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Cite as: AIP Conference Proceedings **269**, 571 (1992); https://doi.org/10.1063/1.42972
Published Online: 29 May 2008

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HALL C BEAM TRANSPORT LINES

The Hall C beam transport lines [1] [2] consists of the separation section, the first match section which match the separator to the arc, the arc section and the second match section matching arc to the target with total length of 146.2 m from the point of tangency to the Hall C target position, including eight 3 meter bending dipole magnets, two 1 meter separation magnets, twenty two 30 cm quadrupole magnets, eight sextupole magnets and several beam correctors distributed along the arc section.

CEBAF beam is transported by waist-to-waist imaging to the point of tangency point, then it is separated by separation section into Hall A, Hall B, and Hall C respectively. Through the first match section the separated Hall C beam enters into the arc section which achromatically bends the beam by 37.5° with a radius of 40 meters and the second match section sends recombined beam to Hall C target position through a distance of 179.47 feet. Figure 1 is a plan view of CEBAF beam line.

The arc section consists of eight 3 meter length dipole magnets, 11 quadrupoles with 1.25cm aperture and 8 sextupoles which provide completely second order achromatic - both of the dispersion and its derivative must be zero. Therefore, the first half of achromat focuses second principal plane of the fourth bending magnet onto the first principal plane of the fifth bending magnet. The effect of the intermediate quadrupole is solely to achieve complete recombination of different momenta.

If the half width of the source is x_0, the the full width of the image is $2x_0M_x$, two different momenta can be resolved if their spatial separation is at least as great as the width of the image of the source. Therefore, momentum resolution is defined as:

$$R_p = \frac{\Delta P}{P} = \frac{2M_x x_0}{D}$$

M_x - magnification in x-direction, D - dispersion in transverse direction. Different momenta can be separated at the intermediate focal plane of arc achromat that is so-called a beam line spectro meter combination in what is known as the energy-loss mode [3] [4] [5] [6]. At the intermediate focal plane of Hall C arc achromat the dispersion is 2.078 cm/% and magnification is about unit. If a focal plane detector can be placed at the midpoint it will be a high resolution achromatic spectrometer that can be used to analyse beam momentum deviation.

MODIFICATION OF HALL C BEAM LINE FOR BEAM ENERGY MEASUREMENT

The intermediate quadrupole is splitted into two 30 cm quadrupoles and between two quadrupoles dispersion is quite flat and it changes very smoothly, that is suitable for arc operation. Then, the optical mode of arc achromat is also changed in order to decouple the tune of each section.

From the point of tangency to the entrance of arc achromat a double waist to waist transport is carried out by slightly adjusting the first match section. This function decouples arc achromat from previous sections by $x|\theta = \theta|x = y|\phi = \phi|y = x|\delta = \theta|\delta = 0$.

From the entrance to the intermediate focal plane between the central two quads , an approximate double waist imaging and angular achromatic transport are realized by $x|\theta = 0$, $y|\phi = 0$, $\theta|\delta = 0$, $\theta|x \approx 0$, and $\phi|y \approx 0$. The first-order transport matrix from the entrance of the arc to the intermediate principle plane is:

−0.61449	0.00000	0.00000	0.00000	0.00000	−2.63656
−0.02078	−1.62737	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.16386	−0.00001	0.00000	0.00000
0.00000	0.00000	0.02401	6.10291	0.00000	0.00000
0.00548	0.42907	0.00000	0.00000	1.00000	−0.24874
0.00000	0.00000	0.00000	0.00000	0.00000	1.00000

At this position the transverse half beam size is about 0.0061 cm, the dispersion is 2.637 meter, so that the momentum resolution at the intermediate image plane is defined as $\Delta P/P = 2\Delta x_{local}/\mathrm{D} = 4.55 \times 10^{-5}$ which is 30% larger than one of original arc achromat and is well adapted for momentum analyse of CEBAF beam. On the other hand, the tuning of dispersive section of achromat is almost independent to previous section by applying double waist image from the point of tangency to the entrance of arc, then to the medpoint of the arc, only the relation between beam position and beam momentum remains. A complete achromatic and double focusing transport is accomplished at the exit of the achromat by $x|\theta = 0$, $y|\phi = 0$, $x|\delta = 0$, and $\theta|\delta = 0$.

In the last match section two quadrupoles can be eliminated from original 5 quadrupoles, three quadrupoles achromatically bring the beam from the exit of the arc into a double focusing image at the Hall C target position by $x|\theta = 0$, $y|\phi = 0$, $x|\delta = 0$, and $\theta|\delta = 0$, where $\Delta x = 0.002$ cm and $\Delta y = 0.007$ cm.

