# Improvement of RF Operation at KURRI FFAG

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# PURPOSE OF THIS TALK

is to clarify how the rf is operated and
and what is the possible improvement in the future.

# CONTENTS

1. How to make rf pattern
    - constant amplitude, constant acc phase
    - AM function is experimentally determined
2. Variable k-index
3. Future improvement (briefly)

# HOW TO DETERMINE THE PATTERN

$$V(t) = V_0(t) \sin \Psi(t)$$

Requirements for V(t) and Ψ(t)

1. V(t) < Vmax , by the power of amplifier
2. $\phi_s \simeq const.$ , or changes very slowly
3. bucket area is wide ( high V, low $\phi$s)

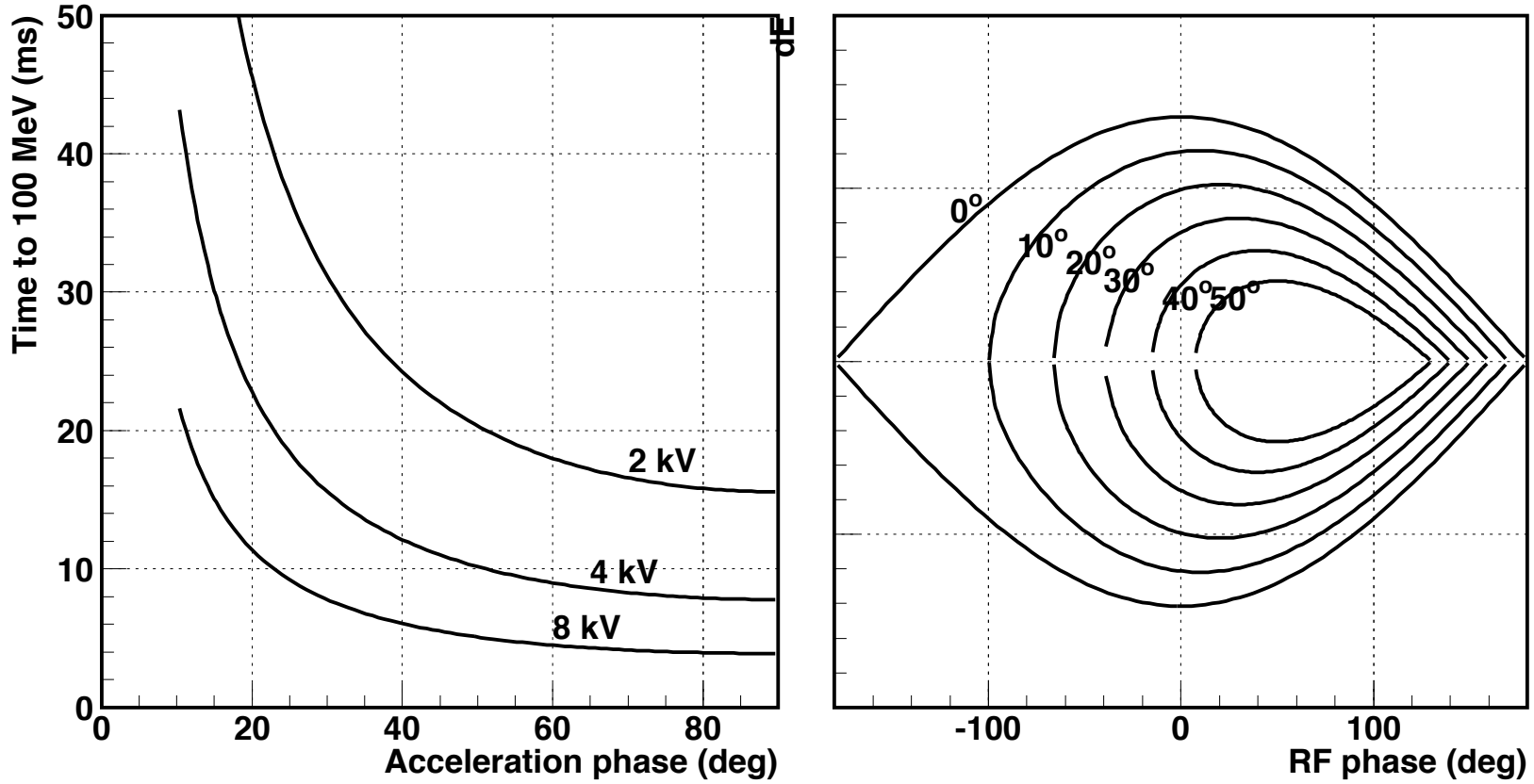
   Acceleration is fast ( high V, high $\phi$s)

Our choice

1. Constant, highest V0 (=4kV)
2. Constant $\phi$s, ( no flatbase, no flattop ! )

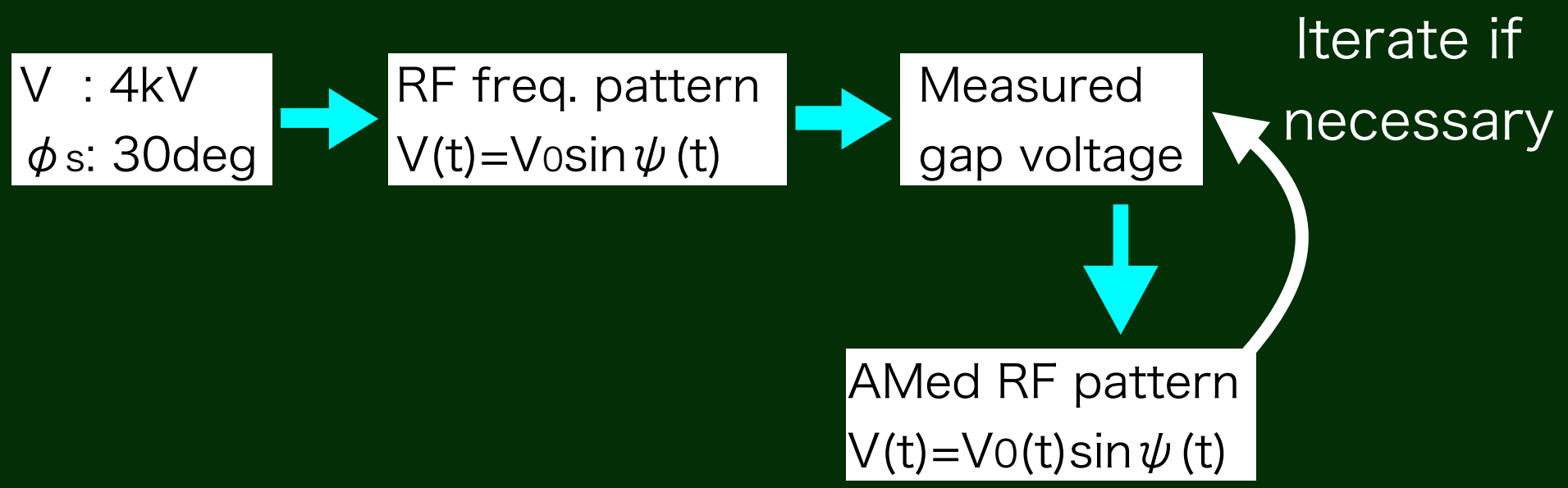
   The value is experimentally determined, such that the accelerated beam intensity takes maximum.

