Decay Ring: lattice, stability, RF

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MAIN ISSUES

- The aimed neutrino flux implies very high intensities to store (4×10^{12} $^{6}He^{2+}$ions and 3.71^{12} $^{18}Ne^{10+}$ions per bunch).
- Huge beam current 50-250 A.
- The collective effects are a big issue for the DR.
  - Direct Space Charge (tune spread). About -0.15 but it should be manageable.
  - Head Tail effects. Source of beam instabilities.
  - Beam loading. RF power consuming, phase shifting and cavity detuning.
  - ...
- These different collective effects give an upper limit for the allowed intensity in the DR.
- The DR lattice was changed to relax the head-tail effects.

Outline

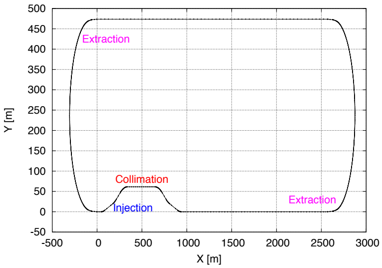
The main changes in the optics of the decay ring (DR) since FP6 are:

- The injection was moved from the arcs to a dedicated chicane:
  - Simpler arcs with more flexibility.
  - The momentum compaction is enlarged which relaxes head-tail effects.
- The momentum collimation section is now located in the injection chicane.
- Open mid-plane dipoles and quadrupoles are used in the arcs and chicane.
  - The same lattice can be used for any species of ion ($^{6}He^{2+}$, $^{18}Ne^{10+}$, $^{8}B^{5+}$, $^{8}Li^{3+}$).
  - The optics was calculated for $^{6}He^{2+}$(largest magnetic rigidity) and the collective effects were studied for $^{18}Ne^{10+}$(largest Z^2/A).

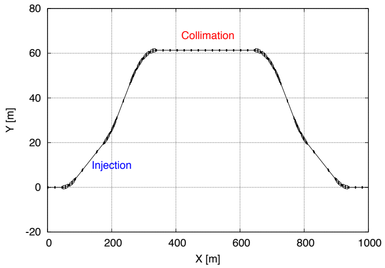
Layout of the decay ring

- Length of the straight section / decay ring = 37.2%.
- 176 superconducting dipoles, 236 quadrupoles, 64 sextupoles.
- The quadrupoles are warm in the collimation section and in the straight sections.

Decay ring



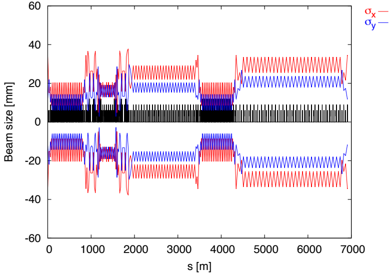
Injection chicane



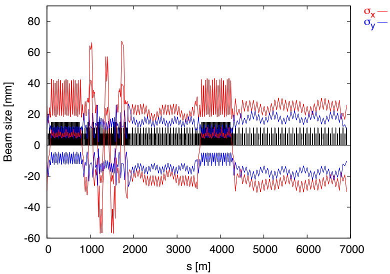
Beam sizes

Beta Beams, EUROnu WP4

Stored beam (6σ)



Injected beam (5σ)

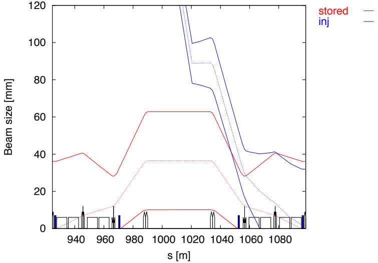


A 60 mm aperture is enough for most quadrupoles.

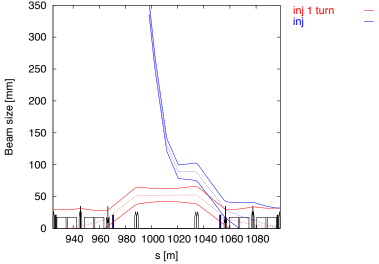
Injection chicane

- 4 kickers are used for a 36.4 mm bump.
- A 1 T 18 m long pulsed septum magnet with a 15 mm thick blade.
- The half-aperture of the quadrupole must be enlarged up to 120 mm.

