The S2C2 from source to extraction

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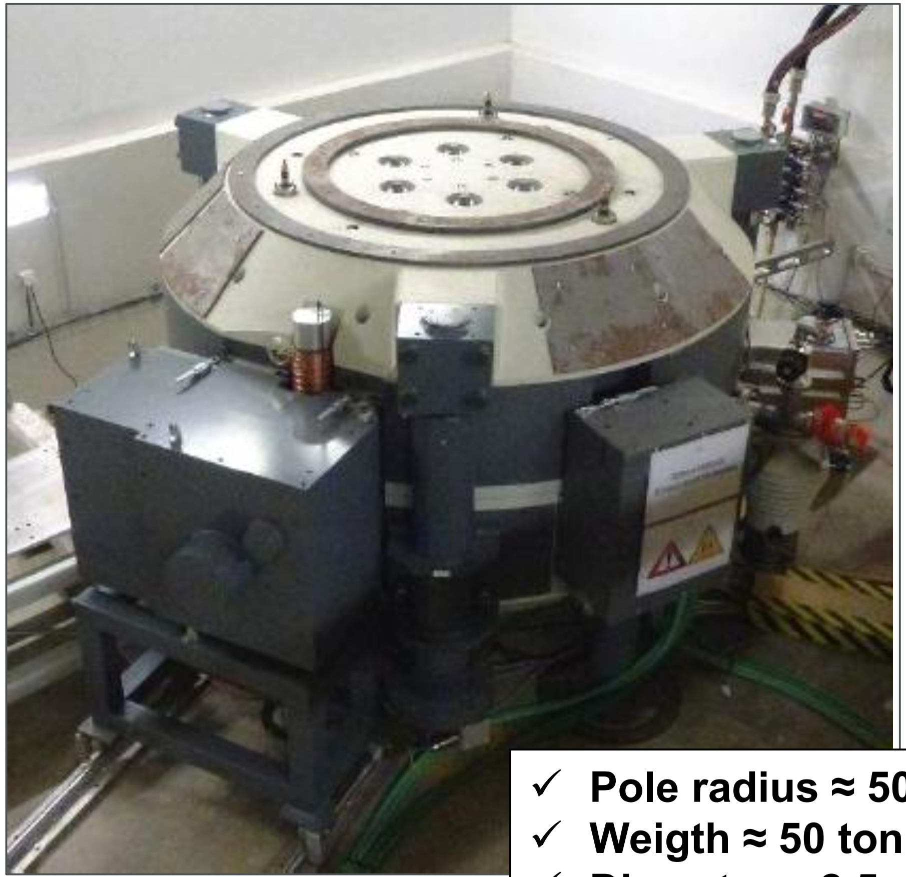
The S2C2 : from source to extraction

S2C2 = SuperConducting SynchroCyclotron

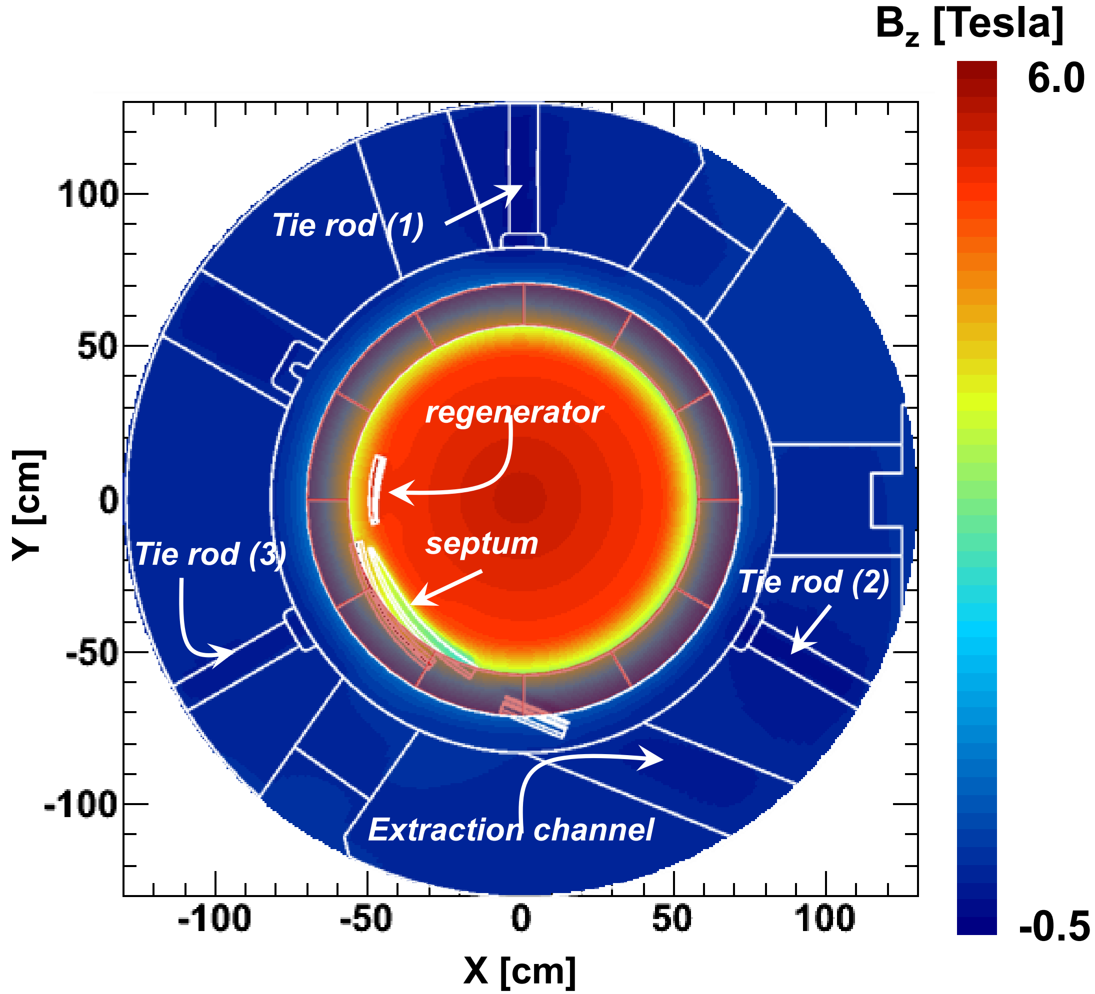
- **General properties**
  - ✓ Layout, RF and magnetic properties
- **Injection**
  - ✓ orbit centering and separatrix filling
- **Acceleration**
  - ✓ The “phase motion code” : RF phase, energy and orbit center tracking
  - ✓ Beam losses
- **Extraction**
  - ✓ Coil positioning, energy, emittance, efficiency, lost protons, …

