HB2016

57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

LHC Injectors Upgrade for the HL-LHC

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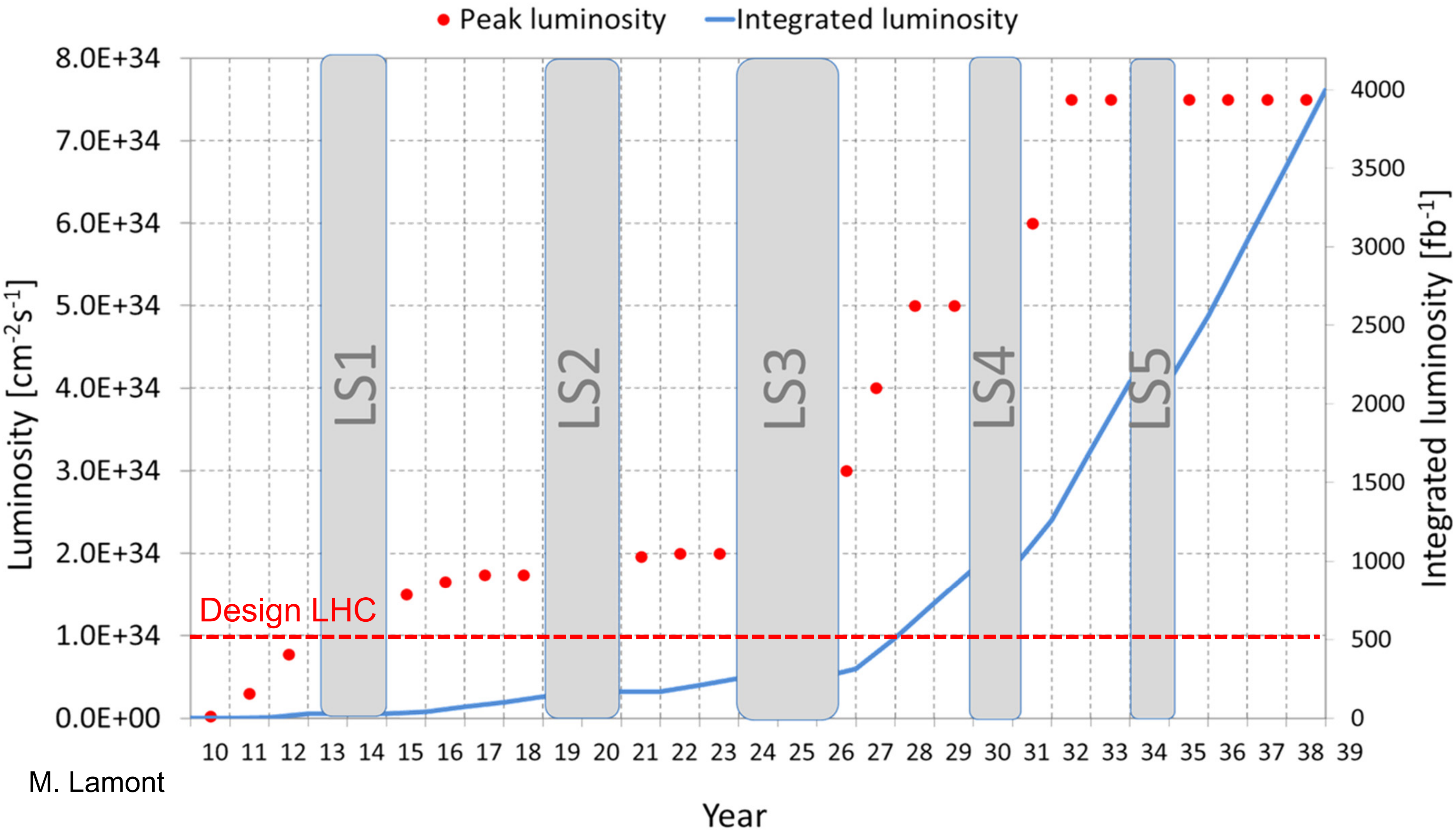
2016 July 3-8
Scandic Triangeln Hotel, Malmö, Sweden

Outline

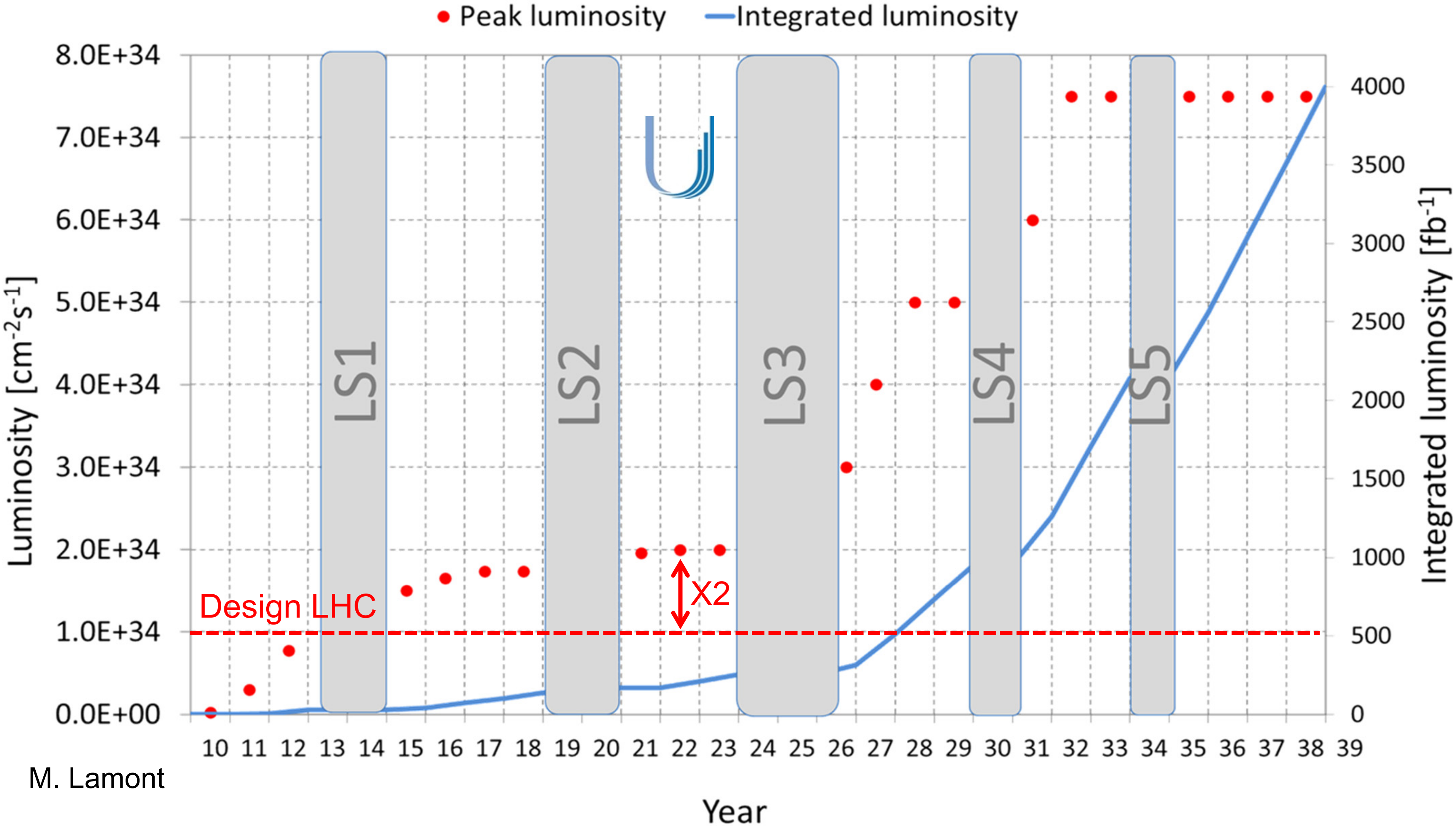
- HL-LHC Luminosity targets
- Injector upgrades overview
- Focus on:
  - Linac4 ➔ PSB Transfer Lines (TL)
  - PSB injection
  - PSB➔ PS 2GeV transfer and injection
  - SPS:
    - Injection system
    - Intercepting devices
- Conclusions

HL-LHC Luminosity Reach



M. Lamont

HL-LHC Luminosity Reach



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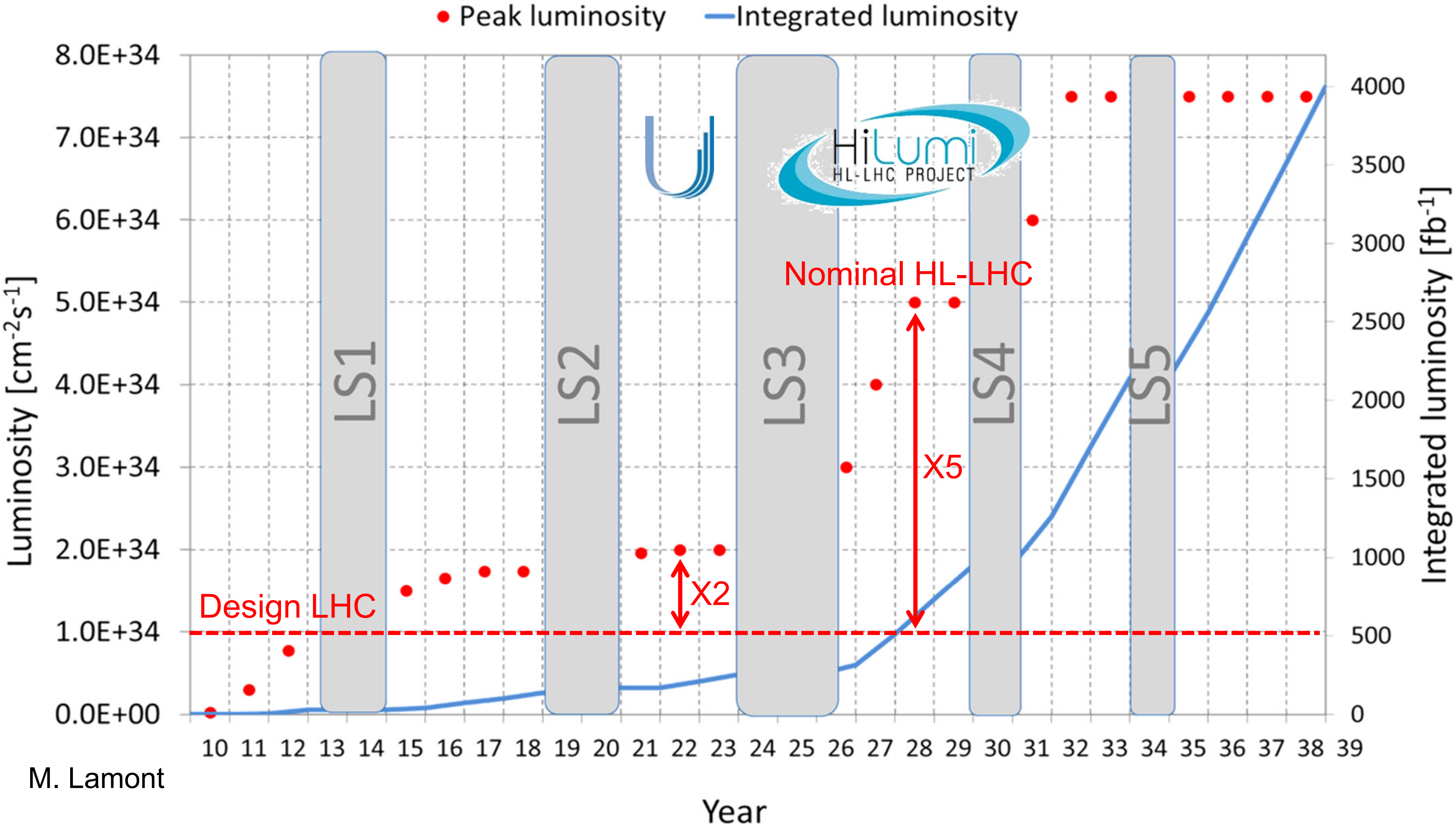

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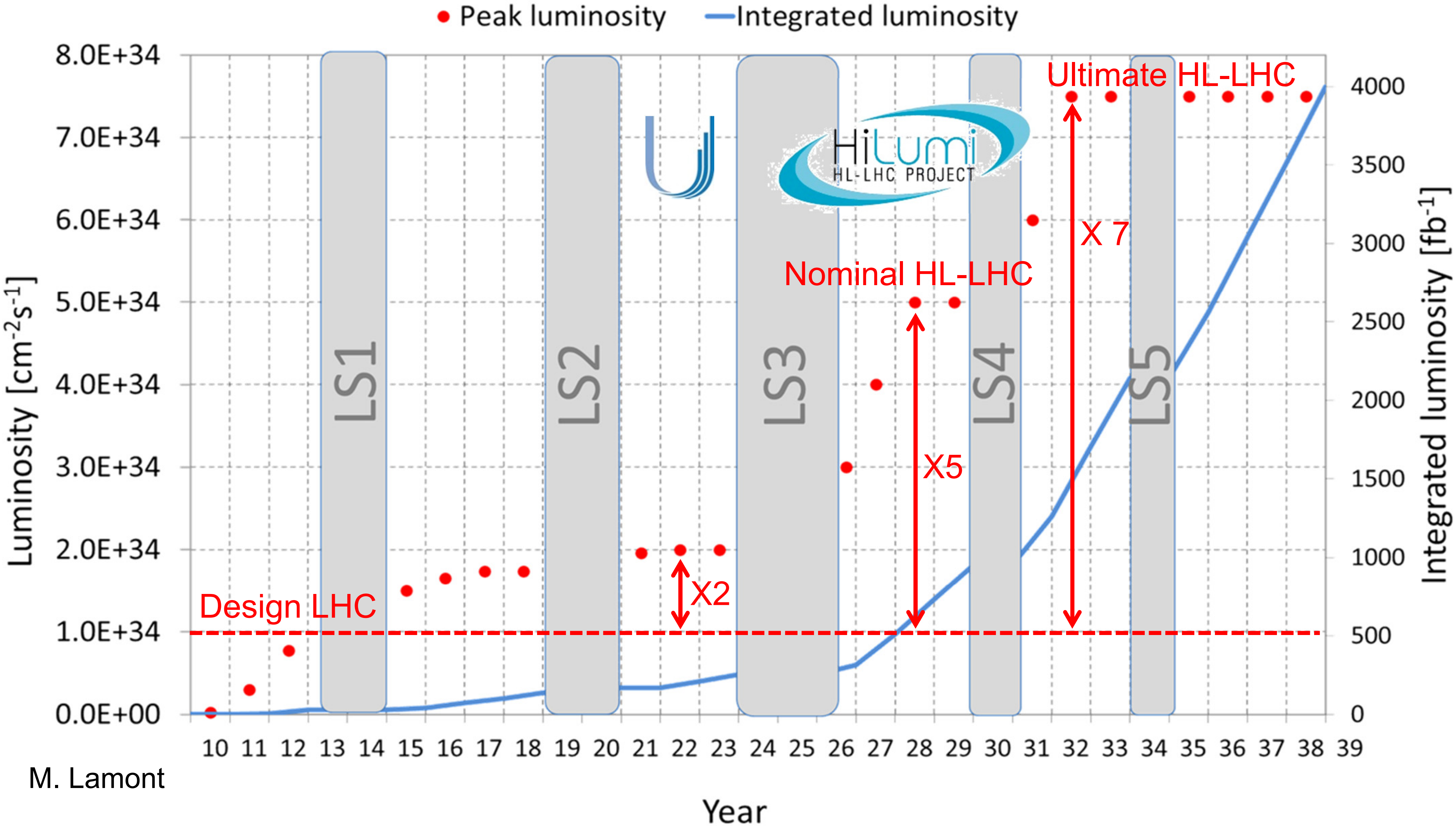
HL-LHC Luminosity Reach



M. Lamont

Beam Parameters

Peak Luminosity:

$$L = \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon\beta^*} F$$

Beam Brightness:

