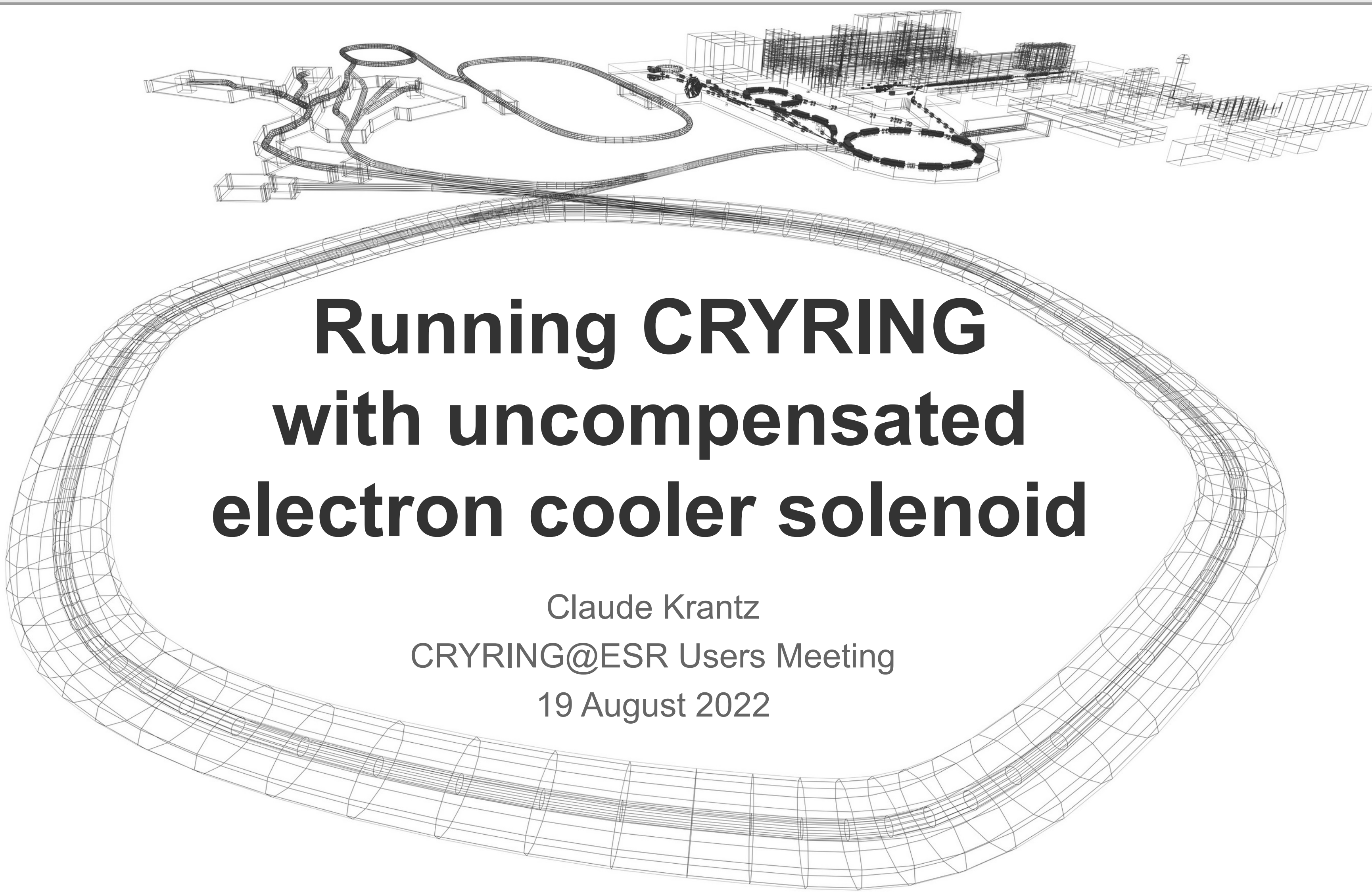


Running CRYRING with uncompensated electron cooler solenoid

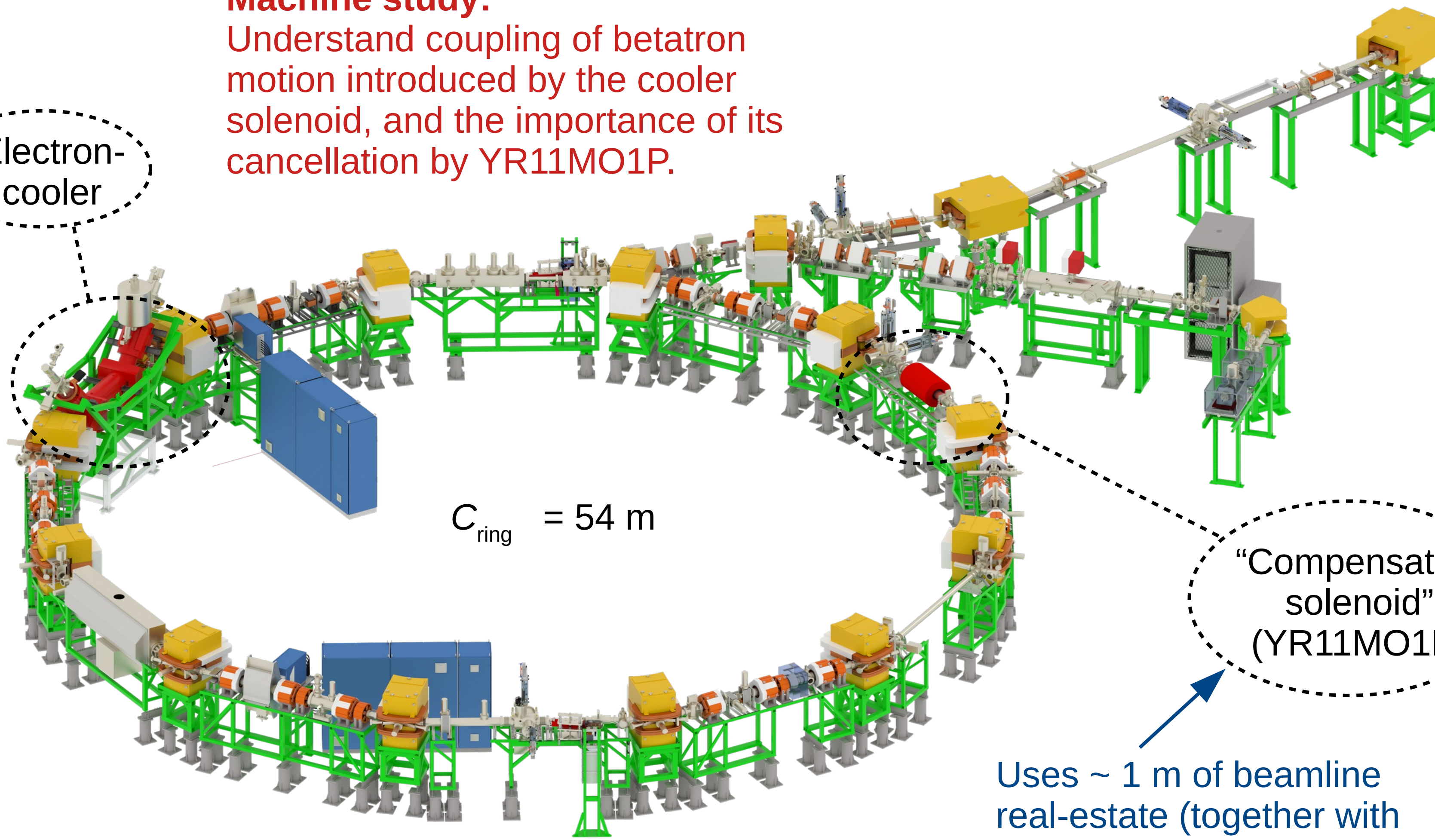
Claude Krantz

CRYRING@ESR Users Meeting

19 August 2022

Motivation

Machine study:
Understand coupling of betatron motion introduced by the cooler solenoid, and the importance of its cancellation by YR11MO1P.

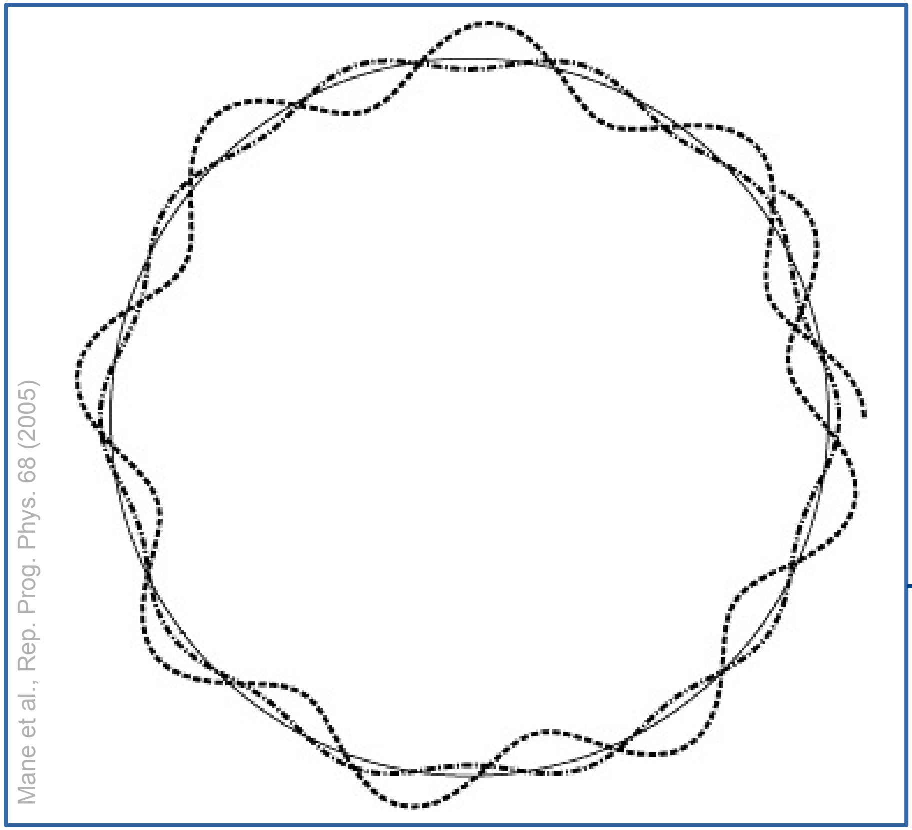


Uses ~ 1 m of beamline real-estate (together with Schottky electrodes)

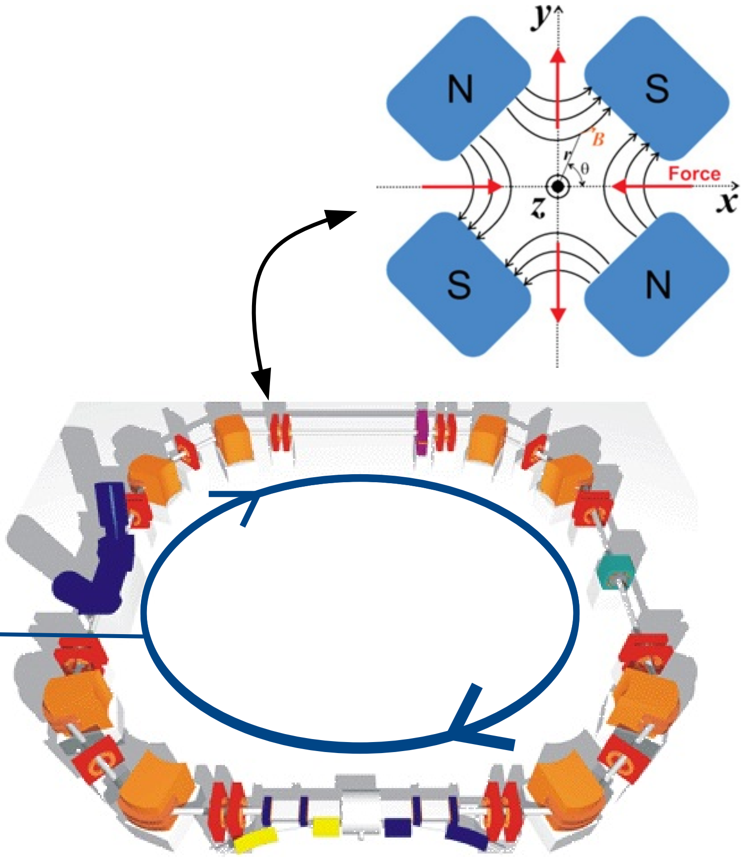
Prelude: Betatron motion

Stored ions do not follow the design orbit precisely (“divergence”).

Need quadrupole magnets to “bend back” their trajectories every now and then.



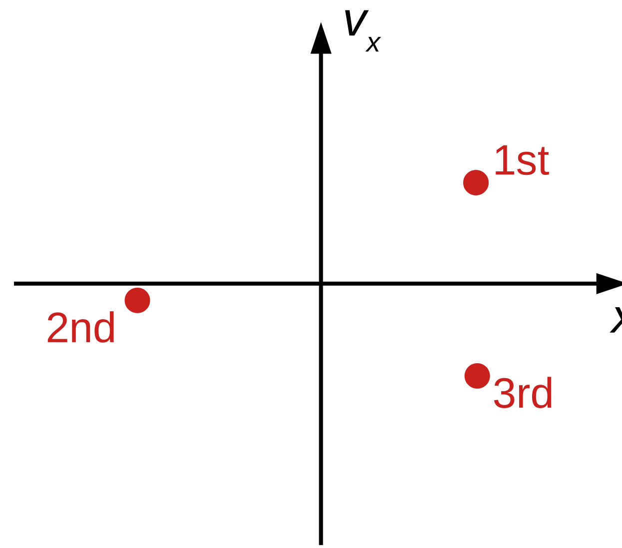
Mane et al., Rep. Prog. Phys. 68 (2005)

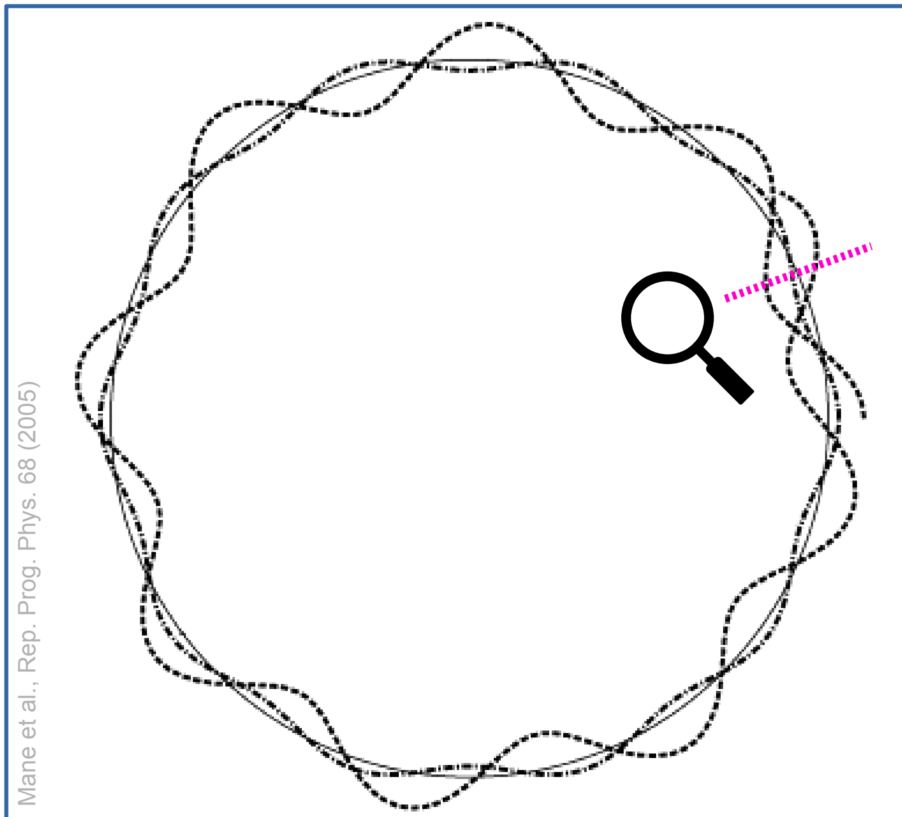


www.mpi-hd.mpg.de

Prelude: Betatron motion

If, in a certain place of the ring, we observed transverse position and velocity of a specific ion over many revolutions ...





