COSY optics and spin tracking using Bmad

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Outline

- COSY accelerator layout and specificities
- Bmad code
- Spin dynamics at COSY
- Amplitude dependent spin tune
- Conclusion

COoler SYnchrotron

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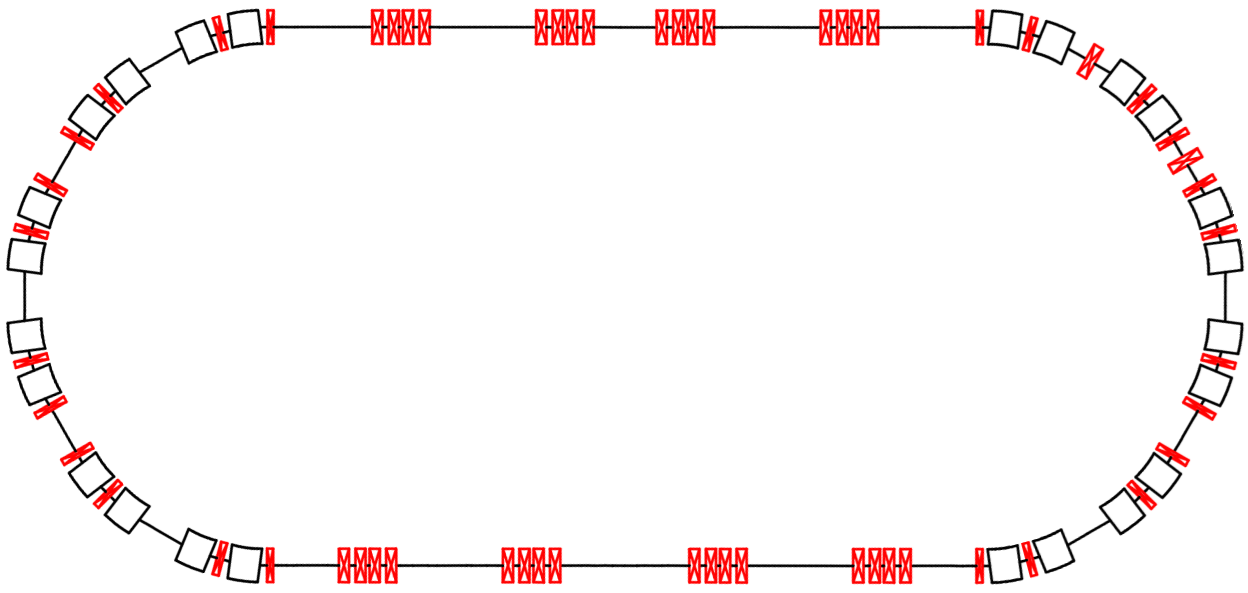

- Polarized protons and deuterons
- Electron and stochastic cooling
- Internal polarimeter
- New superconducting solenoidal snake
- Stripping injection and slow extraction
- Long straight sections