Stored beam



Injection chicane



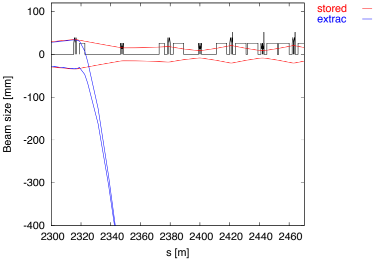
Extraction of the decay products

- 37% of the decays occur in the long straight section.

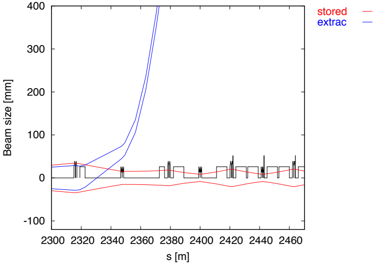
⇒ 30 kW are lost per decay there and must be extracted at the arc entrance.

- A 0.6 T continuous septum magnet is used for extraction.

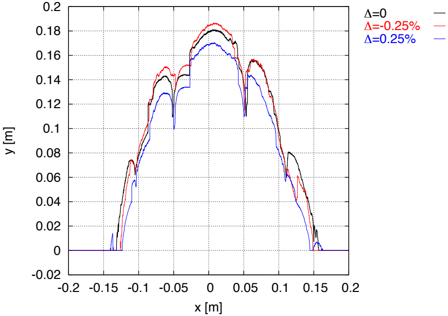
$^{6}He^{2+}$case



$^{18}Ne^{10+}$case



Dynamic aperture at the injection point (10,000 turns)



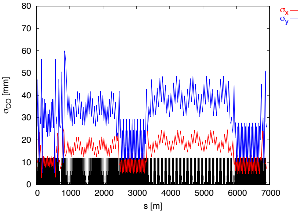
- β_x=25 m, β_y=54 m, σ_x=1.8 mm, σ_y=2.1 mm.
- The dynamic aperture is larger than 35 σ.
- The dynamic aperture is large enough to accept the whole beam.

Misalignment correction

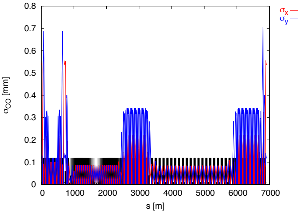
Overestimated tolerances for magnetic elements.

Defect type	Units	RMS value
$\frac{\Delta B}{B}$ dipoles	10^{-3}	0.5
Hor./Vert. misalignment dipoles	mm	0.5
Long. misalignment dipoles	mm	0.5
Rolling error dipoles	mrad	1
$\frac{\Delta k}{k}$ quadrupoles	10^{-3}	1
Hor./Vert. misalignment quadrupoles	mm	0.4

Correctors off



Correctors on



List of the elements

Magnet half-aperture	60 100 (2QP)/120(2QP)	mm
Total number of dipoles	176	-
Dipole length	7	m
Dipole field	6	T
Total number of quadrupoles	236/ 94 SC/ 142 W	-
Quadrupole length	2	m
Max quadrupole gradient	36	T/m
Total number of sextupoles	64	-
Max int sextupole gradient	34	T/m
Total number of kickers	4	-
Kicker length	1	m
Max field of kickers	0.37	T/m
Total number H/V correctors	120/117	-
Total number H/V BPMs	120/117	-
Max int field H/V correctors (3σ)	0.13/0.20	T.m

Outline

Beta Beams, EUROnu WP4

1. Optics
2. Stability
3. RF System models (G. Burt, A. Dexter)
4. Conclusions

Three ways were used to find the Bunch Intensity Limit due to head-tail effects, $\mathbf{N_b^{th}}$ (C. Hansen):