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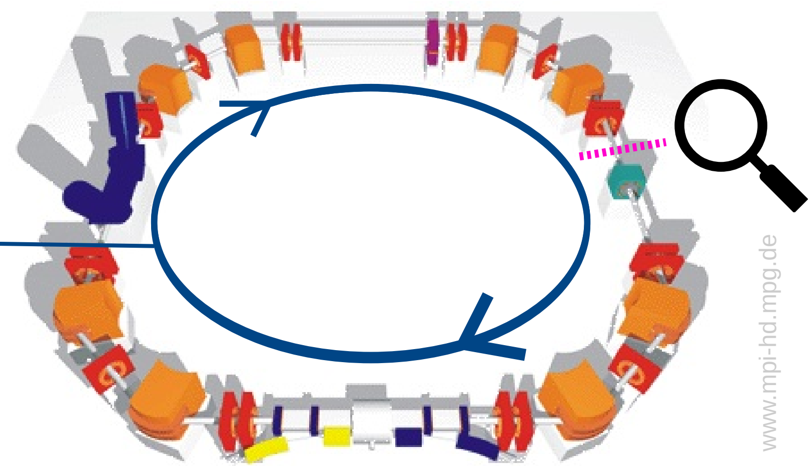

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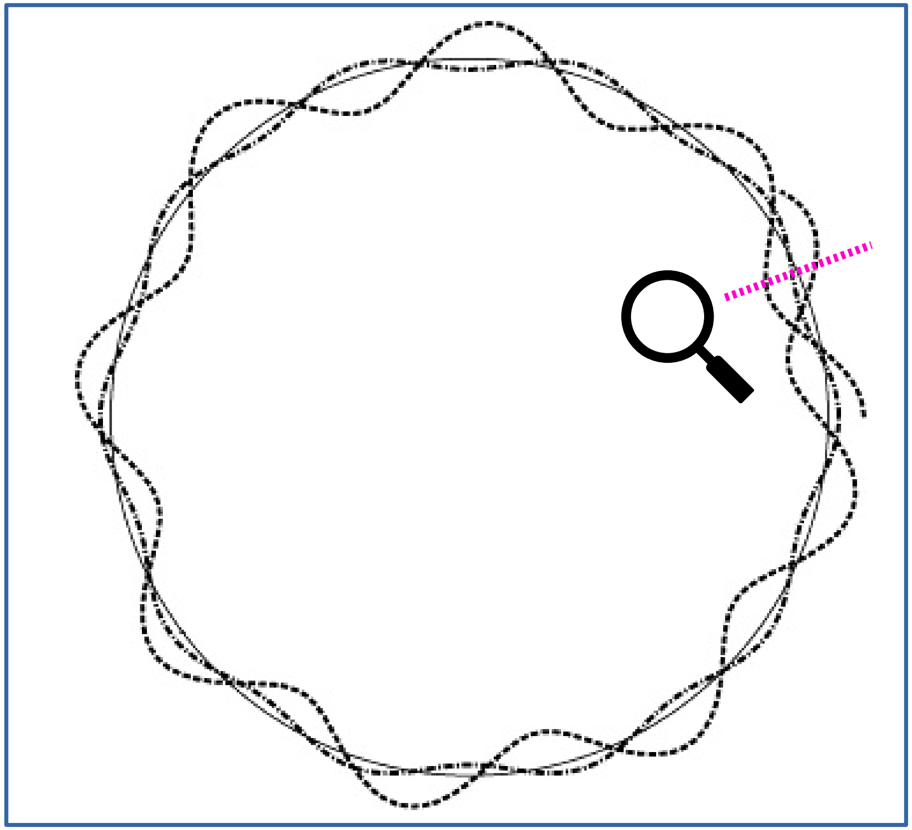
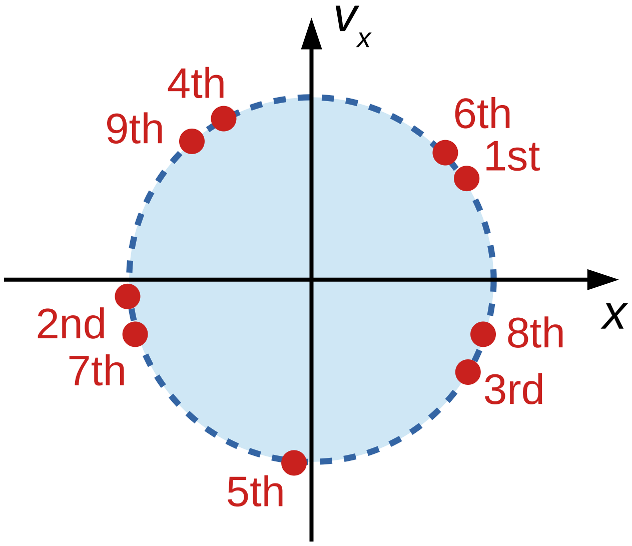


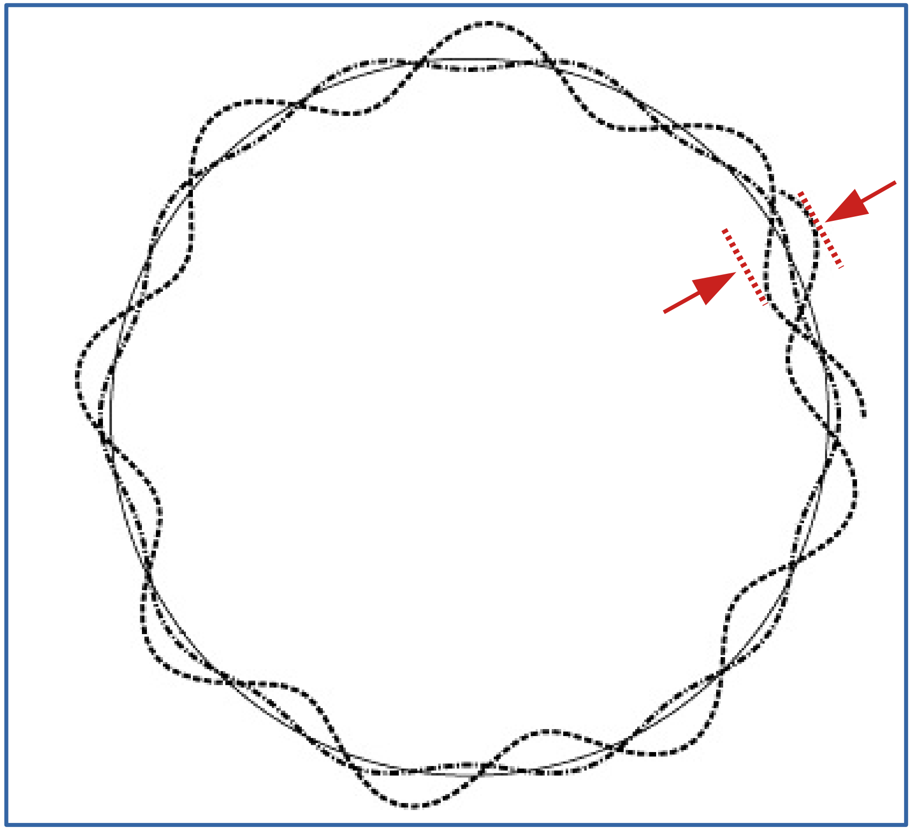


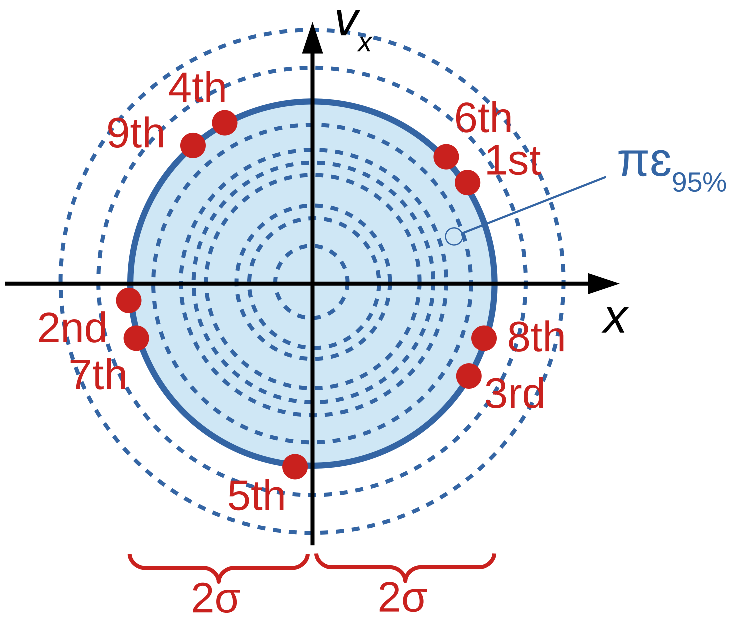
… we'd find that all measured coordinates enclose an elliptic volume of (x, v_x) phase-space.

→ *Reminds of a harmonic oscillator!*

→ **"Betatron oscillation"**

Prelude: Betatron motion





Some "characteristic ion" circles a *larger* ellipse than 95% of its peers:

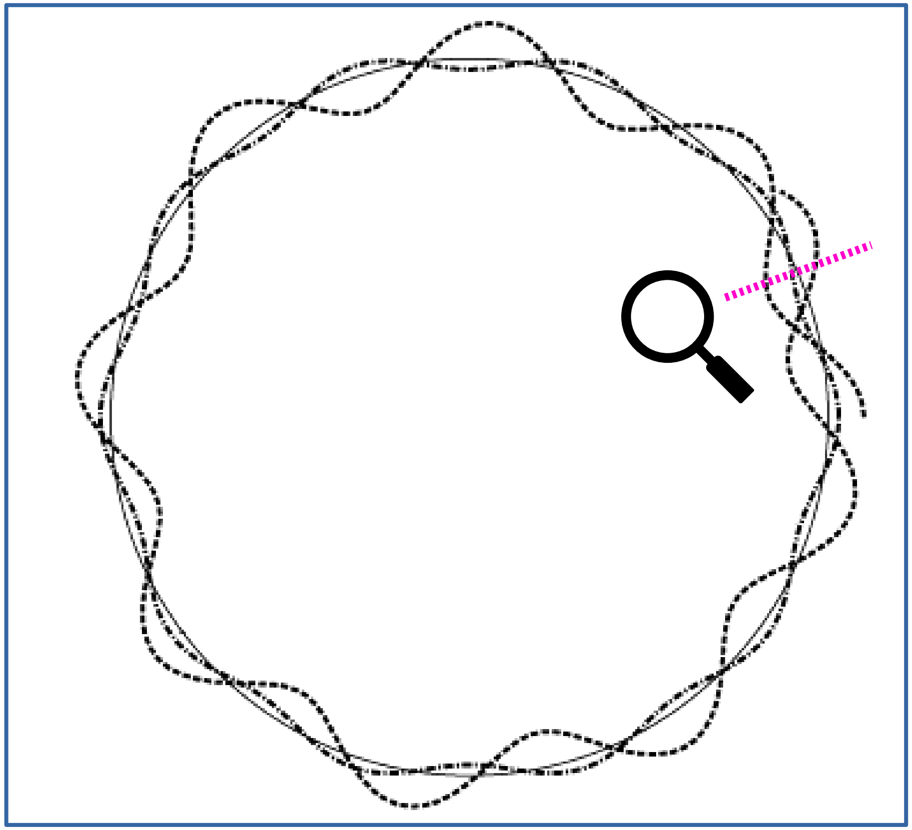
Enclosed area / π = $\varepsilon_{95\%}$ (*beam emittance*)

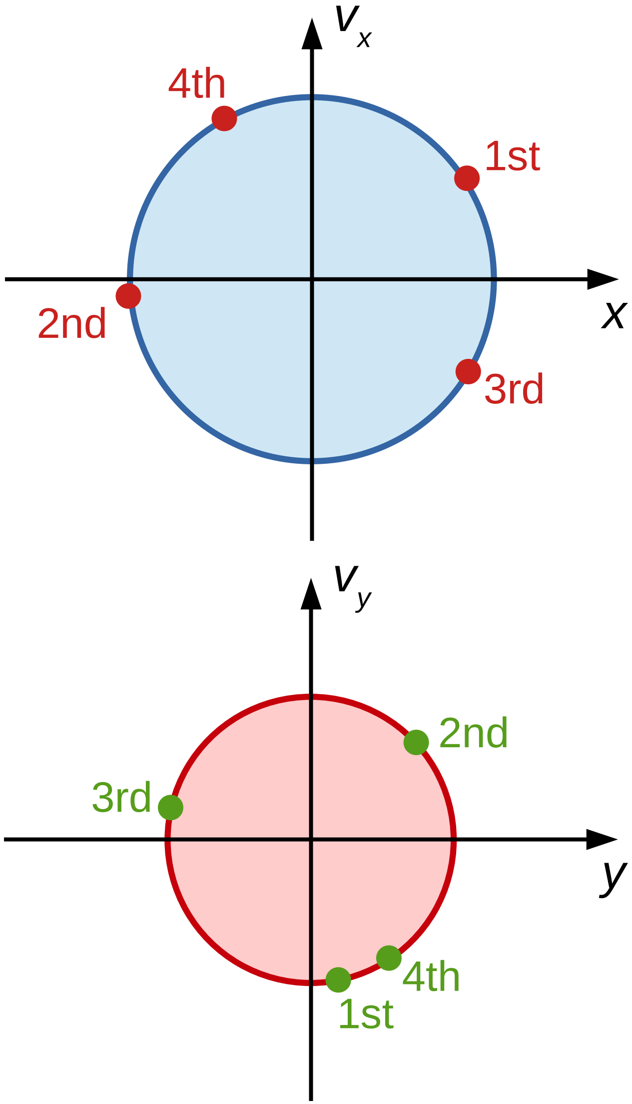
Projection onto x-axis:

→ "2-σ beam diameter"

Prelude: Betatron motion

In a “text book” storage ring, betatron oscillations along x and y are considered *independent*!



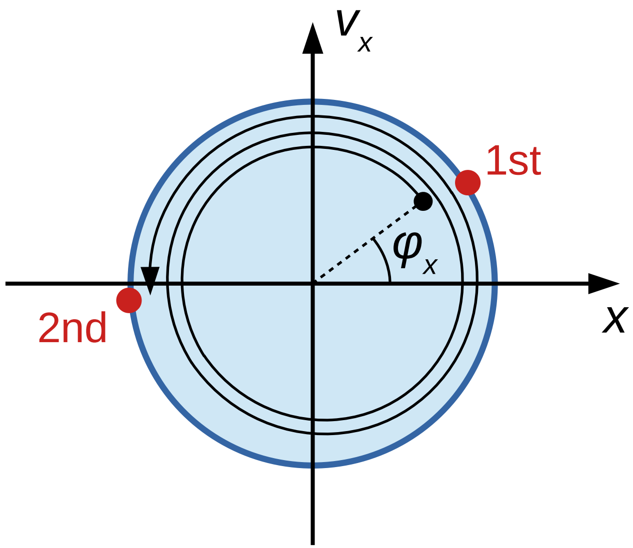


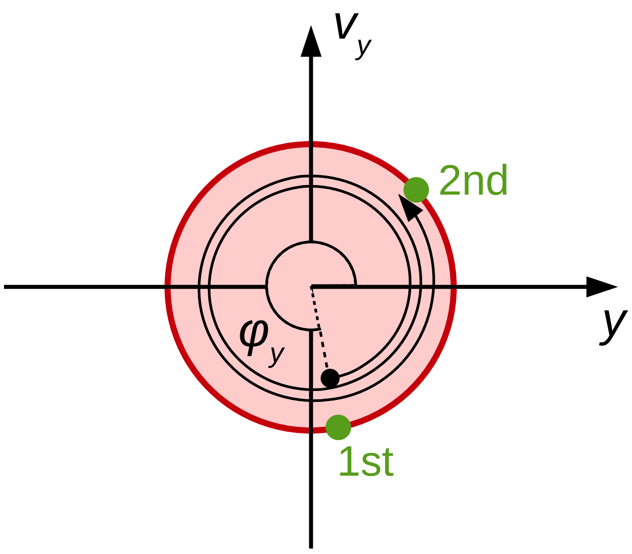
Prelude: Betatron motion

The phase advances between two passages of an ion define the horizontal and vertical “tunes” Q_x and Q_y:

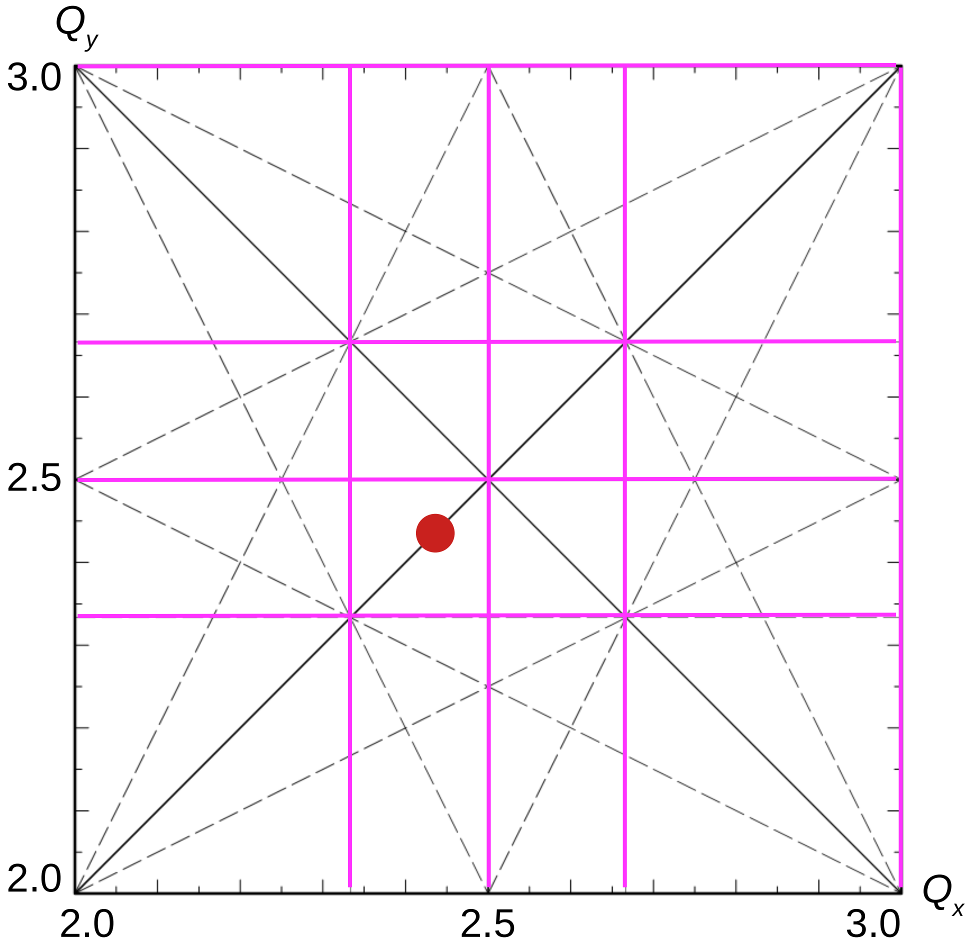
$$Q_{x,y} = \frac{1}{2\pi} \oint_{1turn} d\varphi_{x,y}$$

“Working point”: (Q_x, Q_y)





Prelude: Betatron motion



Working point (Q_x, Q_y):

Chosen in a way to prevent **resonance** of revolution and betatron motions.

