PSB injection: beam dynamics studies

C. Bracco, J. Abelleira Fernandez, E. Benedetto, V. Forte,

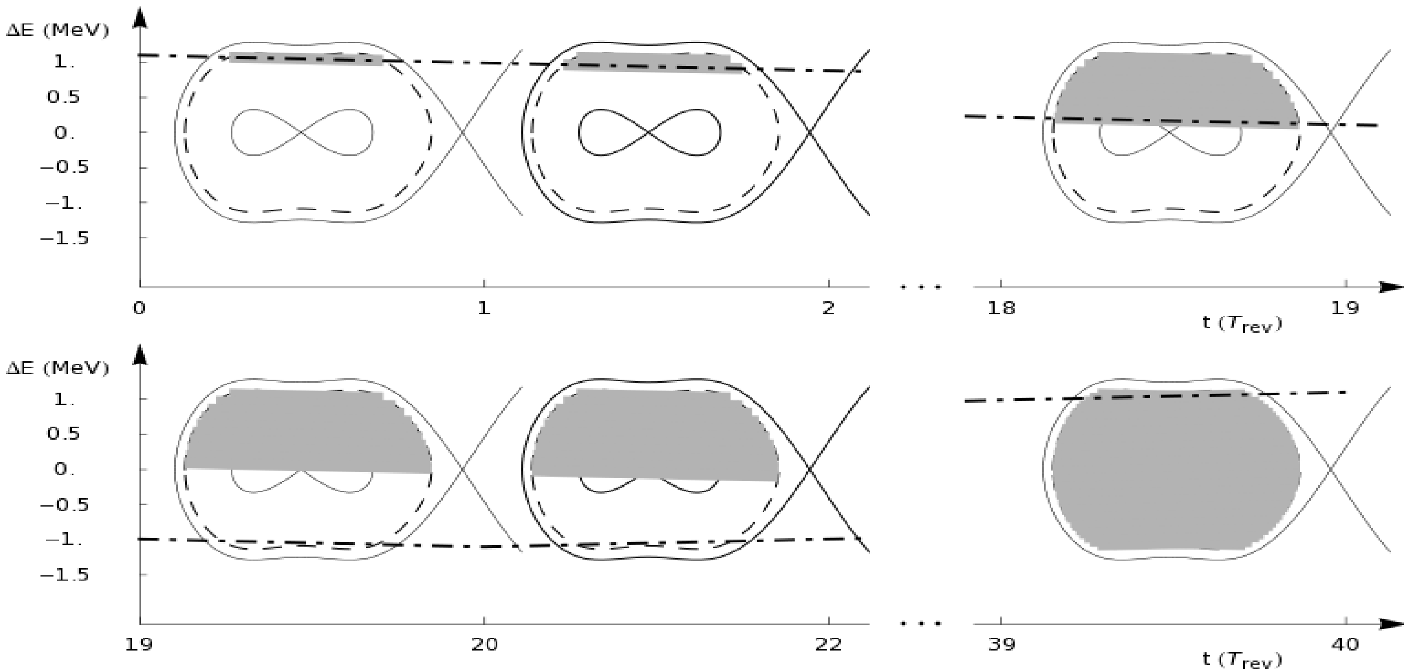
Acknowledgements: D. Aguglia, C. Carli, L. M. Coralejo Feliciano, B. Balhan, J. Borburgh, L. Ducimetiere, T. Fowler, B. Goddard, G. Grawer, A. Lombardi, B. Mikulec, D. Nisbet, W. Weterings

Outline

- Introduction
- Performed studies :
  - High brightness – small emittance beams
  - High intensity – large emittance beams
  - Perturbations induced by chicane BSW magnets
- Next steps

Longitudinal painting

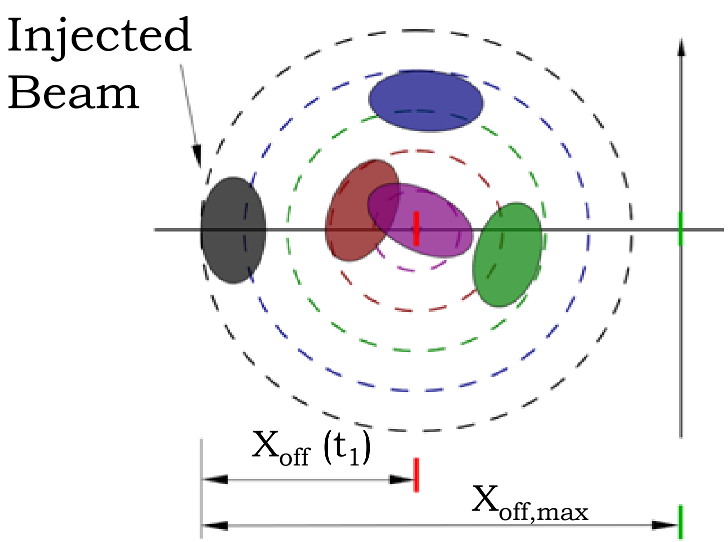
- Attenuation of space charge effects can be obtained by controlling the distribution, in phase space of injected particles
- Energy of the injected beam will be varied to fill the bucket with an equal density distribution.



±1.1 MeV energy distribution over a period of **minimum 40 turns**

Transverse Painting Principle

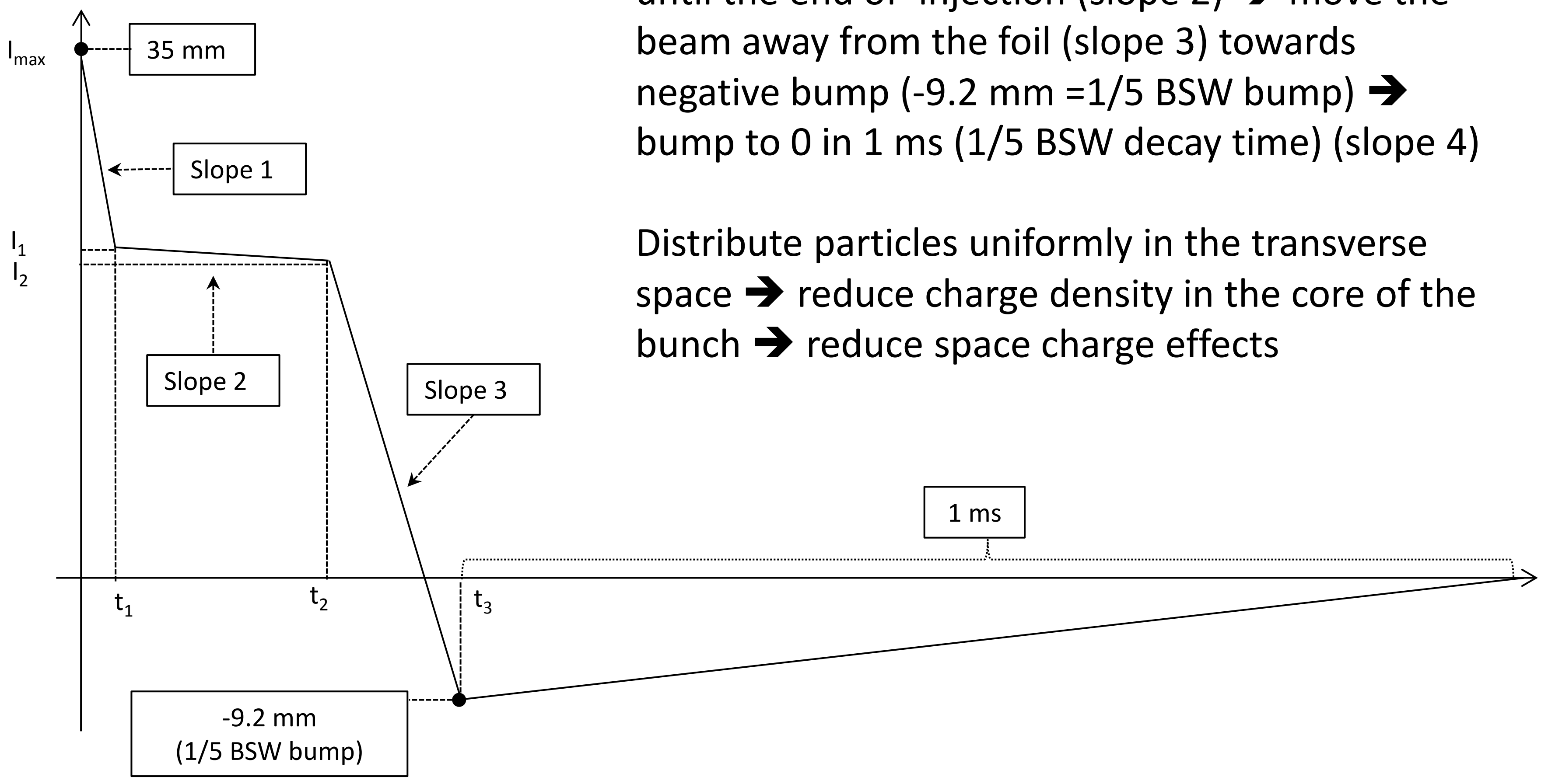
- Horizontal painting bump implemented
- Fill first the centre and then the outer area of the ellipse in the transverse phase space
- Decay time modulation of four kicker magnets (KSW), installed in the PSB lattice, allow to accomplish transverse phase space painting to required emittance and intensity.



Tracking studies with ORBIT (foil scattering, space charge, aperture model, etc.) ➔ define best parameter and injection scheme

Painting with KSW

Original design for KSW transverse painting



Fast decay (slope1) ➔ almost constant slope fall until the end of injection (slope 2) ➔ move the beam away from the foil (slope 3) towards negative bump (-9.2 mm =1/5 BSW bump) ➔ bump to 0 in 1 ms (1/5 BSW decay time) (slope 4)

Distribute particles uniformly in the transverse space ➔ reduce charge density in the core of the bunch ➔ reduce space charge effects

PSB User

User	Intensity/ring	norm. Emittance [mm mrad] H	norm. Emittance [mm mrad] V
LHC25A/B	2.96E+12**	< 2	< 2
LHC BCMS	1.48E+12**	1	1
LHCPILOT	5.00E+09	1	1
LHCINDIV	2.30E+10 / 1.35E+11	2	2
SFTPRO	6.00E+12	8	6
AD	4.00E+12	8	6
TOF	9.00E+12	10	10
EASTA/B/C	1.00E+11 / 4.50E+11	3	1
NORMGPS NORMHRS	1.00E+13 2.50E+13	15	9
STAGISO	3.50E+12	8	4
CNGS-like	6.00E+11 / 8.00E+12	10	8

**G. Rumolo's Tables https://edms.cern.ch/document/1296306/1

PSB User

		norm. Emittance [mm mrad]	
User	**Intensity/ring**	**H**	**V**
LHC25A/B	2.96E+12**	< 2	< 2
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TOF	9.00E+12	10	10
EASTA/B/C	1.00E+11 / 4.50E+11	3	1
NORMGPS **NORMHRS**	1.00E+13 2.50E+13	15	9
STAGISO	3.50E+12	8	4
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**G. Rumolo's Tables https://edms.cern.ch/document/1296306/1

Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize optics parameters
  - Optimize initial distribution (also longitudinal!)
  - Optimize KSW
  - Minimize foil crossings
  - Optimize PSB working point

What shall we expect in case of errors/non optimal parameters?

Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize optics parameters
  - Optimize initial distribution (also longitudinal!)
  - Optimize KSW
  - Minimize foil crossings
  - Optimize PSB working point

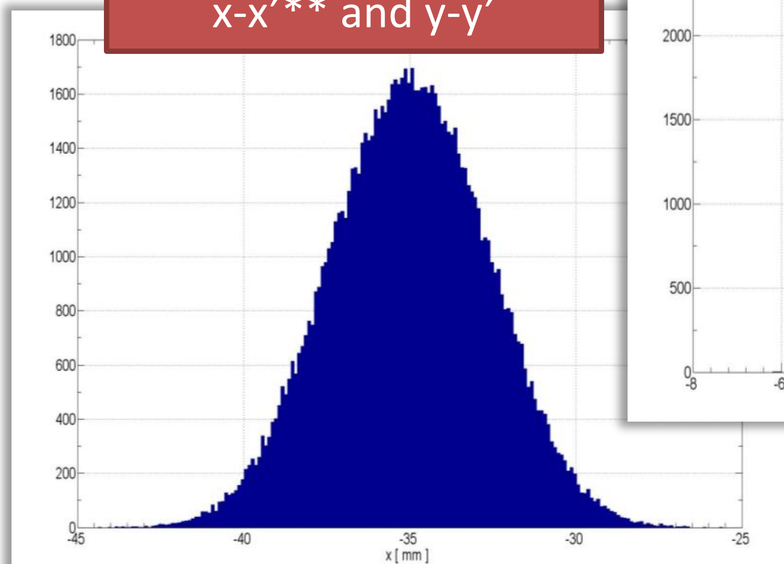
PSB Upgrade
LIU Project

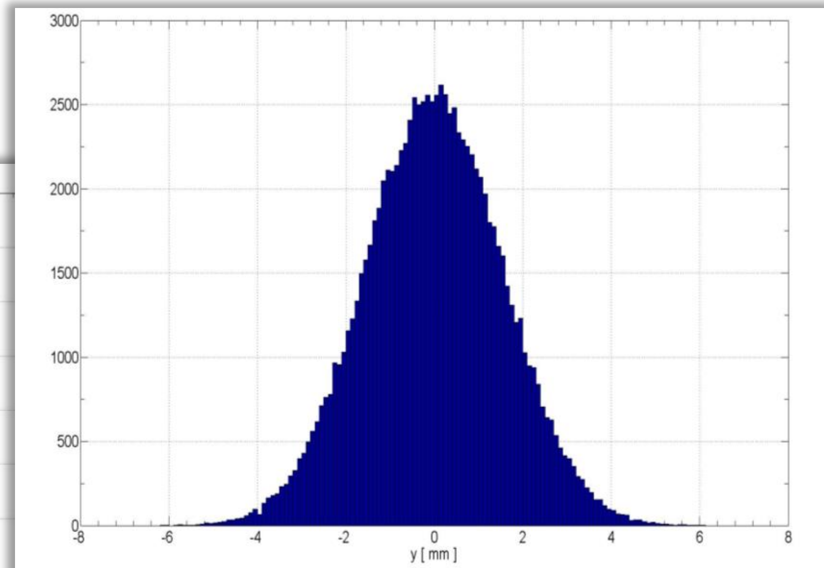
Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize optics parameters
  - Optimize initial distribution (also longitudinal!)

β_x [m]	5.6 m
α_x [rad]	6.5e-5
D_x[m]	-1.4 m
D_x' [rad]	0.2e-3
β_y[m]	3.7 m
α_y[rad]	9.6e-5
D_y[m]	0
D_y' [rad]	0

Fully matched optics
Gaussian distribution
x-x'** and y-y'





No offset in both x-y plane (-35 mm nominal horizontal KSW bump)

r.m.s. normlized emittance ε_0 = 0.4 mm mrad (max. from Linac4)

** it depends on $\Delta p/p$

Linac4 chopped bunches injection in the PSB without energy modulation

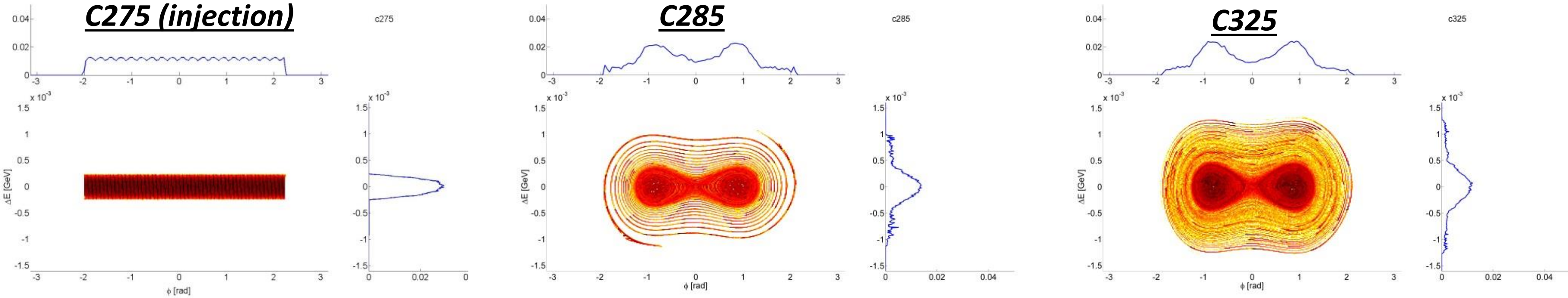
V. Forte

PSB Upgrade
LIU Project

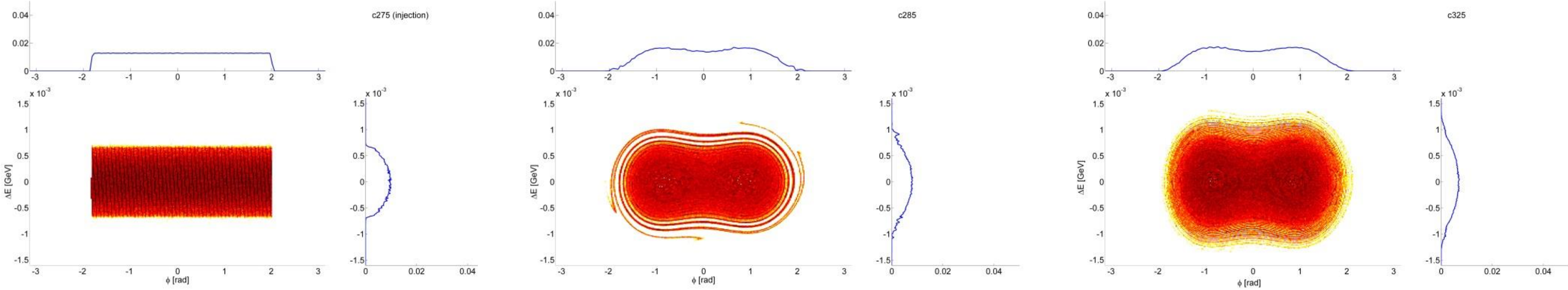
From single Linac4 bunches (thanks to A. Lombardi) It is possible to create injection structures for the PSB, for optimizing…

- **the bunch length to minimize the number of turns injected in the PSB for a certain intensity.**
- **the energy spread to minimize filamentation and peaks in linear density.**

ESME simulations without longitudinal space charge



Min-max 0.5 MeV (113 keV RMS) - 0.38e-3 dp/p rms – 680 ns – 243 Linac4 bunches



Min-max 1.74 MeV (336 keV RMS) - **1.1e-3 dp/p rms** – **616 ns** – 220 Linac4 bunches

To inject 1.65e12 p. in the PSB -> 6.6 turns

(@ 220 Linac4 bunches/turn and 1.14e9 p.p.bunch)

Reference:

C. Carli, R. Garoby - ACTIVE LONGITUDINAL PAINTING FOR THE H- CHARGE EXCHANGE INJECTION OF THE LINAC4 BEAM INTO THE PS BOOSTER - AB-Note-2008-011 ABP

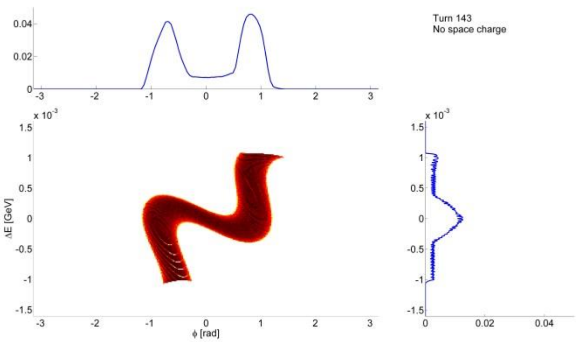
Linac4 chopped bunches injection in the PSB without energy modulation

V. Forte

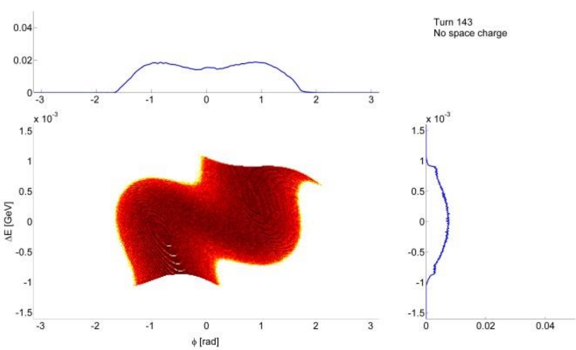
- The optimization requires to choose the optimal injection “train” shape to obtain a homogeneous evolution and avoid peaks in the linear density behavior (for lower tune spread due to space charge).
- **The 113 keV rms** case shows an increase in top linear density of a factor 4 during the first 150 turns .
- **The 336 keV rms** case shows a nicer and smoother behavior in top linear density (lower) .

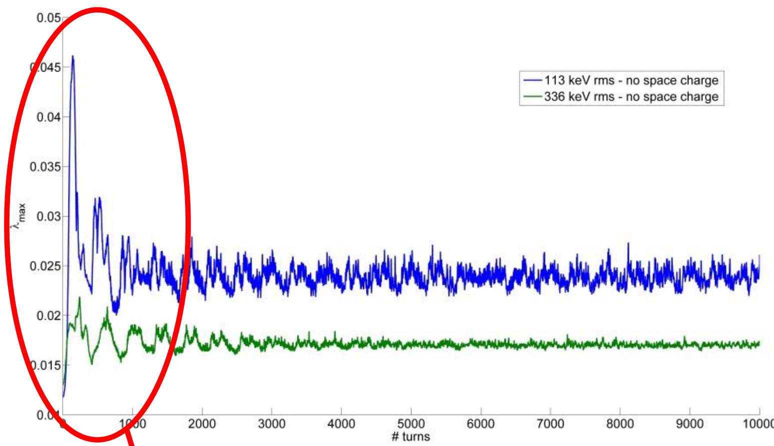
<u>After 143 turns</u>

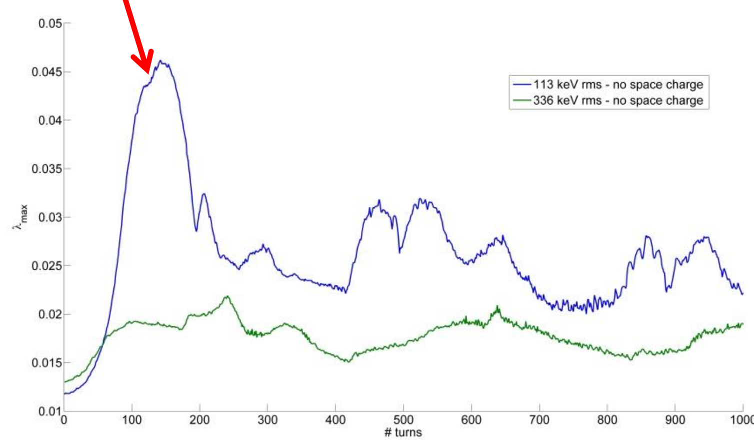
<u>113 keV rms</u>



<u>336 keV rms</u>



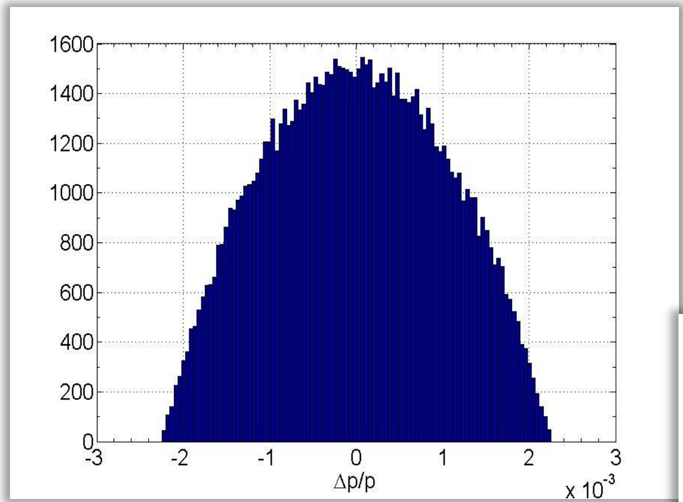




Small Emittance - High Brightness

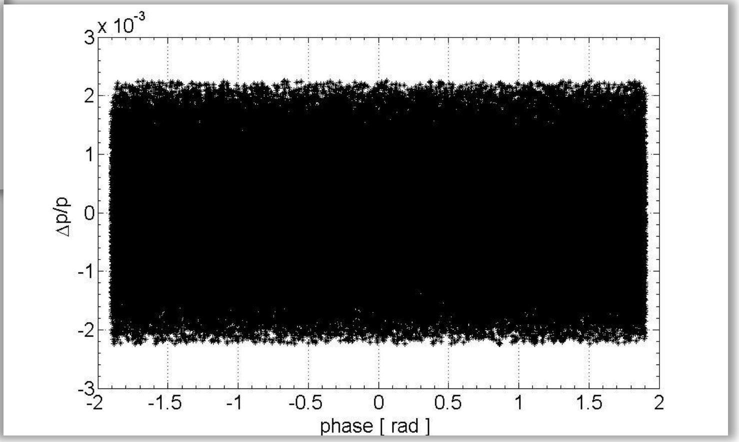
- How to preserve small emittance?
  - Optimize optics parameters
  - Optimize initial distribution (also longitudinal!)

