One-Dimensional Ordering in High-Energy Ion Beams

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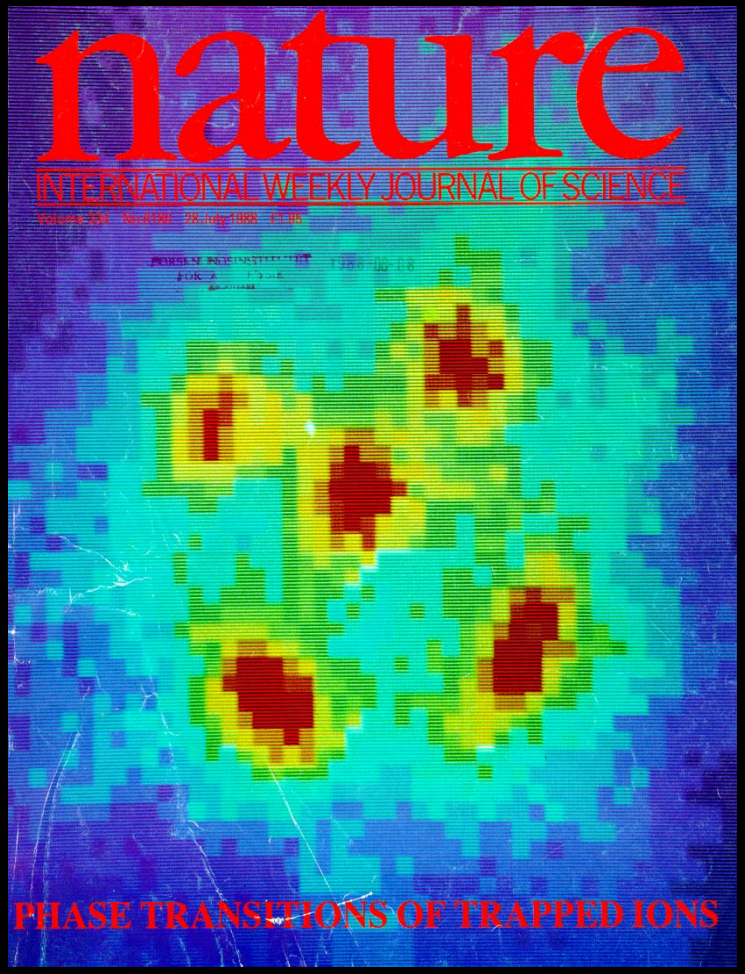
Coulomb crystals in traps – and storage rings?



Coulomb crystals, ordered structures of charged particles, have been observed in ion traps since several decades.

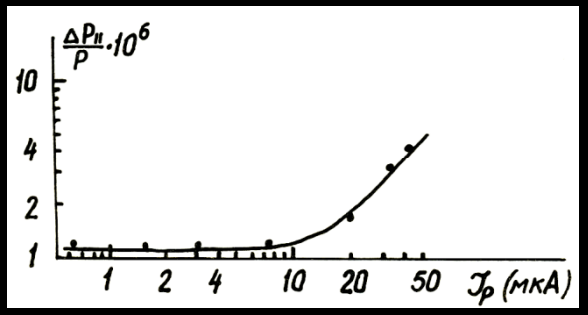
The Nature cover from 1988 shows five Mg^+ ions in a Paul trap (Walther et al.).

Can such order occur in particle beams moving around an accelerator at speeds close to the speed of light?

Could have many applications, such as increased luminosity in colliders.

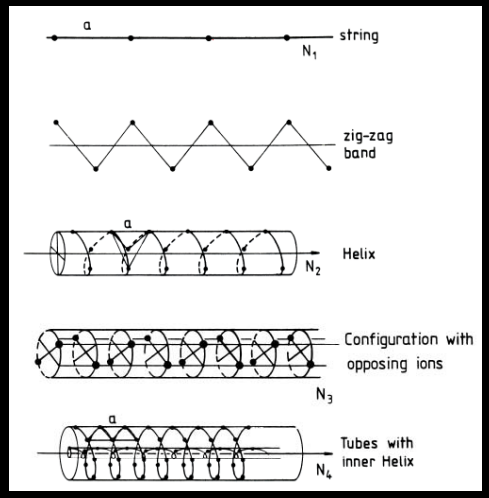
How could order be observed?

Storage ring experiments and theories since 30 years

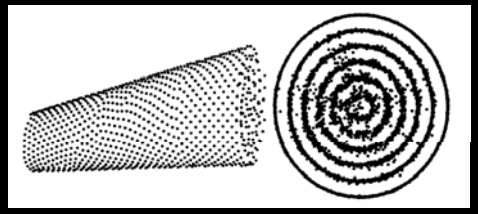


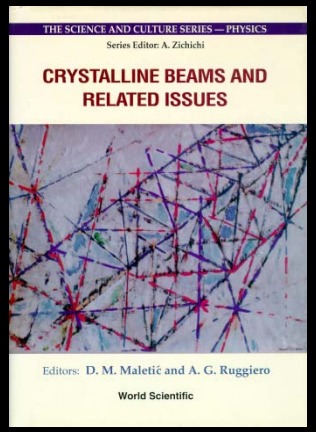
Observations of low Schottky intensity, independent of particle number at NAP-M

Workshops on crystalline beams and related issues



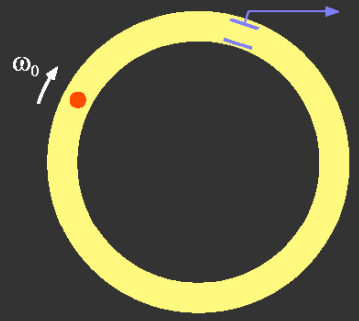
Analytical calculations and numerical simulations of formation and maintenance of beam crystals

