RCS for Project-X

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Fermilab

Design Priorities and Limitations

- Support 2 MW MI operation
  - 2 GeV -> 8 GeV, 2.2 A beam current
- Strip injection
  - Minimum possible injection current
    - 1 mA corresponds to 2 MW installed linac RF
- Do not reproduce Booster problems/limitations
  - Synchro-betatron resonance
    => zero dispersion in cavities
  - Large impedance
    => no laminations seen by the beam
  - No transition crossing
    => operate below transition
    strong focusing => small beam size
- Simple, reliable and inexpensive machine
  - Same acceptance as for Recycler and MI
  - Circumference = 1/6 of MI

Main parameters of the RCS

Energy, min/max, GeV	2/8
Repetition rate, Hz	10
Circumference, m (MI/6)	553.2
Tunes	18.42/18.44
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,1st/2nd harm., MV	1.6/0.7
95% n. emittance, mm mrad	25
Space charge tune shift, inj.	0.06†
Norm. acceptance at inject., mm mrad	40
Injection time for 1 mA, ms	4.3
Linac energy cor. at inject. $\Delta E/E_{kin}$	1.2%
RF bucket size at inject., eV s	0.4
Number of RF cavities, 1st/2nd harm.	16/10
Cavity shunt impedance, kΩ	100

†For KV distribution and longitudinal bunching factor of 2.2

- Repetition rate is set by 60 GeV MI operation
  - 6 of 8 injections (0.8 s) go to MI
- Linac energy follows the RCS energy during 4.3 ms of injection time, $\Delta E/E_{kin}$=1.2%
- Painted KV-like ⊥ distr. reduces the space charge tune shift
- Dual harmonic RF reduces the beam density and improves its stability

Limitations on the Vacuum Chamber Choice

- Mechanical stability of the chamber

$$\sigma_{bend} = \frac{9}{4} P_{atm} \frac{\Delta a_w}{a_w}\left(\frac{a_w}{d_w}\right)^2 \qquad \Rightarrow \quad d_w \propto a_w$$

- Field correction due to eddy currents

$$\frac{\Delta B}{B} = i\left(1+\frac{\pi^2}{12}\right)\frac{4\pi^2 f_{ramp}}{c^2}\left(a_w d_w \sigma_w\right) \xrightarrow{\sigma_{bend}=const} \propto a_w{}^2 \sigma_w$$

- Transverse impedance

$$Z_\perp(\omega) = \frac{Z_0 c^2}{8\pi^3 f_0[\nu]}\left(\sigma_w a_w{}^3 d_w\right)^{-1} \xrightarrow{\sigma_{bend}=const} \propto \left(a_w{}^4 \sigma_w\right)^{-1}$$

- Vacuum chamber heating

$$\frac{dP}{dz} = \frac{4\pi^3 f_{ramp}{}^2 B_{AC}{}^2}{c^2}\left(\sigma_w a_w{}^3 d_w\right) \xrightarrow{\sigma_{bend}=const} \propto a_w{}^4 \sigma_w$$

- Last two limitations are the most critical ones

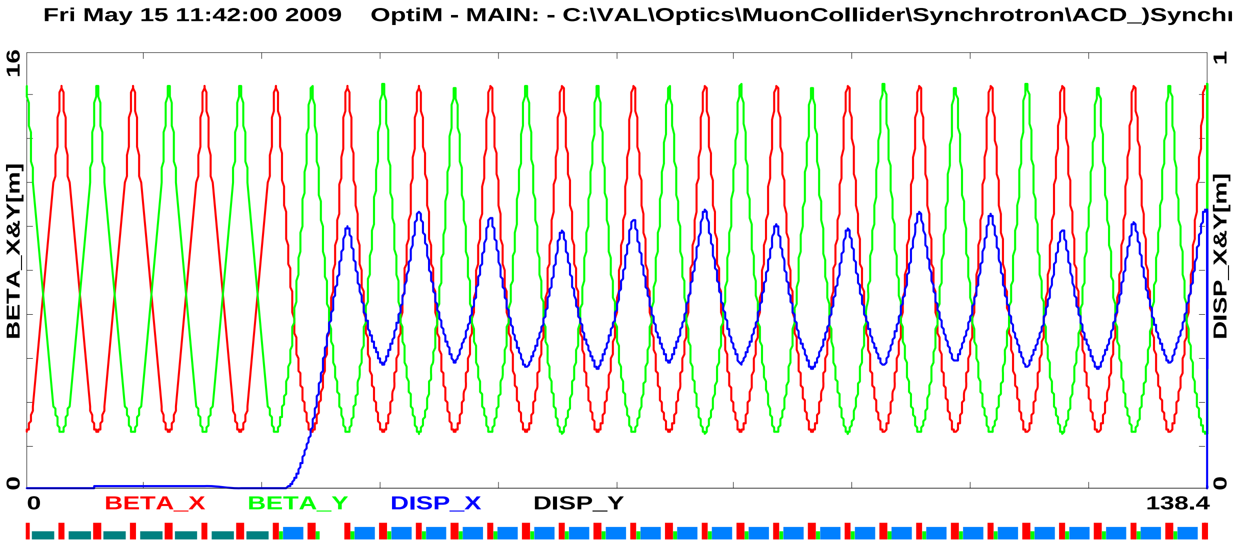
=> *i.e.* the limitation of vacuum chamber heating sets $Z_\perp$ and vice versa

$$Z_\perp(\omega)\frac{dP}{dz} = \frac{Z_0}{8\pi^2}\frac{\omega_{ramp}{}^2}{f_0[\nu]} B_{AC}{}^2$$

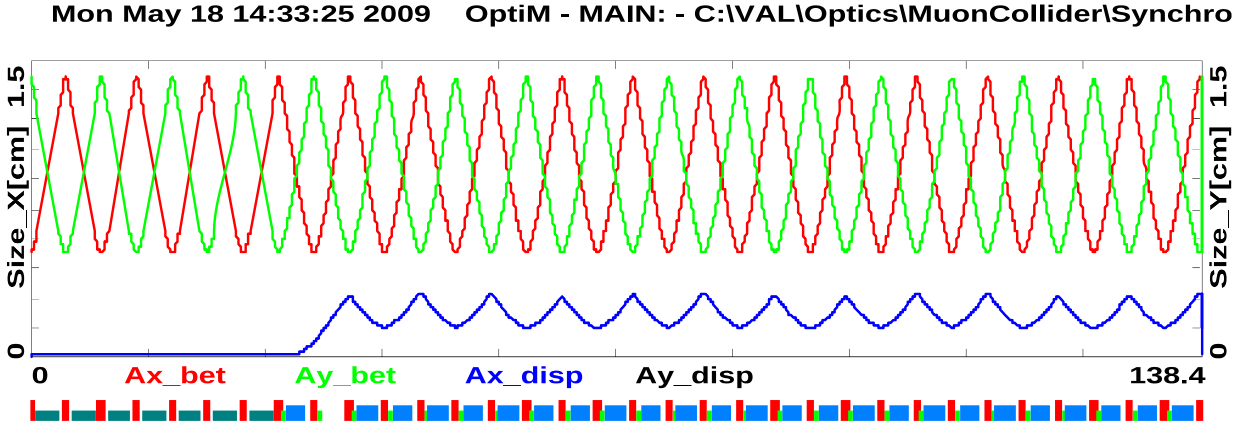
=> i.e. an increase of vacuum chamber radius does not reduce $Z_\perp$

