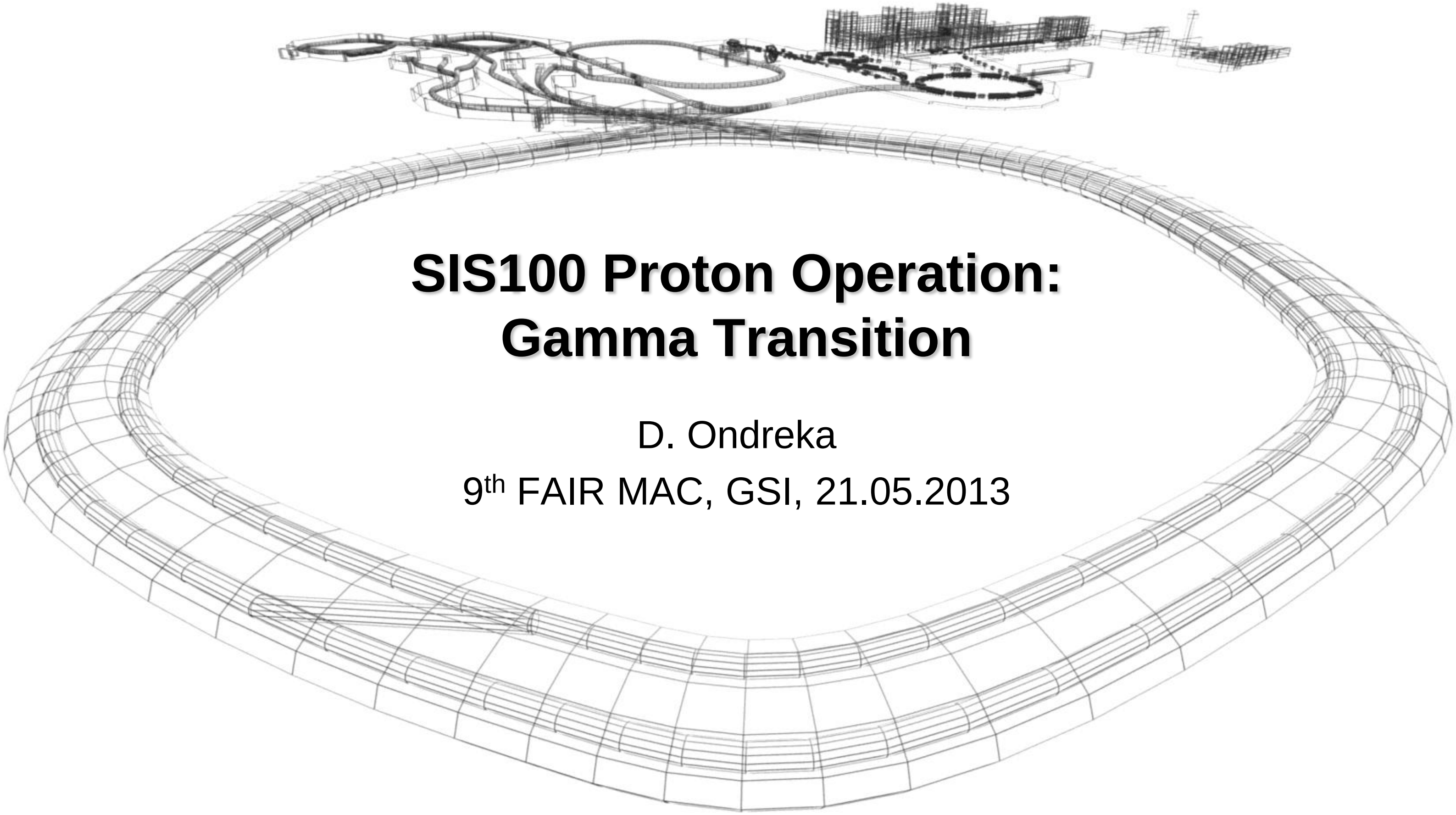
SIS100 Proton Operation: Gamma Transition

D. Ondreka

9^{th} FAIR MAC, GSI, 21.05.2013



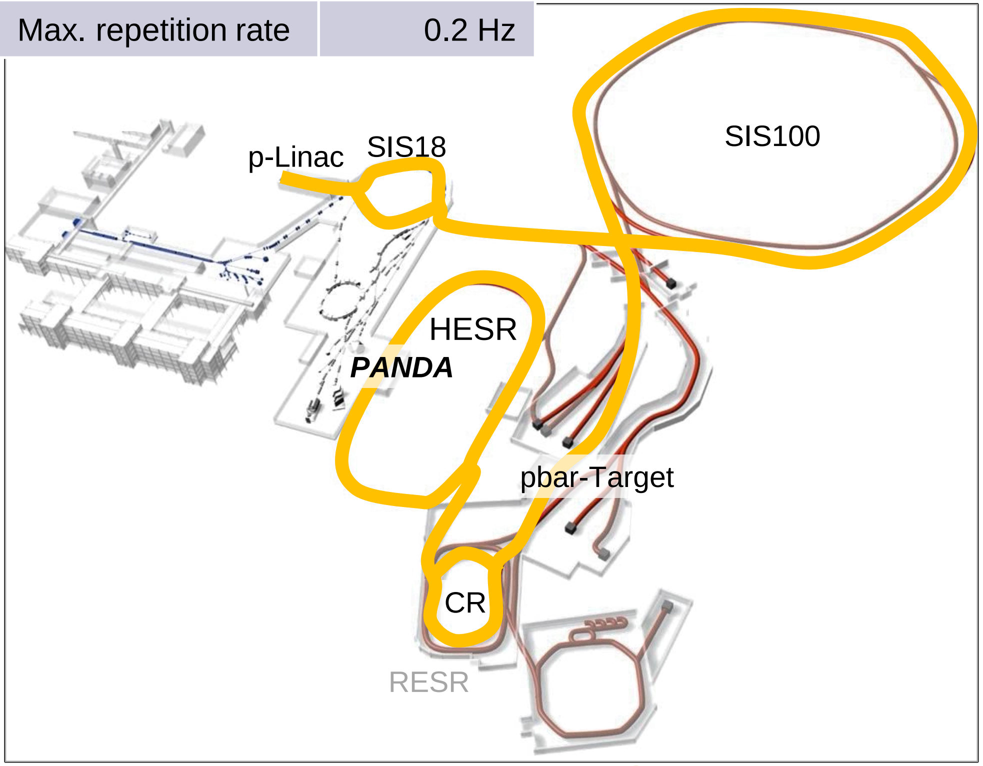
Outline

- Protons in FAIR
- SIS100 Transition Shift Scheme
  - Status of development
  - Concerns about low-η dynamics
  - Conclusions
- SIS100 Transition Jump Scheme
  - Motivation
  - Description
  - Lattice changes
  - Fast jump quadrupoles
  - Conclusions
- Proposal

