DESIGN OF A SUPERCONDUCTING LINAC CAVITY FOR HIGH-CURRENT ENERGY RECOVERY LINAC OPERATION

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Abstract

The RHIC electron cooler as well as other applications (such as a linac-ring version of eRHIC) require a very high average current CW electron linac in an energy recovery mode. In this paper we present the design of a 5-cell superconducting linac cavity for velocity of light particles. This cavity will operate at 703.75 MHz with a large beam pipe aperture of 19 cm diameter and ferrite HOM absorbers in the beam pipe, in addition to the conventional HOM couplers for low frequency HOMs. We will report the design of the cavity geometry using the BuildCavity and Superfish codes, loss factor simulations with ABCI, detailed HOM simulations with MAFIA (with and without the ferrite absorbers) and beam breakup simulations using the code TDBBU.

INTRODUCTIONS

The main goal of the Relativistic Heavy Ion Collider (RHIC) is to provide head-on collisions at energies up to 100 GeV/u per beam for very heavy ions, which are defined to be gold $^{197}Au^{79+}$, but the program also calls for lighter ions all the way down to protons and polarized protons. Luminosity requirements for the heaviest ions are specified to be in the 10^{26}~$10^{27}cm^{-2}s^{-1}$ range. A first upgrade of the luminosity by about a factor four consists of increasing the number of bunches from about 60 to about 120 and decreasing beta* from 2m to 1m. Luminosity can be further enhanced by decreasing the beam emittance by the electron cooling the gold beams at storage energy. With electron cooling the beam emittance can reduced and maintained throughout the store and the luminosity increased until non-linear effects of the two colliding beams on each other limit any further increase (beam-beam limit). The simulations of electron cooling for RHIC show that a high charge electron bunch (10nc) is needed. The resulting average current is about 100mA.

Table 1 Parameters of electron beam for RHIC cooler

Final Beam energy	55MeV
Charge per bunch	10nc
Repetition rate	9.4MHz
Average current	94 mA
Bunch length at Linac	~1cm, rms
Injection energy	2.5 MeV

To accelerate about 100mA electron beam to 55MeV the energy recovery linac (ERL) scheme is proposed to save tremendous power. Beams will go through the linac twice, first to be accelerated up to 55MeV then to be de-accelerated while giving their energy back to the linac. Superconducting radio-frequency cavity technique is assumed in this cw accelerator machine.

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The main issues for the linac cavities are the effects due to the very high current.

1) the power in the HOMs(Higher Order Modes) which depends on the product of bunch charge and the average current.

2) multi-bunch and multi-pass effects which are driven by the high-Q superconducting cavities and limit the average current.

3) effect due to the high charge per bunch (at relatively low energy)

For the RHIC e-cooling project, 1) and 2) are serious concerns and will be discussed in this paper. The cavity-related single bunch effect is discussed in context of linear collider designs. Non-cavity-related single bunch effects (space charge, magnetized beam, etc.) are covered in a separate study.

CAVITY DESIGN

To address above challenging issues a new sc linac cavity is being designed by a collaboration of people from several laboratories.

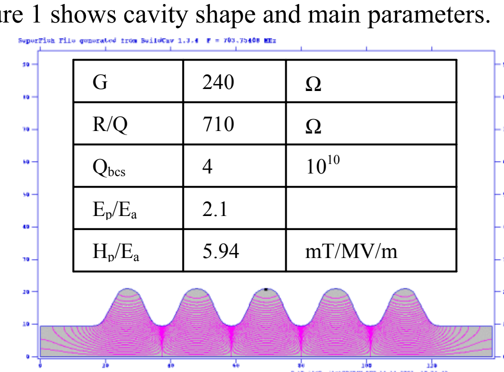
Frequency

A relatively low frequency, say, 700MHz, is chosen to get a reasonably small loss factor. It also allows a longer bunch and larger transverse aperture is another advantage. On the engineering side the availabilities of cw klystrons and cleaning facilities are also the factors in choosing the frequency.

Number of cells

Five-cell structure is adopted since it can keep good acceleration efficiency while making the coupling and propagation of some modes easier, compare to other 7-~9-cell structures.

Cavity geometry is designed with the BuildCavity code. Figure 1 shows cavity shape and main parameters.



