High current superconducting ampere class linacs

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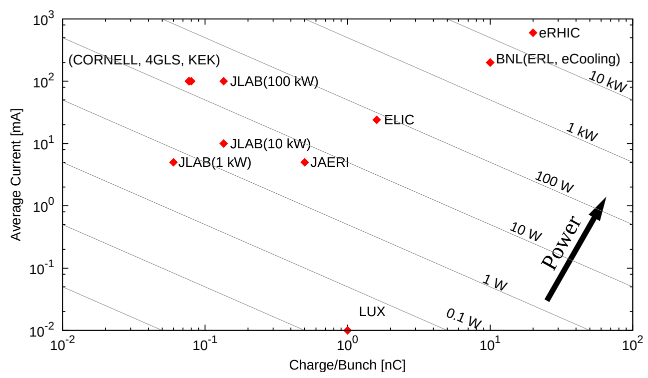
Introduction

Superconducting energy recovery linacs (SERLs) are increasingly becoming an attractive option for light sources, X-FELs, electron coolers and electron-ion colliders.The major challenge to accelerate high current beams is to overcome the dissipation of large amounts beam power into cavity modes making CW operation prohibitive. Average power dissipated due to single bunch losses in accelerating structures for existing and future SERLs is shown in Fig. below (contours normalized to 1 V/pC).

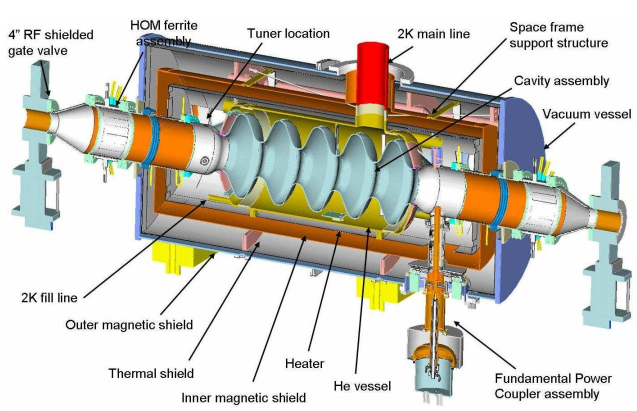


Electron Cooling

Cooling gold beams at 100 GeV/nucleon require an electron beam energy of approximately 54 MeV and a high average current in the range of 50-200 mA. Two variants of the e^- cooling, a non-magnetized version with a simple drift section, and a magnetized version with a 60 m solenoid are being considered as primary and secondary options for cooling sections respectively. Table below lists relevant beam parameters for both non-magnetized and magnetized versions.

Parameter	Magnetized	Non-Magnetized
Injection energy [MeV]	5.2	5.2
Maximum energy [MeV]	20-40	20-40
Avg. beam current [mA]	200	50
Repetition rate [MHz]	9.4	9.4
Charge/Bunch [nC]	10	5
Norm. emittance [mm.mrad]	300	3
Bunch length [cm]	1.0	1.0
Energy recovery efficiency	> 99.95 %	> 99.95 %

A five-cell superconducting cavity is under fabrication as a fundamental unit for the linac structure to accelerate the electron beam from 2.5 MeV to 54 MeV. The cavity design is optimized to strongly suppress the effects of HOMs and increase the threshold currents beyond the ampere level. 3D cut away model of the five-cell cavity, cryostat, power coupler, ferrite absorbers, and feedthroughs (courtesy AES).

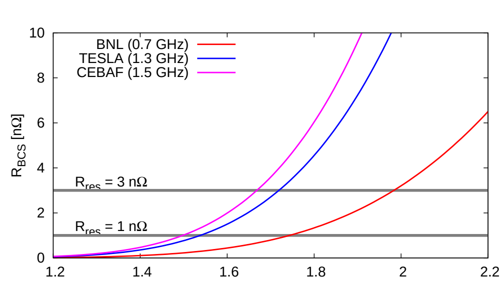


Frequency

The precise frequency of 703.75 MHz is the 25^{th} harmonic of the RHIC bunch repetition frequency with 360 bunches. The power dissipated from cavity walls due to surface fields of the fundamental mode is proportional to

$$P \propto \frac{R_s}{\left(\frac{R}{Q}\right) G} \qquad (1)$$

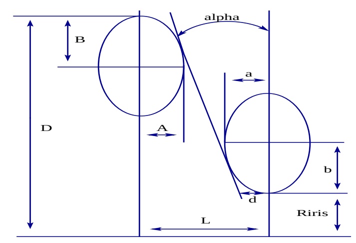
The surface resistance, $R_s = R_{BCS} + R_{res}$. Fig. below shows a plot of R_{BCS} as a function of temperature for three different frequencies that are widely used for superconducting linacs.