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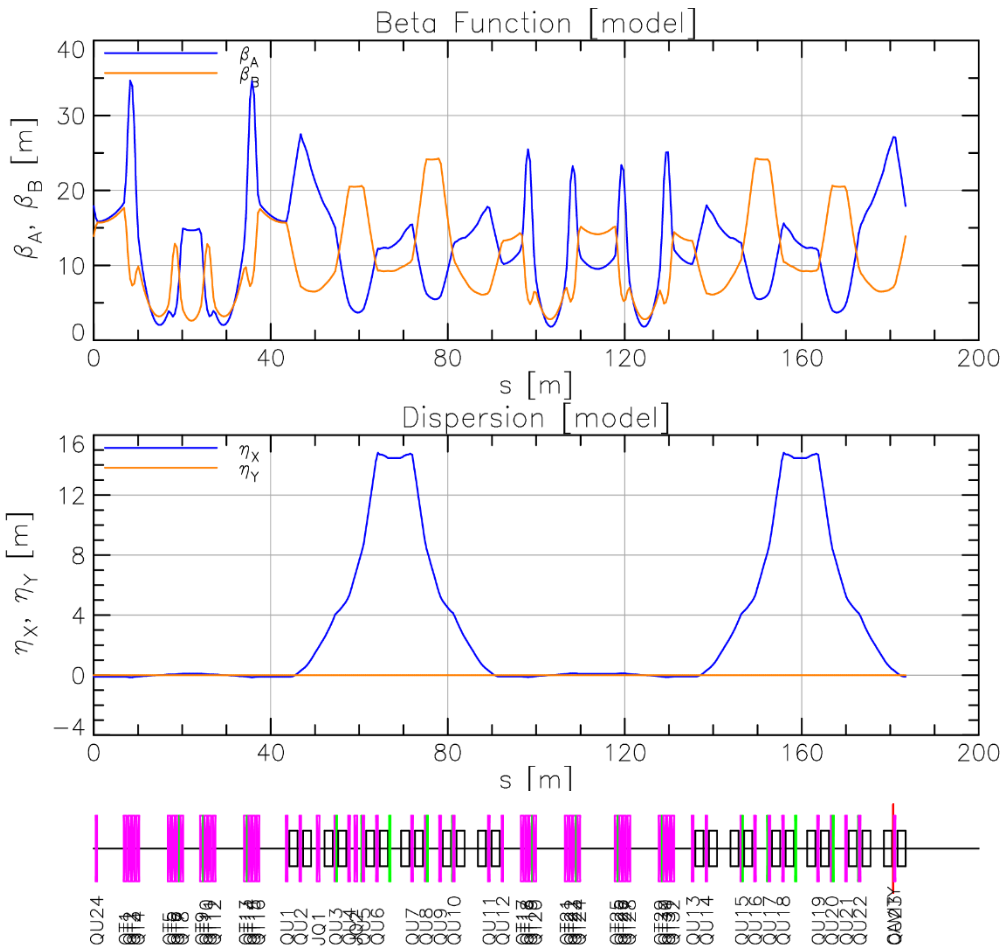
COSY optics



The optics is very versatile due to pure dipoles and multiple quadrupole families.

Typical lattice with dispersion zero in the straight section.

Transverse tunes of 3.6 in both planes.

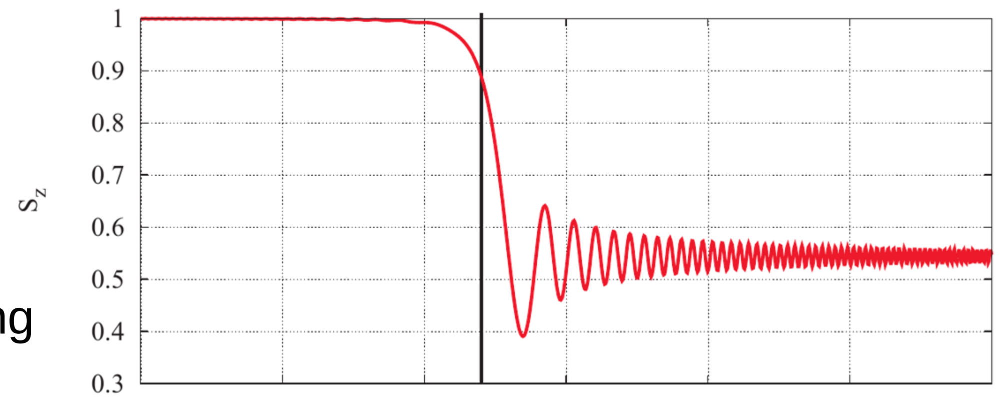
Bmad Library

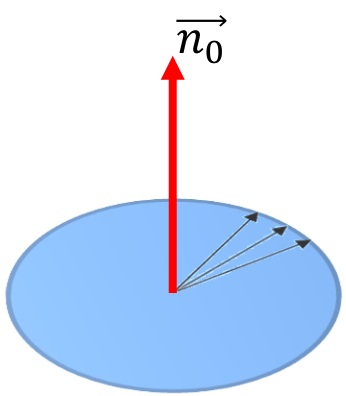
- Developed by David Sagan at the Cornell University, originally for the online modelling of the CESR electron positron collider.
- Object oriented Fortran 90 library.
- Lattice syntax similar to MADX.
- Handles complex geometries and lattice forking.
- Interfaces with Etienne Forest's FPP/PTC code.
- Versatile structure for easy developments.