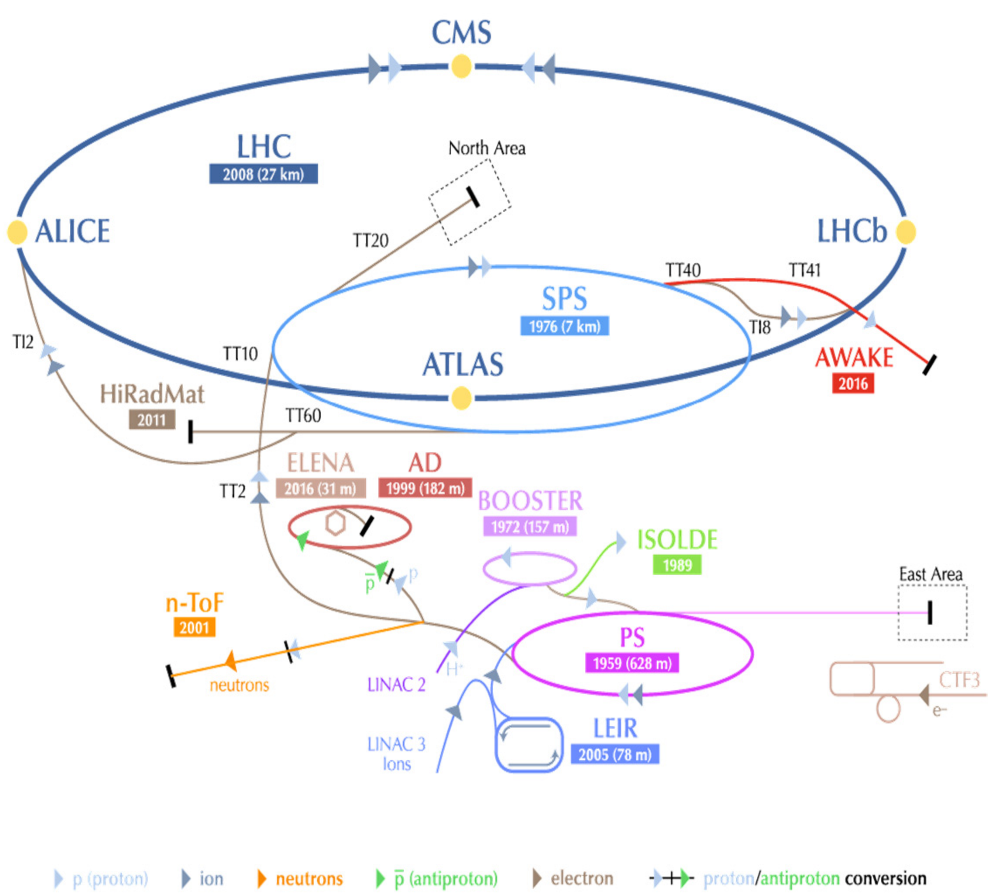
$$B = \frac{I}{\varepsilon^2}$$

To reach the target HL-LHC Luminosity one needs to:

- **Reduce β* and increase the geometric factor F (LHC upgrade)**
- **Increase beam current and brightness (injectors upgrades)**

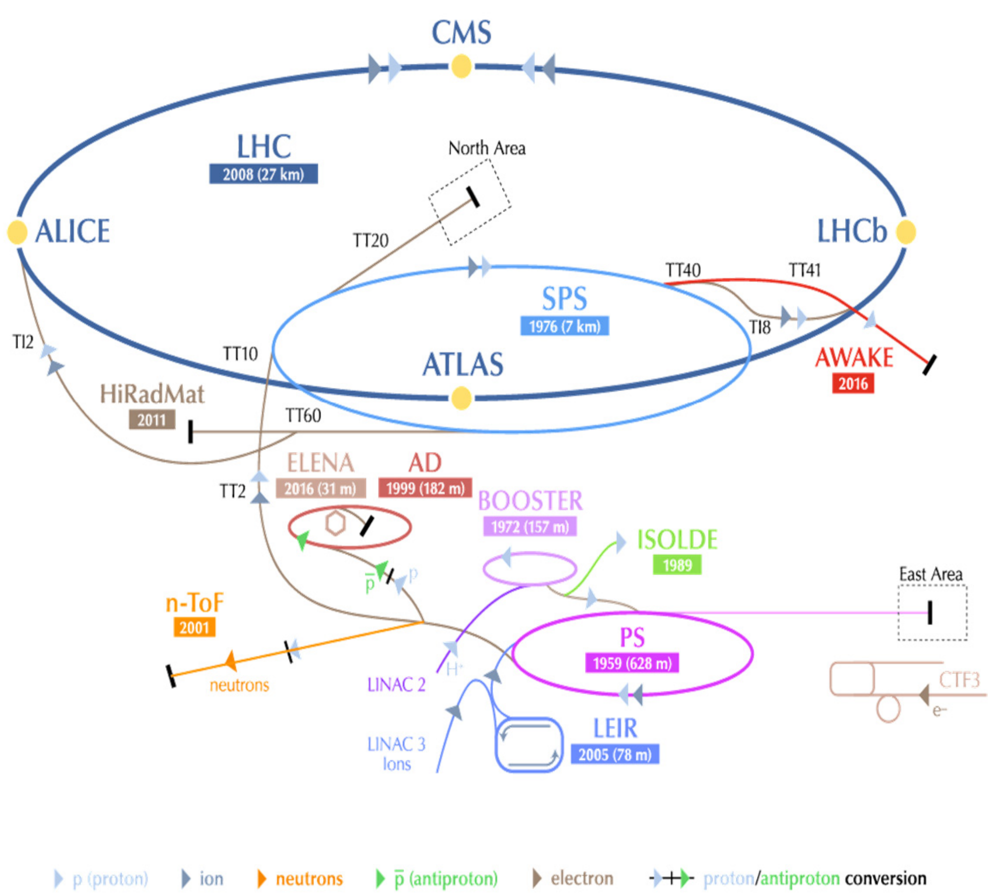
Parameters at 450 GeV	LHC nominal	HL-LHC standard	HL-LHC BCMS
p.p.b (n_b)	1.15e11	2.3e11	2.0e11
# bunches (N_b)	2808	2748	2604
ε [m rad]	7.3e-9	4.4e-9	2.9e-9
B(HL-LHC)/B(LHC)	1	5	10

Injectors Upgrade Overview



- Linac4: 160 MeV H^- (MOAM2P20),
- PSB: New H^- charge exchange injection and acceleration to 2 GeV (MOPR028)
- PS: injection at 2 GeV for protons
- Linac3 and LEIR: increase ion current (TUAM5X01)
- SPS: RF system upgrade, e-cloud mitigation (TUAM4X01), lower impedance and instabilities (MOPR010, MOPR011, MOPR013,TUAM3X01), improved injection and extraction HW, new dump and protection devices (including SPS → LHC Transfer Lines)

Injectors Upgrade Overview



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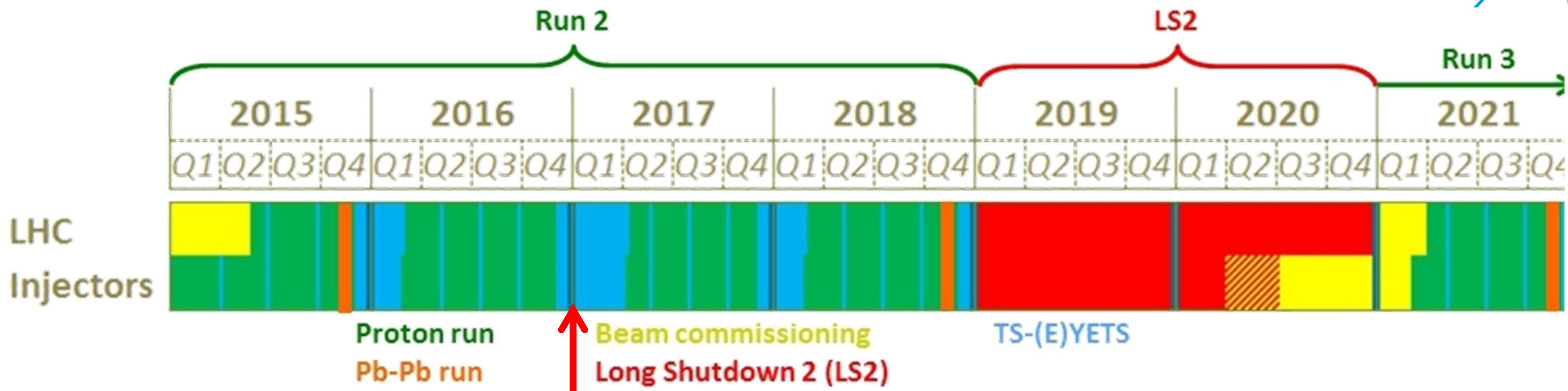
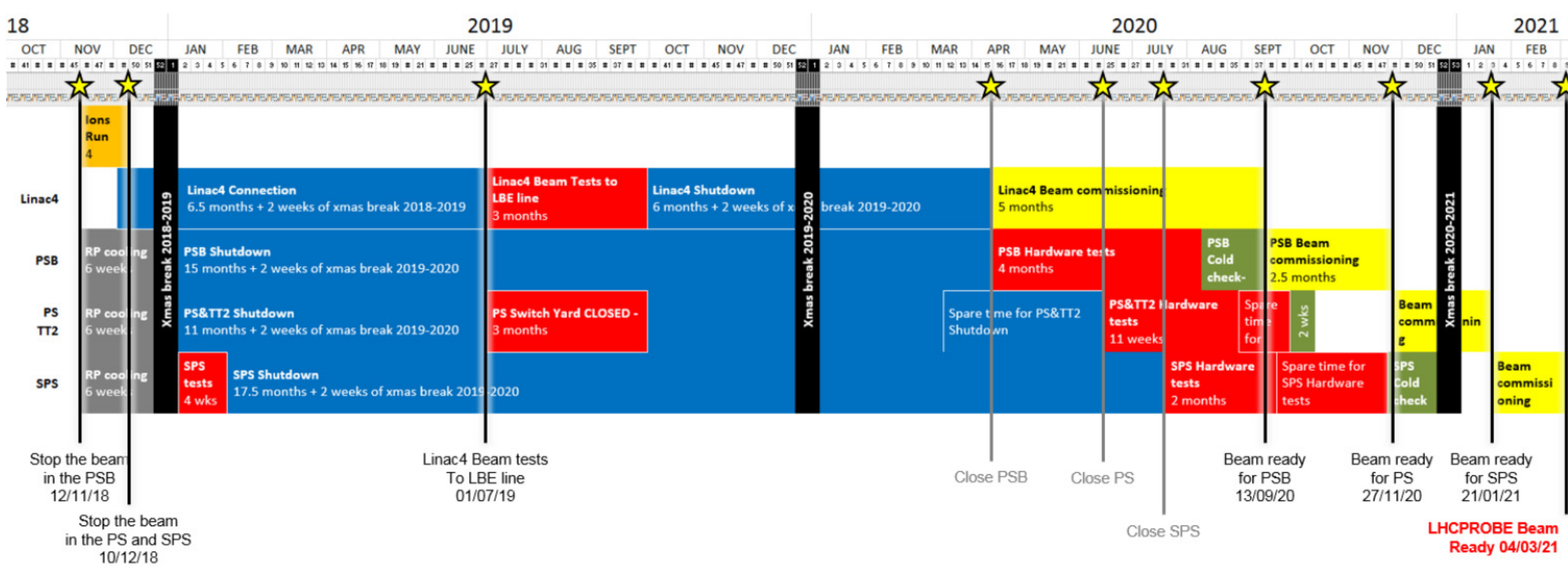
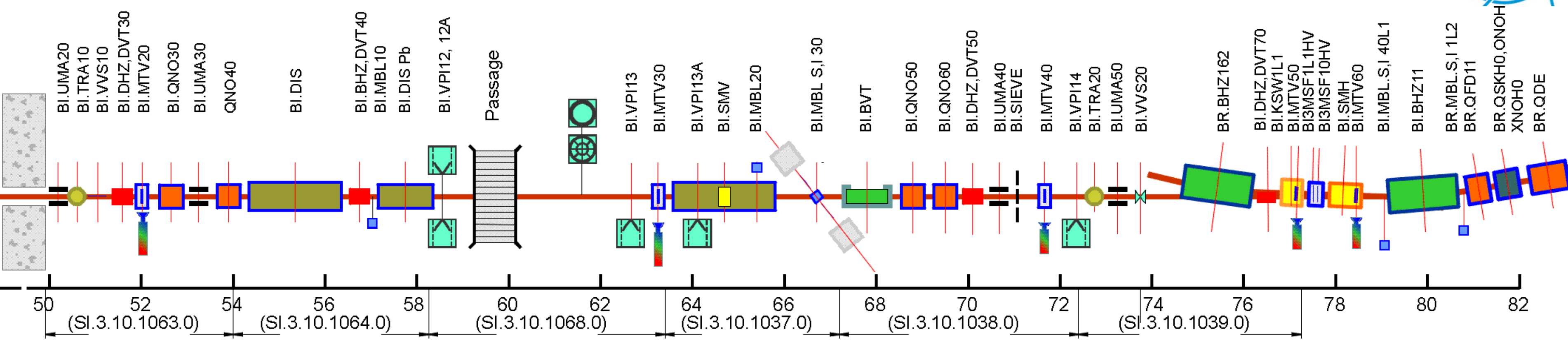
Schedule

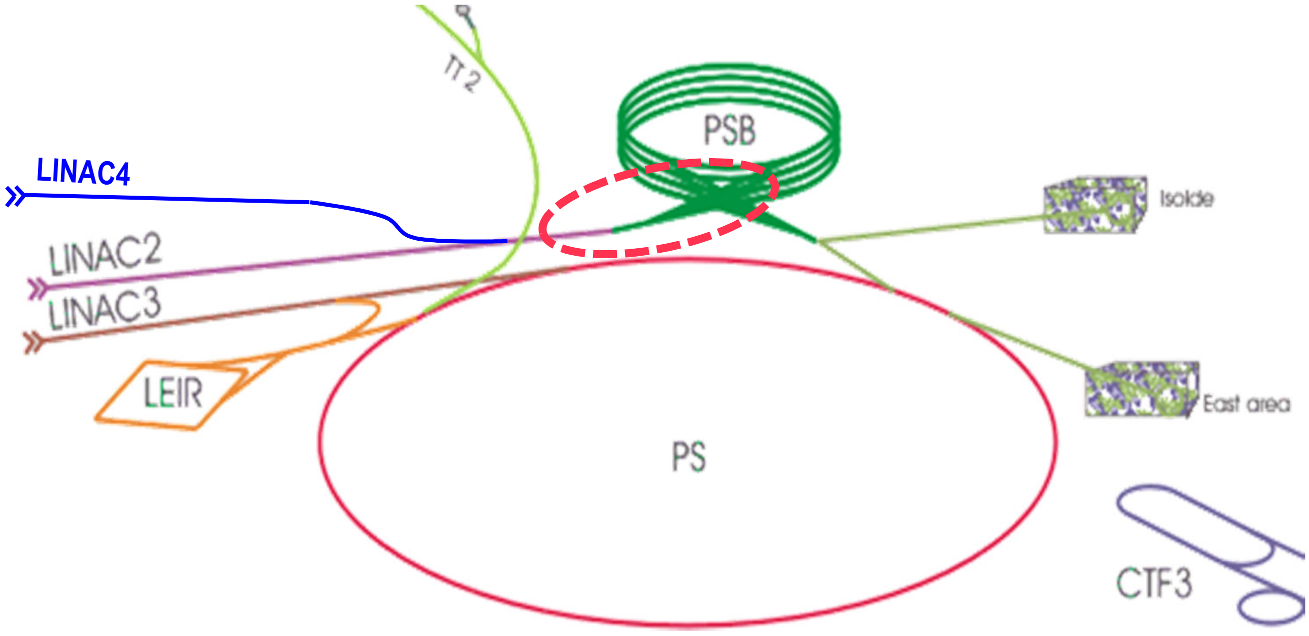


Ready for possible Linac4 connection!