Figure 2 shows the beam envelope of the modified beam line. The detailed beam envelope of arc achromat is shown in Figure 3. Due to the symmetries of quadrupole setting are broken and those second-order chromatic coefficients such as $x|x\theta$, $x|x\delta$, $\theta|x^2$, $\theta|\theta^2$, $\theta|\theta\delta$, and $\theta|\delta^2$, are considerably increased. In fact, the fitting of the eight sextupoles is not necessary because the contribution of the second order chromatic aberrations on the image can be eliminated.

The contribution of beam energy spread is $\Delta E/E = 10^{-4}$ for 4σ to momentum resolution of arc achromat. Within 4σ more than 95% beam particles are included in the Gaussian distribution. The instant energy spread for single bunch is about 2×10^{-5}. If RF jitter and other perturbation was considered it will be reasonable to use $\Delta E/E = 10^{-4}$ as the bottom width of high energy beam with approximate Gaussian distribution. At the midpoint of the arc achromat, where the momentum dispersion is the largest - 2.6 cm/%, the optical beam width is about 120 micron, the width increase due to energy spread is about 260 micron (the bottom width of particle distribution). So that, the total bottom width of fuzzy beam at the midpoint of arc is 290 micron. The momentum resolution must be better than 1.1×10^{-4}. For example, if there is a relative change of beam momentum in 10^{-3}, the corresponding displacement of beam position at the midpoint of the arc will be 2.6 mm, which can be easily measured.

ABSOLUTE BEAM ENERGY MEASUREMENT

Except the beam displacement measurement by achromat, to measure absolute beam energy one has to calibrate the arc achromat absolutely.

$$p = \frac{e}{\Theta} \int B dl$$

where $\int Bdl$ is the magnetic field integral over the path of the electron and Θ is the angle through which the electron is deglected. Take e as a constant, this leads to an uncertainty relation:

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta \int Bdl}{\int Bdl}\right)^2 + \left(\frac{\Delta\Theta}{\Theta}\right)^2}$$

$\int Bdl$ is determined by mapping the bending magnets. CEBAF bending magnets are relatively mapped by the moving wire mapper [7] [8] in which a wire is pass through ths magnet gap and returned outside the magnet to form a closed loop. As reported in [7], all bending magnets are measured relative to a "reference" magnet DR, then, the differences are related to the "standard" magnets to produce absolute field integral profiles for the full population with high precision. The moving wire, or the horizontal translating probe produces a radial profile of longitudinally integrated field. Measurement of the "standard" magnets will have two phases: 1) a series of oint measurements with NMR probe and a Hall probe 2) measurement with the integral coil probe. The point measurements will be used to calibrate the integral probe results. For the measurements of the full population, probes have been manufactured to be identical to 0.025 mm and are rigidly mechanically coupled, probes will be moved through the "reference" magnet DR and the "subject" magnet Dn simultaneously. The analog signal from DR is used to "buck" the analog signal from Dn so that the signal that is digitized is produced by the field differences between them. The differences will be combined with the absolute field data from "standard" magnet to produce absolute field profiles for each magnet.

CEBAF moving wire mapper can reach 10^{-4} accuracy and the experimental $\int Bdl$ can only vary from magnet-to-magnet by 0.05%. The mapper has been sized to accommodate all beam transport magnets for stand-alone measurement and for reference measurements for the main beam transport magnets. The basic requirement of absolute field integral of bending magnets has already been included in the report [7], for beam energy dertermination, an accuracy of absolute field profile better than 5×10^{-4} is expected.

Two pairs of precision beam position monitors with 1m distance between them are placed just before and after the arc achromat for measurement of deflection angle Θ. The accuracy of angular measurement is about 1.7×10^{-4} as discussed in [9].

PRECISION BEAM POSITION MEASUREMENT

For the absolute energy measurement 5 precision beam position monitors with absolute position readout are required. It is difficult to use BPM to do that because it has an limited precision and relative readout.

