LHC Injectors Upgrade

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LHC Injectors Upgrade

PS-LIU Space-charge related issues

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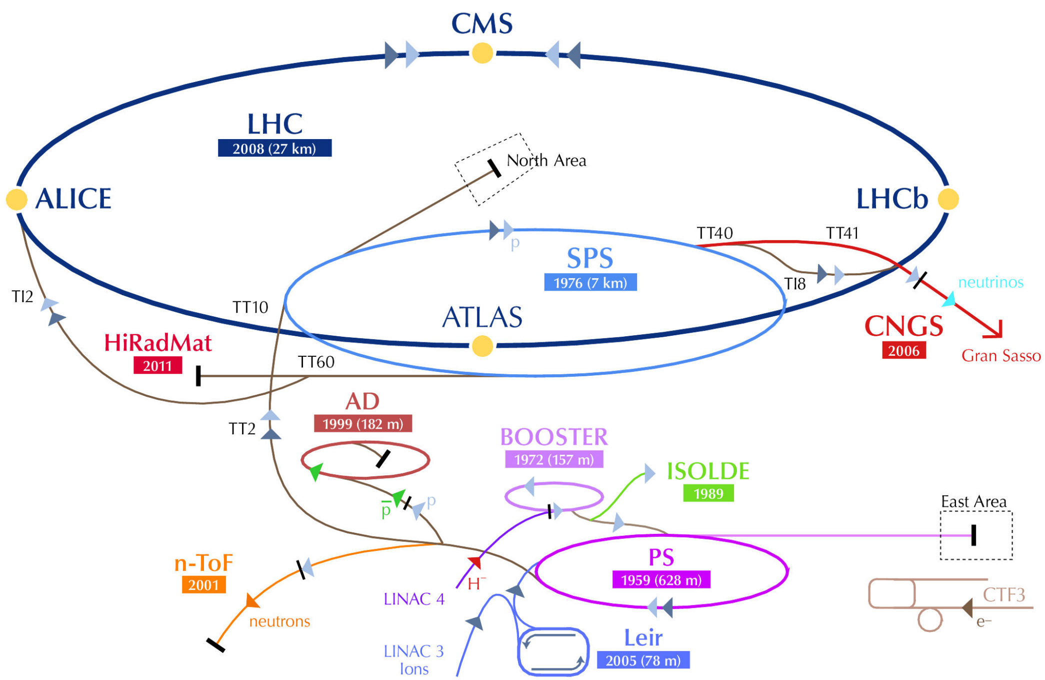
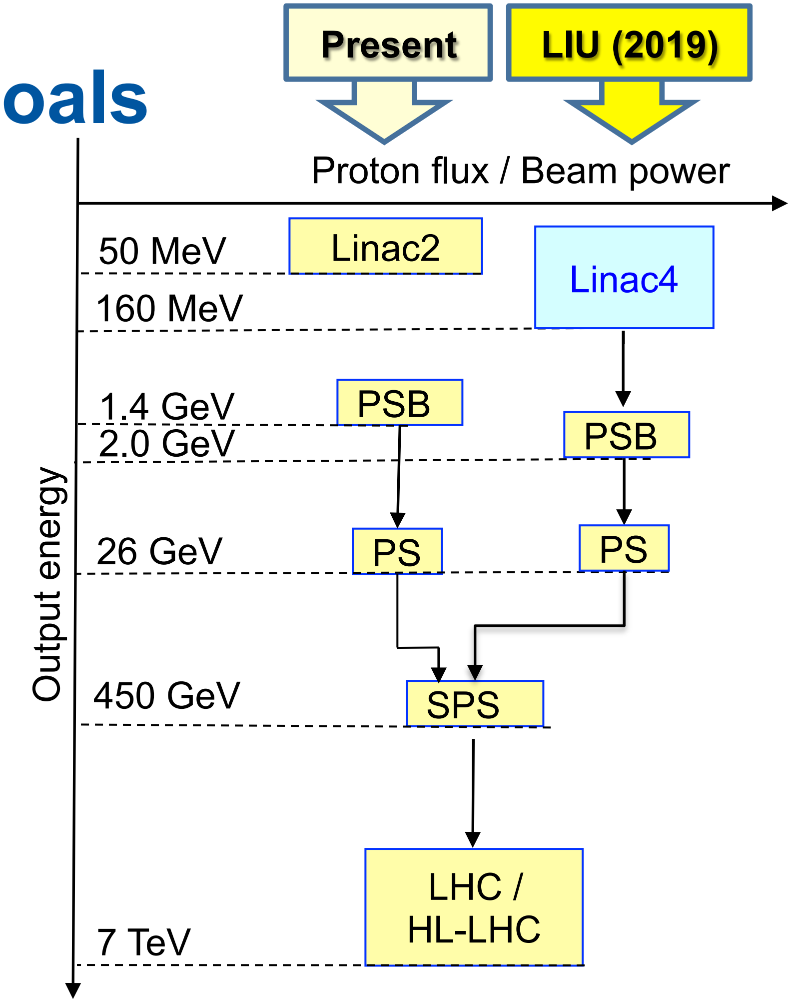
LHC injectors upgrade Goals

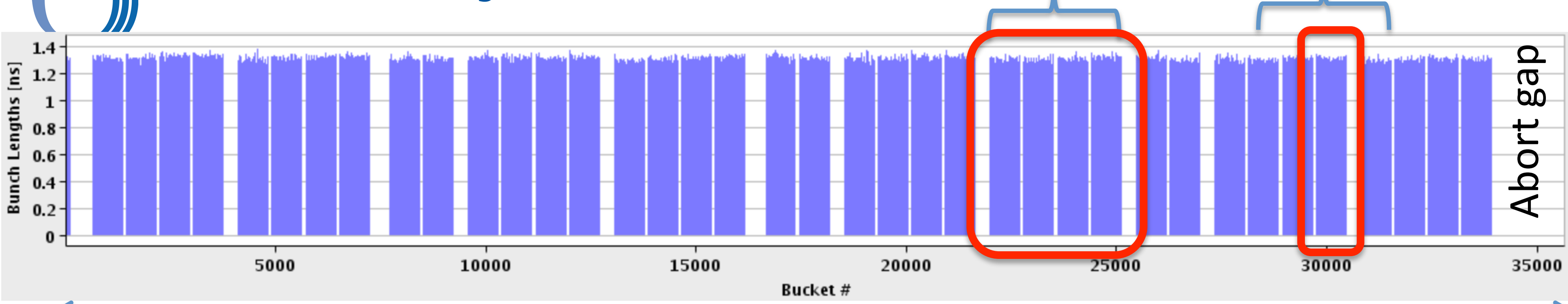




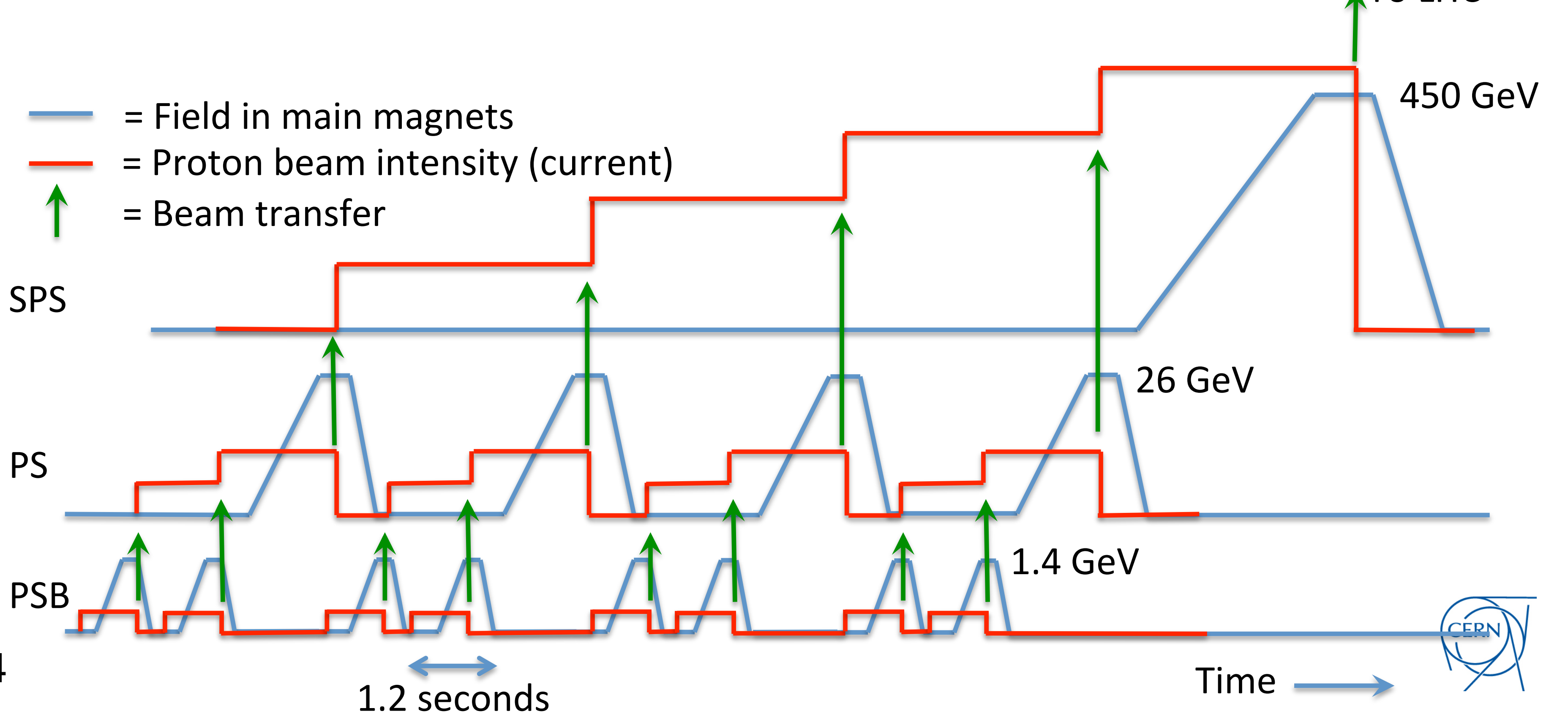
"The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC. This includes LINAC4, the PS booster, the PS, the SPS, as well as the heavy ion chain…"   (This is the mandate … **Upgrade of Brightness**)