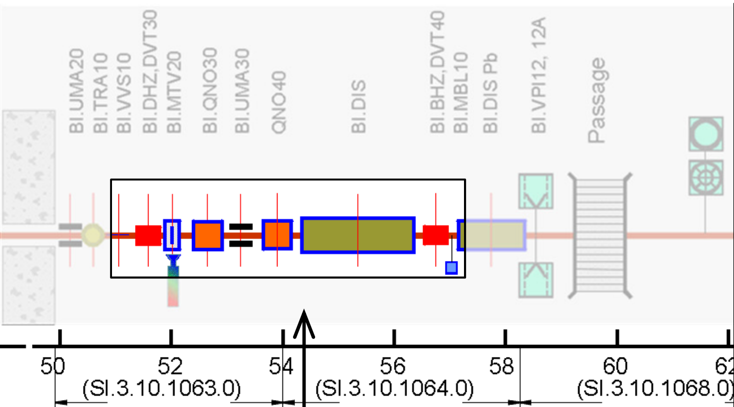
Linac4 → PSB Transfer Line





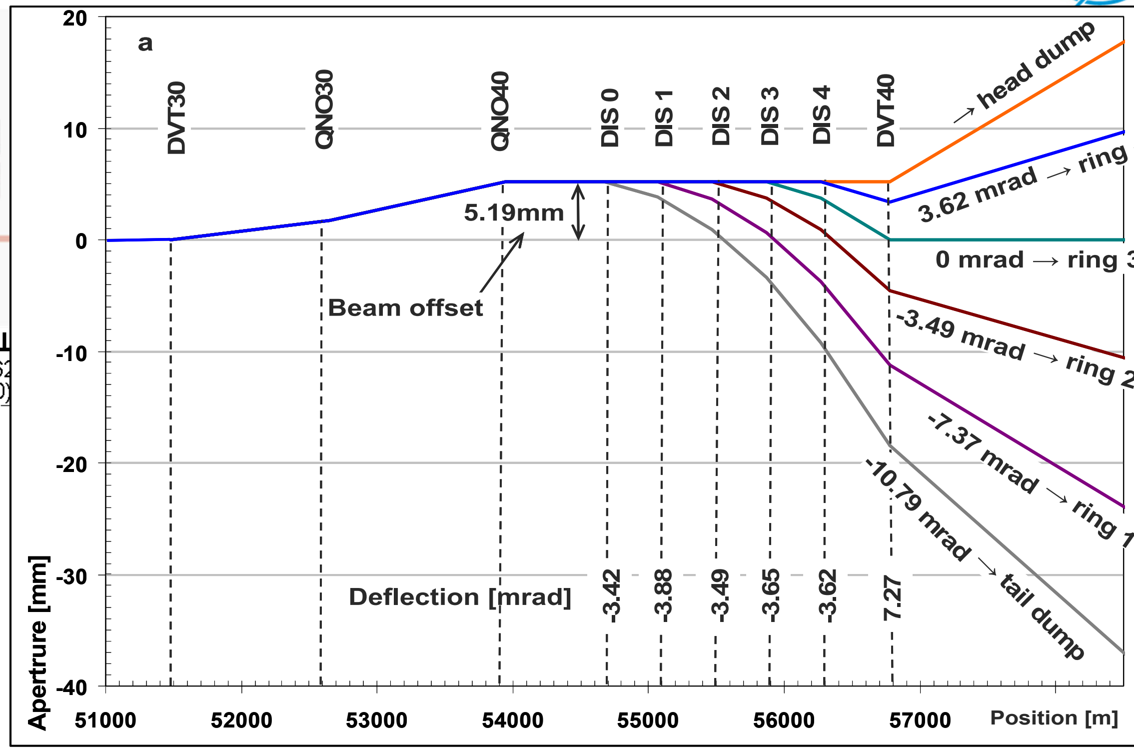
W. Weterings

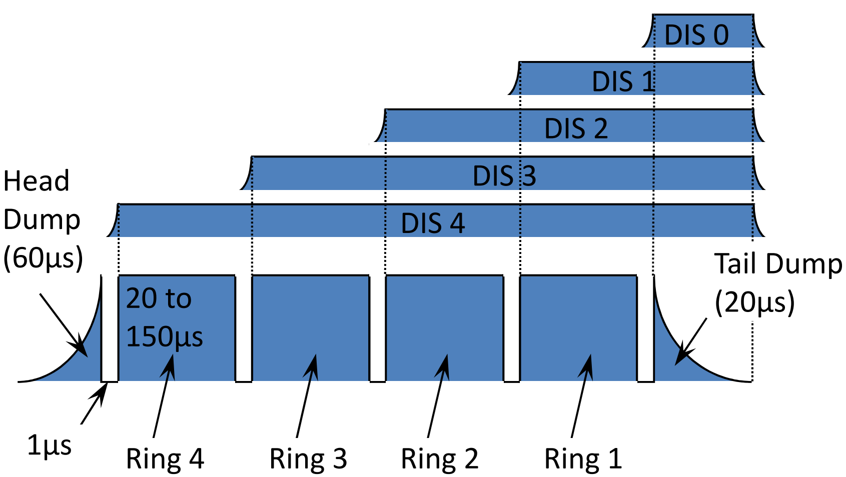
Linac4 → PSB Transfer Line



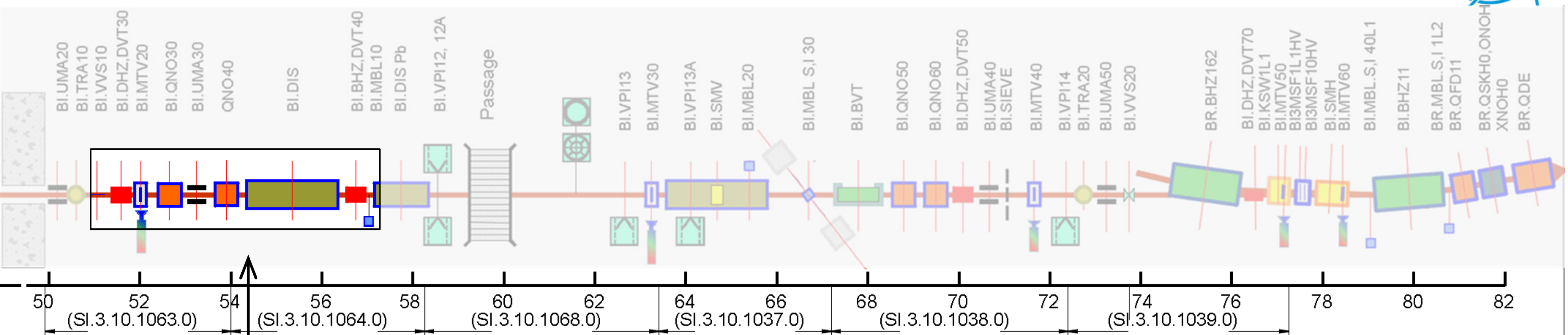
Modify BI.DIS for
4.3 mrad @ 160 MeV

Performance increase of
1.9 in ∫B•dl of
BI.DVT30, BI.QNO30,
BI.QNO40, BI.DVT40.



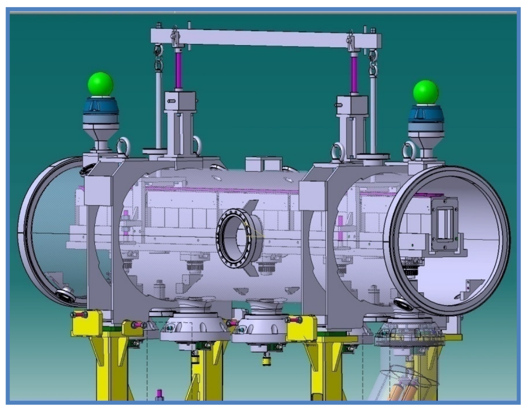


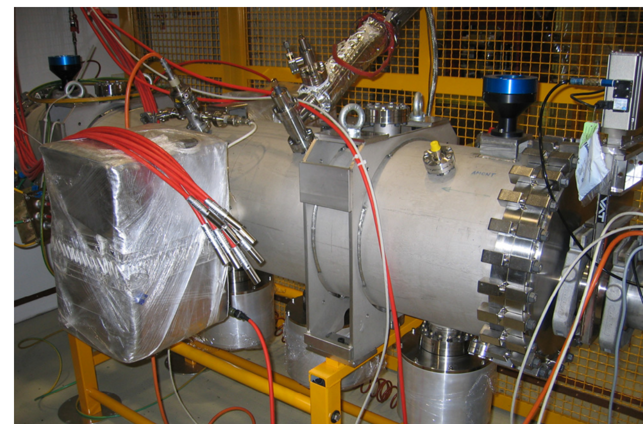
Linac4 → PSB Transfer Line

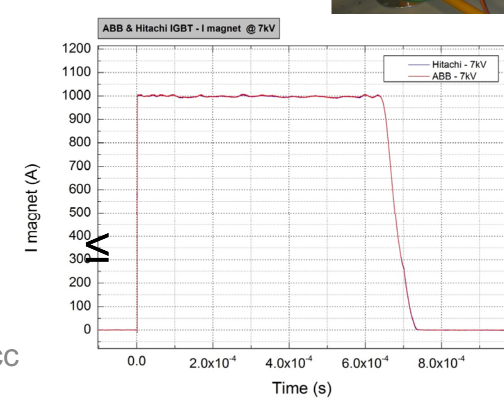


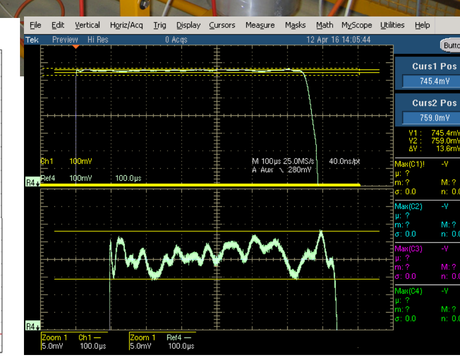
Modify BI.DIS for 4.3 mrad @ 160 MeV

Performance increase of 1.9 in ∫B•dl of BI.DVT30, BI.QNO30, BI.QNO40, BI.DVT40.



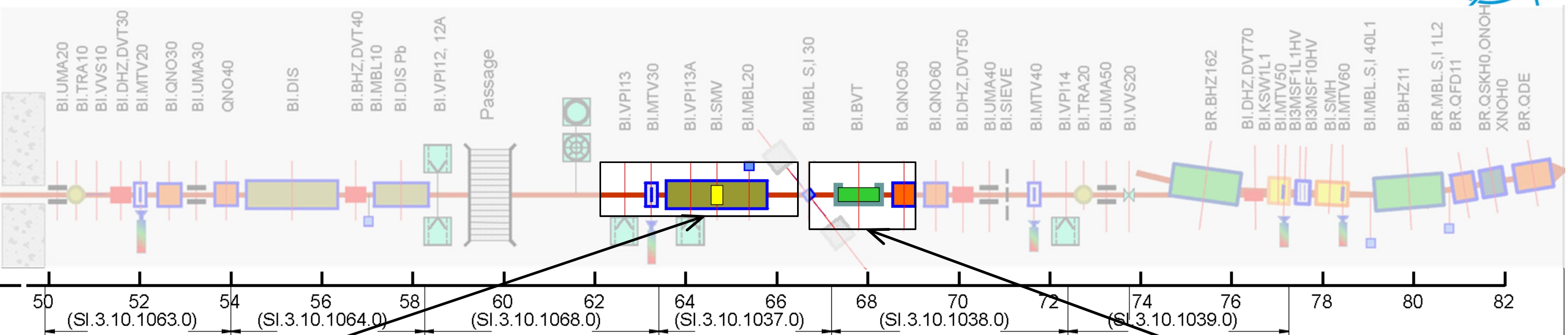




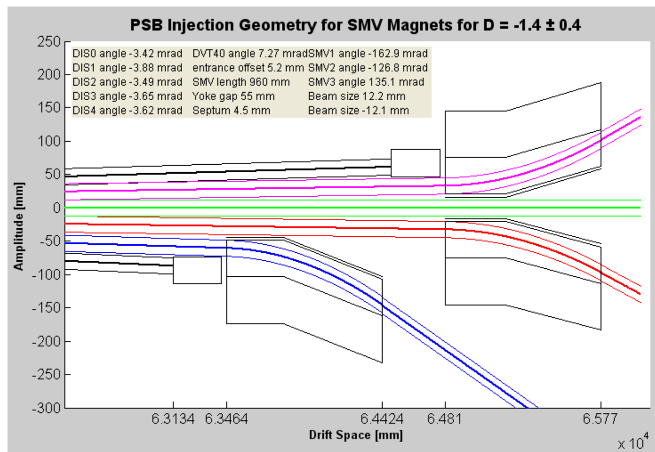


≤ 2 µs rise time and ±1 % ripple achieved

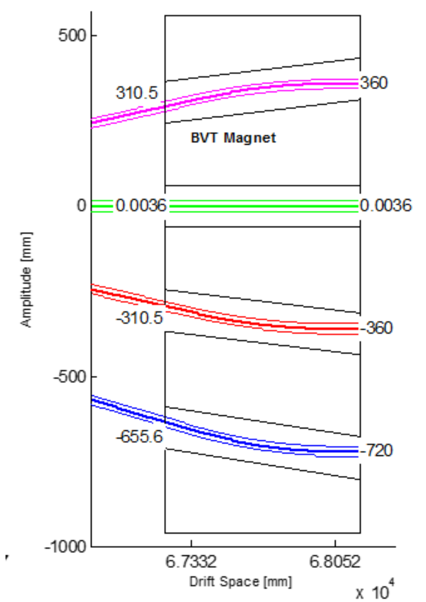
Linac4 → PSB Transfer Line

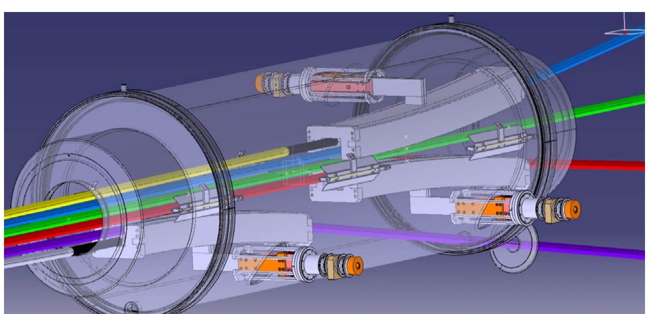


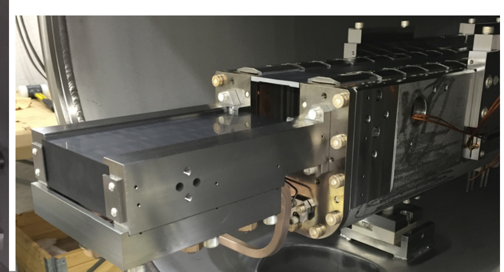
New BI.SMV,
4 mm thick septum and
70 mm horizontal
aperture for
~165 mrad @ 160 MeV
with associated new
pulse generator.



