Technical note

Project X lattice v.4.0.2 with 162.5 *MHz* HWR section

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Introduction

Project X is a proposed multi-MW proton (H^-) accelerator complex which could simultaneously provide beams at different energies for diverse physics program. Protons could be accelerated to create high-intensity neutrino beam for use in such experiments as NOvA and Long Baseline Neutrino Experiment. Project X could also supply 3 *GeV* protons to kaon- and muon- based precision experiments. Current design involves two stages of linear acceleration [Fig 1]. The first stage is a superconducting CW machine which accelerates particles from 2.1 *MeV* to 3 *GeV.* The second is a pulsed linac from *3 GeV* to *8 GeV*.

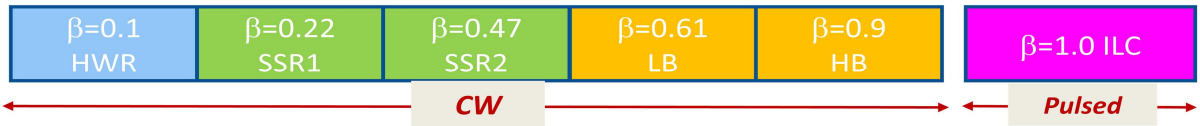

Fig 1.Project X layout

CW 2.1 *MeV*-3 *GeV* linac consists of the room temperature Middle Energy Beam Transport (MEBT) section and 5 cold superconducting sections corresponding to different geometrical β [Fig. 1]. In the current baseline design v.4.0.2 we implemented new 162.5 *MHz* Half-Wave Resonators (HWR) which are being developed at the Argonne National Laboratory. These 162.5 *MHz* HWR cavities are utilized instead of 325 *MHz* SSR0 cavities, which were used in the previous baseline design v. 3.9[1].

Thus, the superconducting linac in the current and former baseline consists of 5 sections. Three low energy sections (HWR/SSR0, SSR1, SSR2), forming the Front End, accelerate beam from 2.1 *MeV* to 165 *MeV* and two high energy sections (Low Beta, High Beta) then accelerate the beam up to energy exceeding 3 *GeV*.

Constrains[2]

In order to keep reasonable beam dynamics and restrict growth of emittances we have to take into account several constrains. To make a transition between sections smooth from beam dynamics point of view we look after the phase advance per meter and try to make it constant in the vicinity of the transition. Thus, phase advance per period has a jump equaled to the ratio of the period length on the right of transition to the period length on the left. Moreover, we want to maintain the system far from resonances and prevent, when possible, intersections of transverse and longitudinal phase advances.

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[1] http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=924

[2] Detailed analysis of constrains and basic concepts of a linac design are considered in "Physics design of the 8 GeV H-minus linac", P. N. Ostroumov, New J. Phys. **8** (2006) 281

Another constrain is an acceptance. Large longitudinal beam size in the beginning of the linac imposes strong limitations on synchronous phase. In order to prevent nonlinear effects we have to keep synchronous phase profile that admits at least 5 rms of beam size.

Not only the beam dynamics creates constrains for lattice design. Superconducting materials properties impose limitations on surface magnetic field. In the current design, which is rather conservative, we limited surface magnetic field by 70 mT to prevent quenches. In high energy sections cryogenic losses are important. Power lost on each cavity is limited by 25 W.

MEBT

In the v.4.0.1 an outdated version of chopper is utilized (a beam envelope of the MEBT and the first superconducting section one can see on [Fig 2]). It is built in the whole lattice for the purpose of studying of behavior of the emittance and gives approximate value of beam size of the further MEBT, which will be used in Project X. Current chopper consists of 4 kickers, that are switched off for passing beam. This chopper is matched with RFQ output Twiss parameters. The MEBT is run at room temperature.

Section	Freq, MHz	Section starts at coordinate	Energy, MeV	Cav/mag/CM	Length of CM
HWR	162.5	13.3 m	2.1 – 10.8	9/6/1	5.26 m
SSR1	325	19.0 m	10.8 – 35.1	16/8/2	4.76 m
SSR2	325	29.5 m	35.1 – 165.4	36/20/4	7.77 m
LB 650	650	65.0 m	165.4 – 556.2	42/14/7	7.1 m
HB 650	650	137.2 m	556.2 – 3064.5	152/19/19	11.21 m

Front End

First three superconducting section accelerate beam from 2.1 Mev to 165 MeV(a beam envelope and a Partran beam envelope one can see on [Fig 3] and Fig[4], a synchronous phase profile and a longitudinal beam size are on [Fig 5]). Transverse defocusing is compensated by cold solenoids, which are located inside of cryostats. In version v4.0.1 9 HW-cavities are arranged in 1 cryostat. Then 16 SSR1 cavities are segmented in 2 cryo-modules and 36 SSR2 cavities are segmented in 4 cryo-modules. Typical distance between cryo-modules is 400 mm, that means length of the drift between rear side of the last element in the previous cryostat and front side of the next element in the next cryostat.