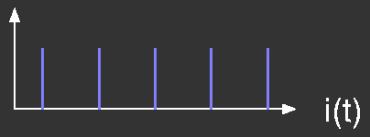


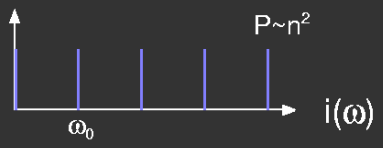


Schottky spectra

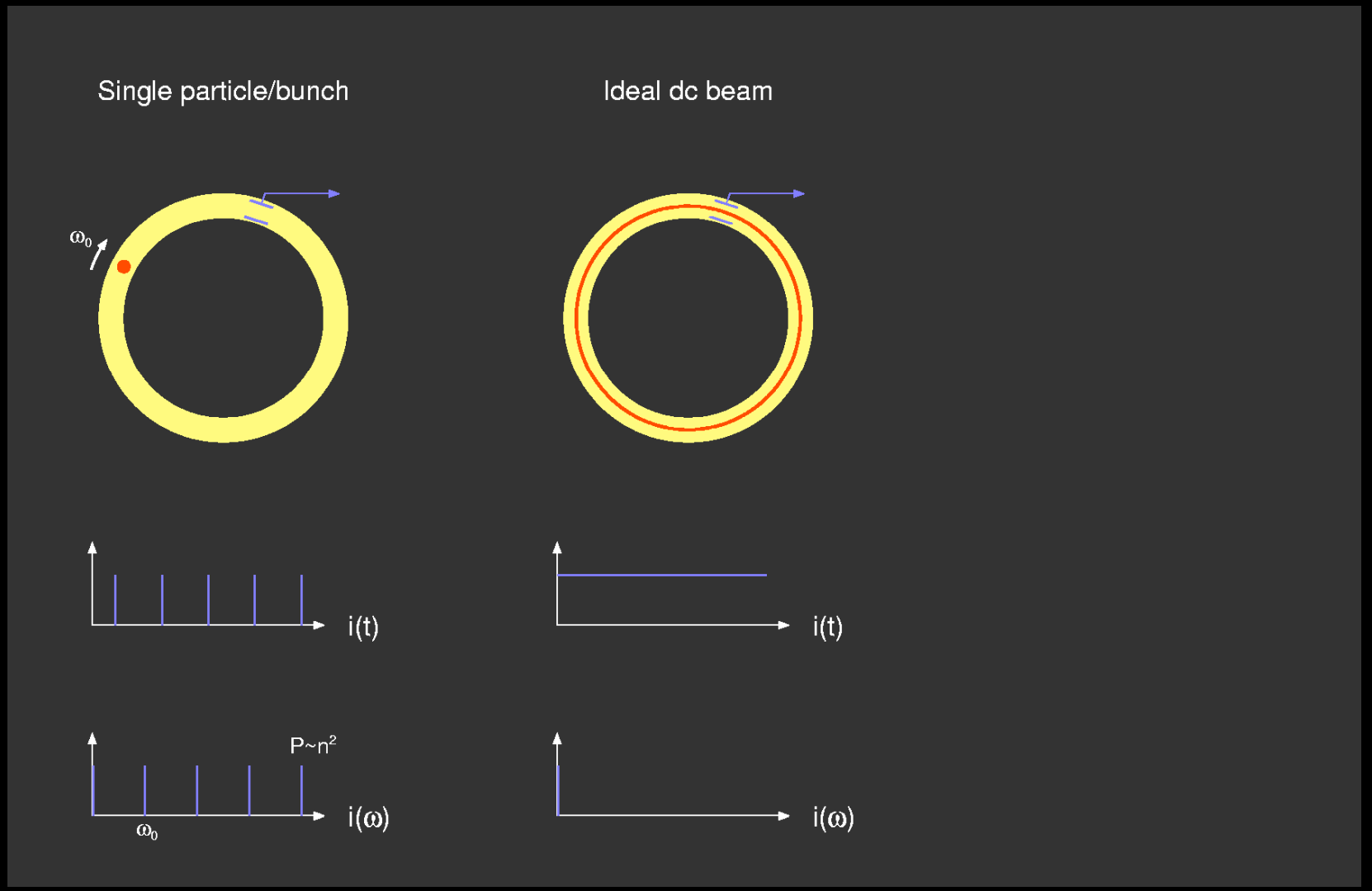
Single particle/bunch



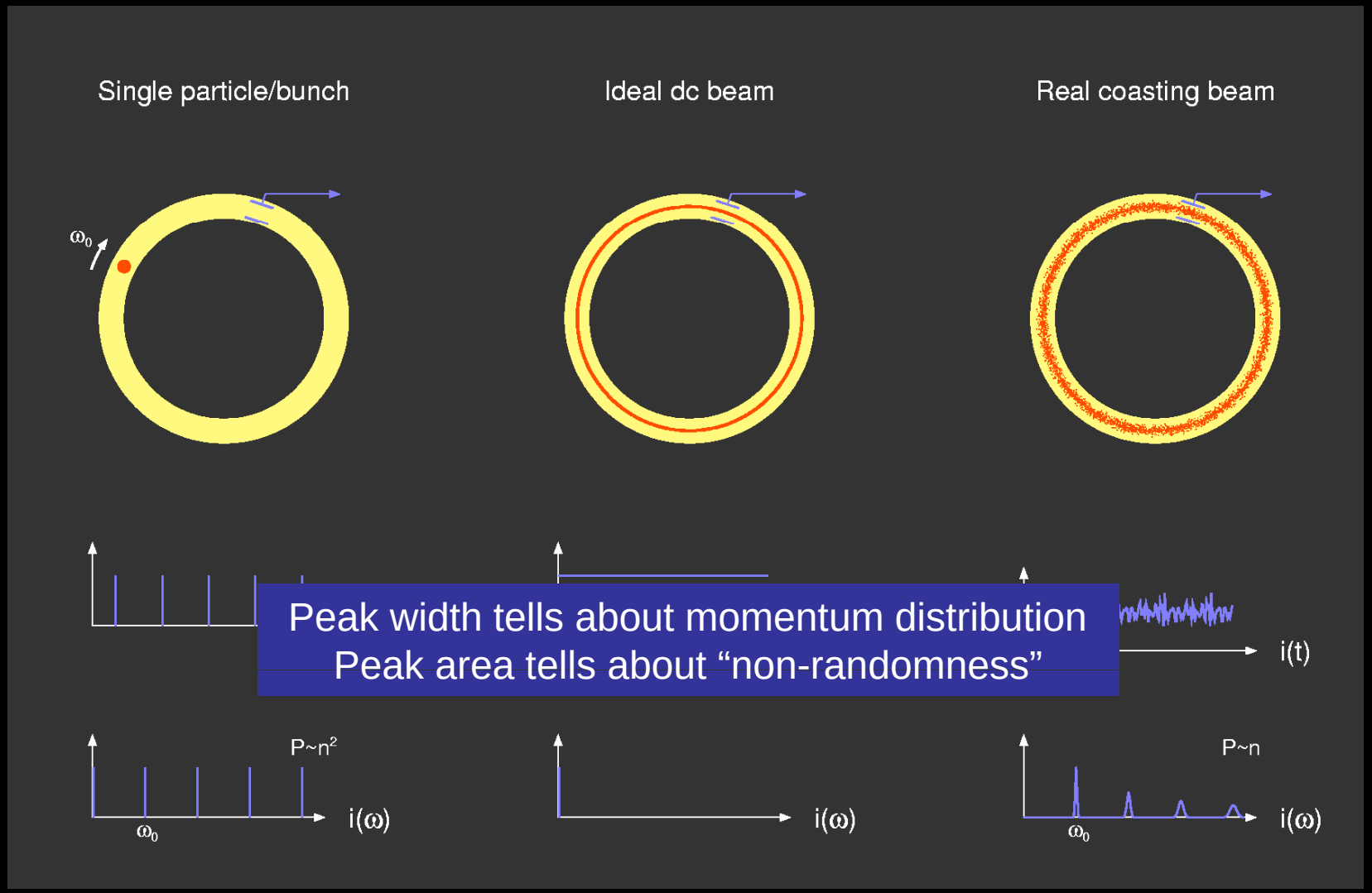




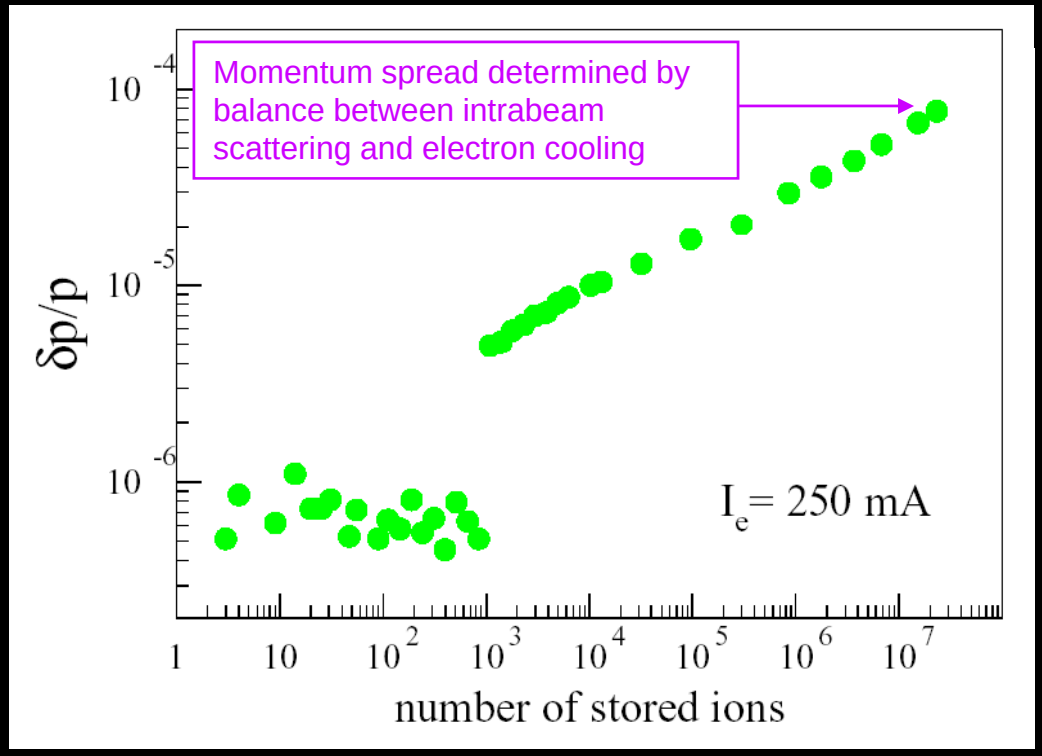
Schottky spectra



Schottky spectra



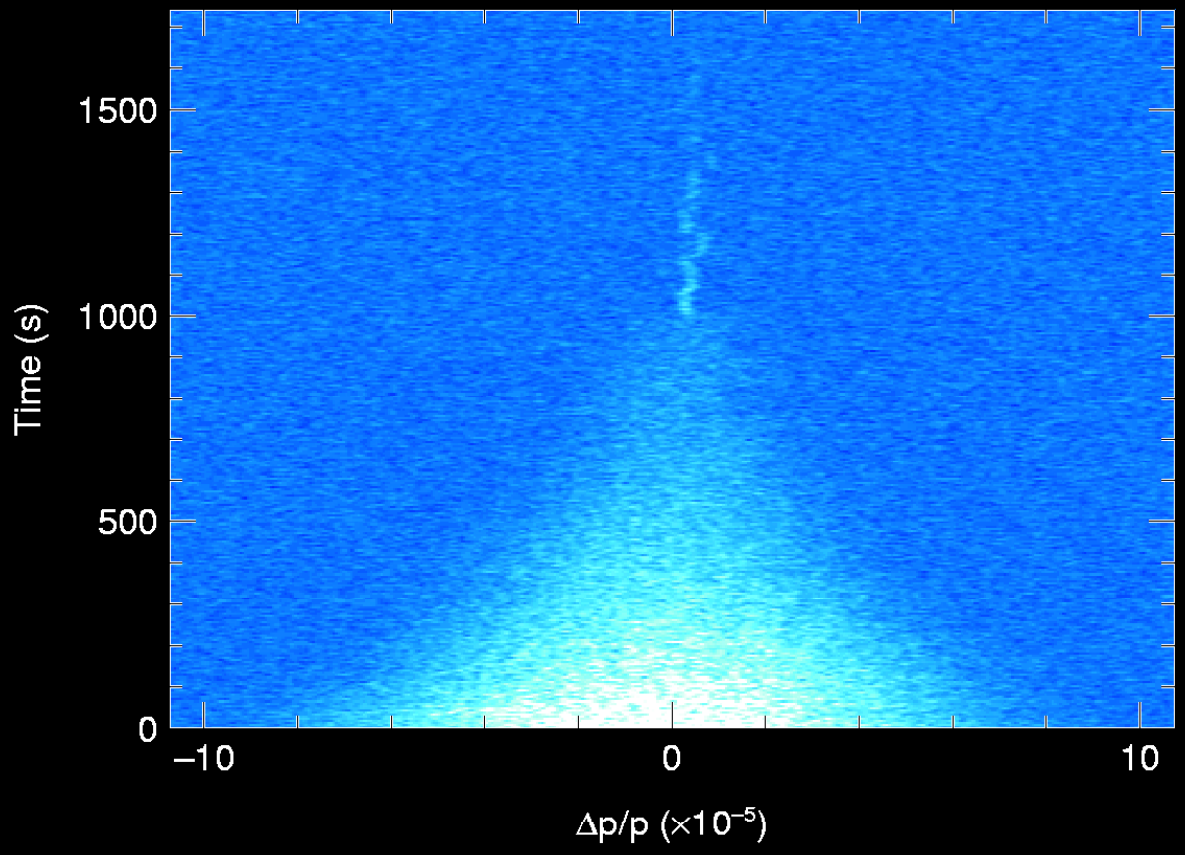
Collapsing momentum spread – vanishing intrabeam scattering



Schottky spectra showing a sudden reduction of the momentum spread of electron-cooled, heavy, highly charged ions was first seen at GSI (Steck *et al.* 1996).

The observations were interpreted as ordering such that the ions line up after one another in the ring (Hasse 2000).

