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KICKER AND DUMP SYSTEMS FOR ERL

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We suggest sectioned kicker magnet able to provide deflection angle ~0.01 rad in ~30 nsec. Magnet yoke made from laminated steel having thickness ~50 μ *m.* The kicker in combination with small-aperture collimator arranges a dump system.

1. OVERVIEW

An undesirable situation could develop anytime during ERL operation, even if this could be treated as a rare event. So the protection system must be designed so that despite its occasional triggering, it must yield a controllable beam dump with ~100% probability. In mostly situations the faster dump system is- the lesser the damage could be.

One typical example could be represented when the injector stops provision of the electron beam while the ERL filled with the electron bunches. Namely, for exclusion of possible harm to ERL caused by this situation it is necessary to install a controllable beam dump at the entrance of North linac, see Section 4. This dump includes a collimator [1], able to absorb full energy of the beam and fast kicker, which directs the beam to the walls of the collimator, see Fig 1. As we mentioned already, the peculiarity of this system is that it operates occasionally, but needs to be ready any time with minimal probability of failure.

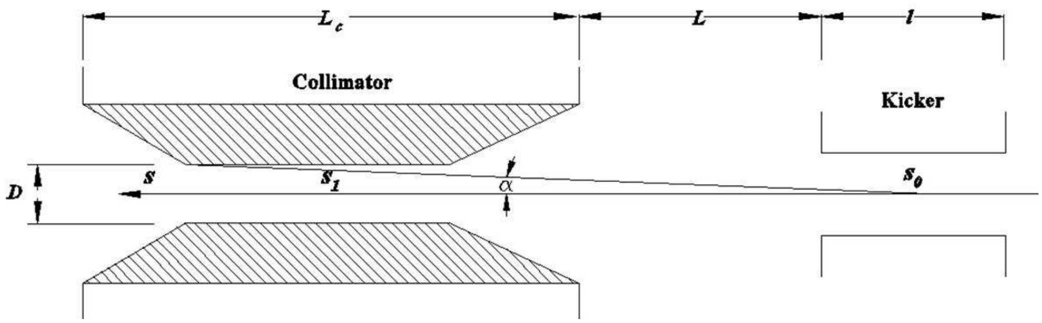

Figure 1: Principle of beam absorber (dump) arranged by combining a kicker with a collimator. Additional collimator is possible at the entrance of the kicker itself (beam is coming from the right).

Propagation of kick $x'(s_0) = \alpha$ from its origin at kicker location s_0 to the collimator located at s_1 described by sin-like trajectory $S(s,s_0)$ having starting point at the kicker location s_0

$$x(s_1) = x_0'(s_0)S(s_1,s_0) = \alpha \cdot S(s_1,s_0)\,, \tag{1}$$

where $S(s_0,s_0) \equiv S(s_0) = 1$, α is a kick angle. By introduction of envelope function and phase as

$$\Phi \equiv \Phi(s_1, s_0) = \int_{s_0}^{s_1} ds / \beta(s)\,, \tag{2}$$

displacement and the slope of the beam centroid at the collimator come to

$$x(s_1) = \alpha\sqrt{\beta(s_1)\beta(s_0)}Sin(\Phi)\,, \quad x'(s_1) = \alpha\sqrt{\frac{\beta(s_0)}{\beta(s_1)}}\left[Cos(\Phi) + \tfrac{1}{2}\beta'(s_1)Sin(\Phi)\right] \tag{3}$$

where $\beta(s_1)$, $\beta(s_0)$ stand for envelope functions values at collimator and kicker respectively. We suggest that the beam size is much smaller, than this displacement

$$\alpha\sqrt{\beta(s_1)\beta(s_0)}Sin(\Phi) \cong \tfrac{1}{2}D > \sqrt{(\gamma\varepsilon)\beta(s_1)/\gamma}\quad . \tag{4}$$

Suggesting $\sqrt{\beta(s_1)\beta(s_0)} \cong 10m$, D=7 *cm*, $Sin(\Phi) \cong 1$one can obtain

$$\alpha \geq \frac{D/2}{\sqrt{\beta(s_1)\beta(s_0)}} \cong 3.5 \cdot 10^{-3} \tag{5}$$

We will use for estimation three times of this, $\alpha \cong 10^{-2}$. At the moment we envision few systems like just described, installed in different parts of ERL complex.