HWR

Since September 2011 162.5 *MHz* half-wave cavities are considered baseline instead of SSR0 cavities. 18 SSR0 cavities in 2 cryostats were replaced by 9 HWR cavities in 1 cryostat. Lattice structure is not periodical. Current layout is **CSCSCSCSCCSCCSC** . Acceleration is very aggressive, that leads to considerable longitudinal focusing. Longitudinal phase advance reaches 120 degrees. If we make transverse phase advance higher than longitudinal it would reach values close to 180 degrees. Thus, we decided to keep it below longitudinal phase advance. However, somewhere downstream we have to overlap transverse and longitudinal phase advances (phase advance and phase advance per meter of the front end are on [Fig 6] and Fig[7]). Further analysis showed that the best place for the overlapping is before SSR2 section (it allows to follow limitations for current design of solenoids). After this point transverse phase advance is always higher than longitudinal and there is no intersection between them.

This design of HWR section is optimistic from the acceptance point of view. A big number of cavities (in the alternative design the same output energy could be obtained by 7 cavities instead of 9 with reasonable phase advance) allows to keep high synchronous phase (from -45° to -25°). This synchronous phase profile admits almost 10 rms at frequency 162.5 *MHz* [Fig 5]. In this section the beam is accelerated from 2.1 *MeV* to 10.8 *MeV.*

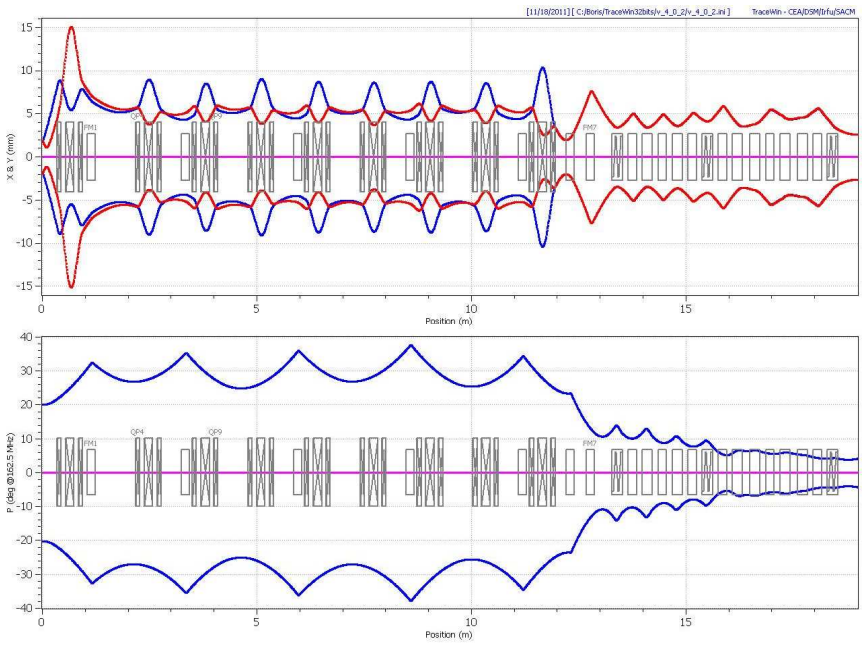

Fig 2.Beam envelope of MEBT and HWR. Top – X&Y, bottom –phase @ 162.5 MHz

SSR1 Section

New layout of SSR1 section(with respect to v.3.9) is periodical. 16 325 *MHz* cavities are segmented in two cryo-modules. Cryo-module structure is **CSCCSCCSCCSC** . in this section beam is accelerated from

10.8 *MeV* to 35.1 *MeV*. In spite of the jump in the longitudinal beam size because of doubling of the frequency of resonators acceptance doesn't suffers. The synchronous phase profile (from-40° to -30°) still admits 10 rms of beam size at 325 *MHz* [Fig 5].