RCS lattice

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



Twiss parameters for quarter of the ring



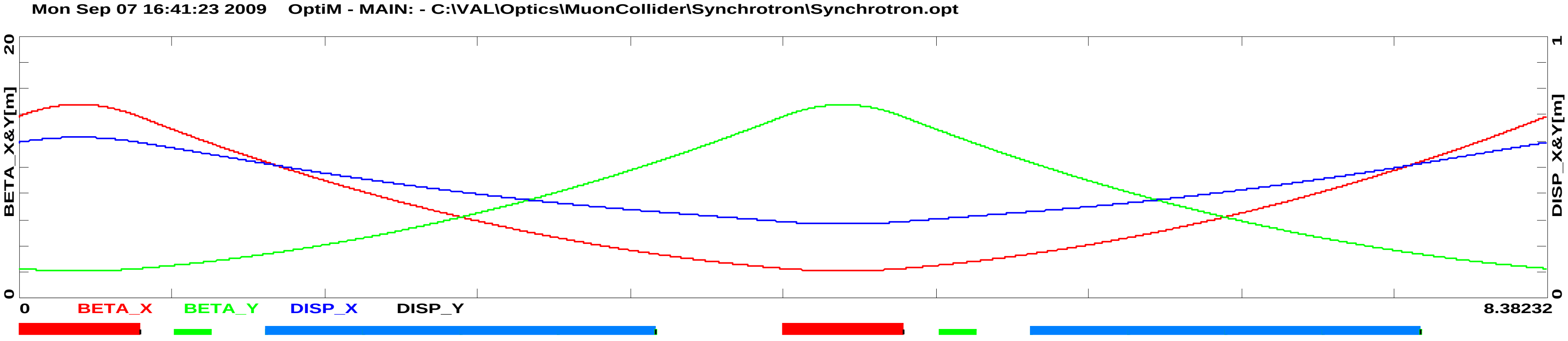
Beam envelopes for quarter of the ring;

ε_n=40 mm mrad (E_k = 2 GeV), $\Delta p/p = 5\cdot10^{-3}$

Structure of periodicity element

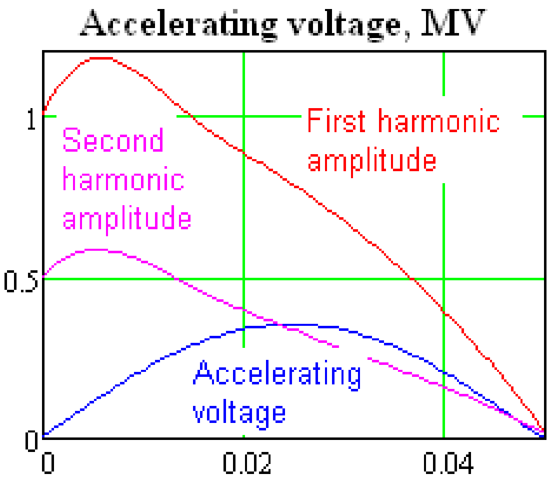
Name	S[cm]	L[cm]	B[kG]	G[kG/cm]	S[kG/cm^2]
qF	65.9	65.9	0	1.7463	0
o2	85.9	20			
sF	105.9	20	0	0	0.180
o1	135.9	30			
bD	349.116	213.216	8.7375	0	0
o	419.116	70			
qD	485.016	65.9	0	-1.7406	0
o2	505.016	20			
sD	525.016	20	0	0	-0.311
o1	555.016	30			
bD	768.232	213.216	8.7375	0	0
o	838.232	70			

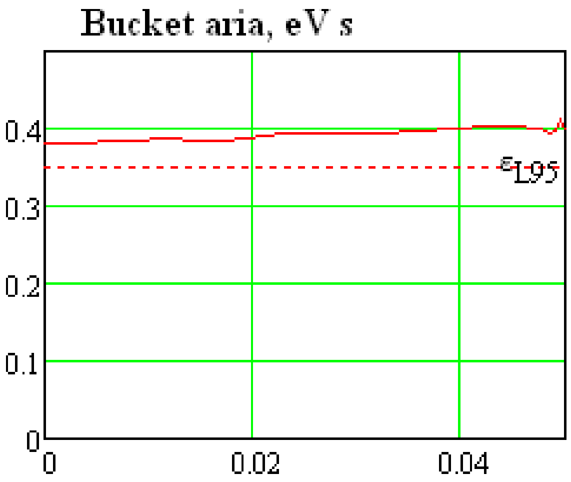
*Sextupole strengths nullify natural chromaticities: ν_x = -25 and ν_y=-25

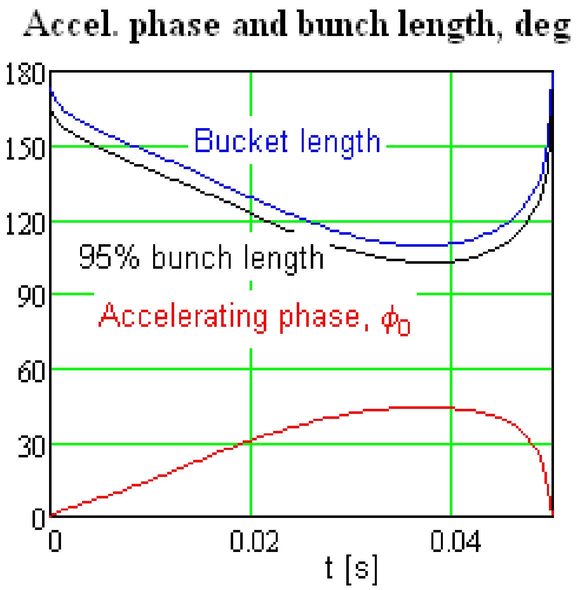


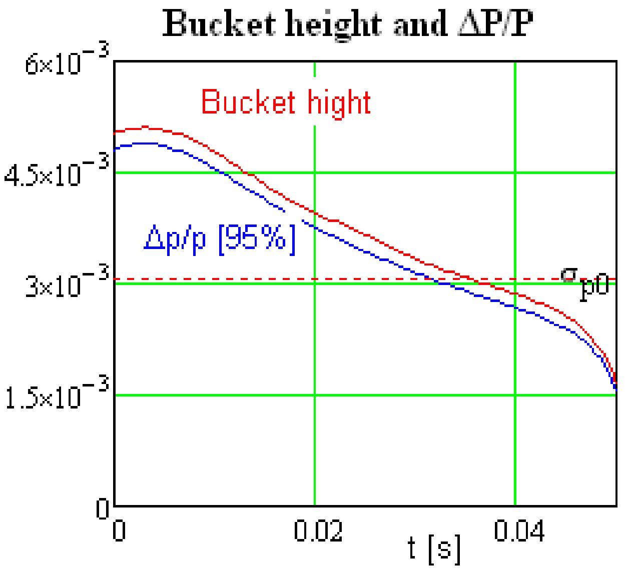
Beam acceleration

- Presented scenario implies the constant RF bucket size and that both RF harmonics are employed through the entire acceleration cycle
- Significant freedom for operational scenario.
  - To match RCS and MI emittances we presently imply
    - longitudinal emittance blowup from 0.4 to 0.6 eV s during acceleration
    - gradual decrease of the second harmonic voltage to the cycle end