If the R_{res} is sufficiently small ($\leq 1\ n\Omega$), a lower frequency significantly reduces cavity losses.
A lower frequency allows a possibility of a large aperture resulting in a significant reduction of both longitudinal and transverse wakefields.
Availability of high power CW RF power sources and compatibility with chemical cleaning facilities also played an important role to converge to 700 MHz region. A potential future use of this cavity in a linac-ring version of eRHIC was also considered.

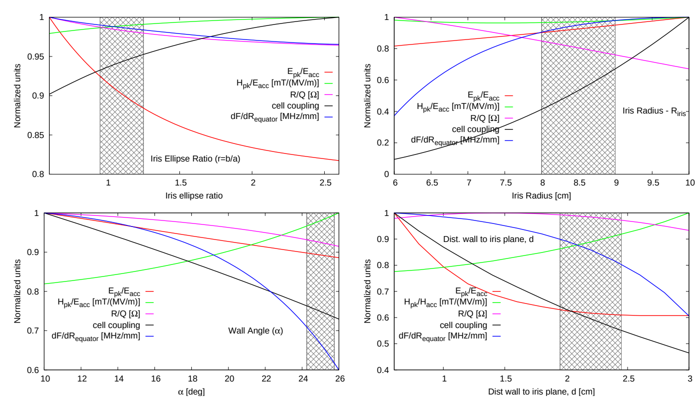
Cavity Geometry

The five-cell cavity is constructed from eight identical inner half cells and two end half cells. Each half cell can be described with the geometrical parameters shown in Fig. below.

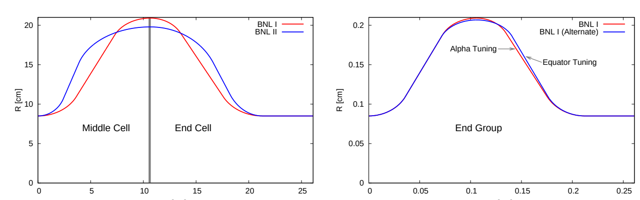


Several criteria were considered to optimize cell shape:

- Minimize peak surface fields ($\frac{E_{peak}}{E_{acc}}$, $\frac{B_{peak}}{E_{acc}}$) to avoid field emission at lower gradients.
- A Large k_{cc} is important to avoid trapped HOMs in long multicell structures.
- Good mechanical stiffness to reduce the effects of microphonics and Lorentz force detuning while allowing a reasonable tuning capability.
- Minimize cavity wall losses by maximizing R/Q of the accelerating mode.



The final optimized parameters describing the cavity geometry are listed in Table below along with two alternate designs.



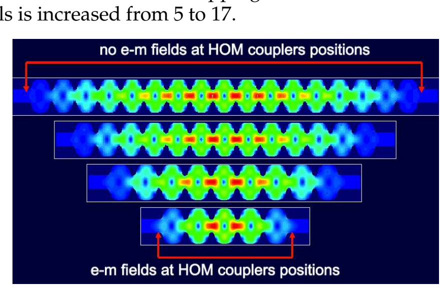
Parameter	BNL I		BNL I-A	BNL II	
	Middle Cell	End Cell	Alt. End Group	Middle Cell	End Cell
Frequency [MHz]	703.75	703.75	703.75	703.75	703.75
Iris Radius, R_{iris} [cm]	8.5	8.5	8.5	8.5	8.5
Wall Angle, α [deg]	25	26.64	25	18	21.6
Equatorial Ellipse, $R = \frac{B}{A}$	1.0	1.1	1.0	0.9	1.2
Iris Ellipse, $r = \frac{b}{a}$	1.1	1.1	1.1	1.4	1.6
Dist. from cavity wall to iris plane, d [cm]	2.5	2.5	2.5	1.7	1.7
Half Cell Length, $L = \frac{\lambda\beta}{4} [cm]$	10.65	10.65	10.65	10.65	10.65
$H = D - (R_{iris} + b + B) [cm]$	4.195	4.160	3.792	1.254	-2.456
Cavity Beta, $\beta = \frac{v}{c}$	1.0	1.0	1.0	1.0	1.0

Number of Cells

A figure of merit that determines the achievable field flatness for multicell cavities can be expressed in terms of a field sensitivity factor given by

$$a = \frac{N^2}{\beta k} \qquad (2)$$

Since HOM damping and extraction in SRF cavities is constrained to the exterior of the structure, propagation of HOMs to the outside the cavity is imperative. Fig. below show an illustration of trapping an HOM in the interior cells as the number of cells is increased from 5 to 17.



Therefore, five cells were chosen to be an optimum number to able to achieve ampere class currents while maintaining a reasonable accelerating gradient.

Some relevant RF parameters of final design are listed in Table below and compared to BNL II, TESLA and CEBAF designs.

