Alternative Design Concept for Project-X 8 GeV complex*

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* Presentation is based on ACD proposal for Project X (Apr. 17, 2009 Kephart, Lebedev & Nagaitsev)

Introduction

Present Strong Points of the Project X Program

- Supports neutrino program with 2 MW MI power from 60 to 120 GeV
- Develops SCRF technology capabilities at Fermilab

Present problems

- Project X ends in the Recycler;
  - there are no 8 GeV users taking beam directly from the Recycler
- Both the ICD and the synchrotron concepts have problems with packaging the beam for potential experiments at 8 GeV
  - Optimistically, slow extraction from Debuncher is limited to about ~150 kW
    - most probably this number is significantly lower
      - loss limit - 1 W/m, uncontrolled loss – 1% => 50 kW beam
  - Rigid time structure
    - does not support Kaon experiments, not perfect for μ-to-e as well
  - Large intensity variation during slow extraction (Imax/Iaverage ~2-3)
- Single user (other experiment implies significant hardware changes)
- The ICD concept has 8 GeV beam power significantly exceeding experiments we presently have in the program
  - started with 1 MW, reduced to 0.5 MW
- Other experiments
  - g-2 looks OK but has potential time conflict with μ-to-e
  - Kaons – are not supported because of time structure requirements (Tevatron?)
  - Transmutation and energy generation - not optimal because of pulsed beam
- This program excludes potential use of antiprotons

Proposal

- Split 8 GeV linac into 2 parts
  - 0-2 GeV, 2-MW CW linac
    - 1 mA CW beam is set by MI (peak current up to 10 mA)
  - 2-8 GeV, 0.22-MW pulsed linac
    - β = 1 (ILC-like):
    - 20 ms @ 1Hz or variations for 2.2 MW at 120 GeV(150 kW @ 8GeV)
    - 40 ms @ 1Hz or variations for 2.2 MW at 60 GeV (300 kW at 8GeV)
- 2-8 GeV acceleration can be also achieved with 10 Hz synchrotron
- At least 1 mA of CW linac is required
  - For pulsed linac it is set by total duration of pulses (5 Hz, 8 ms)
    - o Present ICD 5 ms @ 1Hz (5 Hz, 1 ms)
  - For synchrotron by inj. time (10 Hz, 4 ms of 100 ms cycle, $\Delta p/p=8\cdot10^{-3}$)
  - Higher current would make pulsed linac easier
- CW linac beam can be split to several experiments with RF separators
  - 3 experiments like CEBAF looks reasonable choice
    - $f = f_{RF} / 3$ (~100 MHz, ~1-3 ps rms bunch length)

Physics experiments

- Known experiments
  - μ-to-e (1 GeV is enough)
    - incredibly better than the present scheme,
      - o pion yield at 1 and 2 GeV is about twice of 8 GeV
      - o Easy to control time structure of the beam.
        - Chopping with duty factor ~10% does not affect total power delivered to a hall
      - o Extinction
        - Proton linac does not accelerate electrons or protons with other momentum. Therefore the chopper is the only system which determines the beam extinction
        - Simultaneous operation of 3 halls requires a closer look how chopping has to be done
      - o addresses strong competition from JPARC
      - o addresses upgrade
  - Kaons require at least 2 GeV energy (details will be known soon)
- Additional program is possible
  - Transmutation, medical isotopes production and nuclear physics

Physics experiments (continue)

- This proposal does not require Antiproton source decommissioning
  - Experiments with internal target
    - 80 pbarn^{-1}/week in Accumulator
    - 300 pbarn^{-1}/week are possible in Tevatron
- g-2 and antiproton source can coexist
  - If care will be taken switching from one program to another can be under one week
- μ-to-e and g-2 can potentially use up to 0.5 MW beam power
  - We need other users capable to use other 1.5 MW

