2^{nd} Harmonic RF

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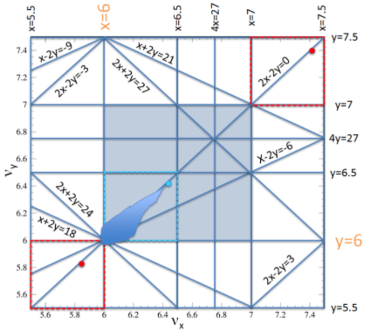
KEK/J-PARC

Question from FNAL

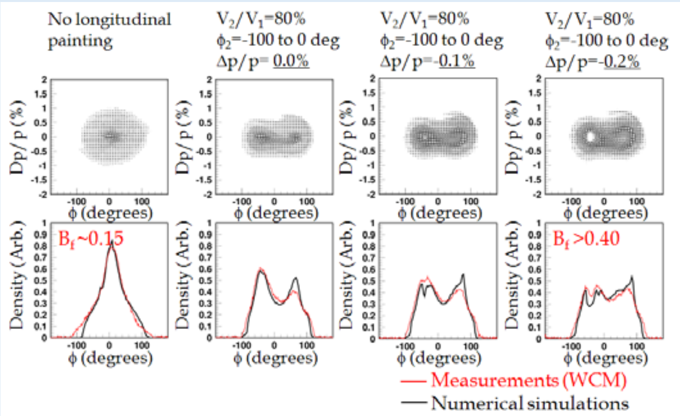
- MR is using the 2nd harmonic cavity for the space change issues. →Both MR & RCS use it.
- If you have some simulation results of space charge effects and beam study results which show how it was cured after the cavity was install, we would like to know.
- The Operation pattern and LLRF control would also be interesting. Is the cavity is running through the cycle? Is there anything we have to be aware of before our operation?

Introduction : 2nd H RF

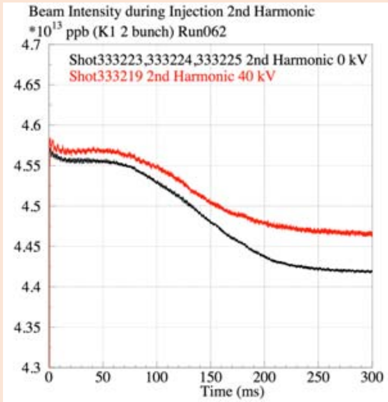
Space charge tune shift (Laslett tune shift): $\Delta\nu_y = \frac{N_p r_p}{2\pi\epsilon_y\beta^2\gamma^3}\frac{1}{B_f}$



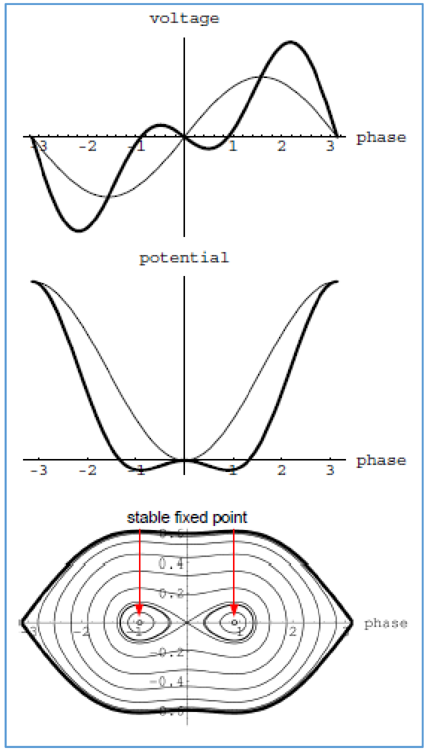
For a large Bunching Factor (=Iav/Ipeak),

