Long Spin Coherence Times and How To Find Them

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744. WE-Heraeus-Seminar, 29-31 March 2021
Towards Storage Ring Electric Dipole Moment Measurements

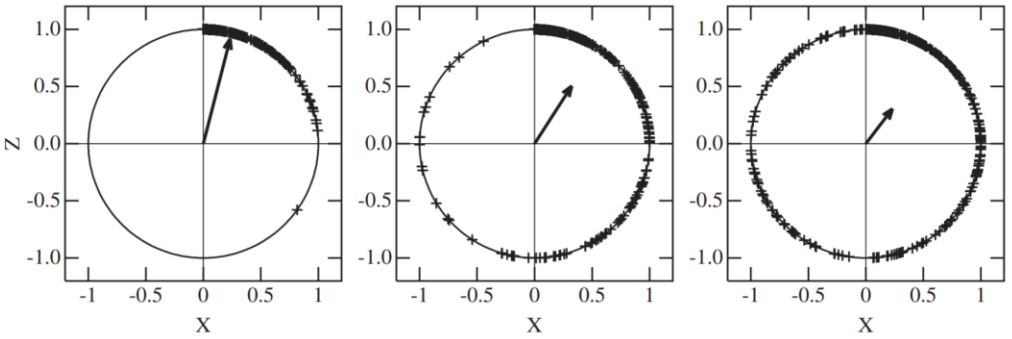
EDM in storage rings

srEDM - prerequisites

- p/d beam circulating in a storage ring
- horizontal polarization
- stable conditions (including beam polarization) to make the measurement feasible
- Long Spin Coherence Times (SCT)

Spin decoherence

- Horizontal precession with $\nu_s = \gamma G$
- Spread of ν_s leads to depolarization

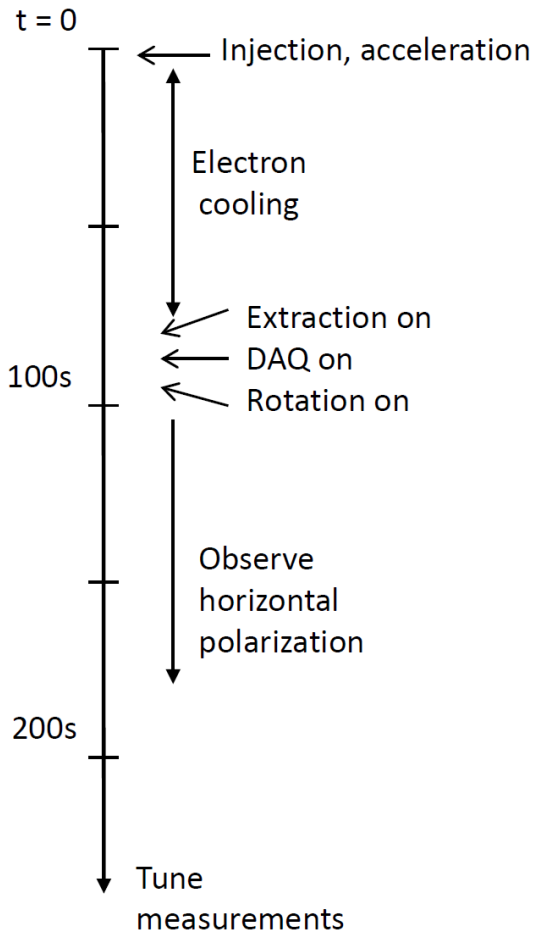


Z. Bagdasaria n et al., PR AB 17 (2014)

Experimental SCT studies at COSY

Beam setup

- Bunched **deuteron** beam
- p=0.97 GeV/c
- Continuous, real-time monitoring of polarization (EDDA, WASA, JEPO)
- Tune and chromaticity measurements

