Optics solutions for the PS2 ring

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February 7th, 2008
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Acknowledgements

Outline

- Motivation and design constraints for PS2
- FODO lattice
- Doublet/Triplet
- Flexible (Negative) Momentum Compaction modules
  - High-filling factor design
  - Tunability and optics’ parameter space scan
  - “Resonant” NMC ring
  - Hybrid solution
- Comparison and perspectives
Motivation – LHC injectors’ upgrade

- Upgrade injector complex.
  - Higher injection energy in the SPS => better SPS performance
  - Higher reliability

Present accelerators

- Linac2
  - Output energy: 160 MeV

- PSB
  - Output energy: 1.4 GeV

- PS
  - Output energy: 4 GeV, 26 GeV, 50 GeV

- SPS
  - Output energy: 450 GeV, 1 TeV

Future accelerators

- Linac4
  - Output energy: 50 MeV

- (LP)SPL
  - Output energy: 1.4 GeV

- PS2
  - Output energy: ~ 5 to 50 GeV – 0.3 Hz

- SPS+
  - Output energy: 50 to 1000 GeV

- SPS
  - Output energy: ~ 14 TeV

- LHC / SLHC

- DLHC

(LP)SPL: (Low Power)
Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS
(~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to 1000 GeV)
SLHC: “Super-luminosity”
LHC (up to $10^{35}$ cm$^{-2}$s$^{-1}$)
DLHC: “Double energy”
LHC (1 to ~14 TeV)
Design and optics constraints for PS2 ring

- Replace the ageing PS and improve options for physics
  - Provide $4 \times 10^{11}$ protons/bunch for LHC (vs. $1.7 \times 10^{11}$)
  - Higher intensity for fixed target experiments
- Integration in existing CERN accelerator complex
- Versatile machine:
  - Many different beams and bunch patterns
  - Protons and ions

### Basic beam parameters

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>PS2</th>
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<tbody>
<tr>
<td>Injection kinetic energy [GeV]</td>
<td>1.4</td>
<td>4</td>
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<tr>
<td>Extraction kinetic energy [GeV]</td>
<td>13/25</td>
<td>50</td>
</tr>
<tr>
<td>Circumference [m]</td>
<td>$200\pi$</td>
<td>1346</td>
</tr>
<tr>
<td>Transition energy [GeV]</td>
<td>6</td>
<td>$\sim 10/10i$</td>
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<tr>
<td>Maximum bending field [T]</td>
<td>1.2</td>
<td>1.8</td>
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<tr>
<td>Maximum quadrupole gradient [T/m]</td>
<td>5</td>
<td>17</td>
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<tr>
<td>Maximum beta functions [m]</td>
<td>23</td>
<td>60</td>
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<tr>
<td>Maximum dispersion function [m]</td>
<td>3</td>
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<tr>
<td>Minimum drift space for dipoles [m]</td>
<td>1</td>
<td>0.5</td>
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<tr>
<td>Minimum drift space for quads [m]</td>
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<td>0.8</td>
</tr>
<tr>
<td>Maximum arc length [m]</td>
<td></td>
<td>510</td>
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</tbody>
</table>

Constrained by incoherent space charge tune-shift

$$\Delta Q_{sc} \propto \frac{N_b}{\epsilon_n \beta \gamma^2 B_f} < 0.2$$

Improve SPS performance

Analysis of possible bunch patterns:

$$C_{PS2} = \frac{15}{77} \quad C_{SPS} = \frac{15}{7} \quad C_{PS}$$

Longitudinal aspects

Normal conducting magnets

Aperture considerations for high intensity SPS physics beam

Space considerations
Racetrack:

- Integration into existing/planned complex:
  - Beam injected from SPL
  - Short transfer to SPS
  - Ions from existing complex
- All transfer channels in one straight
- Minimum number of D suppressors
  - High bending filling factor
  - Required to reach 50GeV
FODO Ring

- Conventional Approach:
  - FODO with missing dipole for dispersion suppression in straights
  - 7 LSS cells, 22 asymmetric FODO arc cells, 2 dipoles per half cell, 2 quadrupole families
  - Phase advance of $88^\circ$, $\gamma_{tr}$ of 11.4
  - 7 cells/straight and 22 cells/arc -> in total 58 cells
  - $Q_{H,V} = 14.1-14.9$
  - Alternative design with matching section and increased number of quadrupole families
  - Transition jump scheme under study

Optics solutions for the PS2 ring
Dispersion suppressor and straight section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Cell length [m]</td>
<td>23.21</td>
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<tr>
<td>Dipole length [m]</td>
<td>3.79</td>
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<tr>
<td>Quadrupole length [m]</td>
<td>1.49</td>
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<tr>
<td>LSS [m]</td>
<td>324.99</td>
</tr>
<tr>
<td>Free drift [m]</td>
<td>10.12</td>
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<tr>
<td># arc cells</td>
<td>22</td>
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<tr>
<td># LSS cells:</td>
<td>7</td>
</tr>
<tr>
<td># dipoles:</td>
<td>168</td>
</tr>
<tr>
<td># quadrupoles:</td>
<td>116</td>
</tr>
<tr>
<td># dipoles/half cell:</td>
<td>2</td>
</tr>
</tbody>
</table>