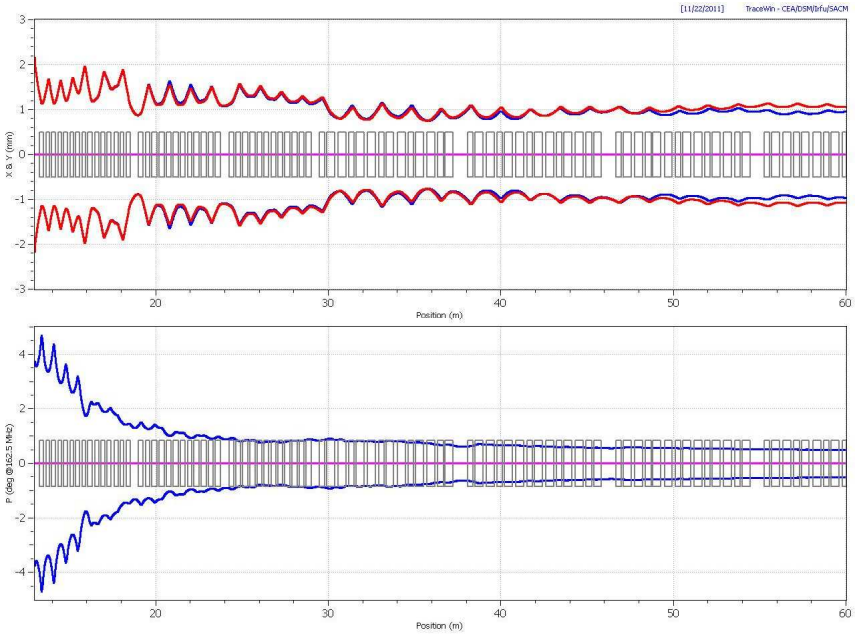

Fig 3. Beam envelope of Front End. Top – X&Y, bottom – phase @ 162.5 MHz

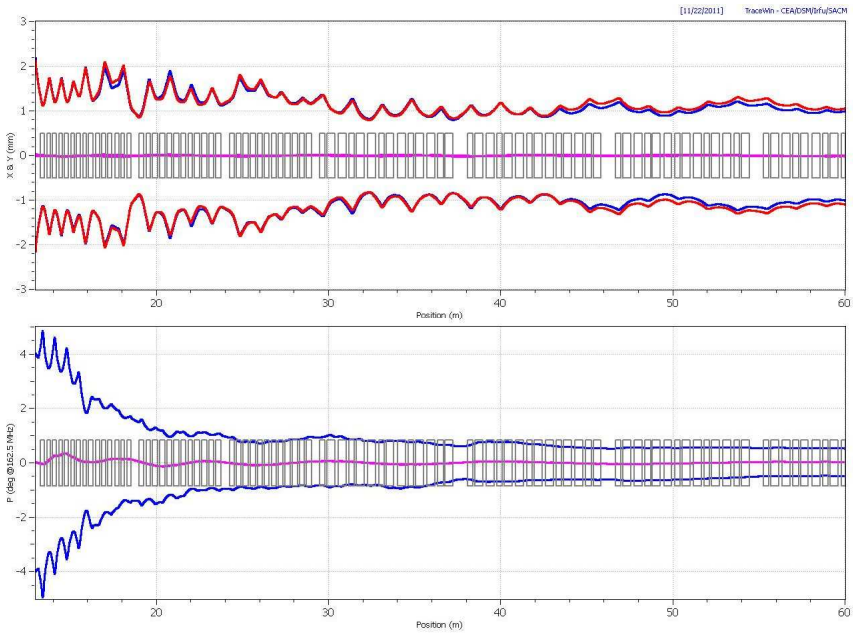

Fig 4.Partran beam envelope of Front End. Top – X&Y, bottom –phase @ 162.5 MHz. Note that centroid oscillation due to focusing asymmetry

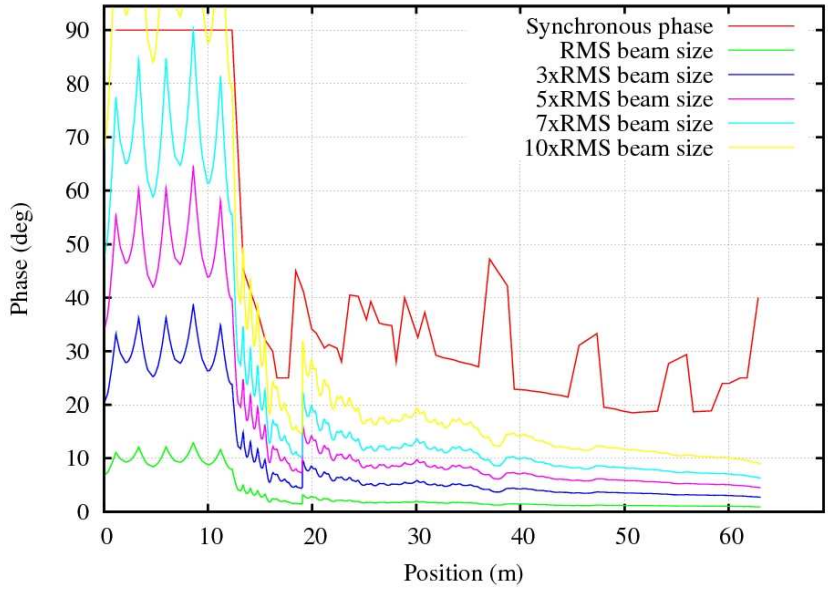

Fig 5. Longitudinal beam size and synchronous phase profile (red). One can see that synchronous phase is chosen in order to admit 10 rms of beam size (yellow) at frequency of each section.

