A 80MHz rf-system for improving spill quality at slow extraction from SIS18

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Peter Hülsmann, GSI

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Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

1. Reactivation of an old single resonator (ER)

- **Basic Idea**
  - Reactivation of an old Single-Resonator (ER) from the UNILAC-RF, since a Resonator of a frequency > 40MHz is required. The ER has a resonance frequency of 108,5MHz
  - The ER has an enormous shunt impedance of 8,4MΩ (measured with a ceramic bead)
  - A 3-4kW solid state broadband amplifier from Rhode&Schwarz, BBL200 with liquid cooling, is available (broadband, of course, is not necessary).

- **Advantages of the ER**
  - The high shunt impedance of the cavity will lead to a very high gap voltage, even with the low RF-power of 3-4kW.
  - The resonance frequency of 108,5MHz is high enough to allow an integration of a beam pipe with ceramic gap without falling below the frequency border of 40MHz.

- **Disadvantages of the ER**
  - The high shunt impedance of the ER will lead to a very high beam loading
  - The ER has some HOM's with a high shunt impedance which have to be damped selectively.
  - The ER has an enormous volume of about 1,7m^3 is not heat able due to the need of some vacuum rubber seals. Thus an integration of a beam pipe with ceramic gap is mandatory to fulfill the vacuum requirements of SIS18.
  - The ER needs vacuum even outside the beam pipe, since the expected field strength at the gap will exceed 1kV/mm, which is the disruptive strength in air.

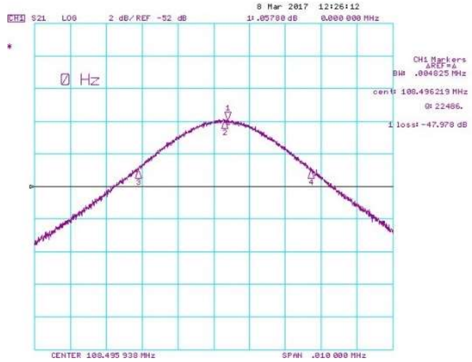
2. How does an ER look like

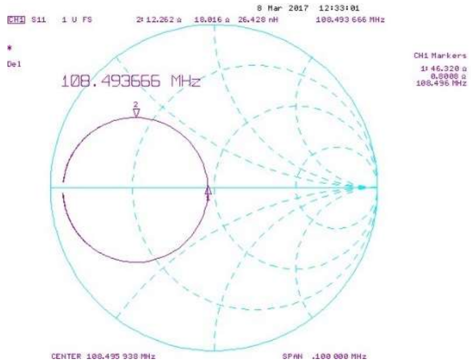
Fig. 1: Some photos of an unchanged ER in the „Großmontage“ during the assembling phase.

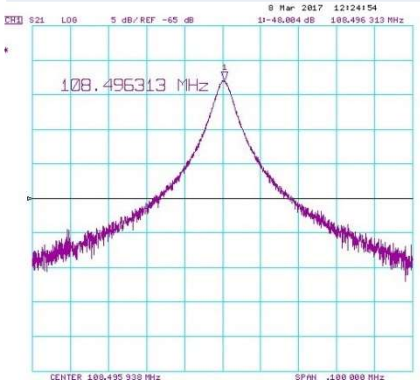
Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

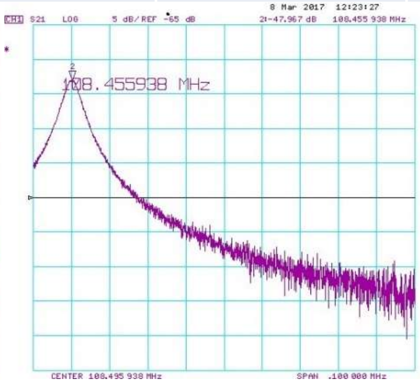
3. Basic parameters of an unchanged ER, measured by perturbation method

Number	Symbol	Qantity
Cavity diameter	D	1477,4mm
Cavity length	L	728,2mm
Distance gap	l_G	100mm
Resonance frequency	f	108,5MHz
Unloaded Q	Q_0	42.734
Shunt impedance	R_P	8,4MΩ
R_P over Q_0	$2R_P/Q_0$	393Ω
Gap Voltage (3-4kW)	U_G	224-259kV









$$\frac{2\Delta\omega}{\omega_0} = -4\chi_e\left(\frac{\omega_0}{4}\frac{R_P}{Q_0}\right), \quad \chi_e = \frac{\alpha_e V_P}{l^2}$$

Fig. 2-5: The two pictures to the left show the effect of using a ceramic stick (diam.=3mm, ε_r=9,8) directly on the middle axis through the cavity. Additionally the Q_L value and the coupling factor K are required (pictures above).