![Graph showing dispersion and injection points within the PS2 Ring FODO]

Optics solutions for the PS2 ring
Doublet and Triplet arc cells

- **Advantages**
  - Long straight sections and small maximum $\beta$’s in bending magnets (especially for triplet)

- **Disadvantage**
  - High focusing gradients
Flexible Momentum Compaction Modules

- Aim at negative momentum compaction (NMC modules), i.e.
  \[ a_c = \frac{1}{C} \int \frac{D(s)}{\rho} ds < 0 \]

- Similar to and inspired from existing modules
  (SY. Lee et al, PRE, 1992, J-PARC high energy ring)

- First approach
  - Module made of three FODO cells
  - Match regular FODO to 90° phase advance
  - Reduced central straight section without bends
  - Re-matched to obtain phase advance (close to three times that of the FODO, i.e. 270°)

- Disadvantage: Maximum vertical \( \beta \) above 80m

- regular FODO 90°/cell
  -> zero dispersion at beginning/end

- reduced drift in center, average 90°/cell
  -> negative dispersion at beginning/end
  \( \gamma_{tr} \sim 10i \)
NMC modules with high filling factor

- Improve filling factor: four FODO per module
- Dispersion beating excited by “kicks” in bends
- Resonant behavior: total phase advance $< 2\pi$
- Large radii of the dispersion vector produce negative momentum compaction
- High phase advance is necessary

C. Carli et al. PAC07

Optics solutions for the PS2 ring
Improving the high filling factor FMC

- The “high-filling” factor arc module
  - Phase advances of 280°, 320° per module
  - $\gamma_t$ of 8.2i
  - Four families of quads, with max. strength of 0.095m$^{-2}$
  - Max. horizontal beta of 67m and vertical of 43m
  - Min. dispersion of -6m and maximum of 4m
  - Chromaticities of -1.96, -1.14
  - Total length of 96.2m

- Slightly high horizontal $\beta$ and particularly long module, leaving very little space for dispersion suppressors and/or long straight sections

- Reduce further the transition energy by moving bends towards areas of negative dispersion and shorten the module
Alternative NMC module

- 1 FODO cell with 4 + 4 bends and an asymmetric low-beta triplet
  - Phase advances of $320^\circ, 320^\circ$ per module
  - $\gamma_t$ of 6.2i
  - Five families of quads, with max. strength of 0.1m$^{-2}$
  - Max. beta of 58m in both planes
  - Min. dispersion of -8m and maximum of 6m
  - Chromaticities of -1.6, -1.3
  - Total length of 90.56m

- Fifth quad family not entirely necessary
- Straight section in the middle can control $\gamma_t$
- Phase advance tunable between $240^\circ$ and $330^\circ$

- Main disadvantage the length of the module, giving an arc of around 560m (5 modules + dispersion suppressors), versus 510m for the FODO cell arc
The “short” NMC module

- Remove middle straight section and reduce the number of dipoles
- 1 asymmetric FODO cell with 4 + 2 bends and a low-beta doublet
  - Phase advances of $272^\circ, 260^\circ$ per module
  - $\gamma_t$ of 10i
  - Five families of quads, with max. strength of 0.1m$^{-2}$
  - Max. beta of around 60m in both planes
  - Min. dispersion of -2.3m and maximum of 4.6m
  - Chromaticities of -1.1,-1.7
  - Total length of 71.72m

- Considering an arc of 6 modules + 2 dispersion suppressors of similar length, the total length of the arc is around 510m
Phase advance tunable between $240^\circ$ and $420^\circ$ in the horizontal and between $250^\circ$ and $320^\circ$ in the vertical plane.
Transition energy versus horizontal phase advance
Almost linear dependence of momentum compaction with dispersion min/max values

Higher dispersion variation for $\gamma_t$ closer to 0

Smaller dispersion variation for higher $\gamma_t$
Transition energy versus chromaticity

- Higher in absolute horizontal chromaticities for smaller transition energies
- Vertical chromaticities between -1.8 and -2 (depending on vertical phase advance)
- Main challenge: design of dispersion suppressor and matching to straights

07/02/08 Optics solutions for the PS2 ring
- Similar half module as for the NMC with \(2+5\) dipoles (instead of \(2+4\))
- Using 4 families of quads to suppress dispersion, while keeping beta functions “small”
- Maximum beta of 70m
- Total length of 77.31m
Adding a straight section with 7 FODO cells, using 2 matching quadrupoles

- Straight drift of **9.5m**
- Tunes of (12.1, 11.4)
- \( \gamma_t \) of **12.9i**
- 13 families of quads, with max. strength of 0.1m\(^{-2}\)
- Max. beta of around **71m** in horizontal and **68m** in the vertical plane
- Dispersion of -2.3m and maximum of **4.6m**
- Chromaticities of -16.7, -25.8
- Total length of **1346m**
The resonant NMC module

