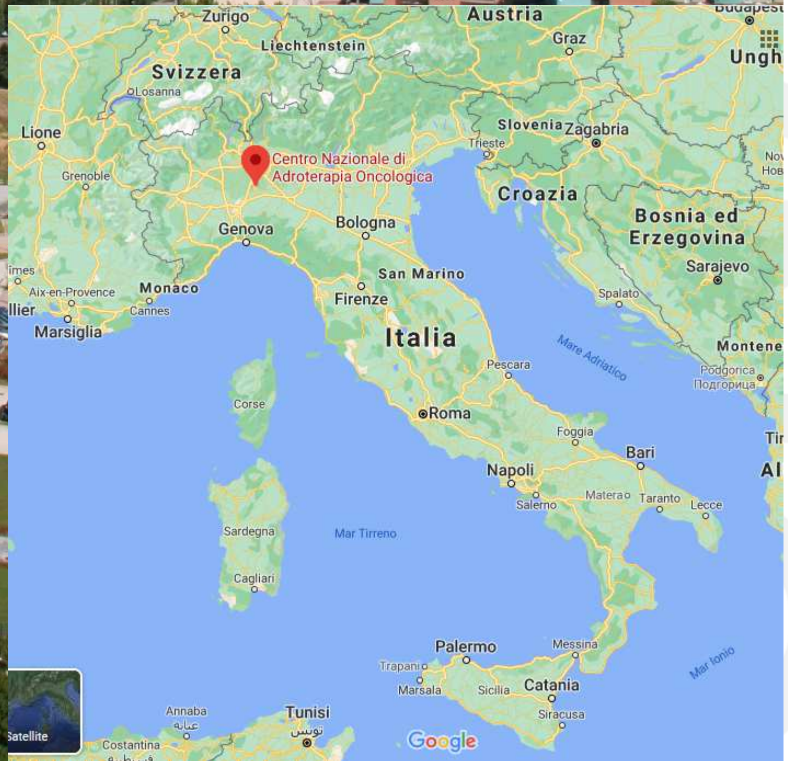
# Slow Extraction at CNAO

Marco Pullia, Luciano Falbo, Paolo Meliga

# CNAO in Pavia

- National Center for Oncological Hadrontherapy.

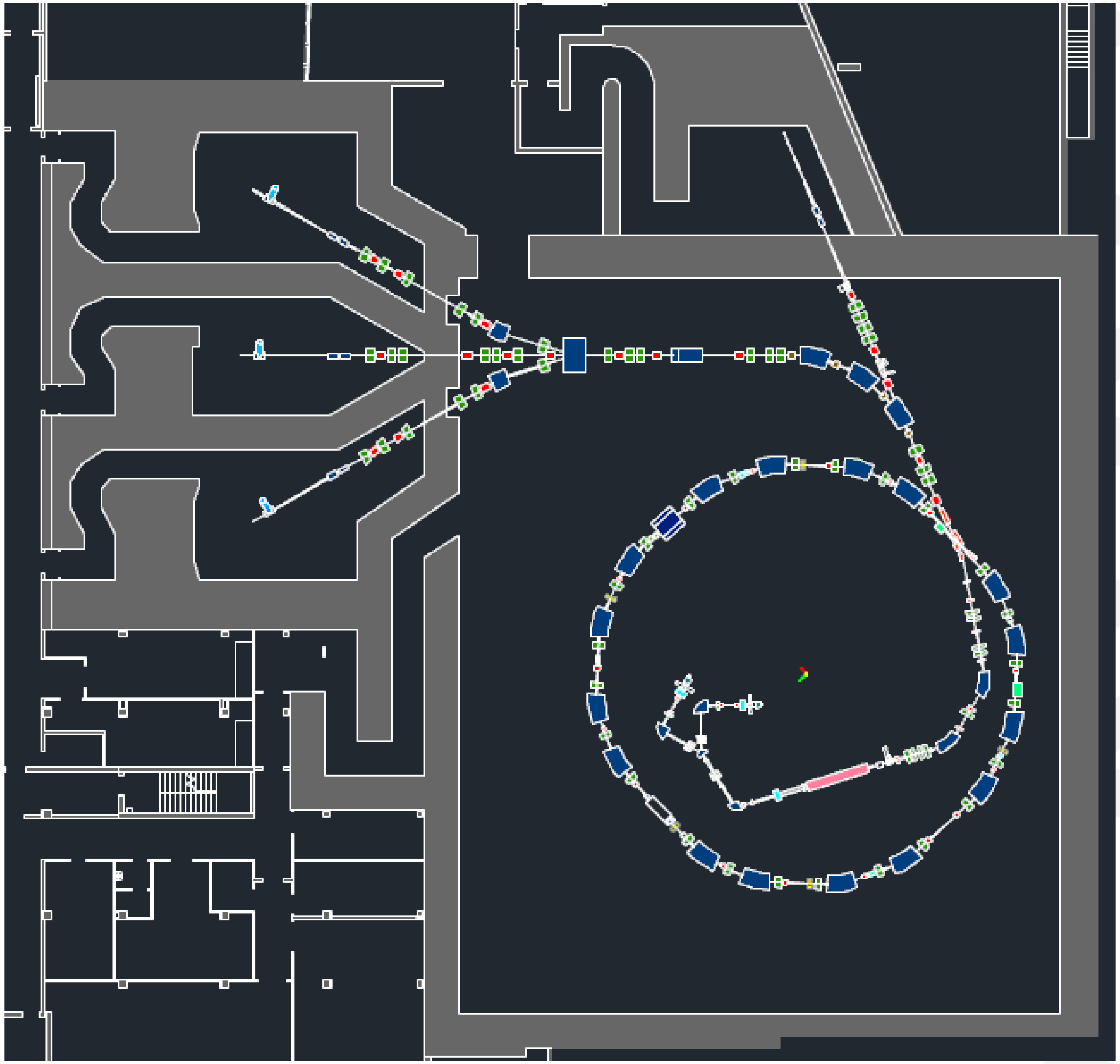


# CNAO

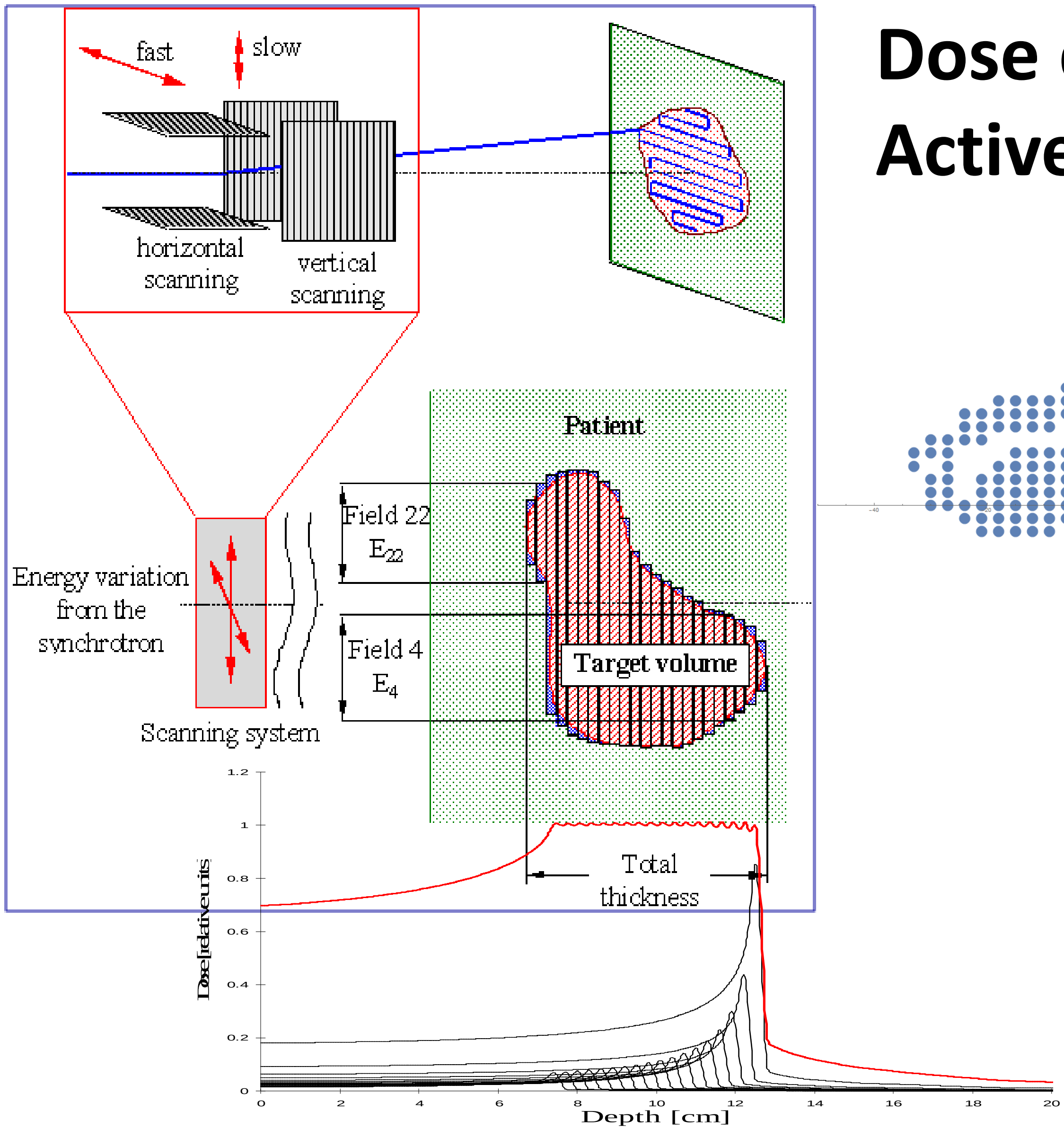
Synchrotron for
Protons (60-250 MeV)
Carbon (120-400 MeV/u)

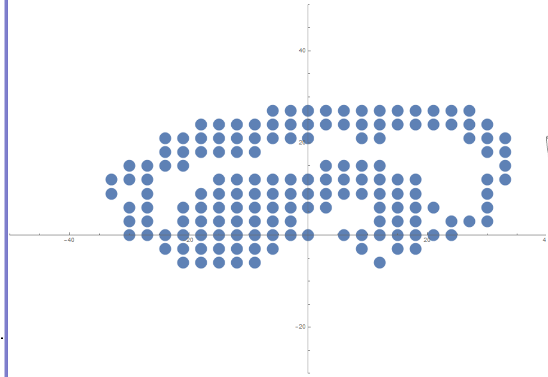
3200 patients treated

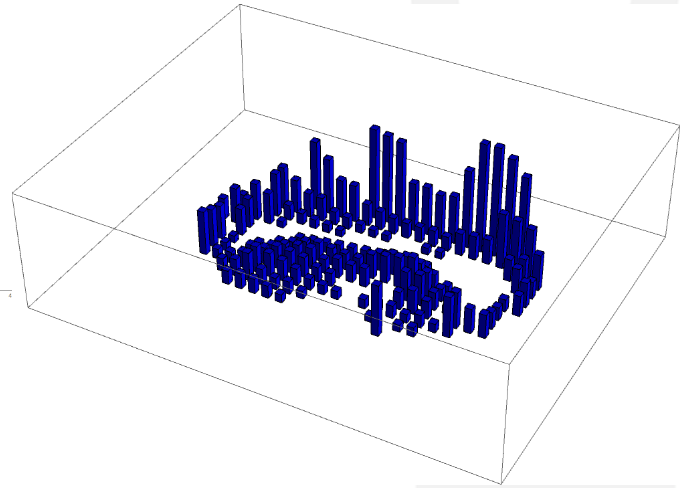
3 Treatment Rooms
1 Experimental room

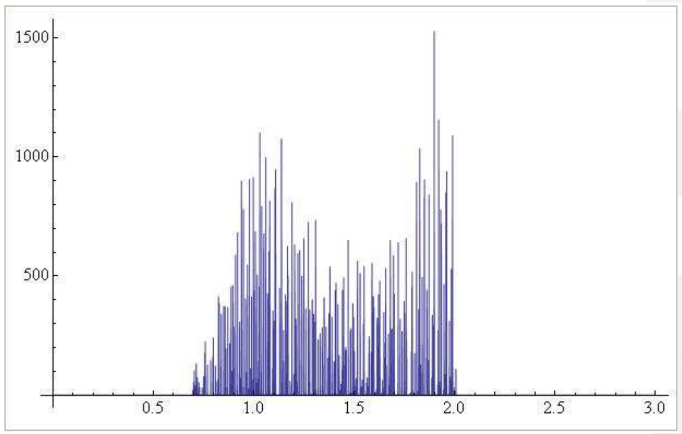


# Dose driven
# Active beam delivery

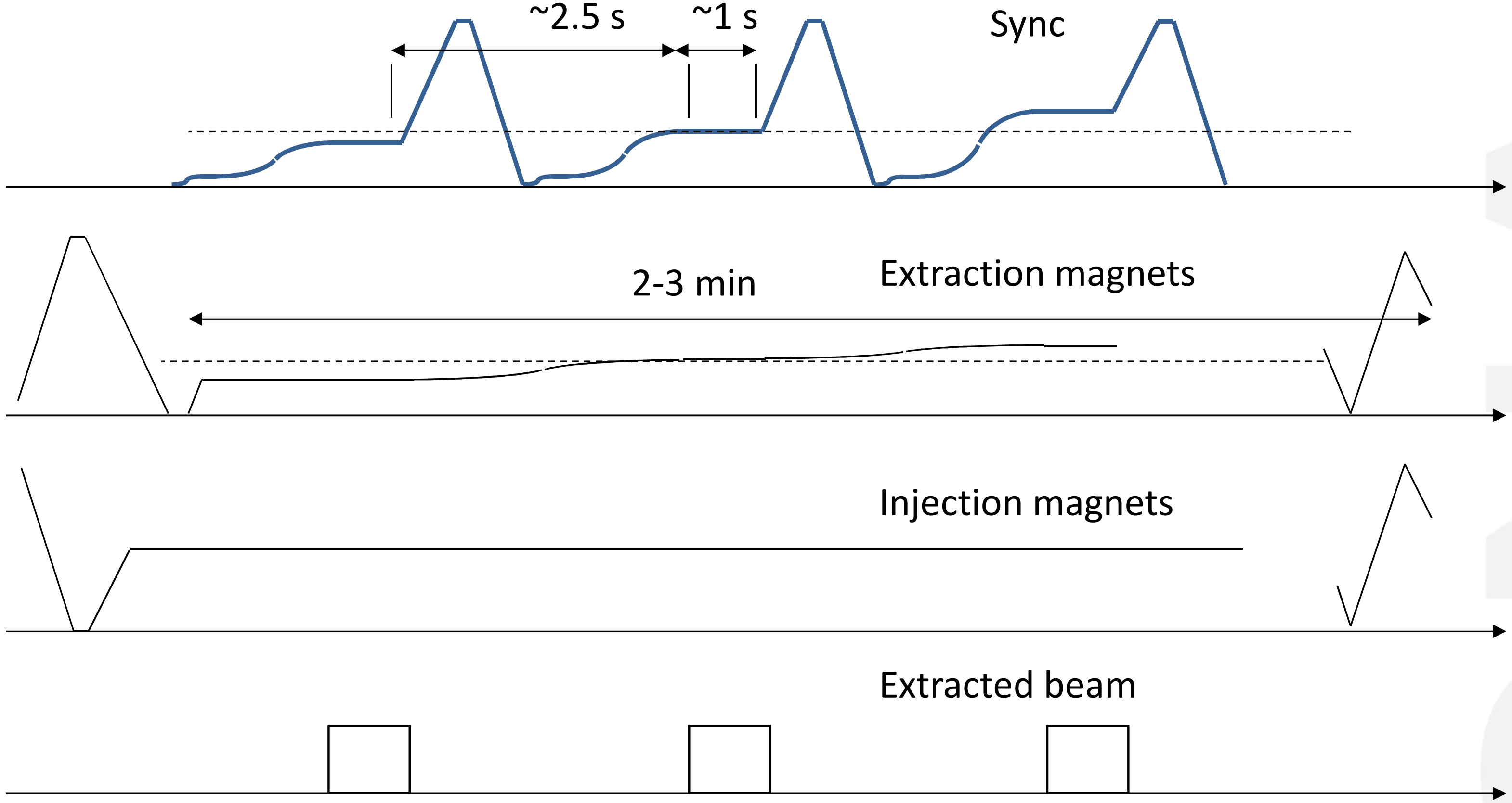


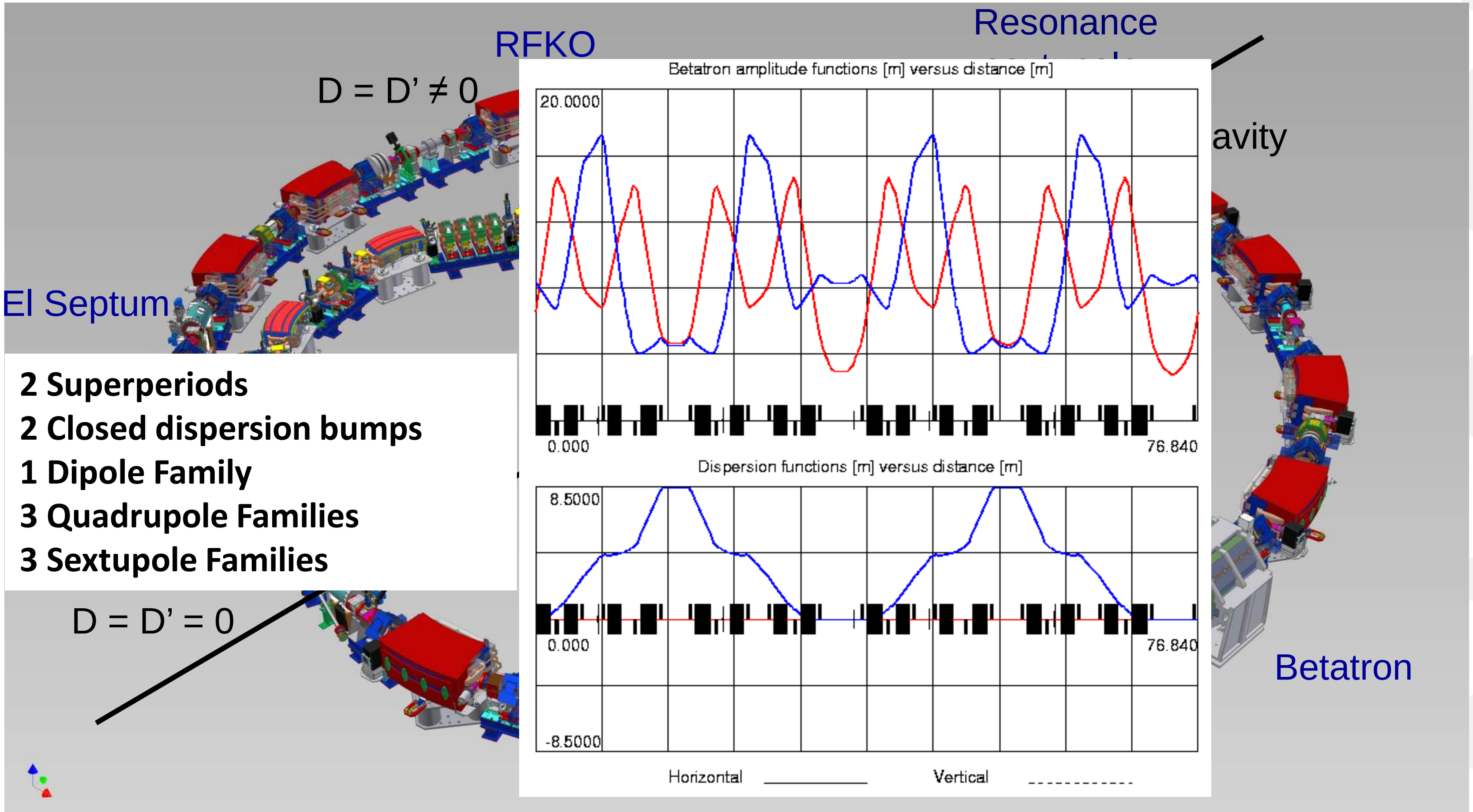







# Treatment execution






| | p inj | p – 60 MeV | p – 250 MeV | $C^{6+}$ inj | $C^{6+}$ – 120 MeV | $C^{6+}$- 400 MeV |
|---|---|---|---|---|---|---|
| Bρ (T m) | 0.4 | 1.1 | 2.4 | 0.8 | 3.3 | 6.4 |