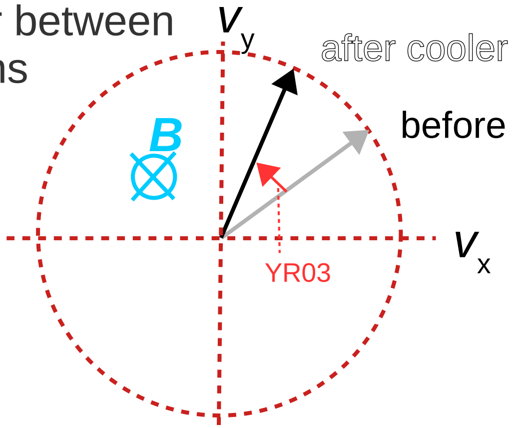
Standard working point of CRYRING:

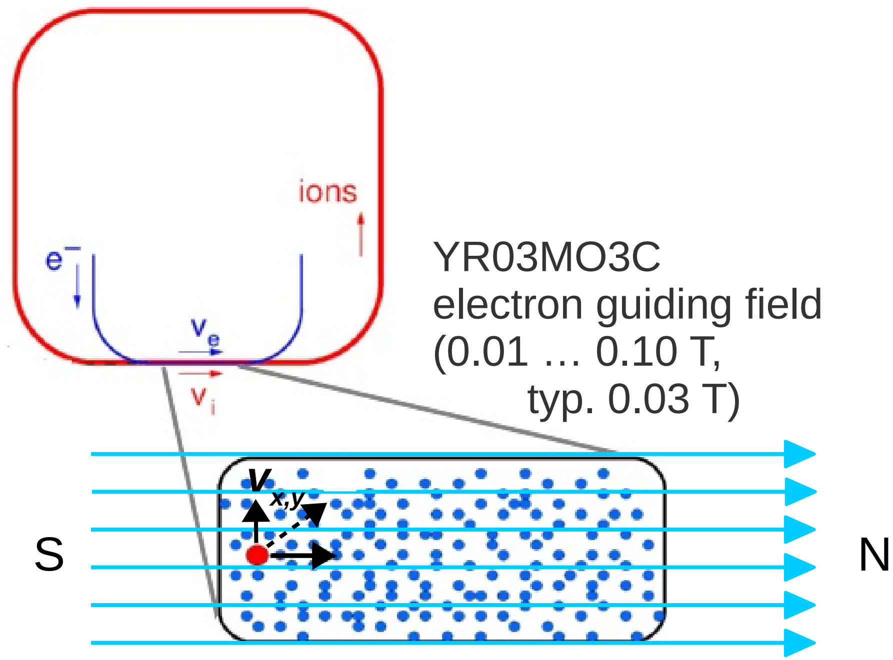
$$(Q_x, Q_y) = (2.42, 2.42)$$

Betatron coupling by cooler solenoid

The electron cooler uses a longitudinal magnetic field for guiding its electrons.

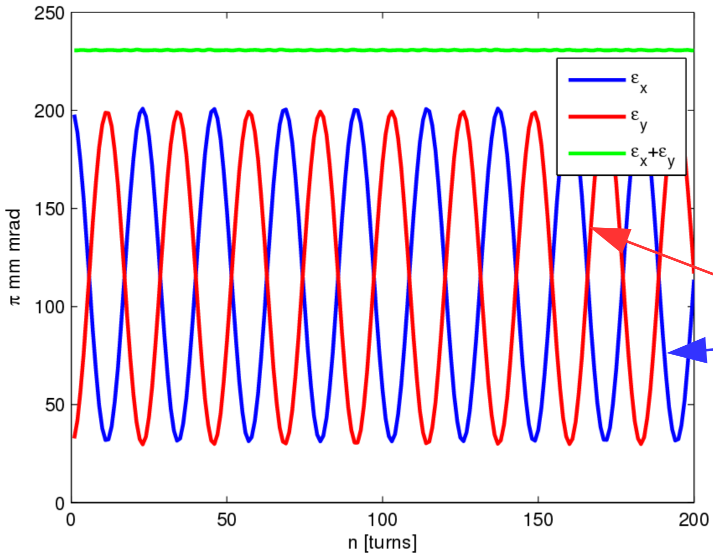
Energy transfer between betatron motions in horizontal (x) and vertical (y) planes!



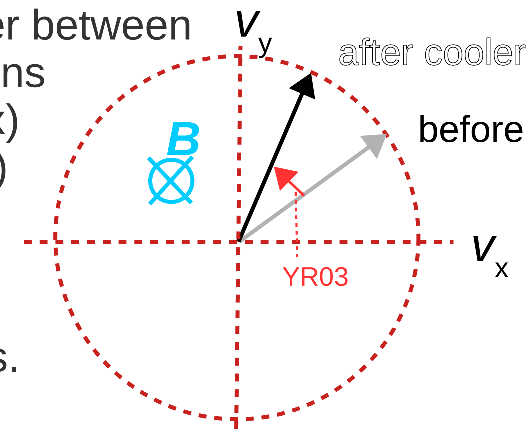


Betatron coupling by cooler solenoid

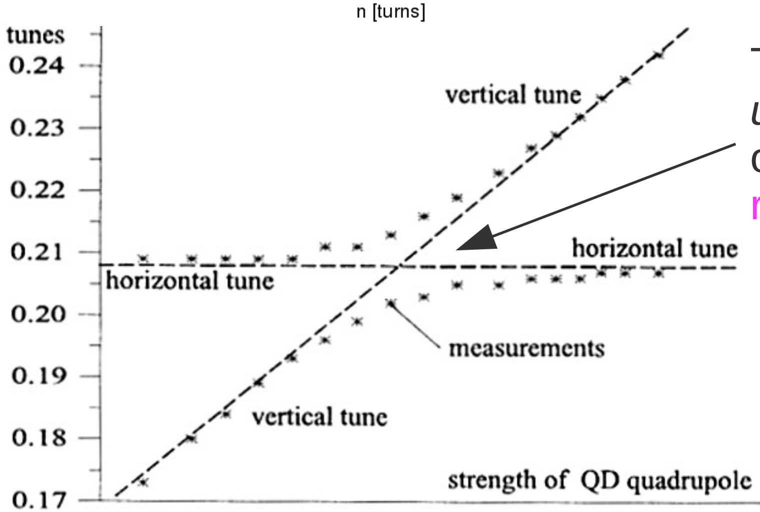
M.-T. Tang et al., arXiv:1508.02472v1 (2015)



Energy transfer between betatron motions in horizontal (x) and vertical (y) planes!

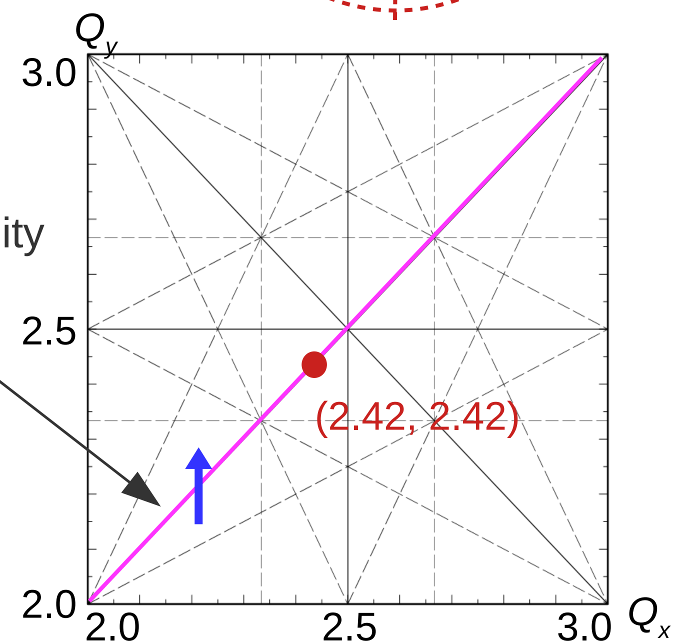


„Pulsing“ of horizontal and vertical emittances.

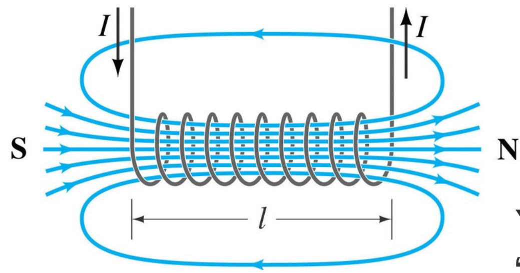


Wiedemann, Particle Accelerator Physics, 2015

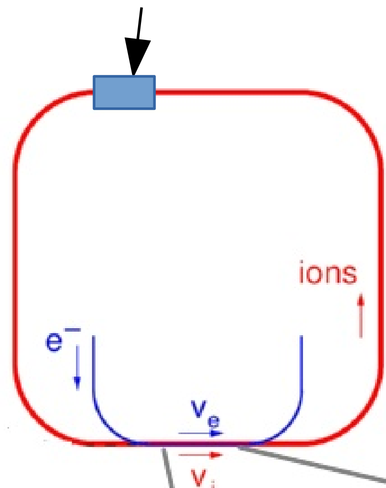
Tunes become *undefined* in vicinity of coupling resonances.



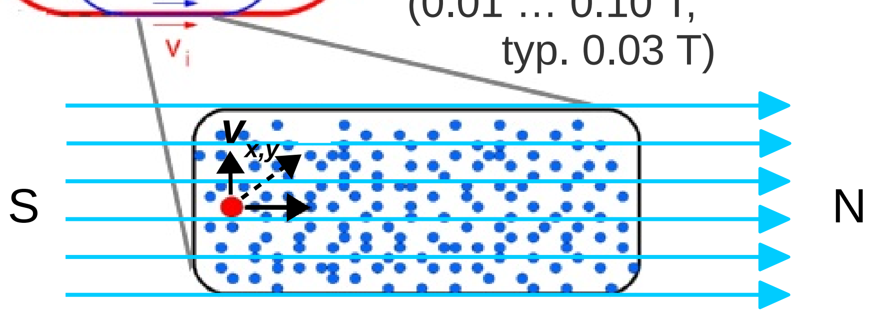
Betatron coupling by cooler solenoid

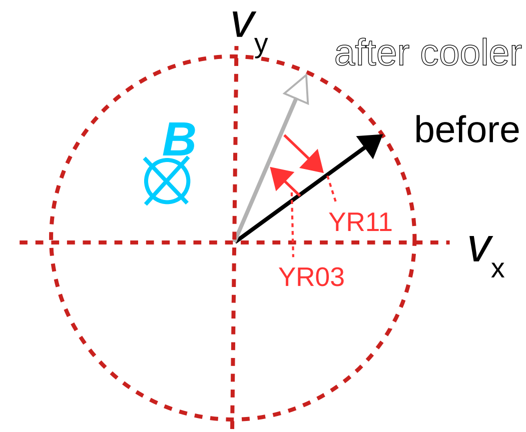


YR11MO1P
“counteracting”
solenoid: equal |*BL*|,
inverted polarity



YR03MO3C
electron guiding field
(0.01 … 0.10 T,
typ. 0.03 T)





Ion motions in horizontal and vertical plane again independent of each other!

List of things to study

Quantify amount of betatron coupling:

How much (additional) coupling if YR11MO1P is disabled?

Is there significant betatron coupling from other sources?

Stability and intensity of stored beams:

Are acceptance and storage affected by betatron coupling?

Quality of electron-cooled beams:

Can the cooler be set-up equally well?

Are cooling rates or final beam sizes affected?

Basic beam parameters

D+, injected at 300 keV/u (3...5 µA) from local source.

For measurements without electron cooling: acceleration to 1 MeV/u (0.29 Tm)
(compromise between sensitivity to solenoid fields and reasonable beam lifetime).

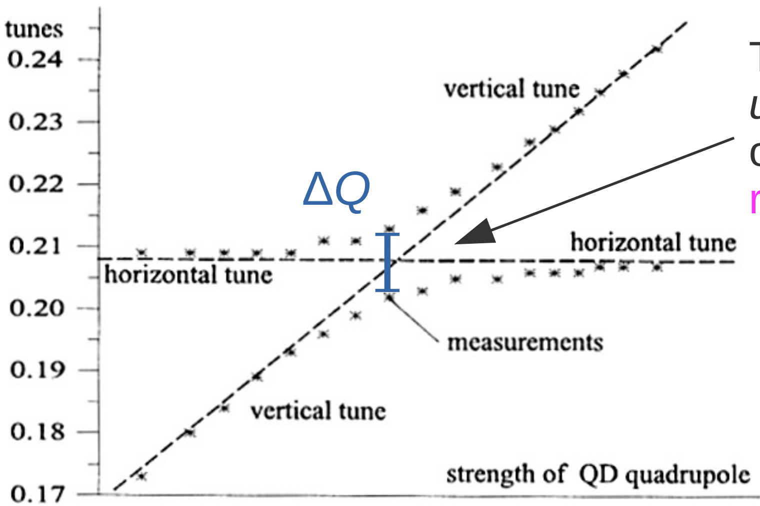
With electron cooling: acceleration to 2 MeV/u (0.41 Tm)
(to avoid running at low-limit of 20-kV HV supply)

All measurements close to design machine tune $(Q_h, Q_v) = (2.42, 2.42)$.

Method of closest tune approach

Vary the settings of the quadrupole magnets in a way to scan the working point across the coupling resonance.

→ *“Distance of closest approach” ΔQ of the measured tunes quantifies the coupling strength.*



Wiedemann, Particle Accelerator Physics, 2015

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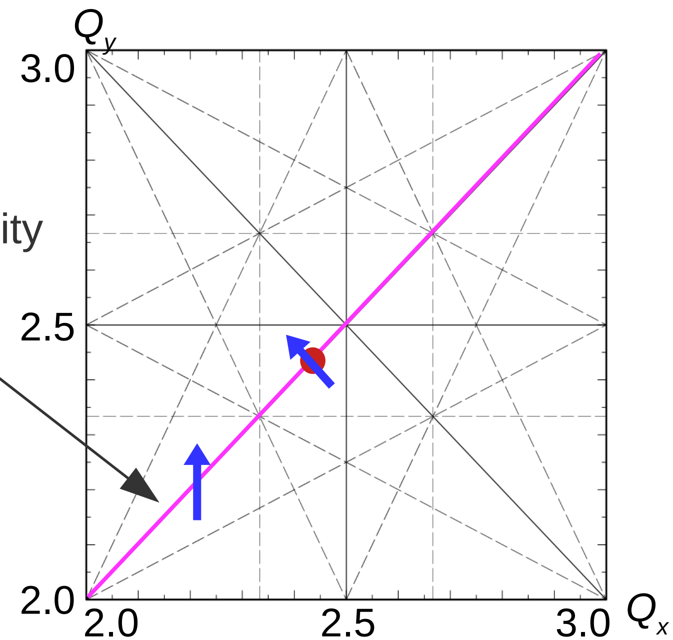


Betatron coupling

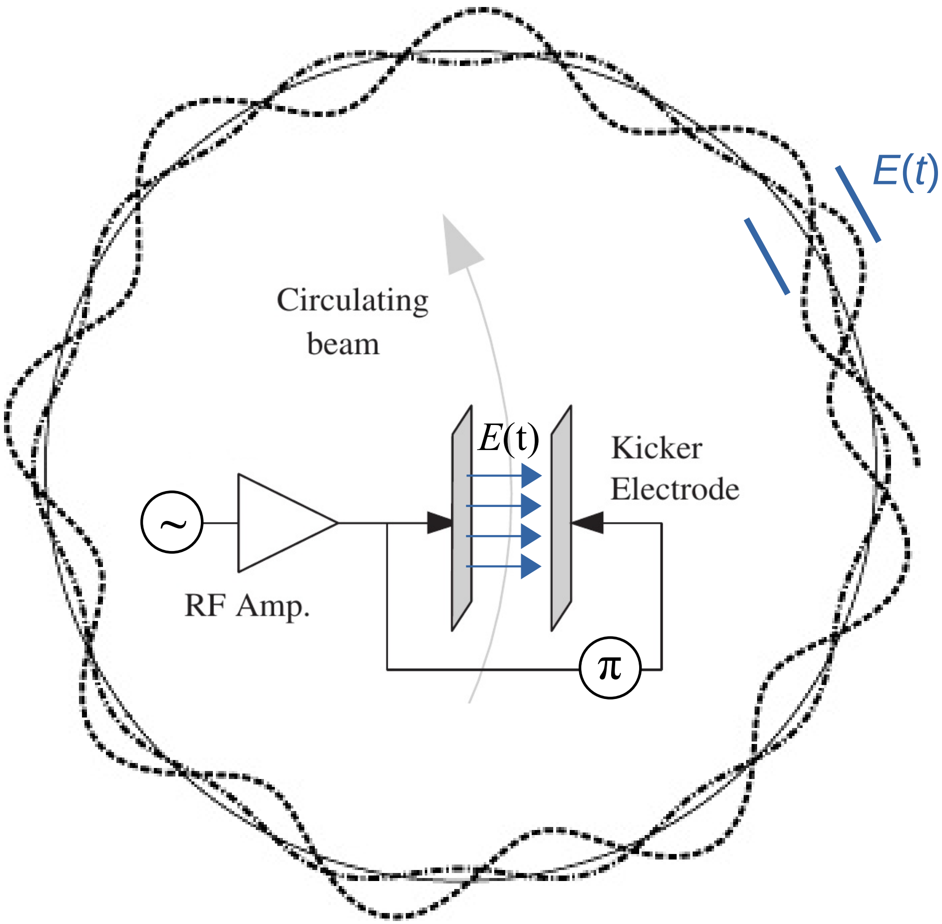
Tune measurements: RF-Knock-Out

Apply a transverse
(horizontal or vertical)
RF kicker field.