+ determine possible improvements for high intensity beams.

LHC and Injectors – 50 ns



2012-2013 LHC - 26.7 km - 1380 bunches – 50 ns



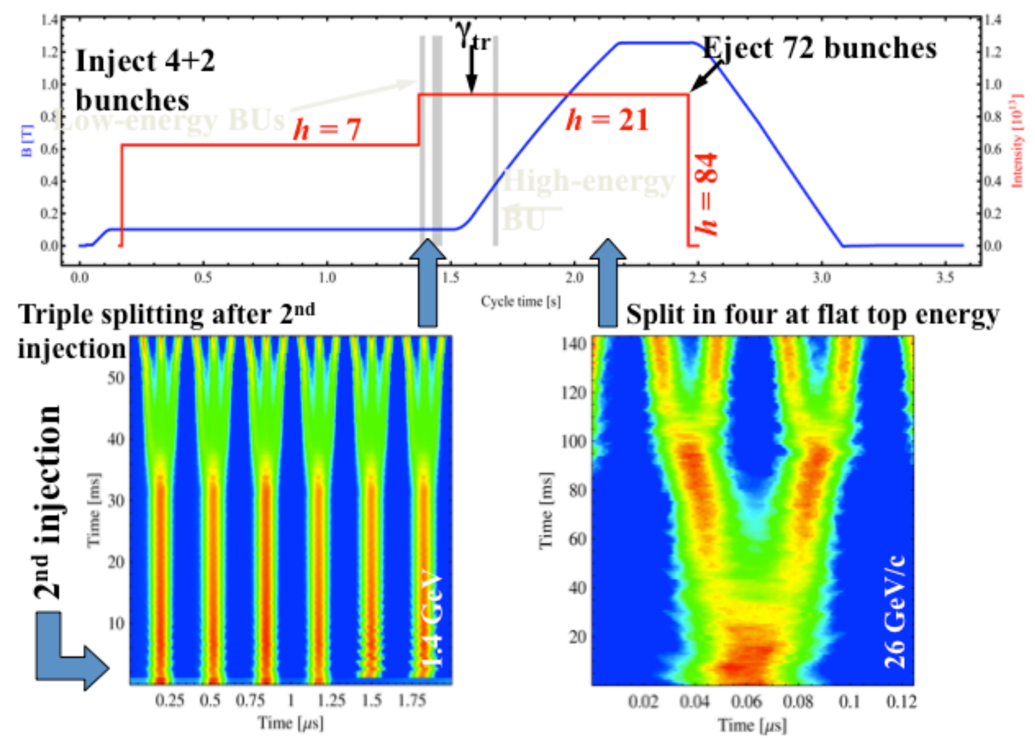
LHC25(50)ns Production Scheme as today

Production scheme:
a) Double batch injection from PSB (**4 + 2 bunches, 6 bunches for PS at h=7**)
b) Up to 4 batches of 72 bunches each transferred to the SPS (288 bunches)

Transverse emittance produced in the PSB, longitudinal in the PS

Multiturn proton injection in PSB
RF gymnastics in PS:

- Triple splitting
- Acceleration
- 2 x Double splittings
  - (1 Double splitting for 50 ns)
- Bunch rotation



→ Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72

➢3 RF systems in PSB
➢5 RF systems in PS
➢2 RF systems in SPS

LHC 25(50)ns alternative Production (BCMS)

BCMS "**B**atch **C**ompression, **M**erging and **S**plitting in PS"

Production scheme:

a) Double batch injection from PSB (**4 + 4 bunches, 8 bunches for PS at h=9**)

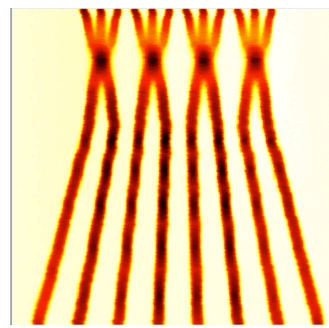
b) Up to 5 batches of 48 bunches each transferred to the SPS (240 bunches)

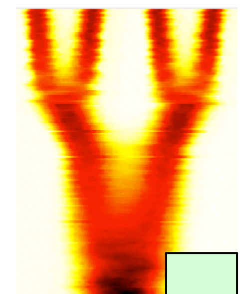
Transverse emittance produced in the PSB, longitudinal in the PS

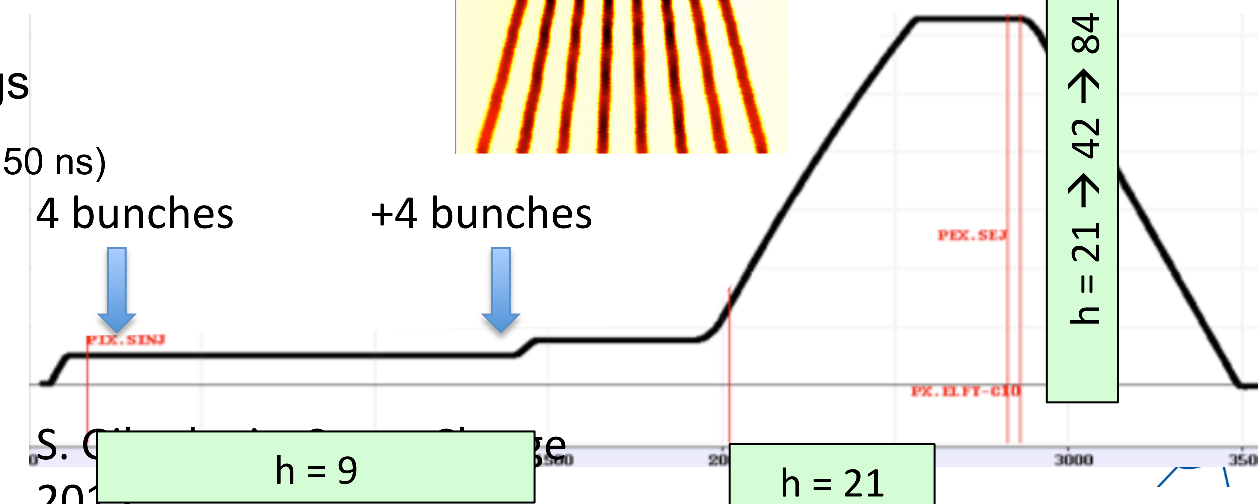
- Multiturn proton injection in PSB with **shaving**
- RF gymnastics in PS:
  - Batch compression
  - Bunch merging
  - Triple splitting
- Acceleration
- 2 x Double splittings

  (1 Double splitting for 50 ns)
- Bunch rotation

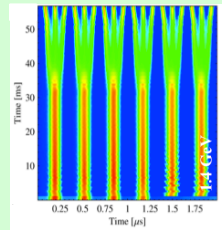
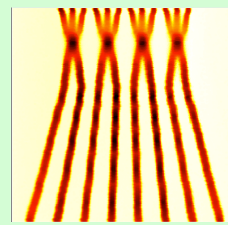
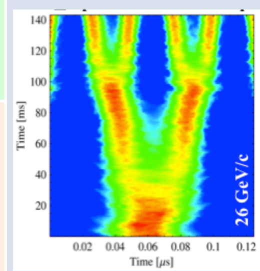
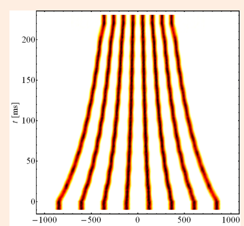
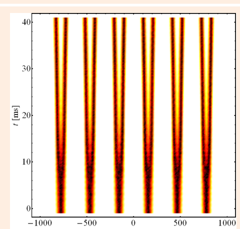
h = 9 →10 → 11→12 → 13 → 14 → 7 → 21







