Simulation of multi-turn injection in the PSB with Linac2: brief summary of past work & plans

LIU-PSB Injection Meeting

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based on the work done by V. Raginel (https://cds.cern.ch/record/1701083?ln=en)
and discussions with E. Benedetto and B. Mikulec

Introduction

- **Motivation:** The original study was carried out in the LIU-PSB context. Check **if the Linac4 could be a reasonable backup for Linac2**, in case of any unfortunate breakdown.

- **Goal:** Estimate **the Linac4 performance as a proton injector @ 50 MeV** (instead of H^- @ 160 MeV).

- **Two-step analysis:**

  1. **Estimate the performance of the current PSB injection model with Linac2 and compare it with the operational beam performance.**
  2. Once the model is validated, use the Linac4 parameters as input and optimize the injection process for the highest brightness.

- **Set of variables investigated:**

  - Normalized RMS emittance, horizontal and vertical.
  - Injection efficiency.
  - Beam intensity at injection.

- **Software: ORBIT**

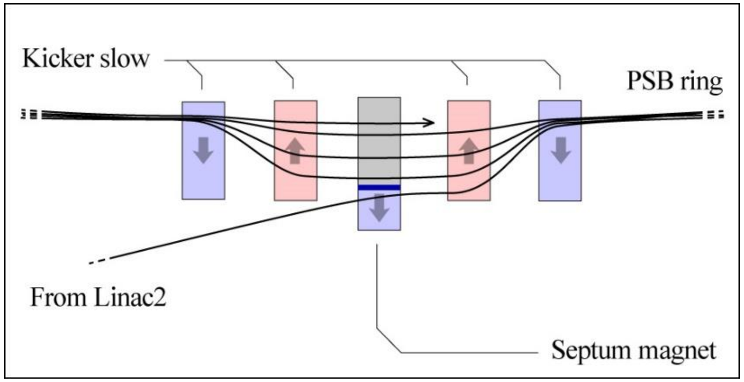
- **This presentation will focus on the status of the Linac2 simulation, so the work done for the Linac4 simulation is not presented, although available in the backup slides.**

PSB Injection Simulation

- **Common for both Linac2 and Linac4 simulations, i.e. only the input parameters would change.**

- **<u>Illustrative sketch of the PSB multi-turn injection</u>:**

  1. 4 kickers slow generate a bump.
  2. The bump moves the closed orbit to the septum.
  3. The beam from Linac2 is deflected to fit in the bump-distorted orbit.
  4. The bump is then reduced up to the reference orbit.



- **Several beam types: LHC @ 25ns, ISOLDE, MD @ 160 MeV.**

- **No RF simulated** as the study was limited to the injection process.

- Simulation carried out for **100000 macro-particles for 100 turns** (the bump decays after ~20 turns).

- **ORBIT code does not provide a septum feature:**
  - Injection Septum, **BI.SMH1L1**, simulated as a **foil of thickness null** at the beginning of the lattice plus an **aperture restriction** at the end of the lattice.
  - The foil at the beginning simulates the septum blade seen at injection.
  - The aperture restriction at the end simulates the septum blade seen by the turning particles.

Linac2 Simulation (I)

- **Input beam parameters from Linac2:**

Parameter	*Symbol*	*Value*	*Remarks*
Linac2 proton energy		50 MeV	
Linac2 normalized beam emittance	$\varepsilon^*_0 = \varepsilon^*_x = \varepsilon^*_y$	1.2 π mm mrad	[7]
Linac2 beam current		160 mA	
Horizontal beam size	βx_{Linac2}	$\beta x_{Linac2} = (\beta x_{PSB})/2$ at injection point	[8]
Waist position horizontal	$\beta' x_{Linac2}$	≈ 0	[8]
Vertical beam size	βy_{Linac2}	$\beta y_{Linac2} = \beta y_{PSB}$ at injection point	[8]
Waist position vertical	$\beta' y_{Linac2}$	≈ 0	[8]
Bump Collapse Time	TIKS	50 μs	Measurements of KSW pulses
Number of Injected turn		2	Presently, 2.2 turns are injected into the PS Booster

α → (Waist position horizontal)

- **Targeted beam parameters at injection for a LHC-type beam @ 25 ns:**
  - An horizontal normalized rms emittance of ~1.90 π mm mrad.
  - A vertical normalized rms emittance of ~1.75 π mm mrad.
  - Injection efficiency of ~57%.
  - Injection intensity of ~1.85E12 protons.