Collimator (see Fig.2) designed to be able to absorb ~4 kJ hit with the possibility to function well after this event [1]. Kicker is a system of pulsed magnet(s) which redirects the beam to the walls of Collimator.

In case of emergency or critical situation, the kicker must be triggered by command pulse with minimal rise time to the full power. Generating of command pulse which triggers the kicker is a part of delay in this system, so processing of parameters of ERL which are be critical, must be done with minimal time. Among parameters involved into controlled chain is the beam current at the exit of injector, energy of the beams and radiation in the ERL tunnels and working areas and others, numerated in sections 4.1-4.8.

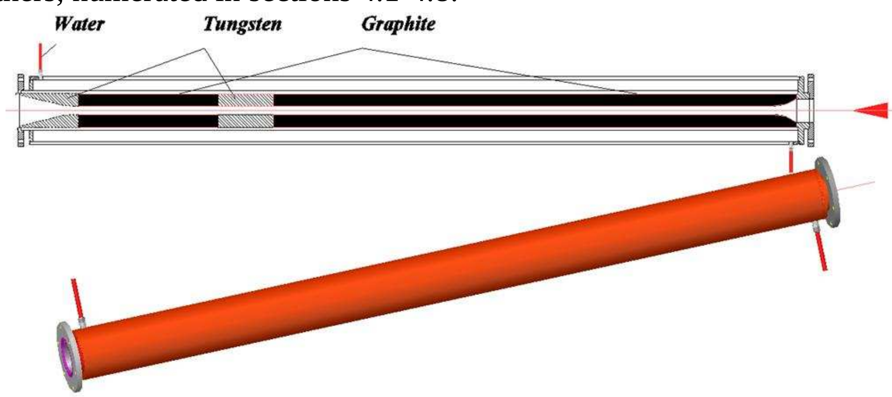

Figure 2: Collimator with Graphite (beam is coming from the right) [1]. Flanges are 4 inch in diameter. Overall length of collimator had shown ~150*cm*. Long Graphite cylinder assembled by many PG discs having a hole at the center. Protection shield not shown here.

One relaxing condition here is that the only front end of the pulse must be short; the tail of the feeding pulse is not important at all, as after the pulse applied there is no beam anymore. Flat top is also not required here; indeed some variation of the pulse top could be helpful in sweeping the beam.

2. PARAMETERS

As the circumference of ERL is about $C \cong 2420m$, period of revolution is $\tau_0 = C/c \cong 2420/3 \cdot 10^8 \cong 8\mu s$ so the kicker must react much faster than this time, especially as the reaction time defined not only by the kicker itself, but by command electronics, which generates the command to trigger the kicker also. Some control signal could be picked up at the far end of the ERL, so the distance of few hundred meters between the crucial pickup station and the processing hardware linked with coaxial cable might be inevitable component of system. So the signal propagation time in this cable might reach microsecond level. Processing time might be of the same order. So the reaction time of kicker itself within few tens of nanoseconds looks adequate.

Kickers with nanosecond level of rise time described in [2], [3]. Basically the kickers described there are the kind of coaxial line shortened at the end.

In [2] the ferrite filling was used, in [3] the thin laminated steel was used. It was found [4] that magnetic field in laminated core could be established in nanoseconds for laminations of 50 μm thick.

Cross section of kickers suggested for ERL is represented in Fig.3.