Parameter	Unit	BNL 1(HC)	BNL 2 (HC)	CEBAF(HG)	TESLA(HG)
Frequency	[MHz]	703.75	703.75	1497	1300
Number of cells	-	5	5	7	9
$(R/Q) * G$	$[\Omega^2]$	9×10^4	9.58×10^4	2.1×10^5	2.8×10^5
E_p/E_a	-	1.97	2.25	1.96	1.98
H_p/E_a	$[mT/MV/m]$	5.78	4.88	4.15	4.15
Cell to cell coupling (k_{cc})	-	3%	4.45%	1.89%	1.87%
Sensitivity Factor ($\frac{N^2}{\beta k_{cc}}$)	-	8.3×10^2	5.6×10^2	2.6×10^3	4.1×10^3
Field Flatness	-	97.2%	97.3%	-	95 %
Lorentz detuning coeff.	$[Hz/(MV/m)^2]$	1.28 (UnStiff)	-	2	1

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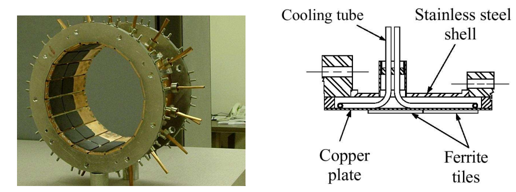
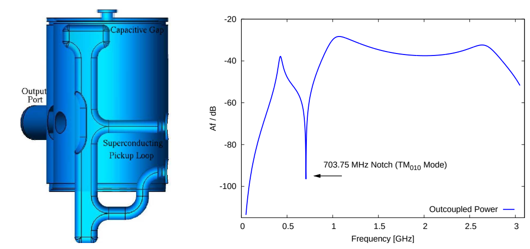
Beam Pipe Ferrite Absorbers

Ferrite absorbers were the choice of HOM load because of their capability to absorb large HOM power and effective broadband damping with a simple and robust design. Fig. below shows a of ferrite assembly with "porcupine like" protrusions for water cooling. These absorbers have been tested upto 15 kW or higher and are very effective with high power beams.



HOM Loop Couplers

HOM loop couplers pose severe problems for high-current cavities due to extraction of large HOM power with a carefully tuned resonant circuit. Issues like the error in the notch frequency and the temperature of the pick up probe can lead to large cryogenic losses making it an undesirable candidate. A 3D model of the HOM loop coupler is designed for the 5 cell cavity with the notch filter optimized for 703.75 MHz as shown in Fig. below.



Beam Pipe Geometry

The damping of HOMs is accomplished with ferrite absorbers in the warm sections. The cutoff frequency for a cylindrical waveguide is given by

$$f_c = \frac{c}{\pi D} X \qquad (3)$$

Fig. below shows plot of aperture size as a function of cutoff frequency for the first few monopole, dipole and quadrupole modes.

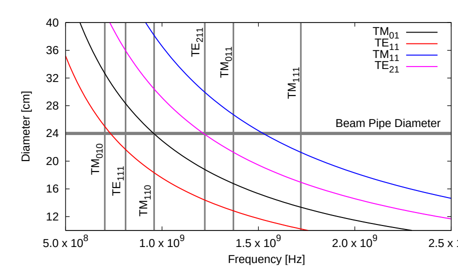
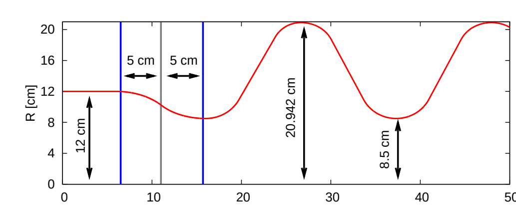


Fig. below shows a schematic of the end cell and beam pipe transition geometry. The transition consists of two elliptical sections of 5 cm each to gradually expand from a 17 cm iris to 24 cm beam pipe diameter. The length of the transition was chosen to be 10 cm to keep the losses in metal outside the superconducting section was less than 10 watts. and reduce short range wakes from abrupt transitions.



Final Design

A graphic of the final design of five-cell SRF cavity along with the coaxial fundamental power coupler (FPC) is shown in Fig. below.

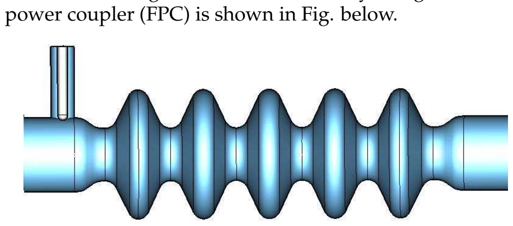


Fig. below shows a comparison of calculated and measured field profile on a copper prototype for the fundamental mode of the 5 cell cavity. The "moderately" tuned copper prototype yields a field flatness of 96 ± 1% which agrees extremely well with electromagnetic (EM) codes giving 96.5%.