Accelerating voltage, MV


Bucket aria, eV s


Accel. phase and bunch length, deg


Bucket height and ΔP/P

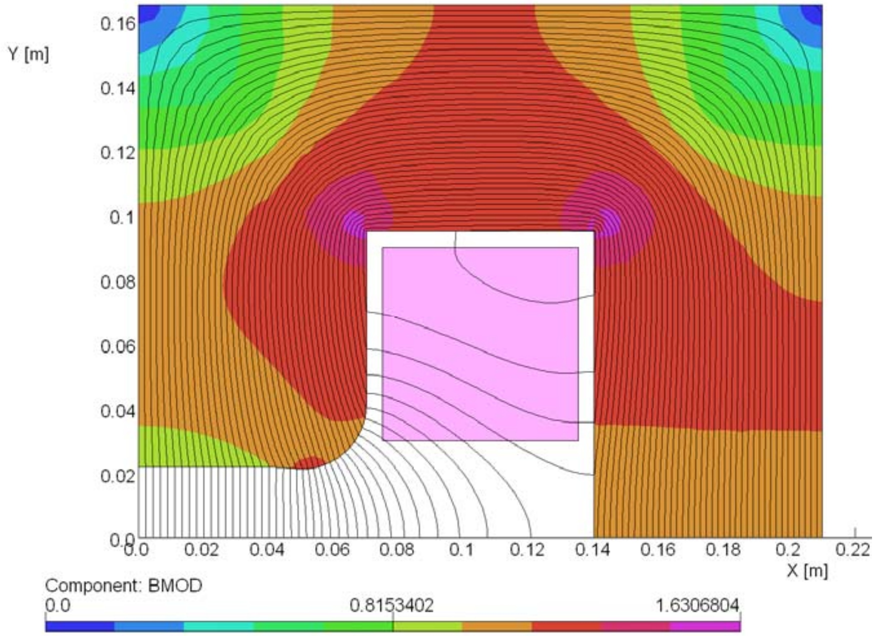
Vacuum chamber

- Round vacuum chamber (bend in dipoles, R=34 m)
  - Stainless steel - 0.7 mm
  - External diameter - 44mm
  - Sagitta – 1.67 cm
  - Eddy currents
    - $(\Delta B/B)_{max} = i \cdot 8.5 \cdot 10^{-4}$ (delayed field)
    - Field non-linearity generates chromaticity of ~1 unit for both planes
    - Power loss - 10 W/m
      - ⇒ Convective cooling – ΔT = 15 C°
  - Stresses
    - Stress due to atmospheric pressure – 3.1 N/mm^2
    - Bend stress for weakly elliptic chamber (a/b-1=0.04) = 9 N/mm^2
    - Yield stress for stainless steel – 200 N/mm^2

Dipoles

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.Kashihkin

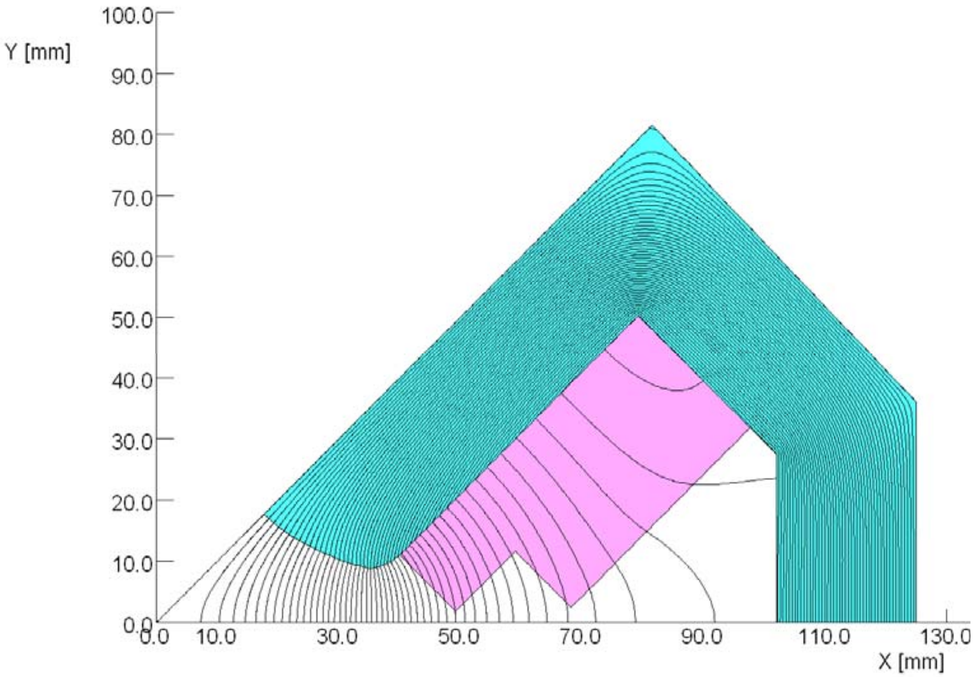


Magnet geometry and flux lines at 1kA current.

- 100 Rectangular dipoles
- Compact low inductance dipole

Regular Quadrupoles

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

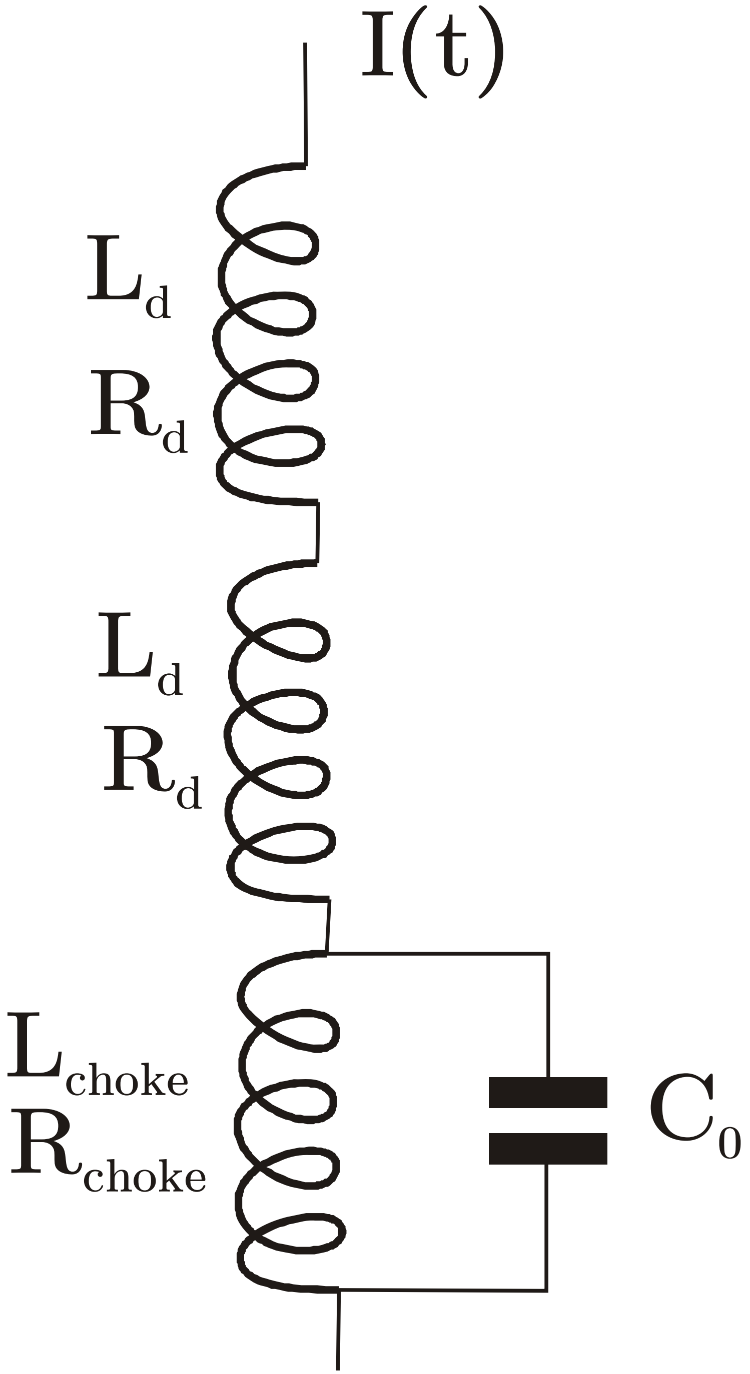


Quad geometry and flux lines at 1kA current.

