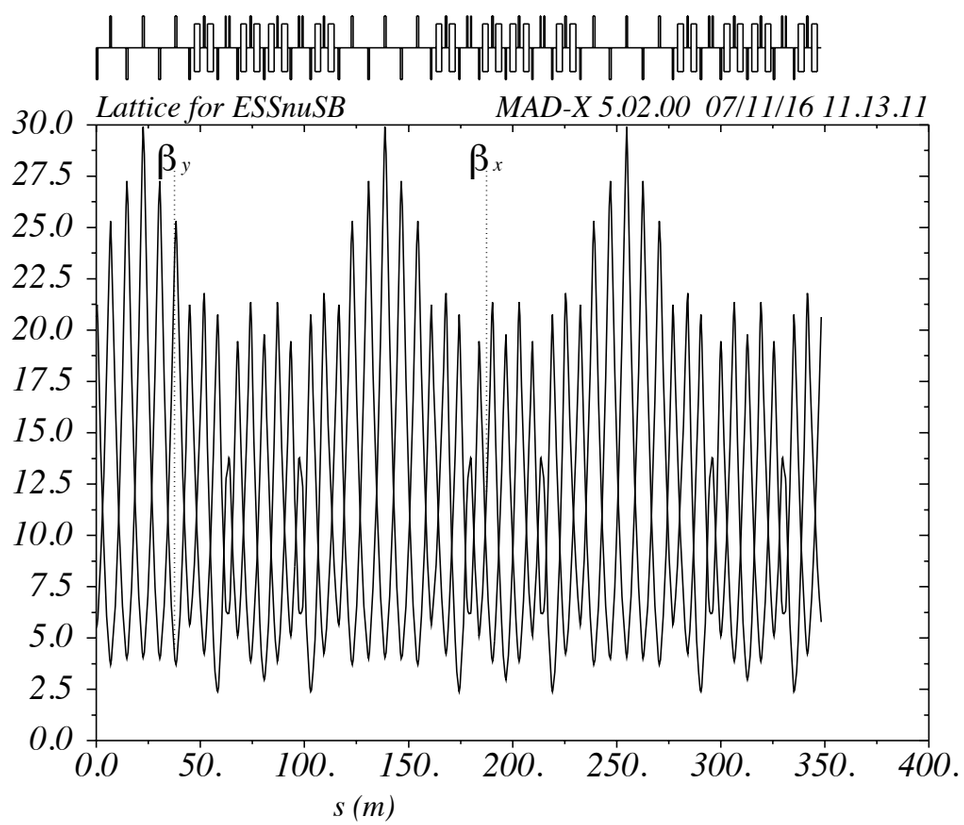
**See Chris Prior's talk in more detail**

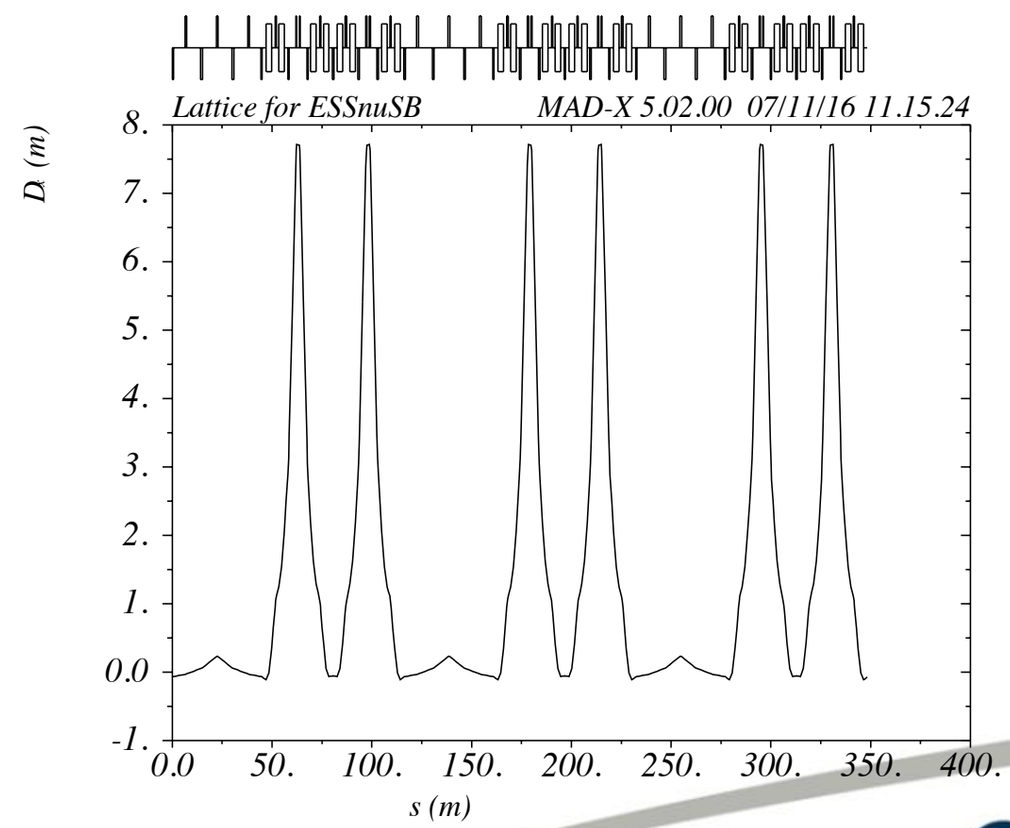
# Space charge simulation with multiturn injection

*with J-PARC RCS lattice*

| | |
|---|---|
| circumference | 348.333 m |
| superperiod | 3 |
| tune | 6.4, 6.4 |
| gamma-t | 9.7 |
| max energy | 3 GeV |

Use this lattice as a 2 GeV storage ring.



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# Space charge simulation with multiturn injection

*keep reasonable # of particles*

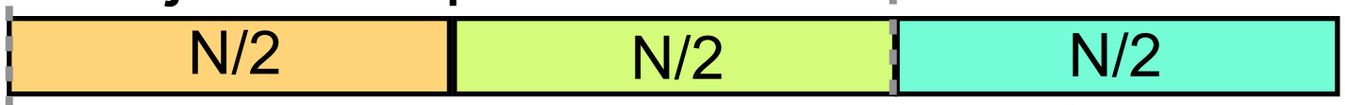
1st turn: Inject N particles.


2nd turn: Inject another N particles.

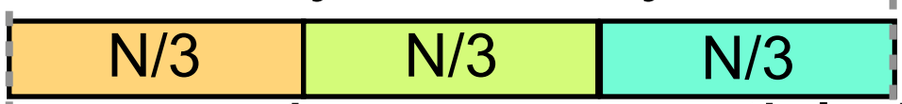

Throw away randomly selected N particles.


Increase charge per particle by 2.

3rd turn: Inject N/2 particles.

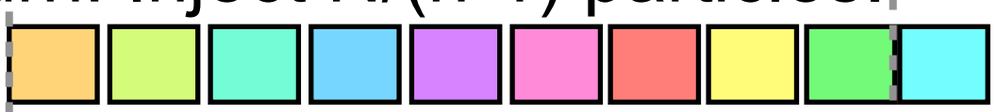



Throw away randomly selected N/2 particles.

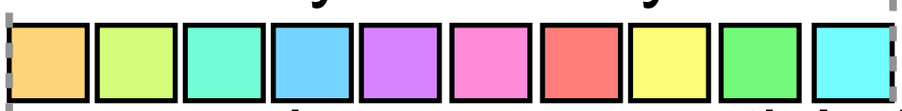



Increase charge per particle by 3/2.

n-th turn: Inject N/(n-1) particles.



Throw away randomly selected N/(n-1) particles.

