Status and Progress in PIMMS-Family Machines

M. Pullia
on behalf of CNAO and MedAustron accelerator groups

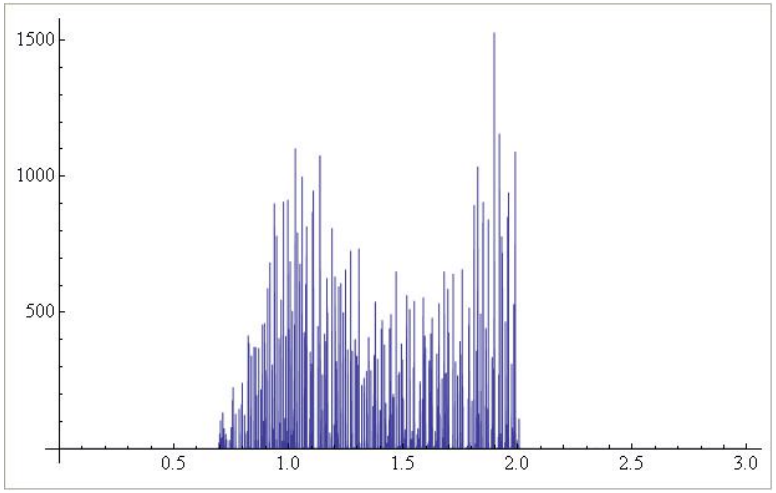
Slow extraction workshop 2019 – Fermilab July 22-24, 2019

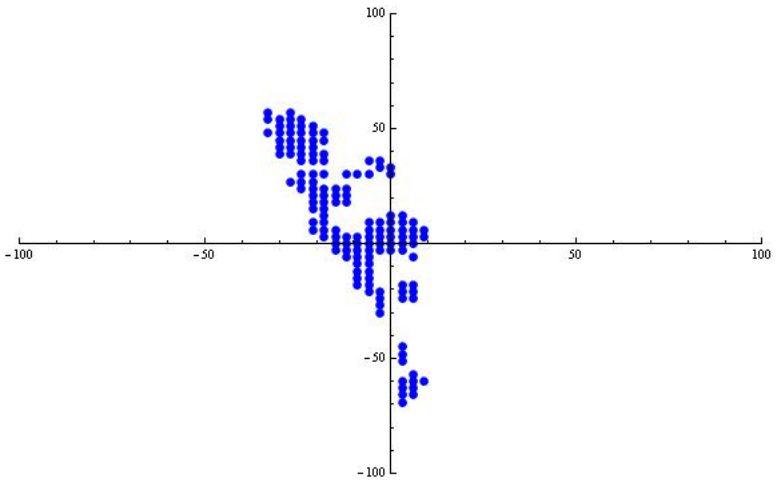
fondazione CNAO
Centro Nazionale di Adroterapia Oncologica

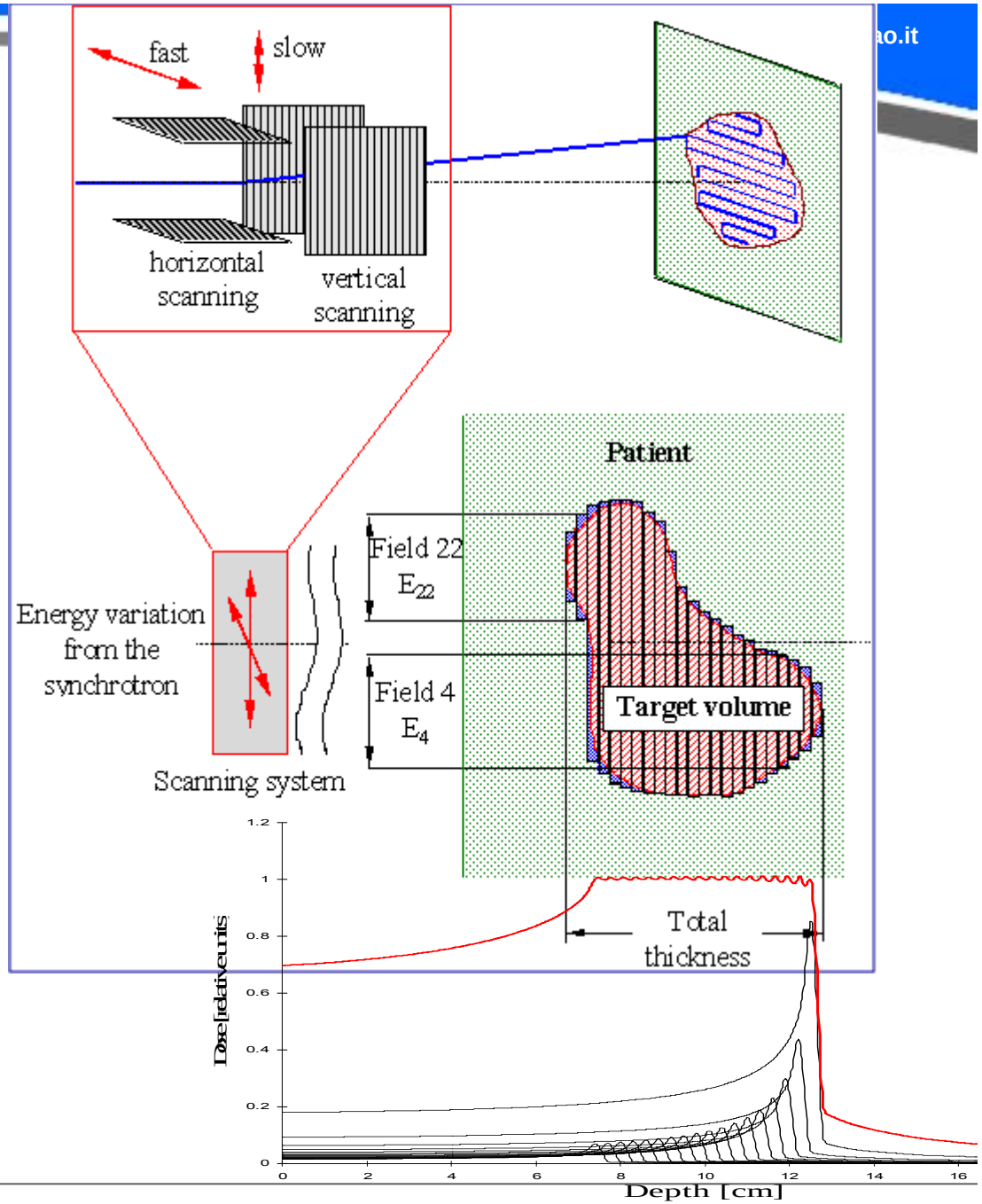
PIMMS

- **Study hosted at CERN, 1995-1999**
- **The Proton-Ion Medical Machine Study (PIMMS) was set up following an agreement between Med-AUSTRON (Austria) and the TERA Foundation (Italy) to join their resources in the design of a medical synchrotron that could later be adapted to individual national needs. CERN agreed to host this collaboration inside its PS Division and to contribute to the study. The group has worked in collaboration with GSI (Germany) and was later joined by Onkologie 2000 (Czech Republic).**
- **Designed keeping in mind that the facility would be operated in a hospital environment**

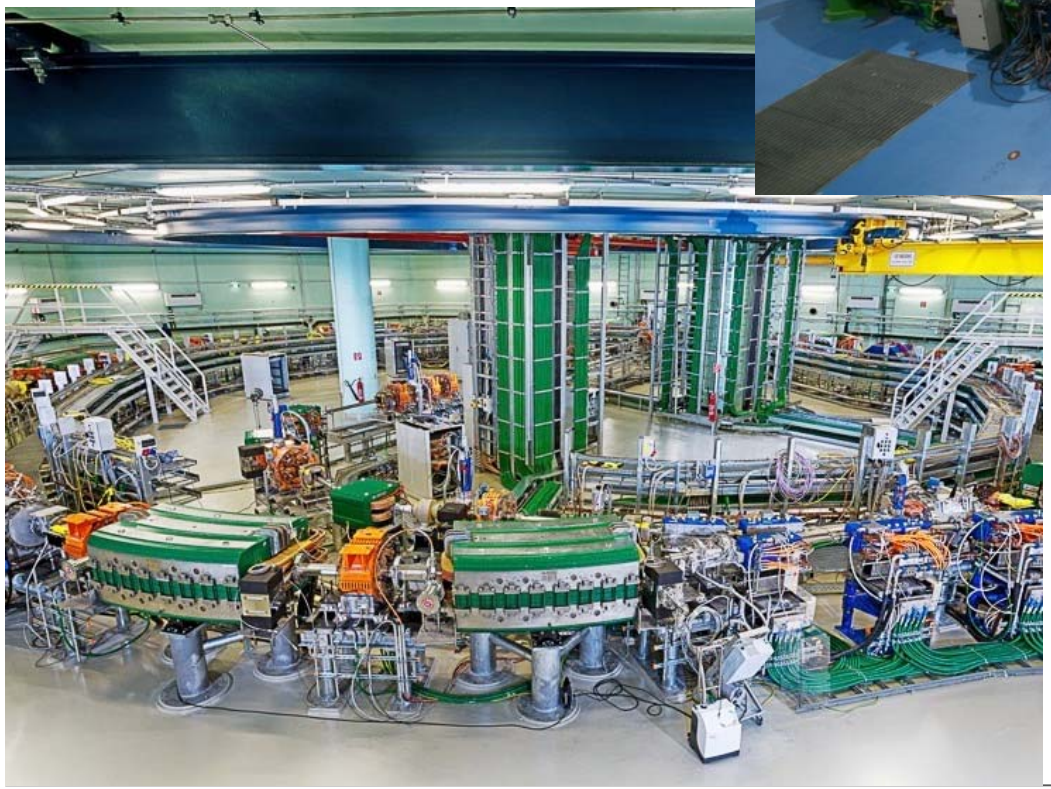
Active systems





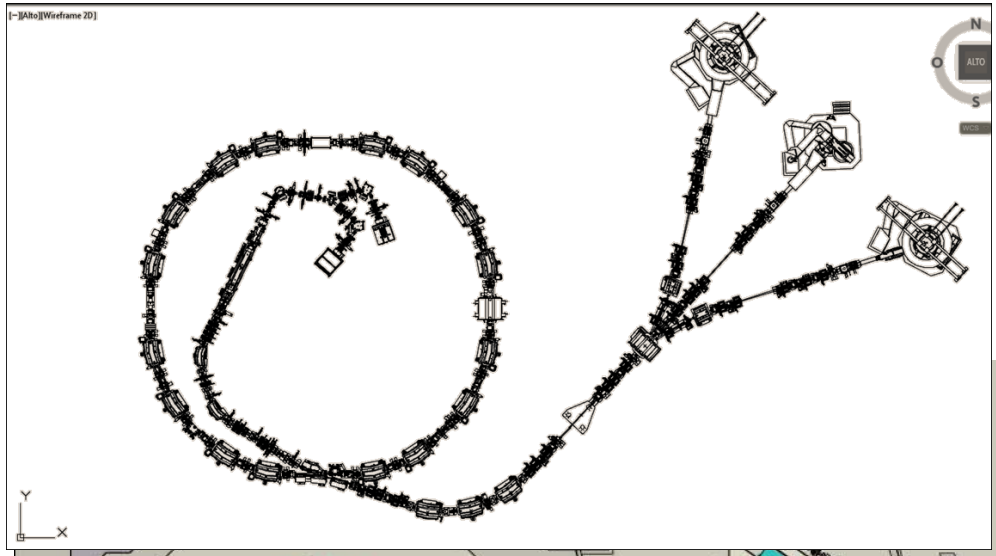


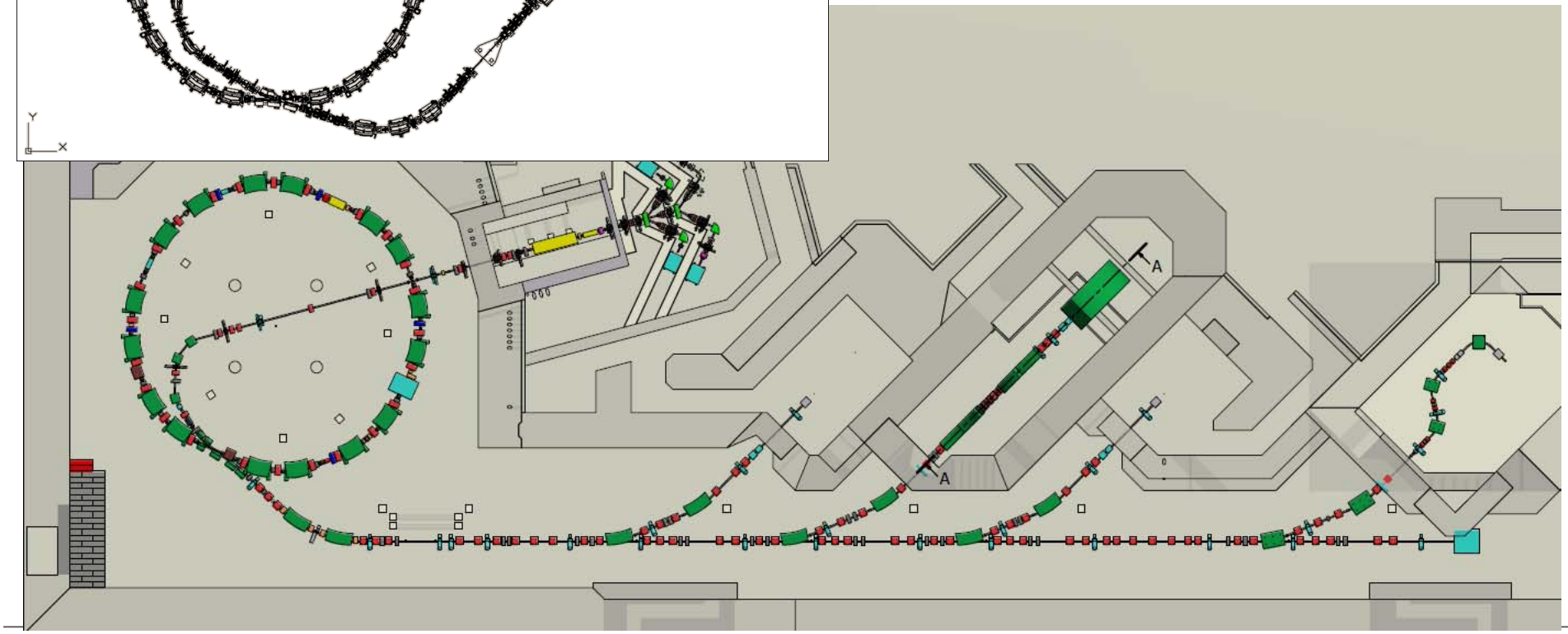
CNAO and MedAustron



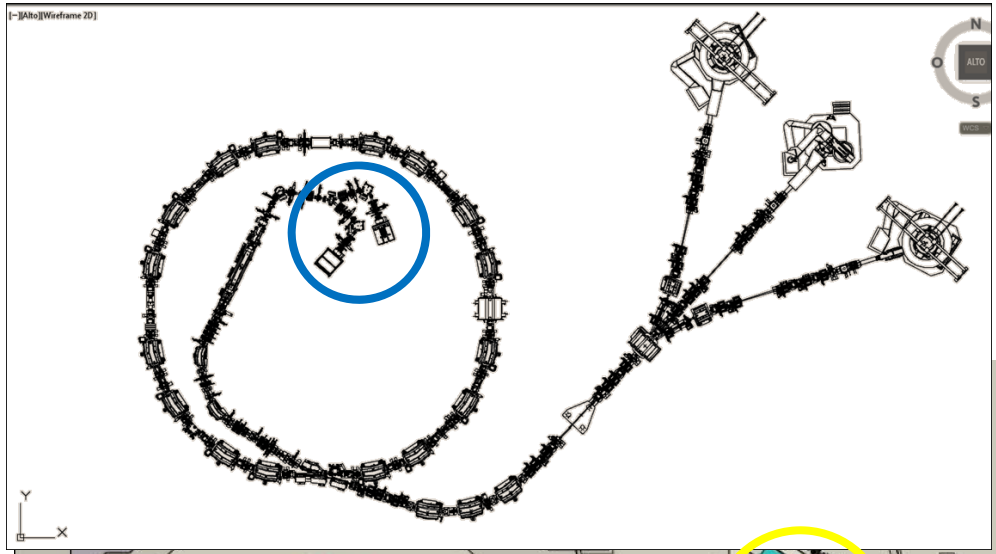
Treatments started in 2011 and 2017 respectively