Linac2 Simulation (II)

- **The work presented in NAPAC2013 only focused on results for the LHC @ 25 ns beam.**
- **Simulation optimized to reach the maximum intensity within the emittance budget.**
- **Tuning several parameters:**
  - Vertical and horizontal beam injection position/angle.
  - Injection delay between the moment when the injection kicker pulses at its maximum and the moment when the beam is injected.
- **The most optimized simulation yielded:**
  - **Normalized rms horizontal emittance of 1.88 π mm mrad (measured is ~1.90 π mm mrad).**
  - **Normalized rms vertical emittance of 1.70 π mm mrad (measured is ~1.75 π mm mrad).**
  - **Injection efficiency of 61% (measured is ~57%).**
  - **Injection intensity of 1.98E12 protons (measured is 1.85E12 protons).**

- **Excellent matching for the normalized rms emittances** measured and simulated, both hor. and vert., **but**

1. The initial **horizontal and vertical offsets adjusted** for optimizing the injection: **could they be measured?**
2. **By using the operational values in simulation, the bump appeared to be not closed.** The closed orbit is displaced by 80 mm at the maximum of the bump (the septum is ~40 mm from the reference orbit).

… More Recent Follow-up Studies (2014)

- Vivien followed up with some additional studies, not drafted in an internal note, but available at https://vraginel.web.cern.ch/vraginel/PSB/InjectionStudies_L2andL4/PSBInjection_Linac2Linac4.pdf.
- Once again the simulations were optimized to reach maximum intensity.
- Simulation were carried out on 100 turns, but also with 10000 turns to check the emittance blow-up which was found to be <4% for the LHC-type beams and <3% for the ISOLDE-type beams.
- **Issues reproducing the vertical emittance in several cases**.

			Beam parameters before capture				Injection parameters			
			Injection efficiency	N (10^{11} p)	ε^*_x [π mm mrad]	ε^*_y [π mm mrad]	Injection delay [us]	Programmed Qx, Qy	Position and angle of the injected beam [mm; mrad] Horizontal	Vertical
Linac2 50 MeV protons beam 155 mA $\varepsilon^*_x = \varepsilon^*_y = 1.2\ \pi$ mm mrad ------- Injection Bump Collapse Time = 50 us	**LHC-25 ns, 2 turns injected**	Real case	57%	18.5	1.93	1.74	17	4.42; 4.49		
		Simulation	56%	18.0	1.84	1.74	17.7		-45.5; 0	0; 0
	LHC-25ns, 4 turns injected	Simulation	48%	30.7	1.82	1.85	14.5	4.42; 4.49	-45.5; 0	0; 0
	NORMGPS, 9 turns injected	Real case	73.2%	104.0	10.0	9.2	21	4.28; 4.65		
		Simulation	75.5%	110.0	10.1	4.2	19.3		-45.5; 0	-5; -2
	160 MeV MD, 4 turns injected	Real case	56.5%	36.5	8.0	4.6		4.26; 4.46		
		Simulation	58.8%	37.9	7.98	□4.47	26.5		-45.5; -1	-5; -2
	160 MeV MD, 6 turns injected	Real case	61.9%	60.0	10.75	6.68		4.28; 4.49		
		Simulation	68.9%	66.7	11.19	4.67	25		-45.5; -1	-5; -2

Plans

- **Reasons to restart the work on the Linac2 simulation:**
    - To keep **benchmarking** the code used for the LIU-PSB simulations.
    - **Operational benefit**: A good simulation will allow a better understanding of the injection process.
      Predictive power to be exploited to possibly improve the current PSB performance.

- **Several issues to tackle:**
    - Work out a **simulation which works for different beam types/turns**.
    - Find out a **common set of input parameters** which can characterize the beam types.
    - Operation challenges: e.g., could we **measure the position and angles programmed in the "WorkingSet"**?

- **Which code to use?**
    - Idea is to try to **reproduce Vivien's results using PTC Orbit** (without PTC libraries) on SLC6.
    - **Eventually migrate the code to pyORBIT,** which is going to be the only supported code in the future.
    - PTC Orbit is being dismissed.