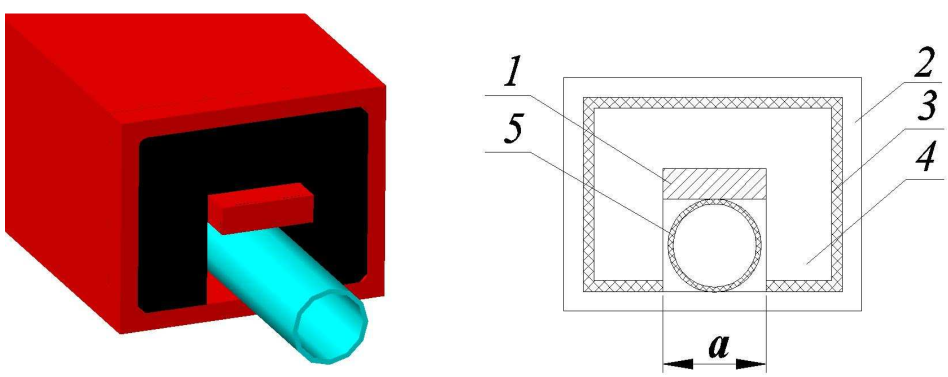

Figure 3: The cross section of the kicker magnet. 1—central electrode; 2—enclosure, second electrode; 3—insulation; 4—laminated Iron (or Ferrite); 5—ceramic chamber.

Basically this is a C-shape magnet with thin laminated core, having galvanic contact with central electrode.

Propagation of feeding pulse (suggesting infinitely short front) in such system is going with speed

$$v_g \cong 1/\sqrt{\varepsilon\mu\varepsilon_0\mu_0} = c/\sqrt{\varepsilon\mu}\ , \tag{6}$$

where μ_0 stands for permeability of vacuum, ε_0 for its permittivity, and μ and ε are relative permeability and permittivity of the kicker line. The field establishes in kicker magnet having the length l (see Fig.1) for the time

$$\tau = 2l / v_g \cong 2l\sqrt{\varepsilon\mu} / c \tag{7}$$

As the kicker is shortened at the end, the magnetic field only acts to the beam. The kick angle defined by the magnetic field strength H_k as

$$\alpha \cong \frac{H_k l}{(HR)}\,, \tag{8}$$

where magnetic rigidity (HR) [$G{\cdot}cm$], defined as $(HR) = pc/300$. For a 5GeV beam $(HR) \cong 1.67 \cdot 10^7\,[G{\cdot}cm]$ or $(HR) \cong 1.67 \cdot 10^4$ [$kG{\cdot}cm$], and the factor $H_k l$ for the kicking angle $\alpha \cong 10^{-2}$ comes to

$$H_k l \cong \alpha \cdot (HR) \cong 10^{-2} \cdot 1.67 \cdot 10^4 = 1.67 \cdot 10^2\,[kG{\cdot}cm]\ . \tag{9}$$

Substitute (8) into (7) one can obtain

$$\boldsymbol{\tau} = \frac{2l}{v_g} = \frac{2l\sqrt{\boldsymbol{\varepsilon\mu}}}{c} = \frac{2\boldsymbol{\alpha} \cdot (HR)\sqrt{\boldsymbol{\varepsilon\mu}}}{cH_k}\,, \tag{10}$$

so one can see, that shortening the time of establishing the field could be reached by increase of achievable magnetic field strength H_k. For laminated core effective values μ and ε are about unity each, for the propagation, but defined by the process of diffusion of magnetic field in laminations. The process speeded up because the initial field value between laminations is $\sim\mu$ times higher, than after establishing the equilibrium [4]. If we chose the magnetic field value in a gap H_k=3 kG, then the total length of kicker comes to

$$l \cong \frac{\alpha \cdot (HR)}{H_k} \cong \frac{1.67 \cdot 10^2}{3} \cong 56cm \tag{11}$$

For generation of the field value H_k=3 kG, the current in the electrode 1 (Fig.3) must be

$$I \cong \frac{H_k}{0.4\pi} \cong \frac{3}{1.2} \cong 2.5kA \tag{12}$$

If we suggest the characteristic impedance of the line (electrode 1) equal to be ρ Ohms, then the voltage from pulser required comes to

$$V \cong I\rho / 2\ , \tag{13}$$

(where factor 2 reflects the fact, that the current doubles its value at the shortened end) which in its turn comes to $V \cong 2.5 \cdot 25/2 = 31.25kV$ in traveling wave.