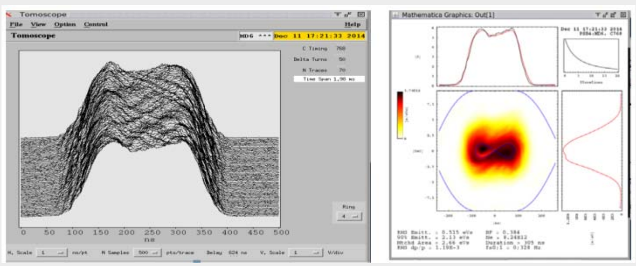


J-PARC RCS: F. Tamura

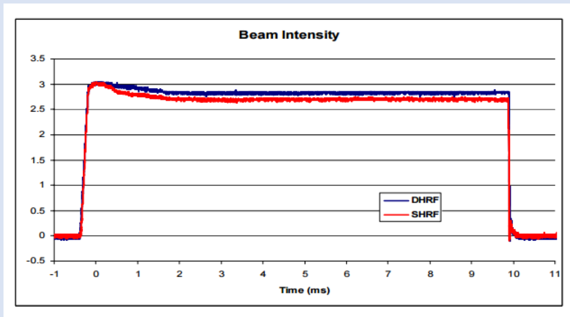


Dual H at J-PARC MR : S. Igarashi





CERN PSB: M. Paoluzzi, IPAC15



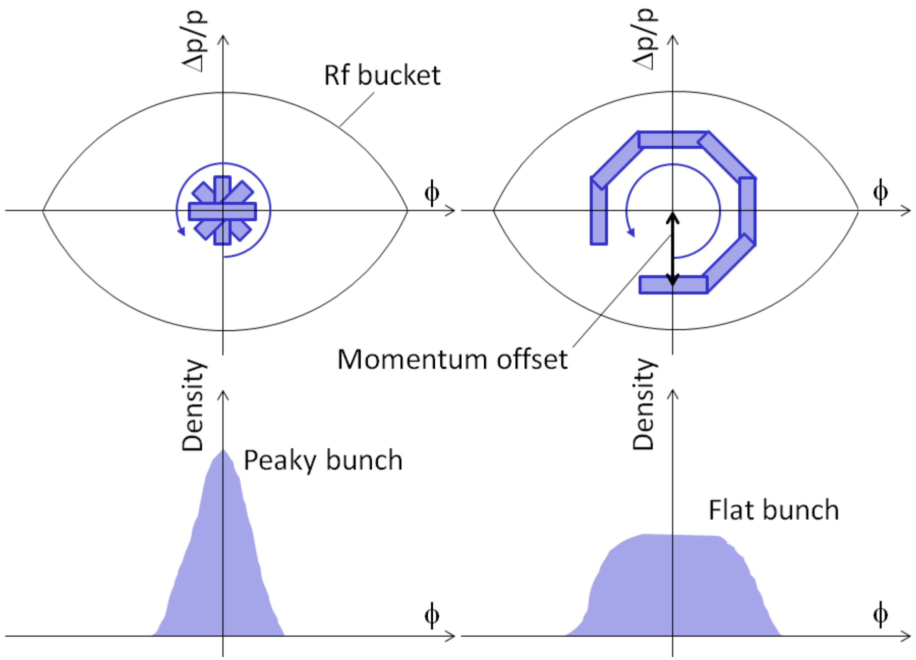
Dual H acc. @ISIS : A. Seville, PAC05

Longitudinal injection painting@ RCS

1 cavity drives both 1st & 2nd H RF

F. Tamura et al, PRST-AB **12**, 041001 (2009).
M. Yamamoto et al, NIM., Sect. A **621**, 15 (2010).

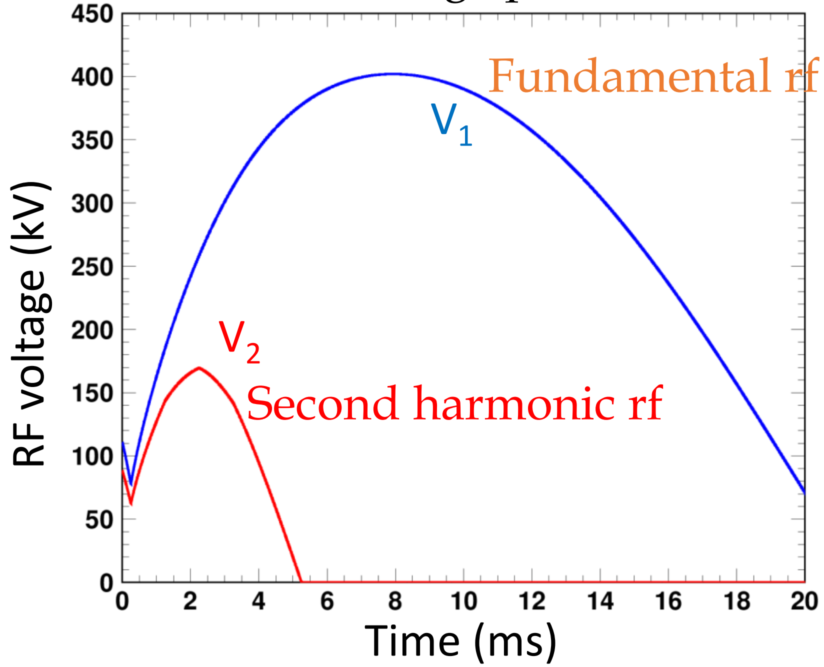
Momentum offset injection



$\Delta p/p$=0, –0.1 and –0.2%

Uniform bunch distribution is formed through emittance dilution by the large synchrotron motion excited by momentum offset.