# cf. ACCELERATION TIME, BUCKET AREA



# RF PATTERN EDIT

1. Assume constant amplitude and accelerating phase.
2. Derive rf pattern $\psi(t)=\cdots$
3. Apply rf pattern to the amplifier
4. Measure the gap voltage amplitude,
   which is affected by cavity impedance
5. AM correction on low level rf.



# PATTERN 1

This assumption was not true (later)

CONSTANT K ←

CONSTANT $V_0$ and $\phi_s$

until Jan. 16, 2014

# RF WAVEFORM

RF waveform is analytically expressed in function of time, if energy gain per turn is constant

$$V \sin\phi_s = \Delta E$$

Scaling rule

$$\frac{B}{B_0} = \left(\frac{r}{r_0}\right)^k \longrightarrow \frac{r}{r_0} = \left(\frac{p}{p_0}\right)^\alpha , \quad \alpha = \frac{1}{k+1}$$

$$\longrightarrow \frac{f}{f_0} = \left(\frac{p}{p_0}\right)^{1-\alpha} \frac{E_0}{E}$$

Thus

$$\frac{dE}{dt} = f V_0 \sin\phi_s = f_0 \Delta E \left(\frac{p}{p_0}\right)^{1-\alpha} \frac{E_0}{E}$$

$$p(t) = p_0 \left[(1+\alpha)\frac{E_0 \Delta E}{p_0^2} f_0 \cdot t + 1\right]^{\frac{1}{1+\alpha}}$$

$$\Psi(t) = 2\pi \frac{E(t) - E_0}{\Delta E}$$

where reference parameters, p0, f0, are evaluated at t=0

# PROGRAMMED WAVEFORM

$$V(t) = \frac{1}{C_{AM}(t)} \sin\left(\sqrt{A_1 + A_2(t + A_3)^B} - A_4\right) \qquad T_{acc} = \frac{1}{C}\left[\left(\frac{p_f}{p_i}\right)^B - 1\right]$$

$$A_1 = \left(\frac{2\pi m}{\Delta E}\right)^2 \qquad A_3 = 1/C - \delta t \qquad \Delta E = V_0 \sin\phi_s$$

$$A_2 = \left(\frac{2\pi p_0}{\Delta E}\right)^2 C^B \qquad B = \frac{2}{1+\alpha} = \frac{2k+2}{k+2} \qquad C = (1+\alpha)\frac{f_0 E_0 \Delta E}{p_0^2}$$

| | | |
|---|---|---|
| $E_0$ | Injection energy | m+11 MeV |
| $f_0$ | Revolution frequency at $E_0$ | —> next slide |
| $k$ | Field index | —> next slide |
| $\Delta E$ | Energy gain per turn | 4kV x sin $\phi_s$ |
| $C_{AM}$ | Amplitude modulation | —> later |
| $\delta t$ | Time offset (energy redundancy) | ~0.5ms, later |

# REFERENCE PARAMETERS

May 2008

1. A set of measured (E,f) determined reference f0

   f = 1591.84 kHz for Ek = 11.57MeV

   measured with injected beam from the booster FFAG.

   k-index was assumed to be 7.5 (designed value)

Jul 2008

2. Another set of measured (E,f) modified k-value

   r = 5039.5 mm (straight section)

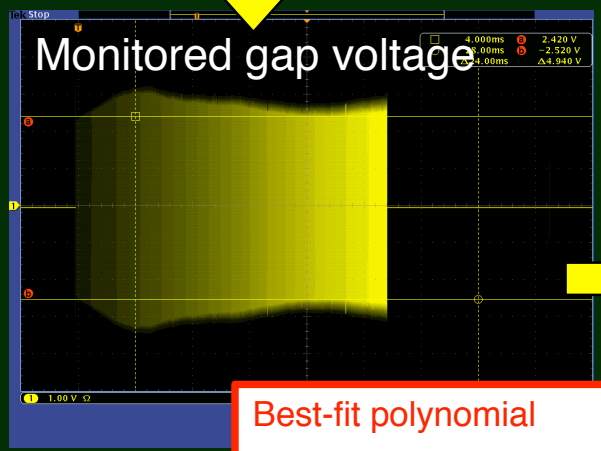
   for f = 3841.7 kHz ( assumed 100 MeV )

   —-> k = 7.645

# AMPLITUDE CORRECTION

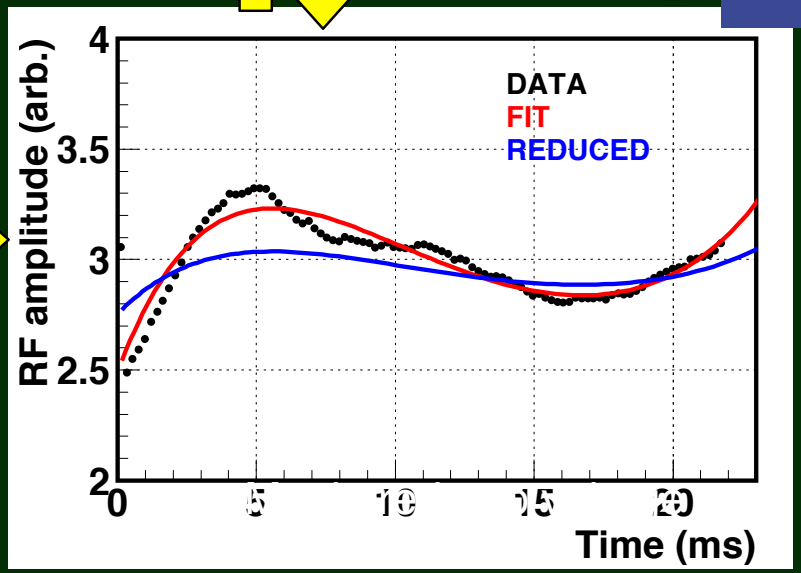
## How the amplitude function $C_{AM}$ was determined