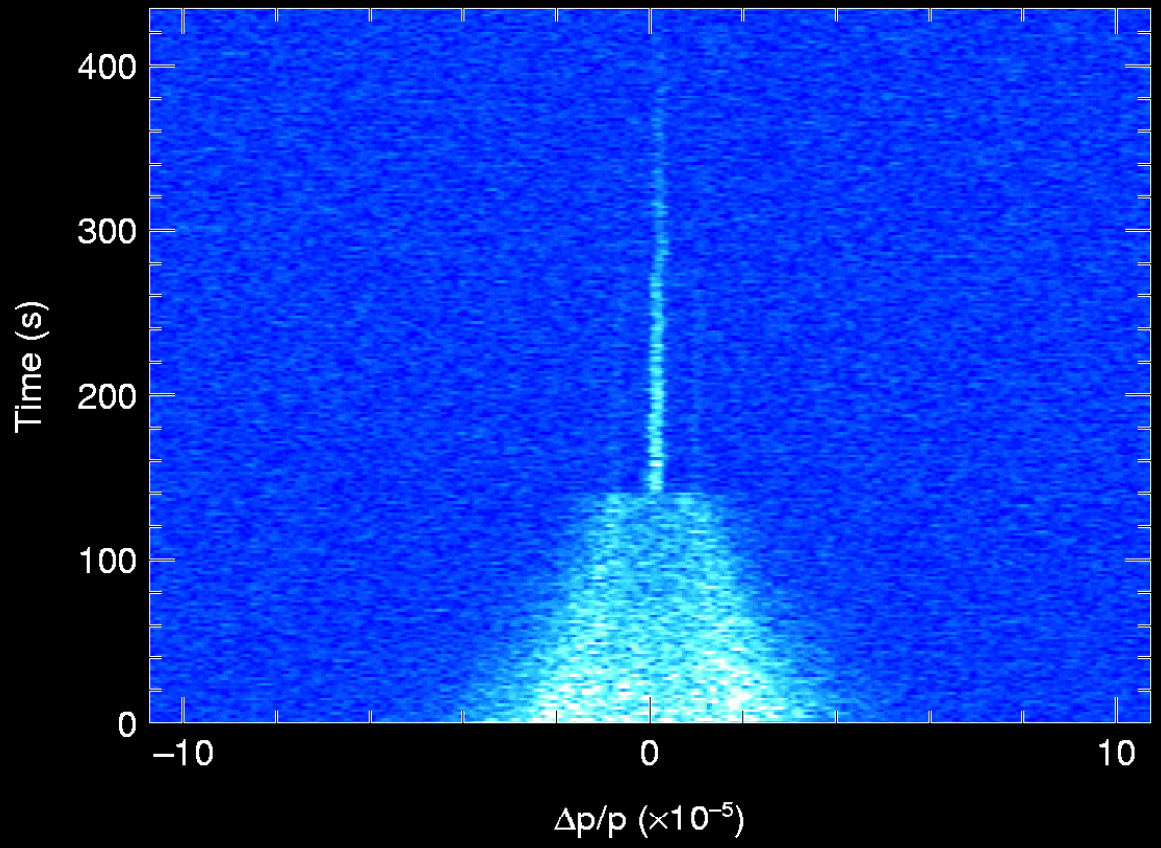
Reduction of momentum spread at CRYRING



Schottky signal from 7.6 MeV/u Xe^{36+} ions

“Weak” cooling

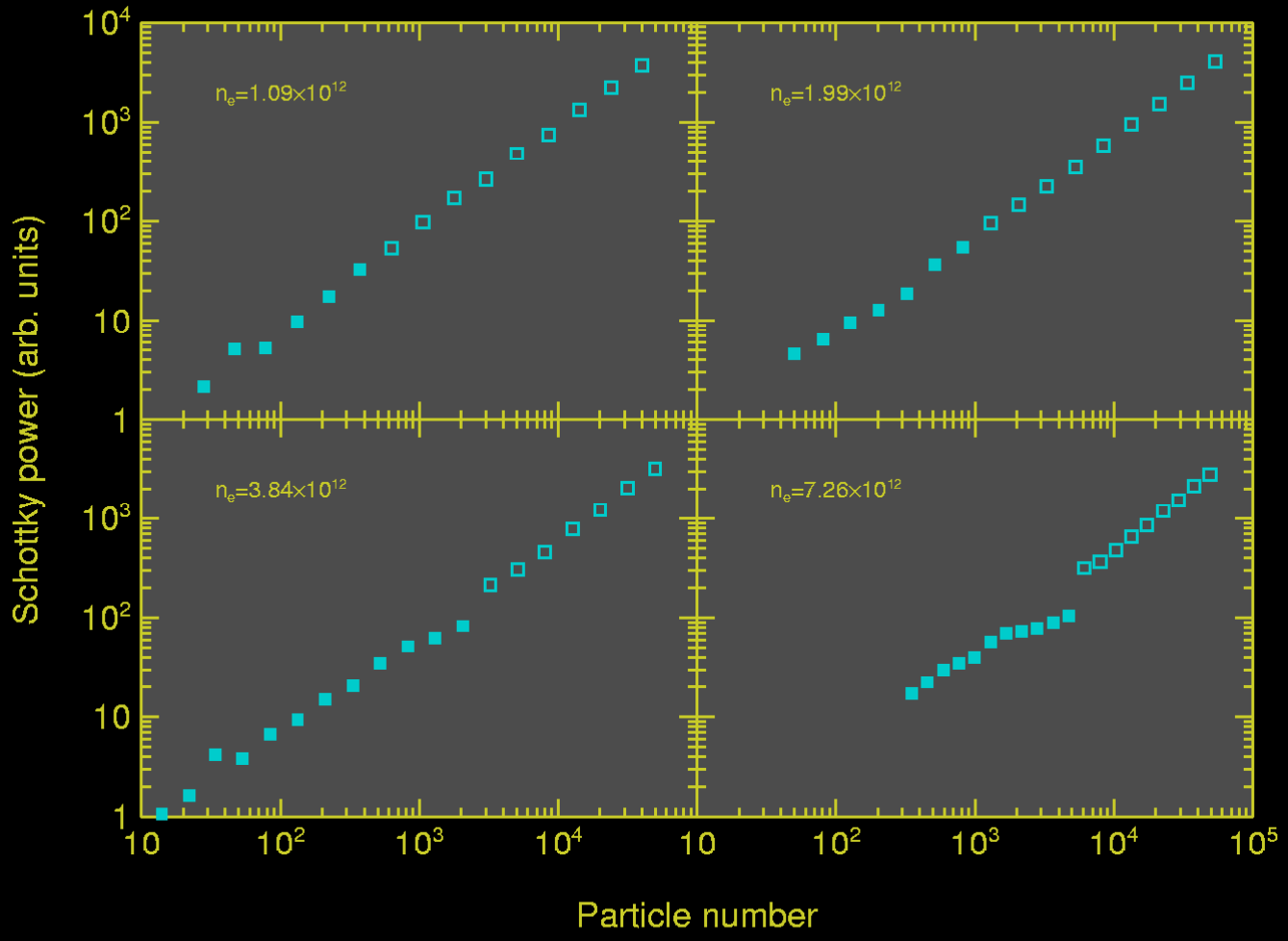
Reduction of momentum spread at CRYRING



Schottky signal from 7.6 MeV/u Xe^{36+} ions

“Strong” cooling

Suppression of Schottky noise power



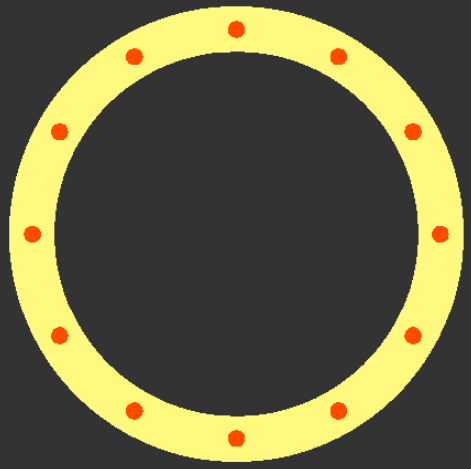
Open symbols: disordered beam (large momentum spread)

Filled symbols: ordered beam (small momentum spread)

What particle configuration can give such dependence of Schottky power on particle number?