CNAO and MedAustron: 2 implementations of PIMMS



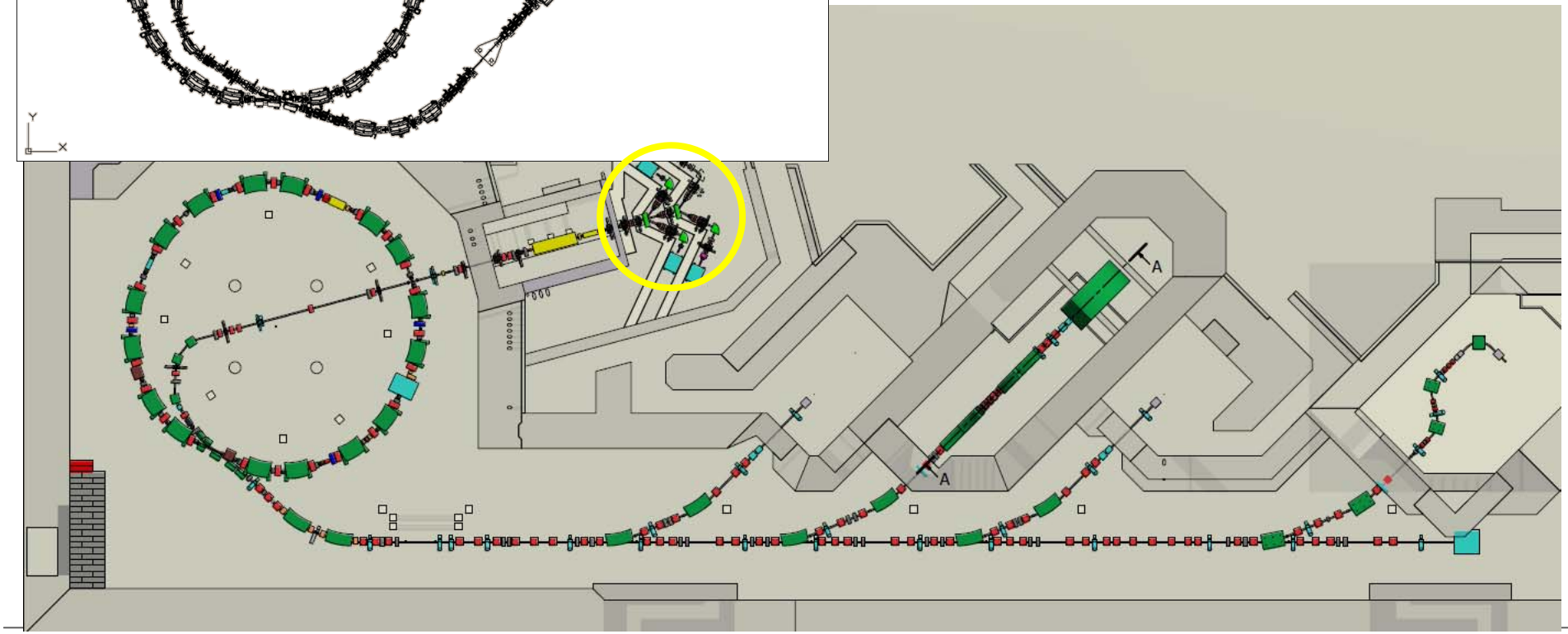


Sources

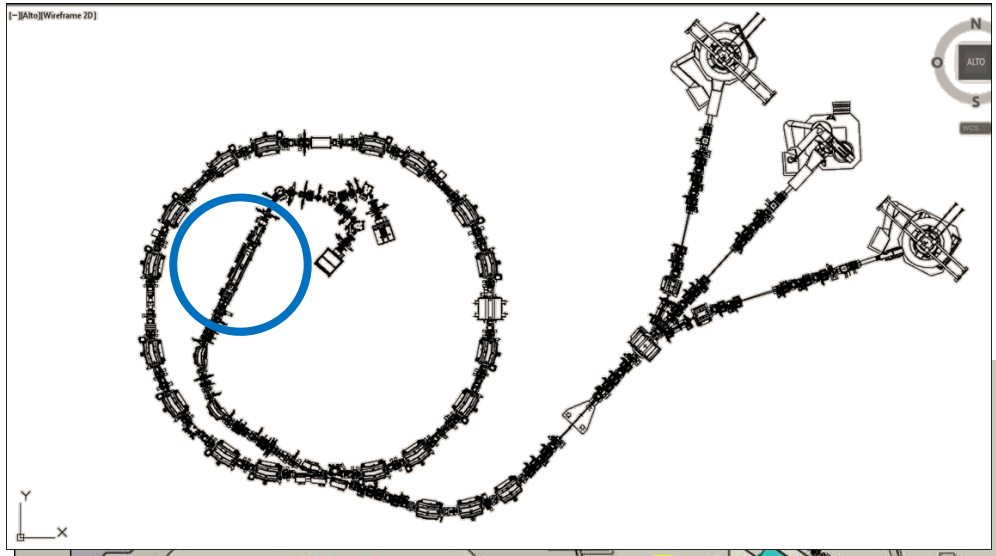


2 (3) Supernanogan ECR sources for fast particle change and stable Operation

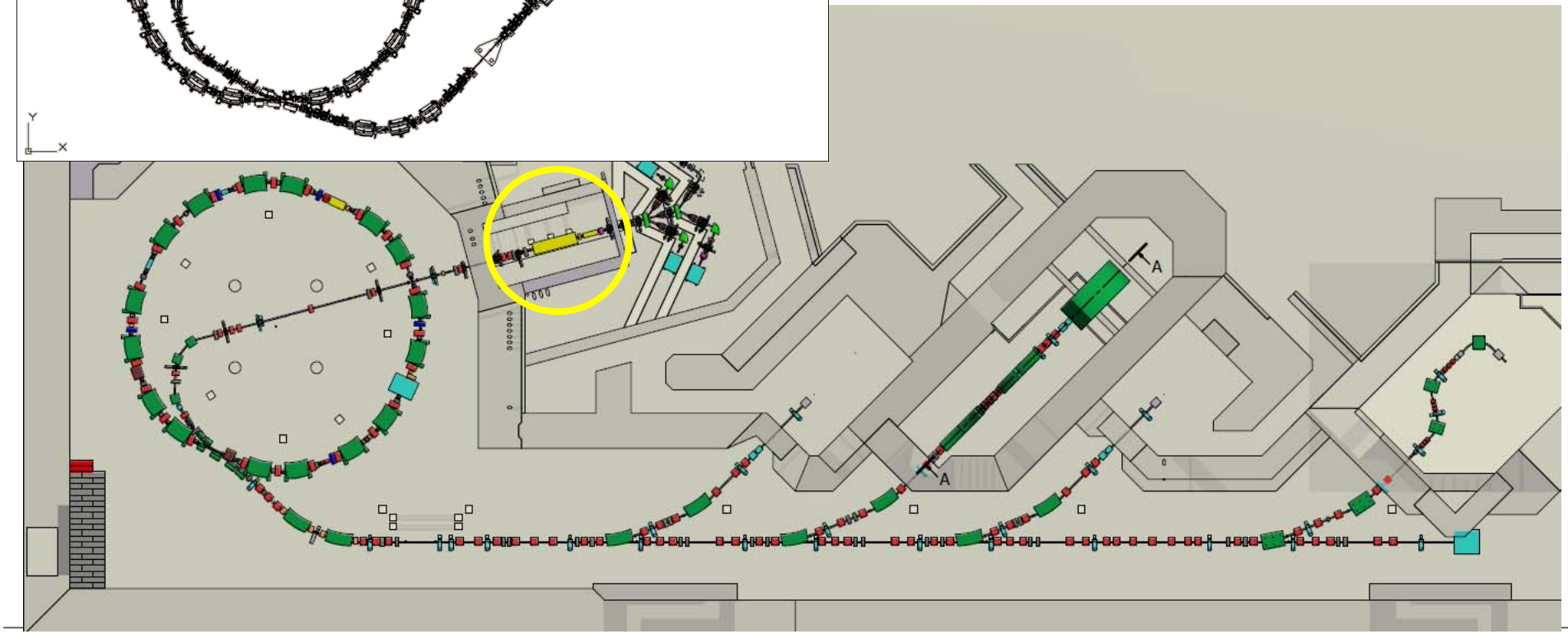
C^{4+} or H_3^+ 8 keV/u



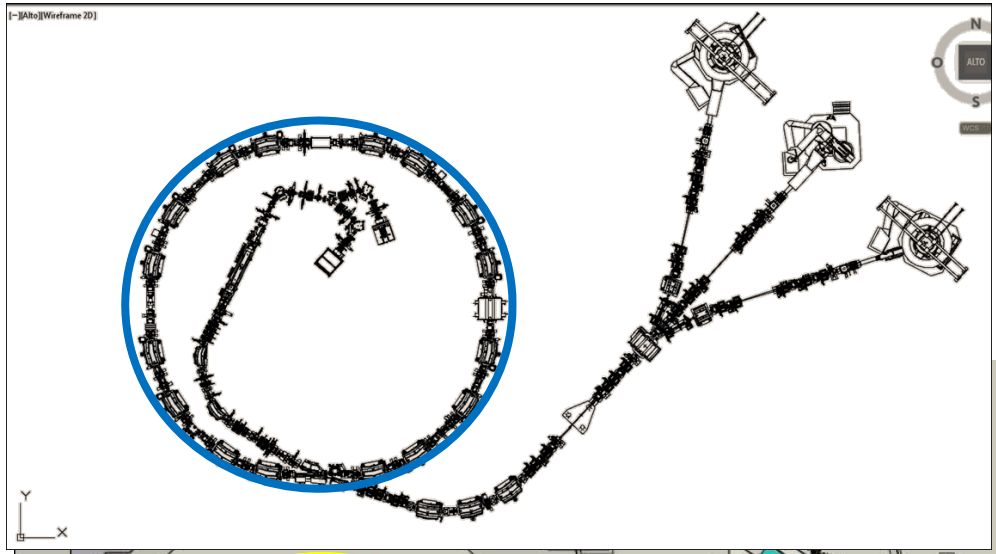
LINAC



Same RFQ+LINAC (GSI design)
400 keV/u RFQ
7 MeV/u LINAC

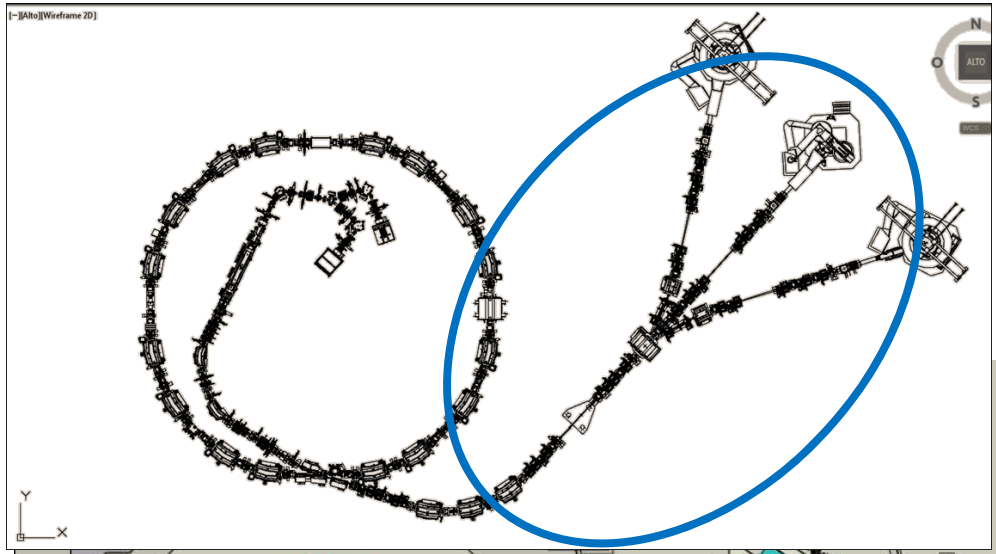


Synchrotron

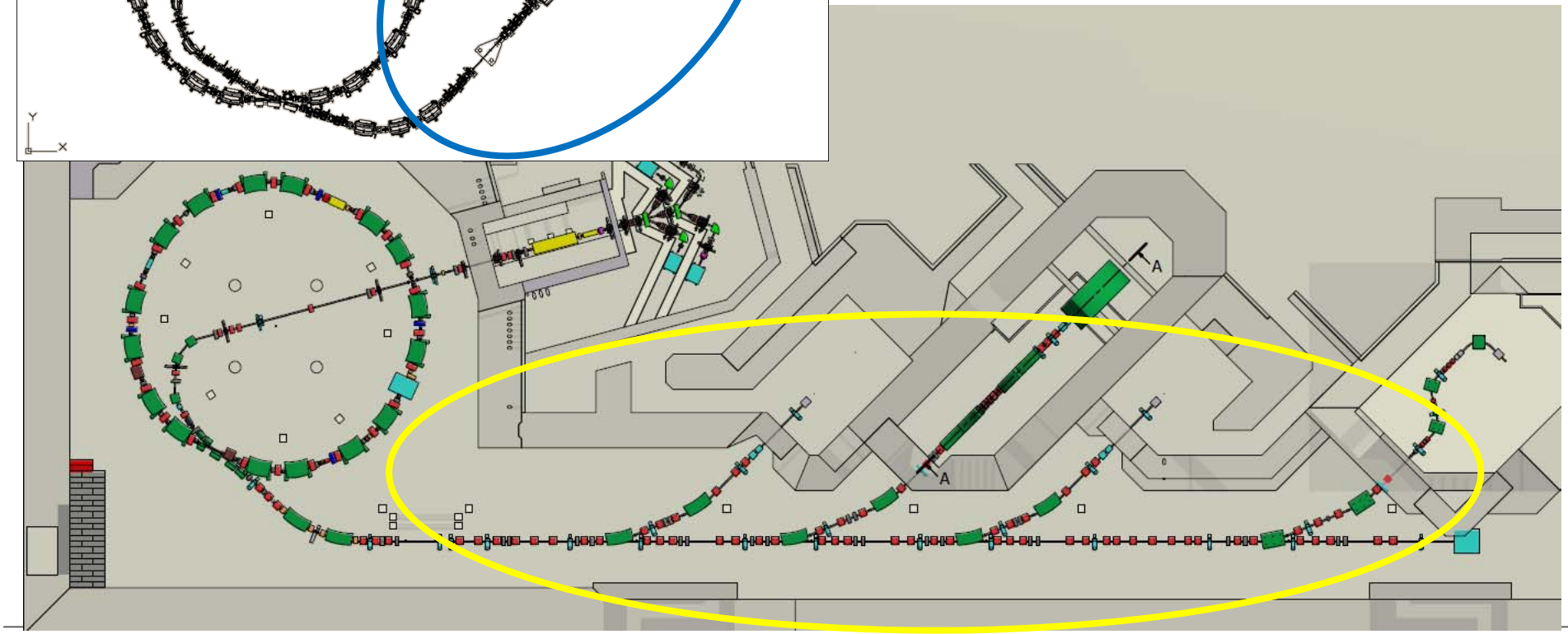


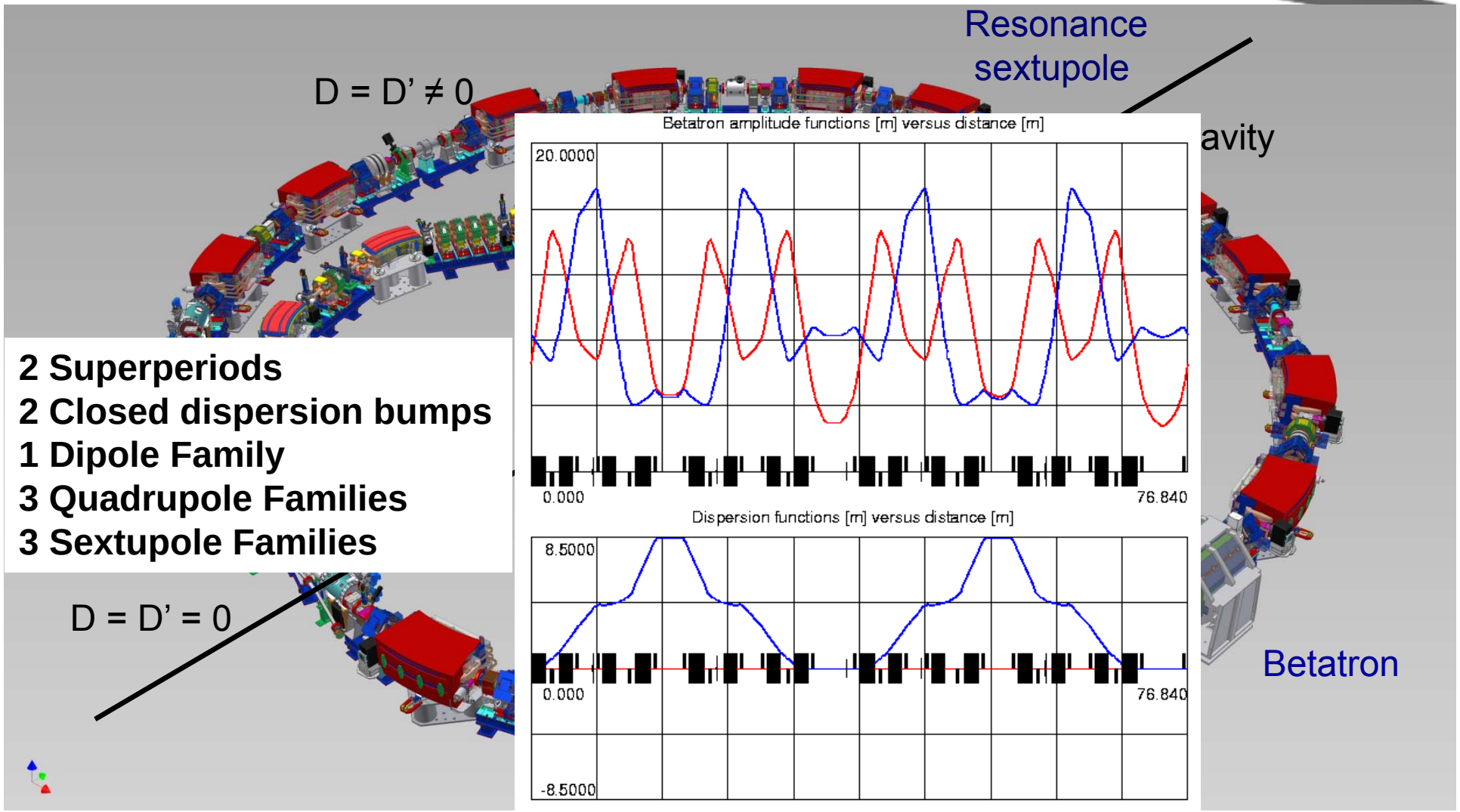
Same Synchrotron design (PIMMS)
60 -250 MeV protons
120-400 MeV/u carbon ions

HEBT



Different HEBT design
Compact vs modular

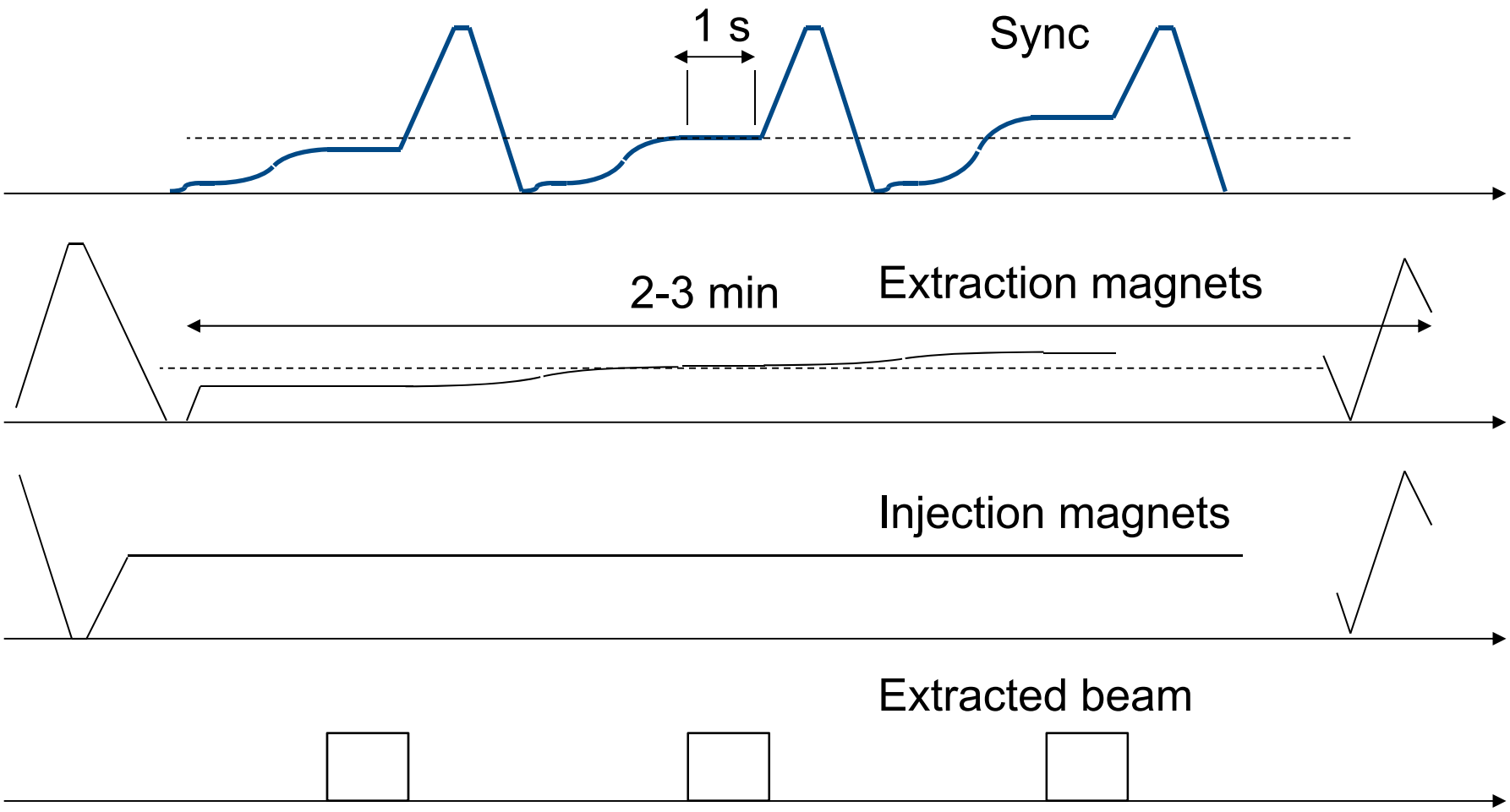




2 Superperiods
2 Closed dispersion bumps
1 Dipole Family
3 Quadrupole Families
3 Sextupole Families

	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

Treatment execution



Extraction setup at CNAO

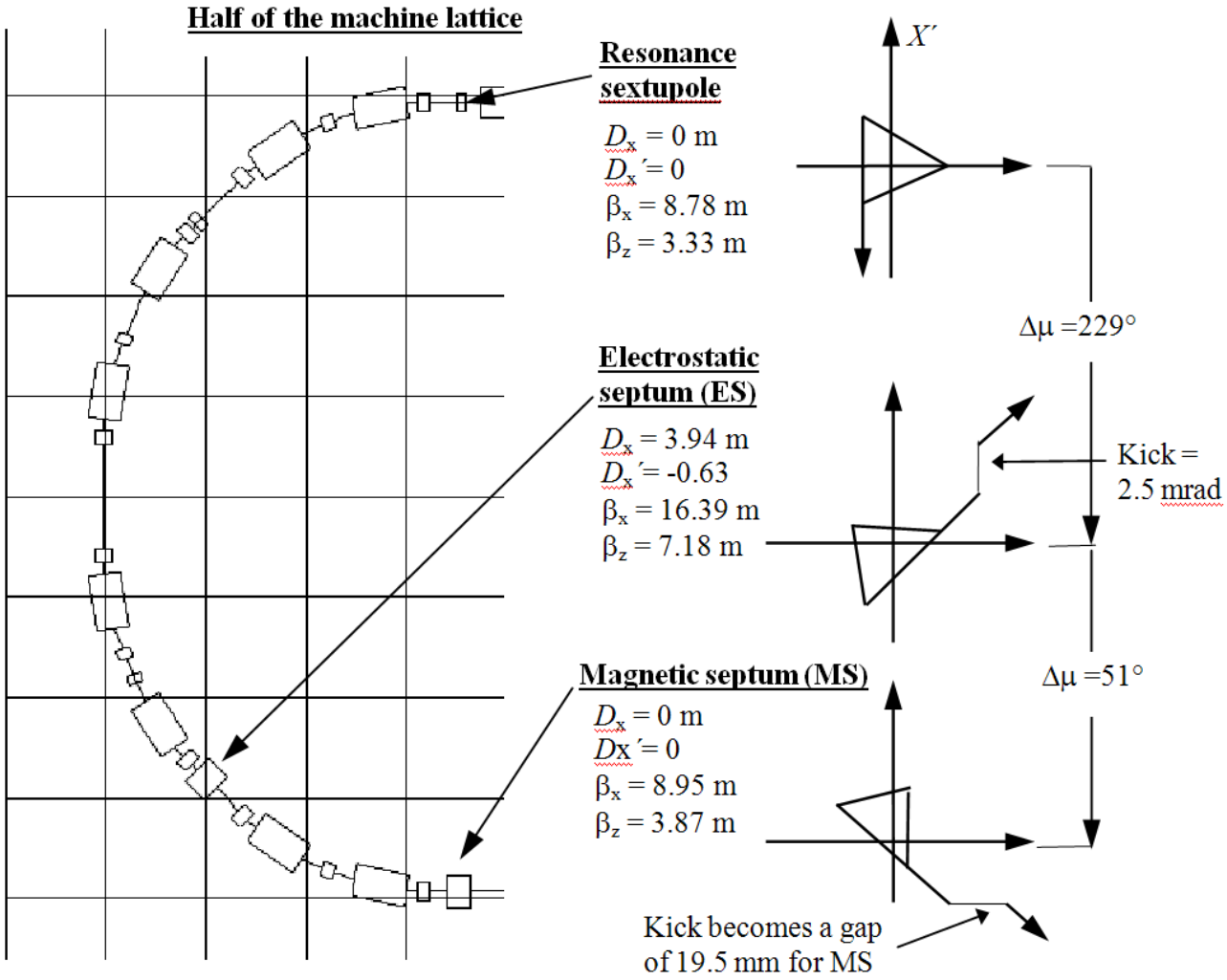
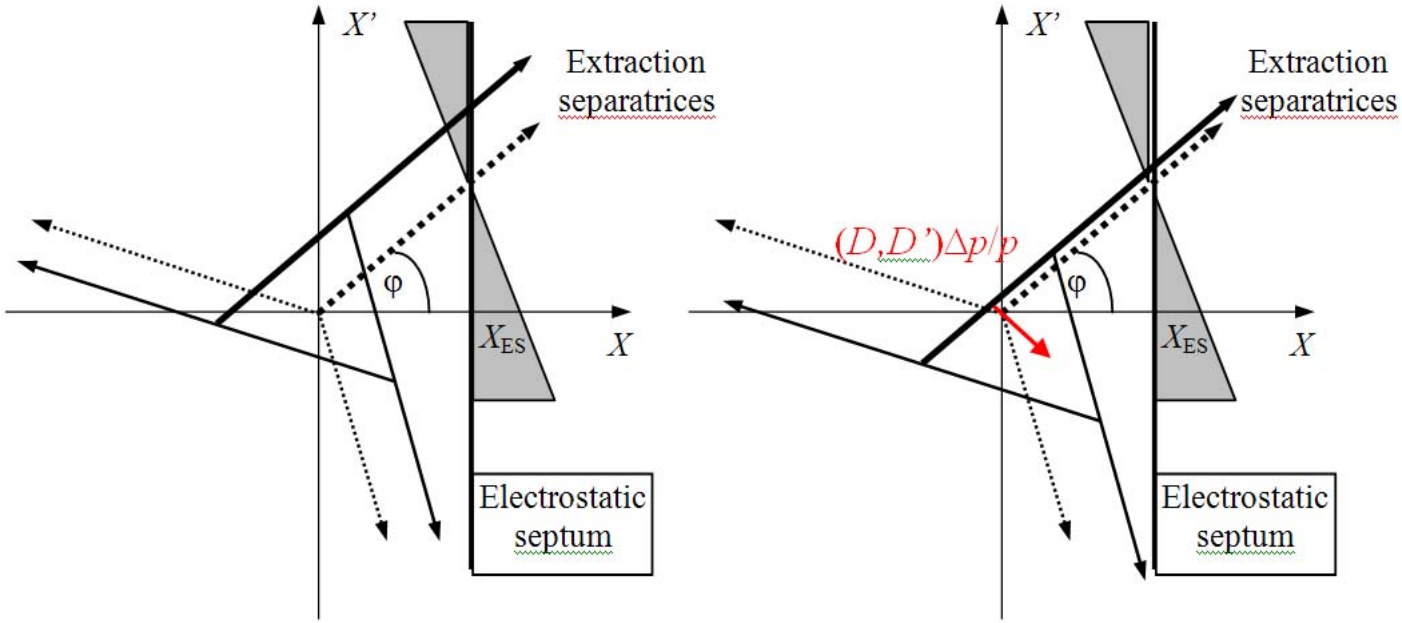