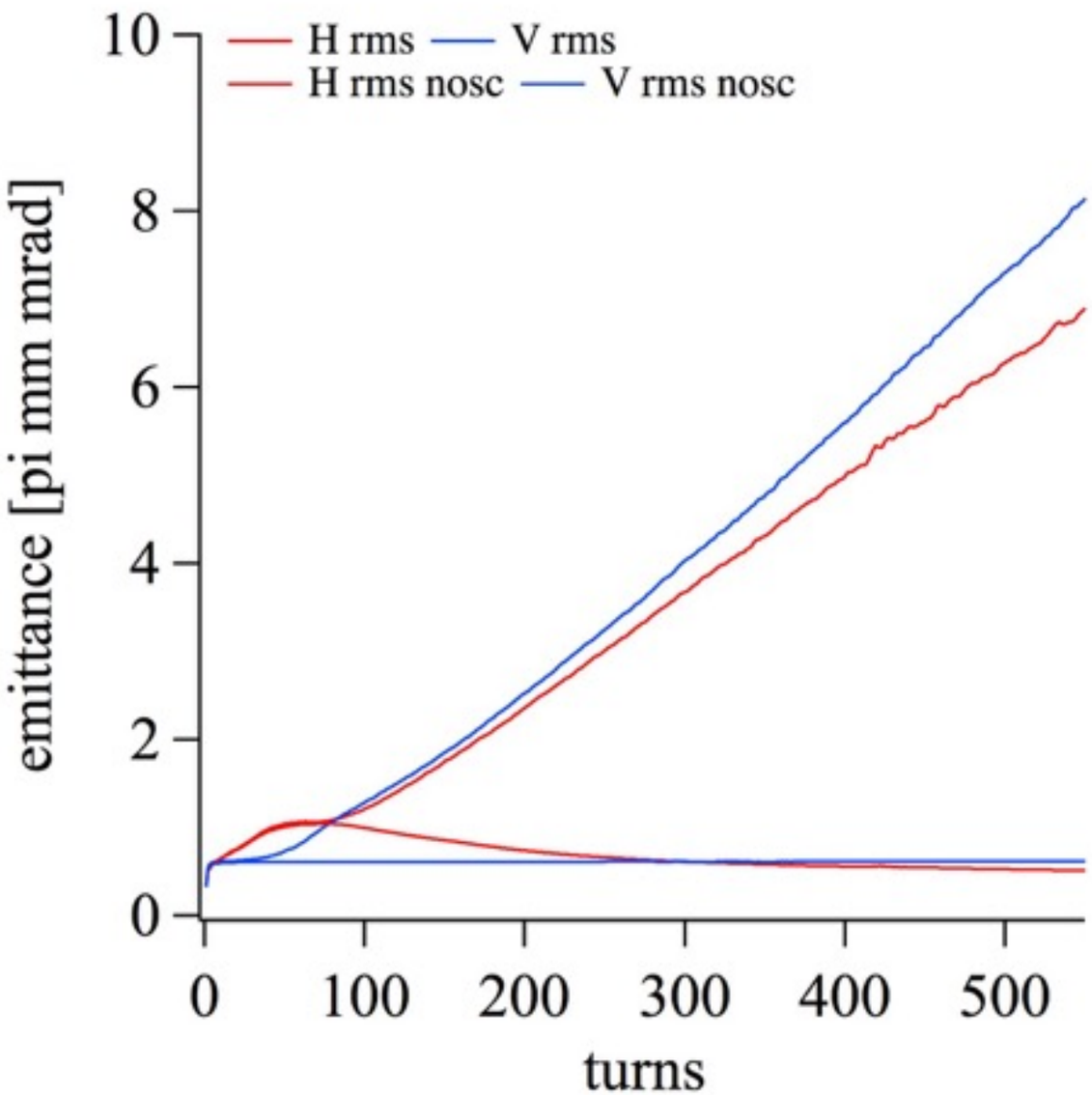


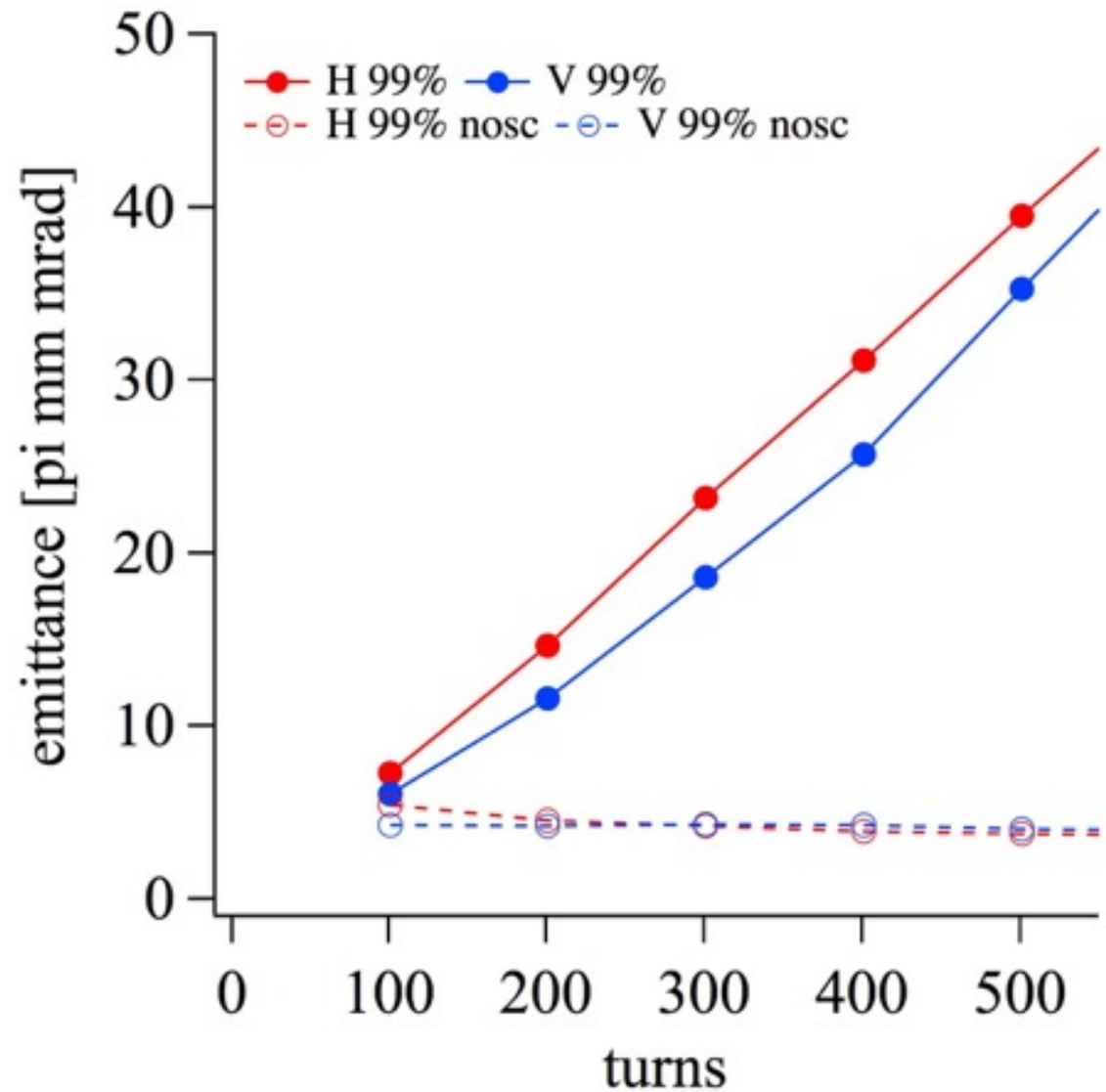
Increase charge per particle by n/(n-1).

The same number of macro particles N are used during injection.

# Space charge simulation with multiturn injection

*no painting*



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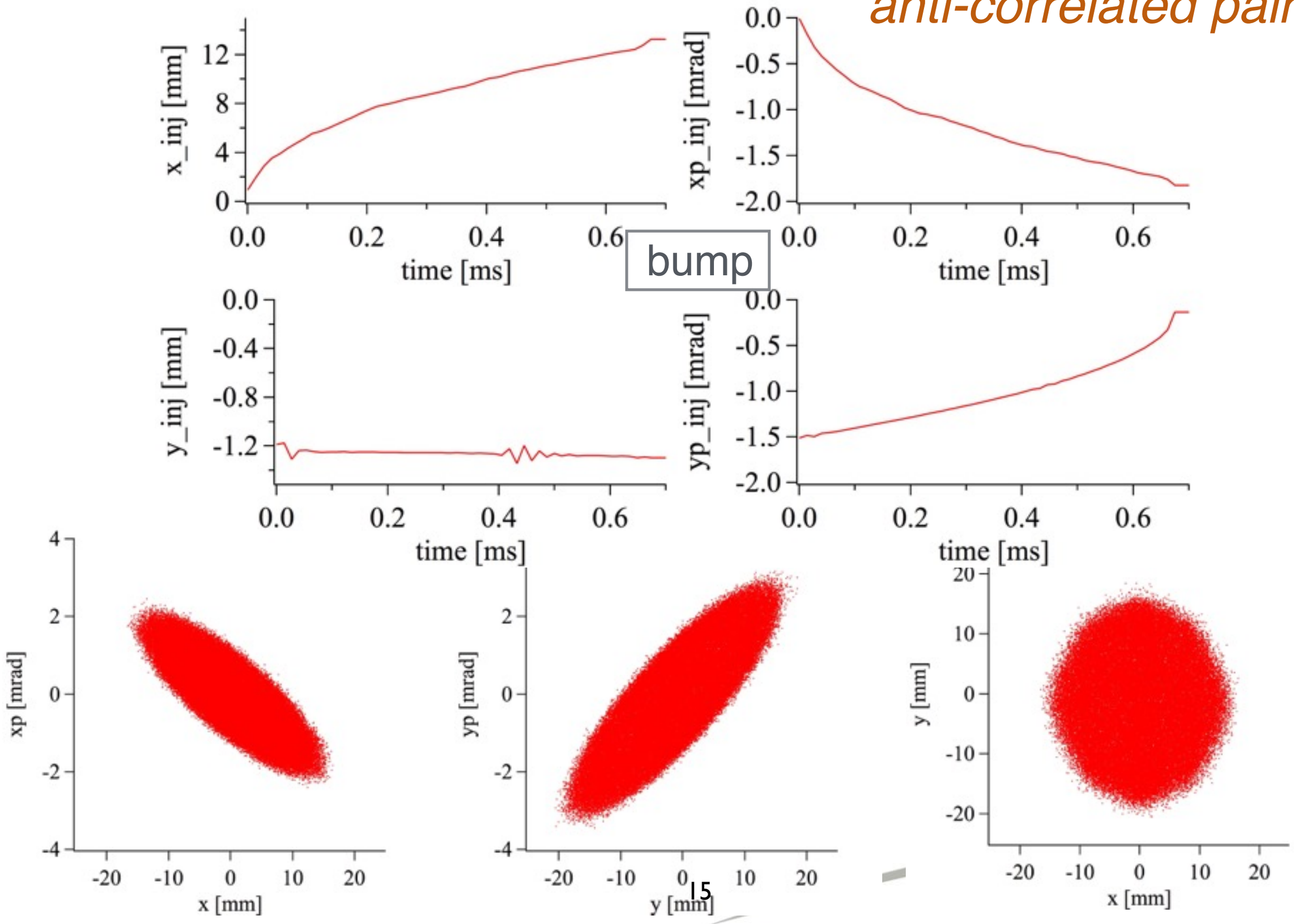
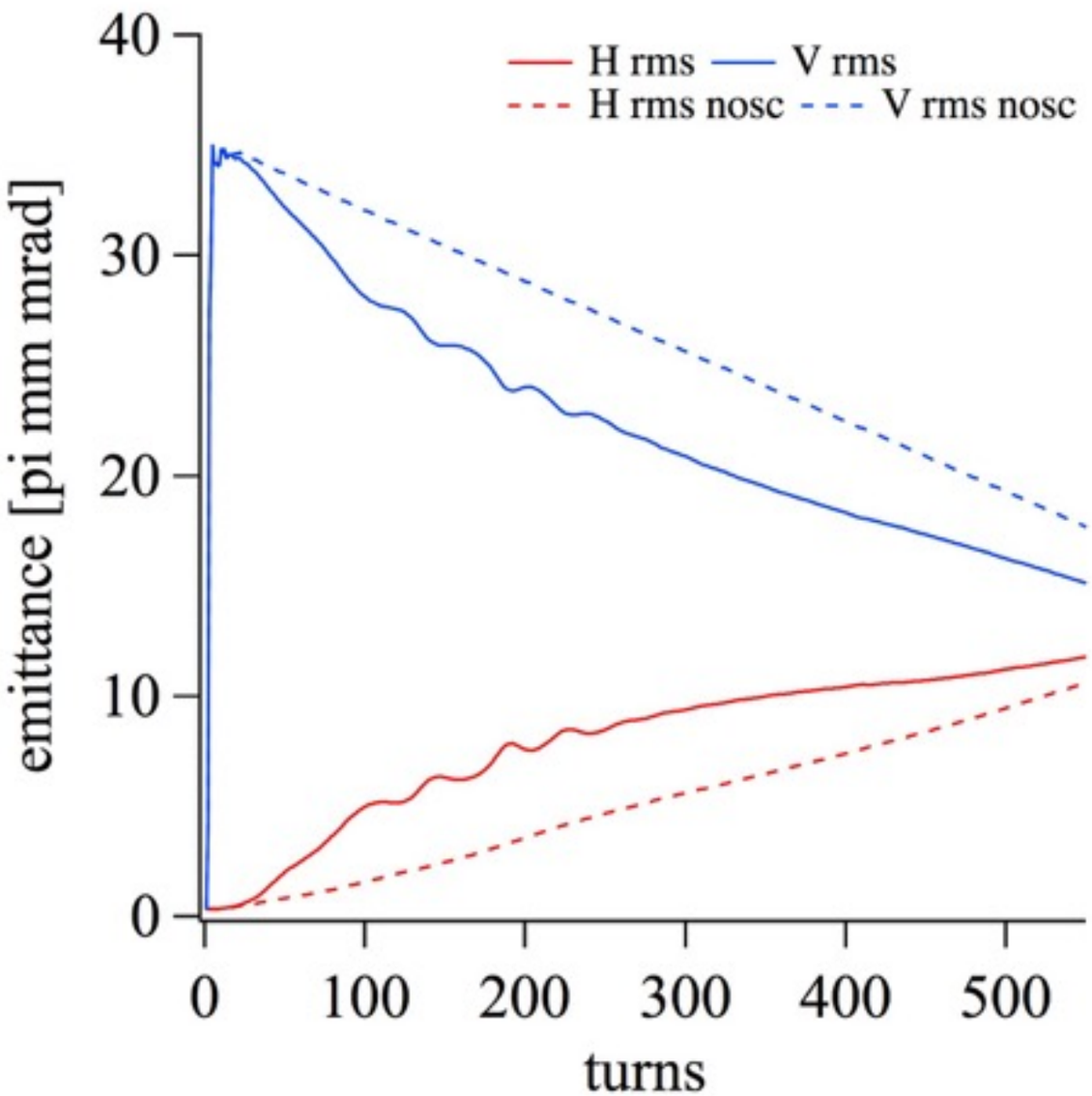
# Space charge simulation with multiturn injection