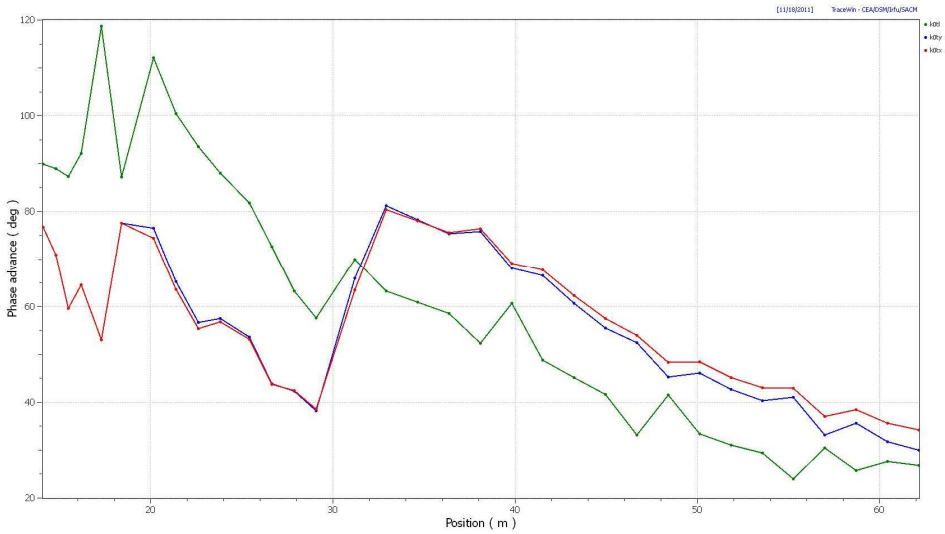

Fig 6. Longitudinal phase advance (green) and transverse phase advance (x - red, y – blue) along Front End Intersection is made before SSR2 section.

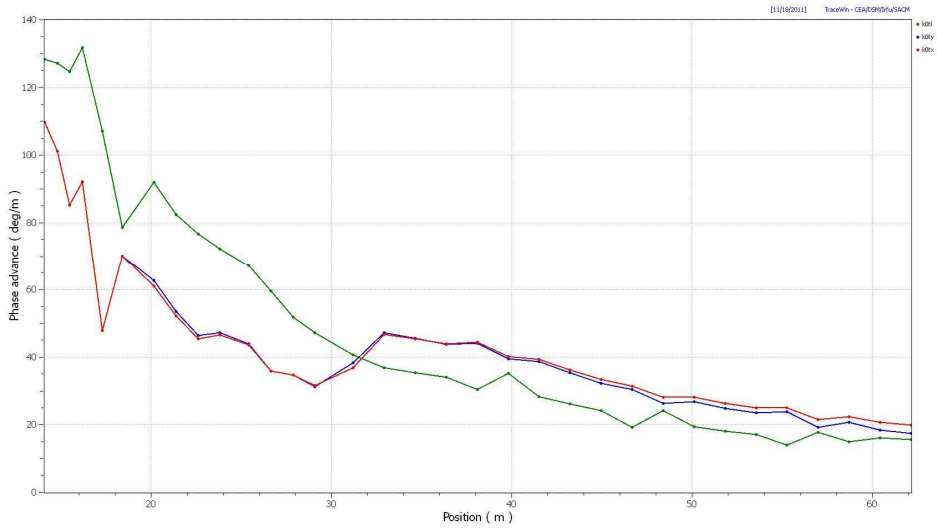

Fig 7. Phase advance per meter along Front End (long. – green, x – red, y - blue).

SSR2 Section

SSR2 section is kept with no changes with respect to the v.3.9. 325 *MHz* cavities with geometrical β=0.47 are implemented. The beam is accelerated from 35.1 *MeV* to 165.4 *MeV*. Transverse phase advance is kept higher than longitudinal. 36 cavities are divided in 4 cryo-modules. Each cryo-module layout is **SCCSCCSCCSCCSC**.

High Energy 650 *MHz* Sections

The design of beta=0.6 and beta=0.9 sections (5-cell elliptical cavities are utilized) completely repeats the former design from v3.9. Transverse focusing accomplished in terms of doublets. In beta=0.6 section one doublet per 3 cavities is used. Every second doublet is warm. Every cryo-module consists of doublet, surrounded by 3 cavities from both sides. And there is a warm doublet between neighboring cryostats. In beta=0.6 section 42 cavities are divided in 7 cryo-modules. Beam is accelerated from 165.4 *MeV* to 556.2 *MeV*. In beta=0.9 section one can find only warm doublets. 152 cavities are divided in 19 cryo-modules. Beam is accelerated from 556.2 *MeV* to 3064.5 *MeV* (Beam envelope of high energy section is on [Fig 8]).

Cavity gradients in all superconducting sections are manifested on [Fig.9]. Cryogenic losses per cavity are shown on [Fig. 10], the maximum value is less than 25 W. Maximum surface magnetic field in SRF cavities is limited by 70 mT [Fig. 11]. Beam power in superconducting linac is on [Fig. 12]. On axis magnetic field in solenoids and gradients in quadruples are shown on [Fig. 13] and [Fig. 14]. The Hoffman diagram is on [Fig. 15]. Behavior of rms. emittances and Halo parameter one can see on [Fig 16] and [Fig. 17].