G	240	Ω
R/Q	710	Ω
Q_{bcs}	4	10^{10}
E_p/E_a	2.1	
H_p/E_a	5.94	mT/MV/m

Figure 1: geometry and main parameters of new cavity

The loss factor is calculated by the ABCI. See Figure 2.

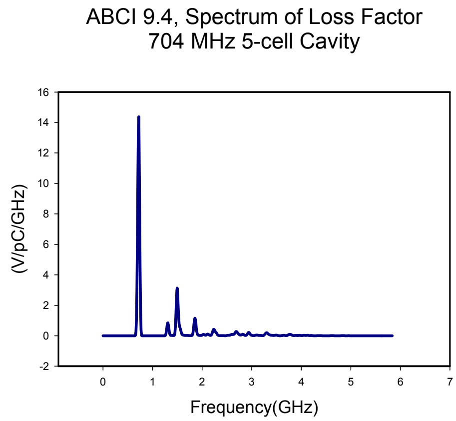


Figure 2: loss factor of new cavity

HIGHER ORDER MODES ISSUE

The HOM (Higher Order Modes) is the key player in the design and operation of this sc cavity. Simulations are carried out with MAFIA. Particularly the low frequency dipole modes are of importance to the instability issues in the linac. Table 2 shows the 30 modes with the lowest frequencies.

Table 2 major dipole higher order modes

	Frequency(GHz)	R/Q (ohm)
1	7.489798350E-01	0.109982526E-02
2	7.569791871E-01	0.136660994E+00
3	7.570094240E-01	0.274434304E-02
4	7.711698536E-01	0.184679902E+01
5	8.032362047E-01	0.305099726E+01
6	8.246061998E-01	0.129250653E+01
7	8.252309047E-01	0.711581113E-01
8	8.401347490E-01	0.484628264E+02
9	8.773347638E-01	0.461812638E+02
10	8.822060575E-01	0.707655746E+01
11	9.214217593E-01	0.308168408E+01
12	9.214559575E-01	0.119930774E+01
13	9.524008689E-01	0.177325199E+00
14	9.567931457E-01	0.312298753E+01
15	9.639985747E-01	0.125690626E+02
16	9.709637992E-01	0.500794841E+01
17	1.010896594E+00	0.143507816E+01
18	1.011128111E+00	0.604053638E-05
19	1.089125001E+00	0.143106632E+01
20	1.089888247E+00	0.367335628E-03
21	1.170296440E+00	0.885562614E+00
22	1.177597825E+00	0.521756140E+00
23	1.210143769E+00	0.219157590E-03
24	1.250641137E+00	0.306075197E-01
25	1.280658315E+00	0.594297261E-03
26	1.310722096E+00	0.142675869E+00
27	1.351442021E+00	0.285837611E-01
28	1.390585487E+00	0.434743738E-01
29	1.420472371E+00	0.419089300E+00
30	1.420472371E+00	0.419089300E+00

Among these dipole modes some may have frequencies below the beam pipe (assuming equal to the iris of the cavity or a little bit larger) cutoff. Electromagnetic fields of these modes are calculated by the MAFIA. See Figure 3 to 11.

Figure 3: TE111, 750 MHz

Figure 4: TE112, 772 MHz

Figure 5: TE113, 803 MHz

Figure 6: TE114, 840 MHz

Figure 7: TE115, 877 MHz

Figure 8: TM11x, 952 MHz

Figure 9: TM11x, 956 MHz

Figure 10: TM11x, 964 MHz

The outer sections of beam pipe are enlarged from 19 cm to 24 cm diameter (about 20cm away from the end cells). From mode analysis and observations some modes may not propagate well through the pipes.

A detailed study is done with method in Ref. [3] to estimate the external Qs of the modes.

Table 3 External Qs of some dipole modes

Mode	Frequency (GHz)	Field Pattern*	R/Q (Ohm)	Qext
1	7.504E-01	TE111	0.001	7600
2	7.722E-01	TE112	1.9	1033
3	8.035E-01	TE113	2.8	258
4	8.404E-01	TE114	48	99
5	8.776E-01	TE115	46	26-29
6	9.520E-01	TM11x	0.16	large
7	9.566E-01	TM11x	2.9	large
8	9.641E-01	TM11x	13	large

The calculations suggest that TM11x modes might have quite high Qs (exact amount are not available with the method) or are difficult to propagate in the pipes. To solve the problem in propagating those modes both the CESR 'flute' structure or larger pipes might be needed.