Of cause total length 56 cm must be sectioned to satisfy the rise time requirements. The length of section suggested being 10 cm, so the number of sections in licker comes to 6, see Fig.4 and Fig.5.

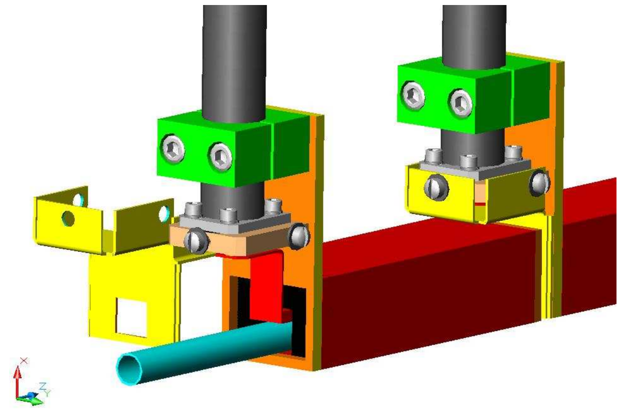

Figure 4: Symmetrical input. Vacuum chamber made from Ceramics. The front cover shown shifted in this Figure.

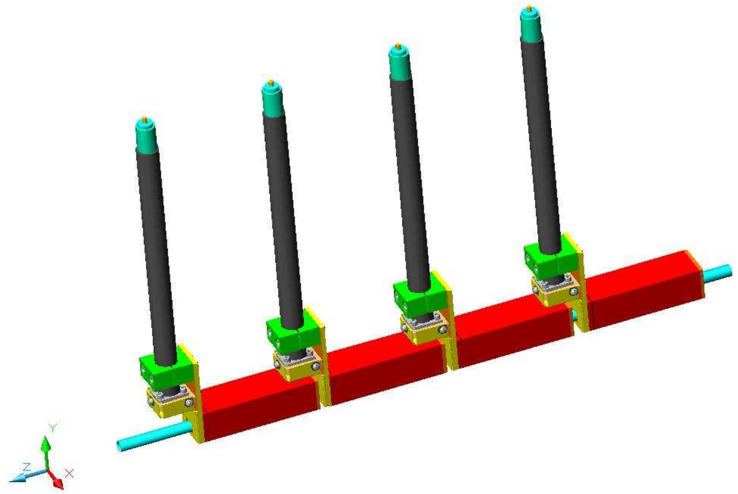

Figure 5: Series of kickers installed in line. Ceramic vacuum chamber runs through all sections of kicker. Four sections of total 6 are shown.

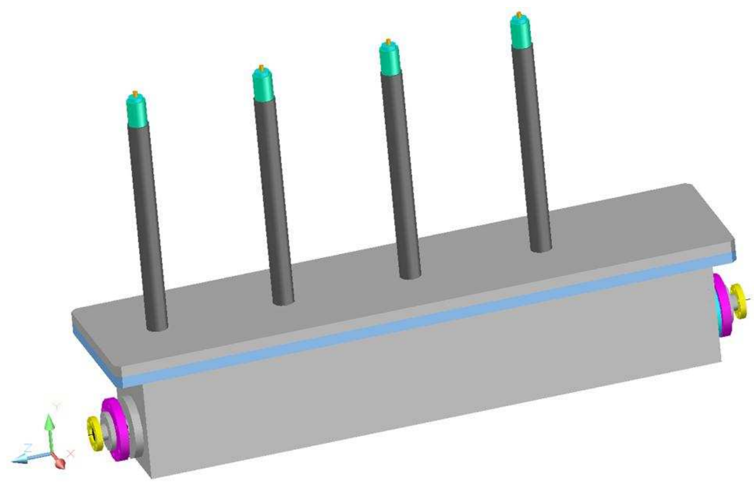

Figure 6: Series of kickers from previous Figure installed in a case.

