# 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 $\mu$-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 $\mu$-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
    - $\beta$ = 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
- $\mu$-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

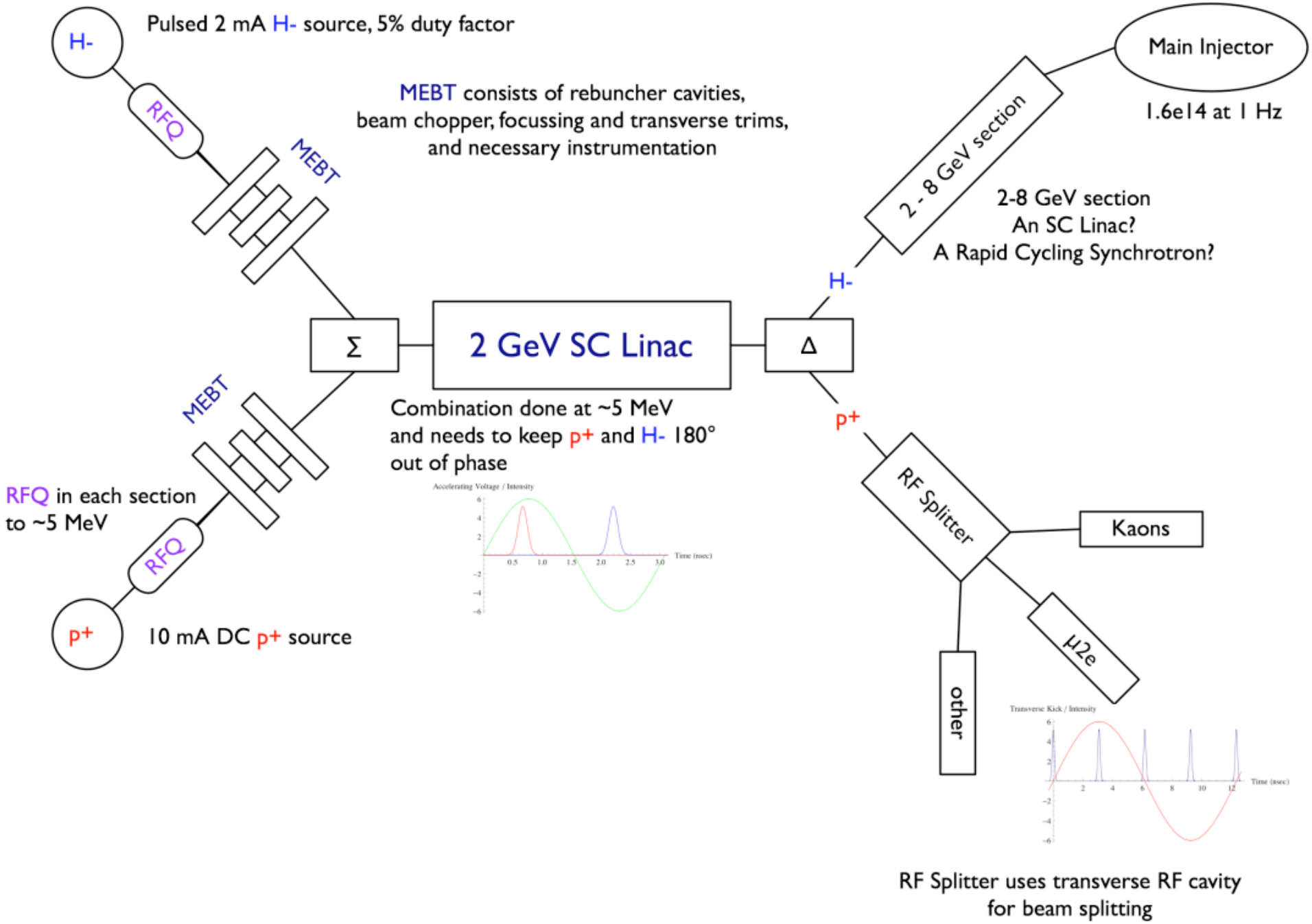
# Conclusions

- 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 $\mu$-to-e

# General machine layout



# Technical details of CW linac

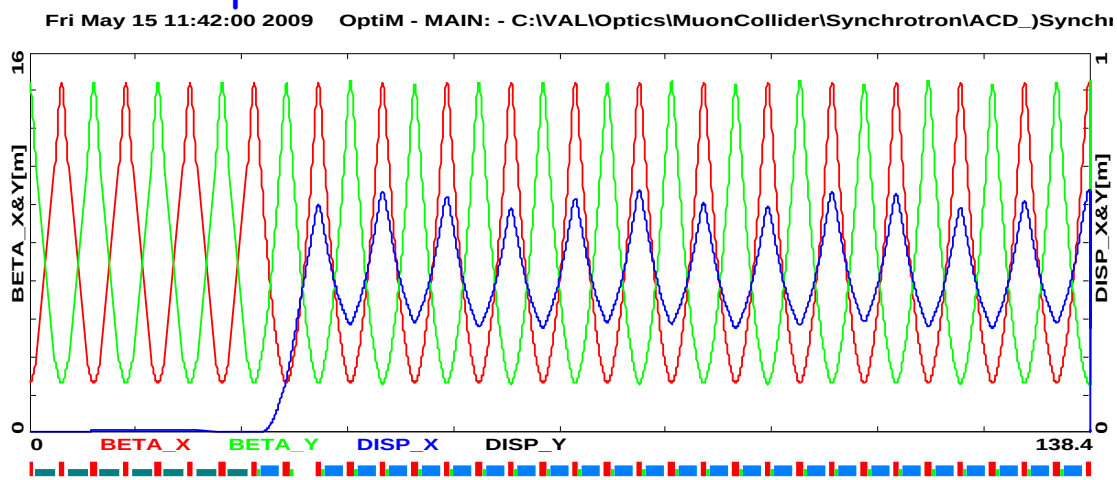
- Length and accelerating gradient
  - 18 MV/m is what CEBAF uses for upgrade
    - We stay with 15 MV/m
  - Length is increased by 1.7 times
- Very rough cost estimate of cost increase for 2 GeV case
  - 500M$ * (2/8) * (1.7-1) = 90M$ (half of this for 1 GeV machine)
  - For now it looks as a conservative 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