CEBAF beam profile monitor [10] is sketched is an intercepting beam diagnostic system. A 10μ wire mounting on a harp driven by a stepping motor is used as an electrode to measure beam current while the wire travels across the beam. The standard CEBAF beam profile monitor provides 25 μm posistion resolution and linear scaning velosity 3.81 mm/s. The beam profile can be obtained from current readout by sensor wire via moving distance determined by stepping motor system. Then the beam position can be expressed as the position of center of mass of beam profile:

$$x_{cm} = \frac{\sum_i n_i x_i}{\sum_i n_i}$$

where x_i and n_i - the position readout and the current readout at i-th step respectively. The accuracy of beam position mainly depends on the precision of translate motion of mechanical driving system. The mechanical driving system can be upgraded by adding an optical encoder or synchro-resolver to a position resolution better than 10 μm. The most important part is the head of wire scanner, therefore, some of calculation about temperature rise, expansion of the wire material, proper tension on the wire sensor are necessary. In order to calculate the temperature rise of wire material due to energy deposit by beam particles following fomula can be used:

$$\Delta T = \frac{I(\frac{1}{\rho}\frac{dE}{dx})N}{n_e v C_v h} \times 10^6$$

Here, I-the average beam current in Ampere (the effective current = I d_w/ d_b), n_e - the charge states of beam particle, d_w - the diameter of sensor wire, d_b - the diameter of beam, v - the linear velocity of wire motion in cm/s, h - the vertical dimension of beam in cm, C_v - the specific heat of wire material in Joule/(gK°), $\frac{1}{\rho}\frac{dE}{dx}$ - the total energy loss in Mev/(mg/cm^2), and N - total number of traversals.

For beam current of 200μA, the temperature rise is about 1356 K° for 10μm carbon fiber and 533 K° for 10μm tungsten wire. Under such a temperature rise the heated wire expands according to its thermal expanssion coefficients, the relative expansion of carbon wire is about 1.07% and 0.22% for tungsten wire. Comparing performance of both expanssion and temperature rise, less than 10μm tungsten wire is preferable. To make thermal expanssion of tungsten wire undeformed a slight pre-tension should be applied to the tungsten wire which has a tension strength of 32.6 g.

The repeativity and accuracy of the motion of wire sensor has been tested on a marble stage by a video microscope system. The repeativity of wire motion is better than 10μ, the smallest step size is about 3μ, and no vibration has been observed during the travel of the wire.

Superharp is an upgrade CEBAF beam profile monitor with absolute position readout by the synchro-resolver which is backlashlessly connected with the movable shaft. The specifications of upgrade CEBAF beam profile monitor (Superharp) are listed below:

Material of sensor wire	ϕ7 - 10 μ tungsten wire
Minimum step size of translation	3 μm (variable)
Accuracy of absolute calibration	better than 10μm
Repeativity of mechanical travel	better than 10μm
Dynamic range of readout	1 - 200 μA
Observable vibration magnitude	less than 5μm
Maximum linear velosity	3.81mm/s (variable)
Total number	5

CHICANE FOR POLARIZED TARGET

The high polarization of the nucleon target is produced when the appropriate target material is irradiated with high frequency microwaves at 1°K in the presence of a strong magnetic field. The UVa polarized target will have a 5 T magnetic field over the active target region with a total Bdl of 2.5 T-m along the axis of the magnet. The bending power of this magnet will require a consideration of the trajectories of the incident beam, the scattered electrons, and any recoil charged particles.

Therefore, a vertical chicane is necessary to transport CEBAF beam to the polarized target as shown in Figure 4. At the entrance of Hall C the incident beam is deflected vertically about 1° by 1m CEBAF bending magnet B1 and is transported into the second bending magnet B2 (3m CEBAF bending magnet) which is at 3 m just before the target. The beam is vertically deflected by this magnet for about 5° towards the target. The 5T magnet of polarized target bends the beam in the opposite direction, by about 4° and another 3m bending magnet B4 bends the beam to the beam dump. These bends will have the effect of keeping $\vec{q}$ close enough to horizontal to be acceptable to the HMS and the plane of the neutron detector close enough to horizontal so its placement will not be constrained by the Hall C layout.

Six beam position monitors will be placed in the exit of B2, the entrance of B2, the both sides of 5T magnet, and the exit of B4 to ensure a reliable beam operation. The polarized target chicane will be also used as beam transport system for HNSS which requires a few cm horizontal offset on the target position. In this case only one 1m and one 3m bending magnets are necessary and the chicane works in the horizontal plane.

BEAM RASTERING SYSTEM

Assume that a beam current of 200 μA was used and the beam spot size was taken to be 0.2 mm diameter. If the beam is not defocussed, the beam spot must scan the target with relatively fast frequency which appears to preclude any mechanical means of physically moving the target. With a sinusoidal motion having frequency /amplitude of 10kHz/20mm in both of the horizontal and vertical directions, the local temperature rise was about 100K over the whole target area.