RF voltage pattern



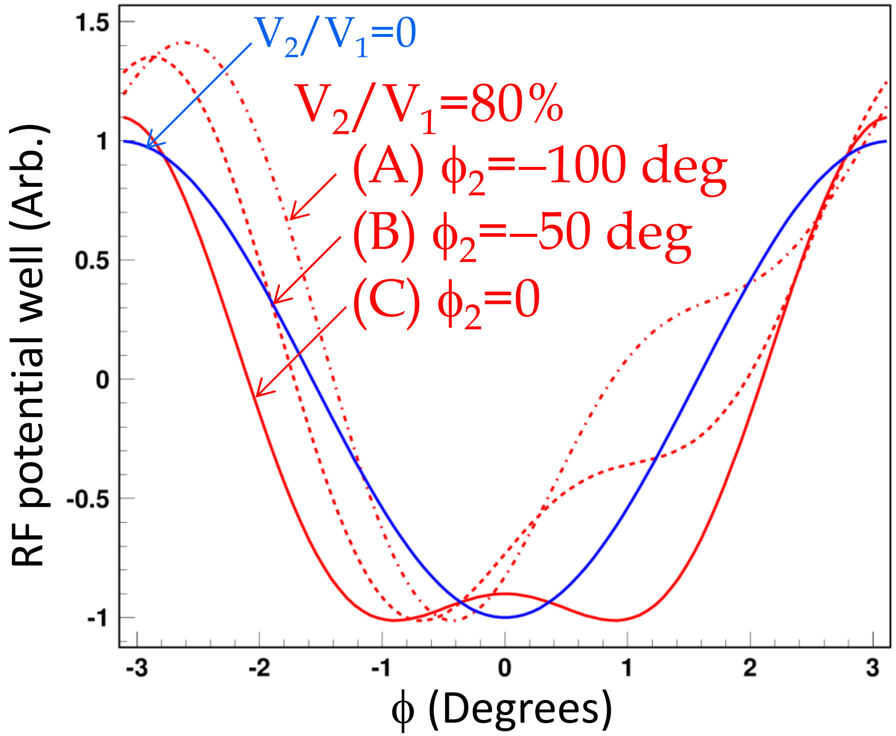
V_2/V_1=80%

The second harmonic rf fills the role in shaping flatter and wider rf bucket potential, leading to better longitudinal motion to make a flatter bunch distribution.

Longitudinal injection painting

Additional control in longitudinal painting ; phase sweep of V_2 during injection