HOMS WITH FERRITE ABSORBERS

Ferrite absorbers have been successfully used in other high current cw RF cavities in colliding beam accelerators like CESR and KEK-B for single cell sc cavities to damp HOMs and absorb huge power up to a few tens of kW.

An attempt to apply the same technology to the multi-cell linac cavity is made in our design. The preliminary simulations are performed with E-module in the MAFIA. Two ferrite absorbers are placed on each side of the beam pipe, a few tens of centimeters from the cavity cells as ferrite sections are in room temperature. Each ferrite absorber has 5 mm thick layer with tapered ends. The eigenmodes are calculated with MAFIA as a lossy problem. By carefully matching the MAFIA options and properties of ferrite materials [5][6] (some permittivity and permeability values may fail) the Qs of monopole and dipole modes can be calculated with high precision (~1E-6). Fig. 11 and Table 4 show the fields and Qs of some major dipole modes. HOM coupler is also planned as it will provide a lot of more flexibility in locations of ferrite absorbers, pipe diameter and cryogenic system designs. To reflect the real environment in the linac the time-domain solutions are being sought in collaboration with other labs to better understand the issue.

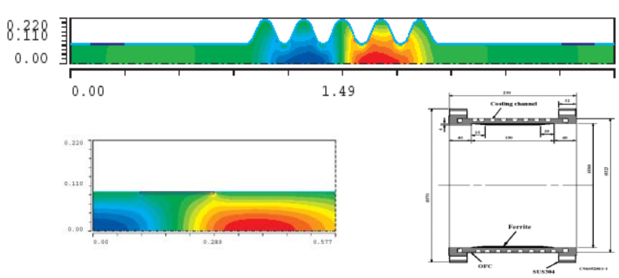


Figure 11: Simulation with ferrite absorbers
Top, field of TM11x mode, in cavity and pipes,
Lower left, local field near ferrite, Lower right, ferrite absorber (used in B-Factories)

Table 4 Dipole modes with ferrites absorbers
Eps=10.0,-1.0 Mu=2.0, -0.5,
(modes with high R/Q are selected)

Mode	Freq.(Re) (MHz)	Freq.(Im) (MHz)	Q with Ferrite
A	877.3	0.1981	4428
B	882.2	0.2094	4212
C	956.7	0.001521	628533
D	963.8	0.02025	47595
E	971.2	0.04392	22112
F	1016	6.741	151
G	1273	7.732	164
H	1311	7.248	181

In a high current superconducting, energy recovery linac machine like RHIC e-cooler there are a number of collective effects that may potentially limit the maximum current. The multi-bunch multi-pass effects which are mainly driven by the high-Q s.c. cavities are our major concerns, particularly the transverse Beam Break-Up(BBU), which results from the interaction of the beam with cavity Higher Order Modes. A preliminary study is performed to investigate the effect of HOMs of newly designed 700 MHz, 5-cell sc cavities on the cumulative Beam Break-Up. The analytical formula of the threshold current exists only for the specific mode in the simplified case. The precise evaluation calls for the numerical method. In our study so far the computer simulation code TDBBU developed in the Jefferson Lab is used. The circumference is around 251 rf wave length, about 108 meters. The bunch repetition rate is 9.4 MHz. The simple transverse optics is assumed as the design of the cavity and transport are still underway. R/Q and Q values of major HOMs with ferrite HOM absorbers are from preliminary MAFIA calculations. Qs are same for both polarizations since there is no fundamental or HOM waveguide coupler in our calculations. The threshold current can be about 500 mA for a uniform distribution of frequencies of the HOMs in all cavities.

SUMMARY

A design of a 700MHz, 5-cell superconducting cavity is performed for the use of high current Energy Recovery Linacs(ERL). Primary concern has been the HOM issue due to very high beam current. Most important deflecting modes with low frequencies are studied by several different methods. Simulations of the cavity with ferrite absorbers are done with MAFIA as a lossy eigenmode problem. Preliminary results are quite interesting. More calculations especially with time-domain method are underway. Design of main and HOM coupler is also going on mainly by J. Sekutowicz.

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