- A multi-particle tracking program in time domain, HEADTAIL
- A theoretical program in frequency domain, MOSES
- Peak current values into a coasting beam formula gives the Coasting Beam Equation

G. Rumolo et al., CERN-SL-Note2002-036-AP

Y. H. Chin, CERN-LEP-TH/88-05

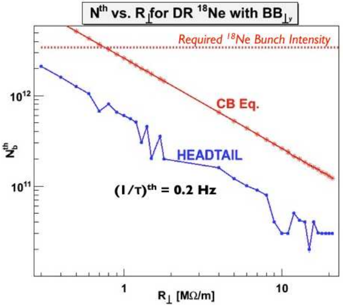
E. Métral, CERN, Overview of Single-Beam Coherent Instabilities in Circular Accelerators

$$N_b^{th} = \frac{32}{3\sqrt{2}\pi} \frac{R\epsilon_l^{2\sigma}\omega_r}{\langle\beta_{x,y}\rangle Z^2\beta^2 c} \frac{|\eta|}{R_\perp}$$

HEAD-TAIL EFFECTS

The FP7 DR lattice improved the intensity limits since FP6 by decreasing the transition gamma.

γ_{tr}=27 → 16.8
V_{RF}=12 MV → 32.5 MV
L_{eff}=36% → 37%



Courtesy:
C. Hansen

$N_b^{th} = 7 \times 10^{11}$ ions/bunch for $(1/\tau)^{th} = 0.2$ Hz and $R_\perp = 1 M\Omega/m$. Gain of a factor $\approx 2-3$ on the intensity limit.
NB: $R_\perp(SPS) = 20\ M\Omega/m$.

$N_b^{th} = 7 \times 10^{11}$ $^{18}Ne^{10+}$ can be used to get N_b^{th} for all other ions by using that CB Eq goes as $N_b^{th} \propto \frac{A}{Z^2}$.

Ions	Fluxes $[10^{18}]$	Years	$(\sin^2 2\theta_{13})_{min}$	NH,$(\sin^2 2\theta_{13})_{min}$	$\frac{N_b^{th}}{N_b^{nom}}$ [%]
^{6}He ^{18}Ne	$\overline{\Phi}_0 = 2.9$ $\Phi_0 = 1.1$	5 5	5×10^{-4}	No sensitivity	131 20
^{6}He ^{18}Ne	$\overline{\Phi}_0 \times 2$ $\Phi_0/2$	2 8	6×10^{-4}	No sensitivity	65 41
^{6}He ^{18}Ne	$\overline{\Phi}_0 \times 2$ $\Phi_0/2$	2 8	1×10^{-3}	No sensitivity	65 102
^{8}Li ^{8}B	$\overline{\Phi}_0$ Φ_0	5 5	1.5×10^{-3}	3×10^{-2}	75 74
^{8}Li ^{8}B	$\overline{\Phi}_0 \times 2$ $\Phi_0 \times 2$	5 5	7×10^{-4}	1.5×10^{-2}	38 37
^{8}Li ^{8}B	$\overline{\Phi}_0 \times 5$ $\Phi_0 \times 5$	5 5	2×10^{-4}	8×10^{-3}	15 15

The head tail effects dramatically limit the intensity in the DR and thus the neutrino fluxes we can reach (a factor of 2 is missing in the best case).

How to push this limit?

- Some classical approaches as introducing tune spread with chromaticity or amplitude detuning with octupoles were studied. No gain was observed in both cases.
- HEADTAIL was modified to take into account the tune spread due to direct space charge effects. First results showed a mitigation of head tail effects. More studies are necessary to confirm or infirm this result.
- To relax the suppression factor.
  - The number of bunches can increase (from 20 to 80 for example).

  ⇒ The number of ions per bunch decreases.

  ⇒ The required intensity becomes lower than the intensity limit.