If RF signal and betatron motion are in phase,
kicks add up.

→ Blow-up of betatron amplitudes.

→ Particles lost from acceptance.



Tune measurements: RF-Knock-Out

FM of RF-KO exciter (~ 1 s^{-1})

Step-wise beam loss observed at resonance conditions.

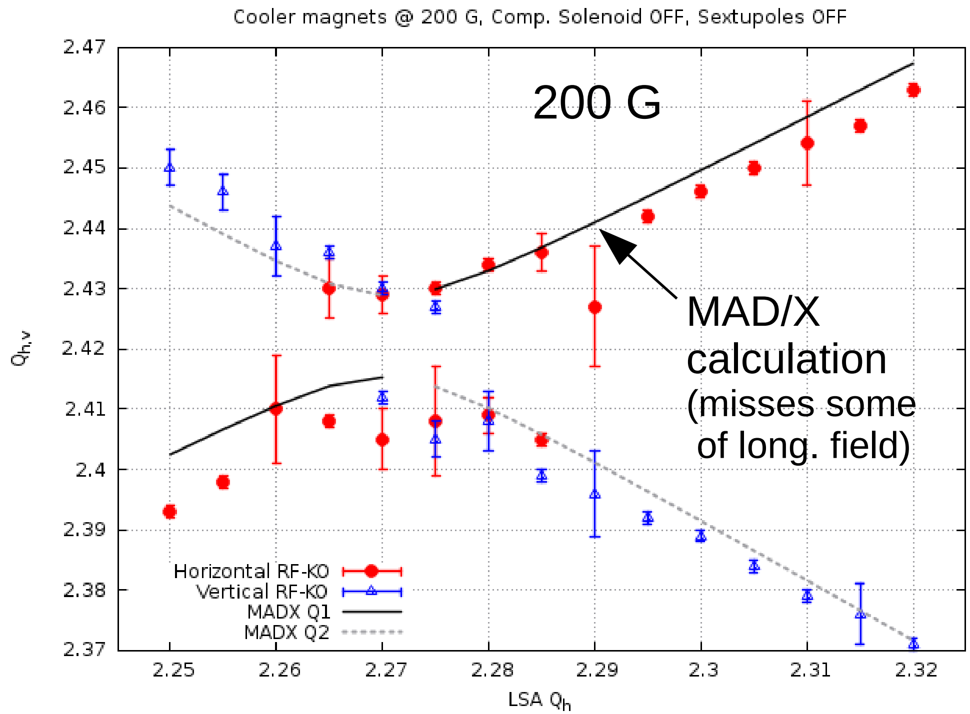
storage time

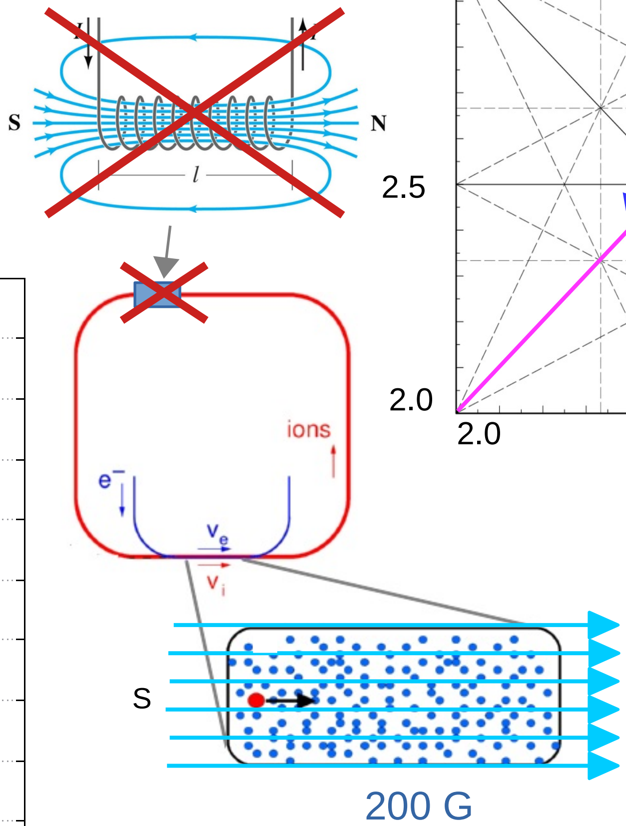
Betatron coupling

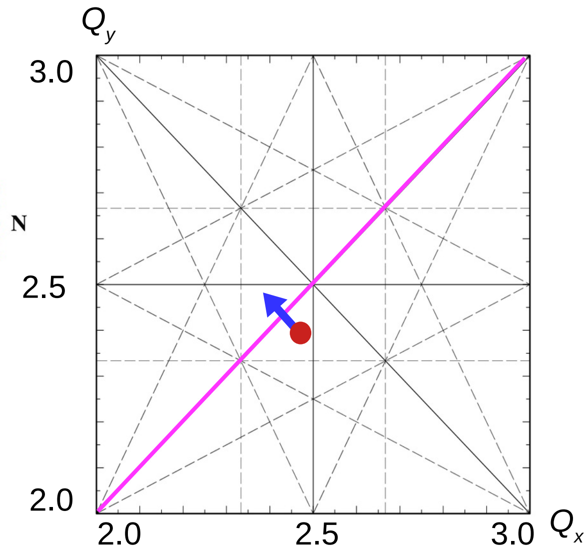
Cooler solenoid @ 200 G
(*but no electron cooling*)

+

compensation solenoid disabled.





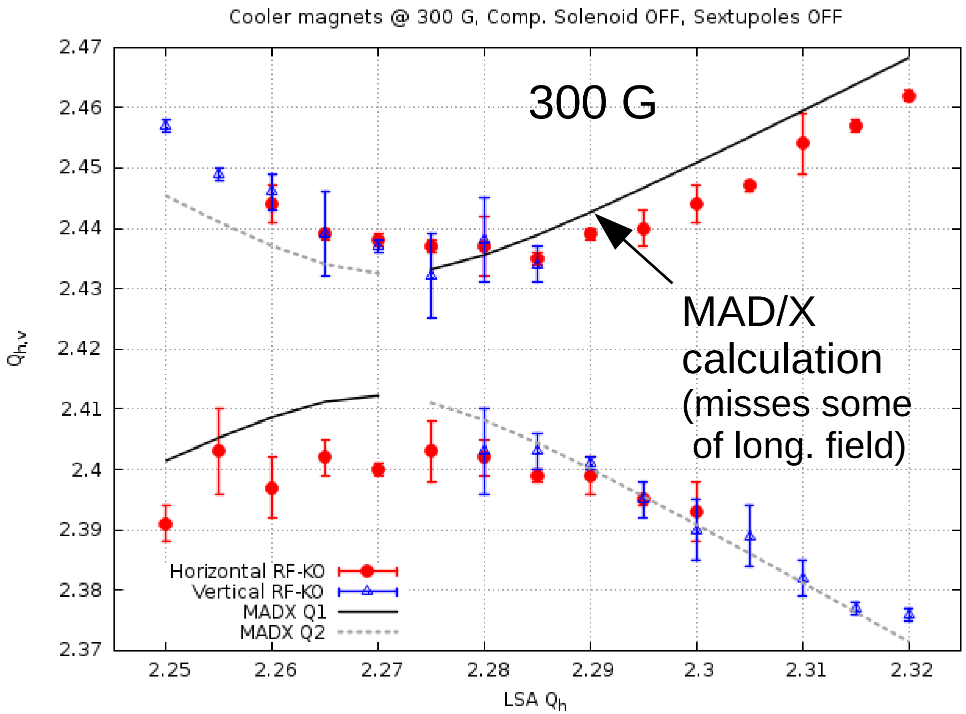


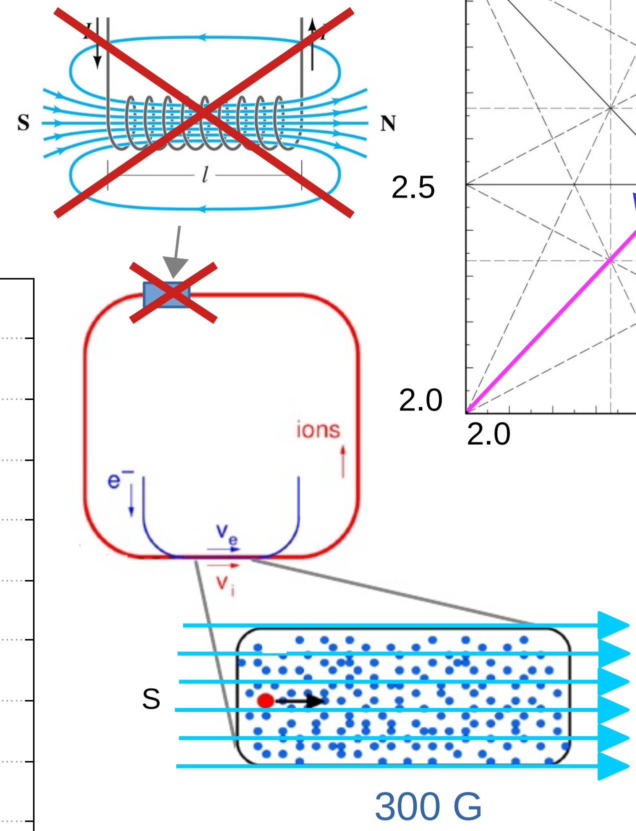
Betatron coupling

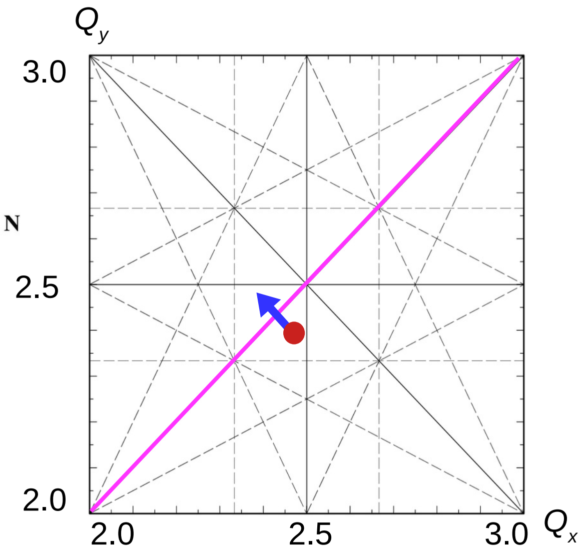
Cooler solenoid @ **300 G**
(*but no electron cooling*)

+

compensation solenoid disabled.





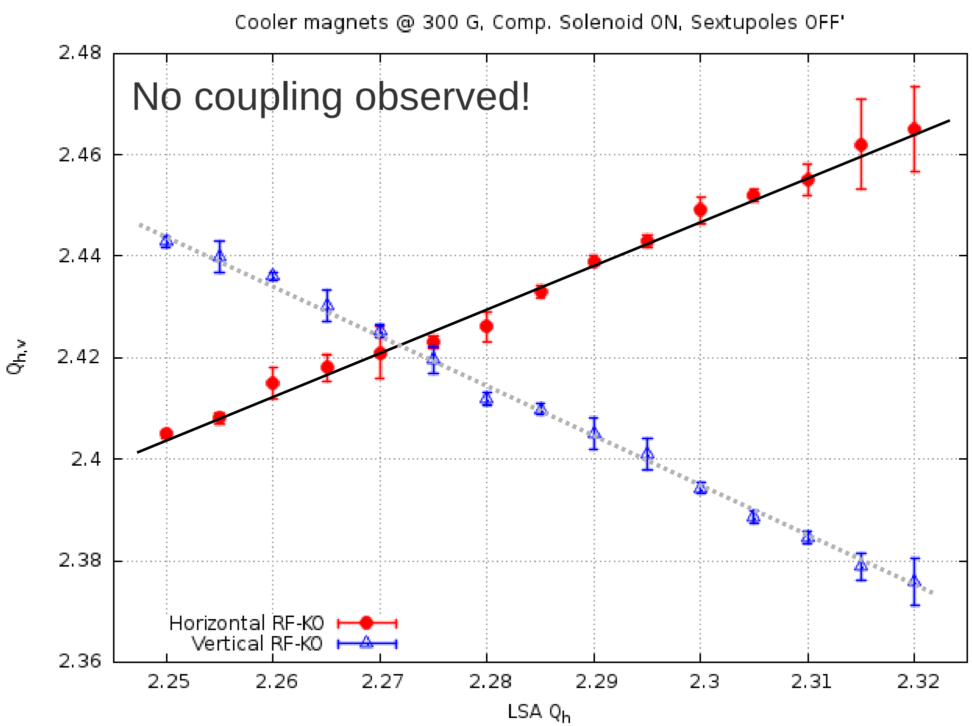


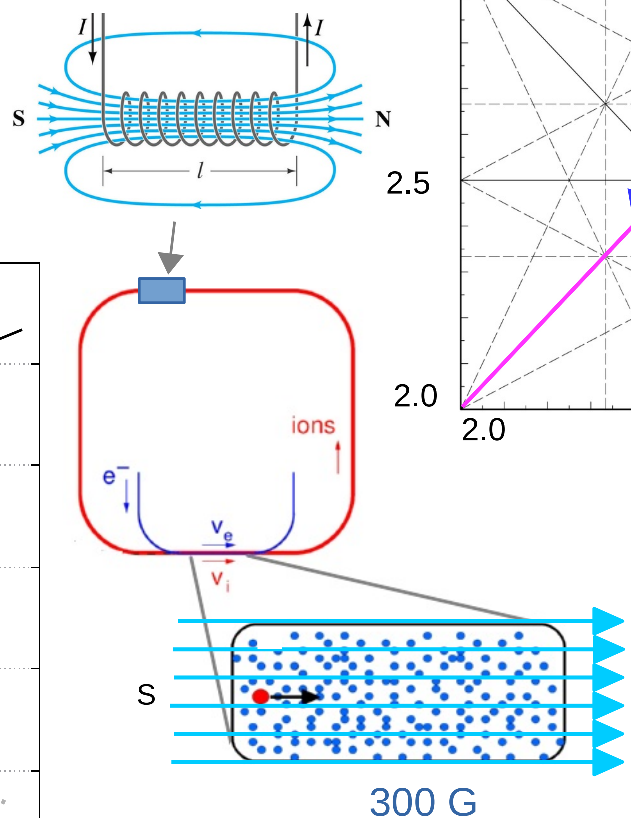
Betatron coupling

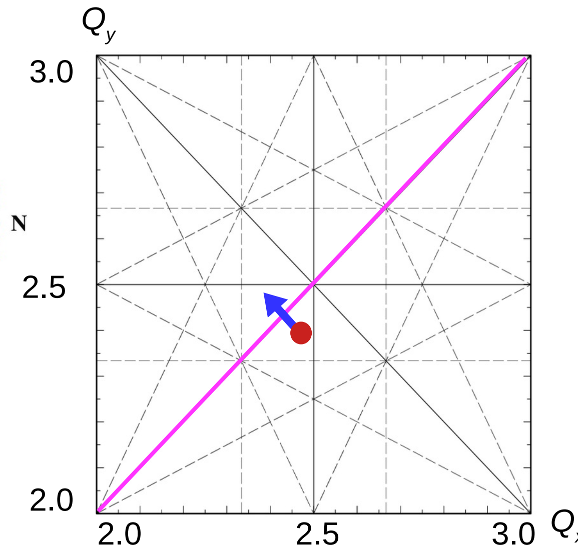
Cooler solenoid @ 300 G
(*but no electron cooling*)

+

compensation solenoid enabled.