(Anti-)Protons in FAIR

- Main Experiment ***PANDA@HESR***
- Anti-Proton production
  - Proton production chain:
    p-Linac -> SIS18 -> SIS100 -> pbar-Target
  - Anti-Proton production chain:
    pbar-Target -> CR (-> RESR) -> HESR
- Design goal: up to $4{\cdot}10^7$ anti-protons/s
  - SIS100 output per cycle: $2{\cdot}10^{13}$ p
  - CR output per cycle: $2{\cdot}10^8$ pbar
  - Cooling time in CR: 5...10 s
  - Accumulation rate dominated by:
    - Number of protons from SIS100
    - Cooling time in CR
- Challenges for SIS100
  - Escaping transition
  - Intense compressed single bunch

SIS100 Design Parameters	
Energy (Inj.)	4.2 GeV/u
Energy (Ext.)	29.0 Gev/u
#Particles/Bunch	$2{\cdot}10^{13}$
Final bunch length	50 ns
Max. repetition rate	0.2 Hz



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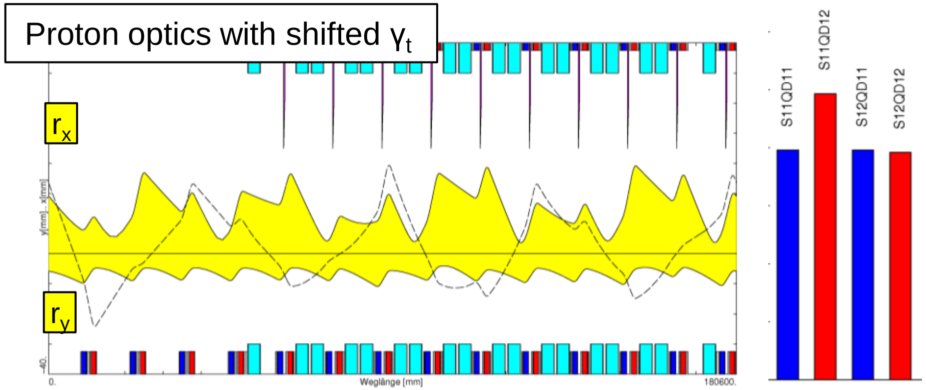
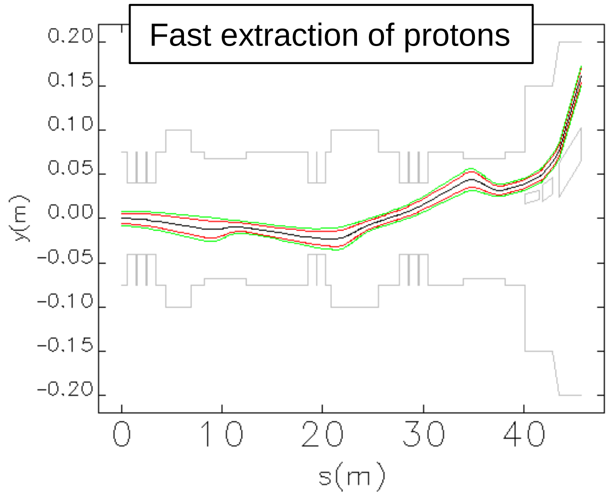
Transition Shift Scheme: Optics

- Operation scheme for ions can't be used:
  - Optics for ion operation have $\gamma_t \approx 15$
  - During ramp $\gamma = 5.3 \ldots 32.1$
  - Transition crossing unavoidable
- Idea: Distort optics to shift γ_t up
  - Increase γ_t by increasing tune to $Q_h = 21.8$
  - Split focusing quads in two families F1 and F2
  - Increase strength of F1 to create negative dispersion in the arcs such that $\gamma_t = 45$
  - Optics distortions tolerable due to small transverse beam emittances
- Basic linear properties are okay
  - Fast extraction mainly unaffected (vert. plane!)
  - Closed orbit correction works as for ions



Q_h	Q_v	γ_t
21.80	17.70	45.0



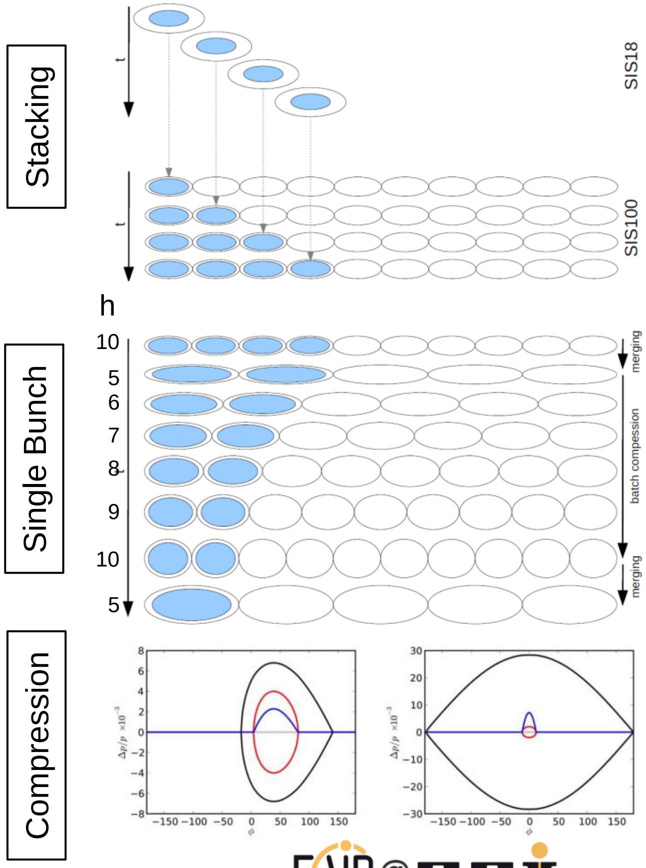
Transition Shift Scheme: Creation of Single Compressed Bunch