β_x [m]	5.6 m
α_x [rad]	6.5e-5
D_x[m]	-1.4 m
D_x' [rad]	0.2e-3
β_y[m]	3.7 m
α_y[rad]	9.6e-5
D_y[m]	0
D_y' [rad]	0



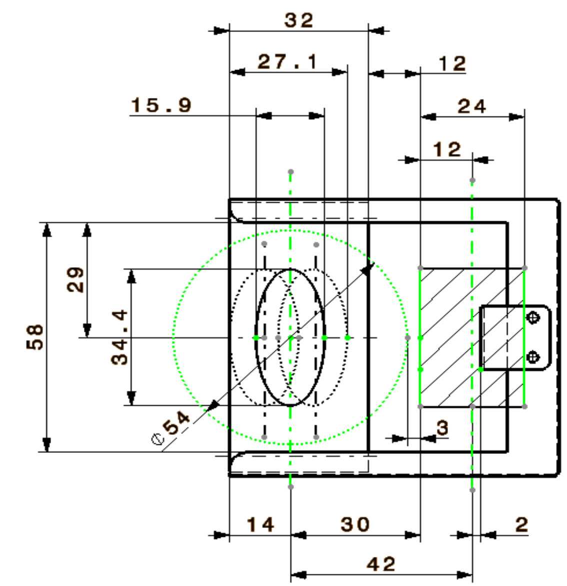
Parabolic distribution in Δp/p and uniform in phase

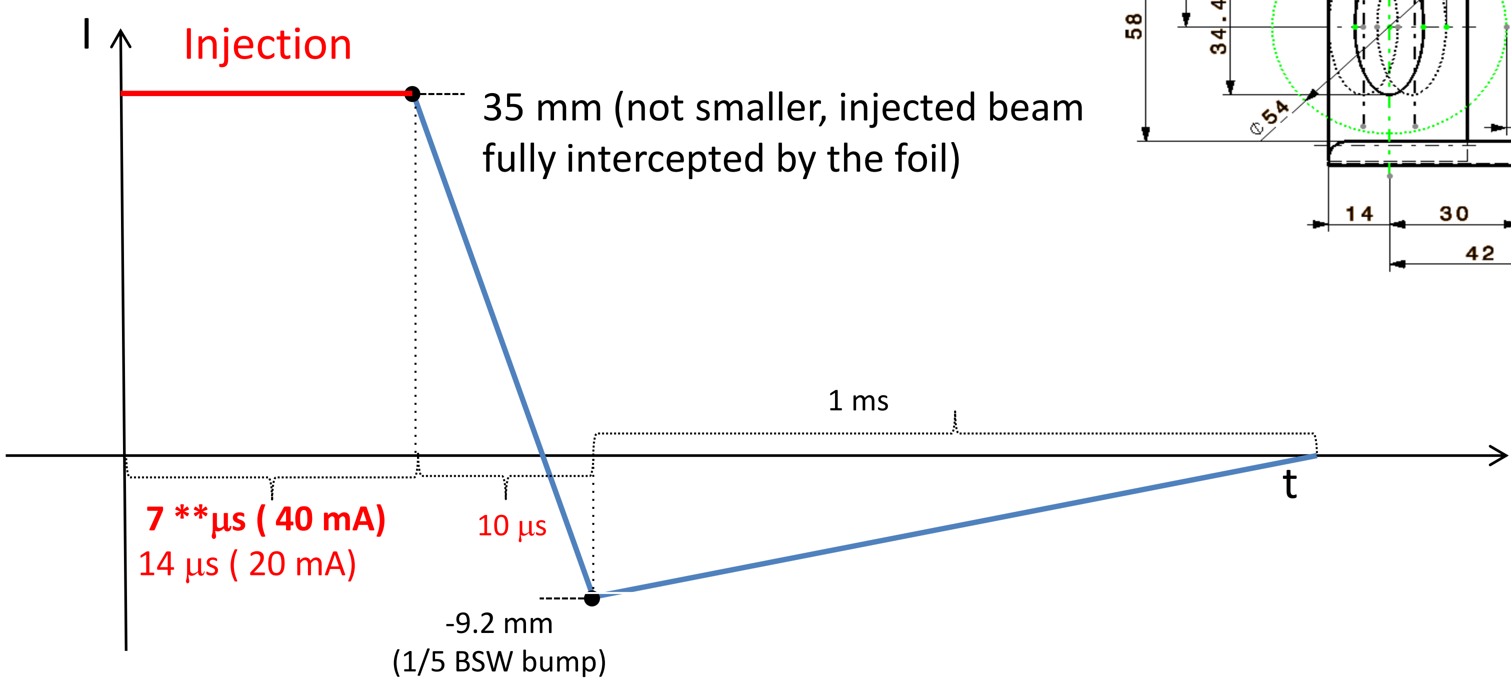
Δp/p = 1.1 e-3 (336 keV)
Phase = 1.9 rad (616 ns)



Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize KSW
  - Minimize foil crossings
  - Optimize PSB working point

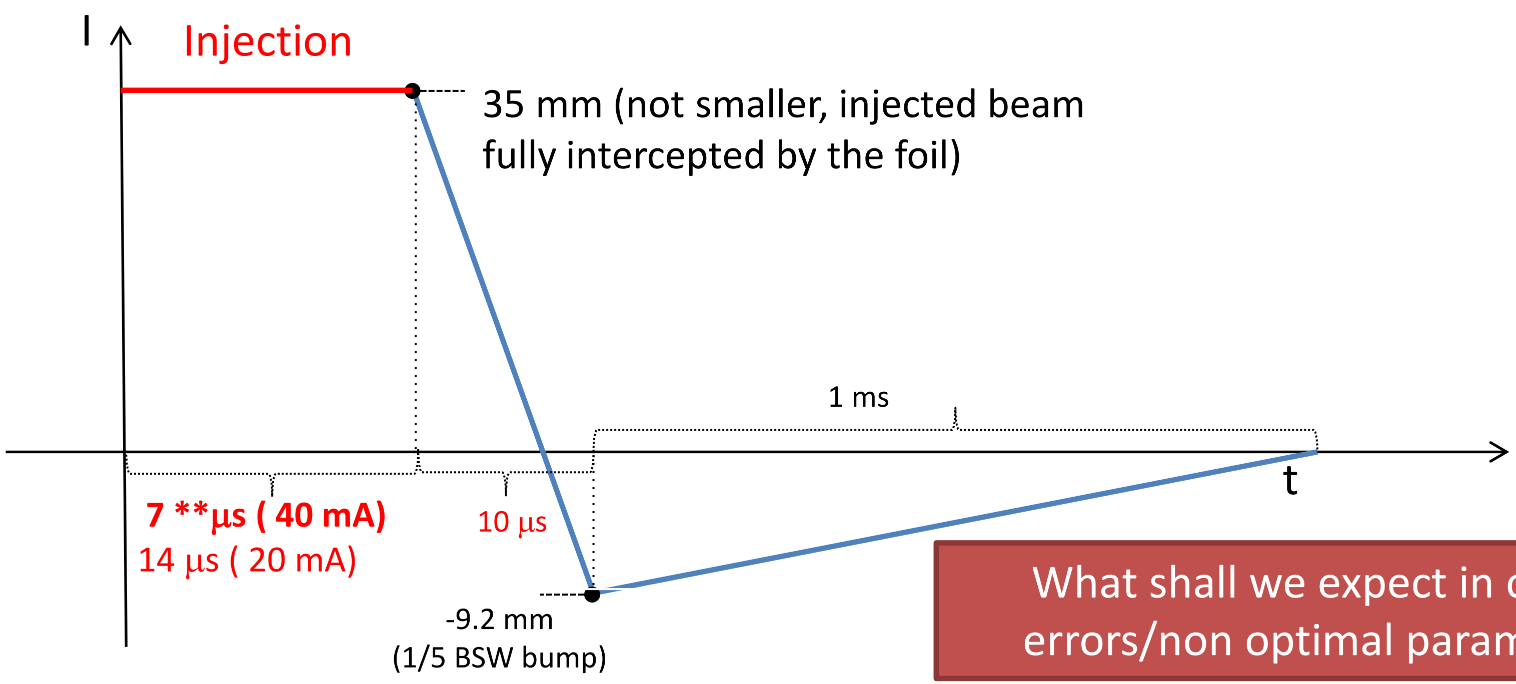




* 1.65E12 p+ per ring

Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize KSW
  - Minimize foil crossings
  - Optimize PSB working point? (**Q_H = 4.28;** Q_V = 4.55)

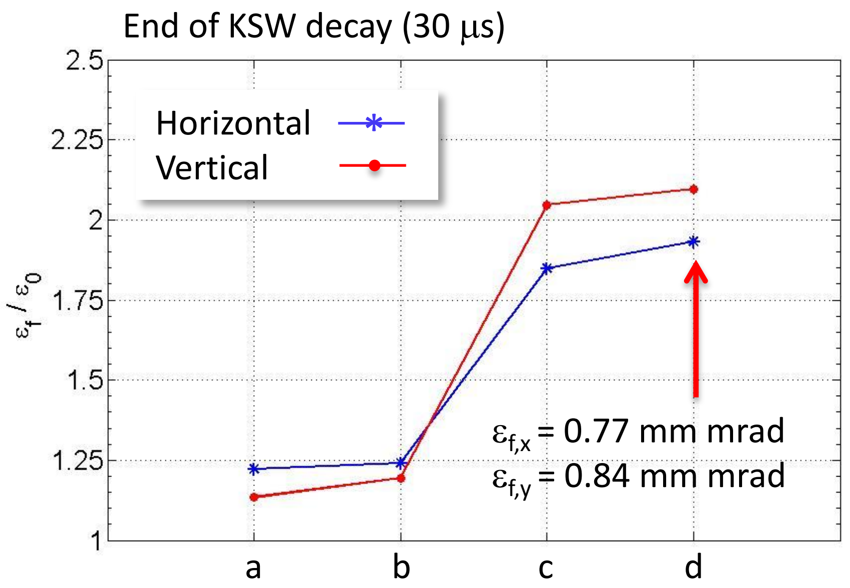


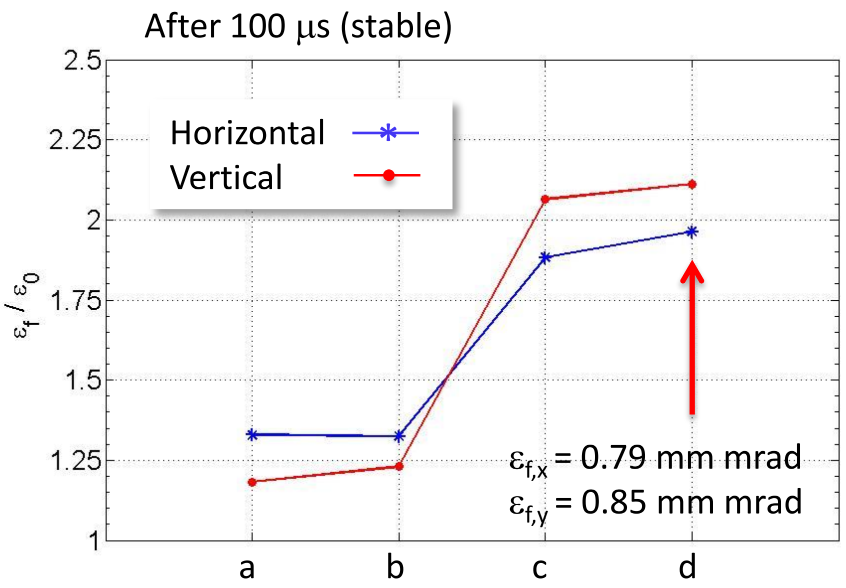
What shall we expect in case of errors/non optimal parameters?