General properties

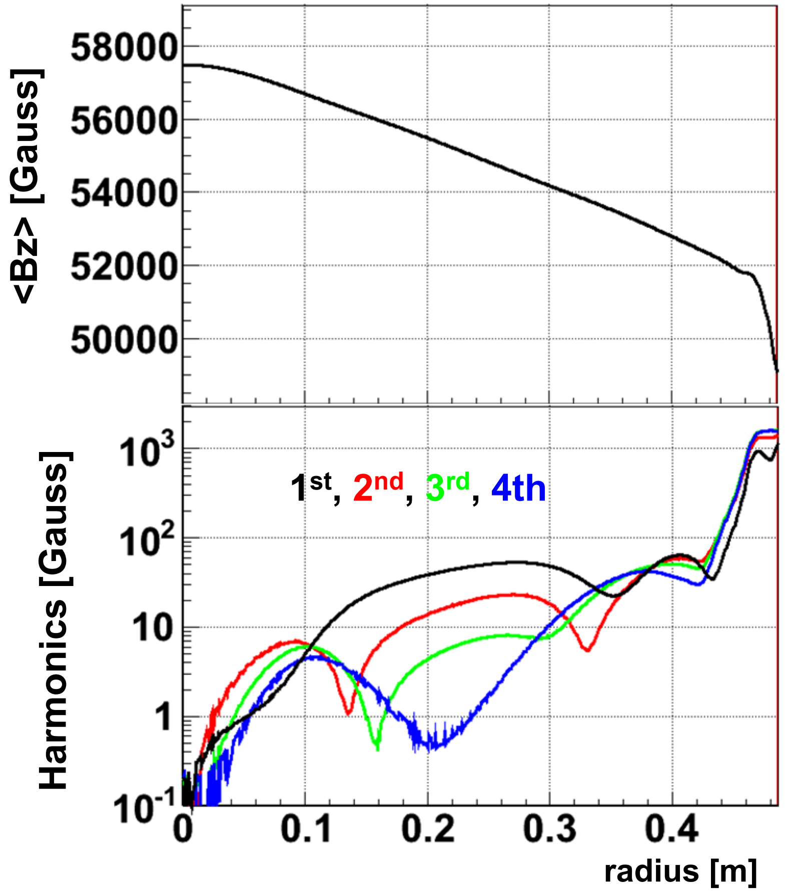
General properties : layout

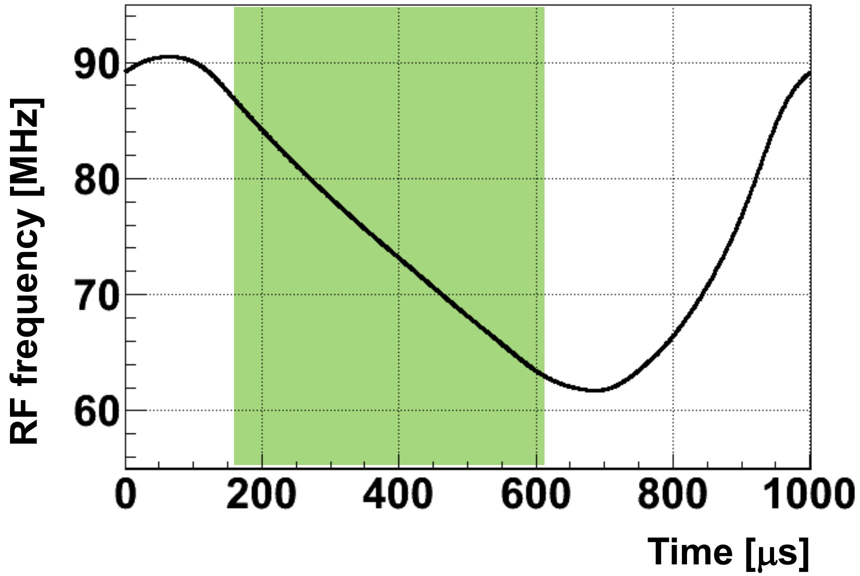


- ✓ **Pole radius ≈ 50 cm**
- ✓ **Weigth ≈ 50 ton**
- ✓ **Diameter ≈ 2.5 m**



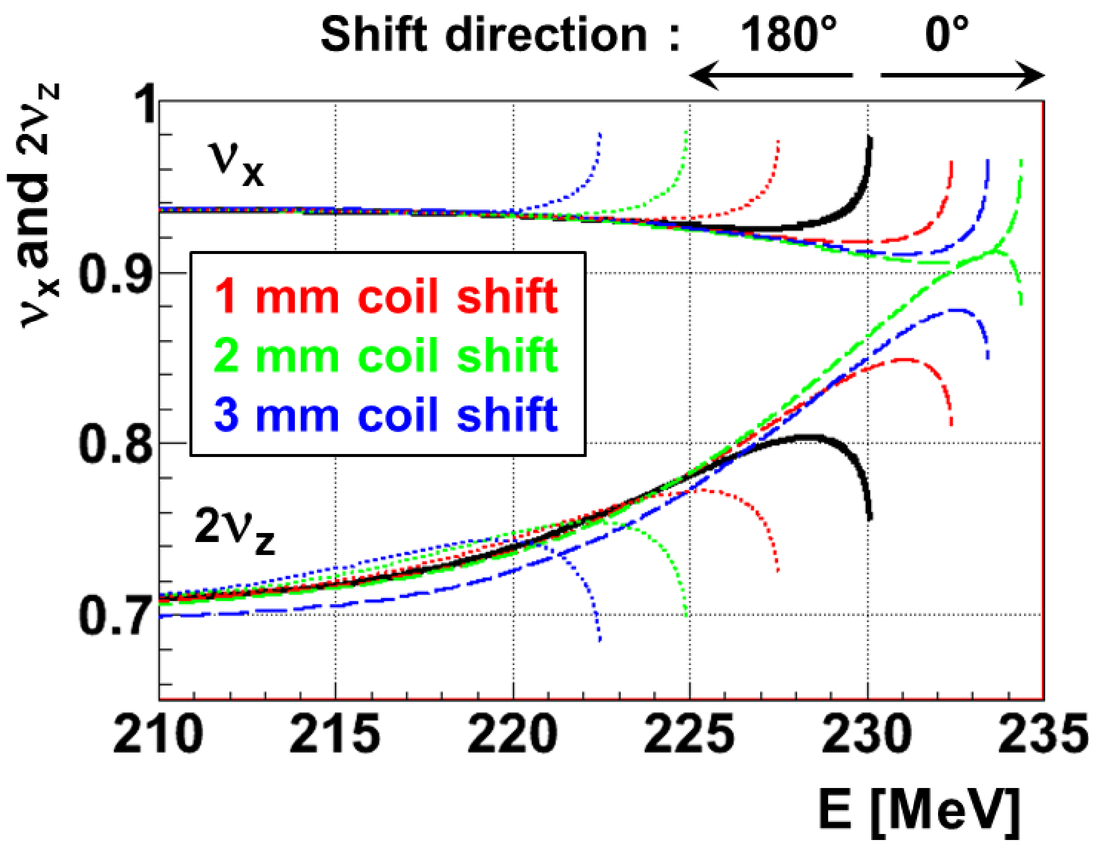
General properties : harmonics and frequency sweep





- ✓ Weak focusing – peak field = **6.1 T** (regenerator)
- ✓ Frequency modulation (**90→60 MHz**) @ **1 kHz** ⇨ pulsed beam
- ✓ Dee voltage : **7 → 10 kV**
- ✓ Injection frequency **87 MHz**
- ✓ Extraction frequency **63 MHz**
- ✓ Acceleration time ≈ **450 μs**
- ✓ Half-integer regenerative extraction (**$2\nu_r=2$**)

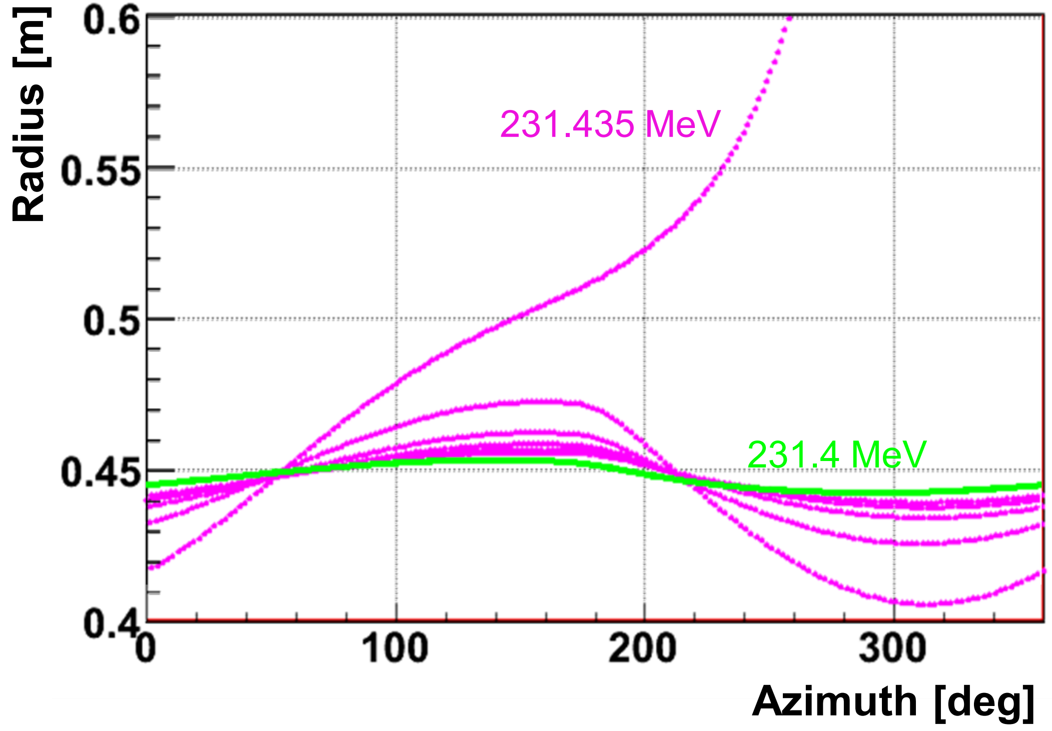
General properties : horizontal coil position