Synchrotron frequency f_s	
Ions (Ext.)	760 Hz
Protons (Inj.)	350 Hz
Protons (Ext.)	**16 Hz**

- Operation scheme for ions can't be used:
  - Stacking of 4 batches at injection
  - Pre-compression and bunch-rotation at flattop
  - Not suitable for protons due to small synchrotron frequency at flattop:

$$\eta = \frac{1}{\gamma^2} - \frac{1}{{\gamma_t}^2} = 0.0005 \quad \rightarrow \quad f_s = 16\ \mathrm{Hz}$$

- Proton scheme
  - Stacking of 4 bunches at injection
    - Acceleration of single bunch at h=1 in SIS18
    - Transfer of four cycles into SIS100 at h=10
    - Matching with higher harmonics in SIS18
  - Creation of single bunch
    - Bunch merging to 2 bunches @ h=5
    - Batch compression to 2 bunches @ h=10
    - Bunch merging to 1 bunch @ h=5
  - Compression
    - Acceleration with constant voltage
    - Adiabatic compression to final bunch length



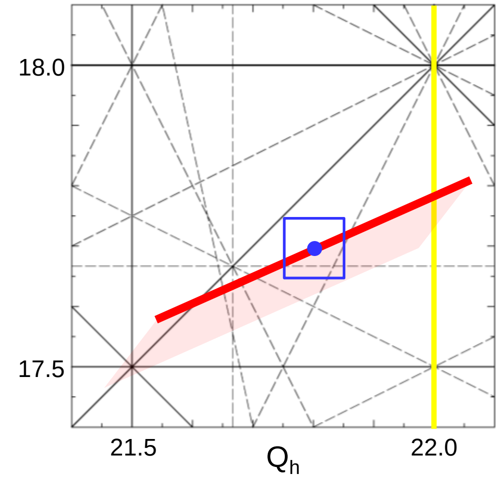
Transverse Dynamics: Chromaticity Correction

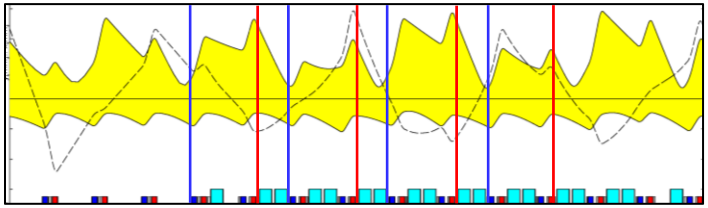
- Large chromatic tune spread
  - Large chromaticities in shifted optics
  - Large momentum spread of single bunch

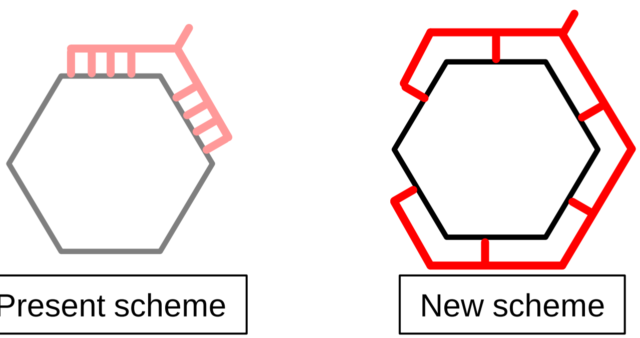
- Chromaticity correction mandatory
  - Target value for tune spread: $\Delta Q = \pm 0.05$
  - Correction scheme different from ions due to oscillating dispersion function
  - C-Sextupoles in one sector can't have same sign

- Change of sextupole powering scheme
  - Present scheme incompatible with protons
    - 6 families, each linking 4 CH/CV of two adjacent sectors
    - Effectively only 2 families due to symmetry breaking
  - New scheme required
    - Group 6 CH/CV of identical cells into a family
    - 8 families respecting symmetry
    - Disadvantage: longer cable lengths
    - Change request in preparation

	p	Ion
γ_t	45.0	15.3
dp/p	$5\cdot10^{-3}$	10^{-3}
C_h	-53.0	-22.6
ΔQ_h	**±0.26**	±0.02
C_v	-24.1	-22.6
ΔQ_v	**±0.12**	±0.02

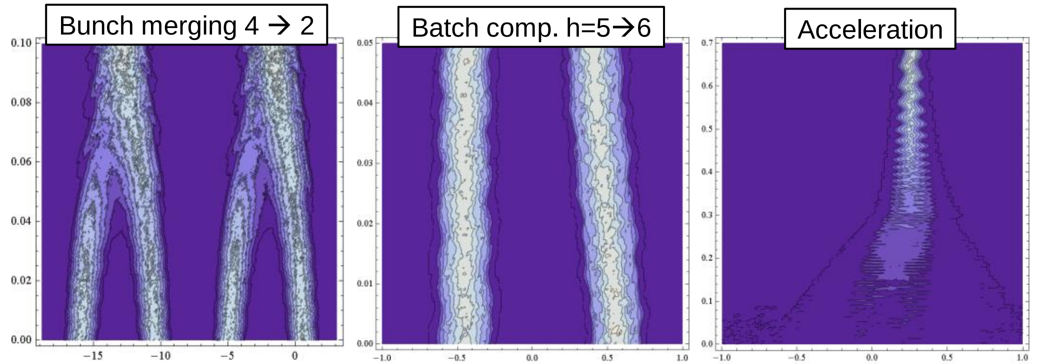


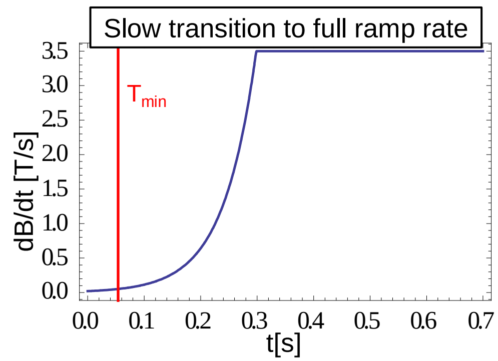




Transition Shift Scheme: Longitudinal Dynamics

- Longitudinal simulations
  - Inclusion of longitudinal space charge
  - Inclusion of beam loading
- Results
  - Merging and batch compression
    - Feasible within reasonable times
    - Beam loading has significant influence
    - Emittance dilution of injected beam by factor 3 required to alleviate beam loading effects
  - Acceleration
    - Emittance dilution leads to
      - Slow transition to full ramp rate
      - Slight reduction of full ramp rate
    - Simulation can't be trusted close to flattop because effect of η_1 not included