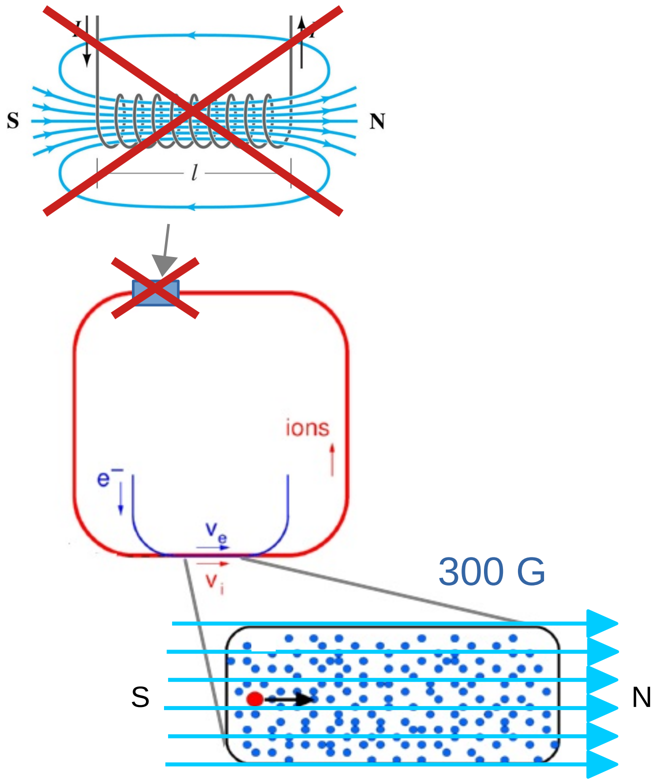


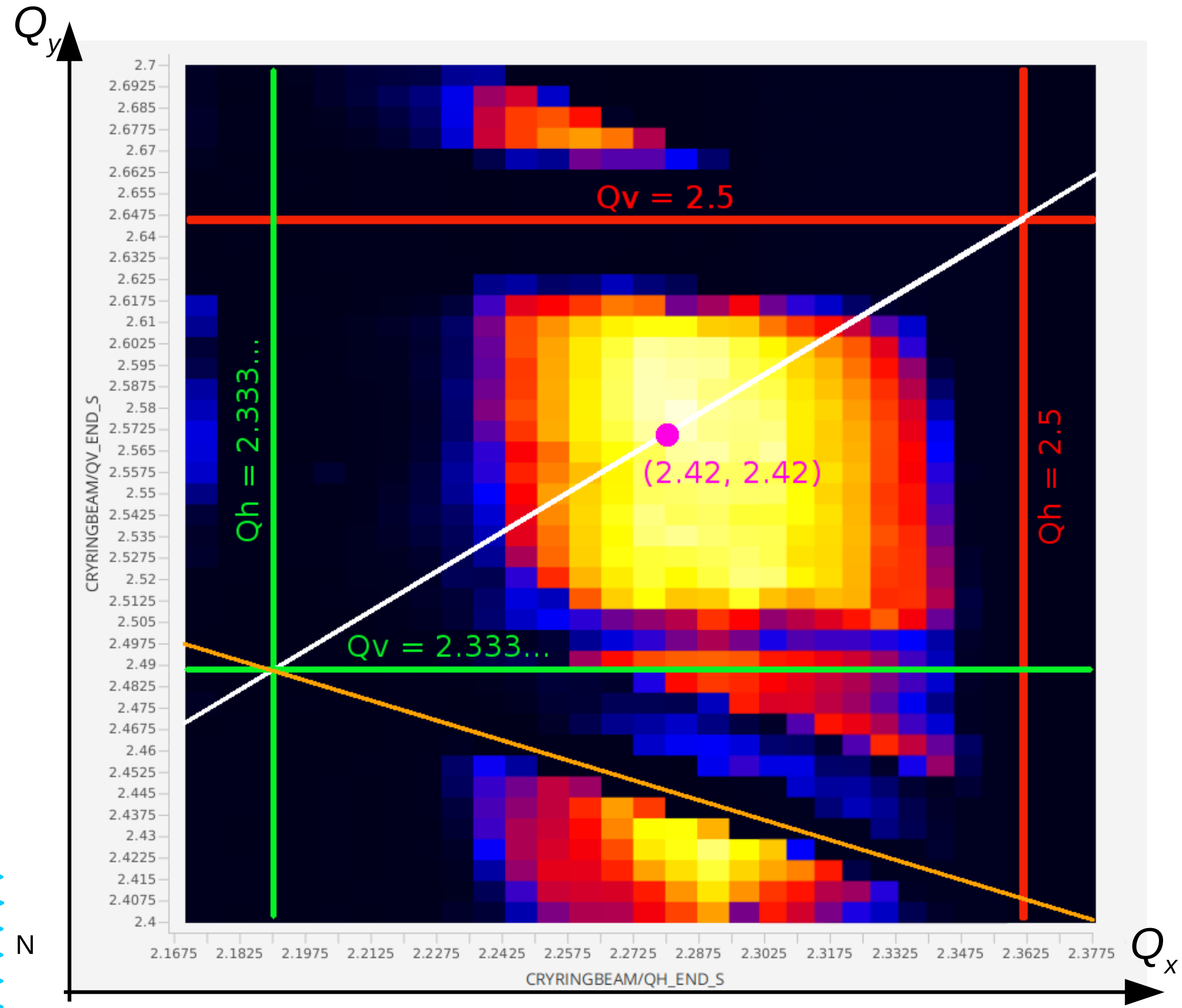
→ Compensation seems near-perfect!

Intensity and stability

Varied working point at injection ***and*** on 1-MeV/u flattop.

No cooling, no chromaticity correction





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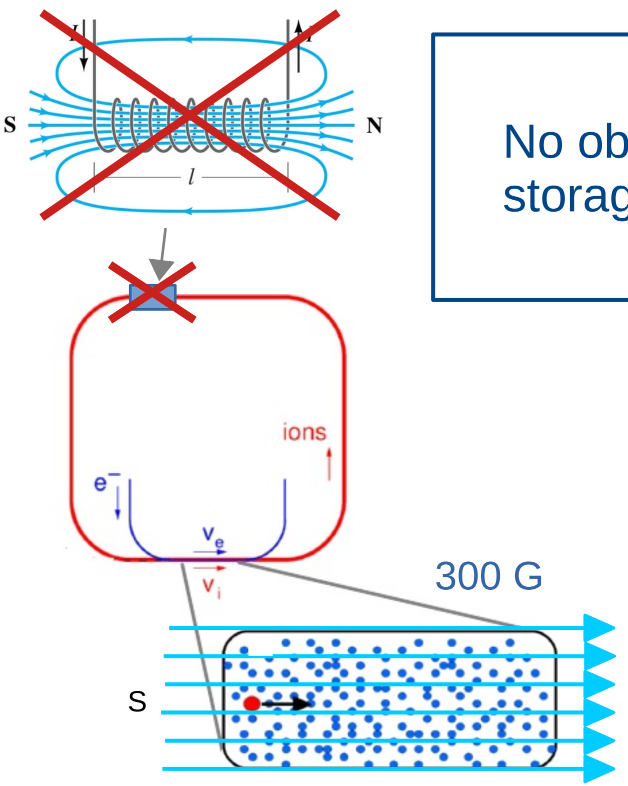
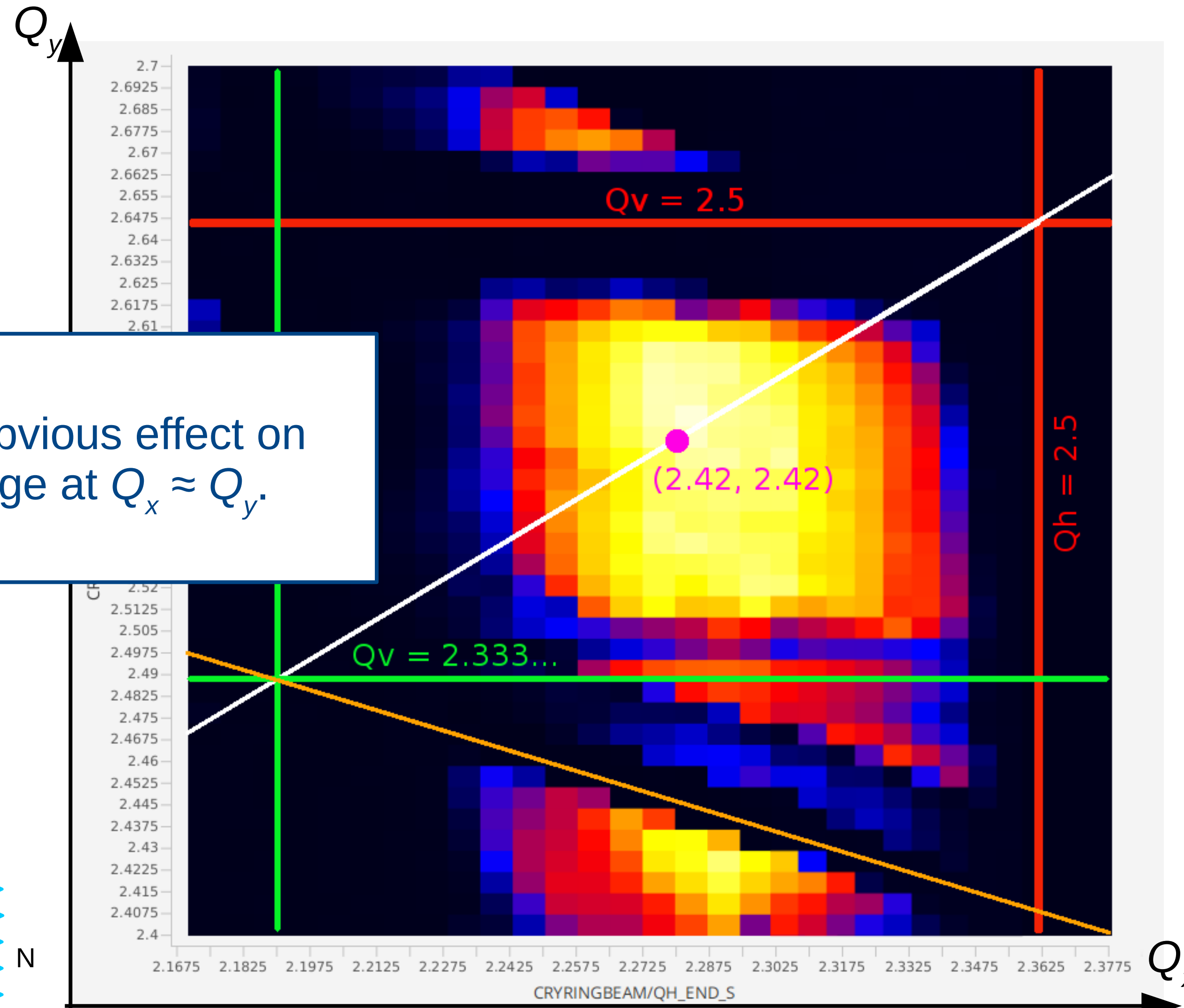
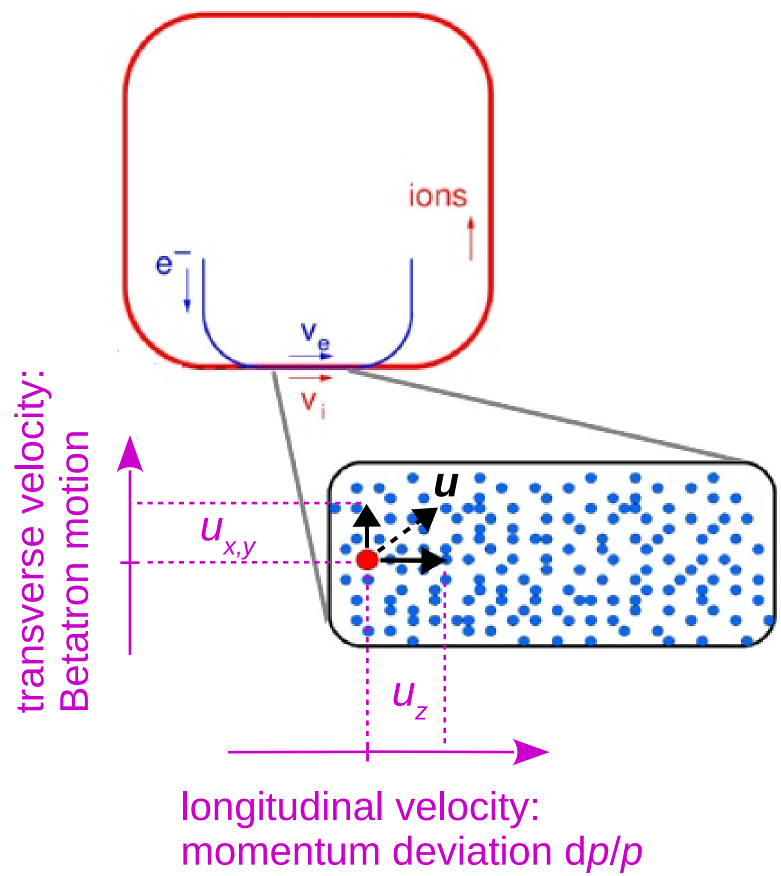
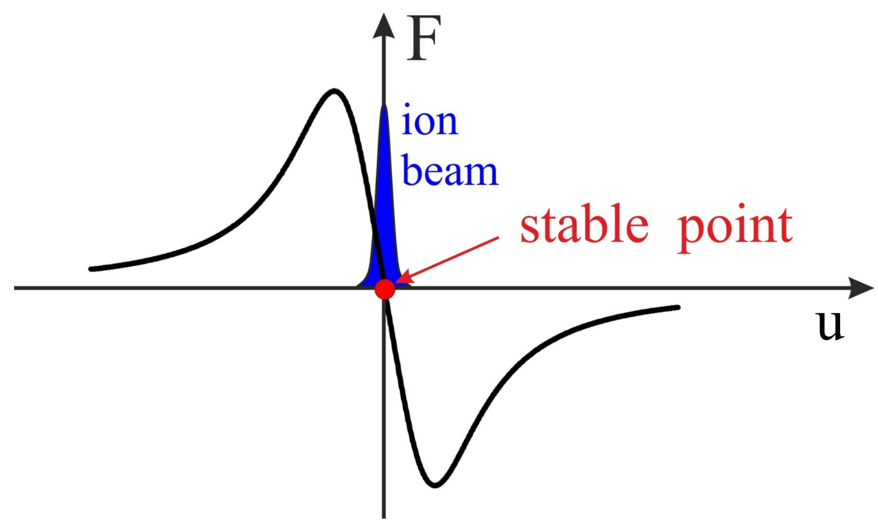




No obvious effect on storage at $Q_x \approx Q_y$.

Electron cooling

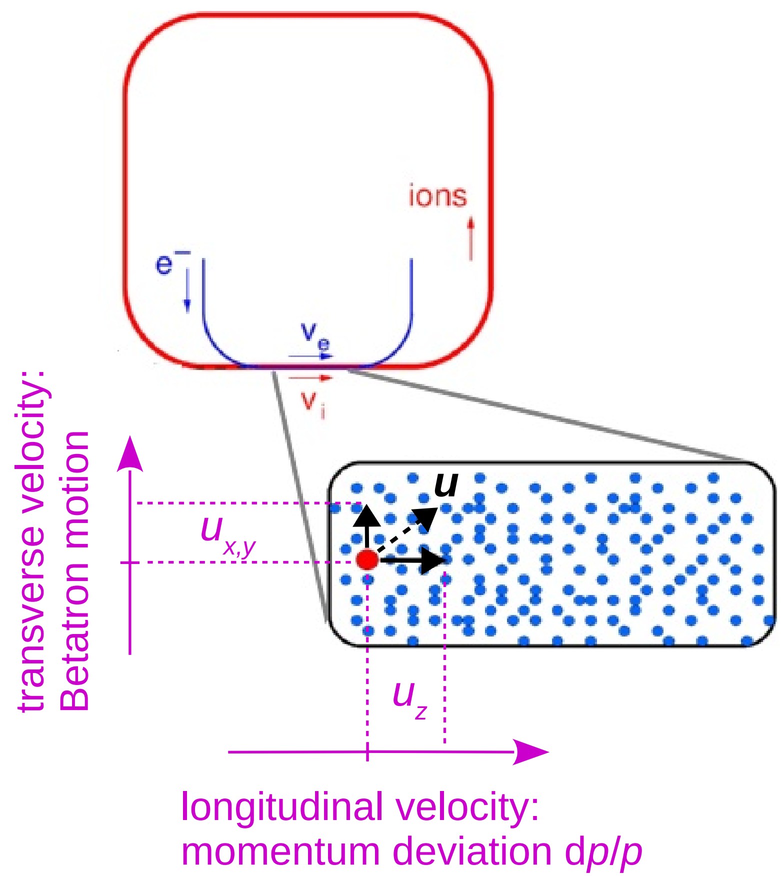


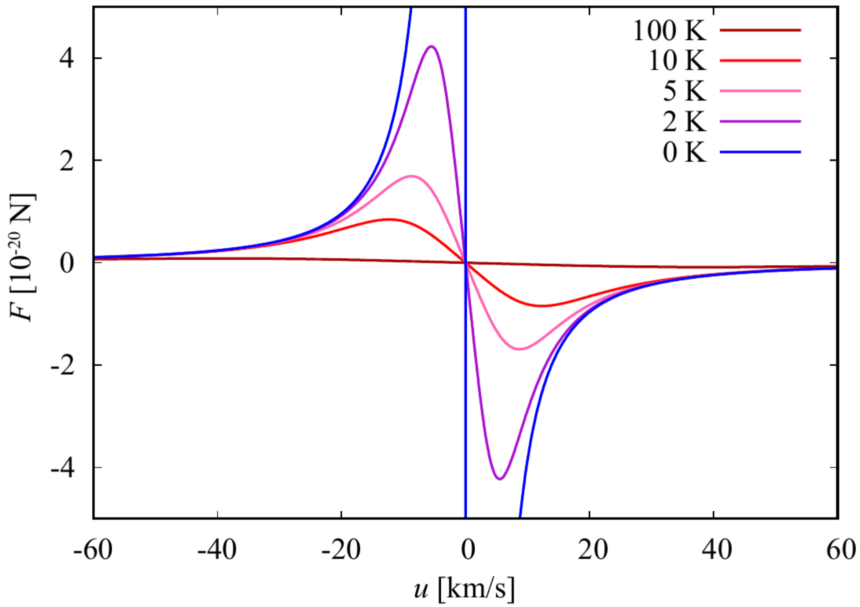


For small relative ion velocity $\boldsymbol{u} = (u_x, u_y, u_z)$:
"damping" force $\boldsymbol{F} \sim \boldsymbol{u}$:

$$F_{x,y} \approx -a_{x,y} \cdot u_{x,y} \qquad \text{(trans.)}$$
$$F_z \approx -a_z \cdot u_z \qquad \text{(long.)}$$