4. A modification for the ER: beam pipe with ceramic gap

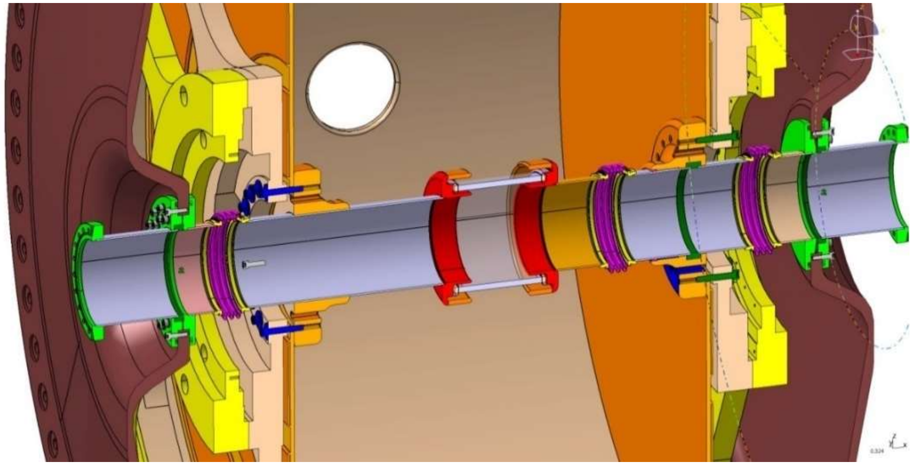


Fig. 6: The beam pipe with the gap integrated into the cavity

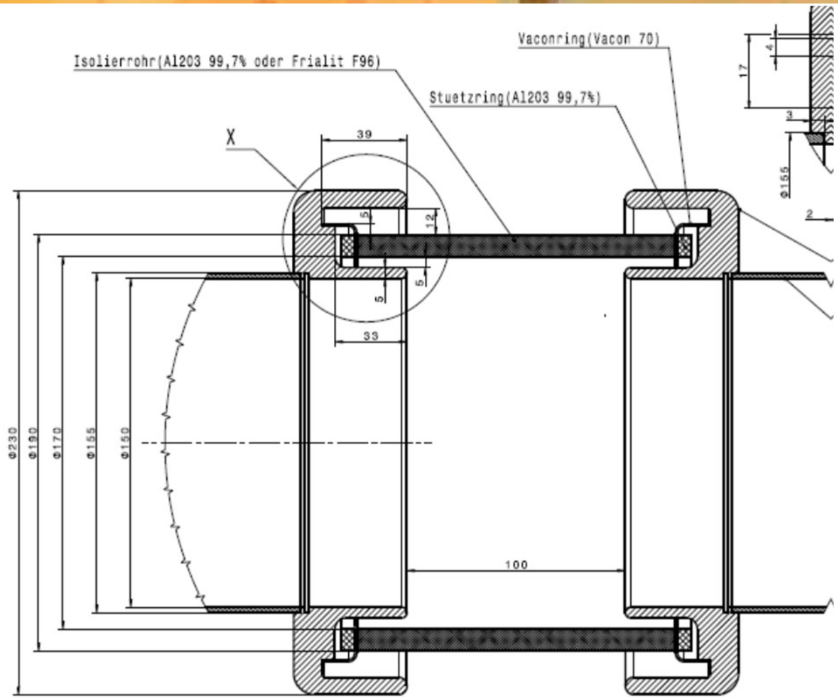
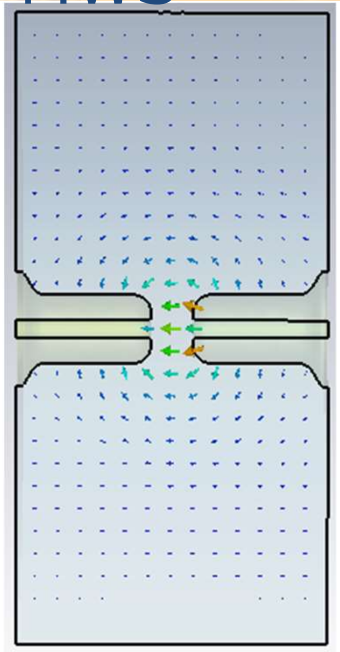


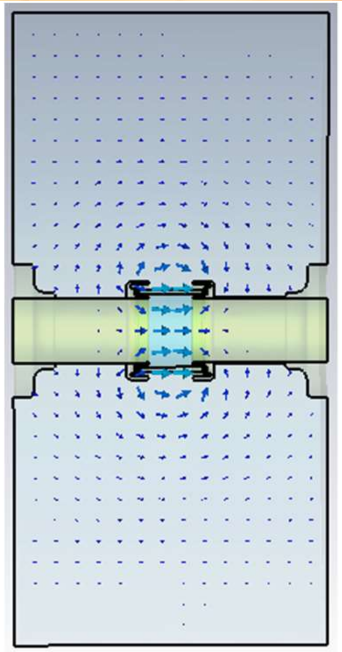
Fig. 7: Construction of the gap adaptor

The vacon rings were the ceramic is soldered on are deeply enwrapped between the electrode lips in the gap adaptors in order to reduce the field strength as low as possible.

5. How does the parameters of the ER will change due to the presence of the beam pipe, calculated by CST-MWS



Fig, 8: The TM_{010}-mode in the unmodified ER



Fig, 9: The TM_{010}-mode in the ER with beam pipe and ceramic gap

	Resonance	Q_0	$2R_p/Q_0$	R_p
ER (CST-MWS)	108,5MHz	46700	402Ω	9,4MΩ
ER (measured)	108,5MHz	42700	392Ω	8,4MΩ
ER with beam pipe (CST-MWS)	82,4MHz	33000	310Ω	5,1MΩ
ER with beam pipe (realistic)	82,4MHz	29500	310Ω	4,6MΩ

6. Beam pipe pure stainless steel or coated by copper?

Number	f	R_P	Q_0	$2R_P/Q_0$	U_G (3-4kW)
Beampipe coated by copper ($\sigma=5{,}8\cdot10^7 1/\Omega m$)	82,4MHz	4,6MΩ	29.500	300Ω	173-200kV
Beampipe stainless steel ($\sigma=1{,}4\cdot10^7 1/\Omega m$)	82,4MHz	1,1MΩ	7.333	300Ω	85-98kV

Thus the decision is: Copper coating is mandatory, since there will be some additional losses in the rf-supply transmission line from the rf amplifier to the cavity (25m, about 500W).