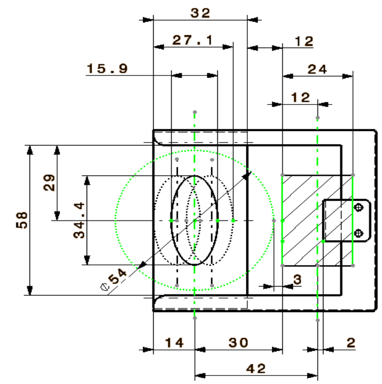
~0.36 Tm required
from BI.BVT for ~175
mrad @ 160 MeV





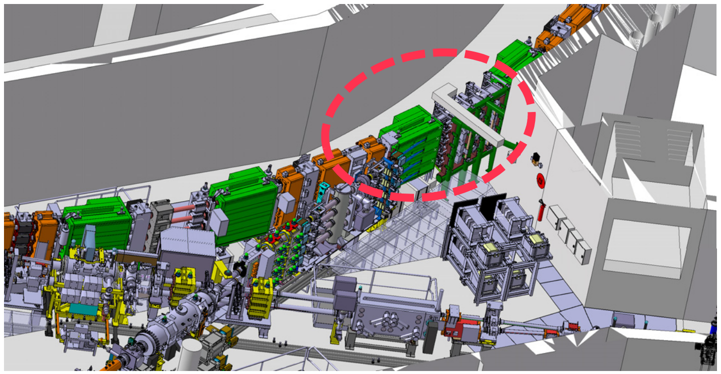


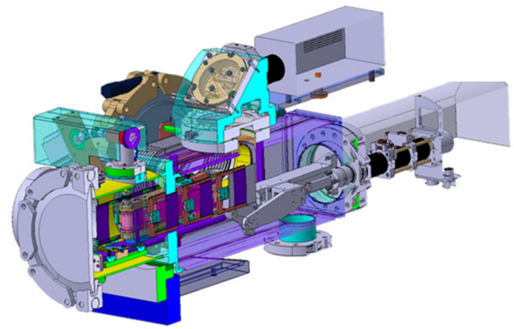
PSB Injection

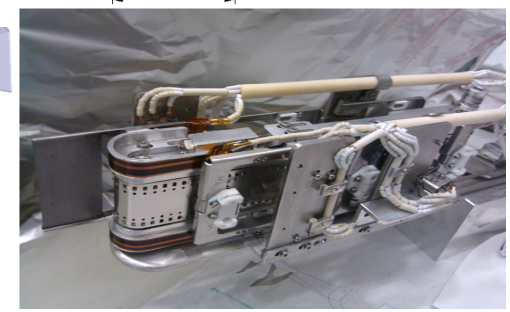


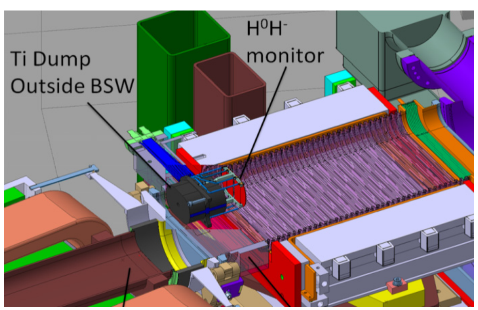
R. Nouilbos

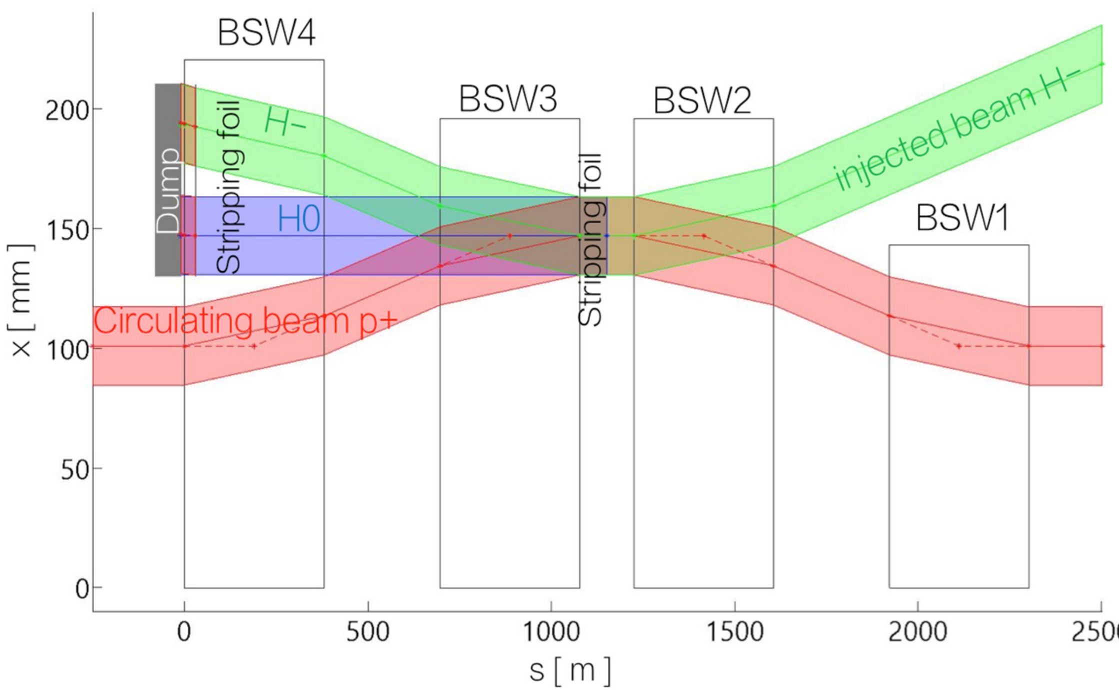
H^- charge-exchange injection



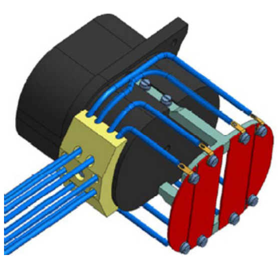






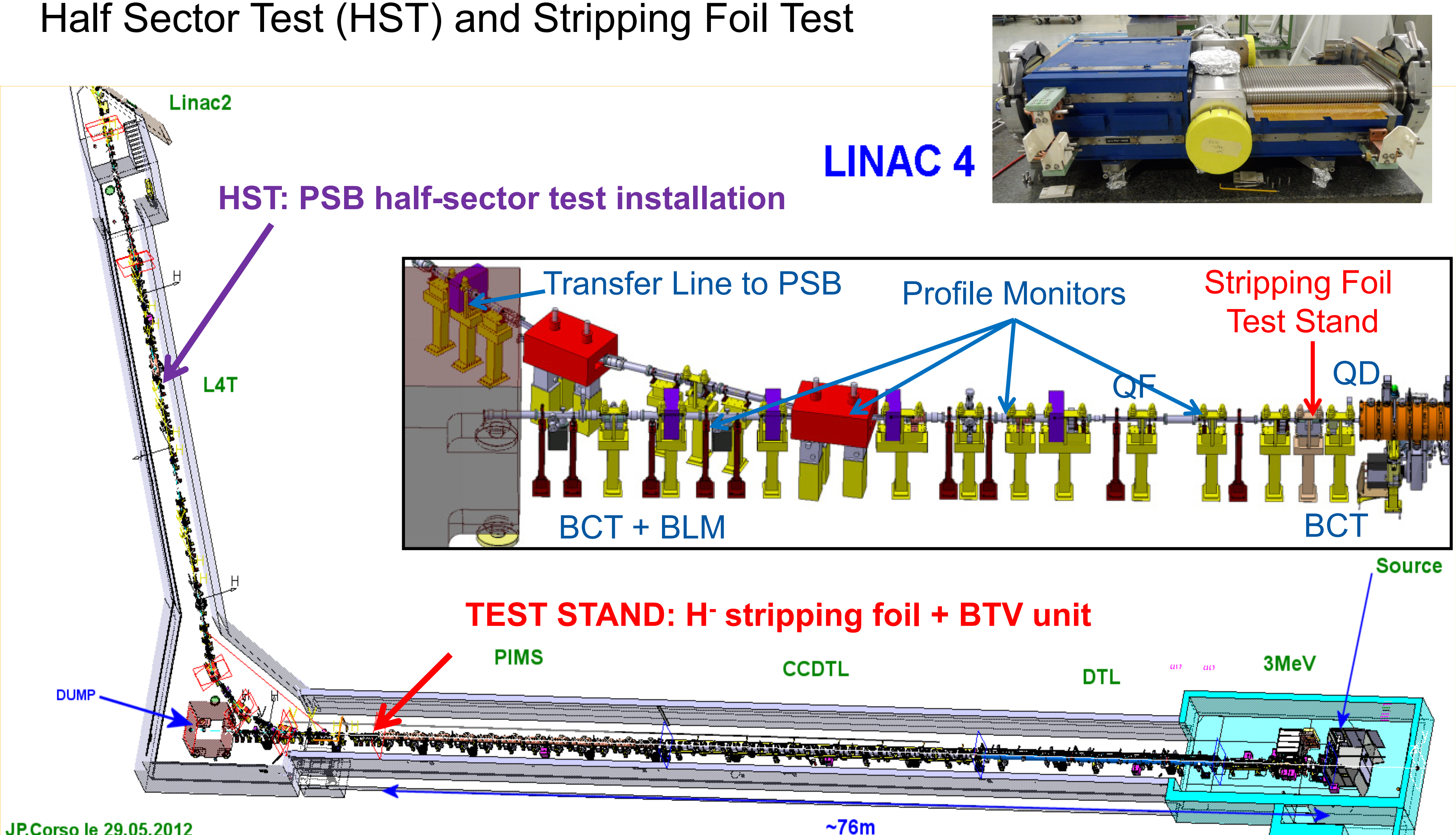


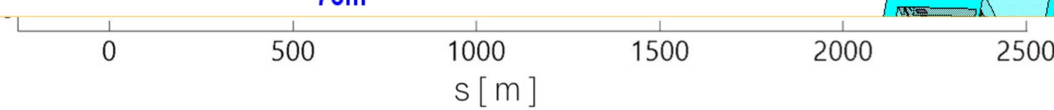
F. Roncarolo



PSB Injection

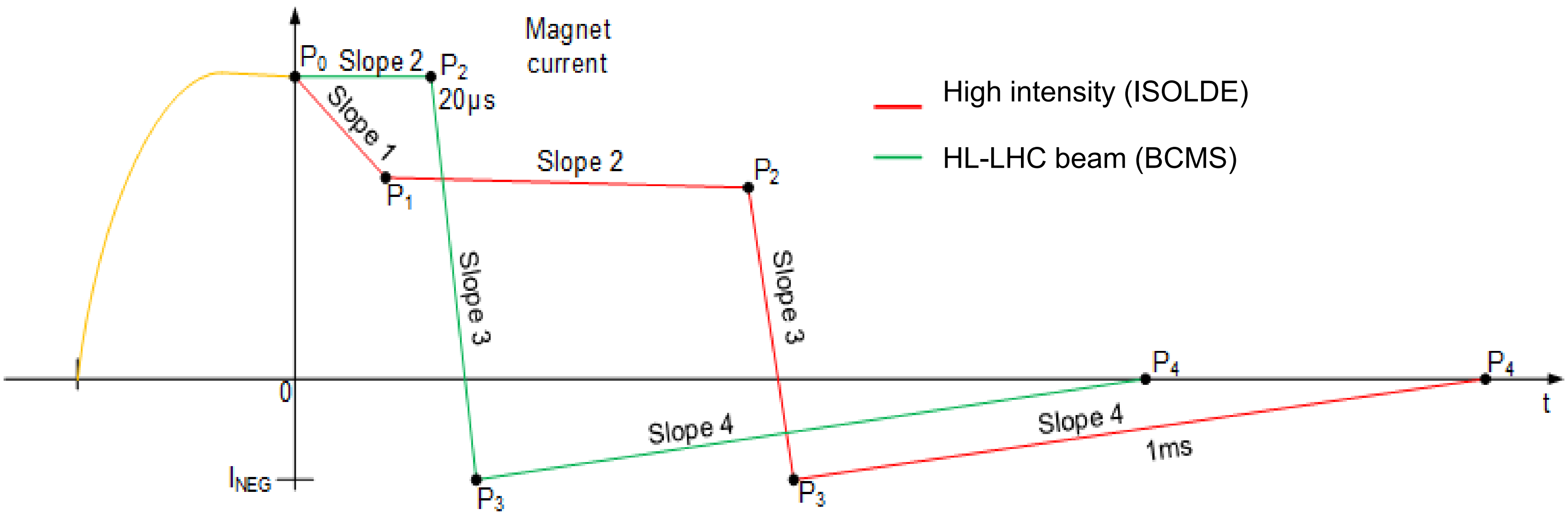
Half Sector Test (HST) and Stripping Foil Test





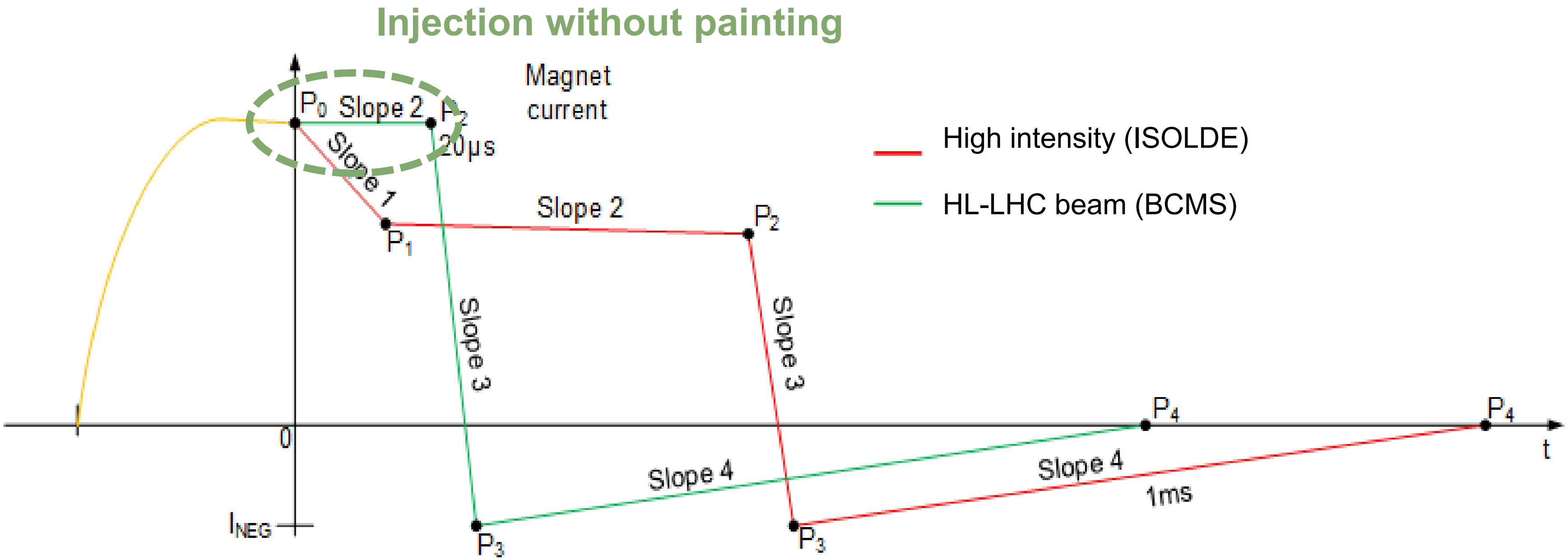
PSB Injection

KSW modulation

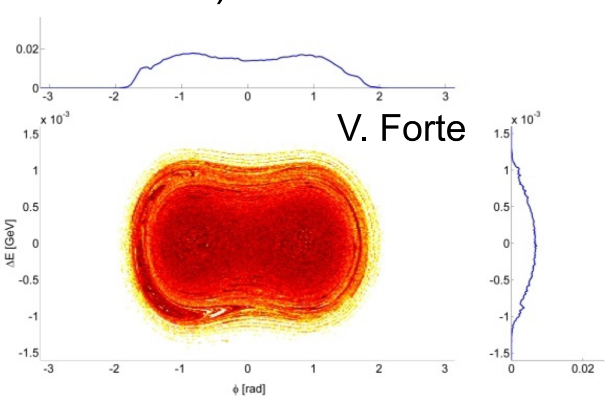


PSB Injection

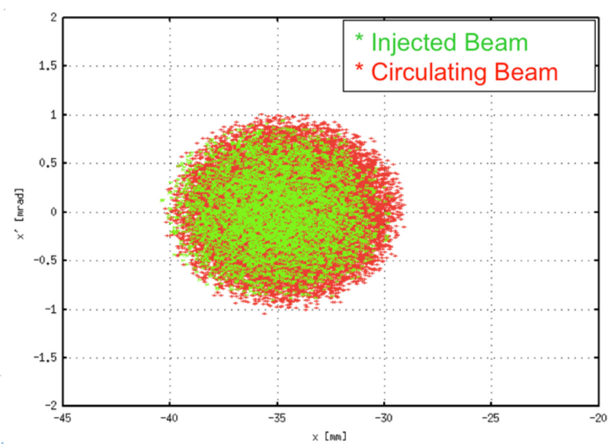
KSW modulation



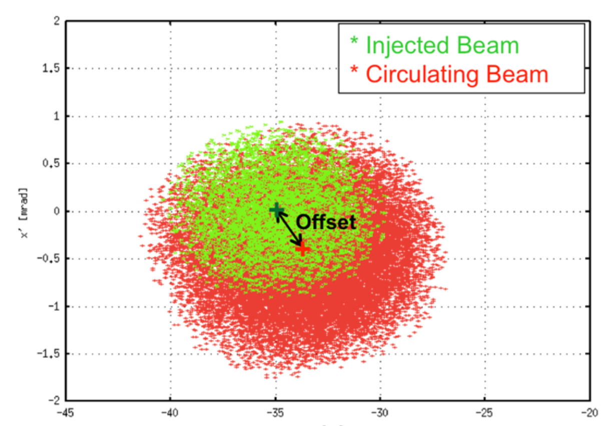
Fixed energy spread (1.1e-3 dp/p
336 keV RMS) - **616 ns**