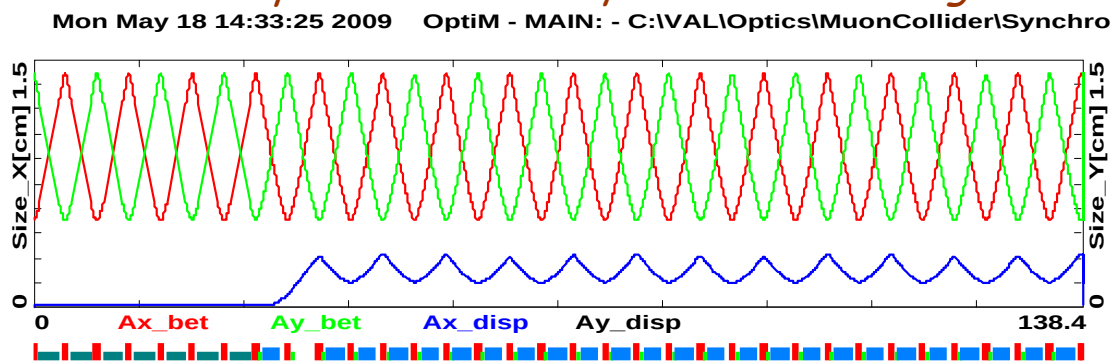
| | |
|---|---|
| Energy, min/max, GeV | 2/8 |
| Repetition rate, Hz | 10 |
| Circumference, m (MI/6) | 553.2 |
| Tunes | 18.44 |
| Transition energy, GeV | 13.36 |
| Number of particles | 2.67E13 |
| Beam current at injection, A | 2.2 |
| Harmonic number | 98 |
| RF frequency, MHz | 50.33 – 52.81 |
| Maximum RF voltage, MV | 1.9 |
| 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 | 0.4 |
| Number of RF cavities | 16 |
| 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