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

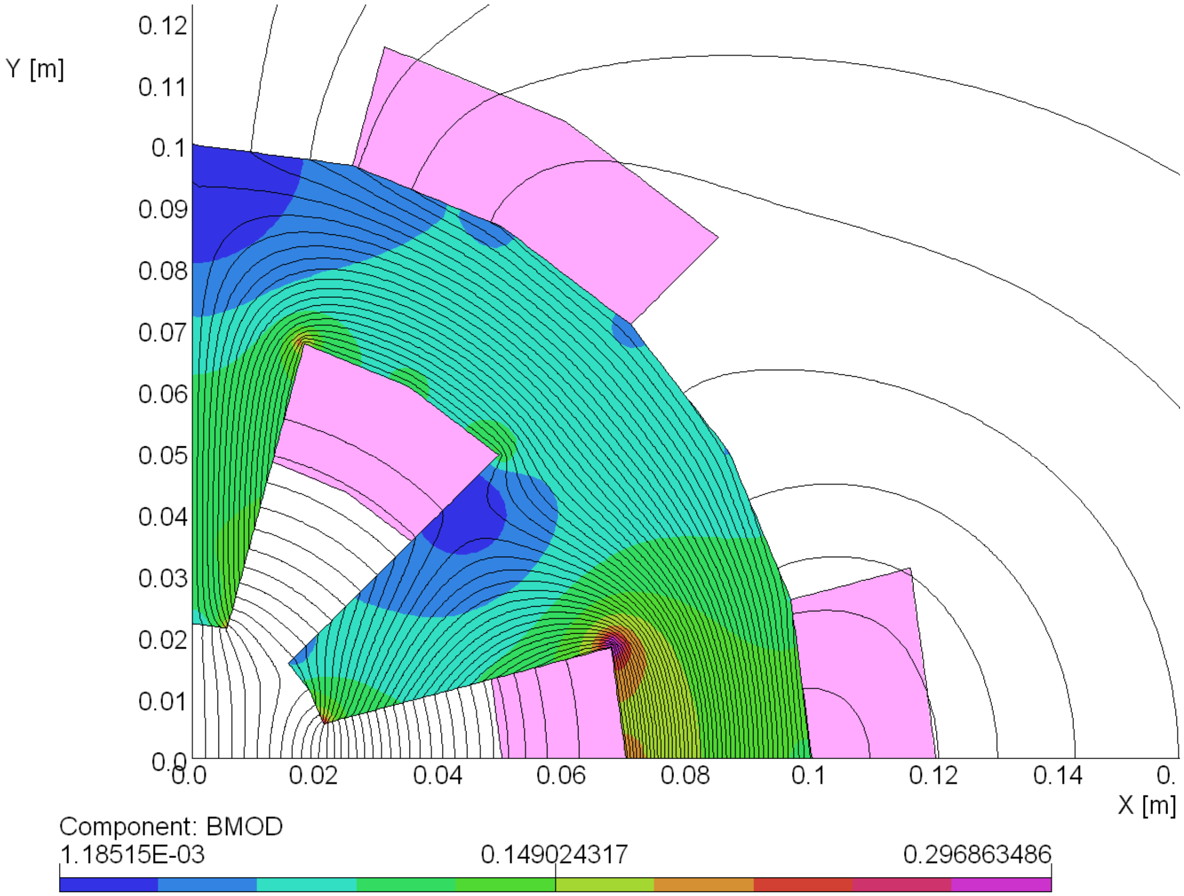
Dipole resonance circuit

- Resonance circuit is similar to the Booster one
    - One choke and one capacitor per cell (2 dipoles and 2 quads)
- Power supply
    - Total power - 900 kW
    - Total DC – 1.2 kV
    - Total AC (ampl) – 1.1 kV



Corrector packs

- Corrector pack near each quad (134)
    - (H or V)
      + (Q or Skew)
      + (S)
- Fast correctors for injection painting
    - 4 in each plane



Parameters of trim packages

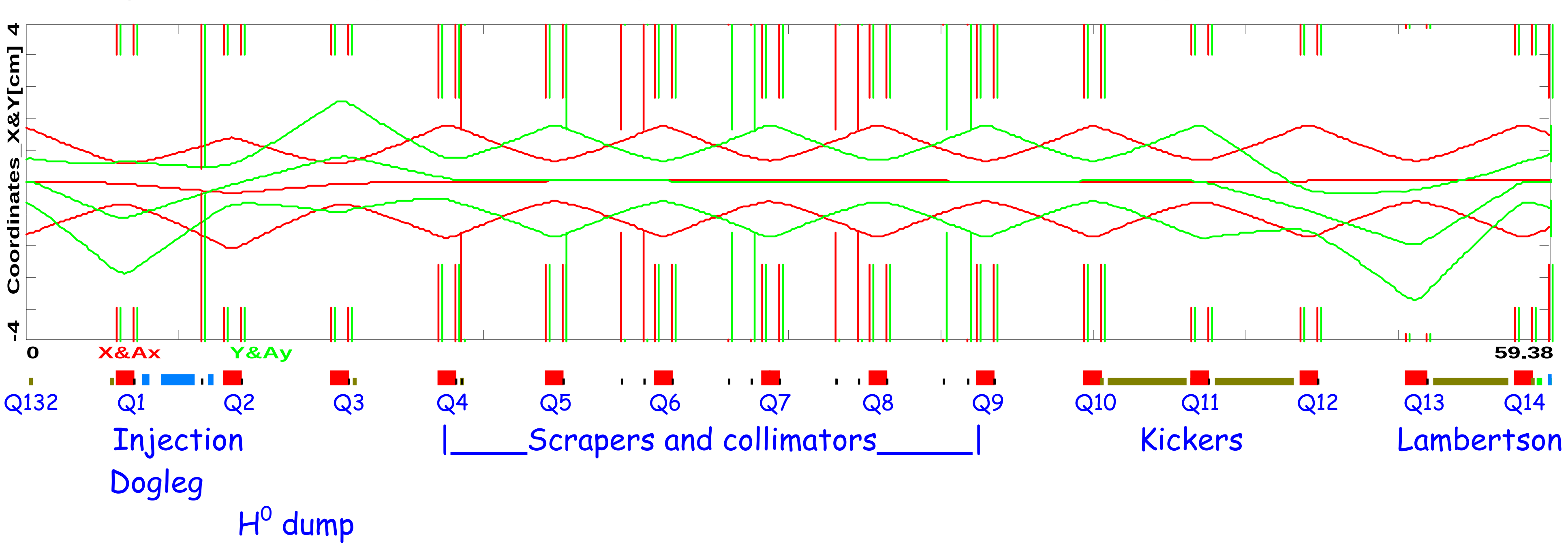
Name	L[cm]	B_H[G]	B_V[G]	G[G/cm]	S[G/cm^2]
Regular H	20	550	-	55	200
Regular V	20	-	550	55	200
Optics cor. H	20	550	-	110	200
Optics cor. V	20	-	550	110	200
Injection	30	1000	1000	-	-

Injection

- Small injection current (~1/20 of ICD I) makes it challenging
- Strip injection
  - comparatively well understood, reliable at 1/3 of nominal current
  - Optics change in the injection straight (~3$\beta_{x,y}$*3) resolves problem
    - Lost symmetry, space charge, ???
- Laser striping – needs better understanding