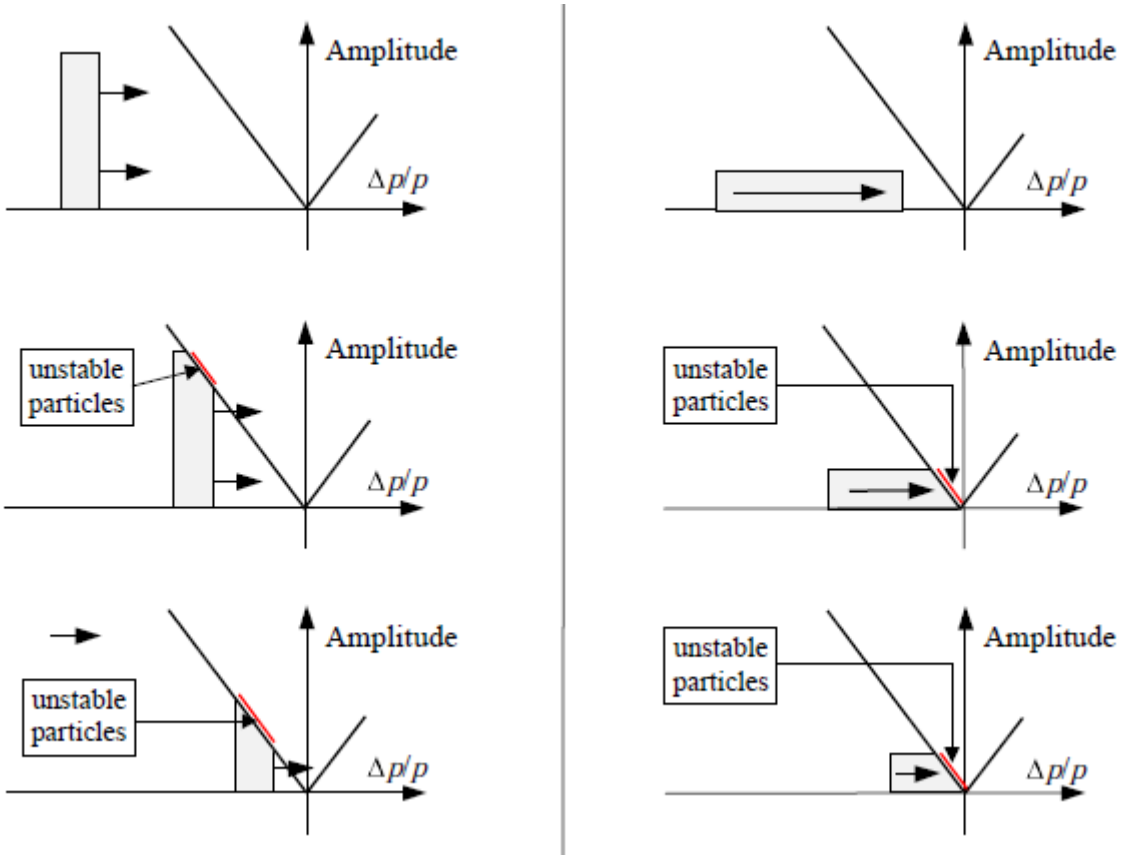
Figure 3 *Extraction configuration*

Hardt condition

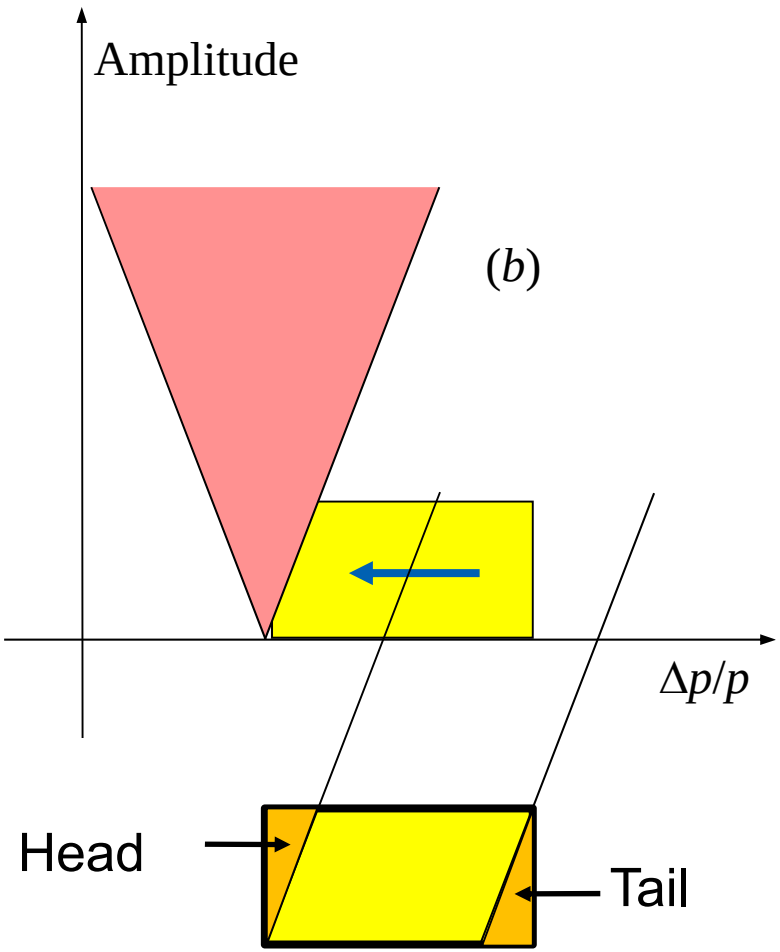


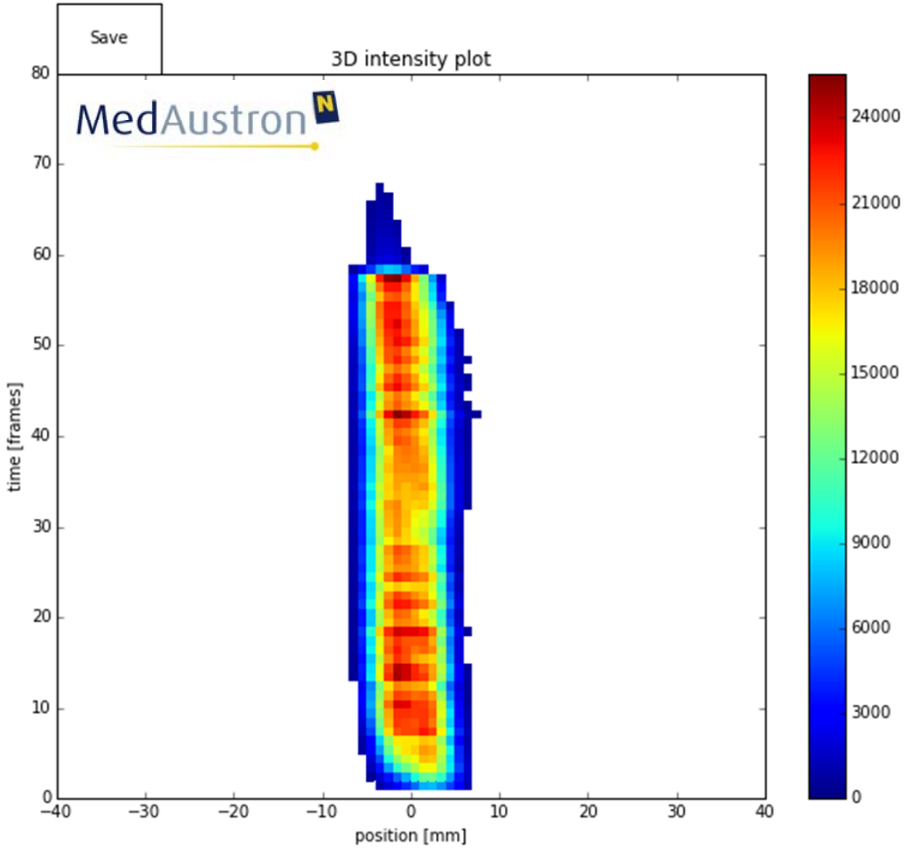
$$D_n \cos(\alpha_0 - \Delta\mu) + D'_n \sin(\alpha_0 - \Delta\mu) = -\frac{4\pi}{S} Q'$$

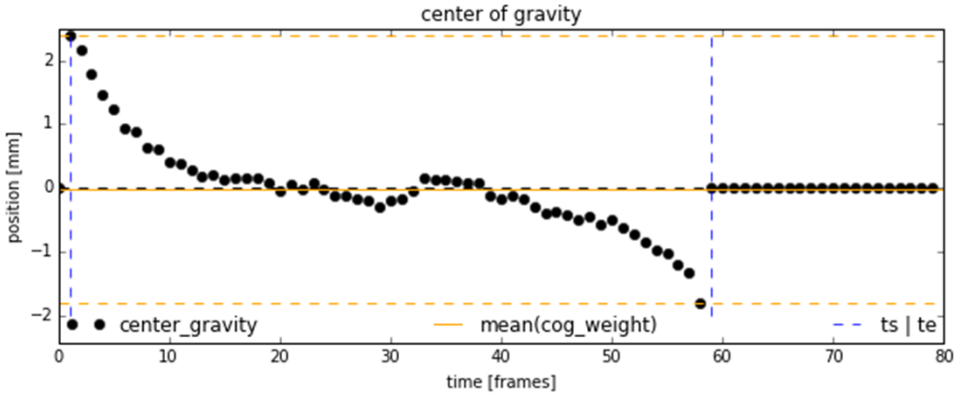
Betatron extraction



Head and tail of extraction

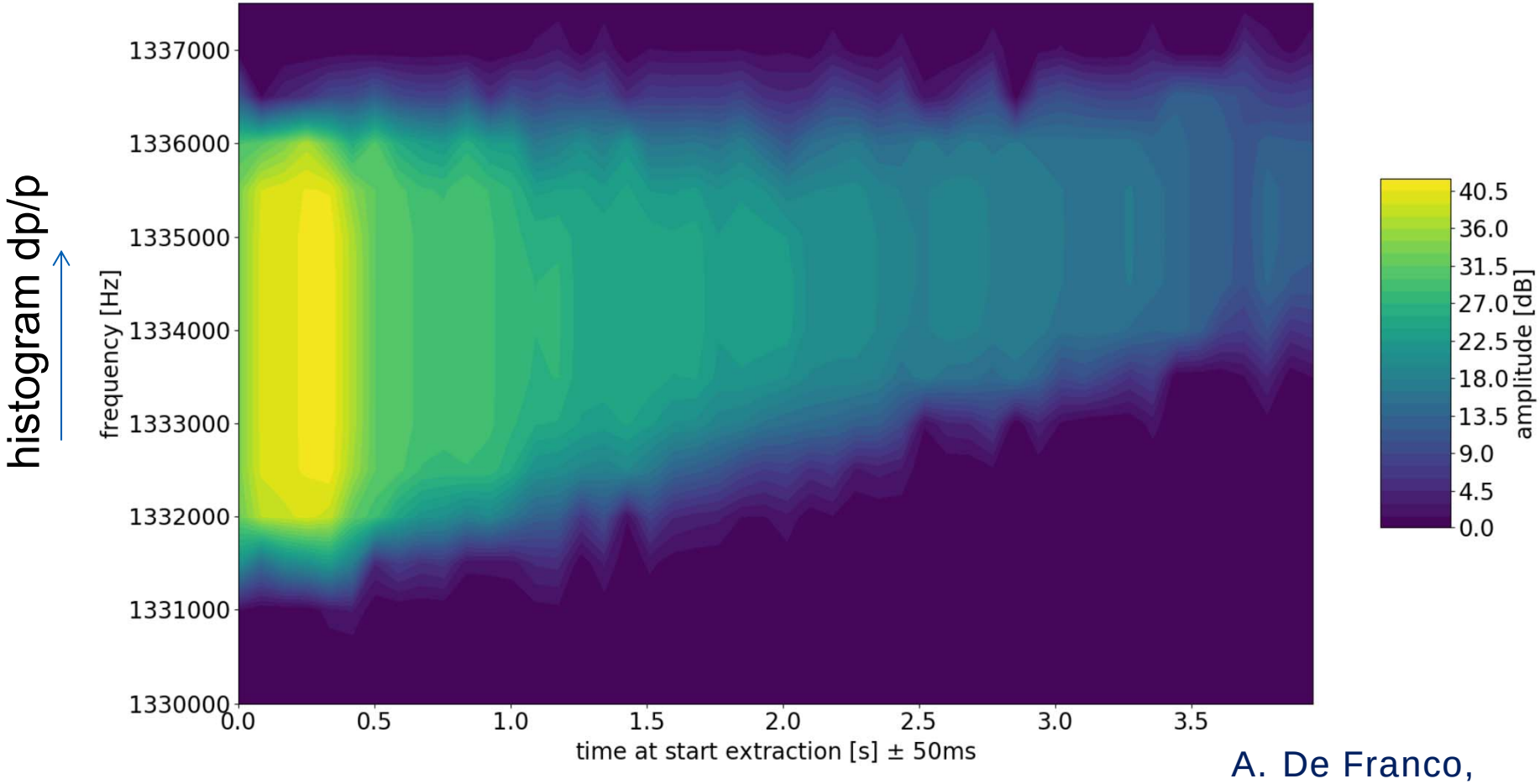






Momentum distribution driven into resonance by Betatron core

Schottky monitor Vert.



∑. En:62.4 MeV, 1st Harm

A. De Franco,
A. Goetz

Extraction features at CNAO

Betatron core

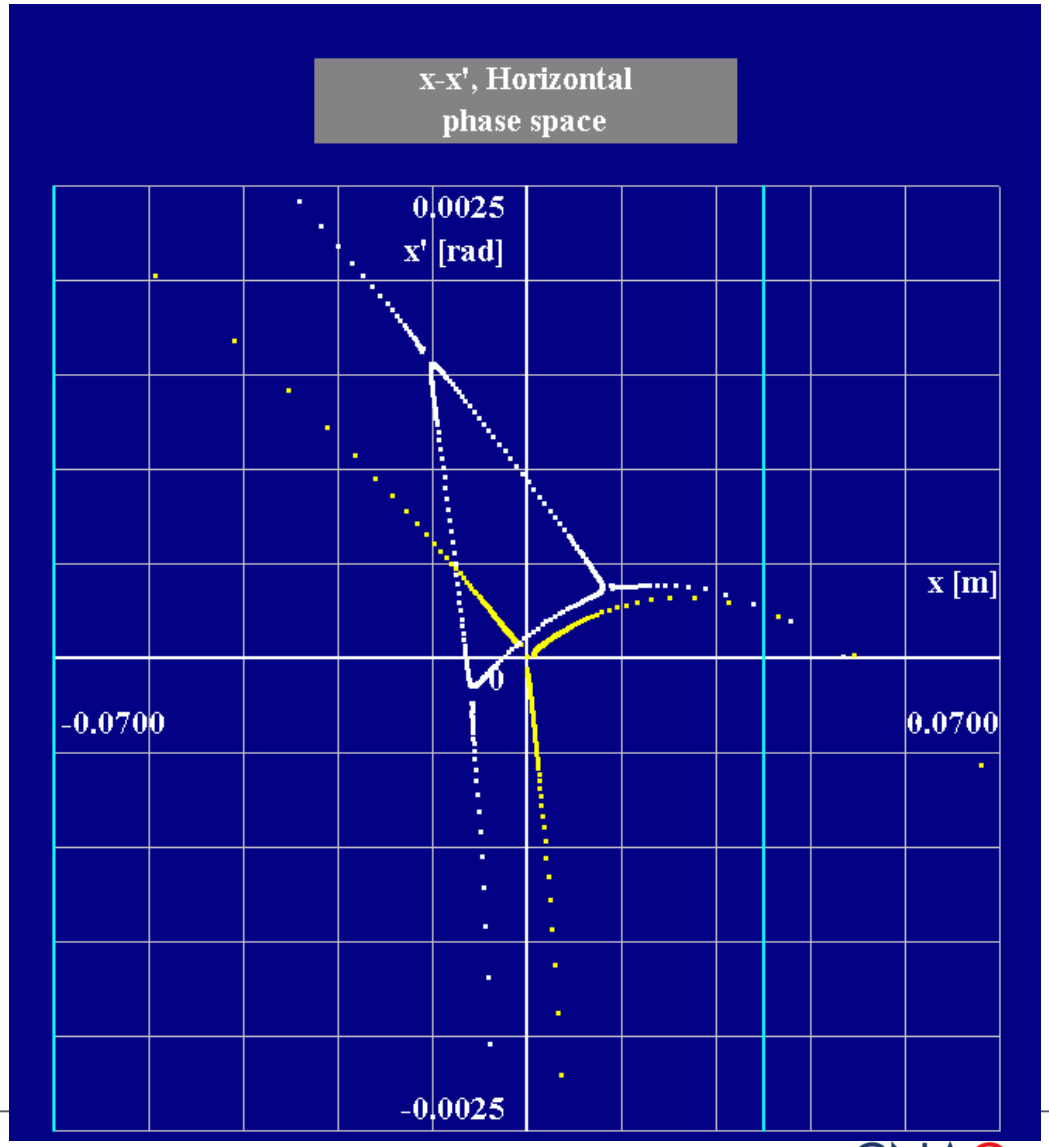
Empty bucket channelling

Air core quadrupole

RF-KO with new exciter

Beam shaping with Schottky PU

Additional quad winding

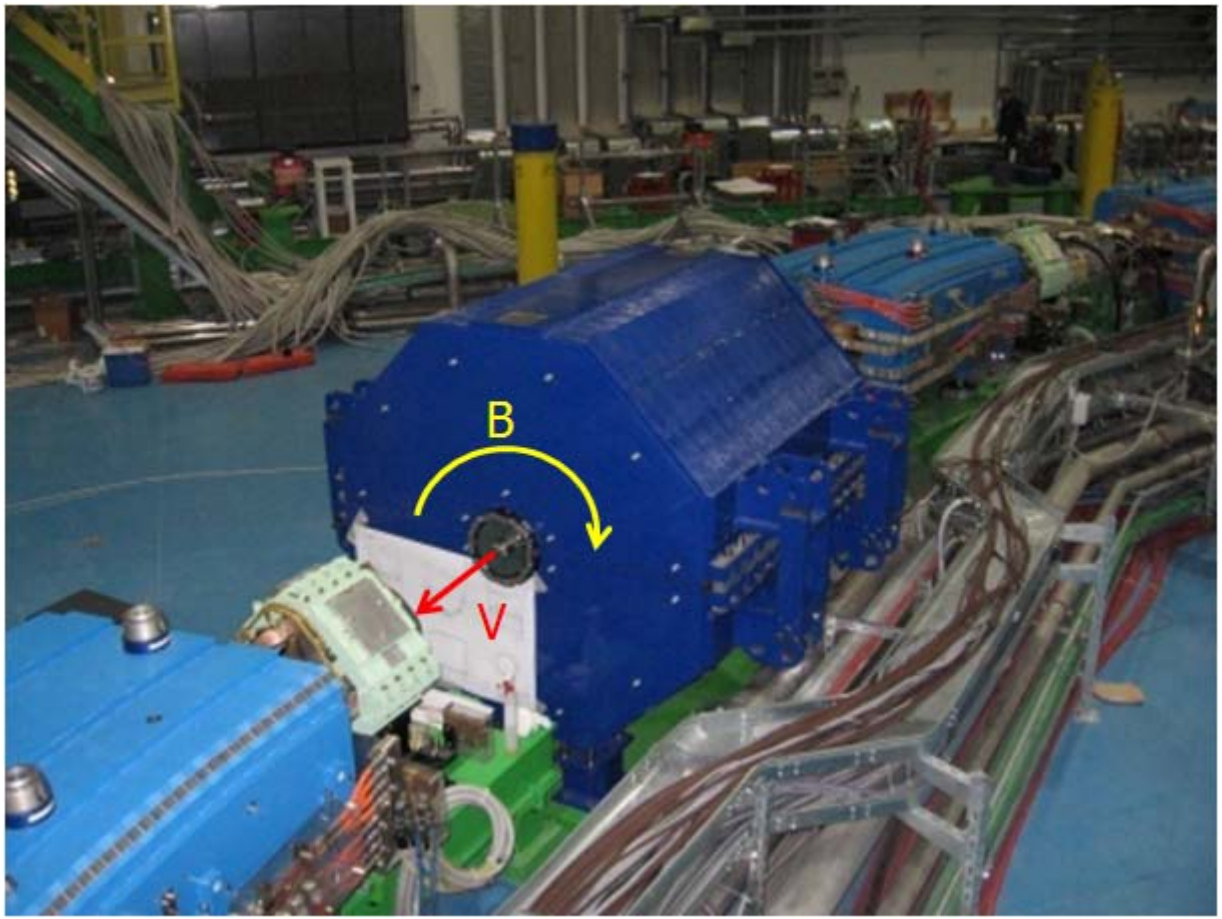


Betatron core

$\Delta\Phi$ = 2.46 Wb

Sensitivity to gap between halves

Magnetic screen needed

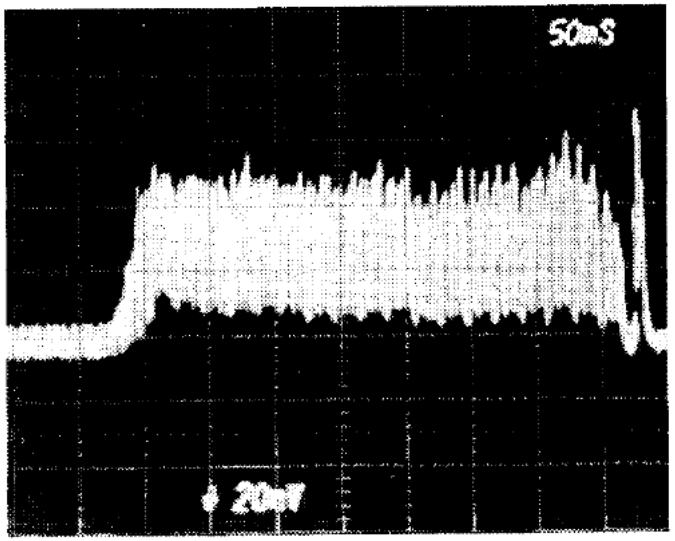


Empty bucket channelling

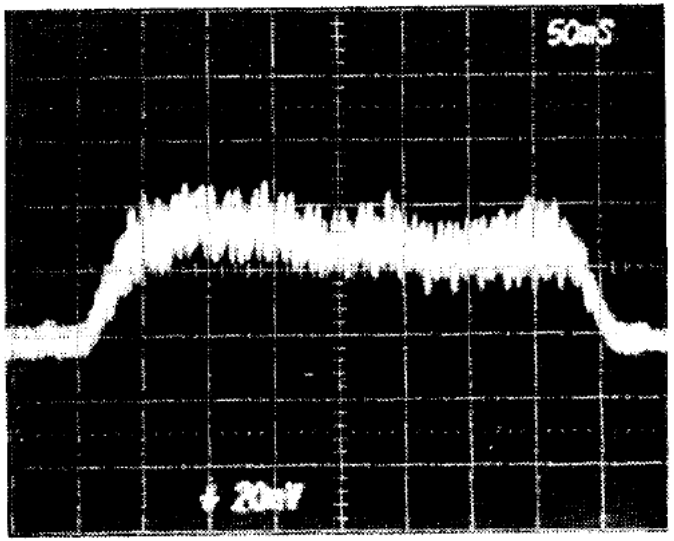
IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