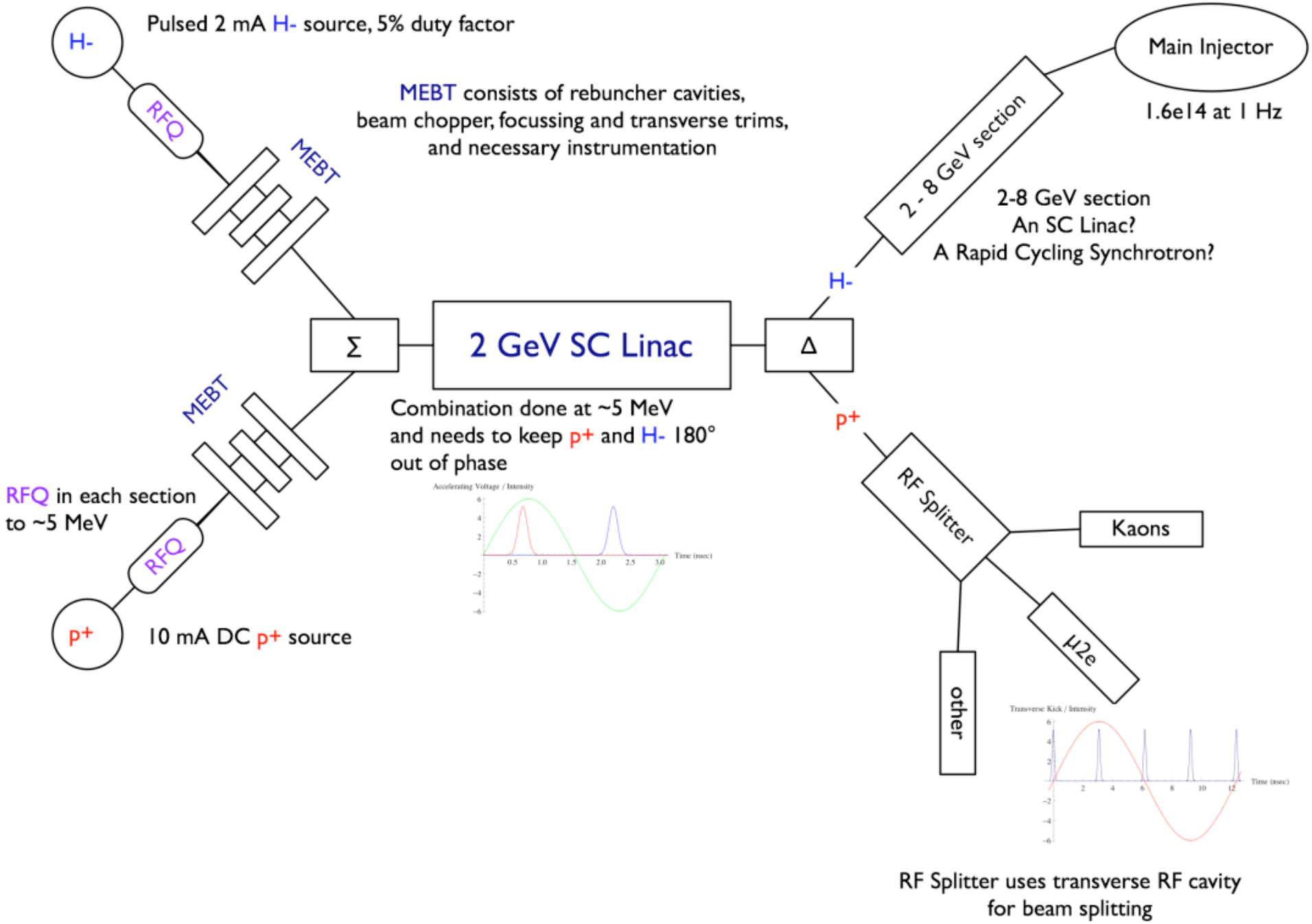
Conclusions

- This proposal retains the 2-MW MI program but moves 8-GeV slow extraction program to 2 GeV
- It does not exclude experiments which use fast extraction from Recycler
- Benefits
  - Diverse physics program at low energy
    - The gain in physics should override some price increase
      - ⇒ Additional expenses for CW linac will be partially compensated by savings on reconstruction of Debuncher and Accumulator for μ-to-e
    - If money is the major issue than 2-to-8 GeV synchrotron should bring us to the price below present ICD
  - Potential improvements of μ-to-e sensitivity can be more than an order of magnitude – it makes it really competitive
- Drawbacks
  - More complications for upgrade to MW scale beam power at 8 GeV required for neutrino factory or muon collider

- Time and schedule
  - Front end (CW part) can start producing physics before neutrino program
    - 2016 for μ-to-e does not look impossible but still risky
- Proof of Existence
    - Present CEBAF 1 GeV, 1 mA, 1 MW electrons, 5 pass recirculation
    - CEBAF after upgrade 2 GeV, 0.5 mA, 1 MW
- Problems
  - Same as for Project X stronger physics case support for low energy portion is required
- Both Synchrotron and Pulsed linac can coexist with CW linac
  - Final choice will be compromise between
    - Cost
    - Political implications
    - Long term plans

Pion yield for μ-to-e

General machine layout



Technical details of CW linac

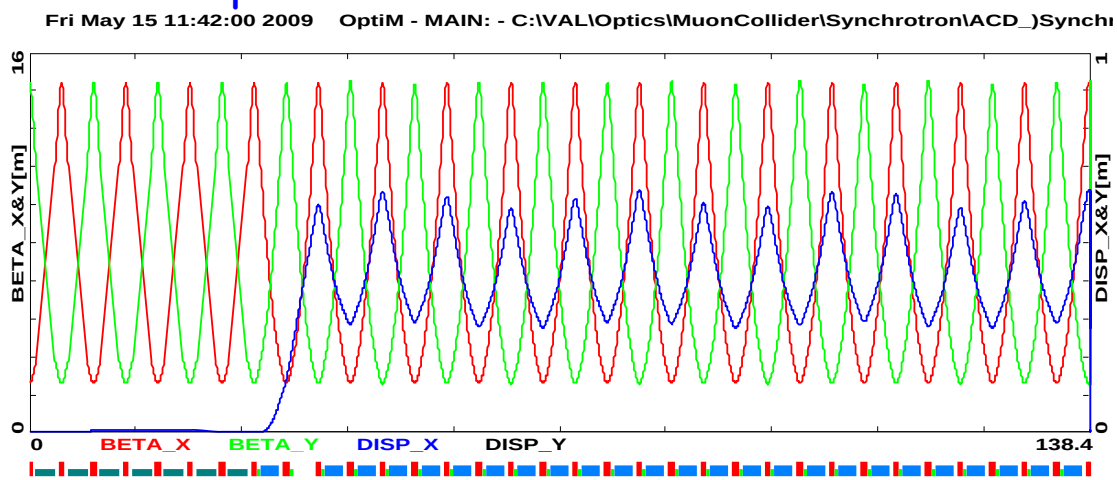
- Length and accelerating gradient
  - 18 MV/m is what CEBAF uses for upgrade
    - We stay with 15 MV/m
  - Length is increased by 1.7 times
- Very rough cost estimate of cost increase for 2 GeV case
  - 500M$ * (2/8) * (1.7-1) = 90M$ (half of this for 1 GeV machine)
  - For now it looks as a conservative estimate
  - Subtract cost of pbar source conversion to slow extraction
    - Transfer line price is the same and should be included
  - We save antiproton source – it is quite expensive machine (certainly more than 90M$)
- RF power
  - 16 kW per cavity
- CW RFQ is not a problem (was already demonstrated)
- Cryogenics
  - 17 kW/cavity power (from AC power line)

Synchrotron

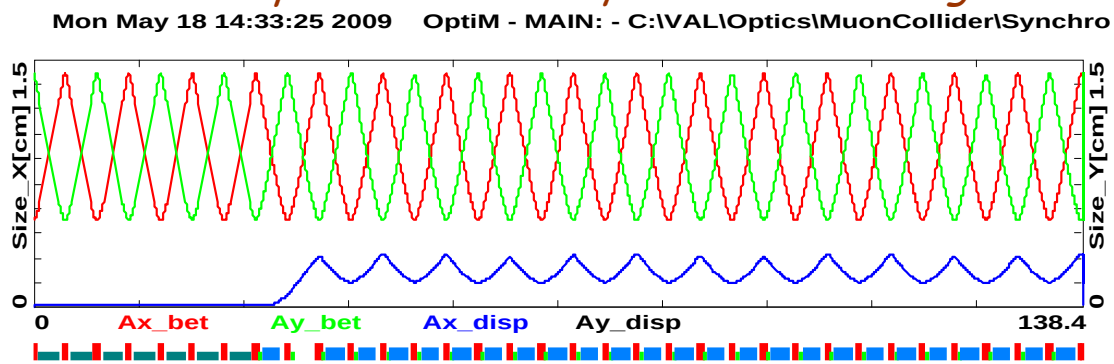
Energy, min/max, GeV	2/8
Repetition rate, Hz	10
Circumference, m (MI/6)	553.2
Tunes	18.44
Transition energy, GeV	13.36
Number of particles	2.67E13
Beam current at injection, A	2.2
Harmonic number	98
RF frequency, MHz	50.33 – 52.81
Maximum RF voltage, MV	1.2
95% n. emittance, mm mrad	25
Space charge tune shift, inj.	0.16†
Norm. acceptance, mm mrad	40
Injection time for 1 mA, ms	4.3
Linac energy cor. at inject.	0.8%
RF bucket size, eV s	0.25
Number of RF cavities	10
Cavity shunt impedance, kΩ	100

†For Gaussian beam at injection. The tune shift will be 3 times less for the KV distribution.