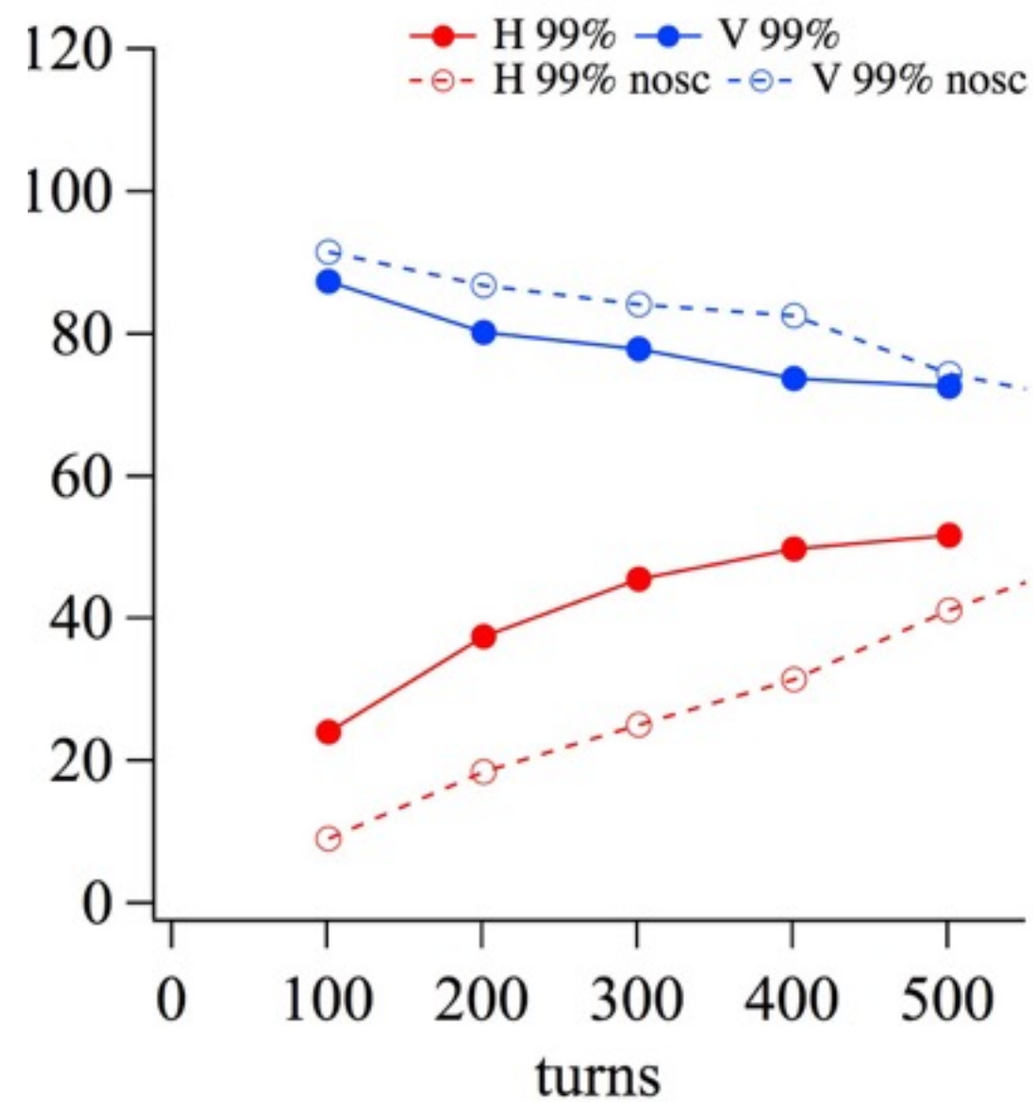
*anti-correlated painting*



# Space charge simulation with multiturn injection

*anti-correlated painting*



# Injection and simulation

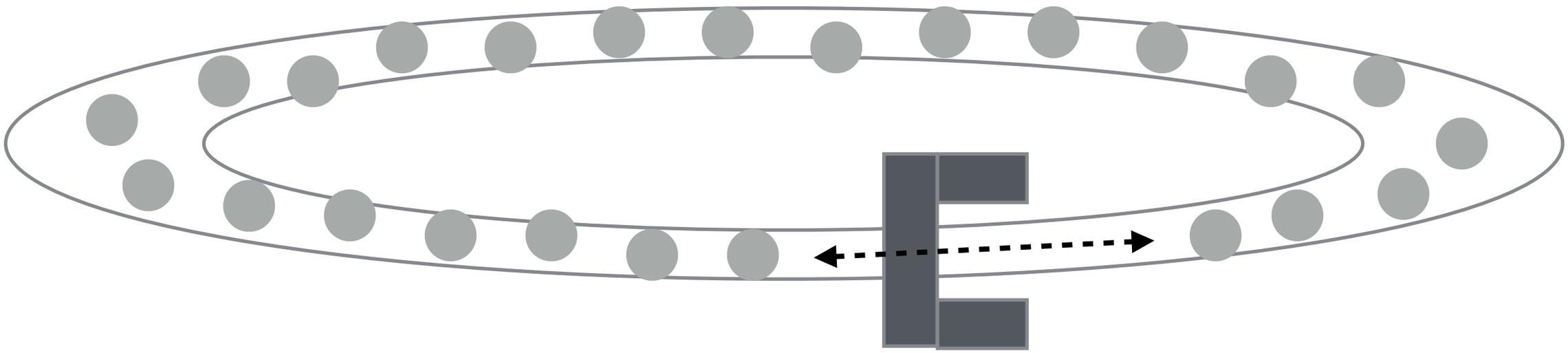
*summary*

- Splitting 5 MW into 4 pulses is a good idea.
- Space charge effects does not seem to be an issue.

# Capture

## *longitudinal phase space*

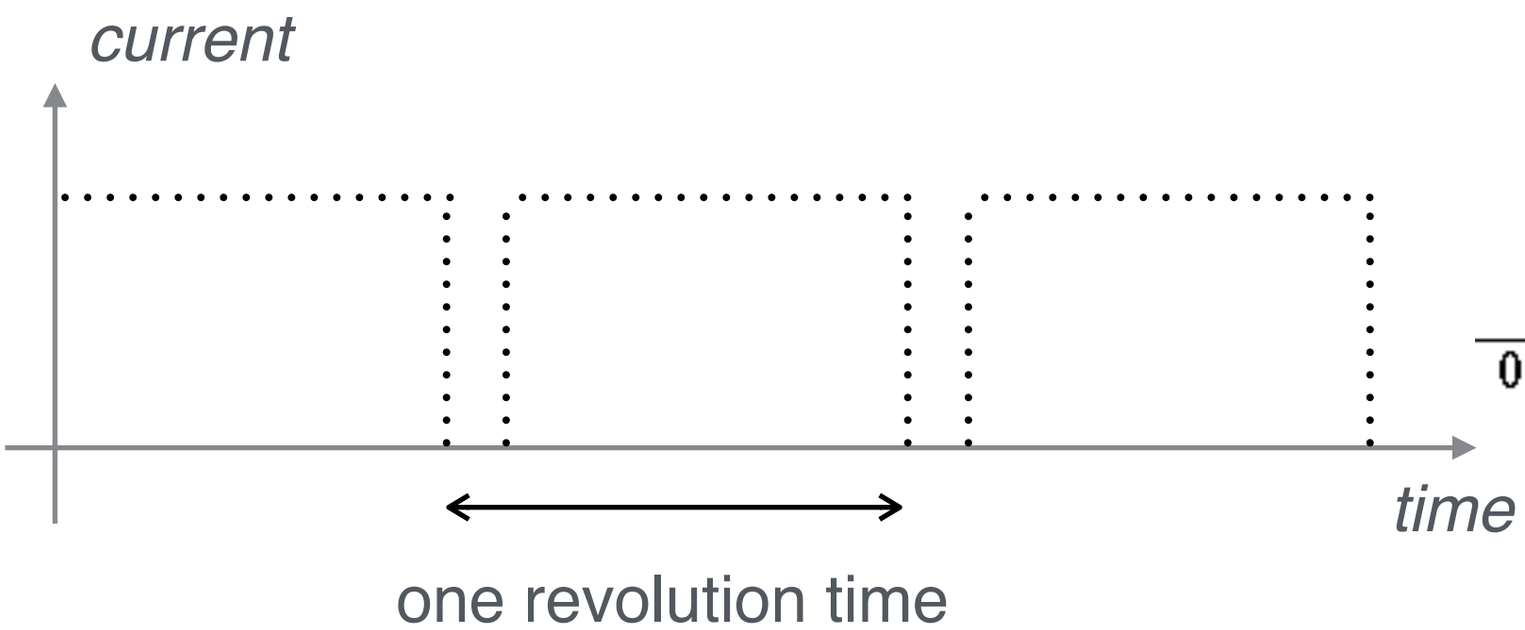
Need a gap in longitudinal phase space for extraction kicker rise time.