Extraction

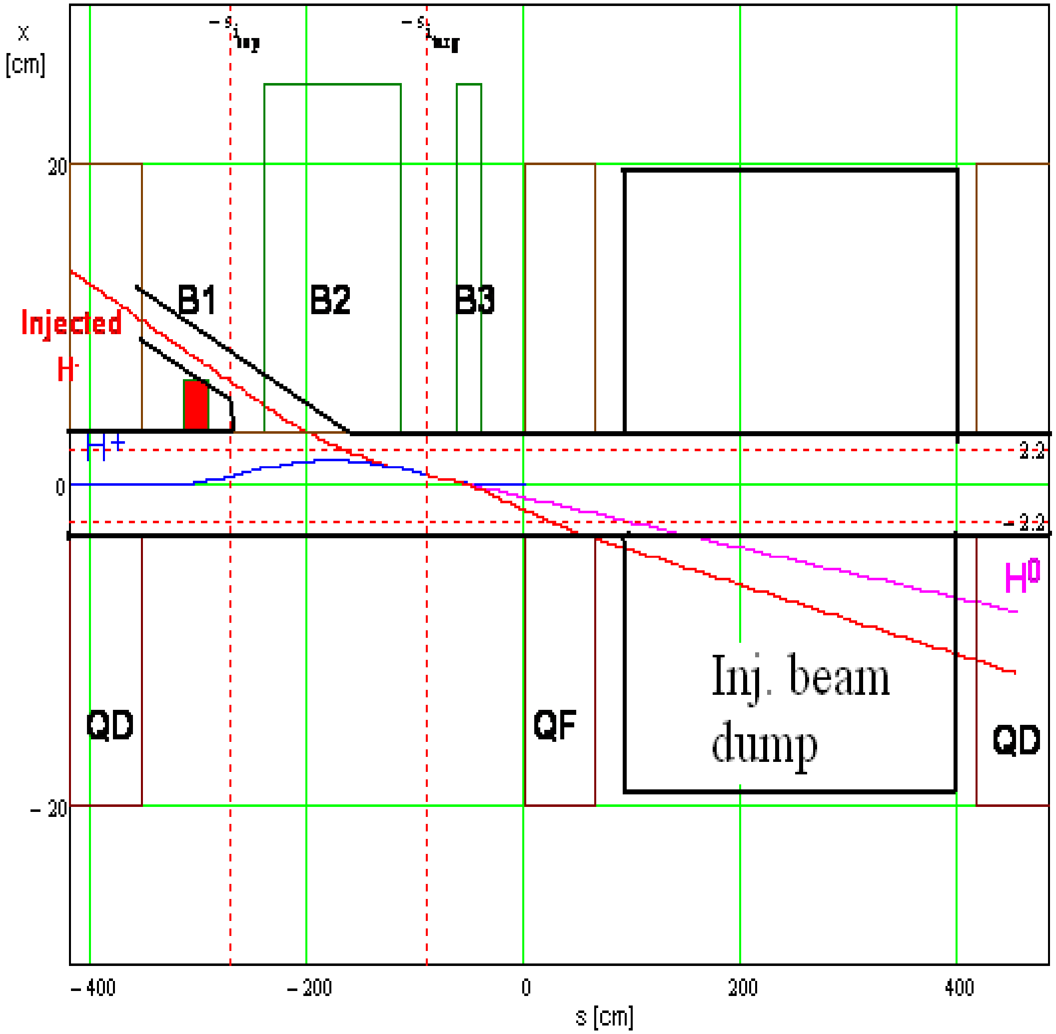
Single turn extraction - 2 kickers, increased aperture in quads, V. bump

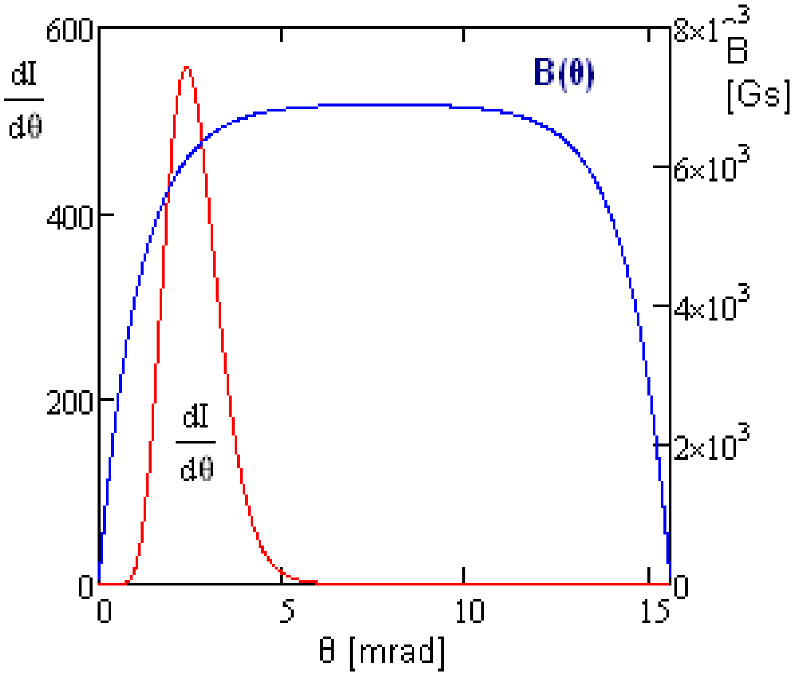


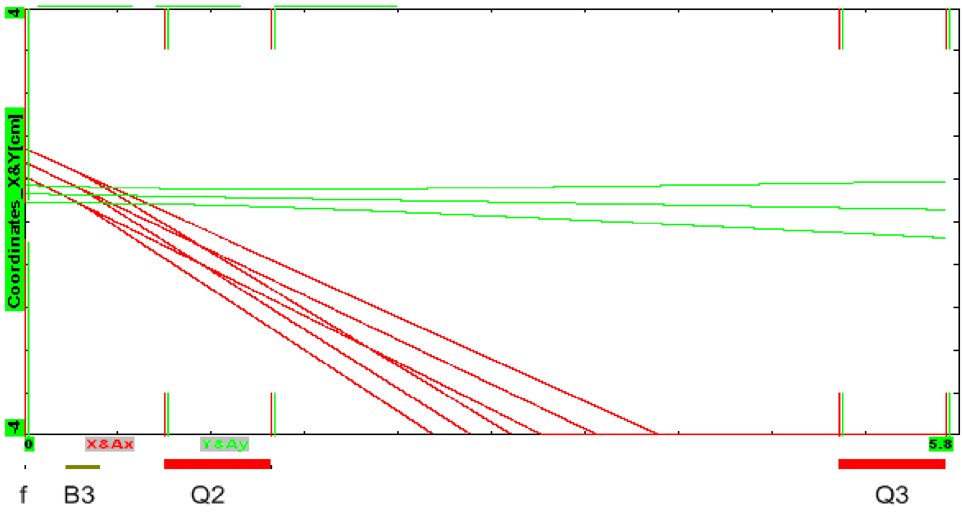
RCS for Project X, Valeri Lebedev, September 2009

Strip injection

- Total power of injected beam
  - 85 kW - each pulse operation
- H^- field stripping limits B2 field to 2.3 kG
  - Stripping probability is $4{\cdot}10^{-5}$
- B3 strips H- which missed foil
  - Survival probability ~10^{-17} (6.9kG)
  - Average deflection before stripping - 3 mrad