Supporting Slides

Linac2 Simulation (CERN-ATS-Note-2012-047 PERF)

- **Simulation results for different configurations:**

Simulation input				Resulting beam		
Initial horizontal offset of the injected beam [mm]	Initial vertical offset of the injected beam [mm]	Injection timing [μs]	Space Charge	Beam Intensity	Normalized RMS Emittance Horizontal [π mm mrad]	Normalized RMS Emittance Vertical [π mm mrad]
44.5	4	27	On	1.621E+12	2.40	1.64
45.5	4	27	On	1.670E+12	2.42	1.63
46.5	4	27	On	1.649E+12	2.36	1.59
45.5	4	28	On	1.699E+12	2.66	1.65
46.5	4	28	On	1.680E+12	2.56	1.61
46.5	4	28	Off	1.547E+12	2.23	1.73
45.5	4	29	On	1.716E+12	2.92	1.68

- **Excellent matching for the normalized rms emittances** measured and simulated, both hor. and vert., **but**

1. The initial **horizontal and vertical offsets adjusted** for optimizing the injection: **could they be measured?**
2. **The power converter settings of the operational beam** was found to be **different from the simulations** expectations **and the original specifications.**
3. **By using the operational values in simulation, the bump appeared to be not closed.** The closed orbit is displaced by 80 mm at the maximum of the bump (the septum is ~40 mm from the reference orbit).

Linac4 Simulation (I)

- As the simulation of the Linac2 mutli-turn injection process was assumed to be generally satisfactory, the second step is to study the Linac4 case.

- **Linac4 injection parameters used:**

Parameter	*Value*
Linac4 proton energy	50 MeV
Linac4 normalized beam emittance	0.4 π mm mrad
Linac4 beam current	40 mA

- **GOAL:** Estimate the parameters values needed to reach the highest possible intensity, within the required emittance budget.

- **Tunable Parameters:**
    - Number of injected turns.
    - Injection bump collapse time.
    - Initial horizontal and vertical offsets.
    - Injection timing, i.e. the delay between the time when the kicker pulse reaches its maximum and the time when the beam is injected.

- Simulations were carried out for 200 turns using 20000, 25000, 100000 macro-particles, to ensure that the results were not depending on the number of macro-particles.

Linac4 Simulation (II)

- Simulation results for an horizontal beam offset of 43 mm and a vertical beam offset of 6 mm.

Simulation input				Resulting beam		
Injected Turns	Bump Collapse Time [μs]	Injection timing [μs]	Space Charge	Beam Intensity	Normalized RMS Emittance Horizontal [π mm mrad]	Normalized RMS Emittance Vertical [π mm mrad]
1	50	40	On	0.34E+12	0.38	0.40
2	50	28	On	0.57E+12	2.66	1.95
4	60	30	On	0.90E+12	2.82	1.70
7	70	30.5	On	0.85E+12	2.03	1.78
7	70	32.5	On	1.09E+12	2.53	1.55
7	70	32.5	Off	0.82E+12	2.95	1.76
7	90	44	On	0.92E+12	2.20	1.48
8	70	33	On	1.41E+12	3.23	1.54
8	90	44	On	1.13E+12	2.54	1.42
9	**90**	**42.5**	**On**	**1.21E+12**	**2.58**	**1.42**
9	90	42.5	Off	0.82E+12	3.47	1.99
9	110	55.5	On	1.15E+12	2.62	1.35
9	110	55.5	Off	0.72E+12	3.54	1.98

- The bump collapse time is compatible with the available range of 45-150 μs.

Linac4 Simulation Summary

- **For an LHC-type beam:**
    - Optimal results obtained for **9 turns, a bump collapse time of 90 μs and an injection delay of 43 μs**.
    - **Optimistic results** in terms of beam intensity and normalized emittances.
    - In particular, the **beam intensity** resulted to be **higher** than what one would **expect rescaling the brightness from Linacs**, as reported in the IEFC workshop in 2011.
    - The brightness scaling factor Linac4/Linac2 was found to be ~83%.
    - **A shorter injection bump collapse time results in higher injection efficiency** at the expense of an higher horizontal emittance.
    - **Earlier start of the injection bump would result in higher efficiency**, again at the expense of an higher horizontal emittance.