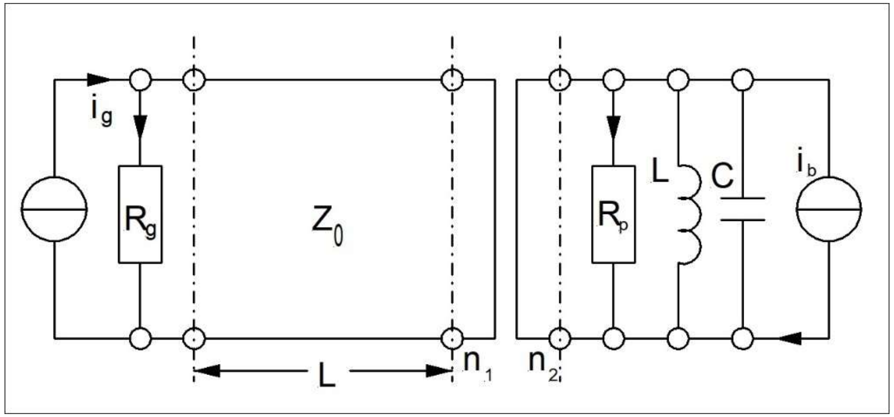


Fig. 10: The equivalent circuit model for cavity-generator-beam-interaction

Equivalent circuit parameters	
R_p	4,6MΩ
L	301nH
C	12,4pF
Q_0	29.500

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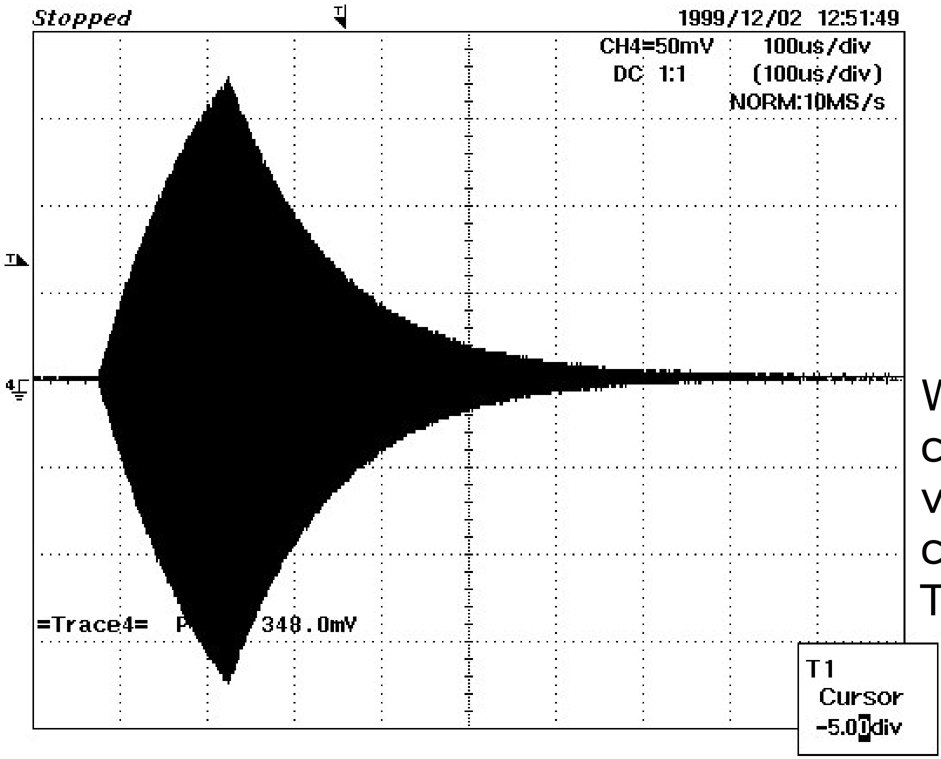
7. What beam intensity is reasonable?



$$U(t) = U_0\left(1 - e^{-\frac{\omega}{2Q_0}t}\right) \qquad U(t) = U_0 e^{-\frac{\omega}{2Q_0}t}$$

From the damping part of the black curve one may calculate the unloaded Q_0-value