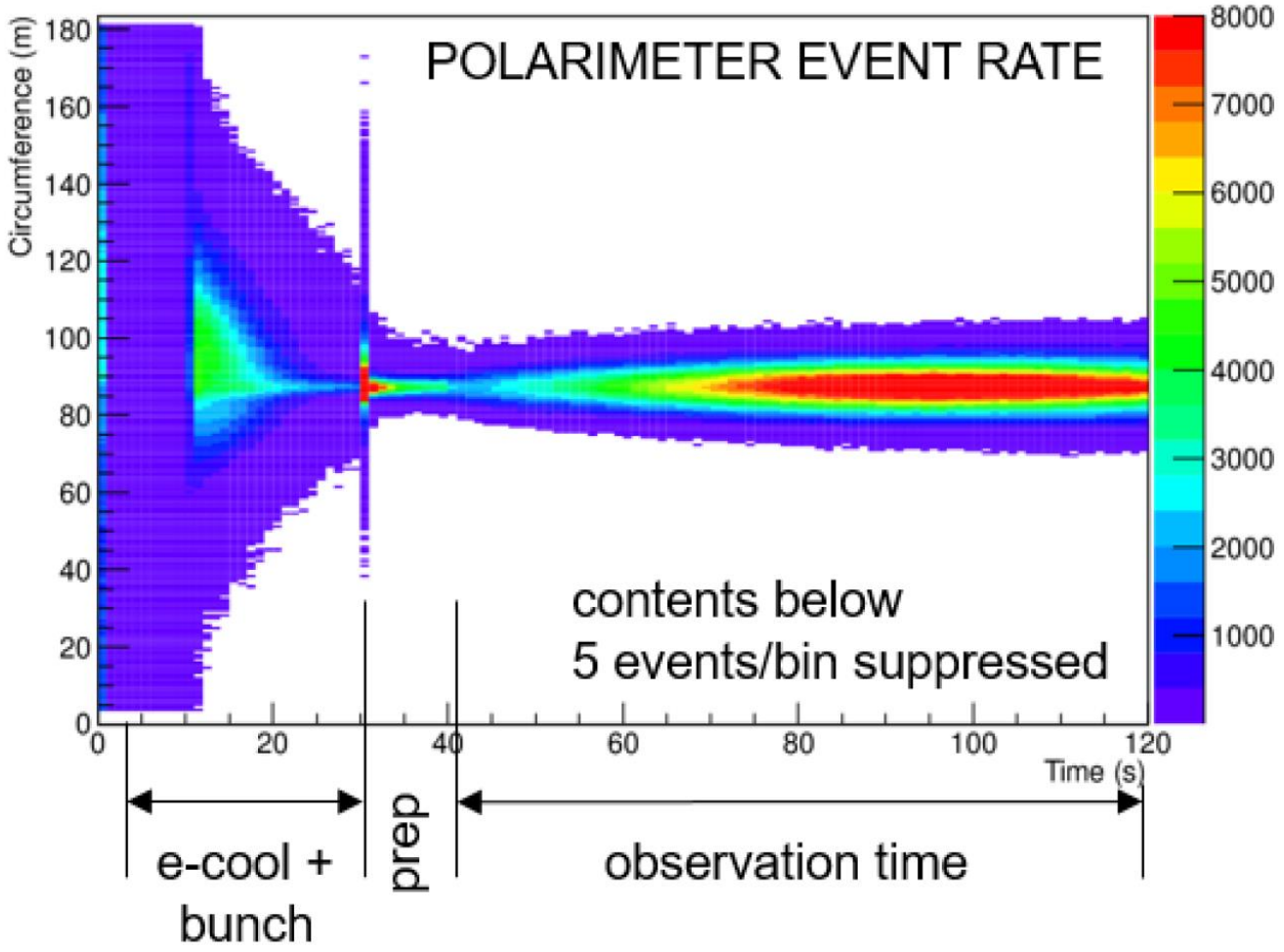


Studied effects

- Sextupole settings
- Electron cooling

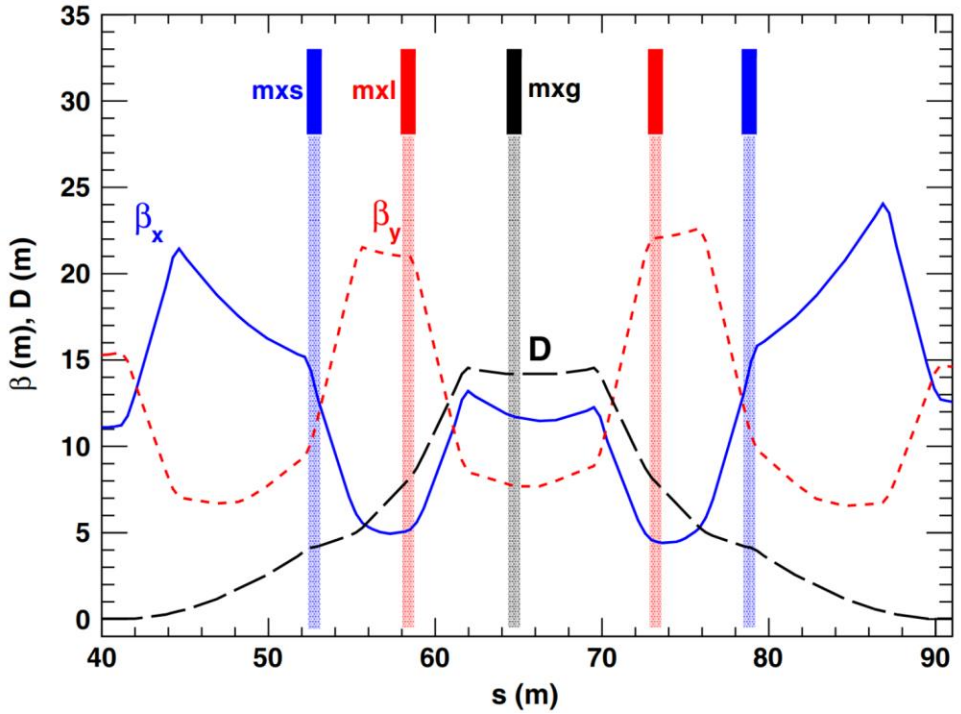
Typical COSY beam setup

Distribution of particles along the ring as a function of time in the cycle



Effect of sextupoles

- SCT limited by spread of ν_s. For a bunched beam, it is related to different orbit lengths for different betatron oscillation amplitudes, $\nu_s \sim A^2$
- Fractional change of the orbit length depends on chromaticity:
  $\Delta C/C_0 \sim \zeta_{nat}$
- Additional sextupole fields change the orbit location and length
- Cancellation of depolarization possible!



$$\frac{1}{\tau_{SCT}} = |A + a_1 S + a_2 L + a_3 G|\theta_X^2 + |B + b_1 S + b_2 L + b_3 G|\theta_Y^2 + |C + c_1 S + c_2 L + c_3 G|\sigma_P^2$$

natural value

sensitivities

drivers: emittance, sync. osc.

sextupole currents (MXS, MXL, MXG)

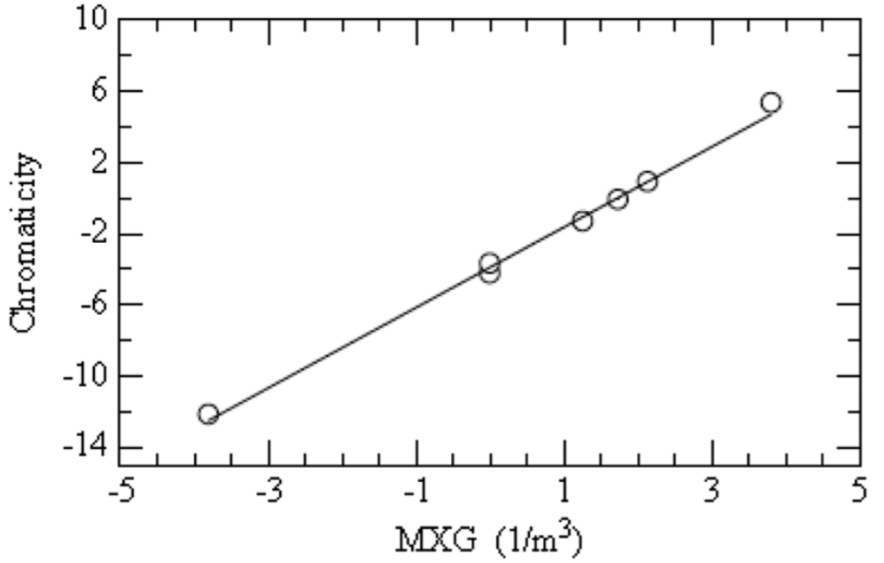
G. Guidoboni et al., PRL 117 (2016)

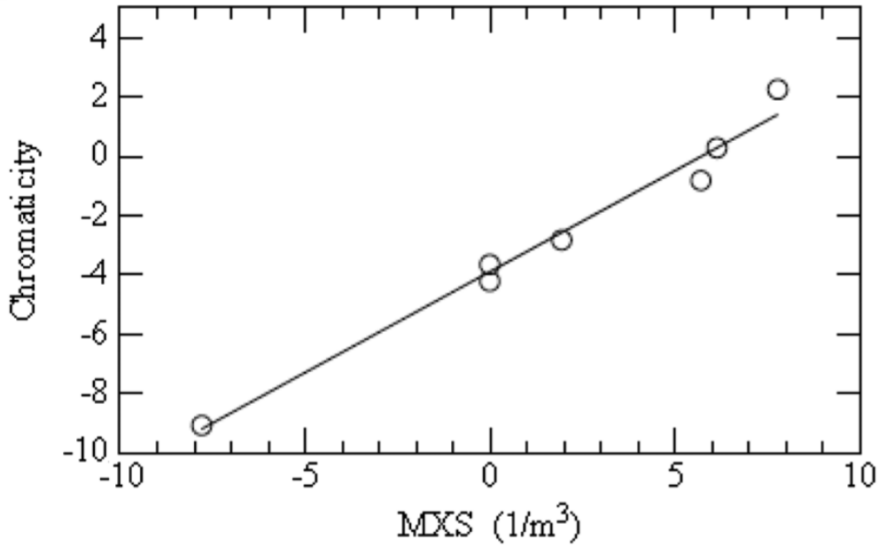
G. Guidoboni et al., PR AB 21 (2018)

Chromaticity survey

2014

- $\zeta_{x,y} = f(I_L, I_S, I_G)$
  a hyperplane, with a weak dependence on I_L
- Parametrization via a set of 1d scans (other currents held at zero)





Chromaticity survey

2014

- 2d representation of chromaticity functions at MXL=-0.145 m^{-3}.
- Relative position and distance of the $\zeta_{x,y}$=0 lines depends (weakly) on MXL.