# Extraction setup at CNAO

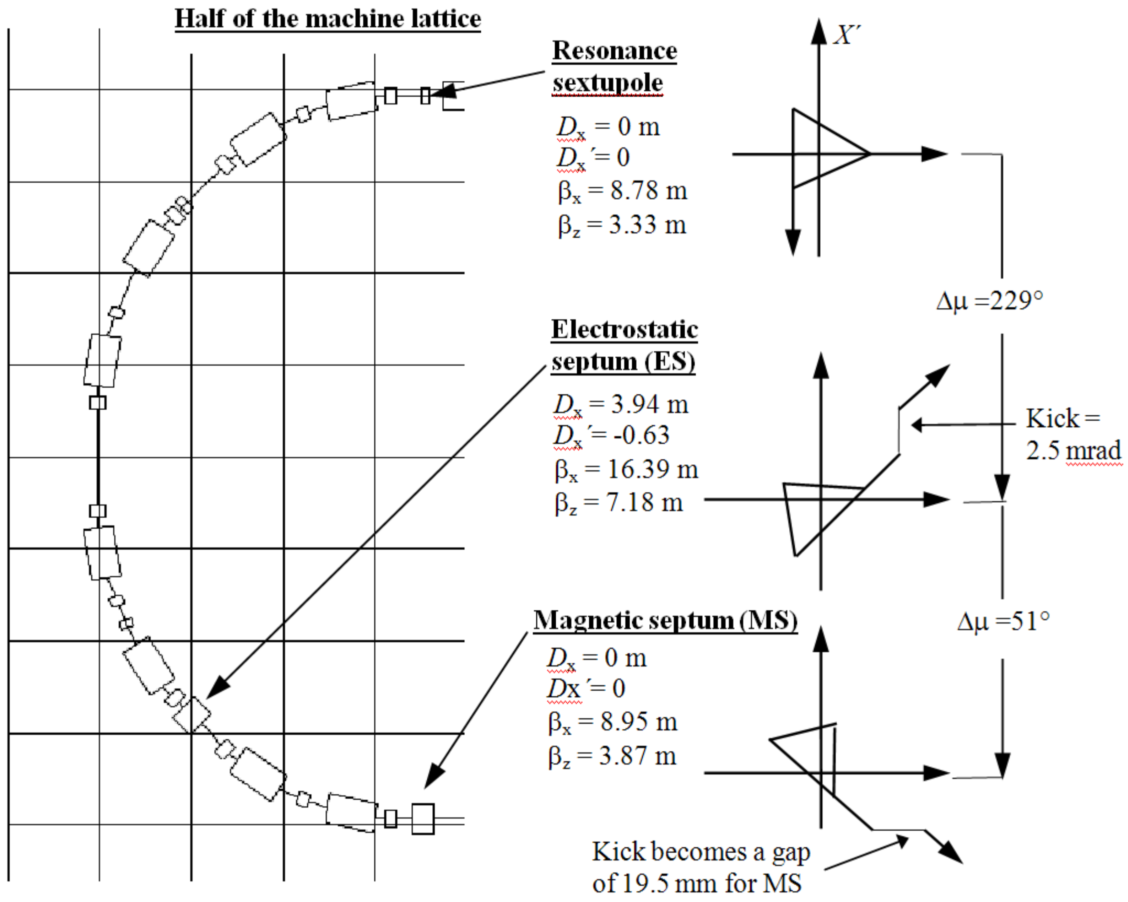
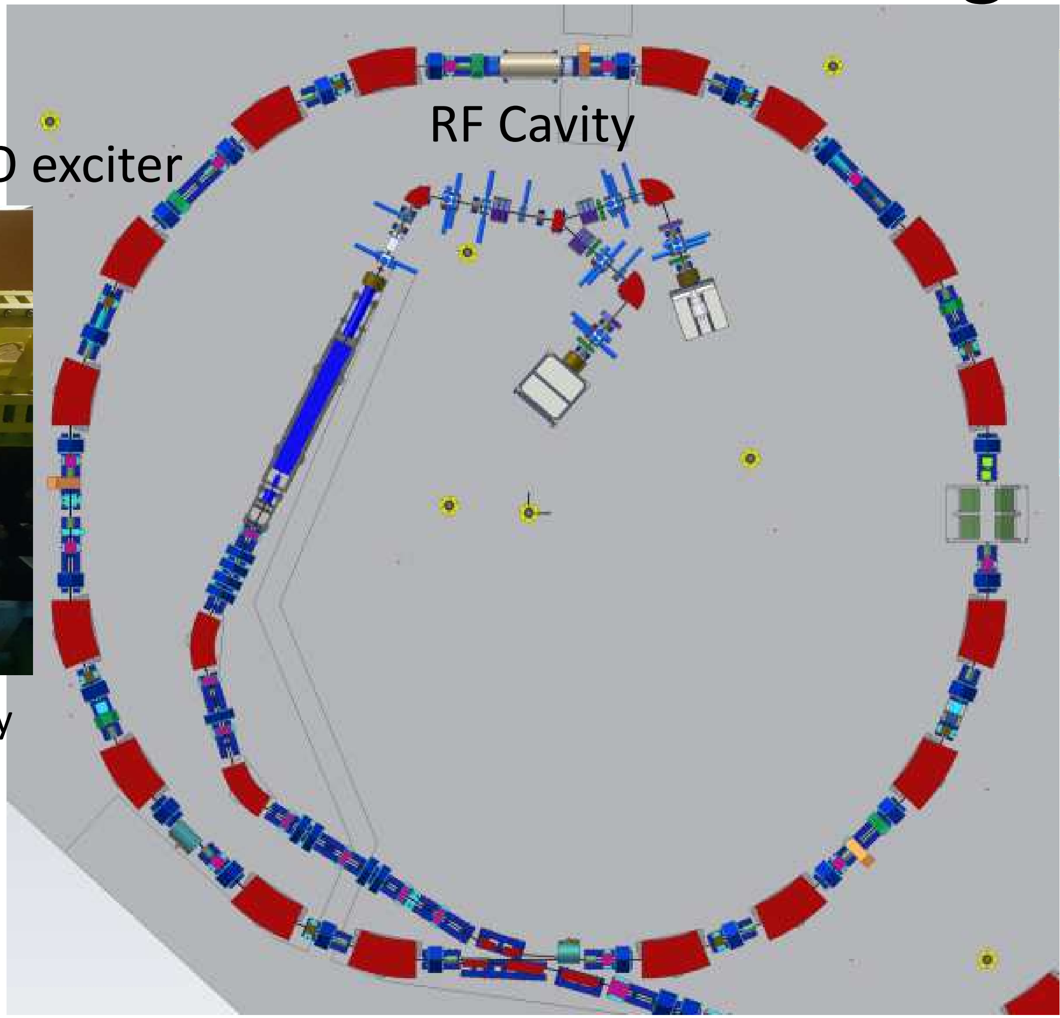


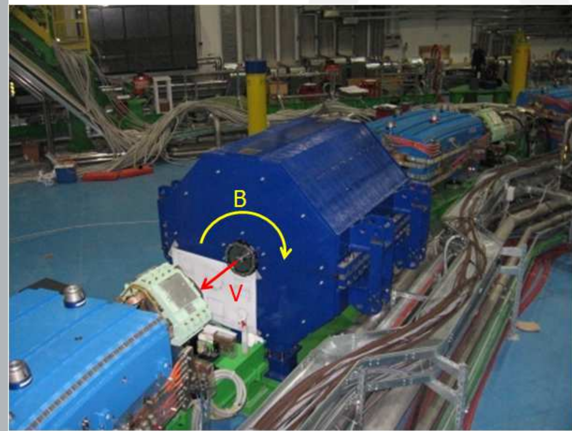

***Figure 3*** *Extraction configuration*

# Driving the beam into the unstable region

RFKO exciter

Blows up emittance transversally
(~1 μrad kicks)



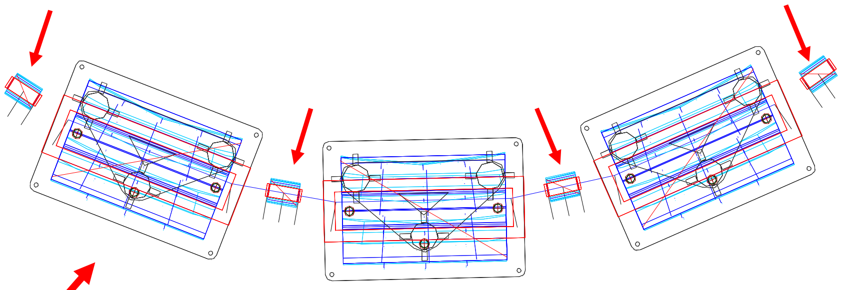



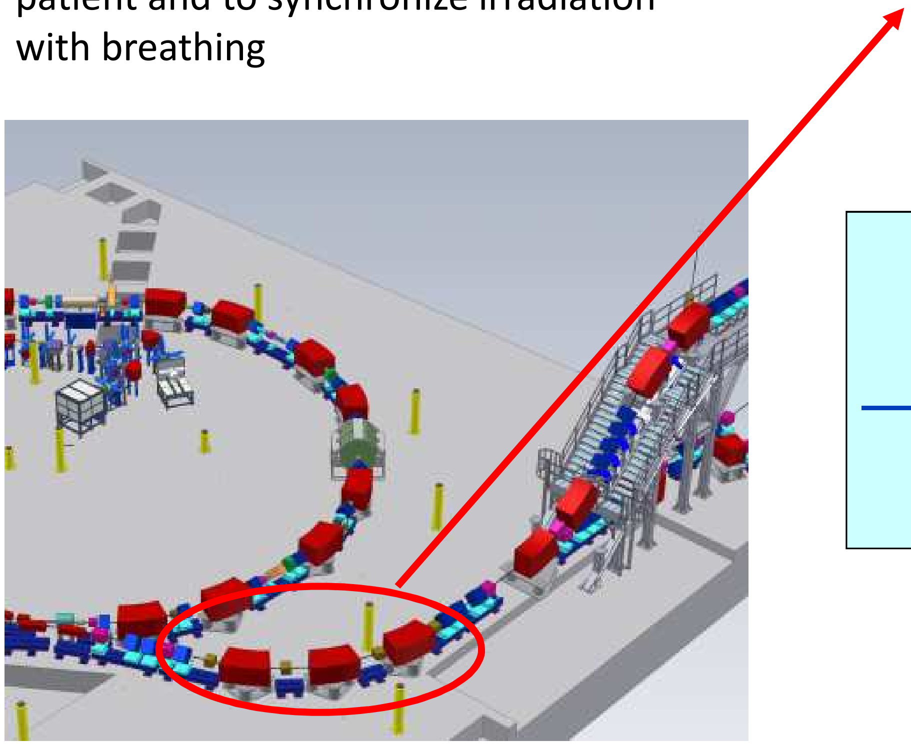

Betatron core

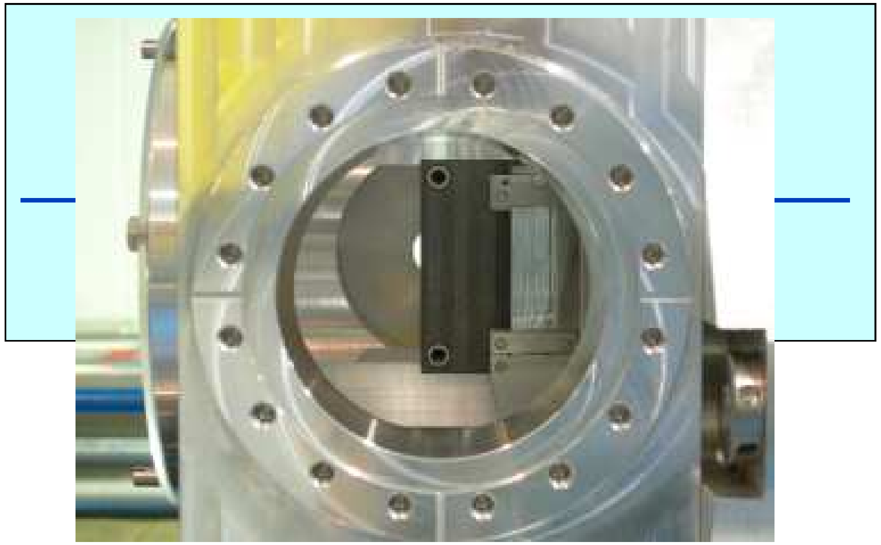
Pushes the beam in resonance
(~1V acceleration)

# HEBT Chopper

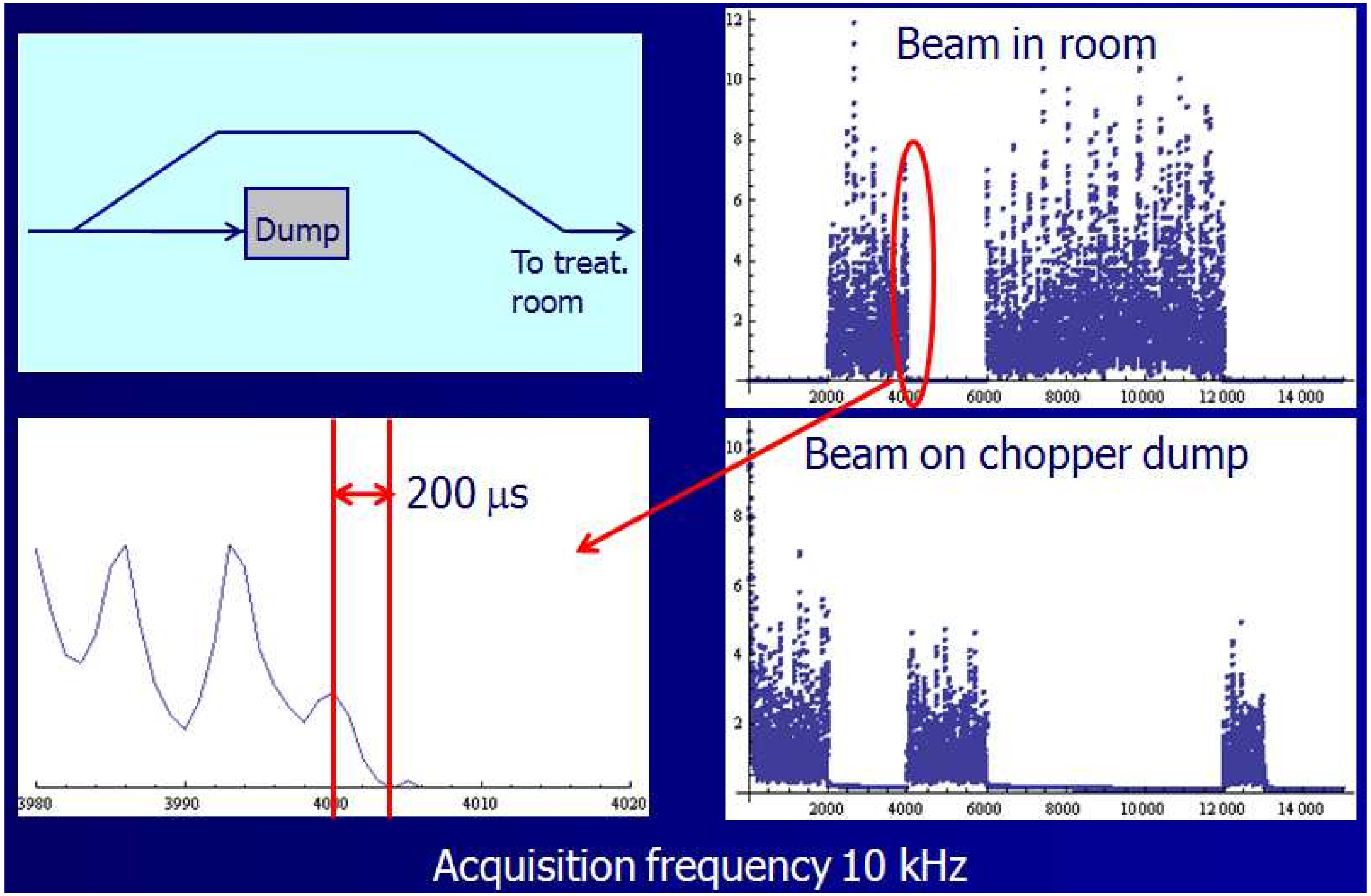
- **Fast turn on/off for the beam**
- **Intrinsically safe**
- used to control the dose delivered to the patient and to synchronize irradiation with breathing



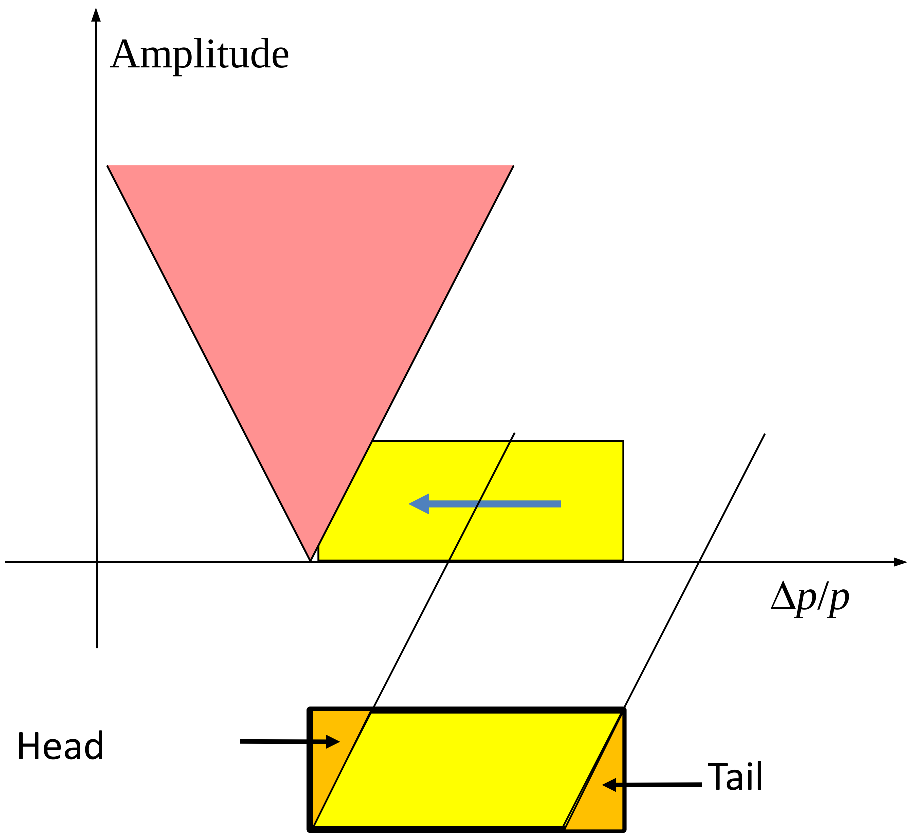




# Chopped beam



# Head and tail of extraction




Head and tail have a different beam position and shape.
They are "cut out" with the chopper

# Resonant extraction

# Stable and unstable regions generated by sextupole

$$B_x(x,z) = -6B_3 xz \qquad B_z(x,z) = -3B_3(x^2 - z^2)$$

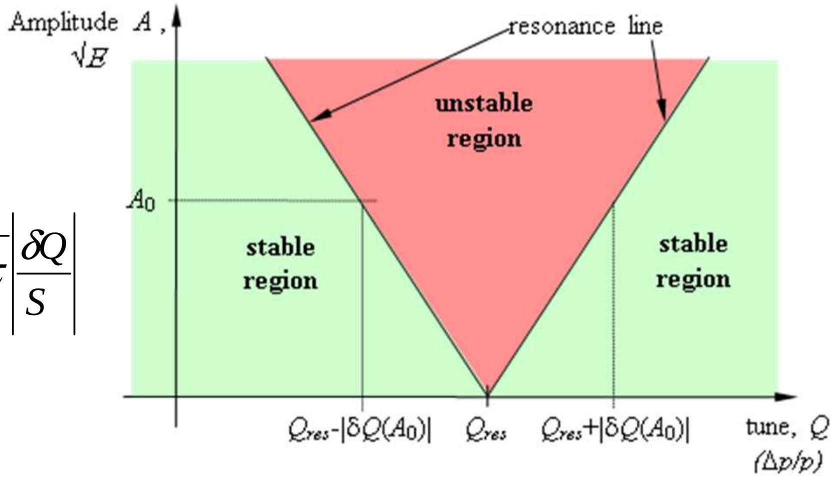
$$S = \frac{1}{2}\beta_x^{3/2}\frac{\lambda_S}{|B\rho|}\left(\frac{d^2B_z}{dx^2}\right)_0 = \frac{1}{2}\beta_x^{3/2}\lambda_S k'$$

$\varepsilon = 6\,\pi\, dQ$

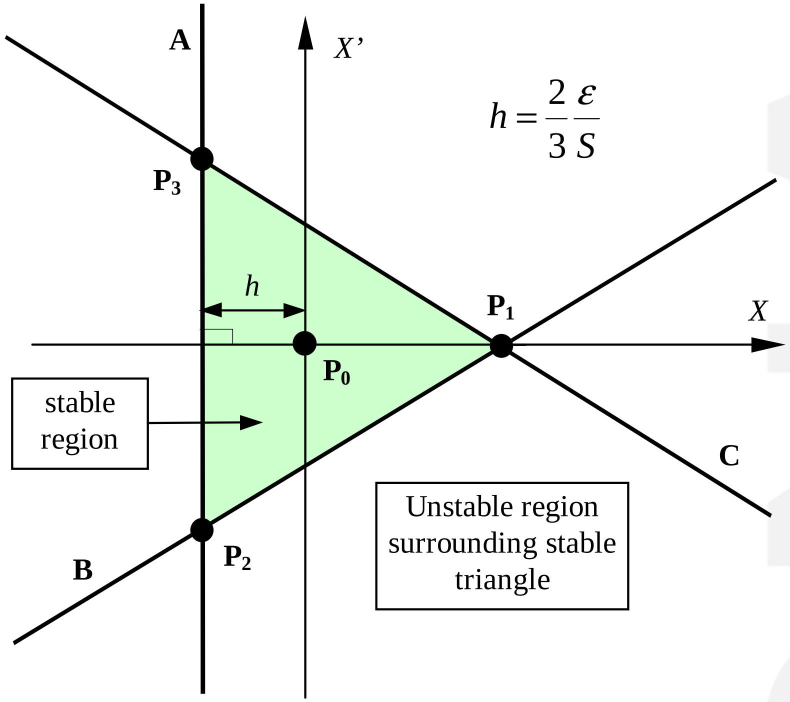
$$\boldsymbol{H} = \frac{\varepsilon}{2}\left(X^2 + X'^2\right) + \frac{S}{4}\left(3XX'^2 - X^3\right)$$

$$h = \frac{2}{3}\frac{\varepsilon}{S}$$

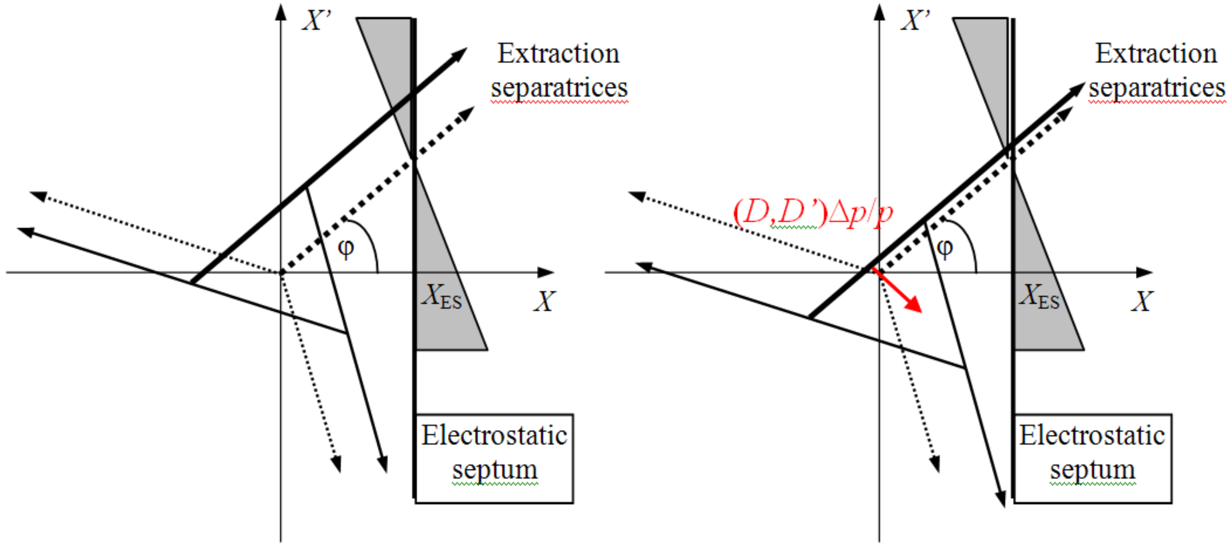
$$A = \sqrt{48\sqrt{3}\pi}\left|\frac{\delta Q}{S}\right|$$