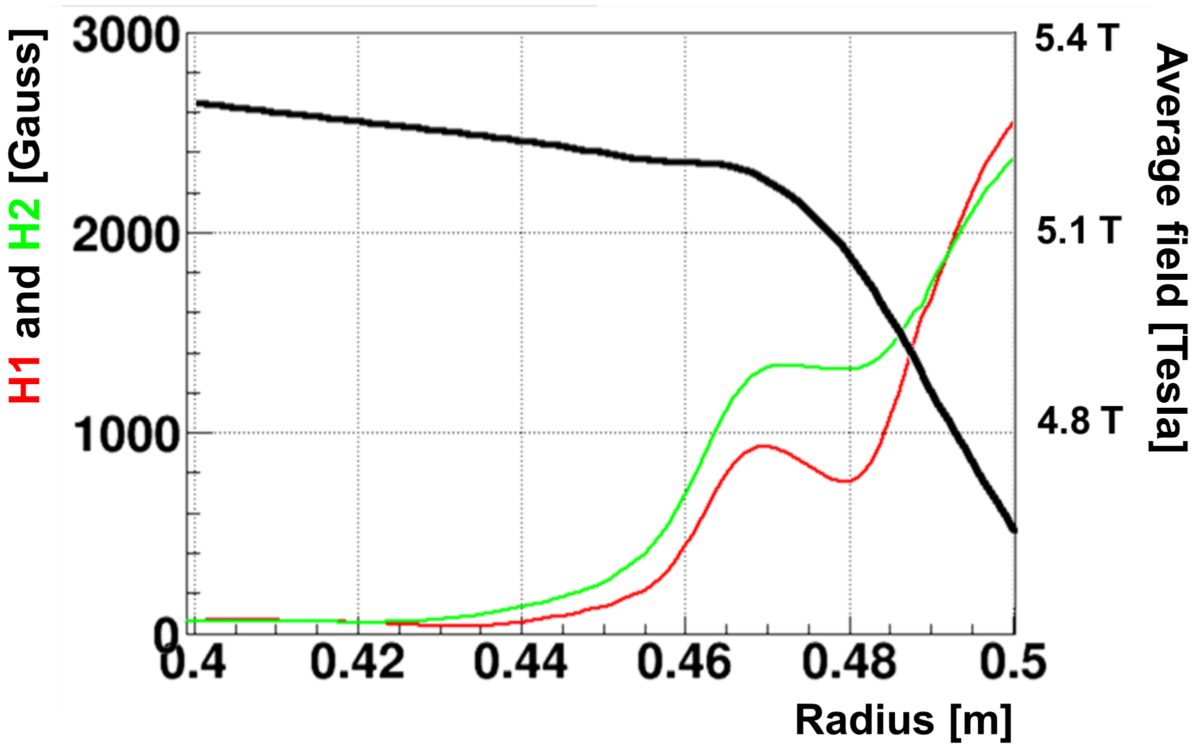


The horizontal coil position determines :

- proximity of the Walkinshaw resonance
- extraction energy ($\nu_r \rightarrow 1$)

General properties : half-integer regenerative extraction





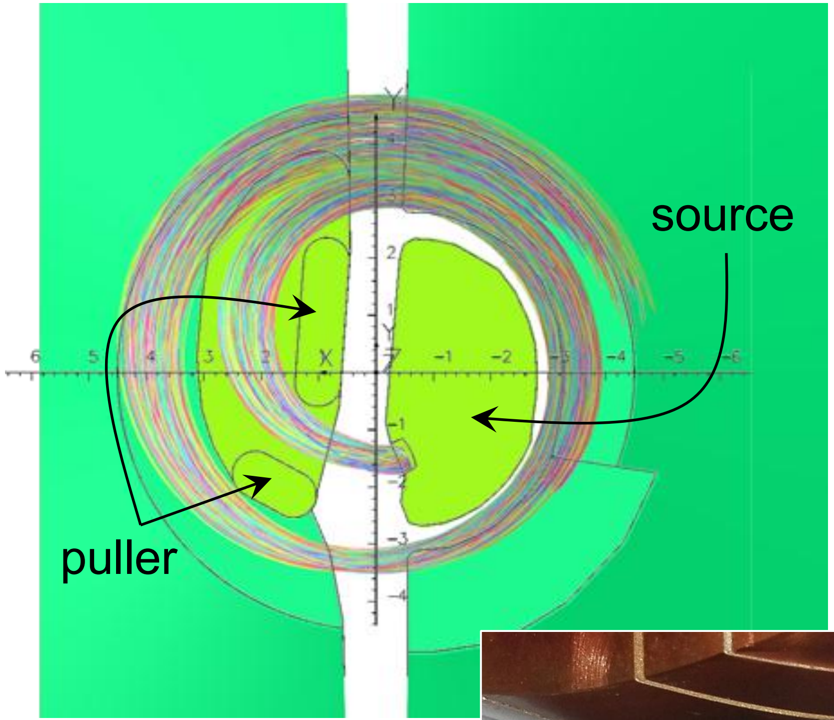
✓ **Last stable closed orbit in the S2C2 (231.4 MeV) : $\nu_r \rightarrow 1$**

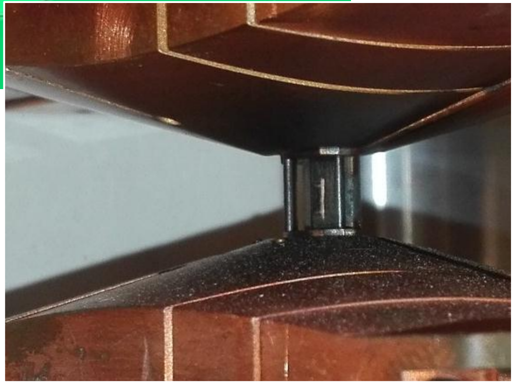
✓ **$2\nu_r$=2 resonance : the orbit center becomes unstable**
✓ **≈ 5 more turns before the proton is extracted**

Injection

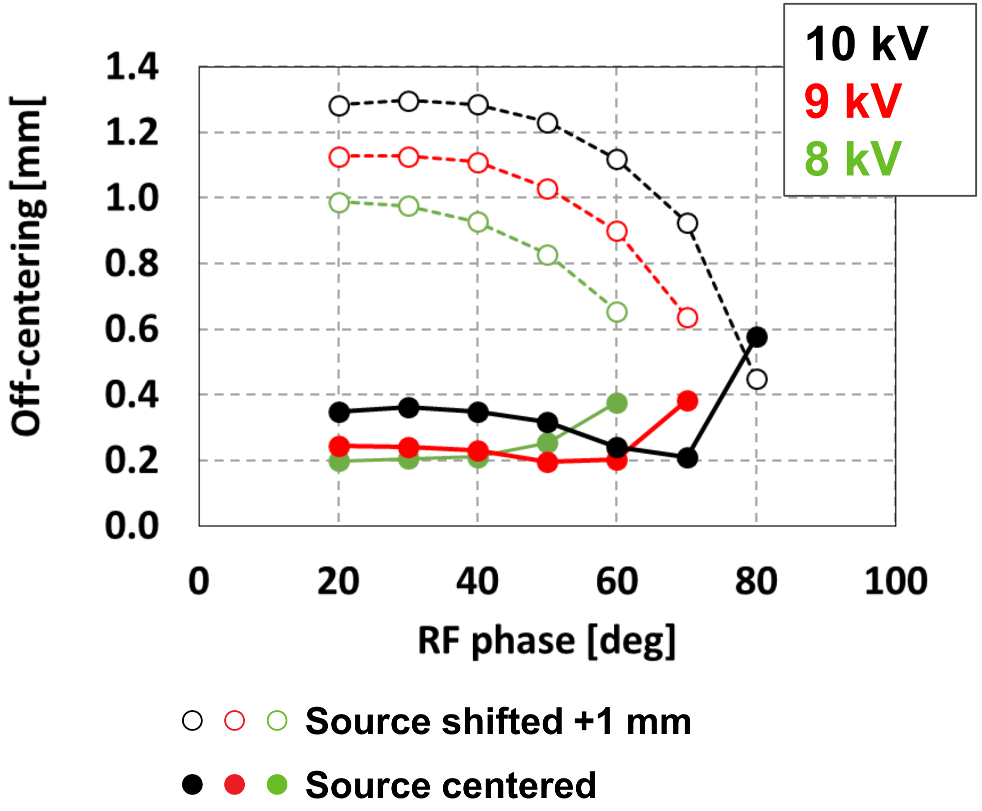
Injection : orbit centering at injection (1)