* 1.65E12 p+ per ring

Small Emittance - High Brightness

- Effect of errors and/or non nominal parameters





a) Ideal case (total intensity = 1.65e12 protons per ring)

b) 25 % $\beta_{x,y}$ error & 0.3 m $D_{x,y}$ error

c) 25 % $\beta_{x,y}$ error & 0.3 m $D_{x,y}$ error & 2 mm x,y offset

d) 25 % $\beta_{x,y}$ error & 0.3 m $D_{x,y}$ error & 2 mm x,y offset & 50% Linac4 current

$\varepsilon_{x,y}$ (BCMS) ≤ 1 mm mrad

PSB User

		norm. Emittance [mm mrad]	
User	Intensity/ring	H	V
LHC25A/B	2.96E+12**	< 2	< 2
LHC BCMS	1.48E+12**	1	1
LHCPILOT	5.00E+09	1	1
LHCINDIV	2.30E+10 / 1.35E+11	2	2
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AD	4.00E+12	8	6
TOF	9.00E+12	10	10
EASTA/B/C	1.00E+11 / 4.50E+11	3	1
NORMGPS NORMHRS	1.00E+13 2.50E+13	15	9
STAGISO	3.50E+12	8	4
CNGS-like	6.00E+11 / 8.00E+12	10	8

ISOLDE

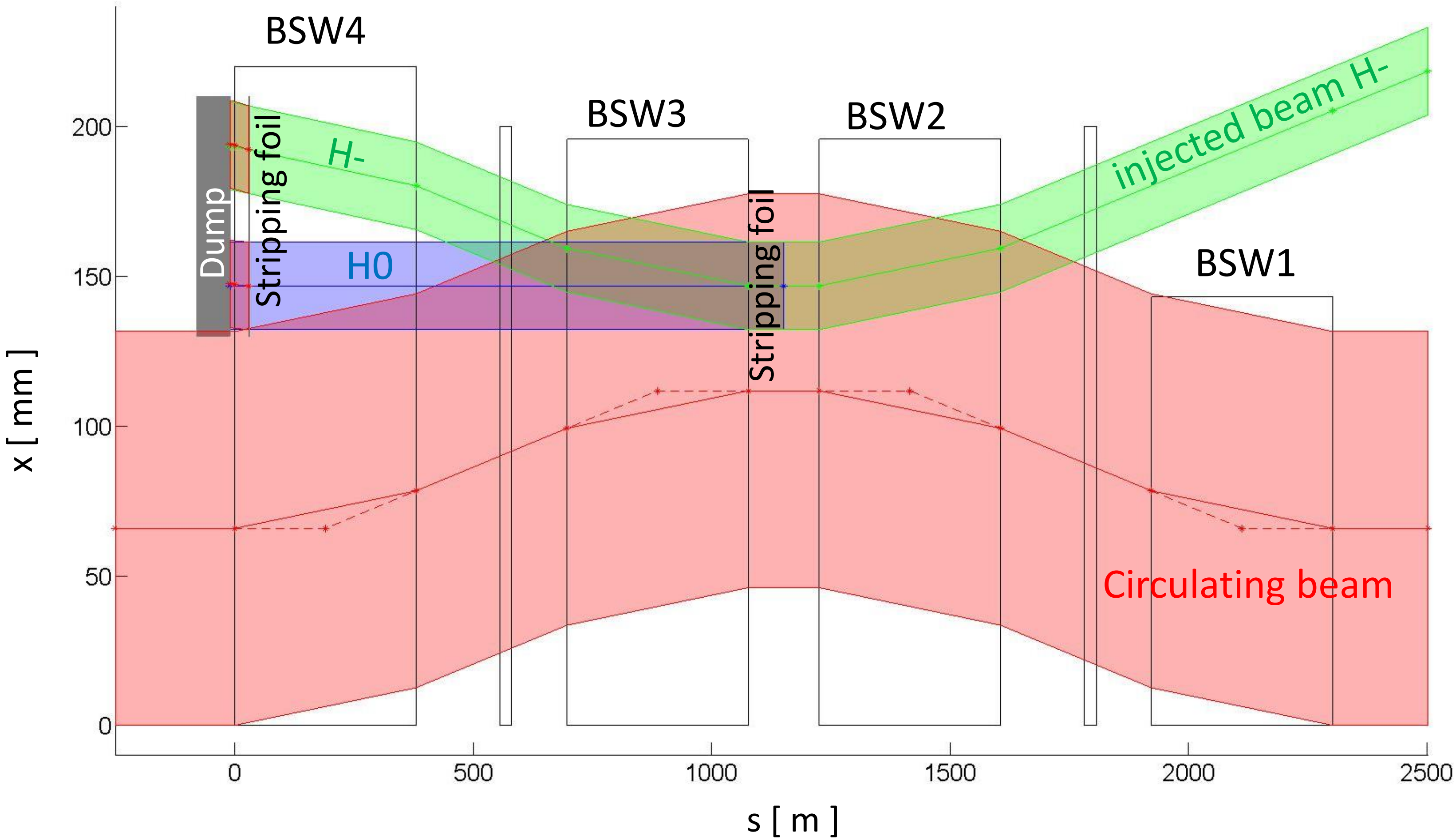
Assumptions to calculate beam envelope in the injection region (r.m.s normalized emittance 15 x 9 mm mrad):

Horizontal		
Geometric emittance	mm mrad	24.7
Beta	m	5.6
Beta-beat	%	25
Max beta	m	7
Betatron env. 4sigma	mm	52.60
Dispersion	m	1.4
Dp/p		0.0044
Max. momentum displacement	mm	6.16
Mech. Tol.	mm	1
orbit	mm	4.00
Max. offset for painting	mm	2.00
Max. Beam env.	±mm	65.8

Vertical		
Geometric emittance	mm mrad	14.8
Beta	m	3.7
Beta-beat	%	25
Max beta	m	4.625
Betatron env. 4sigma	mm	33.09
Dispersion	m	0
Dp/p		0.0044
Max. momentum displacement	mm	0
Mech. Tol.	mm	1
orbit	mm	4.00
Max. offset for painting	mm	8.00
Max. Beam env.	±mm	46.1

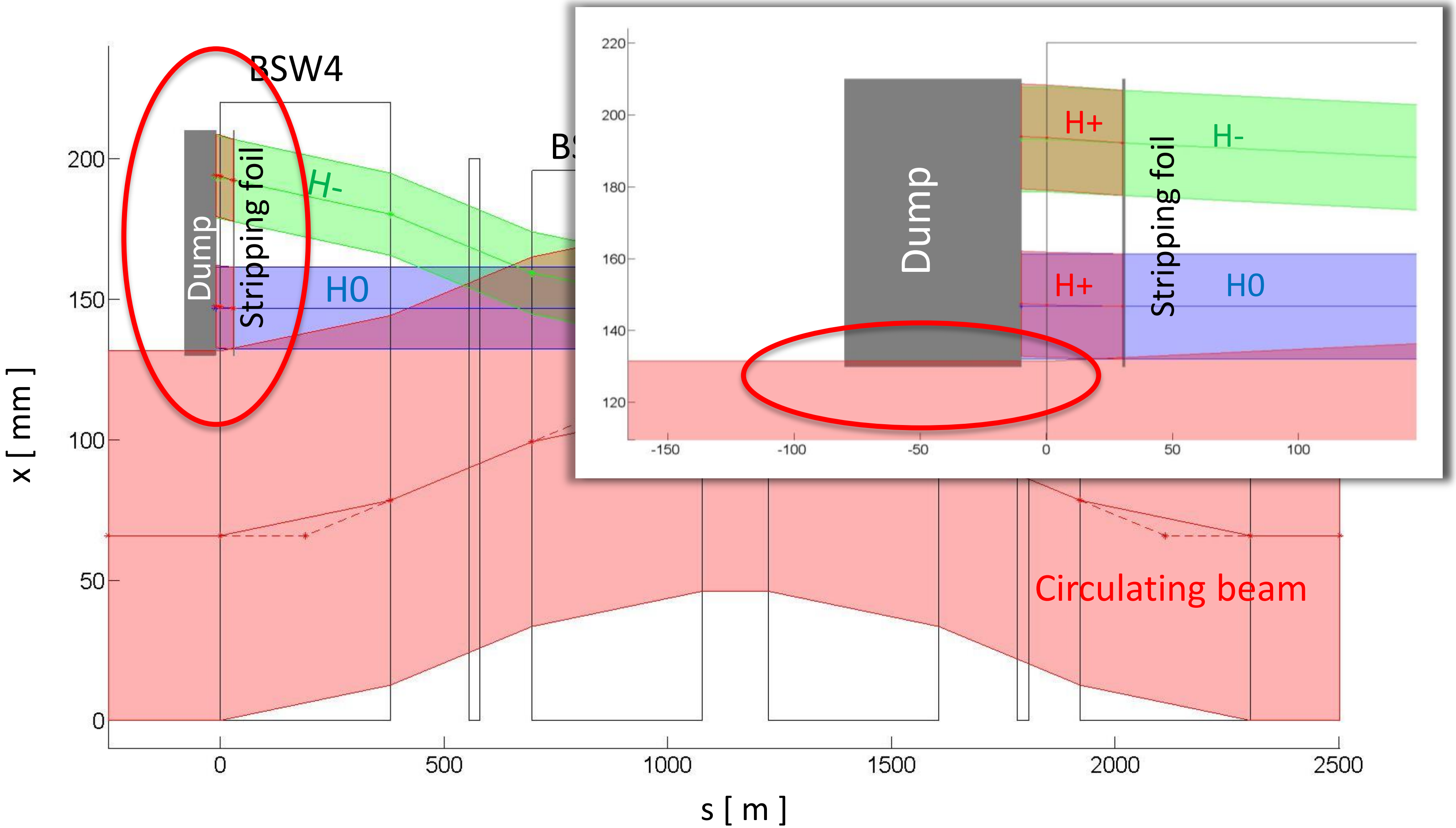
ISOLDE

Beam envelope at the end of injection (KSW bump = 0 mm, BSW bump = 45.9 mm):