Steinbach diagram

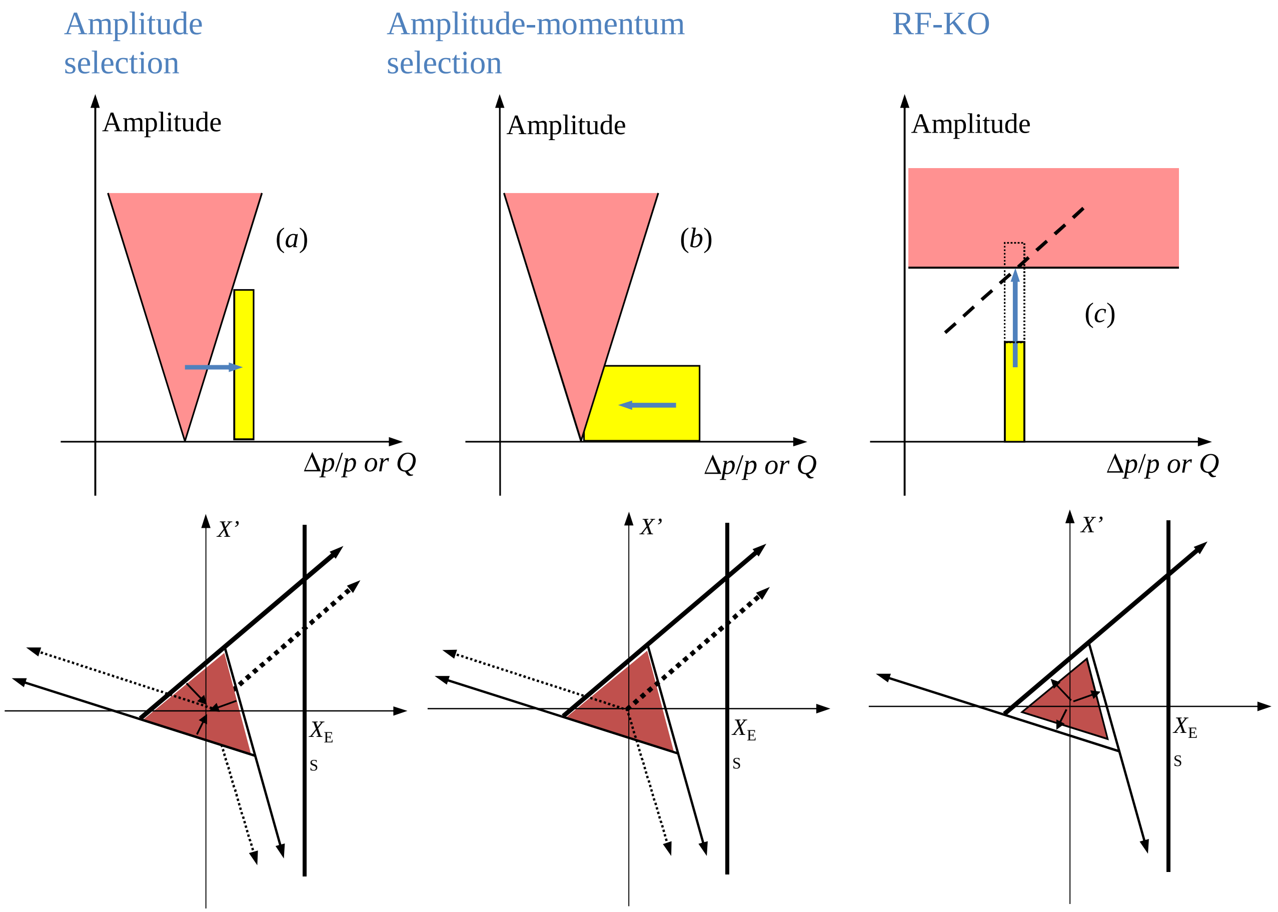


# Hardt condition

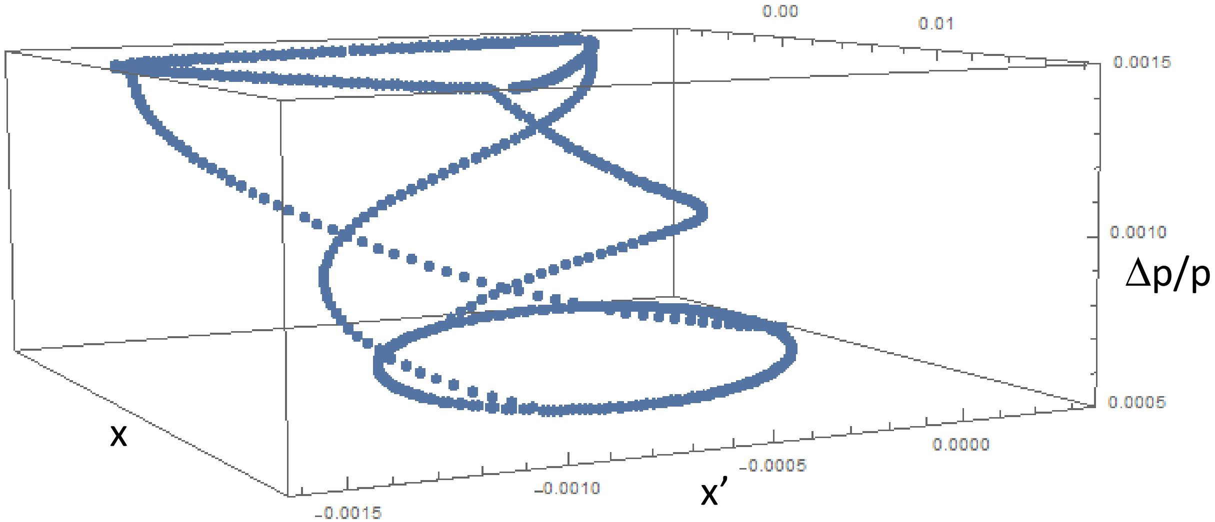


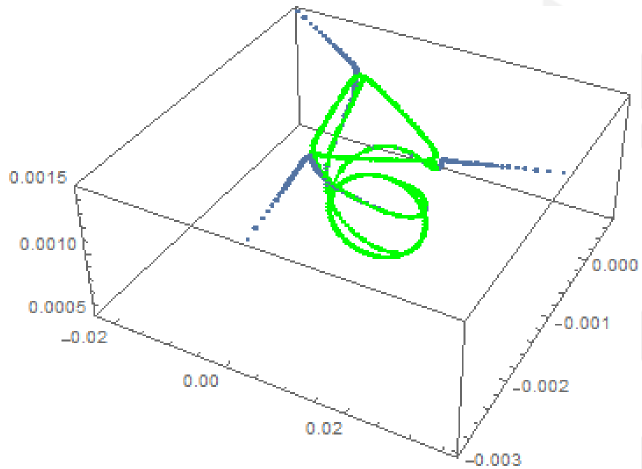

$$D_n \cos(\alpha_0 - \Delta\mu) + D'_n \sin(\alpha_0 - \Delta\mu) = -\frac{4\pi}{S} Q'$$

# Extraction methods

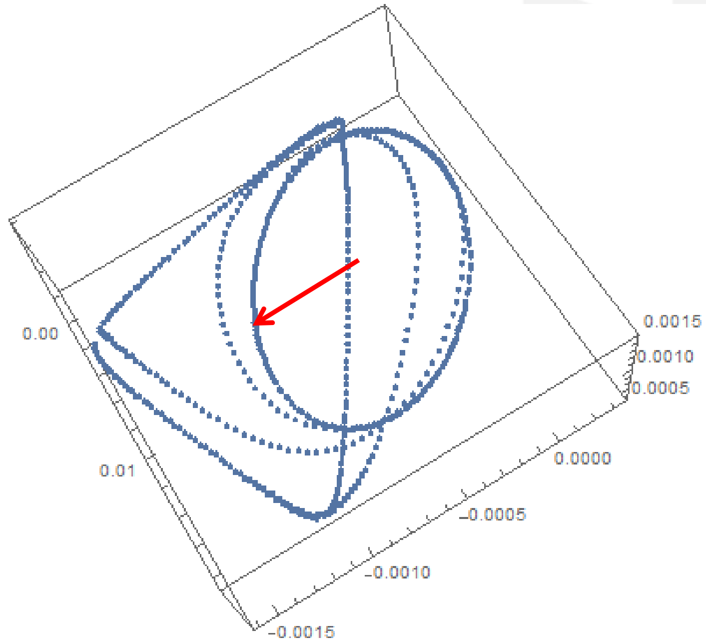


# Pushing into the resonance

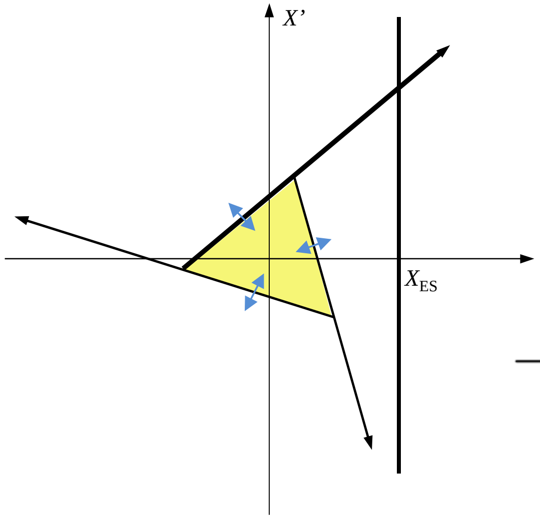


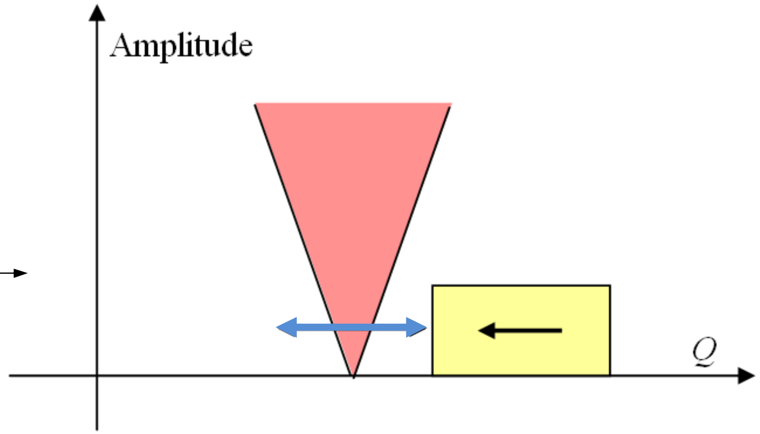




(D, D')·Δp/p



# Tune ripple




Instantaneous transfer model

$$\frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt} = \chi \cdot \left(\dot{Q}_0 + \dot{Q}_r\right) = \chi \cdot \left(\dot{Q}_0 + \omega\delta Q_R \cos(\omega t)\right)$$

The higher the frequency (ω) the lower the acceptable ripple amplitude ($\delta Q_R$).

# Spill quality

Spill quality can be described using:

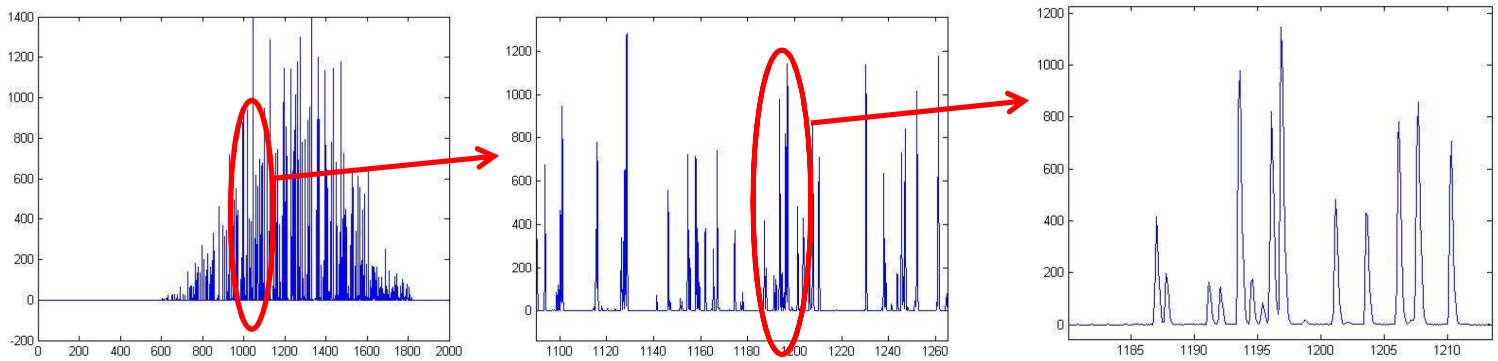
- Max/Average
- RMS duty factor

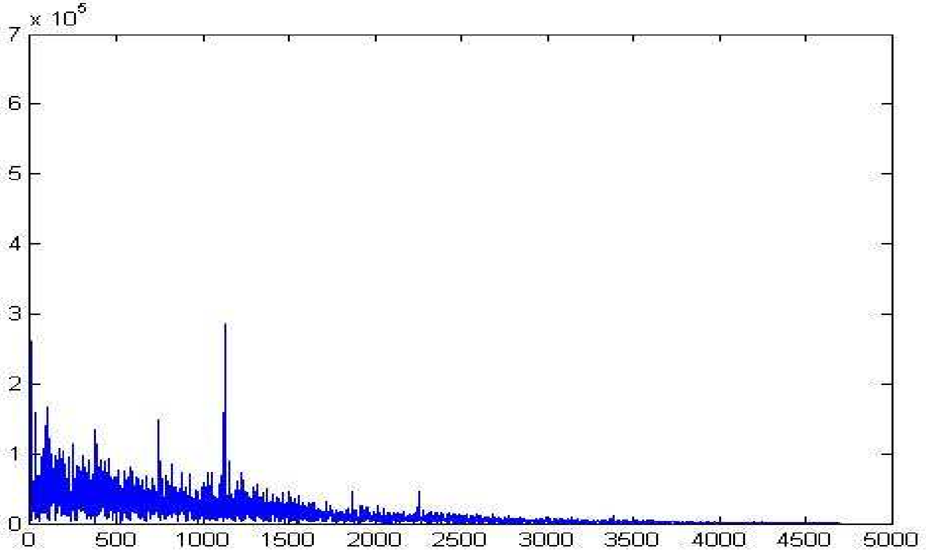
Rms duty factor is defined as

$$\frac{\left(\sum_{i=1}^{N} C_i\right)^2}{N\sum_{i=1}^{N} C^2}$$

To evaluate Max/Average and RMS duty factor, the spill (beam current) is acquired at 10 kHz

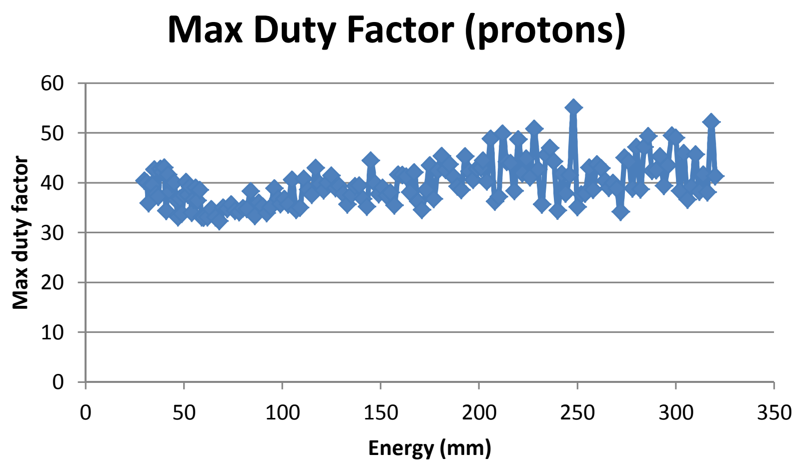
# “Natural” Spill

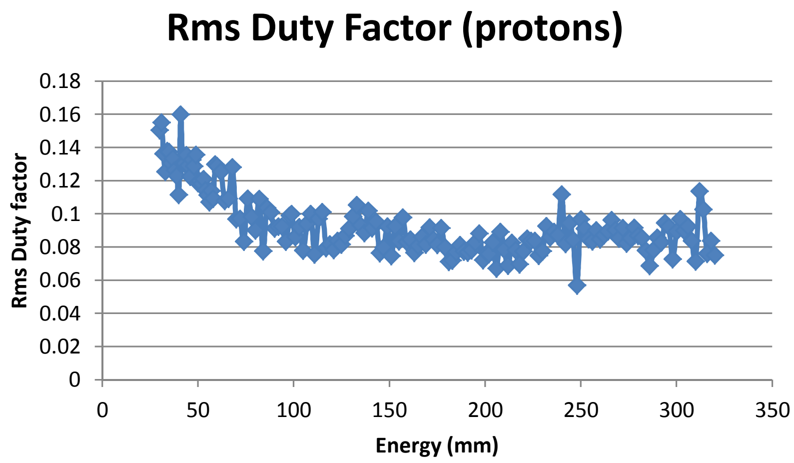


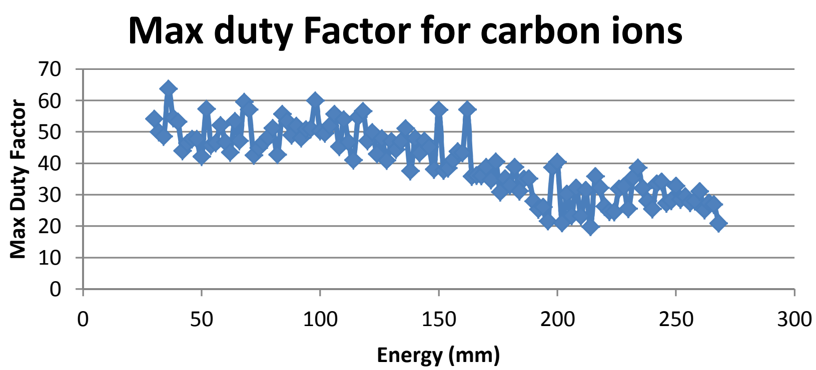


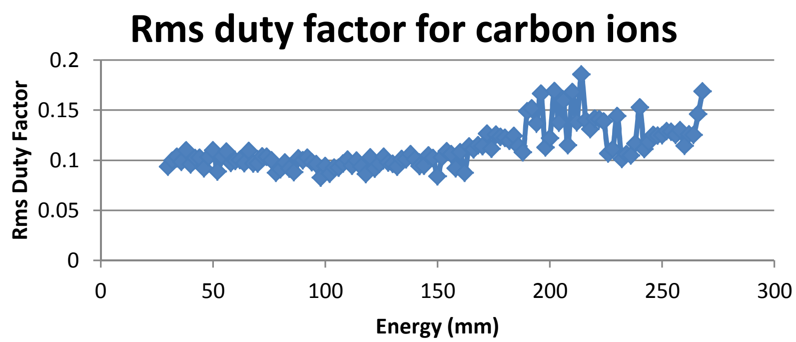
FFT of the current signal: Several contributions at low Frequencies with a peak at 1.2kHz

# “Natural” Spill quality



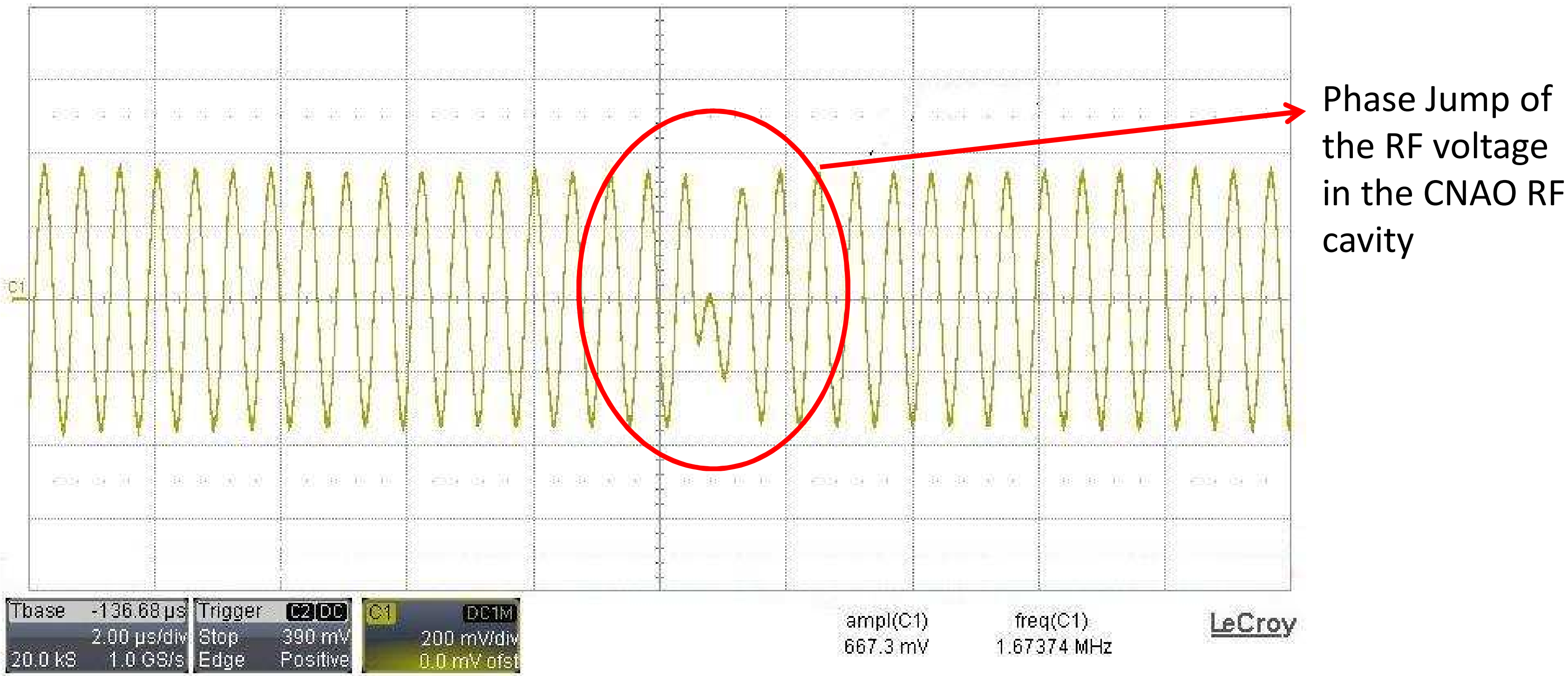



# RF Gymnastics for beam preparation

After acceleration beam is shaped in momentum space in order to obtain a uniform momentum distribution with a larger momentum spread.

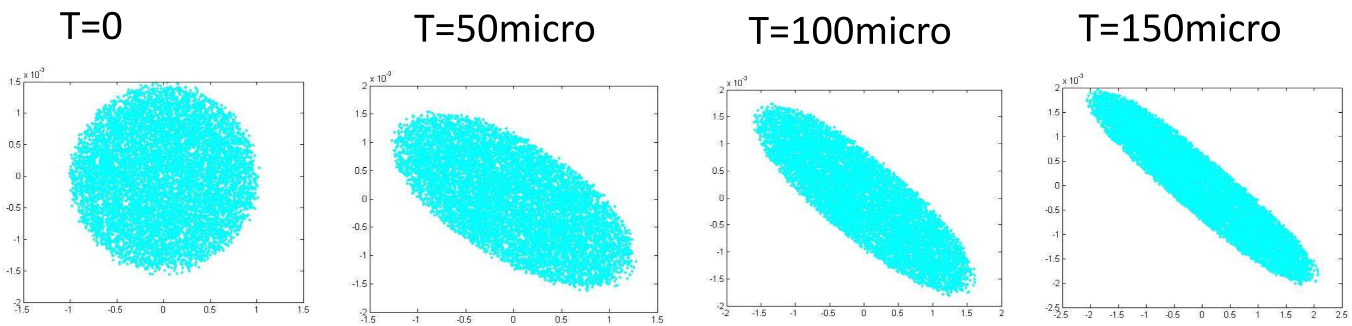
The RF gymnastics consists in a 180 degree phase jump («RF jump») to increase and flatten the momentum distribution before switching off the RF («RF OFF») for the debunching.