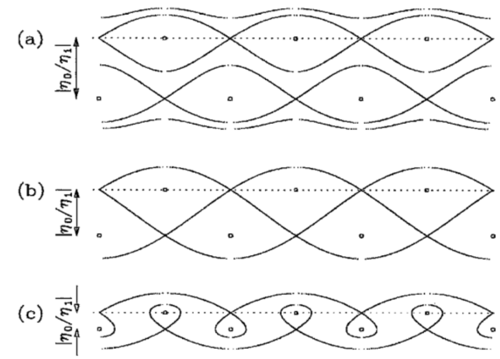
Step	Time [ms]
Merging 4 -> 2	50
Batch compression	110
Merging 2 -> 1	100
Transition to max. rate	300
Acceleration	420
Total time	**980**

[*Images and data courtesy of O. Chorniy*]

Transition Shift Scheme: Distorted Buckets Near Flattop

- Longitudinal dynamics near flattop
  - Phase slip becomes very small
  - Higher orders can't be neglected
  - Bucket dominated by new fixed point
    - Shorter bunches with higher momentum spread
    - Asymmetry in momentum distribution
  - Chromaticity correction to ΔQ = ±0.05 helps
    - Larger bucket due to reduction of η_1

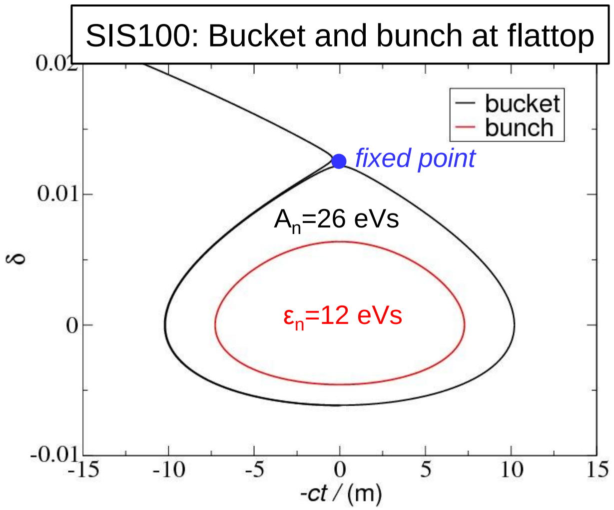
$$\eta = \eta_0 + \eta_1\delta = \frac{1}{\gamma^2} - \frac{1}{{\gamma_t}^2} + \eta_1\delta$$

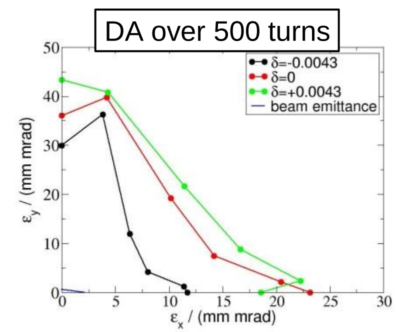


$$\delta_{\text{fp}} = \left|\frac{\eta_0}{\eta_1}\right|$$

[*Ng, NIM A 404, 1998*]

- Implications
  - Without field errors no problems
  - Results with field errors ambiguous
    - Short-term (500 turn) dynamic aperture reasonable
    - Long-term tracking simulations (32000 turns) give losses of few per cent





Simulation of losses over 32000 turns	
Field errors off	<0.1 %
Field errors on	2.0 %

- Limitation of present studies
  - Only stationary buckets, no beam loading
  - Origin of losses needs to be better understood
  - Further studies necessary

[*Images and data courtesy of S. Sorge*]

HELMHOLTZ GEMEINSCHAFT

FAIR@GSI

Transition Shift Scheme: Conclusions

- Basic properties of the scheme seem okay
  - Injection, extraction
  - Orbit and chromaticity correction

- Non-linear aspects raise some concerns
  - η_1-dominated buckets near flattop
    - Shouldn't we rather avoid this regime?
    - What about beam stability in this regime?
  - Horizontal beta functions
    - Large peak values amplify non-linear field errors
    - Easily distorted by gradient errors

- Feasibility of the transition shift scheme can't be granted as of today
  - Further studies necessary
  - Time consuming and involved

- Can we afford uncertainty without fallback?
  - Design decisions have to be taken **now**!

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Transition Jump Scheme: Motivation

- Concerns with transition shift scheme require fallback option
- Idea: Implement transition jump scheme
  - Time-honored scheme for proton accelerators in relevant energy range (PS, AGS)
- Advantages for SIS100
  - Avoid η_1-dominated regime at flattop
  - Avoid creation of single bunch at injection (reduces all intensity effects until flattop)
- Challenges:
  - Lattice layout
  - Integration of jump quadrupoles
  - Creation of single bunch at flattop

	SIS100	PS (AD)	AGS (SE)
#protons/cycle	$2\cdot10^{13}$	$2\cdot10^{13}$	$7\cdot10^{13}$
Circumference [m]	1083.6	628.3	807.0
Gamma transition	8.9	6.1	8.5
RF Voltage [kV]	280	200	400
Injection			
Energy [GeV/u]	4.0	1.4	1.9
#bunches	4	4	6
Harmonic number	10 (5)	8	6
Extraction			
Energy [GeV/u]	29.0	25.1	24.0
#bunches	1	4	dc
Harmonic number	5	20	–
RF gymnastics	merging + batch comp.	batch comp. + bunch rot.	debunching + spreading

Transition Jump Scheme: General Features

- Figure of merit: speed of transition crossing
  - Typical values for jump: $\Delta\gamma_t = 1...2$
  - Typical jump time: 0.5 ms