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



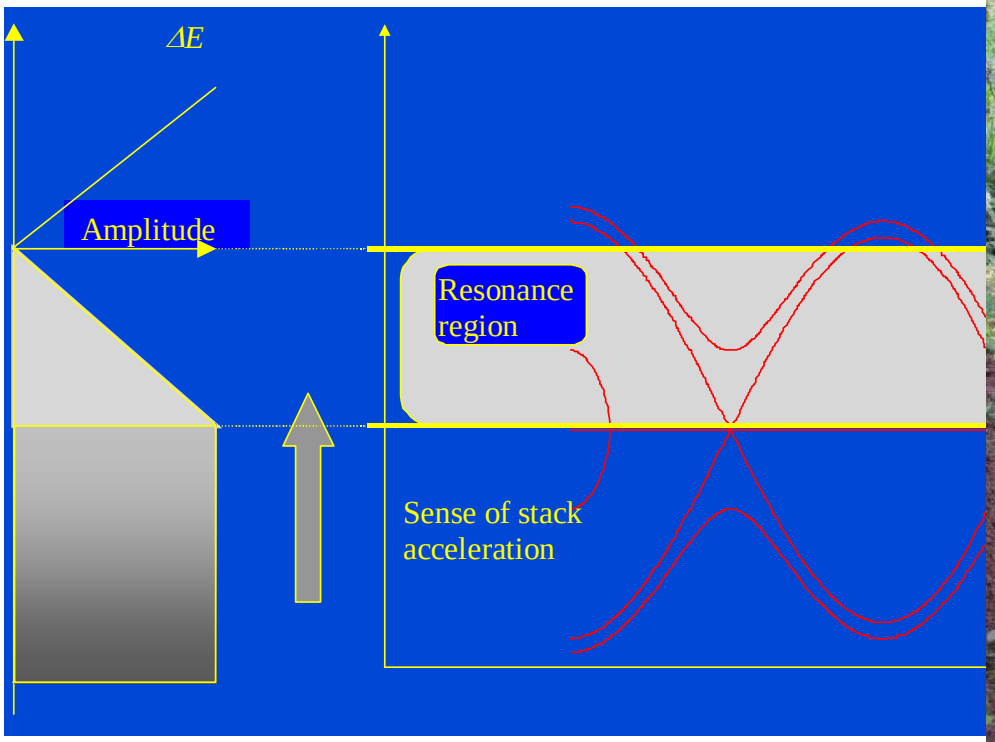
a) RF off

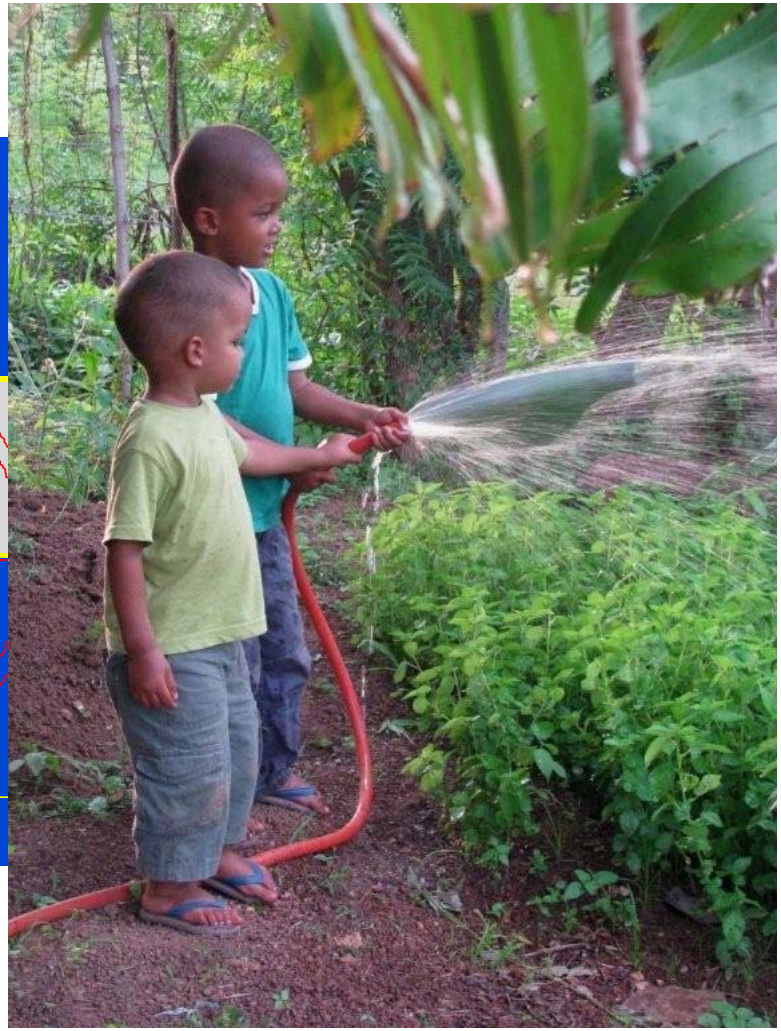


b) RF on

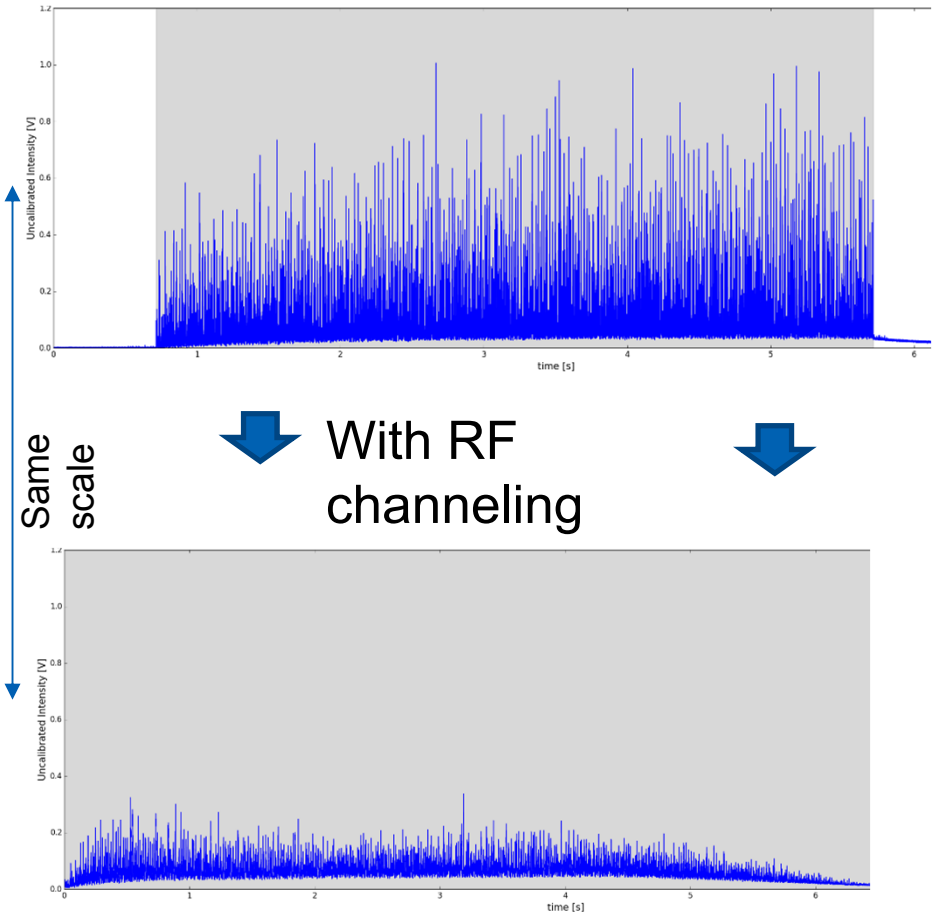
Fig. 2 : Slow extraction spill (50 ms/div.)

Empty bucket



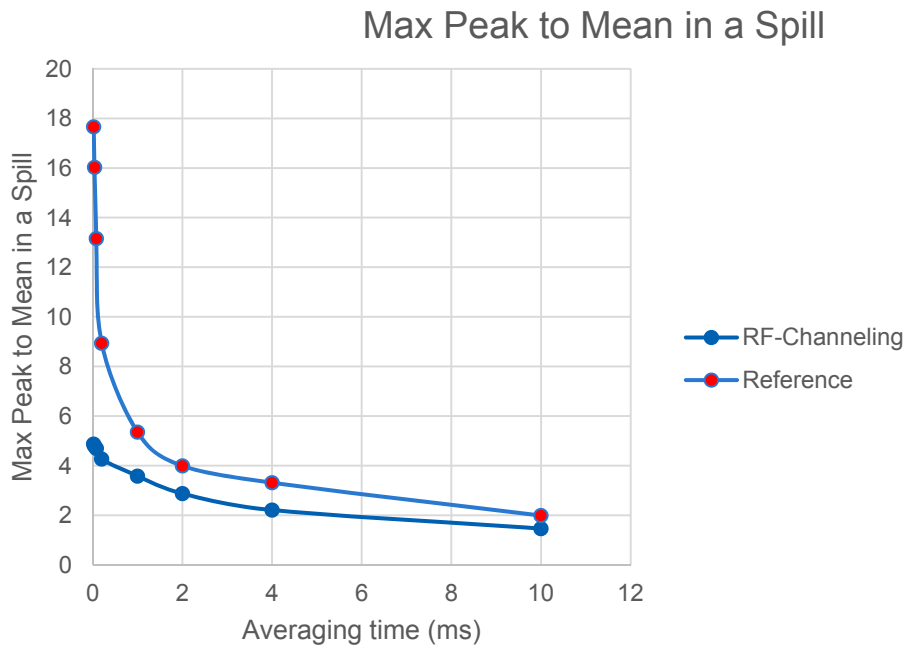


RF-Channeling spill smoothening



Spill time structure (50kHz)

Change Spot Sizes!!!
→ Re-commissioning

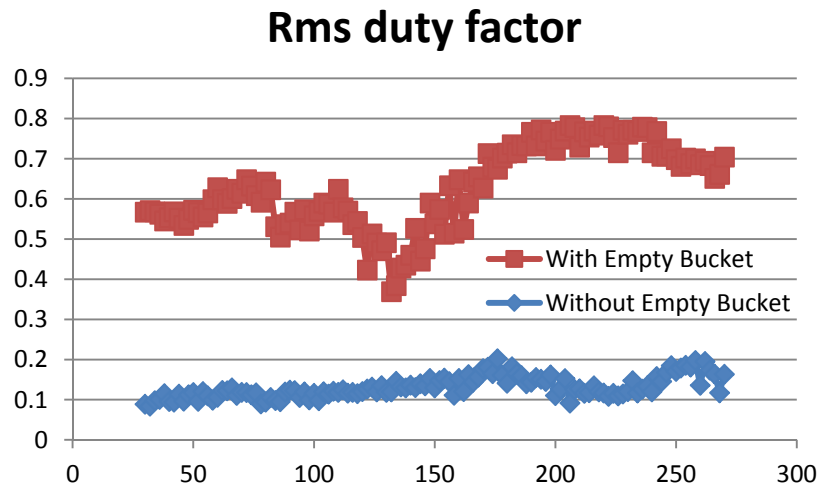


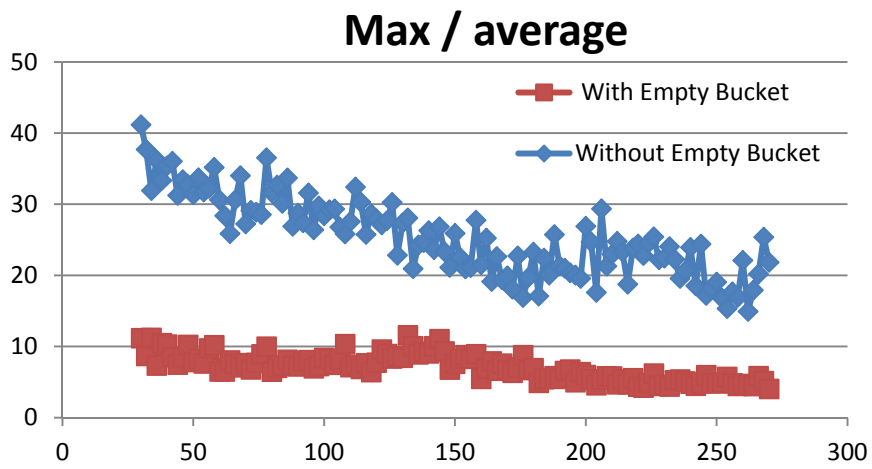
En:62.4 MeV - F_{rev}: 1.33 MHz.
ΔF_{ch}:15kHz – 1500V
Negligible losses