Spin dynamics in COSY

For high energy polarized hadron machines the preservation of polarization trough crossing of resonances is critical.

In COSY the spin tune is relatively small, hence associated depolarizing resonances are comparably weak.





In the context of proton and deuteron EDM studies the polarization is placed in the horizontal placed in the horizontal plane. Since the stable spin direction is vertical the spread of the spin tune becomes a source of depolarization.
Therefore a major theme of studies at COSY is the amplitude dependent spin tune.

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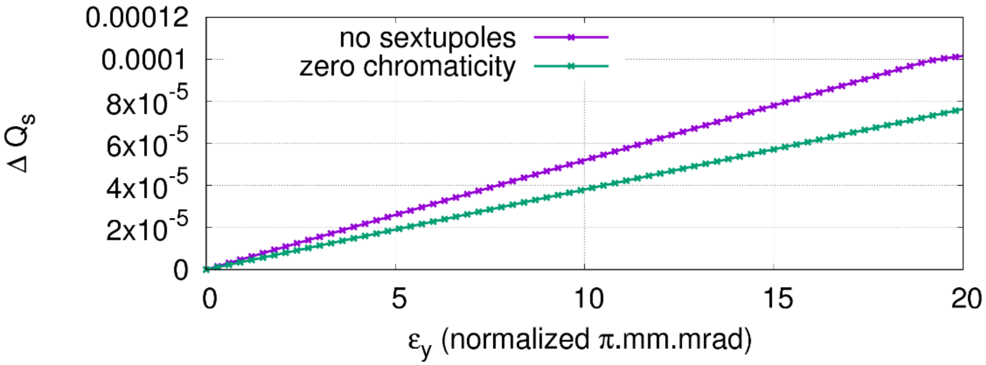
Amplitude dependent spin tune

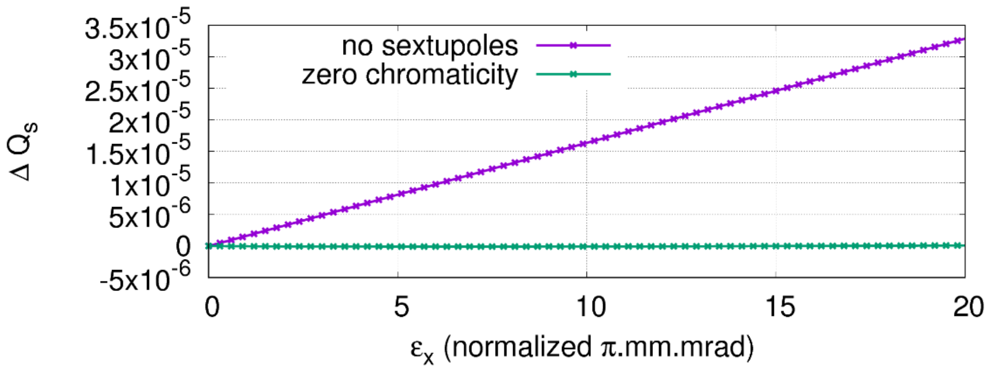
Amplitude dependent spin tune can be determined by frequency analysis of tracking data.

1. Choose an amplitude in each of the 3 phase spaces
2. Track for a ~1000 turns one particle with spin perpendicular to the stable spin direction
3. Frequency analysis of the spin motion in the plane perpendicular to the stable spin direction