- 1 symmetric FODO cell with 3 + 3 bends and a low-beta doublet
- Phase advances of $315^\circ, 270^\circ$ per module
  - $8 \times 315^\circ \rightarrow 7 \times 2\pi$
  - $8 \times 270^\circ \rightarrow 6 \times 2\pi$
- $\gamma_t$ of 5.7i!!!
- Four families of quads, with max. strength of 0.1m$^2$
- Max. beta of around 59m in both planes
- Min. and max. dispersion of -8.5m and 8.9m
- Chromaticities of -1.5, -1.7
- Length of 1.2m between QF and D
- Total length of 64.8m
Dispersion is suppressed by fixing horizontal phase advance to multiple of $2\pi$

Solution with **odd** number of $2\pi$ multiples is preferable for getting **lower imaginary $\gamma_t$**
The “resonant” NMC arc

- 8 NMC modules
- Total horizontal phase advance multiple of $2\pi$
- Maximum $\beta$ of 59m
- Total length of 518m
- Adding a straight section with 7 FODO cells, using 2 matching quadrupoles
  - Straight drift of $9.4\text{m}$
  - Tunes of $(16.8,9.8)$
  - $\gamma_t$ of $10.7i$
  - 8 families of quads, with max. strength of $0.1\text{m}^{-2}$
    - Extra families for phase advance flexibility in the straight section
  - Max beta of around $60.5\text{m}$ in horizontal and vertical plane
  - Min. and max. dispersion of $-8.5\text{m}$ and $8.9\text{m}$
  - Chromaticities of $-21.7$, $-19.8$
  - Total length of $1346\text{m}$
An optimized NMC module

- 1 asymmetric FODO cell with 4 + 3 bends and a low-beta doublet
  - Phase advances of $316^\circ, 300^\circ$ per module
  - $\gamma_t$ of 5.6i!!!
  - Four families of quads, with max. strength of 0.1m$^2$
  - Max. beta of around 54m and 58m
  - Min. and max. dispersion of -7.8m and 10.2m
  - Chromaticities of -1.3, -2
  - Total length of 73m

![Diagram showing beta and dispersion profiles](image)
Hybrid approach:

- Phase advance close to multiple of $2\pi$ and 2 extra quad families
The arc III

- 7 NMC modules
- Phase advances of $5.8 \times 2\pi$ and $5.5 \times 2\pi$
- Maximum $\beta$ of 60m
- Total length of 511m
Adding a straight section with 7 FODO cells, using 2 matching quadrupoles

- Straight drift of 9.5m
- Tunes of (13.8, 13.4)
- $\gamma_t$ of 10.9i
- 10 families of quads, with max. strength of 0.1m$^{-2}$
  - Extra families for phase advance flexibility in the straight
- Max beta of around 58m in horizontal and 56m in the vertical plane
- Min. and max. dispersion of -8.2m and 10.2m
- Chromaticities of -18.7, -29.5
- Total length of 1346m
## Comparison

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RING I</th>
<th>RING II</th>
<th>RING II</th>
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<tr>
<td>Transition energy</td>
<td>12.9i</td>
<td>10.7i</td>
<td>10.9i</td>
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<tr>
<td>Number of dipoles</td>
<td>172</td>
<td>192</td>
<td>196</td>
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<tr>
<td>Dipole length [m]</td>
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<td>3.11</td>
<td>3.03</td>
</tr>
<tr>
<td>Arc module length [m]</td>
<td>71.7</td>
<td>64.8</td>
<td>73</td>
</tr>
<tr>
<td>Number of arc modules</td>
<td>5+2</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Arc length [m]</td>
<td>513.5</td>
<td>518</td>
<td>511</td>
</tr>
<tr>
<td>Straight section drift length [m]</td>
<td>9.5</td>
<td>9.4</td>
<td>9.5</td>
</tr>
<tr>
<td>Quadrupole families</td>
<td>13</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Arc phase advance [2\pi]</td>
<td>5.2/5.2</td>
<td>7/6</td>
<td>5.8/5.5</td>
</tr>
<tr>
<td>Maximum beta functions [m]</td>
<td>71/68</td>
<td>61/61</td>
<td>58/56</td>
</tr>
<tr>
<td>Maximum dispersion function [m]</td>
<td>4.7</td>
<td>8.9</td>
<td>10.2</td>
</tr>
<tr>
<td>Tunes</td>
<td>12.1/11.4</td>
<td>16.8/9.8</td>
<td>13.8/13.4</td>
</tr>
<tr>
<td>Chromaticity</td>
<td>-16.7/-26.8</td>
<td>-21.7/-19.8</td>
<td>-18.7/-29.5</td>
</tr>
</tbody>
</table>
Summary

- Different lattice types for PS2 optics investigated
  - FODO type lattice a straightforward solution
    - Challenge: Transition crossing scheme
  - NMC lattice possible alternative
    - No transition crossing
    - Challenge: low imaginary transition energy

- Perspectives:
  - Complete the lattice design including chromaticity correction and dynamic aperture evaluation
  - Detailed comparison based on performance with respect to beam losses
    - Collimation system
    - Non-linear dynamics
    - Collective effects