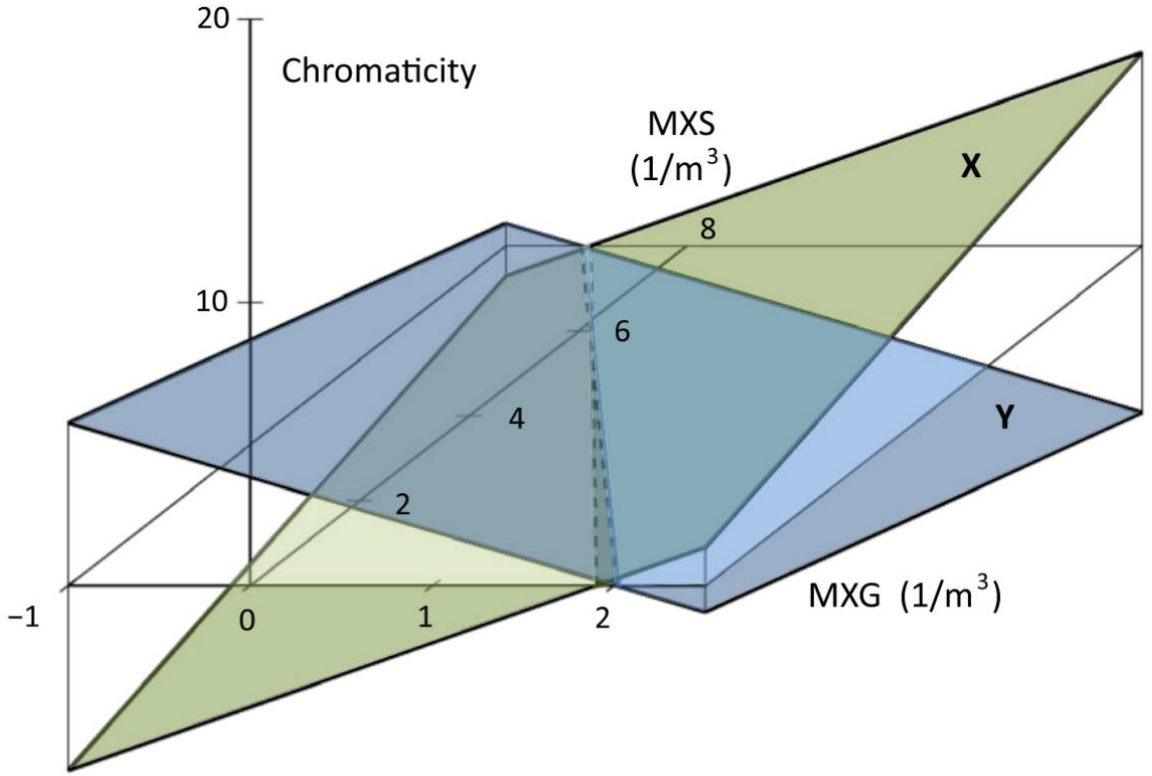


FIG. 6. Values of the x (green) and y (blue) chromaticities as a function of the fields in the S and G sextupole magnet families. The planes are fits to a set of individual chromaticity measurements. The place where each plane crosses zero chromaticity is indicated by a dashed line.

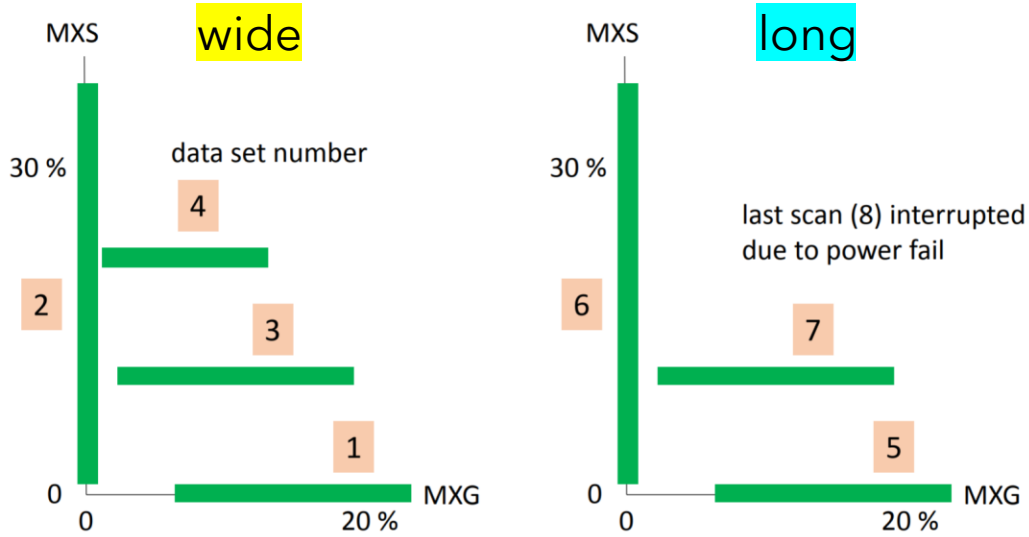
Survey of sextupole space

Table 1: *List of analyzed sextupole scans.*

Set	beam	MXS	MXG	MXL
SET01	wide	0	variable	-1.45%
SET02	wide	variable	0	-1.45%
SET03	wide	10%	variable	-1.45%
SET04	wide	20%	variable	-1.45%
SET05	long	0	variable	-1.45%
SET06	long	variable	0	-1.45%
SET07	long	10%	variable	-1.45%

- Two beam settings:
  - wide beam (cooling while bunching, then horizontal heating to expand betatron motion)
  - long beam (electron-cooled, then bunched to have a longer bunch)
- Polarization monitored using EDDA

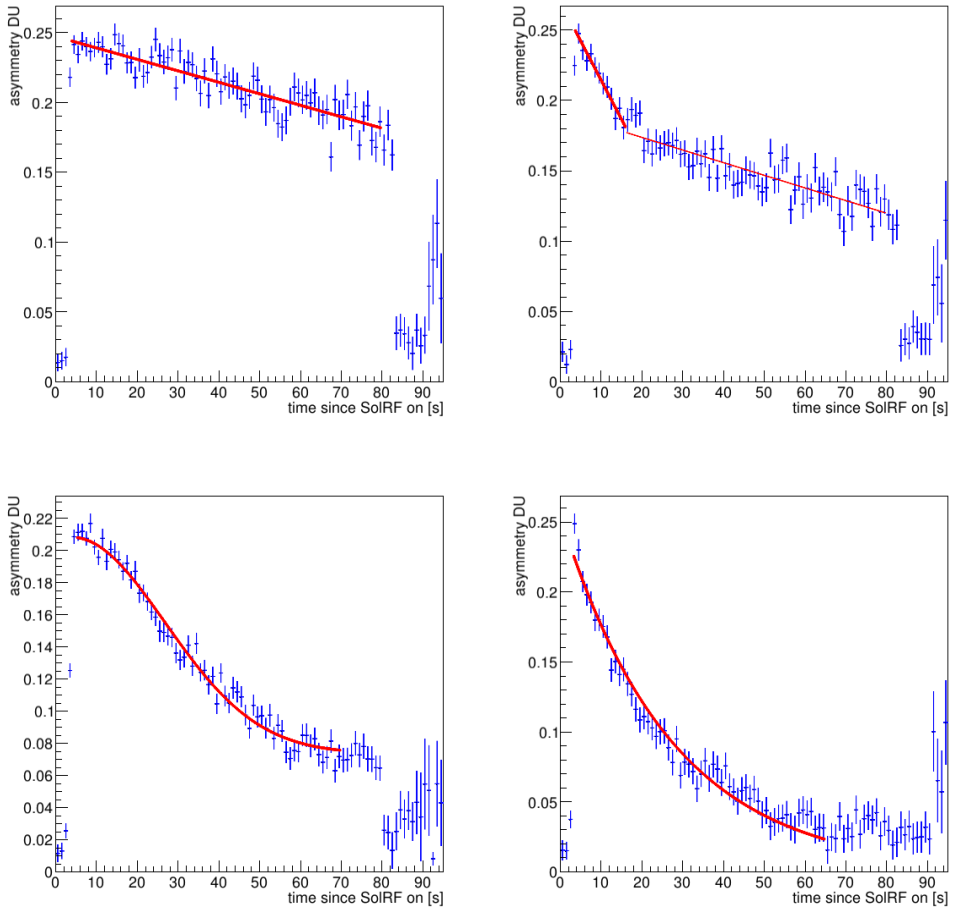
2014

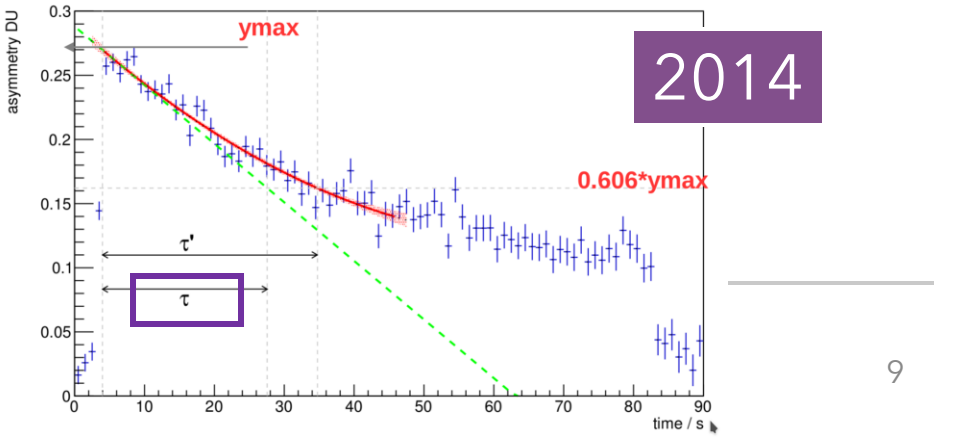


SCT - definition

Whole variety of polarization histories in cycles, possible description:

- Linear (*-b/a*, down to 0)
- Bi-linear (?)
- Exponential (τ, *1/e*)
- Gaussian (σ, 0.606)
- Any other function (?)