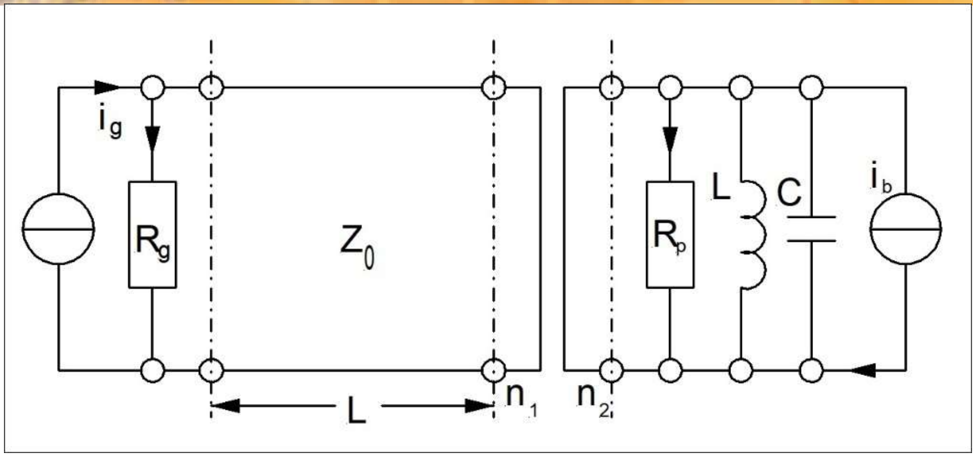
$$Q_0 = \frac{\omega}{2} \frac{(t_2 - t_1)}{\ln\left(\frac{U(t_2)}{U(t_1)}\right)} = \frac{2\pi \cdot 108 \cdot 10^6 \frac{1}{s}}{2} \cdot \frac{260 \cdot 10^{-6} s}{\ln\left(\frac{17{,}2}{2}\right)} = 40670$$

With the knowledge of the rf-beam-current, namely 7mA and the achieved voltage within 150ms one is able to calculate the shuntimpedance to 9MΩ.
The settling voltage would be:

$$U_0 = R_P 2 I_{DC} = 9 \cdot 10^6 \Omega \cdot 7 \cdot 10^{-3} A = 63.000V = 63kV$$

Fig. 11: The reaction of an ER's on an excitation by an ion beam (black curve). The macro pulse has a duration of 150ms and the DC-current during the macro puls was 3,5mA. This measurement was made by W. Vinzenz in 1999.

7. What beam intensity is reasonable ?



Equivalent circuit parameters	
R_p	4,6MΩ
L	301nH
C	12,4pF
Q_0	29.500

Example: Lets assume a nitrogen beam with the following parameteres

$$N_{14}^{7+}, E_{kin} = \frac{2GeV}{u}, number\ of\ particles = 10^{11}, \frac{\Delta p}{p} = 5 \times 10^{-4}$$

82,4MHz, h=63, the beam is captured in 63 buckets filled by 2/3. The DC-current of such a circulating beam would be I_{DC}=200mA.

To capture the beam we need 50kV rf gap voltage and, due to the enormous shunt impedance of 4,6MΩ one would need I_{rf}=11mA to generate the 50kV.

That means in other words: 11mA driving current from the rf-generator but 400mA driving current from the beam.

Thus, the beam intensity has to be restricted to 10^8 or 10^7 particles.
Otherwise, due to the control system, no stabil operation is possible!
The rf driver current must be much larger than the rf-beam current.

Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

8. Selective filtering for dangerous HOM's is necessary

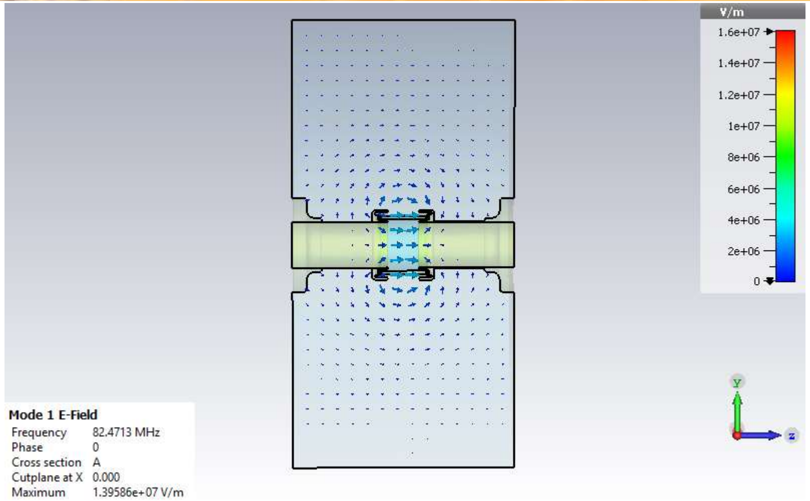


Fig. 12: Again the basic mode at 82,4MHz

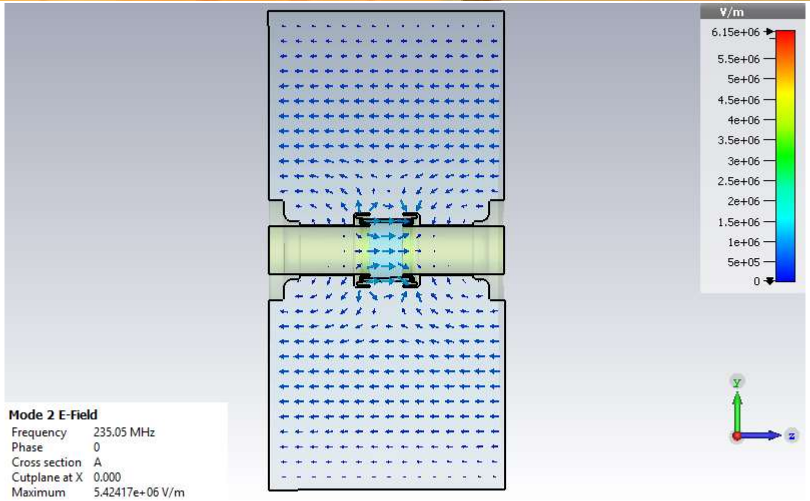
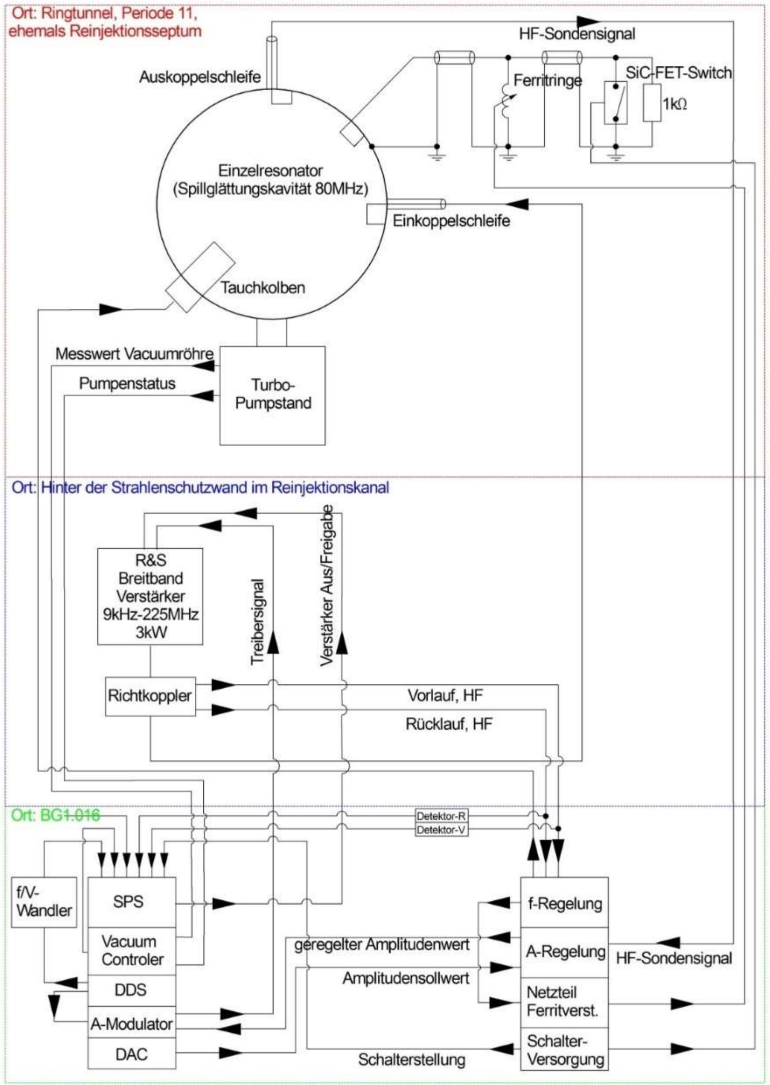


Fig. 13: The next HOM at 235 MHz with significant shunt impedance on axis.

Mode	Frequency	Q_0	$2R_p/Q_0$	R_p
1	82,40MHz	33000	310Ω	5,1MΩ
2	235,03MHz	41000	16Ω	330kΩ
3	332,93MHz	95000	0Ω	0Ω
4	432,72MHz	73500	3Ω	115kΩ
5	456,82MHz	89000	0Ω	0Ω

Even the HOM's have to be considered with respect to the allowable beam intensities. Mode 2 may lead to a longitudinal instability. Selective filtering will lower the growth rate of the instability or even remove it.

9. Amplitude- and phase-control



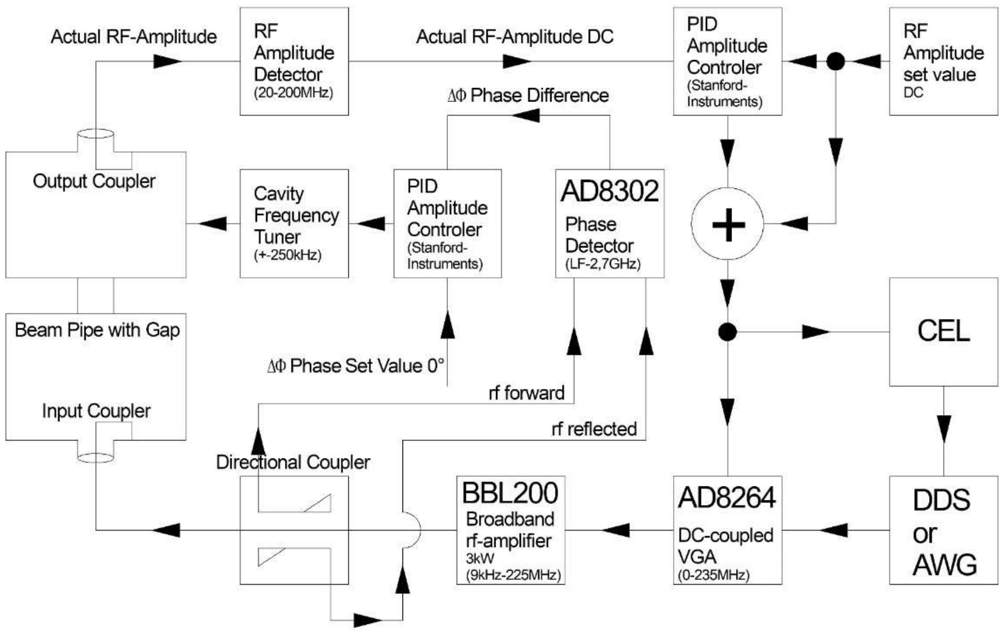


Fig. 14: The outer control loop is the amplitude- and the inner loop the phase-control-loop