A. De Franco,
C. Schmitzer

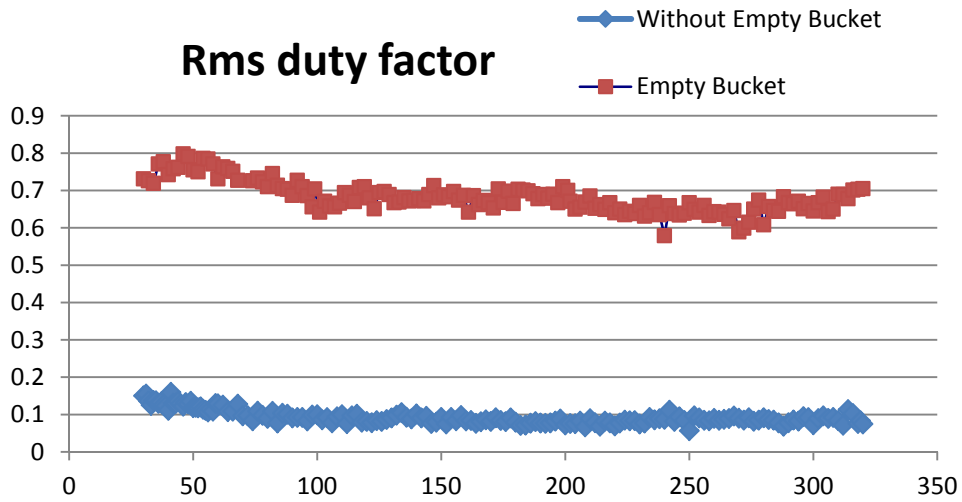
Empty Bucket results

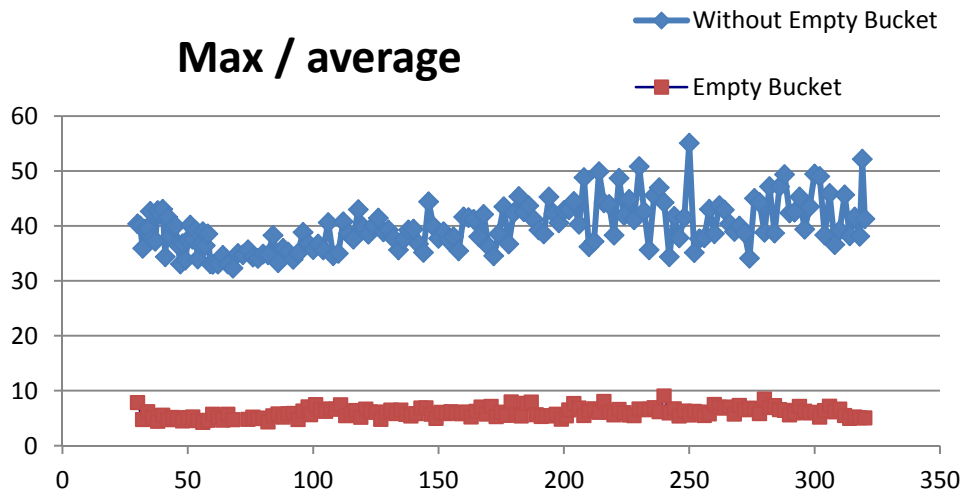
Carbon ions





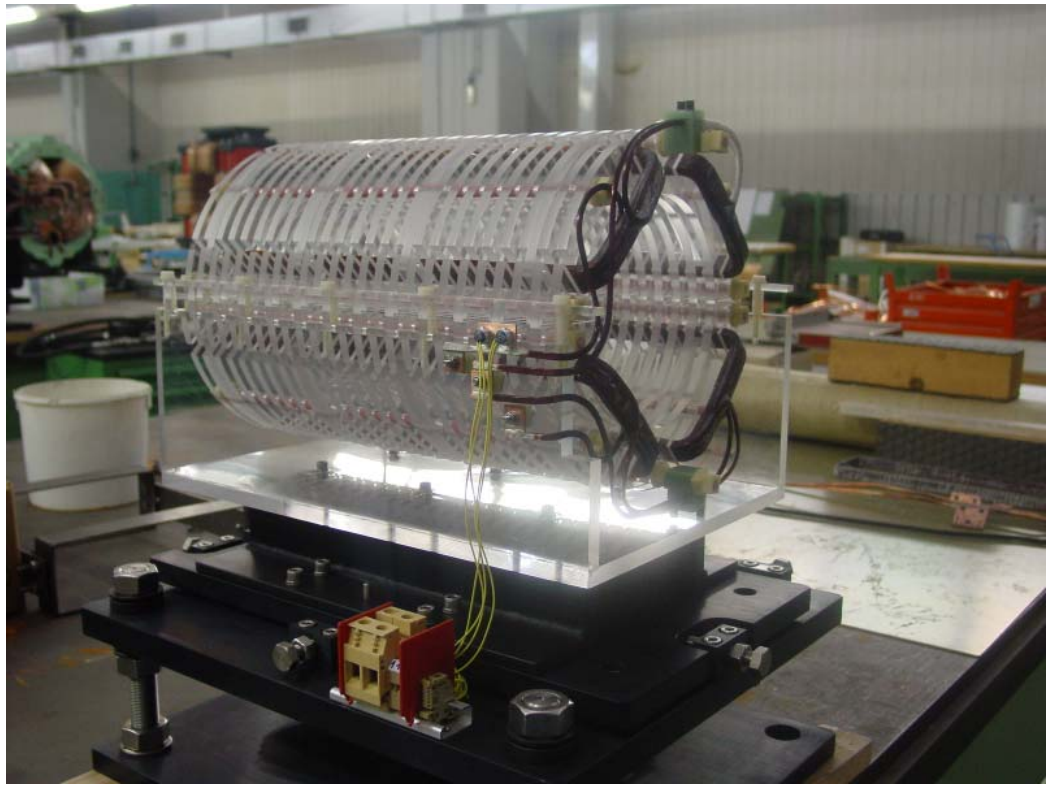
Protons



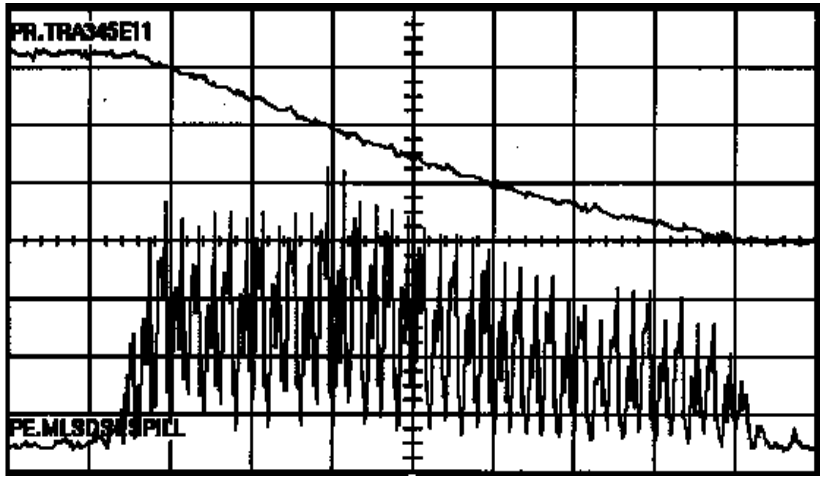


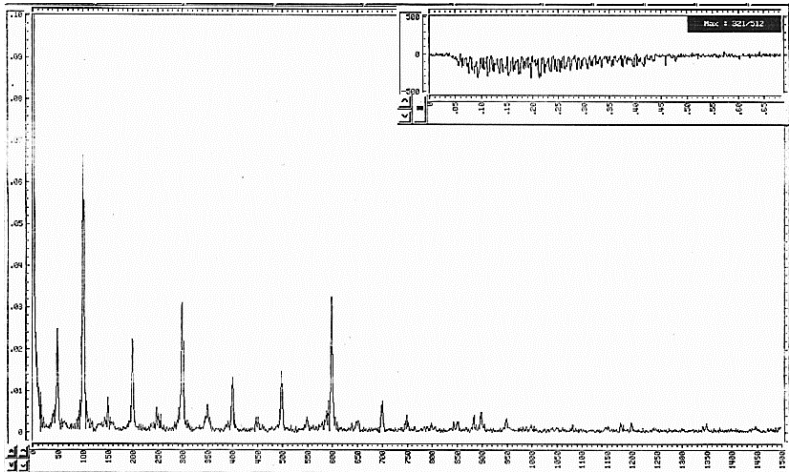
Courtesy of L. Falbo

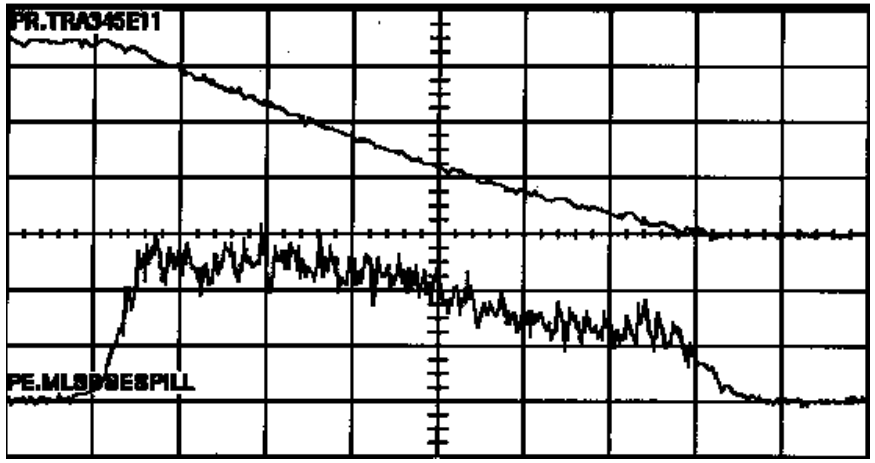
Air core quadrupole

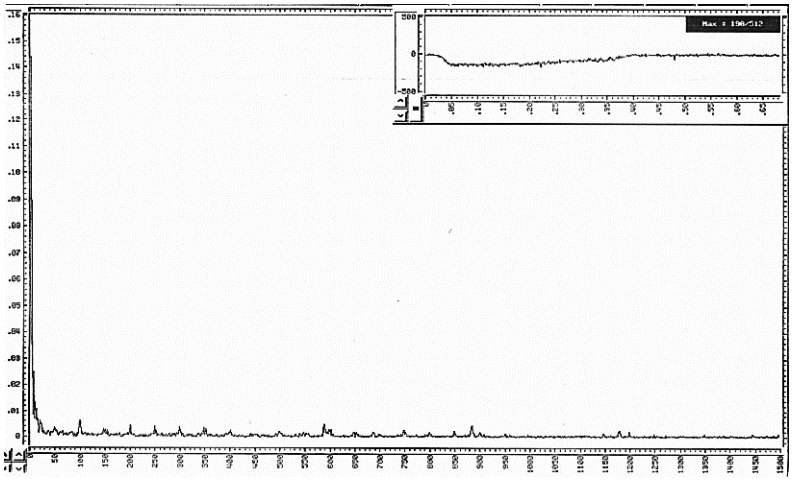


Air core quad feed forward









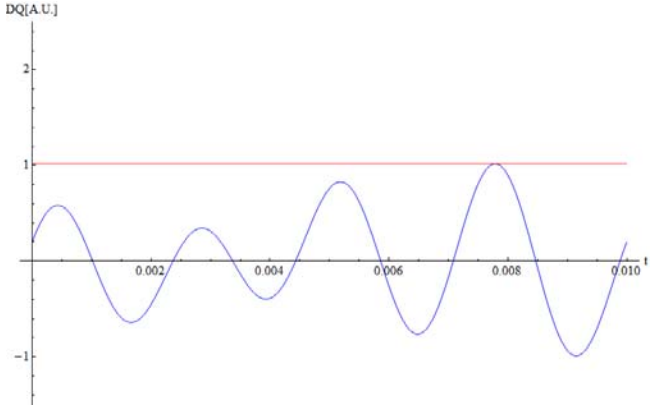
Automatic feed forward

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).

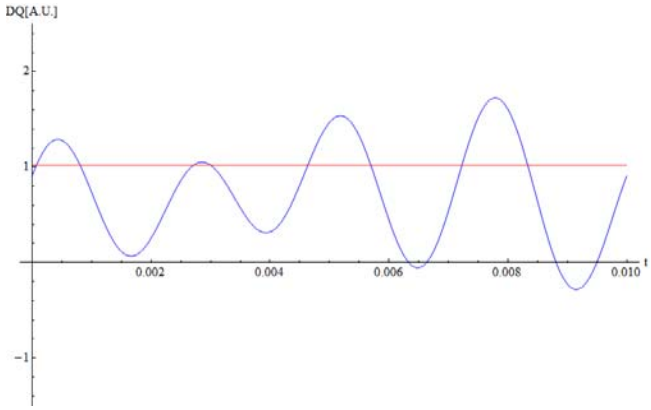
In the days following the air core quad feed forward MD, R. Cappi set up a system performing FFT and applying the correction at the following spill.

High Frequency Ripple Injection

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



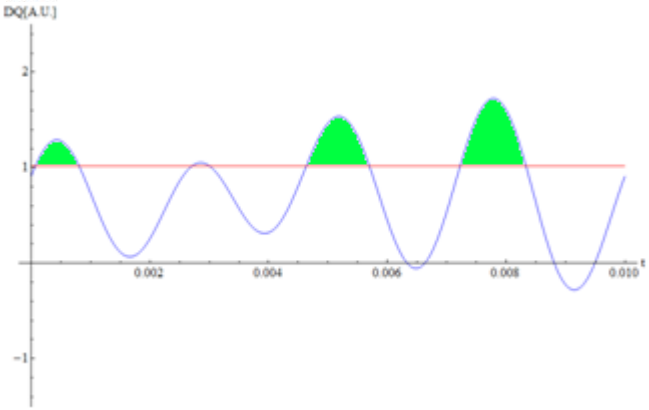
Ripple with betatron off.
Brushing against the resonance

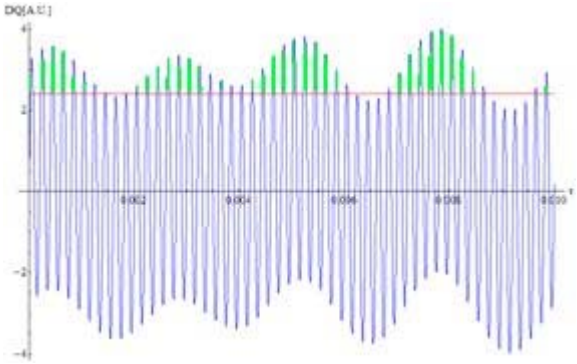


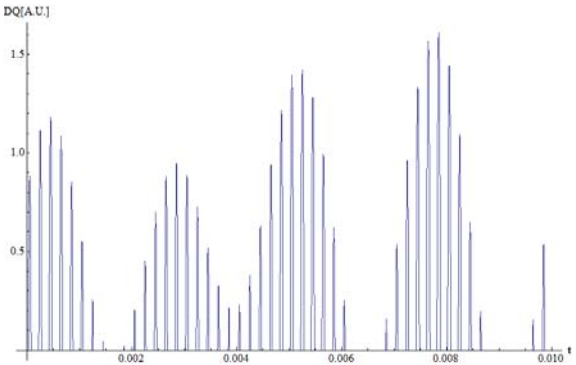
Ripple with betatron on.
Irregular spill with strong modulation

High Frquency Ripple Injection

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



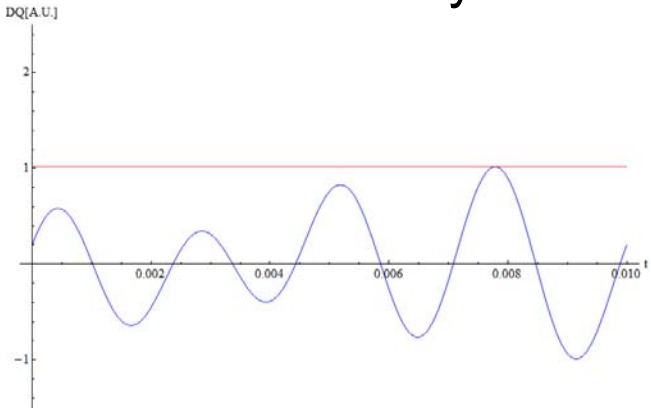


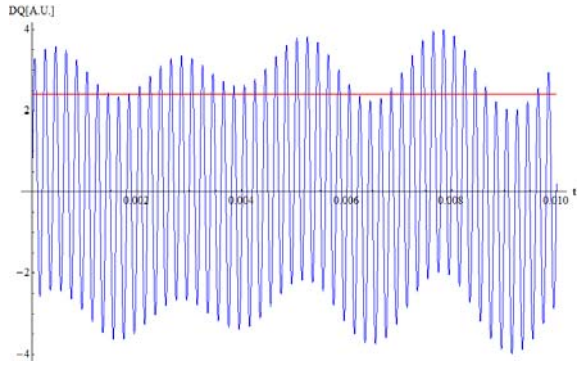


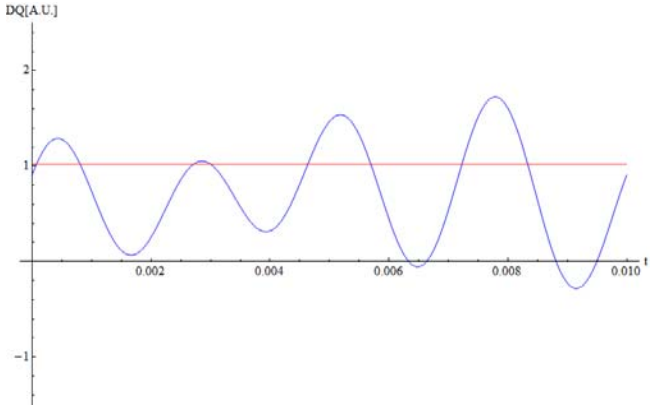
The amount of extracted beam depends only on the betatron, thus an apparently more homegeneous spill is obtained.

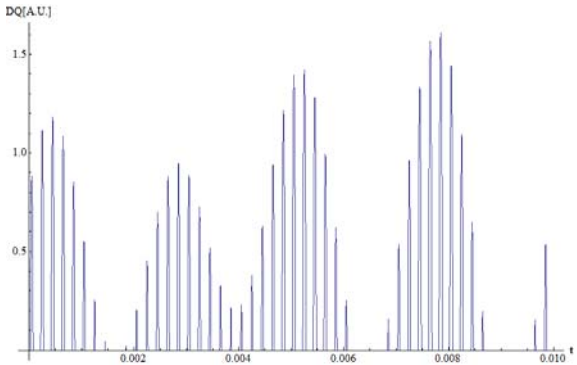
High Frquency Ripple Injection

Feed forward does not work at CNAO,
not even on the very short time scale (1 second)

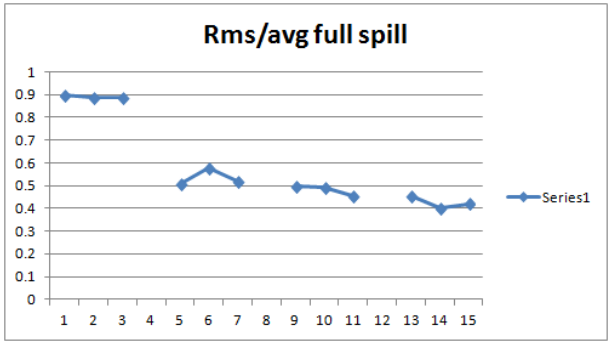


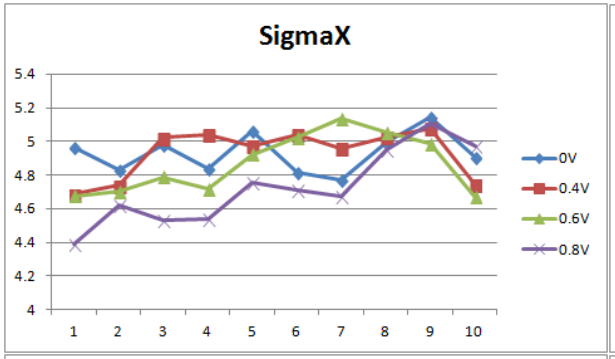


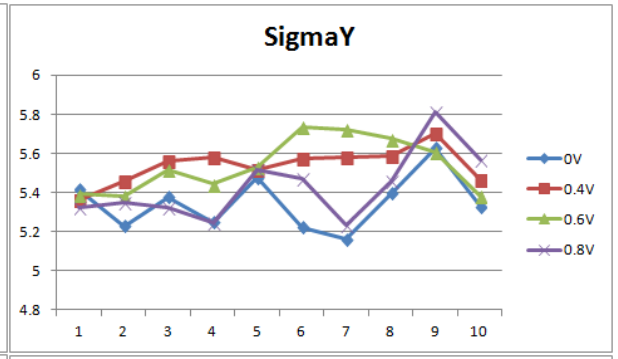


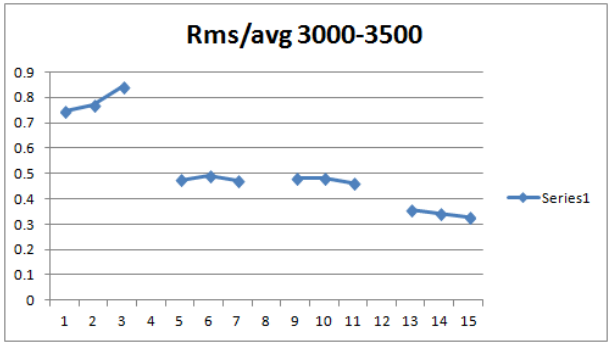


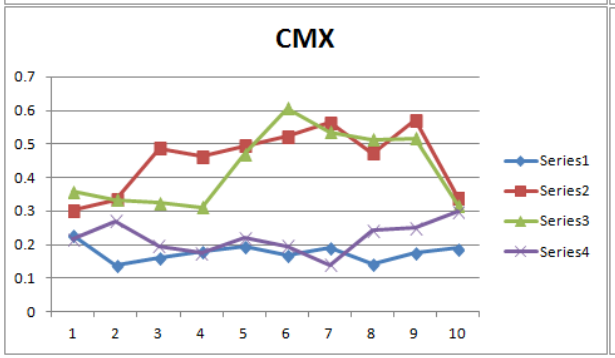
Effect on the beam at isocenter

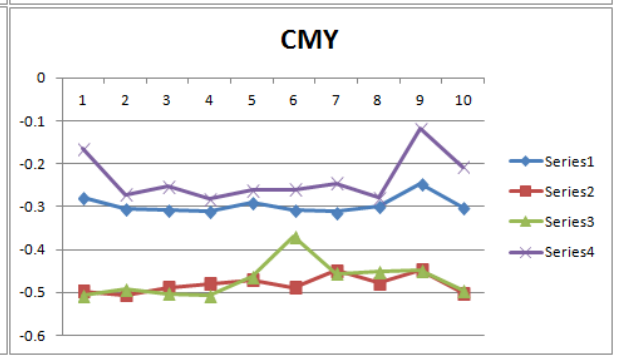






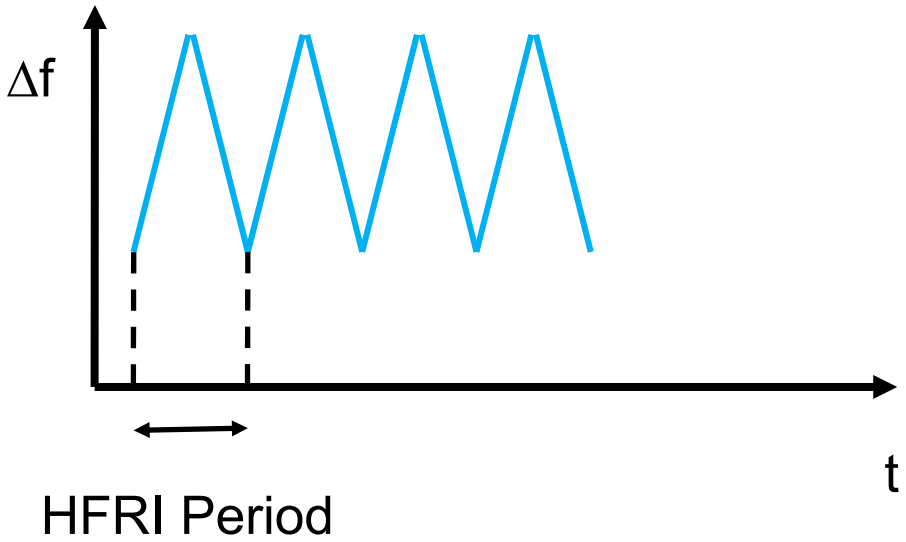






Off 0.6 0.8 0.95
a.u. excitation

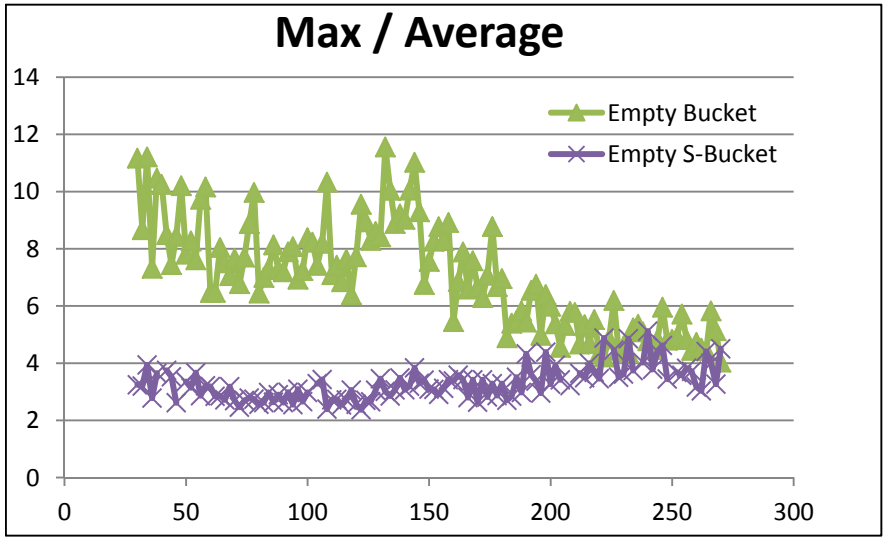
RF frequency sweeping HFRI

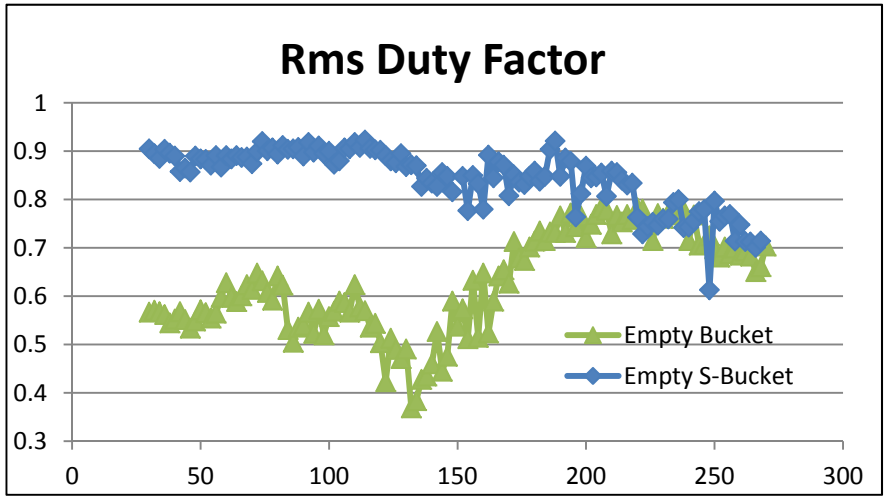


The same effect can be obtained with every means that can bring
The beam towards and away from the resonance