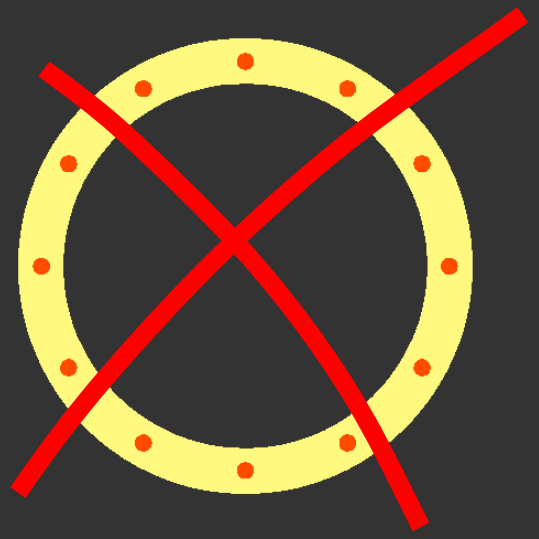
Not so good beam models

Equidistant



Not so good beam models

Equidistant



Not so good beam models

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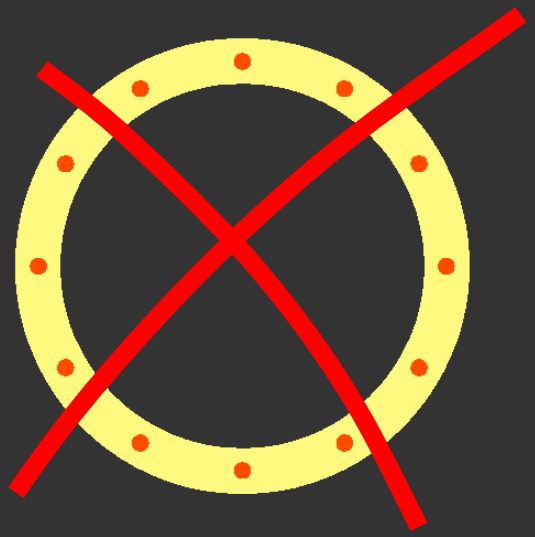
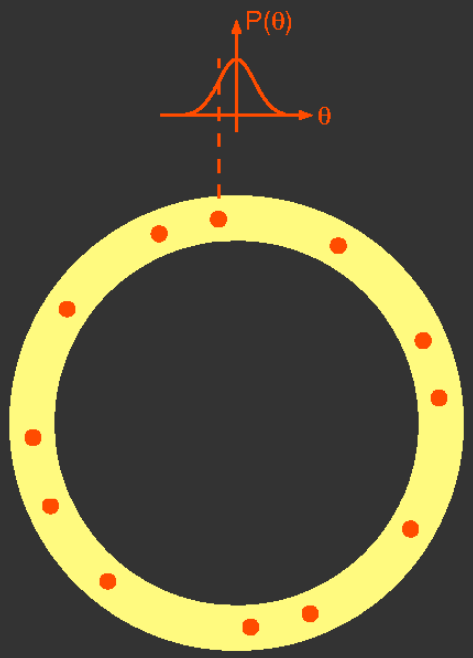


Equidistant plus "thermal" displacement according to some distribution function



Not so good beam models

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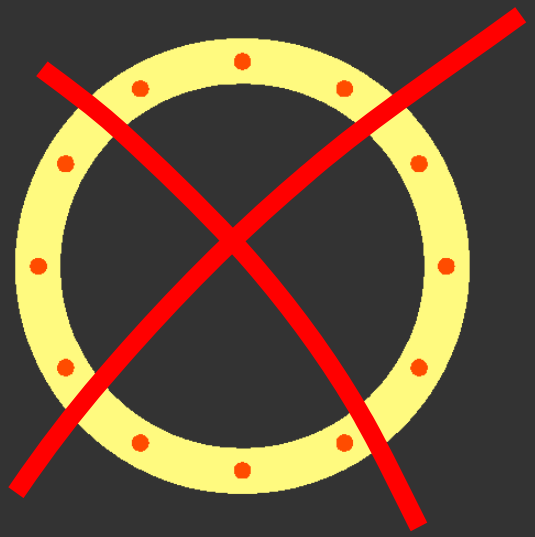

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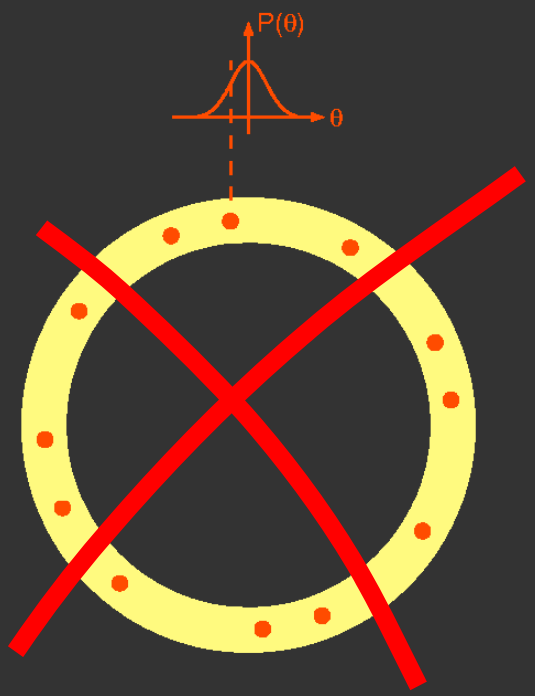
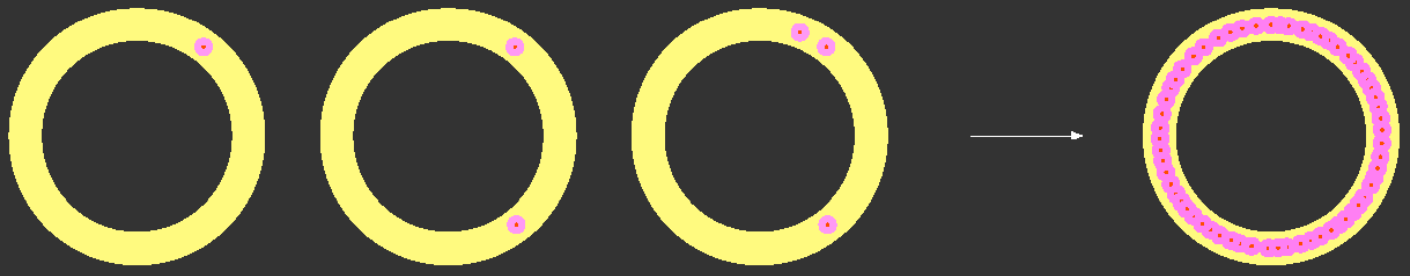