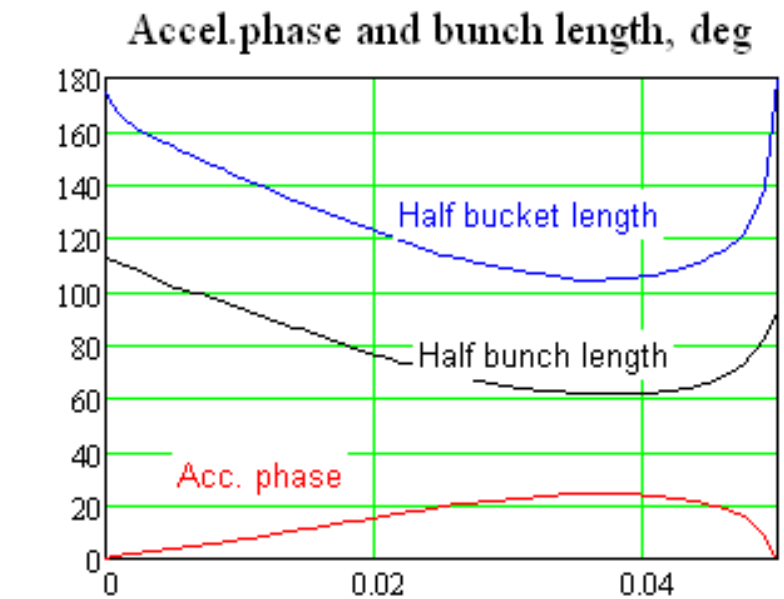


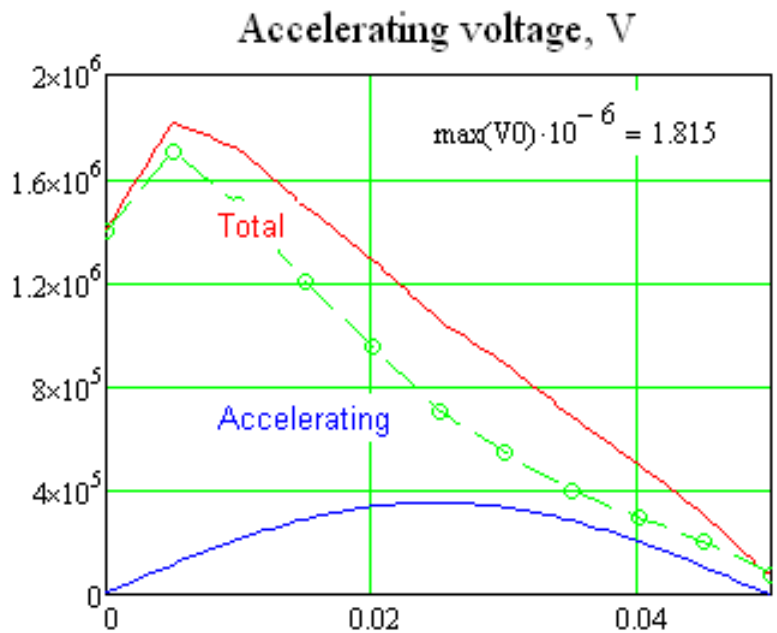

*Twiss parameters for quarter of the ring*

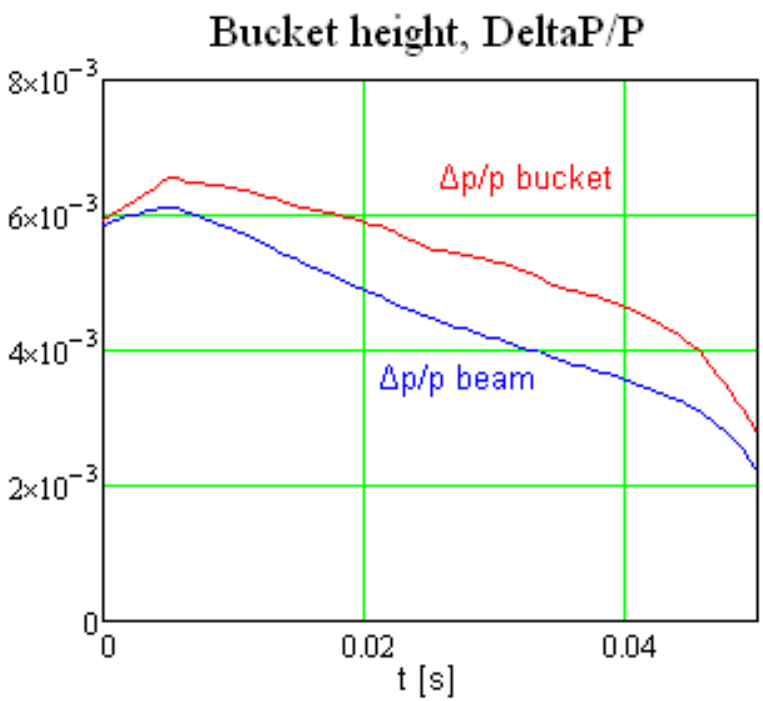


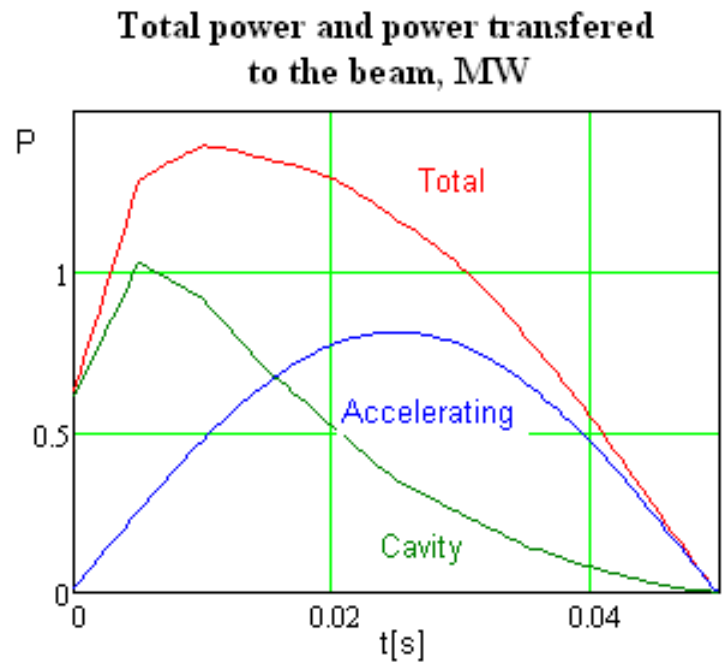

*Beam envelopes for quarter of the ring;*
*$\varepsilon_n$=40 mm mrad ($E_k$ = 2 GeV), $\Delta p/p = 5\cdot10^{-3}$*