Outline

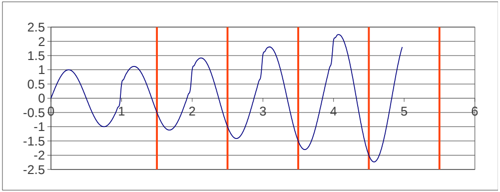
Issues

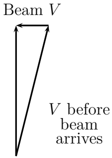
- Huge beam current 50-250 A.
- Huge RF power is required.
- Beam Current in quadrature with the RF (cavity will be detuned when the beam arrives).
- Very transient, ring partially filled with 20 bunches (500 ns).

- A tuner could not react that fast.

Solution suggested by E. Jensen

- If we split the RF into real and imaginary parts, the beam loading adds $I_b R/Q$ to the real voltage at 40 MHz.





- Detune the cavity so that the cavity phase is advanced between bunches (real part becomes finite and negative).
  - This causes a phase (and frequency) shift as the imaginary part remains the same.
  - With correct cavity frequency, beam loading is reduced as the real parts cancel. Imaginary part also changes.

Example System

Input data

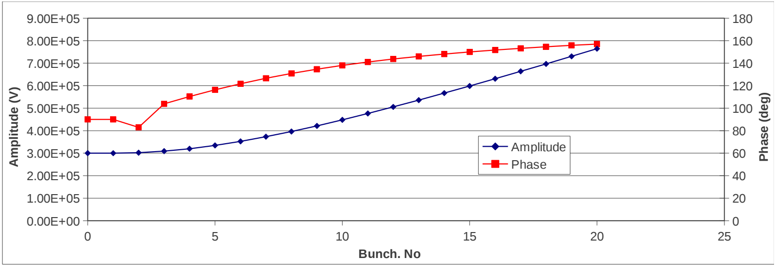
In the case of a PS-like cavity:

- I_b=224 A
- V_g=300 kV
- R/Q=25 Ω
- Q=20,000
- f_1=40.0 MHz
- f_2=39.2 MHz

A simple code has been written to understand the behaviour of such a system.
It includes a simple LLRF system that responds instantly (unrealistic) and can look at the effect of a varying current or frequency.

No detuning

If we do not detune the cavity and we only have a small RF power available the gap voltage quickly rises to 750 kV and the phase tends towards 180°.

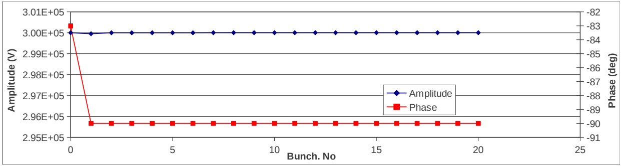


To keep the cavity on amplitude and phase with the cavity tuned to 40 MHz takes ≈9 MW.

With detuning

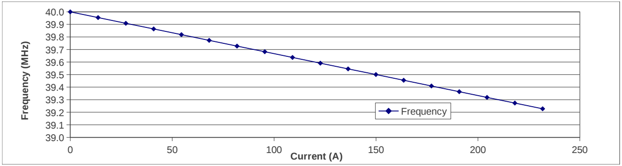
- To get the phase and amplitude correct with a detuned cavity requires 200 kW in this case with no charge or frequency errors.
- This is significantly less than the 9 MW required for a non-detuned system.
- Power not linear with charge ($P \propto Q^4$).

$\Rightarrow$ Sensitive to charge errors.



Filling

- As the decay ring fills the bunch charge will vary.
- This means the beam-loading/detuning will also vary.



- We will have to change the cavity frequency. 23 μs is very fast and probably not possible.
- Will be difficult to keep phase correct during a frequency sweep.