- ✓ 1st turn radius ≈ 3 mm



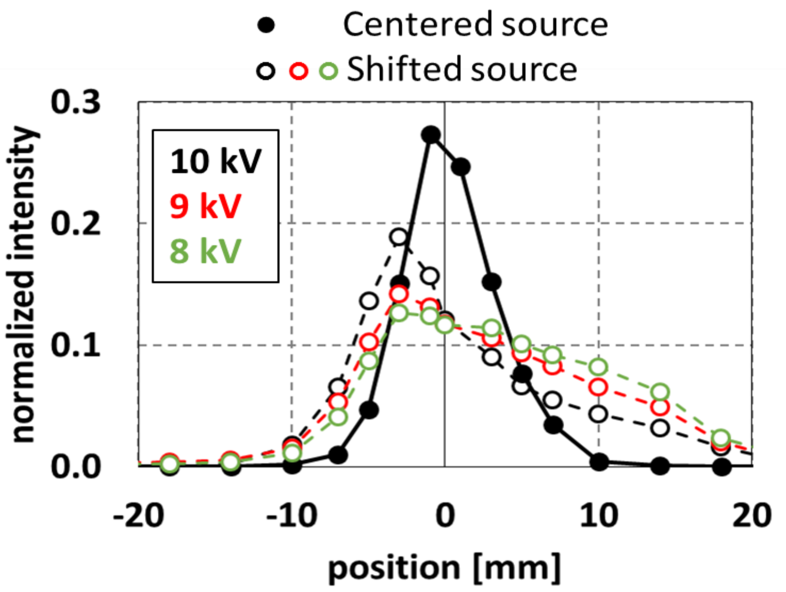


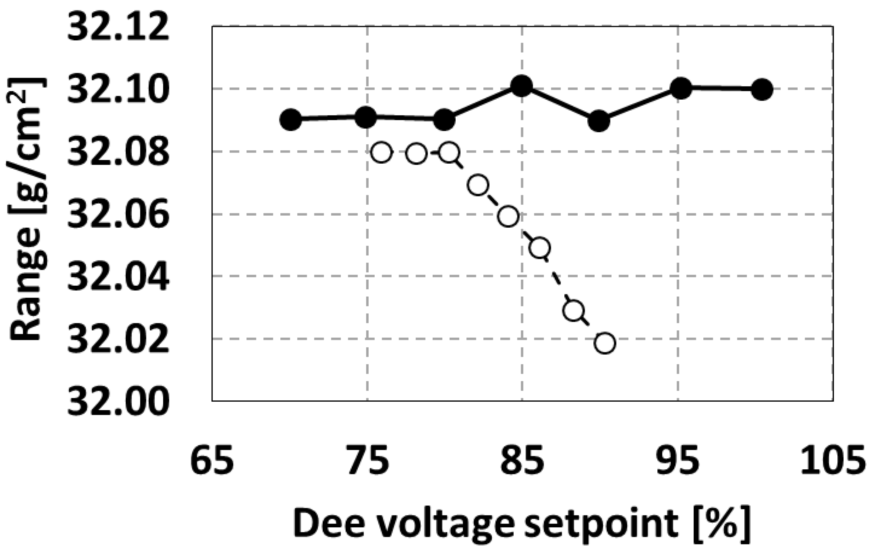
- ✓ Orbit center after 30 turns



Source positioning is very delicate !
Consequences for extraction energy !

Injection : orbit centering at injection (2)





- ✓ Jump forward – into the gantry – at the end of the energy selection system

See TUP07 (poster session Tuesday)

- ✓ Jump forward : at isocenter – range measurements in a water phantom

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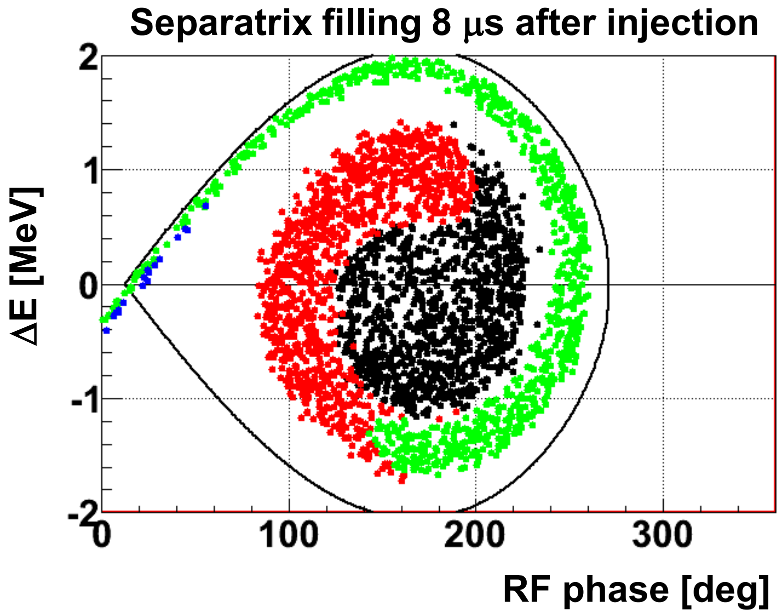
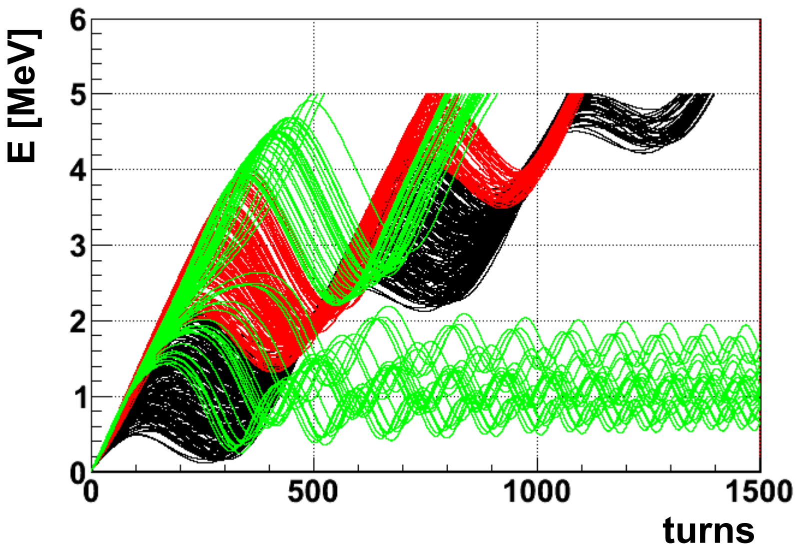
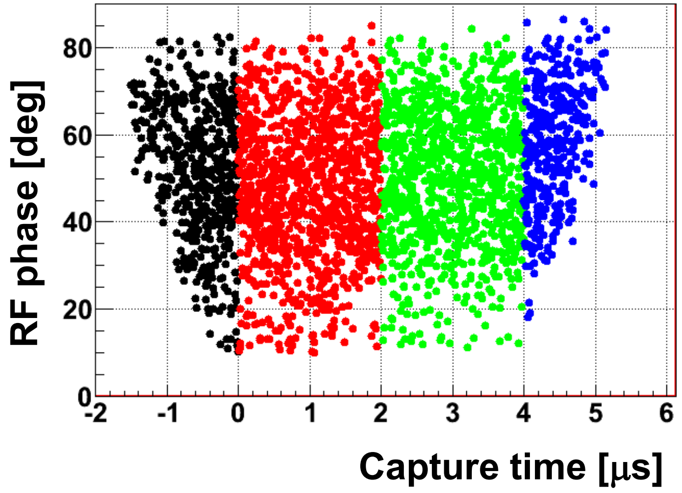
Injection : separatrix filling







- ✓ Protons near the border of the separatrix are captured “late”
- ✓ The total injection time is about 5 μs