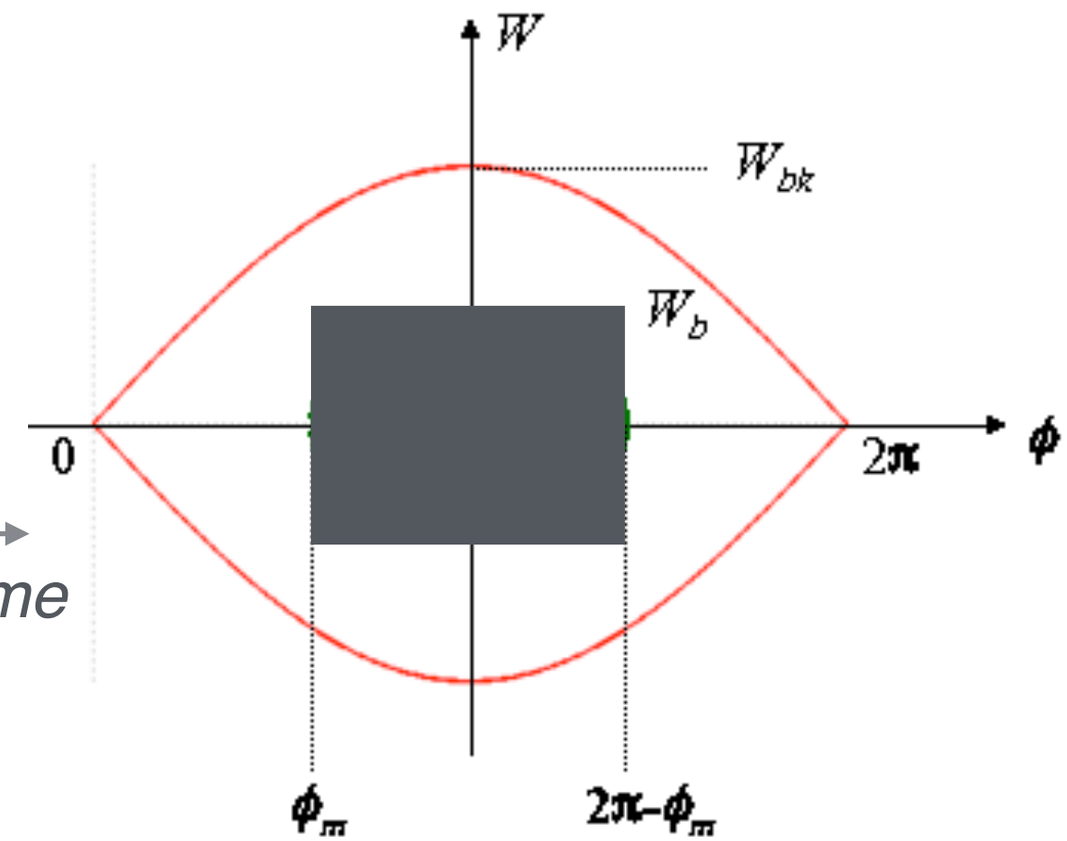


- Rise time of a kicker magnet is roughly 100 ns. Circulating beam should not feel this transient magnetic field.
- Revolution time is about 1 micro-s (1000 ns) so that we should keep empty space of at least one tenth of the circumference.
- The more the particles spread out, the less the peak intensity is and collective effects are reduced.

# Capture

## *LEBT/MEBT chopper*



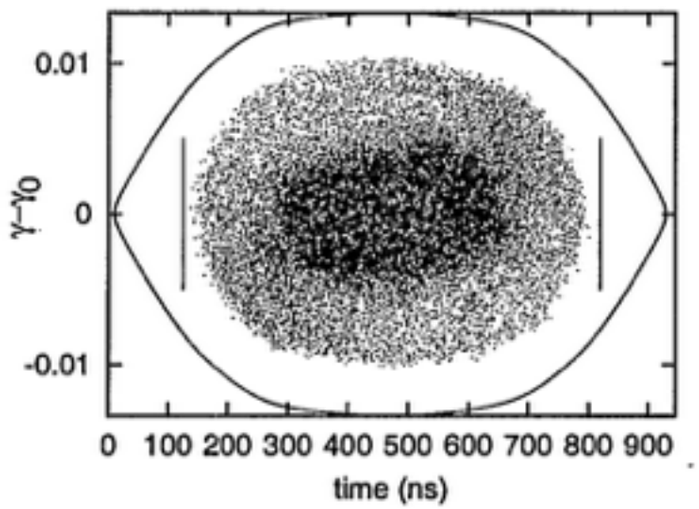



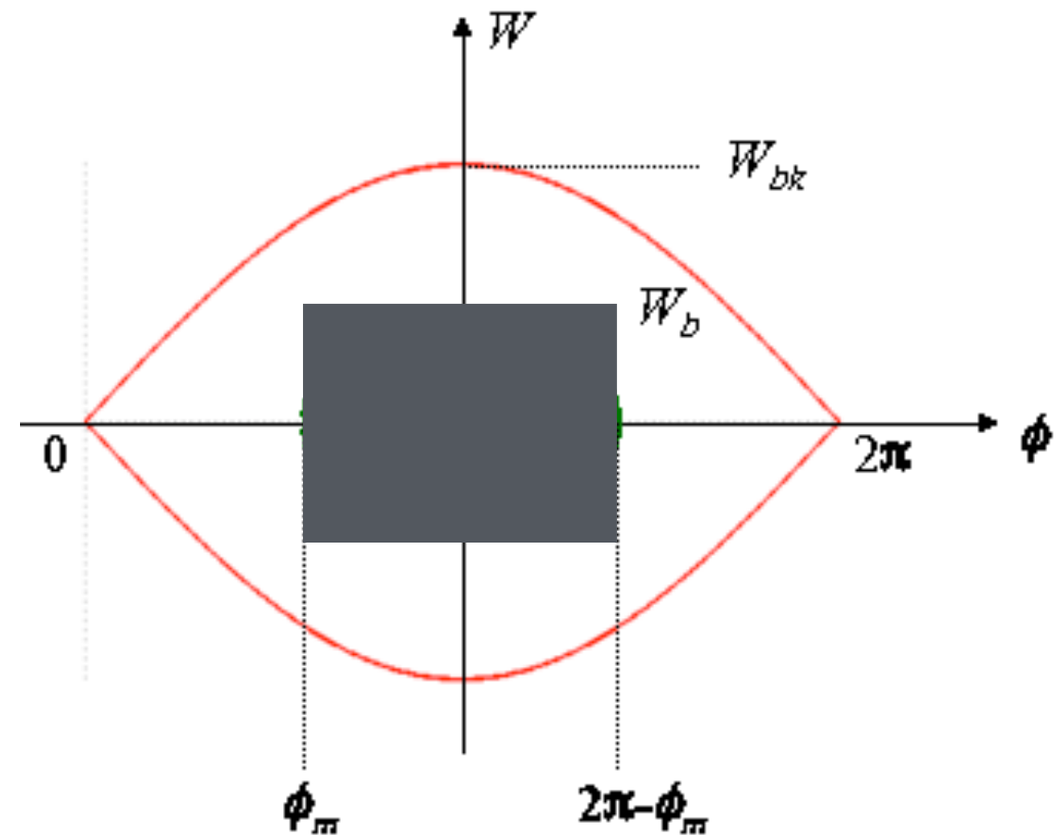

One way is to create a gap in LEBT and/or MEBT by a beam chopper whose frequency is the same as revolution frequency of the ring.

# Capture

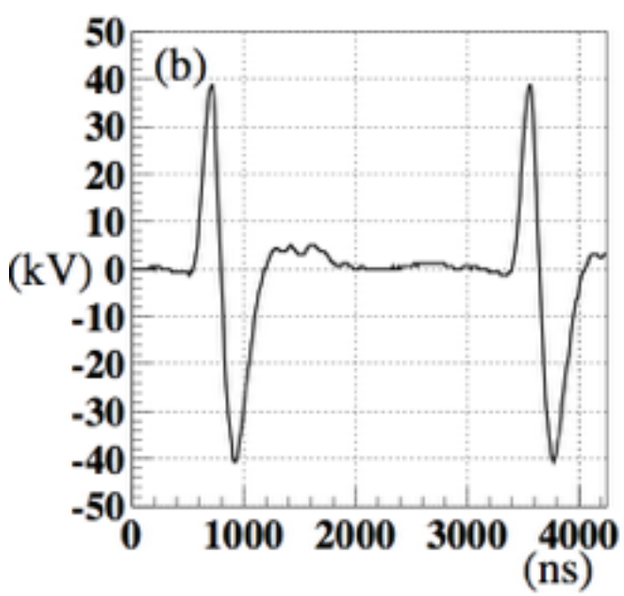
## *RF bucket shape*

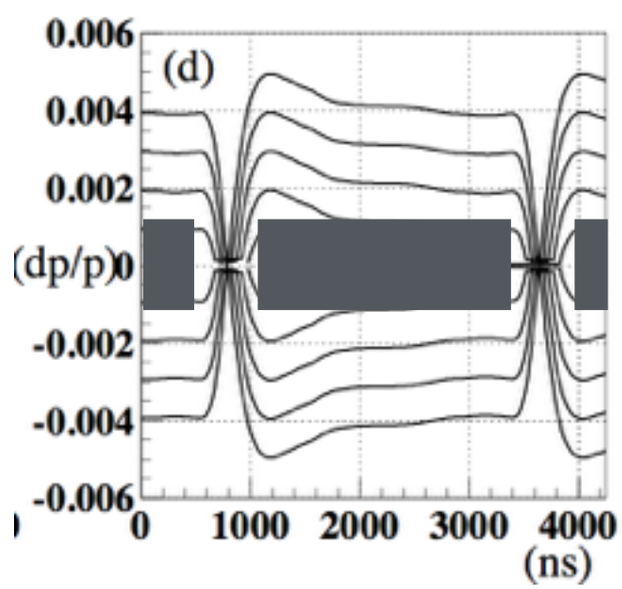
RF bucket can be more flattened by adding second harmonic RF.




And even more flattened by barrier bucket (pulsed single wave RF).