Better beam model



$$d_{min} = \frac{(Zq)^2}{4\pi\varepsilon_0 kT}$$

Z = 36

$kT_{//}$ = 0.05-0.15 meV

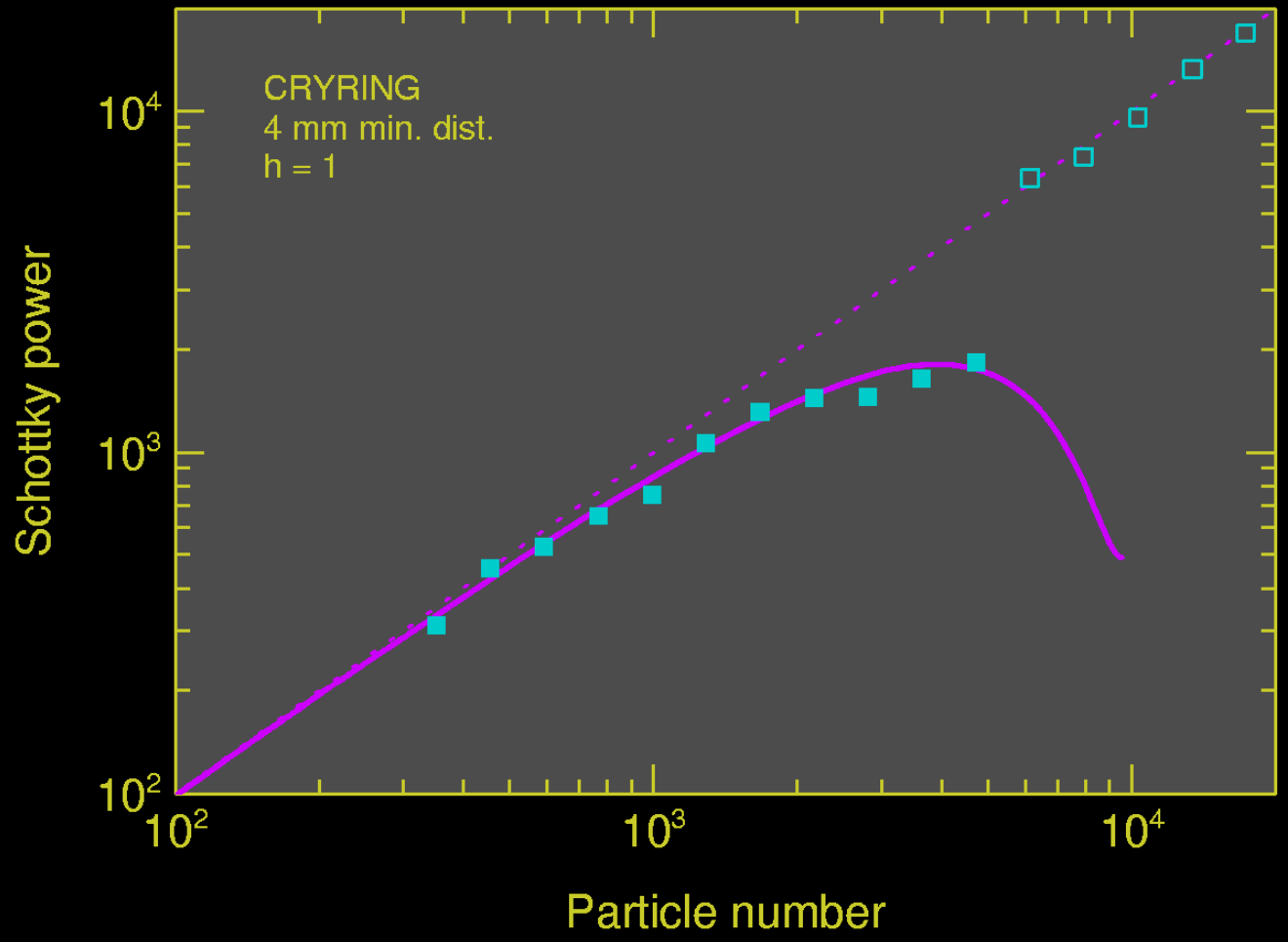
$kT_{\perp}$ = 1-3 meV

kT = 0.5 meV

d_{min} = 4 mm

This is a very particular state with strong local correlations, all distances are between d_{min} and $2d_{min}$.