Fig. 14.1: The complete rf-system with all parts at three different lacations and cabeling

Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

Feeding the resonance

- **Phase displacement acceleration**
  Empty rf buckets are created outside the waiting stack and then the bucket energy is decreased so that it traverses the beam. A rf-frequency variation of the rf-system is necessary and lead to a complicate low level rf system (at the beginning not possible).
- **Unstacking**
  Small rf buckets can be created with a high harmonic rf system at the lower edge of the stack. A small fraction of the stack is than trapped and accelerated inside the small buckets to a different energy. This is a complicate procedure with the need of a complicate LLRF-system (certainly not possible.
- **Front end acceleration by empty rf bucket channeling**
  Relatively simple single frequency procedure which should be possible.
- **Capture the waiting stack in stationary buckets and extract the beam with a chopped spill**
  A simple isoadiabatical rf-capture process at a single frequency which should be possible.

11. Empty rf-bucket channeling

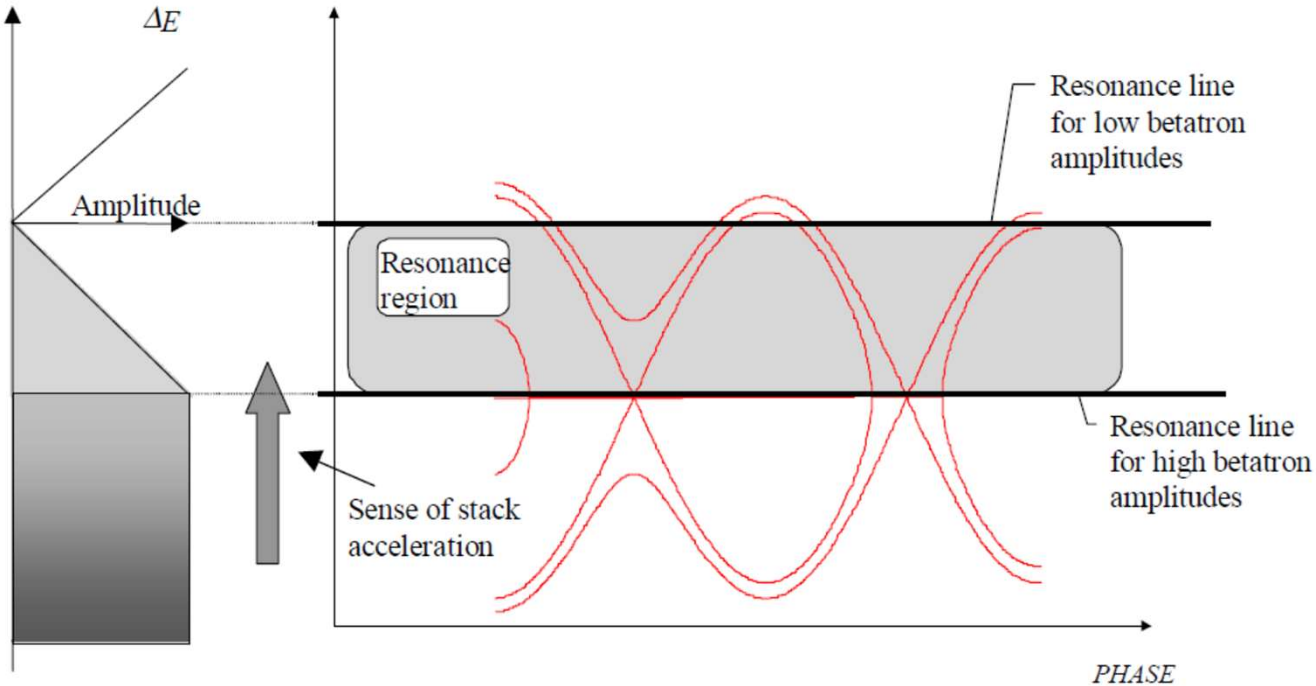


Fig. 16: The exact position of the buckets are shown for a situation below transition.

Negative quasi stationary buckets are created. The particles are swept into the bottle necks between the buckets and start to move around the buckets anti clockwise. The voltage requirement is given by the width of the resonance region: The width of the resonance region has to be smaller than the bucket half hight.