On-axis injection



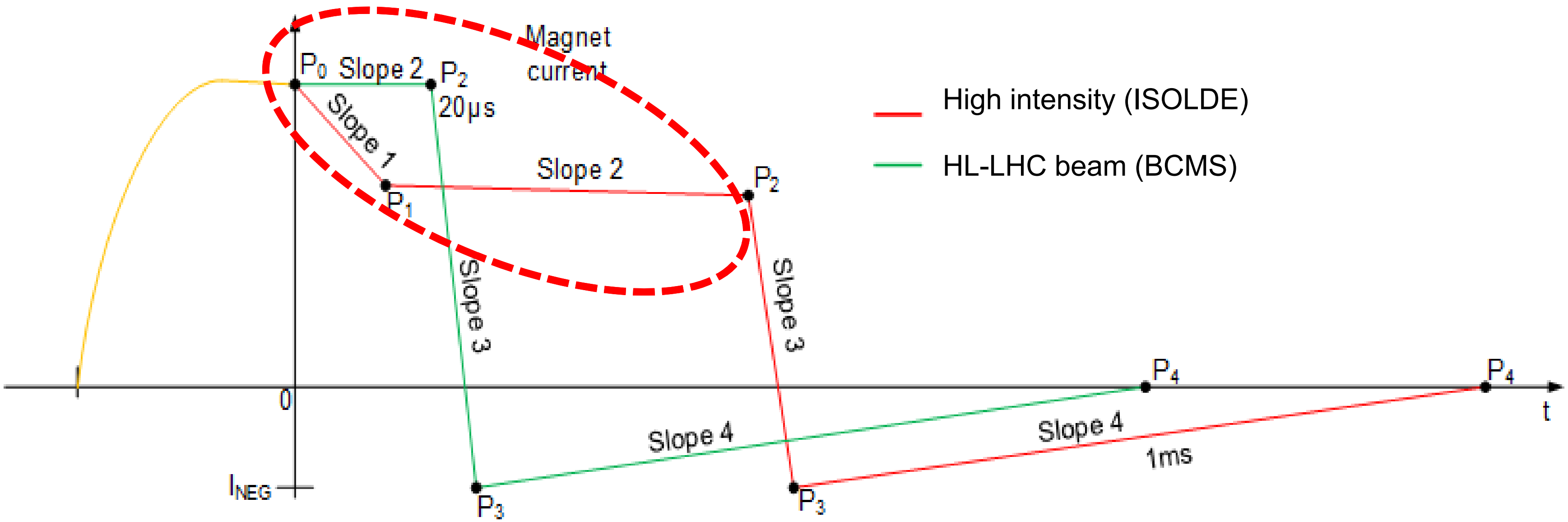
Offset injection



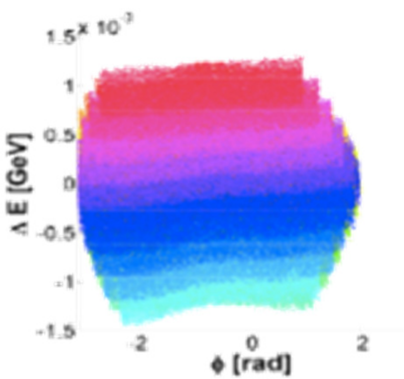
PSB Injection

KSW modulation

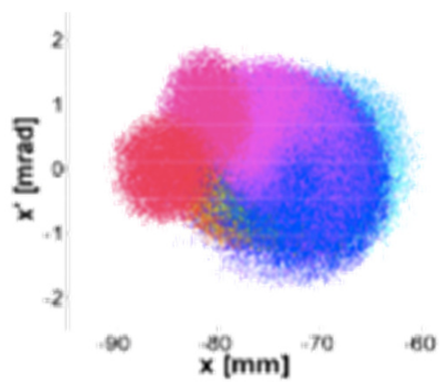
Injection with painting



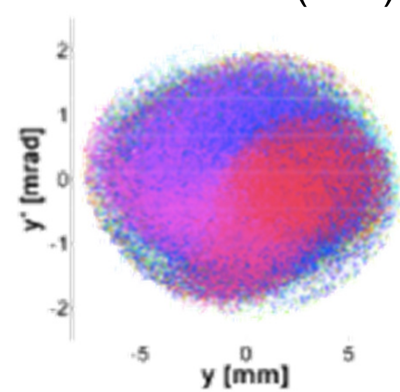
Longitudinal painting (wsc)



Horizontal painting (wsc)



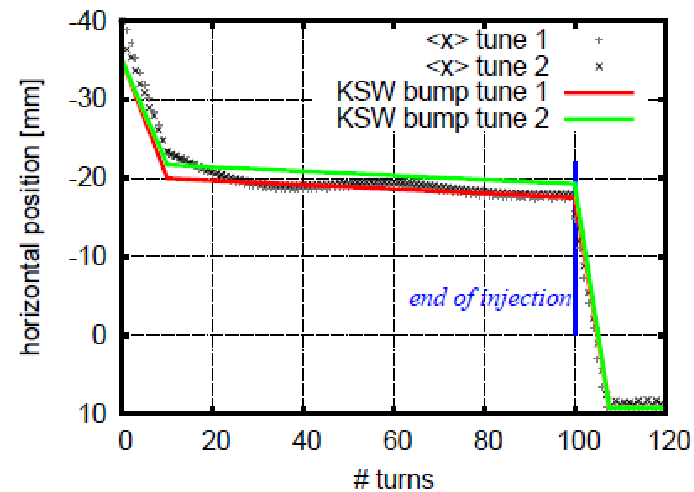
Vertical offset (wsc)



PSB Injection

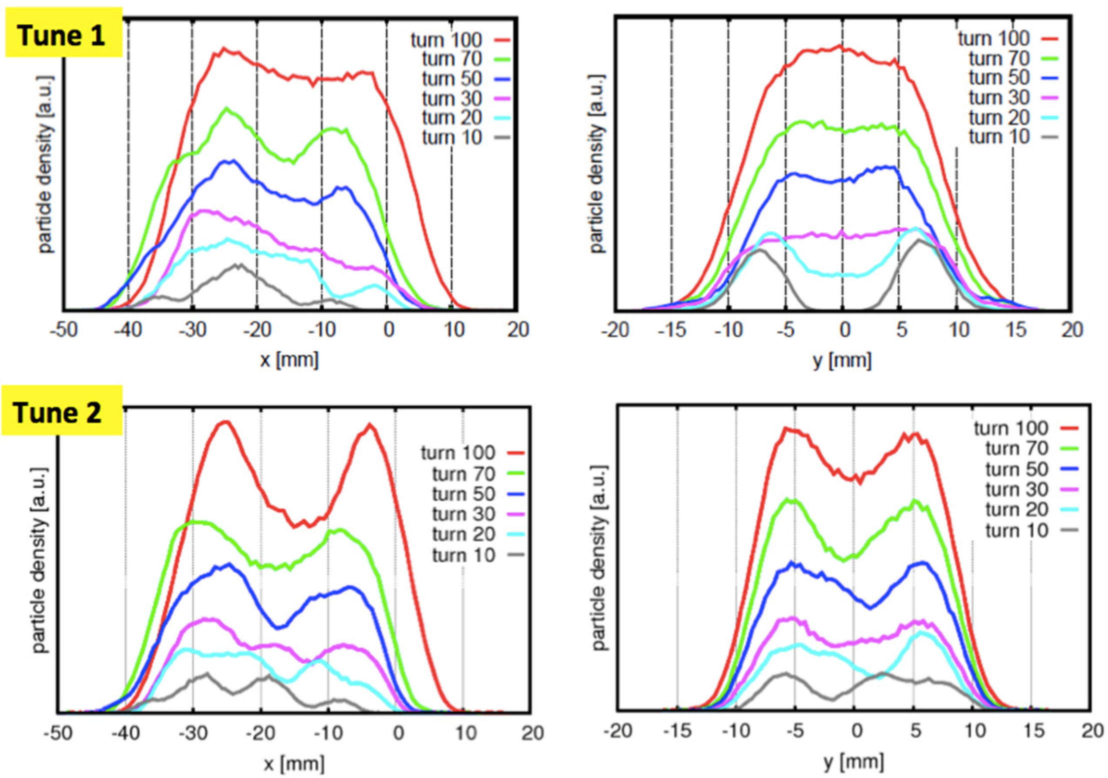
Optimization studies (see also THPM9X01)

J.L. Abelleira Fernandez

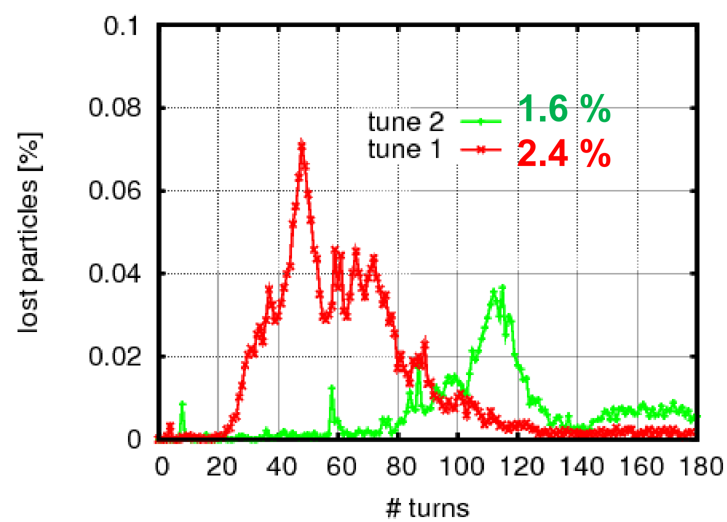


Effect of tune on transverse painting:
Tune 1: Q_x=4.28, Q_y=4.55 (baseline)
Tune 2: Q_x=4.43, Q_y=4.60 (alternative)

Evolution particle distribution ISOLDE beam



Beam loss evolution



PSB Injection

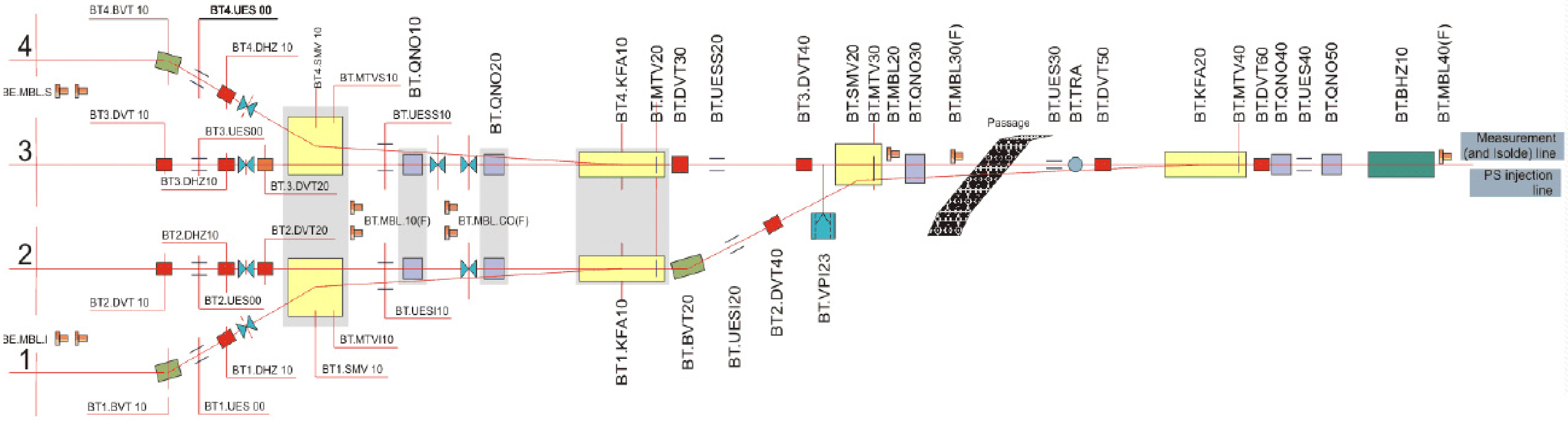
J.L. Abelleira Fernandez

USER	ppr [10^{12}]	Y_{off} [mm]	$\varepsilon_{N,x}$ (H/V) [mm mrad]	$\varepsilon_{N,y}$ [mm mrad]	Longitu-dinal painting	KSW waveforms				
						t_1 [μs]	I_1/I_0	t_2 [μs]	I_2/I_0	t_3 [μs]
NORMGPS/HRS*	16	8	13(15)	6(8)	yes	20	0.53	100	0.52	107.82
NORMGPS/HRS*	13	8	13(15)	6(8)	yes	22	0.51	80	0.50	87.62
STAGISO	6.6	6.5	5	4	yes	15	0.70	40	0.69	49.52
STAGISO	3.4	6.5	5	4	no	16	0.61	20	0.60	28.62
CNGS like*	8	8	10	6(8)	yes	20	0.55	50	0.54	58.02
NTOF*	9	8	10	6(10)	yes	18	0.58	60	0.57	68.32
AD	6.5	8	8	6	yes	16	0.61	40	0.60	48.62
AD	4	8	8	6	no	23	0.44	25	0.43	31.92
SFTPRO	6	8	8	6	yes	17	0.6	40	0.59	48.52
SFTPRO	6	8	8	6	no	17	0.59	37	0.58	45.42
LHC 1	3.42	3	1.2	1.2	no	10	0.88	21	0.87	32.32
LHC2	3.42	0	0.6	0.6	no	10	1.00	21	1.00	33.62

* Emittance which fits in HW acceptance

PSB → PS @ 2 GeV

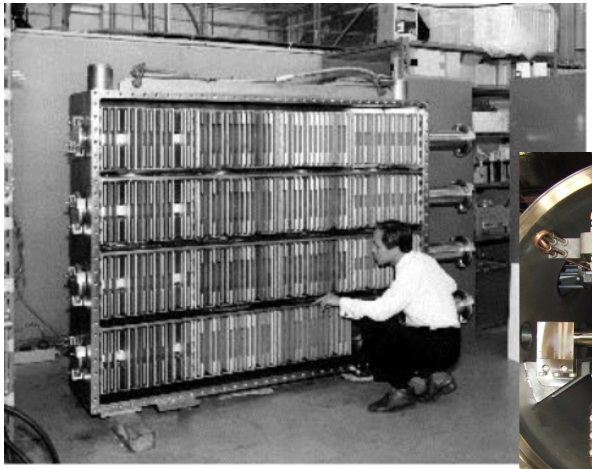
- After Linac4 and PSB injection upgrade, the injection in the PS would be the new bottleneck due to space charge → 1.4 to 2 GeV to mitigate space charge
- Required upgrades
  - All magnets have to cope with 30% increase in rigidity
  - Transfer LHC beams with minimal possible emittance growth and large emittance fixed target beams with reduced losses → TL with pulse to pulse modulated (ppm) capability which allows for different optics from cycle to cycle
  - Maintain 1.4 GeV transfer possibility (i.e. ISOLDE)

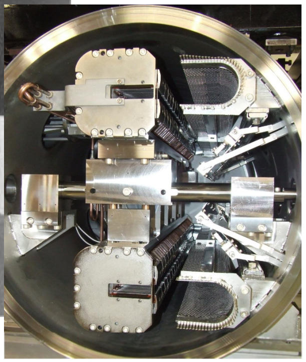


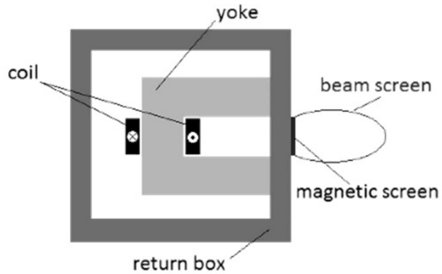
PSB → PS @ 2 GeV

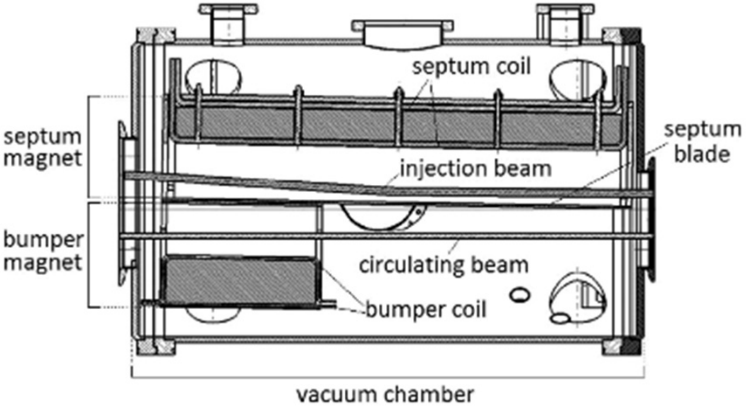
HW changes:

- PSB extraction system with minor modifications (powering margins)
- Recombination septa length increased (same cross section, same tank)
- Need of upgrading recombination kickers (KFA10 and KFA20) is being investigated
- New recombination and switching dipoles, new quadrupoles, new powering
- New dumps (already installed) and beam stoppers
- New eddy current injection septum
- Reconfiguration of PS injection kicker into permanent short-circuit mode





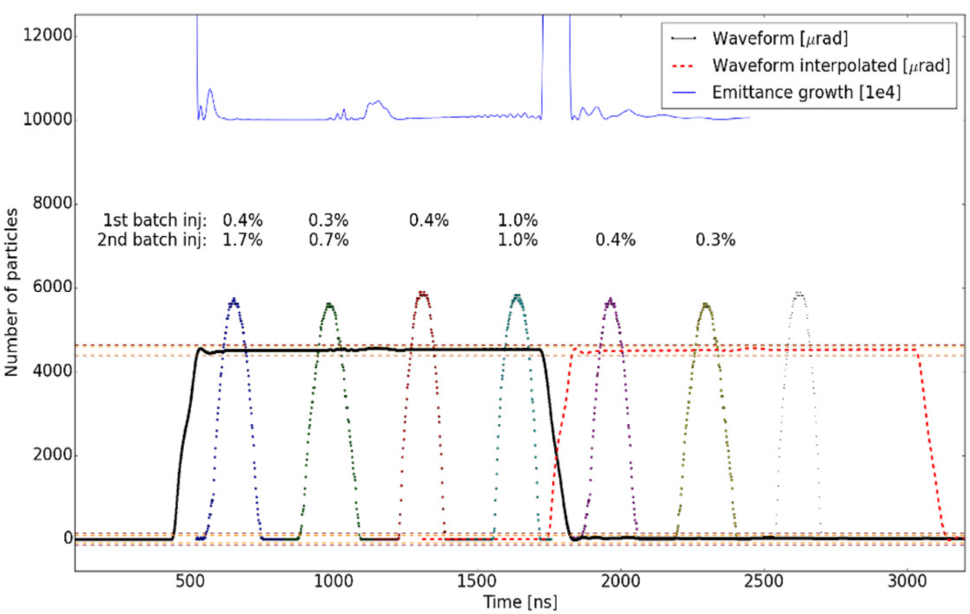




PSB → PS @ 2 GeV

Optics, stability and emittance growth:

- Unavoidable optics mismatch dominates the emittance growth → minimise the spread in betatron and dispersion functions between the different lines.
- The emittance growth due to dynamic magnet errors was studied and used for magnet specifications
- Systematic errors from kicker waveforms have been studied by folding longitudinal bunch profiles and kicker waveforms in order to get a weighted effect of emittance growth from kicker field ripple.



W. Bartmann

	Hor/Ver Emittance growth [%]		
Mismatch	LHC	HL-LHC	High Int.
Steering	0.3/1.5	0.3/1.5	0.1/0.5
Betatron	4.6/6.8	1.3/0.0	2.0/0.0
Dispersion	4.4/8.8	0.2/2.4	0.0/5.3
Total	6.3/11.2	1.3/2.8	2.0/5.3

PSB → PS @ 2 GeV

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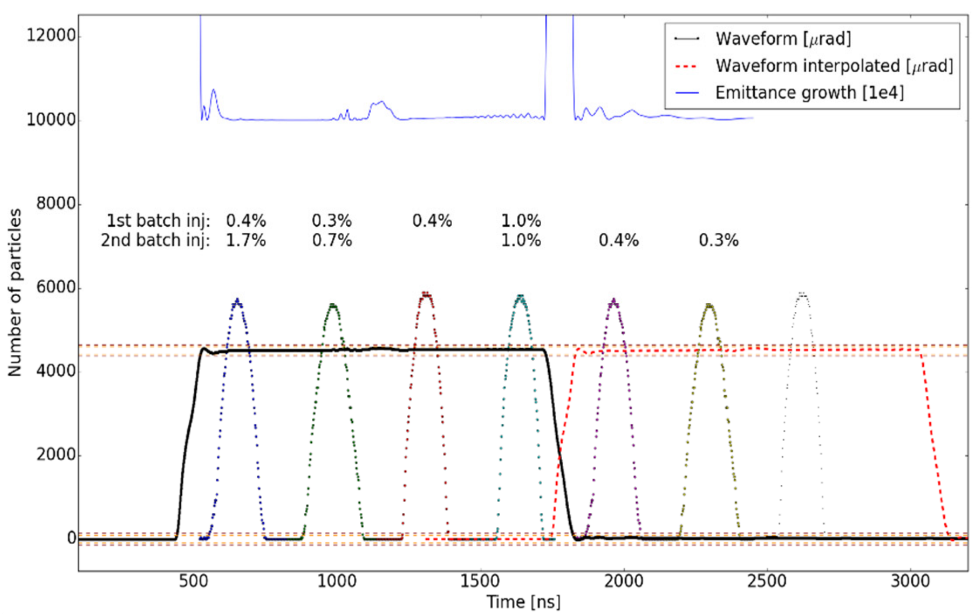
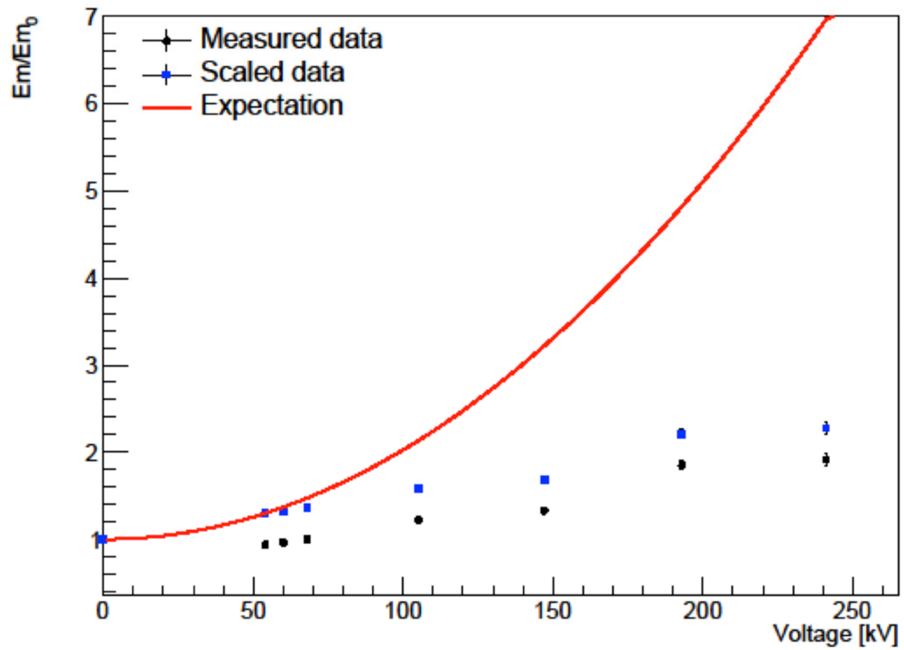
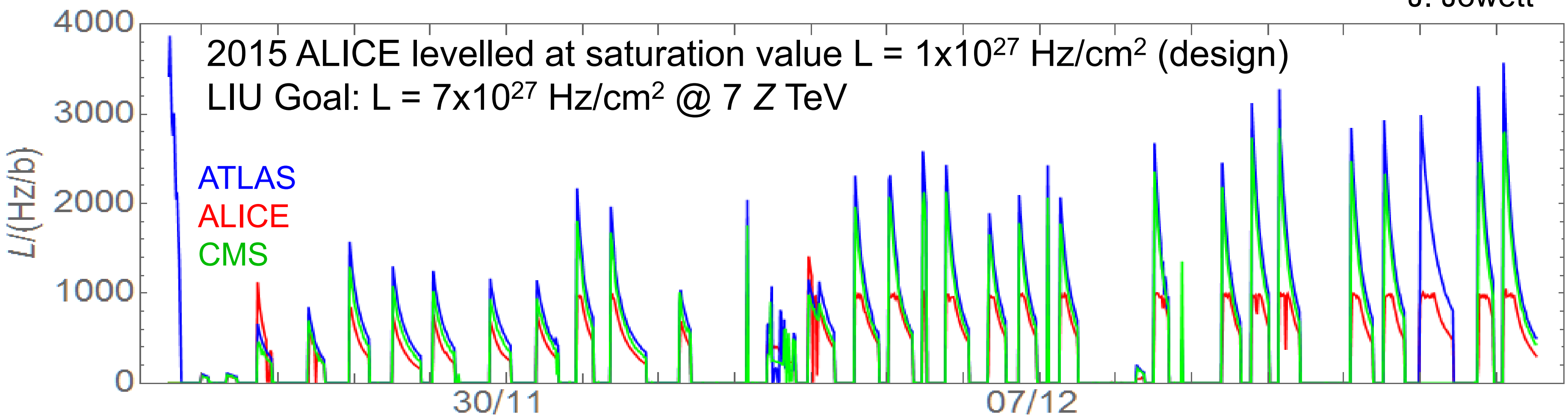




LIU Goal for Ions

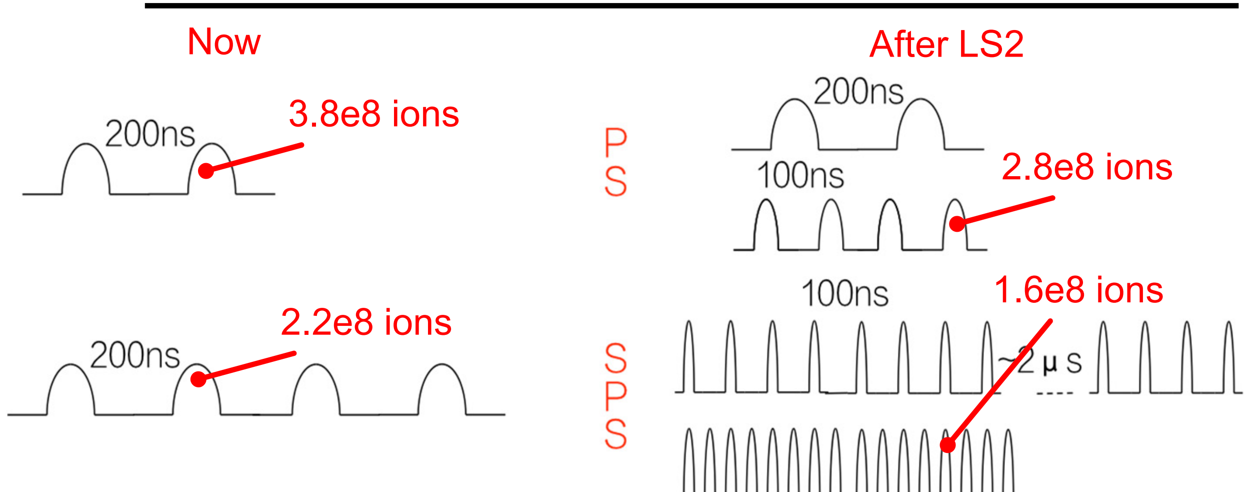
J. Jowett



	Achieved 2015	LIU-Ions
Ions Before RF Capture	7.8 x10^{8} /bunch	9.3 x10^{8} /bunch
Ions At LEIR Extraction	6.0 x10^{8} /bunch	7.4 x10^{8} /bunch

➢ Increase ion current from LEIR

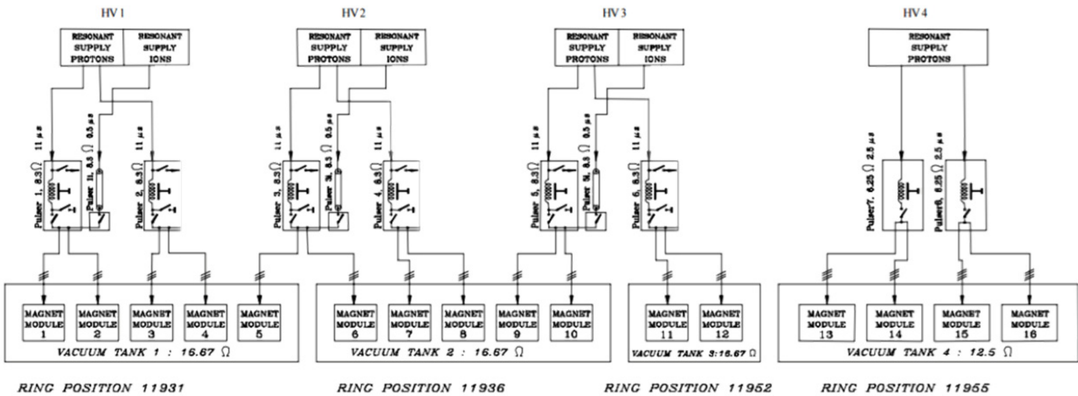
➢ Decrease bunch spacing



SPS Injection Upgrade

SPS injection kickers MKP:

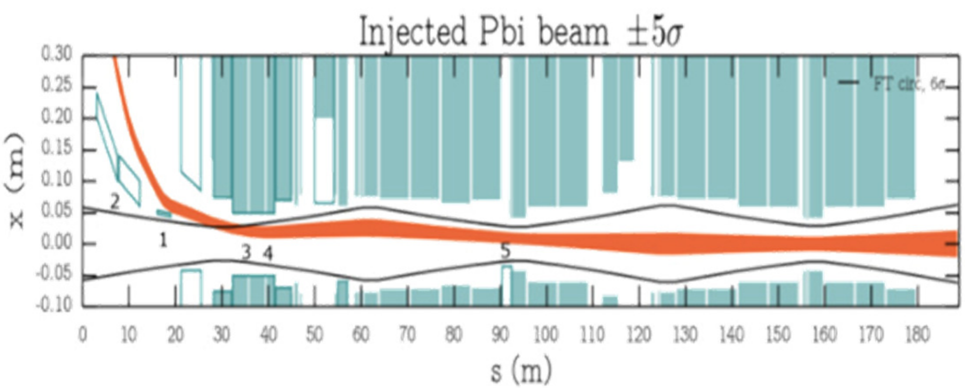
- 3 tanks with 5-5-2 fast kickers MKP-S (150 ns rise time 2-98%)
- 1 tank with 4 slow kickers MKP-L (**225 ns**)

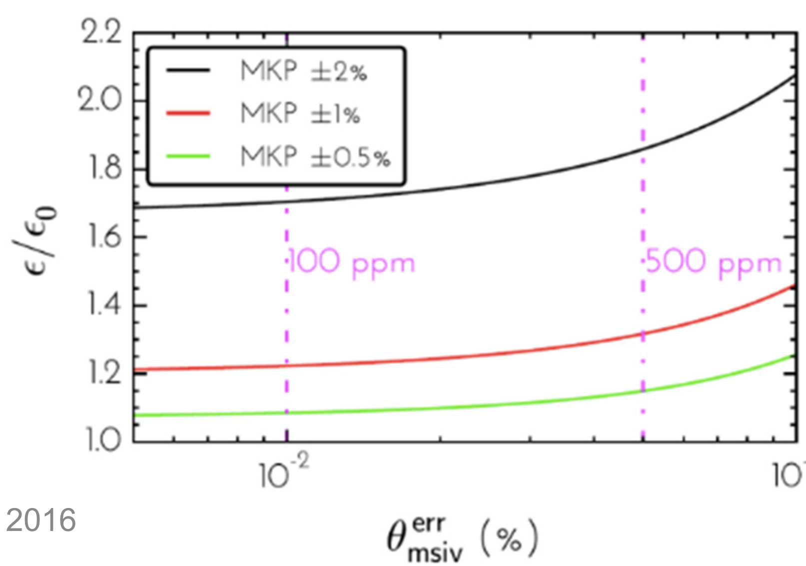


Reduced ion bunch spacing at injection ➔ injection kicker rise time down to 100 ns (**additional PFL in parallel to existing PFN**) less strong kick ➔ additional septa MSIV.