- **High number of injected turns is needed**.

- **Impact of space-charge mechanism:**
    - The results of the simulations **without space charge** and under the same conditions showed **degraded performances in all parameters**.
    - **Not completely understood why**.

Linac2 Simulation: Emittance vs Efficiency

- **For an LHC-type beam:**
  - **A shorter injection bump collapse time results in higher injection efficiency** at the expense of an higher horizontal emittance.
  - **Earlier start of the injection bump would result in higher efficiency**, again at the expense of an higher horizontal emittance.

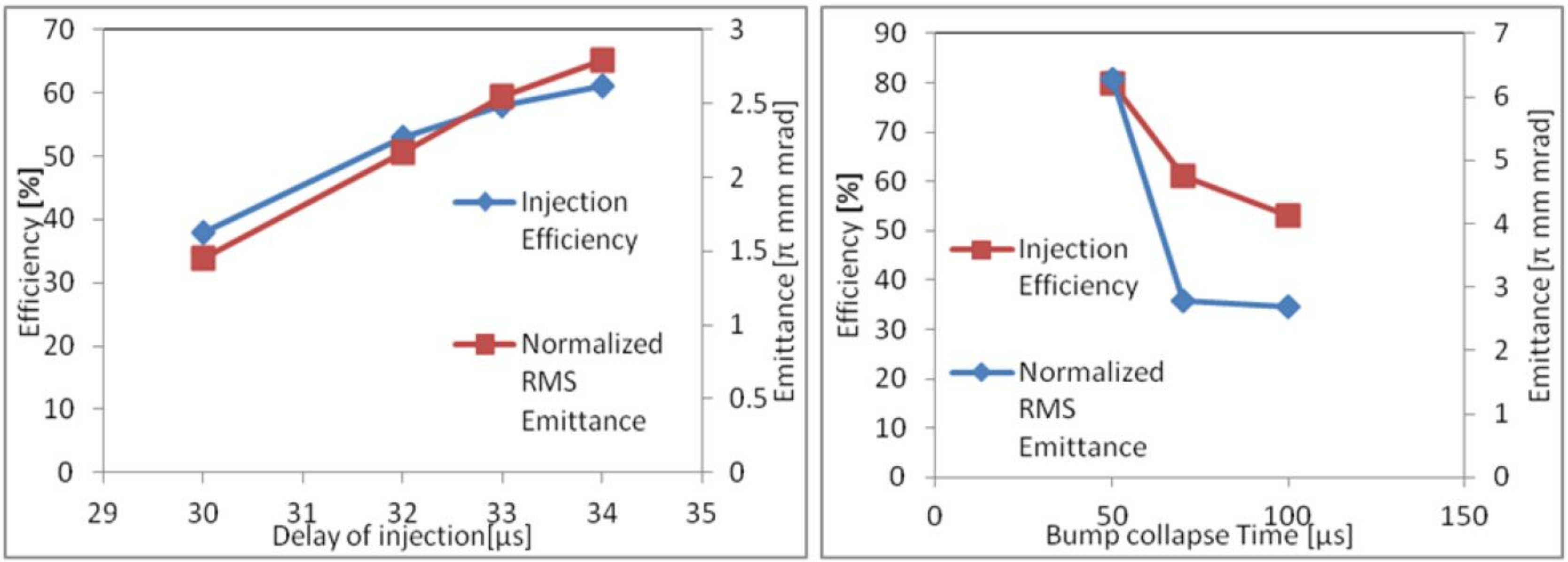


Figure 2: Influence of the injection timing (left) and of the bump collapse time (right) on the horizontal emittance and the injection efficiency for the case of a 7-turn injection.