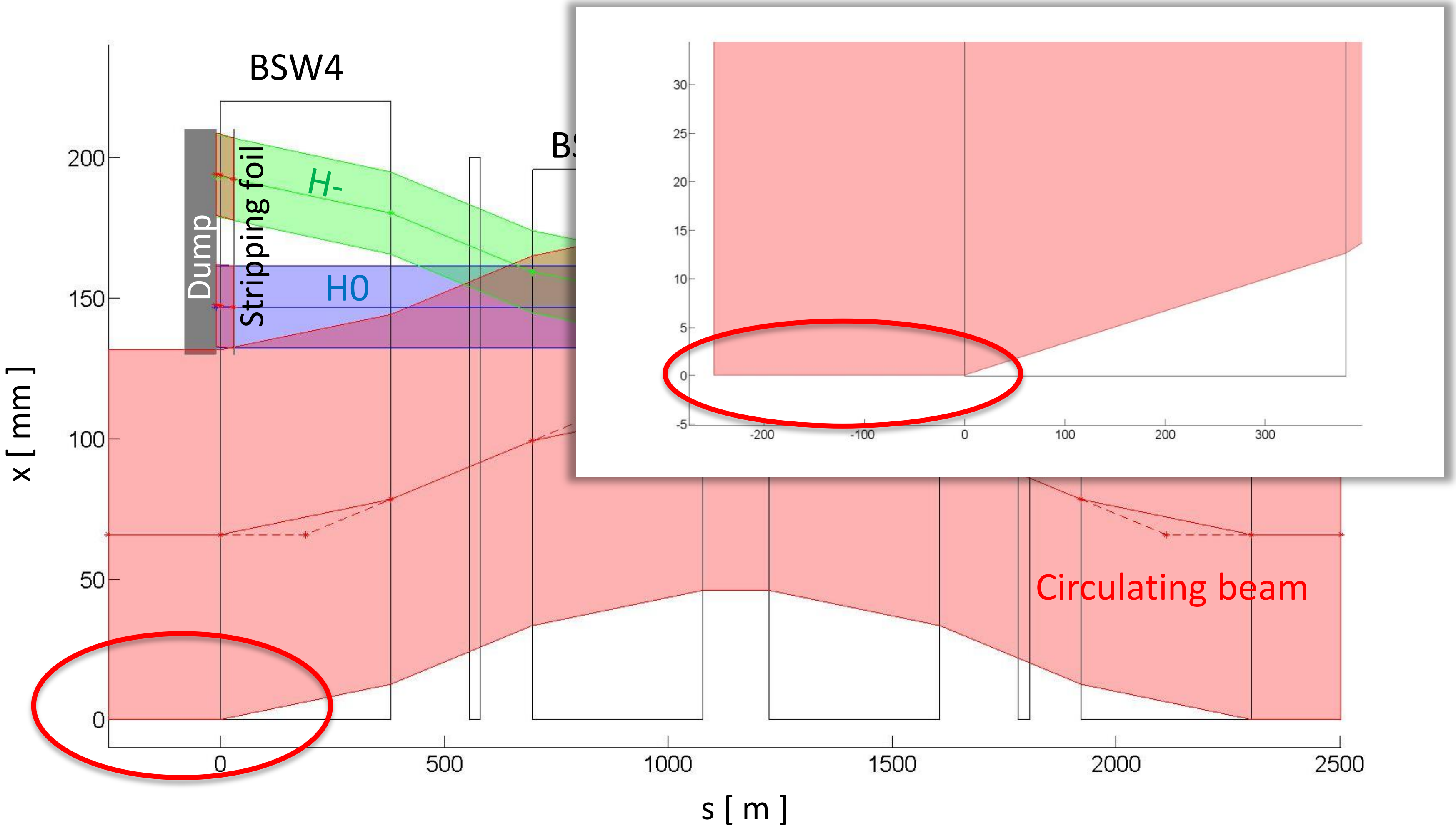
ISOLDE

Beam envelope at the end of injection (KSW bump = 0 mm, BSW bump = 45.9 mm):



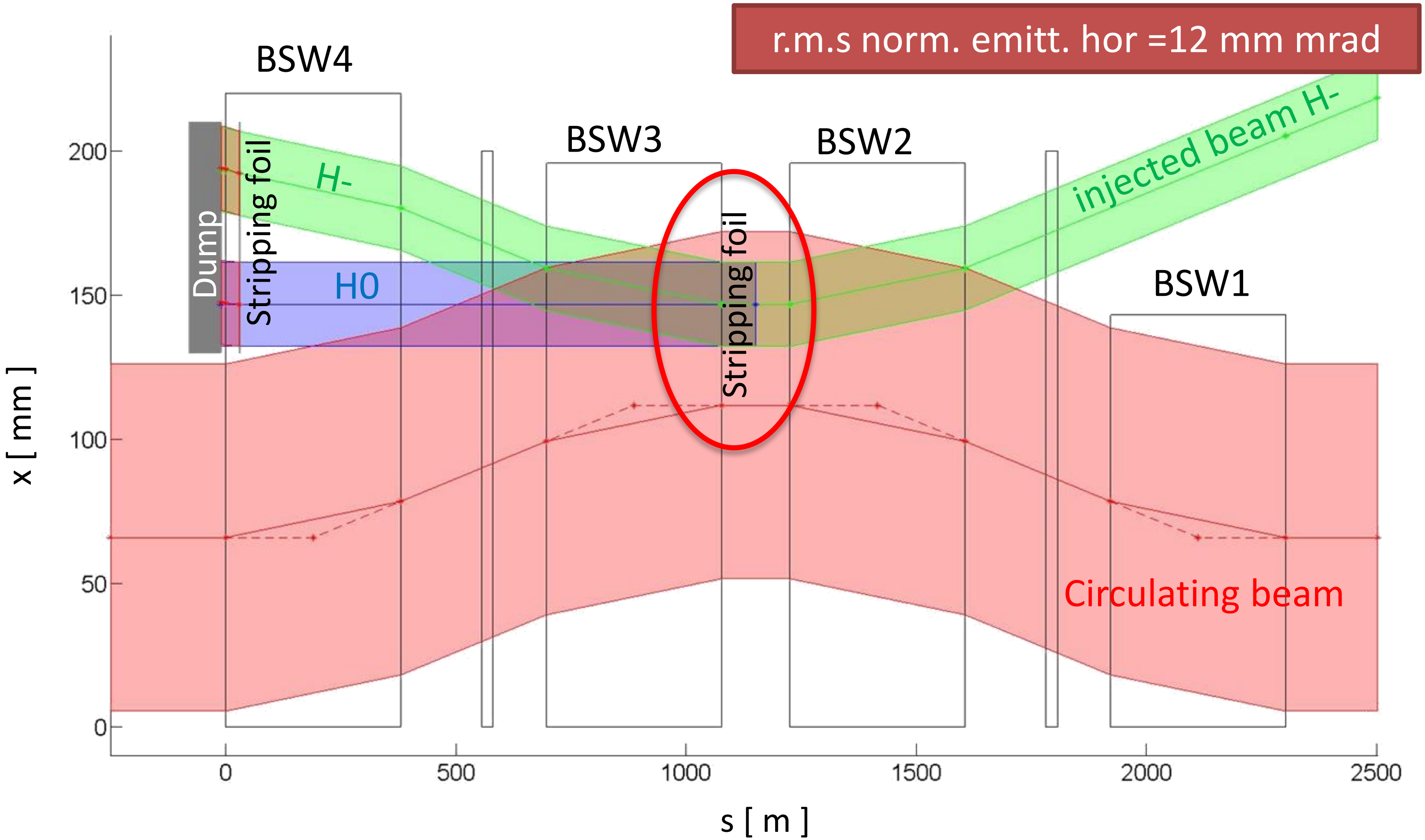
ISOLDE

Beam envelope at the end of injection (KSW bump = 0 mm, BSW bump = 45.9 mm):



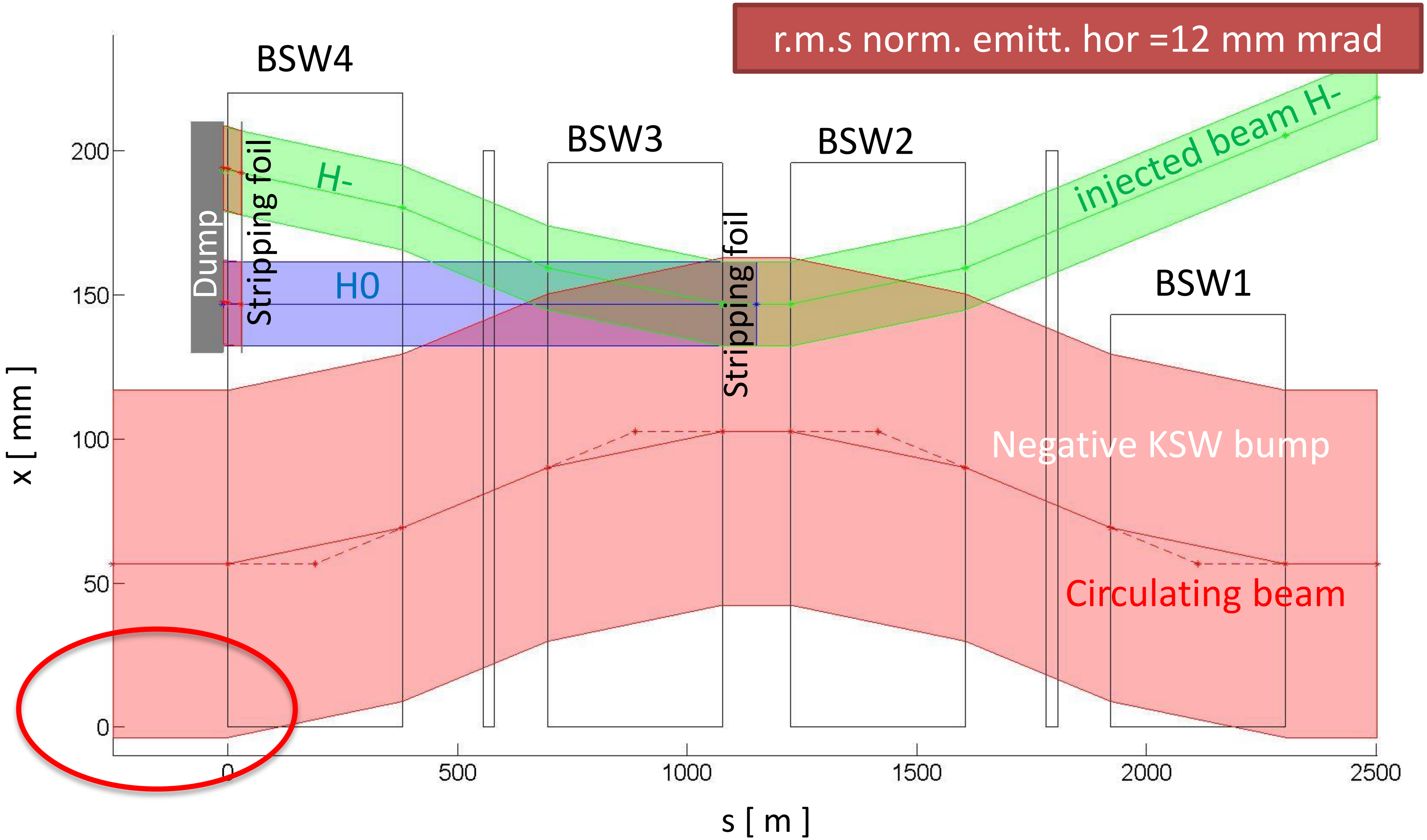
ISOLDE

Beam envelope at the end of injection (KSW bump = 0 mm, BSW bump = 45.9 mm):