- Racetrack
- Dispersion is zeroed by missed dipole
- One type of quadrupoles
- All quads and dipoles are on the same bus
- Corrector pack includes dipoles quads and sextupoles

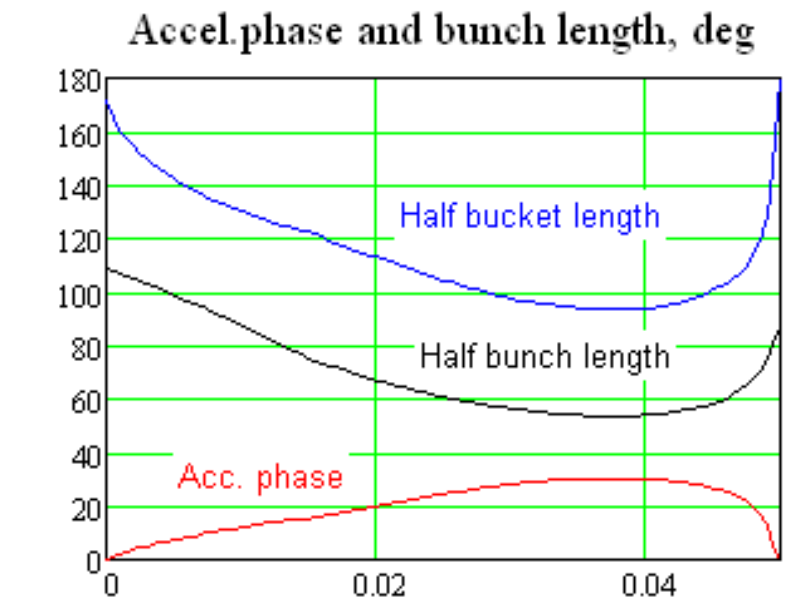


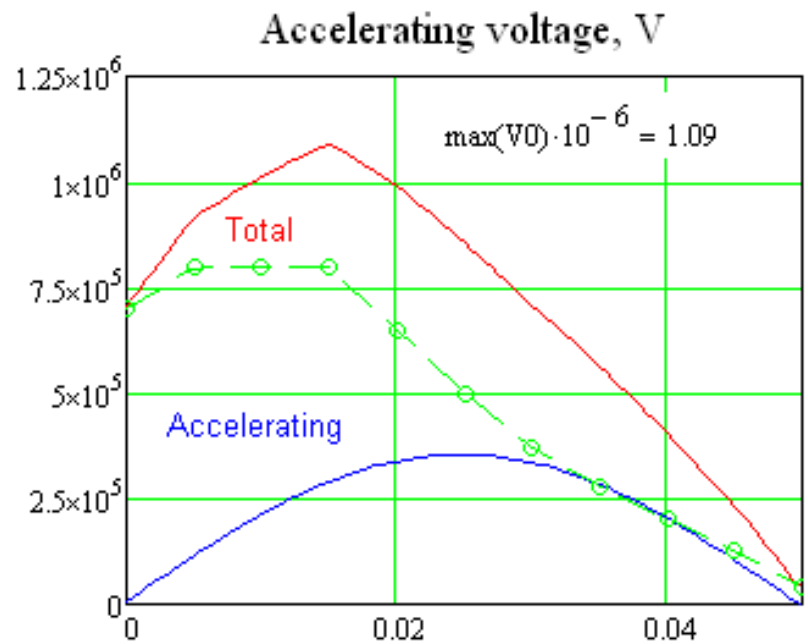
Twiss parameters for quarter of the ring

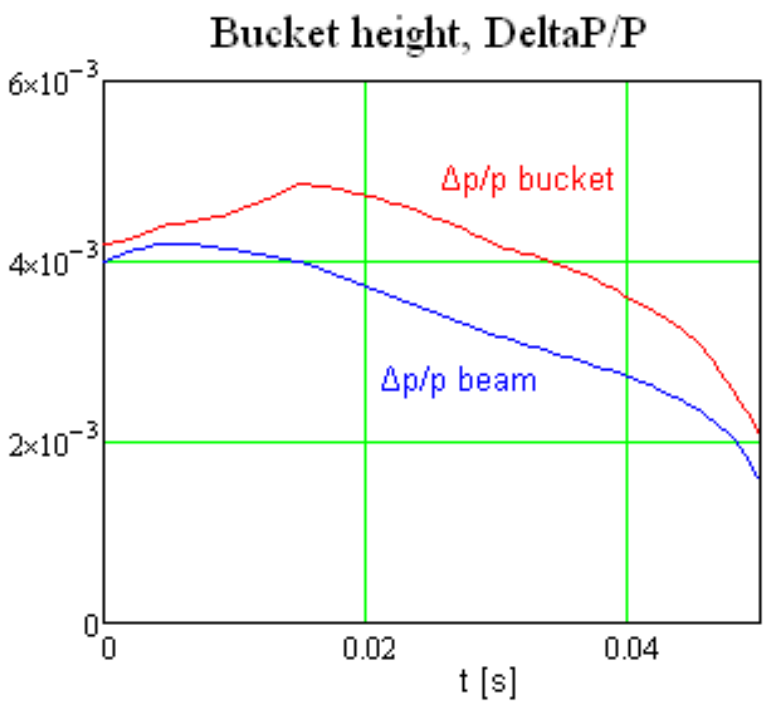


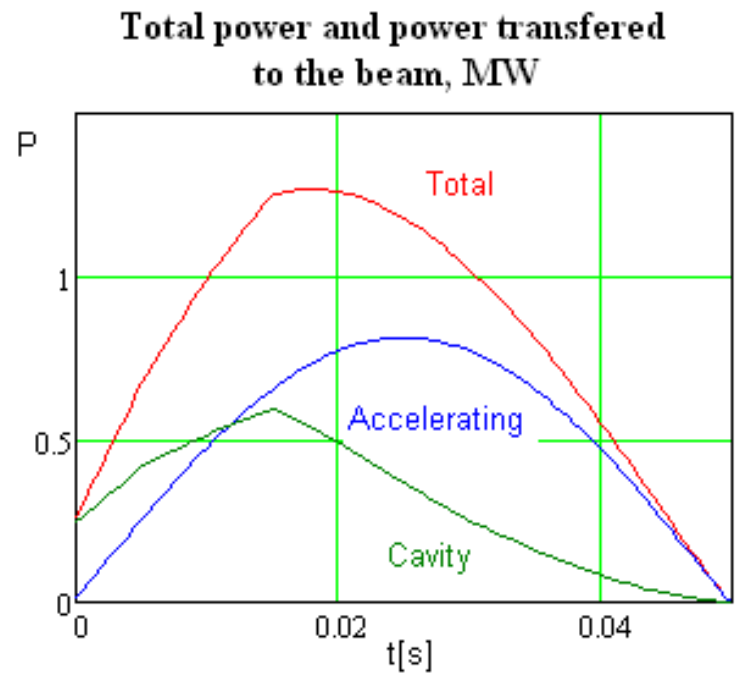
Beam envelopes for quarter of the ring;
ε_n=40 mm mrad (E_k = 2 GeV), $\Delta p/p = 5\cdot10^{-3}$