# Beam acceleration



# Transverse Instabilities and their damping

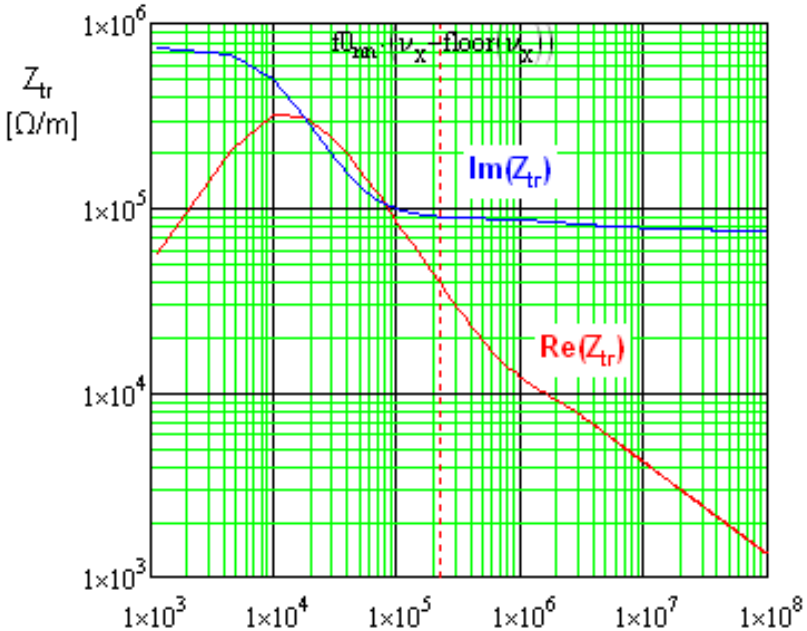
- Eddy currents in vacuum chamber excite magnetic field correction
  - Eddy current reflection in the steel of dipoles increases the correction and makes it non-linear even in round vacuum chamber

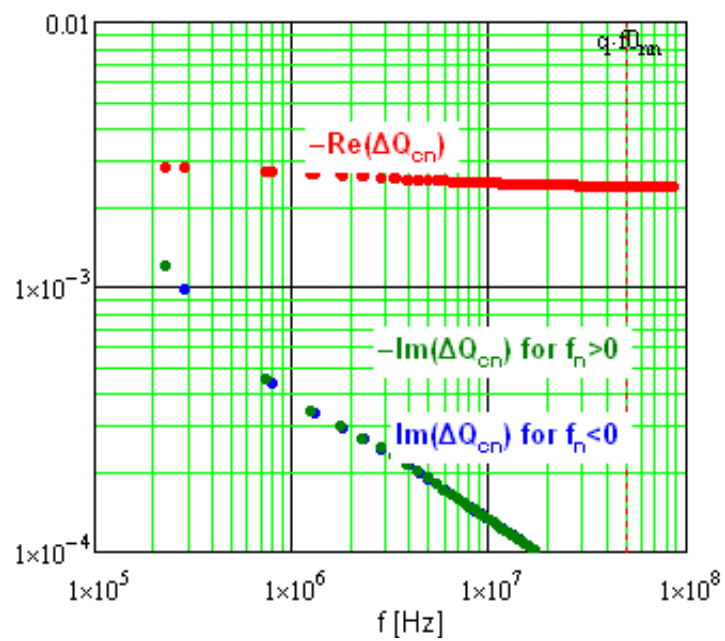
$$\frac{\Delta B_y}{B_0} = i\left(1+\frac{\pi^2}{12}+\frac{\pi^4}{240}\frac{y^2}{a^2}+\ldots\right)\frac{ad}{\delta_r^{\,2}}, \quad \delta_r = \frac{c}{\sqrt{2\pi\sigma\omega_{ramp}}}$$

  - That requires minimum $\sigma d$ for the wall
- Transverse impedance for the lowest mode is also determined by $\sigma d$

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

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



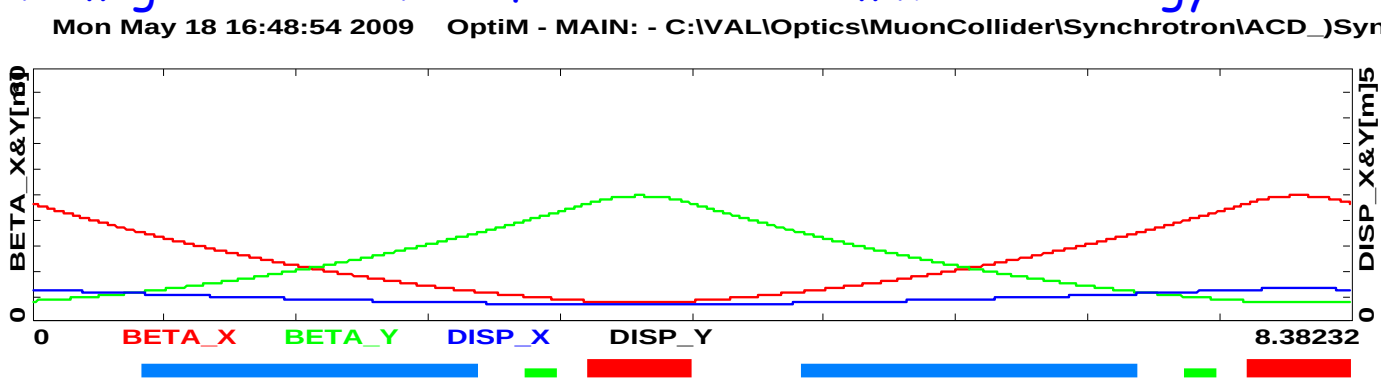



# Structure of periodicity element

| 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: $\nu_x$ = -25 and $\nu_y$=-25