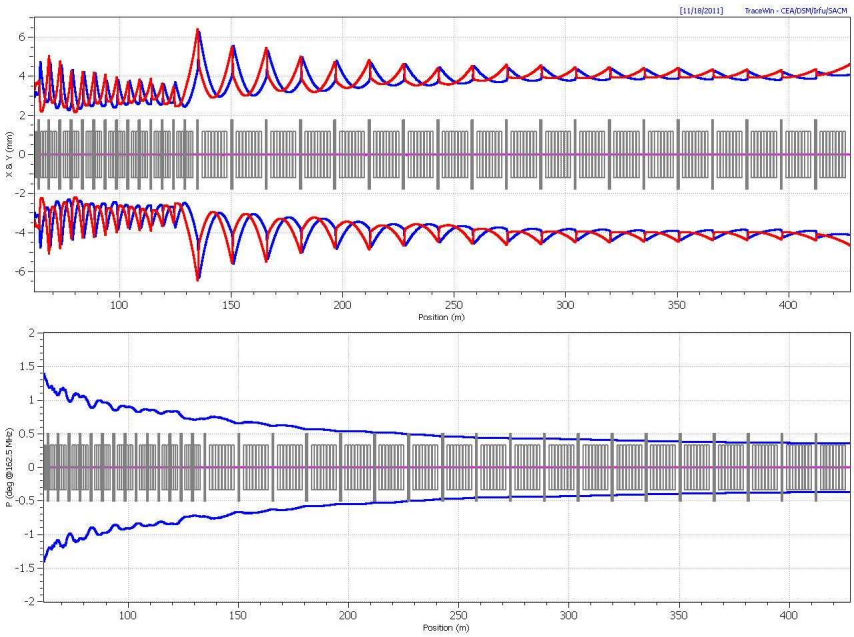

Fig 8. Beam envelope. High energy sections.

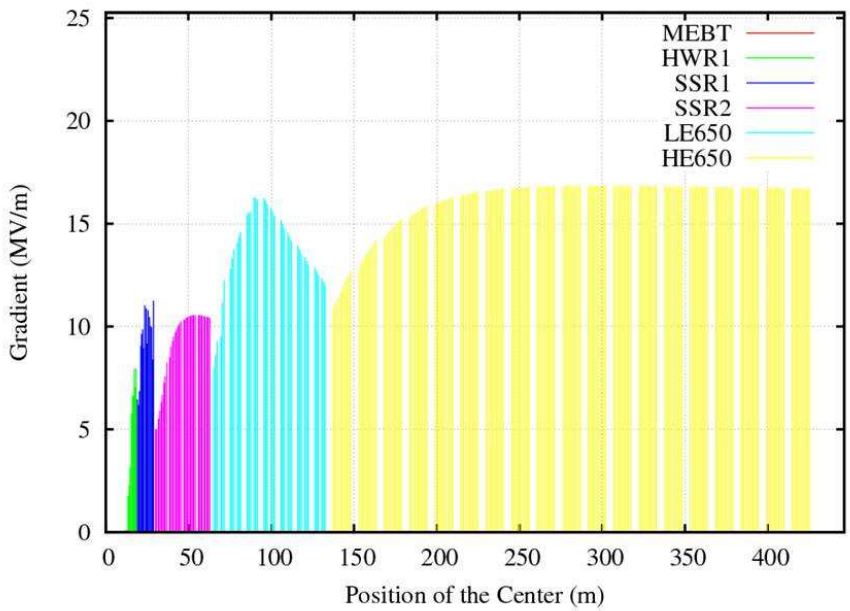

Fig 9. Gradient in cavities.