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# Capture

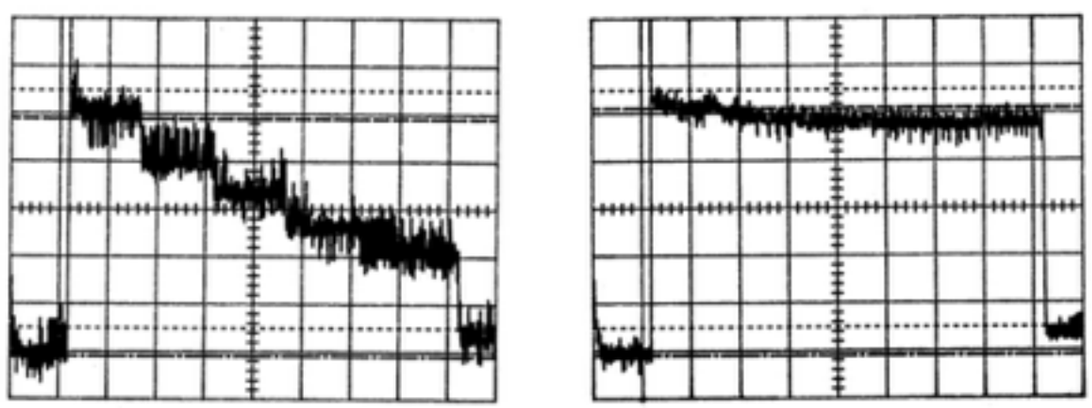
## *barrier bucket test at the AGS*

TABLE I. Barrier cavities parameters.

| | MA cavity | Ferrite cavity |
|---|---|---|
| The number of gaps | 4 | 4 |
| Total rf voltage (kV) | 40 | 40 |
| Tube power (kW) | 30 × 2 | 600 |
| Tube operation | class B push-pull | class AB single ended |
| $Q$ value | 0.6 | 30 |
| $R/Q$ per cavity (kΩ) | 6.0 | 0.72 |
| Resonant frequency (MHz) | 1.5 | 2.6 |
| Beam loading correction | feed forward | none |

- Magnetic Alloy (MA) cavity can create single pulse RF wave form because Q is less than unity (0.6).
- Experimental test of stacking with barrier bucket was done at AGS in 1998 under the Japan-US collaboration.

PRST-AB 2 M. FUJIEDA *et al.* 122001 (1999)



0.1s/div. without barriers

0.1s/div. with barriers

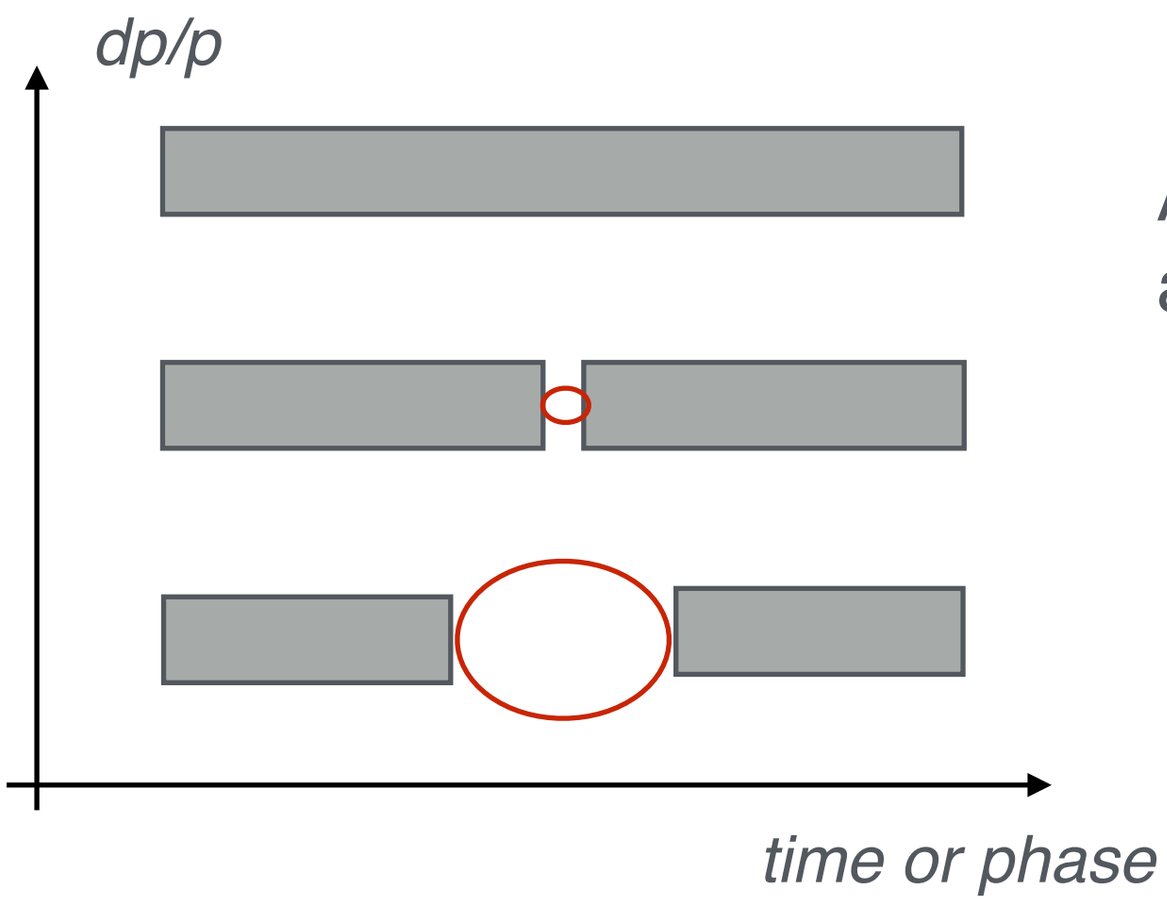
FIG. 7. Slow intensity monitor signals when the injection kicker was fired five times. The horizontal axis is time with 0.1 s/division. The vertical axis is 50 mV/division. One bunch was injected and the intensity was $1.9 \times 10^{12}$ protons. Left: without barriers; right: phase gap of 97° was made by barriers to avoid beam loss.

# Capture
*summary*

- Bunch structure created by a chopper at LEBT and/or MEBT is preserved by RF bucket in the ring.
- RF bucket can be single frequency, adding second harmonics or barrier bucket with single isolated RF pulse.

# Barrier bucket
## *can eliminate chopper?*

*"Can we eliminate LEBT/MEBT chopper if we uses barrier bucket?"*
Ryoichi asked me the other day.




Adiabatically creates barrier bucket after injection is finished.

# Barrier bucket

## *time scale of adiabaticity*

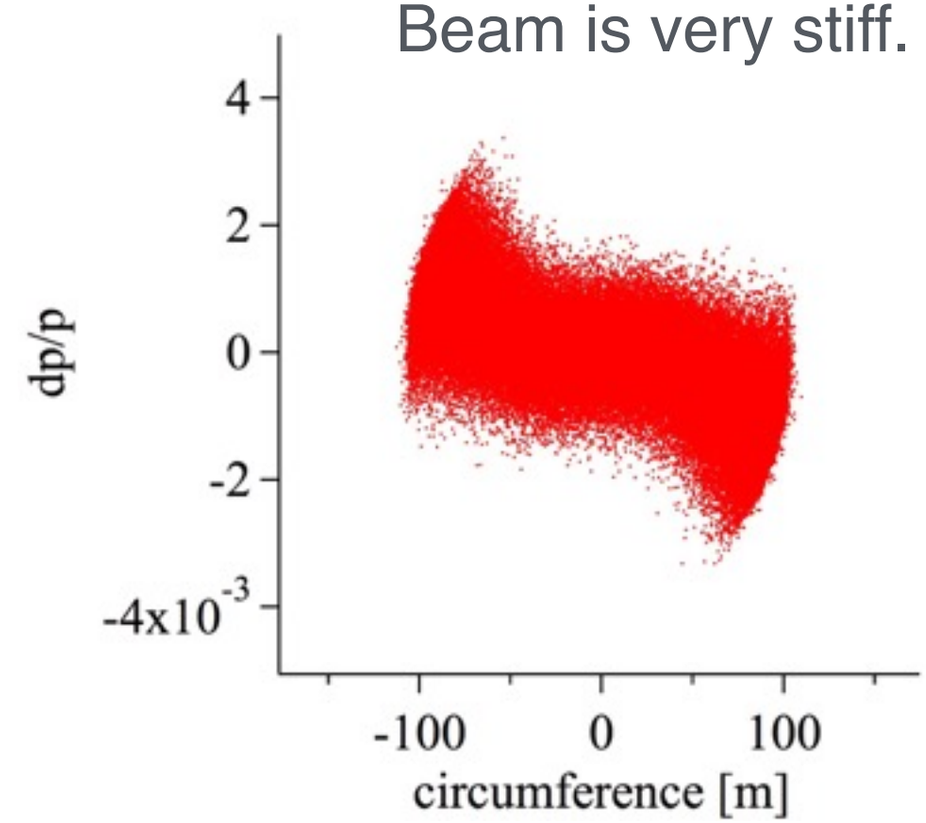
How much time does it take to make a gap?

Takes long time because

$$\frac{\Delta t}{t} = \left(\alpha_p - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}$$

- Momentum spread is small, ~0.001.
- Slippage factor is small, ~0.07.

Beam is very stiff.

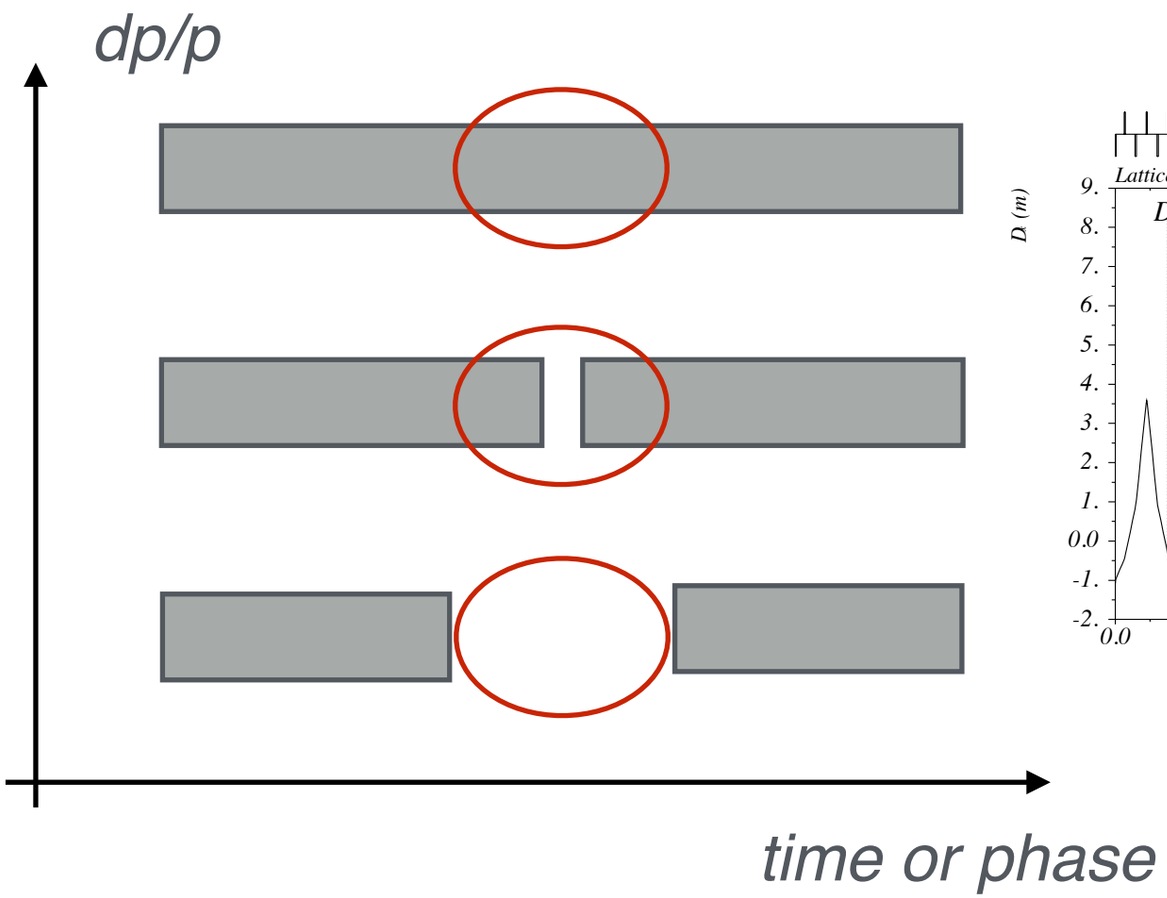



Order of 10k turns!