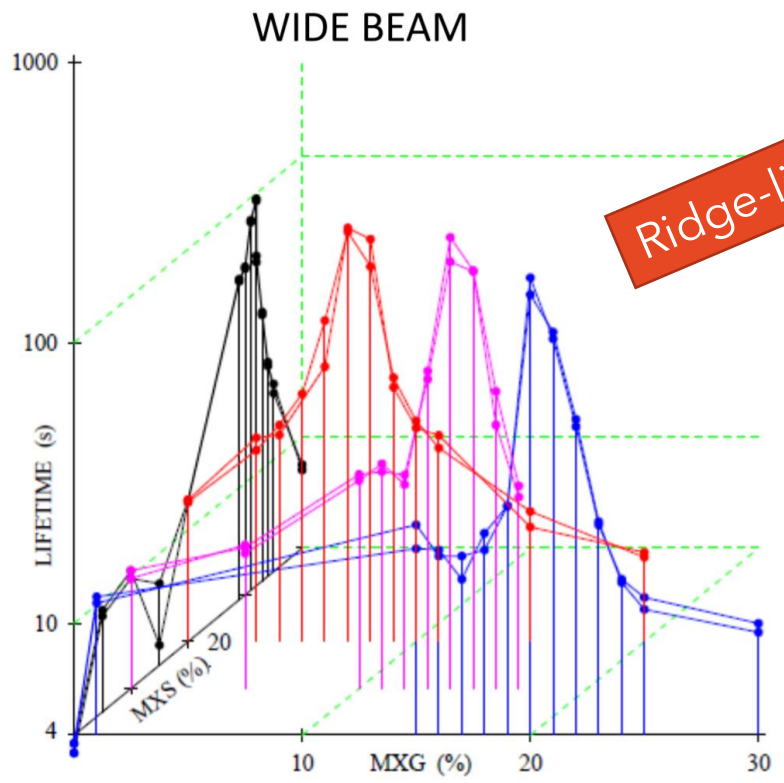




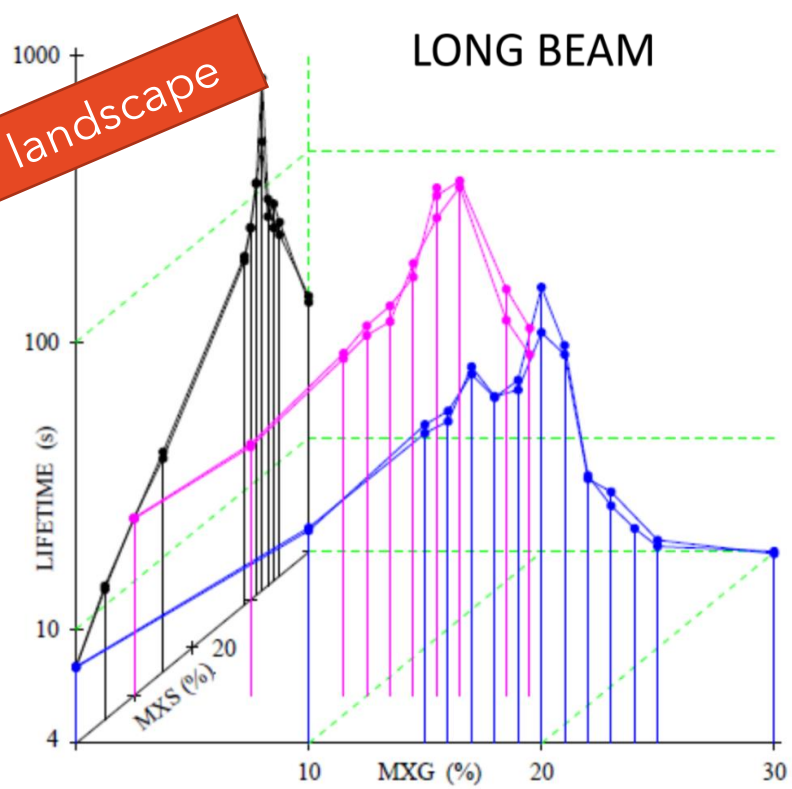
2014

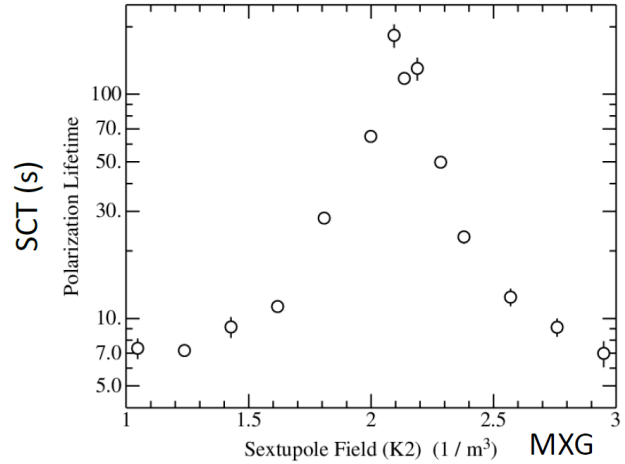
Survey of sextupole space

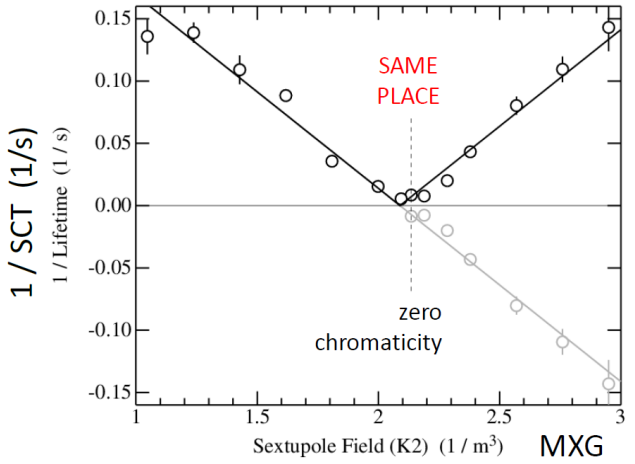
How to find a maximum of a single scan?