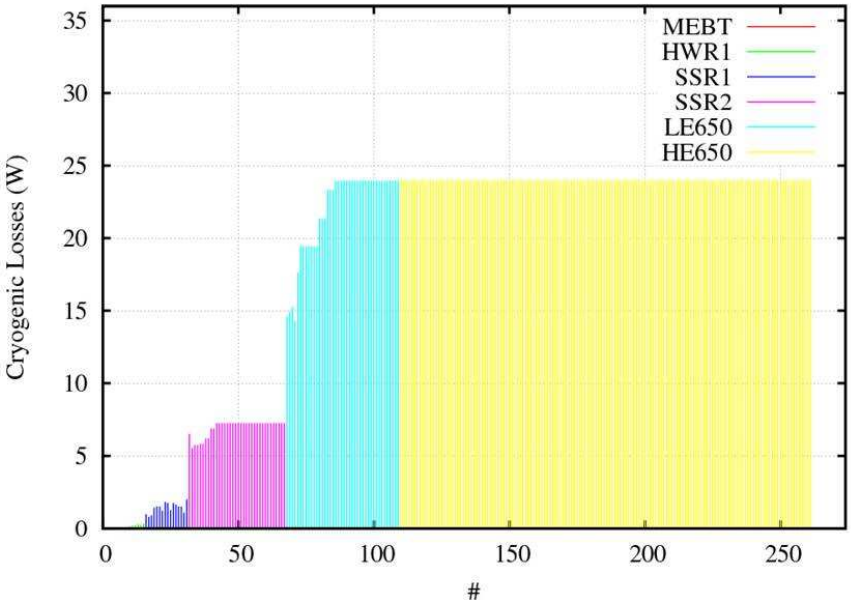

Fig 10. Cryogenic losses per cavity

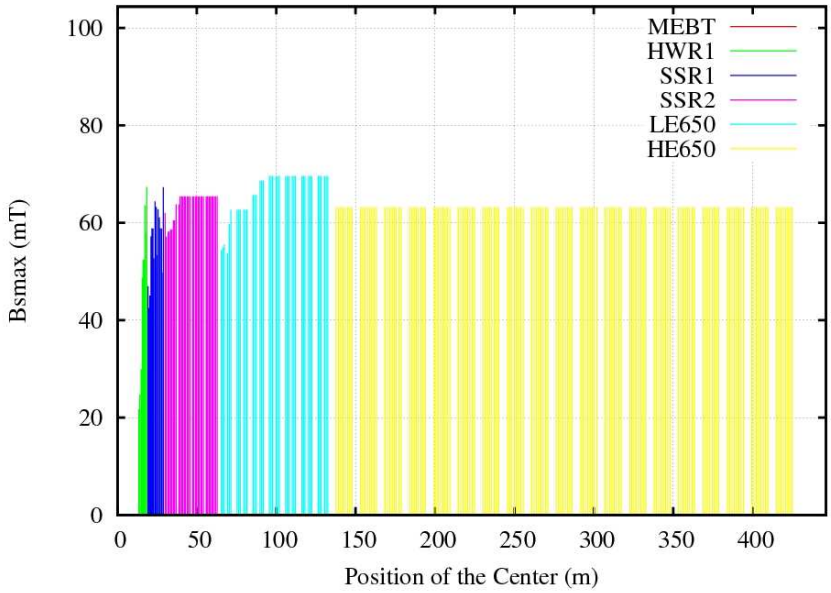

Fig 11. Maximum value of surface magnetic field in cavities

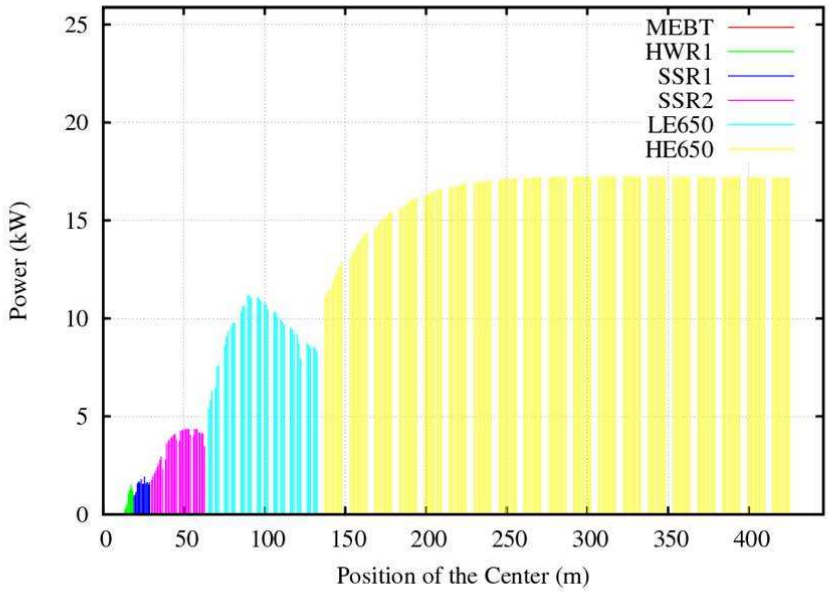

Fig 12. Beam power P=UIcosφ

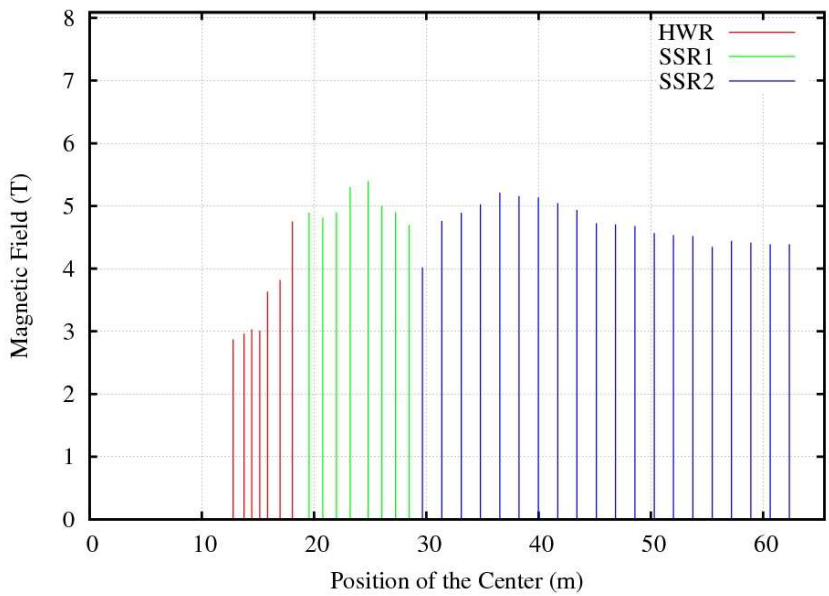

Fig 13. Maximum magnetic field in solenoids on axis.