Input rf without AM




Best-fit polynomial

$$\bar{V}\left(1+\sum_{k=1}^{5} D_k t^k\right)$$

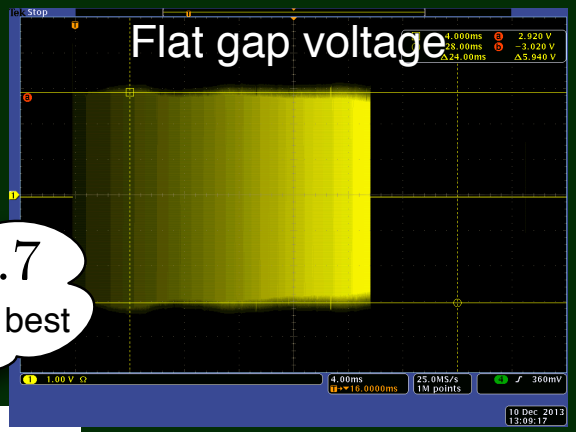



Reduced AM factor

$$C_{AM} = 1 + \epsilon \sum_{k=1}^{5} D_k t^k$$

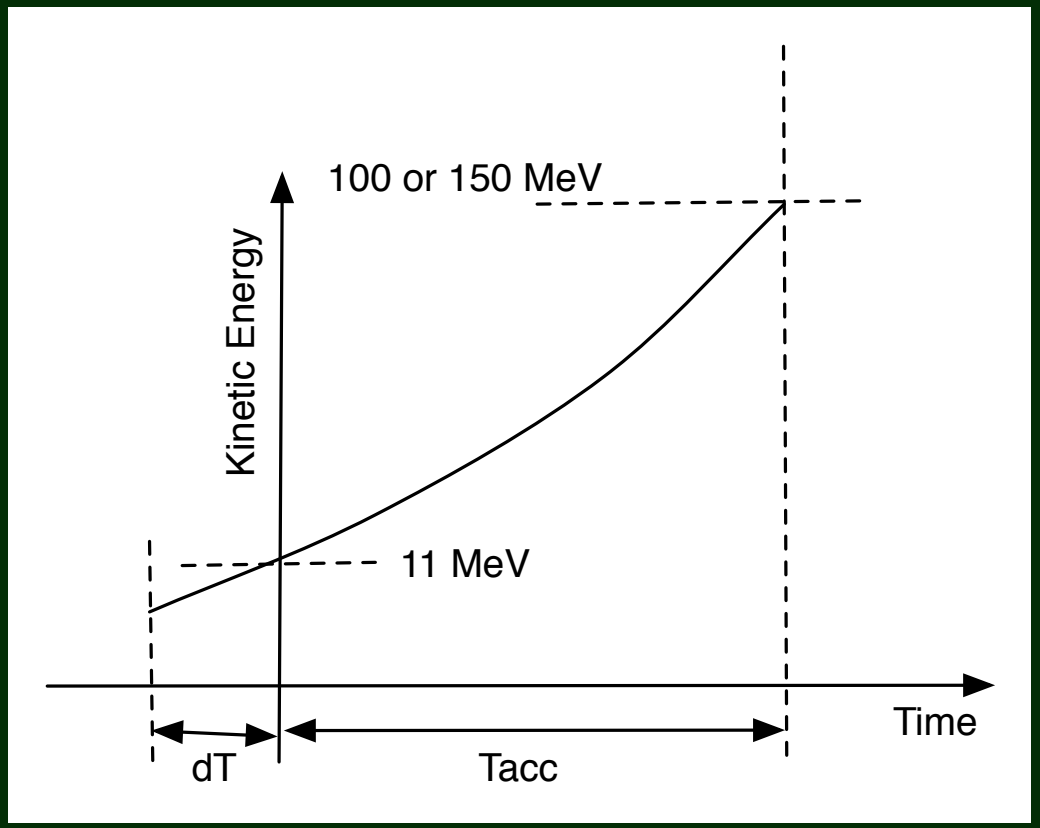
$\epsilon \sim 0.7$

seems the best

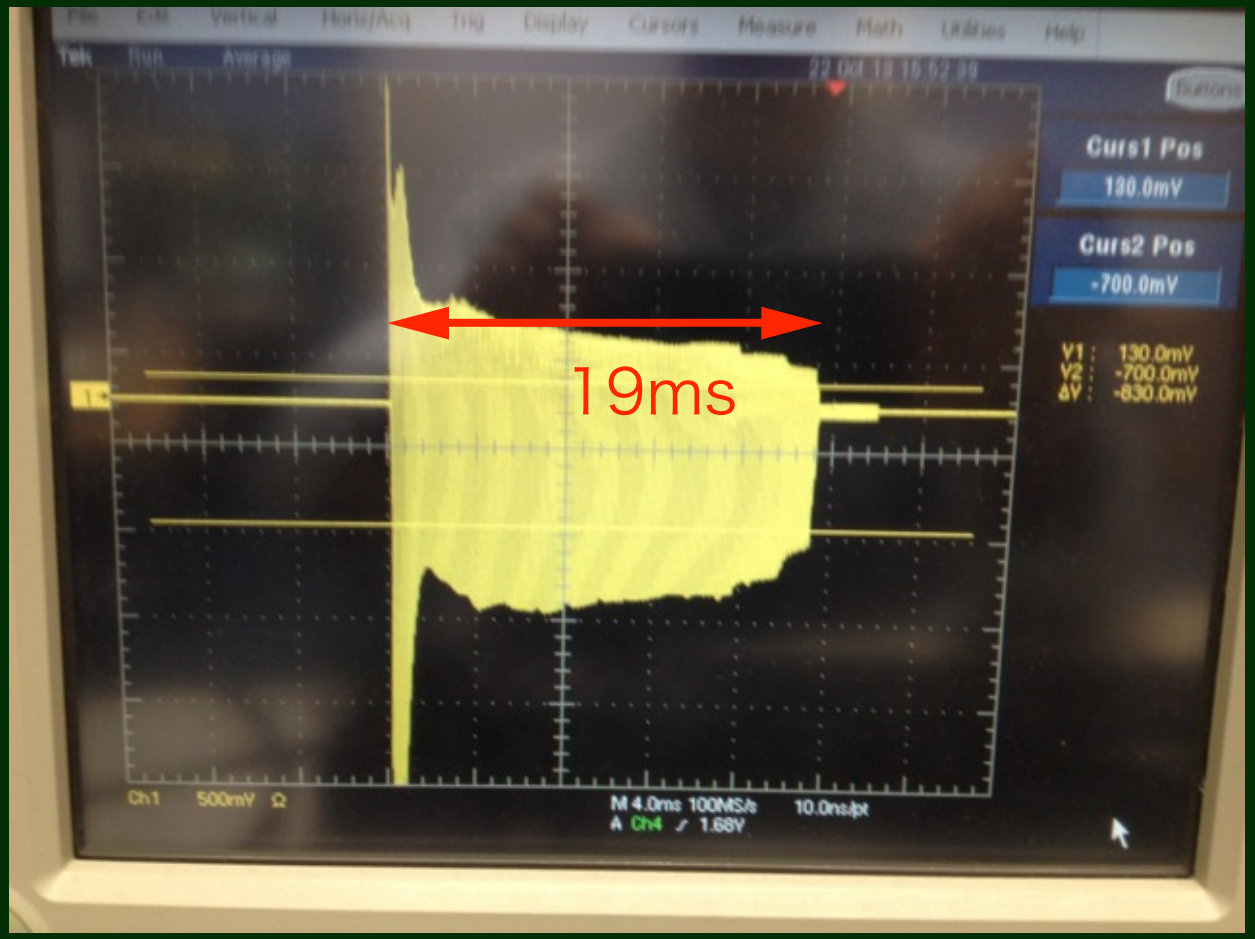


# TIME OFFSET

The rf pattern starts below the injection energy,
to have energy-redundancy.
Everyday before operating, RF trigger delay, relative to the ion-source, is optimized with monitoring captured intensity.



# ACCELERATED BEAM INTENSITY




Fast loss at very beginning of the acceleration.