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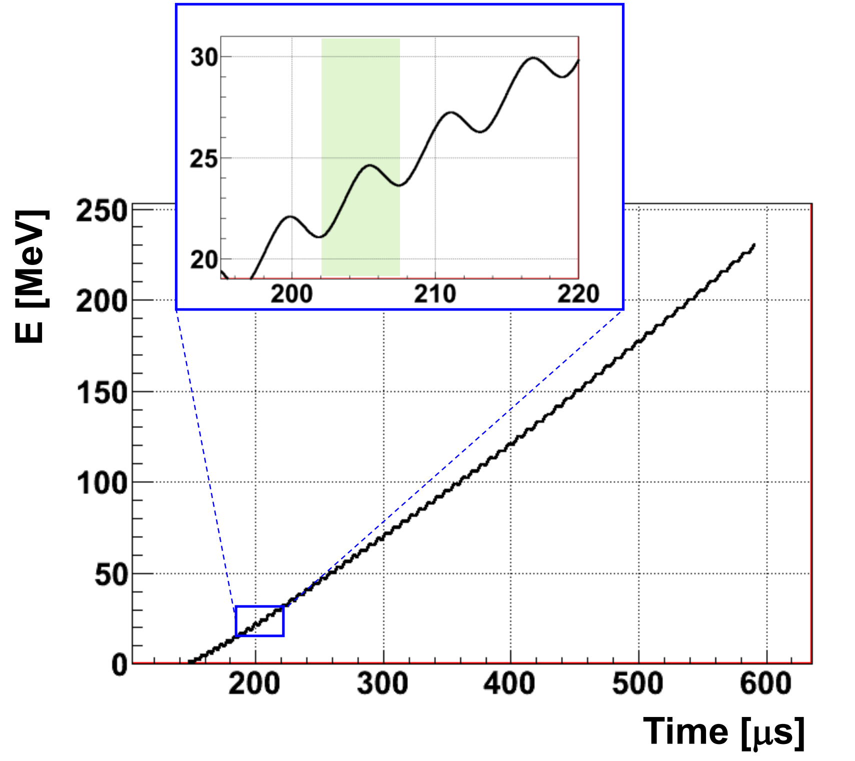
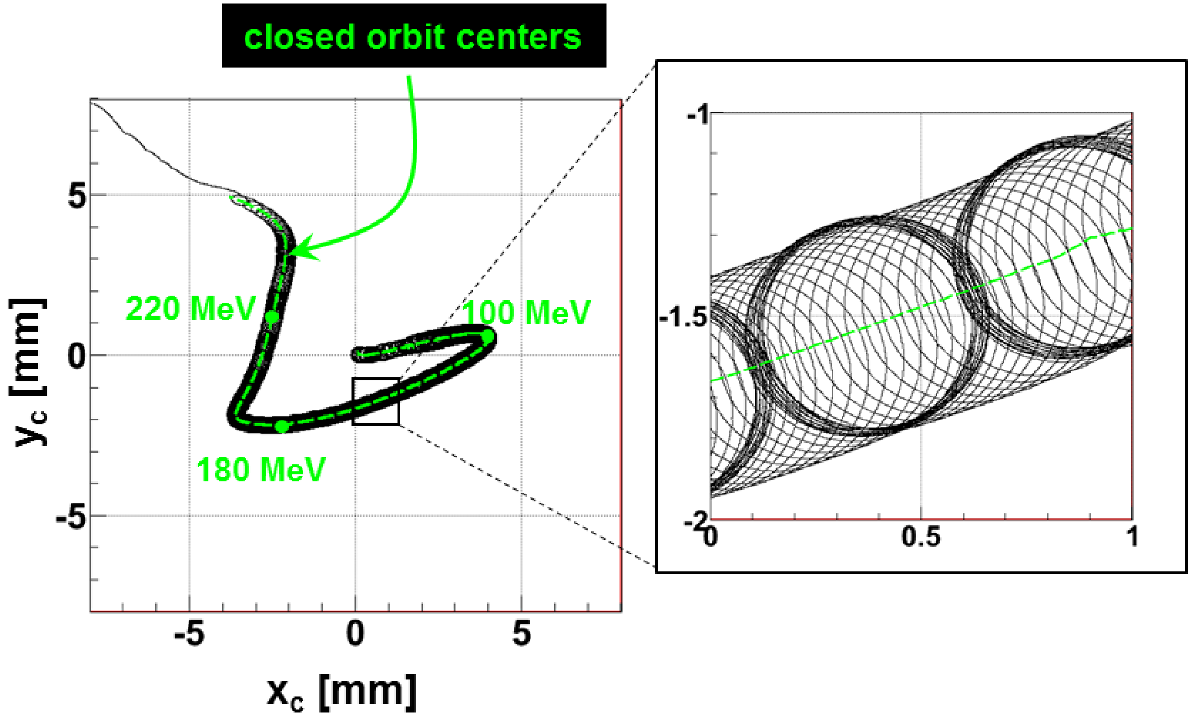
Acceleration

Acceleration : detailed tracking of protons

- ✓ Simulating **~50.000 turns from source to extraction**
- ✓ **"Advanced Orbit Code"** (AOC) by W. Kleeven : full tracking in magnetic and electric field maps (time consuming : ~30' / proton)

Synchrotron period @ 22 MeV = 7.4 μs or ≈ 600 turns





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Acceleration : the « phase motion » code

- ✓ Simulating **~50.000 turns from source to extraction**
- ✓ **“Advanced Orbit Code”** (AOC) by W. Kleeven : full tracking in magnetic and electric field maps (time consuming : ~30’ / proton)

- ✓ **ALTERNATIVE** : tracking of **main beam properties** (phase motion code)

Energy $$\frac{dE}{dt} = e.F_{RF}.V_{RF}.\sin(\varphi)$$

RF phase $$\frac{d\varphi}{dt} = 2\pi\left(F_{RF} - F_p\right)$$

Orbit center $$\frac{dx_c}{dt}, \frac{dy_c}{dt}$$

E = kinetic energy of the proton
F_{RF} = frequency of the RF system
F_p = revolution frequency of the proton
V_{RF} = voltage on the dee
φ = RF phase of the proton

Input :
1/ AOC beam properties at 3 MeV
2/ measured : B(r) and F_{RF} (*)
3/ closed orbits : B(r), E, F_p

(*) measured frequency profiles have to be smooth to integrate the phase with high precision !

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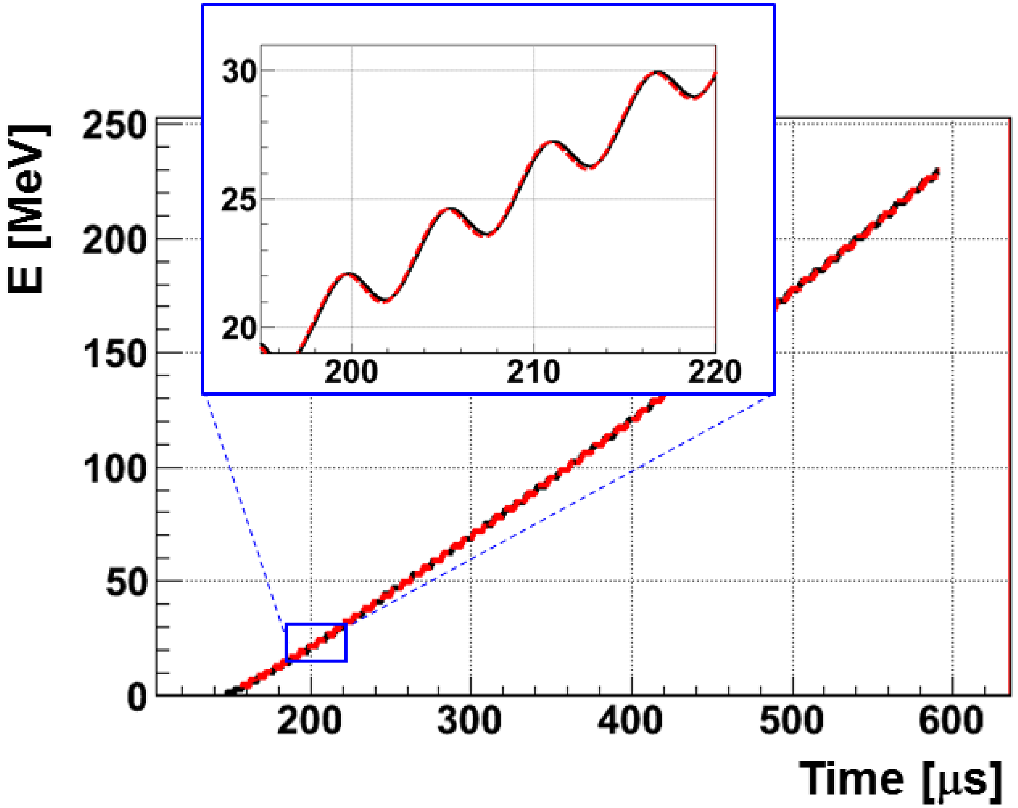
Acceleration : energy and RF phase tracking

✓ Energy and RF phase tracking : comparison with AOC



✓

Energy	$\frac{dE}{dt} = e.F_{RF}.V_{RF}.\sin(\varphi)$
RF phase	$\frac{d\varphi}{dt} = 2\pi\left(F_{RF} - F_p\right)$

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Acceleration : orbit center tracking