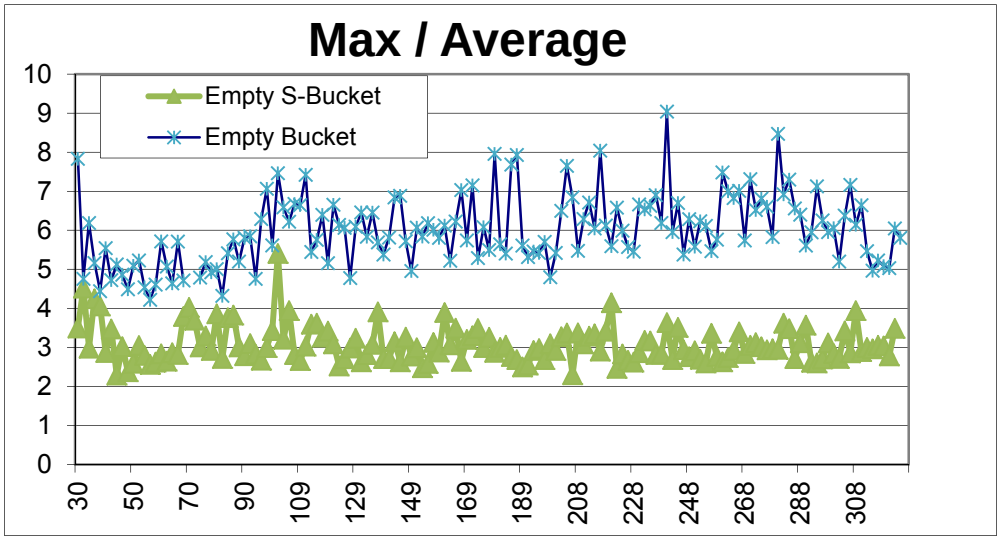
Empty Sweeping Bucket vs Empty Bucket

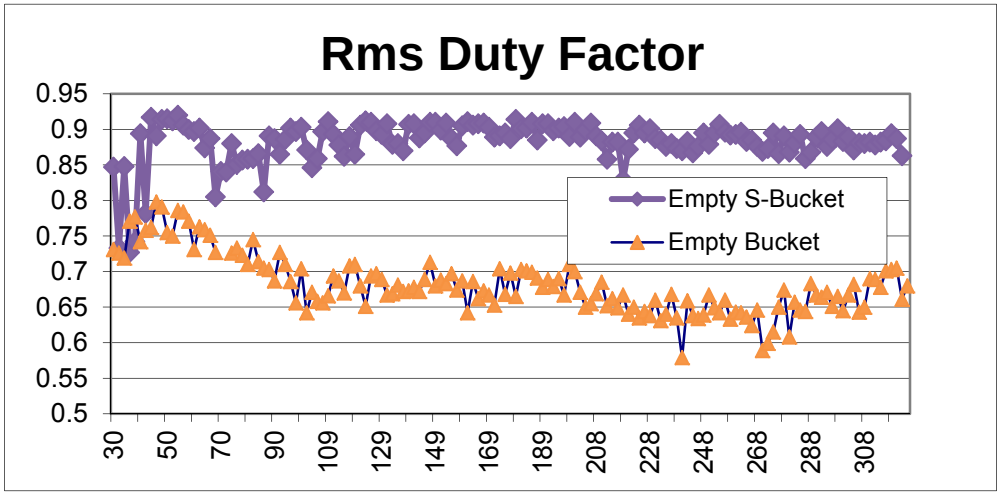
Carbon ions





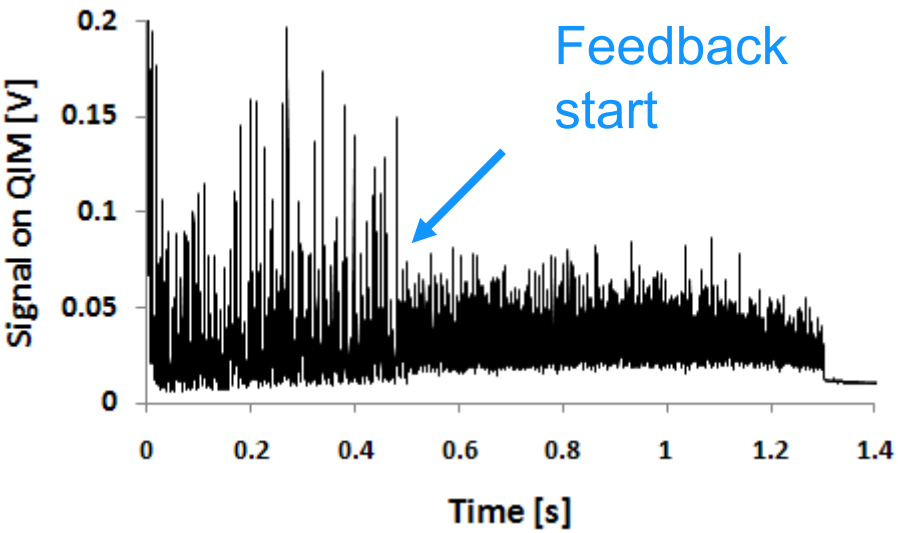
Proton ions

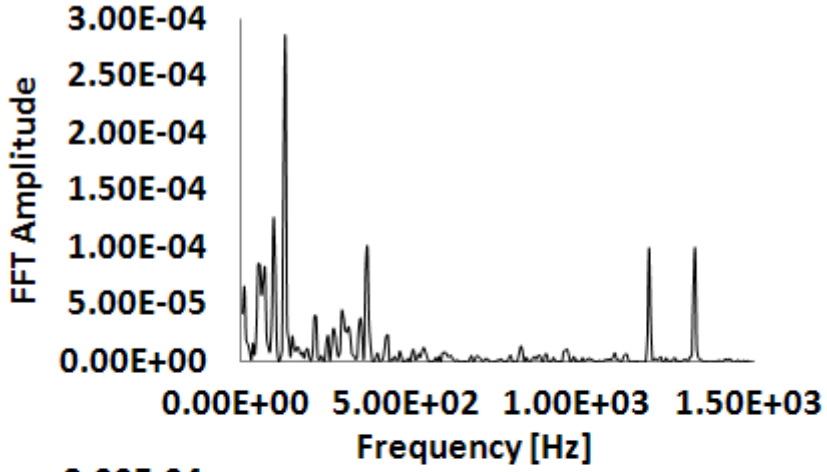


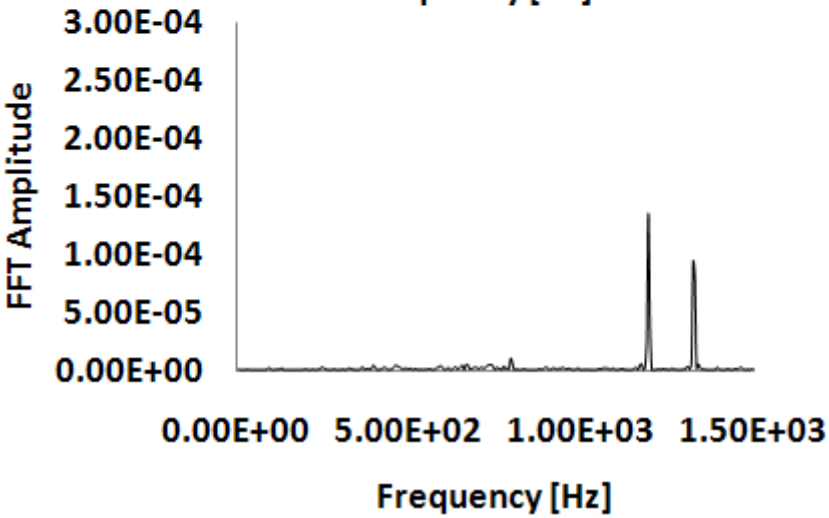


Courtesy of L. Falbo

Air core quad with feedback



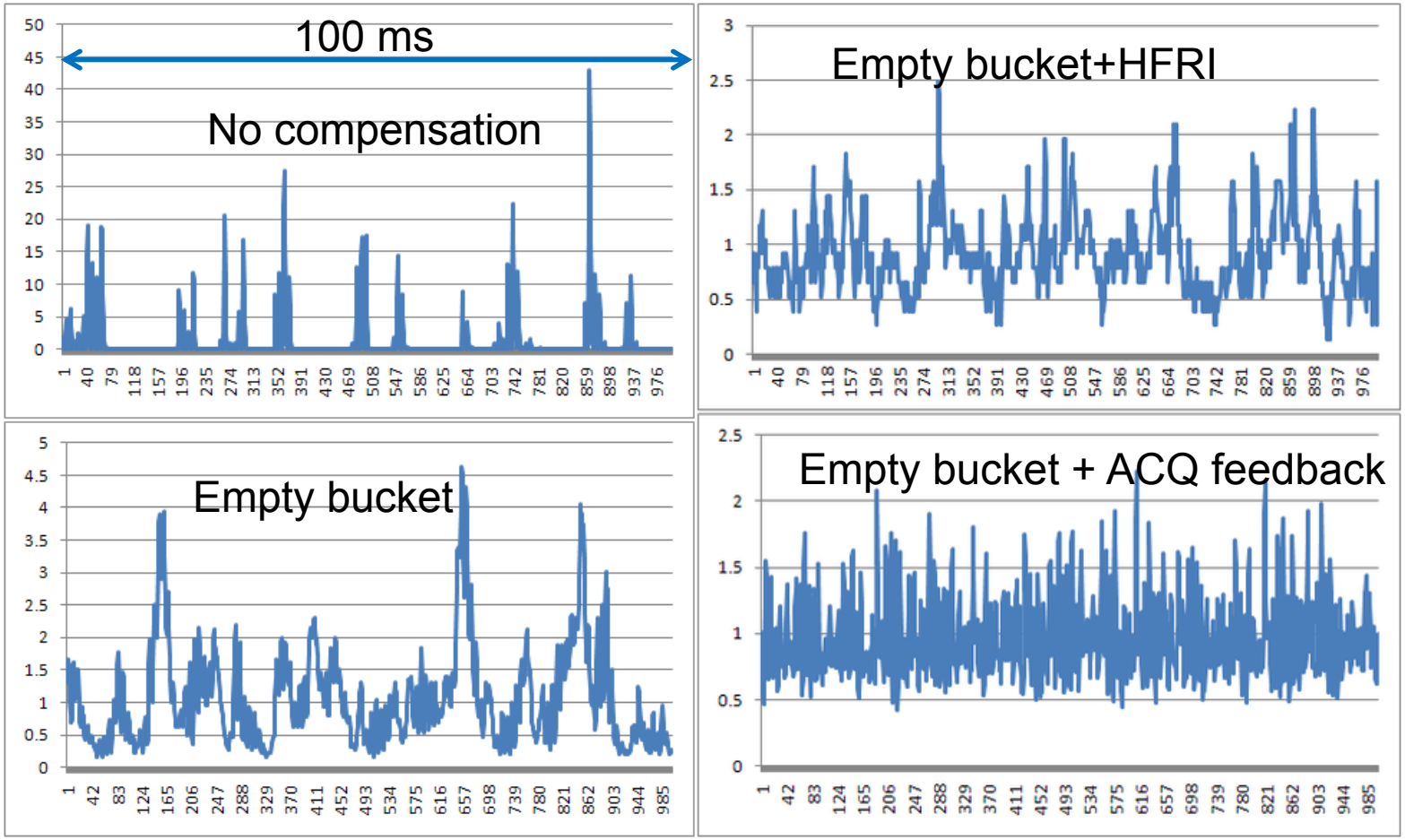




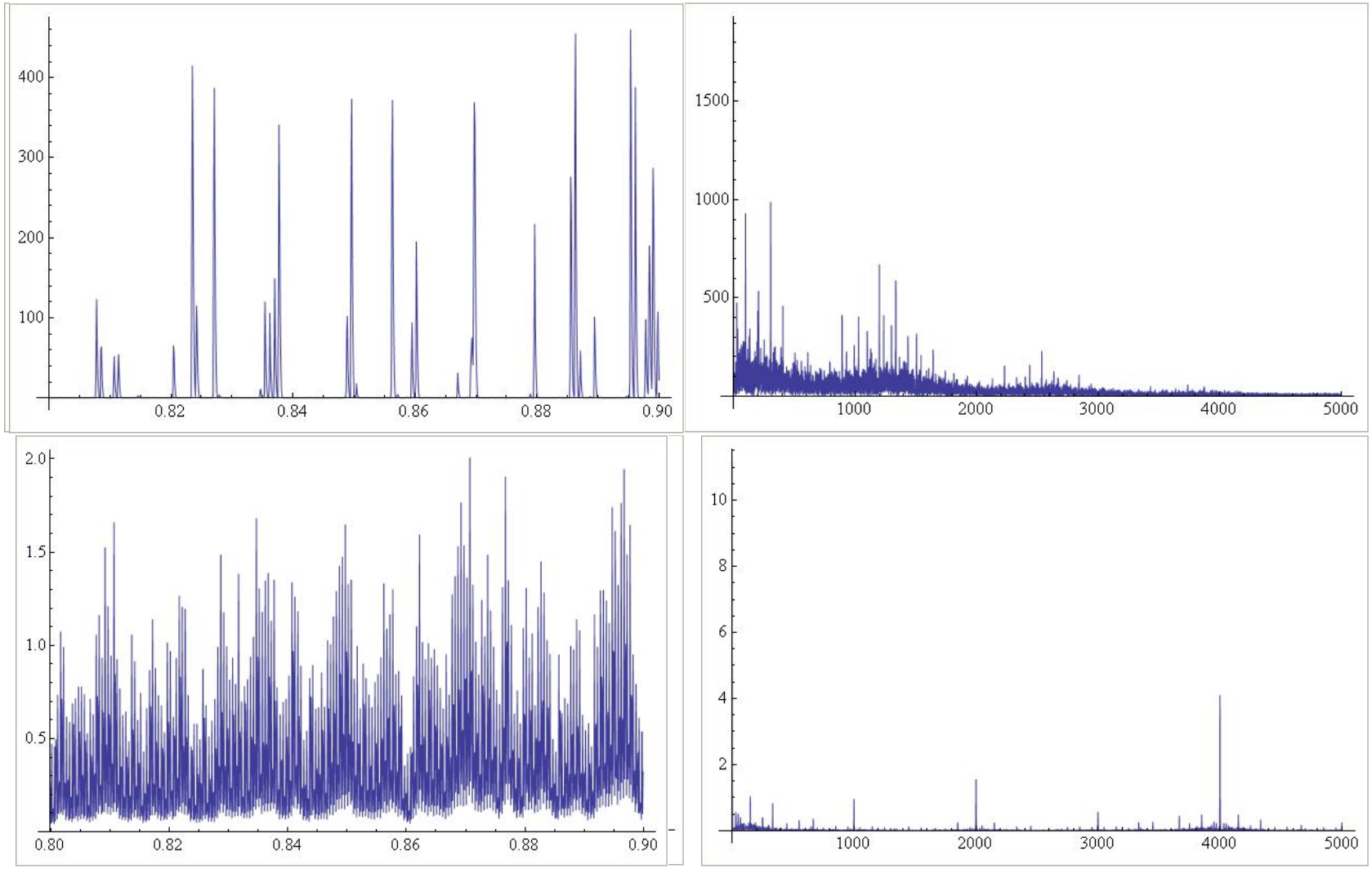
Signal from a scintillator
(qualification monitor in the HEBT)

Ripple compensation

Integration time 100 us (10 kHz data)

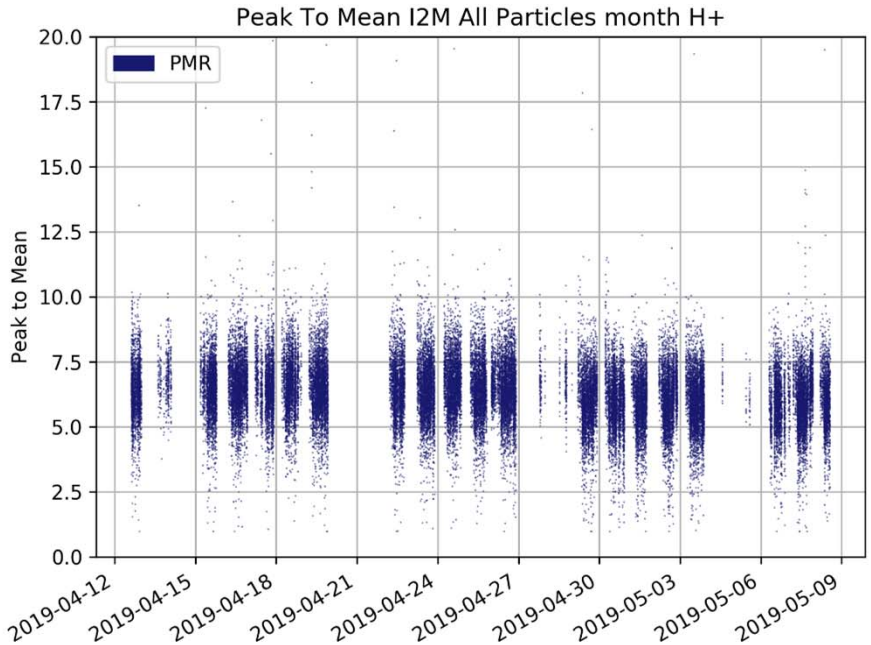


Different ripple spectra at CNAO and MedAustron

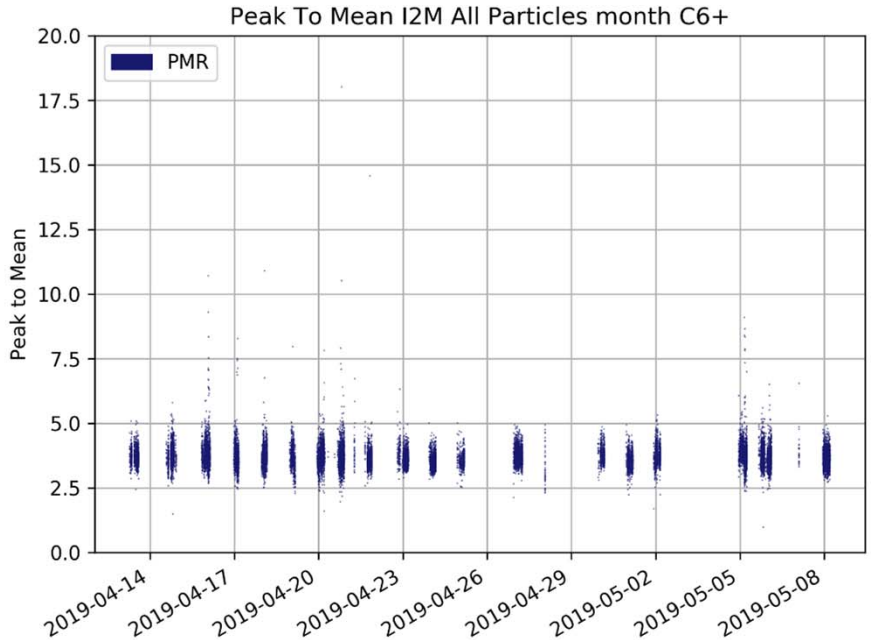


Carbon & proton ripples

Proton



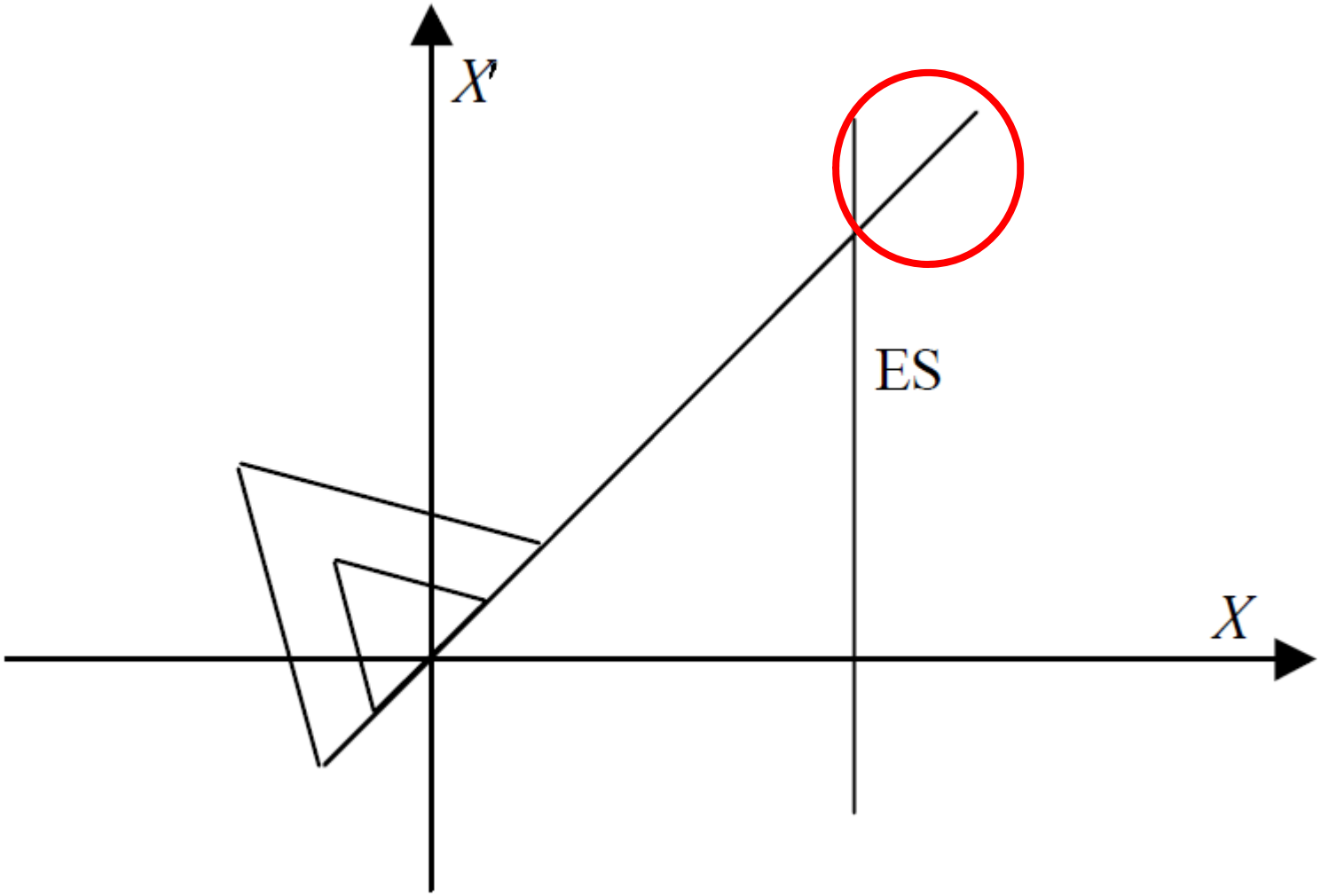
Carbon



1ms sampling frequency.
All shift included (also few Machine Dev.)