$$V_{rf}=V_1\sin\phi-V_2\sin\{2(\phi-\phi_s)+\phi_2\}$$



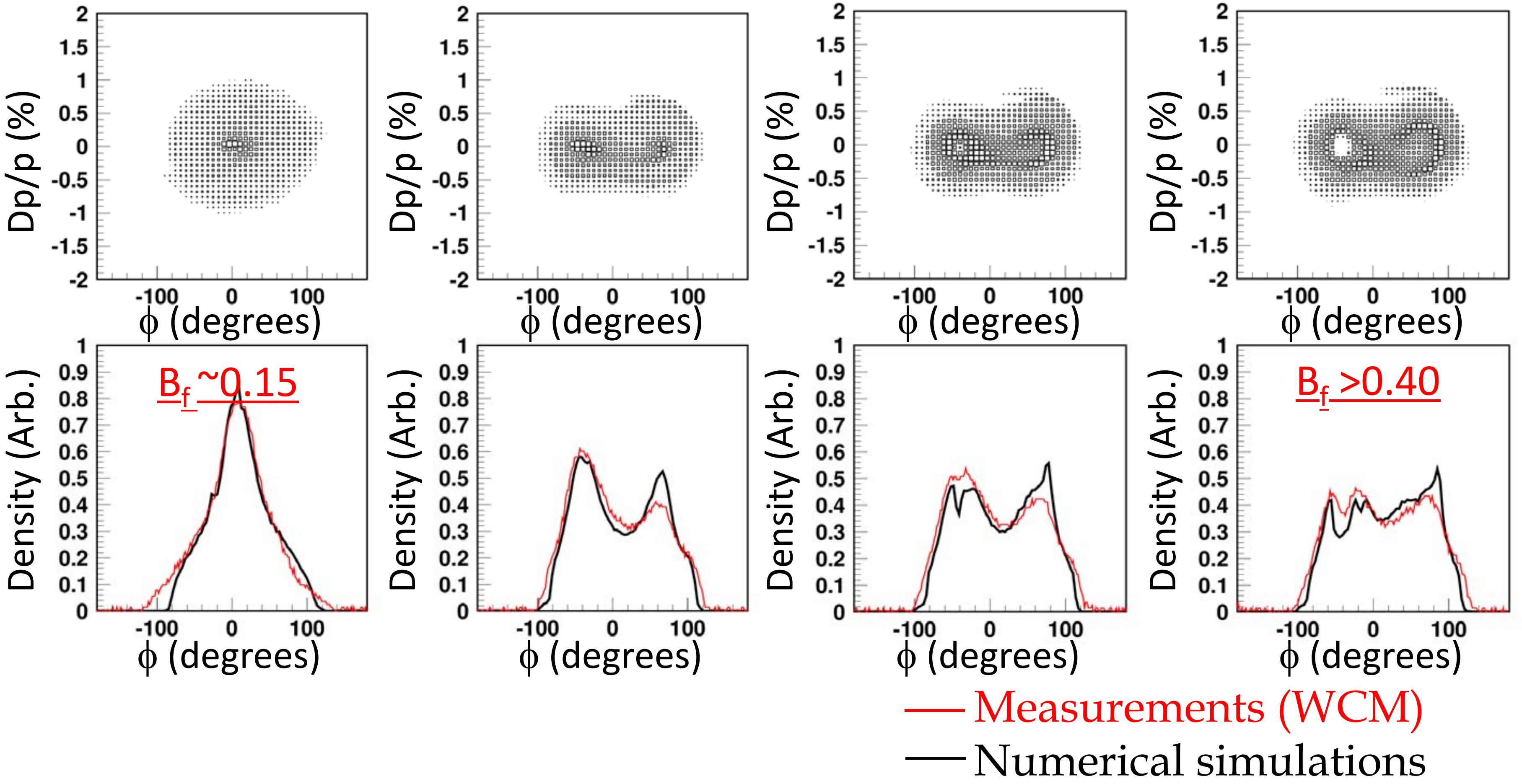
$\phi_2=-100\Rightarrow0$ deg

The second harmonic phase sweep method enables further bunch distribution control through a dynamical change of the rf bucket potential during injection.

Longitudinal injection painting

Longitudinal beam distribution just after beam injection (at 0.5 ms)

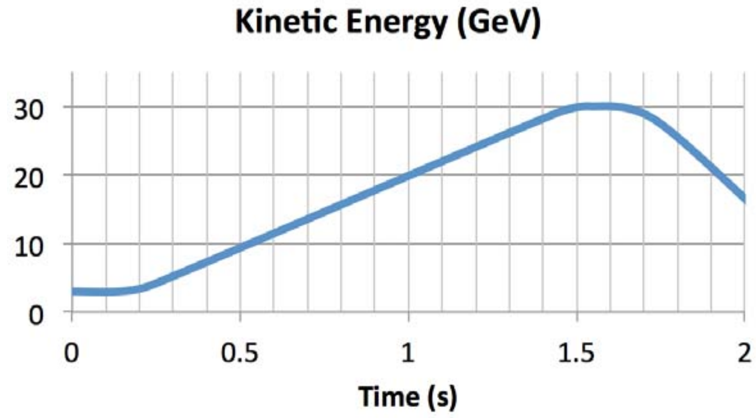
No longitudinal painting	V_2/V_1=80%	V_2/V_1=80%	V_2/V_1=80%
	ϕ_2=-100 to 0 deg	ϕ_2=-100 to 0 deg	ϕ_2=-100 to 0 deg
	$\Delta p/p$= 0.0%	$\Delta p/p$=-0.1%	$\Delta p/p$=-0.2%

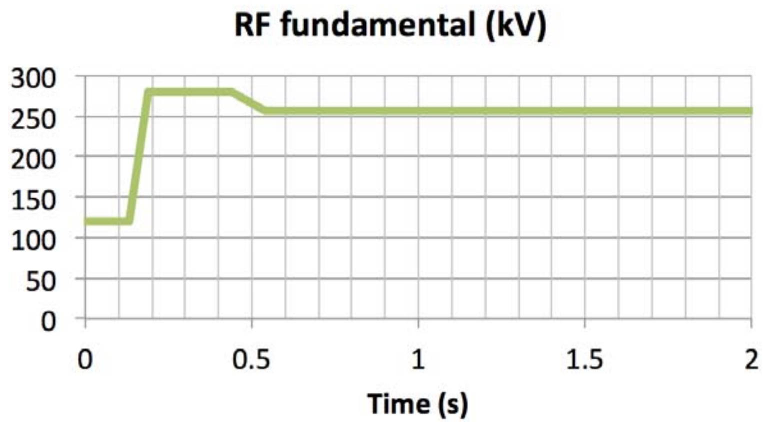


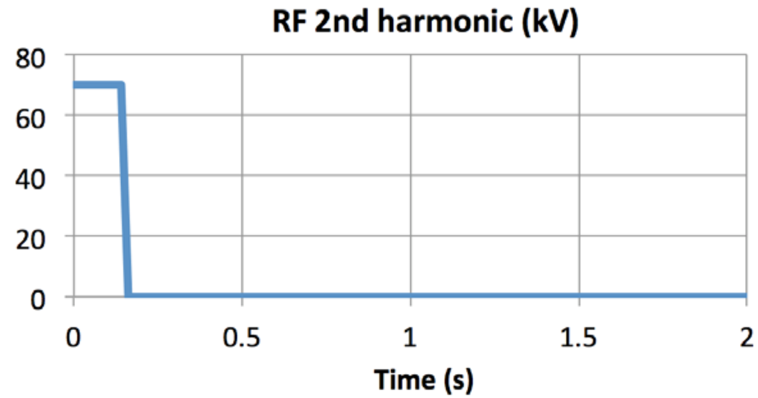
from H. Hotchi et. al., PRST-AB **15**, 040402 (2011).