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

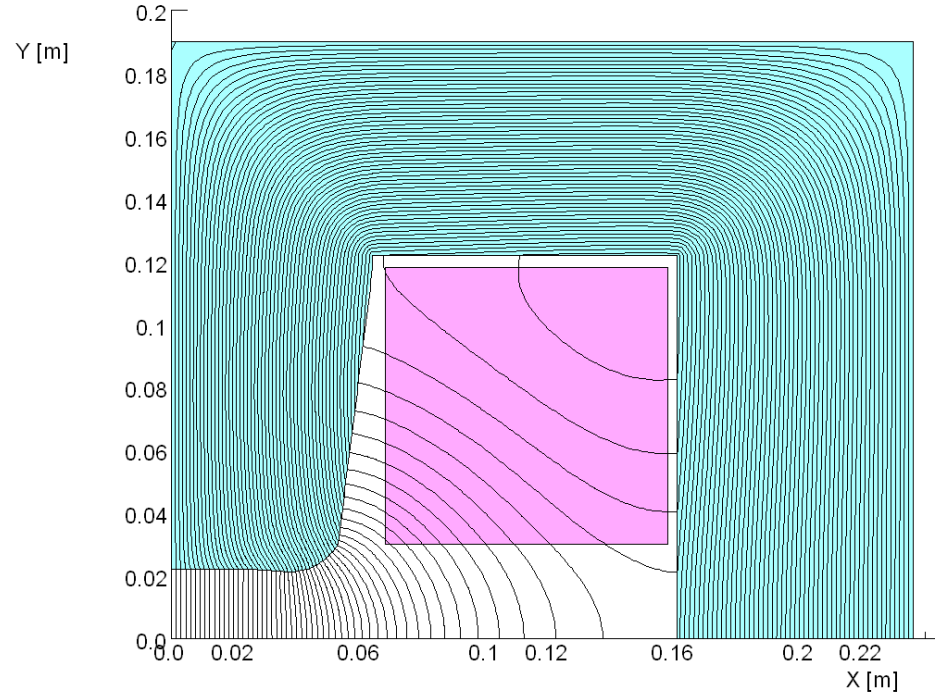


# Dipole parameters†

| 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



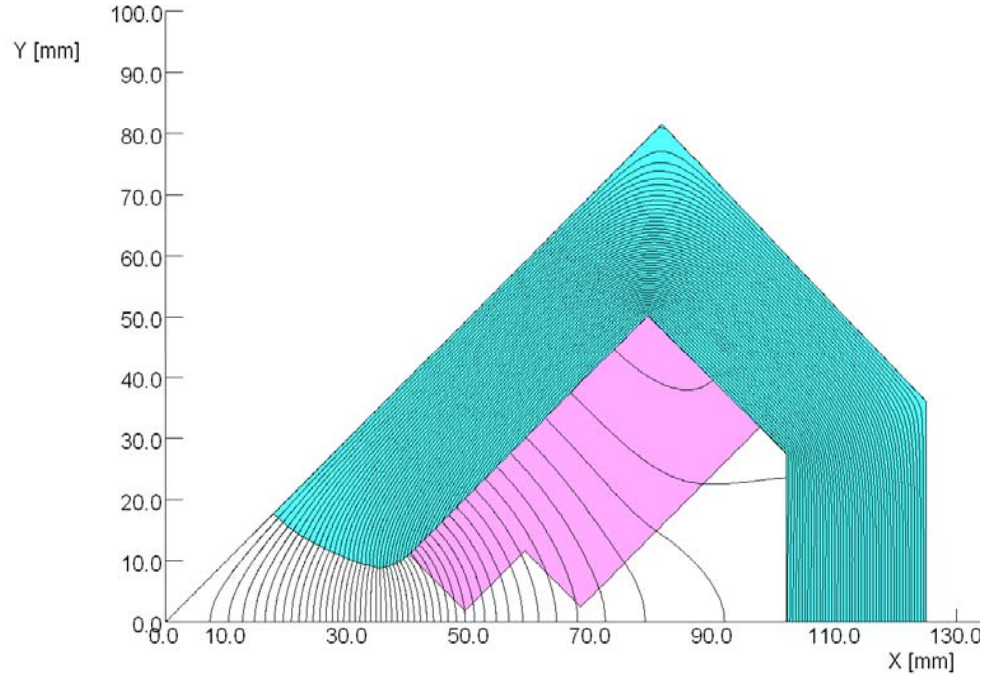

*Magnet geometry and flux lines at 1kA current.*

- 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

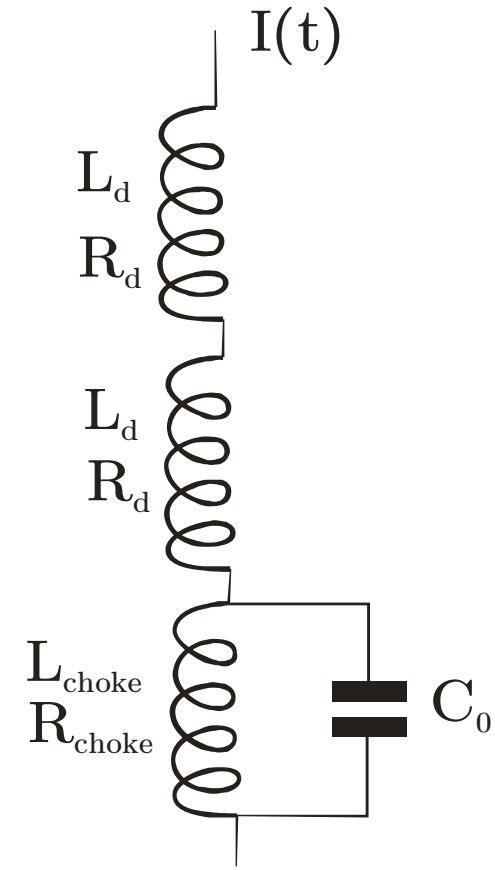
$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{C_0}\left(\frac{1}{2L_d}+\frac{1}{L_{choke}}\right)}$$