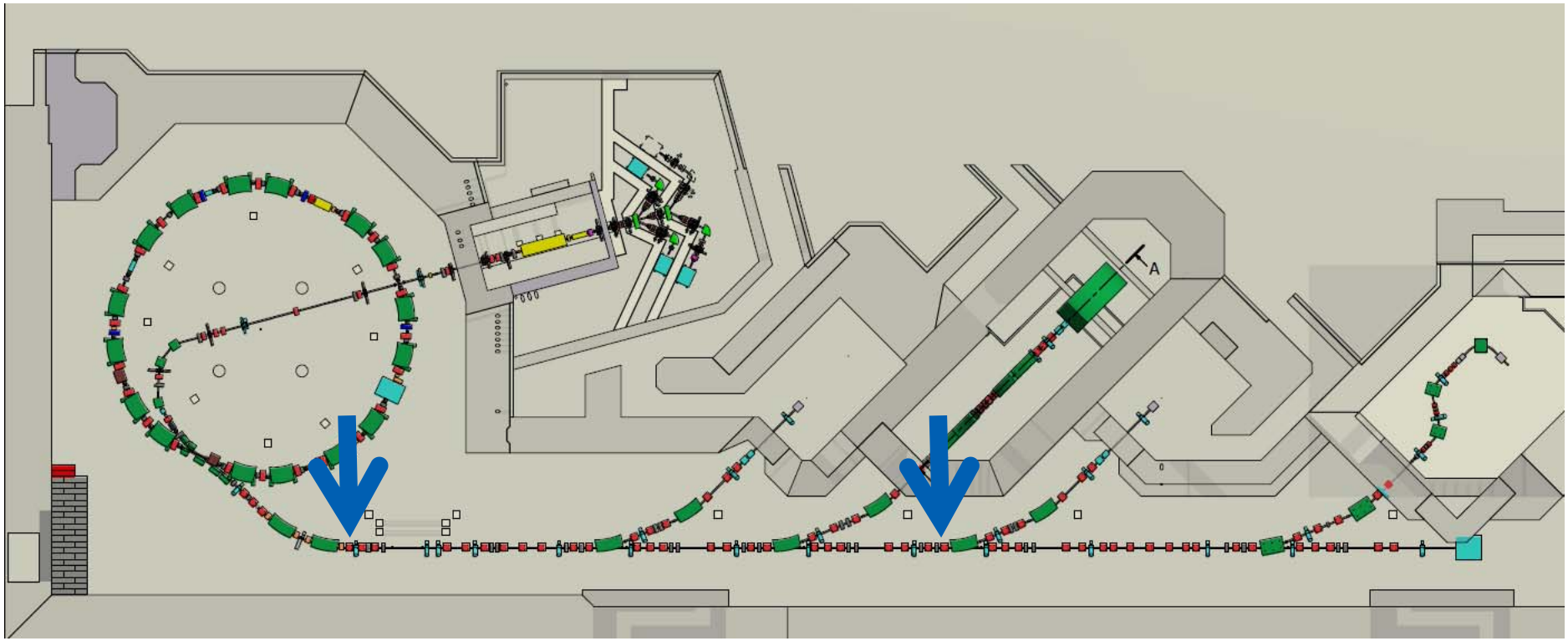
S. Waid, A. De Franco

Bar of charge



Bar of charge measurement at MedAustron

Use 8 monitors in the long straight section and match Twiss parameters

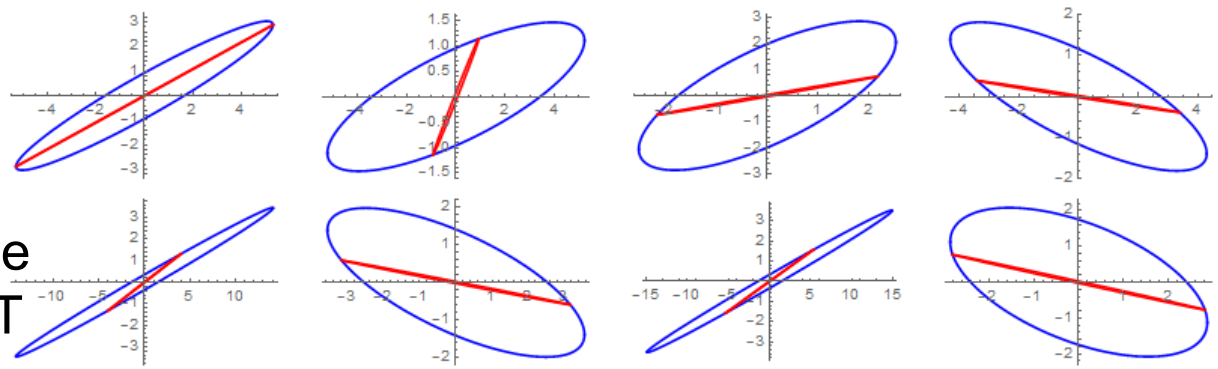


Bar of charge at MedAustron

Twiss parameters at EX-01-000-SFX-A from matching HWHM			
Ex [p mm mrad]	0.076	Ey [p mm mrad]	6.270
Bx	374.22	By	17.98
ax	-203.12	Ay	9.96
Gx	110.25	Gy	5.57

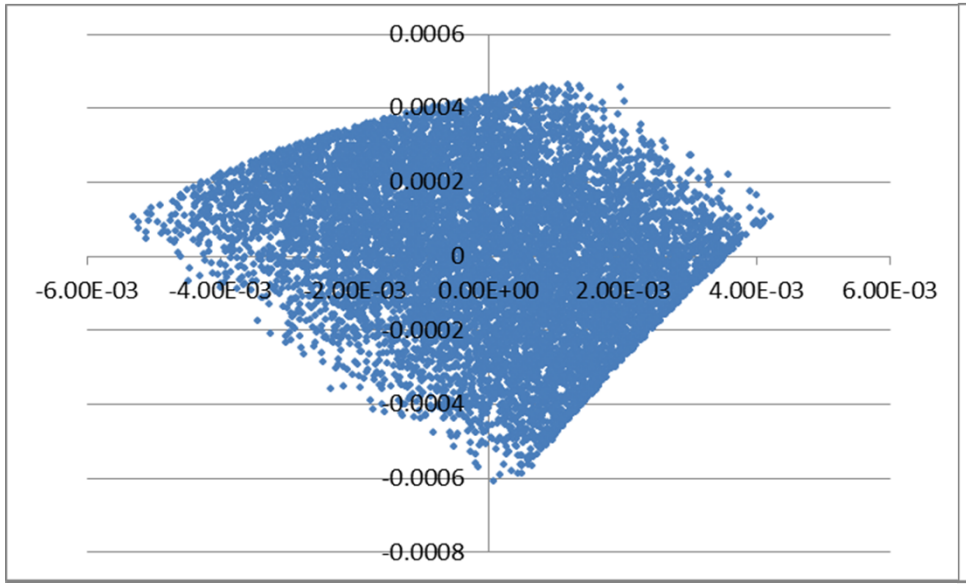
Beam size calculated with matched parameters and beam size measured				
62 MeV	CalcX	MeasX	CalcY	MeasY
EX-01-000-SFX-A	5.33	5.18	10.62	10.63
EX-01-001-SFX-A	0.93	0.87	3.34	3.37
EX-01-002-SFX-A	2.16	2.26	8.05	8.05
EX-01-003-SFX-A	3.40	3.30	3.21	3.14
EX-02-000-SFX-A	4.00	3.78	5.71	5.94
EX-02-001-SFX-A	3.16	3.35	3.21	3.27
EX-03-000-SFX-A	5.33	5.58	5.71	5.47

Bar of charge (red)
Drawn inside a
5π mm mrad empty ellipse
at 8 monitors in the HEBT