The time required for the pulse to run forward and back at the beginning of the process, according to (9) comes to be $\tau = \frac{2l\sqrt{\varepsilon\mu}}{c} \cong 0.7ns$ only, but the time of establishing field value defined by relaxation is [4]

$$\tau \cong \frac{d \cdot l_g \sigma\mu\mu_0}{3} \cdot \frac{2}{\mu}, \qquad (14)$$

where σ stands for the electric conductivity of the steel laminations, $2d$ –is the thickness of laminated sheet, $2l_g$ is the gap between laminations. Substitute here $2d \cong l_g \cong 50\mu m$, $1/\sigma \cong 9.7 \cdot 10^{-8} Ohm \cdot cm$, $\mu_0 \cong 4 \cdot \pi 10^{-7} H/m$, one can obtain

$$\tau \cong 10ns. \qquad (15)$$

For guarantied service the number of kicker sections could be increased. All kickers could be made immersed into transformer oil for protection against sparking. Ceramic chamber covered by conducting layer from inside or even made from low conducting ceramics. Adequate thickness required for mechanical strength.

By summarizing, we can say that for operation the voltage required pulser with pulsed voltage ~30kV , current ~2.5kA, time duration ~8 μs maximum.

3. PULSER

As we mentioned the kicker must be ready any moment so the pulser must be designed adequately. Faster reaction –less energy deposition is in walls, RF structure etc. We suggest two types of pulser—with thyratron and with three-electrode spark key. Parameters of HV line are chosen so the voltage drop associated with intrinsic impedance is minimal (low impedance artificial line).

3.1. Thyratrons. There are some appropriate types available at the market.

(1) TGI1-5000/50, 5kA, 50 kV, water cooled.

(2) CX1174, 5 kA, 40 kV, air cooled, deuterium filled ceramic thyratron –GEC Electronic Tube Company Limited.

(3) HY-5; HY-53, 5 kA, 40kV, air cooled –PerkinElmer™ optoelectronics, Dimensions of this last model are 5 in high and 4.5in in diameter.

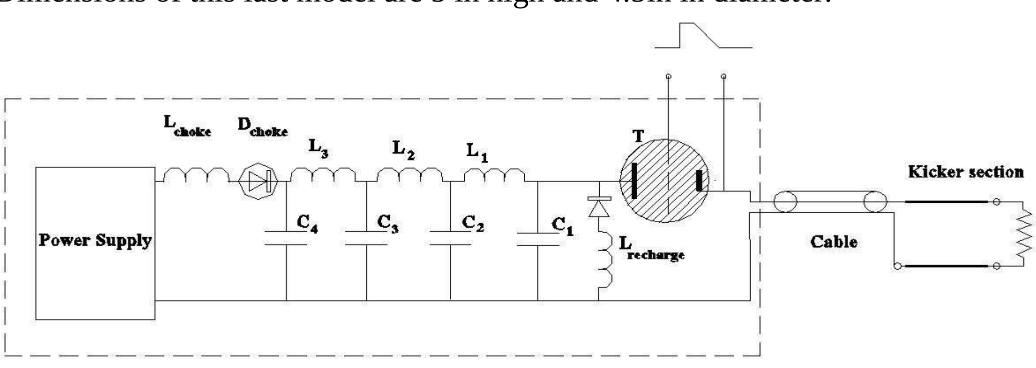

Figure 7: Pulser with thyratron switch. Each kicker section has individual pulser like it is shown here.

Total time of field establishment if the kicker feed with thyratron switch one can expect to be ~30 nsec.

3.2. Triode sparking chamber for fast pulsing originated in [6]. Further development was carried in BINP, Novosibirsk. The triode high pressure trigger gap operates with 40 atm of N_2; adjustable gaps. Synchronization of the order of nsec level reached here. Namely such system used in [2], [3] for pulsing with repetition rate ~1 Hz. Such system is in use for ~40 years now in BINP, without serious problem.