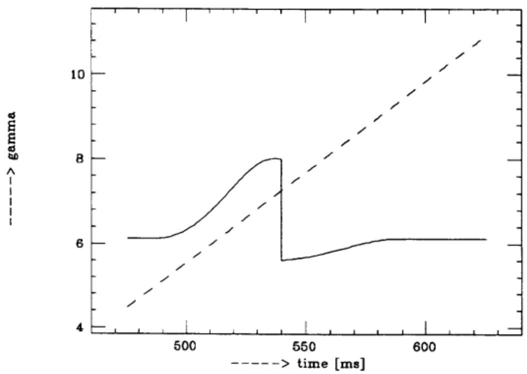
- How to modify γ_t?
  - γ_t depends on dispersion:

$$\alpha_c = \frac{1}{{\gamma_t}^2} = \oint \frac{D(s)}{\rho(s)} ds$$

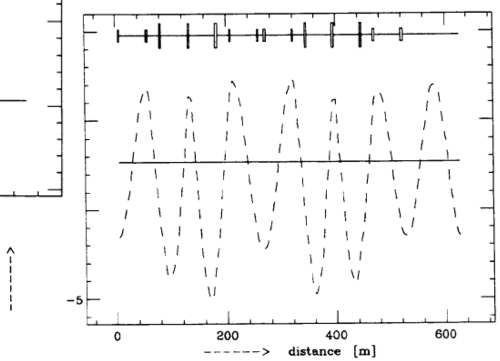
  - Modify dispersion **in the arcs** to change γ_t

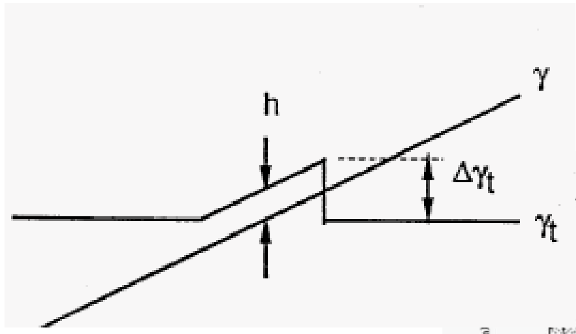
- Standard strategy: use of π-doublets
  - Two quadrupoles of opposite strengths separated by π in horizontal phase advance
  - Tune shifts zero by construction
  - Local modification of beta function
  - Global modification of dispersion function
  - $\Delta\gamma_t$ linear in strength for adequate dispersion

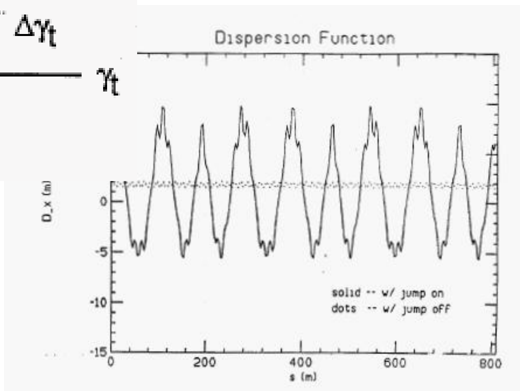
$$\Delta\gamma_t \sim k\left({D_1}^2 - {D_2}^2\right) + O(k^2)$$



PS @ CERN (bipolar jump)



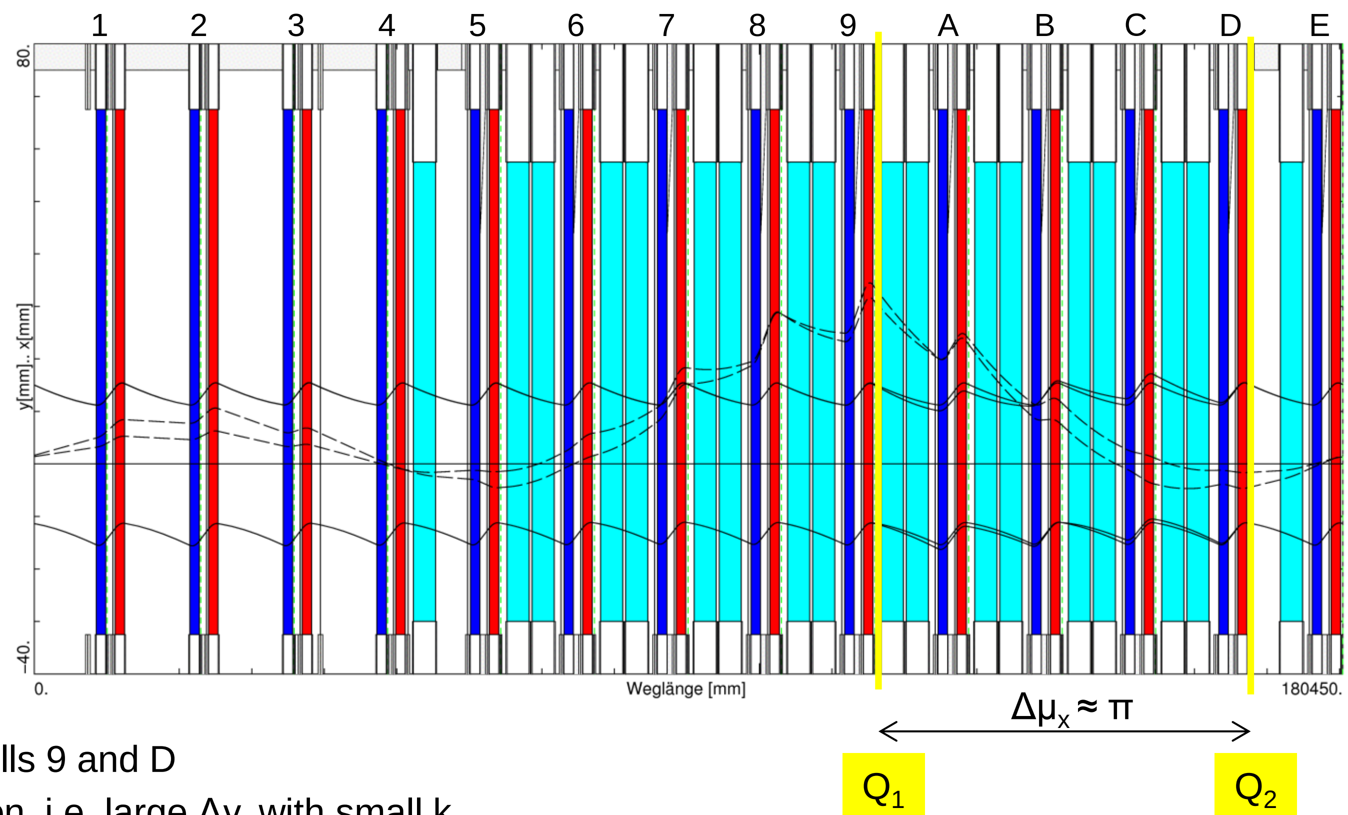




AGS @ BNL (unipolar jump)