Beam acceleration









Transverse Instabilities and their damping

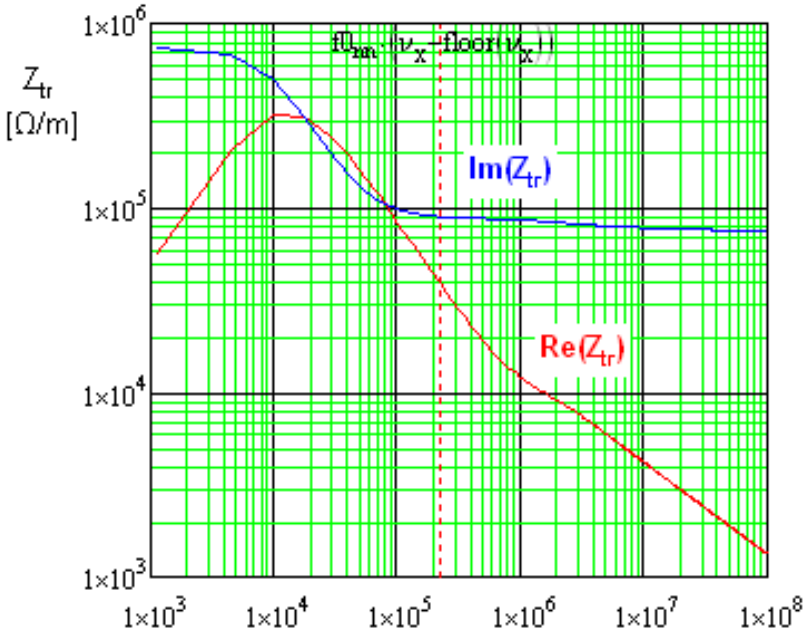
- Eddy currents in vacuum chamber excite magnetic field correction
  - Eddy current reflection in the steel of dipoles increases the correction and makes it non-linear even in round vacuum chamber

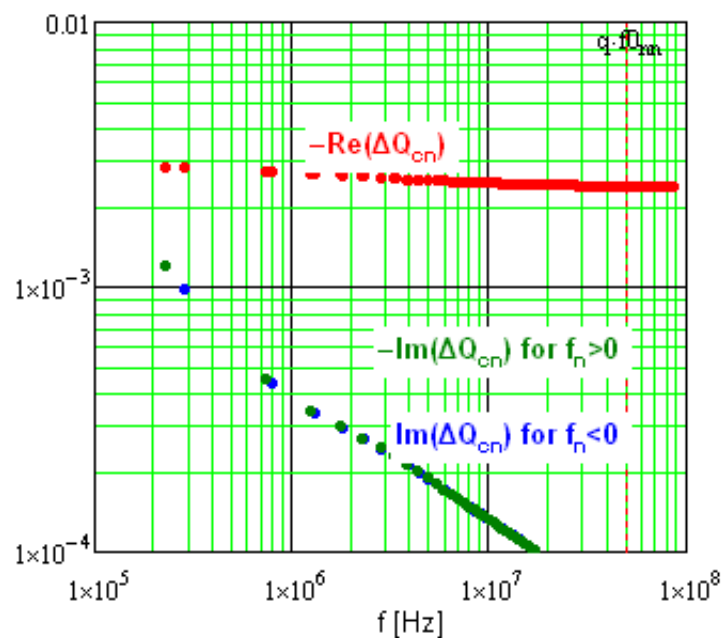
$$\frac{\Delta B_y}{B_0} = i\left(1+\frac{\pi^2}{12}+\frac{\pi^4}{240}\frac{y^2}{a^2}+\ldots\right)\frac{ad}{\delta_r^{\,2}}, \quad \delta_r = \frac{c}{\sqrt{2\pi\sigma\omega_{ramp}}}$$

  - That requires minimum σd for the wall
- Transverse impedance for the lowest mode is also determined by σd

$$\mathrm{Re}(Z_\perp) = Z_0\frac{c^2}{4\pi^2\sigma_R\omega a^3 d}, \quad \sqrt{ad} \ge \delta \ge d$$

- Instability will be stabilized by ⊥ dampers (low frequencies) and by chromaticity (high frequencies)



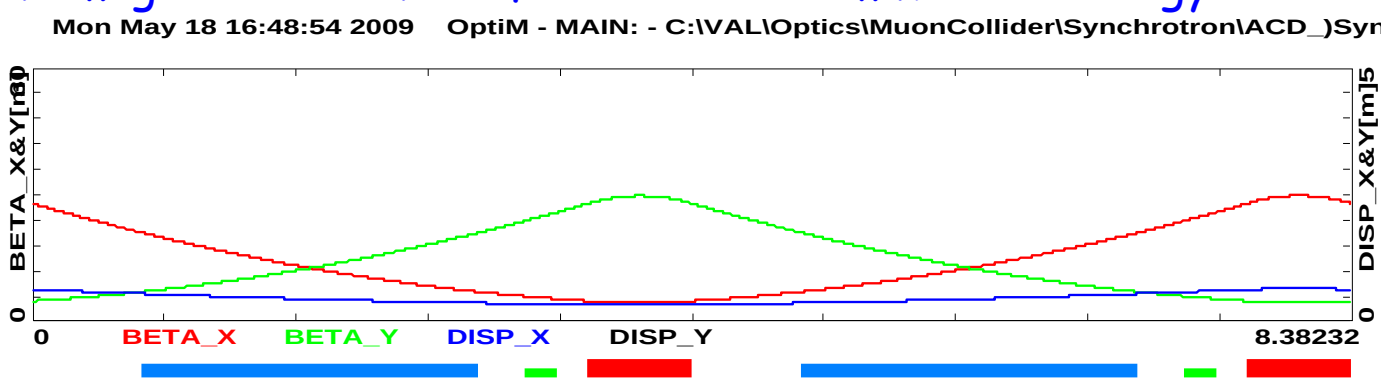


Structure of periodicity element

Name	S[cm]	L[cm]	B[kG]	G[kG/cm]	S[kG/cm/cm]
qF	65.9	65.9	0	2.141	0
o2	85.9	20			
sF	105.9	20	0	0	0.22*
o1	135.9	30			
bD	349.116	213.216	10.7123	0	0
o	419.116	70			
qD	485.016	65.9	0	-2.134	0
o2	505.016	20			
sD	525.016	20	0	0	-0.38*
o1	555.016	30			
bD	768.232	213.216	10.7123	0	0
o	838.232	70			