Emittance growth calculations for unmatched trajectories (MSIV and MKP ripples). For MKD ripple > 1% damper needed!

F.M. Velotti





B 2016

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Possible reduce rise time from 250 ns to 150-175 ns with present system?

Beam quality: emittance growth and tails population?

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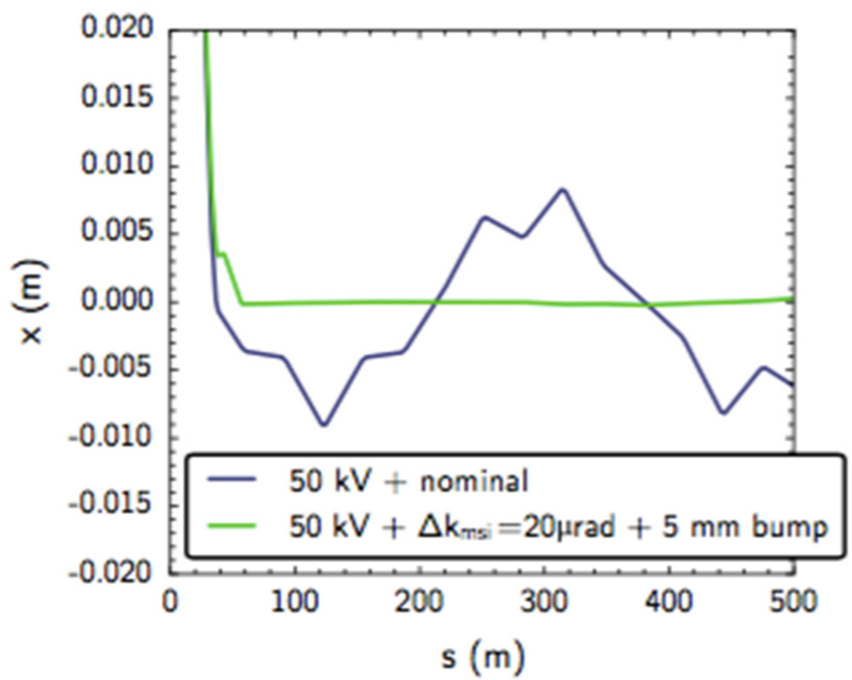
Idea: use only the fast MKP-S (49 kV) and reduce the required kick by introducing an injection bump (plus improved synchronization between different modules ➔ 30 ns gain in jitter).

B. Goddard, E. Carlier and F.M. Velotti



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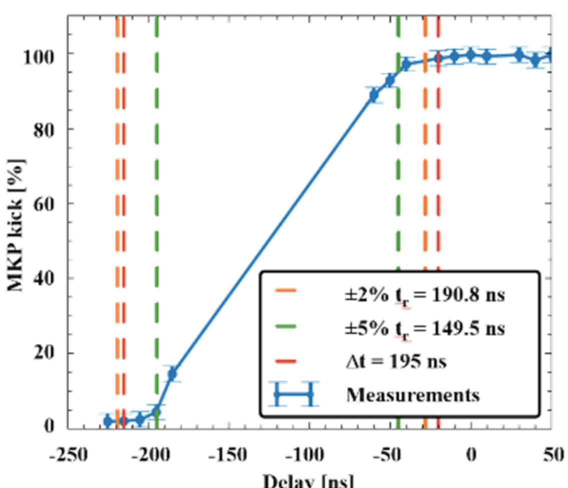
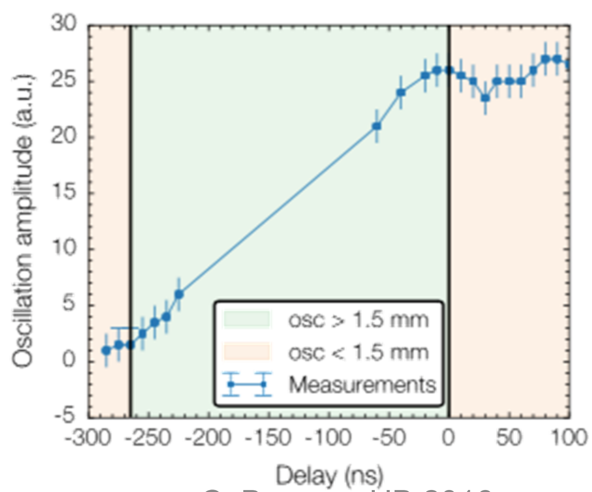
Measured waveform and residual oscillations for:

- 150 ns spaced ion bunches ➔ ~ 6 mm (need transverse damper!)
- 225 ns spaced proton bunches ➔ 1.5-2 mm





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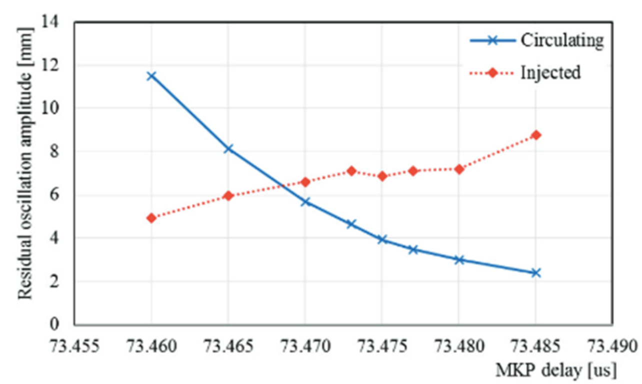

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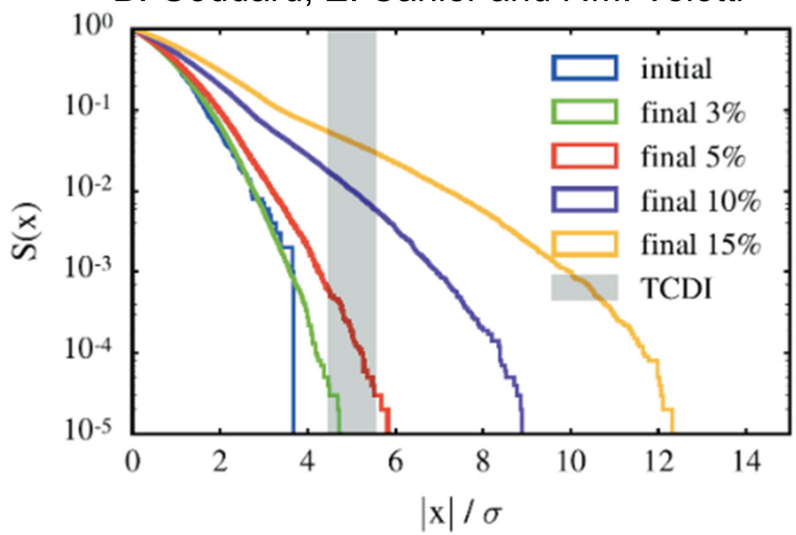
No measurable emittance growth was observed after adjusting the synchronization between the modules.

Tail population was calculated as a function of the MKP residual kick

B. Goddard, E. Carlier and F.M. Velotti



Intercepting Devices

Device	Comment	Material
TIDVG	Sweep, intensity limitation not brightness. Continuous dumping problematic	Sandwich: Graphite, Al,Cu, W
TIDH	Sweep. Dump at 28 GeV	Al
TBSJ	Injection dump: 26 GeV. Max intensity: 72 (48) bunches per shot	Stainless steel
TED LHC	450 GeV. Continuous dumping problematic. Graphite not in vacuum	Sandwich: Graphite, Al, Cu-Be, Cu
TED HiRadMat	450 GeV	
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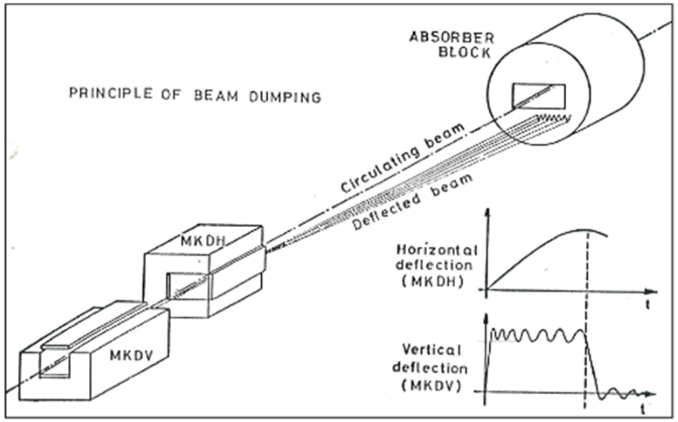
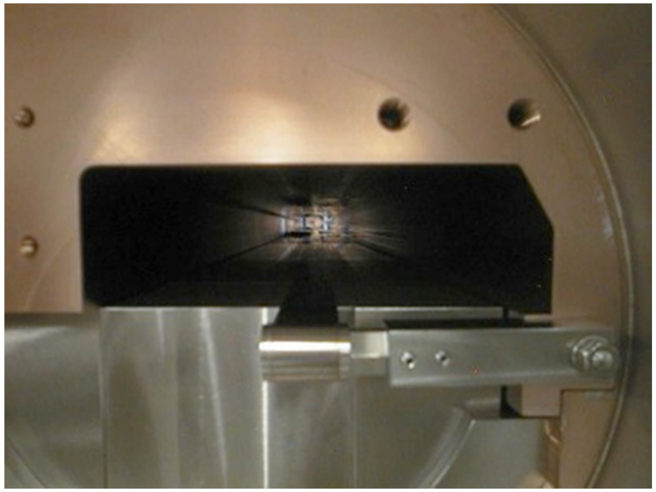
SPS internal dumps





V. Kain

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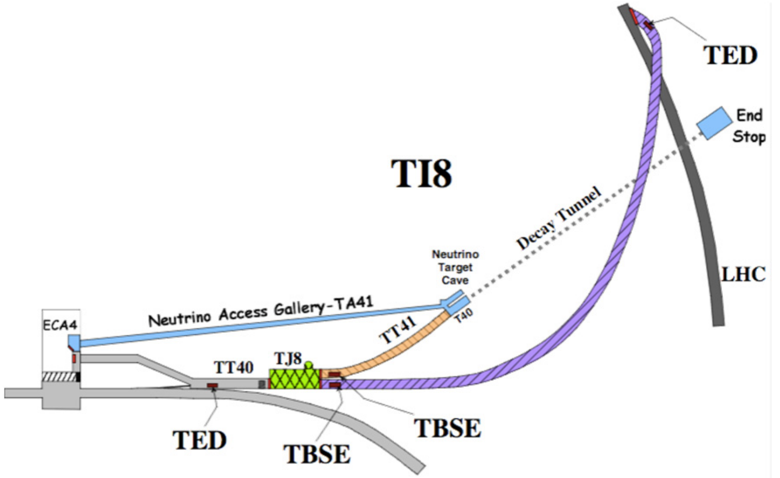
TL dump and stoppers



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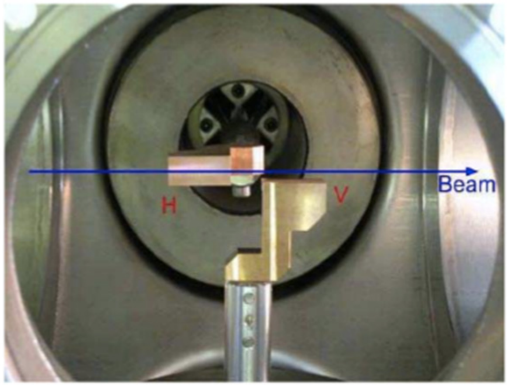
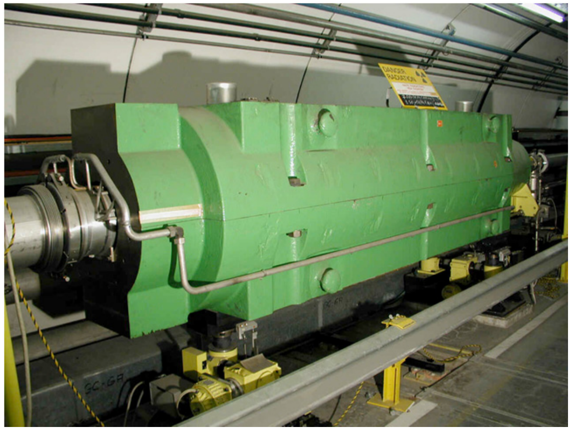
SPS betatron and momentum (TIDP) scrapers





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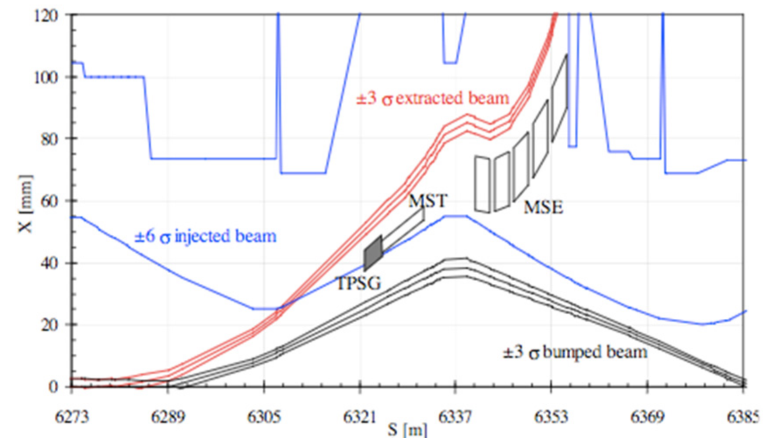
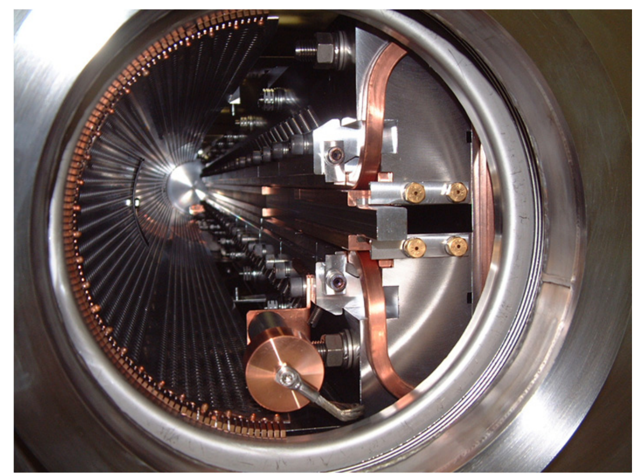
SPS protection elements (TPSG)