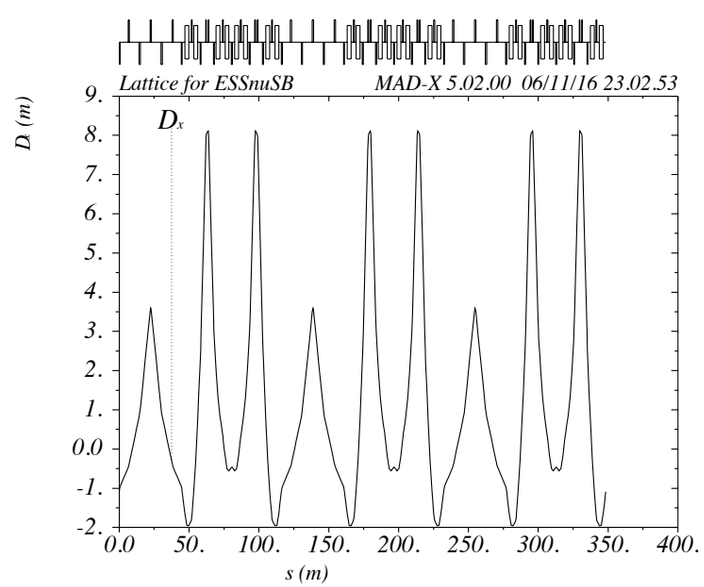
# Barrier bucket

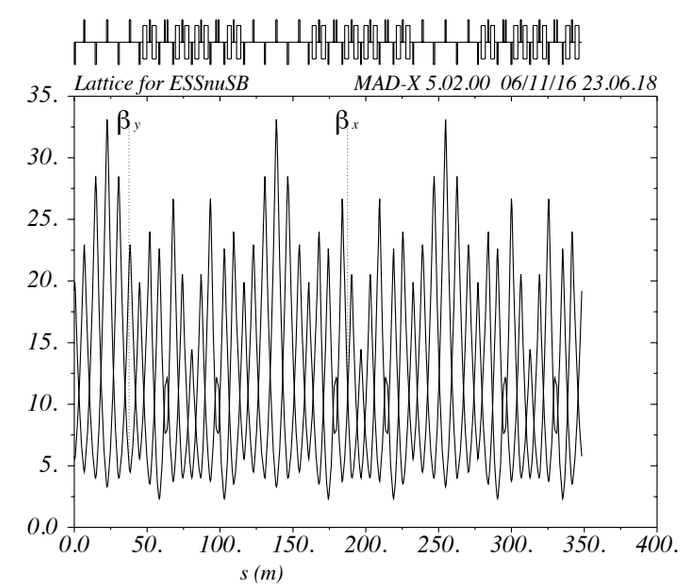
## *gap forming with non-adiabatic process*

- Increase of momentum spread if a buncher at the end of linac is available (but let not assume this).
- Slippage factor can be larger with imaginary gamma-t lattice.
- Apply RF full voltage from the beginning (non-adiabatic process).




alpha-p=-0.004 (gamma-t=16i)



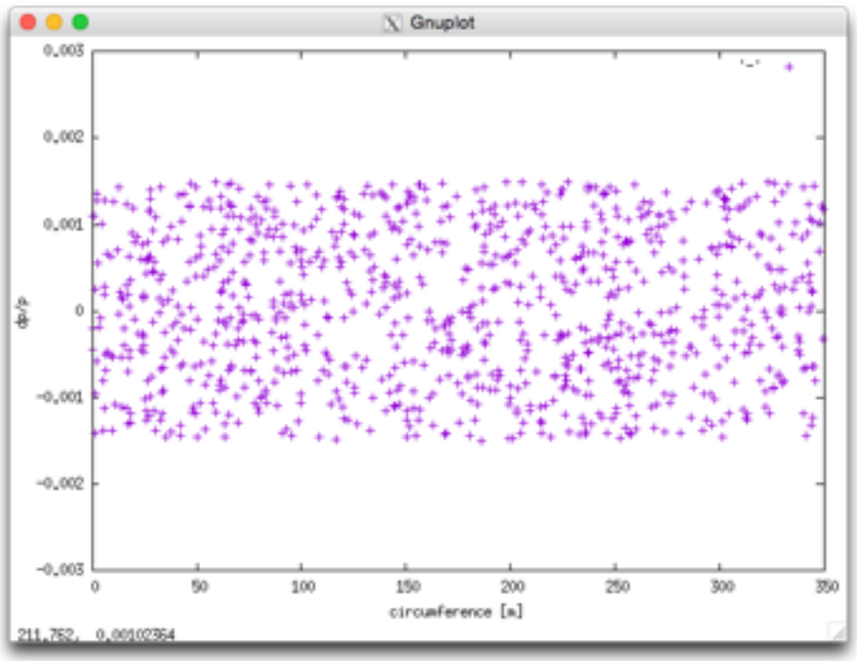



# Barrier bucket

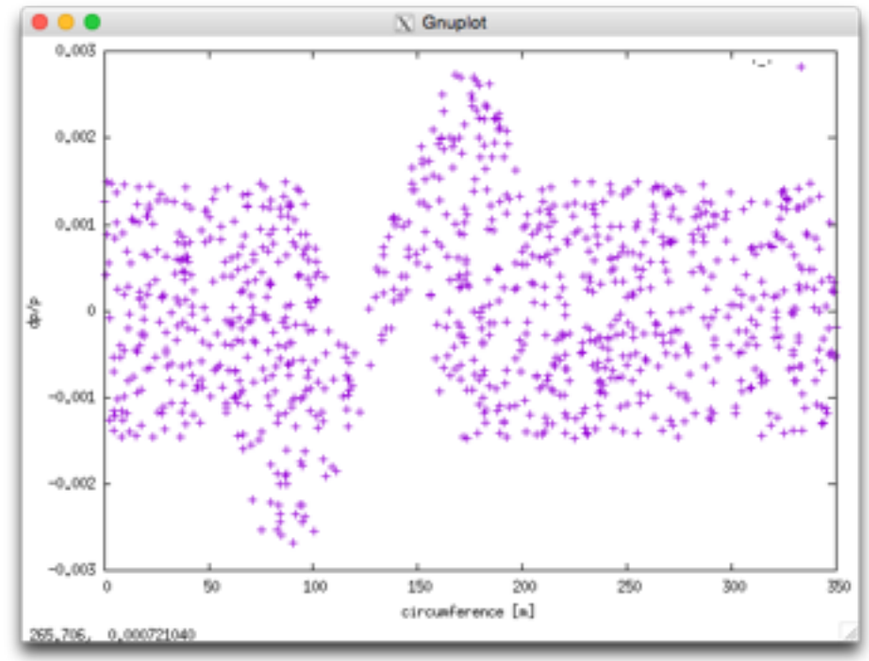
*creating a gap after injection*

h=4 (3.25 MHz), V=10 kV

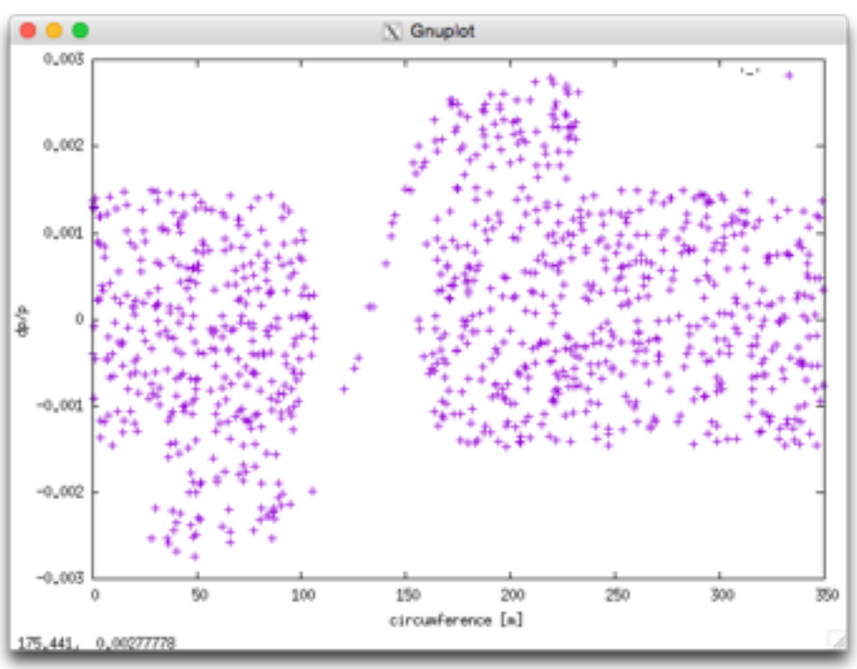
1turn



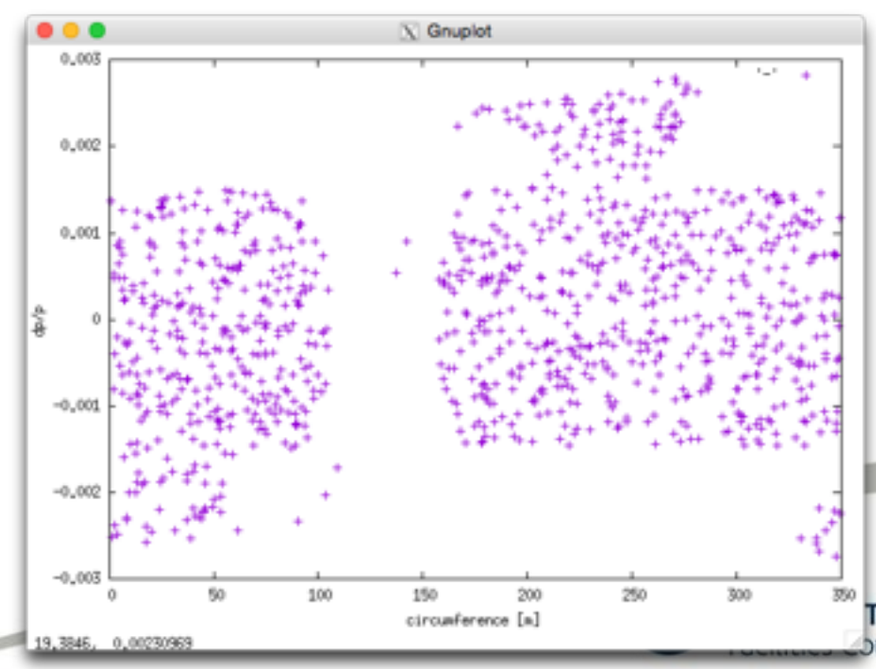

500turn




1000turn




1500turn



# Barrier bucket
## *summary*

- Barrier bucket applied non-adiabatically create a gap.
- It takes another 1500 turns after completing 550 turns injection.
- Both buncher at the end of linac to increase dp/p and imaginary gamma-t lattice to increase slippage factor help to speed up the process.
- This is an option, but chopper is more straightforward to create a gap.