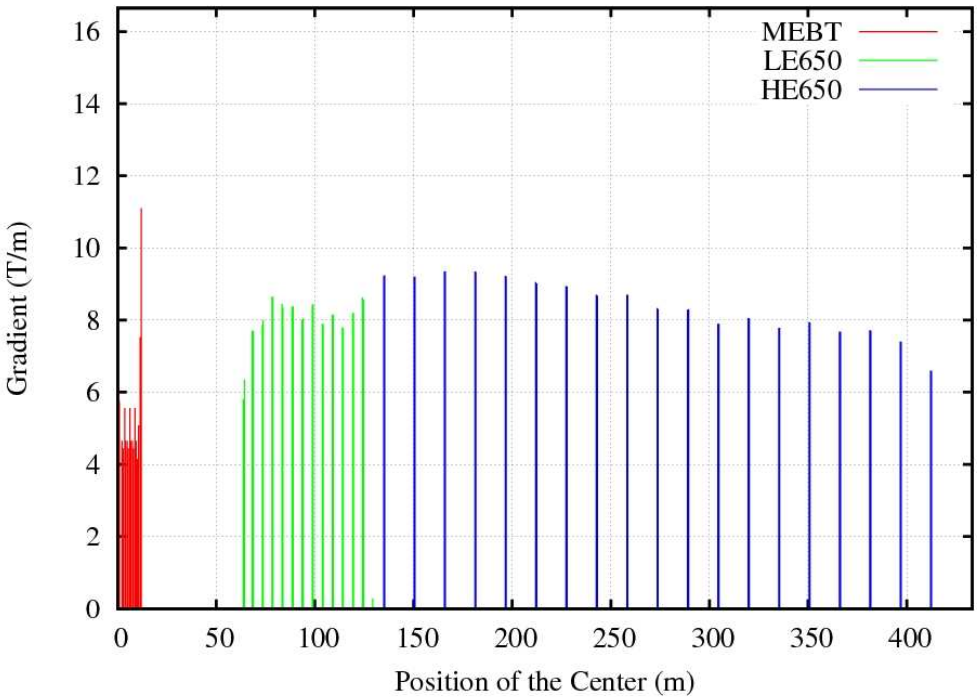

Fig 14. Gradient in quadruples (T/m).