*Sextupole strengths nullify natural chromaticities: ν_x = -25 and ν_y=-25

Strength of the magnets are shown for 10 GeV beam kinetic energy

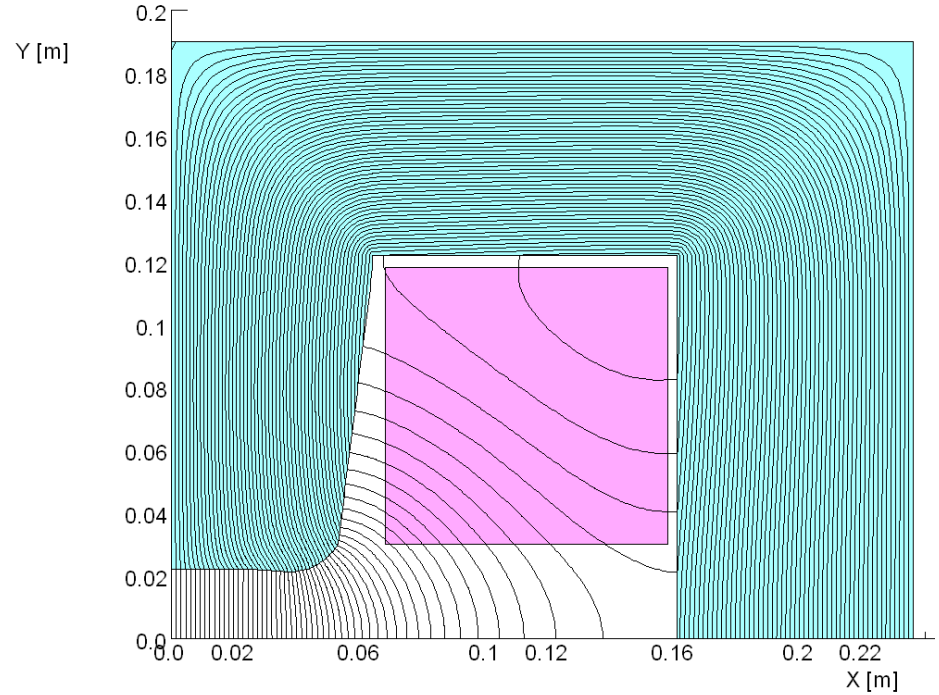


Dipole parameters†

Parameter	Unit	Value
Field at 8 GeV (672 A)	T	0.874
Field at injection (211 A)	T	0.274
Magnet gap	mm	44
Good field area diameter	mm	40
Field homogeneity		0.02 %
Effective length	m	2.13
Current frequency	Hz	10
Number of turns/pole		24
Copper conductor	mmxmm	15x20.2
Conductor cooling hole ∅	mm	10
Lamination material		M17
Lamination thickness	mm	0.35
Inductance	mH	24
DC resistance	mΩ	21
Stored energy	kJ	5.4
Power losses (no eddy cur.)	kW	4
Peak voltage	V	530
Cooling circuits/magnet		1
Water pressure drop	Mpa	0.5
Water flow	*l* / min	5
Water temperature rise	C°	12

†V.Kashikhin

Dipoles and vacuum chamber



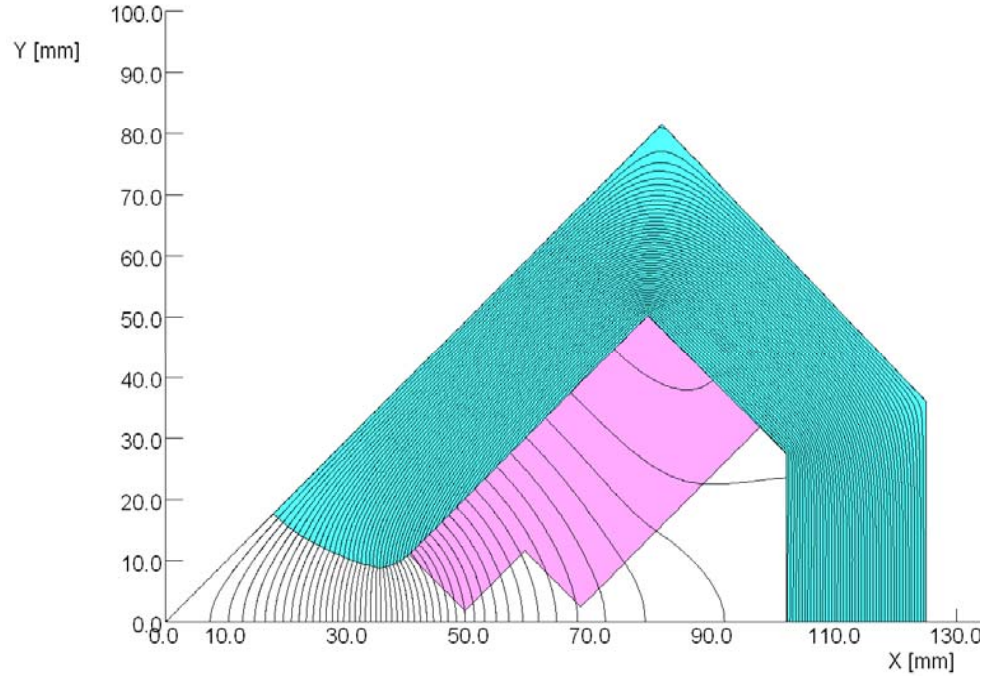
Magnet geometry and flux lines at 1kA current.

- 100 Rectangular dipoles
- Round vacuum chamber (bend in dipoles, R=34 m)
  - Stainless steel - 0.7 mm
  - External diameter - 44mm
  - Sagitta – 1.67 cm
  - Eddy currents
    - $\Delta B/B$ - $i \cdot 1.4 \cdot 10^{-3}$
    - Power loss(B_m=8 GeV)-11W/m

Quadrupole parameters

Parameter	Unit	Value
Gradient at 8 GeV (672 A)	T/cm	0.1743
Gradient at inj. (211 A)	T/cm	0.0546
Pole tip radius	mm	25
Good field area diameter	mm	40
Field homogeneity		0.03 %
Effective length	m	0.659
Current frequency	Hz	10
Number of turns/pole		7
Copper conductor	mmxmm	10x10
Conductor cooling hole ∅	mm	5
Lamination material		M17
Lamination thickness	mm	0.35
Inductance	mH	1.15
DC resistance	mΩ	12
Stored energy	J	260
Water pressure drop	Mpa	1.9
Water flow	l/min	0.5
Water temperature rise	C°	16

Quadrupoles



Quad geometry and flux lines at 1kA current.