RF Pattern of MR RF

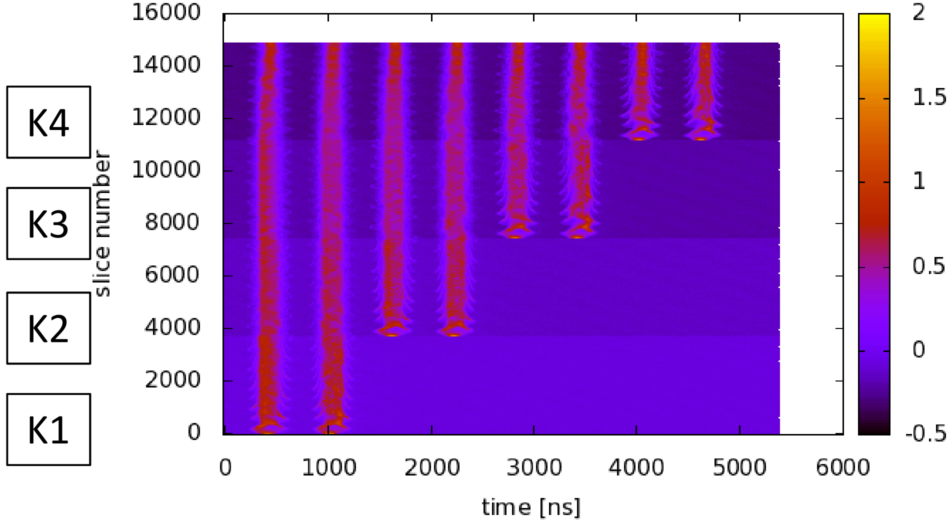
- RF pattern :
  - Injection : ~~120~~ 160kV kV (fundamental), ~~70~~ 85kV kV (2nd harmmonic)
  - Acceleration : 280 kV → 256 kV (fundamental)
- Beam loading compensation effectively works to damp the synchrotron oscillation.
- Bunching factor was measured to be 0.3 during injection.







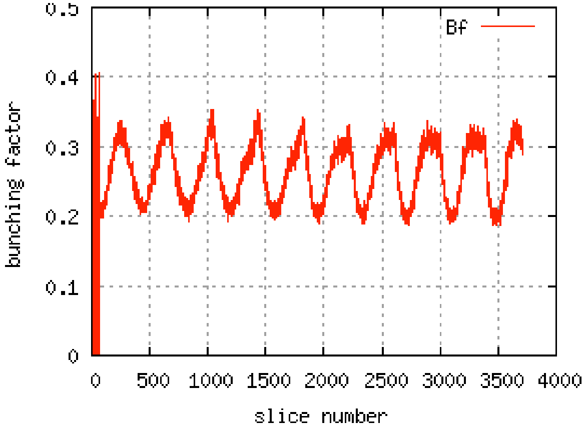
Longitudinal wave forms
during injection
with wall current monitor



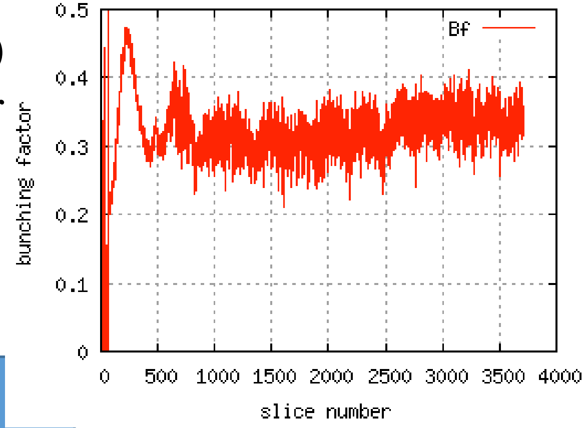
Longitudinal Profiles with High Intensity Beam of 500 kW equivalent

Tamura

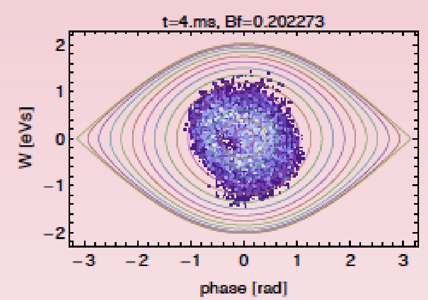
(100 kV, 0 kV)
Bunching factor
0.2 ~ 0.3
Bunch length
~200 ns