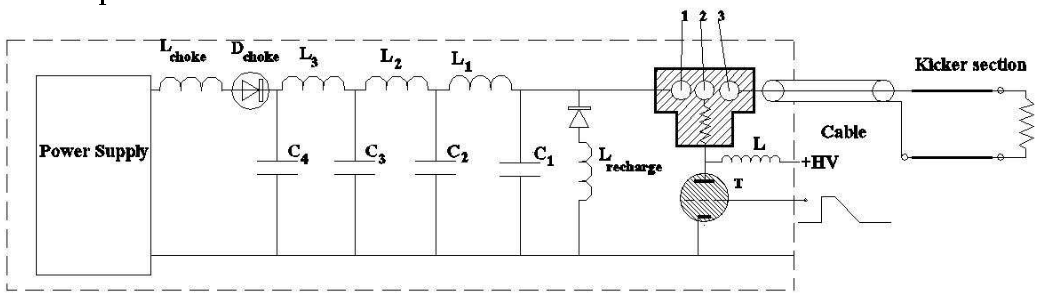

Figure 8: Pulser with triode spark chamber. Electrodes 1, 2, 3 immersed in atmosphere of N_2 pressurized up to 40 atm. Electrodes 1 and 2 could be moved inside for adjusting the sparking threshold.

When a positive pulse applied to the thyratron grid, electrode 2 reduces it potential from a positive, HV, to ~zero. So the gap between electrode 1 and 2 becomes overloaded and the spark developed between 1 and 2, which immediately triggers the spark between 2 and 3. So the line now attached to the load cable. The reaction time of this system is of the order of 1-2 nsec. Thyratron in scheme on Fig.8 is a low power one.

The rise time for the pulse front one can expect for triode sparking system is ~1-2 nsec. Total time of field establishment in the kicker feed with triode spark switch one can expect to be ~10 nsec defined by the time required for relaxation of field in laminated core. Parameters of the kicker summarized in a Table 1.

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Table 1. Parameters of the kicker system.

Parameter	**Value**
Number of sections	6
Length of section	<10cm
Voltage	30kV
Current	2.5kA
Impedance	~25Ohm
Minimal time of establishing field	~10ns
Aperture	~1cm
Pulser/ Rise time	Thyratron/30 nsec
Pulser/ Rise time	Triode/10 nsec

4. TRIGGERING OF KICKERS

Operational scheme for ERL system at Cornell is described in [5], see Fig. 9 below. Each dump includes a collimator itself and a fast kicker (described above), which directs the beam to the walls of the collimator. Dump system should be installed at the entrance of North linac and at the entrance of the second (south) SRF accelerating section of ERL after the turning arc –this is, probably, minimal configuration. ERL requires the presence of these two collimators, able to withstand a direct hit of one full-circumference bunch train in its structure.
Additional dump systems could be installed after exit from CESR and before entrance to experimental area nearby the Demerger, see Fig.9. The same type of collimator and kicker could be used for protection of low –aperture SR insertion devices. The arguments for this are straightforward.

In ERL there is no self balanced mechanism of equalizing energies at the exit of linac as it is in a cyclic machine with auto-phasing. The only parameter in hand is the controllable RF power from additional low-power RF generators which makes the energy of one beam higher, but the energy of other beam lower at the same time. The energy of one beam could be kept equal to the energy of another one by a sophisticated feedback system operating just this active RF power supply. This feedback system must analyze the energies of these bunches (and/or theirs currents and transform theses readings into RF feeding power.) Basically, one need to be prepared that the energies of two beams running in the return loop might be different and varying in time. This difference is defined by a dynamic range and functional stability of this feedback system in general.