Linac4 Simulation: Space-Charge (I)

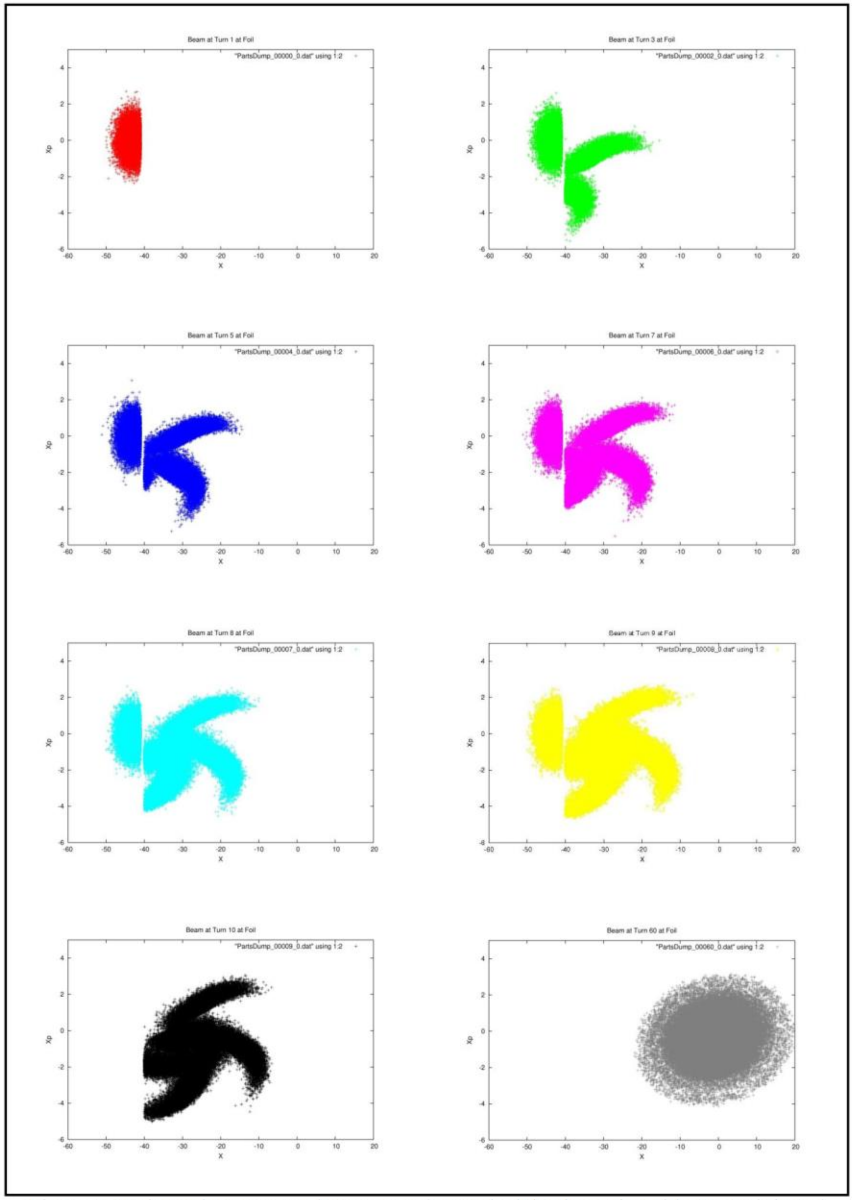


Figure 3: Horizontal transverse phase space plots at the injection point with 9 turns injected from a Linac4 50 MeV proton beam (at 1st, 3rd, 5th, 7th, 8th,9th, 10th and 60th turn) with a bump collapse time of 90 μs and an injection timing of 42.5 μs, with space charge effect. The initial offsets of the injected beam are set to 43mm (horizontal) and 6 mm (vertical).