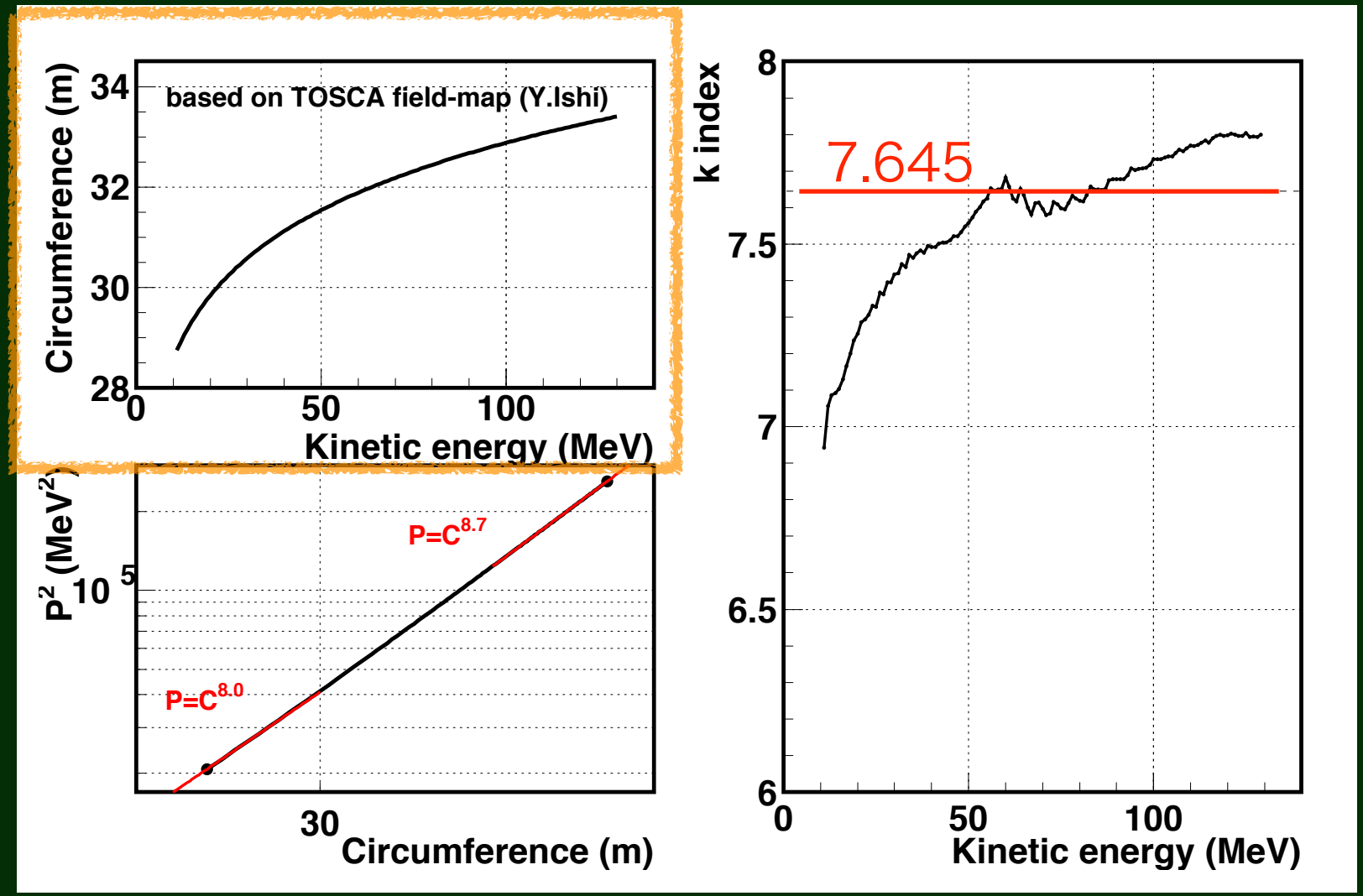
# PATTERN 2

SIMULATED VARIABLE K
CONSTANT $V_0$ and $\phi s$

since Jan. 16, 2014

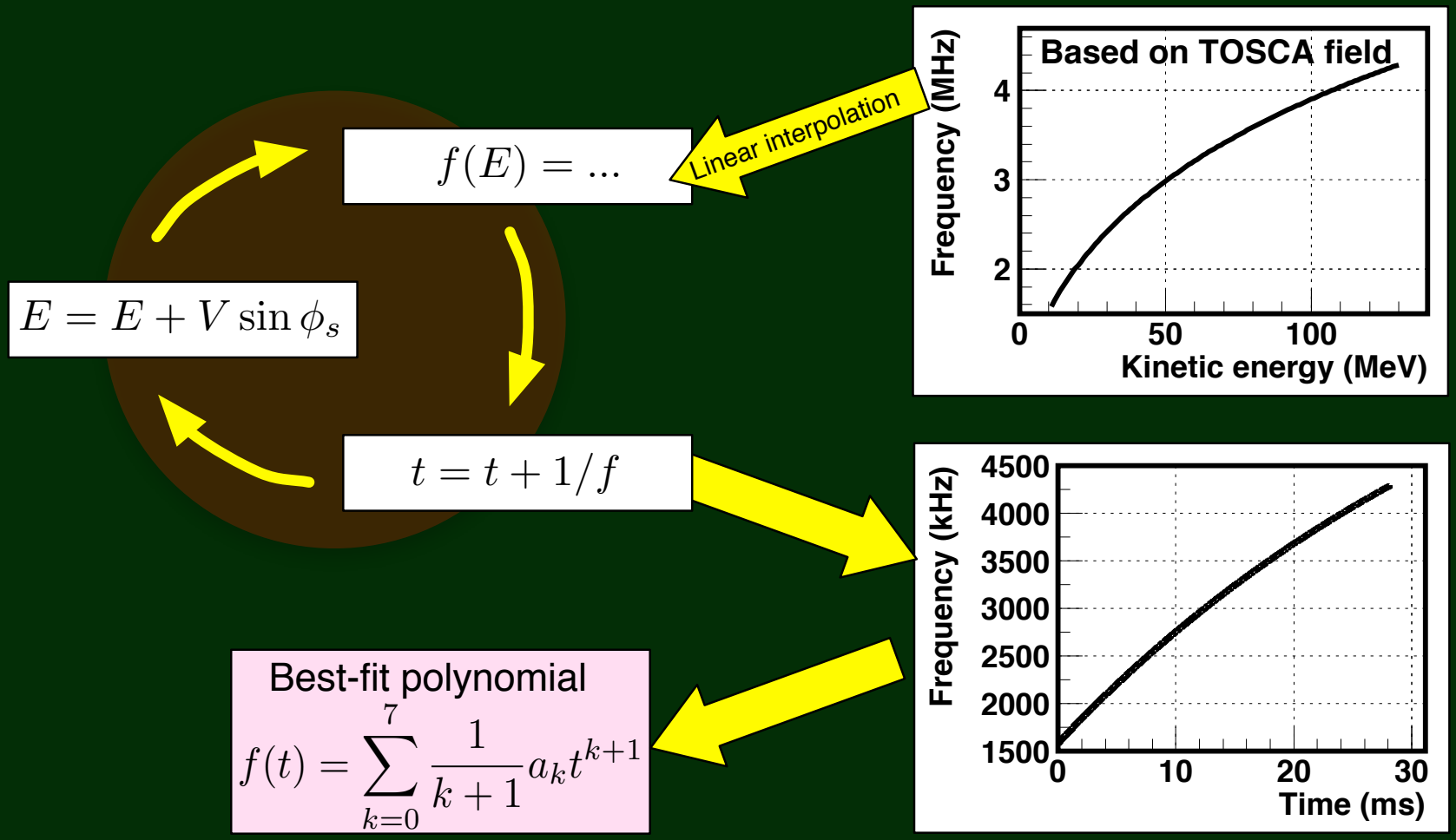
# SIMULATED K

According to simulation based on TOSCA field-map, k-index is not constant.