Electron cooling





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"damping" force $\boldsymbol{F} \sim \boldsymbol{u}$:

$$F \approx -a \cdot u \quad \text{with}$$

$$a \sim \frac{Z_{ion}^2 n_e}{T_e^{3/2}}$$

"Effective electron temperature"

Electron cooling

“Effective temperature” of electron beam

Defines:

Maxima of cooling force at $|u| \sim \sqrt{\frac{k T_e}{m_e}}$

Damping rate for $|u| \ll \sqrt{\frac{k T_e}{m_e}}$

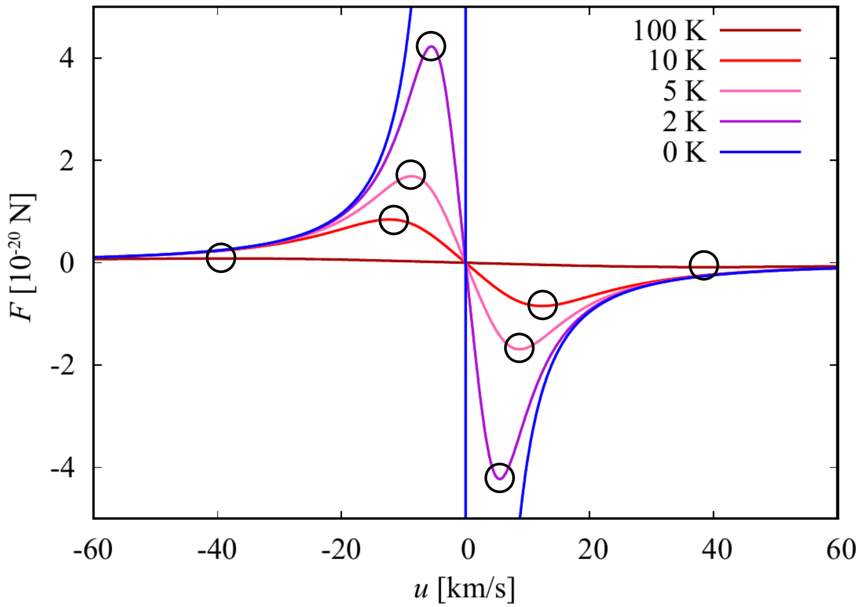
Sources of T_e:

Hot cathode.

Cooling/heating during e-beam formation + transport.

Magnetic field imperfections.

Alignment errors.



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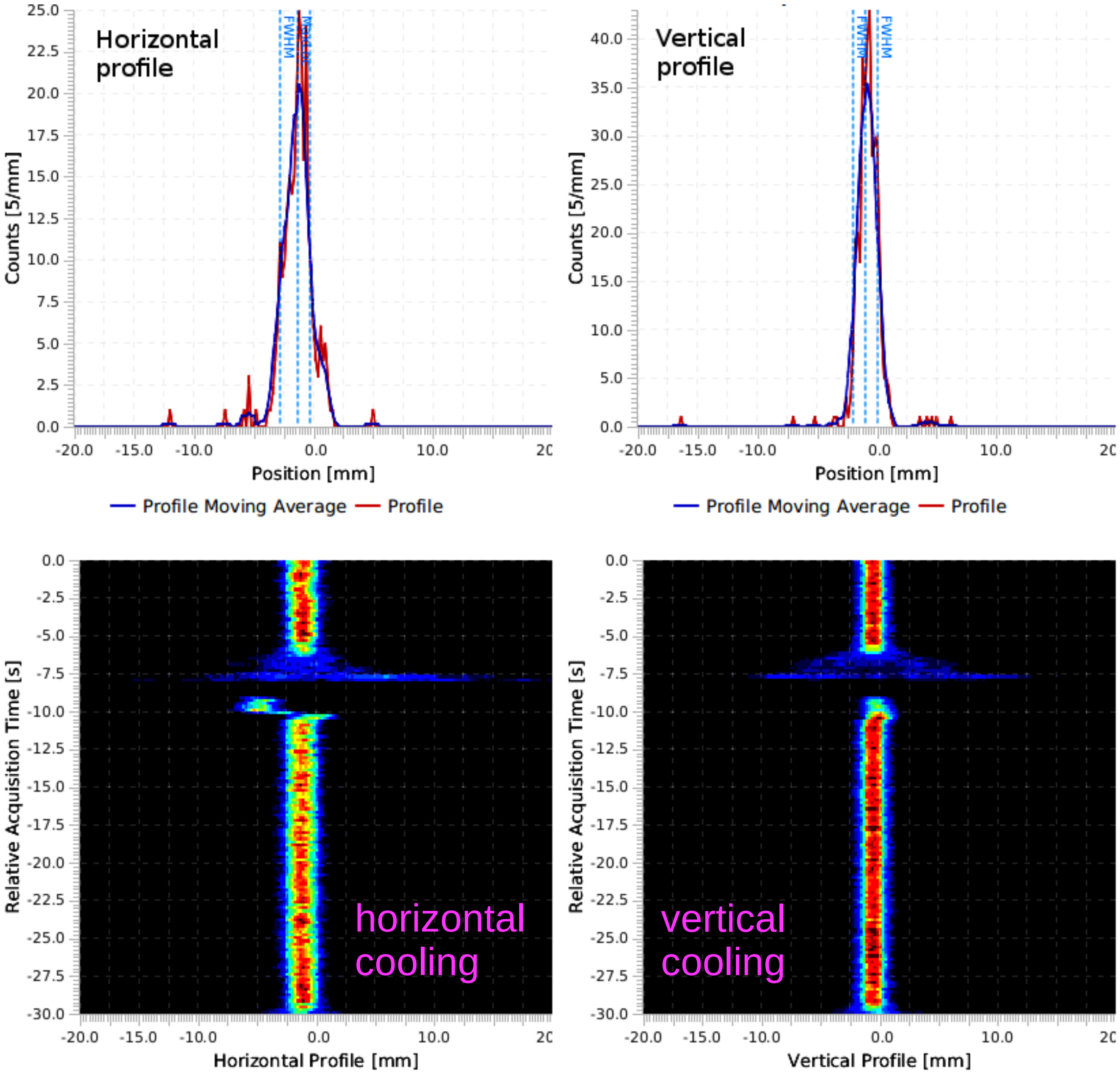
“Effective electron temperature”

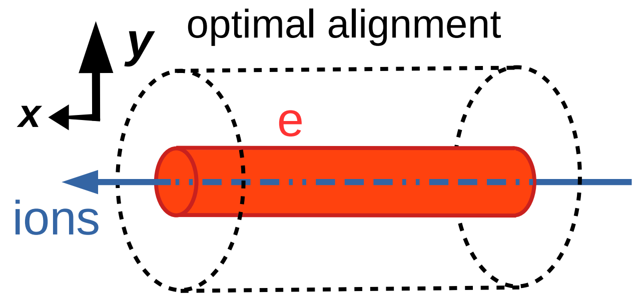
Electron cooling



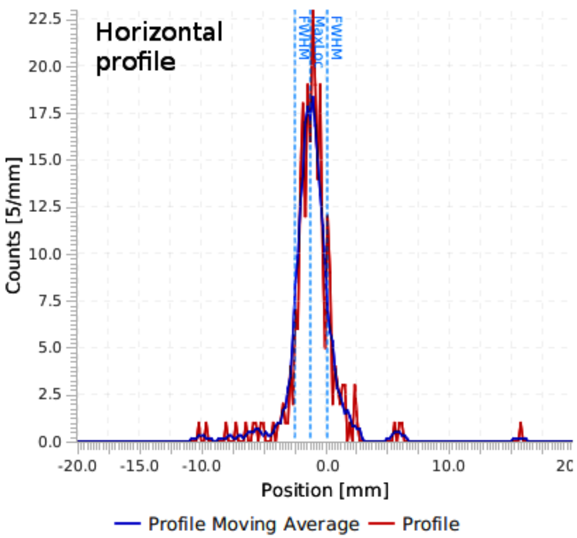
Alignment of electron and ion beams:

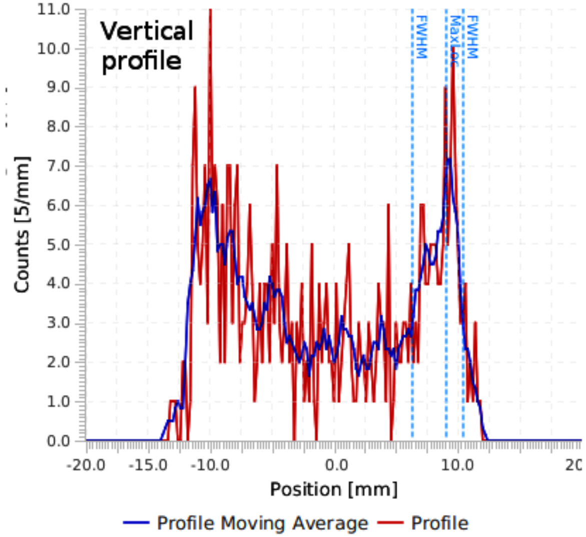
Observation of ion beam response on IPMs.

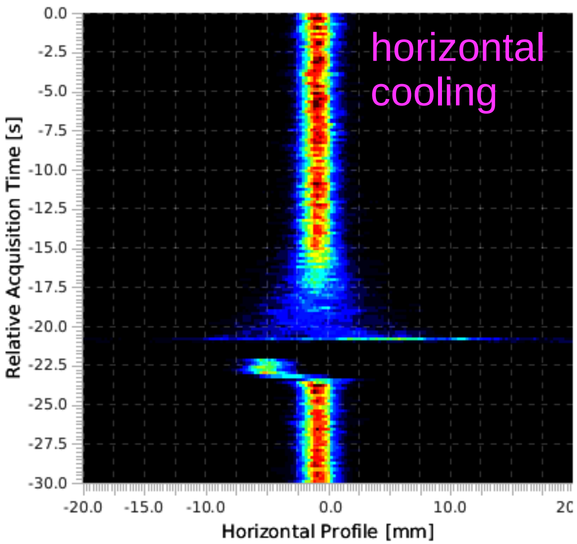
(*ionisation beam profile monitors*)

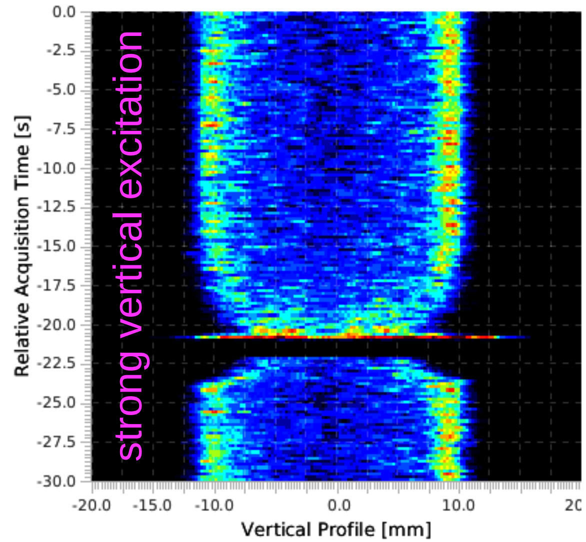


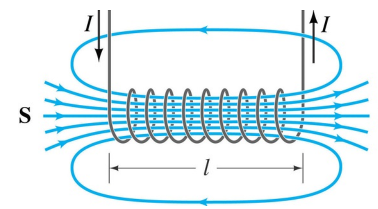
Electron cooling



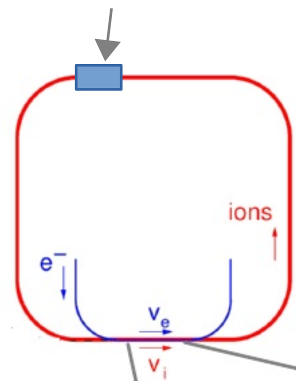


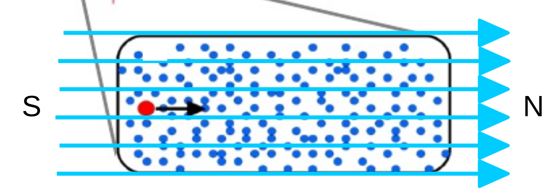




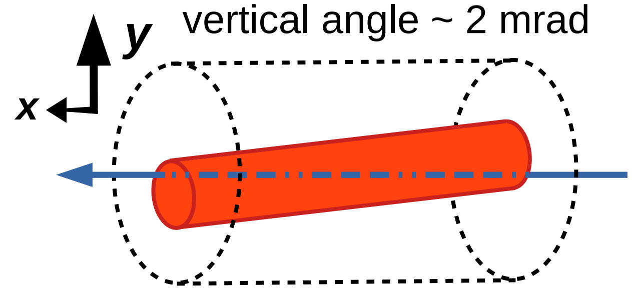


compensation solenoid enabled.

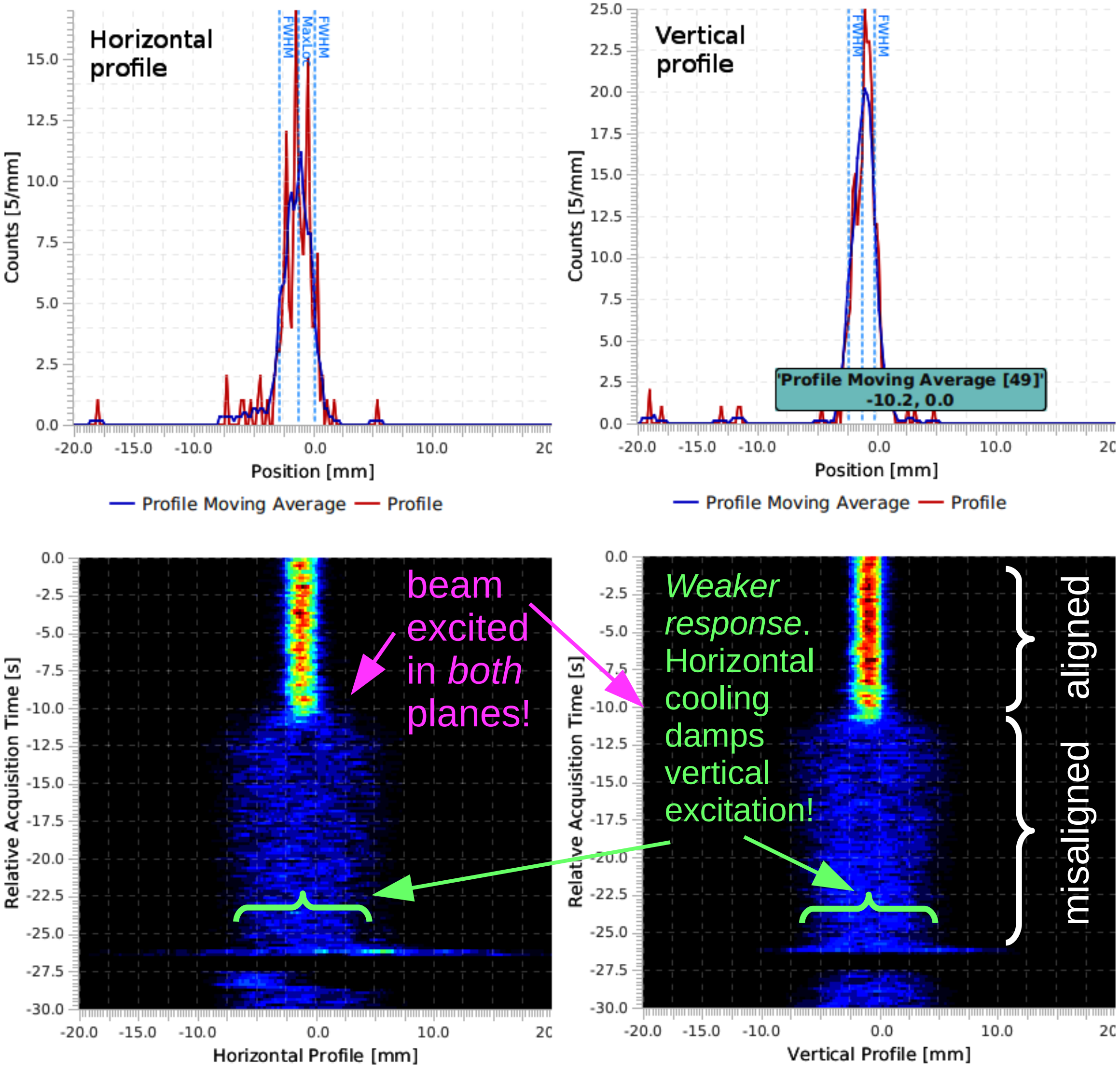


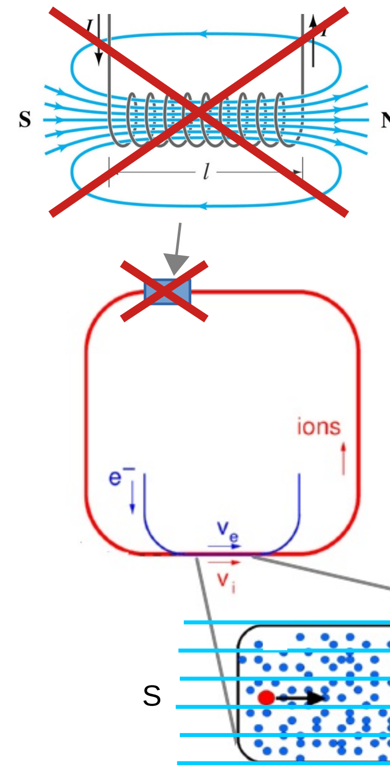


vertical angle ~ 2 mrad



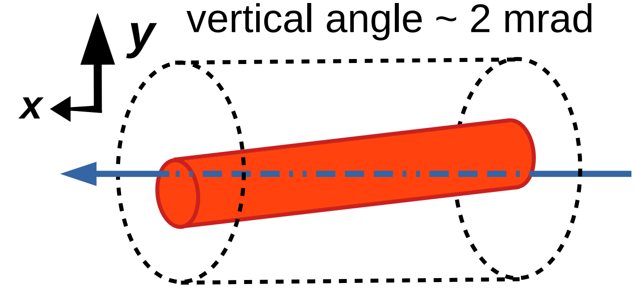
Electron cooling





compensation solenoid disabled.

vertical angle ~ 2 mrad



Electron cooling

The *apparently* weaker beam response could make optimal alignment of the cooler practically more difficult ...