An air core saddle magnet is desined to serve this purpose as shown in Figure 5. The major parameters of Hall C rastering system are listed in the table:

Structure	Air core saddle coils or ferrite magnet
Max. central field	700 Gauss
Effective length	20 cm
Innner aperture	38 mm
NI number for air core	2500 Ampere-turns
Inductance	less than 1 mH
Distance to the target	1600 cm
Rastering area	4 cm^2
Max. rastering frequency	less than 15 KHz
Type of driving power supply	EMI BOS/S 400W

A synchronized sinusoidal generator or simple computer control program will be used to setup x-y direction rastering patterns, rastering area, and rastering rate.

DISTRIBUTION OF BEAM DIAGNOSTIC ELEMENTS

Two cascade beam current monitors are located in the back of Hall C target. One of them will be used to take on-line beam current data for accelecrator operation and another one with 10^{-3} accuracy will be used for experiments.

The criteria for placing beam profile monitors are near the position of a waist and near the position where the momentum dispersion function is zero. Two pairs of beam profile monitors will be placed just before and after the arc section as a indicator of the tuning of arc section. Those monitors will also be used in beam energy measurement for deflection angle dertermination, therefore, the four monitors should be the Superharps which are the upgrade CEBAF profile monitor with absolute position readout.

BPMs will provide on line beam position information for both of beam line tuning and experiments. Besides the assigned standard BPM positions in the beam switchyard, two BPMs will be placed in front of Hall C target, one for on line monitor of beam line operation and another will be used as part of control system for experiments, speciall for rastering system. Additional 6 BPMs are required by polarized target chicane.

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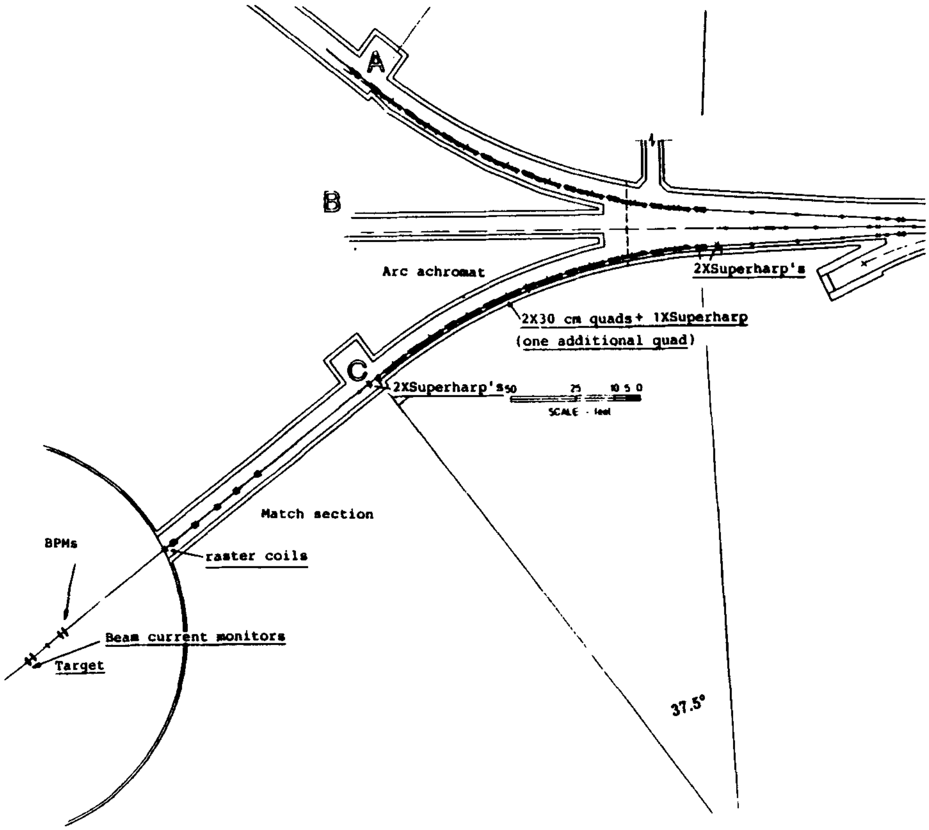

Figure 1. A plan view of Hall C beam line and the distribution of the beam diagnostic elements