# Others
*collimator*

- Essential
- Beam loss due to foil scattering cannot be eliminated if H- injection.

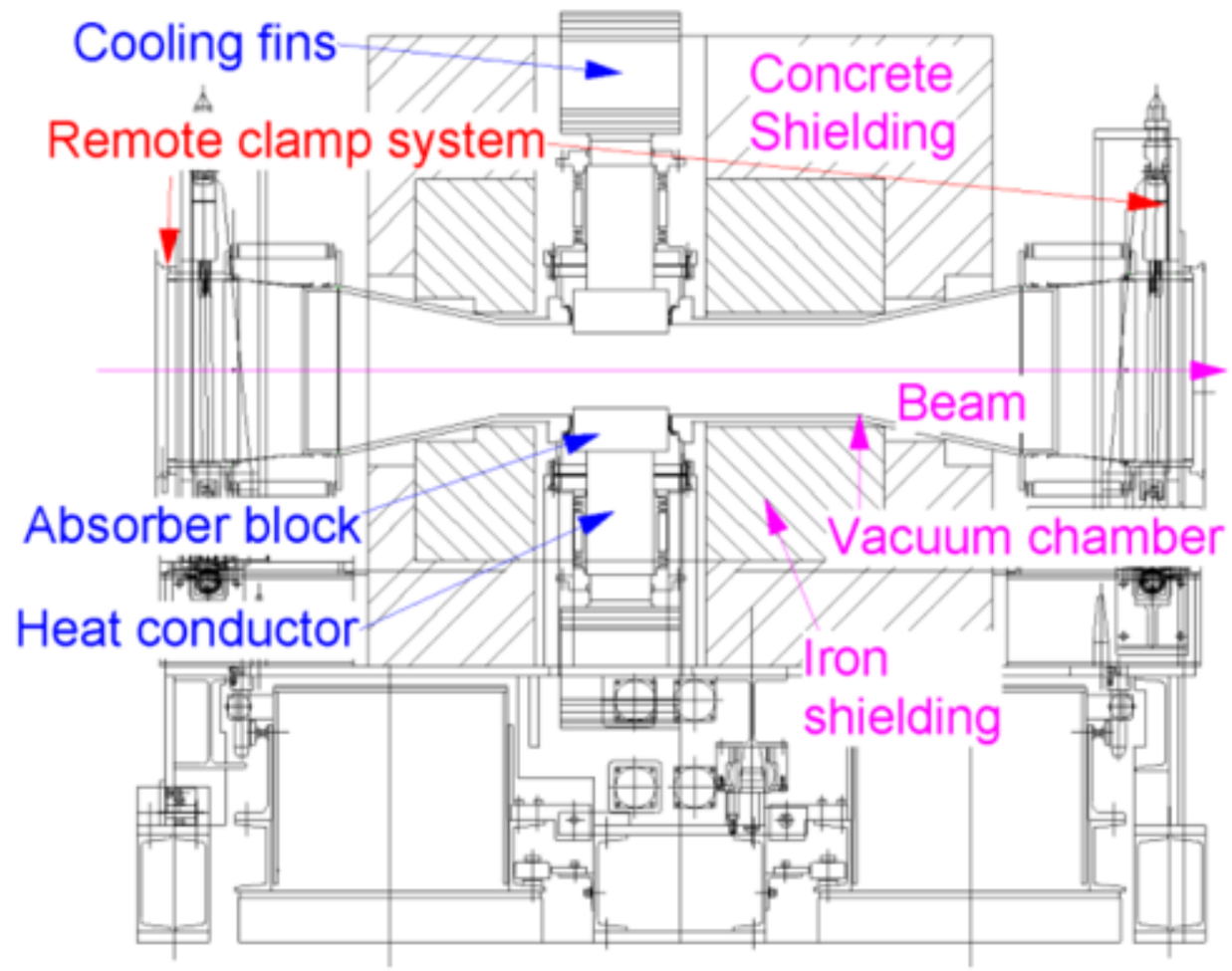



Figure 1. Schematic of J-PARC RCS collimator

Yamamoto, EPAC206

# Others
## *extraction*

- Single turn extraction is the simplest and easiest way to extract the beam.
- It could be easier than the J-PARC RCS extraction which extract the beam of 3 GeV.
- Is there any requirement of the transverse beam profile? Neutron target requires uniform (not peaked) beam profile. Is it the same for neutrino target?
- Octupole lens if the flat profile is necessary.

# Others
## *instability*

- Beam circulates only 550 turns.
- Any long term instability does not have to be worried.
- Still some impedance source such as the kicker should be reasonably minimised.
- e-p instability is another concern because the beam is almost coasting without long clearing gap.
    - TiN coating

# Remark

I do not see any show stopper. Mostly the concept was proven in other places.

# Back-up

backup

# New configuration of short pulse proton source

If a short pulse is the requirement, a ring accumulator/accelerator has to be added.

| SNS configuration | J-Parc (ISIS) configuration |
|---|---|
| full energy 1 GeV linac + accumulator ring | injector linac (400 MeV) + 3 GeV synchrotron |
| • Full energy linac is long and costly both in construction and operation. | • Repetition rate is limited (25 - 50 Hz). |

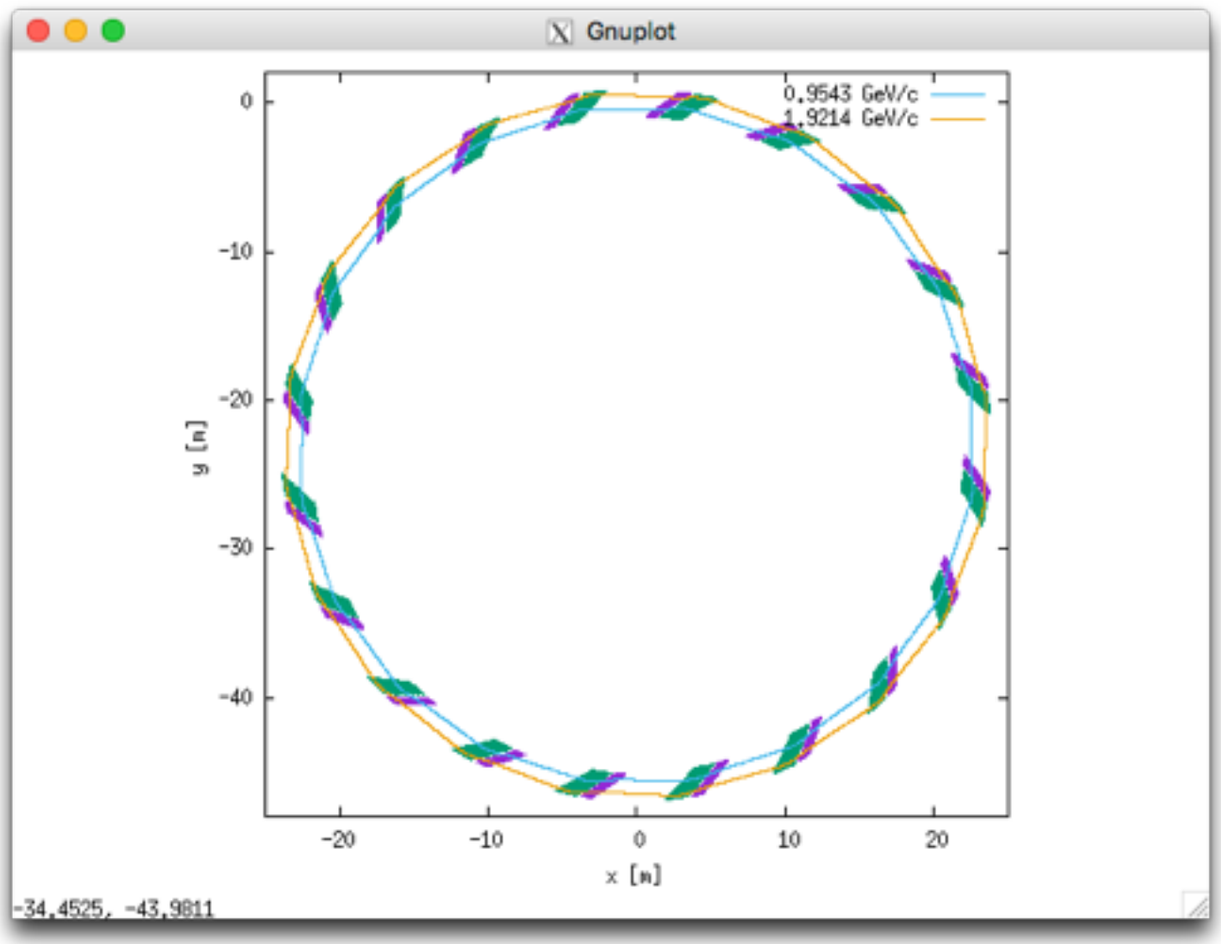
| New configuration |
|---|
| injector linac (400 MeV) + 1.2 GeV FFAG |
| • Moderate energy linac and ring with high repetition rate (100 - 200 Hz).<br>• Provide a variety of time structure of neutrons.<br>• Best match with multiple target stations.<br>• Muon benefits from high repetition rate.<br>• Target is not ready for a few MW peak beam power yet. |