→ **Idea:**

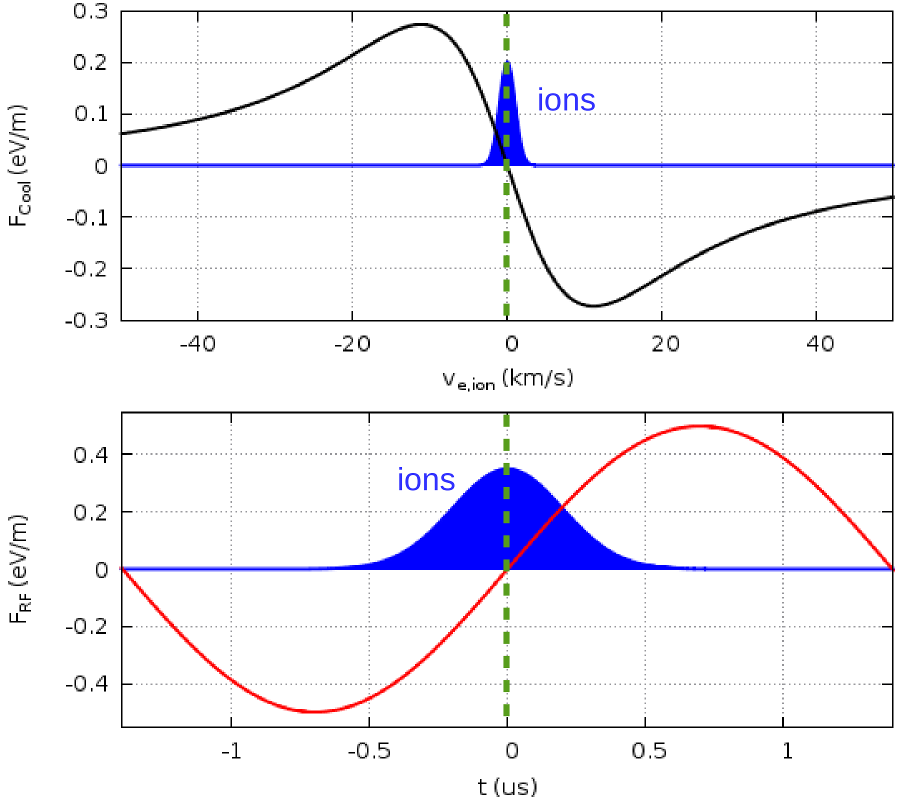
1) Set-up electron cooling with compensation solenoid disabled and enabled, starting with the more “difficult” case.

2) Measure ***electron cooler performance*** for both cases.

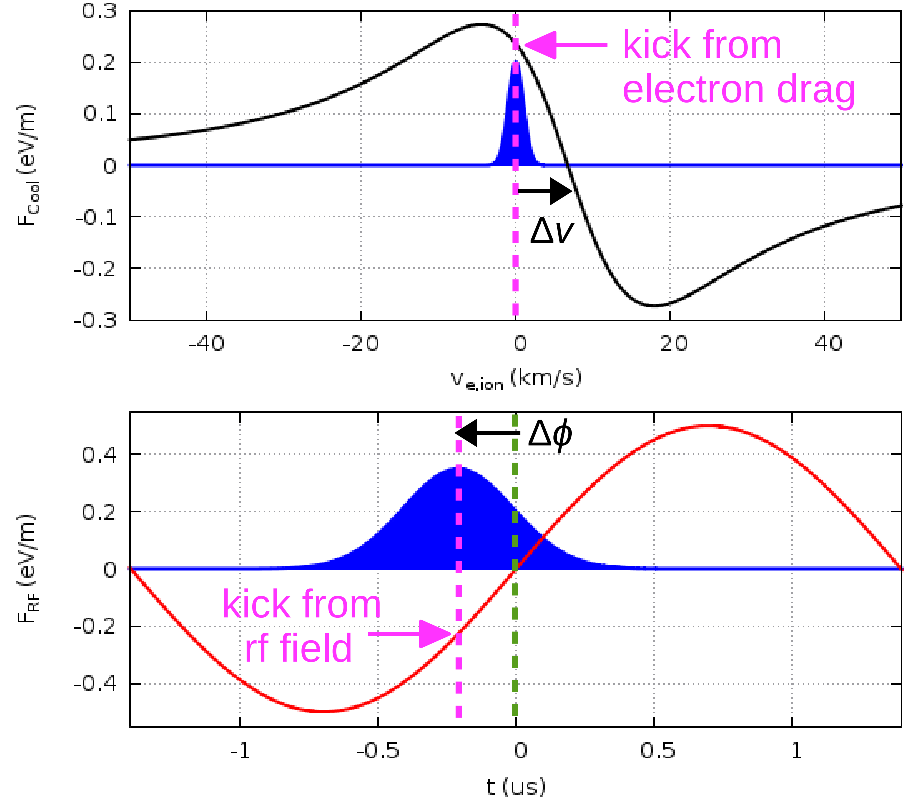
Electron cooling

Longitudinal cooling force measurement: “Bunch phase shift method”

Cooler velocity matched to rf-bunched ions



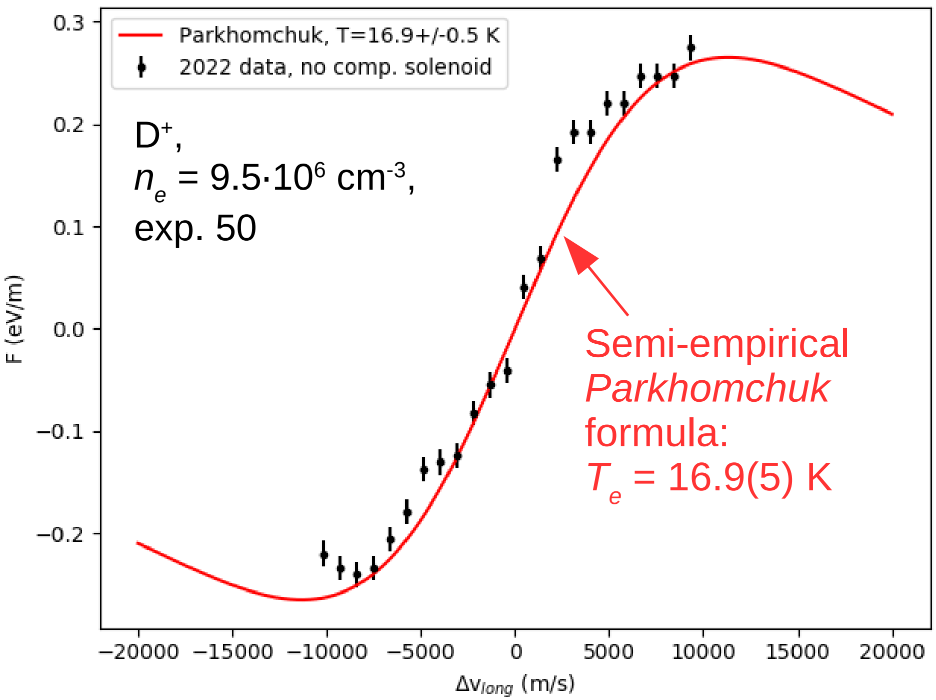
Cooler velocity detuned from bunch velocity



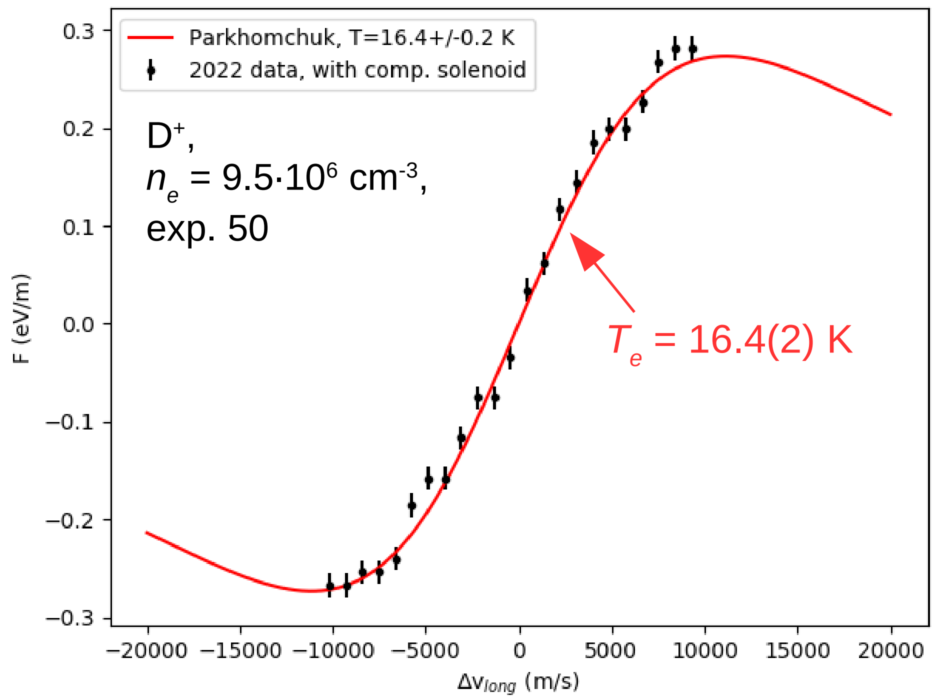
$$F_{cool}(\Delta v) = Z_{ion}\, e\, U_{RF} \sin(\Delta\phi) / L_{cool}$$

Electron cooling

Compensation solenoid disabled:

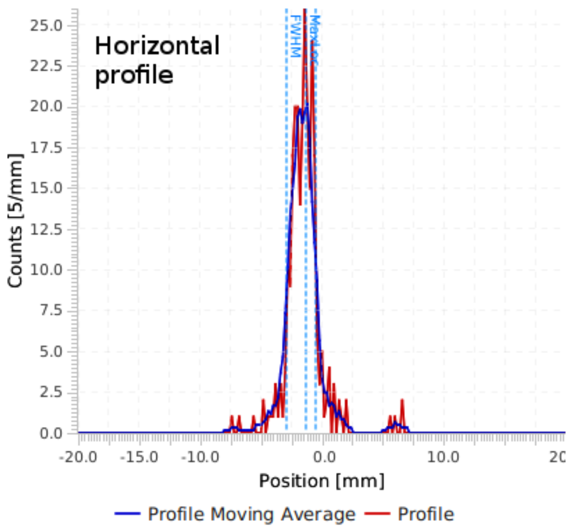


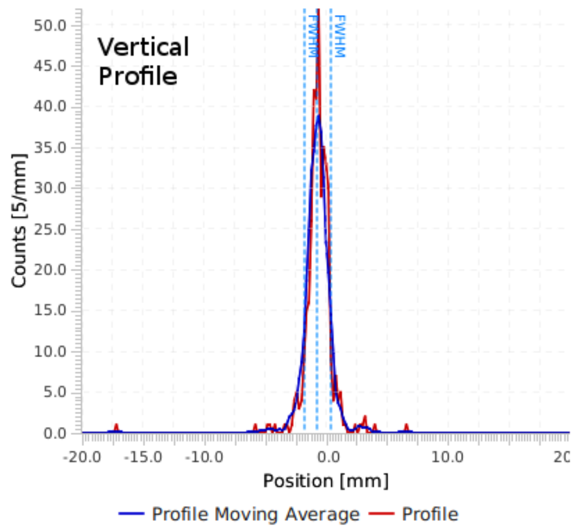
Compensation solenoid enabled:

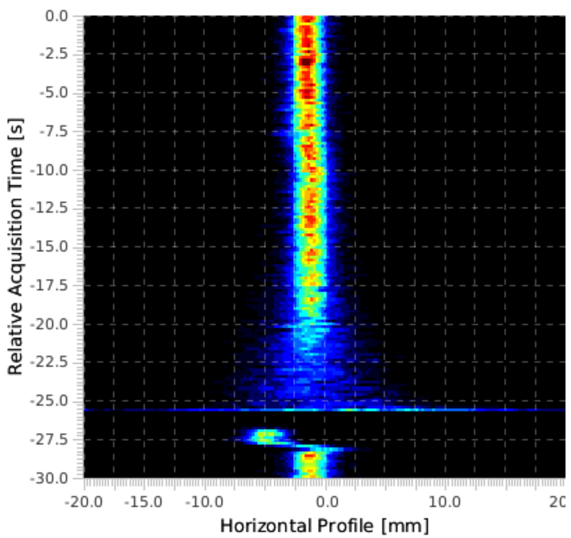


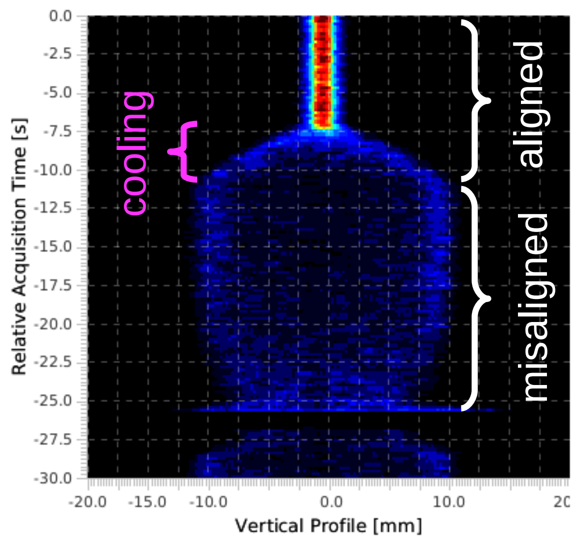
→ No difference observed!

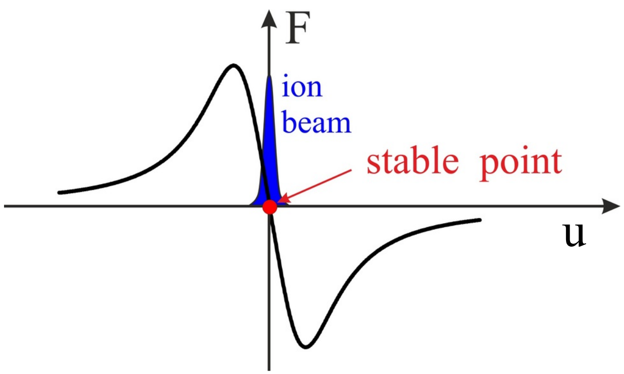
Electron cooling











Transverse cooling force for small amplitudes: $F \sim u$:

$$F \approx -a \cdot u \quad \text{with}$$

$$a \sim \frac{Z_{ion}^2 n_e}{T_e^{3/2}}$$

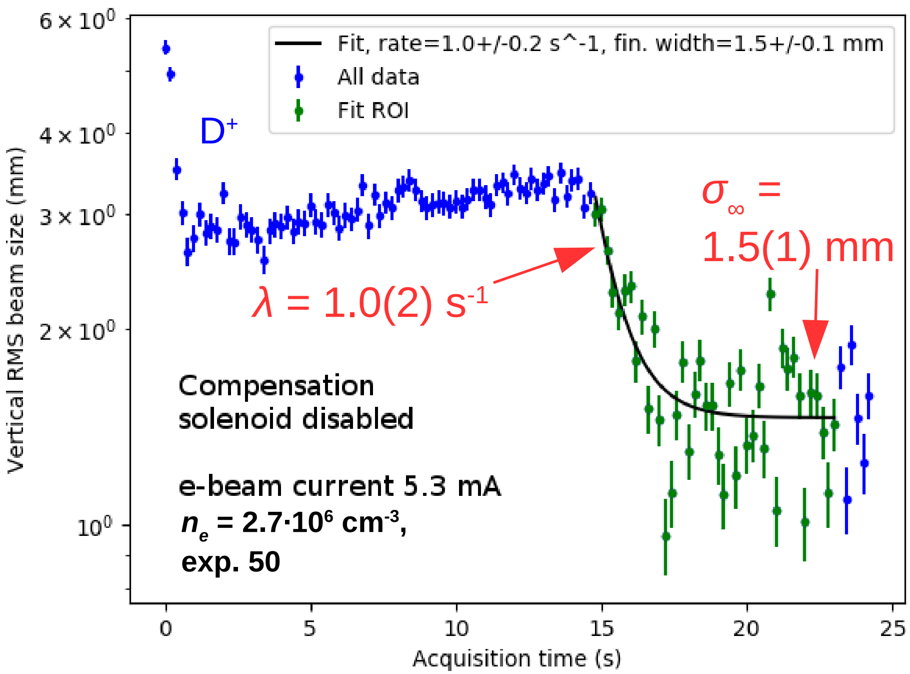
→ All betatron amplitudes damped at the same rate λ.