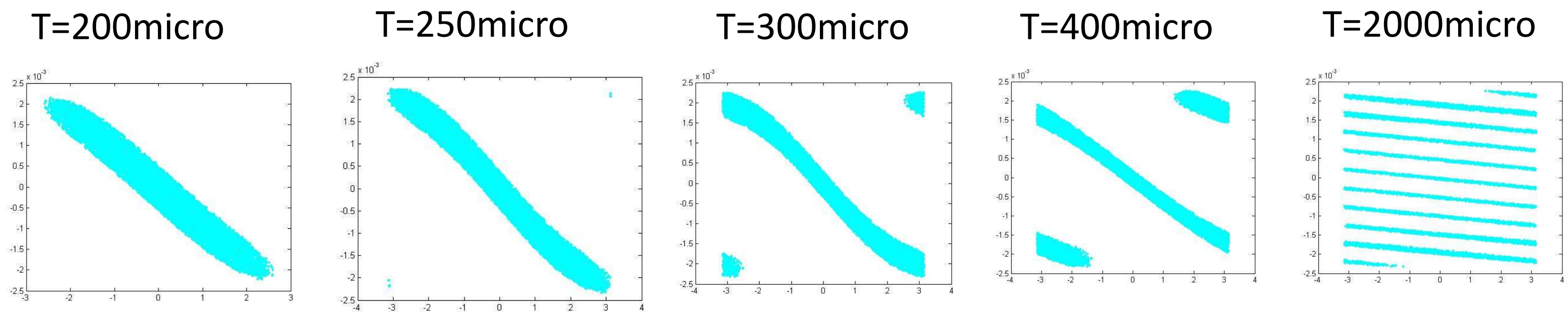


# Phase Jump and RF OFF: phase space evolution

0 microsec: end of acceleration and RF Phase Jump
300 microsec: RF OFF

X axis: phase
Y axis: $\Delta p/p$

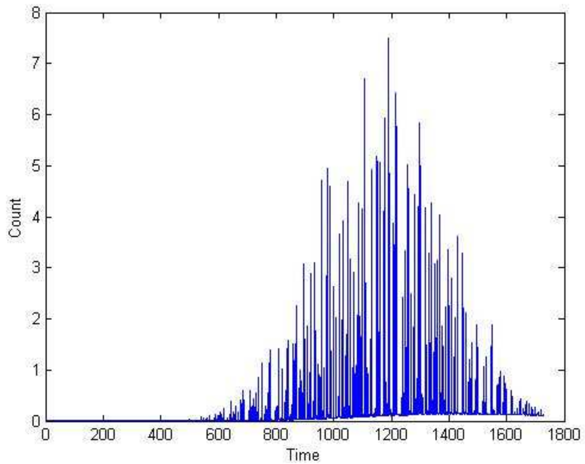


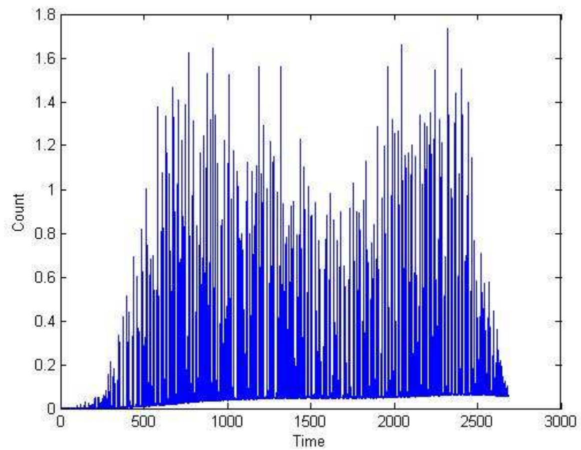
# Beam Time Profile

Considering the amplitude-momentum extraction, the time profile of the beam arriving at the isocenter is an indirect measurement of the momentum spread distribution

Without phase Jump

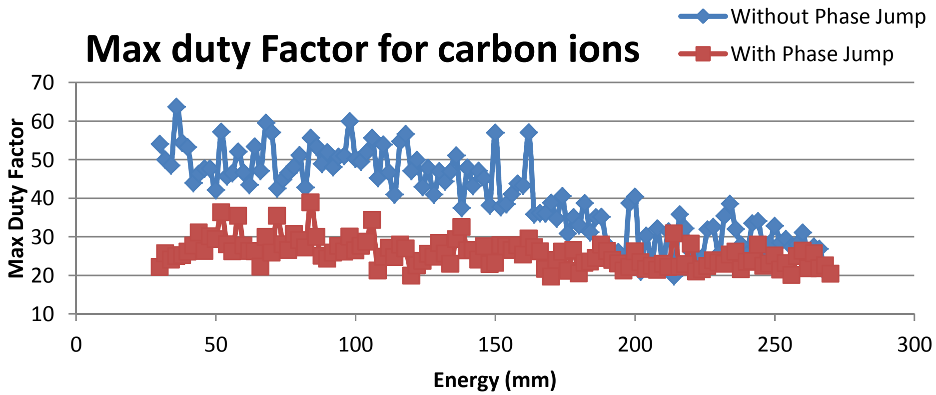


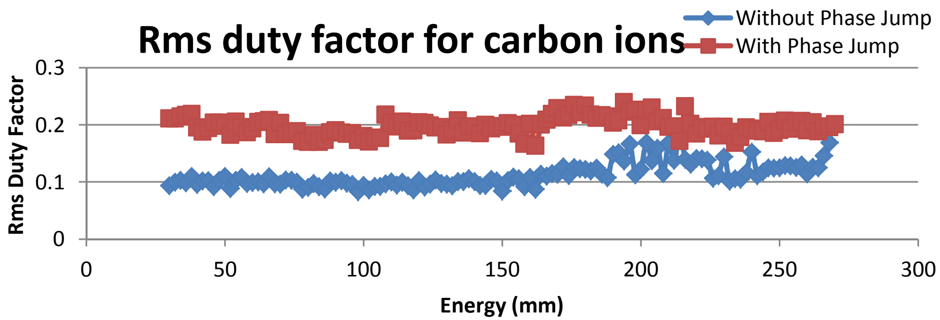

With phase Jump



# Phase Jump effects

Increase the time/speed of extraction
Improve Spill duty factors



# Empty bucket channelling

IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

LOW FREQUENCY DUTY FACTOR IMPROVEMENT FOR THE
CERN PS SLOW EXTRACTION USING RF PHASE DISPLACEMENT TECHNIQUES

R. Cappi, Ch. Steinbach
CERN, CH-1211 Geneva 23, Switzerland

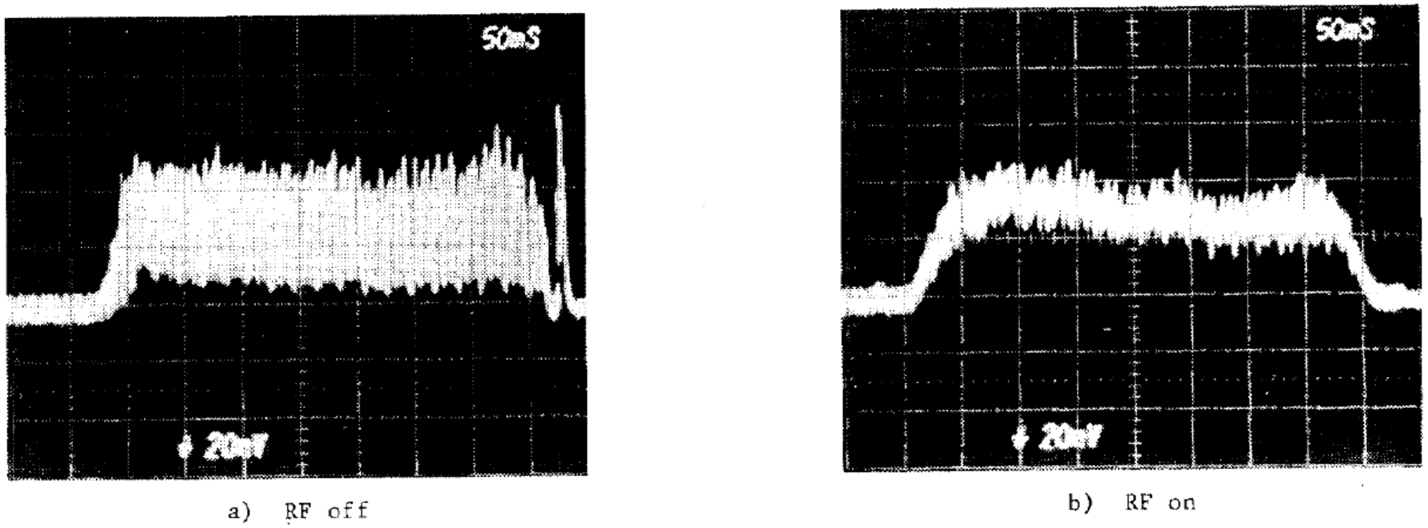
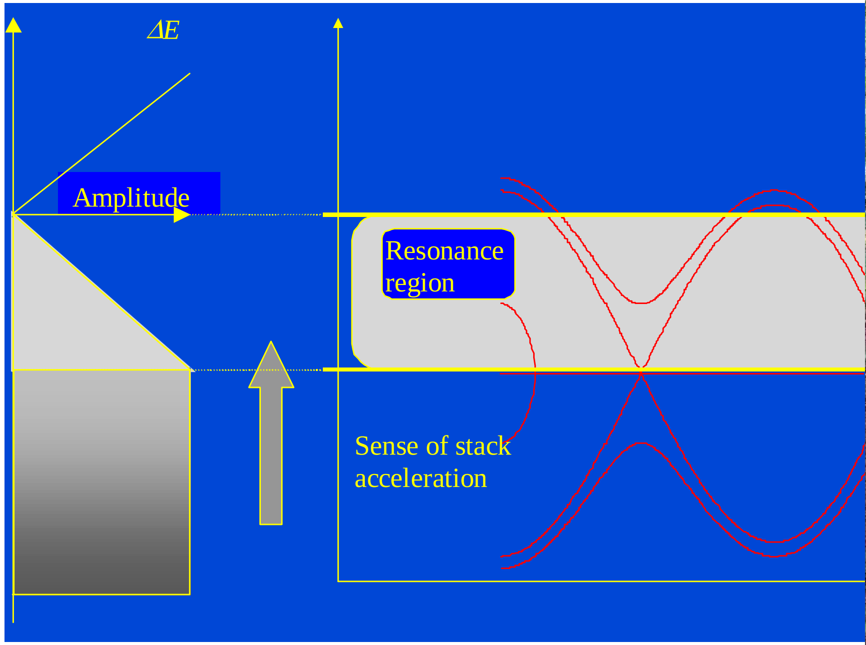


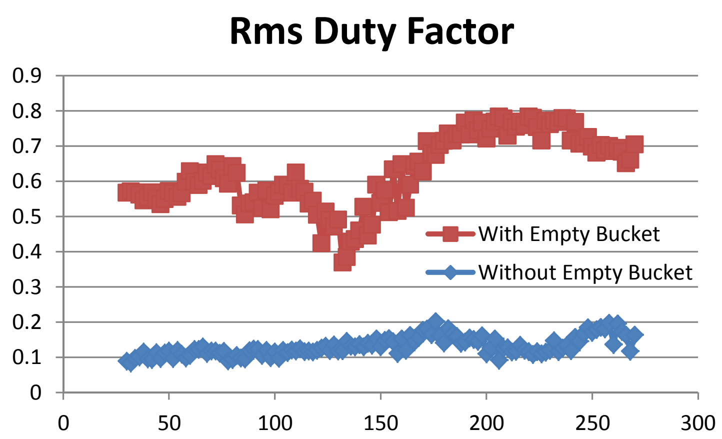

Fig. 2 : Slow extraction spill (50 ms/div.)

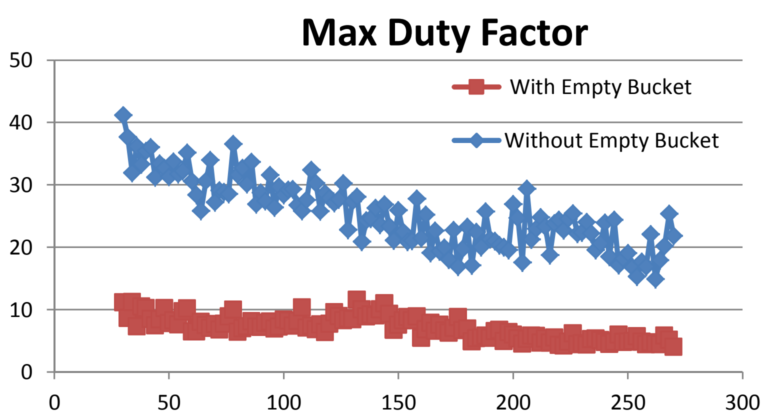
# Empty bucket channelling



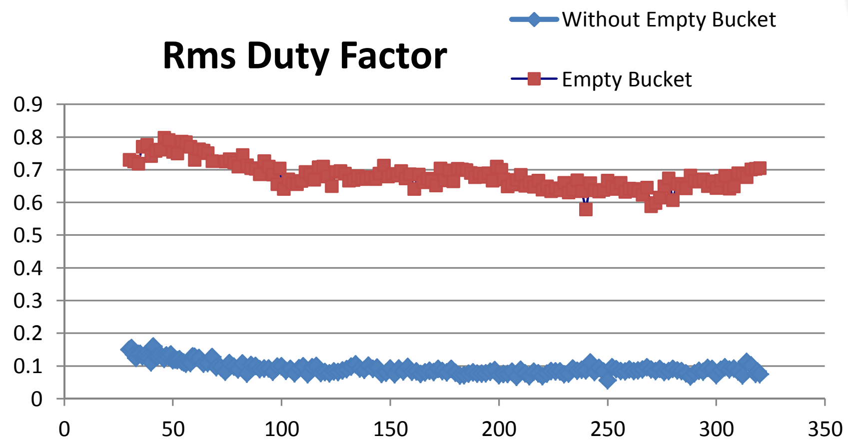

# Empty bucket channelling

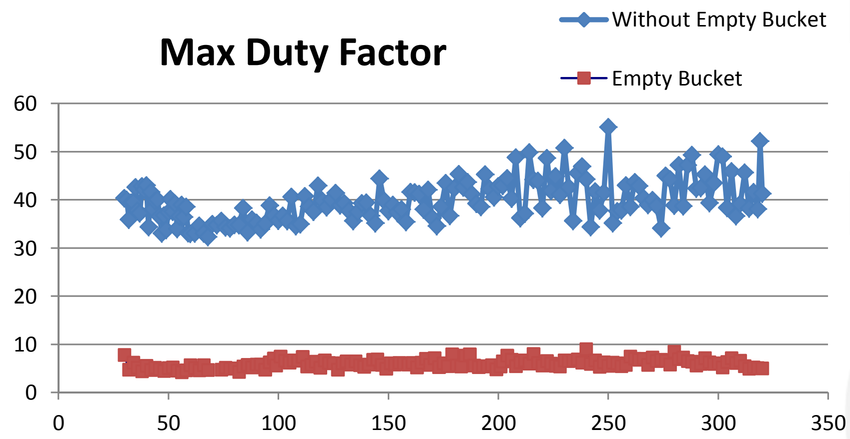
**Carbon ions**



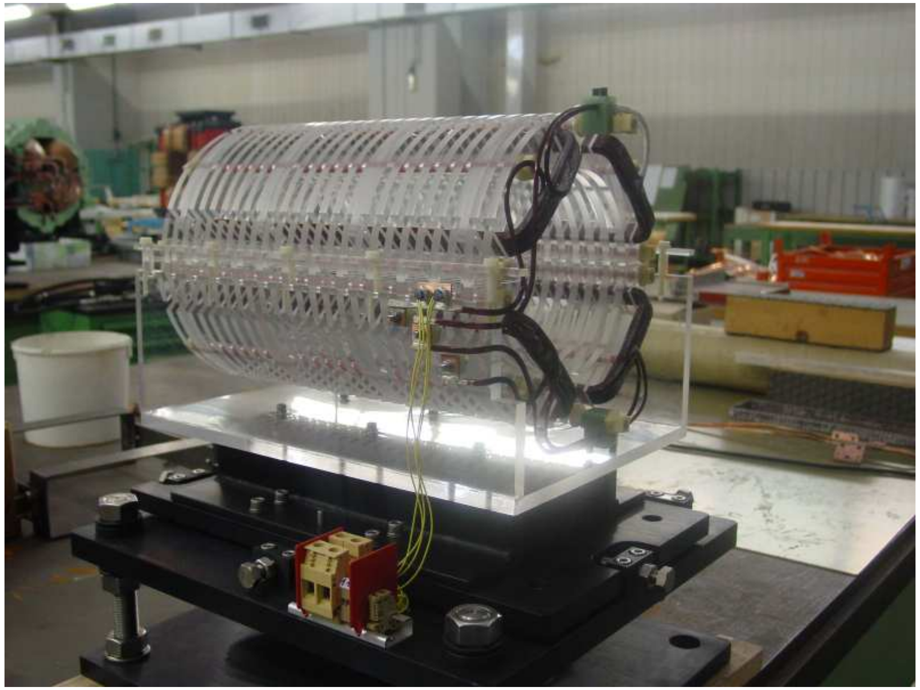

**Protons**



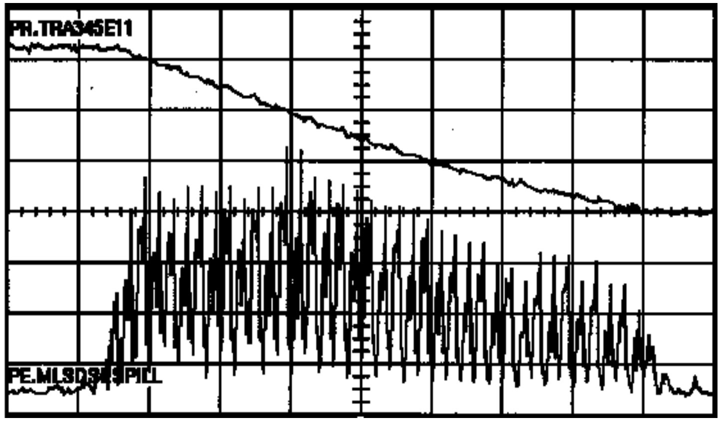



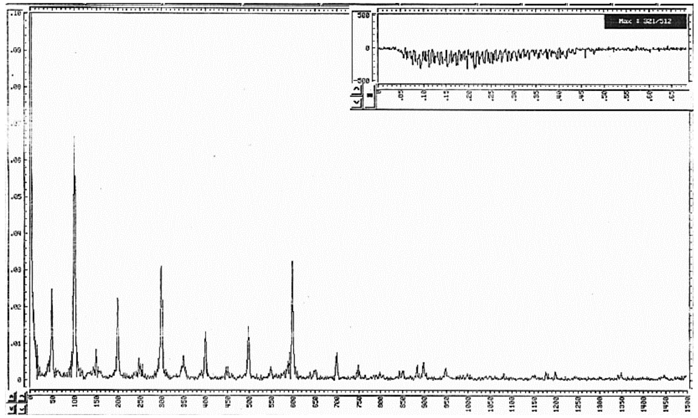
# Air core quad

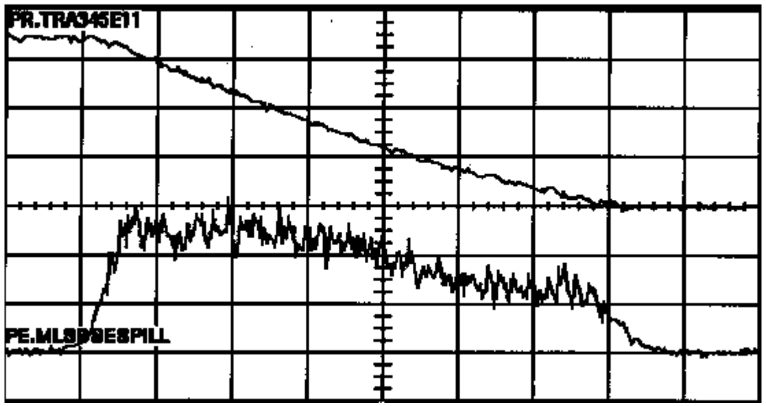
$\Delta Q < 0.001$
BW 20 kHz

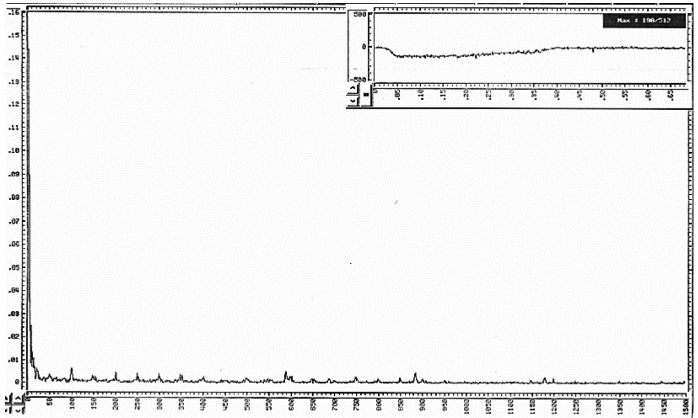


# Air core quad feed forward at CERN





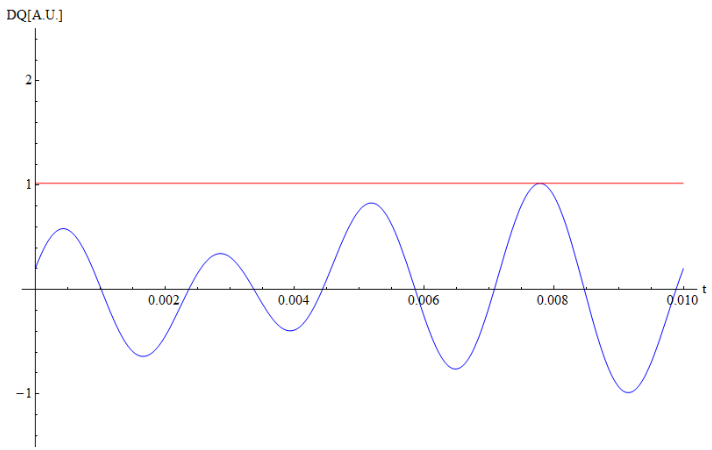
# Automatic feed forward

Feed forward correction requires repeatability, which was the case in the medium term (one day), but the correction parameters could vary over longer time (week).

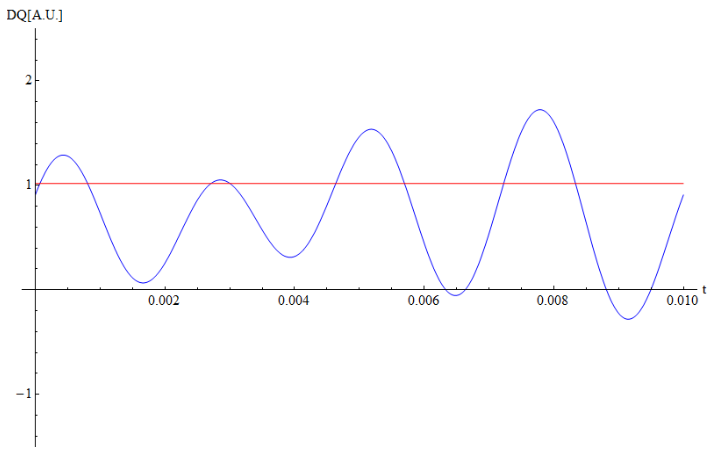
In the days following the air core quad feed forward MD, R. Cappi set up a system performing FFT and applying the correction at the following spill.

Unluckily feed forward does not work at CNAO, not even on the very short time scale (1 second). We need an alternative.