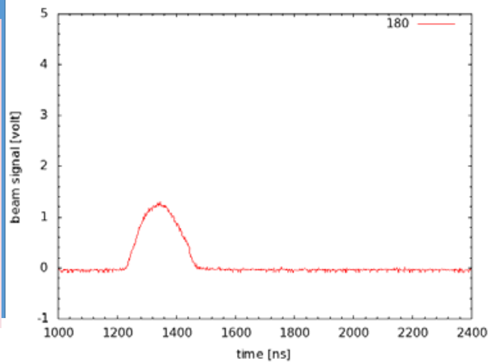


(100 kV, 70 kV)
Bunching factor
0.3 ~ 0.4
Bunch length
~400 ns

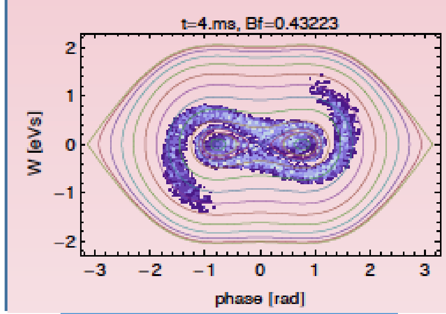


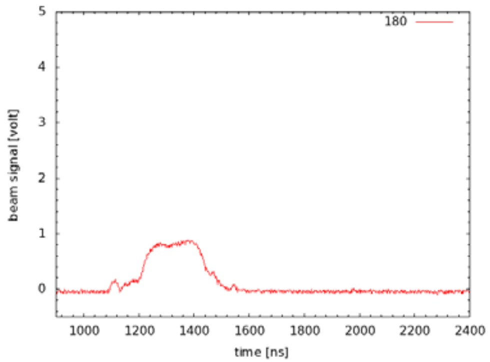
Simulation
(100 kV, 0 kV)

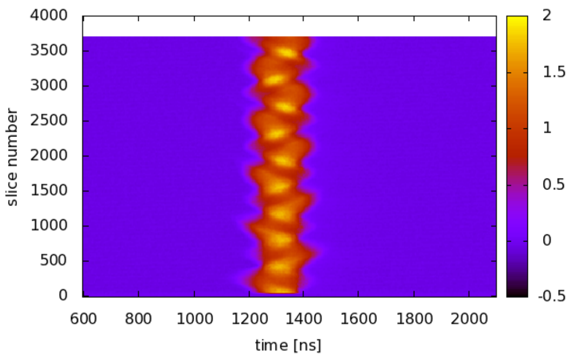


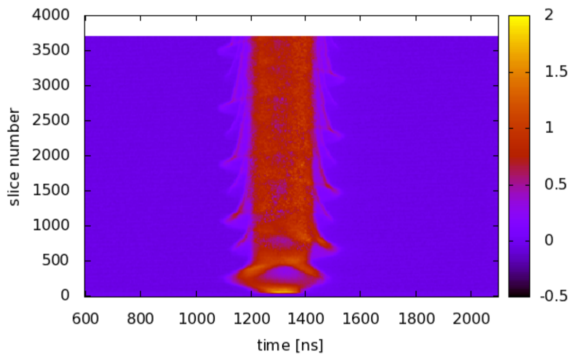


Simulation
(100 kV, 70 kV)