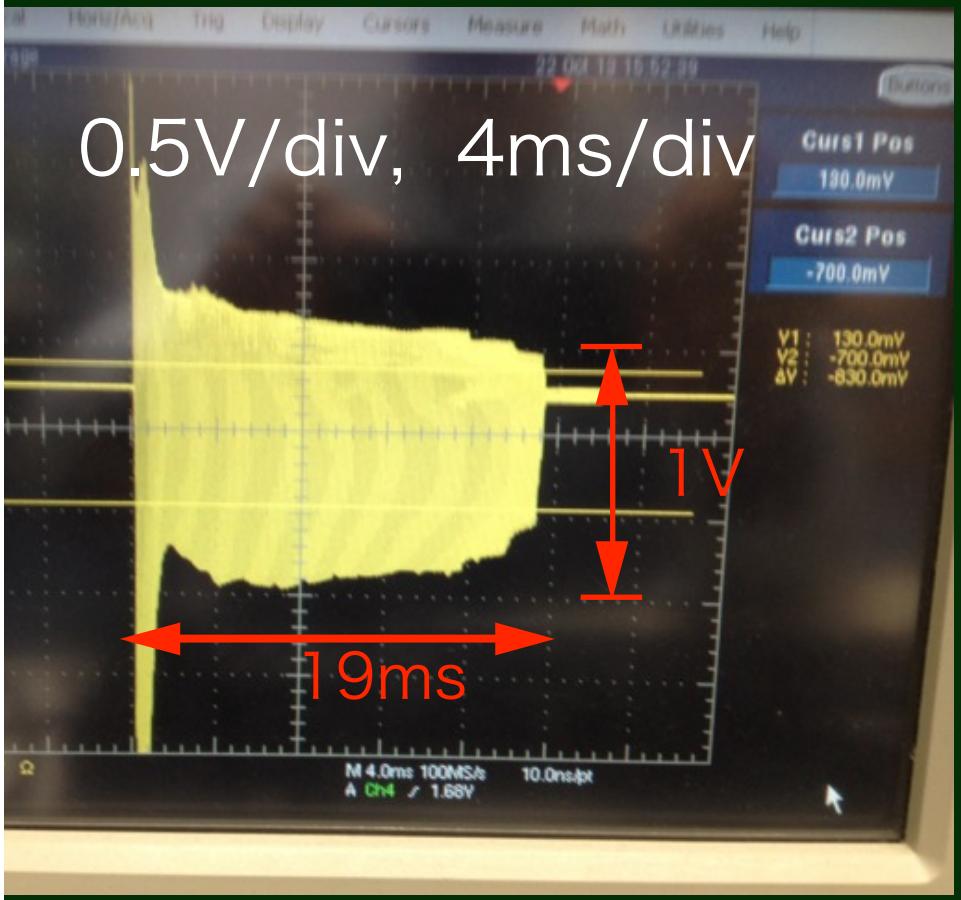
# PROGRAMED WAVEFORM

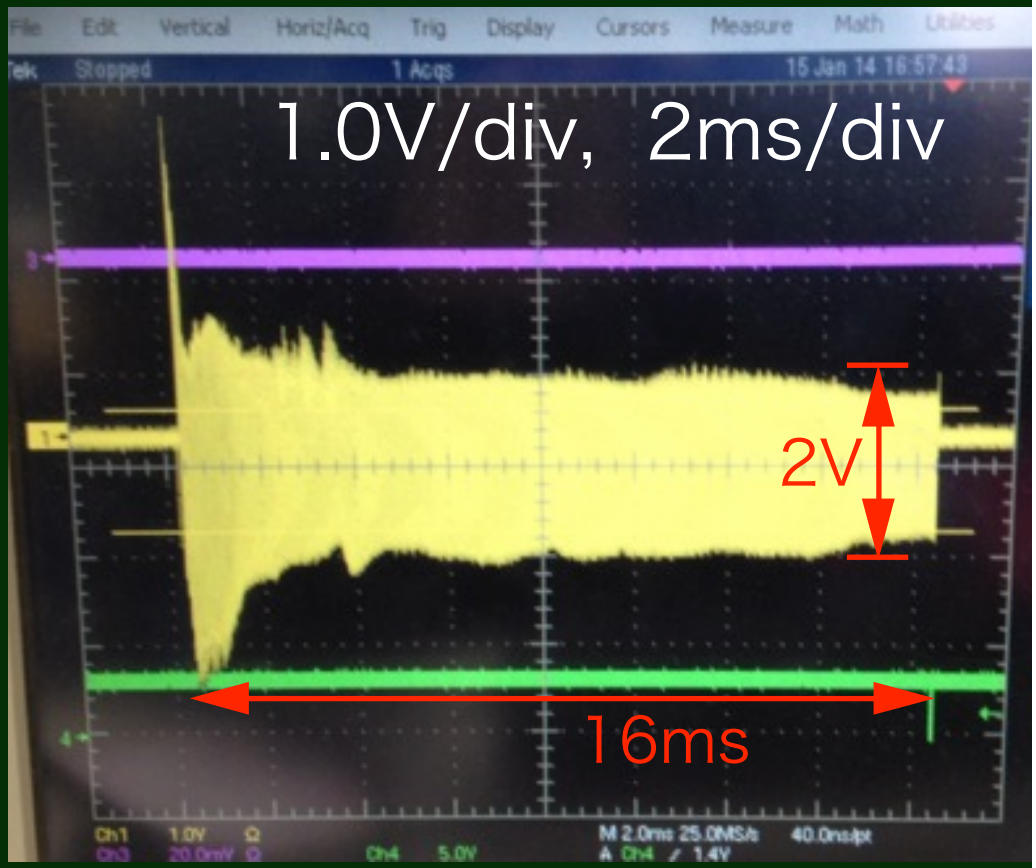
$$V(t) = \frac{1}{C_{AM}} \sin\left(2\pi \sum_{7}^{k=1} a_k (t - \delta t)^k\right)$$