Theory vs. experiment



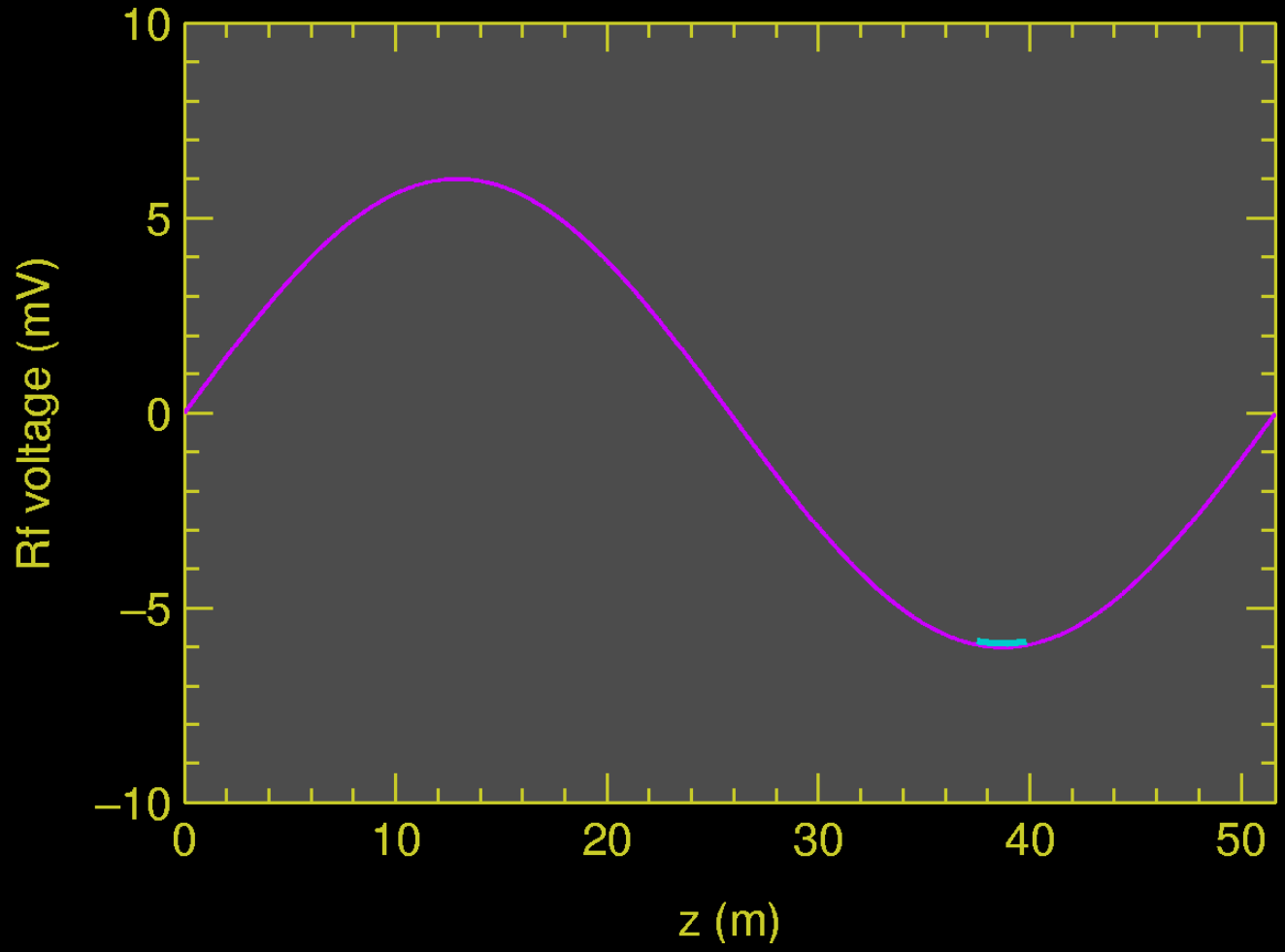
Open symbols:
disordered beam

Filled symbols:
ordered beam

Curve:
model calculation

Conclusion: It seems as if we observe a spatially ordered ion beam

Ordering in bunched beams

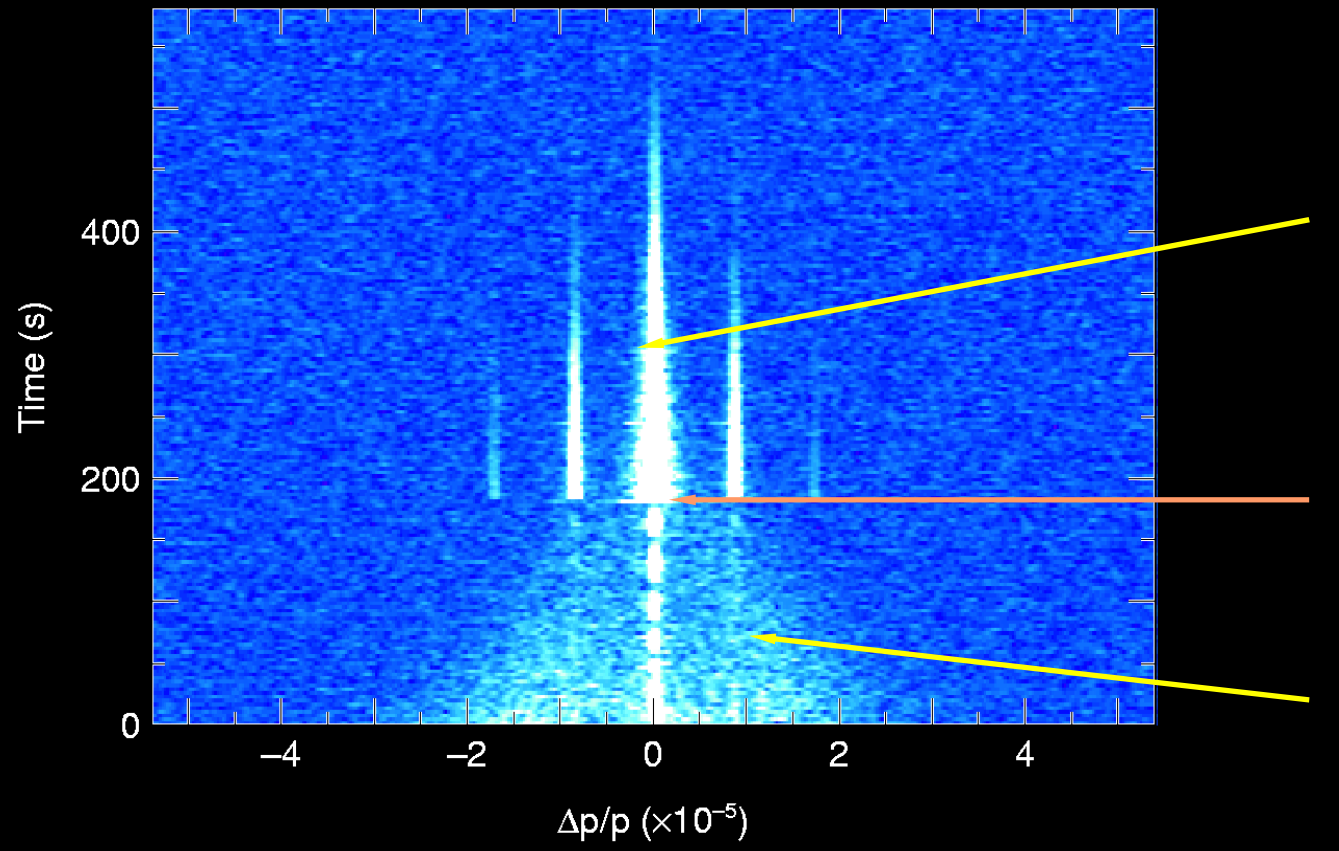


Is it possible to have ordering also in a bunch of particle confined in three dimensions?

Could give handle on particle density

To get particle densities similar to those in a coasting beam, the rf voltage must be very low…