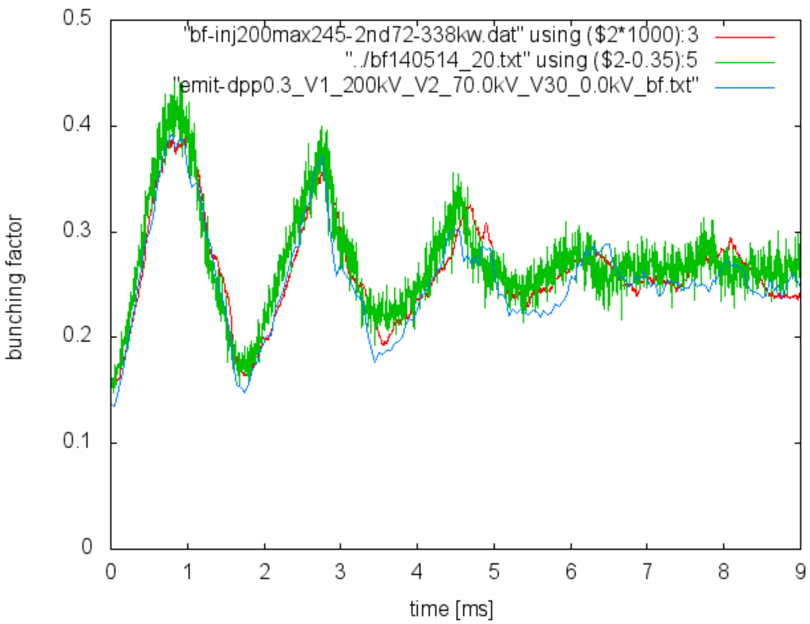




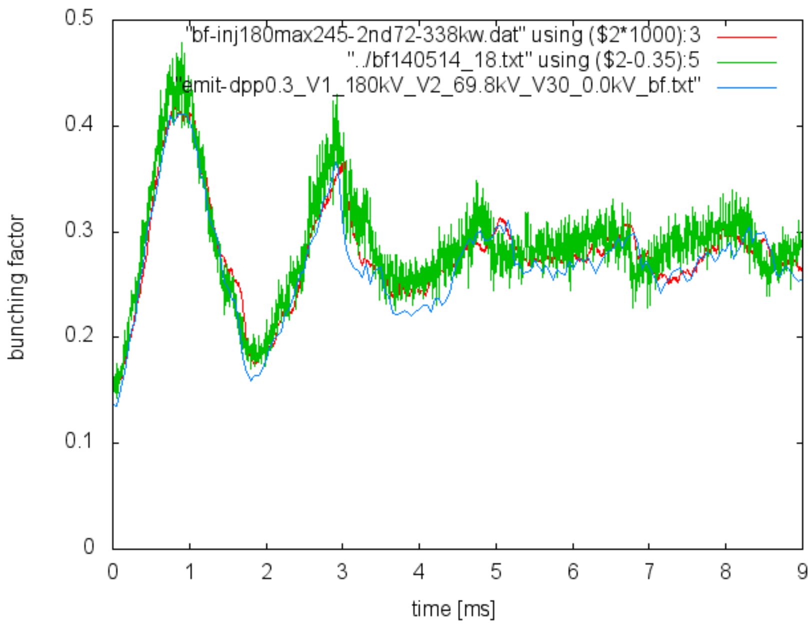


Simulation agrees the results
140514 田村

RCS : extraction 150 kV
MR: 1^{st} 200 kV, 2^{nd} 70 kV



RCS : extraction 150 kV
MR: 1^{st} 180 kV, 2^{nd} 70 kV

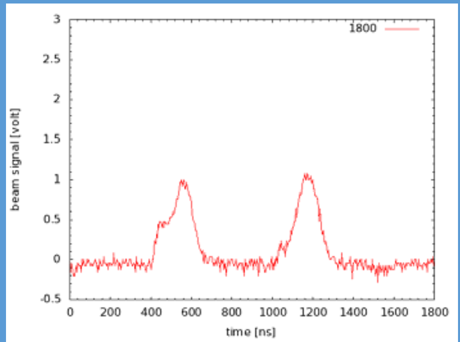


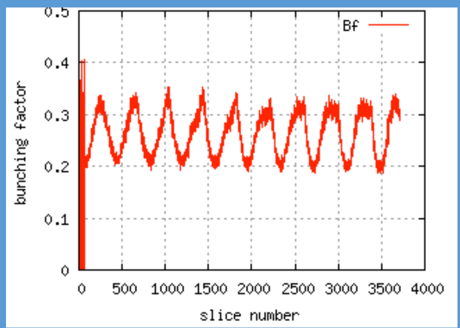
Simulation agrees the measurements

2nd H RF at MR

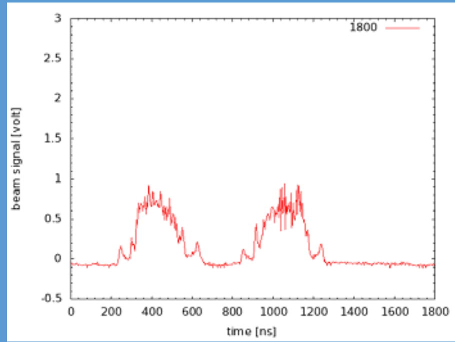
- Necessary to accelerate 2E14ppp
  - Lower peak beam current
  - Quadrupole oscillation damped quickly.