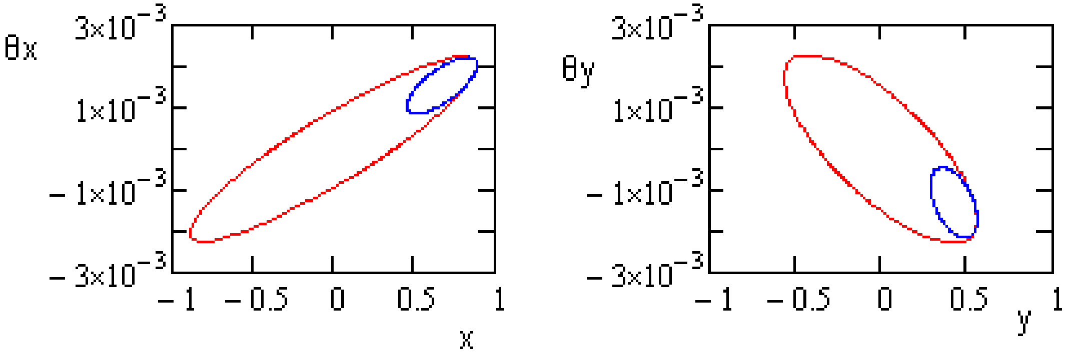


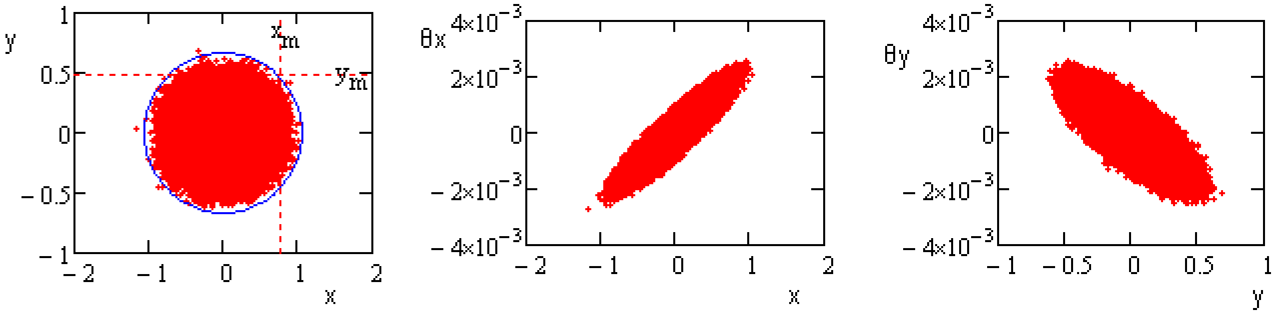


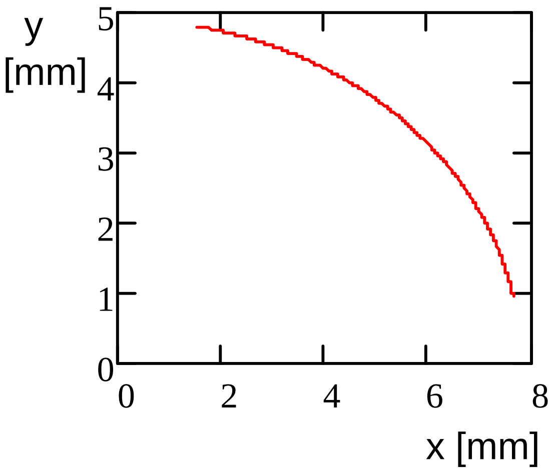


Transverse painting at Injection (rms norm. linac emit. – 0.5 mm mrad)

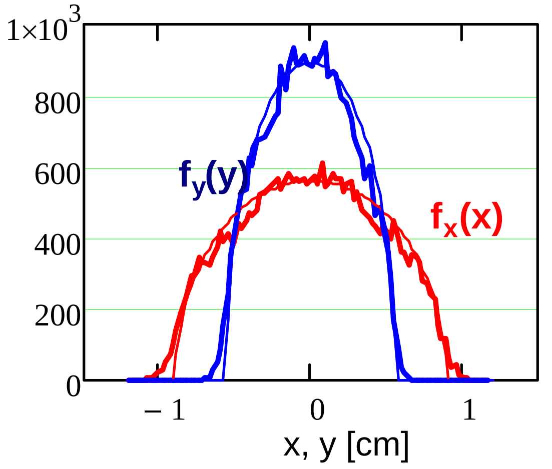
- Optimization of injection beta-functions: $\beta_L=0.345\beta_R$, $\alpha_L=0.345\alpha_R$
- KV-like distribution with 25 mm mrad KV boundary
  - 99% in 35 mm mrad
  - x-y anti-correlated painting
  - angles correlated with positions to minimize betatron amplitudes
  - 2 pass: forward &back

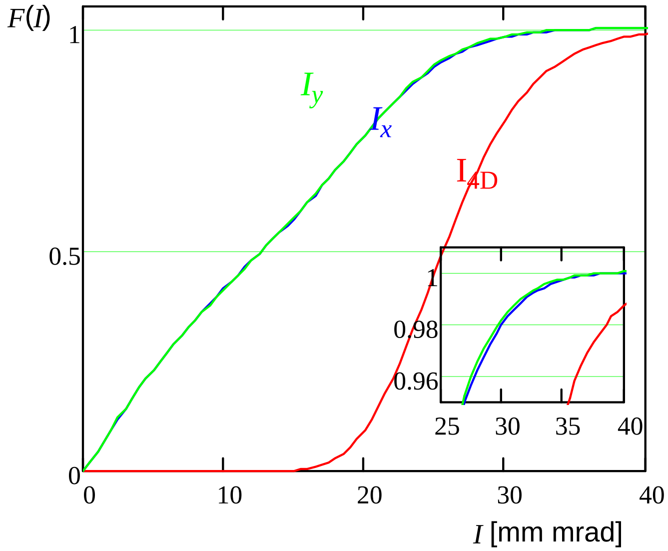






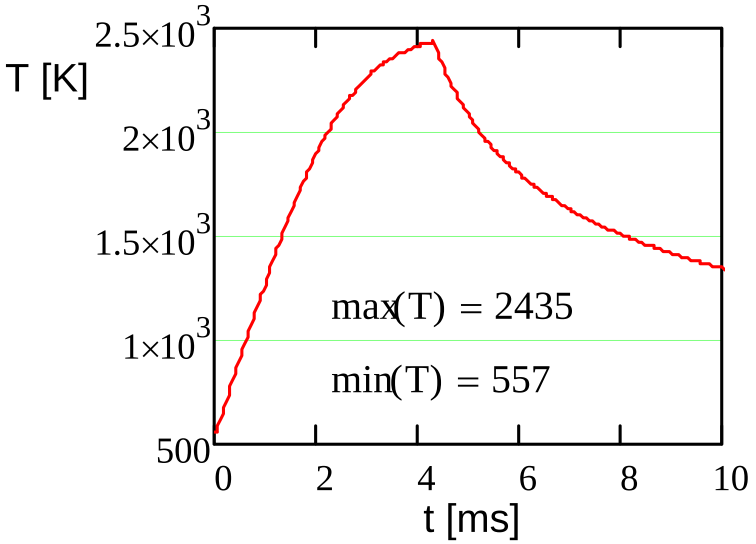
Single dimentional beam density at injection point at the end of painting