Ridge-like landscape

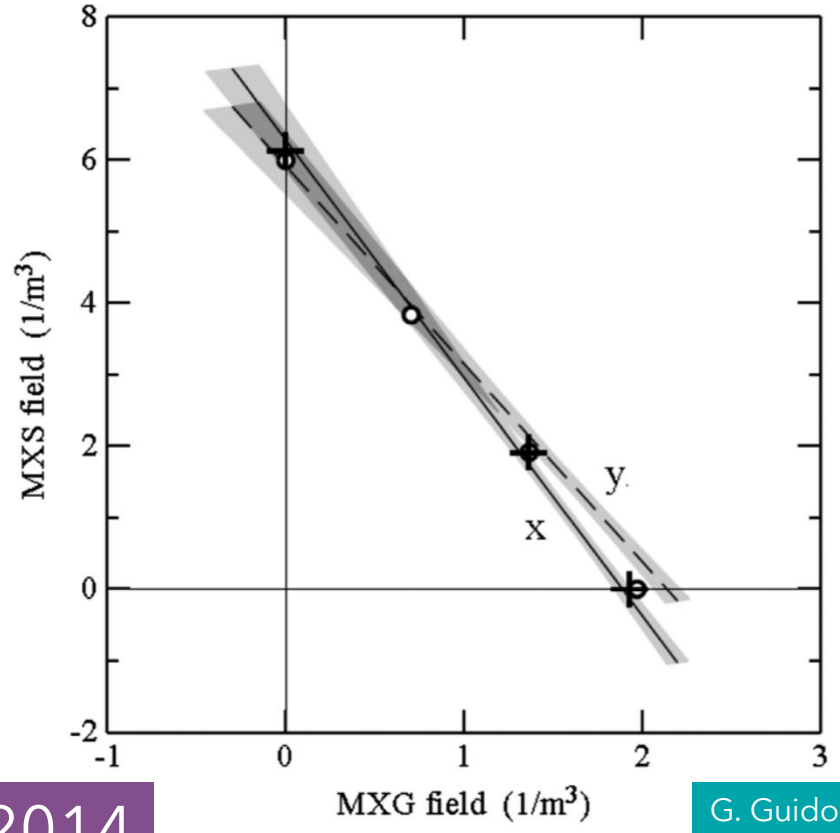






2014

Survey of sextupole space



2014

- Results for wide and long beam settings are consistent with each other
- The maximum SCT points form a ridge in the MXG-MXS space close/between the $\zeta_{x,y} = 0$ lines.

G. Guidoboni et al., PR AB 21 (2018)

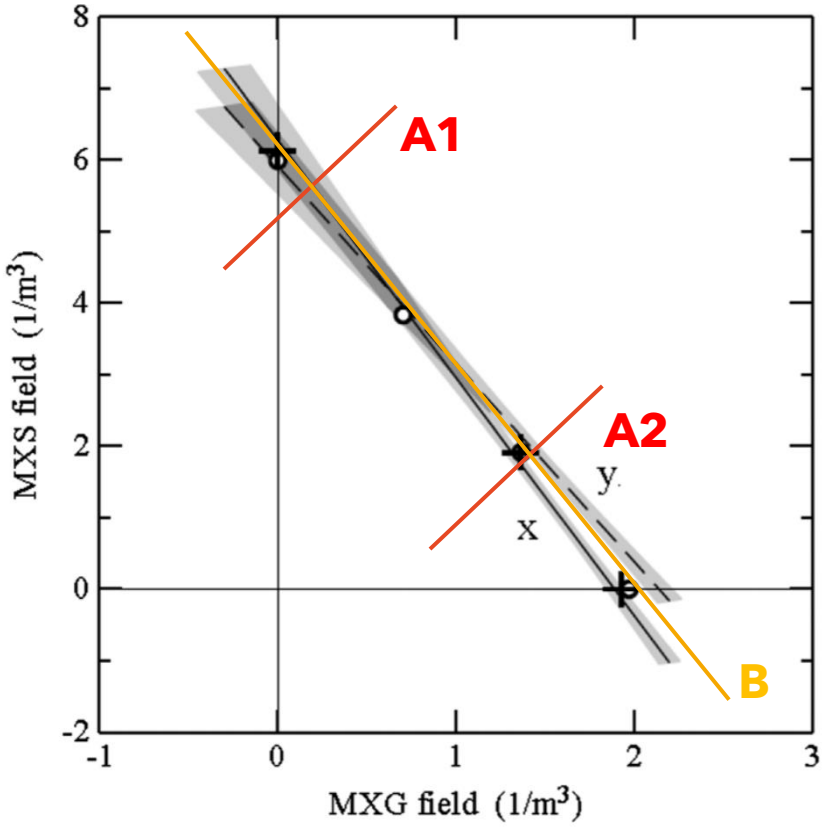
Sextupoles – lesson learned

Strategy to search for long-SCT working point (applied ever since):

- Make 2 SCT scans across the expected ridge **(A1, A2)** to determine its location
- Make an SCT scan along the ridge to find the maximum **(B)**
- Routinely find SCT~1000 s working points

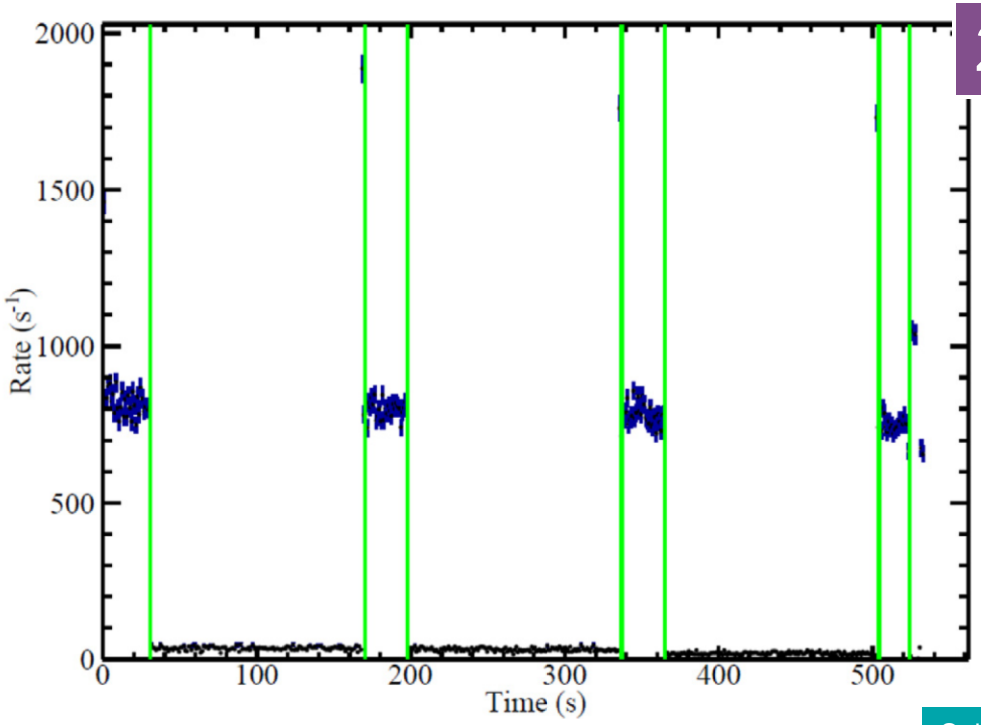
Keep in mind:

- MXL tuning may be necessary
- $1/\tau \sim I_i$, thus SCT very sensitive to sextupole currents
- Other machine issues may be limiting



Cooling scheme

- **Can we do even better than 1000 s** exploiting cooling differently?
- Explore electron cooling scheme: pre-cooled beam (standard) versus continuosly cooled beam
- Set up longer cycles to observe polarization longer (EDDA)
- Switch on the extraction only for short periods to save the beam