→ Beam envelopes evolve as

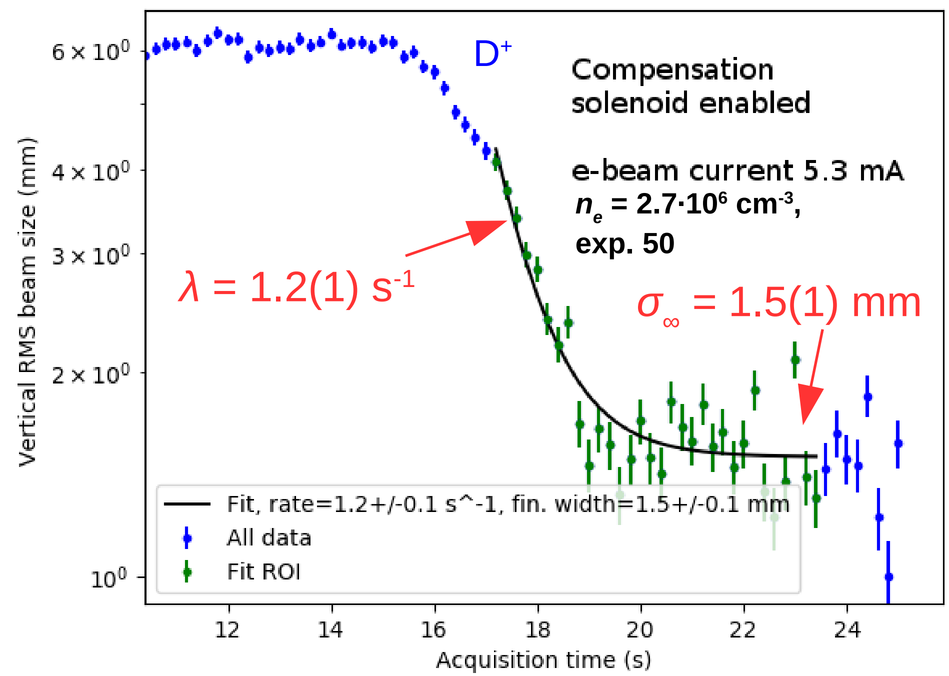
$$\sigma(t) = A_0 \exp(-\lambda t) + \sigma_\infty$$

Electron cooling

Compensation solenoid **disabled**:



Compensation solenoid **enabled**:



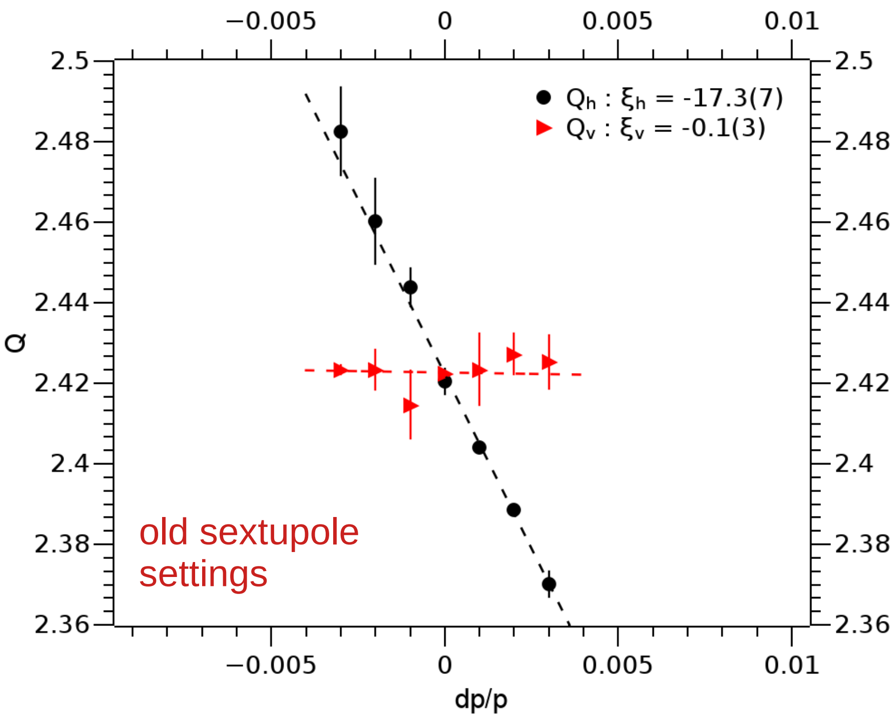
→ No difference observed!

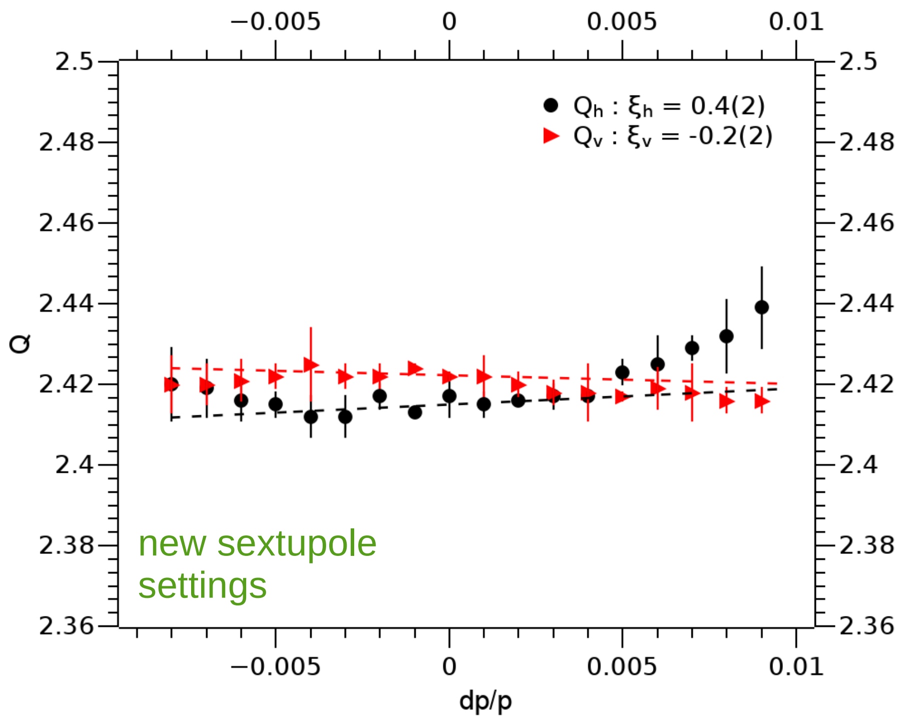
Additional remarks

By chance, found a long-standing bug in computation of chromaticity correction.

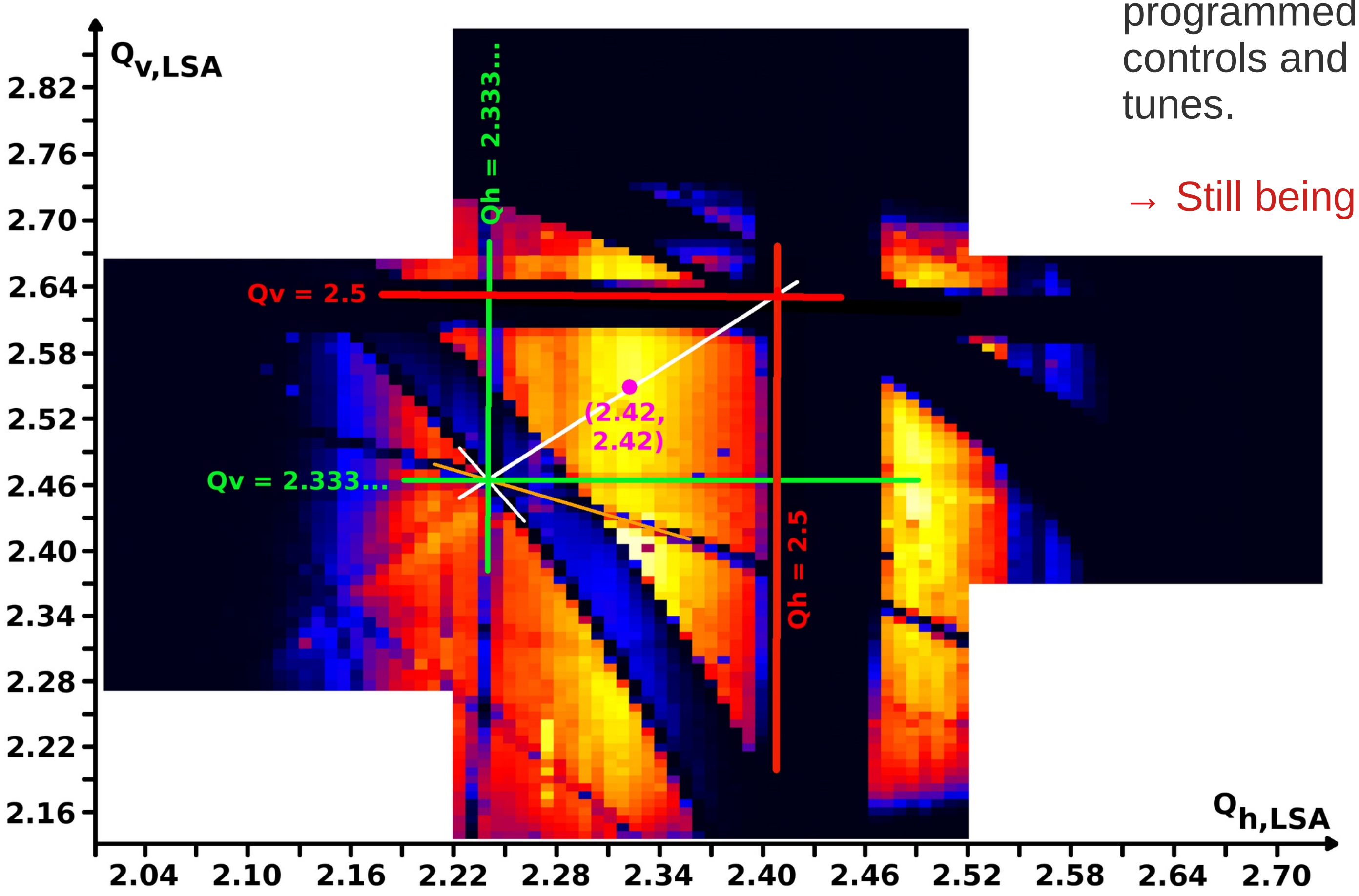
$$\xi = \frac{dQ}{d(\delta p / p)}$$

→ *Much improved momentum acceptance with new sextupole magnet settings*.





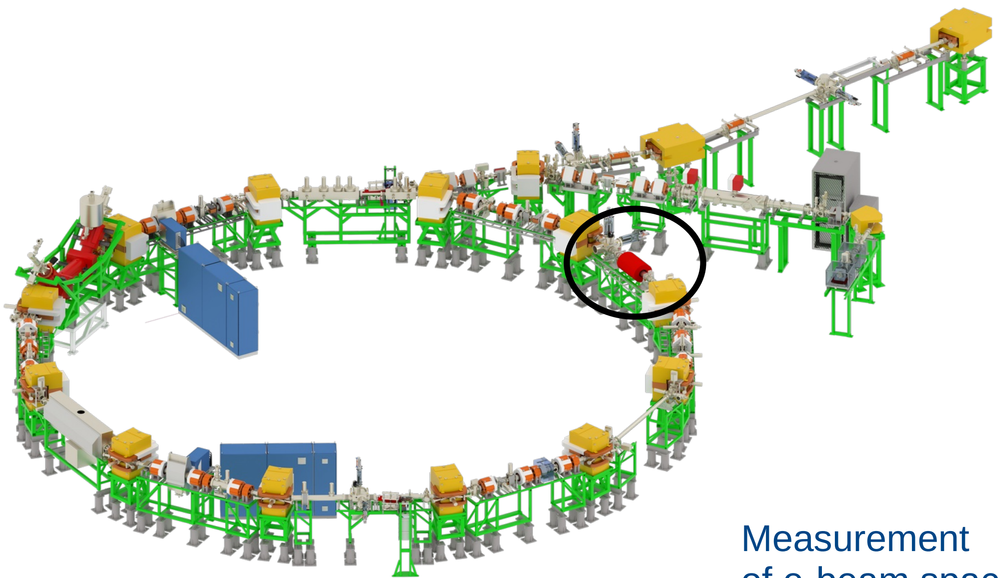
Additional remarks



"Re-discovered" a significant offset between the working point programmed via accelerator controls and the true measured tunes.

→ Still being worked on ...

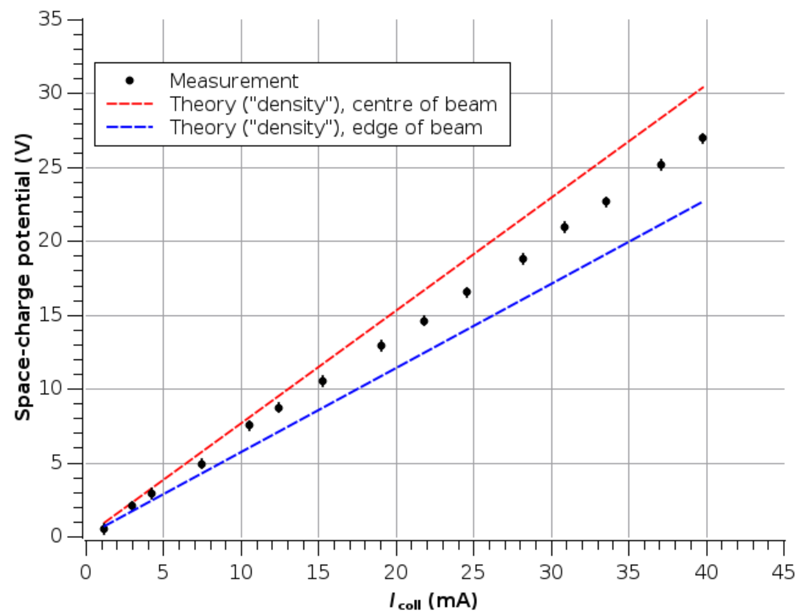
Additional remarks



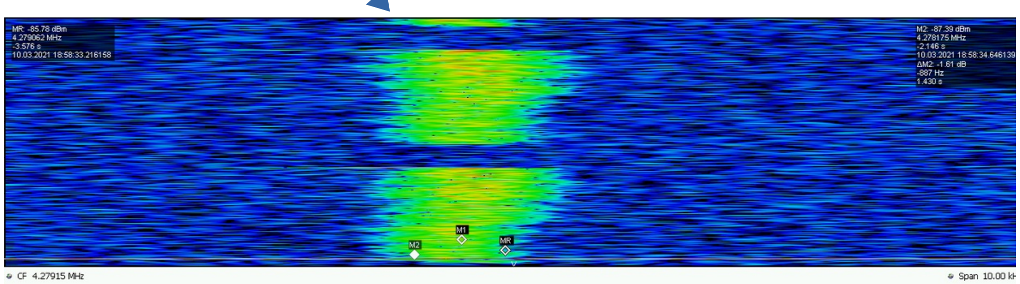
Compensation solenoid contains the **Schottky pickups** of CRYRING.

→ *Very important diagnostics for operation with and experiments on coasting beams!!*

Measurement of e-beam space-charge potential



Checking stability of ion momenta during DR experiments.



Summary

We tested CRYRING operation with the cooler compensation solenoid YR11MO1P disabled.

The effect of betatron coupling is clearly observed in the beam response to transverse excitations (by RF-KO or cooler).

The standard W.P. becomes undefined, as predicted by calculations.

No adverse effect on storage stability.

No effect on quality of electron cooling.

If enabled, YR11MO1P seems to compensate betatron coupling *perfectly*.

Tentative verdict:

Unless for the most exotic beam manipulations (1-D excitation ...), we can probably run just fine without YR11MO1P, if a new Schottky detector is installed.

Thanks

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C. K., S. Khammee, I. Kraus, A. Reiter,

B. Rück, S. Trotsenko, G. Vorobjev