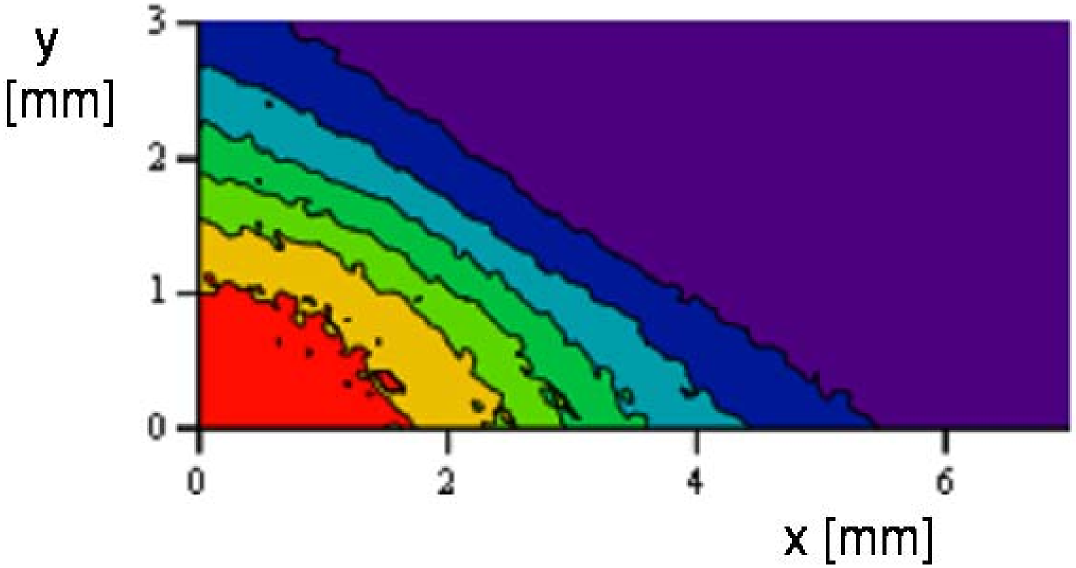


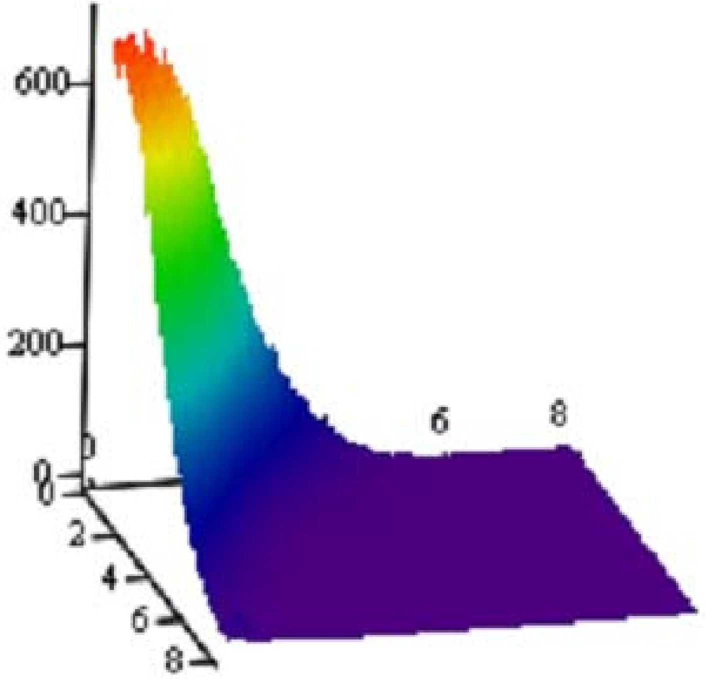


Heating of Striping Foil

- 600 $\mu g/cm^2$
  - 99% stripping efficiency
- Secondary foil passages - major source of foil heating
  - 38 hits per particle
  - 7 passages per particle per mm^2
    - $0.45*3\ mm^{-2}$ for injected H^- beam
  - Aver. heating ~50 W/cm^2
- Mitigation of foil heating
  - 45 deg. foil roll (425 $\mu g/cm^2$)
  - δ-electrons remove ~25% of heating



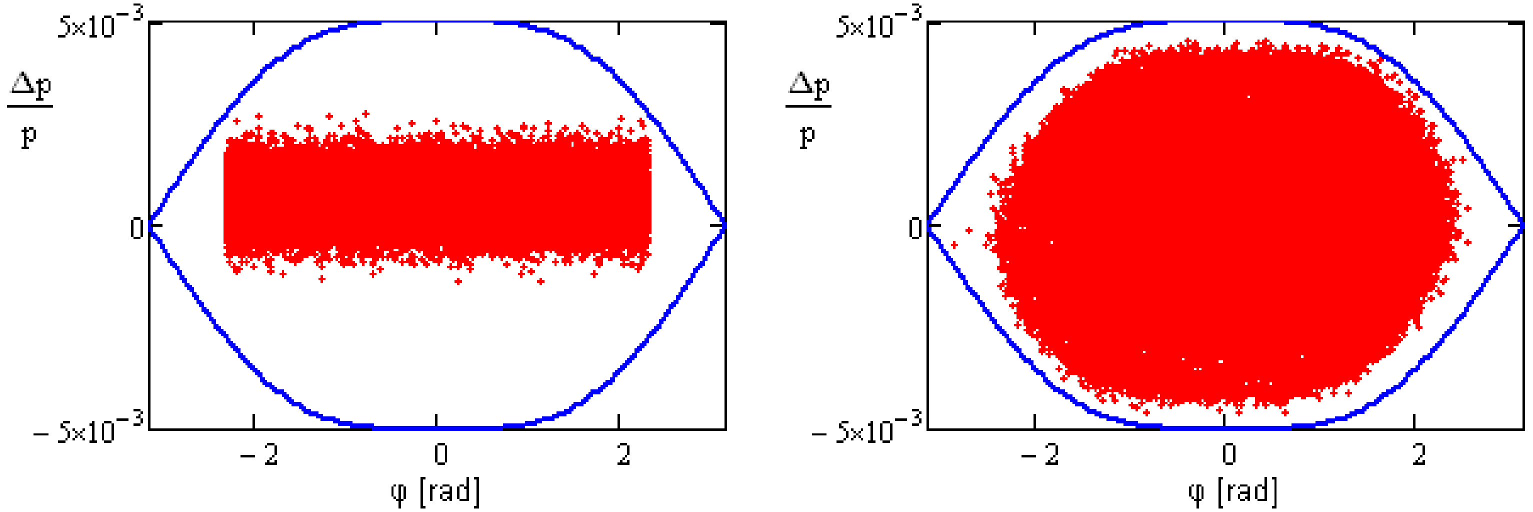




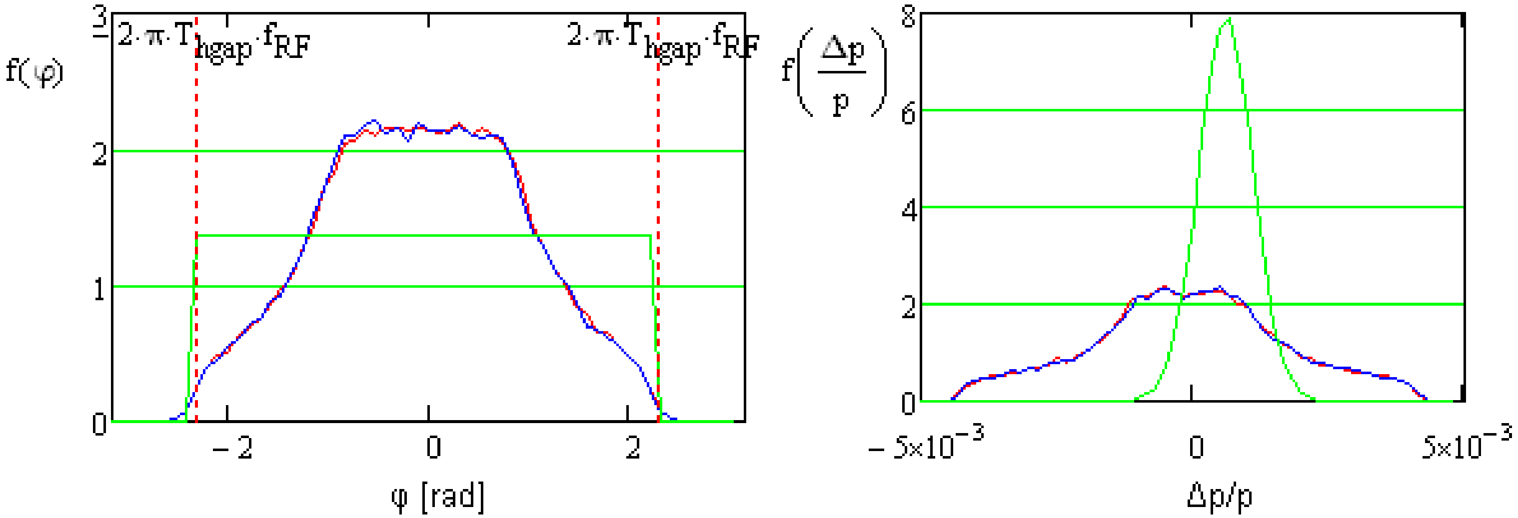
- 3 times reduction of power density would result in comfortable T≈1500 K

Longitudinal painting

- Flat bottom potential well: $V_1=V_0/2$ (V_0 = 1 MV, V_1 = 0.5 MV, ε_{tot}=0.38 eV s)



Phase space for injected particles and at the end of injection (σ_p=5e-4, Δp=7e-4, T_w=14.6 ns (73%))



Particle distributions: green -injected particles, red – after injection, blue - 500 turns after injection (bunching factor = 2.2)