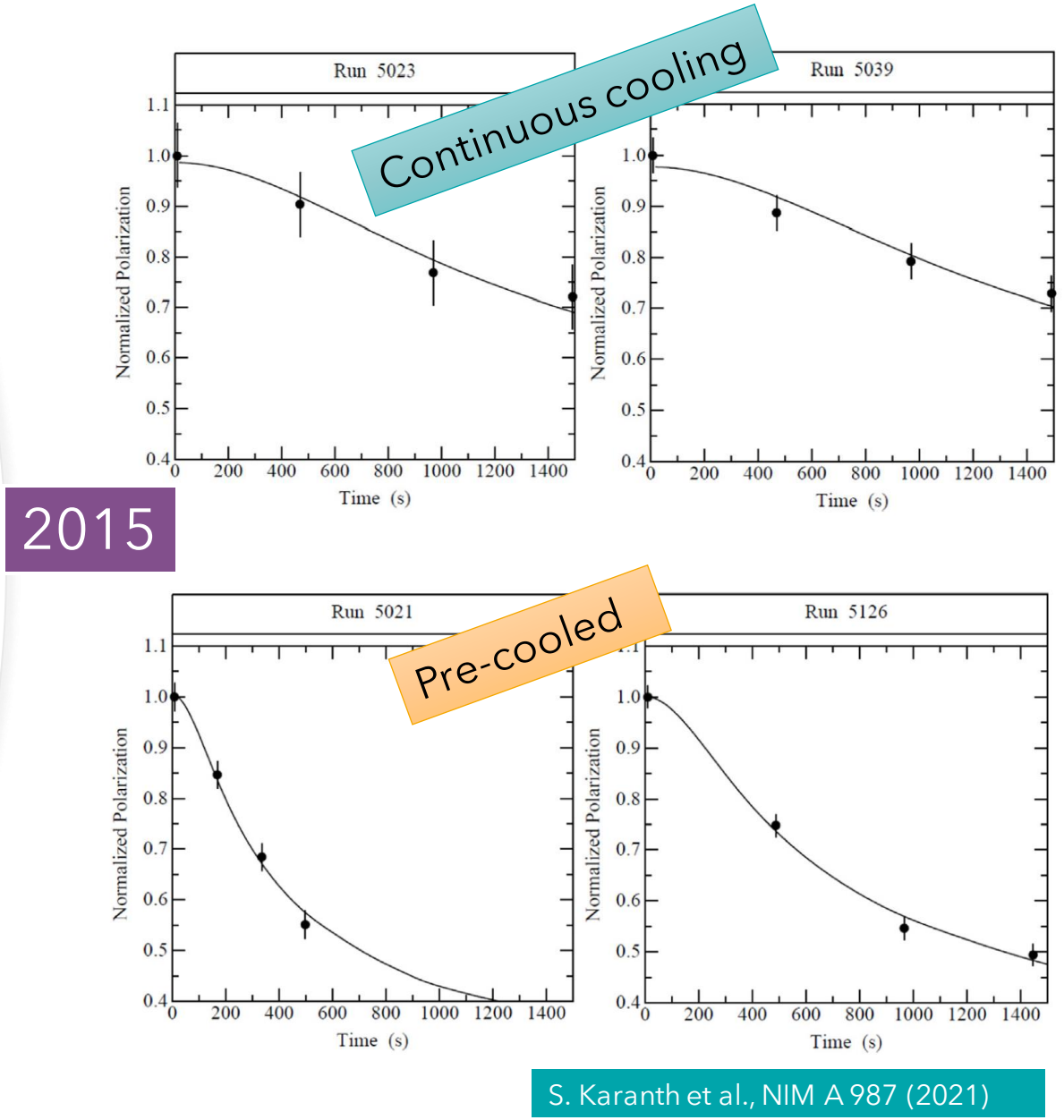


Run number	E-cooling type	Cycle length (s)
5018	Fully cooled	564
5019	Fully cooled	564
5021	Pre-cooled	564
5023	Fully cooled	1562
5039	Fully cooled	1564
5126	Pre-cooled	1564
5127	Fully cooled	1564

S. Karanth et al., NIM A 987 (2021)

Cooling scheme - results

- SCT extracted using model calculation based on initial spin tune distribution (E. Stephenson)
- Model delivered template curves which were fitted to the experimental data
- SCT = time after which polarization drops to 0.606 of initial value



S. Karanth et al., NIM A 987 (2021)

Cooling scheme – lesson learned

- Continuous cooling throughout the whole cycle leads to even longer SCTs (>2000 s)
- Electron cooling is incompatible with the EDM search scheme though
- **Is stochastic cooling an option?**

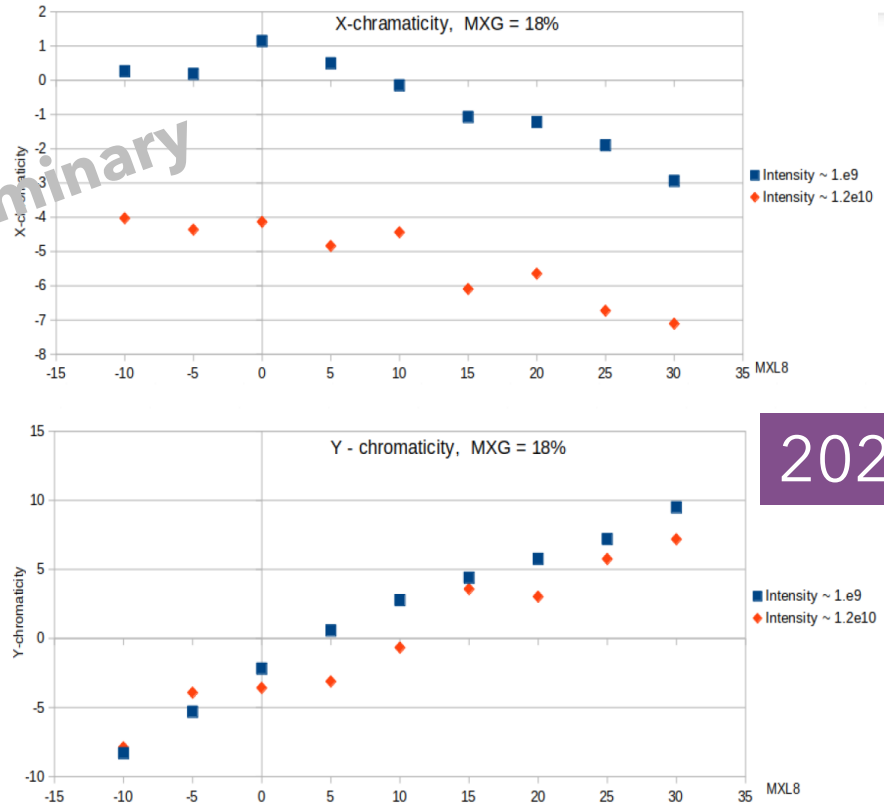
Run number	E-cooling type	Cycle length (s)	IPP lifetime (s)	Total error
5018	Fully cooled	564	1721	1044
5019	Fully cooled	564	1263	325
5021	Pre-cooled	564	436	68
5023	Fully cooled	1562	2108	714
5039	Fully cooled	1564	2234	523
5126	Pre-cooled	1564	825	108
5127	Fully cooled	1564	987	180