  - 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

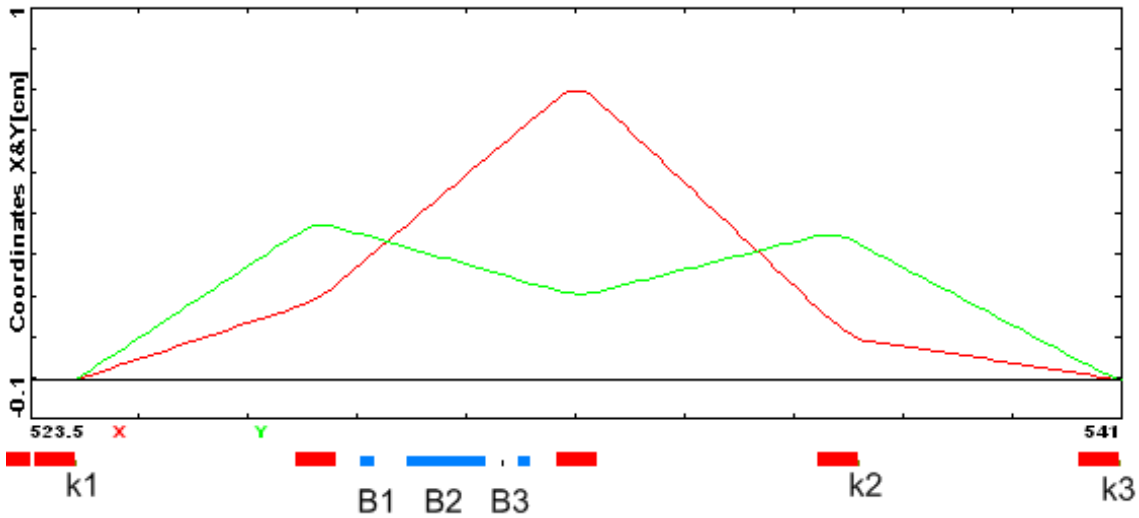
- For estimates we use the effective length of 15 cm
- Total number of packs is equal to 134 (number of quads)
- Dipole corrections (total 134)
  - Horizontal near F quads and vertical ones near D quads
  - Maximum field integral is 9 kG cm (equal to quad displacement of 0.8 mm, and 0.5% of field of 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

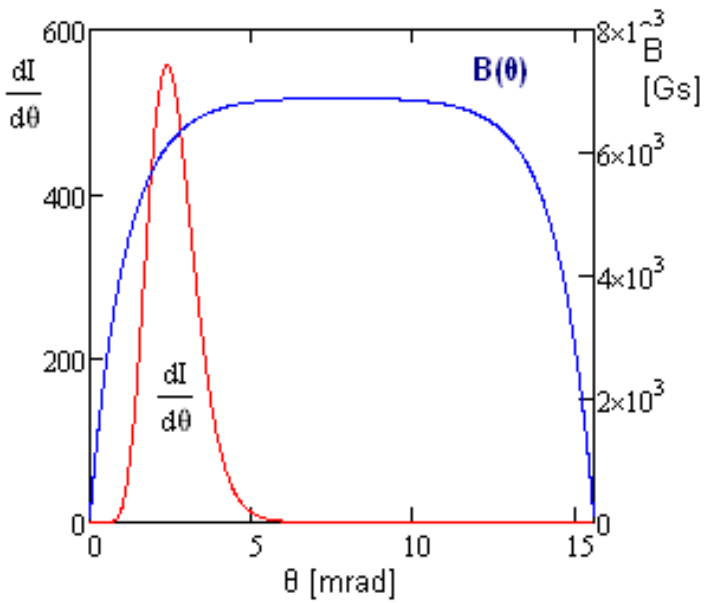
| Name | L[cm] | B[kG] | G[kG/cm] |
|---|---|---|---|
| qD | 65.9 | 0 | -1.74 |
| oInj | 40 | | |
| B1 | 21 | -6.9 | |
| oInj1 | 52.608 | | |
| B2 | 126 | 2.3 | |
| oInj2 | 26.304 | | |
| iFOIL | 0 | | |
| oInj2 | 26.304 | | |
| B3 | 21 | -6.9 | |
| oInj | 40 | | |
| qF | 65.9 | 0 | 1.74 |