- 134 Quadrupoles
- Eddy currents in vacuum chamber
  - $\Delta G/G$ - $\sim i \cdot 5 \cdot 10^{-4}$ (half of the skin correction in dipoles)

Dipole resonance circuit

- Resonance circuit is similar to the Booster one
  - One choke and one capacitor per cell (2 dipoles and 2 quads)
- Following simple relations determine the circuit parameters
  - Resonant frequency

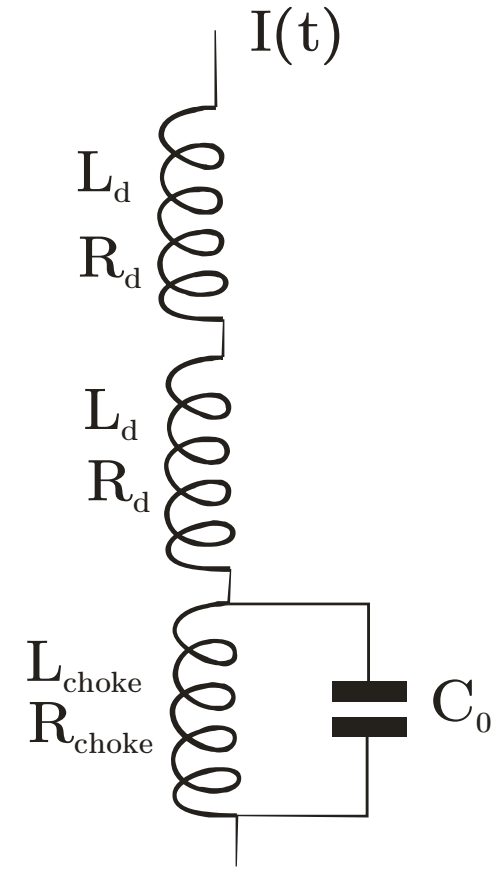
$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{C_0}\left(\frac{1}{2L_d}+\frac{1}{L_{choke}}\right)}$$

  - Circuit impedance in vicinity of resonance

$$Z(\delta f) = 2R_d + R_{choke}\left(\frac{2L_d}{L_{choke}}\right)^2 + 8\pi i L_d\left(1+\frac{2L_d}{L_{choke}}\right)\delta f$$

$2L_d$ and $2R_d$ are the total inductance and resistance of two dipoles and 2 quads

- Increase of L_{choke} results in
  - decrease of the impedance resistive part
  - reduction of its dependence on frequency
  - decrease of capacitance value
  - But it also increases resistance and price of the chokes



L_d = 25 mH, R_d = 33 mΩ
L_{choke}=32mH, R_{choke}=12 mΩ
C_0 = 13 mF
Capacitor volt.- V_C =725 V
Power supply(quads &dip.)
Total power - 900 kW
Total DC – 1.2 kV
Total AC (ampl) – 1.1 kV

Corrector packs

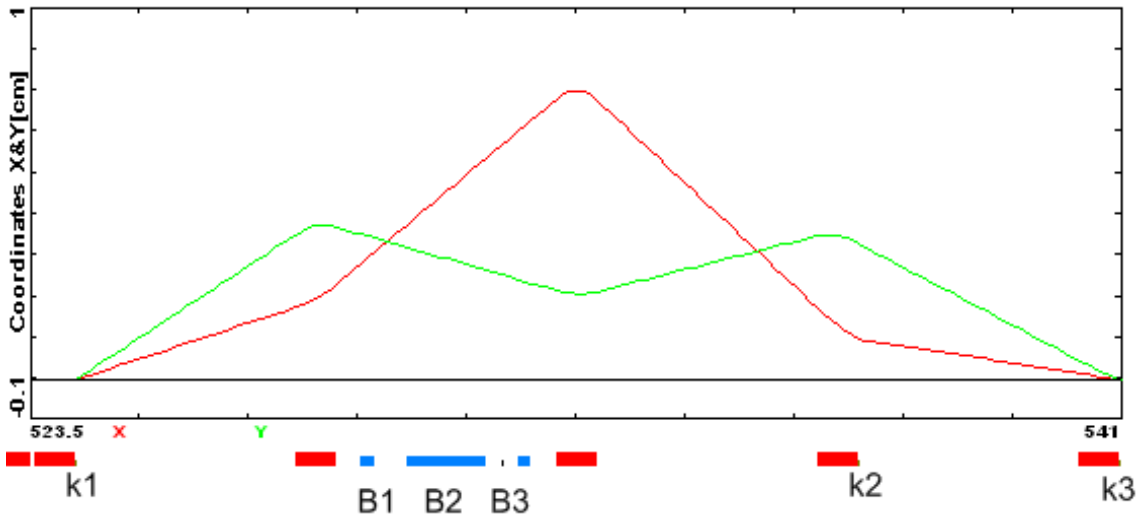
- For estimates we use the effective length of 15 cm
- Total number of packs is equal to 134 (number of quads)
- Dipole corrections (total 134)
  - Horizontal near F quads and vertical ones near D quads
  - Maximum field integral is 9 kG cm (equal to quad displacement of 0.8 mm, and 0.5% of field of the dipole)
    - Maximum field - 600 G
- Quadrupole corrections
  - Maximum field integral 3 kG (2% of quad field)
    - Maximum field at r=2.2 cm - 440 G
  - 32 have independent power supplies (6 near each dispersion suppressor and 4 in the center of each arc)
  - The rest are split into 2 groups (F and D) with 56 quads in each
- Sextupole corrections
  - Two groups of 50 correctors
  - at maximum energy they compensate half of natural chromaticity
  - Maximum strength – 3.8 kG/cm
    - Maximum field at r=2.2 cm – 600 G

Injection

- Strip H^- injection: in a straight line, horizontally (radially outside)
- 3 quads in the injection region have increased aperture
  - 12 turns per pole (instead of 6)
  - a = 33.2 mm (instead of 23.48 mm)
- 3 injection dipoles in one straight section
  - B1 – DC septum, B2 and B3 - permanent magnets or powered by DC
- 3 fast correctors for x-y painting in each plane

Injection cell structure

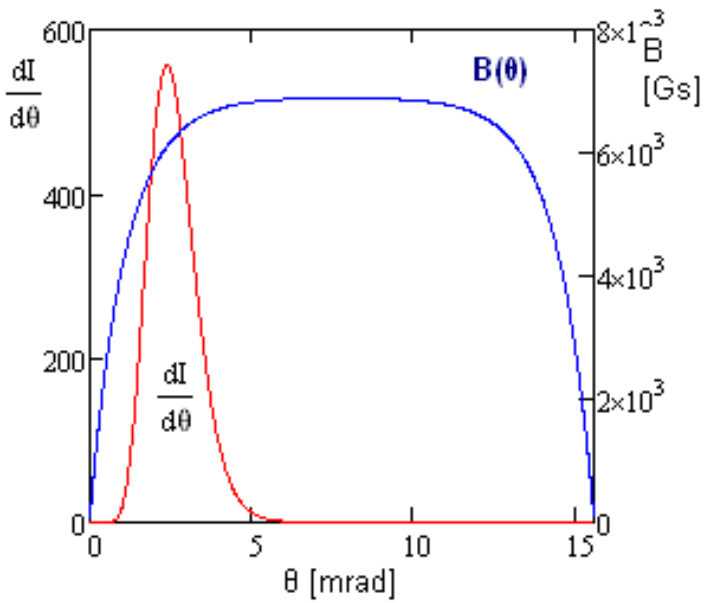
Name	L[cm]	B[kG]	G[kG/cm]
qD	65.9	0	-1.74
oInj	40		
B1	21	-6.9	
oInj1	52.608		
B2	126	2.3	
oInj2	26.304		
iFOIL	0		
oInj2	26.304		
B3	21	-6.9	
oInj	40		
qF	65.9	0	1.74