“Schottky signal” from bunched beam

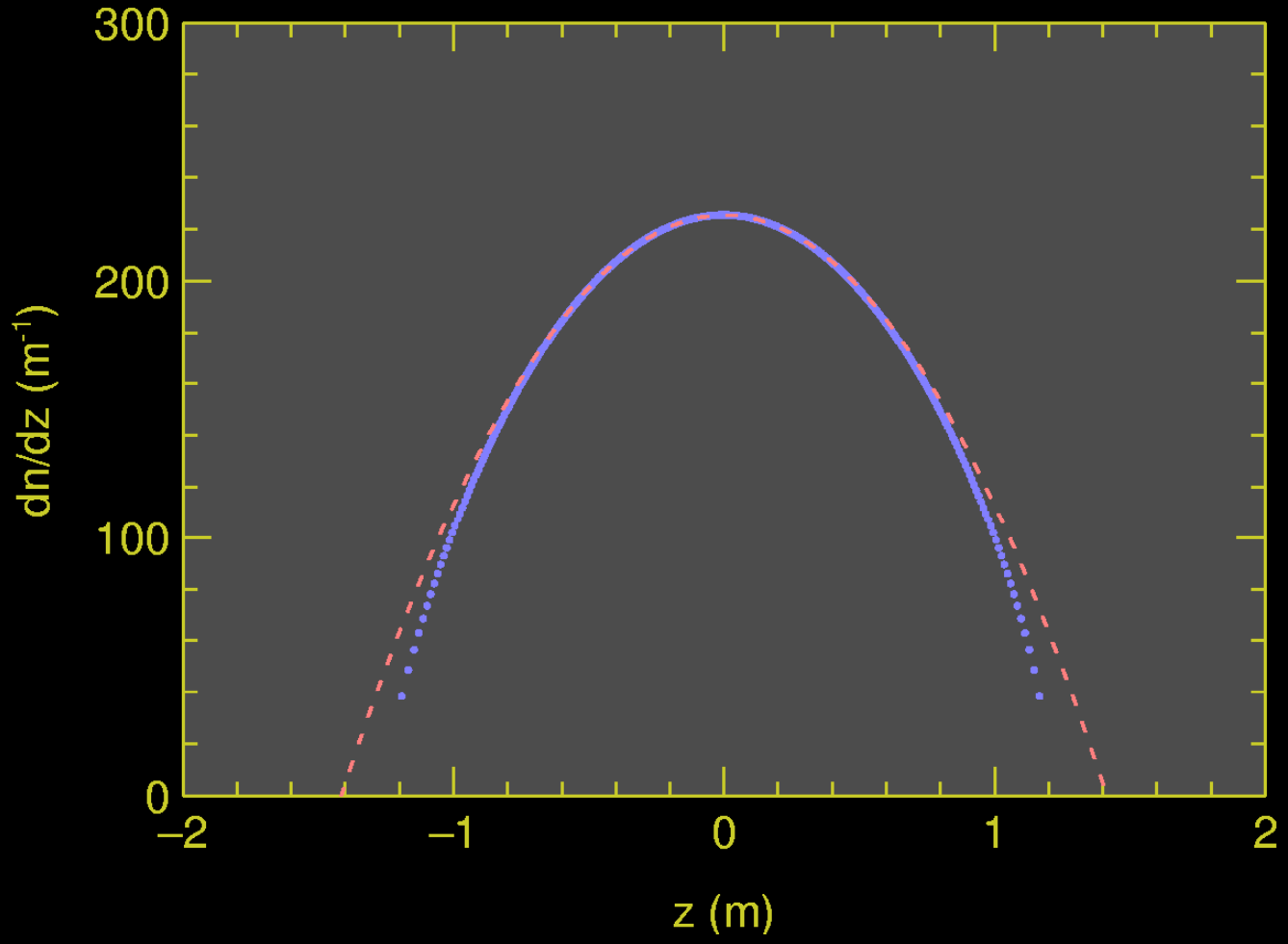


Energy spread has dropped and all ions are captured by the rf

Transition at 400 particles and 3 m bunch length

Hot ions not captured in the rf bucket

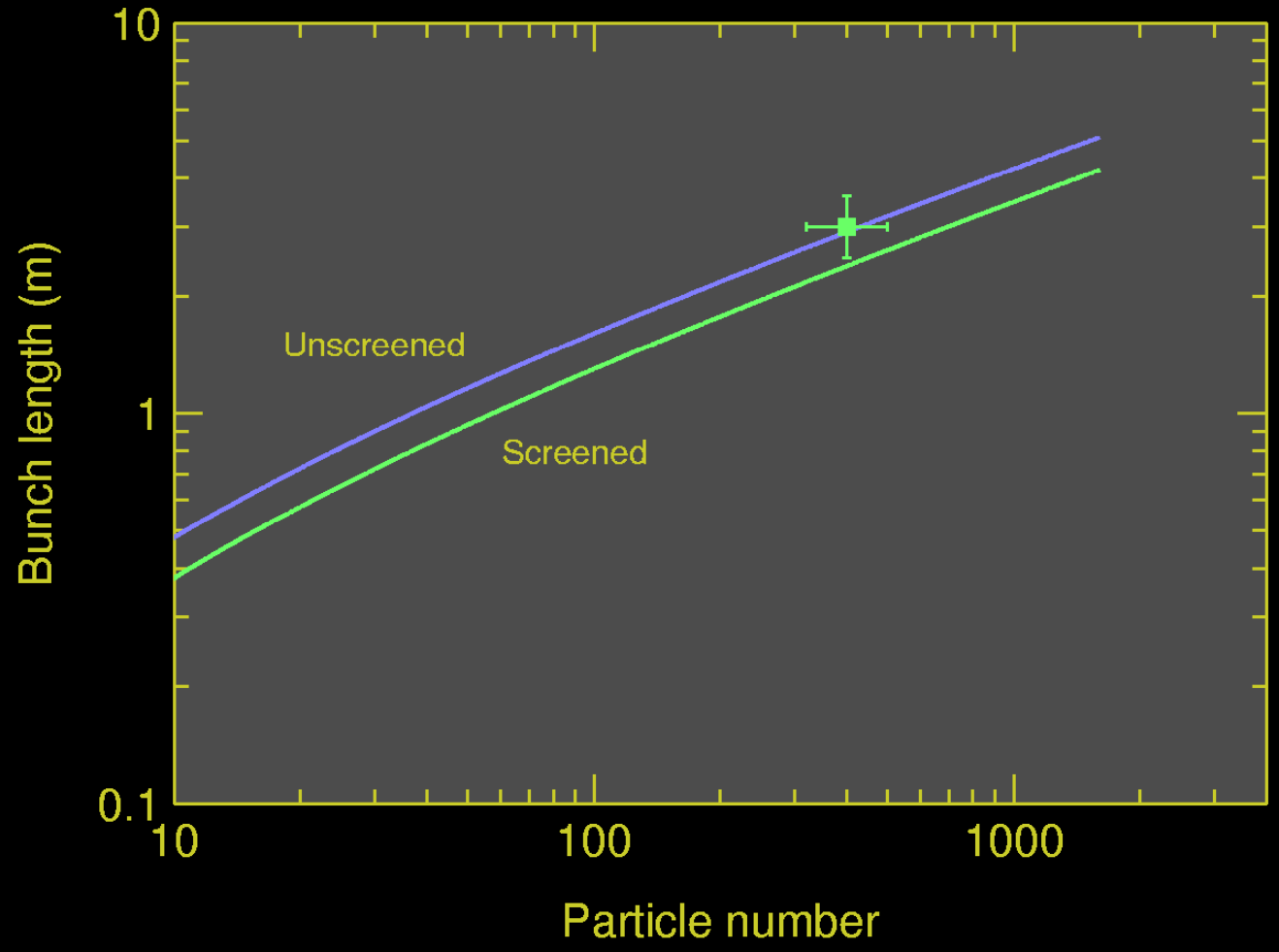
Theoretical bunch length



Blue: calculated particle distribution with 6 mV rf amplitude and 400 particles

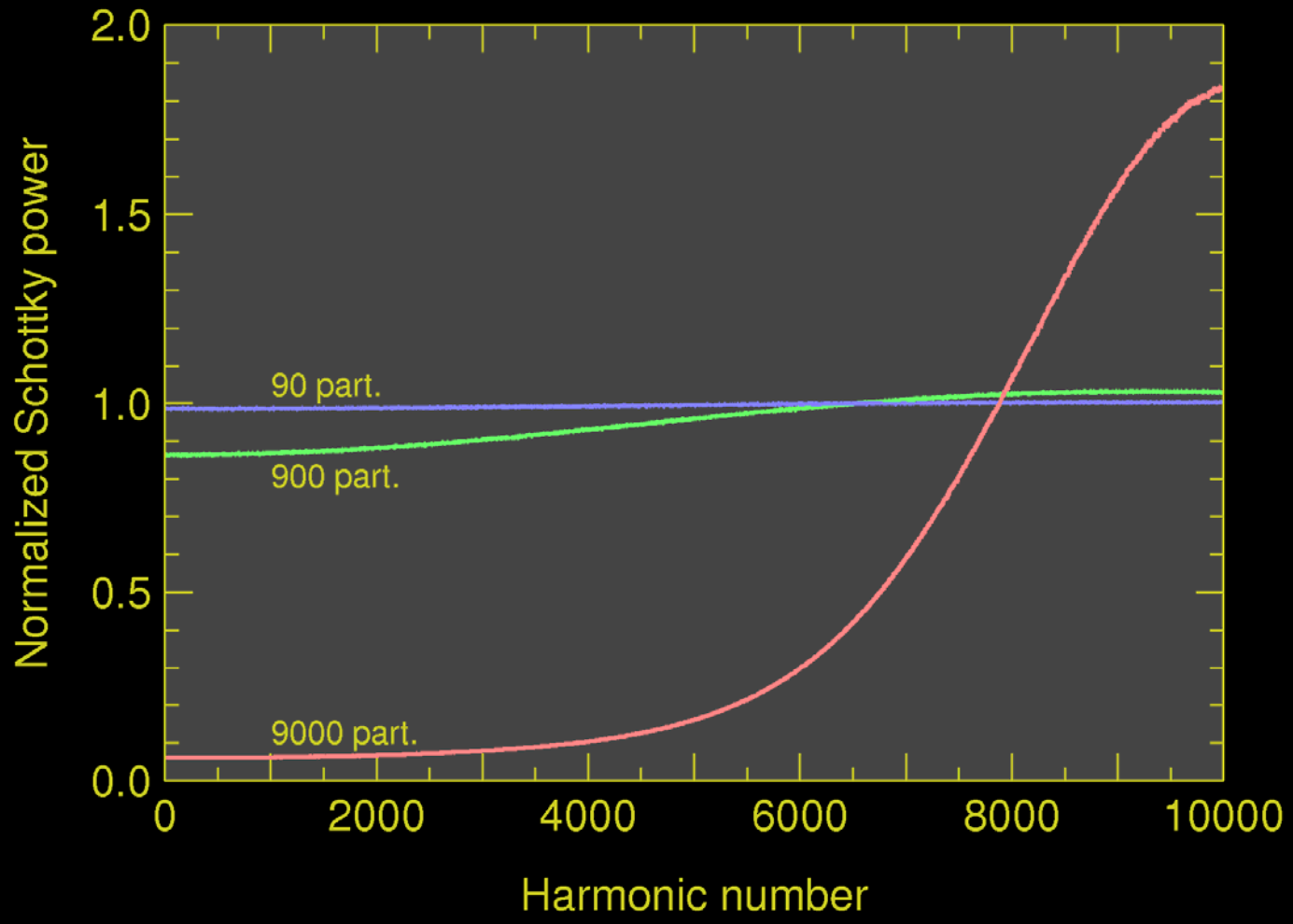
Red: parabola for comparison

Theory vs. experiment



Conclusion: We observe ordering also in bunched beams, with particle densities similar to those in coasting beams.

Long-range and short-range order



In a beam with long-range order and *n* particles, one would expect a strong Schottky signal at the *n*:th harmonic.

This is not seen in our model beam since only short-range correlations exist (liquid-like order), except at the highest particle numbers.

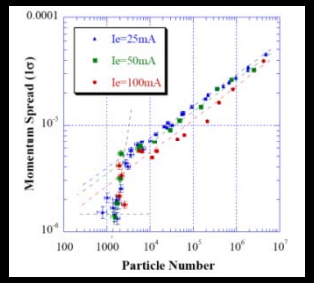
Outlook

Experiments with beam ordering at CRYRING discontinued, EBIS ion source taken out of operation.

No test with bunch shortening (“evapouration” not studied)

New storage ring built for crystallization,
S-LSR, taken into operation in Kyoto, theoretical studies continued

Ordering of proton beam observed at S-LSR, experiments with dispersion-free bends in preparation



Electron cooling of highly relativistic beams in preparation at BNL

Laser cooling of highly relativistic beams proposed at FAIR

Perhaps new potential applications can motivate intensified efforts to search for 3d crystalline/ordered beams?

This work was performed by

Håkan Danared
Anders Källberg
Ansgar Simonsson
The rest of the CRYRING staff

More information in

Phys. Rev. Lett. 88, 174801 (2002)
J. Phys. B 36, 1003 (2003)