# High Frequency Ripple Injection



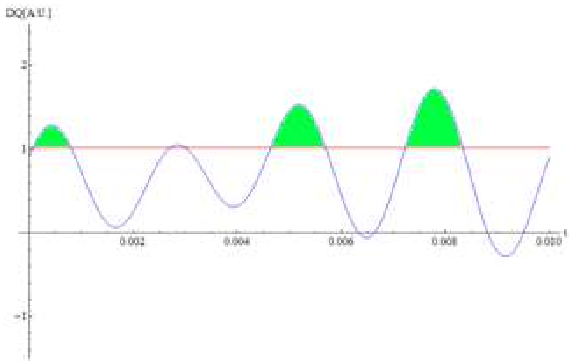

Ripple with betatron off.
Brushing against the resonance

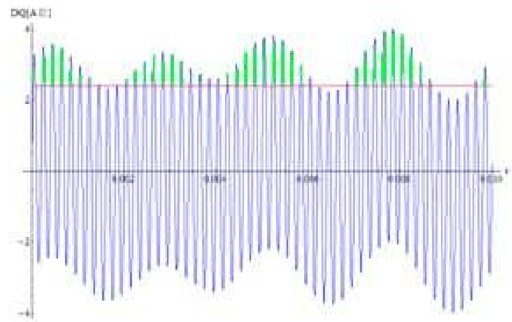



Ripple with betatron on.
Irregular spill with strong modulation

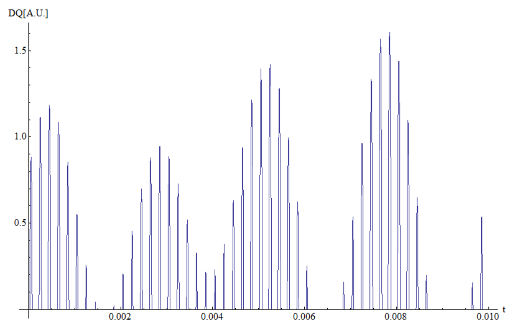
# High Frequency Ripple Injection

Inject a large ripple with a frequency higher than the one you are interested in

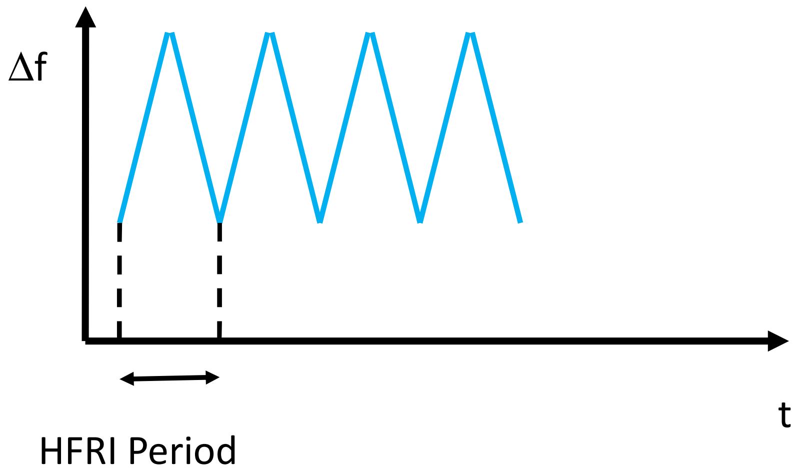



The amount of extracted beam depends only on the betatron,
thus an apparently more homegeneous spill is obtained.



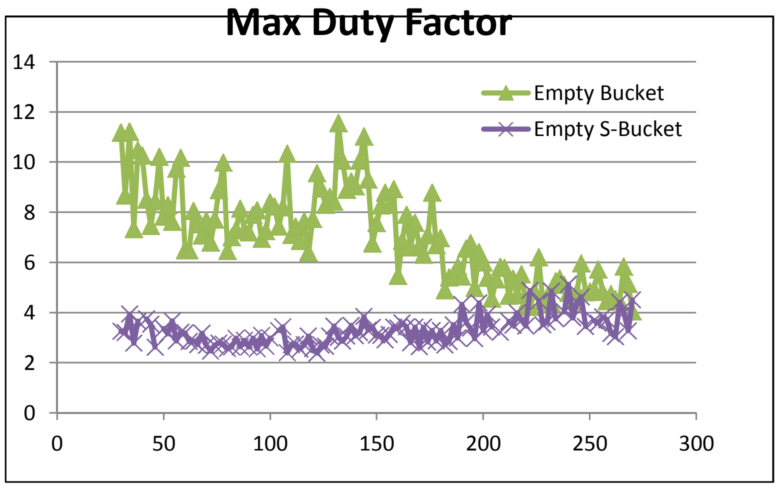
# RF frequency sweeping HFRI

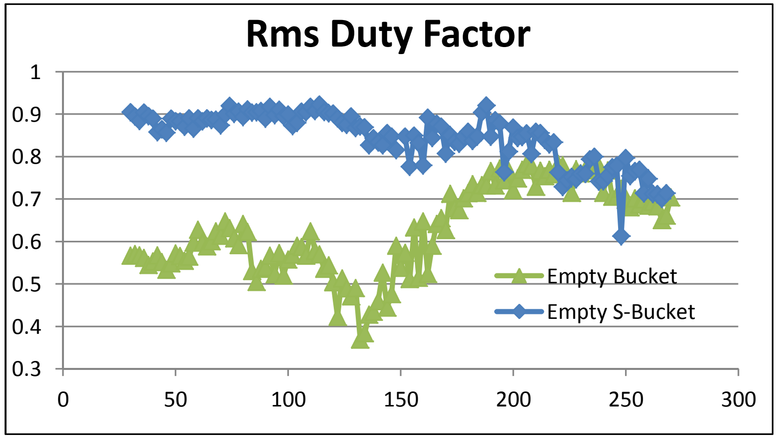



The same effect can be obtained with every means that can bring
The beam towards and away from the resonance
We do it by sweeping the empty bucket back and forth

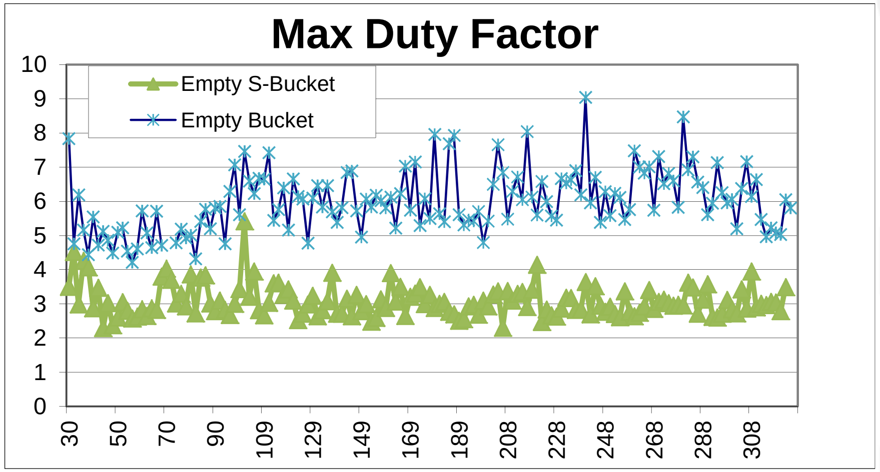
# Empty Sweeping Bucket vs Empty Bucket

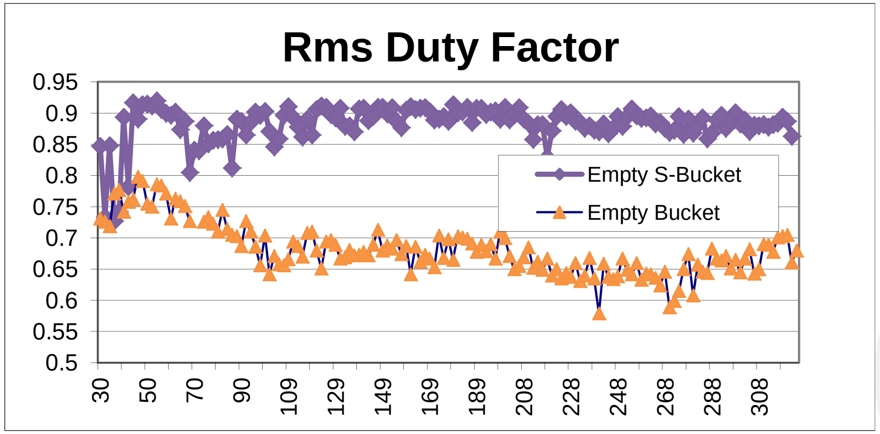
**Carbon ions**



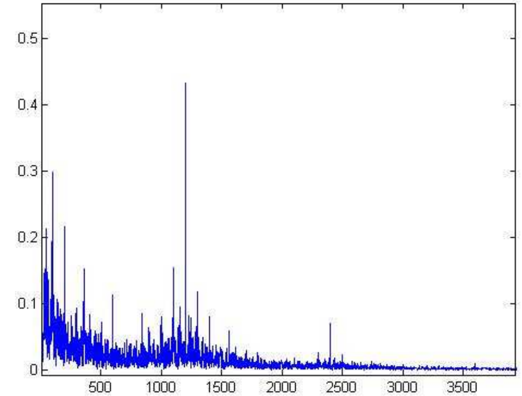

**Proton ions**



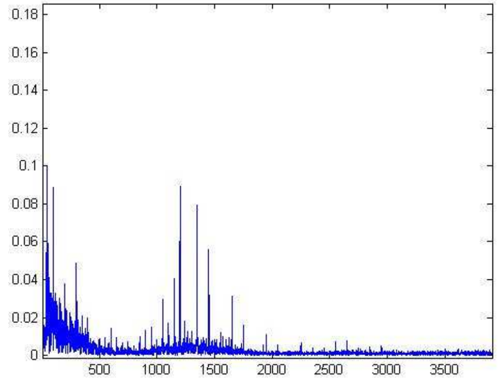



# Frequency domain comparisons

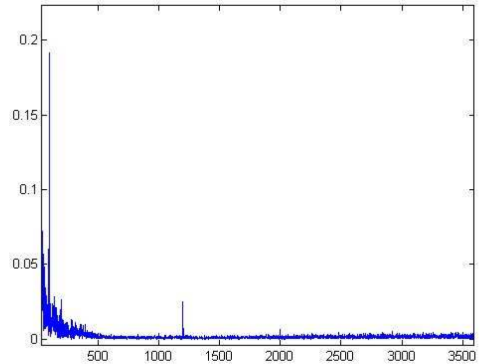
No Empty Bucket



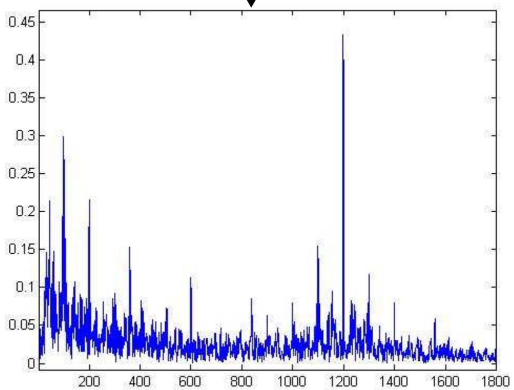

Empty Bucket



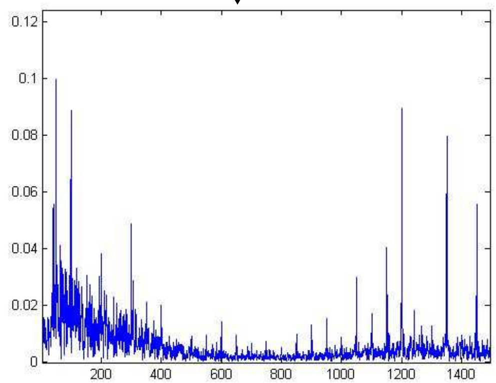

Empty Sweeping Bucket



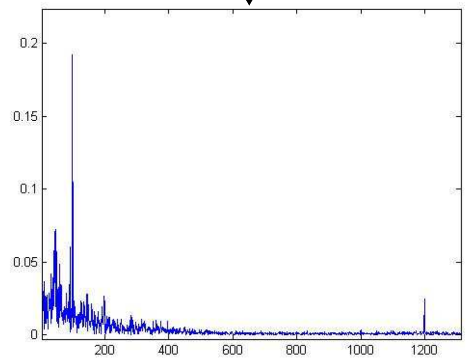

zoom



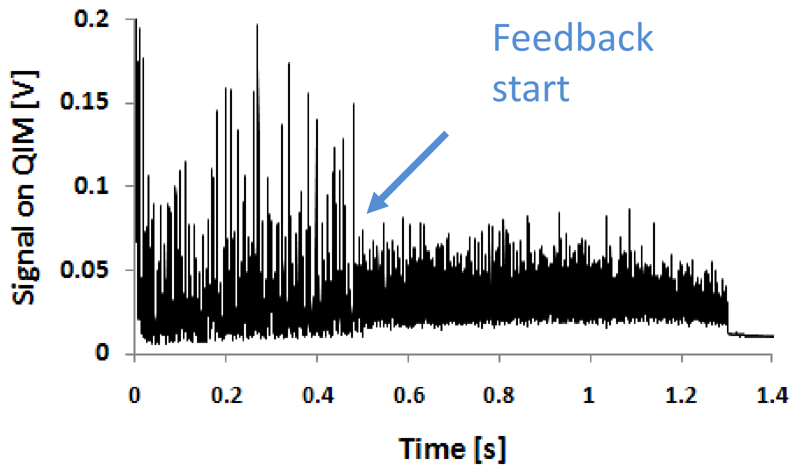

zoom

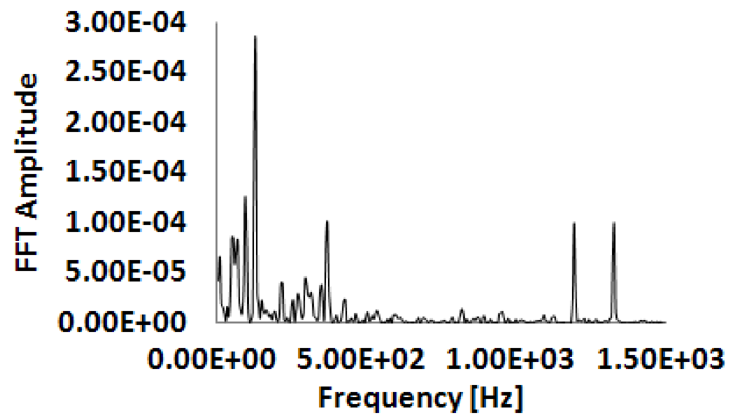


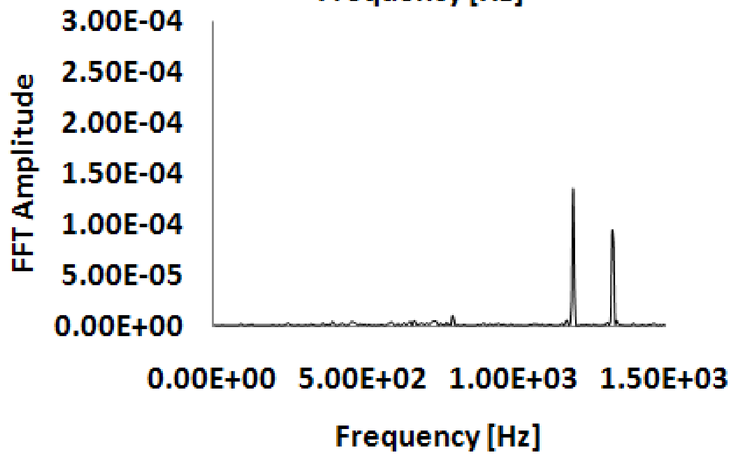

zoom



# Air core quad with feedback



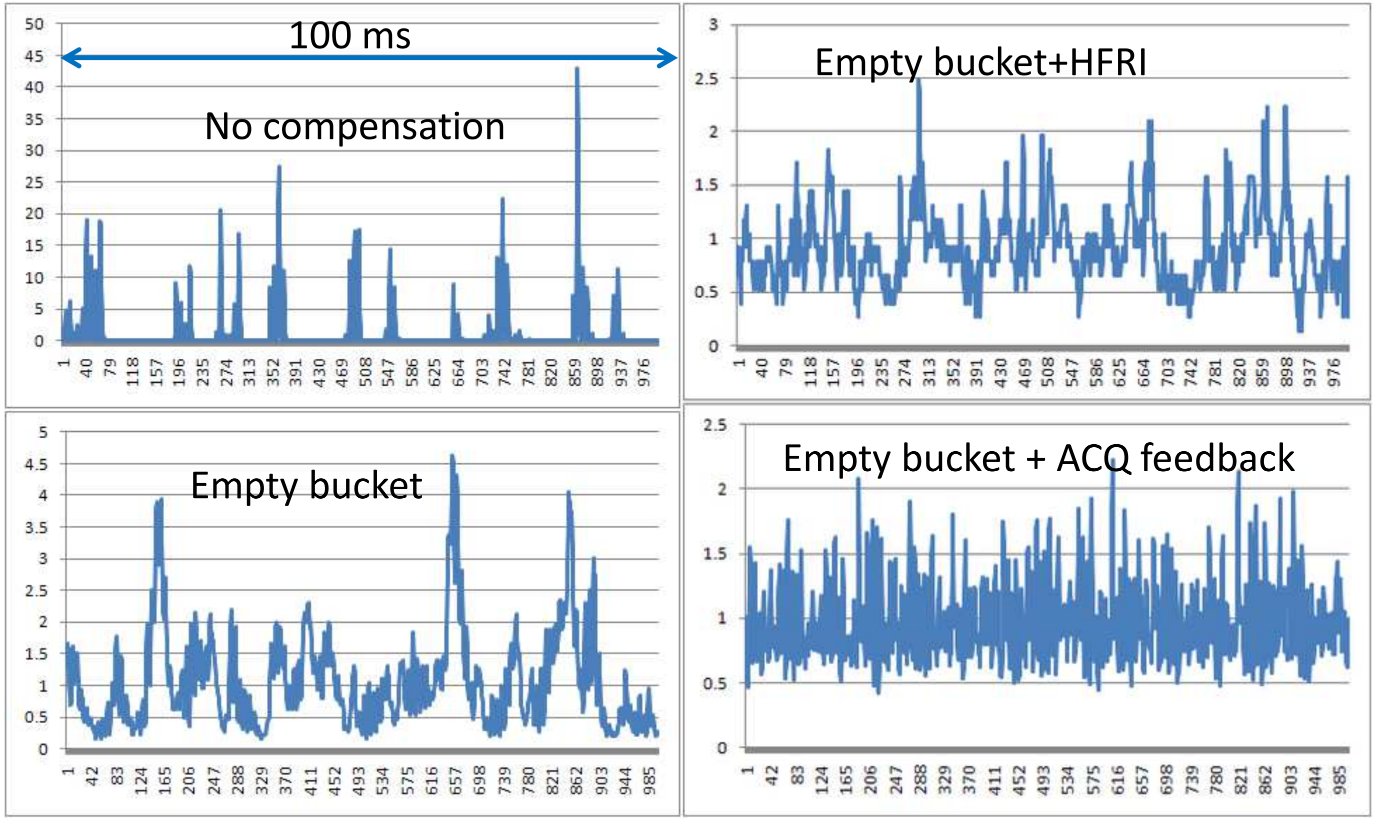




Signal from a scintillator
(qualification monitor in the HEBT)

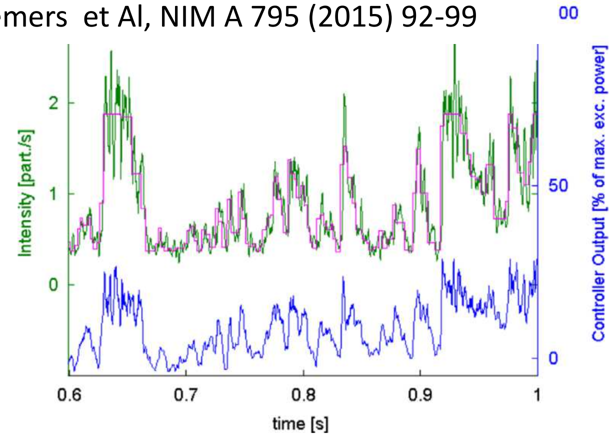
# Ripple compensation

Integration time 100 us (10 kHz data)

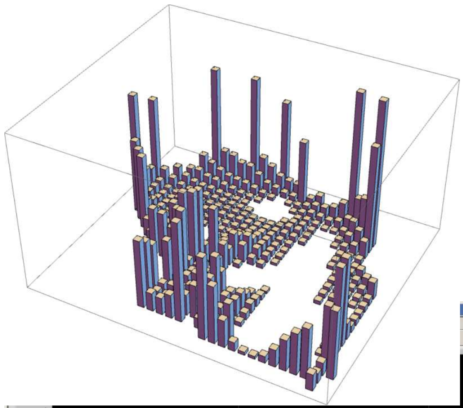


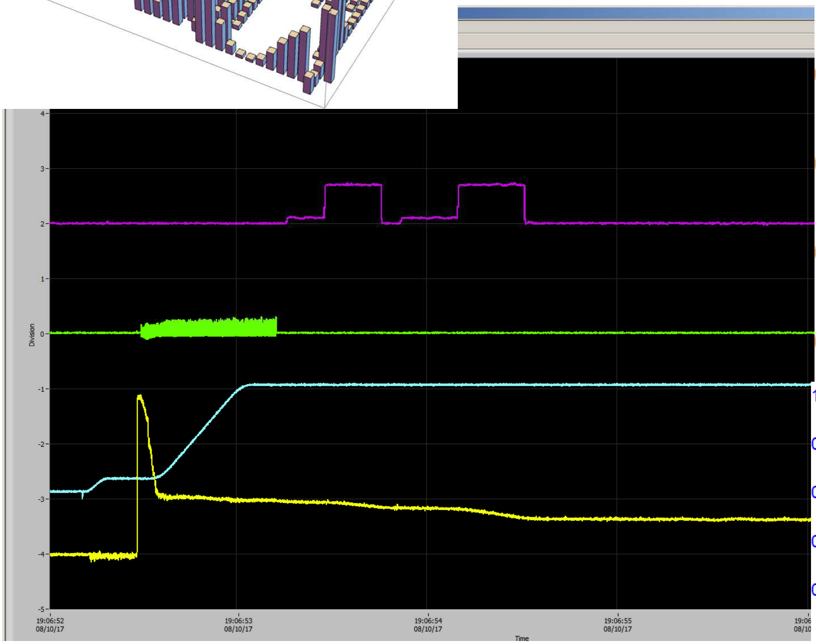
# Intensity modulation

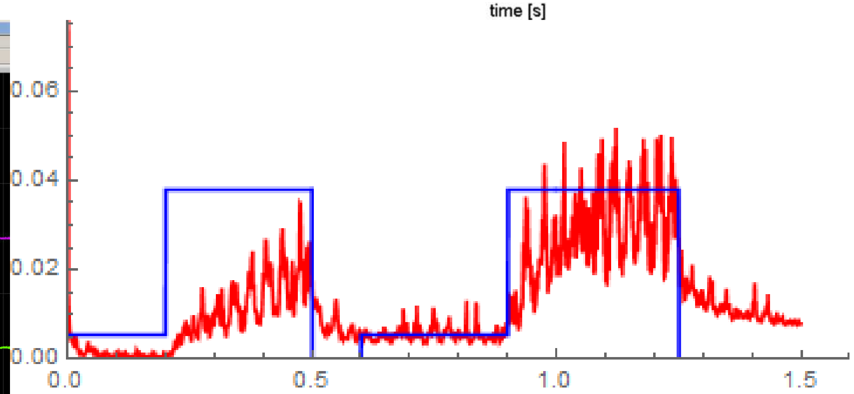
Schoemers et Al, NIM A 795 (2015) 92-99

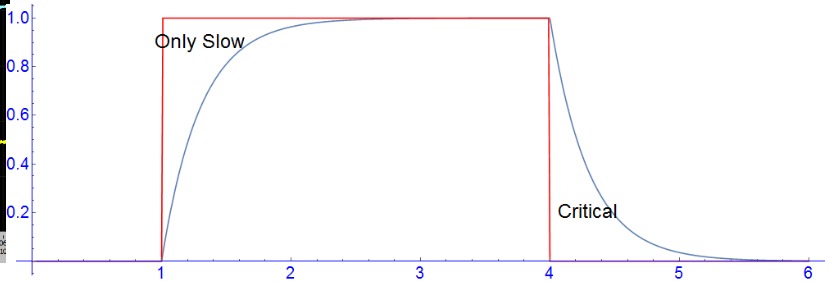



The number of required particles varies a lot in spots of the same slice. Adapt intensity to spot!