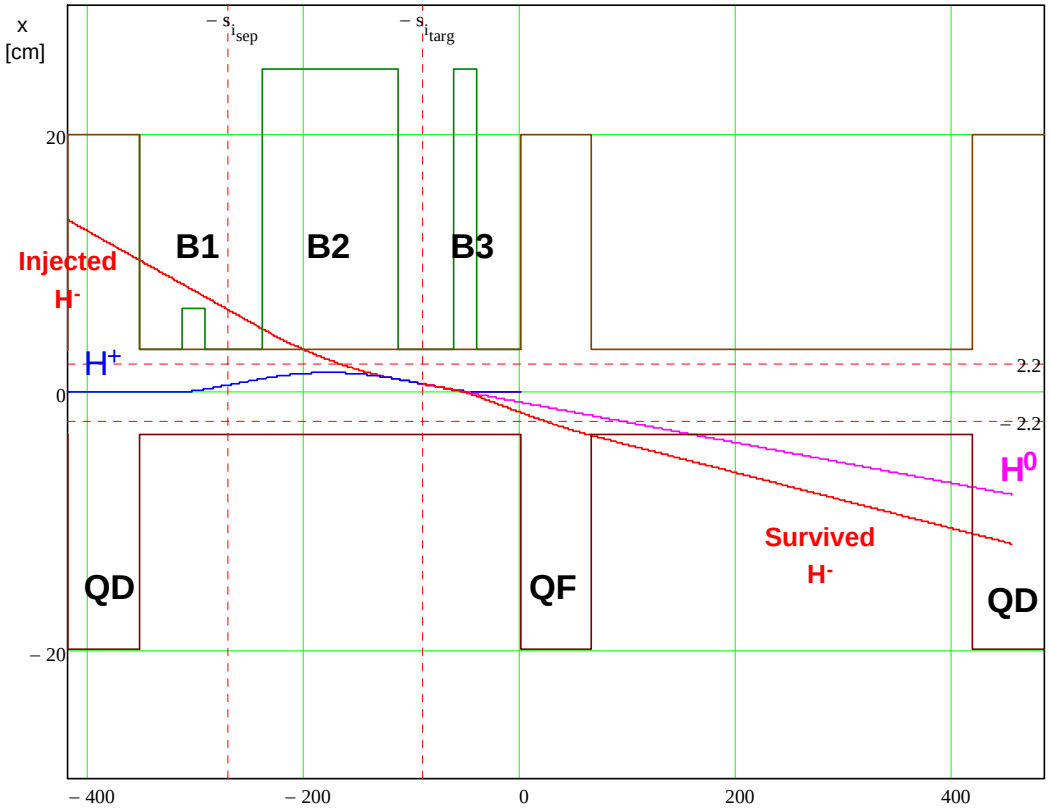


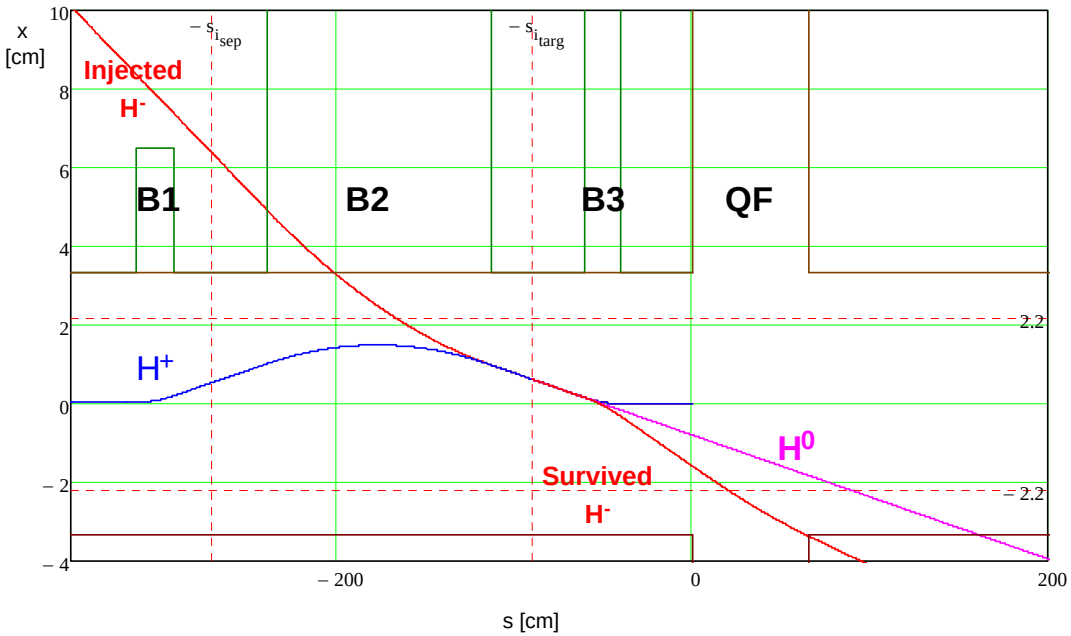

Local orbit bump for painting;
Maximum corrector strength – 15 kG cm
Swiping time – 4 ms

