Development of Barrier Bucket RF Systems for ESR and SIS100

M. Frey, 14. June 2018
outline

- motivation/history at ESR
- ESR BB system
  - requirements
  - theory of operation
  - choice of ring core material
- ESR BB cavity design
  - prototype ring core impedance measurement+modeling
  - PSpice simulation of full cavity
- ESR BB cavity properties
- ESR BB pre-distortion
- ESR BB signal generation
- ESR BB full system results
- ESR BB outlook

- SIS100 BB system
motivation

- RF pulses create potential barriers
- Barrier creation allows longitudinal beam manipulation, e.g., confinement of a bunch
- When barriers are moved, beams can be compressed -> intensity increases
- Multiple injections between compression operations lead to further intensity increase ("longitudinal stacking")
demonstration at ESR

- ferrite acceleration cavities were used with single sine + offset pulses

- hardly feasible due to extreme sensitivity concerning pulse parameters

development of a specialized BB cavity
motivation/history at ESR

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ESR BB cavity design
  - prototype ring core impedance measurement+modeling
  - PSpice simulation of full cavity

ESR BB cavity properties

ESR BB pre-distortion

ESR BB signal generation

ESR BB full system results

ESR BB outlook

SIS100 BB system
ESR requirements

- single sine pulses of $T_1=200$ ns ($f_{BB}=5$ MHz)

- pulse amplitude $\tilde{U} = 1$ kV

- flexible control of amplitude and repetition period $T_2$ at injection energy: 4-400 MeV (between $f_{rep}=250$ kHz and $f_{rep}=2$ MHz)

- symmetry and low ringing
ESR cavity design – theory of operation

- Cavities with ring cores are transformers: ring core = iron core, housing = secondary winding, gap capacity = load
- Ring cores are a lossy inductance defined by geometry and complex $\mu_r$

$$L_0 = l \frac{\mu_0}{2\pi} \ln \left( \frac{d_o}{d_i} \right) \quad L = L_0 \mu_r' \quad R = \omega L_0 \mu_r''$$

- Ring core inductance L, resistance R and gap capacity C form RLC circuit
- Loss effects in ring cores described by $\mu_r''$ ($\sim R$) -> define oscillation damping -> bandwidth
ESR cavity design – ring core material

- ferrites: high Q-value -> narrowband cavities 😞
- iron-based nanocrystalline Magnetic Alloy (MA) ring cores: very low Q-value -> broadband cavities 😊

- cores are wound from thin ribbon: side surfaces are roughly textured because layers tend to misalign (important for cooling)
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strategy: ring cores dominate cavity
  -> analyse prototype core to enable simulation of full cavity
  -> obtain amplifiers load impedance
ESR cavity design – impedance measurement and PSpice modeling

- Impedance measurement of prototype core in test box
- Subtraction of test box influence (estimated with CST simulation)

Identification of lumped-element equivalent circuit using „vector-fitting“ algorithm

1 ring core at 5 MHz: \(|Z|\approx 200 \, \Omega\)
ESR cavity idea

- 4 ring cores connected in parallel
  -> gap voltage
  = 4 x voltage at load

- one cavity per pulse
  (2 in same housing)

P. Hülsmann, RRF department, GSI
### ESR simulation of full cavity

- **sufficient matching between amplifier and cavity at 5 MHz**
- **at 5 MHz and \(|Z|=25 \, \Omega\), \(U=4 \times 225 \, V = 900 \, V\) possible with 1 kW**

**satisfying results — production approval**
ESR cavity design – CAD and production

- based on extensive testing with ARD broadband test cavity
- very short beam pipe requested (for Schottky pick-up on same base-frame)
- large ESR beam pipe diameter -> little space for ring core material
- power range of amplifiers 1 kW -> air cooling necessary

unspectacular but huge milestone!
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measurement result:

- frequency response results in distortion of input voltage
- pre-distortion of signals is necessary

|Z|/Ohm

f/MHz

|Z| Measurement

|Z| Simulation

Phase/°

f/MHz

Phase Measurement

Phase Simulation

simulation without gap voltage divider

Distortion
LLRF - pre-distortion of signals

1. measure transfer function $H$

2. calculate Fourier-coefficients of pre-distorted signal

3. transformation to time-domain + application

![Graph showing the transfer function $H$ and its Fourier coefficients.](image)
problem with linear pre-distortion: amplifier characteristic

- Amplifier characteristic differs from datasheet values.

no datasheet value depicts this characteristic -> amplifier selection by testing
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LLRF – re-triggering

- when barriers are moved, consecutive pre-distorted waveforms may overlap
  
  ![Waveform Image]

- signal generation must detect new trigger while output still active
- -> 2 alternating signal generators

- produces alternating trigger pulses

![Signal Generation Diagram]

K. Groß, H. Klingbeil, Temf, TU Darmstadt
linear pre-distortion:
- $U_b = 520 \text{ V}$
- good quality

non-linear pre-distortion:
- $U_b = 800 \text{ V}$
- improvement in ringing after pulse
- symmetry insufficient (internal amplifier limitation?)
ESR BB system – full system results II