# RESULTS

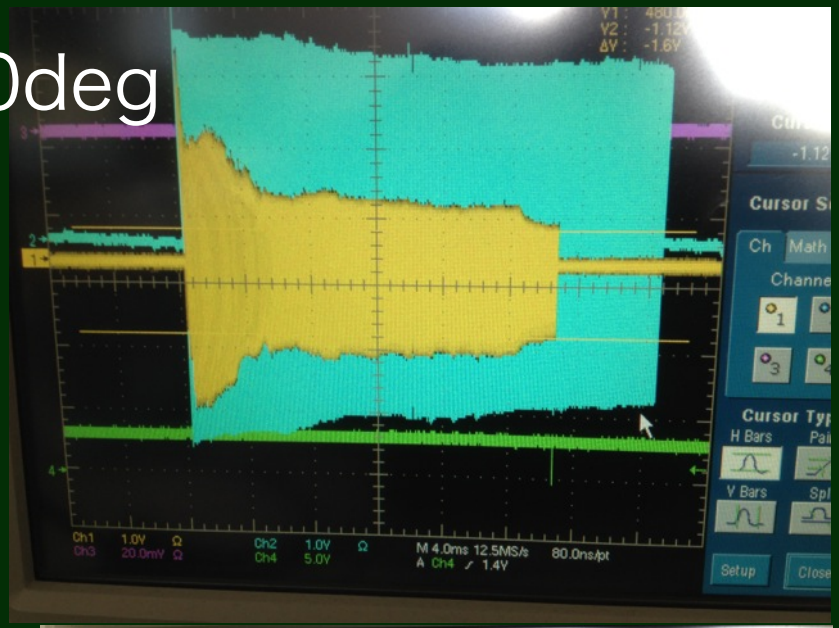
constant k → variable k



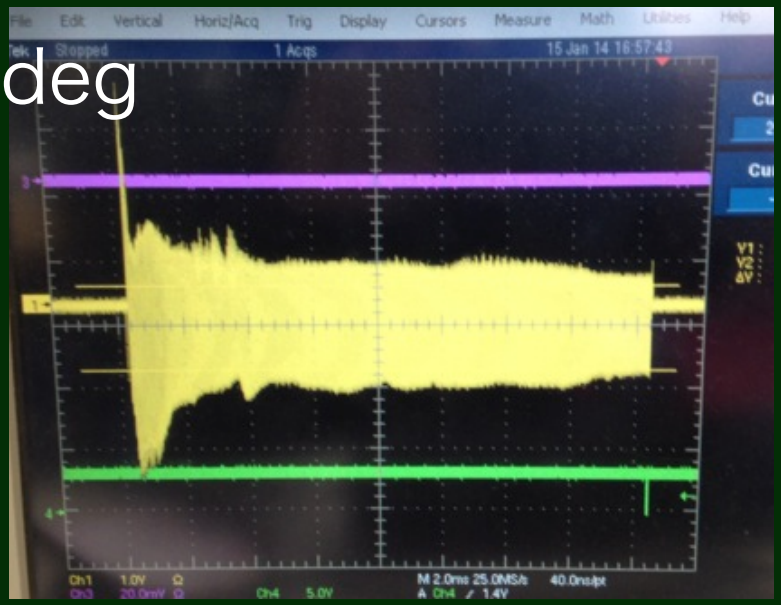



# BEST $\phi_s$ IS 20deg ?

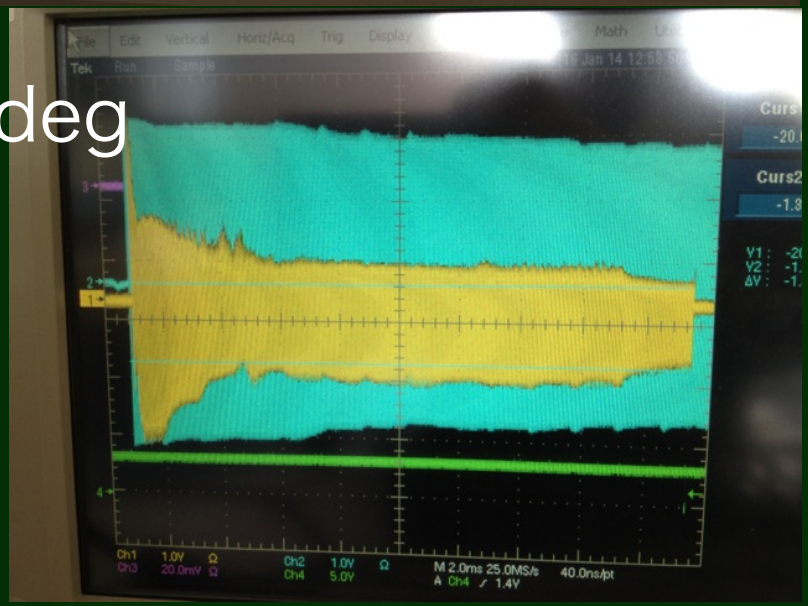
20deg



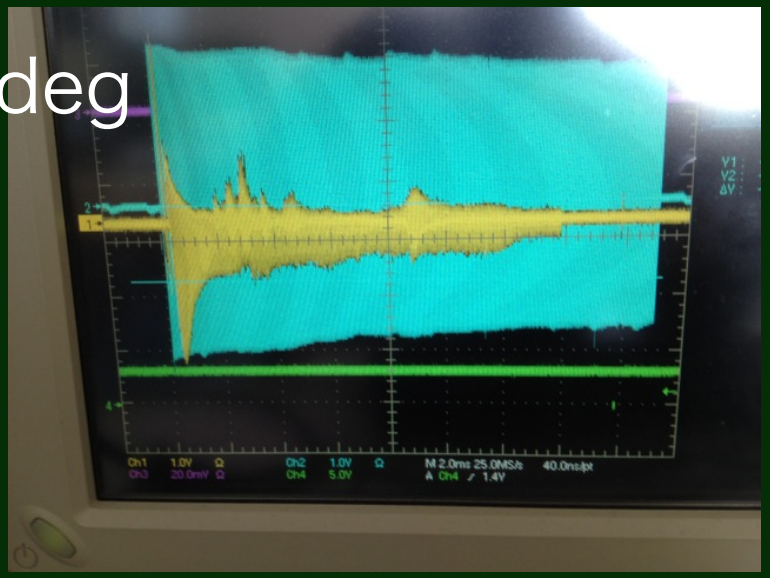

30deg




25deg




35deg

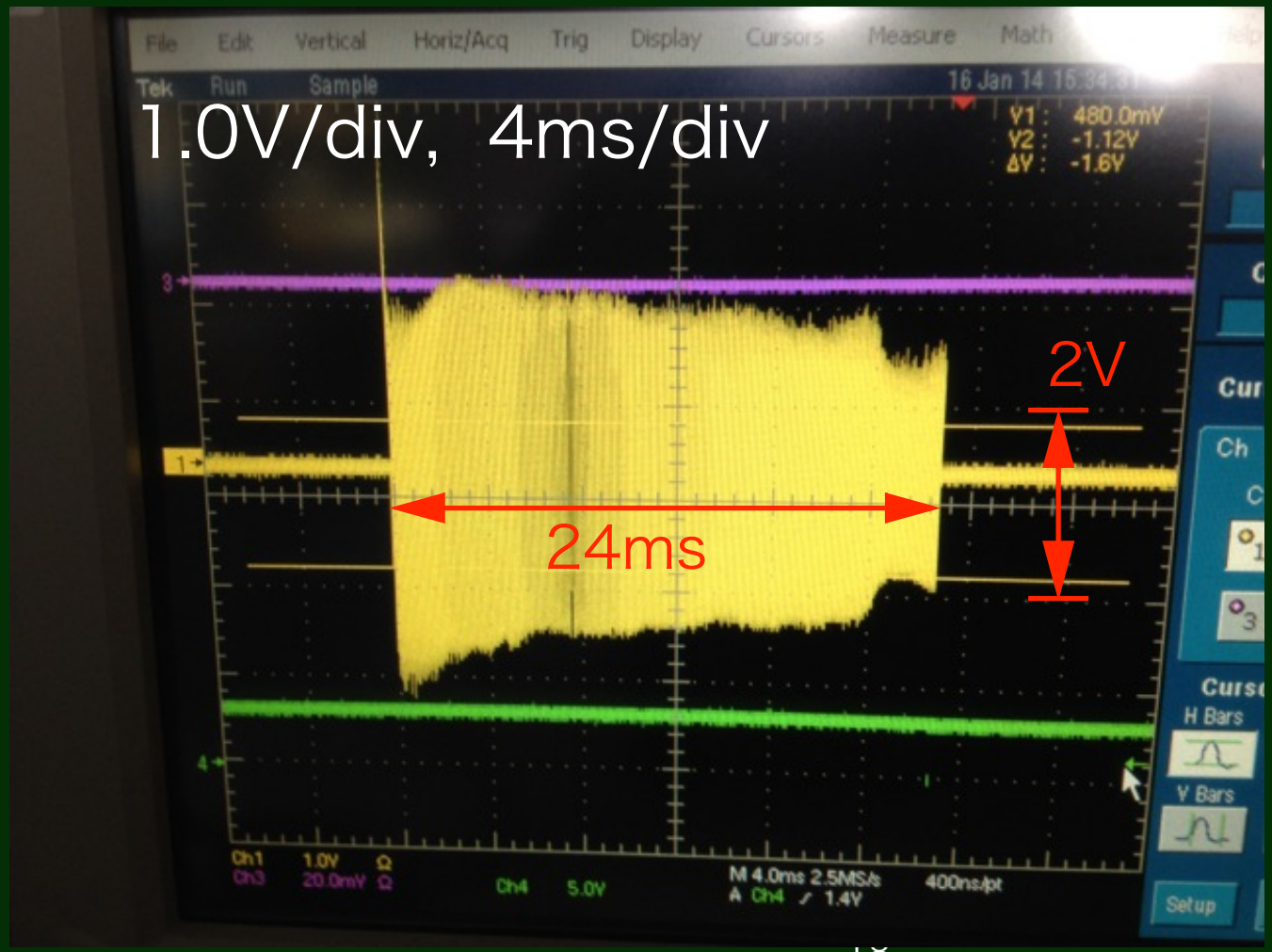