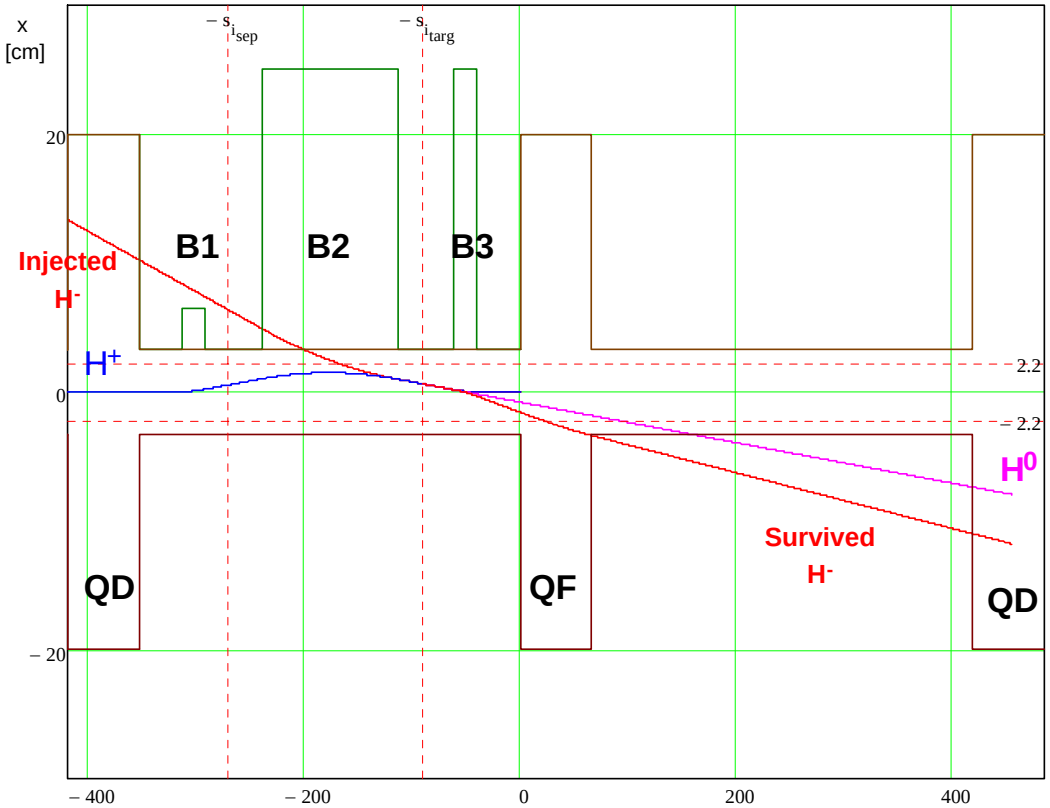


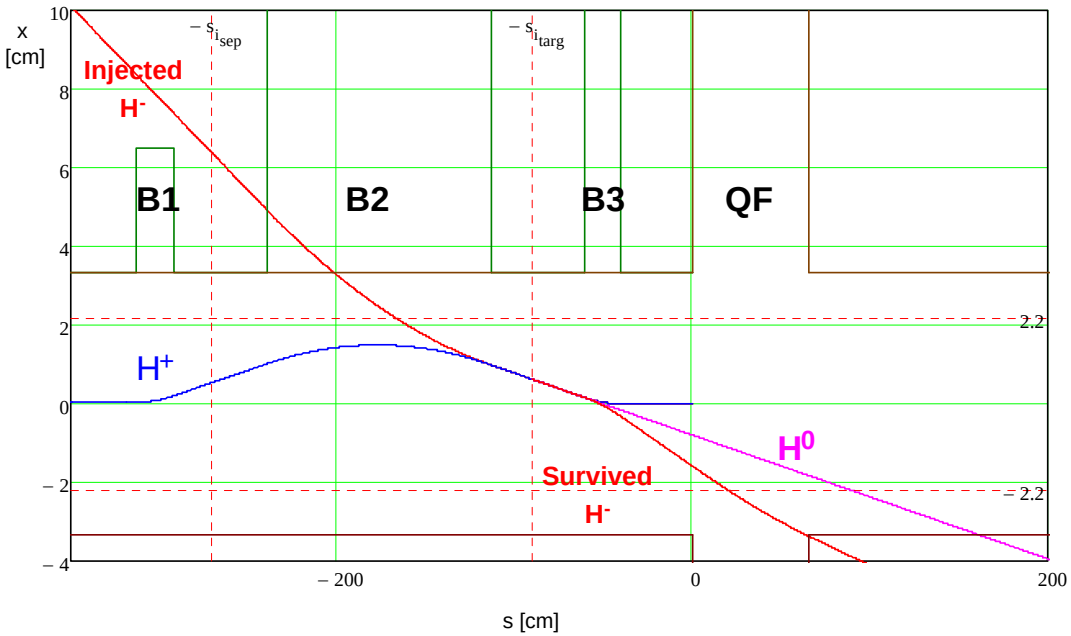
Local orbit bump for painting;
Maximum corrector strength – 15 kG cm
Swiping time – 4 ms

Injection (continue)

- Total power of injected beam
  - 75 kW for 60 GeV MI operation
  - 37 kW for 120 GeV MI operat.
- H^- field stripping limits B2 field
  - Stripping probability is $4 \cdot 10^{-5}$
- B3 strips H- which missed foil
  - Survival probability ~10^{-17}
  - Average deflection before stripping - 3 mrad

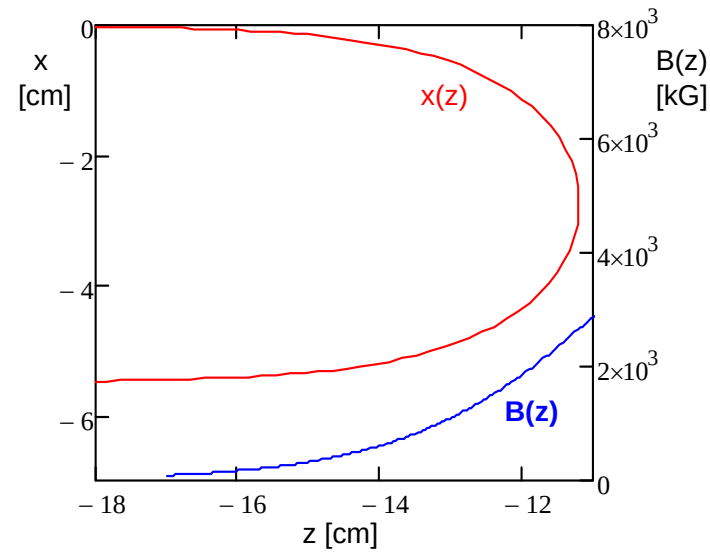






Injection (continue)