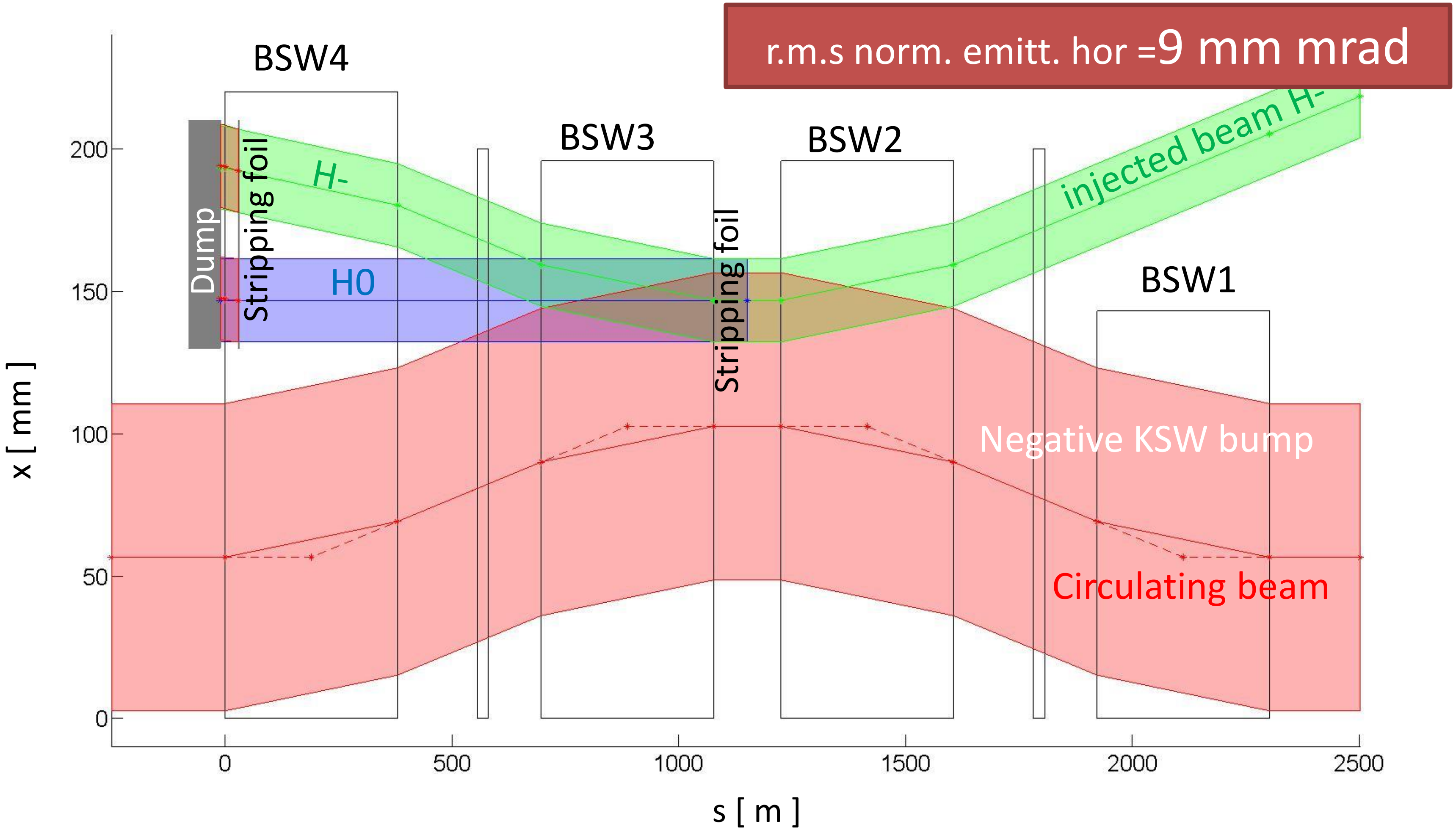
ISOLDE

Beam envelope at the end of injection (KSW bump = -9.2 mm, BSW bump = 45.9 mm):



ISOLDE

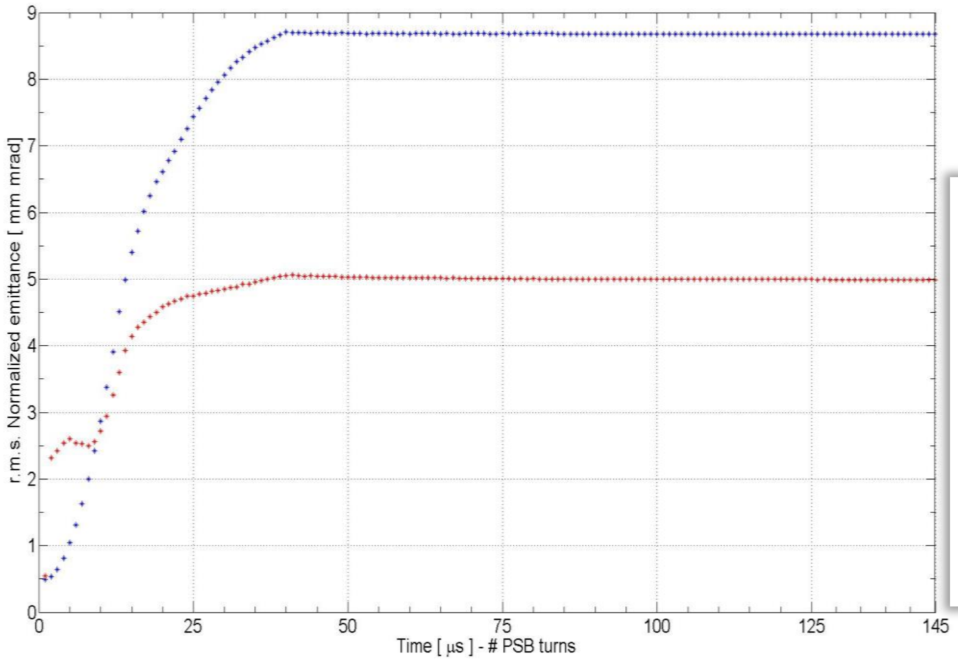
Beam envelope at the end of injection (KSW bump = -9.2 mm, BSW bump = 45.9 mm):

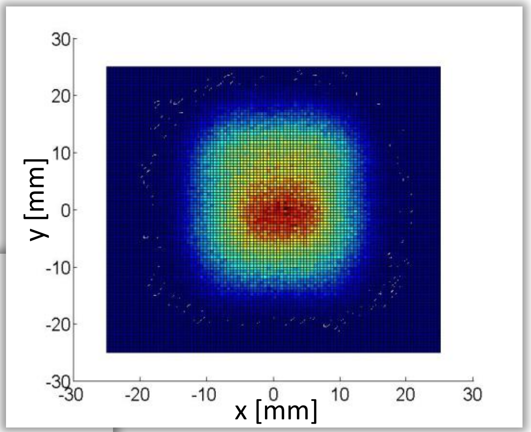


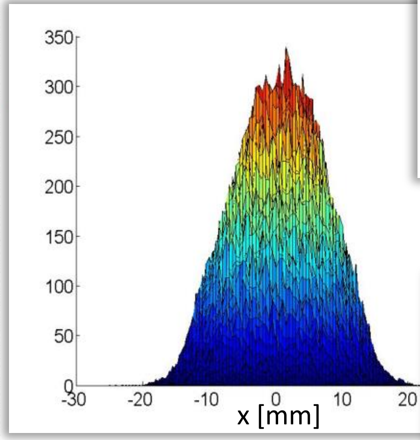
ISOLDE

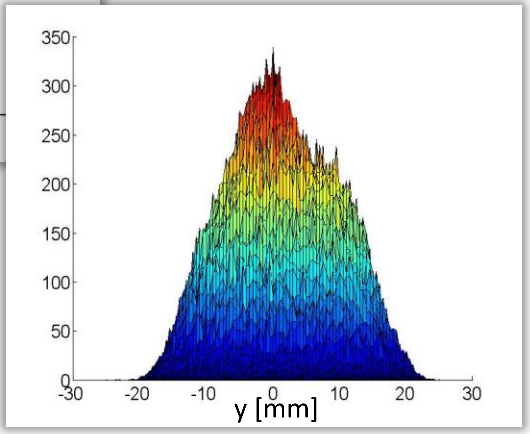
Injection over 40 turns (1e13 p+ per ring, 40 mA current from Linac4)
Longitudinal painting
Matched optics in **beta** and **dispersion**
Initial vertical offset of 7.5 mm

100% I_{max} → 60% I_{max} in 12 μs (t1 = 12 μs)
60% I_{max} → 59 % I_{max} in 28 μs (t2 = 40 μs)
59% I_{max} → -0.26% I_{max} in 15 μs (t3 = 55 μs)





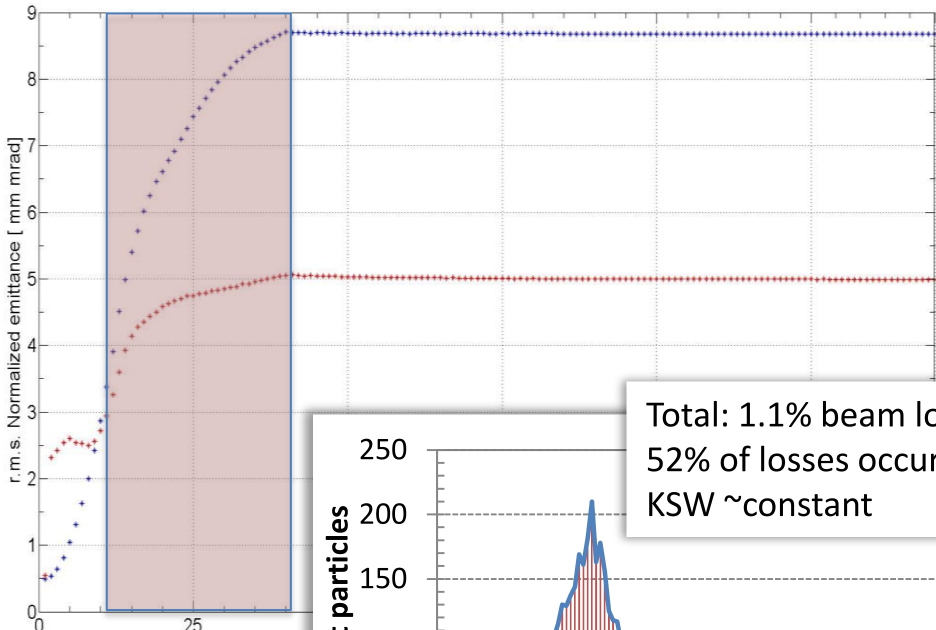


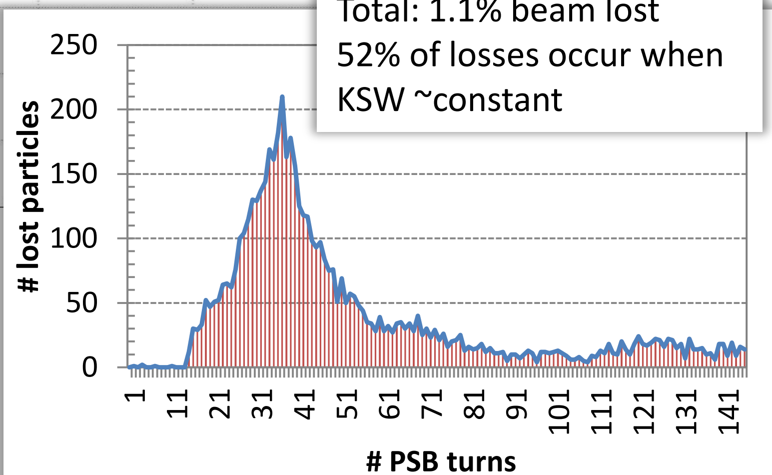


ISOLDE

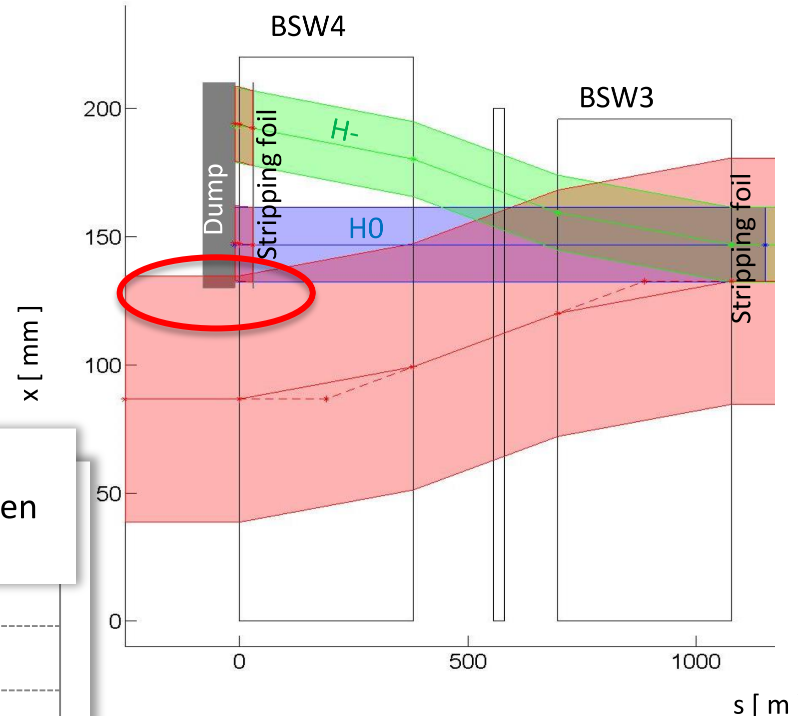
Injection over 40 turns (1e13 p+ per ring, 40 mA current from Linac4)
Longitudinal painting
Matched optics in **beta** and **dispersion**
Initial vertical offset of 7.5 mm

100% I_{max} ➔ 60% I_{max} in 12 μs (t1 = 12 μs)
60% I_{max} ➔ 59 % I_{max} in 28 μs (t2 = 40 μs)
59% I_{max} ➔ -0.26% I_{max} in 15 μs (t3 = 55 μs)