Protons at Gγ~2.5

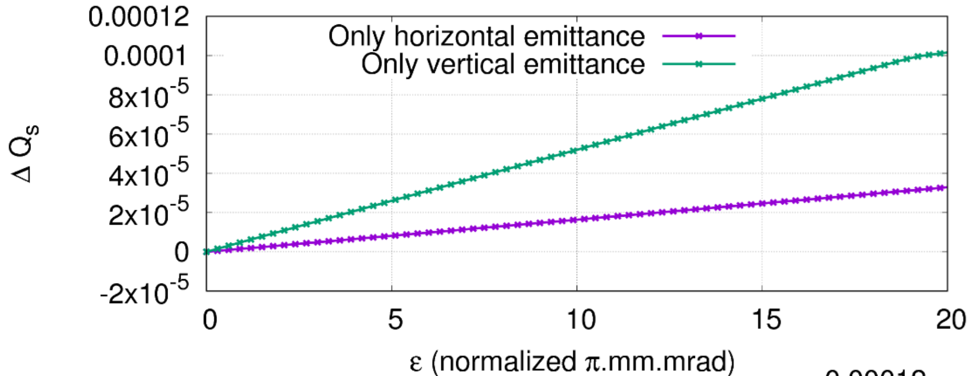
Example of the effect of chromaticity on the spin tune shift as a function of particle amplitude in the vertical and horizontal planes



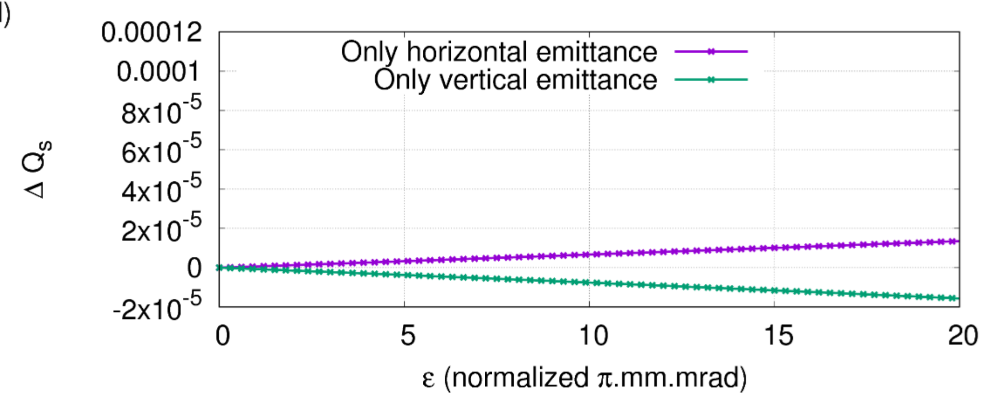
Amplitude dependent spin tune
optimization

The spin coherence time corresponds to the horizontal polarization lifetime.

Maximization of spin coherence time involves multiple evaluations. Global maximum found with a genetic algorithm which requires evaluation of amplitude dependent spin tune for a large number of lattices (10^3 to 10^4). This corresponds to many days of computing.



Protons at Gγ~2.5



[1] Y.Dutheil, Bmad model of COSY status and progress, IPAC16 THPMR021

Spin normal form

Recent developments by Etienne Forest to his code (PTC) give access to the normal form formalism for the spin. Additional collaboration between him and David Sagan make all the PTC functions accessible within the Bmad environment.

A clever set of data structures and operations overloading makes the generation and manipulation of maps and normal forms particularly easy.

```
call bmad_parser ("COSY.bmad", lat)

call lat_to_ptc_layout (lat)
als => m_u%start
p=>als%start

state = nocavity0
CALL FIND_ORBIT(ALS,closed_orbit,1,STATE,1.d-5)
state=state+SPIN0

ID_S = 1
XS0=closed_orbit
XS=XS0+ID_S
CALL propagate(ALS,XS,+STATE,FIBRE1=1)
map_c=XS

call c_normal(map_c,c_n,dospin=my_true)

U=c_n%As*c_n%A_t
id_s=U**(-1)*map_c*U
call c_full_canonise(id_s,U_c,D,f,A,b,R,phase,nu_spin)
call print (nu_spin , fracQ)
```