# 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

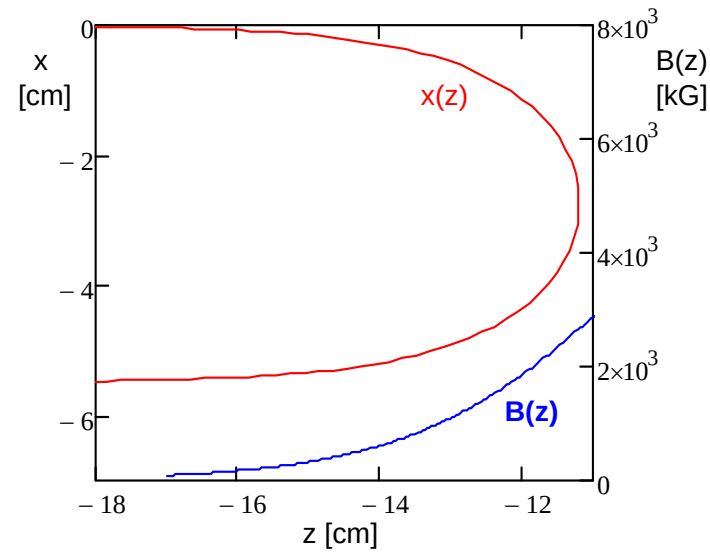


# Injection (continue)

- 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

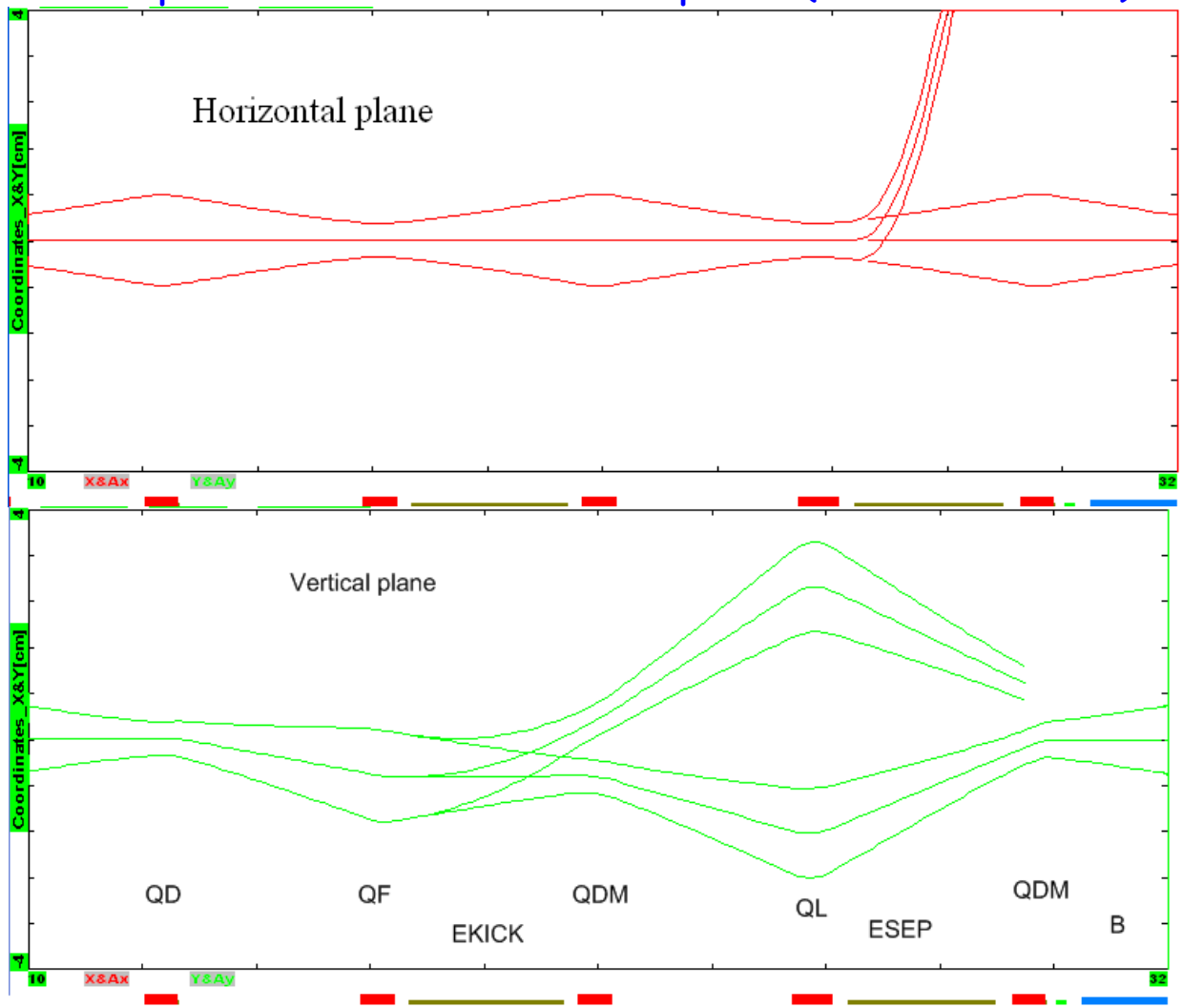
## Extraction structure

| 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

- To minimize beam space charge effects at injection there is additional RF system operating at second harmonic (h=196)
  - Its maximum voltage is 700 kV (half voltage of main RF system at injection)
- Space available for cavities – 14 sections of 3 m long (3.53 m between cores of quadrupoles)

# 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
- Beam loss monitors
- Instrumentation for injection region

## 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