Transition Jump Scheme: Optics Design

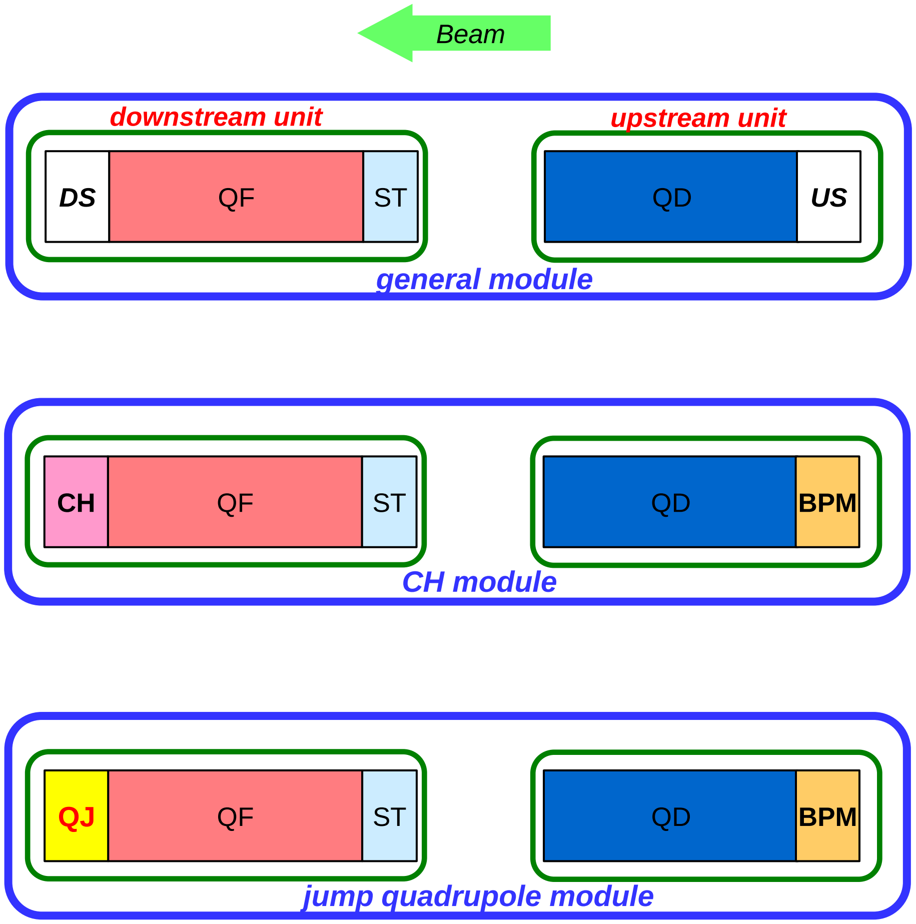
Optical Properties	
Q_h, Q_v	10.4, 10.3
γ_t	8.9
ξ_h, ξ_v	+1, +1
D_{max} [m]	6.8
$\beta_{xy,max}$ [m]	23.5
$\Delta\gamma_t$	±1



- π-doublet quadrupoles in cells 9 and D
- Large difference in dispersion, i.e. large $\Delta\gamma_t$ with small k
- Close to ideal phase advance
- Small distortion of dispersion (little change in max!)
- Negligible distortion of beta functions
- Chromaticity slightly positive to avoid instabilities after crossing

Transition Jump Scheme: Quadrupole Module Integration

- General layout of arc module
  - Upstream unit with QD and position *US*
  - Downstream unit with QF, ST, and position *DS*
  - Positions *US, DS* used alternatively for chromaticity sextupoles C{H,V} and BPMs
- Integration of jump quadrupoles QJ
  - Need to be placed into *DS* position
  - Same module configuration for cells 9 and D
  - Identical to existing CH-module when CH is replaced by QJ
  - QJ will be integrated like other correctors
- Replace present modules for cells 9 and D by new jump quadrupole module
  - Leads to omission of CV in cell 9
  - Chromaticity correction possible without this magnet for all operation modes
  - Saves 6 magnets + 1 power converter



Transition Jump Scheme: Jump Quadrupoles

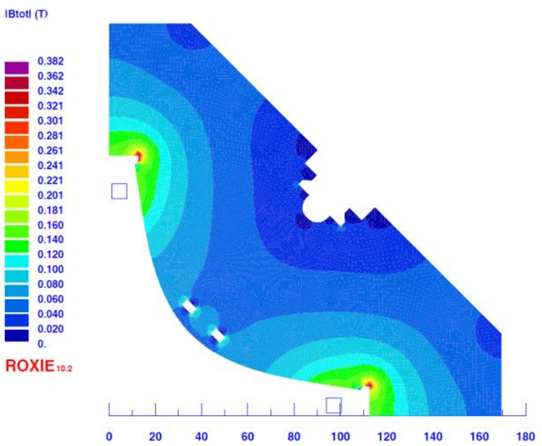
- Number of magnets: 6x2 (2 per sector)

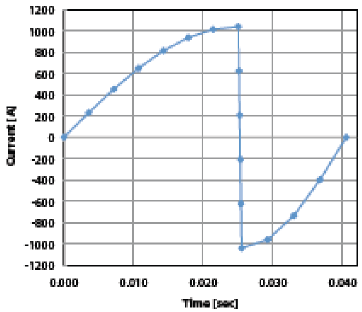
- Placement in cryostat
  - Same location as chromaticity sextupole
  - Same current leads as chrom. sextupoles
  - Mounting onto main quadrupole yoke using standard adapter