# BEST

( After optimizing injection angle etc. )

Fast beam loss disappeared and

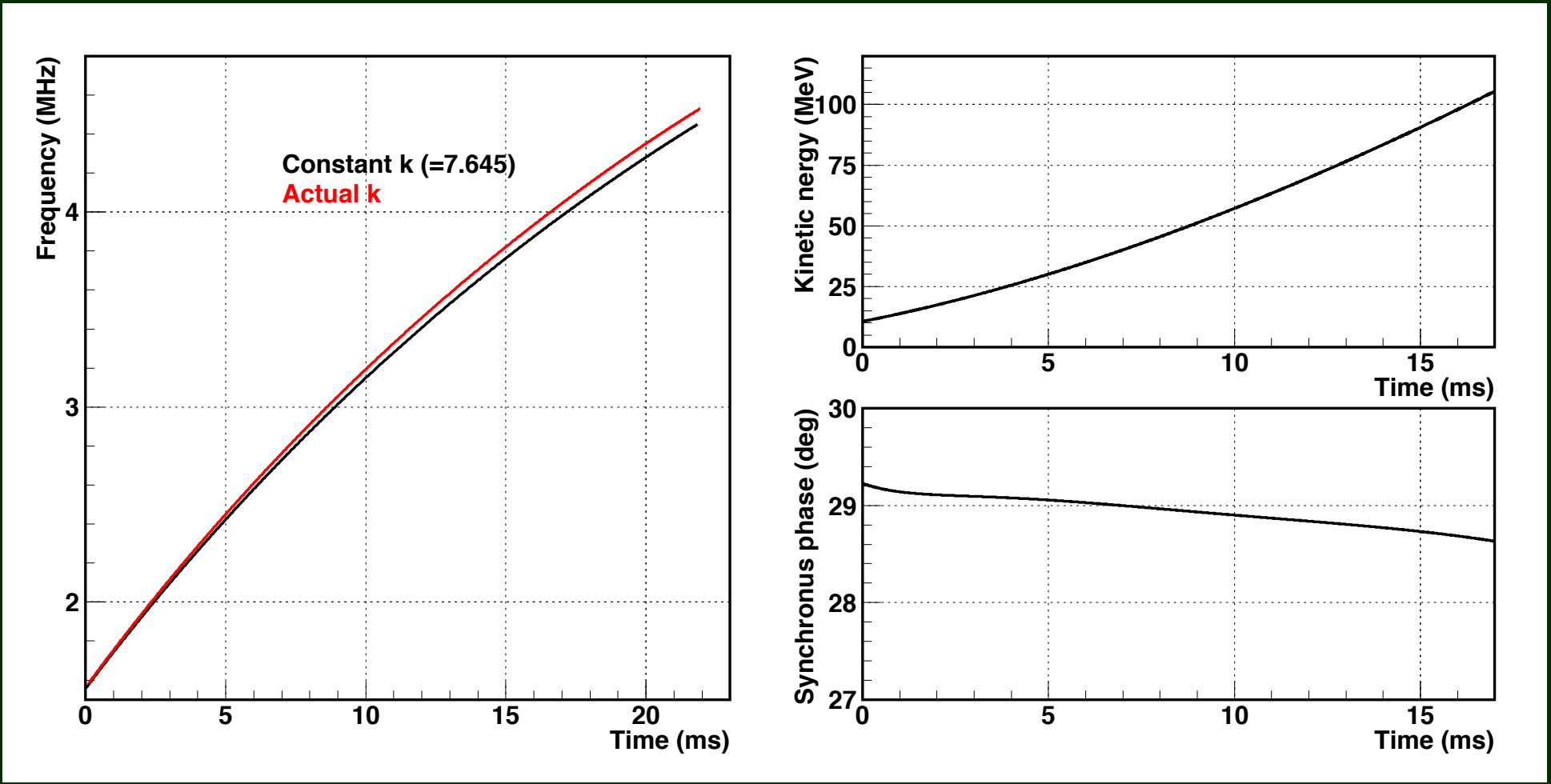
beam intensity became twice !




But ⋯ ⟶

# FREQUENCY DIFFERENCE

## Pattern 1 (constant k) on simulated k




Variation of $\phi_s$ is only 1 deg ?