- phase shifting of moving barriers demonstrated with full system (manual data supply from PC to SCU)

- two revolution periods are shown

- here barriers are created at equal phase angle (amplitude doubles)

- one barrier is shifted by 180° in both directions

full system works as intended! -> installation appproval
ESR BB system – status + outlook

status:
- function of full system demonstrated
- pulse amplitude $U_b=520$ V with high quality achieved (1 kW amplifier)
- installation in ESR finished

to do:
- software development for unit controller (task: e.g. calculation of pre-distorted waveforms, control of signal generators)
- adaption of control system connection (e.g. phase ramp in FESA-class for ramped-devices?)
- ESR BB system
- SIS100 BB system: pre-development phase
  - requirements
- SIS100 BB cavity design
  - oil cooling
- SIS100 BB power amplifier design
- SIS100 BB simulation results
  - frequency domain
  - time domain
- SIS100 BB outlook

procurement starts 2019
### SIS100 requirements

- **creation of 2 barriers in two empty buckets** -> single sine pulses of $T_1=666$ ns ($f_{BB}=1.5$ MHz)
- **flexible control of amplitude and repetition period** $T_2$ between $f_{rep}=110$ kHz and $f_{rep}=270$ kHz
- **pulse amplitude** $\mathcal{U} = 15$ kV
- **maximum beam impedance** 1000 Ω (cavity+amplifier)
- **cavity length** $<1.3$ m, but only 1.0 m for housing (due to feasibility of flange mounting)
- **usability of identical cavities and amplifiers** for SIS100 Longitudinal Feedback workpackage
SIS100 BB cavity design

design goals:
- broadband behaviour (→ MA cores)
- voltage gradient 15 kV/m (MA cores)
- matching with tetrode amplifier at tetrode’s working point
- cavity’s resonance frequency at or below barrier-bucket frequency $f_{BB}$

=> very similar to SIS18 h=2 cavity requirements!

working hypothesis:
- use h=2 cavity with less MA cores in order to increase resonant frequency
SIS100 BB – oil cooling

- due to magnetic loss effects, ring cores heat up during operation
- heat conductivity in FT-3M is anisotropic

- heat can only be removed through side surface, which is not flat
- insufficient heat transfer to cooling disks or air makes direct liquid cooling (oil) necessary
outline

- ESR BB system

- SIS100 BB system: pre-development phase
  - requirements

- SIS100 BB cavity design
  - oil cooling

- SIS100 BB power amplifier design

- SIS100 BB simulation results
  - frequency domain
  - time domain

- SIS100 BB outlook

strategy:
  - PSpice simulation of planned SIS100 BB cavity system
  - comparison with measurements from mock-up of SIS100 BB cavity (with h=2 components)
SIS100 BB power amplifier design

- required signal quality
  -> class A amplifier (to avoid distortion in push-pull configuration)

- tetrode capable of the expected anode dissipation power at working point above 15 kV -> Thales TH555

- compensation of anode currents by opposing winding directions of coupling loops
SIS100 BB simulation results – frequency domain

cavity: shown is one of four ring core stacks

tetrode model includes non-linearity
- deviations now understood
- sufficient matching between cavity and tetrode ($R_i \approx 1500\Omega$)
- resonant frequency $f_r \approx 1.5$ MHz

power amplifier

cavity without amplifier (measured at h=2 cavity):

- simulation
- measurement data
SIS100 BB simulation results – time domain

- Desired pulse amplitude of 15 kV is achieved (7.5 kV across each gap)
- Ringing at the pulse’s end is below 5% even with linear pre-distortion
- Desired bandwidth for input signal transmitting components: from 20 kHz to 30 MHz

Input voltage in time domain (linear pre-distortion, 0.02-30 MHz):
SIS100 BB status and outlook

- Technical Concept document finished
- Considerable effort was made to reduce technical risks by investigating (mostly at ARD broadband test cavity):
  - Frequency dependent ring core properties
  - Cavity bandwidth
  - Ring core cooling
  - Frequency- and time-domain simulations of full cavity/amplifier system
  - Impedance reduction by cavity detuning
  - Beam loading (effect of DC-fraction)
  - Signal generation (LLRF system)
- Technical Concept proved feasible through all tests (15 kV, <5% ringing expected with non-linear pre-distortion)
- Detailed Specification 95% finished
- Start of procurement is planned for June 2019
Thanks to all contributors
Development of Barrier Bucket RF Systems for ESR and SIS100

M. Frey, 14. June 2018
Appendix - gap voltage measurement

- distortion in measurement chain directly alters gap voltage signal
- high effort necessary to reach convenient frequency-response
- high impedance part kept as short as possible (reduce reflections)

130 m ½” Cellflex: 5% distortion

2000 m optical fiber: 2% distortion (but synchronisation with SIS18 not possible yet)