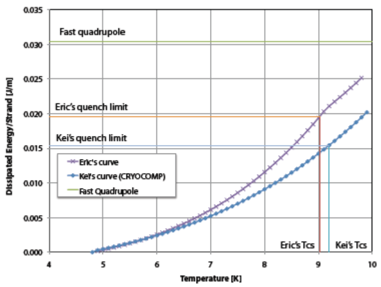
- Preliminary s.c. magnet design exists
  - Based on main quadrupole yoke
  - Uses nuclotron cable
  - Quench margin critical, but seems reachable
- N.c. design also possible due to short pulse

- Heat load in vacuum chamber
  - Average load below 1W despite large ramp rate
  - No problems for chamber cooling expected

Jump Quadrupole Parameters	
B'·L [(T/m)*m]	±0.4
I_{max} [A]	±250
Rise time [ms]	25
Jump time [ms]	**0.5**
Fall time [ms]	15
Rep. rate [Hz]	0.5
Av. heat load [W]	<10

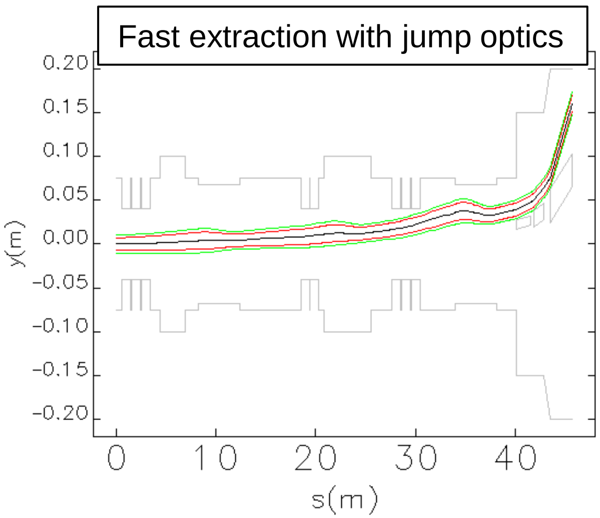


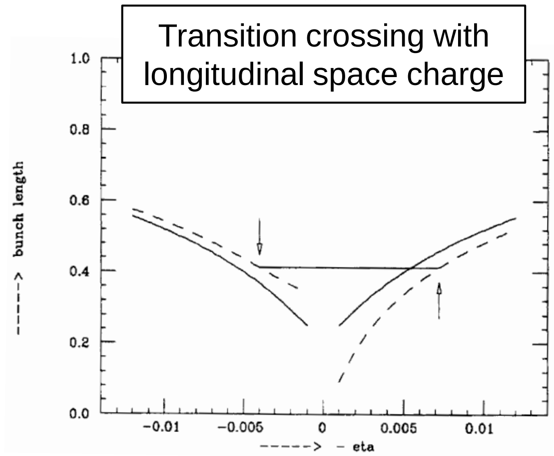




Transition Jump Scheme: Conclusions

- SIS100 lattice can easily be rearranged to support a transition jump scheme
  - Optics with sufficient γ_t variation defined
    - Basic properties checked
    - All requirements for jump scheme satisfied
  - Simple change of quadrupole module configuration without side effects
- Jump quadrupole design feasible
  - Integration into cryostat possible
  - Average heat load within limits
  - Preliminary s.c. design exists
  - Alternatively n.c. design possible
- Furthers studies necessary to verify scheme
  - Long. dynamics and timing of transition crossing
  - Creation of compressed single bunch at flattop





[*Risselada, CAS 1992*]

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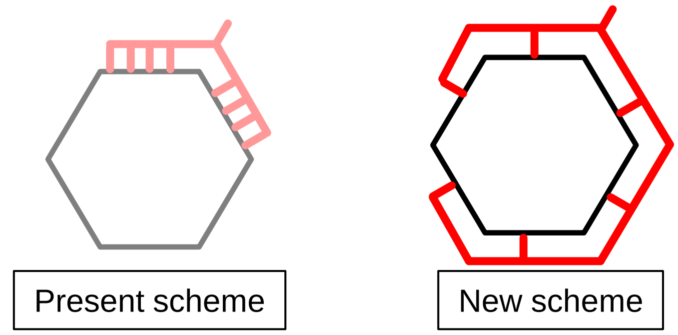
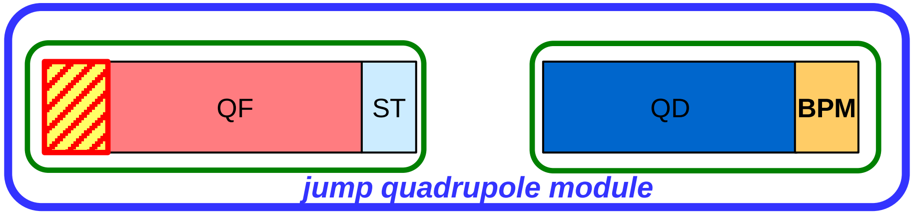
Proposal

- Change of powering scheme for chromaticity sextupoles
  - Mandatory for shift and jump scheme



- Change lattice to support jump scheme
  - Replace quadrupole modules in cells 9 and D by jump quadrupole module
  - Reserve space for jump quadrupoles
  - Make sure jump quadrupoles can be integrated
  - Omit CV from cell 9 (saves 6 magnets + 1 PC)
  - Jump quadrupole design can be done later



- Support of both shift and jump scheme
  - Further studies on both schemes
  - Based on results decide whether to implement jump scheme or leave as an upgrade option

Acknowledgements

I want to thank the following people for their contributions to the presentation:

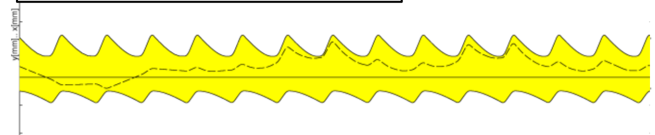
- ***S. Sorge**:* Transverse dynamics of transition shift scheme
  - Orbit correction
  - Chromaticity correction
  - Dynamic aperture
  - Loss calculations
  - Dynamics in η_1-dominated buckets
- ***O. Chorniy**:* Longitudinal dynamics of transition shift scheme
  - Merging and batch compression
  - Acceleration
- ***K. Sugita/E. Floch***: Preliminary design of s.c. jump quadrupoles
- ***S. Wilfert/C. Mühle***: Estimates of eddy current losses
- ***J.P. Meyer***: Module integration of jump quadrupoles

Thank you for your attention!