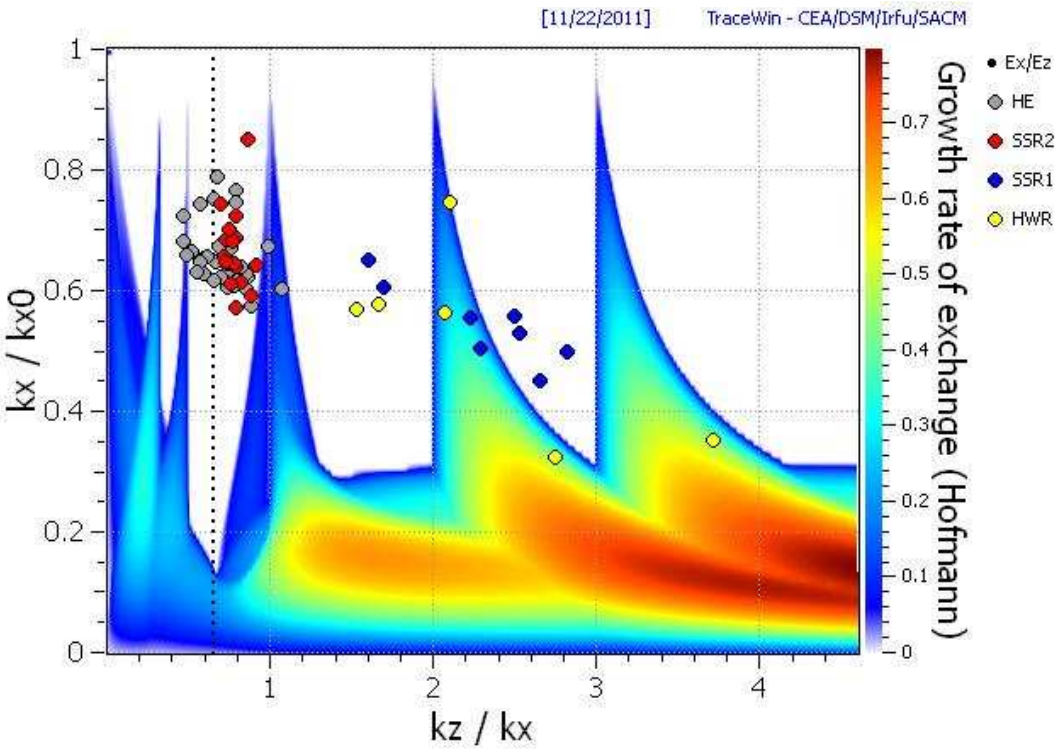

Fig 15 Hofmann diagram. Ratio of longitudinal to transverse emittance is1.55

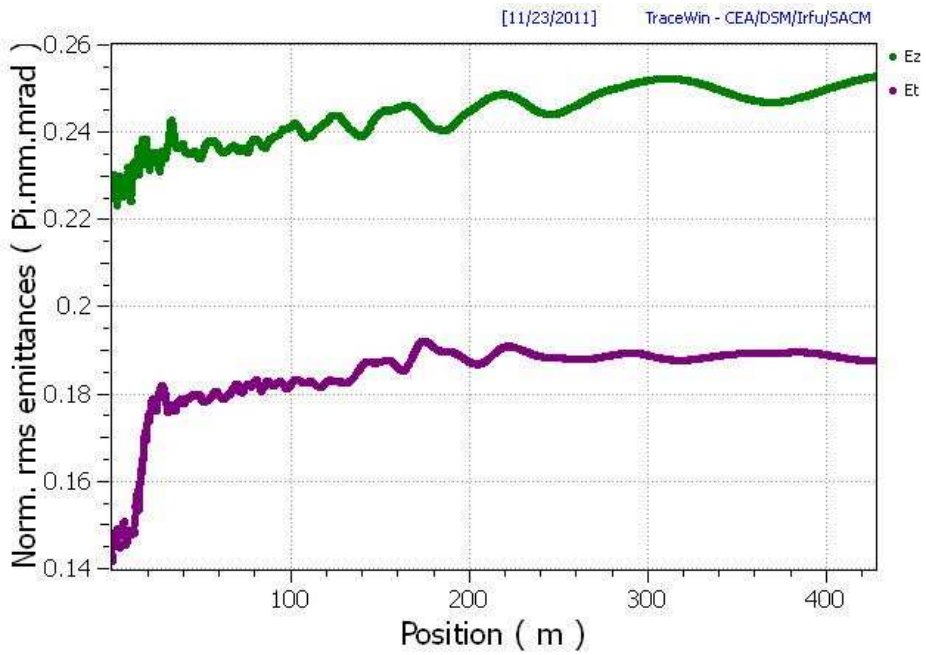

Fig 16. Longitudinal (green) and transverse(purple)normalized rms emittance

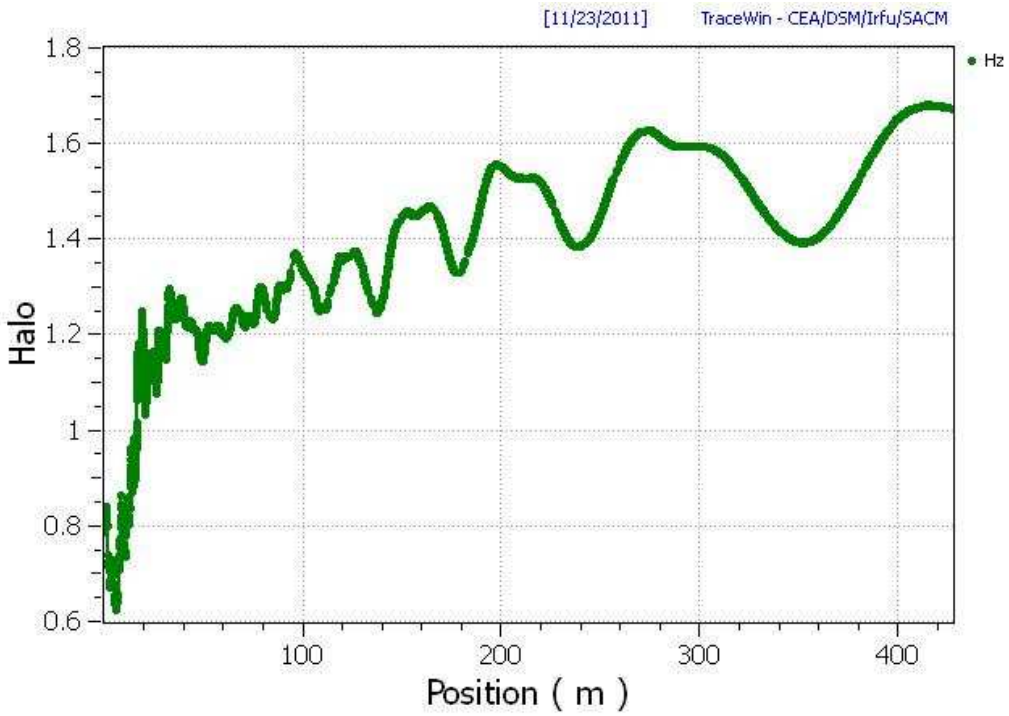

Fig 17. Longitudinal Halo parameter