S. Karanth et al., NIM A 987 (2021)

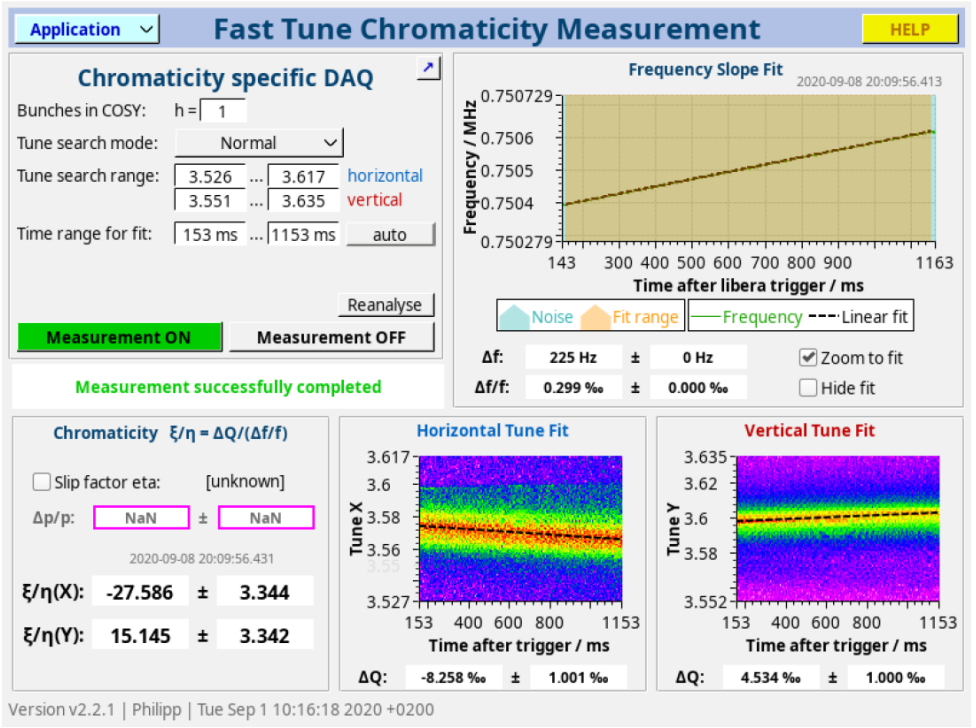
2015

More recent experience

- New tool for fast chromaticity measurement available since 2020 (B. Breitkreutz, P. Niedemayer)
- First important results: chromaticity depends on beam intensity (Sep'2020 beam time)
- Usually, ζ measurement at the end of cycle, at lower beam intensity – relevant for SCT?



2020



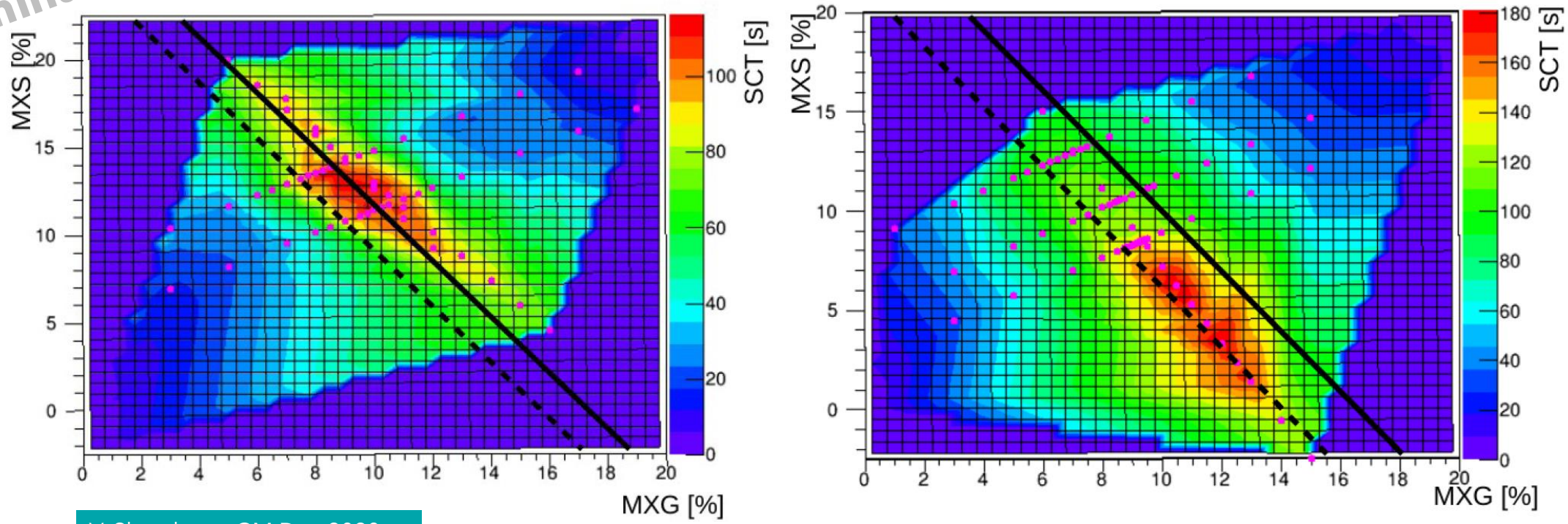
V. Shmakova, CM Dec 2020

SCT in Sep'2020

- Two beam setups, though appeared identical
- JEPO polarimeter
- Lines (solid, dashed) show $\zeta_{x,y}=0$
- Magenta dots – SCT measurements
- Colours – inter/extrapolation
- Maximum SCT ridge is not quite between the lines, as would be expected...

preliminary

2020

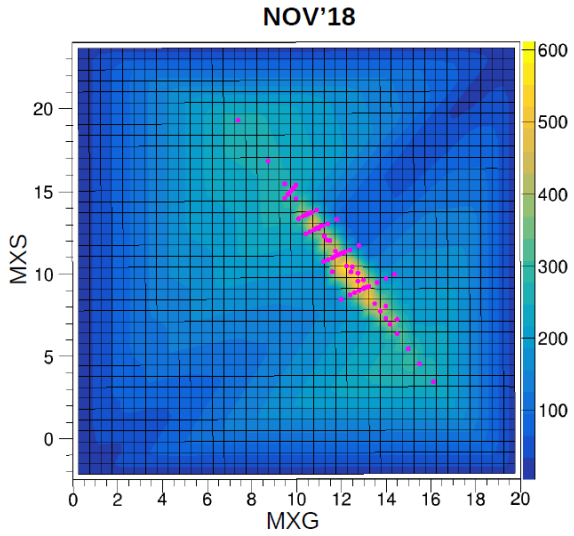


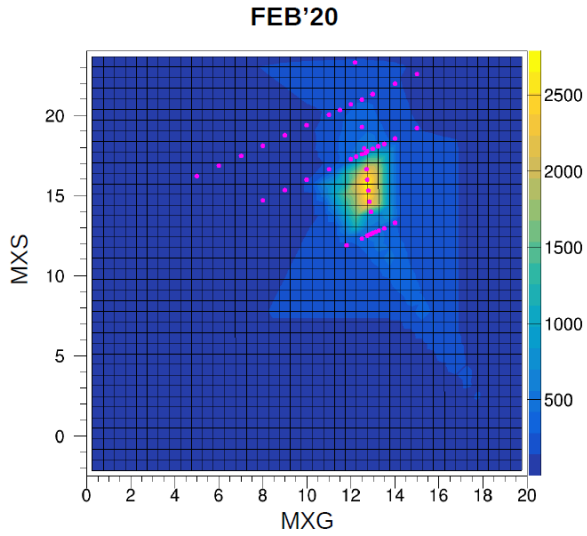
V. Shmakova, CM Dec 2020

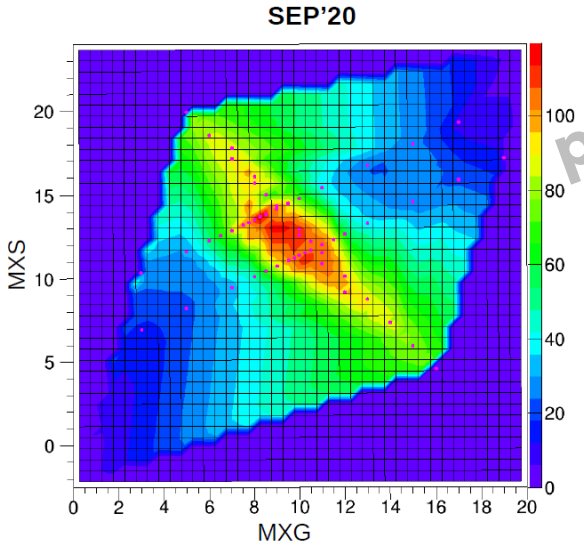
SCT over the last beam times

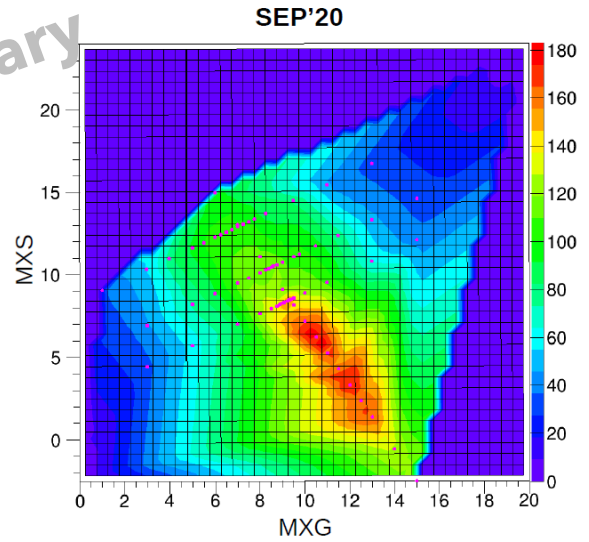
- Quite different landscapes
- Different max SCTs (180-2500 s)
- Sep'2020 beam time did not require long SCT, but the scans did not go beyond 180 s