Catalogue of Possible production schemes - 25 ns

Schemes 25 ns	PSB – PS bunches	RF gym. in PS	RF gym. at injection	RF gym. at extraction	b/Train to SPS	SPS injections
3-spitting (standard scheme)	4 + 2	/3 ↗ /2 /2			72	4
BCMS	4 + 4	+2C/3↗/2 /2			48	5
BCS	4 + 4	C ↗ /2 /2			32	5
8b+4e	4 + 2	/2 ↗ /2 /2			48	5

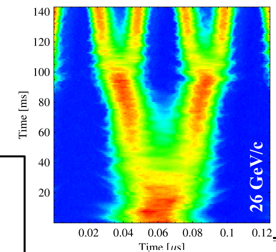
/ Splitting C Batch Compression + Merging ↗Acceleration to 26 GeV/c

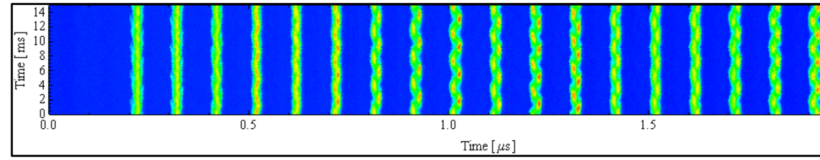
Present and future performance @ SPS extraction (in terms of beam power for Neutrino beams)

	Operation		SPS record		After LIU (2020)	
					Aim	Study
	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity/10^{11}	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS beam intensity/10^{13}	2.3	4.4	3.75	5.3	6.35	7.0*
PS beam intensity/10^{13}	0.6	**2.3**	1.0	**3.0**	1.75	**4.0***
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2/2.4*
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	6.0/7.2
PS momentum [GeV/c]	26	14	26	14	26	14
average current [μA]	0.17	1.17	0.28	1.4	0.47	1.9/1.6
power [kW]	77	470	125	565	211	747/622

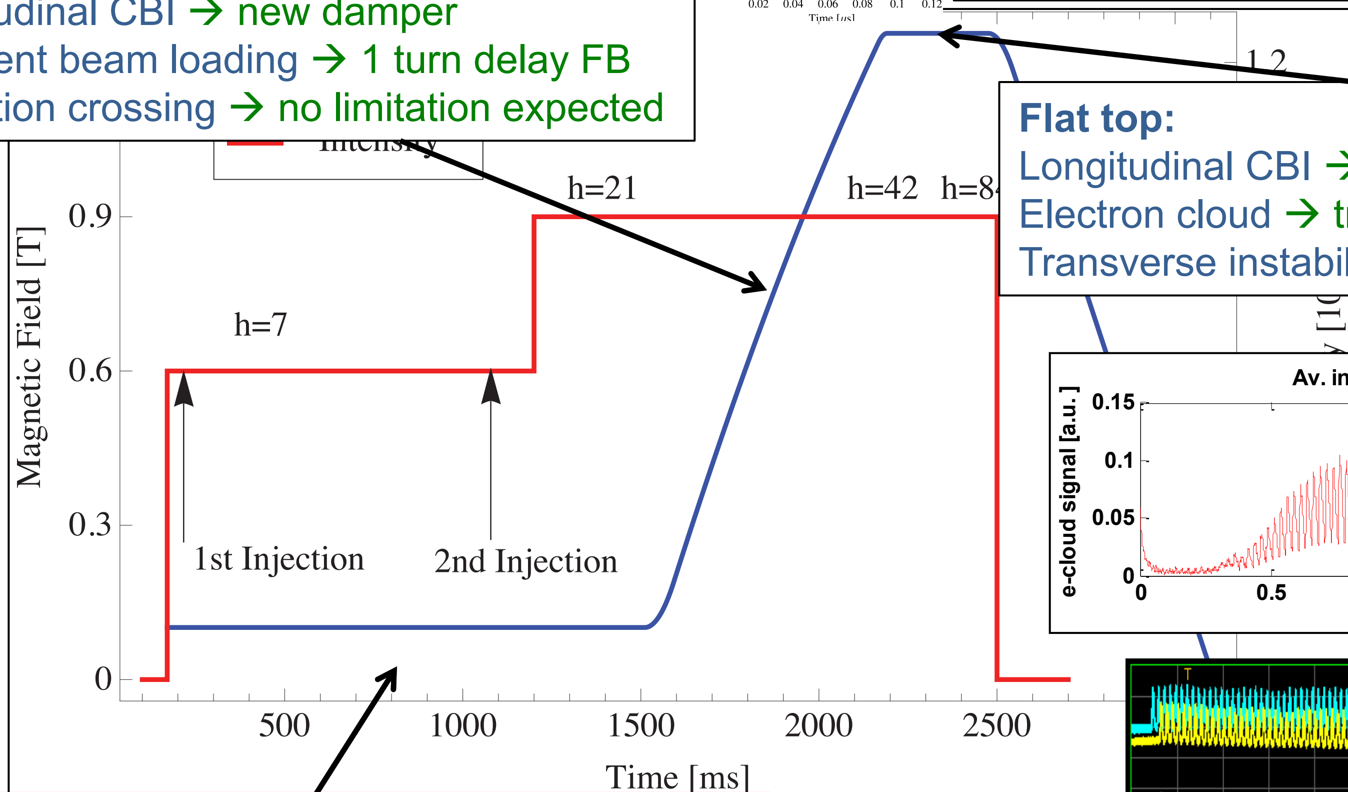
***Feasibility including operational viability (especially in PS) remains to be demonstrated**

Challenges in the PS

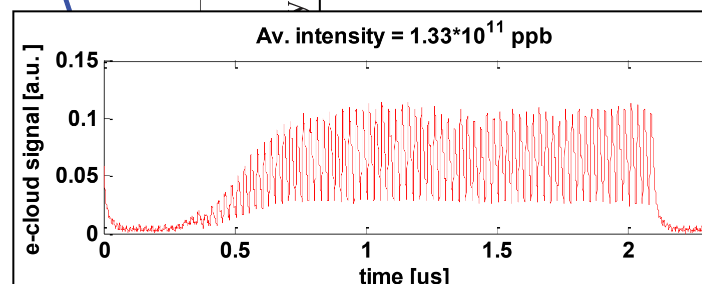


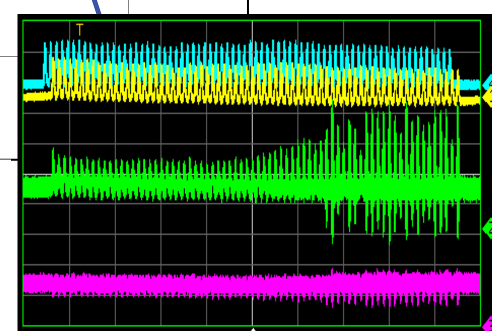


Acceleration/Bunch splittings
Longitudinal CBI → new damper
Transient beam loading → 1 turn delay FB
Transition crossing → no limitation expected

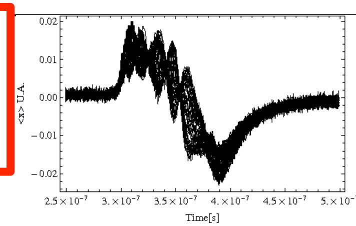


Flat top:
Longitudinal CBI → new damper
Electron cloud → transverse FB
Transverse instabilities → transverse FB





Injection flat bottom:
Space charge → 2 GeV injection upgrade
Headtail instability → transverse FB



Space Charge at injection (1.4 GeV - 2 GeV)

Study to determine largest acceptable tune spread.

Today max acceptable: $\Delta Qy \sim |0.3|$ @ 1.4 GeV
HL-LHC max needed: $\Delta Qy > |0.3|$ @ 2 GeV

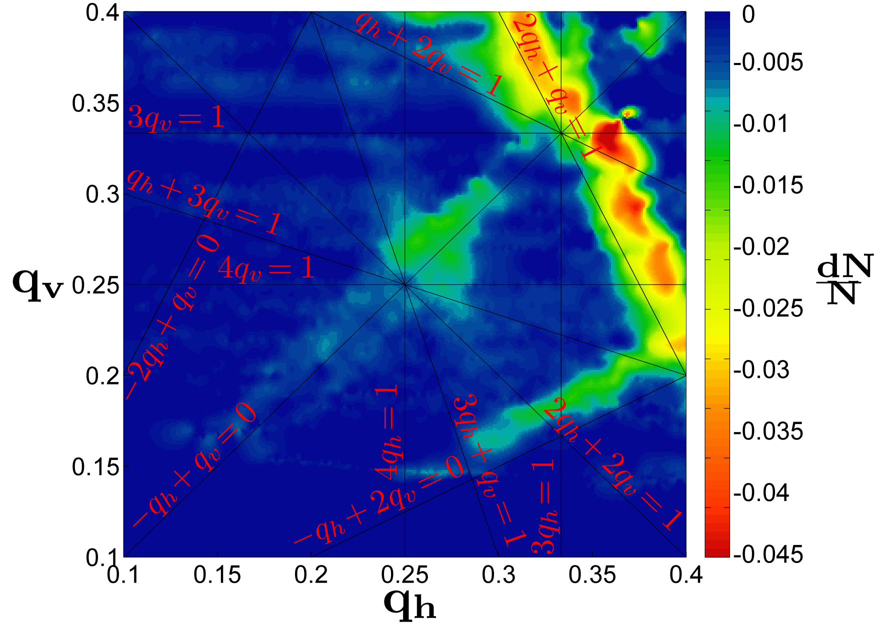
Goal: demonstrate that possible to inject a beam with $\Delta Q > |0.3|$ with limited emittance blowup (max 5%)

Experimental studies:

- ✓ Learn from operational beams experience. Current Laslett at about -0.28 with Qy<0.25
- ✓ Tune scan to identify via beam losses dangerous resonances
- ✓ *Driving terms measurements*
- ✓ Compensate resonances (as done already in 1975 with injection at 50 MeV)

Simulation studies:

- **PTC–Orbit simulations**
- **IMPACT – MADX-FZM simulations**
- ✓ Lack of good magnetic error model
  - – No error tables from magnetic measurements (à la LHC) available from 1958
  - – Opera©-based magnetic error simulations

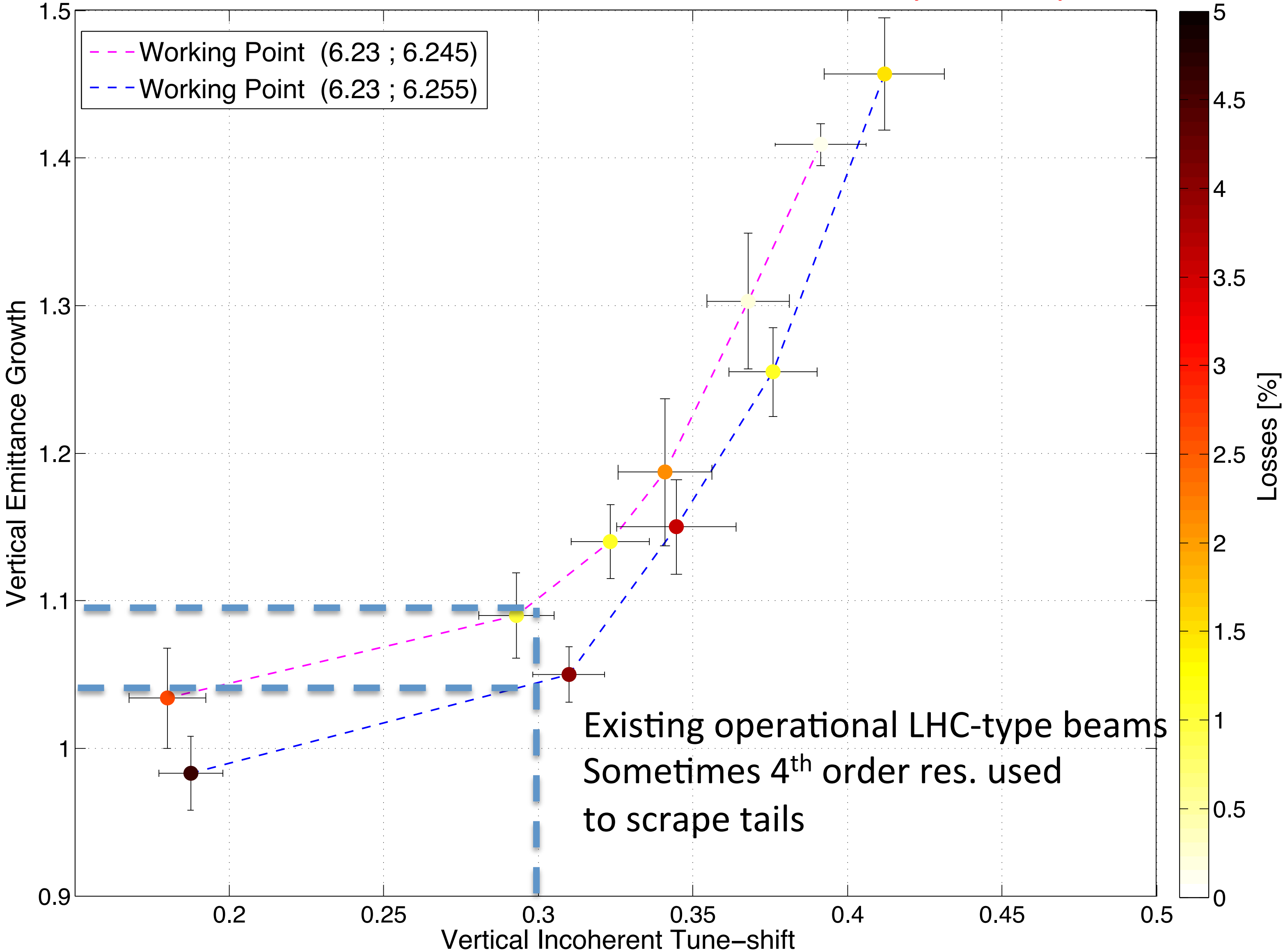


2013-2014 important results:

- Better understanding of integer resonance
- Better understanding of 4th (or 8th) order resonance

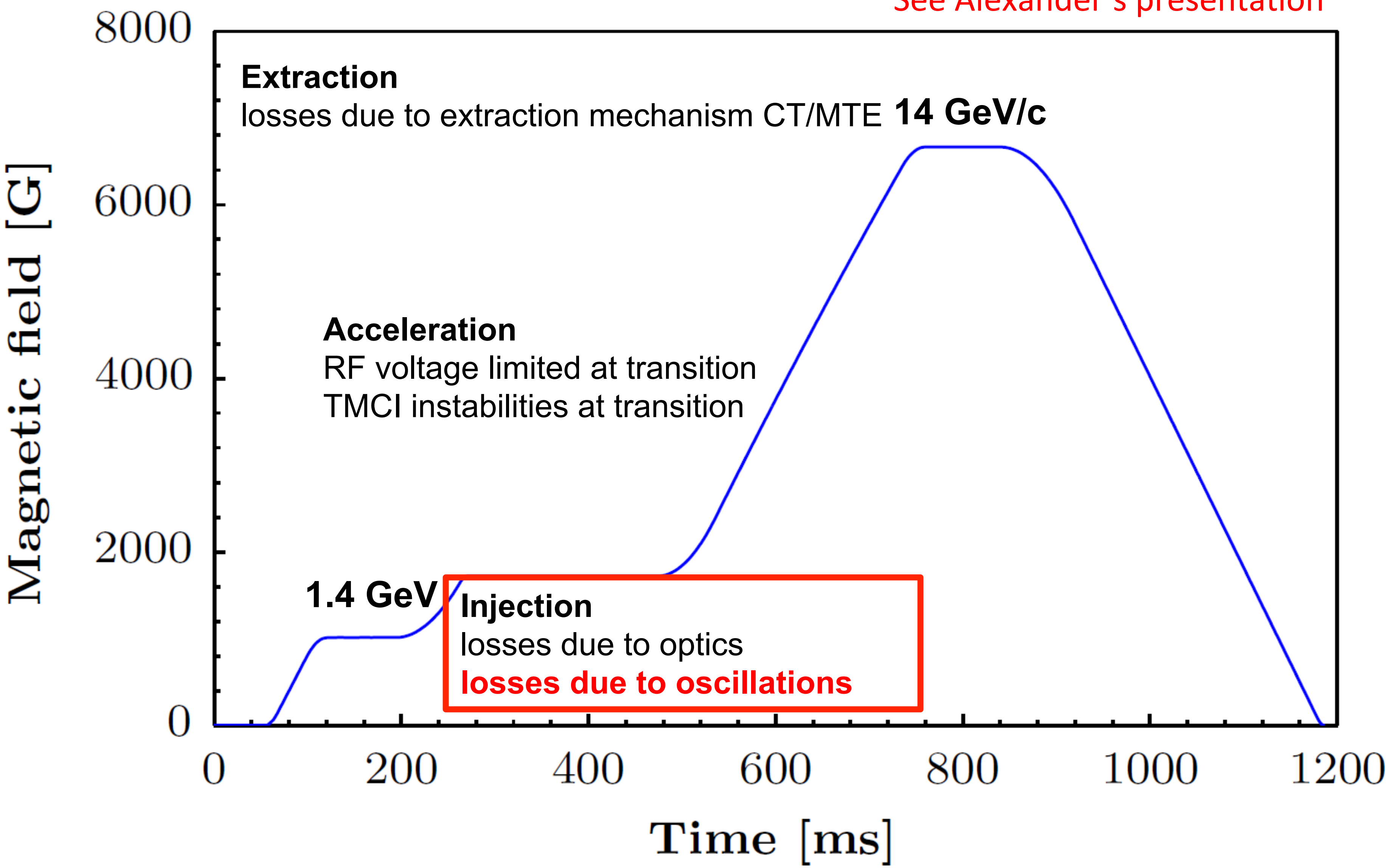
Space charge issue: Vertical growth vs. Tune-spread vs. Losses

See Raymond's presentation



PS Limitations for high-intensity beams: what we learned from the CNGS run

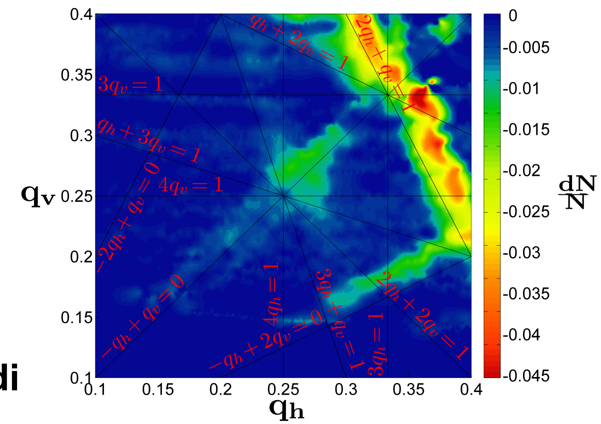
See Alexander's presentation



Current activities (mainly presented later by Raymond, Alex, Shinji, Ji and Adrian)

- **Improve understanding of existing space charge limits**
  - Integer resonance (in collaboration with LBL)
  - 4th order resonance (in collaboration with RAL, talks of Raymond and Shinji)
  - Normal 3rd order resonance (in collaboration with GSI, talks of Raymond and Giuliano)
  - Understand indirect space charge effects (talk of Alexander)

- **Improve machine modeling**
  - Random multipoles errors from geometry
  - Machine alignment
  - Longitudinal and transverse impedance model
  - Still missing : chromo-geometric terms modeling



- **Investigate alternative solution to increase maximum acceptable di tune shift on top of the 2 GeV injection energy upgrade (baseline)**
  - Hollow bunches in the longitudinal plane (talk of Adrian)
  - Horizontal dispersion increase
  - Resonance compensation
  - Fully coupled optics : generate vertical dispersion by linear coupling

Proton Synchrotron main magnetic unit

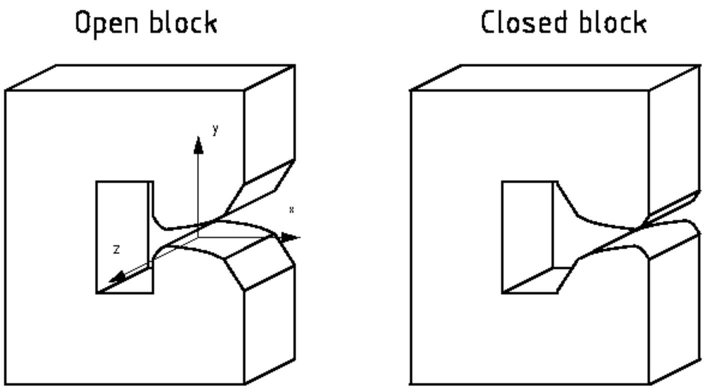
Combined-function magnet with hyperbolic pole shape

- Dipole field – guiding
- Quadrupole field – focusing
- Higher component from axiliary circuits
- Higher component also present due to saturation at 26 GeV/c

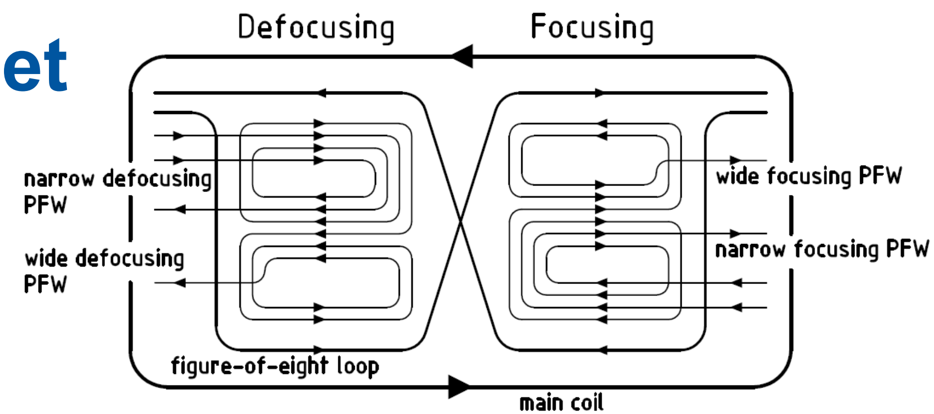
Focusing and defocusing half (FDDF)

- 5 C-shaped block in each half
- Wedge shaped air gaps between blocks

Complex geometry of coils system
In total 100+1 main units of four different types.



Coils of the PS magnet



Main coil

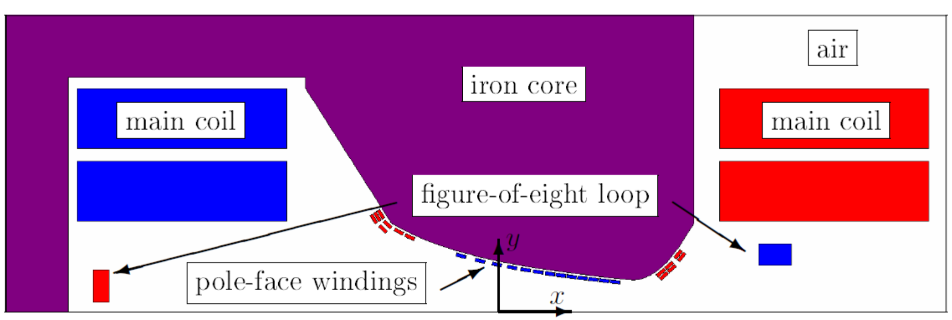
- Dipole and quadrupole field mostly

Figure-of-eight loop

- Adjusts quadrupole field but also contributes to dipole field

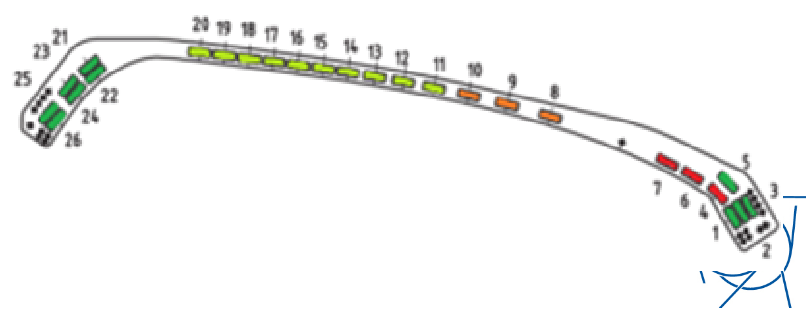
Pole-face windings (PFW)

- Separately for focusing and defocusing half
- Each winding has narrow and wide circuit
- Corrects higher components of the field



PFW Powering

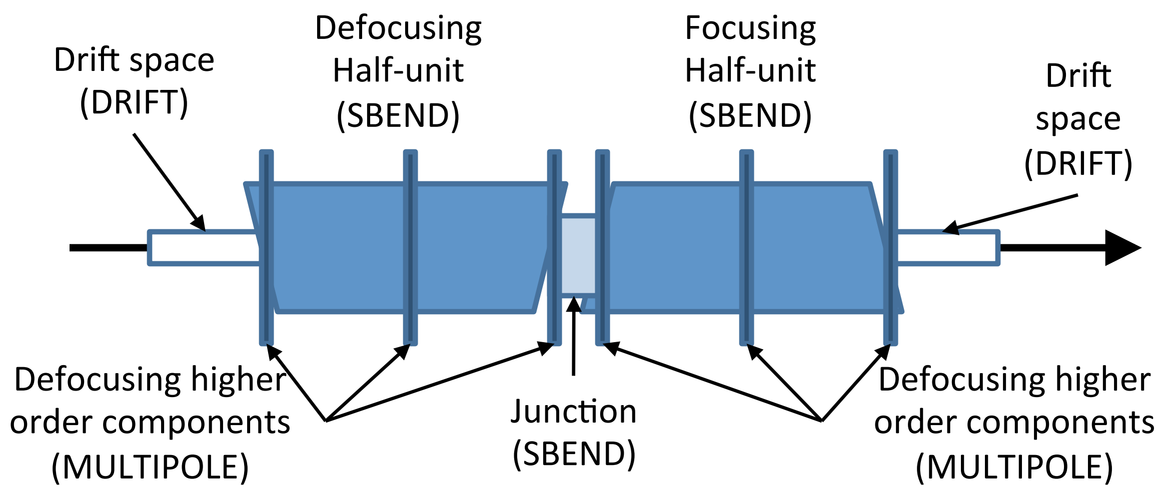
- 5 currents
- Control of the four beam parameters Q_h, Q_v, ξ_h, ξ_v
- One current remains free for controlling an additional physical parameter



Magnet representation in the optical model

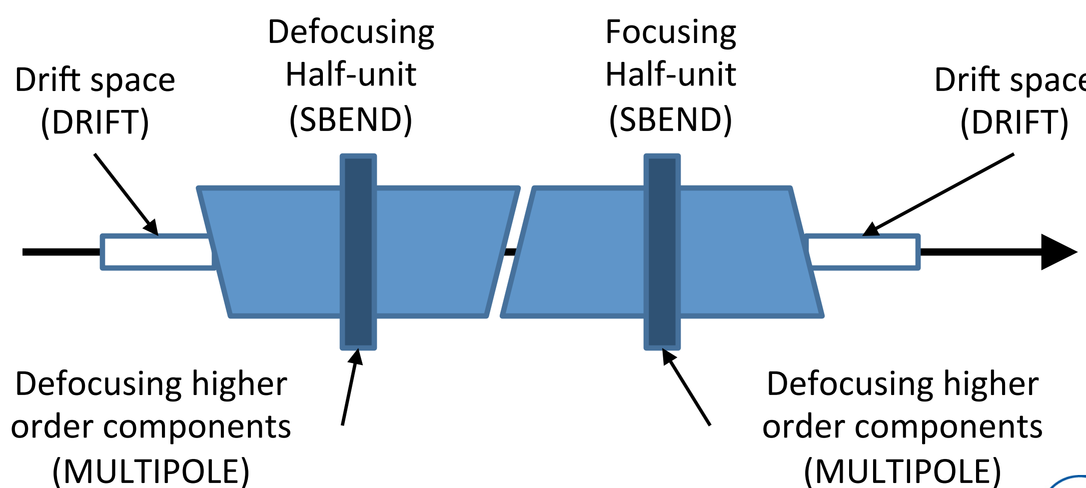
Official optics

- Static elements length
- SBEND
  - Bare machine quadrupolar component
  - No pole-face angle
- MULTIPOLE
  - Beam-based fit of NL-chroma
- JUNCTION=DRIFT



Model optics

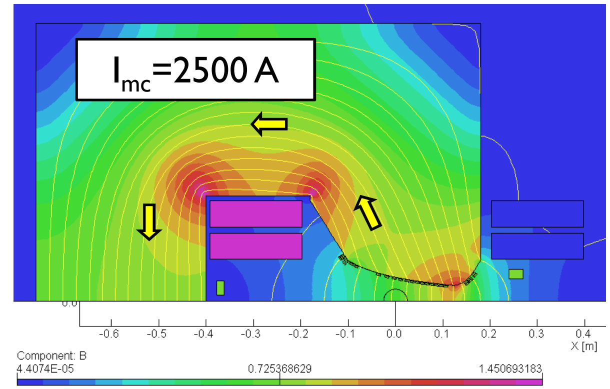
- Dynamic elements length – effective length correction
- SBEND
  - Up to K2 from the model
  - Integrated pole-face angle effect
- MULTIPOLES
  - K3 (and higher if needed)
- No JUNCTION element
- Beam-based matched effective lengths corrections

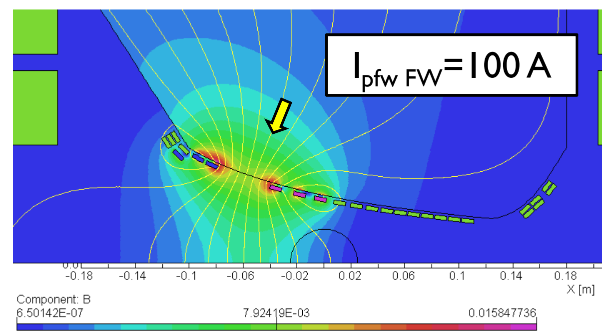


Magnets (Opera© 2/3D model, measurements)

Geometry and magnetic measurements

Opera© model (2-3D)

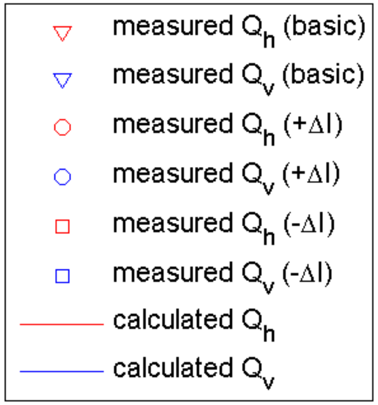




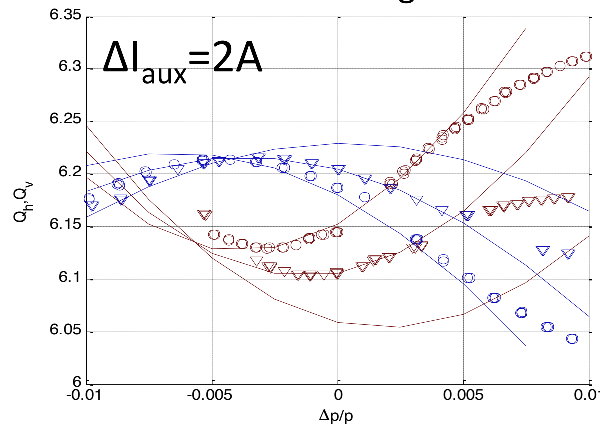
Simulated normal and skew components and errors

		b_2, 1/m	b_3, 1/m^2	b_4, 1/m^3	a_1, 10^{-3}	a_2, 1/m	a_3, 1/m^2	a_4, 1/m^3
2D FEM simulations, N = 1000								
C	μ	4.105	-0.083	1.93	0	0	0	0
	s	0.001	0.011	0.10	$7 \cdot 10^{-2}$	$9 \cdot 10^{-4}$	$2 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
O	μ	-4.116	-0.004	-1.78	0	0	0	0
	s	0.001	0.01	0.08	$7 \cdot 10^{-2}$	$8 \cdot 10^{-4}$	$2 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
3D FEM simulations, N = 935								
C	μ	3.983	0.30	-42	1.4	-0.03	0.56	-16
	s	0.001	0.02	4	0.8	0.007	0.03	4
O	μ	-3.988	0.35	41	-0.3	-0.02	-0.22	-6
	s	0.001	0.02	4	0.8	0.007	0.03	4

Nonlinear chromaticity (2 GeV)



Narrow focusing PFW variation



Narrow defocusing PFW variation

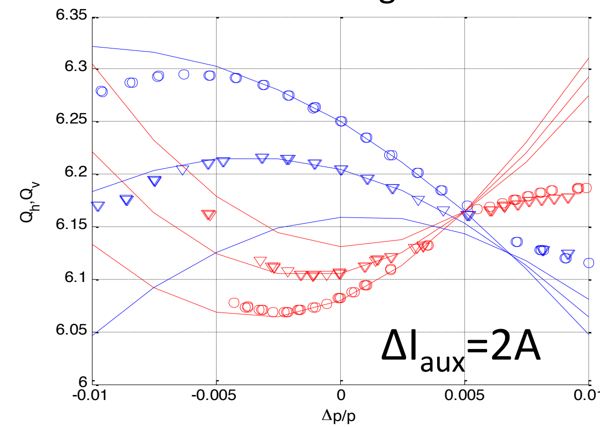
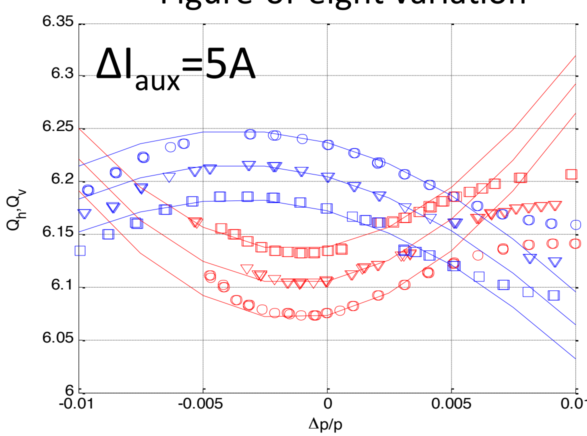
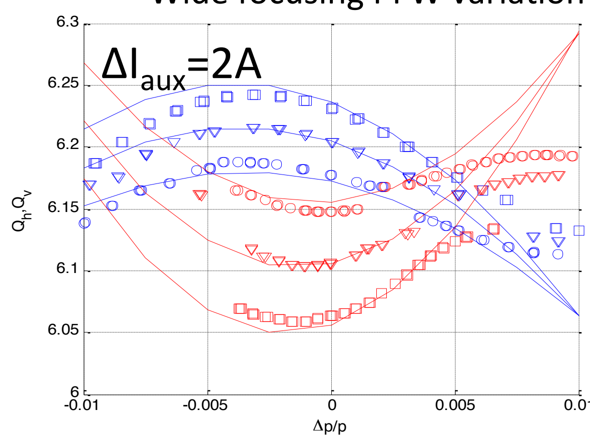


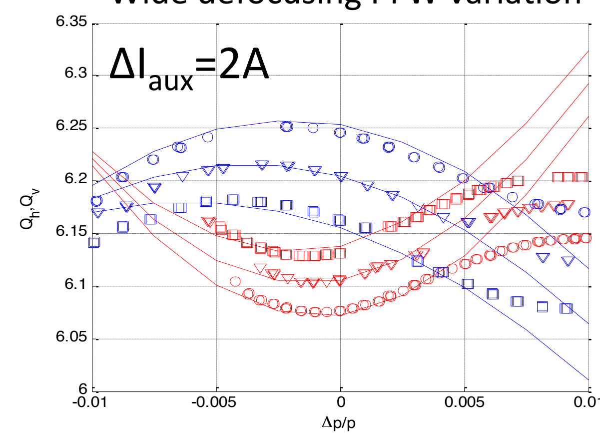
Figure-of-eight variation



Wide focusing PFW variation



Wide defocusing PFW variation

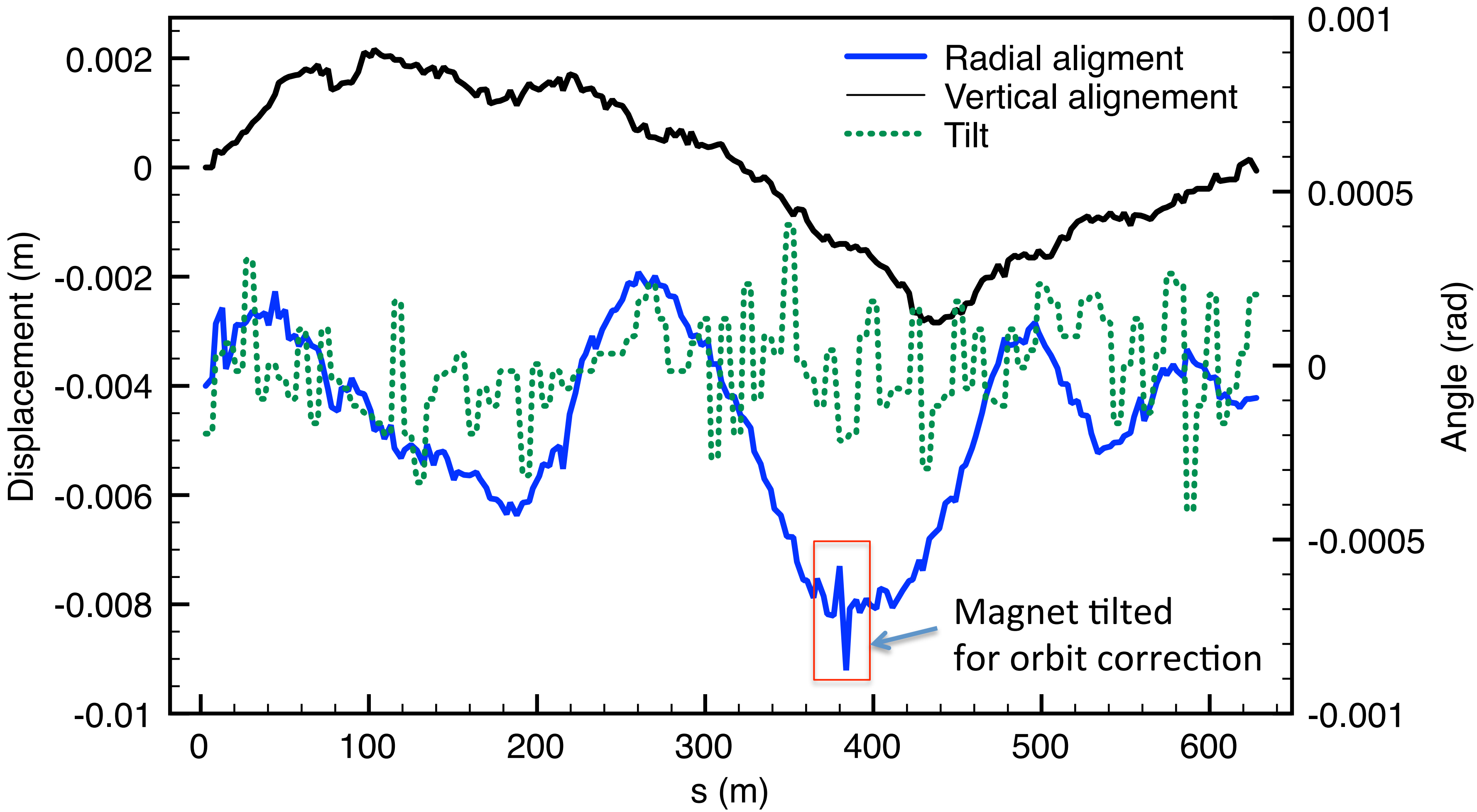


I_{f8}=-0.018 A I_{fn}=-0.015A I_{fw}=-14.545A I_{dn}=-4.669A I_{dw}=-8.235A

M. Juchno Thesis

Measurement data: A. Huschauer
Simulation: M. Juchno

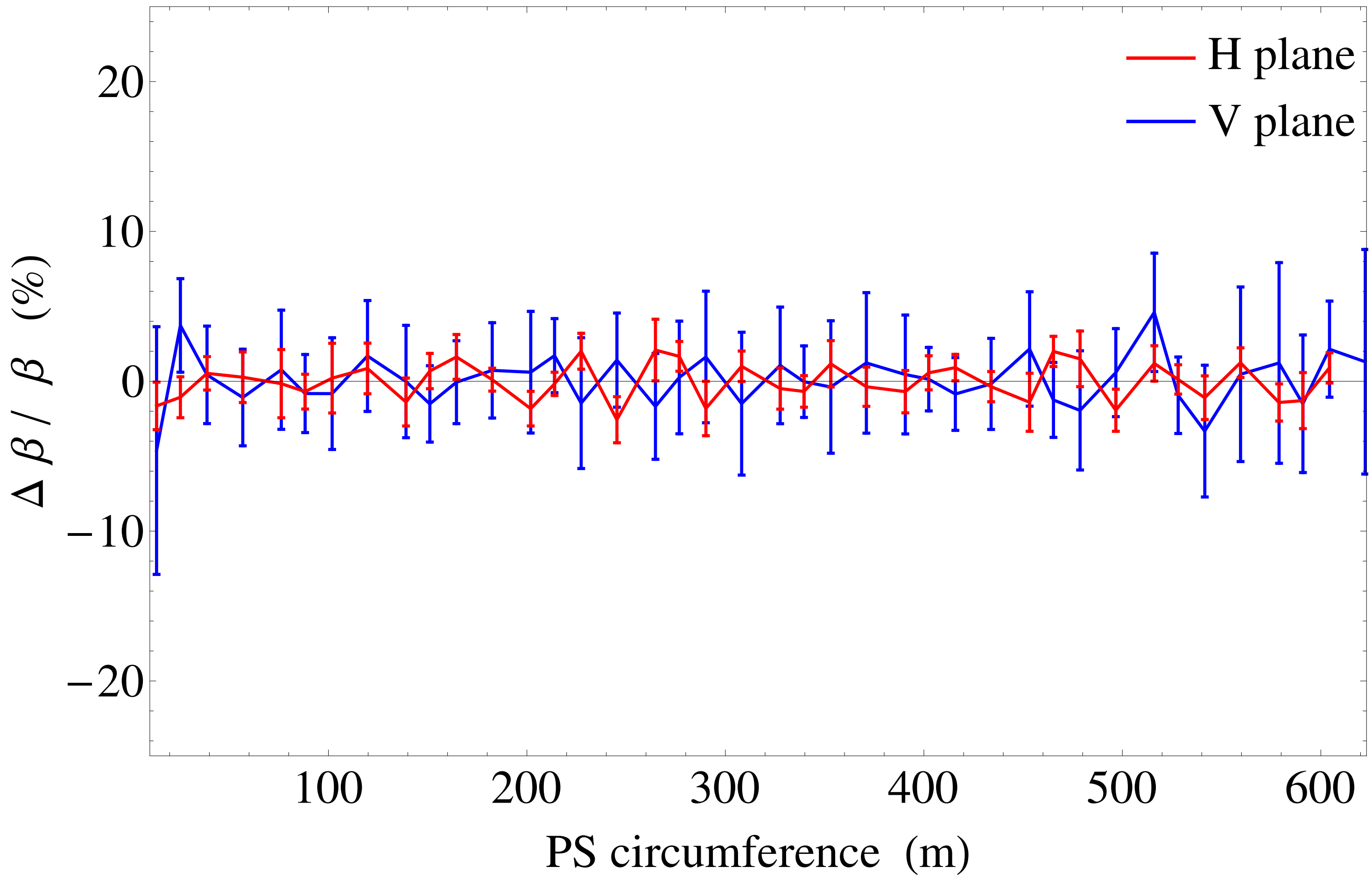
Machine alignment 2014 (only main magnets)



Magnet alignements known but not included in MADX model yet

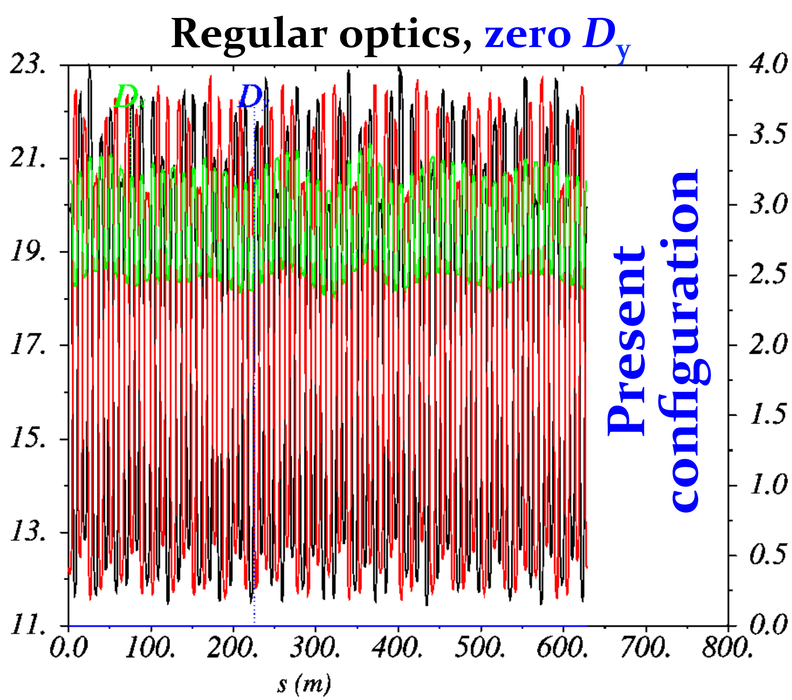
Beta-beating @ 1.4 GeV

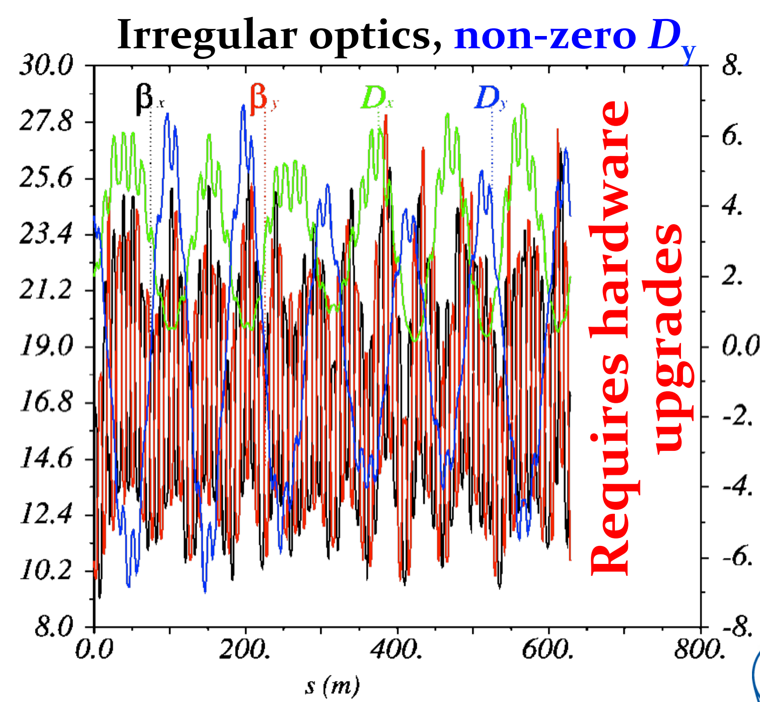
T. Bach et. al, IPAC2013



Space charge reduction, transverse

1. Compensation of resonances ($Q_{x/y}$=0.21/0.24)
   - → Closest resonance $4Q_y = 1$ difficult as excited by space charge
   - → Compensation of $2Q_x + Q_y = 1$ and $3Q_y = 1$ lines during studies in 2013
2. Special optics with vertical dispersion
   - → Introduce vertical dispersion to maximize beam size and reduce DQ_{sc}
   - → Optics becomes very irregular, needs simulations and beam studies
   - → Evaluate potential benefit with first beam studies after LS1





Experimental study 2014

- Compensation of 4Qv=1 with quadrupoles/breaking sym. or with octupoles
- Integer tune split of two units for 4th order resonance
- Integer resonance scan
- Special large horizontal dispersion optics
- Fully coupled optics at injection
- Space charge study with Quadrupolar PU

Space Charge and resonances

- Transfer of longer bunches from PSB
- Hollow bunches

Longit. plane

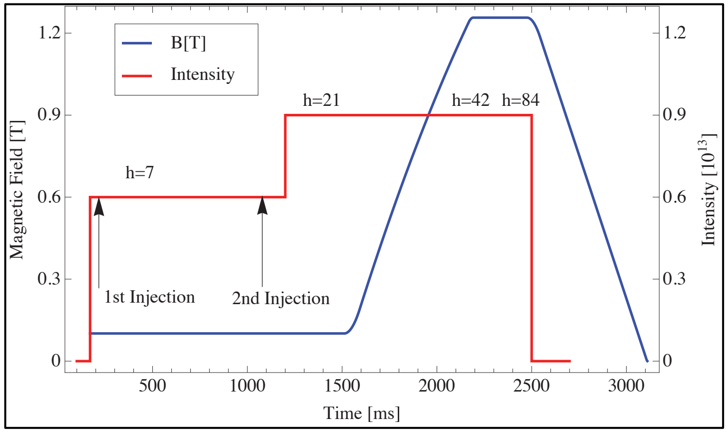
- Tune vs kick strenght at different dp/p for chromo-geom. terms at 2 GeV
- Kick response measurements
- Beta-beating and loss maps before and after orbit correction

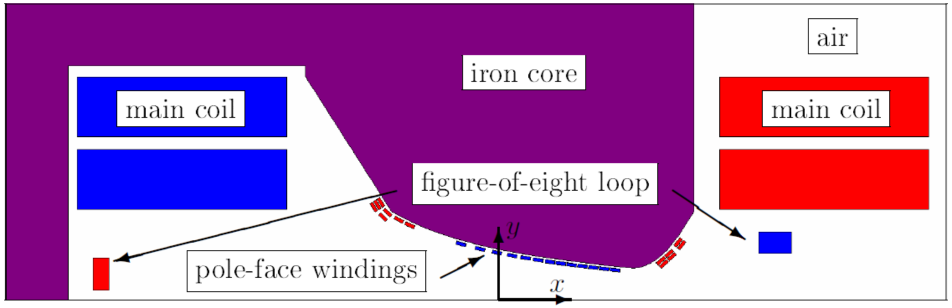
Model

Simulation codes requirements

- Combined function magnets, with proper treatment of stray fields
- Inclusion of multipoles (eventually up to octupole)
- Inclusion of skew component (normal and error)
- Inclusion of alignment errors (x,y and tilts)
- Inclusion of time-varying field (injection bump and RF fields for gymns)

- Long term simulations (up to 1.2 s)





Conclusions

- Outcome of 2013-14 analysis: the beam characteristics foreseen after implementation of all of LIU(25 ns, 2E11 p/b, 1.9 μm) are good enough for reaching the HL-LHC goal.
- 2 GeV injection energy upgrade is the baseline as solution to reduce direct-space charge effects
- Better understanding of different phenomena limiting performances thanks to simulations and improved experiments analysis
- We are in condition to choose between PIC and FZM codes depending on the time scale needed for the simulations thanks to the code development of this year
- Intense MD program for 2014 (as btw in 2012-2013)
- Thanks to all the collaborators inside and outside CERN for the progresses done so far.