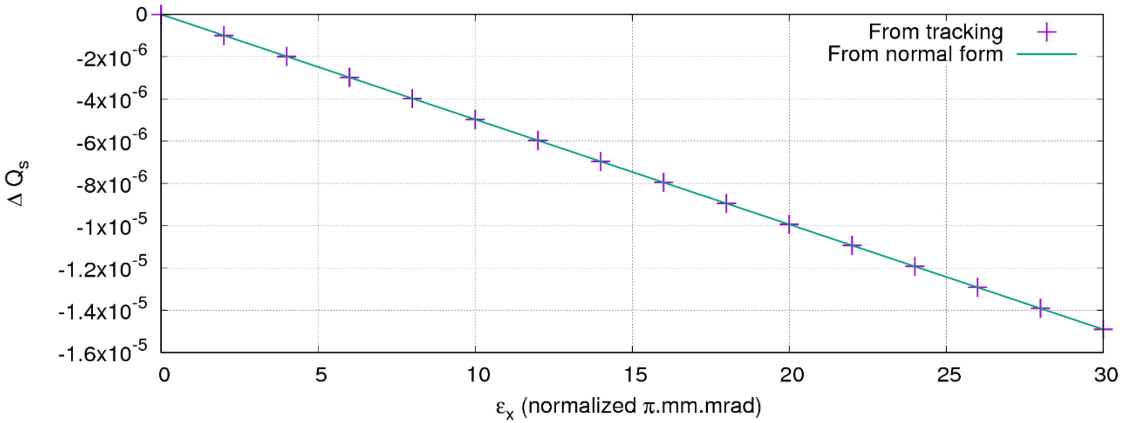
```
|          1, NO =    4, NV =    6, INA =  205
 ********************************************

  I  COEFFICIENT          ORDER   EXPONENTS
    NO =      4       NV =      6                   X  x'  y  y' dp  s
  0  0.1609661451078323       0.000000000000000     0  0  0  0  0  0
  1  0.4507788617591107E-01   0.000000000000000     0  0  0  0  1  0
  2  0.8180211163784833E-01   0.000000000000000     1  1  0  0  0  0
  2 -0.9398478186765889E-01   0.000000000000000     0  0  1  1  0  0
  2  0.8564548956954930       0.000000000000000     0  0  0  0  2  0
  3  0.8838268064268773E-01   0.000000000000000     1  1  0  0  1  0
  3  0.5147227107641363       0.000000000000000     0  0  1  1  1  0
  3  -6.985451330028138       0.000000000000000     0  0  0  0  3  0
  4 -0.7754784994728646E-03   0.000000000000000     2  2  0  0  0  0
  4  0.1719404683184889       0.000000000000000     1  1  1  1  0  0
  4  0.9928565484310506E-01   0.000000000000000     0  0  2  2  0  0
  4   6.849048918274089       0.000000000000000     1  1  0  0  2  0
  4  -3.619458977162996       0.000000000000000     0  0  1  1  2  0
  4   194.6837484452160       0.000000000000000     0  0  0  0  4  0
```

[1] From Tracking Code to Analysis, Etienne Forest, Springer, 2015

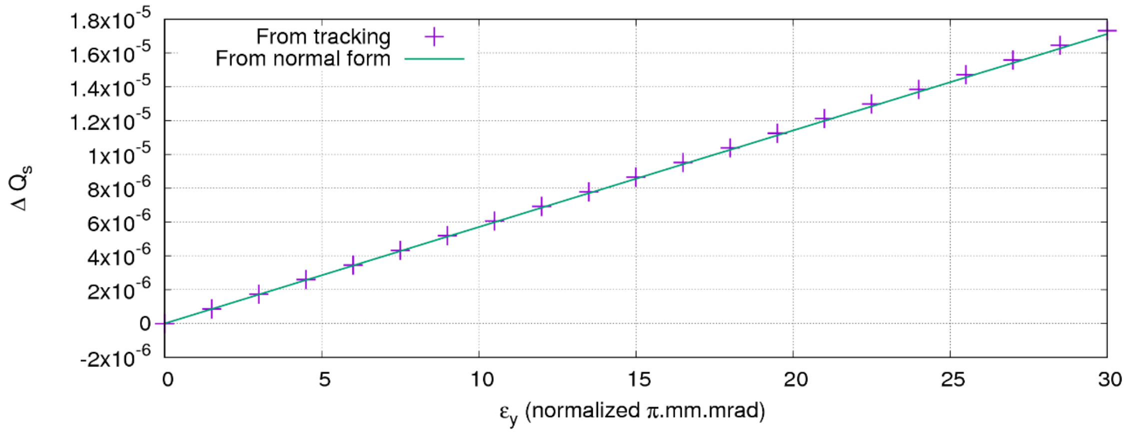
Comparison

Case of deuteron at p=970 MeV/c and Gγ~-0.16. Lattice without sextupoles.