✓ Equations of motion for the orbit center are derived from the following Hamiltonian
*[Hagedoorn and Verster, NIM **18,19** (1962) p. 201-228]*

$$H(x_c, y_c) = \frac{r}{2}\left(\bar{A}_1 x_c + \bar{B}_1 y_c\right) + \frac{1}{2}\left(\nu_r - 1 + \frac{1}{2}A_0'\right)\left(x_c^2 + y_c^2\right)$$
$$+ \frac{1}{4}(A_2 + \frac{1}{2}A_2')\left(x_c^2 - y_c^2\right) + \frac{1}{2}(B_2 + \frac{1}{2}B_2')x_c y_c$$
$$+ \frac{1}{48r}\left(D_1[4x_c^3 - 3x_c(x_c^2 + y_c^2)] + D_2[3y_c(x_c^2 + y_c^2) - 4y_c^3]\right.$$
$$\left. + [D_3 x_c + D_4 y_c]\left[x_c^2 + y_c^2\right]\right) + \mathcal{O}(4)$$

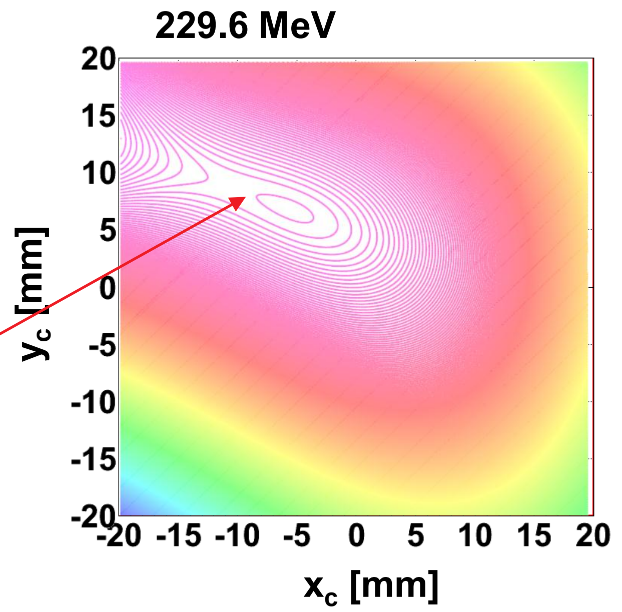
Average field | 1st harmonic | 2nd harmonic | 3rd harmonic

INPUT = detailed and smooth magnetic map

Orbit center motion

$$\frac{dx_c}{dt}, \frac{dy_c}{dt}$$

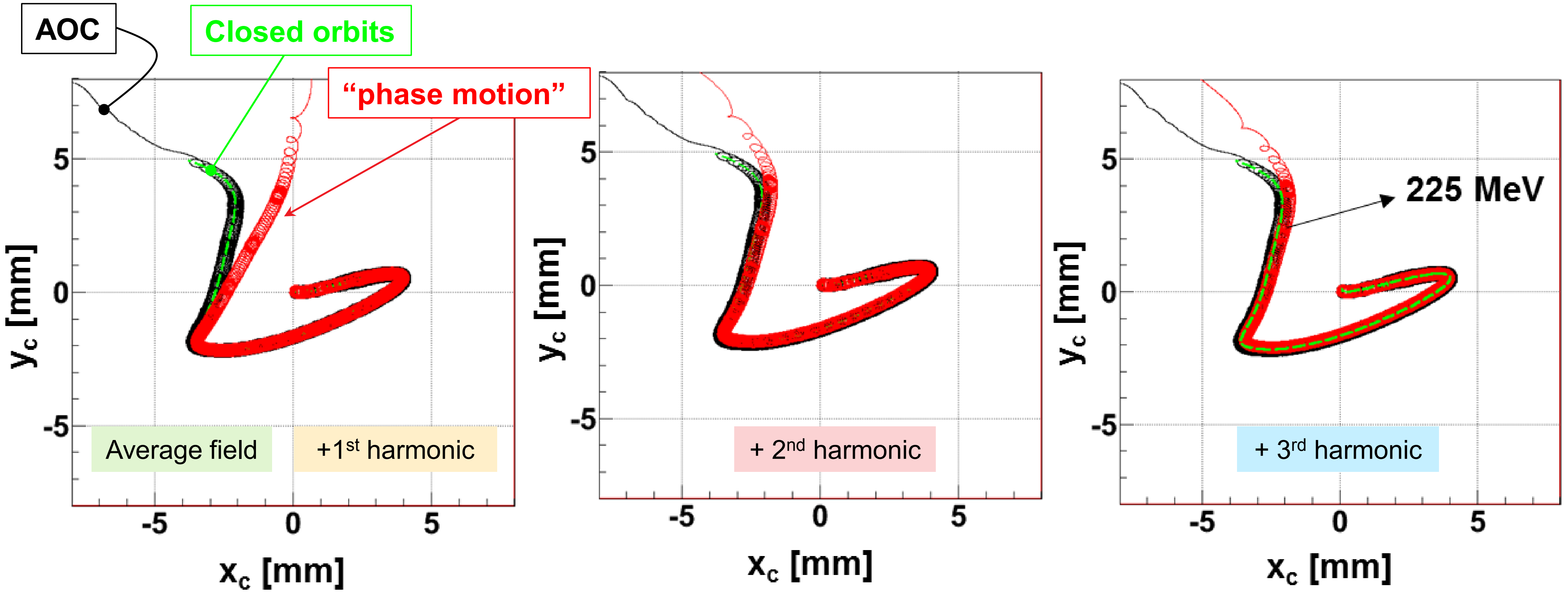
✓ Potential energy surfaces



Instability of the orbit center !

Acceleration : orbit center tracking

- ✓ Comparison of orbit center motion : AOC vs phase motion
- ✓ **Up to 3rd harmonics** included in "phase motion" code



Acceleration : applications of the « phase-motion » code

<u>Application of the code :</u>

✓ Study of beam losses inside the S2C2
- How is beam lost (where, when, why)
- How to avoid beam loss
- What happens to lost protons

✓ Realistic beam properties at 225 MeV as input to AOC for extraction studies :
- Extracted emittance
- Extraction efficiency
- Mean energy and its relation with source positioning precision requirement
- Energy spread of the beam
- Temporal profile of the pulse (γ-prompt studies)

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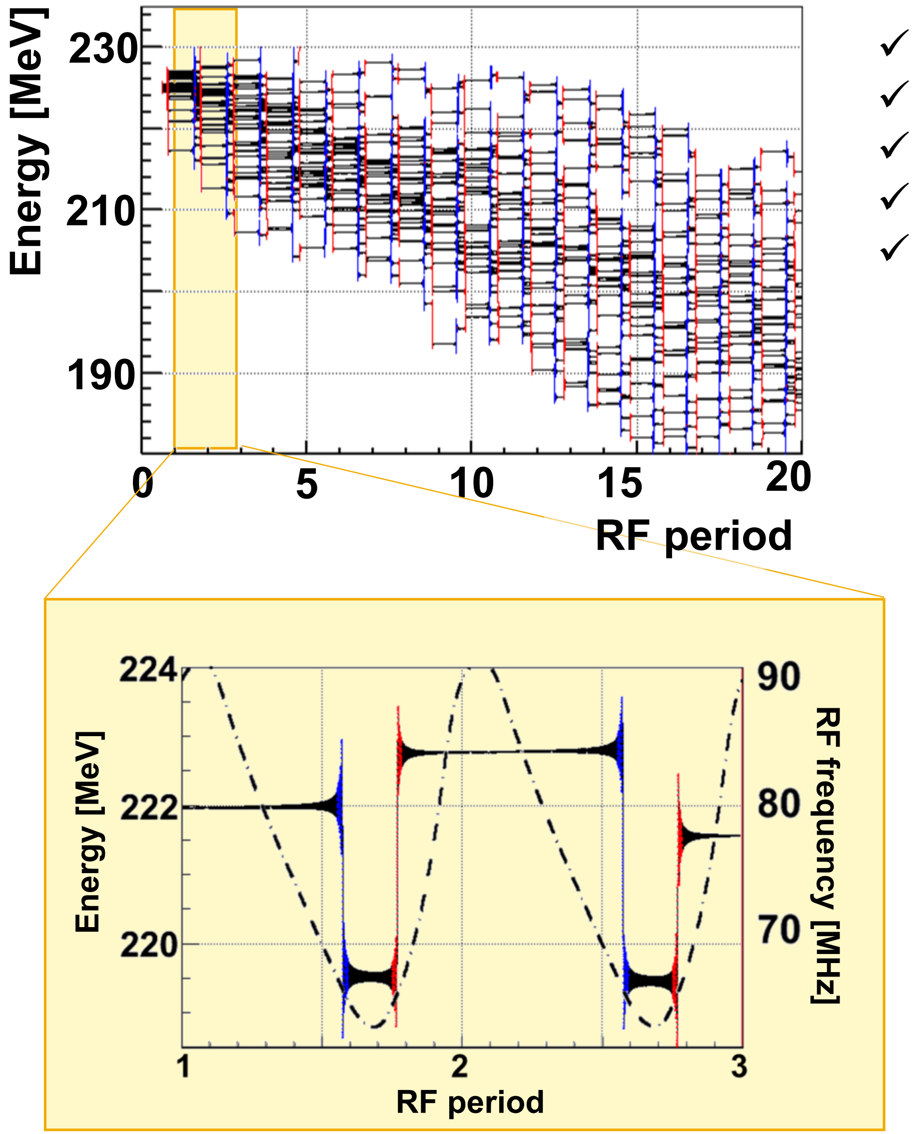
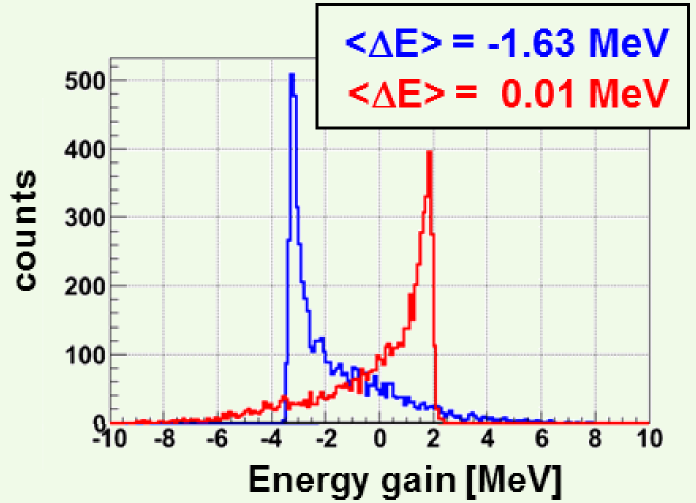
Acceleration : what happens to « lost » protons (1)