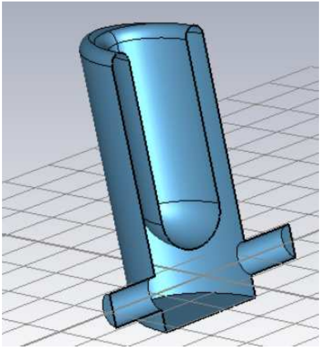
Options

- Ferrite based cavity – Maximum voltage is around 20 kV. Would require 1000 cavities (too many).
- Broadband Cavity – To cover the full frequency range would require a Q of 40. This needs 45 MW of RF to fill without ferrites (too power consuming).
- Use a cavity just broadband enough to cover the frequency jump of one injection and slowly tune the cavity between injections.
  - In the earlier calculations (assuming the PS buncher cavity) the cavity frequency changed by 50 kHz everytime a new bunch is injected and merged.
  - This would require a cavity with a Q of around 400.
  - This requires 3.5 MW of RF power to fill the cavity when the beam is not present which is too high.
- Use brute force- low R/Q SRF cavity. Last option studied

Brute force approach

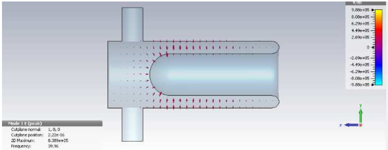
- If we design a cavity to have a low R/Q we can minimise the impact of the beam.
- If we use an SRF cavity we can reduce the power overhead to 450 kW.
  - This requires a very low R/Q of only 2 Ω (PS buncher cavity is 33 Ω by comparison).
  - As there is only small detuning (1.6 kHz) it operates very stably during filling.
- A standard quarter wave resonator is chosen as the cavity. The R/Q can be reduced by moving the beam away from the peak electric field.
- However the cavity must carefully be designed to keep the surface fields low while achieving a reasonable voltage.
- The beam now also experiences a transverse kick so every other cavity must be rotated to cancel the kicks.

Low Shunt Impedance Cavity Design



- Length: 452 mm
- Height: 1.9 m
- The cavities must flip orientation every other cavity.
- Total width: 3.8 m.
- Total cryostat width: 4.5-5 m.

- The peak electric field at the design voltage of 600 kV is 30 MV/m.



Costs

- Difficult to estimate the cost of this system.
  - Bulk Niobium probably the best option.
  - Cryostat plant not evaluated here (certainly significant cost).
  - HOM damping neglected here (significant however due to the high beam current).
- The RF source should be specified to 1 MW peak and 50 kW average and at 40 MHz.
- As an initial costing the RF power and distribution would be about 1-2 MCHF each station and the cavity would be 2-3 MCHF.
  - Total of up to 5 MCHF per RF station.
  - 56 RF stations are required giving a total cost of 280 MCHF and a total voltage of 32.5 MV.

Outline

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2. Stability
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Optics

- The solution with open mid-plane magnets is definitively adopted.
- The injection has been moved from the arcs to one of the long straight sections.
- The optics suits to a decay ring for $^{6}He^{2+}$, $^{18}Ne^{10+}$, $^{8}Li^{3+}$ or $^{8}B^{5+}$ ions.
- The transverse properties (dynamic aperture, needed apertures, needed elements) show that the optics are not the stopping point.
- Tracking studies to check the magnet tolerances are to be done.
- The collimation should be studied more precisely with its impact on the vacuum.

Stability

- Huge intensities must be stored in the DR.
- Collective effects and more particularly head-tail effects are one of the main issues for the DR.
- The intensity limits due to head tail effects are less than the required intensities.
- Some ways to mitigate head-tail effects were studied without success.
- A Beta-Beams with a larger suppression factor could be the key by relaxing the peak intensities in the DR.

RF system

- A solution based on phase quadrature is proposed for the DR 40 MHz RF system.
  - 56 cavities.
  - Total RF peak power of 27.5 MW.
  - Total average power of 1.8 MW.
  - Phase to be linearly increased during bunch merging, which may increase the required RF power.
- Total cavity width: 1.9 m for a length of 0.452 m.
  - A cryostat is likely to be 4.5-5 m wide and 1.5 m long.
  - For a packing factor of 1.5 and 56 cavities the total RF section length will be about 37 m long.
- The 80 MHz system must be looked at.