V. Shmakova, CM Dec 2020









preliminary

Towards SCT of proton beams

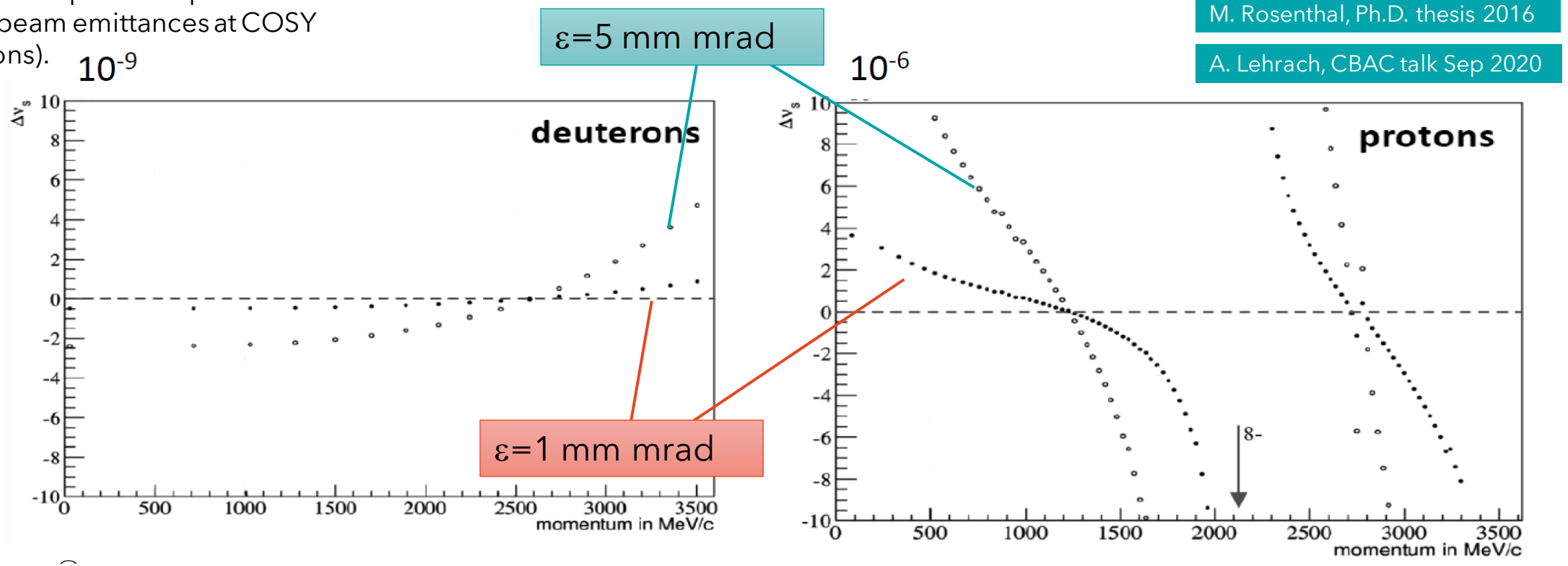
Protons are more difficult in SCT optimization than deuterons:

- $|G_p/G_d|$ ~15
- intrinsic resonances for protons, ~10x more and ~10x stronger than for deuterons
- First simulation results obtained
- More simulations and experimental efforts to come...

Influence of a single, isolated resonance on spin tune spread for different beam emittances at COSY (simulations).

M. Rosenthal, Ph.D. thesis 2016

A. Lehrach, CBAC talk Sep 2020

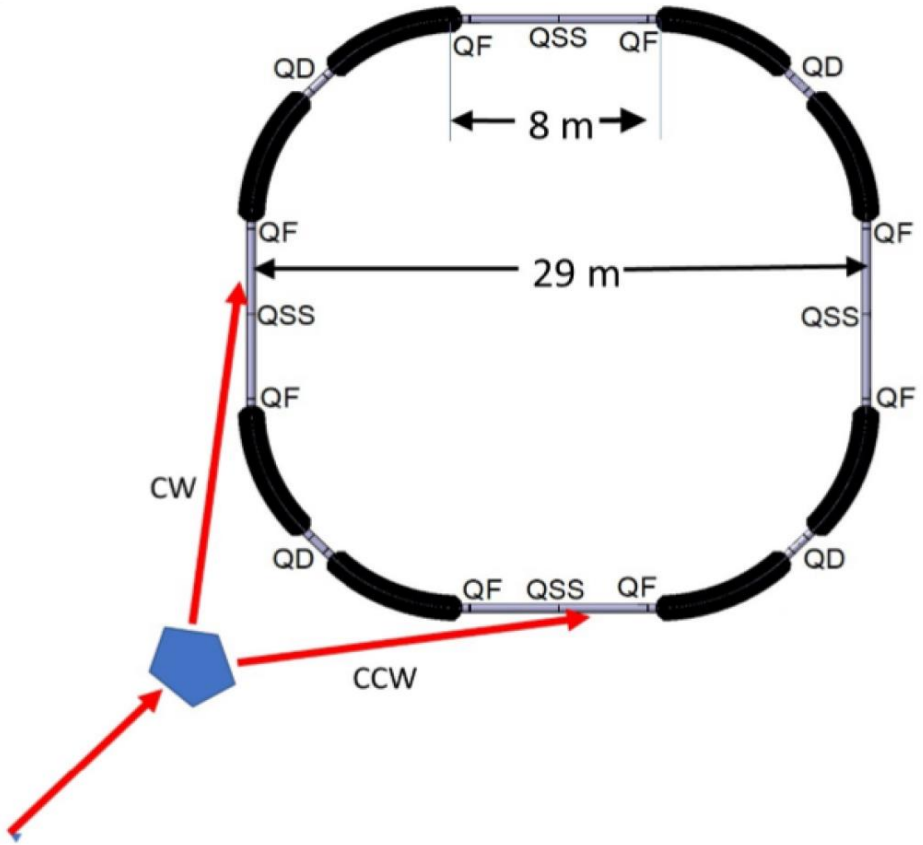


Proton SCT - outlook

S. Martin, R. Talman, A. Lehrach, PoS 144 (2018)

Investigation of SCT in a prototype ring (frozen spin) via BMad simulations

- T_p = 45 MeV
- Obtained SCT of ~5 s only
- Spin tune spread minimal at ζ_y=-5.33
- SCT maximal at ζ_y=-3.88.
- **Open question:**
  - **WHY don't they coincide??**



M. Vitz, M.Sc. thesis 2020

Summary

Deuterons:

- Extensive experimental effort
- Long SCTs are connected with zero-chromaticity, can be optimized using sextupole families at COSY
- Use of continuous cooling allows to extend SCT even more
- At COSY well established procedures allow to find working points with SCT~1000 s (almost) routinely

Protons:

- Simulations for COSY indicate difficulties resulting from the presence of multiple intrinsic resonances
- First simulations for a prototype ring yield unresolved, puzzling results

Contributors: Ed Stephenson, Swathi Karanth, Greta Guidoboni, Vera Shmakova, Max Vitz, Andreas Lehrach, JEDI Collaboration