- ✓ Protons at 225 MeV outside the separatrix
- ✓ Tracking over **20 RF periods**
- ✓ Falling RF frequency : 10 kV dee voltage
- ✓ Rising RF frequency : 5 kV dee voltage
- ✓ resonances appear on the **rising** and the **falling** RF frequency flank



- ✓ The net energy gain :
  - **rising** flank : on average ≈ 0 MeV
  - **falling** flank : **-1.63 MeV**

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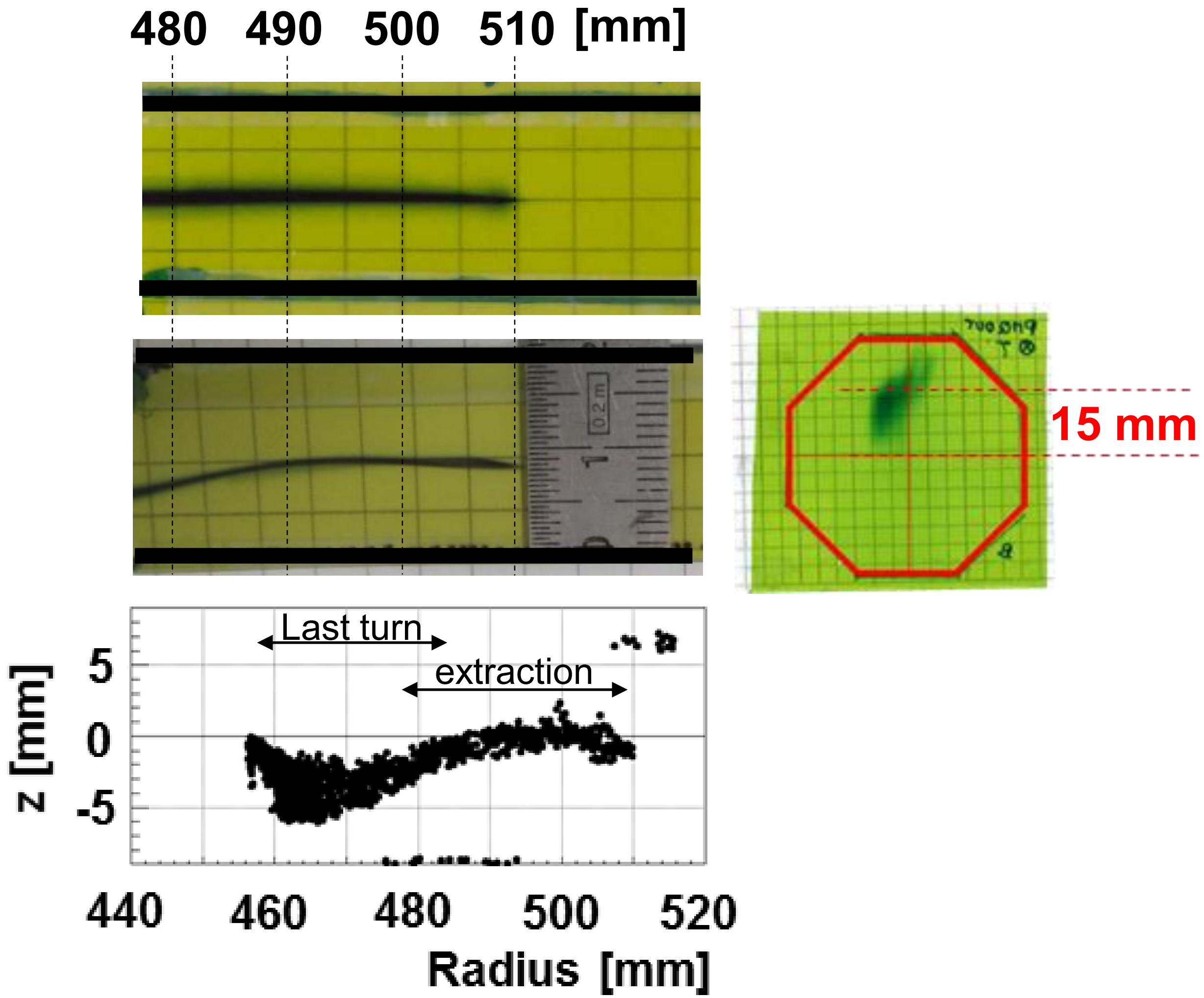
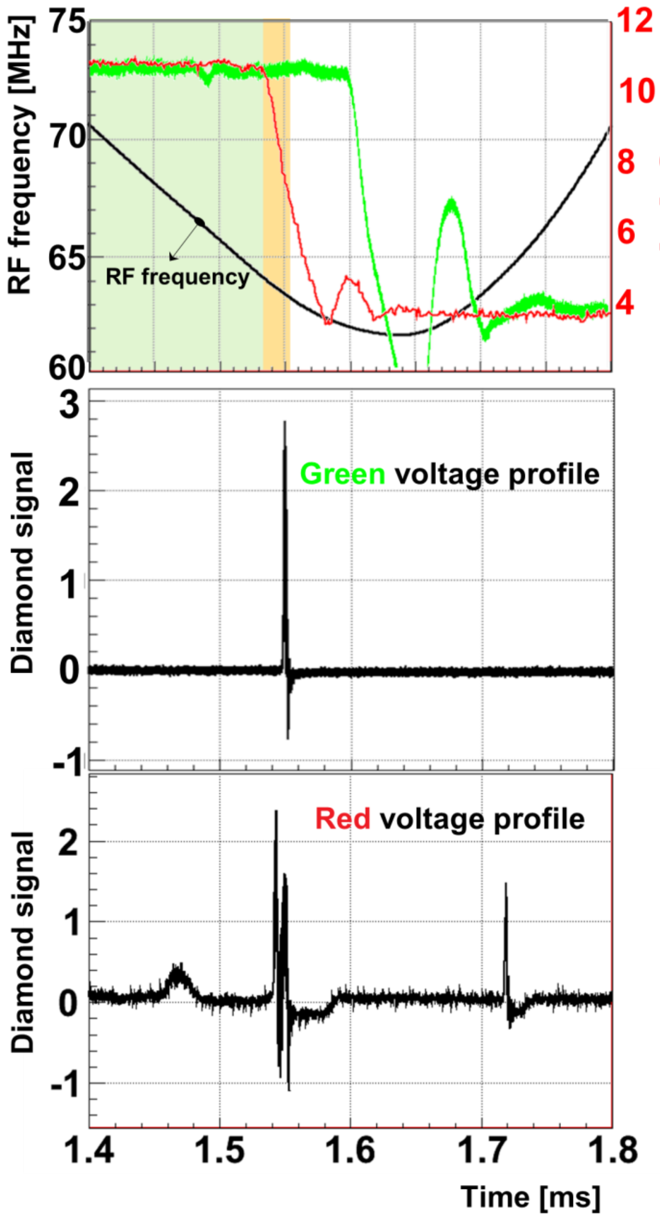
Extraction

Extraction : vertical coil positioning



- ✓ Vertical coil positioning :
  < 0.25 mm precision needed
- ✓ Vertical displacement in the last turn is linear with the coil displacement
- ✓ Fast, precise and easy on-site coil positioning

Extraction : what happens to « lost » protons (2)



<u>What if …</u> We intentionally loose beam very close to extraction ?