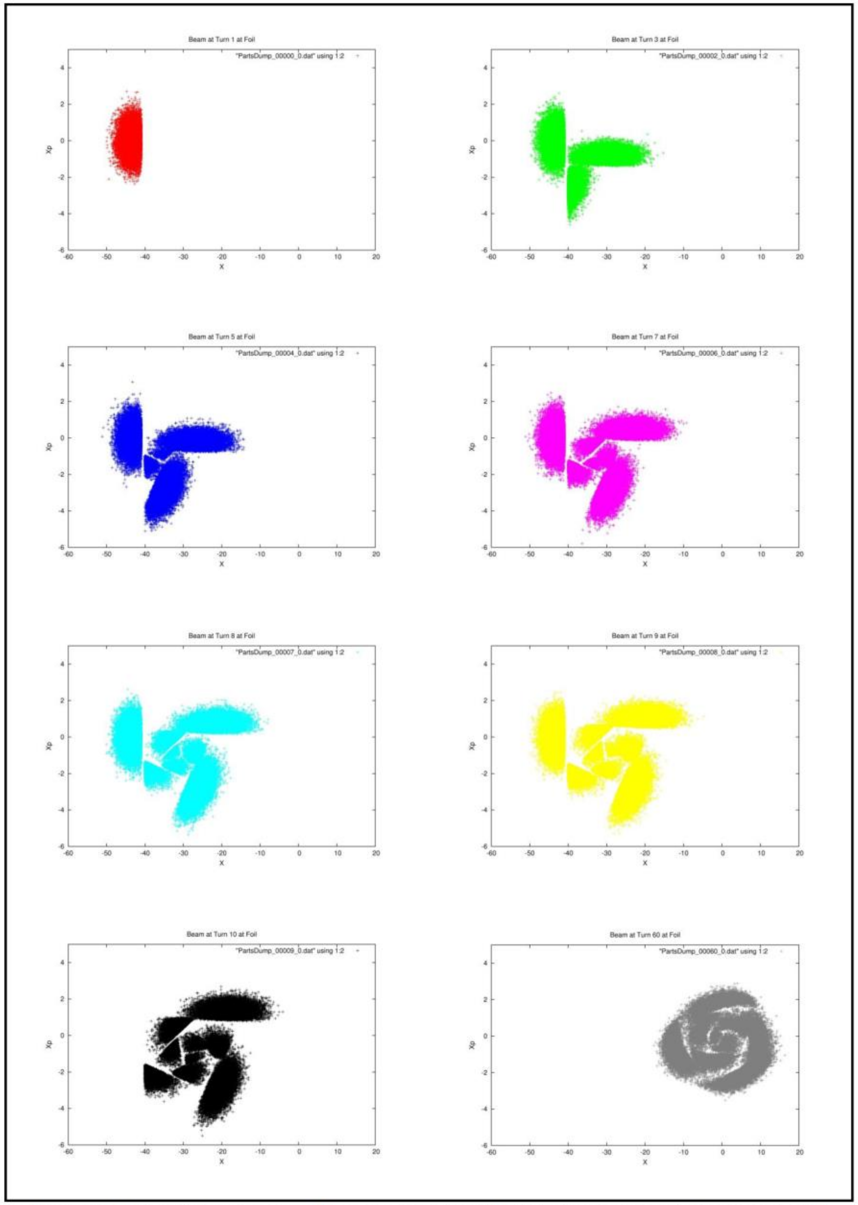


Figure 4: Horizontal transverse phase space plots at the injection point with 9 turns injected from a Linac4 50 MeV proton beam (at 1st, 3rd, 5th, 7th, 8th, 9th, 10th and 60th turn) with a bump collapse time of 90 μs and an injection timing of 42.5 μs, without space charge effect. The initial offsets of the injected beam are set to 43mm (horizontal) and 6 mm (vertical).

Linac4 Simulation: Space-Charge (II)

- **Some conjectures to try to explain why the simulation with SC yields better results:**
  - **SC introduces a defocusing effect** dependent on the particles position in the bunch and on the bunch distribution.
  - If **no SC mechanism** is added the **beamletrs rotate rigidly** around the closed orbit only because of betatron oscillations.
  - The **simulated model of the PSB does not have any non-linear effect described**, as can be seen from the behaviour in case of no SC mechanism.
  - With **no SC mechanism and a tune of 4.28** every **beamlet interacts with the septum 3 turns after it is injected** and this will cause particle losses.
  - With the **SC mechanism**, the particles within a beamlet will end up having **different tunes**, depending on their position within the bunch**: the rotation of particles closer to the centre will be slowed down**. These particles will eventually **end up not interacting with the septum blade** as at the time they should interact **the painting bump would be reduced enough to keep them away from the septum**.

KSW: Power Setting Mismatch

- The current of each KSW was measured in the rack with some active device, but the results are not coherent with the total current read in the control panel , Bix.KSW/AQN.

- H. Gaudillet reported that the calibration of such devices should be reviewed.

- For the simulation, the strength of the KSWs is found by matching the model to obtain a closed bump having as constraint the total current of the power supply per ring (~1080 A).

- The matching yields a bump closed with a maximum height of 56 mm at the septum blade.

- The septum blade is located at 40 mm with respect to the reference closed orbit.