Total: 1.1% beam lost
52% of losses occur when KSW ~constant

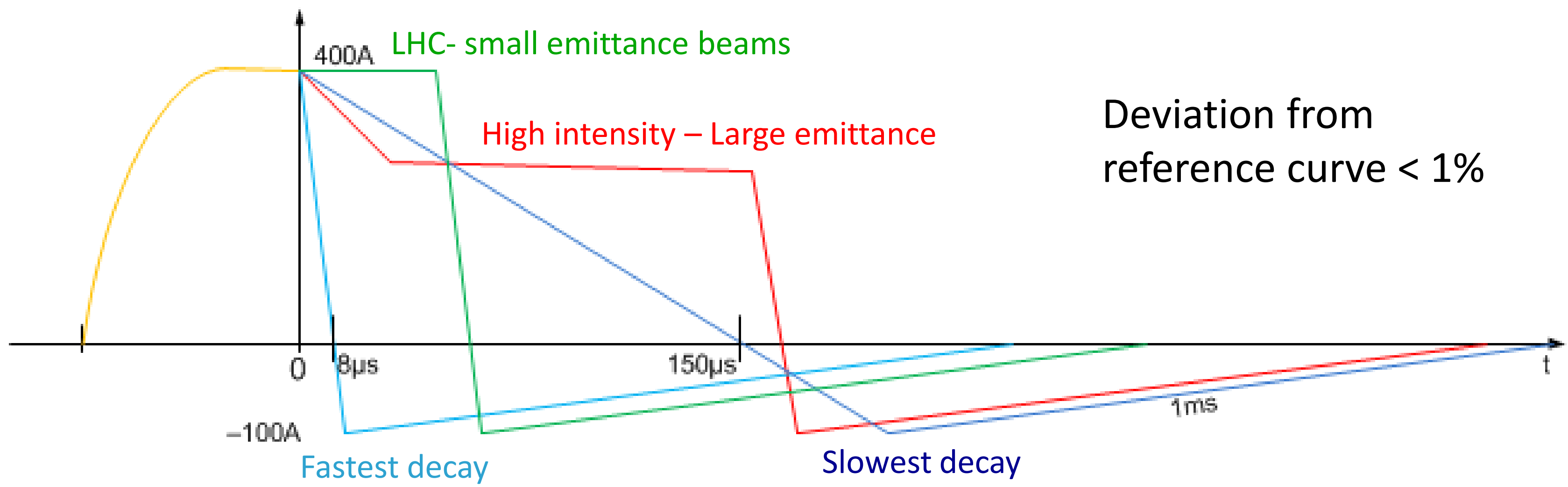


Faster decay??
Tradeoff distribution "quality" – losses – foil heating

KSW Envelope Specifications

G.Grawer

KSW Magnet Current



Deviation from reference curve < 1%

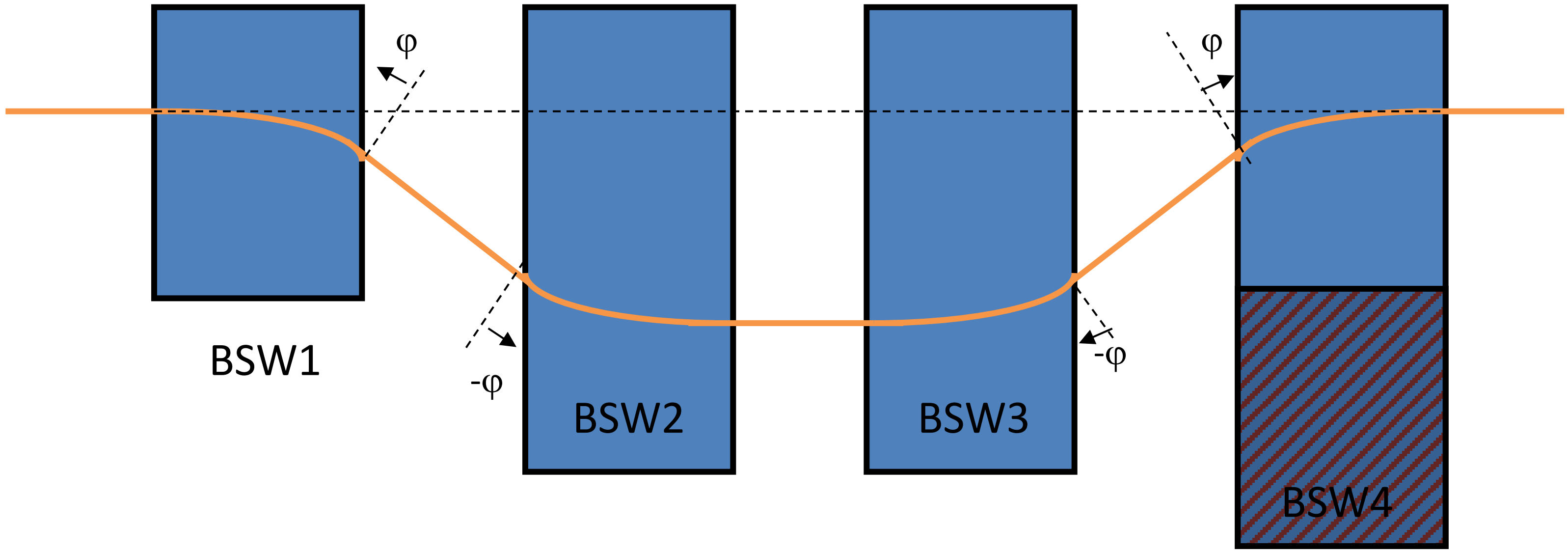
User	# turns	I_1 [% I_{max}]	I_2 [% I_{max}]	t_1	t_2	$t_{fall\ const}$	Vert offset
LHC25	40	90	89	10	40	55	3.5
CNGS	40	68	67	15	40	55	7
SFTPRO	40	70	69	22	40	55	6
AD	40	70	69	22	40	55	6.5
TOF	40	68	67	15	40	55	8
NORMGPS NORMHRS	40	60	59	12	40	55	7.5
STAGISO	40	70	69	22	40	55	5

Old values

Perturbation induced by the chicane BSW magnets

PSB Upgrade LIU Project

E. Benedetto



- Edge effects (rectangular magnets)
- Proposed corrugated Inconel vacuum chamber new baseline (ceramic in the original design)
- Influence on beam dynamics of induced Eddy currents:
  - Delay of ~50us
  - Higher order field components (sextupolar)
    - Quadrupolar feed-down
    - Excitation 3rd order resonance

3D magnet simulation by B. Balhan, J. Borburgh

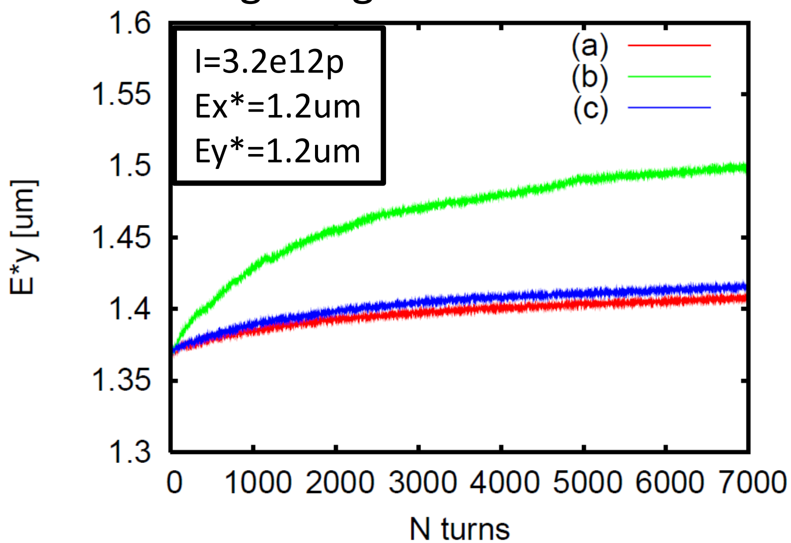
Inconel vacuum chamber

E. Benedetto

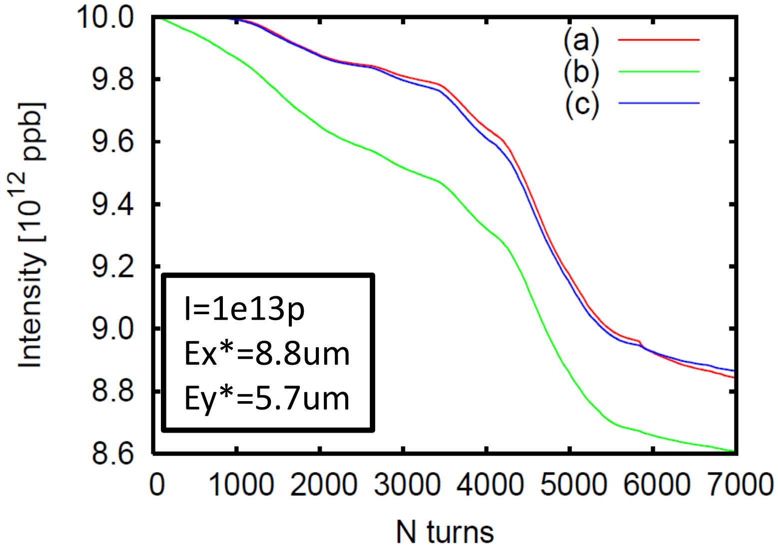
- No showstoppers for the inconel chamber are found, but compensation is required (E.Benedetto et al, @ LIU-PSB Meeting, 26/9/2013)
- Simulations results are valid only in relative, to discriminate between ceramic and inconel chamber
  - optics model as simple as possible
  - no errors except in BSW magnets

(a) Ceramic chamber
(b) Inconel, wo correction
(c) Inconel, all corrected.

"High brigthness" beam



"Isolde-like" beam



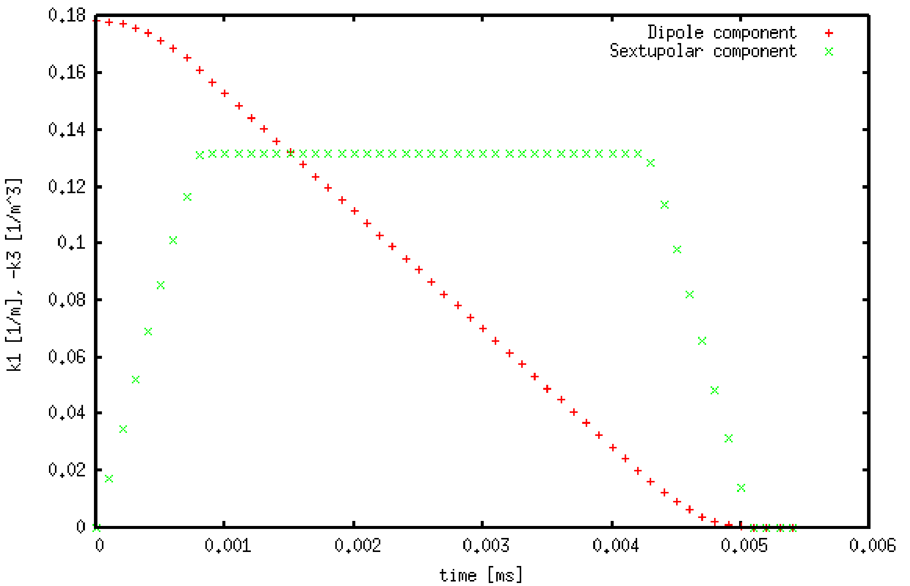
Studies on the shape for the chicane ramp down

E. Benedetto

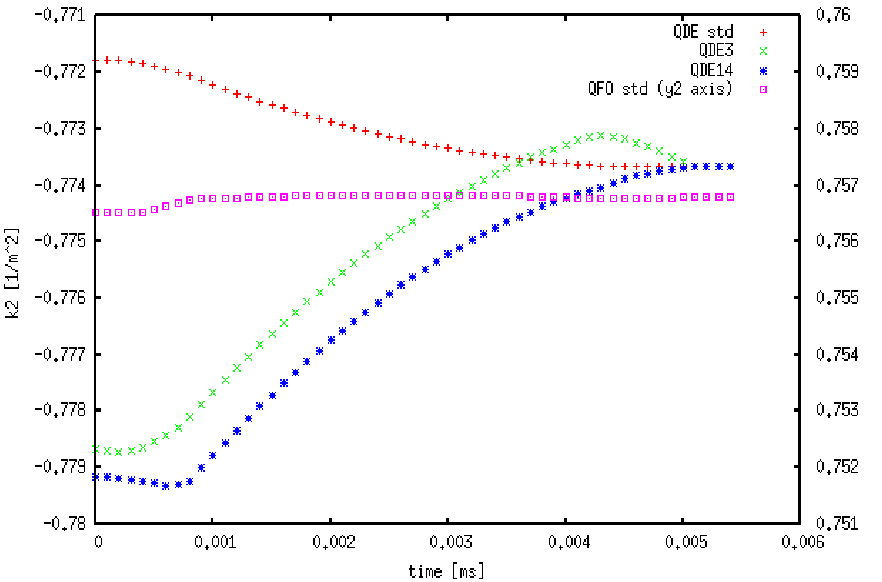
- Realistic shape with a 125Hz content (So far, assumed linear decay in 5ms)

Input from D. Aguglia, D. Nisbet

- Correction for V Beta-Beating has been computed
- Almost identical results (blow-up and/or losses) than with the linear decay



BSW ramp-down function and sextupolar component generated by eddy-currents



Computed strength in the QDE3, QDE14 and in the other quadrupoles

Next Steps

- LHC: possible further optimizations (tune, long. distribution)?
- High intensity beams
  - Agree target values (intensity and emittance!)
  - Define KSW modulations:
    - With/without longitudinal painting (injection turns)
    - Trade-off optimum distribution – minimum losses - foil scattering/heating (all users)
    - Imperfections (delays from eddy currents induced by Ti layer)
    - Other options: mismatch and/or offset (?)
  - Losses in injection region
- Quadrupolar component in BSW1 (C-shaped)
- Final crosscheck with HW experts (specs and tolerances)

PSB Upgrade
LIU Project

Thank you for your attention!