We drop the dee voltage a few μs before extraction …

<u>Observation during 2nd RF frequency sweep :</u>

(1) protons coming out on the rising frequency flank

⇨ **Explained from energy resonances (see previous)**

$$f_{RF} = f_p$$

(2) protons coming out before the extraction frequency

⇨ **Explained from emittance blow-up and orbit center instability when off-centering becomes too large.**

$$f_{RF} = f_p \pm (\nu_r - 1) f_p$$

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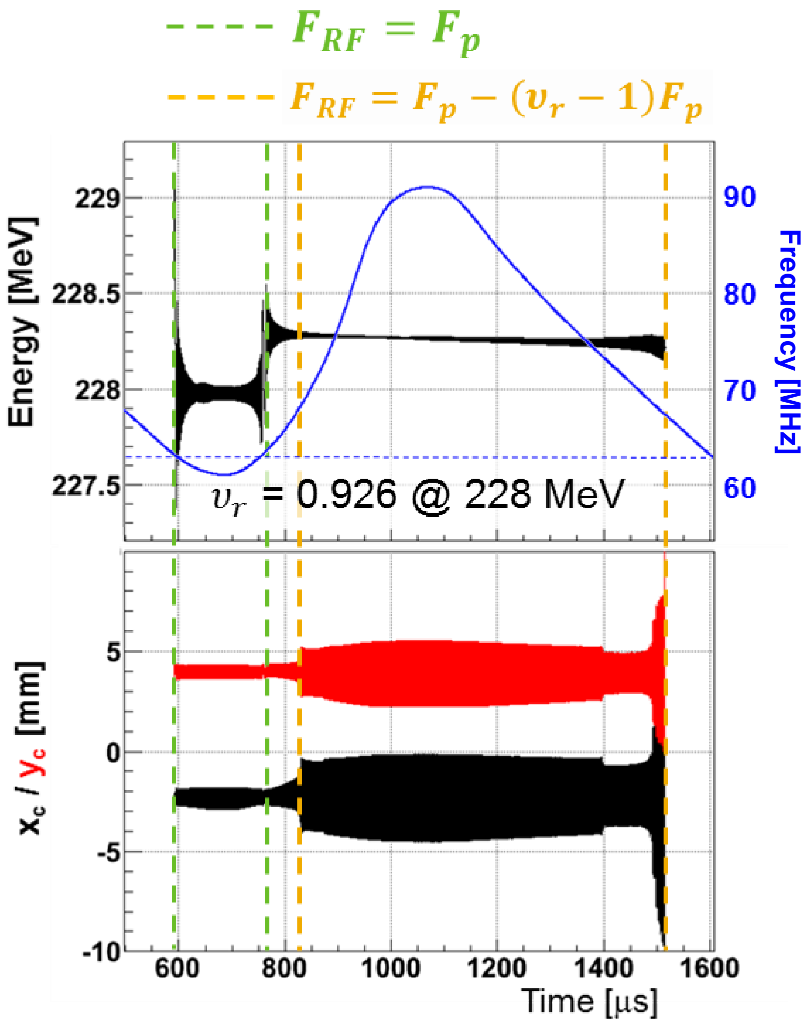
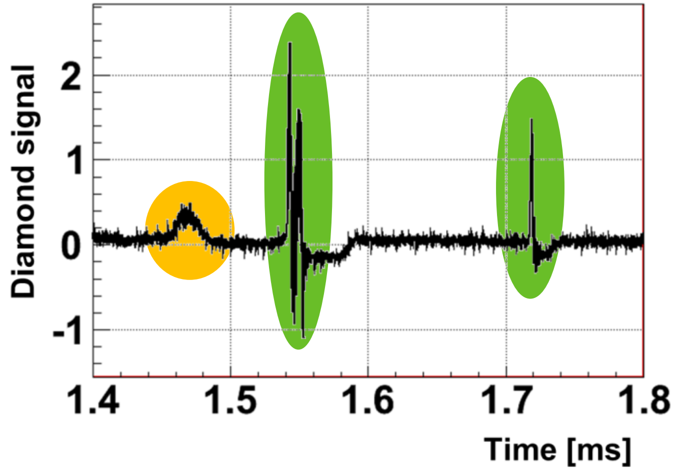
Extraction : what happens to « lost » protons (2)



$$\frac{dx_c}{dt} = (\nu_r - 1)y_c + (\dots) + \beta_2 x_c + (\dots)$$

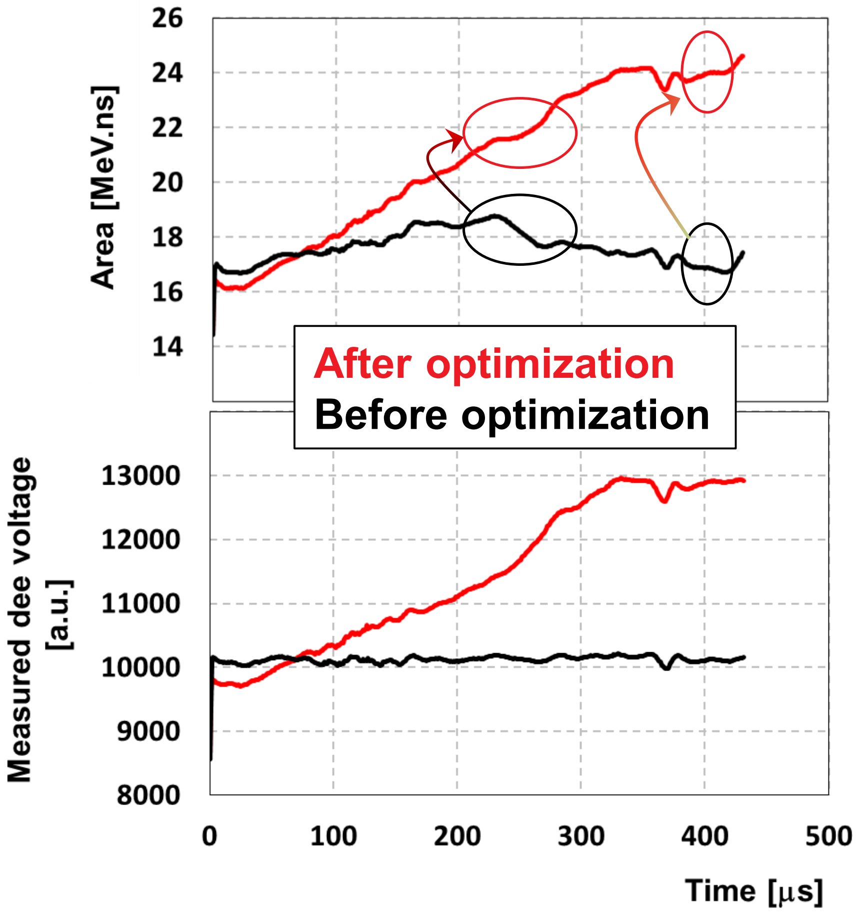
β_2 oscillates with the same frequency as the energy : $(f_{RF} - f_p)$
x_c oscillates with the frequency $(\upsilon_r - 1)f_p$

If $f_{RF} = f_p \pm (\upsilon_r - 1)f_p$: resonance effect



Extraction : how to avoid unwanted extraction

$$\text{Bucket area [MeV.ns]} = 16\sqrt{\frac{eV}{2\pi\beta^2(T+E_0)|\eta|}}\,.\,\alpha_b\,.\,\frac{(T+E_0)\beta^2}{2\pi f_p}10^3$$



- ✓ Important step during commissioning !
- ✓ Iterative, time consuming
- ✓ Optimization by observation of “ghost beam”

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Extraction : simulated vs measured beam properties

Property	Simulated	Measured
Energy spread	150 keV	≈900 keV
$\Delta E/\Delta I_{coil}$	440 keV/A	440 keV/A
ΔE / mm source shift	200 keV/mm	≈ 200 keV/mm
Pulse duration (total)	8 μs	8 μs
1-σ pulse duration	2 μs	2 μs
Extraction efficiency	50%	≈ 35%
Horizontal emittance	24 π.mm.mrad	23.2 π.mm.mrad
Vertical emittance	5 π.mm.mrad	4.0 π.mm.mrad
Max. clinical intensity		134 pC/pulse

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Thank you !

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