12. Capture the waiting stack in stationary buckets

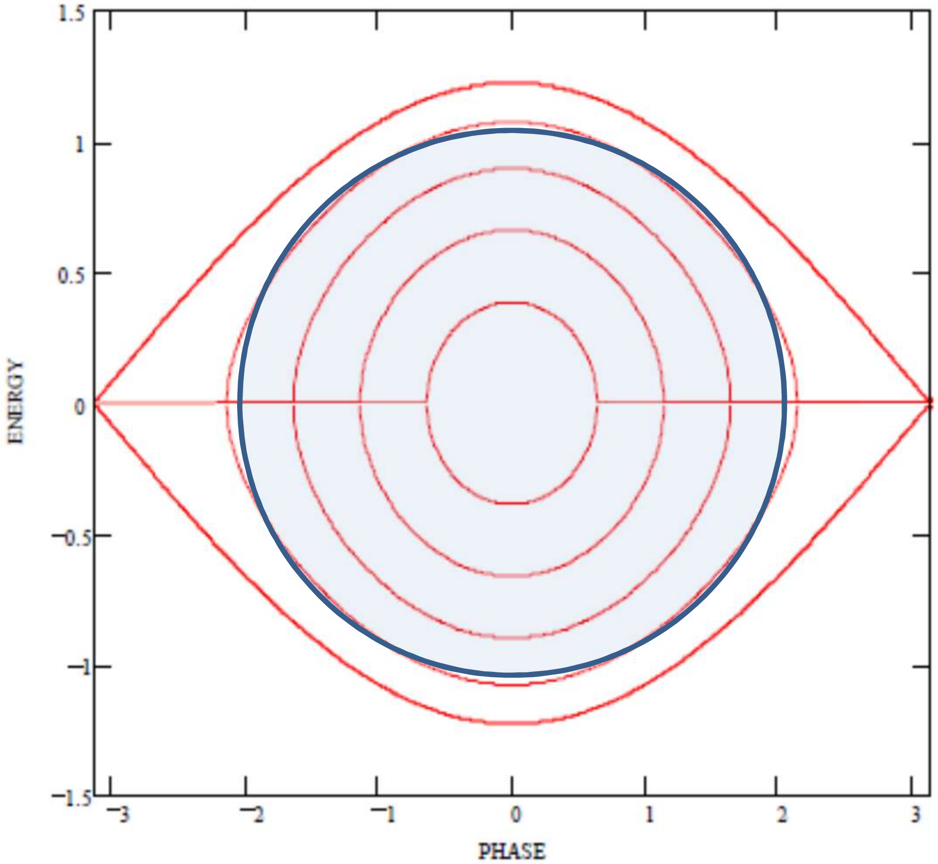
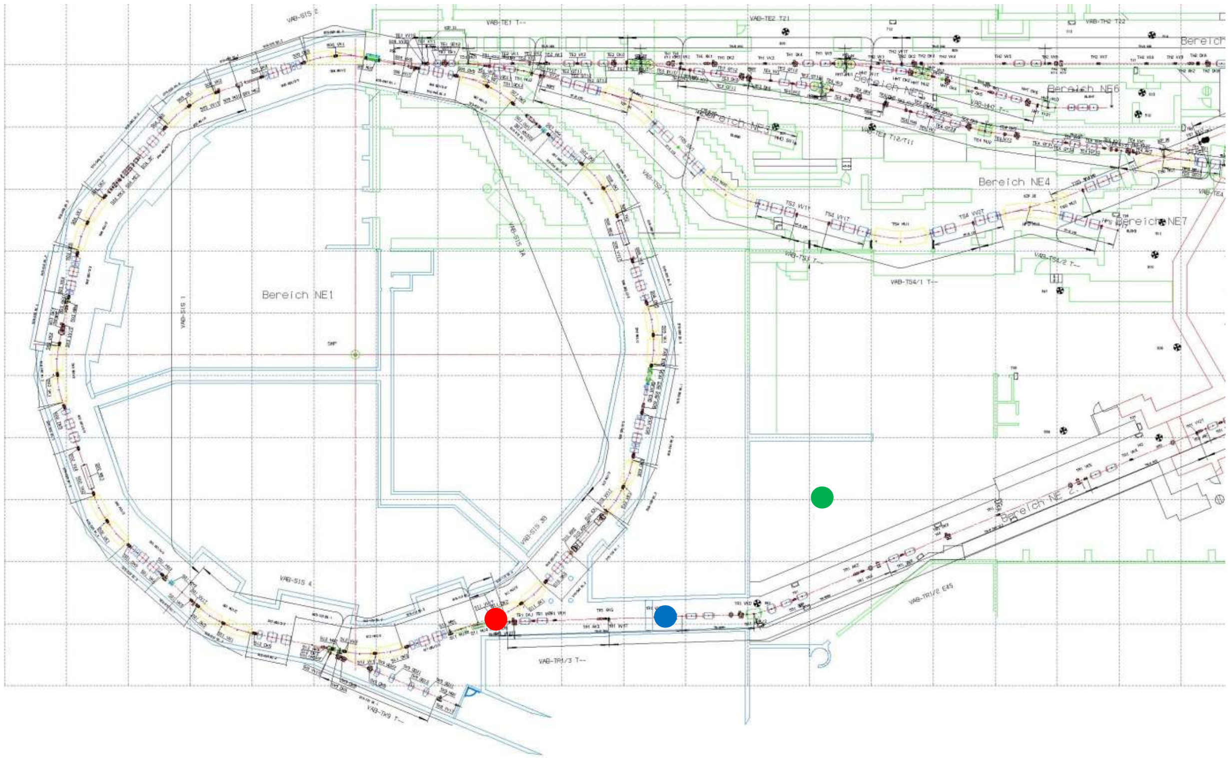


Fig. 16: The stack is captured in 63 stationary buckets

First the waiting stack will be captured isoadiabatically within 25ms < t < 100ms. Than the resonance is moved into the bunched stack. As a result the extracted beam will have a chopped structure. For our example, the nitrogen beam, the synchrotron frequency in the 50kV Buckets is 4.5kHz.

Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

13. The different locations of the rf-installation



The complete cable installation will be done fom 14. -29. of July by Mr. Jöhnke.
The location in S11 is nearly completely prepared for the integration of the cavity
Some additional cable trays have to be installed

Fig. 17: The 3kW solid state amplifier will be located next to the former reinjection channel (blue dot), 25m away from the cavity, which will be located in period 11 (red dot)
The PLC, the steering- and control racks will be located in the RRF-supply-room, BG1.016 (green dot)

Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

14. The installation situation in period 11

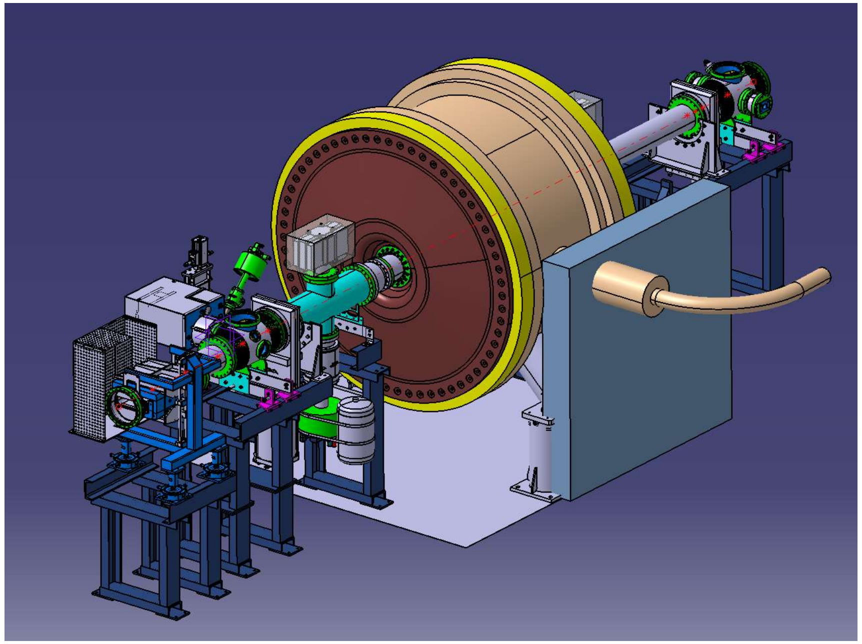


Fig. 18: The picture shows the straight beam line in period 11 (not the actual situation)

Fig. 19: The picture shows the straight beam line in period 11 (not the actual situation)

Peter Hülsmann, GSI, Email: P.Huelsmann@gsi.de, Phone: ++49 (0)6159 71 2066

15. Intention of the project

- Proof of principle
- Machine experiment
- Work out in collaboration with experimenters what quantities are of most importance
- Show that for small to moderate intensities $(10^6 - 10^8$ particles in the stack)
  - the pile-up and the spill quality can be improved
  - breaks can be avoided
- If the pilot study proves successful a new, more appropriate VHF cavity is thinkable. More appropriate means a low shuntimpedance, low quality factor, single mode structure in order to handle the higher beam intensities with no need to take attention to any HOM's. Of course, such a cavity needs a tetrode power amplifier of about 50kW rf-power, which has to be designed for this purpose.

16. Acknowledgement

Peter Spiller, Wolfgang Vinzenz, Niels Pyka, Peter Schmid, Bernhard Zipfel, Robert Balss, Jens Stadlmann, David Ondreka, Harald Klingbeil, Gerald Schreiber, Calina Christoph, Michael Frey, Hans-Günther König, Dieter Lens, Eberhard Merz, Norbert Bönsch, Mario Bevcic, Reinhard Wettengl, Markus Romig, Wilfried Sturm, Ludwig Heyl, Elena Nickchen, Jörg Jöhnke, Georg Gruber, Volker Fuhr, Michael Roth, Andreas Krämer, Stefan Wilfert, Maria Cristina Bellachioma and so on…

Number	Symbol	Qantity
Cavity diameter	D	1477,4mm
Cavity length	L	728,2mm
Distance gap	l_G	100mm
Resonance frequency	f	82,4MHz
Unloaded Q	Q_0	29.500
Shunt impedance	R_P	4,6MΩ
R_P over Q_0	$2R_P/Q_0$	310Ω
Settling time τ_0	$2Q_0/\omega_0$	114μsec
Gap Voltage (3-4kW)	U_G	166-192kV

$$Stickstoffstrahl, N_{14}^{7+}, E_{kin} = \frac{2GeV}{u}, number\ of\ particles = 10^{11}, \frac{\Delta p}{p} = 5 \times 10^{-4}$$

Quantity	Formular	Number
relativistic γ	$\gamma = 1 + \frac{E_{kin}}{E_{ruh}}$	3,15
relativistic β	$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$	0,95
revolution time τ	$\tau = \frac{L}{\beta c_0}$	$0{,}76 \mu sec$
revolution frequency f_0	$f_0 = \frac{1}{\tau}$	$1{,}31 MHz$
angular revolution frequency ω_0	$\omega_0 = 2\pi f_0$	$8{,}24 MHz$
ion energy E	$E = N m_0 \gamma c_0^2$	$41{,}04 GeV$