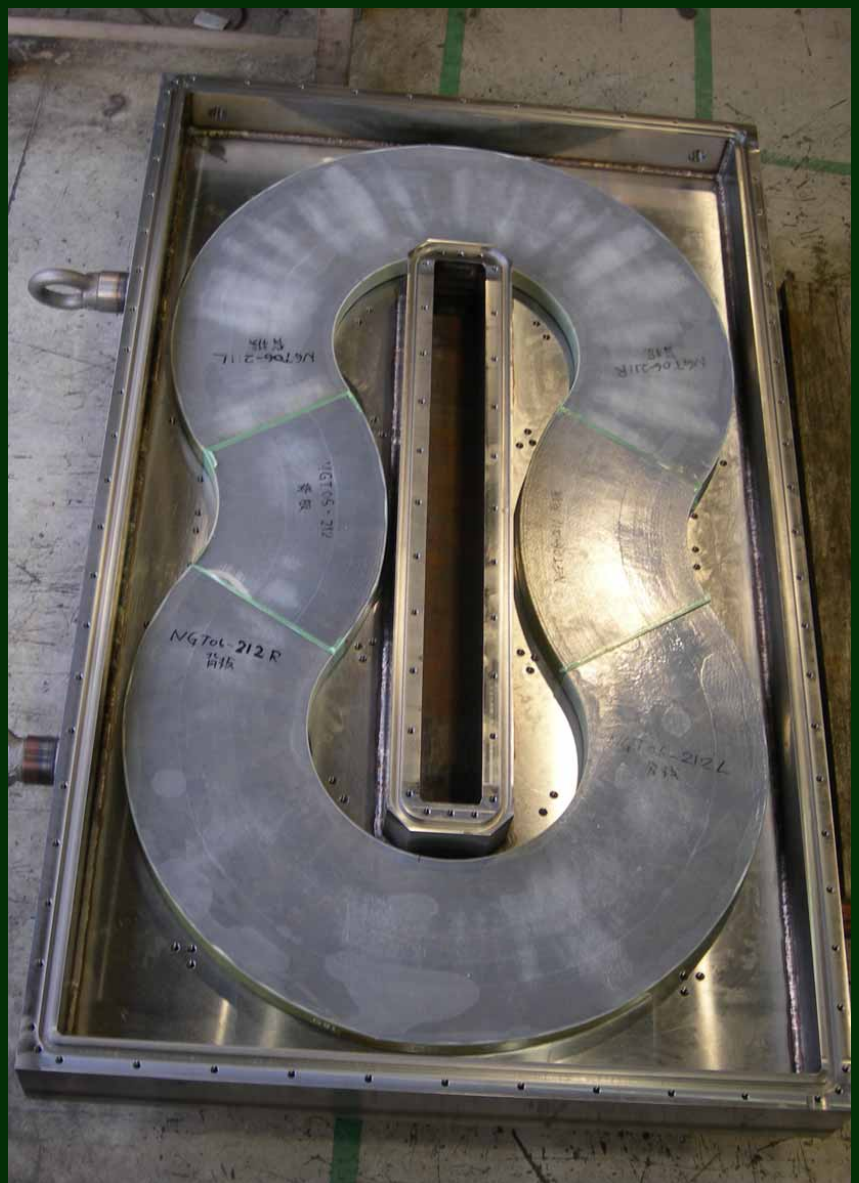
# WHY PATTERN2 IMPROVED?

# FURTHER IMPROVEMENT

# ADDITIONAL RF CAVITY

will be installed on Jan. 2015.

With this cavity, the rf voltage is becomes twice?  and thus



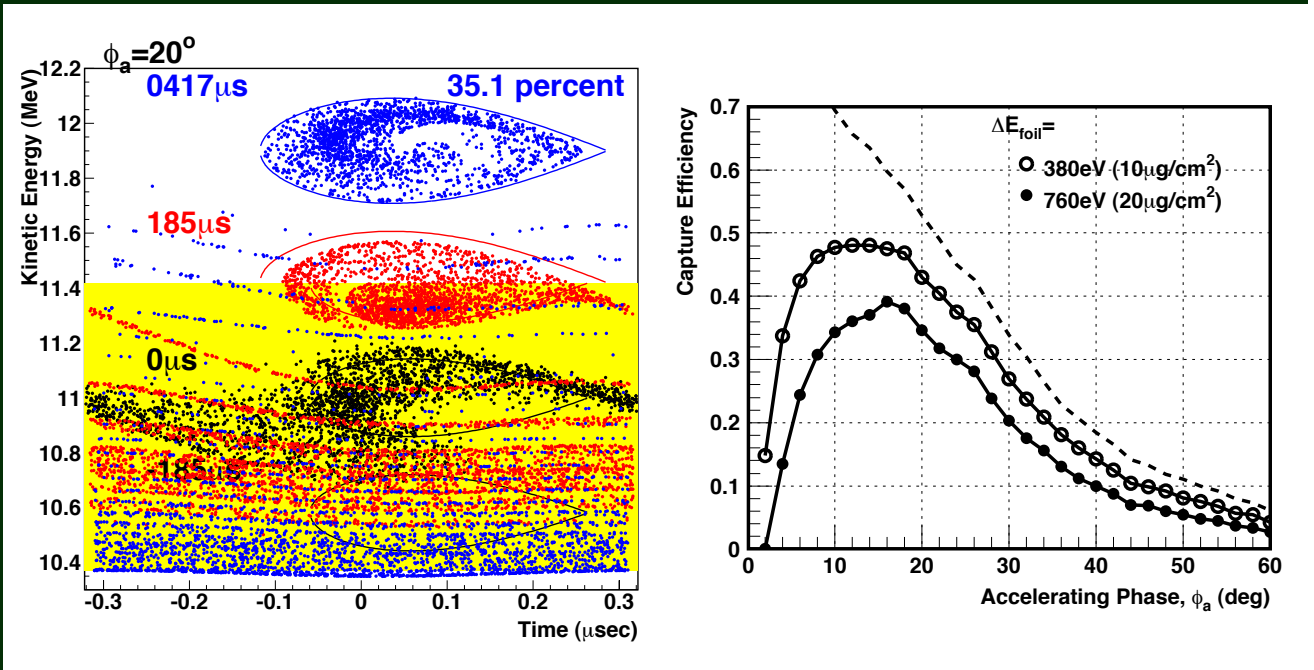
(1) fast acceleration for
  (1A) higher repetition, and/or
  (1B) larger turn separation at inj.
(2) wide (stable) bucket area
(3) Suppress harmonic field components
  excited by rf cavity.

# MODIFICATION OF V OR $\phi_s$

RF amplitude and/or synchronous phase is not necessarily constant, but can be changed with energy.  for example,

(1) Higher V and lower $\phi_s$ only in the injection energy region,  where the beam is affected the energy loss at the charge stripping foil

(2) V decreased along with the beam energy,
to keep bucket area ?  ( V proportional to 1/sqrt(E) )



# SUMMARY

In the KURRI FFAG, the rf is operated very simply in constant V and $\phi$s. No flat base nor flat top is made. By considering the variable k-index, which is obtained by TOSCA-based simulation, the beam intensity has been increased by more than twice.

Future improvement will be done by

(1) Install additional cavity

(2) Introducing more sophisticated pattern