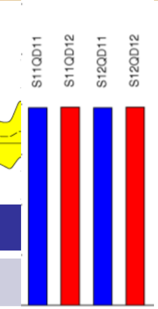
Transition Shift Scheme: Optics Change

- Shifted optics less favorable at low energy
  - Dynamic aperture tight for larger beam size
  - Increased losses due to larger amplitudes
- Solution: Optics change during ramp
  - Use symmetric optics at injection
    - Smaller beta functions and dispersion
    - Smaller horizontal chromaticity
    - Dynamic aperture much larger
    - No losses observable for energies below 22 GeV
  - Challenges
    - Control of chromaticity during optics change
    - Design of optimal transition to shifted optics

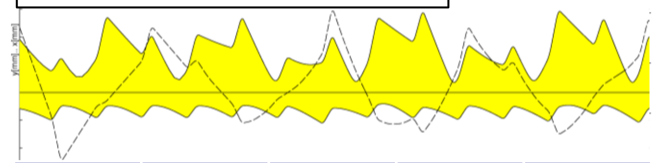
Symmetric proton optics



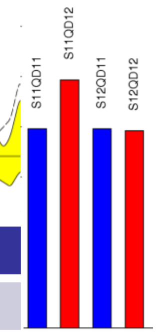
Q_h	Q_v	γ_t	C_h	C_v
21.8	17.70	18.3	-26.0	-22.9

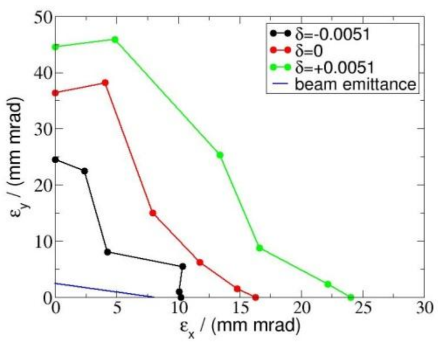


Proton optics with shifted γ_t

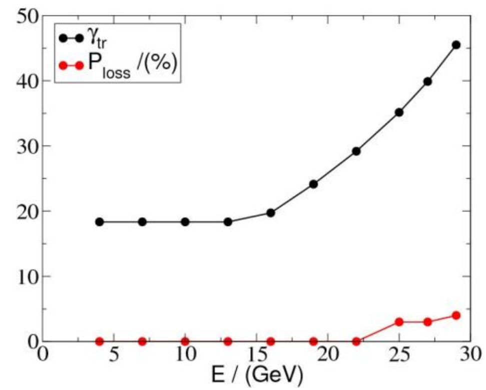


Q_h	Q_v	γ_t	C_h	C_v
21.8	17.70	45.0	-53.0	-24.1





DA for shifted optics at E = 7 GeV

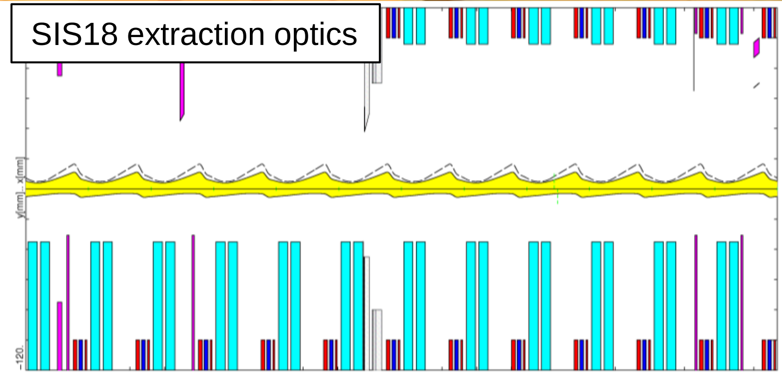


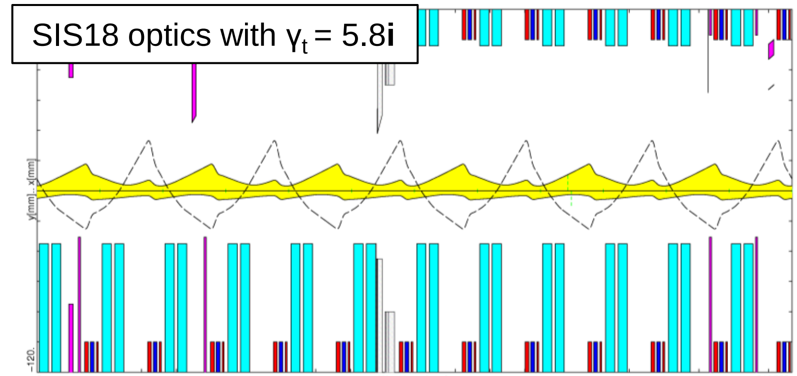
Relative losses as function of beam energy

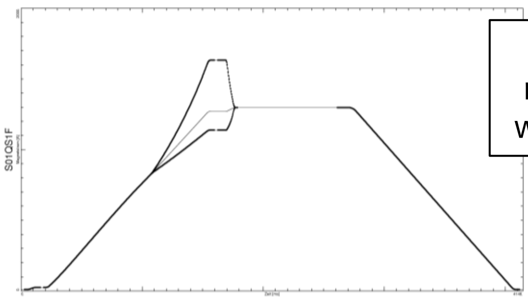
[Images courtesy of S. Sorge]

Transition Shift Scheme: SIS18

- Slow extraction from SIS18
  - SIS18 extraction optics has $\gamma_t = 5.6$
  - Max. energy for protons 4.7GeV/u → $\gamma = 6.1$
  - Transition crossing during acceleration does not work
- Shifted optics with imaginary γ_t
  - Oscillating dispersion
  - Large beta functions
  - Slow extraction impossible with this optics
- Working scheme:
  - Inject with normal injection optics
  - Pass through extraction optics during ramp
  - Shift to imaginary γ_t at end of ramp
  - Debunch beam in shifted optics
  - Restore extraction optics moving γ_t through beam
  - Possible due to low intensity







Main quadrupole ramp during cycle with p @ 4.7GeV/u