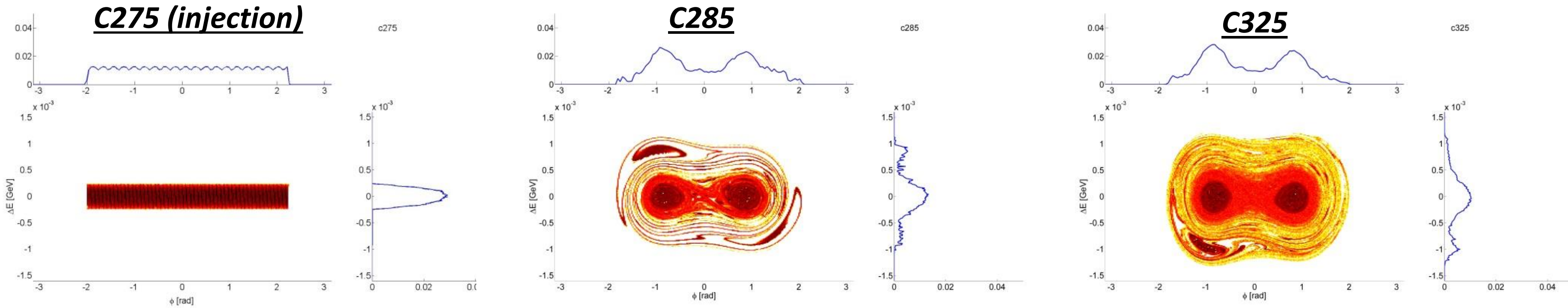
PSB Upgrade
LIU Project

Linac4 chopped bunches injection in the PSB without energy modulation

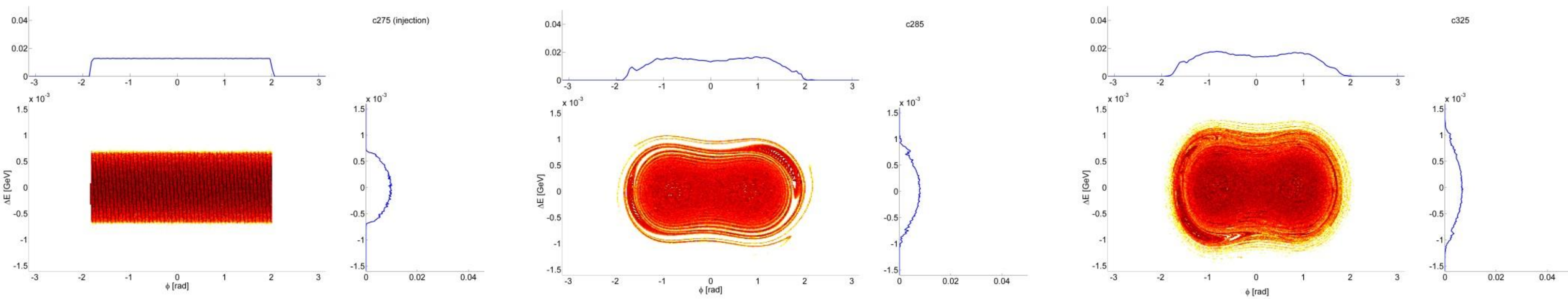
V. Forte

- **Optimize…**
  - **the bunch length to minimize the number of turns injected in the PSB for a certain intensity.**
  - **the energy spread to minimize filamentation and peaks in linear density.**

ESME simulations (29.55E11)



Min-max 0.5 MeV (113 keV RMS) - 0.38e-3 dp/p rms – 680 ns – 243 Linac4 bunches



Min-max 1.74 MeV (336 keV RMS) - **1.1e-3 dp/p rms** – **616 ns** – 220 Linac4 bunches

<u>To inject 1.65e12 p. in the PSB -> 6.6 turns</u>

(@ 220 Linac4 bunches/turn and 1.14e9 p.p.bunch)

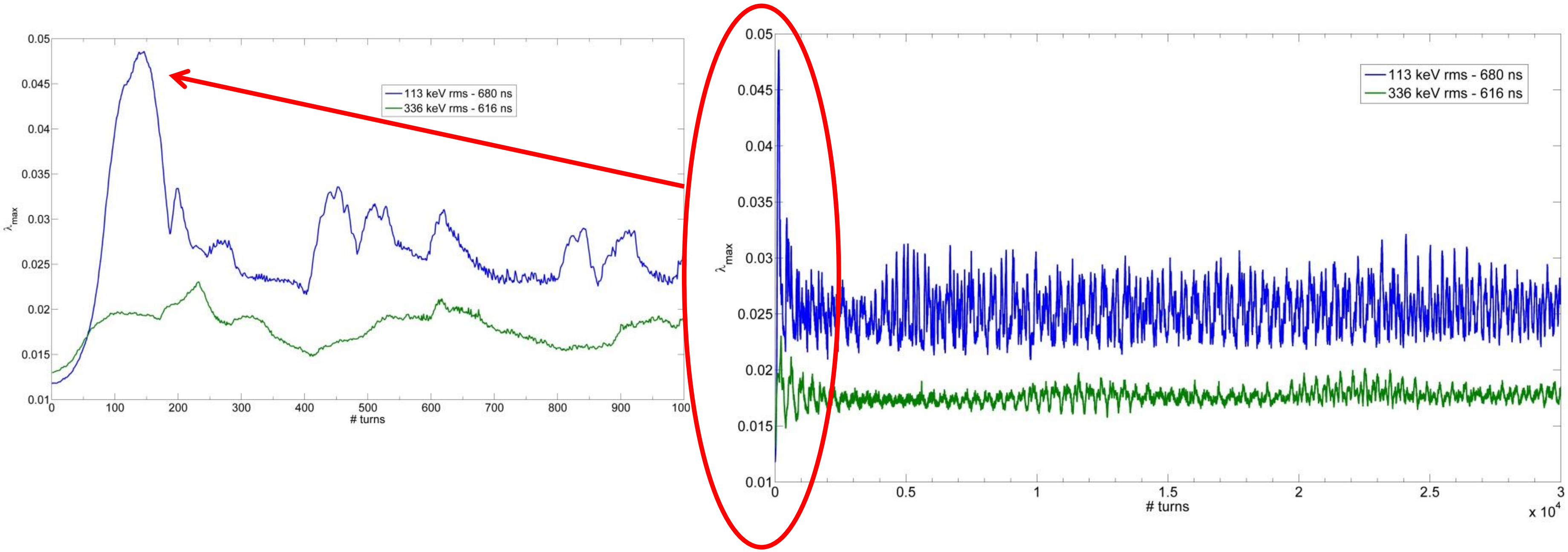
Reference:

C. Carli, R. Garoby - ACTIVE LONGITUDINAL PAINTING FOR THE H- CHARGE EXCHANGE INJECTION OF THE LINAC4 BEAM INTO THE PS BOOSTER - AB-Note-2008-011 ABP

Linac4 chopped bunches injection in the PSB without energy modulation

V. Forte

From ESME simulations (with longitudinal space charge and I=29.55e11)



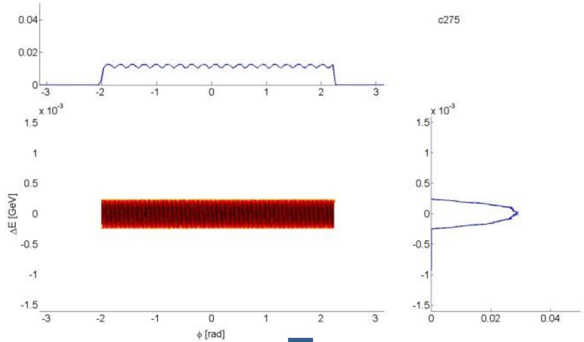
PSB Upgrade
LIU Project

Linac4 chopped bunches injection in the PSB without energy modulation

V. Forte

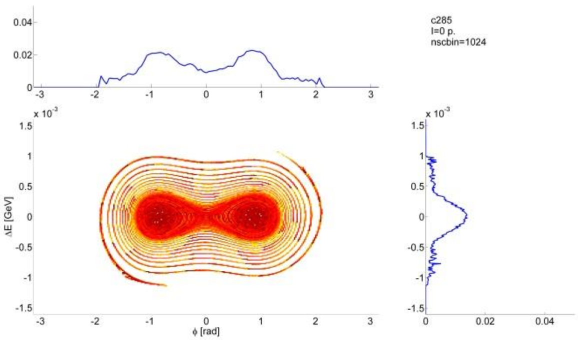
- **The longitudinal “islands” creation is an intensity-dependent phenomenon (increases with intensity).**
- **It happens when the space charge module is activated in ESME (to be understood).**

C275 (injection)

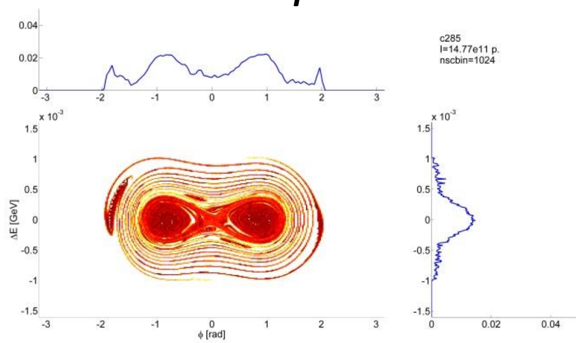


C285

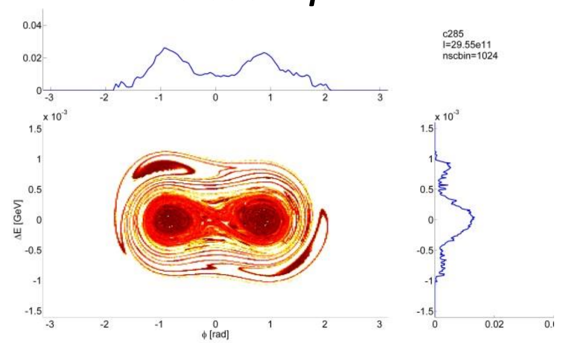
I=0



I=14.77e11 p.



I=29.55e11 p.



ISOLDE

Injection over 80 turns (2e13 p+ per ring or 20 mA current from Linac4)
Longitudinal painting
Matched optics in **beta** and **dispersion**
Initial vertical offset of 6 mm

100% I_{max} ➔ 40% I_{max} in 80 μs (t1 = 80 μs)
40% I_{max} ➔ -0.26 % I_{max} in 15 μs (t2 = 95 μs)