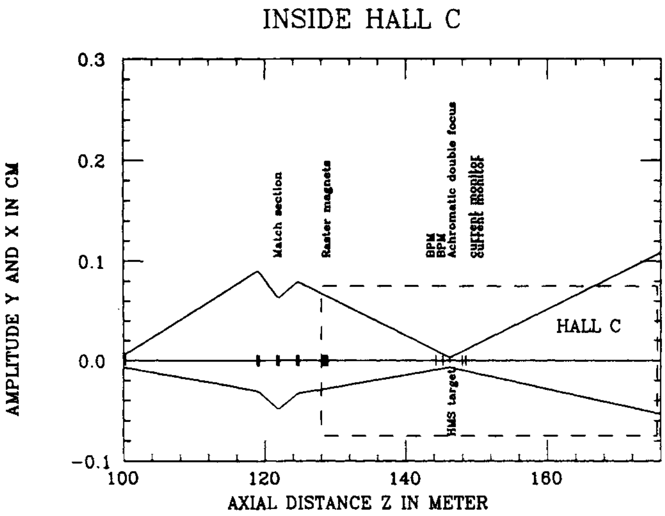

Figure 2. Second order envelope along the match section and inside Hall C.

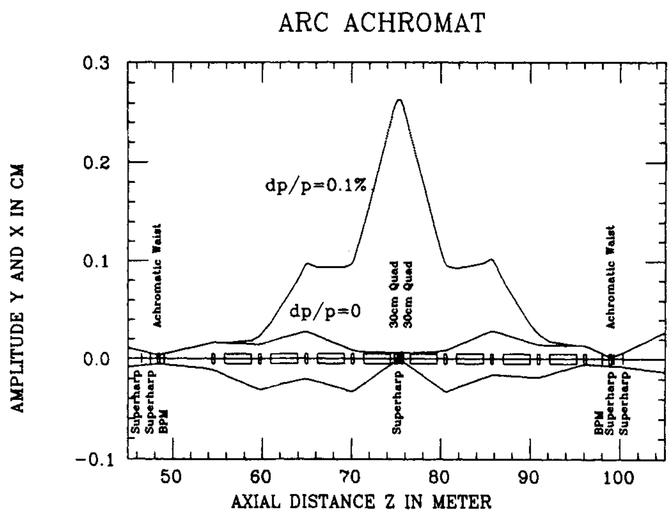

Figure 3. Second order beam envelope along the arc achromat and the distribution of beam diagnostic elements.

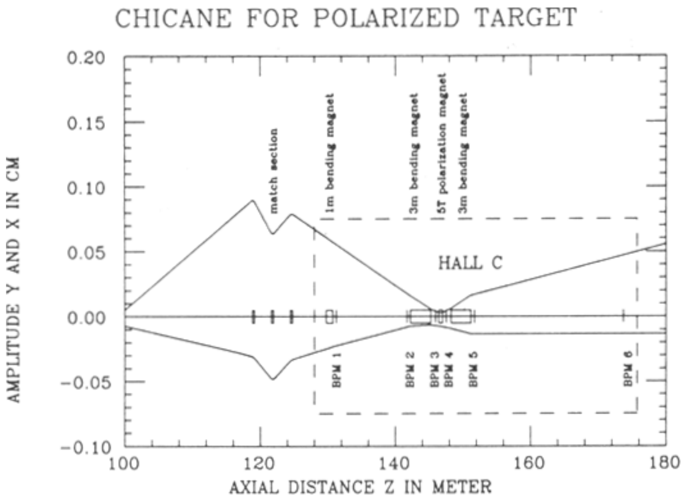

Figure 4. The chicane for polarized target: the second order beam envelope and the distribution of beam position monitors.

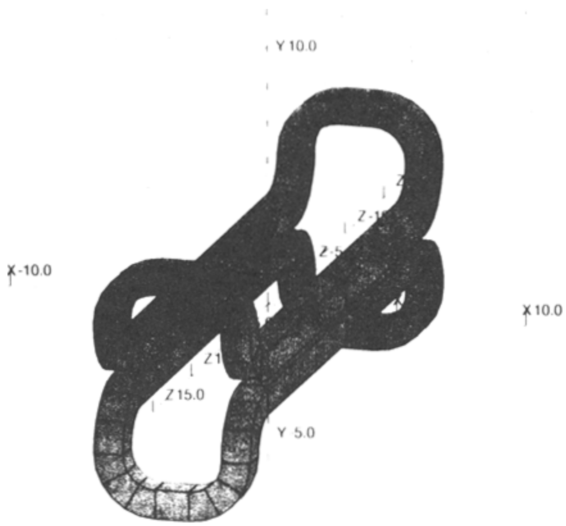

Figure 5. An aircore saddle coil for the beam raster.