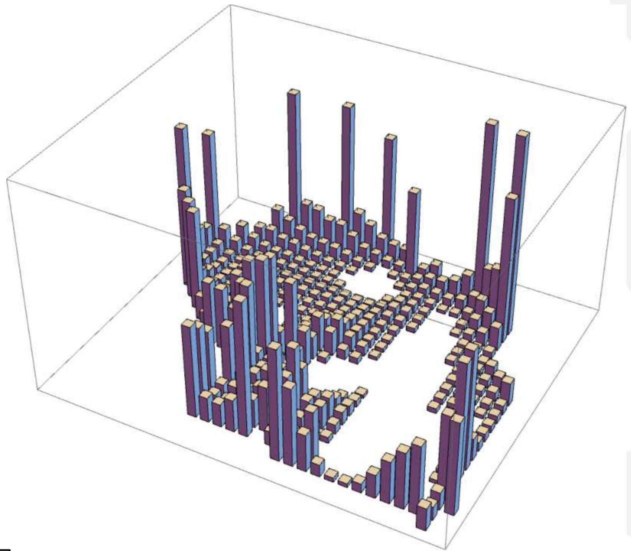




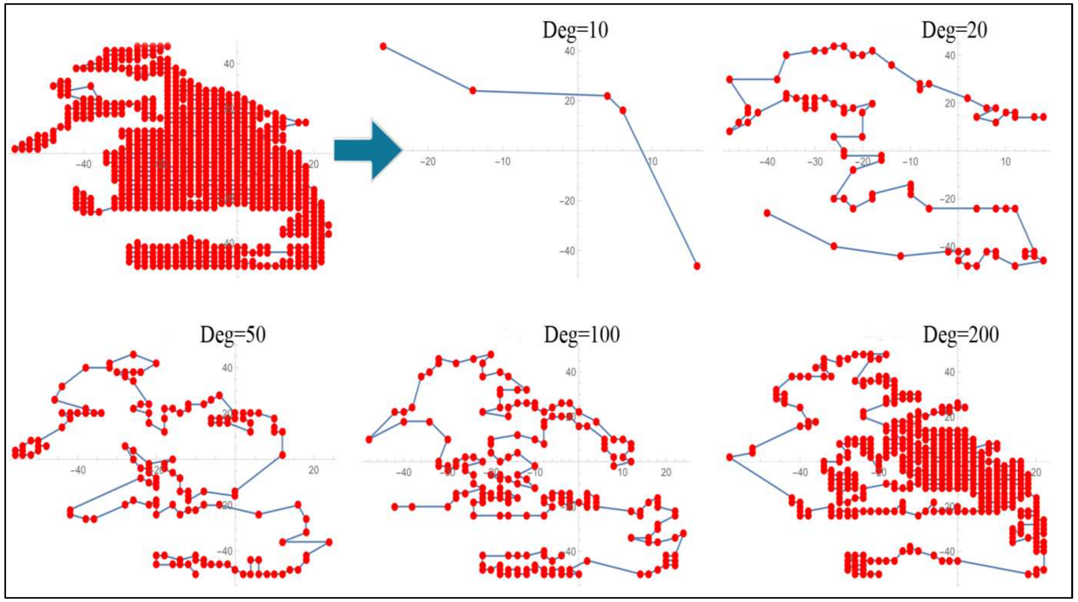


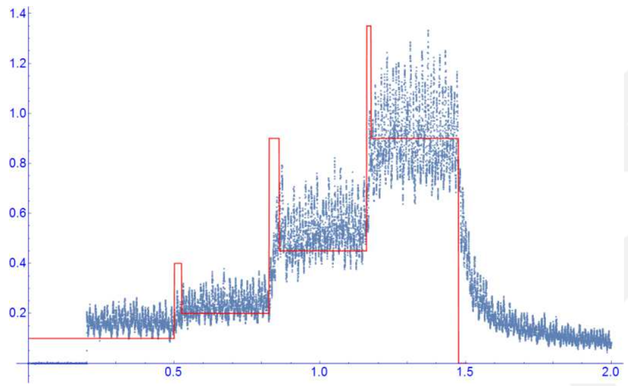



# Intensity modulation

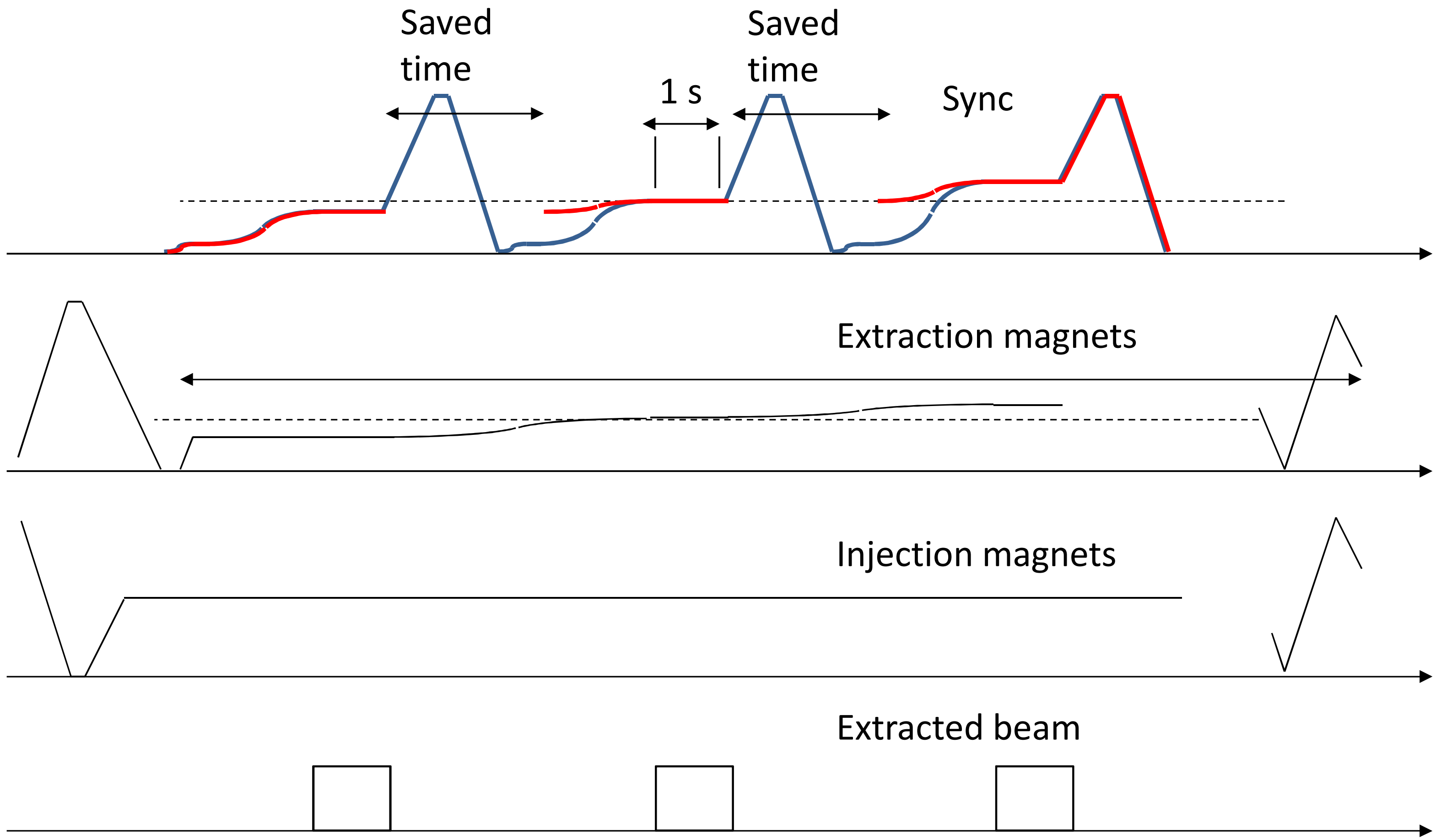


Subdivide slice in classes and re-sort in order to treat spots with increasing intensity.



# Multi Energy Extraction



# RFKO

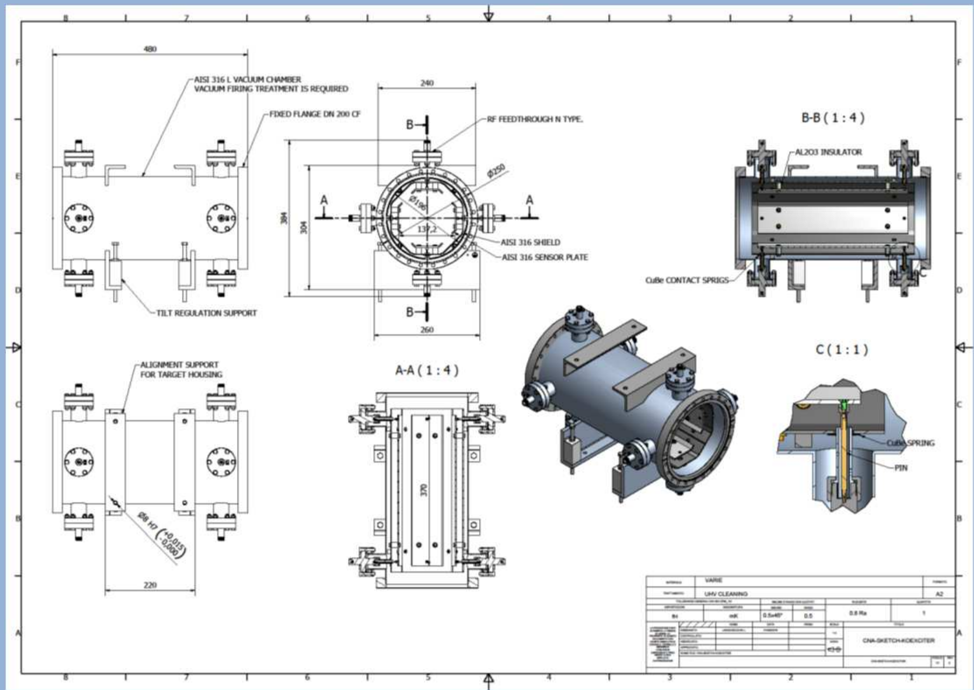
With RFKO the beam remains inside the bucket and it is easier and more natural to reaccelerate the remaining particles.

More suitable for multi energy extraction

# RFKO

A RF kicker has been installed in the ring

Kicker

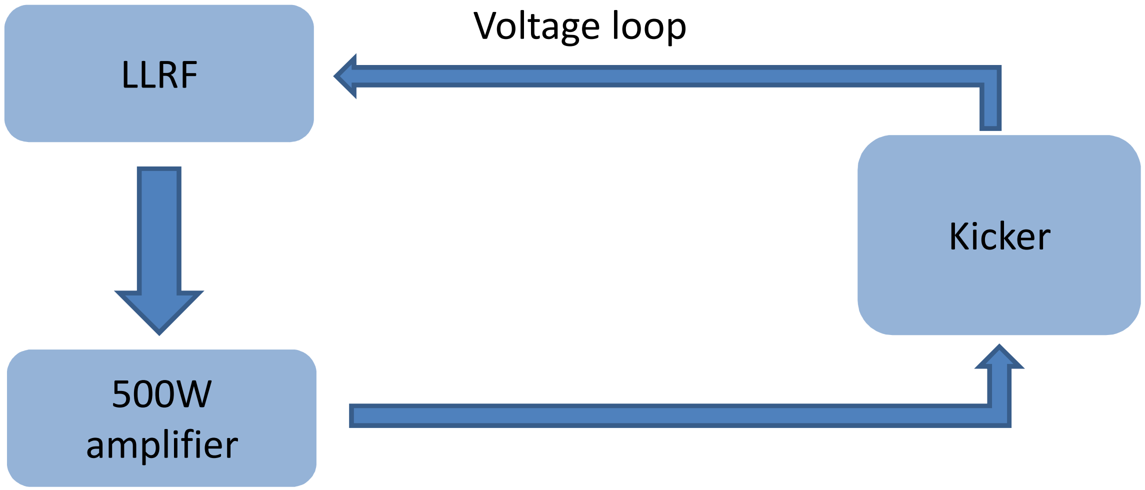



Kick with 500 W:

$$\begin{cases} 2.52\mu rad\!:\ 320mm\ proton \\ 0.79\mu rad\ :\ 270mm\ carbon \end{cases}$$

# RFKO

The system used at the beginning was simply the kicker fed by 500 W amplifier controlled by a spare of the RF cavity LLRF with upgraded firmwares and softwares.



# Synchrotron optimization for RFKO

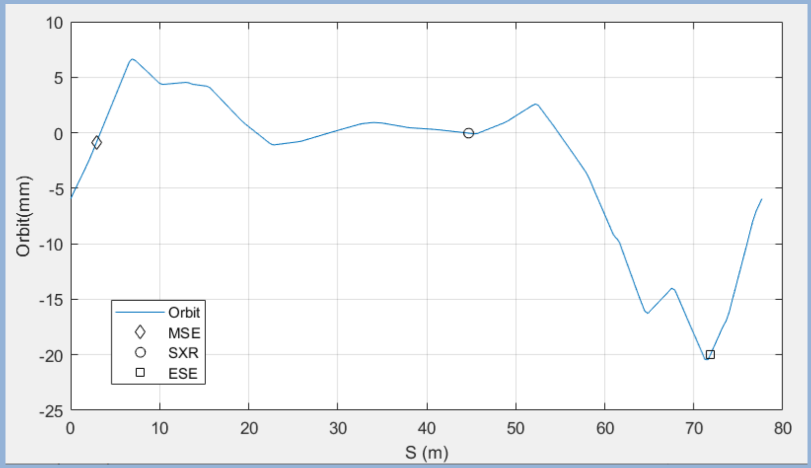
The passage from betatron to RFKO needed many optimizations:

- horizontal chromaticity (finally we choosed -1)
- average momentum spread (finally we choosed -7E-4)
- orbit corrections in particular adjusting position and angle at ESE
- horizontal tune
- RF cavity voltage reduction in order to reduce beam momentum spread

# Machine parameters: bump at ESE

Using all horizontal correctors is possible to create a bump in beam's orbit

The bump is defined by three parameters:
- Beam position at ESE
- Beam divergence at ESE
- Beam position at MSE

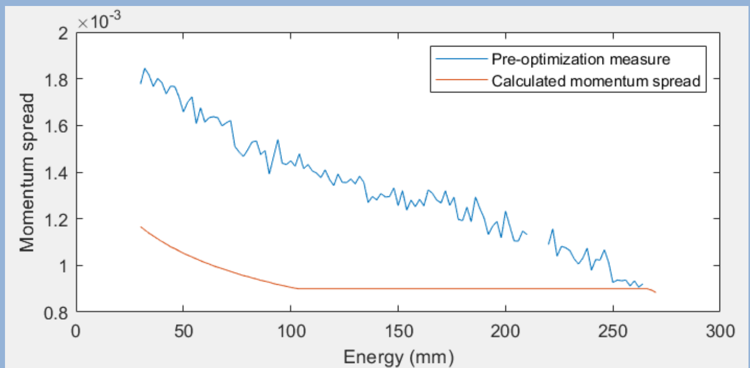


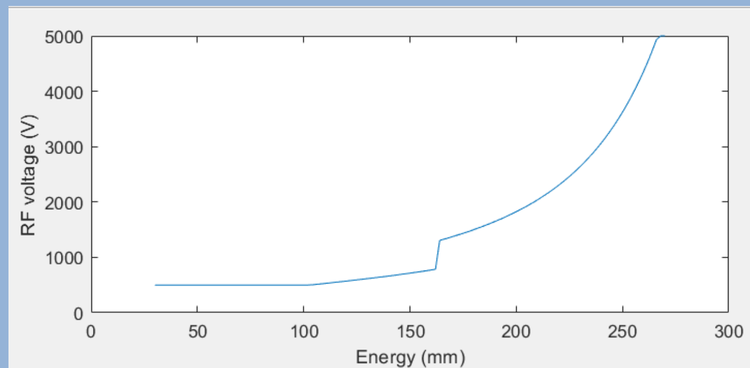

The best configuration to increase extraction efficiency results $(-20mm, 2mrad, 0mm)$

# Machine parameters: RF Voltage

To reduce beam momentum spread we reduce the RF cavity voltage after acceleration

At low energies the voltage requested was 200-300V, too low to confine the beam into the bucket. We set a limit of 500V.



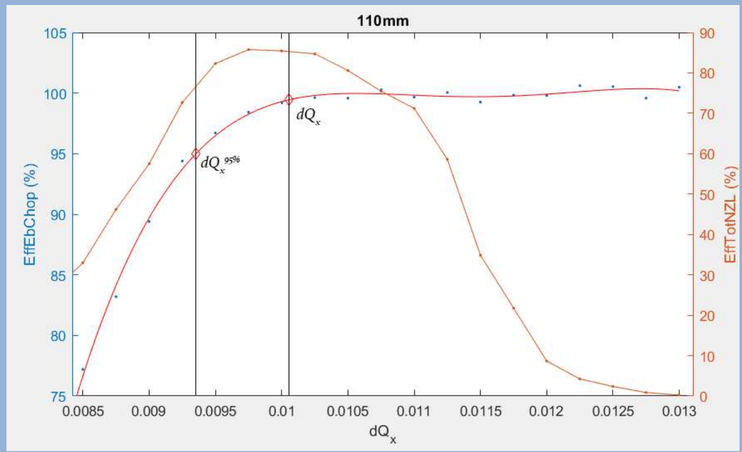



# Machine parameters: tune

Beam *tune* has been chosen properly to reduce particle losses due to resonance sextupole

We performed scans on beam *tune* to optimize:

$$Eff_{EbChop} = \frac{charge\ at\ start\ extraction}{charge\ at\ end\ acceleration}$$



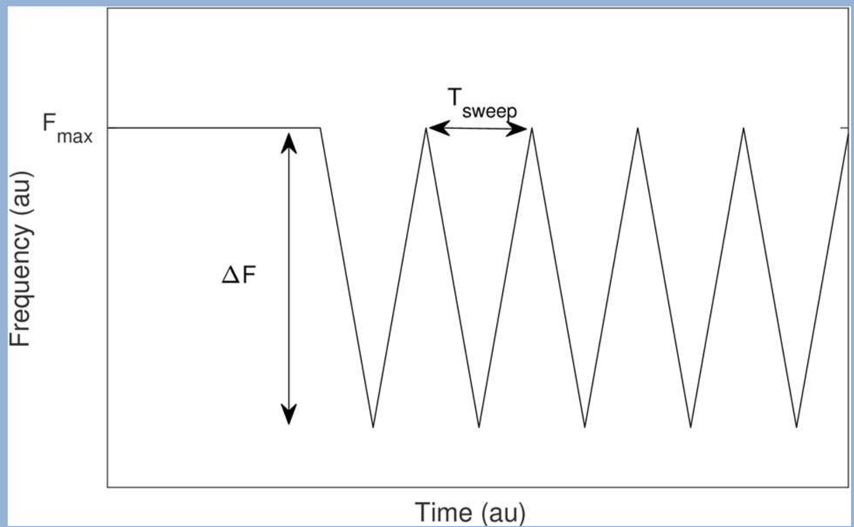

$$dQ_x = dQ_x^{95\%} + \delta Q$$

With $\delta Q$ depending on energy

# RFKO parameters

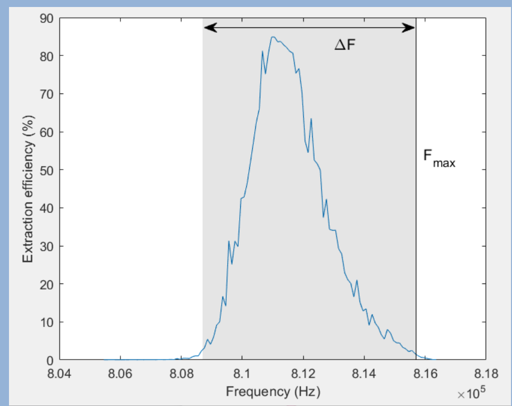
The signal used by RFKO is a single tone RF signal at harmonic number 0.
FM modulation and AM modulation are perfomed to extract a uniform spill

# RFKO parameters – FM modulation




Scan on RFKO frequency (0.8 µrad constant kick)

$F_{max}, \Delta F$ from efficiency curves




$T_{sweep} = 1ms$

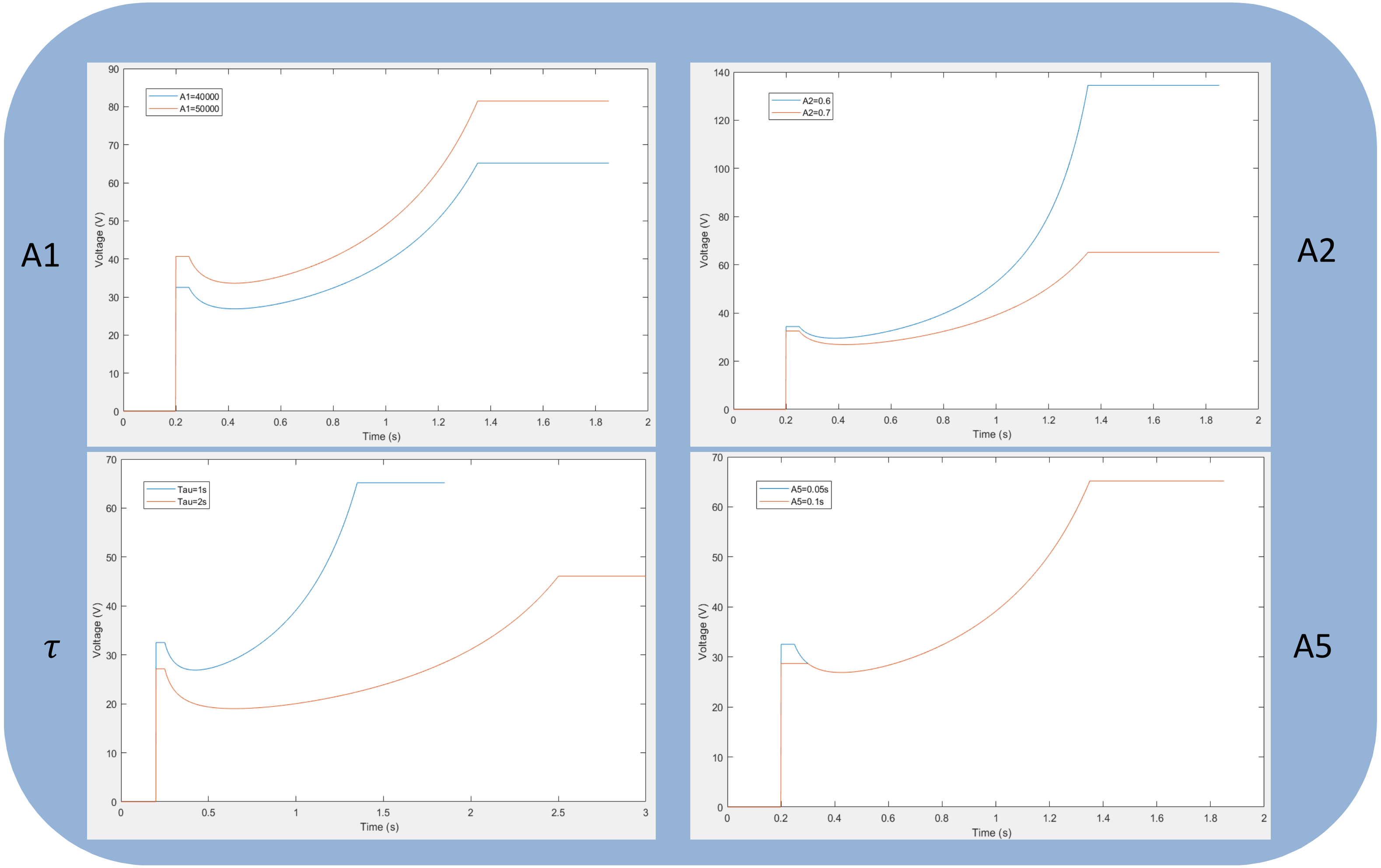
# RFKO parameters – AM modulation

We took as model voltage ramp presented in
T. Furukawa et al. "Global spill control in RF-knockout slow-extraction“

i.e. a 3 parameters dependent voltage ramp that allows to change the extracted intensity.