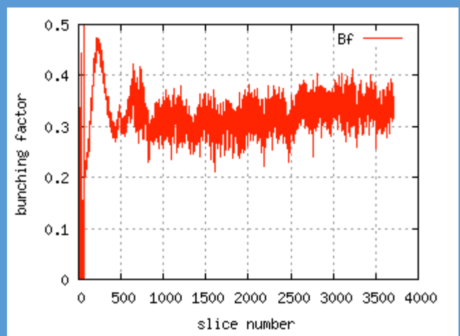
w/o 2nd H

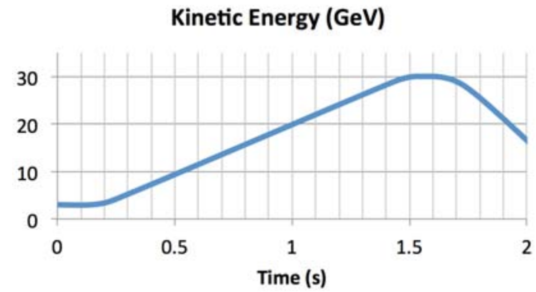


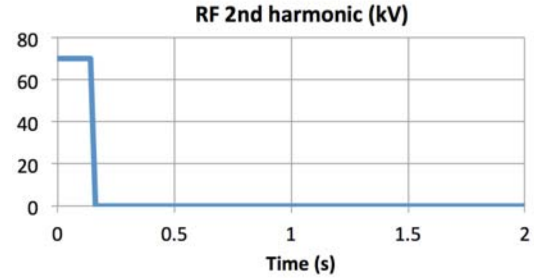


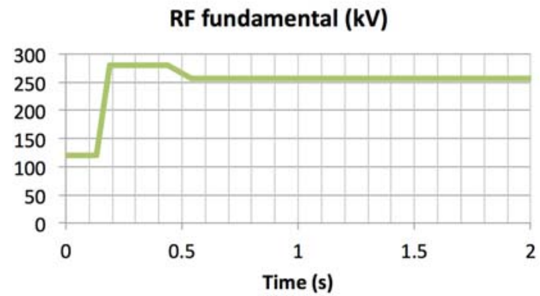
With 2nd H

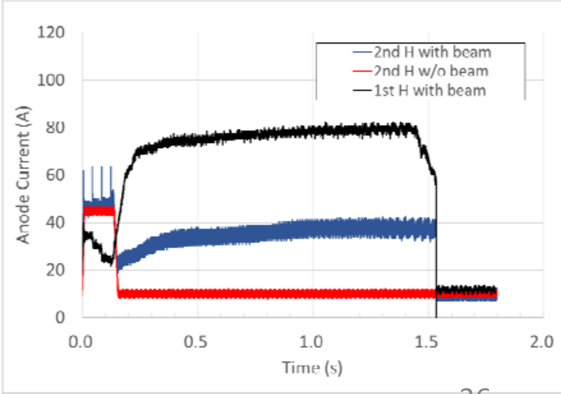






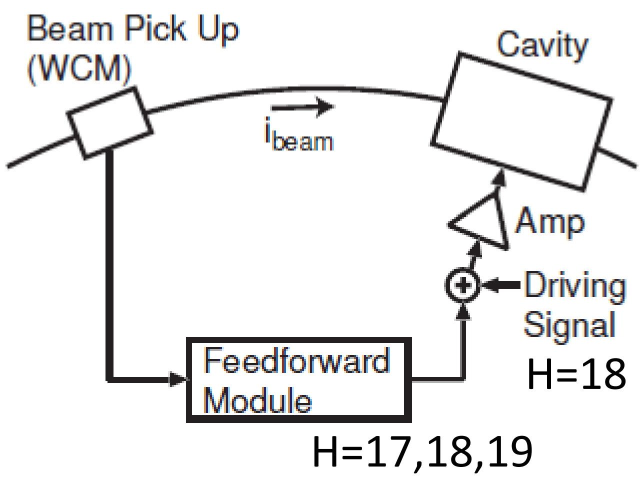


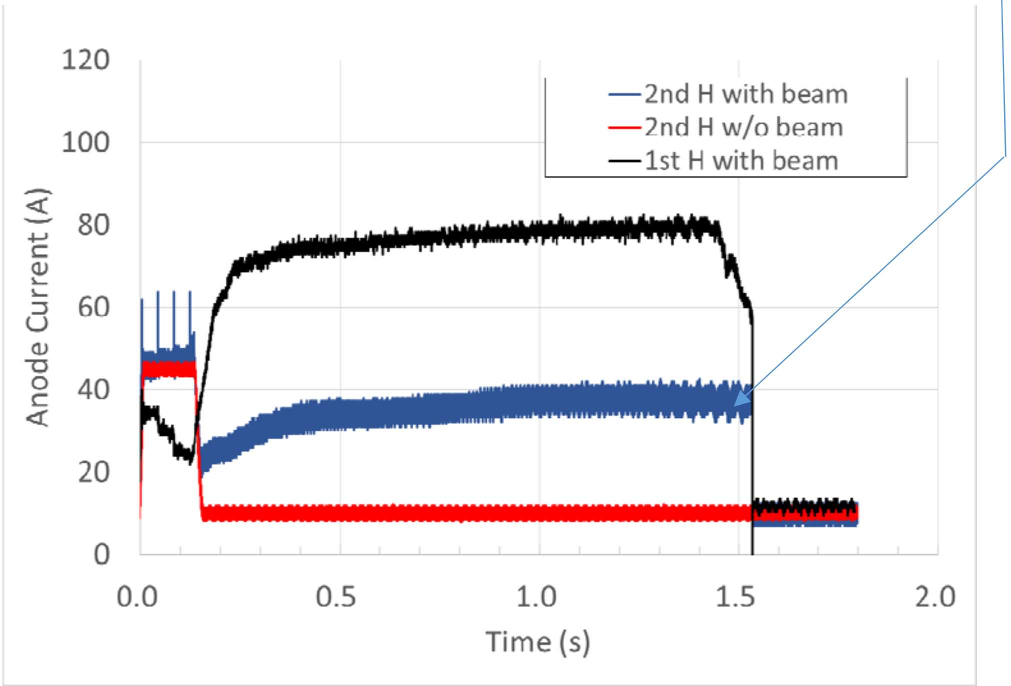




Hardware of 2nd H RF

- Cavity: 1st RF cavity was modified to resonate at 3.44 MHz by removing resonant capacitors.
- RF input circuit of tube AMP was modified.
- APS, driver-AMP, cavity main body are same.
- LLRF was set to compensate H=17,18,19 instead of H=8,9,10 for 1st harmonics.
- Cavity gaps are always “open”. When RF voltage is not needed, still beam loading was compensated.





Answers

- Is the 2nd H cavity is running through the cycle?
  - Yes. The voltage is applied around the injection.
  - When programed RF voltage is 0 V, still beam loading compensation is working.
- Is there anything we have to be aware of before our operation?
  - For 2E14 ppp, we needed 40 A for the old 3-gap cavity to cancel the beam loading.