# Parameters for 1.2 GeV FFAG (20 cell)

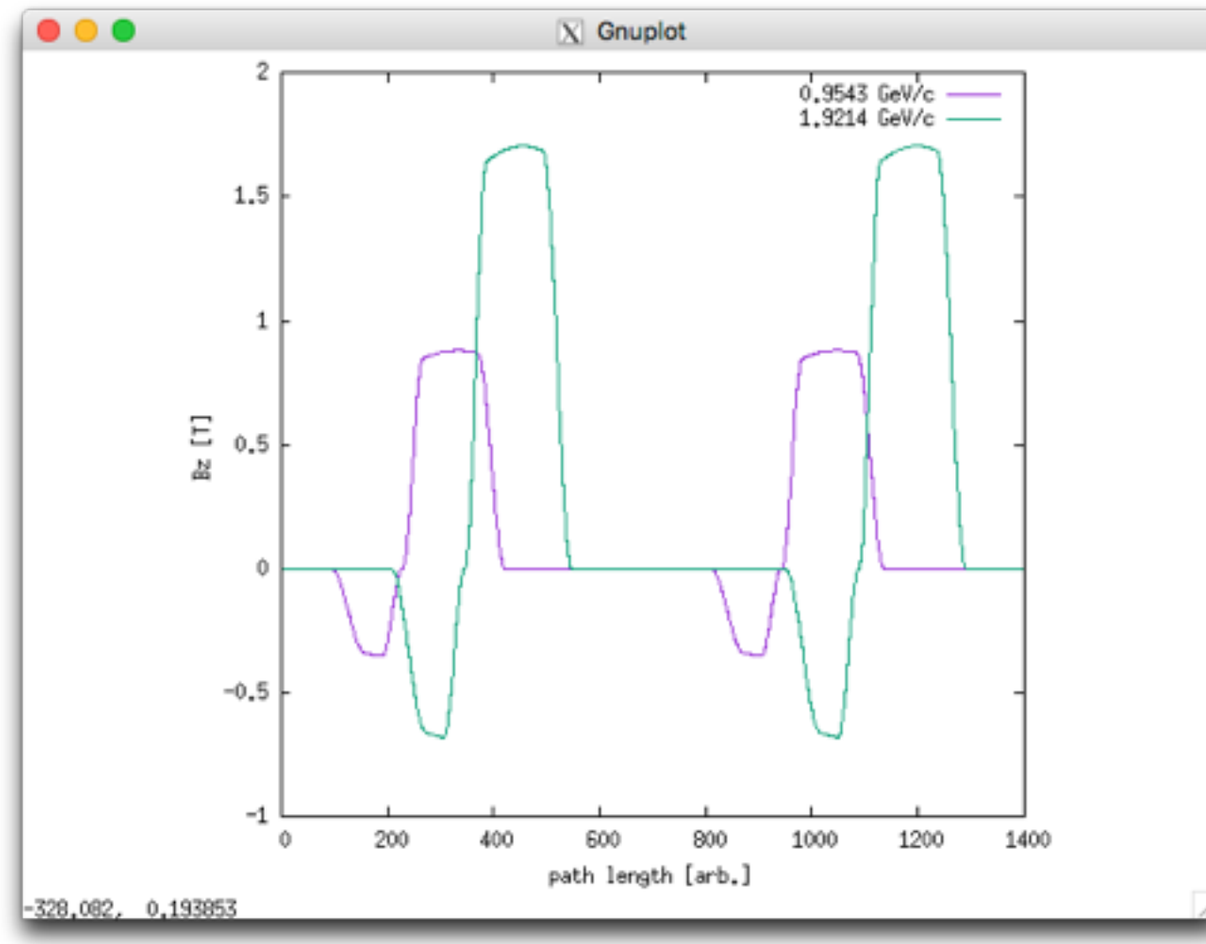
| | |
|---|---|
| kinetic energy | 0.4 - 1.2 GeV |
| mean radius at injection | **23 m** |
| number of cell | 20 |
| magnet longitudinal length (D, F) | **(0.72, 1.45) m** |
| packing factor | 0.34 |
| straight section | 4.76 m |
| spiral angle | **50 degree** |
| k index | **17** |
| orbit excursion | **0.90 m** |
| cell tune (H, V) | (0.2443, 0.2456) |
| ring tune (H, V) | (4.8856, 4.9126) |
| number of particles per pulse | $8 \times 10^{13}$ - $2 \times 10^{14}$ |
| repetition | 100 Hz |
| beam power | 1.6 - 3.8 MW |
| linac current | 100 mA |
| total linac geo. emittance | 4.92 pi mm mrad |
| number of injection | 175 - 420 turns |
| painted geo. emittance (H, V) | (270, 135) pi mm mrad |
| space charge tune shift | -0.20 [*Bf=0.25] |
| revolution time | 0.674 - 0.508 us |

# Footprint of 1.2 GeV FFAG (20 cell)

R = 23 m




bending field



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# At ESS site

“Unfortunately”, you will have a full energy linac and no point to invest an accelerator like synchrotrons and FFAGs.

Simplest accumulator ring with reasonable size of bends and quads is more than enough to achieve the goal.

SNS

# Menu of Initial Investments and Payoff

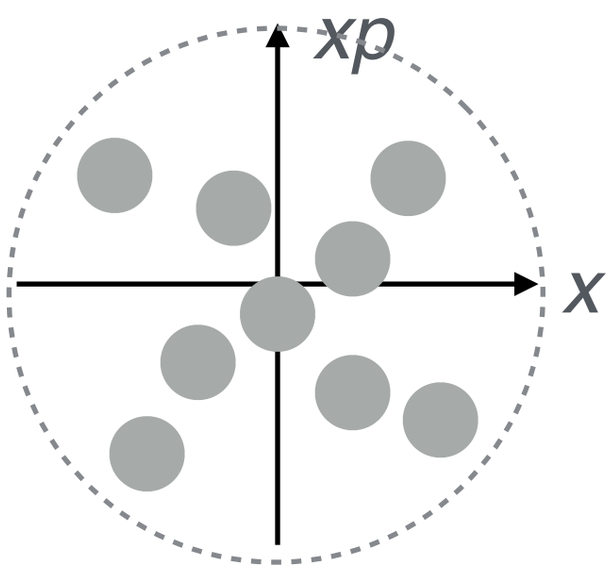
| Feature | Cost | Payoff So Far |
|---|---|---|
| Large Aperture | $$$$ | High |
| Injection Painting | $$$ | High |
| Collimation | $$$ | High |
| TiN coating | $$$ | Unknown |
| 2nd harmonic RF | $$ | Medium |
| Main sextupoles | $$ | Low |
| Main octupoles | $$ | None |
| Sextupole correctors | $ | None |
| Octupole correctors | $ | None |
| Clearing solenoids | $ | None |
| Beam in gap kicker | $ | None |
| Clearing electrodes | $ | None |

We spent the big bucks where it counted most.

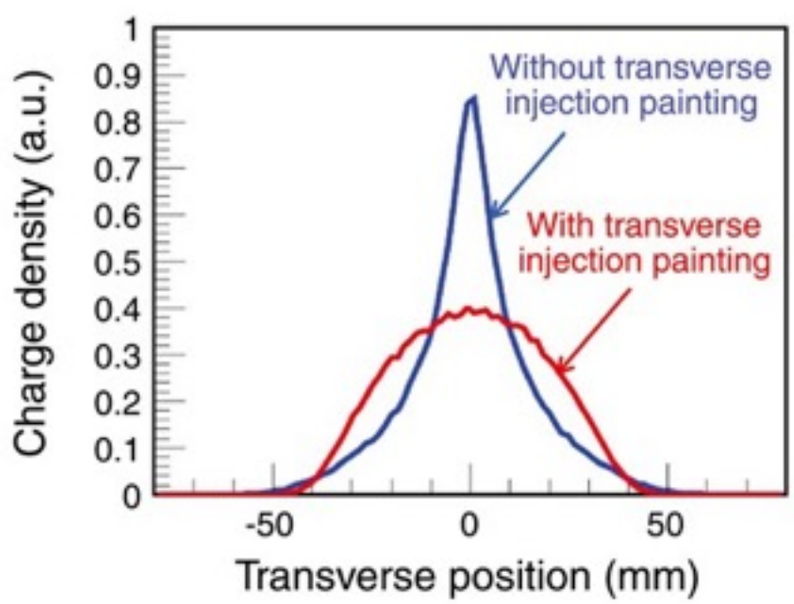
# Injection
## *painting*

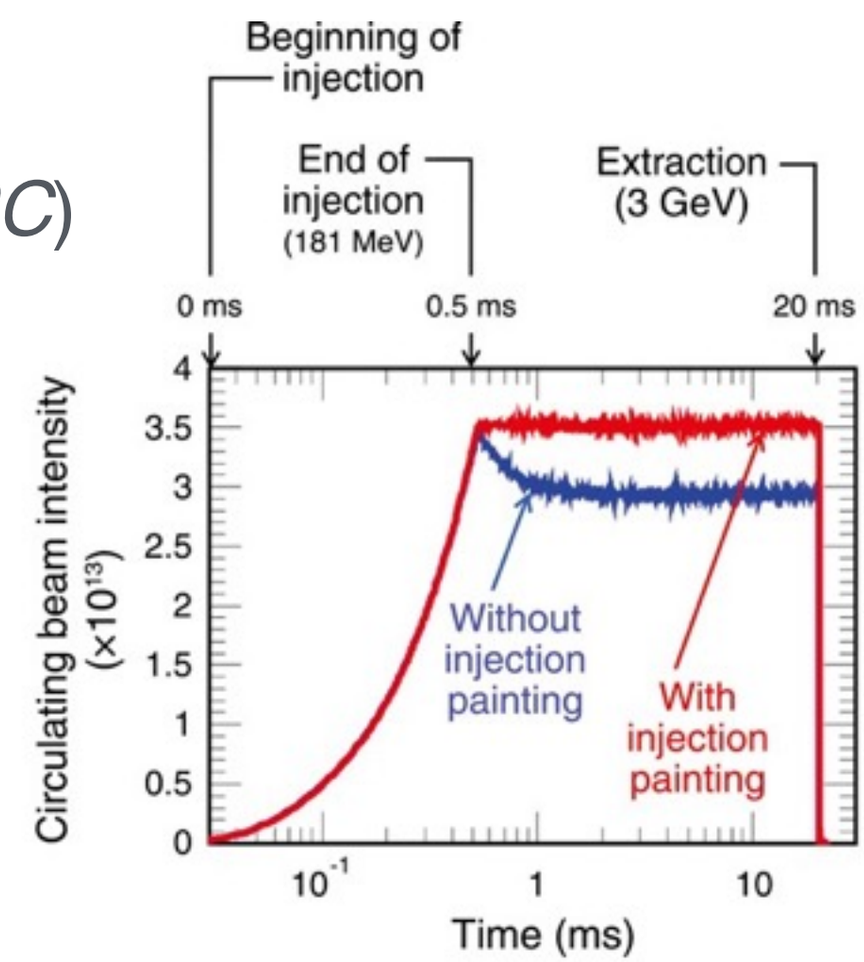
Beam emittance in the ring should be enlarged at injection.

- 0.333 pi (RMS, normalised) is about 1 pi (95%, unnormalised).
- Collimator acceptance is between 100 and 400 pi mm mrad.




(*from J-PARC*)



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