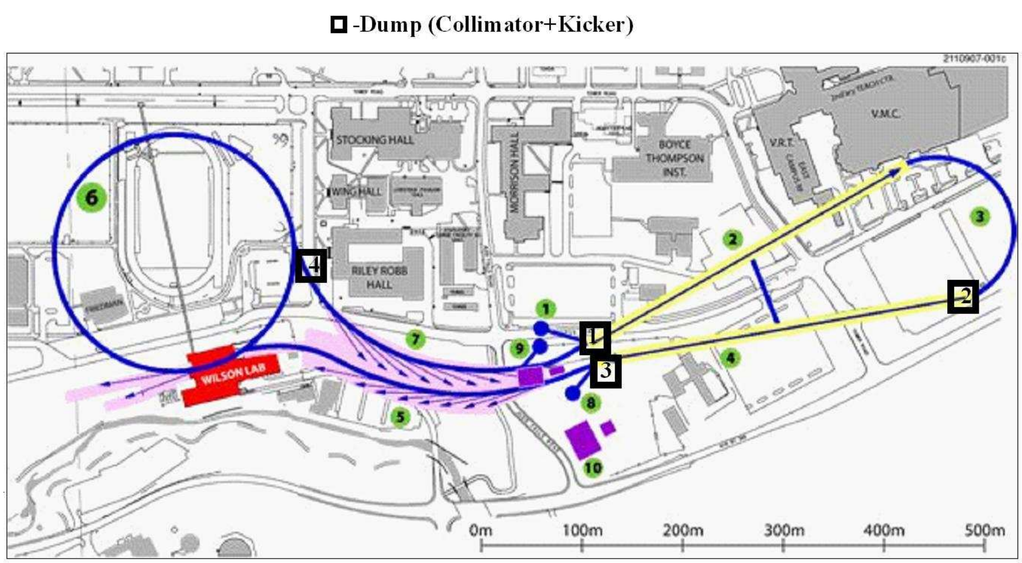

Figure 9: Schematic ERL layout incorporating the existing Cornell Electron Storage Ring (CESR) [5]. Location of kickers/collimators indicated by numbers 1, 2, 3, 4 in big squares. Other numbers in circles: 1–injector, 2,4–SRF linacs, 3–return arc, 5,7–SR lines, 6–CESR, 8–beam dump, 9–test source; explanation of operations one can find in [5].

Electrons are injected (1) and are accelerated to the right a 2.5 GeV linac (2), loop through a turn-around arc (3), and accelerate to the left through an additional 2.5 GeV linac (4) to 5 GeV, total. Beam lines located in the areas painted pink/red. Bunches then pass clockwise around CESR (6). Bunches may be compressed to <100 fs (7) and feed more undulators before being uncompressed, energy recovered in second passes though Linacs (2) and (4), and finally dumped at (8). A second injector (9) provides large bunches for pump-probe experiments (mode c of Table B-1). These are accelerated to 2.5 GeV through linac (4), pass through a long undulator, and are dumped without energy recovery at (8). The pump-probe station is at (10).

Collimator at the entrance of North SRF linac (#1, Fig.9) must be able to absorb full energy accumulated in bunches filling all perimeter of ERL. With additional collimator #4 this can be reduced to only ¼ of this value. The dump system at location #4 is desirable for protection of experimental areas.

Collimator at location #2 serves for protection of SRF structure from SR radiation generated in bending magnets.

As the beam size is extremely small, the density of energy deposition during direct beam hit could reach destruction limit for material of absorber. As we mentioned, an undesirable situation could develop any time and conditions for this numerated in sections 4.1-4.9. The length of the train in worst case scenario could reach the full circumference of system carrying ~10k bunches with 5GeV each having up to 77pC with total energy $E_{tot} \cong 4\ kJ$ which must be absorbed in collimator after the kick applied. So, again, design of collimator allows extension its functions so it becomes able to absorb full energy accumulated in many bunches.