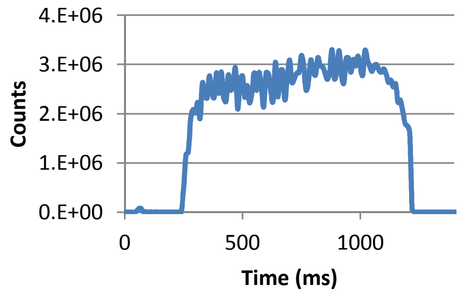
$$(t) = \begin{cases} 0, & t < T_{in} \\ -\dfrac{a_1}{\sqrt{f_{rev} a_5}[a_2 + \ln(1 - a_2) + \ln(\frac{a_5}{\tau})]}, & T_{in} \leq t < T_{in} + a_5 \\ -\dfrac{a_1}{\sqrt{f_{rev}(t - T_{in})}[a_2 + \ln(1 - a_2) + \ln(\frac{t - T_{in}}{\tau})]}, & T_{in} + a_5 \leq t < T_{fin} \\ -\dfrac{a_1}{\sqrt{f_{rev}(T_{fin} - T_{in})}[a_2 + \ln(1 - a_2) + \ln(\frac{T_{fin} - T_{in}}{\tau})]}, & t \geq T_{fin} \end{cases}$$

# RFKO parameters - Kicker voltage

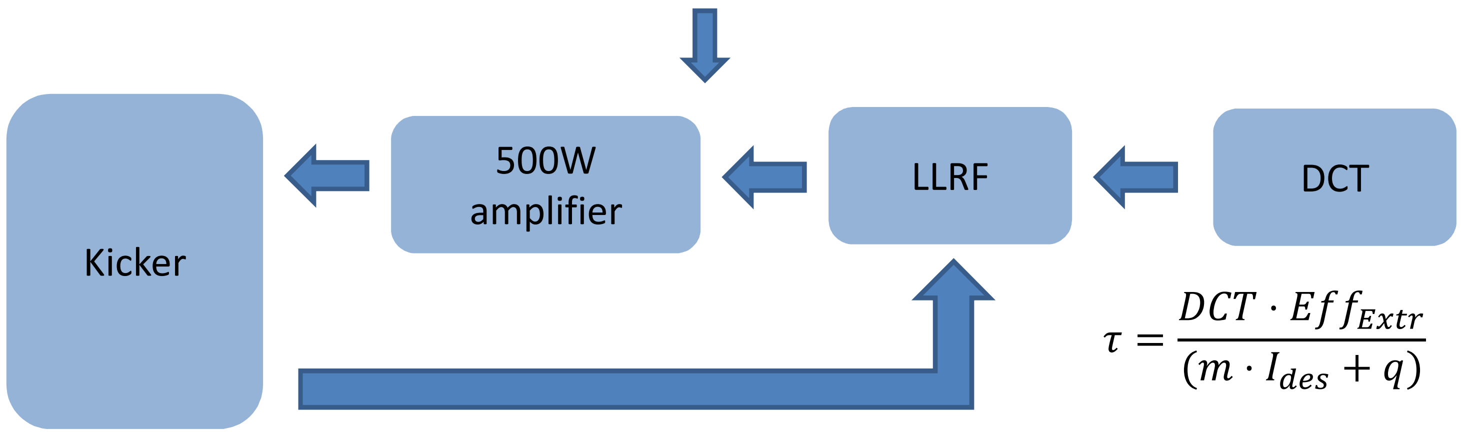


# RFKO parameters - Kicker voltage

A1, A2 and A5 optimized for each energy to have a uniform spill profile at 100 $Hz$



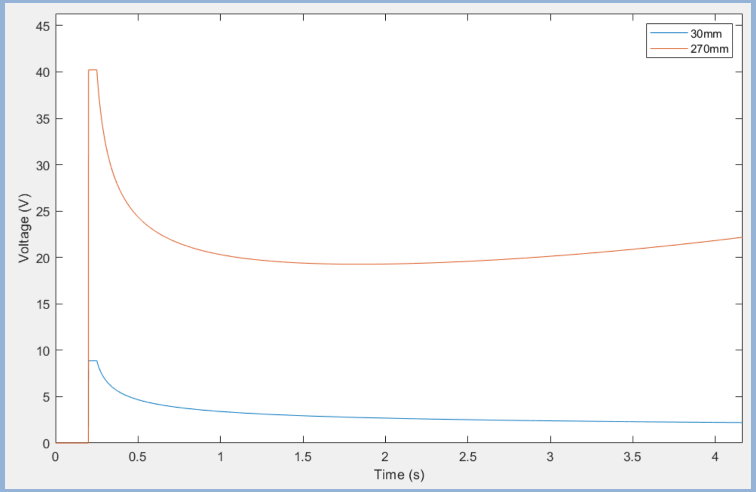

To have constant extraction intensity, $\tau$ is calculated for every extraction cycle using accelerated current (from DCT)



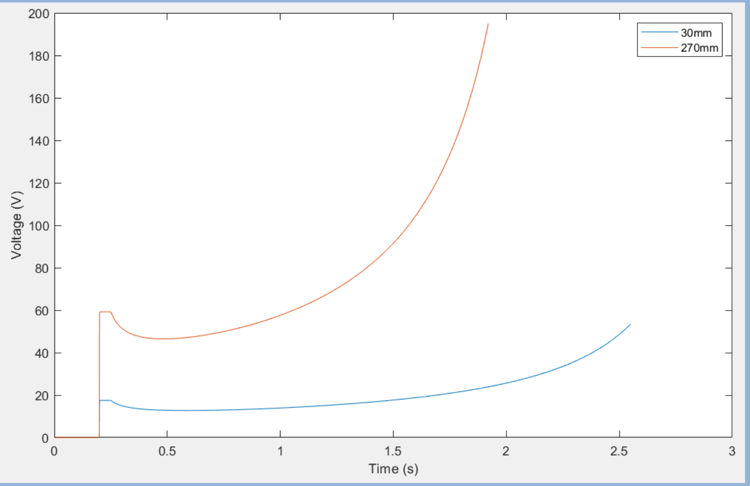

$$\tau = \frac{DCT \cdot Eff_{Extr}}{(m \cdot I_{des} + q)}$$

# RFKO parameters - Kicker voltage

RFKO voltage ramp for 30 and 270mm carbon ions at minimum beam intensity $(8 \times 10^6 part/s)$




RFKO voltage ramp for 30 and 270mm carbon ions at maximum beam intensity $(8 \times 10^7 part/s)$

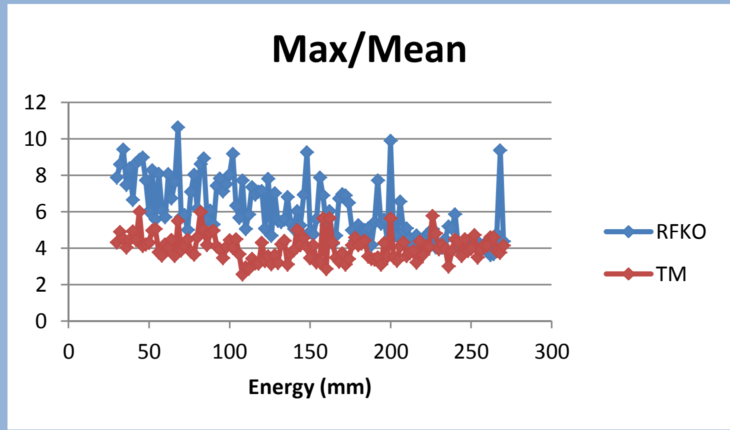


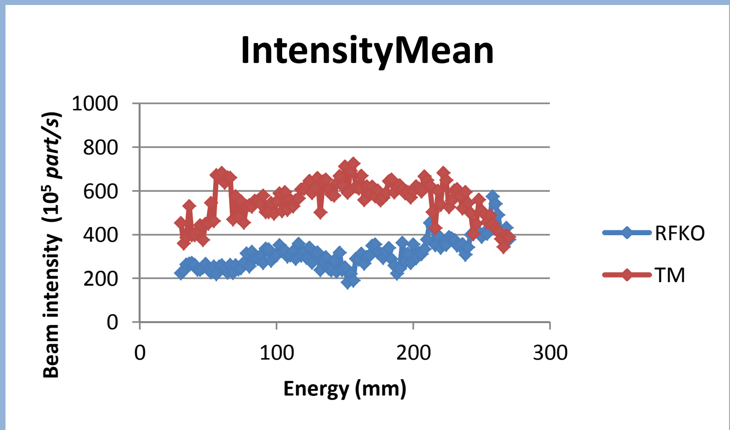
# Spill quality

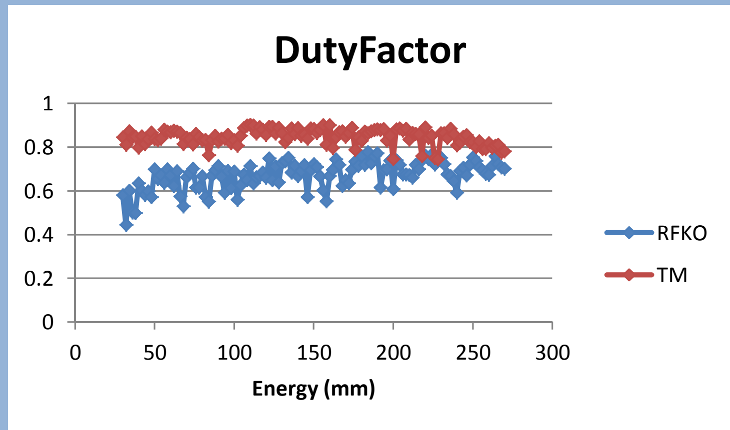
Comparison between RFKO and betatron core extraction methods.

Intensity requested: $4 \times 10^7 part/s$

Sample rate: $10\ kHz$



# Feedback implementation

In order to improve beam quality, two different feedback were implemented using the dose read by the Dose delivery system:

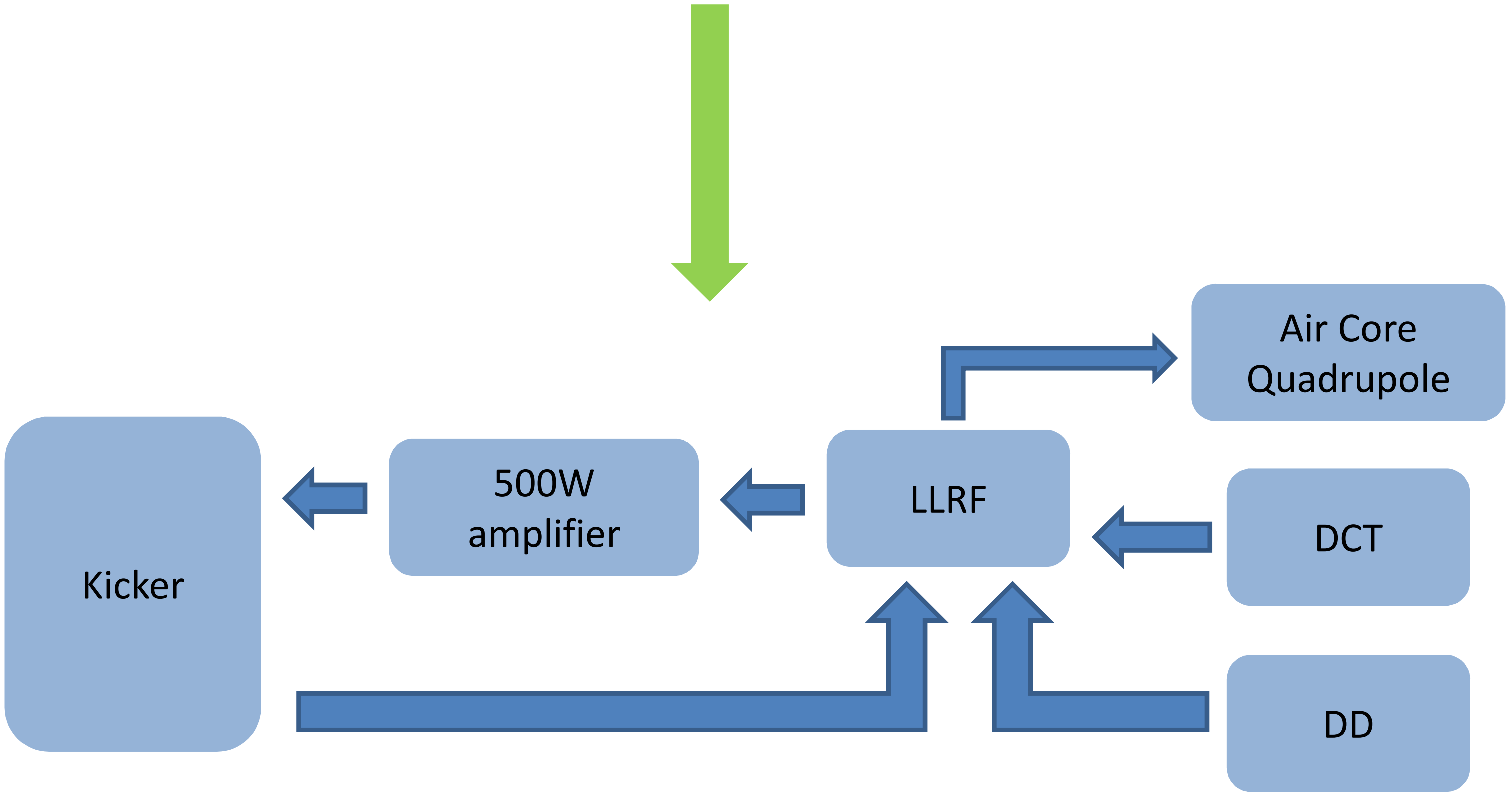
- Air Core Quadrupole feedback
- Voltage feedback

Voltage feedback is a PI feedback acting on RFKO voltage to have a uniform beam sampled **at 500 Hz**

Air core quadrupole feedback is an AC IIR feedback that acts **at 10 kHz** on the field of an air core quadrupole installed in the ring

# Layout of the system

Considering the two feedbacks, the final layout of the system is



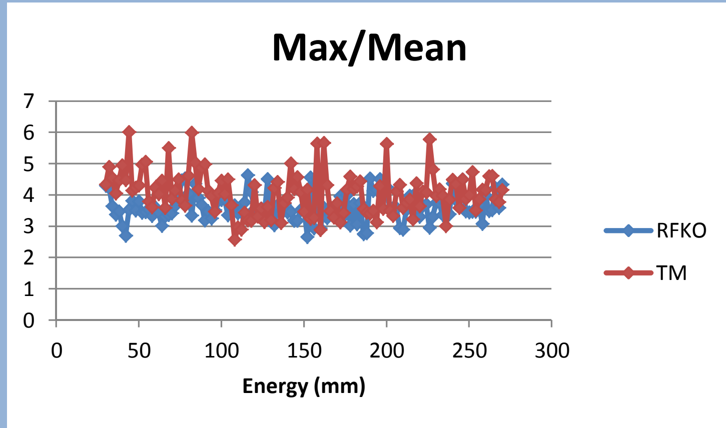
# Results with feedback

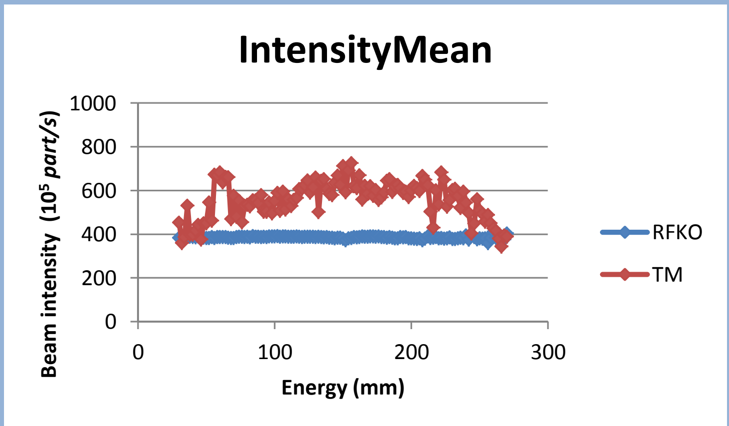
Comparison between RFKO and betatron core extraction methods.

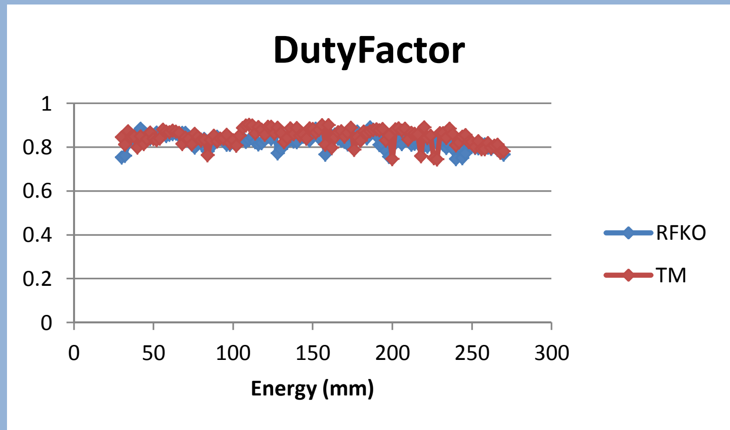
RFKO extraction with both Air Core Quadrupole and voltage feedback.

Intensity requested: $4 \times 10^7 part/s$

Sample rate: $10\ kHz$



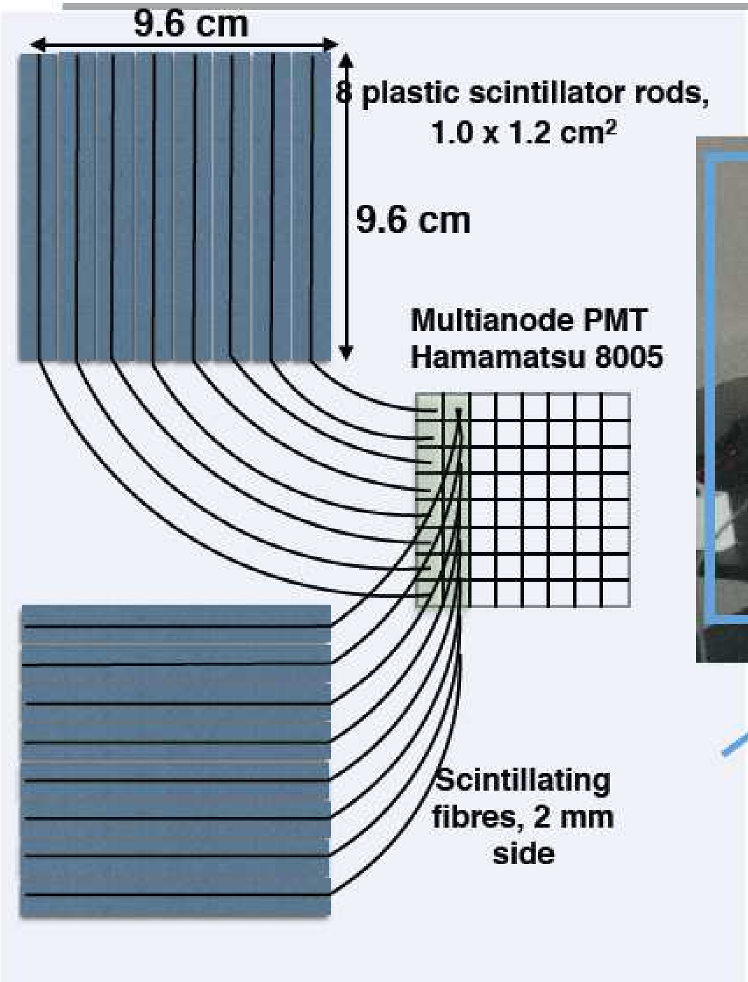



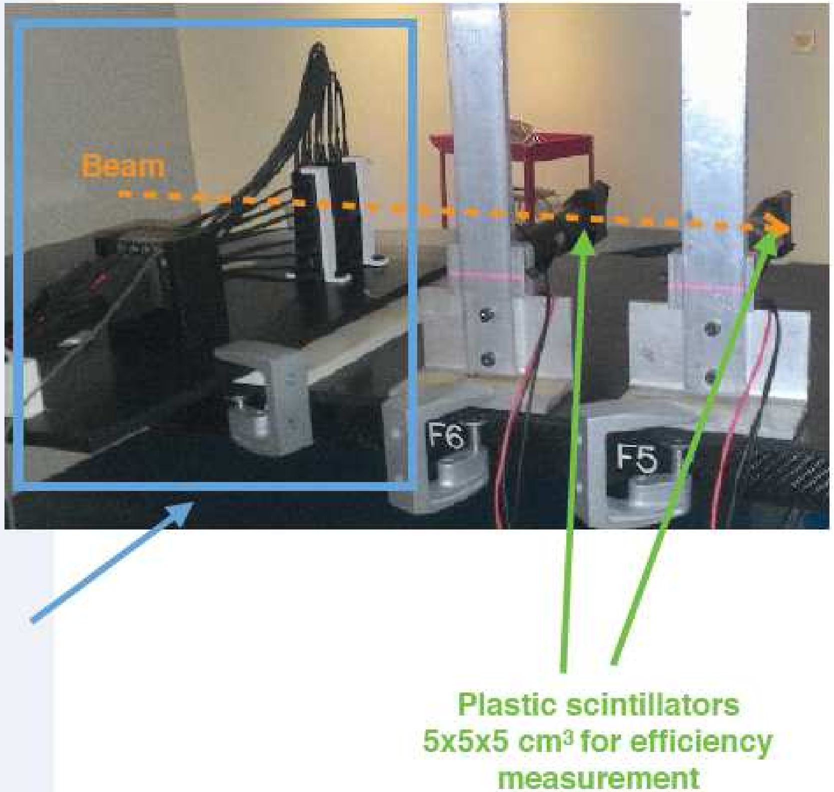
# Other extraction modalities

# Low intensities

- For some applications like detector tests, some nuclear physics experiments (see FOOT exp.) a very low intensity ($10^3$ - $10^4$ particles/s) is required
- Such low intensities are out of the measurement range of the DDS
- In general feedback is provided by the user (by voice)
- A dedicated detector, capable to count the incoming ions and to monitor the beam position in the x-y plane, was provided by the Foot group (INFN - Roma - SBAI)