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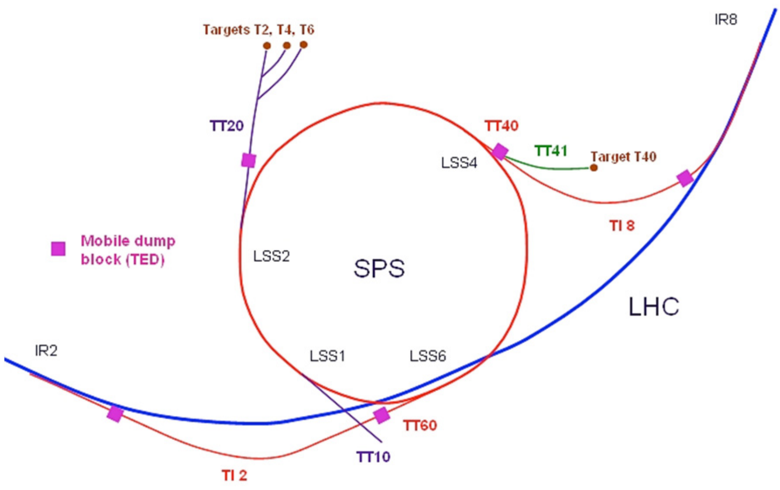
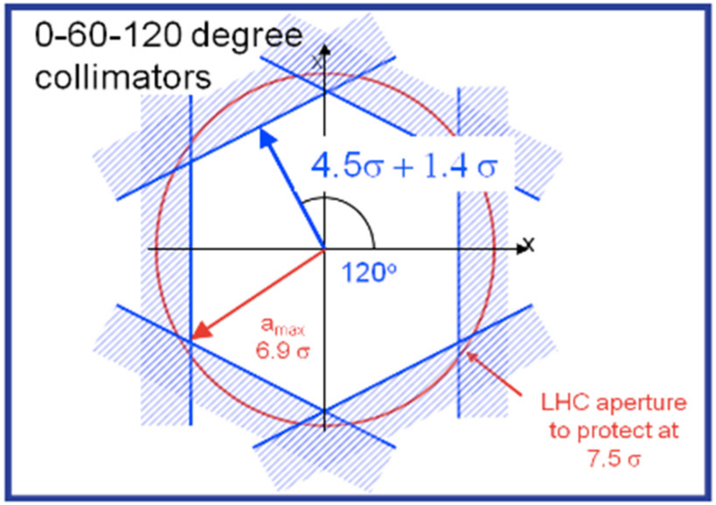
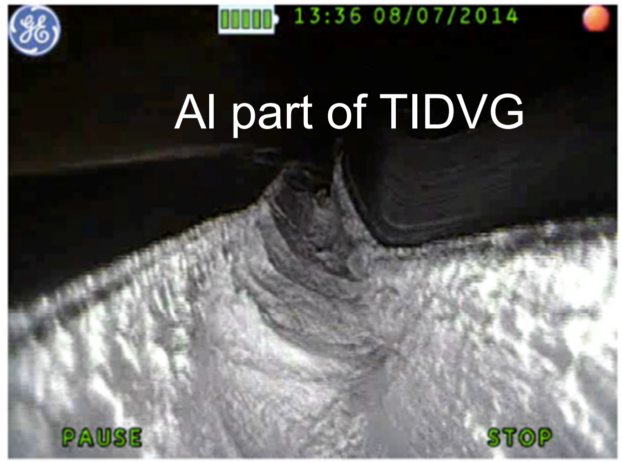
TL collimators

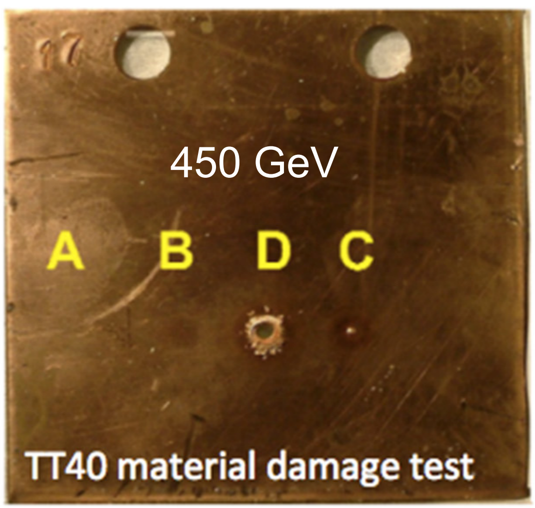




Intercepting Devices

Dealing with high power beams!





Intensity	# protons	Comment
A	1.2e12	No effect
B	2.4e12	Decolouration
C	4.8e12	Melting
D	7.2e12	Fragment ejections

Nominal LHC: 288x1.15e11= 3.3e13

Goal:
- Intercepting devices surviving
- Downstream elements protected
- Minimize activation (ALARA)

Intercepting Devices

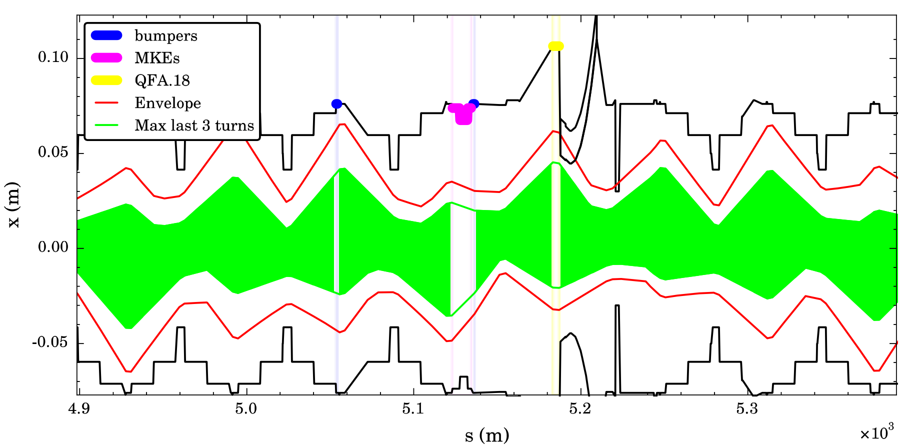
Device	Comment	Material	Upgrade for LIU
TIDVG	Sweep, intensity limitation not brightness. Continuous dumping problematic	Sandwich: Graphite, Al,Cu, W	**YES. LSS5 internal dump**
TIDH	Sweep. Dump at 28 GeV	Al	**OK**
TBSJ	Injection dump: 26 GeV. Max intensity: 72 (48) bunches per shot	Stainless steel	**OK, SPS 2 PS injection inhibit required**
TED LHC	450 GeV. Continuous dumping problematic. Graphite not in vacuum	Sandwich: Graphite, Al, Cu-Be, Cu	**NO, intensity interlocking upgrade**
TED HiRadMat	450 GeV		**TBD**
TBSE	450 GeV. Should survive one shot		**NO**
Scraper		Graphite	**OK, need fast BLMs**
TIDP	Momentum collimator. n/a		n/a
TPSG	450 GeV: Assume all beam in one spot	Sandwich: graphite <-> CfC, Ti, Inconel	**YES, material choice being finalized**
TCDIs	450 GeV.		**YES (HiRadMat, masks)**

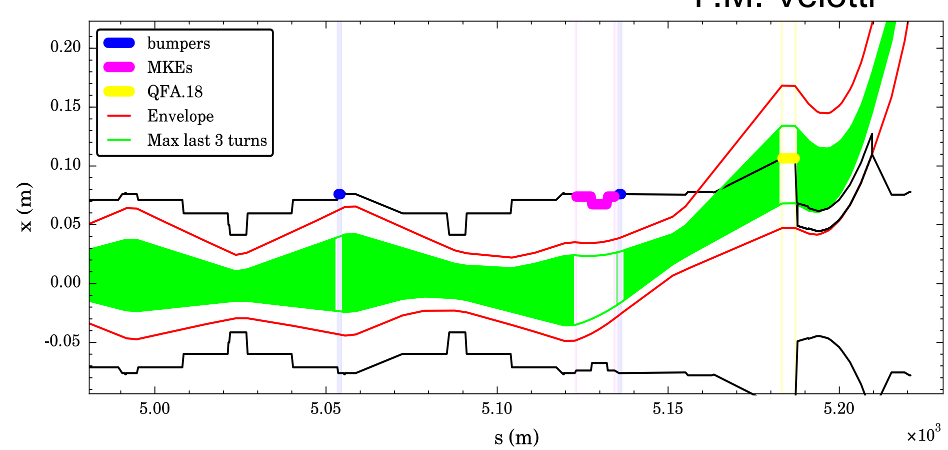
V. Kain

SPS Dump Upgrade

- Option of having a dedicated external system (for **ALL SPS beams: all energies and including Fixed Target FT beams**) with a dump block in a separated shielded cavern was investigated.
- LSS5 proposed for the extraction channel
- Unsuitable because:
  - Low energy beams (< 200 GeV) do not match aperture requirements at the extraction elements
  - The remaining part of FT beams, after slow extraction, is too large for the current extraction channels
  - Very big civil engineering footprint, very difficult for LS2 and extremely expensive

F.M. Velotti

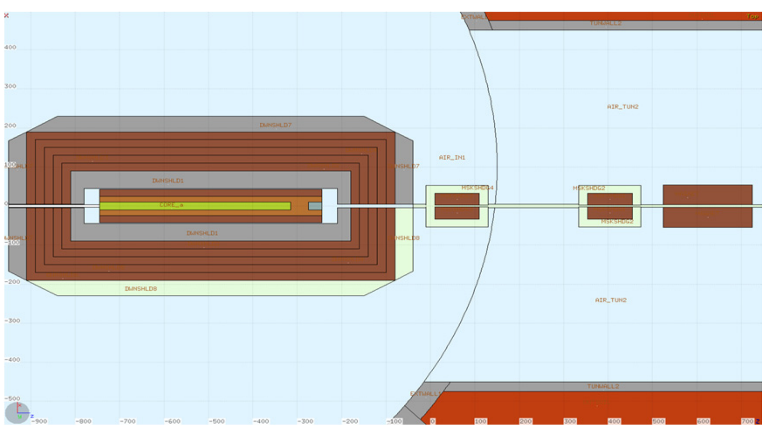


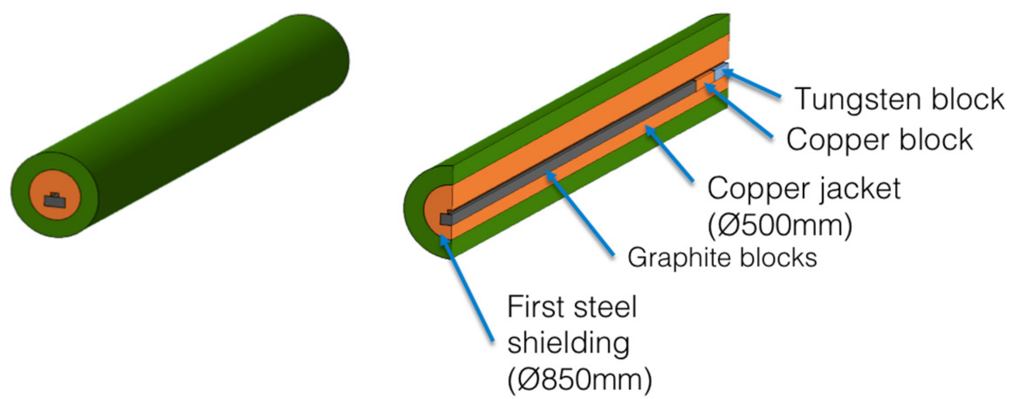


SPS Dump Upgrade

- Keep internal dump option but move it to LSS5 (reduce activation in LSS1 where now also injection system is hosted)
- Remove TIDH
- Upgrade extraction kickers (MKDV) system ➔ dump all energies including FT residual beam
- Upgrade TIDVG design (6 m instead of 4 m long, different materials and shielding)

F. Pasdeloup, A. Perillo Marcone, G.E. Steele





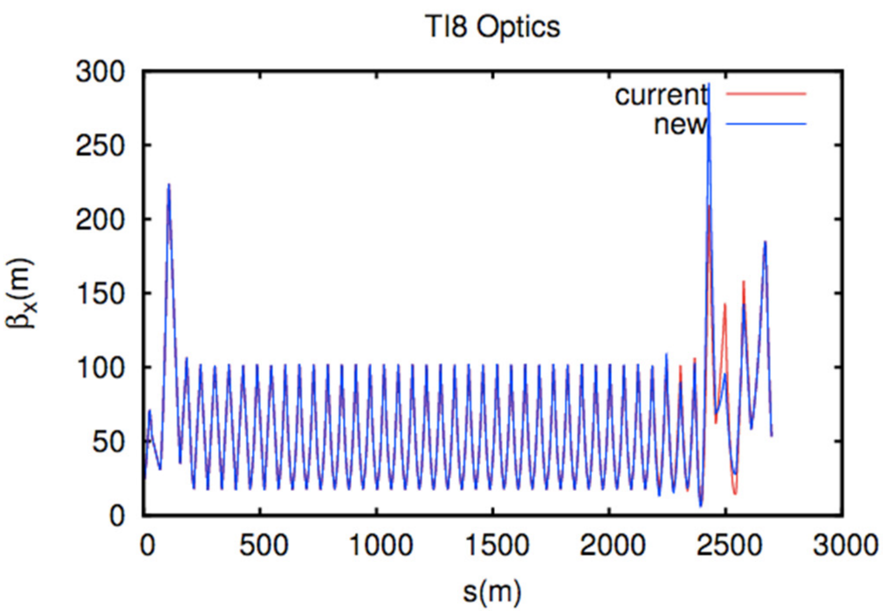
TCDIs Upgrade

Attenuation factor:

$$\frac{N_{\text{afterTCDI}}}{\varepsilon_{\text{afterTCDI}}} = \frac{1}{20} \times \frac{N_{\text{ultimate}}}{\varepsilon_{\text{ultimate}}} = \frac{1}{70} \times \frac{N_{\text{BCMS}}}{\varepsilon_{\text{BCMS}}}$$

Full SPS BCMS batch needs to be attenuated by x70 to avoid damage of downstream equipment ➔ longer TCDIs (1.2 m ➔ 2.1 m graphite or 3D C-C)

Robustness: strong dependence on beam size at collimators ➔ some TCDIs relocated and optics modified (additional power converters) to increase beam size (β_x x β_y > 3600 m^2)



E. Gianfelice Wendt

TCDI	s [m]	β_x [m]	β_y [m]	$\Delta\mu$ [°]
TCDIH.NEW1	2509.0	65.5	81.3	0.0
TCDIH.87904	2547.3	34.7	261.8	60.6
TCDIH.88121	2623.1	74.4	195.7	57.7
TCDIV.NEW1	2440.9	173.0	28.1	0.0
TCDIV.NEW2	2488.7	86.9	42.1	60.0
TCDIV.88123	2620.5	70.6	210.1	59.3

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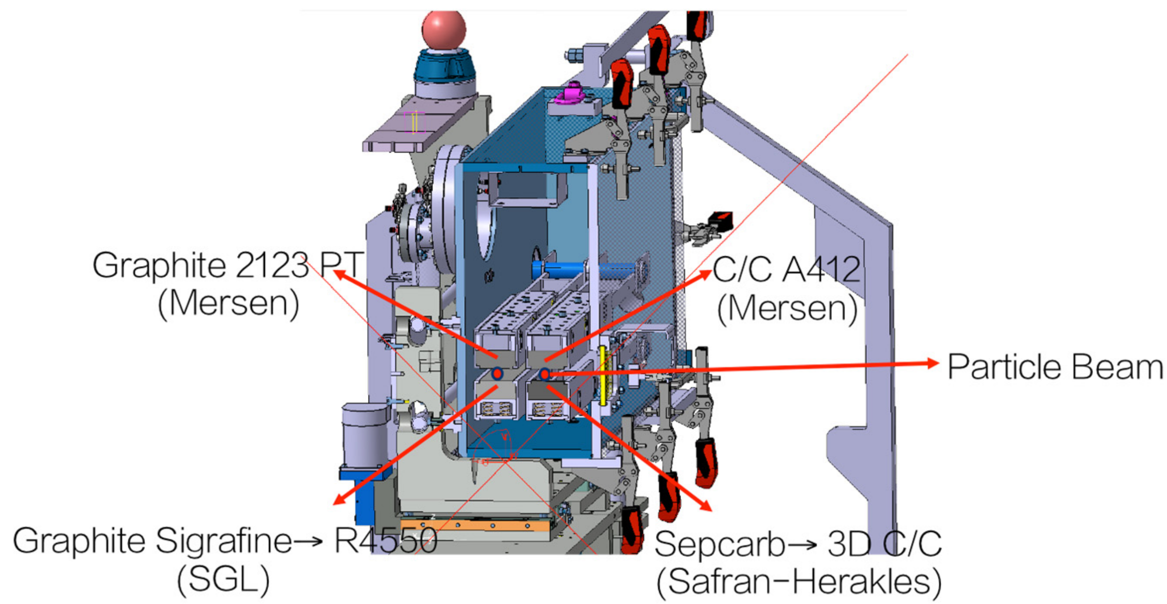
HiRadMat tests performed to asses material robustness (graphite or 3D C-C).
Performed in 2016 but beam not small enough ➔ tbr in 2017



F.L. Maciariello and F.X. Nuiry

Conclusions

- The HL-LHC nominal and ultimate luminosity goals require an important upgrade of the full chain of injectors (several talks presented at this workshop on different topics)
- PSB and PS injection systems and TL have to be upgraded to handle higher intensity beams (160 MeV and 2 GeV respectively) ➔ mitigate space charge
- The SPS injection system has to be modified to increase the current of ions
- Intercepting devices in the SPS and TLs have to withstand high energy densities and protect the downstream equipment ➔ HW upgrade and improved interlock logic

Thank you for your attention!