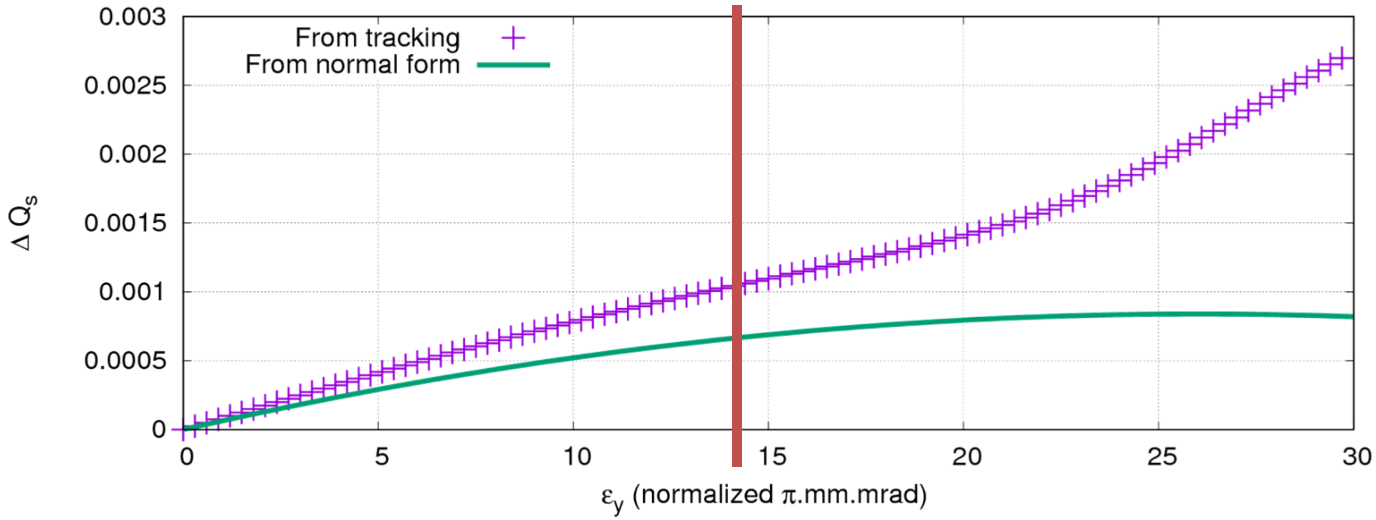
Spin tune shift computed from tracking perfectly superimposes with the predictions from the normal form method.

The normal form method was here orders of magnitude faster.
It also give easier access to the amplitude dependent spin tune in different dimensions.



Comparison on resonance

Specific case across weak intrinsic spin resonance. COSY lattice with protons at Gγ~38.62 with strong sextupoles for demonstration.



The Taylor expansion of the spin tune works best at lower amplitude and quickly breaks down at higher amplitudes.
However the normal form formalism allows to study spin resonances through other means, more directly.

Advantages of normal form

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- The normal form formalism also gives access to the invariant spin field.
- Much more easily than trough tracking it gives access to the non linear spin phase advance. The phase advance of the spin motion as a function of the position in the phase-space.
- Smarter schemes to minimize amplitude dependent spin tune using the non-linear spin phase advance could be investigated.
- The PTC/FPP code is capable of producing Taylor expansion in system parameters.

Conclusion

- Spin dynamics studies at COSY are particularly detailed and target minute phenomena such as the amplitude dependent spin detuning.
- Amplitude dependent spin tune is usually studied from tracking data .The use of normal form formalism can considerably reduce the computing time required to estimate it.
- The Bmad code allows for fast modelling of complex systems and can be easily integrated into existing system due to its architecture.
- Recent development in the PTC code by Etienne Forest gives easy access to the normal form formalism.
- The integration of PTC in Bmad provides the user with a wide range of tools, in particular for spin dynamics.

Acknowledgment

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Thank You