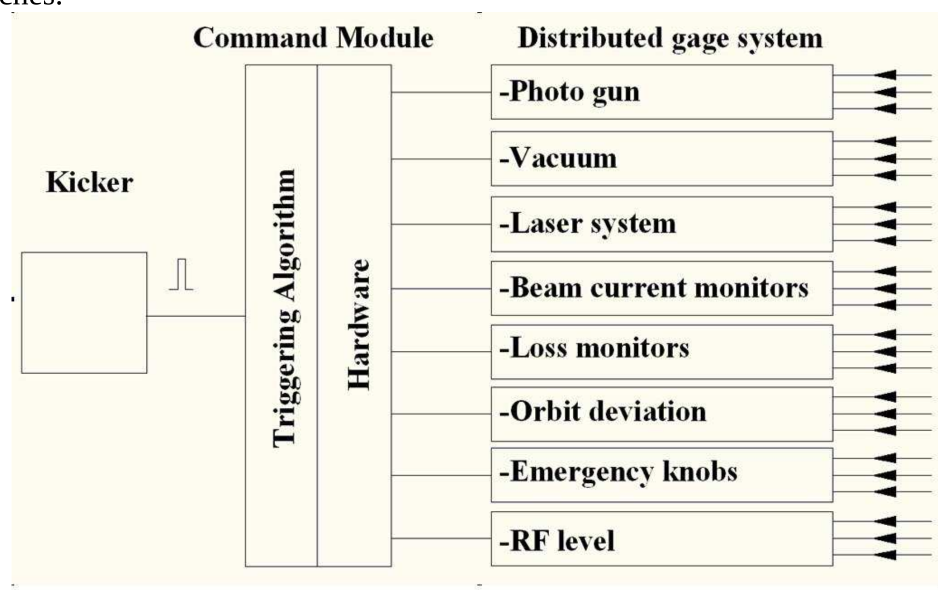

Figure 10: Block scheme of protection triggering system.

4.1 Photo gun HV.

Termination of current production by photo-gun immediately yields a misbalance in RF power and rise of voltage across accelerating structures. As there will be no operational possibility to compensate the absence of beam induced losses of power from accelerating structure, the structure more likely will quench. The share of beam which will be dumped could reach ~half of the full train.

4.2 Laser System

While the laser system stops generating radiation, the gun stops generation of current. So some simple optical monitors can arrange a triggering pulse while the laser radiation is out of specifications.

4.3 Vacuum.

Vacuum monitors are the standard ones, and generate triggering signal to appropriate kicker while the vacuum drops below controlled level.

4.4 Loss monitors.

Loss monitors are the components of general safety system

4.5 Orbit deviation (BPM).

ERL has a system of BPMs controlling the orbit of the beams. So while the readings run out of specification, the triggering signal to appropriate kicker generated.

4.6 Beam Current monitors.

Beam current monitors include button-type ones located inside each SRF cryomodule. The BPMs located here are not able to resolve the beams having different energies. In returning loops the button-type BPMs, located in separate return channels allow resolving the individual bunch population for each beam.

Some optical BPMs are also possible here. If inside some focusing block inside cryomodule the helical windings installed also, this will allow distinguishing the radiation from different components of bunches, having different energy. As the helical field has minimal value at the axis, this allows positioning of the beam at the center by minimizing radiation.

4.7. RF levels

Stationary RF signal acquired from each accelerating structure serves for feedback regulation of power delivered by/from klystrons to each SRF structure. If, however, for some reason, the RF level comes out of margins established by feed back system (overregulation) the command generated for upstream kicker for delivering the beam train into collimator body (absorption).

4.8. Emergency knobs.

Emergency knobs distributed around ERL in critical points allowing manual discharging all equipment responsible for the beam generation. These knobs are triggering the kicker(s) in appropriate upstream sector(s), so the beam goes to the dump(s) before the area, where the knob is triggered.

4.9 Energy deposition.

Triggering of kicker brings beam to the walls of collimator and deposition of its energy in its material (Graphite).

Reaction time has component associated with propagation of signal across ERL plus time required for processing plus reaction time, which in its turn composed by pulser rise time plus time required for the field installation.

Table 2. Energy deposited in collimators while beam dump.

Collimator #	1	2	3	4
Max energy deposited, *kJ*	4	4	4	4
Minimal energy deposited, *kJ*	0.7	1.0	0.7	1.5
Max reaction time, μs	8	8	8	8
Min reaction time, *ns*	30	30	30	30

5. SUMMARY

We suggested a kicker in combination with collimator for controllable beam dump.Few collimators must be installed in ERL for safe operation of this complex. One collimator installed at the entrance of North linac combined with fast kicker serves for protection of North SRF module triggered by failure of electron source and in case of emergency. Pulser with thyratrons is adequate to the ERL requirements. Similar system must be installed at the entrance of south SRF module and the other one in front of user area, right after the south linac.

All elements of kicker are within present day technologies and with no doubt could be implemented into ERL scheme

6. REFERENCES

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