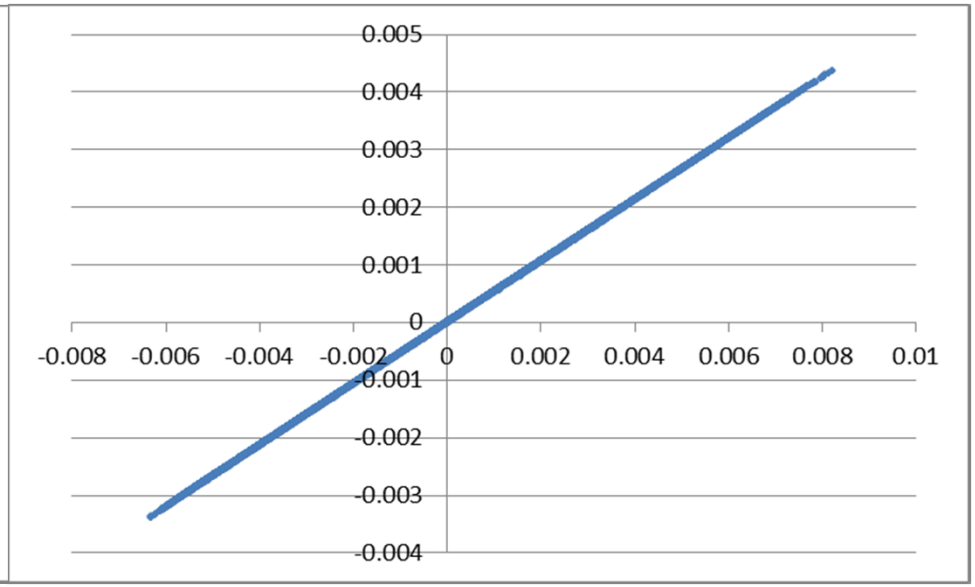
Courtesy of A. Wastl

Simulated particle distribution at magnetic septum



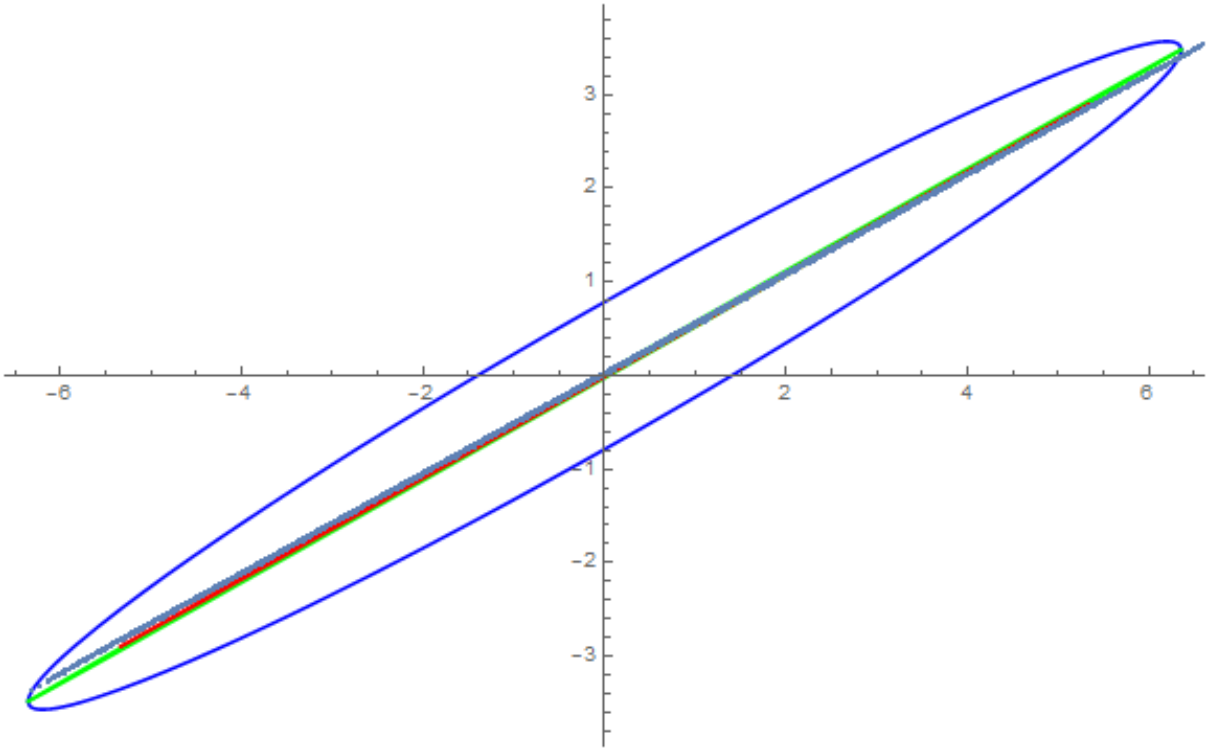
Dispersive region

Particles tracked at first monitor



Non dispersive region

Particles tracked at monitor
With measured ellipse and 5π empty ellipse

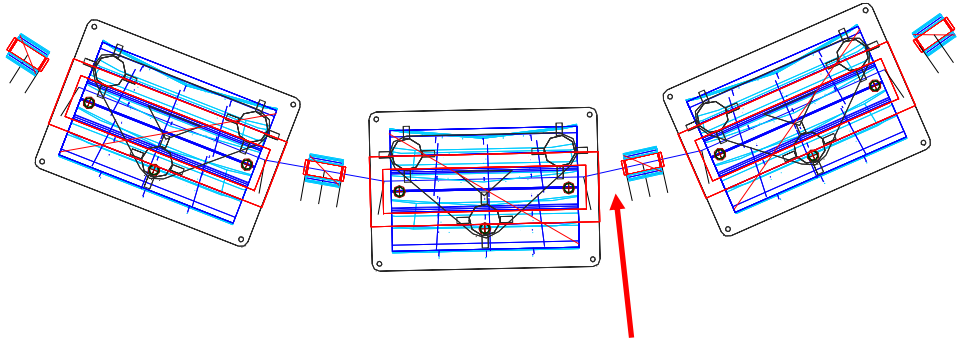


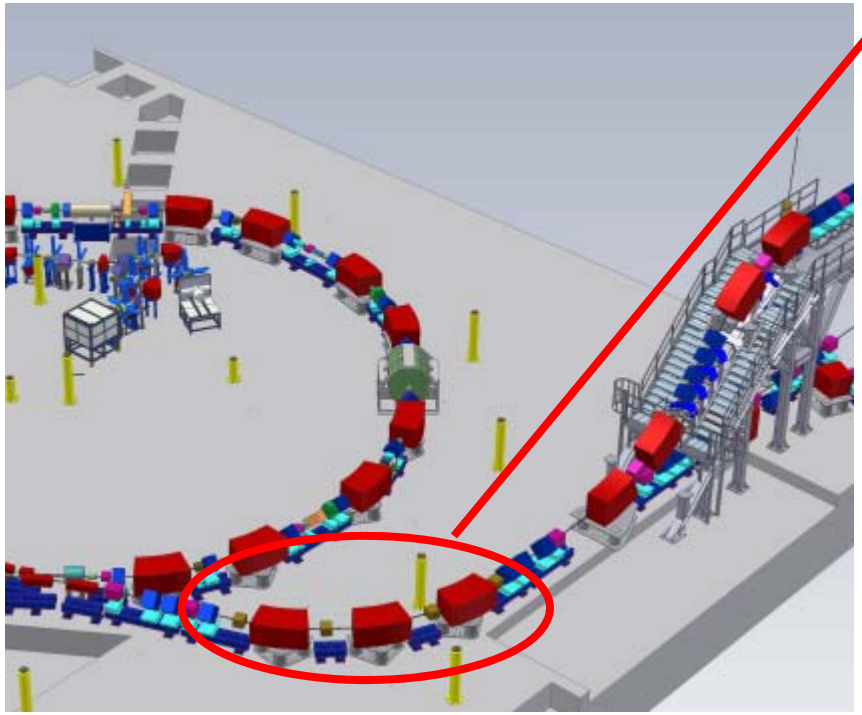
HEBT Chopper

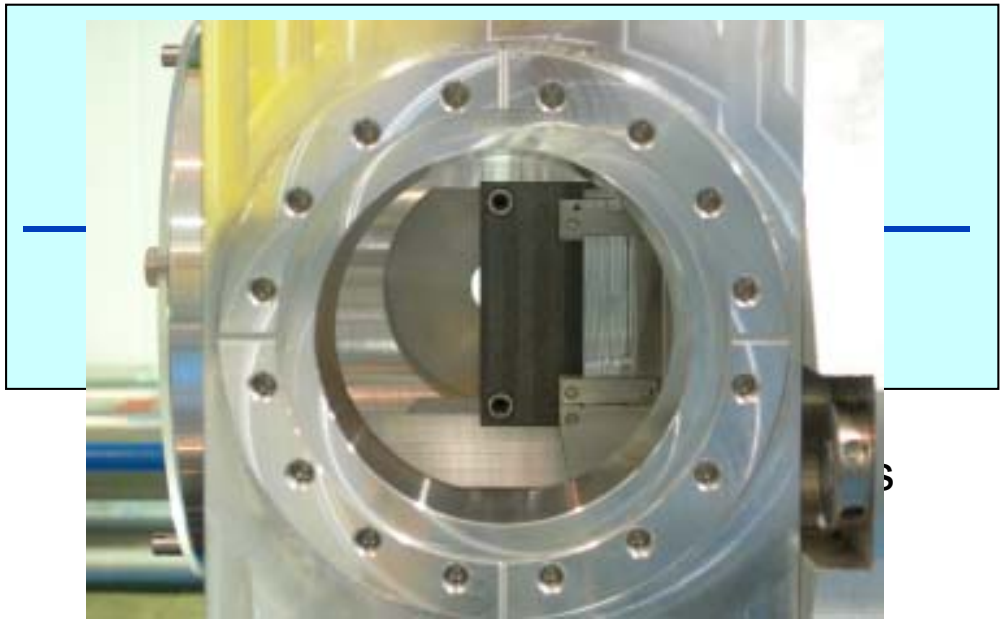
Fast turn on/off for the beam

Intrinsically safe

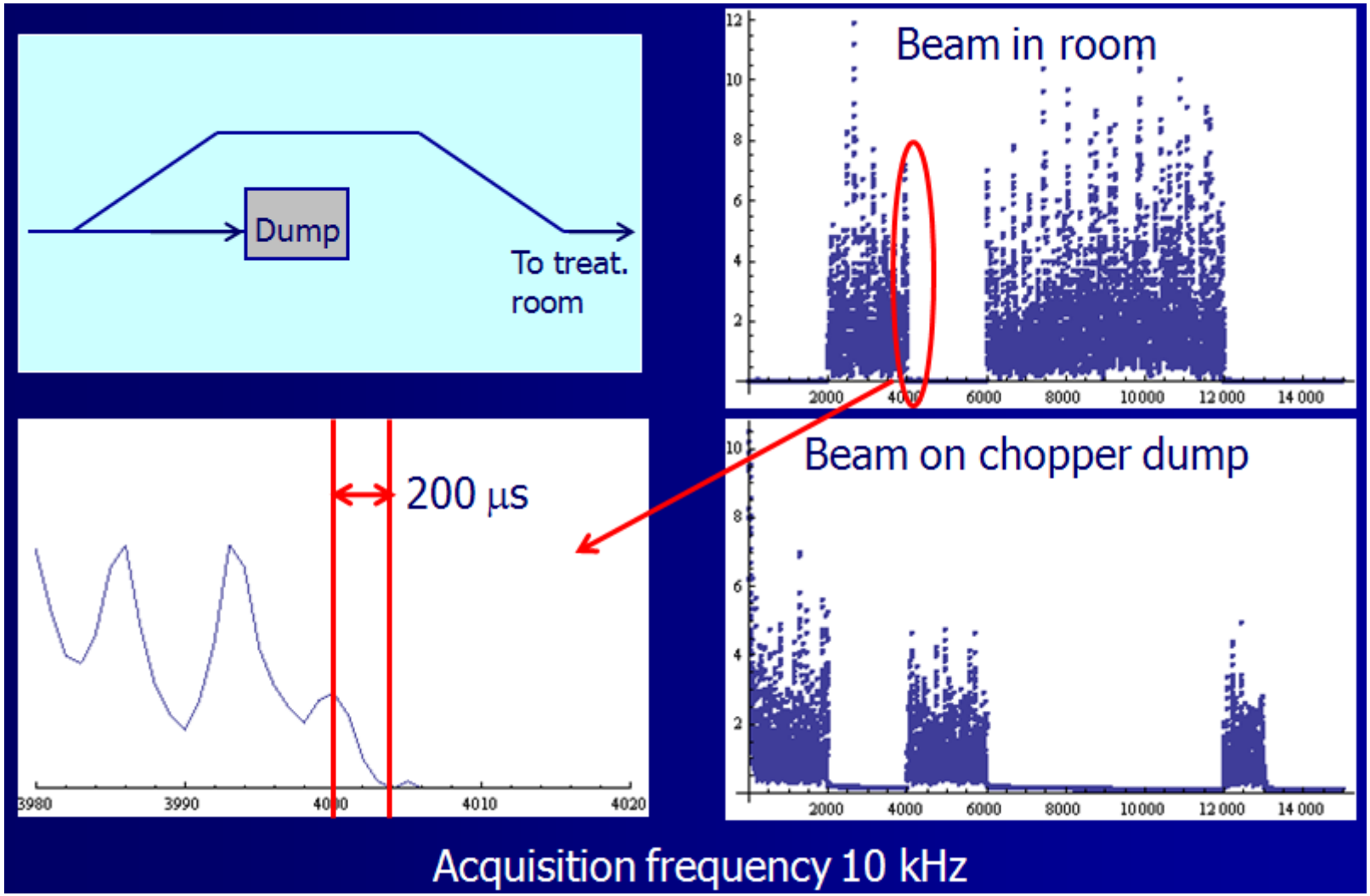
Allows beam qualification





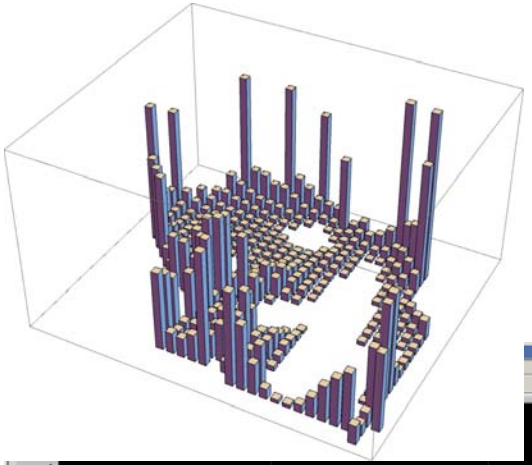


Chopped beam

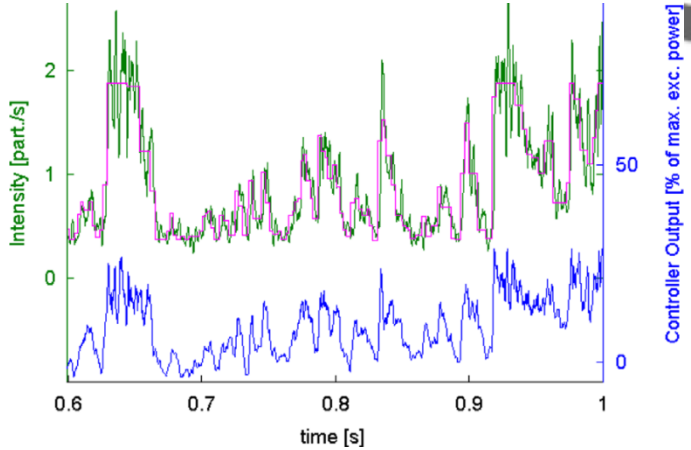


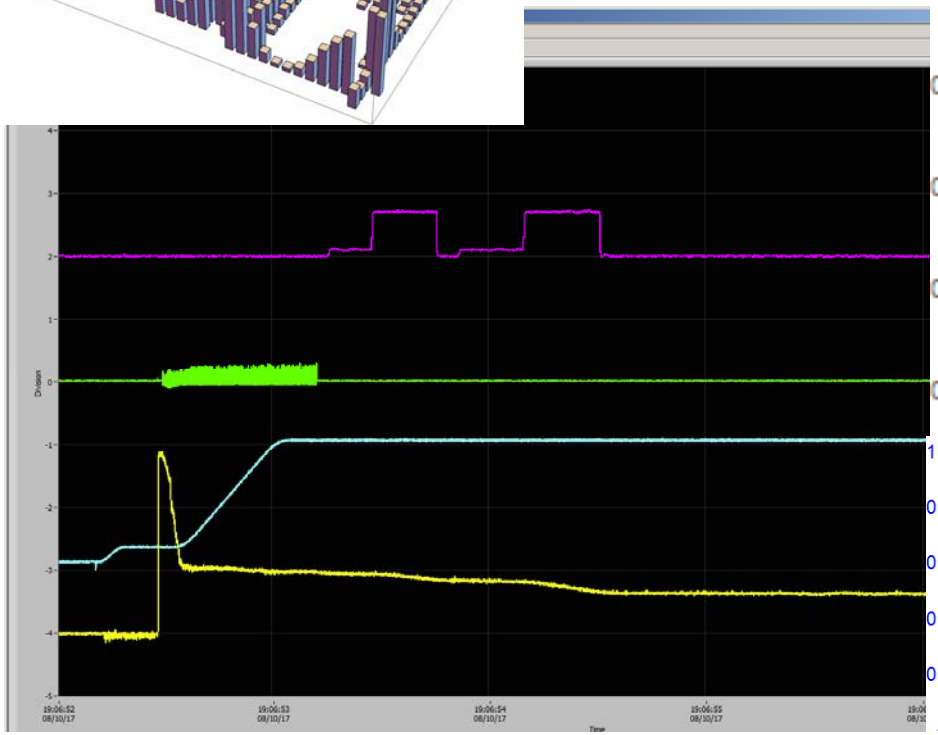
Schoemers et Al, NIM A 795 (2015) 92-99

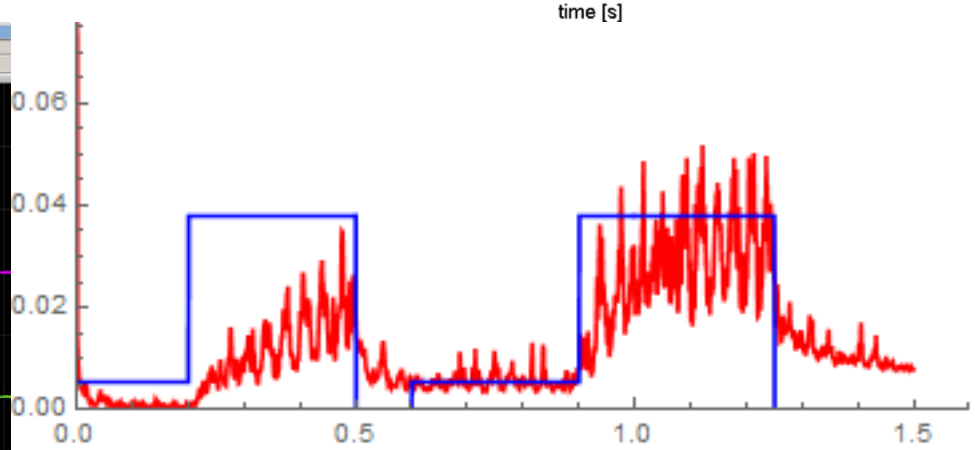
Intensity modulation

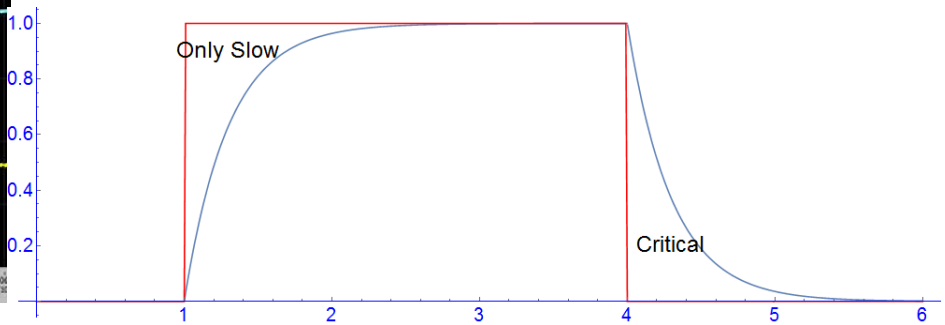


The number of required particles varies a lot in spots of the same slice. Adapt intensity to spot!



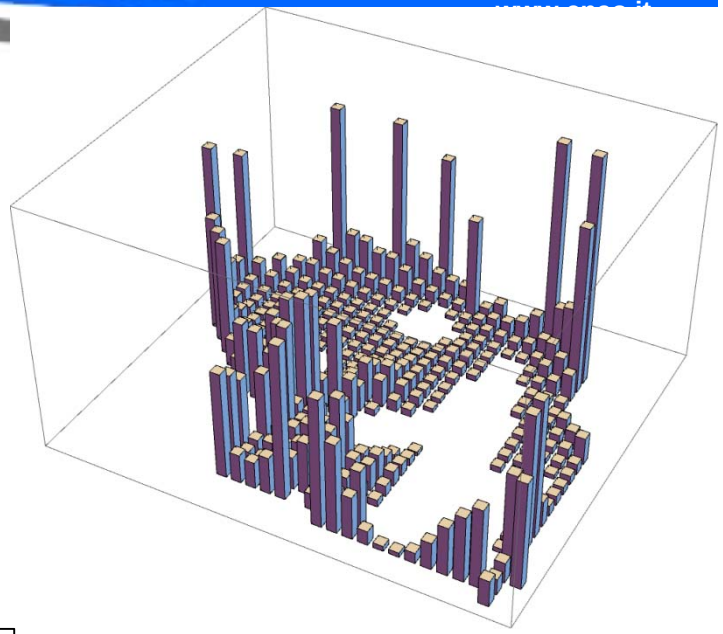


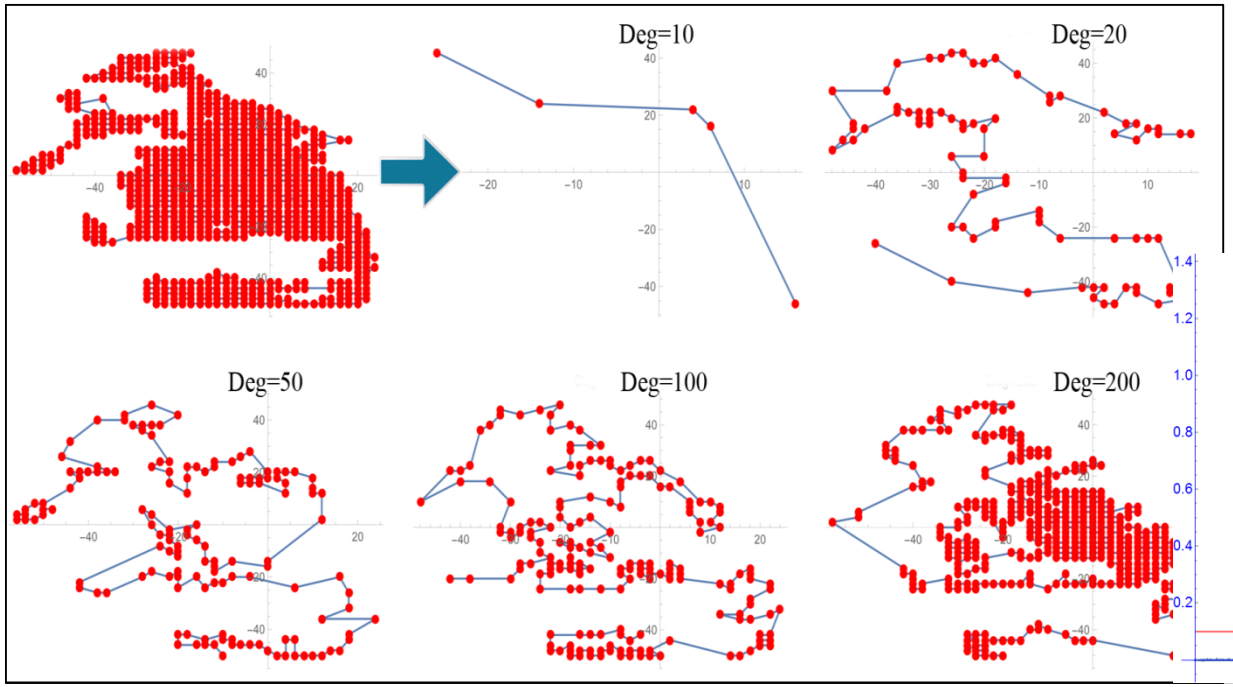


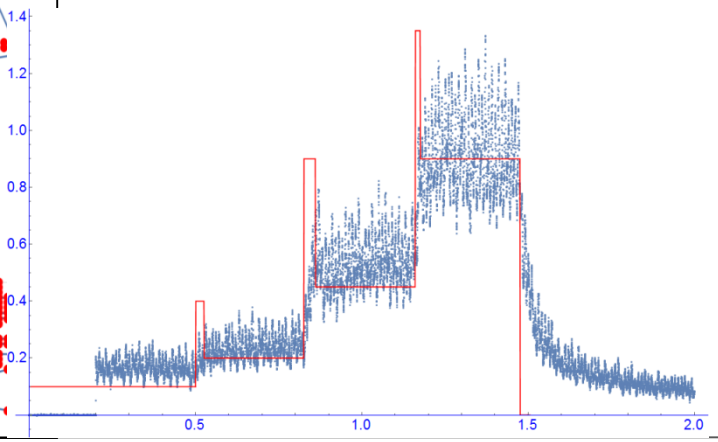


Intensity modulation

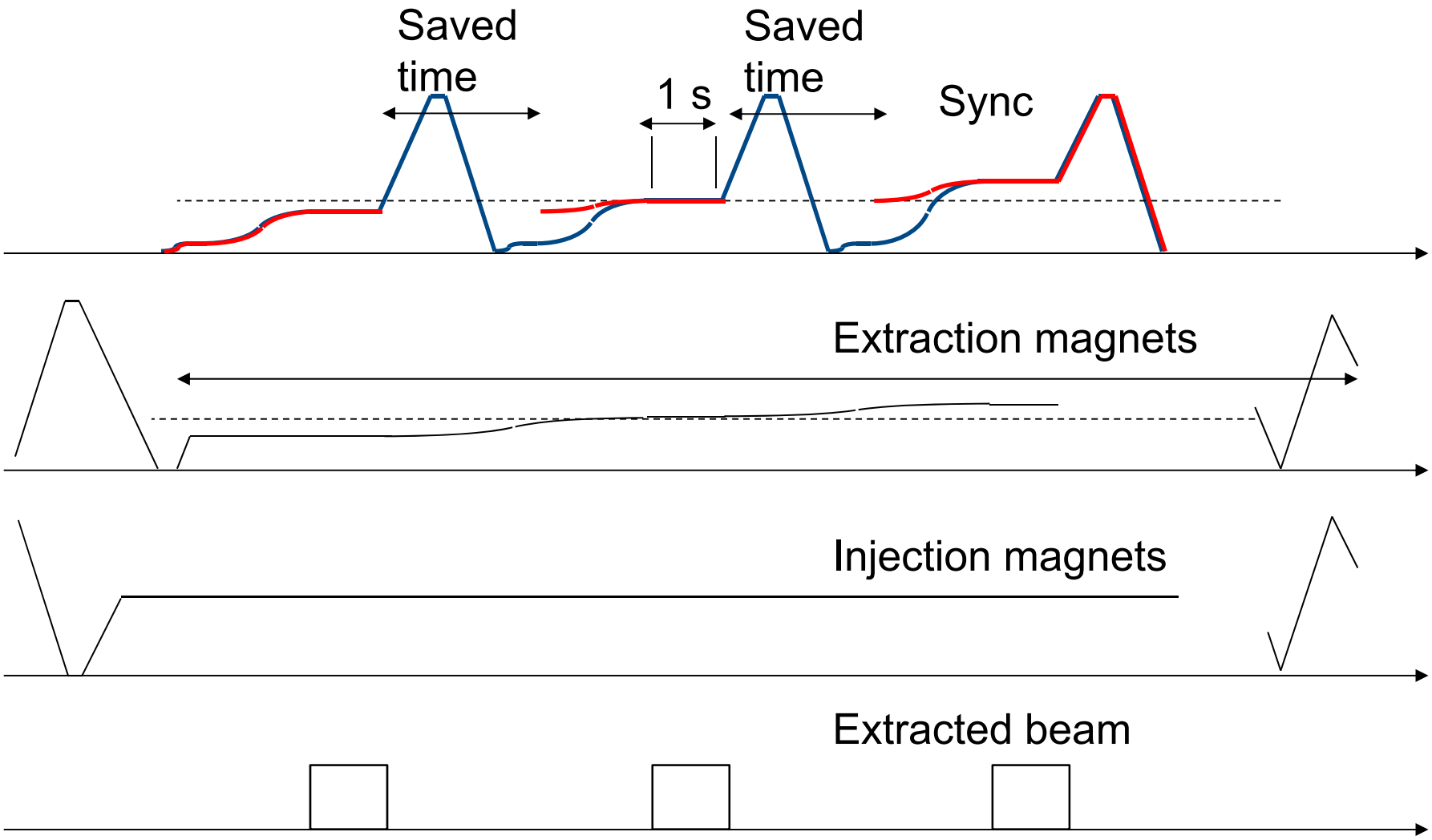
Subdivide slice in classes and re-sort in order to treat spots with increasing intensity.





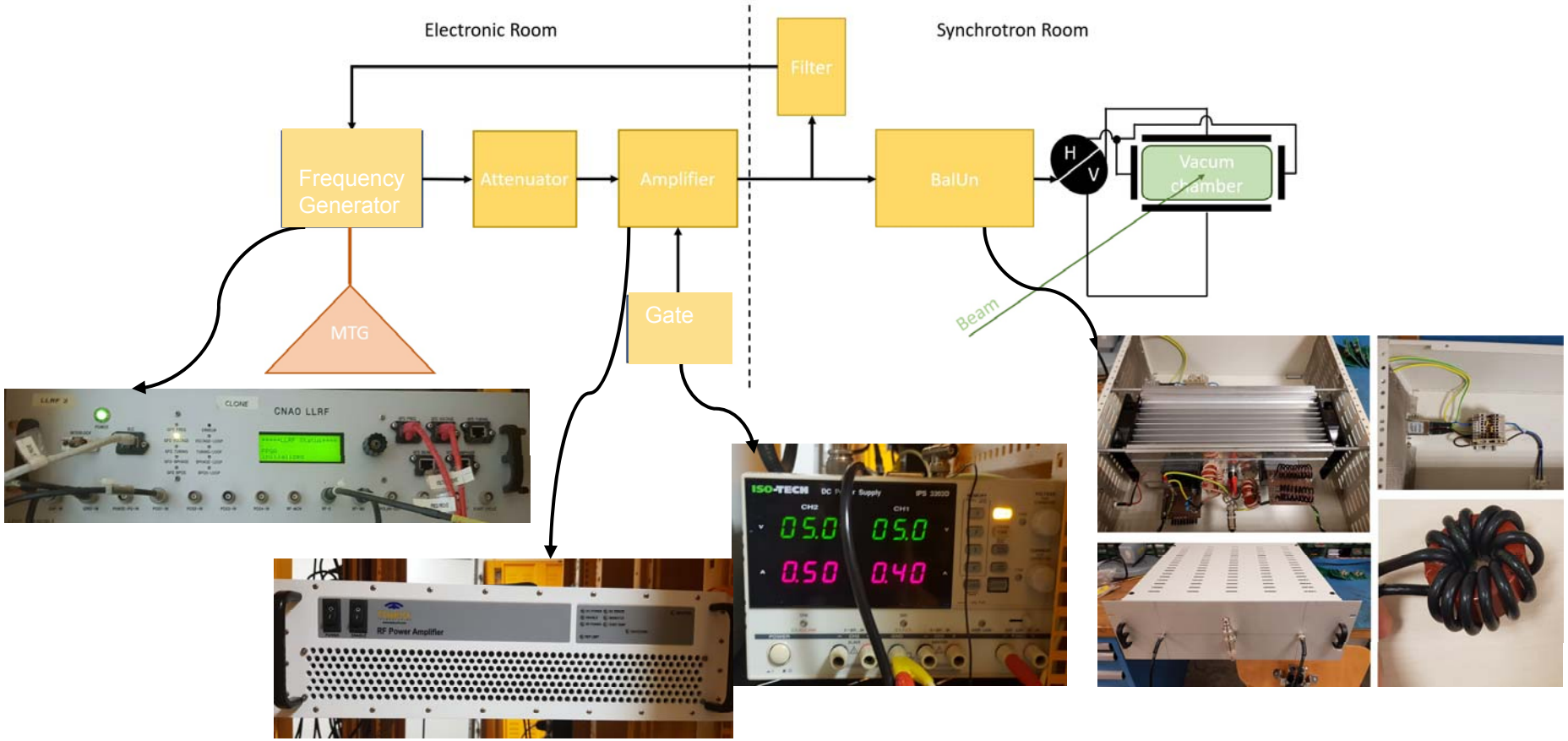


Multi-Energy Extraction



RFKO kicker in place

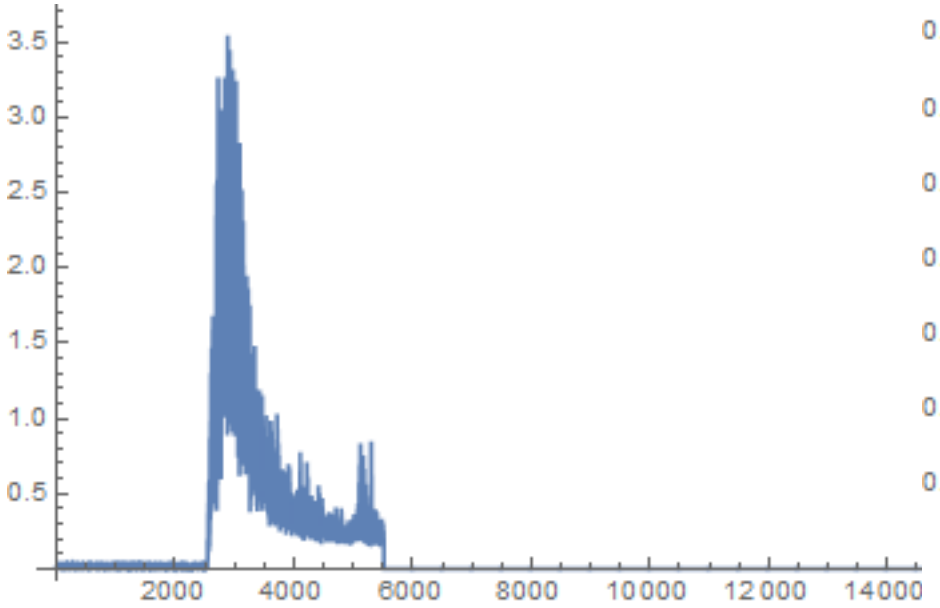
RFKO installed



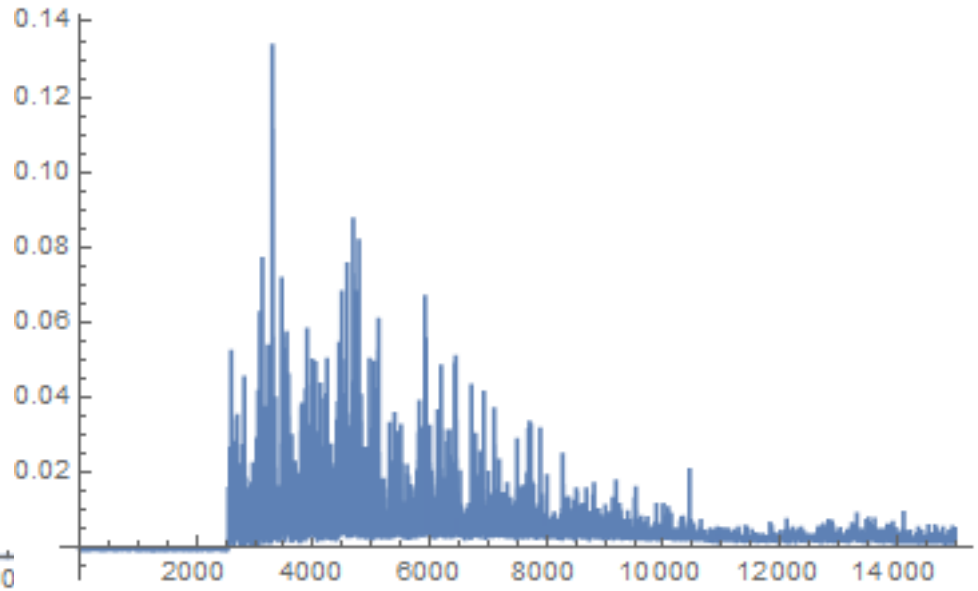
RFKO Commissioning started

VERY preliminary

Bunched RFKO



Debunched RFKO



Work just started and low priority, still low extraction efficiency,
many aspects still to be understood and implemented… more to come

Recent news and short future

CNAO

- Experimental room under commissioning
- Single room facility for protons being acquired
- Third source for other ions

MedAustron

- Carbon treatments started
- Gantry installation coming soon
- First rotator

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. Feynmann

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica