Startup planning for the LHC and operation scenario for forward physics

by Helmut Burkhardt / CERN for the LHC commissioning team

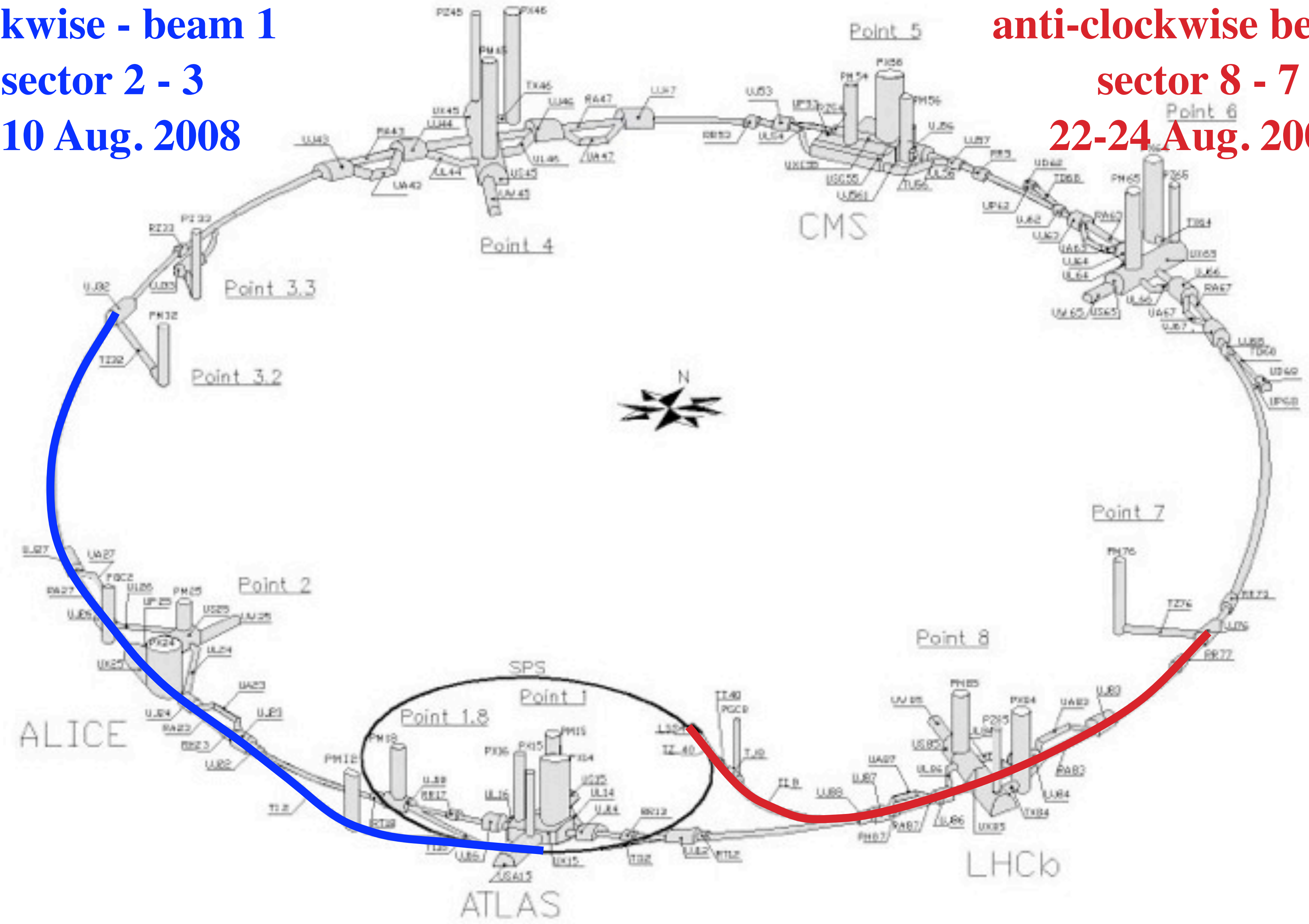
- **LHC status,** 1st experience with beams and status following the incident *
- **Forward experiments at the LHC and requirements for the machine**
- **Commissioning steps and expected beam parameters**
- **High-beta TOTEM and ALFA optics**

Acknowledgements :
Simon White, Massimo Giovannozzi ; optics matching and aperture
Steve Myers ; material on LHC status; * more details in his presentation on Thu 2 nd July
Massimiliano Ferro-Luzzi ; LHC parameters and physics program

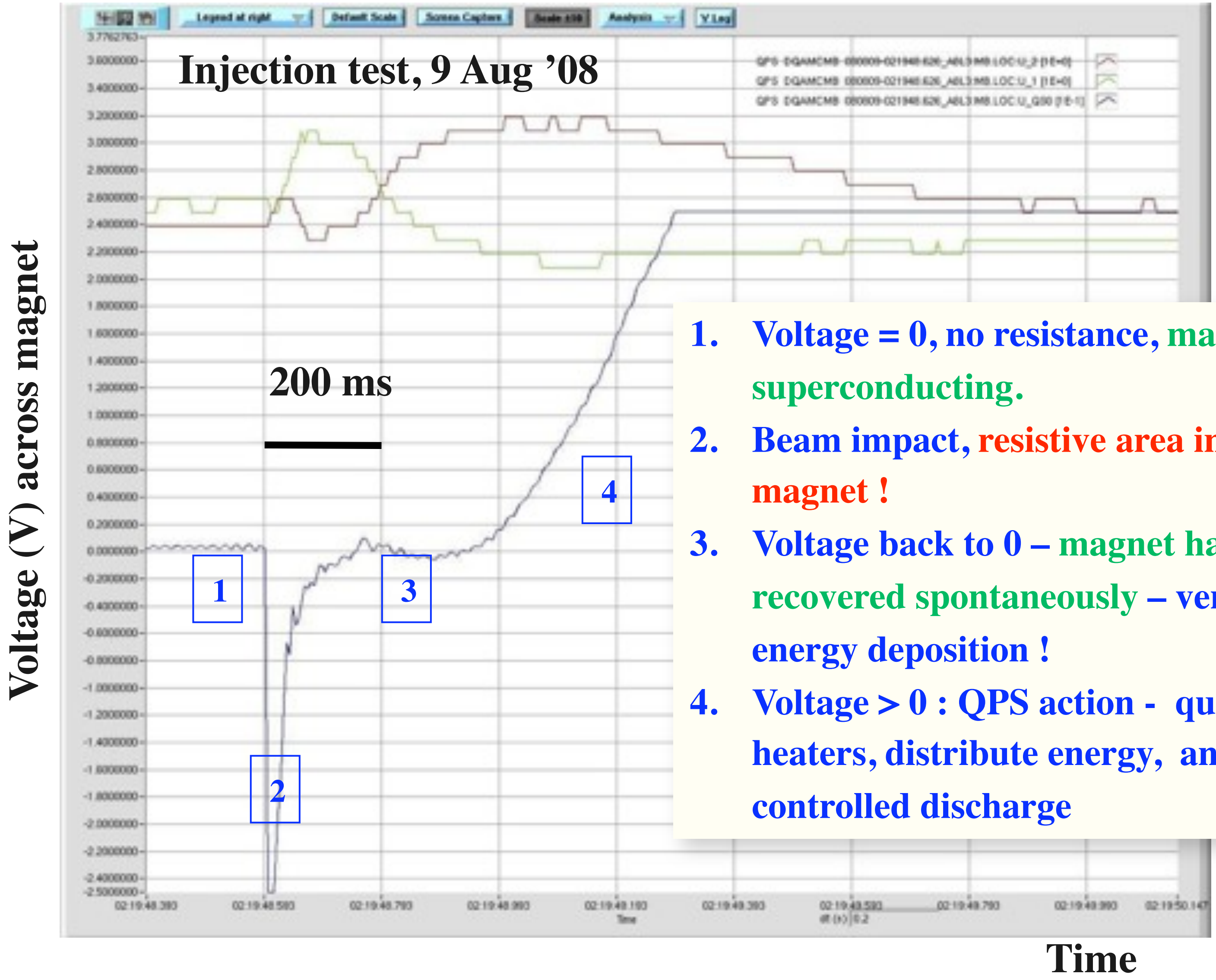
LHC Commissioning : injection tests in August'08

1st Injection
clockwise - beam 1
sector 2 - 3
8-10 Aug. 2008

2nd Injection
anti-clockwise beam 2
sector 8 - 7
22-24 Aug. 2008



Experience with beam : first beam induced quench



1. Voltage = 0, no resistance, magnet is superconducting.
2. Beam impact, resistive area in the magnet !
3. Voltage back to 0 – magnet has recovered spontaneously – very little energy deposition !
4. Voltage > 0 : QPS action - quench heaters, distribute energy, and controlled discharge

Local mini-quench
“quenchino”

verification of quench limit in magnets ~2×10^9 protons @ 450 GeV and calibration of BLM system

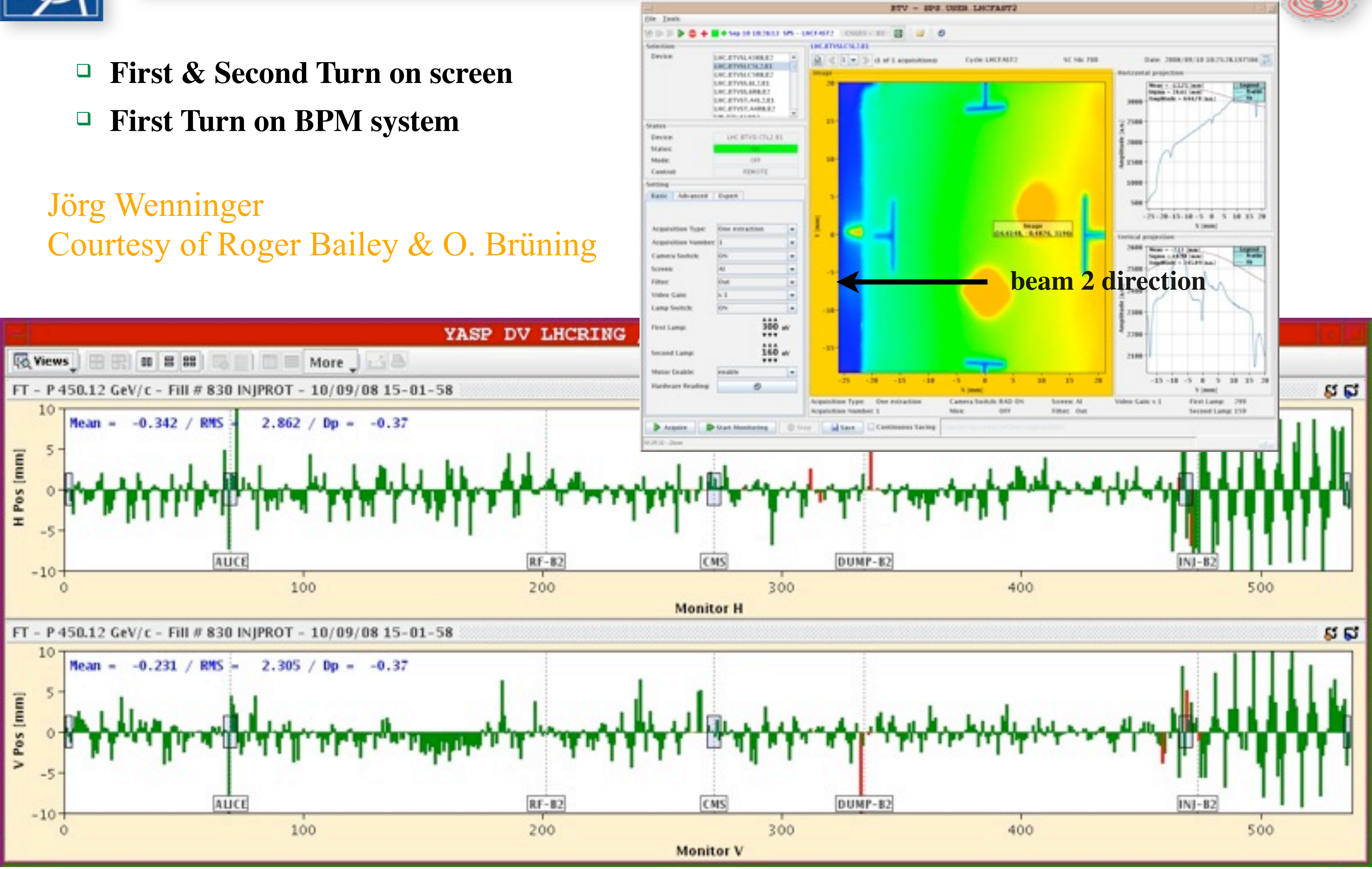
10 September 2008

10:30 beam 1 3 turns
15:00 beam 2 3 turns
22:00 beam 2 several 100 turns

First turn. 10 September 2008

- **First & Second Turn on screen**
- **First Turn on BPM system**

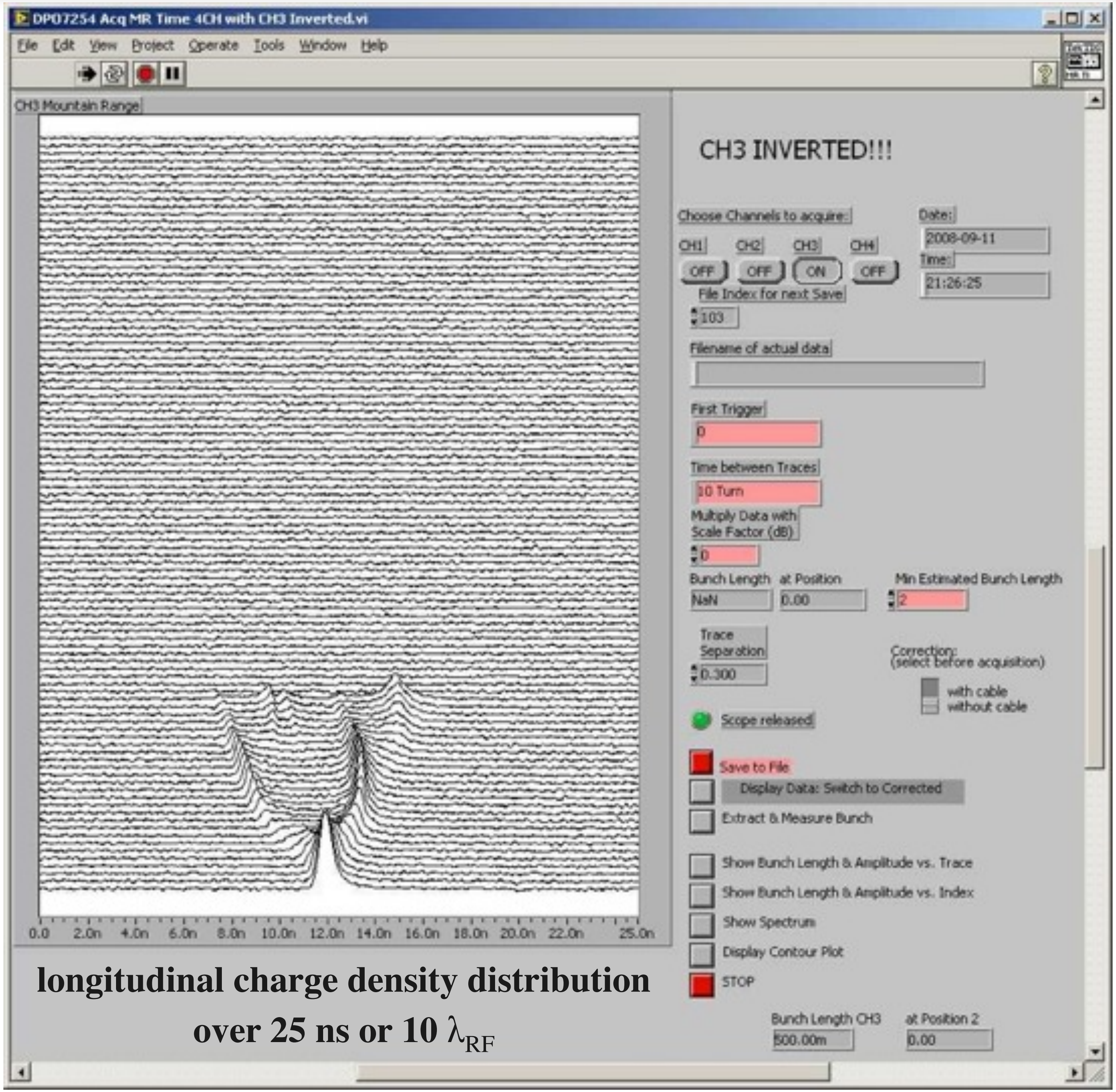
Jörg Wenninger
Courtesy of Roger Bailey & O. Brüning



longitudinal position around the ring, s [m], here by monitor number

Textbook example : from first attempt to RF capture

one trace every 10 turns

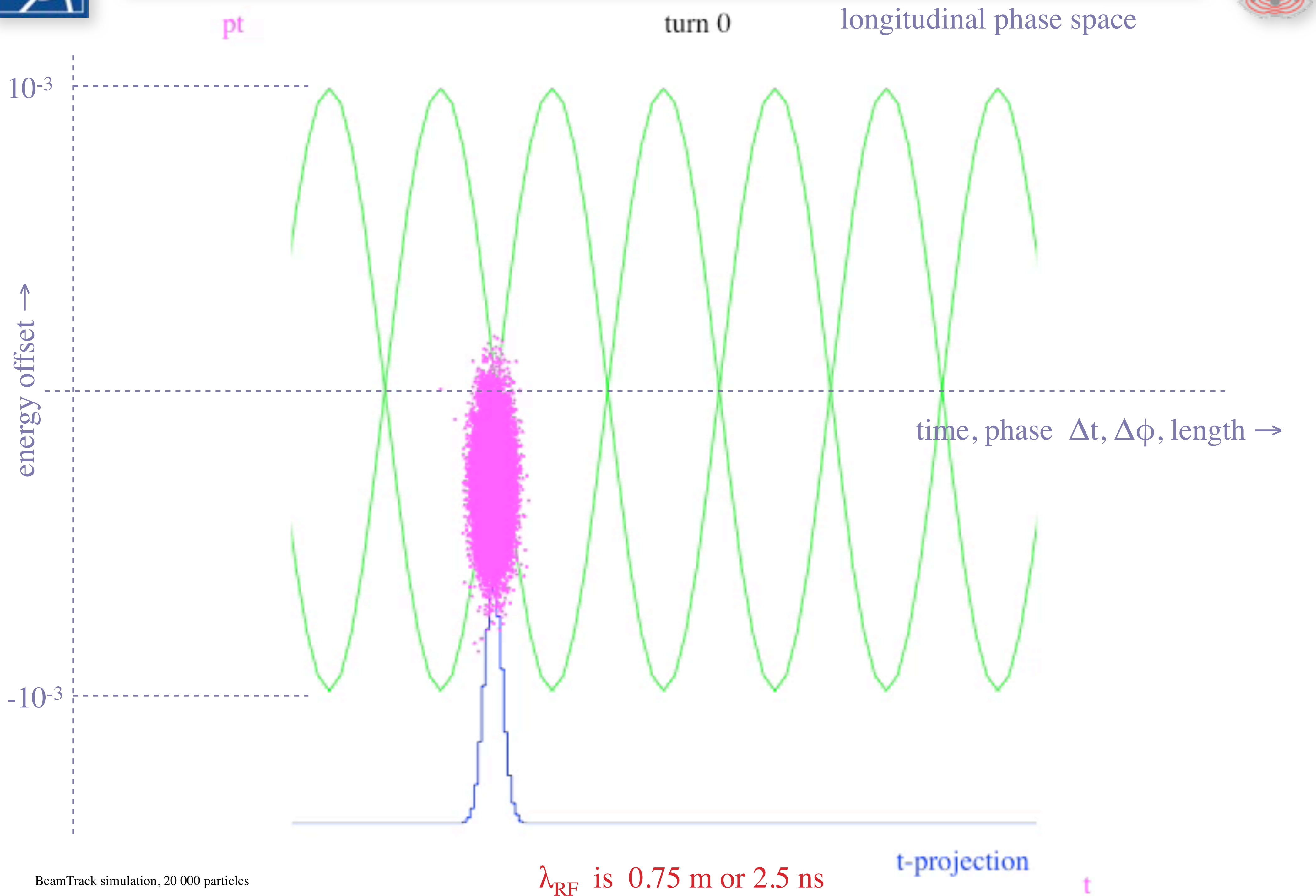


CH1 OFF
CH2 OFF
CH3 ON
CH4 OFF

Date: 2008-09-11
Time: 21:26:25
File Index for next Save: 103
Filename of actual data:
First Trigger: 0
Time between Traces: 10 Turn
Multiply Data with Scale Factor (dB): 0
Bunch Length: NaN
at Position: 0.00
Min Estimated Bunch Length: 2
Trace Separation: 0.300
Correction: (select before acquisition)
▨ with cable
☐ without cable
● Scope released
Bunch Length CH3: 500.00m
at Position 2: 0.00

longitudinal charge density distribution over 25 ns or 10 λ_{RF}

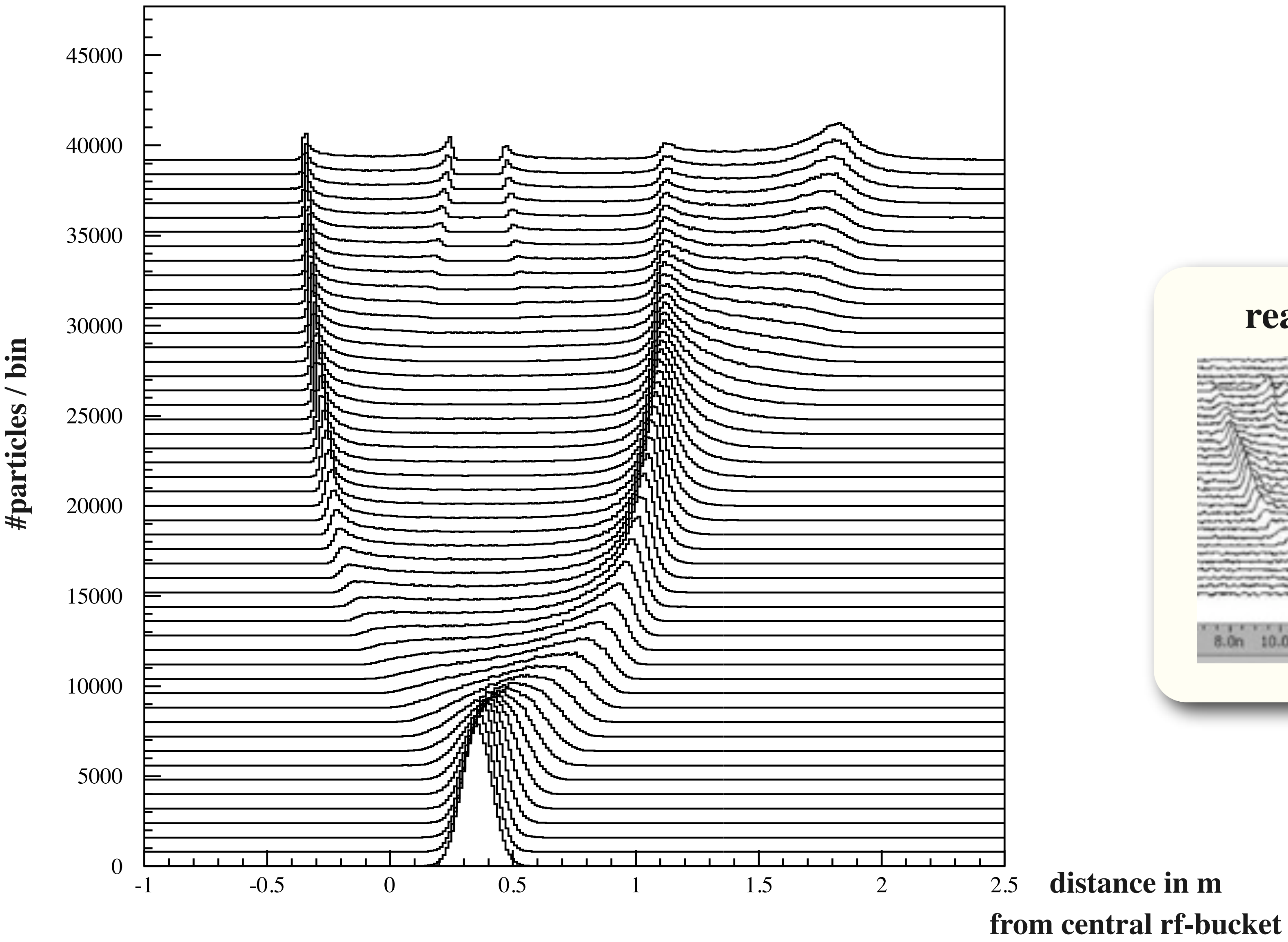
Simulation of injection with 170º injection phase offset



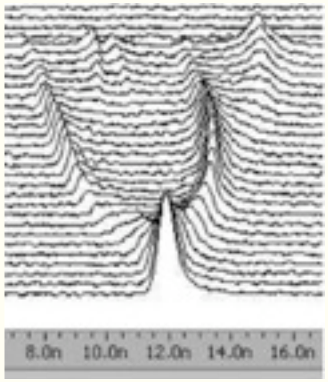
BeamTrack simulation, 20 000 particles

λ_{RF} is 0.75 m or 2.5 ns

Simulation of injection with 170º injection phase offset



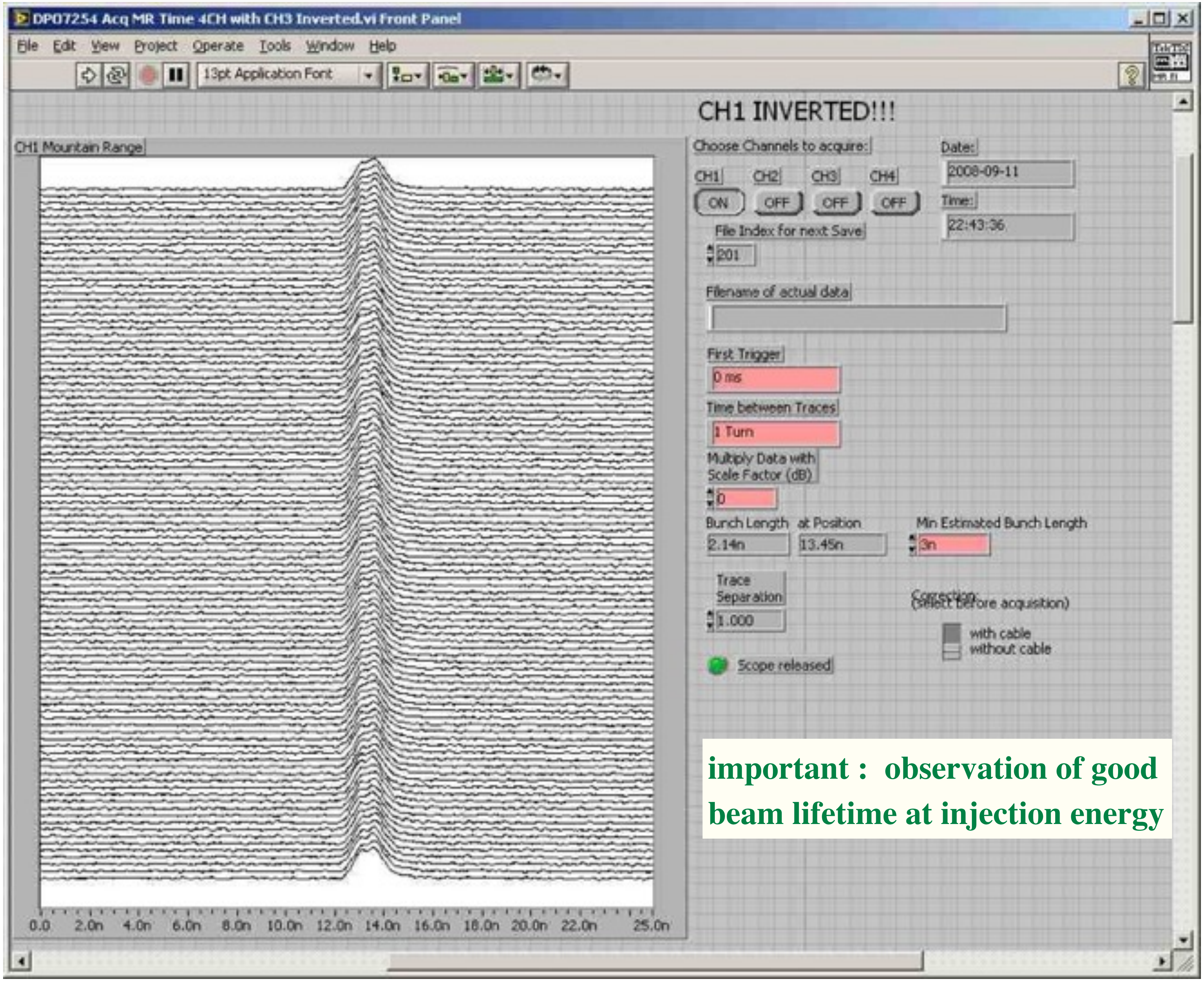
real LHC



projection of previous plot : longitudinal charge density distribution

BeamTrack simulation, 100 000 particles

LHC beam 2 with well adjusted RF capture



CH1 INVERTED!!!

Choose Channels to acquire:

CH1: ON
CH2: OFF
CH3: OFF
CH4: OFF

Date: 2008-09-11
Time: 22:43:36

File Index for next Save: 201

Filename of actual data:

First Trigger: 0 ms
Time between Traces: 1 Turn
Multiply Data with Scale Factor (dB): 0

Bunch Length: 2.14n
at Position: 13.45n
Min Estimated Bunch Length: 3n

Trace Separation: 1.000

Correction: (Select before acquisition)
with cable
without cable

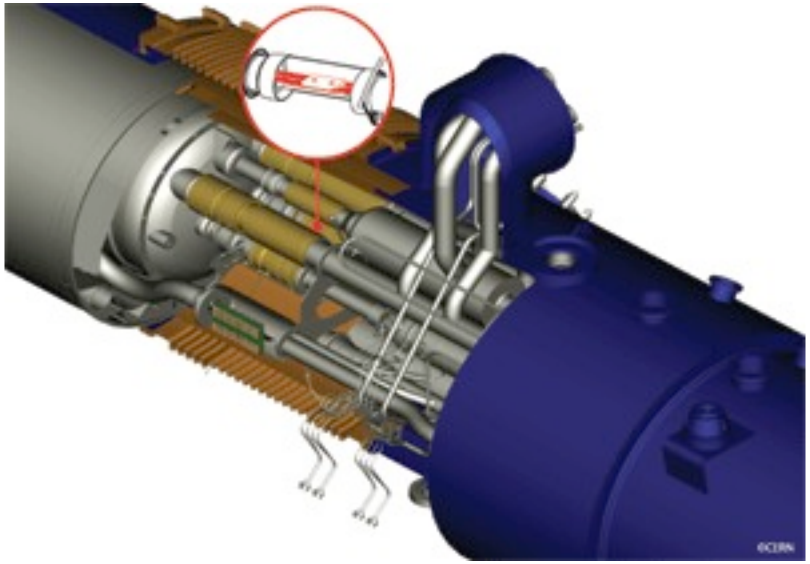
● Scope released

important : observation of good beam lifetime at injection energy

After 3 days of excellent progress with beams

Commissioning with beam interrupted by a series of hardware failures - not related to beams

- **two large transformers ; 13 - 18 September**
- **19 September** at 11:18:36**, incident during hardware commissioning of sector 3-4 towards 5.5 GeV/ 9.3 kA, at 8.7 kA or ~ 5.2 TeV,** of the 340 MJ stored energy about 180 MJ or 2/3 went to the dump resistors ; 1 MJ melts 2.4 kg Cu



bad splice at electrical connection between dipole and quad Q23, 6 t He or 1/2 of arc lost; pressure built up in adjacent each 107 m long, vacuum subsectors causing significant collateral damage

some typical numbers and back of envelope estimates :

good splice ~ $0.3\ \mathrm{n\Omega}$, $I = 13$ kA, $U = R I = 4\ \mu\mathrm{V}$ (now) possible to check - done for dipoles in 1/2 of LHC

$P = R I^2 = 0.05$ W quench would need locally > 10 W - depending on position - less critical in magnet

QPS triggered at 0.1 V (asym) > 10 ms ; ~ 30 - 50 ms for quench heater

LHC dipole $L = 100$ mH stored energy in single dipole $I^2 L/2 = 8.45$ MJ $\times 1232 = 10.4$ GJ

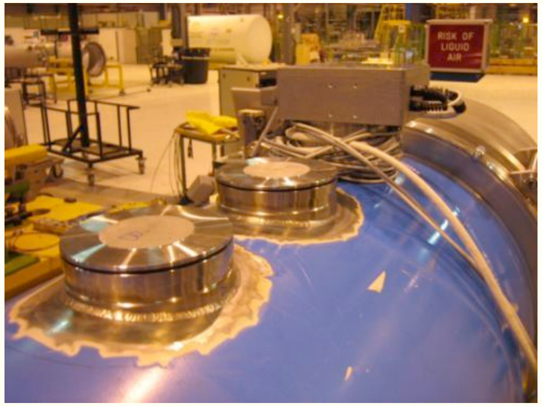
Current status - June 2009

damage repair

- **39 dipoles and 14 quadrupoles removed - and re-installed. Last magnet back in tunnel on 30/04/2009, electrical connections finished 2nd June**

avoid re-occurance

- **Improved diagnostics, measurements of magnet interconnects - splice resistance; Measurements at 80 K revealed a potential splice-problem in sector 4-5, which has just been warmed up**



- **> 50 % of machine (sectors, 1-2, 3-4, 5-6, 6-7, all standalone magnets) with fast pressure release valves**
- **improved anchoring on vaccuum barriers**
- **enhanced Quench Protection System**

aperture symmetric quenches
and joints in magnets

- **Remaining risks minimized by keeping maximum beam energy limited to 4 - 5 TeV for the first run**

Major amount of work - much of the hardware work is finished, ~ within schedule as reviewed in Chamonix in Feb.'09 (few weeks delay)

More later this week : R. Heuer and S. Myers, presentation to CERN personnel, [2nd of July](#).

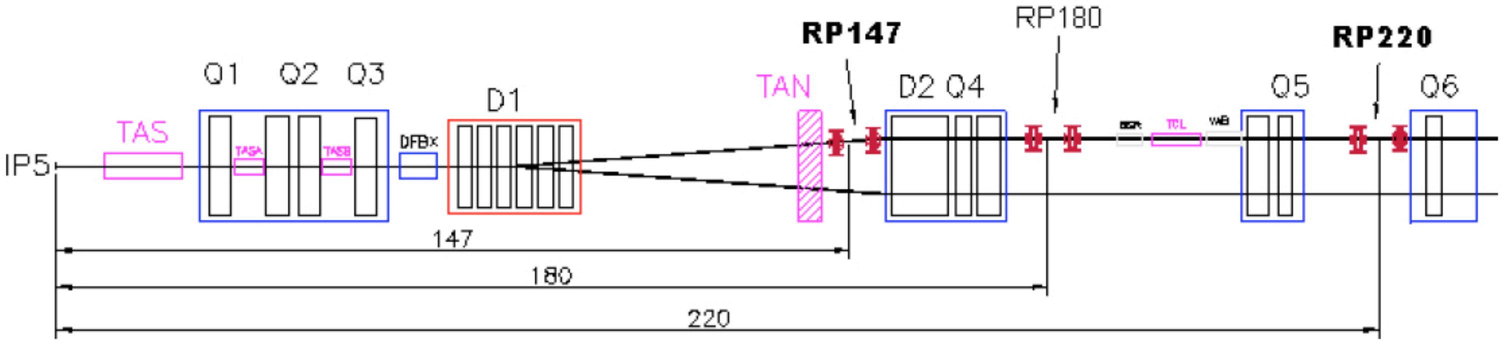
Forward experiments at the LHC

close collaboration - machine / experiment   on beam aspects and requirements

- **TOTEM, β* ~ 1500 m;   In first LHC run request for operation at 90 m.   K. Eggert, M. Deile, V. Avati, H. Niewiadomski.** Roman pots installed and ready for parasitic data taking in normal running at safe positions agreed with the collimation team
- **ALFA ,** ATLAS Forward Detectors for Measurement of Elastic Scattering and Luminosity**, β*= 2450 m, TDR Jan 2008; P. Grafstrom, P. Puzo, S. Cavalier, M. Heller, H. Stenzel**
- **LHCf,** installed in the TAN at IP1, verification of cosmic ray physics at 10^{17} eV; L < 10^{30} $cm^{-2}s^{-1}$; **D. Macina, A.-L. Perrot**
- **FP420,** plans for very forward proton tagging. both ATLAS and CMS, **F. Roncarolo**

+ as part of ATLAS, CMS :   ZDC, zero degree calorimeters, in the TAN

Layout



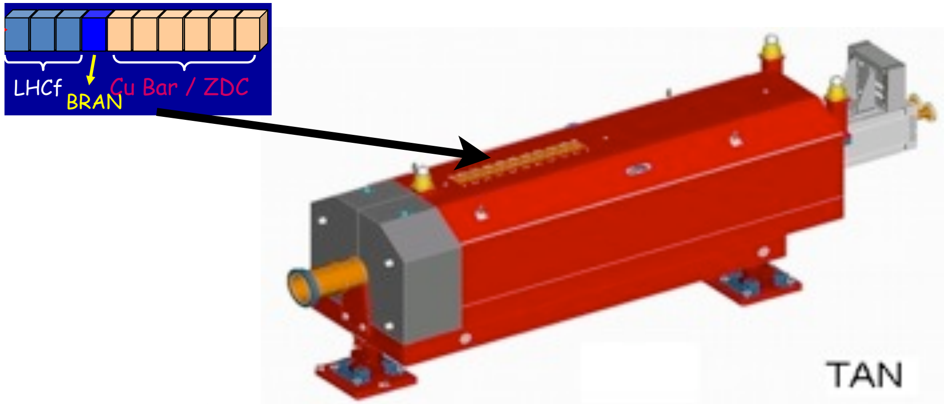
Schematic layout, right of IR5, with TAN position and TOTEM roman pots

The roman pots are movable detectors.

In the LHC - all movable devices which can move into the beam are controlled from the CCC

TAN - absorber for neutral particles

instrumented with LHCf, BRAN and ZDCs.



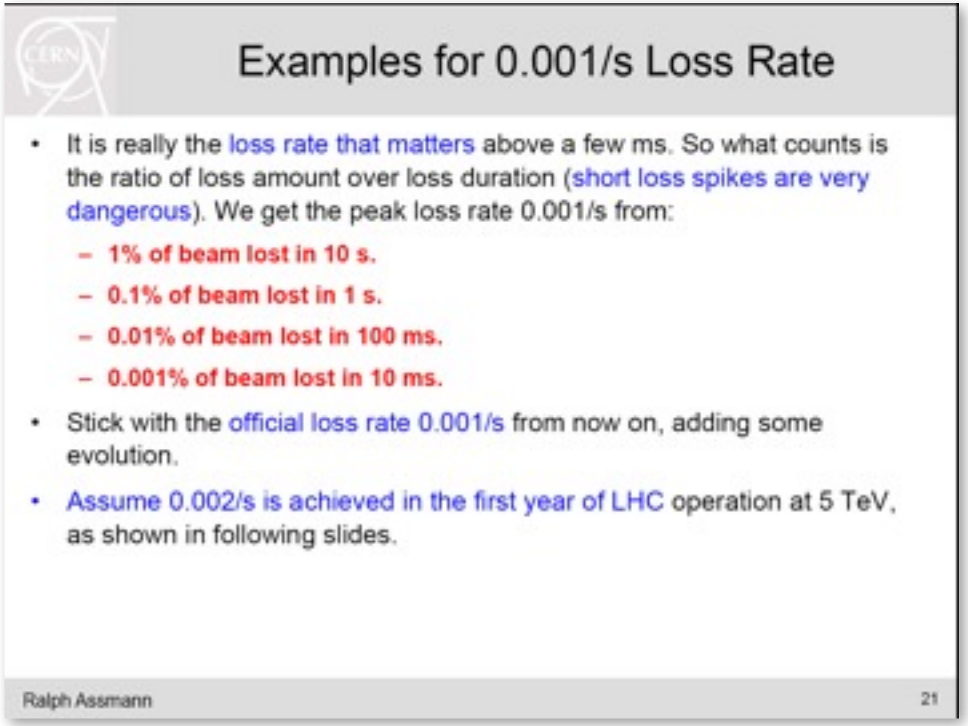
FP420 : 420 m from the IP, beginning of the arc in the *dispersion suppressor*

Maximum beam intensity LHC year 1

the design LHC luminosity : 3.23×10^{14} protons / beam

limited by magnet quench / collimation

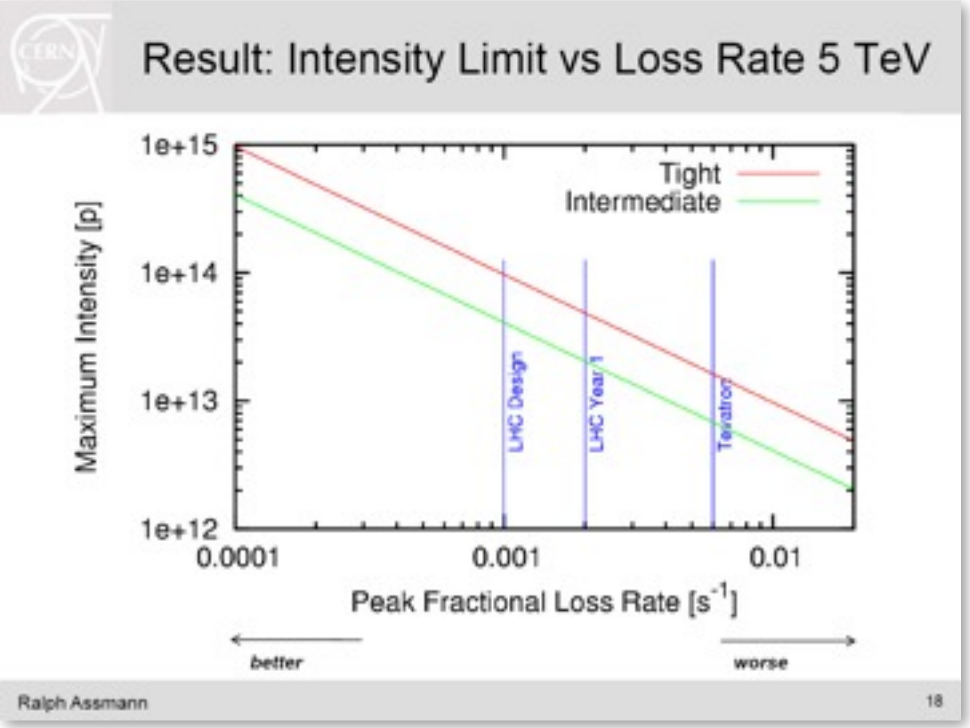
maximum beam loss rate ~ 10^{-3} /s fraction or ~4×10^{11} p/s



Examples for 0.001/s Loss Rate

- It is really the loss rate that matters above a few ms. So what counts is the ratio of loss amount over loss duration (short loss spikes are very dangerous). We get the peak loss rate 0.001/s from:
  - 1% of beam lost in 10 s.
  - 0.1% of beam lost in 1 s.
  - 0.01% of beam lost in 100 ms.
  - 0.001% of beam lost in 10 ms.
- Stick with the official loss rate 0.001/s from now on, adding some evolution.
- Assume 0.002/s is achieved in the first year of LHC operation at 5 TeV, as shown in following slides.

Ralph Assmann 21



Result: Intensity Limit vs Loss Rate 5 TeV

Ralph Assmann 18

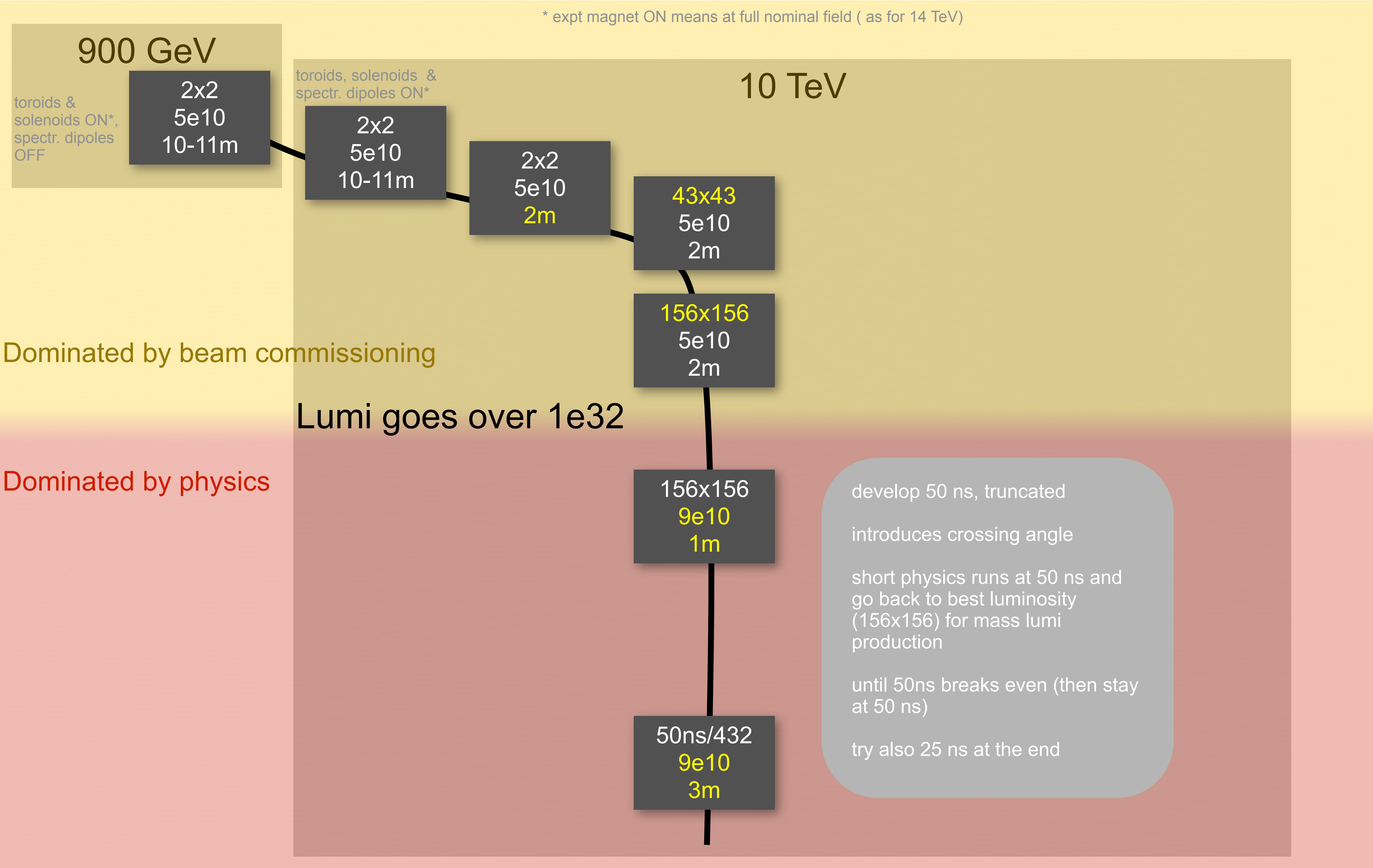
 # bunches : nominal is 2808 bunches, 25 ns spacing

LHC year 1 : Important to go in small steps - minimize beam losses. Max. total intensity ~ 1/10 nominal.

start of physics run : $I < 2\times10^{13}$ p with intermediate coll. settings

later : $I < 5\times10^{13}$ p with tight coll. settings.

Physics run modes



* expt magnet ON means at full nominal field (as for 14 TeV)

900 GeV

toroids & solenoids ON*, spectr. dipoles OFF

2x2
5e10
10-11m

10 TeV

toroids, solenoids & spectr. dipoles ON*

2x2
5e10
10-11m

2x2
5e10
2m

43x43
5e10
2m

156x156
5e10
2m

Dominated by beam commissioning

Lumi goes over 1e32

Dominated by physics

156x156
9e10
1m

50ns/432
9e10
3m

develop 50 ns, truncated

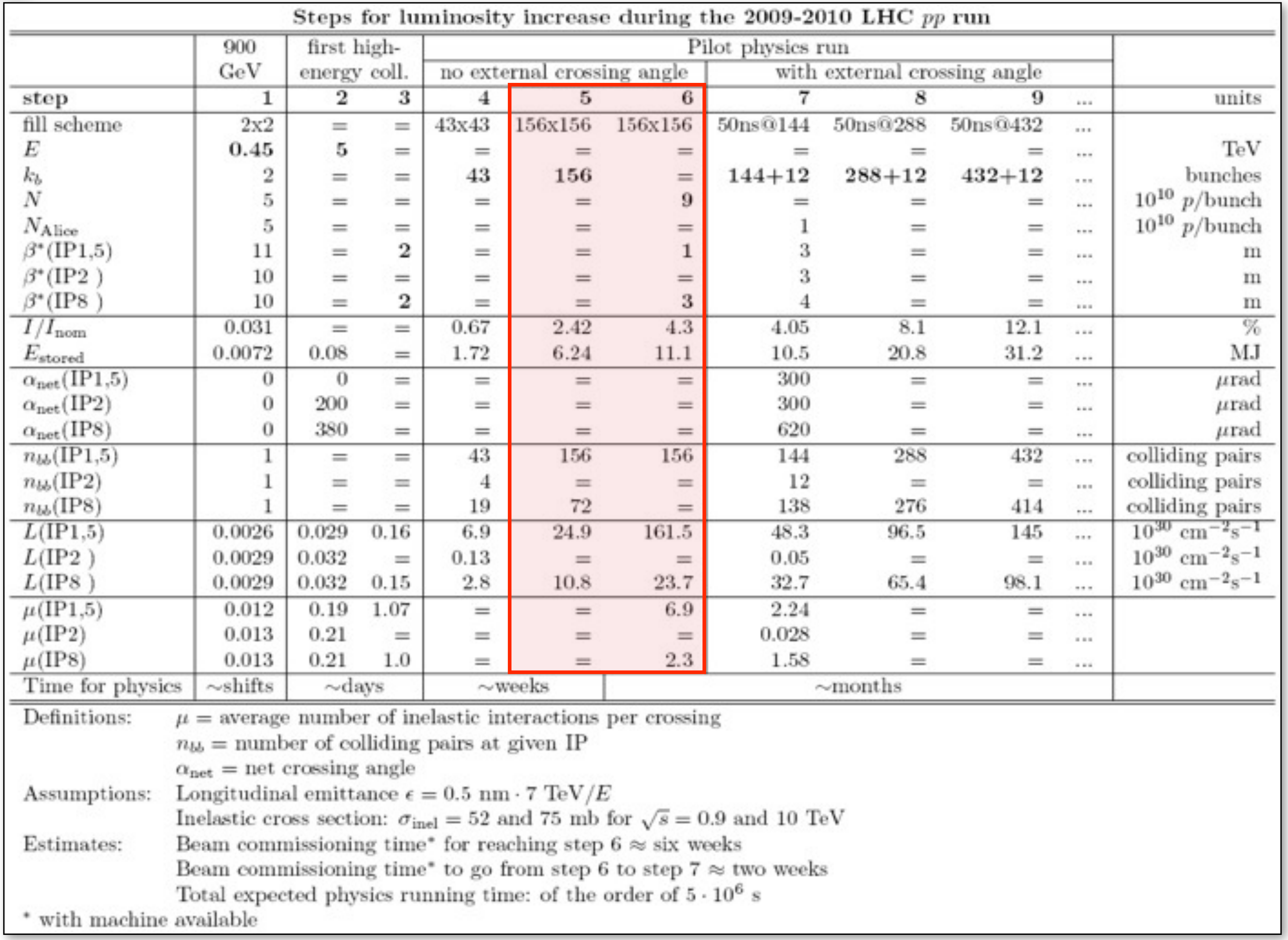
introduces crossing angle

short physics runs at 50 ns and go back to best luminosity (156x156) for mass lumi production

until 50ns breaks even (then stay at 50 ns)

try also 25 ns at the end

Beam parameters, LHC year 1



Steps for luminosity increase during the 2009-2010 LHC *pp* run

	900 GeV	first high-energy coll.		Pilot physics run							
				no external crossing angle			with external crossing angle				
step	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	...	units
fill scheme	2x2	=	=	43x43	156x156	156x156	50ns@144	50ns@288	50ns@432	...	
E	**0.45**	**5**	=	=	=	=	=	=	=	...	TeV
k_b	2	=	=	**43**	**156**	=	**144+12**	**288+12**	**432+12**	...	bunches
N	5	=	=	=	=	**9**	=	=	=	...	10^{10} p/bunch
N_{Alice}	5	=	=	=	=	=	1	=	=	...	10^{10} p/bunch
β^*(IP1,5)	11	=	**2**	=	=	**1**	3	=	=	...	m
β^*(IP2)	10	=	=	=	=	=	3	=	=	...	m
β^*(IP8)	10	=	**2**	=	=	**3**	4	=	=	...	m
I/I_{nom}	0.031	=	=	0.67	2.42	4.3	4.05	8.1	12.1	...	%
E_{stored}	0.0072	0.08	=	1.72	6.24	11.1	10.5	20.8	31.2	...	MJ
α_{net}(IP1,5)	0	0	=	=	=	=	300	=	=	...	μrad
α_{net}(IP2)	0	200	=	=	=	=	300	=	=	...	μrad
α_{net}(IP8)	0	380	=	=	=	=	620	=	=	...	μrad
n_{bb}(IP1,5)	1	=	=	43	156	156	144	288	432	...	colliding pairs
n_{bb}(IP2)	1	=	=	4	=	=	12	=	=	...	colliding pairs
n_{bb}(IP8)	1	=	=	19	72	=	138	276	414	...	colliding pairs
L(IP1,5)	0.0026	0.029	0.16	6.9	24.9	161.5	48.3	96.5	145	...	10^{30} cm^{-2}s^{-1}
L(IP2)	0.0029	0.032	=	0.13	=	=	0.05	=	=	...	10^{30} cm^{-2}s^{-1}
L(IP8)	0.0029	0.032	0.15	2.8	10.8	23.7	32.7	65.4	98.1	...	10^{30} cm^{-2}s^{-1}
μ(IP1,5)	0.012	0.19	1.07	=	=	6.9	2.24	=	=	...	
μ(IP2)	0.013	0.21	=	=	=	=	0.028	=	=	...	
μ(IP8)	0.013	0.21	1.0	=	=	2.3	1.58	=	=	...	
Time for physics	~shifts	~days		~weeks		~months					

Definitions: μ = average number of inelastic interactions per crossing
n_{bb} = number of colliding pairs at given IP
α_{net} = net crossing angle

Assumptions: Longitudinal emittance $\epsilon = 0.5$ nm $\cdot$ 7 TeV/E
Inelastic cross section: $\sigma_{\text{inel}} = 52$ and 75 mb for $\sqrt{s} = 0.9$ and 10 TeV

Estimates: Beam commissioning time* for reaching step 6 ≈ six weeks
Beam commissioning time* to go from step 6 to step 7 ≈ two weeks
Total expected physics running time: of the order of $5 \cdot 10^6$ s

* with machine available

Beam parameters for forward physics

LHC year 1 : likely to run for month's in steps 5 - 6

No crossing angle. $E_b = 5$ TeV ; $k_b = 156\times156$, $N_p = 5\times10^{10} - 9\times10^{10}$

Run in some fills with $\beta^* = 90$ m in IR5, peak luminosity :

$N_p = 5\times10^{10}$ $L = 5.5\times10^{29}\ \mathrm{cm^{-2}s^{-1}}$ $\sigma_{x,y} = 252\ \mu\mathrm{m}$ divergence $\sigma'_{x,y} = 2.8\ \mu\mathrm{rad}$

$N_p = 9\times10^{10}$ $L = 1.8\times10^{30}\ \mathrm{cm^{-2}s^{-1}}$

Or also : un-squeeze to 90 m at the end of some fills

Later years

$E_b = 7$ TeV. Dedicated high $\beta^* > 1500$ m runs. No crossing angle, maximum $k_b = 156\times156$

Requires reduced emittance $\varepsilon_N = 1\ \mu\mathrm{m}$ – which will be difficult and may require scraping

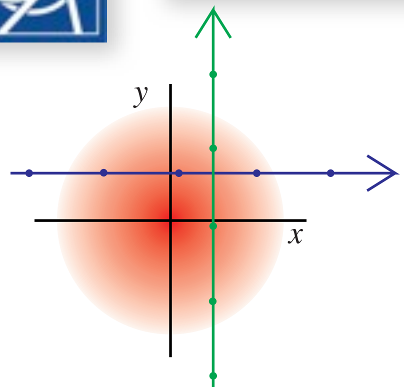
maximum bunch intensity $\sim 3\times10^{10}$

TOTEM $\beta^* = 1535$ m; $N_p = 3\times10^{10}$; $L = 6\times10^{28}\ \mathrm{cm^{-2}s^{-1}}$; $\sigma_{x,y} = 454\ \mu\mathrm{m}$ $\sigma'_{x,y} = 0.30\ \mu\mathrm{rad}$

ATLAS $\beta^* = 2625$ m; $N_p = 3\times10^{10}$; $L = 4\times10^{28}\ \mathrm{cm^{-2}s^{-1}}$; $\sigma_{x,y} = 593\ \mu\mathrm{m}$ $\sigma'_{x,y} = 0.23\ \mu\mathrm{rad}$

Luminosity scans and absolute luminosity

(pioneered by Van der Meer @ ISR)



Orthogonal x / y scans to determine $\sigma_{x,y}{}^*$

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi\, \sigma_x\, \sigma_y}$$

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left[-\left(\frac{\delta x}{2\sigma_x}\right)^2 - \left(\frac{\delta y}{2\sigma_y}\right)^2\right]$$

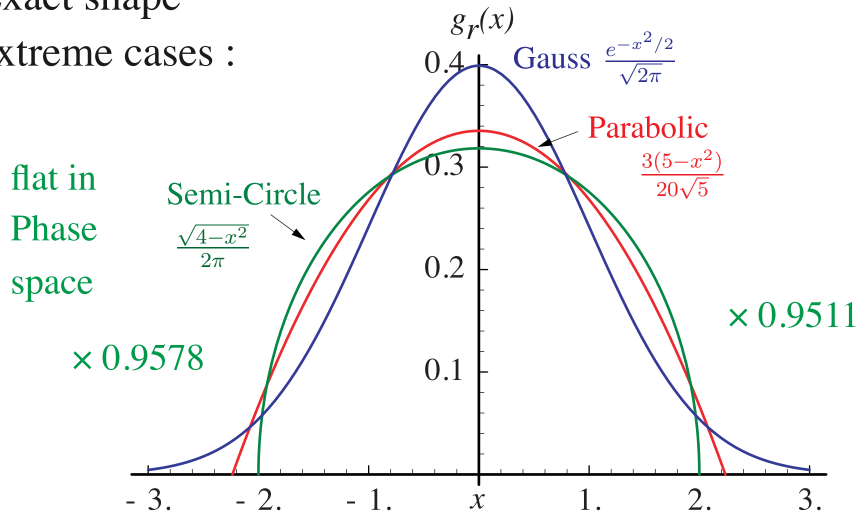
Accuracy : better than **1% at ISR**

Aim for **early LHC ~10 %** (done @ RHIC)

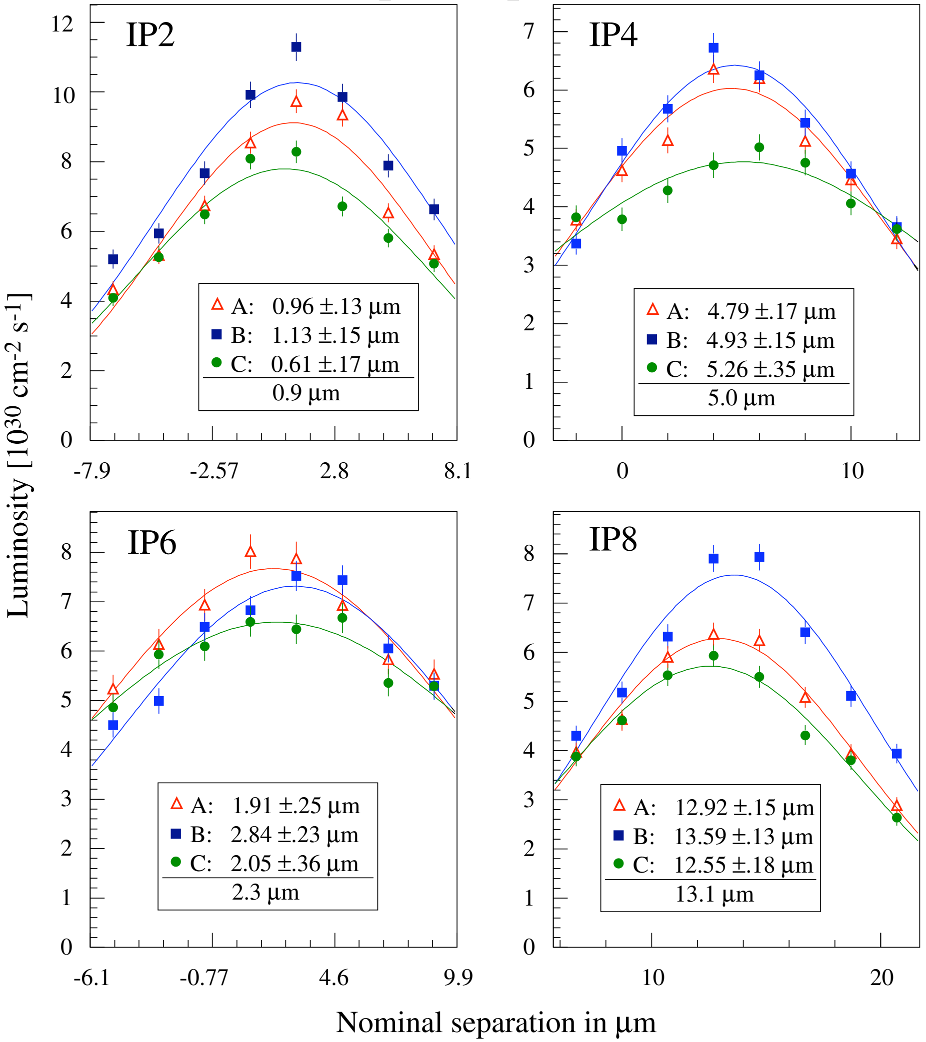
Contributions :

- Intensity $N_{1,2}$ BCT ~1%
- Length scale - from BPM, bumps optics, few %
- Particles in tails
- Exact shape

  extreme cases :



LEP example, V-plane, 3 bunches



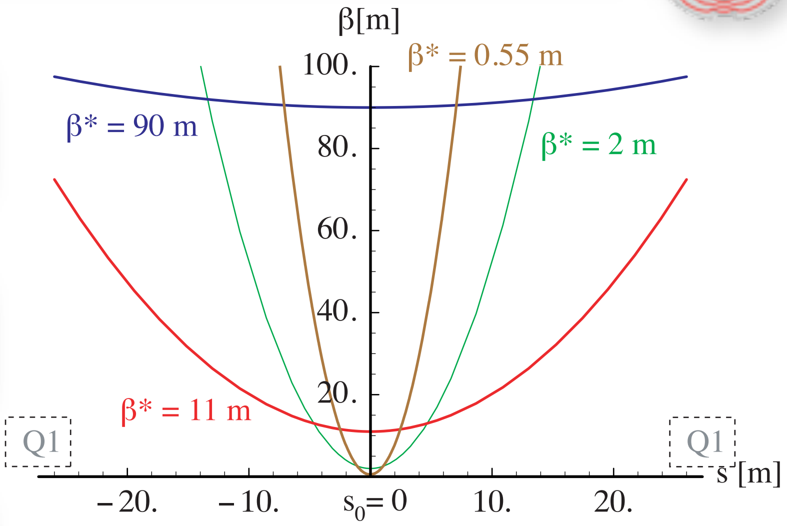
studied by Simon White - as PhD thesis.

principle : H.B. and Per Grafstrom; LHC Report 1019 from 23 May 2007 http://cdsweb.cern.ch/record/1056691
and H.B., R. Schmidt, *Intensity and Luminosity after Beam Scraping*, CERN-AB-2004-032

Low β insertion ; LHC

the β-function in a field free region has a form of a parabola with

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}$$

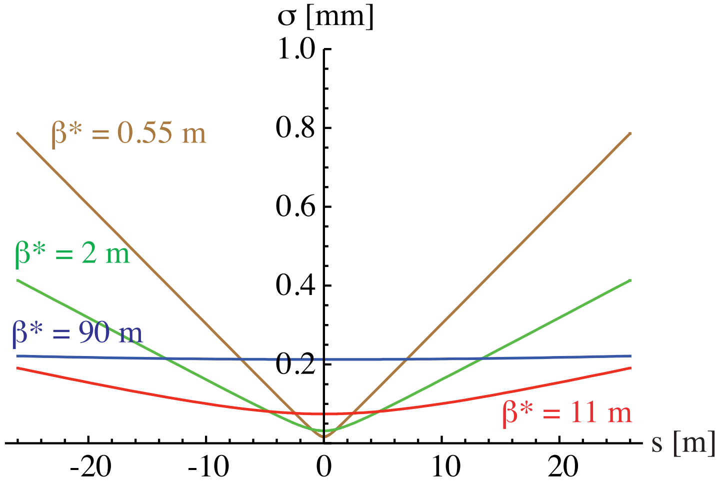


the beam size of a beam of emittance ε

$$\sigma = \sqrt{\beta\,\varepsilon}$$

and the angular beam size divergence

$$\sigma' = \sqrt{\frac{\varepsilon}{\beta}}$$



the beam size increases about linearly from the IP to the first quadrupole, by a factor s / β* (for s >> β*)

→ aperture limit for low β*; upgrade plans for larger aperture triplet;

High β* beam size instead flat - potential conflict for reduced pipe at IP

For illustration, using simplified expressions
σ, σ' for negligible dispersion and σ' for β' = 0 ;
normally the case at the IP

for the nominal emittance
ε_N = 3.75 μm, $\varepsilon_N = \varepsilon\,\beta\,\gamma$
ε = 0.503 nm at 7 TeV

β-function, phase advance and tune

relation between phase advance φ(s),
β(s) and tune Q(s) = φ(s) / 2π

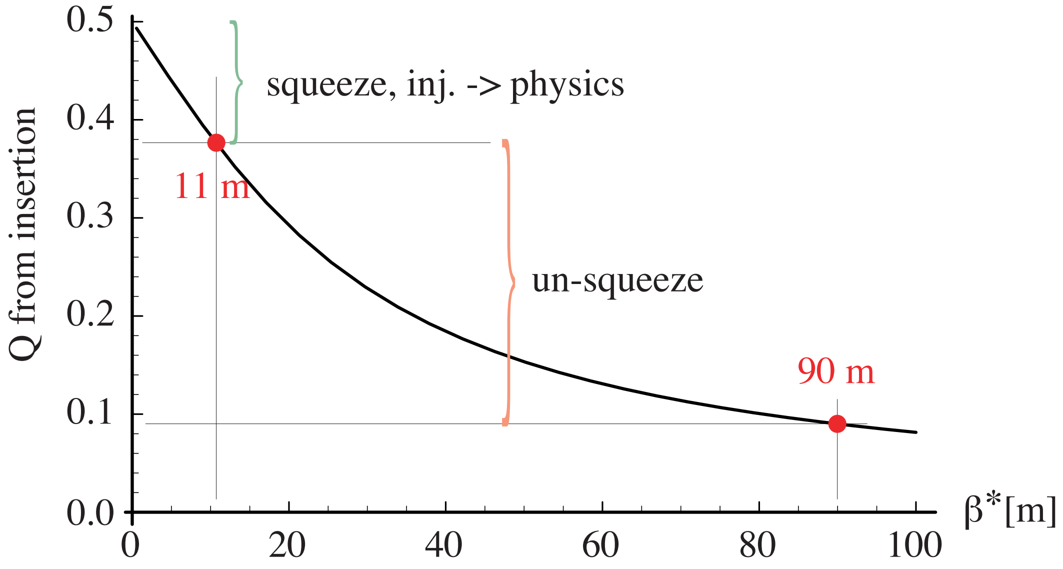
$$\Phi(s) = \int \frac{1}{\beta(s)}\,ds$$

integrated symmetrically around the minimum

$$Q = \frac{1}{2\pi}\int_{s_0-l}^{s_0+l} \frac{1}{\beta(s)}\,ds = \frac{1}{\pi}\arctan\left(\frac{l}{\beta^*}\right)$$

contributes 0.5 in tune (π in phase) for low β* << *l*
going to 0 for high β* >> *l*

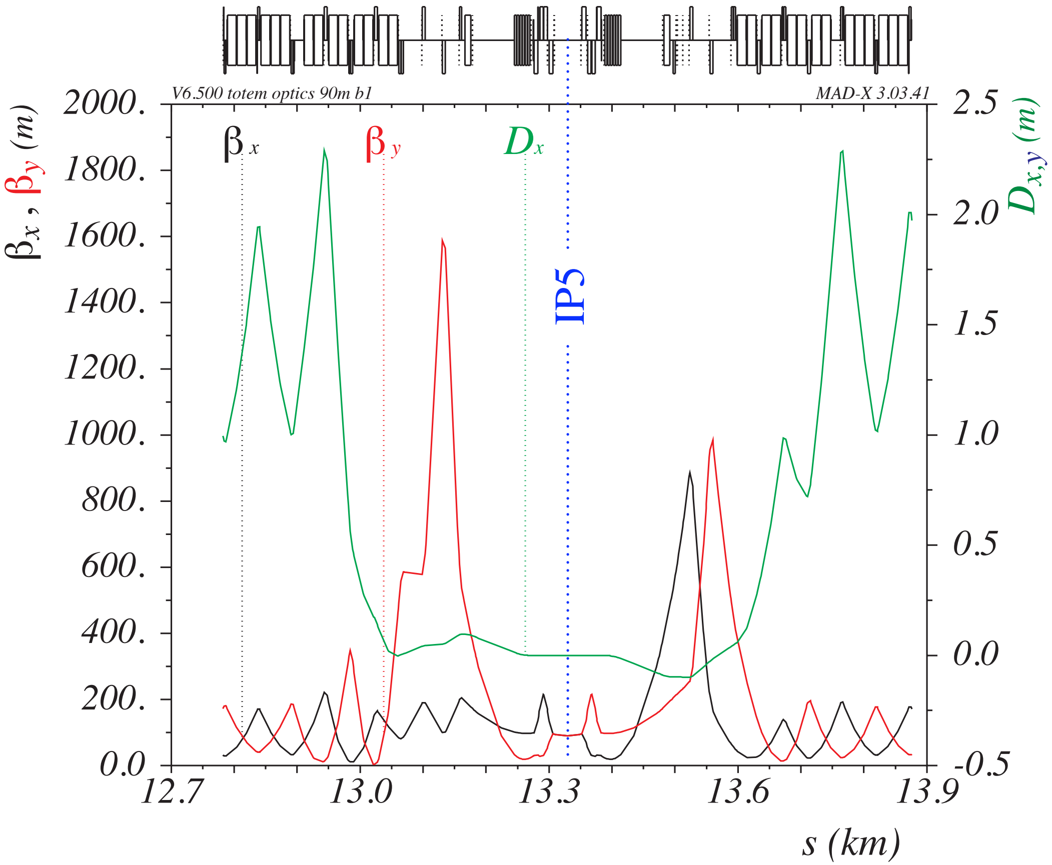
for the LHC with
l = 26.15 m from
IP to centre of Q1



90 m

normal injection, ramp ; standard beam, compatible with low β physics in other points

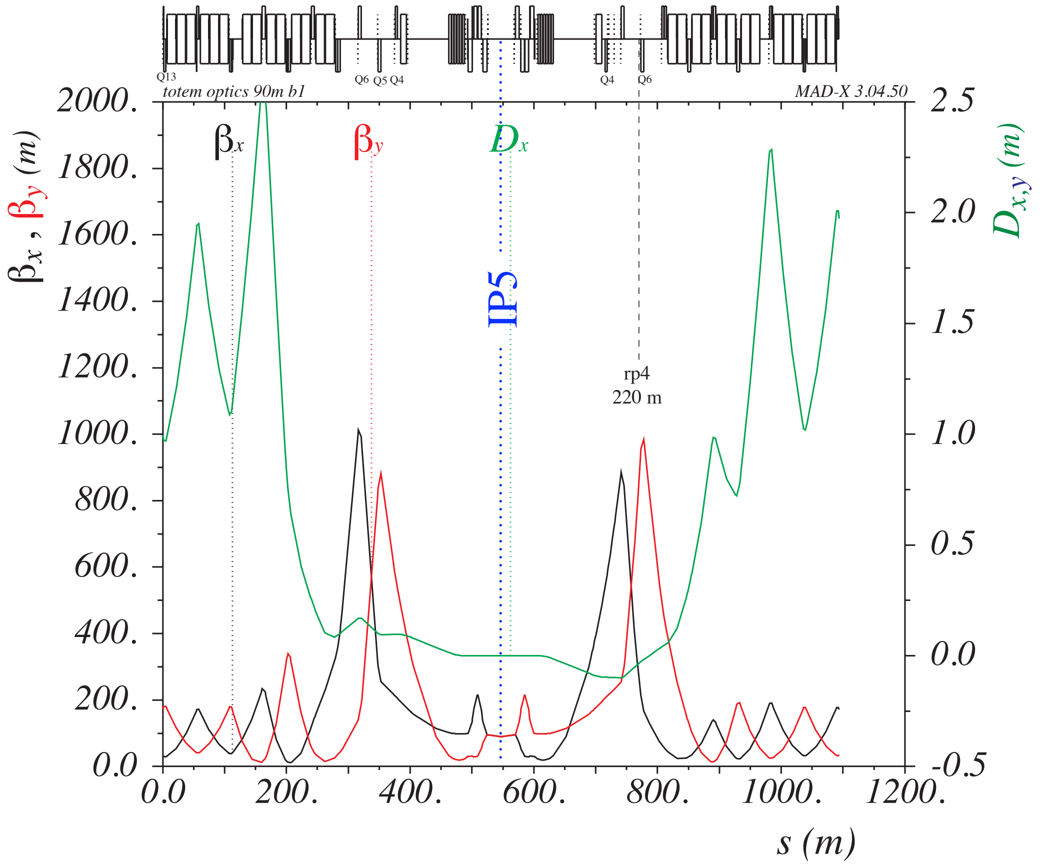
IP5 to RP 220 $\Delta\mu_x = \pi$ $\Delta\mu_y = \pi / 2$



2007 version

ΔQx = 0.10 ΔQy = 0.03

/afs/cern.ch/eng/lhc/optics/V6.501/HiBeta/IP5_beta90.str



90 m optics, 2009 version

0.5 < beam1/beam2 strength < 2.

ΔQx = 0.20 ΔQy = 0.045

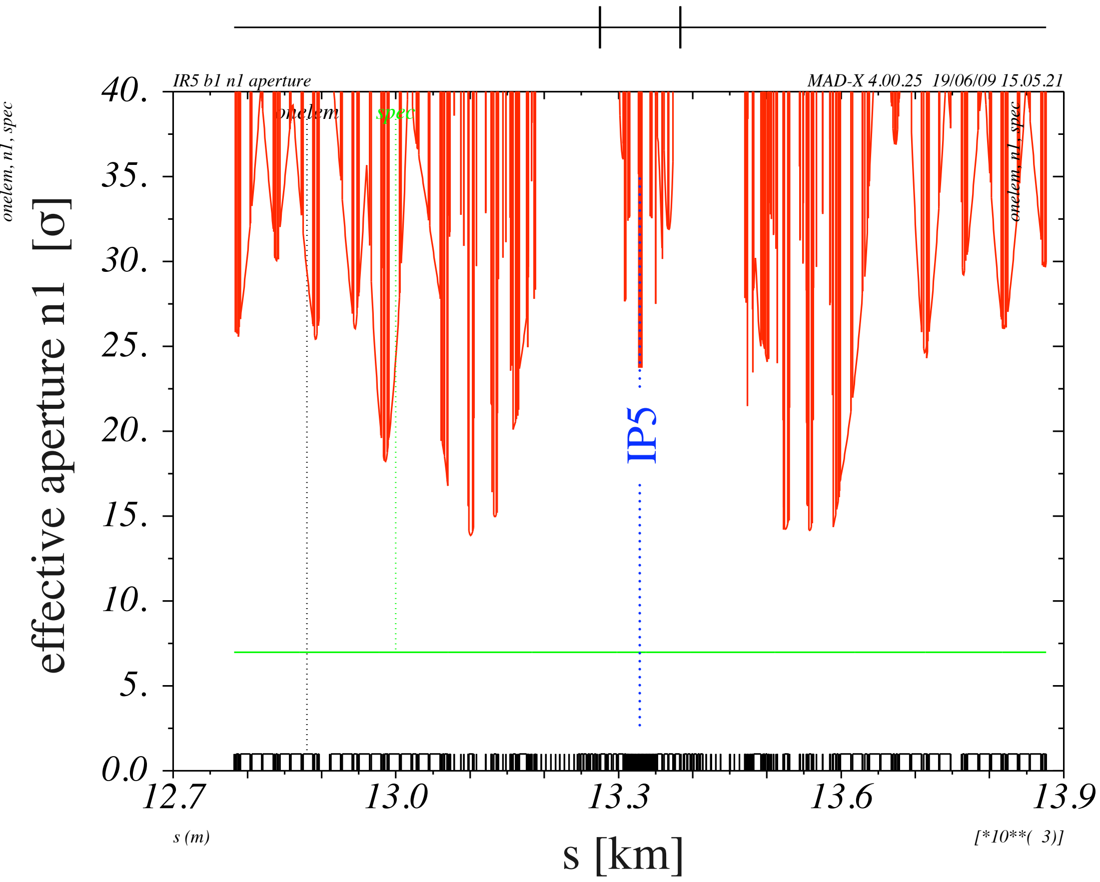
/afs/cern.ch/eng/lhc/optics/V6.503/HiBeta/IP5_beta90.str

Recent reference : Study of High Beta Optics Solution for TOTEM, H. Burkhardt, S. M.White, Y. Lenvinsen, WE6PFP016, PAC’09

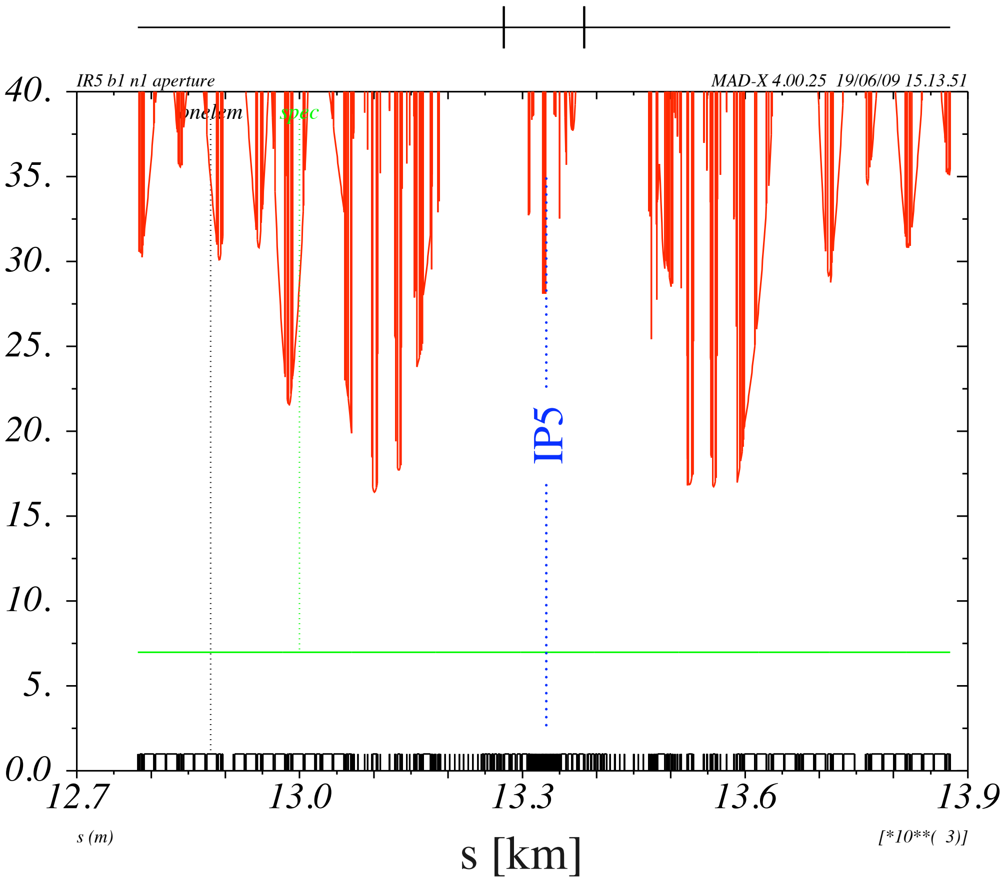
Aperture for the 90 m optics, 2009 version, 5 and 7 TeV

n1 : effective aperture including alignment and tolerances ; required > 7 σ

5 TeV, separated beams



7 TeV, separated beams



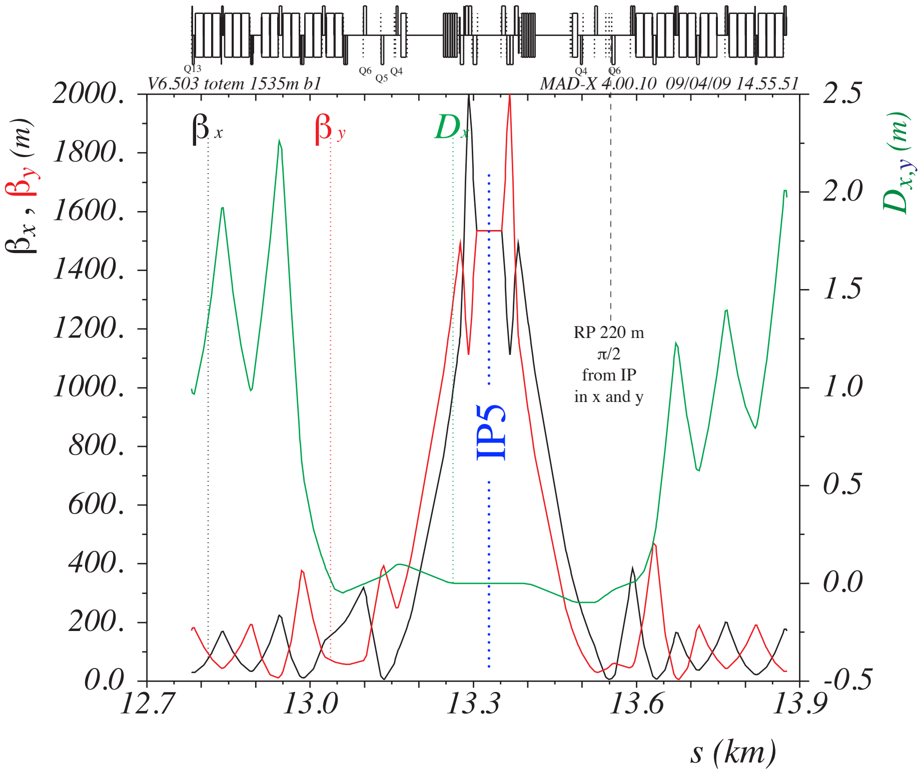
```
MQML.6L5.B1    n1 = 14.1
MQML.5L5.B1    n1 = 15.3
MQY.4L5.B1     n1 = 20.1
IP5            n1 = 23.8
MQY.4R5.B1     n1 = 24.8
MQML.5R5.B1    n1 = 14.3
MQML.6R5.B1    n1 = 14.3
```

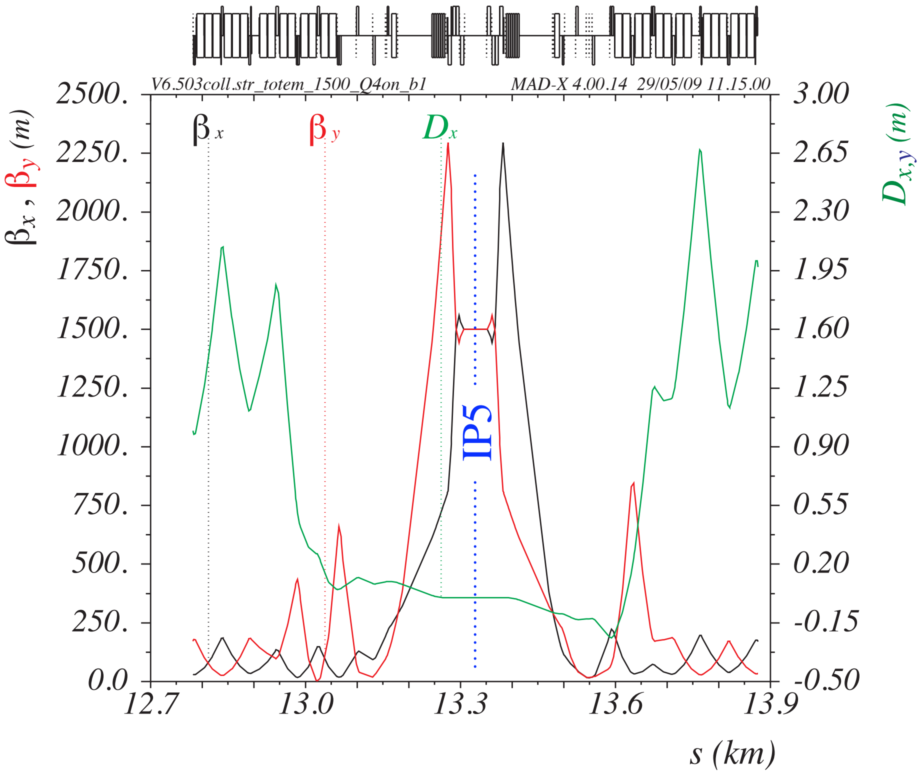
V6.503
standard emittance $\varepsilon_N = 3.75\ \mu m$
reachable from standard injection & ramp
by un-squeeze

TOTEM optics, high β*

special runs - with reduced emittance and intensity

IP5 to RP 220 $\Delta\mu_x = \Delta\mu_y = \pi / 2$





Baseline Totem 1535 m, as inherited
from A.V. in 2005 with some issues:
Q4 = 0, strengths exceeding limits
ΔQx = -0.06 ΔQy = 0.56

PAC'09 V6.503 Q4on alternative, β* = 1500 m
potentially reachable by un-squeeze
ΔQx = 0.43 ΔQy = 0.33 (PAC'09)
can be further optimized

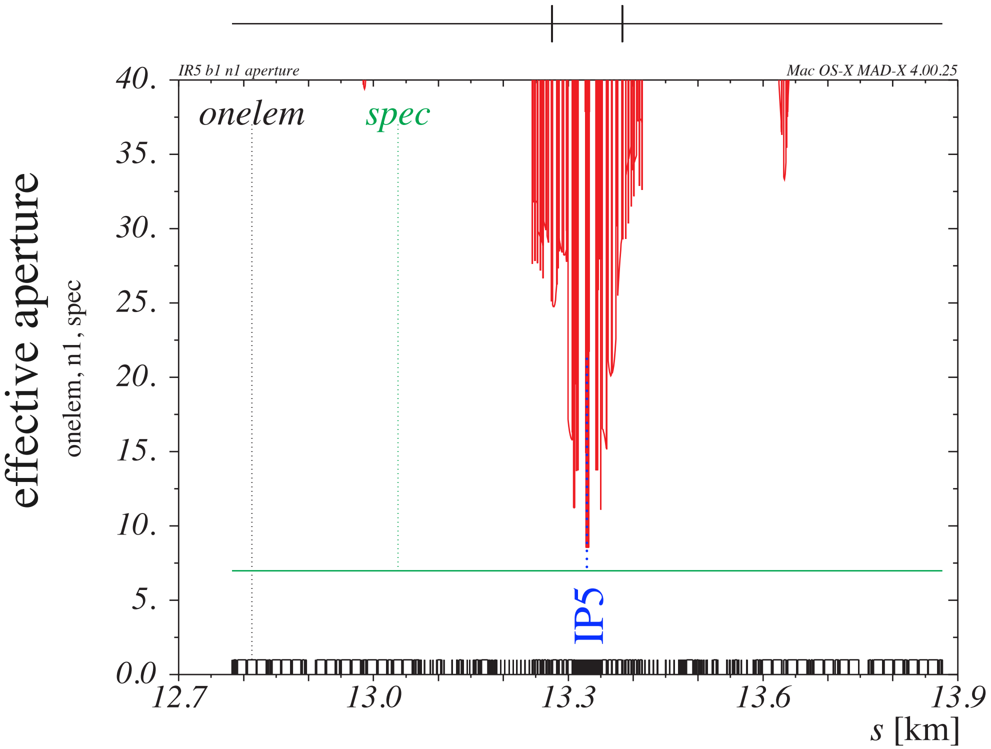
V6.5/Totem/IP5_beta1535.str

V6.503/HiBeta/IP5_1500_Q4on_prelim.str

Recent reference : Study of High Beta Optics Solution for TOTEM, H. Burkhardt, S. M.White, Y. Lenvinsen, WE6PFP016, PAC'09

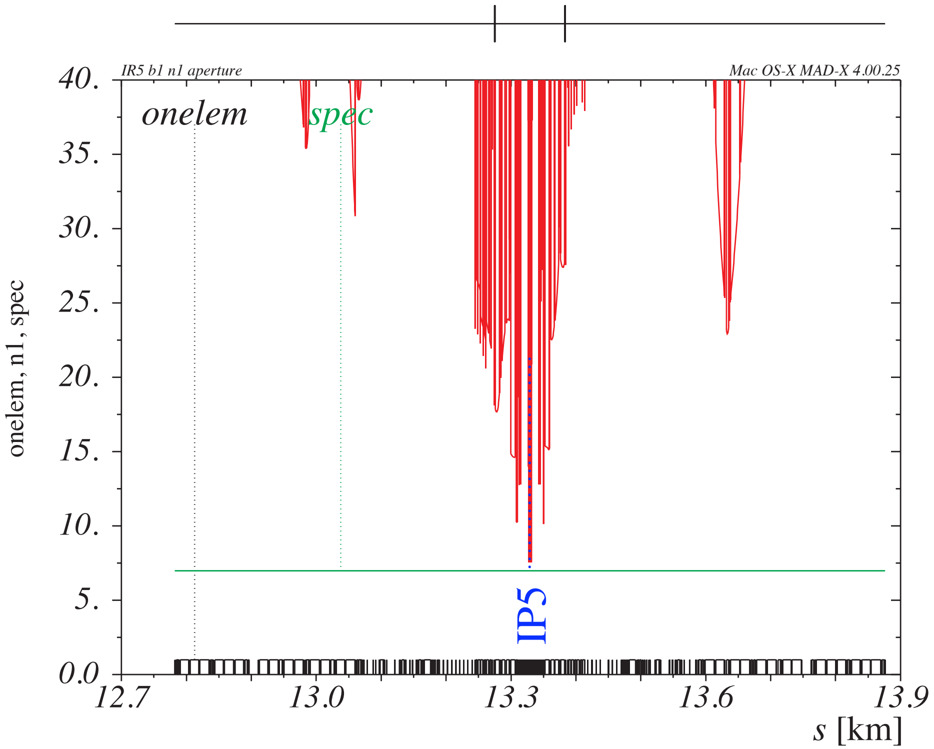
Aperture n1, high β* Totem, 7 TeV, separated beams

Totem 1535 m, A.V. version



"IP5" n1 = 8.5

V6.503 Q4on, β* = 1500 m



"IP5" n1 = 7.5

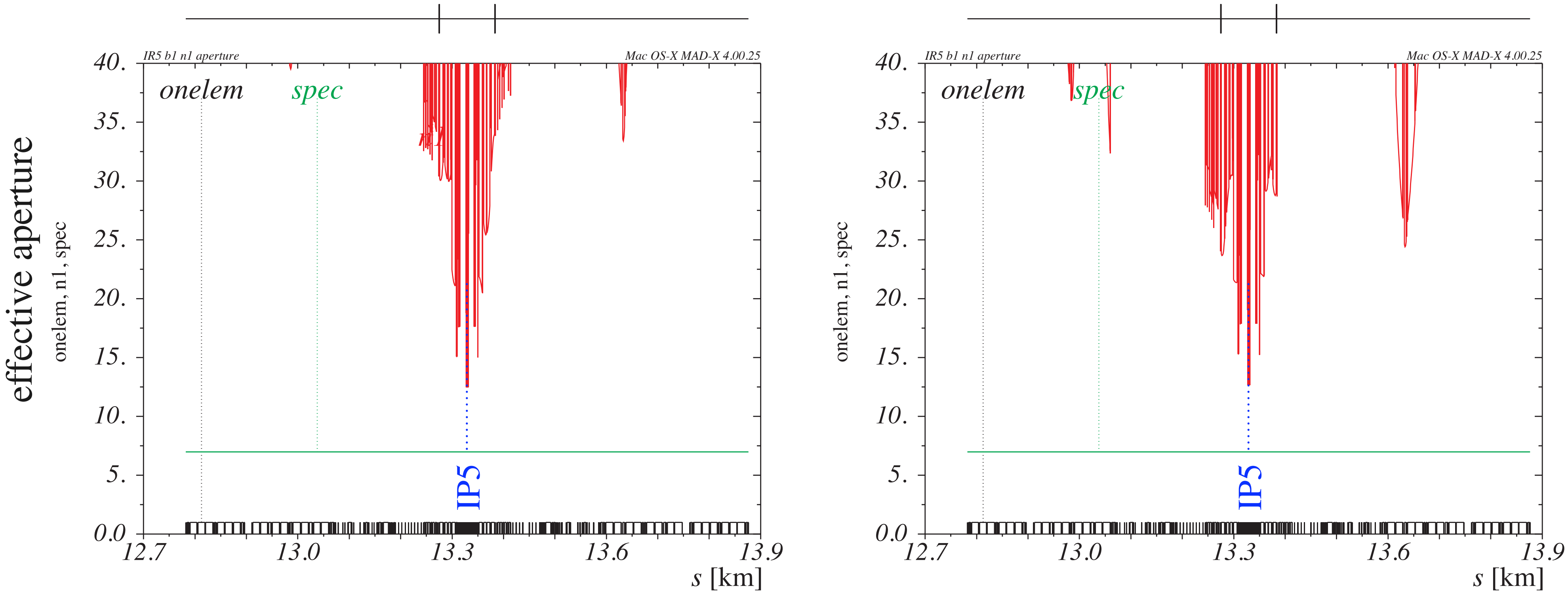
bump with mcbx = -24 µrad
to reduce Dy

Tightest at IP. Still within spec of n1 = 7 with separation, ε_N = 1 µm

Aperture n1, high β* Totem, 7 TeV, in collision

Totem 1535 m, A.V. version

V6.503 Q4on, β* = 1500 m



"IP5" n1 = 12.48

"IP5" n1 = 12.67

ATLAS high β* optics

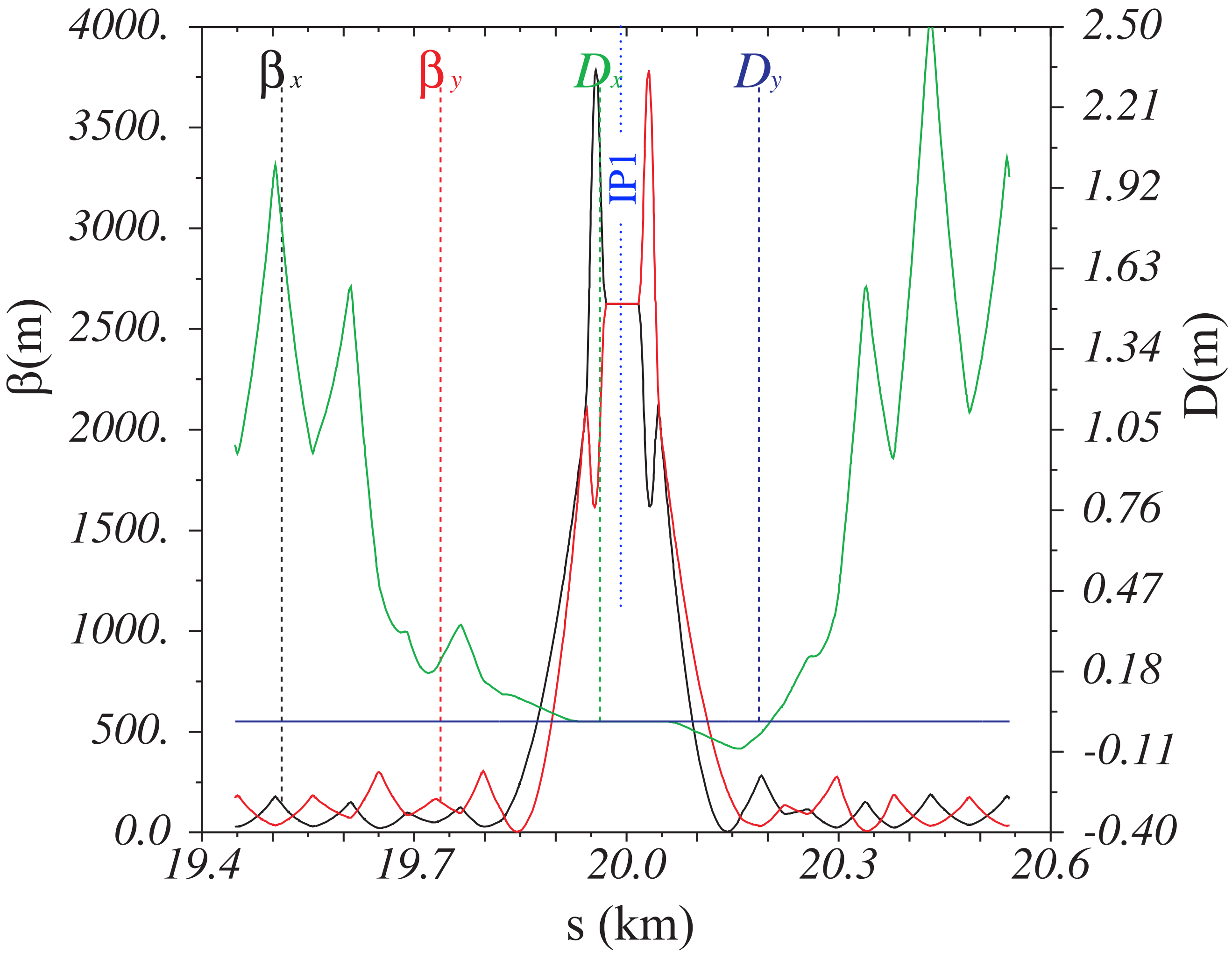
β* = 2625 m

roman pot at
240 m from IP1

$\Delta\mu_y = \pi / 2$

$\varepsilon_N = 1\ \mu m$

Q4 polarity
inverted



Reference : Overall Optics Solution for very high-beta in ATLAS; S. White, H. Burkhardt, P. Puzo, S. Cavalier, M. Heller ; Proc. EPAC 2008 and LHC-PROJECT-Report-1135

Commissioning of the un-squeeze to 90 m

top - energy, no crossing angle
procedure similar to commissioning of the squeeze to reduce β (to 3m, later 1m)
here in addition need for tune compensation of $\Delta Qx = 0.20$, $\Delta Qy = 0.045$
using IR4 and or arcs, check and if necessary correct β-beat

- 1st time single beam, minimum intensity, check and correct separation bump closure
- repeat with two beams; measure and correct, collide

Also consider - un-squeeze end of fill :

- mode to adjust, collimators to coarse setting, re-separate
- un-squeeze to end of ramp $\beta^* = 11$ m
- un-squeeze to $\beta^* = 90$ m

Commissioning of very high-β optics

Not relevant for the 1st year of LHC operation

Somewhat pre-mature to look at the details now - will depend on experience with squeeze and un-squeeze in the 1st year.

Optics wise - two main cases :

1. optics with Q4 on normal polarity; potential to reach about β* = 1500 m for TOTEM
2. optics with Q4 inverted. Required for ATLAS β* = 2625 m and as option for TOTEM

   requires commissioning of injection and ramp at β* ≈ 180 m ; with an aperture of n1 ≈ 7 for separated beams at $\varepsilon_N = 1$ μm

In both cases: Needs preparation of very low $\varepsilon_N = 1$ μm emittance beams :

- work in injectors, may require scraping in SPS
- minimize any emittance-blow up in the LHC; kickers, mismatch, feedbacks ...
- better understand and simulate physics limitations - intrabeam scattering
- may require scraping in the LHC

Request for very precise optics measurements. ALFA:

- β* known to ±1 %
- Δμ at RPs to ±2 %
- beam divergence ~ 0.23 μrad known to 10%
- crossing angle 0 ±0.2 μrad

Concluding remarks

- **The LHC is a large and very complex machine and will require long, careful commissioning with a gradual increase in intensity and luminosity**
- **The LHC has a very broad physics potential which includes forward physics ; the requirements in intensity and luminosity are generally modest and could potentially fit well in the earlier running**
- **The very high-β optics and reduced emittance will be challenging ; will be good to review this after initial experience with LHC operation and the commissioning of the 90 m optics.**

for further follow up

with extra time and resources, would be good to do more work on (help welcome)

- experimental conditions / background studies for forward physics, integrated in LBS
  simulations side : full tracking, etc
  experimental side : background signals for forward detectors, signal exchange
- combined efforts on vertex and alignment : optics, survey group, vertex information from LHC experiments
- compatibility of forward physics and LHC upgrade

Backup Slides

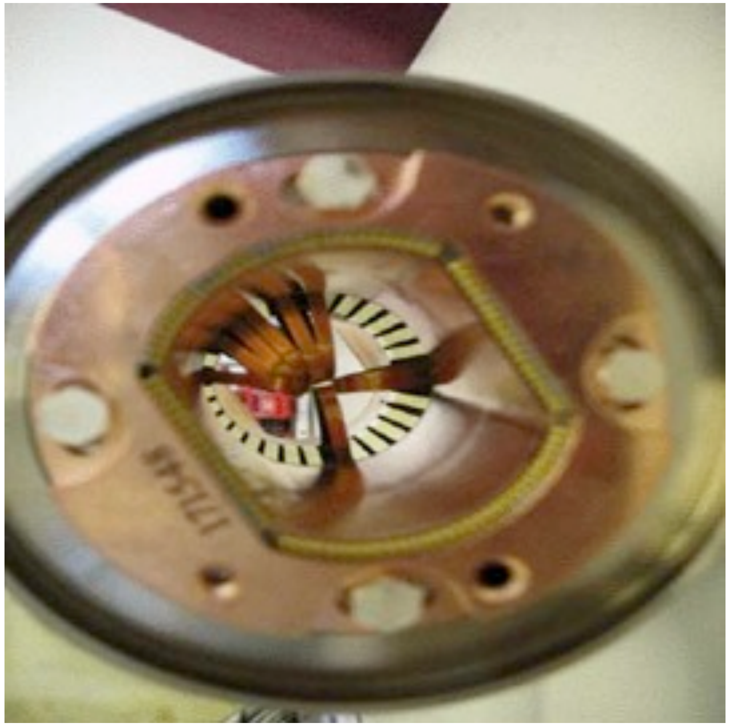
Critical Issues

Past

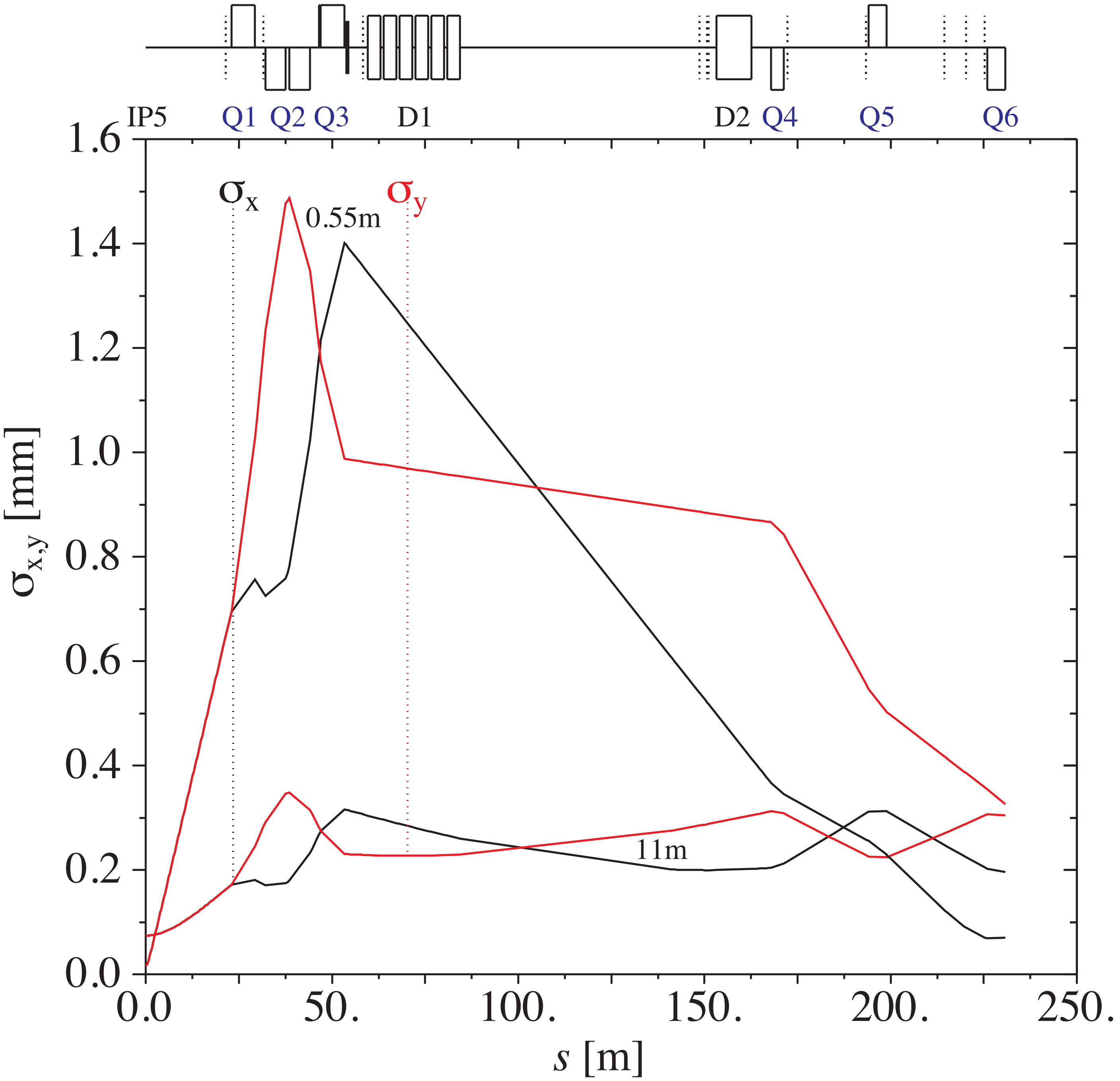
- QRL cryo line (He supply)
- DFB power connections, warm to cold transition
- Triplet quadrupoles - differential pressure

Recent

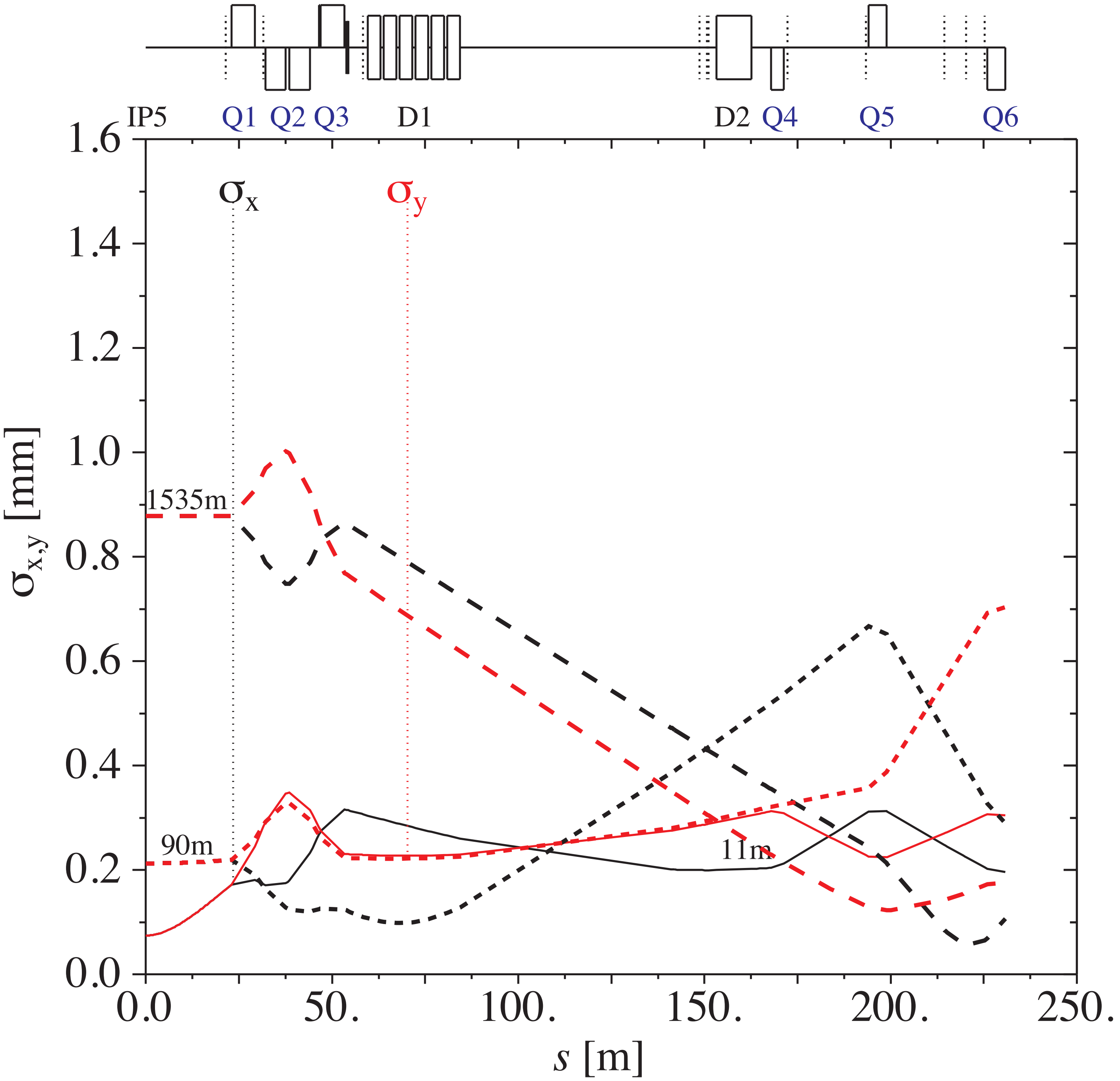
- Vacuum leaks, condensation - humidity sector 3 - 4
- Magnet powering check / correct : min/max, cabling - polarity
- PIM plug in module with bellow
- Magnet re-training few magnets quenched well below what was reached in SM18



Beam sizes, squeeze 11 m ➘ 0.55 m

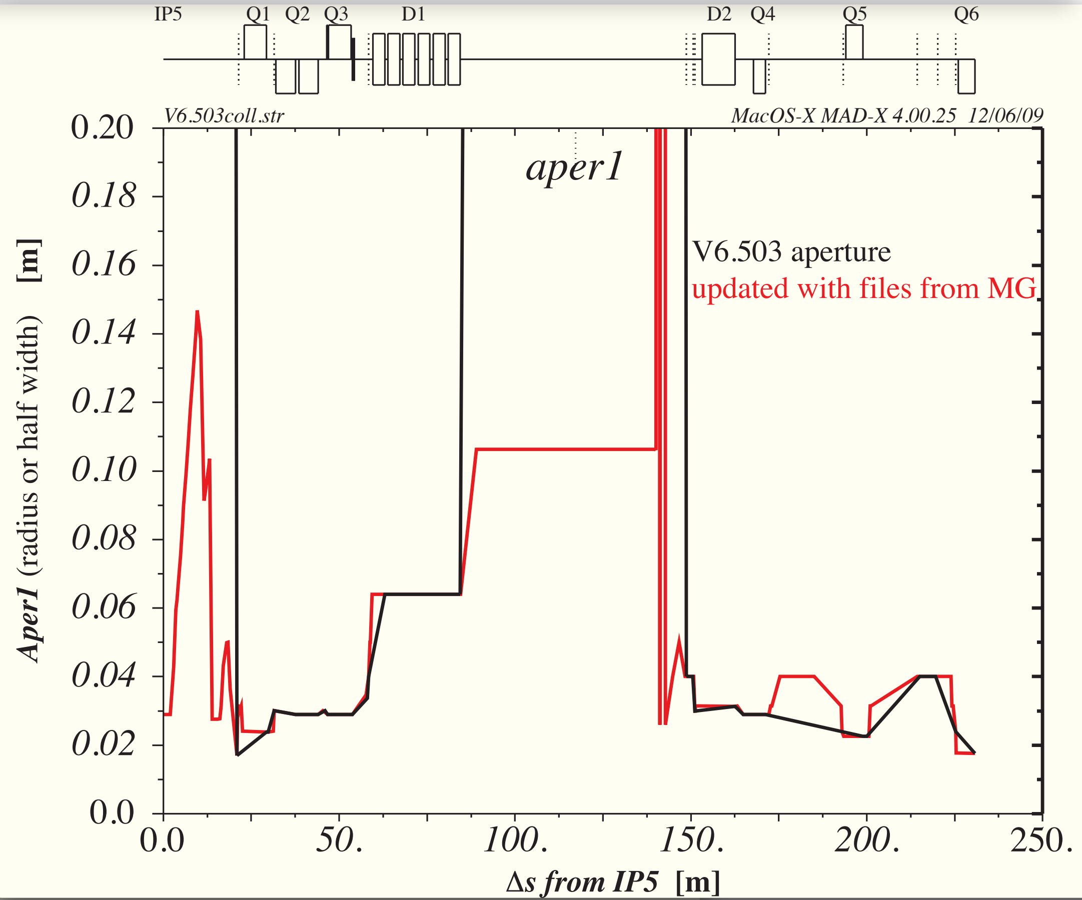


Beam sizes, squeeze 11 m ➚ 90 m ➚ 1535 m



More detailed MAD-X aperture input for IR5

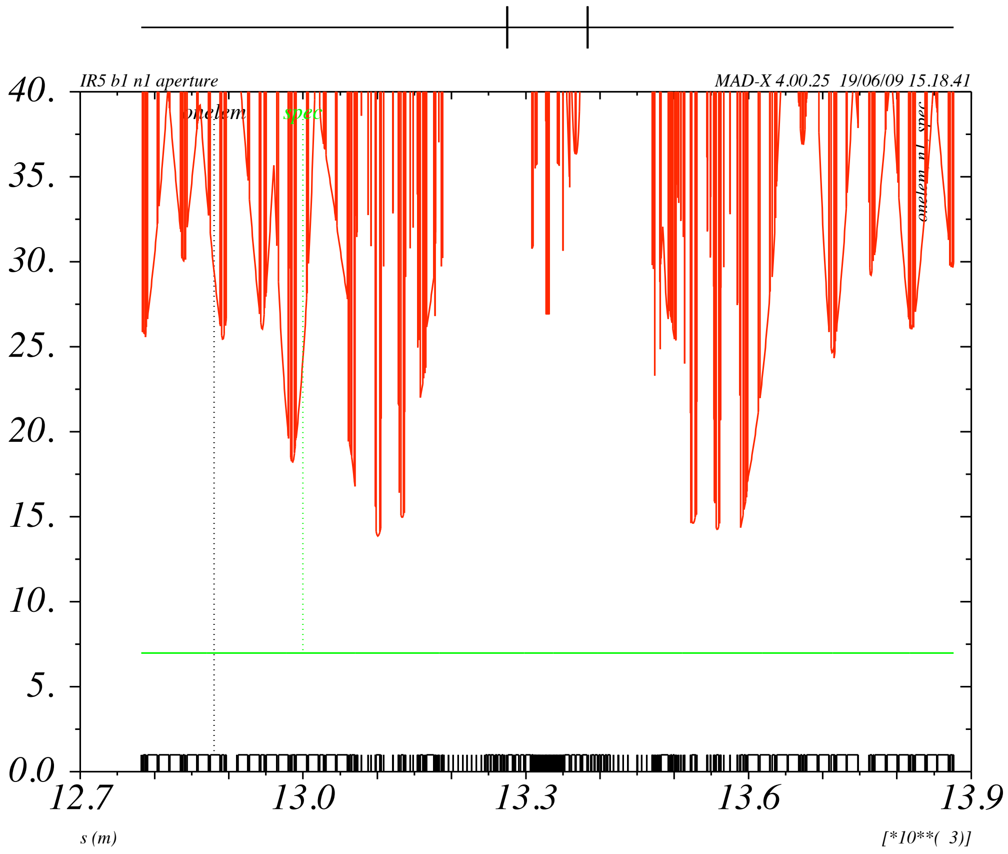
MAD-X 4.00.25
using the recent files provided my Massimo
/afs/cern.ch/user/g/giovanno/w1/aperture/V6.503/
Jun 10 16:31 aperture.b1.madx
Jun 10 16:32 aperture.b2.madx
Jun 10 16:33 aper_tol.b2.madx
Jun 10 16:33 aper_tol.b1.madx
Jun 8 16:38 exp_pipe_install.madx
Jun 10 15:38 CMS_exp_pipe_model.madx



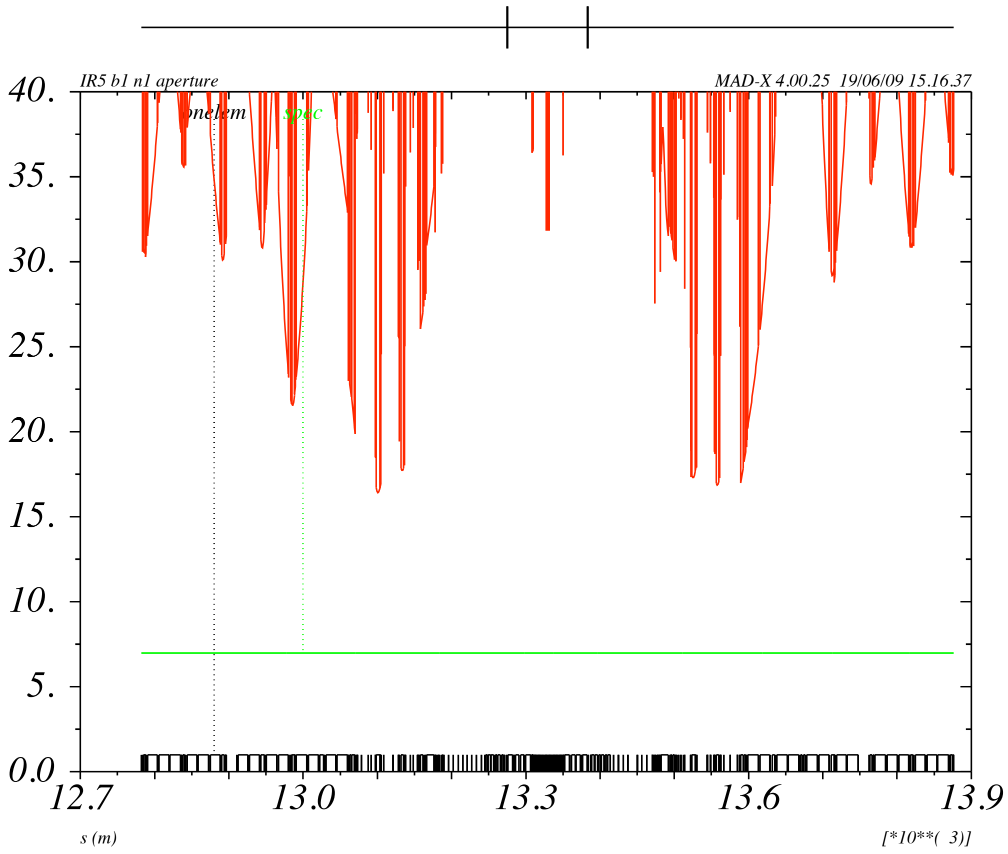
```
Previously the aperture started at the TAS
IP1,            APERTYPE=RECTELLIPSE, APERTURE={ 9.999999,    9.999999,    9.999999,  9.999999 }; ! s = 0
MBAS2.1R1,      APERTYPE=RECTELLIPSE, APERTURE={ 9.999999,    9.999999,    9.999999,  9.999999 }; ! s = 3.00000
TAS.1R1,        APERTYPE=RECTELLIPSE, APERTURE={ 0.017000,    0.017000,    0.017000,  0.017000 }; ! s = 20.915000
BPMSW.1R1.B1,   APERTYPE=RECTELLIPSE, APERTURE={ 0.030000,    0.030000,    0.030000,  0.030000 }; ! s = 21.475000

IP5,            APERTYPE=RECTELLIPSE, APERTURE={ 9.999999,    9.999999,    9.999999,  9.999999 }; ! ds = 0
MBCS2.1R5,      APERTYPE=RECTELLIPSE, APERTURE={ 9.999999,    9.999999,    9.999999,  9.999999 }; ! ds = 6.500000
TAS.1R5,        APERTYPE=RECTELLIPSE, APERTURE={ 0.017000,    0.017000,    0.017000,  0.017000 }; ! ds = 20.915000
BPMSW.1R5.B1,   APERTYPE=RECTELLIPSE, APERTURE={ 0.030000,    0.030000,    0.030000,  0.030000 }; ! ds = 21.475000

now      used with  CT2tol := 0.005;
CMSpipe1     : marker, APERTYPE=CIRCLE, APERTURE={0.02900}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 0.000000
CMSpipe2.l5  : marker, APERTYPE=CIRCLE, APERTURE={0.02900}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 0.321667
 .....
CMSpipe7.l5  : marker, APERTYPE=CIRCLE, APERTURE={0.02900}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 1.930000
CMSpipe8.l5  : marker, APERTYPE=CIRCLE, APERTURE={0.03341}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 2.251667
CMSpipe9.l5  : marker, APERTYPE=CIRCLE, APERTURE={0.03811}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 2.573333
CMSpipe10.l5: marker, APERTYPE=CIRCLE, APERTURE={0.04281}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 2.895000
CMSpipe11.l5: marker, APERTYPE=CIRCLE, APERTURE={0.04938}, APER_TOL = {0.015, 0.0, 0.0}; ! s = 3.216667
.....
```

Aperture n1, 90 m, 2009 version, 5 and 7 TeV

5 TeV, in collision



7 TeV, in collision



```
MQML.6L5.B1    n1 = 14.13
MQML.5L5.B1    n1 = 15.28
MQY.4L5.B1     n1 = 22.02
IP5            n1 = 26.91
MQY.4R5.B1     n1 = 26.33
MQML.5R5.B1    n1 = 14.74
MQML.6R5.B1    n1 = 14.51
```

V6.503
standard emittance $\varepsilon_N = 3.75\ \mu m$
reachable from standard injection & ramp
by un-squeeze