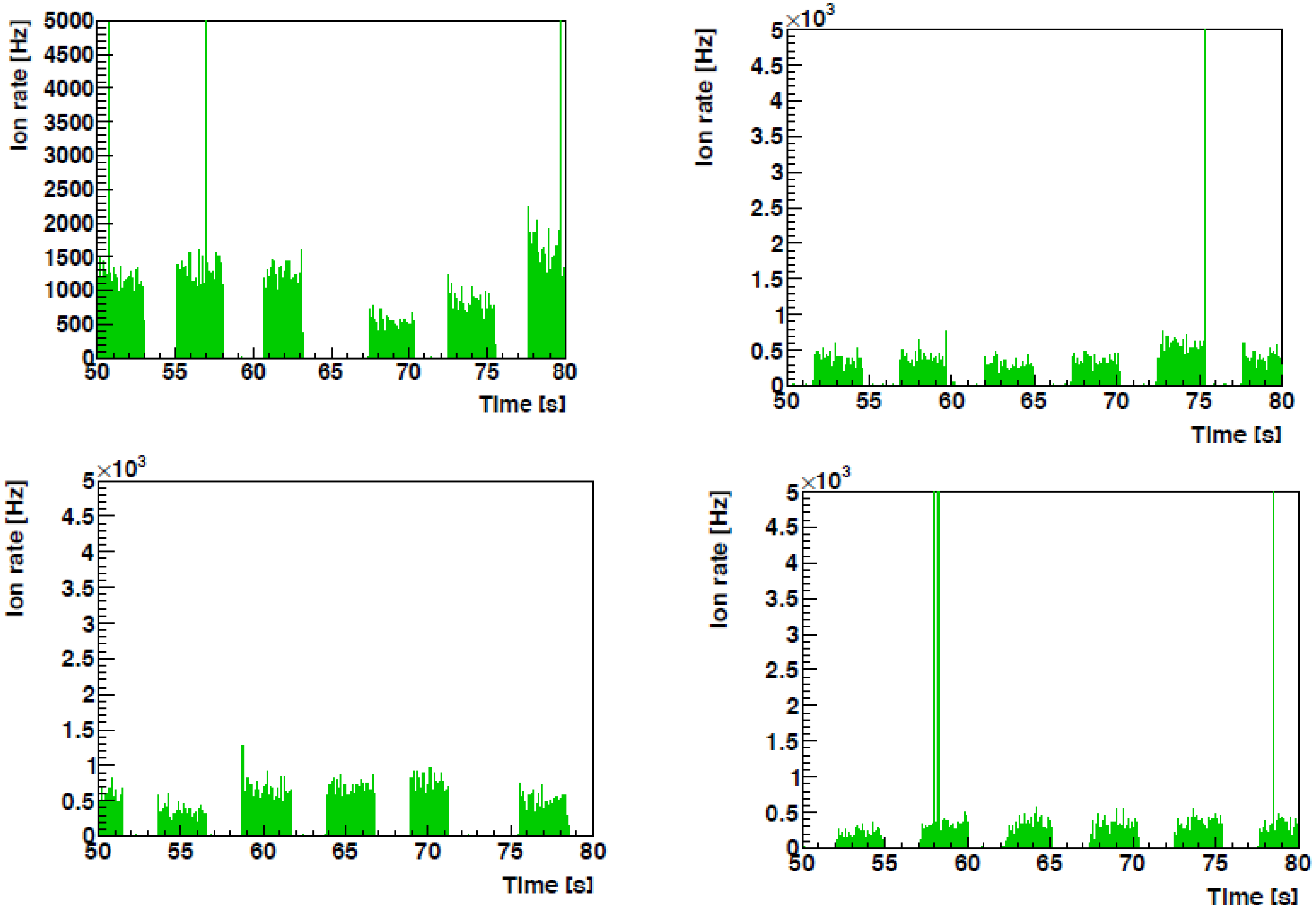
# Experimental setup




(Courtesy of Giacomo Traini)

# Proton beam - Intensities vs time

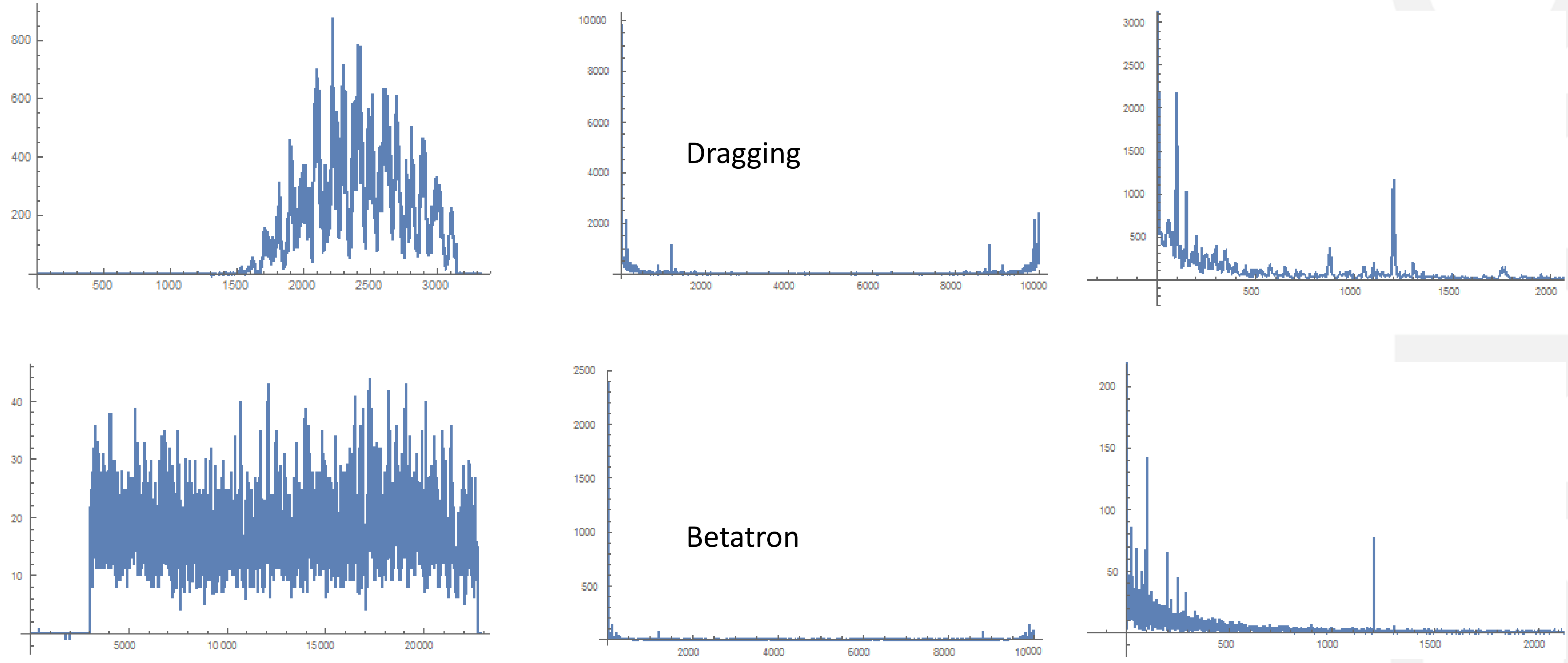



(Courtesy of Giacomo Traini)

The low intensity beam is obtained by turning the betatron off, placing a small empty bucket (a few 100s V) with a small sweep (100 Hz) and placing the beam away from the resonance.

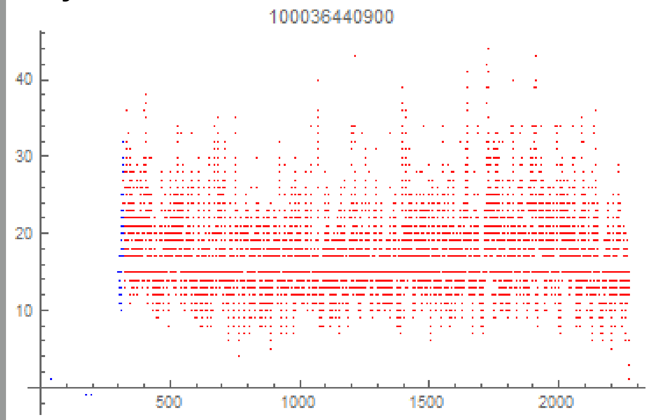
# Dragging the beam into the resonance with RF

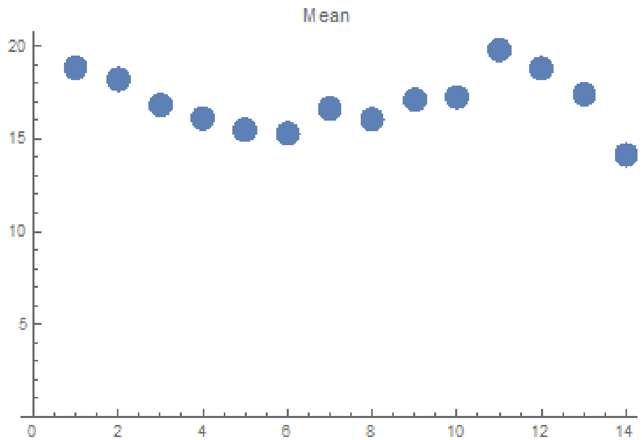
An orbit bump can be programmed in the LLRF to bring the beam into the unstable region

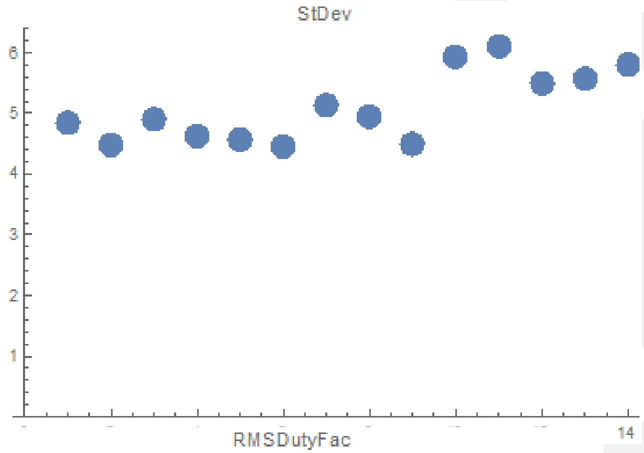


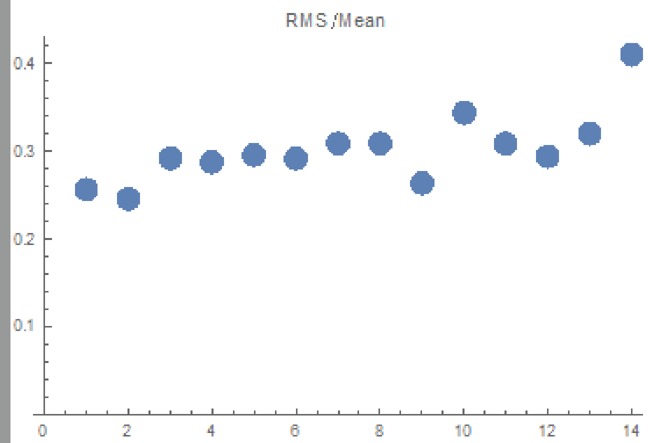
# Betatron

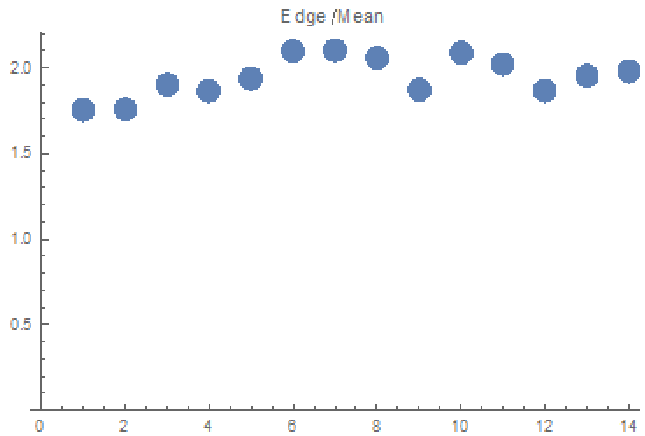
CyPr 178820552

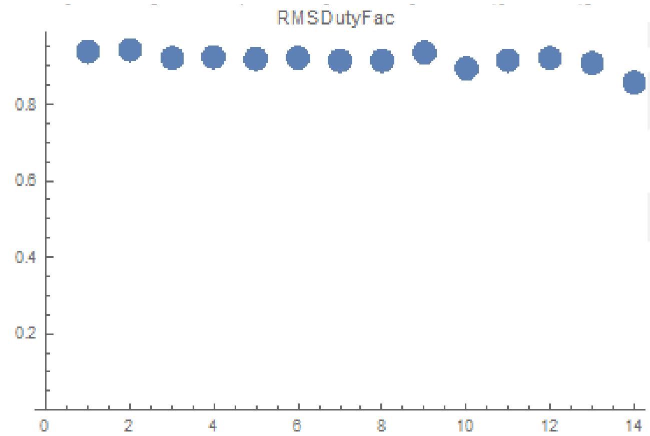


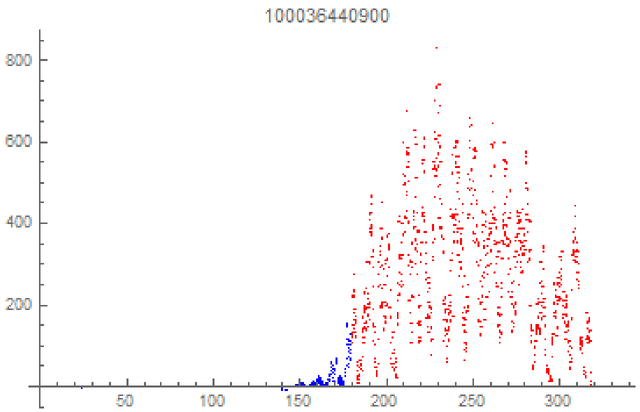



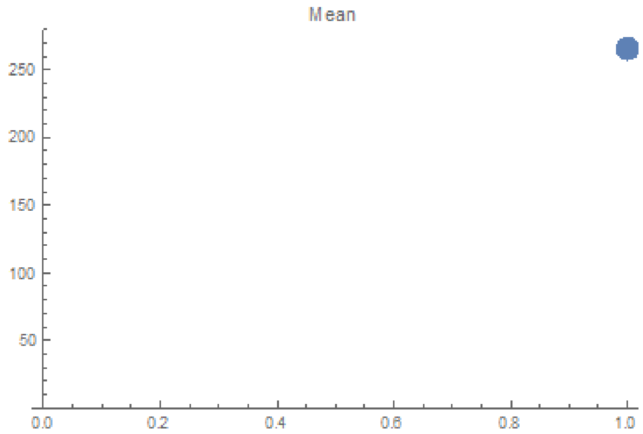



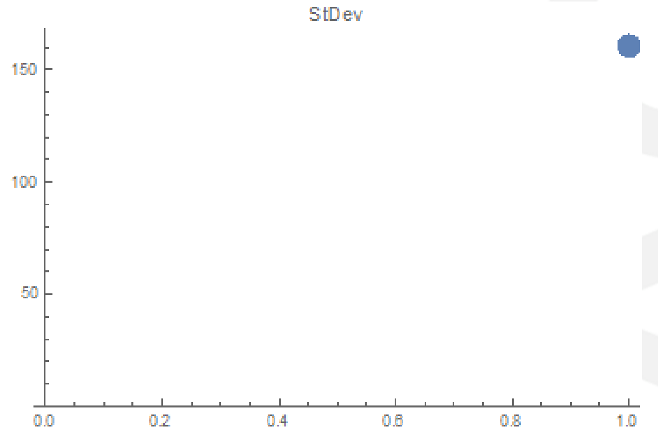



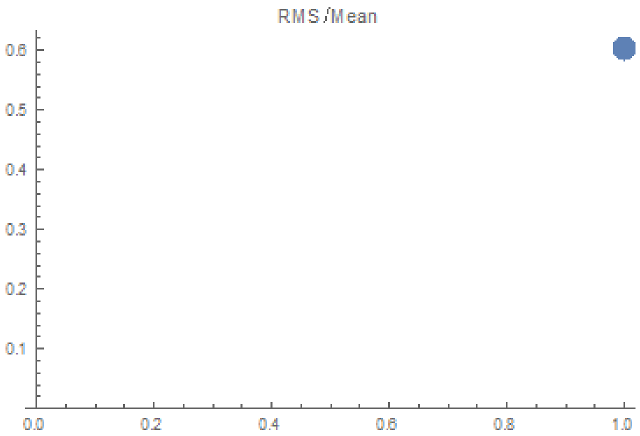
# Dragging

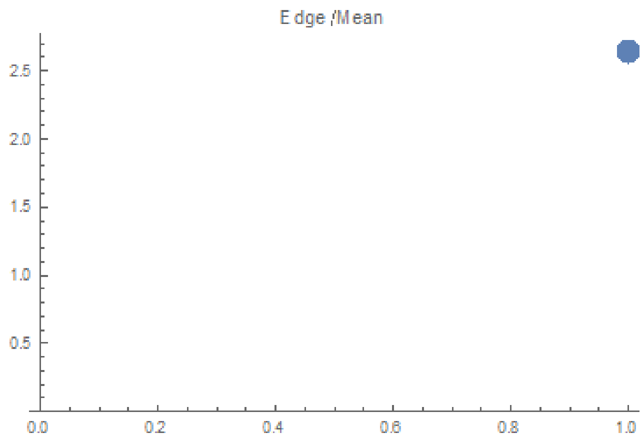
CyPr 178820691

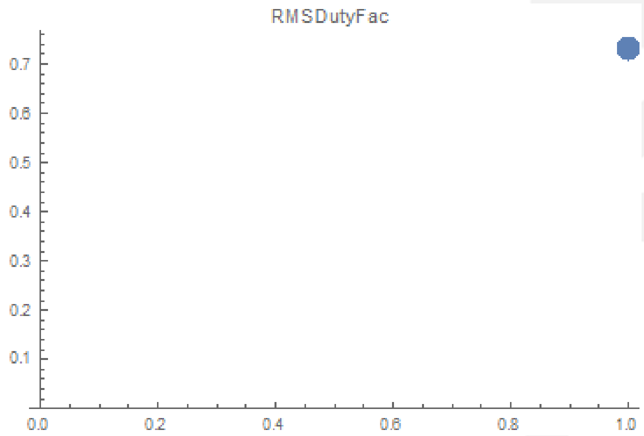


# Conclusions

Betatron core is still the main extraction modality

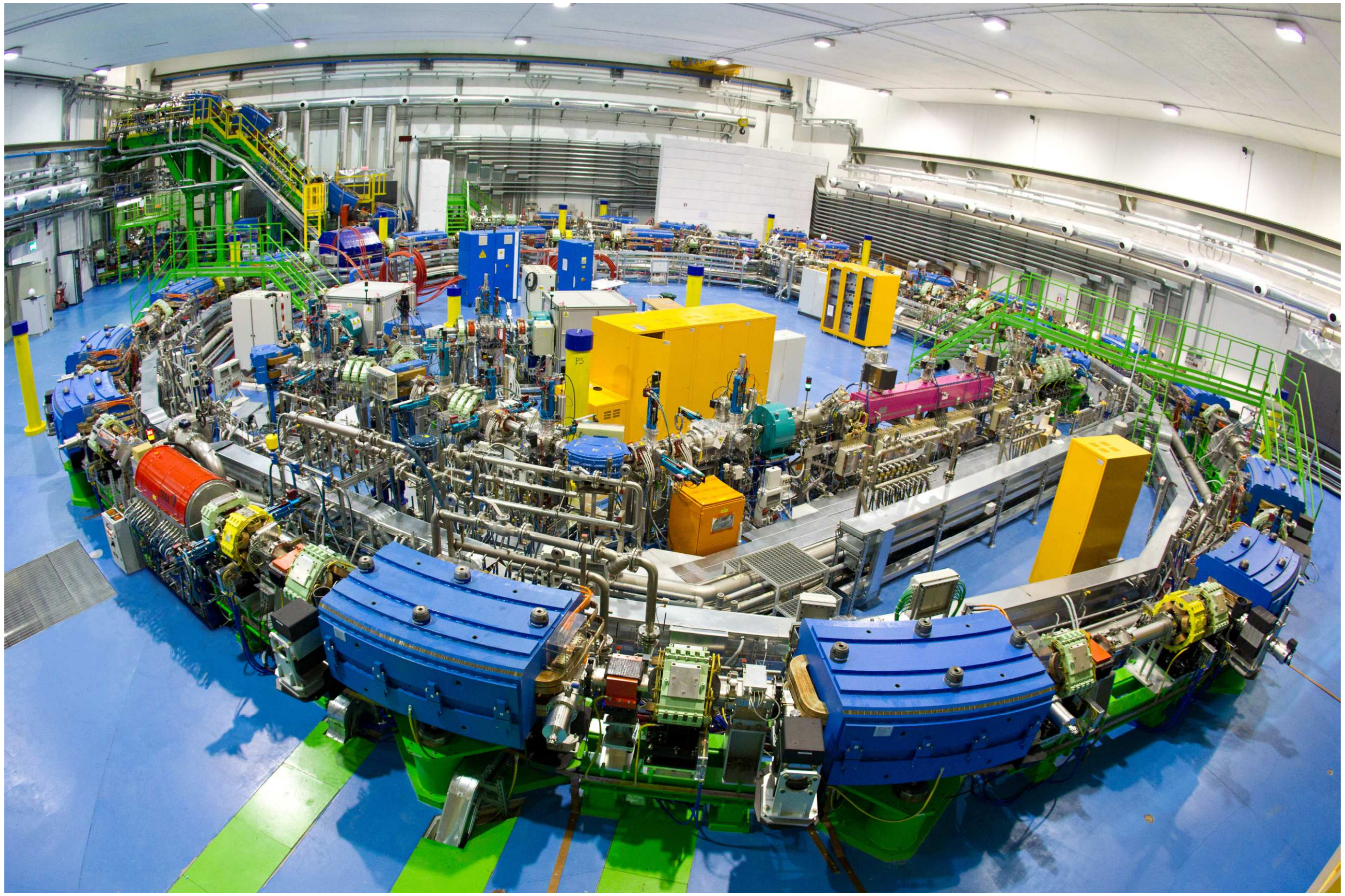
RFKO is being implemented and is now working well

Many different schemes can be put in operation to control spill quality including empty bucket channelling, HFRI, feedback

Beam reacceleration (Multi Energy Extraction) will be implemented in the next future

Very low intensities are possible

# Thank you for your attention



Physics is like sex: sure, it may give some practical results, but that's not why we do it.
R. Feynman