- Single and multiple scattering in the foil (thickness - 450 $\mu g/cm^2$)
  - Emittance increase due to multiple scattering is not a problem
    - Emittance increase per foil crossing:
      $\Delta\varepsilon_{xn95\%} = 8.5\cdot10^{-3}$ mm mrad; $\Delta\varepsilon_{yn95\%} = 3.3\cdot10^{-3}$ mm mrad
      $\Rightarrow$ for expected 50 crossings per particle $\Delta\varepsilon_{n95\%} < 0.5$ mm mrad
  - Particle loss due to single scattering
    - For 40 mm mrad acceptance the loss has approximately equal contributions from nuclear and electromagnetic scatterings ($\sigma_{em} \approx 200$ mbarn, $\sigma_n \approx 340$ mbarn)
      $\Rightarrow$ beam loss - $1.4\cdot10^{-5}$ per foil crossing
    - With expected 50 crossings per particle
      $\Rightarrow$ Total loss ~0.07% or 200 W for 300 kW operation



- Injection beam dump is located after QF. It will intercept particles scattered in the foil and H^0.
  - It has to be rated to 3 kW
- Stripped electrons are reflected from field of B3 dipole and intercepted by electron beam dump (located radially inside)
  - Total power – 300 W for 300 kW operation

Injection Magnets

Extraction

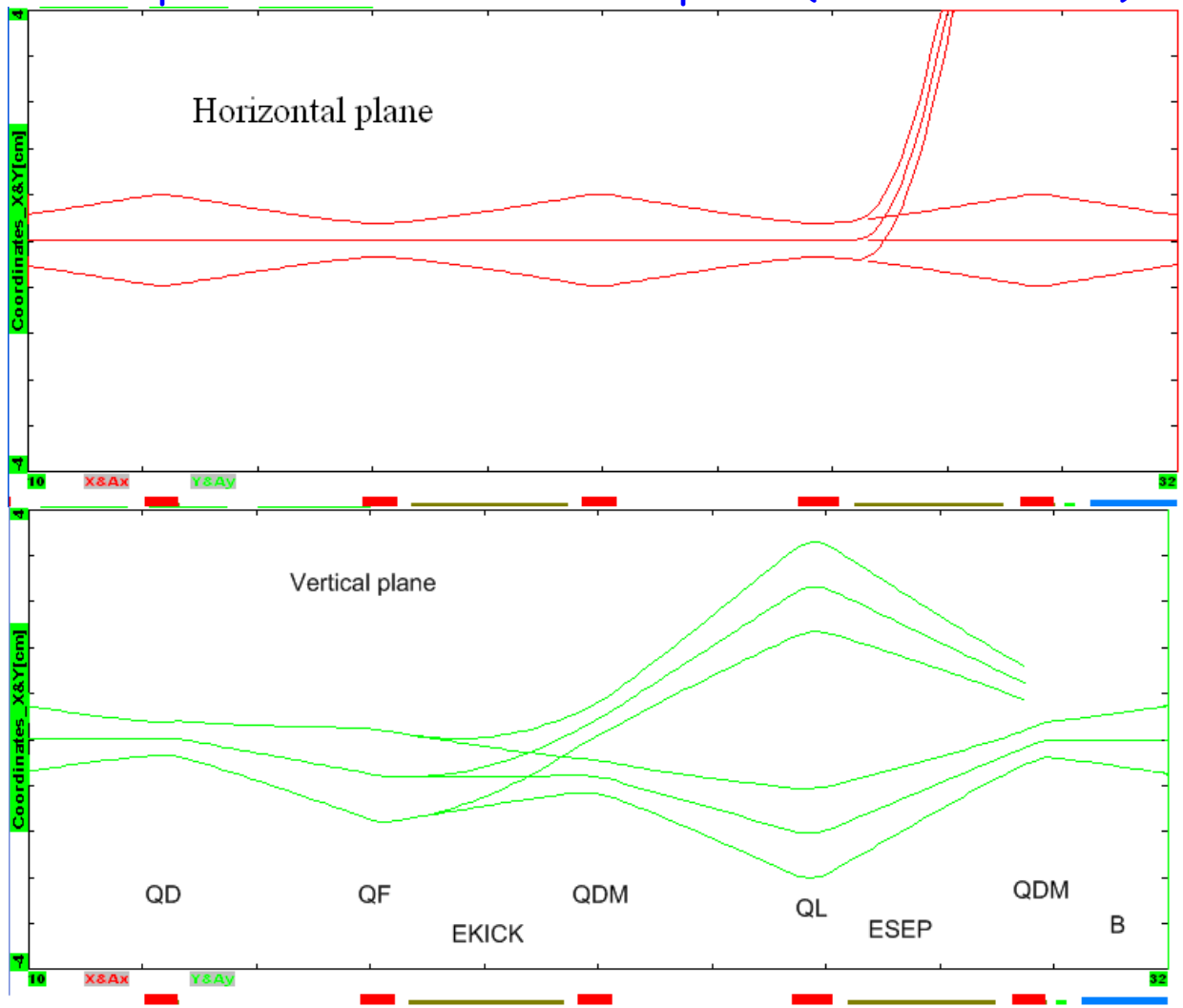
Extraction structure

Name	L[cm]	B[kG]	G[kG/cm]
qF	65.9	0	1.746
ky1e	1e-06	-4.89e+7	
oS	353.216		
ky2e	1e-06	-2.25e+7	
qD	65.9	0	-1.740
oEKICK	26.608		
kEKICK	300	0.448 0	
oEKICK	26.608		
qF	65.9	0	1.746
oQL	346.4		
qL	79.39	0	-1.457
oSep	30.73		
kESEP	285	7.75	
oSep	30.7336		
qF	65.9	0	1.74
ky3e	1e-06	-9.90e+7	

- QL has increased aperture and length and decreased gradient (a = 40 mm)

QDMs are the same as injection quads with increased aperture (a = 33.2 mm)

- Vertical kick
- Vertical orbit bump of 16 mm at septum location with normal machine correctors
- Septum kicks in horizontal plane (width – 10 mm)



Extraction Magnets

RF cavities

Vacuum System

Instrumentation and Feedback systems

- DCCT
- Toroid for AC beam current measurements
- Resistive wall monitor
- BPMs (should be able to operate at 0.1% intensity)
  - x near each F quad,
  - y – near D quad
  - 134 BPMs altogether
- Viewers and pickups for injection tuning
- Additional H&V pickups for beam dynamics studies
- Horizontal and vertical IPMs
  - H&V in a straight line
  - H in a non-zero dispersion (missed dipole)
- Horizontal and vertical flying wires in a straight line
  - H&V in a straight line
  - H in a non-zero dispersion (missed dipole)
- Horizontal and vertical bunch-by-bunch dampers
- Longitudinal bunch-by-bunch damper

Questions to be clarified for synchrotron

- Location on FNAL site
- RF cavities
- Dipoles and quads for extraction and injection
- Discrepancy between fields of dipoles and quadrupoles
- Costing