R&D plans

- Build and test half cell (dipole, quad and vacuum chamber)
- Build a first-harmonic RF cavity
- Choose injection type
  - If laser stripping – start corresponding hardware work
  - If foil striping – modify lattice in the injection straight
  - Final proposal cannot be made until we resolve this issue
- Simulations
  - Experience obtained with ORTIT suggests that it will satisfy our immediate needs
    - Orbit can account the space charge and impedance but cannot do multi-bunch simulations
      - Instabilities can be addressed separately
      - Better simulations are not expected to change main features of the design
  - Simulations of beam collimation and beam dump have been started
  - Beam RF loading and longitudinal instabilities require detailed study

Backup Slides

Transverse Instabilities and their damping

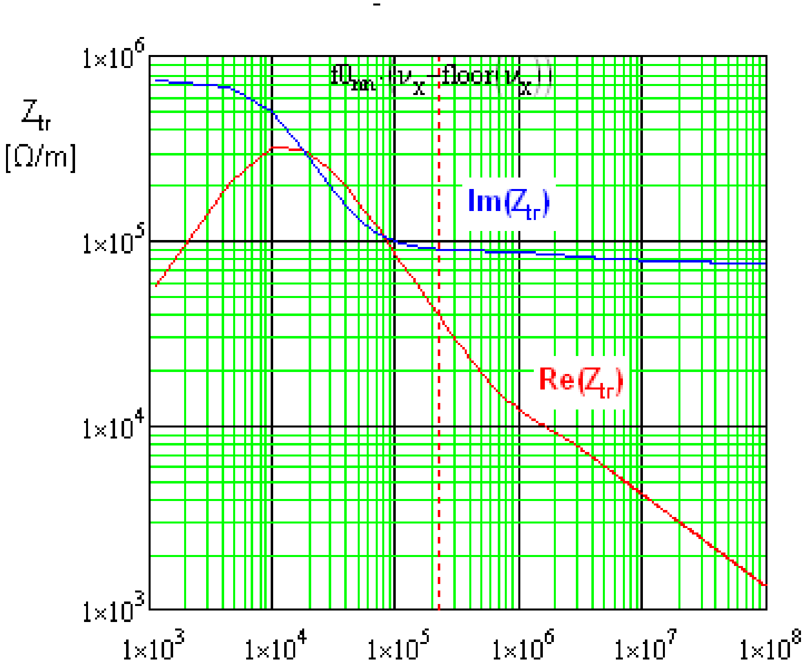
- Eddy currents in vacuum chamber excite magnetic field correction
  - Eddy current reflection in the steel of dipoles increases the correction and makes it non-linear even in round vacuum chamber

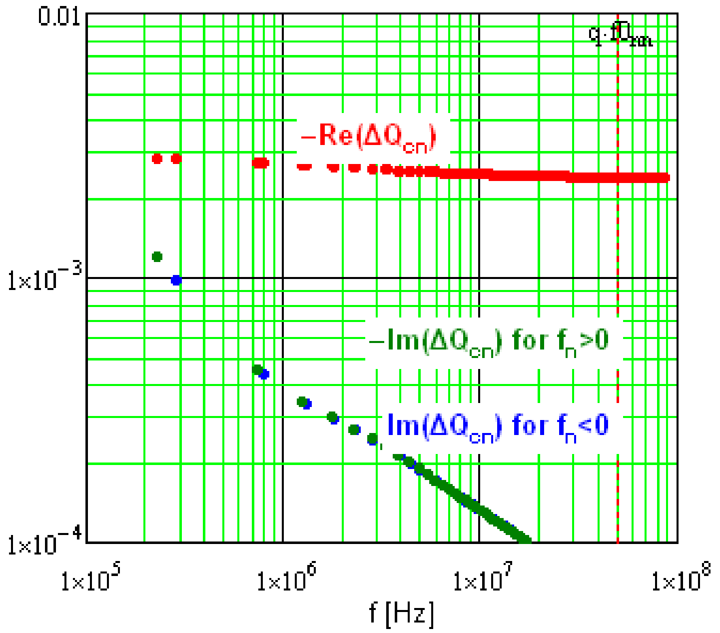
$$\frac{\Delta B_y}{B_0} = i\left(1 + \frac{\pi^2}{12} + \frac{\pi^4}{240}\frac{y^2}{a^2} + \ldots\right)\frac{ad}{\delta_r^{\,2}}, \qquad \delta_r = \frac{c}{\sqrt{2\pi\sigma\omega_{ramp}}}$$

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

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

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





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

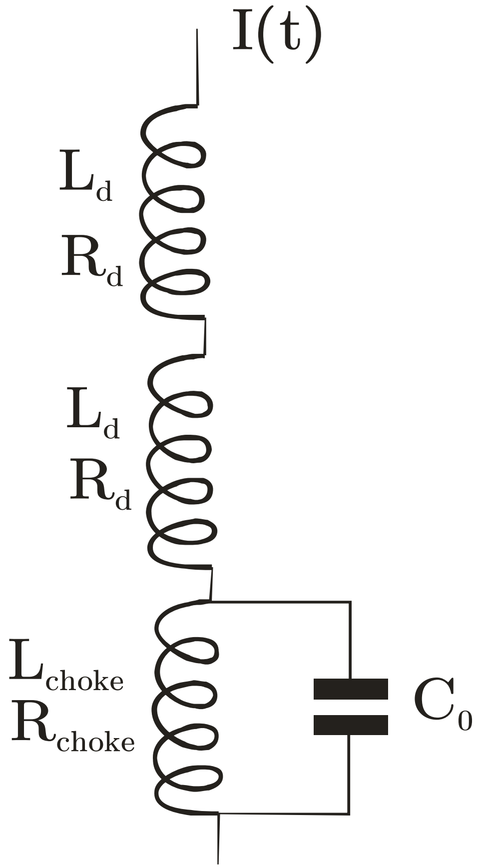
$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{C_0}\left(\frac{1}{2L_d}+\frac{1}{L_{choke}}\right)}$$

  - 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

Strip H^- injection

- At the beginning of injection straight
- Horizontally, from radially outside
- Anti-correlated painting to paint KV-like distribution
- 3 quads in the injection region have increased aperture (Q1, Q2, Q3)
    - 12 turns per pole (instead of 6)
    - a = 33.2 mm (instead of 23.48 mm)
    - No quad offsets from the straight line
- 3 injection dipoles in one straight section
    - B1 – DC septum, B2 and B3 - permanent magnets or powered by DC
- 4 fast correctors in each plane for painting
    - Maximum strength ±30 kG cm
    - Frequency band of 500 Hz to be able to follow required time dependence
- H^- missing or coming out of stripping foil are stripped to H^0 in field of B3
    - Beam damp for H^0 is in the next half cell after injection cell

Injection half-cell structure

Name	L[cm]	B[kG]	G[kG/cm]
Q1	65.9	0	-1.7
oInj	40		
B1	21	-6.9	
oInj1	52.608		
B2	126	2.3	
oInj2	26.304		
FOIL	0		
oInj2	26.304		
B3	21	-6.9	
oInj	40		
Q2	65.9	0	1.74

$$A_x(t) = -A_{x0}\cos(\varphi(t))$$

$$A_y(t) = -A_{y0}\sin(\varphi(t))$$

$$\varphi(t) = \varphi_0 + \left(\frac{\pi}{2} - 2\varphi_0\right)\frac{t}{T_{inj}}$$

At foil: A_{x0}=0.78 cm, A_{y0}=0.49 cm, $\phi_0=\pi/32$, T_{inj}=4.2 ms

Details of painting scheme

- For each plane there are two overlaying orbit bumps in the injection aria
  - ♦ Injection bump to minimize the required aperture in quadrupoles
  - ♦ Painting bump to paint the required beam distribution
- Injected H- are directed along proton trajectory of the injection bump on the foil
  - ♦ H^- beam coordinates at foil location relative to the injection dogleg
    - x=5.34 mm, y=5.08 mm
    - θ_x=1.20 mrad, θ_y=-0.51 mrad
  - ♦ Coordinates of foil corner
    - X=3.28 mm, y=3.79 mm (2.32σ, 2% particles miss the foil)

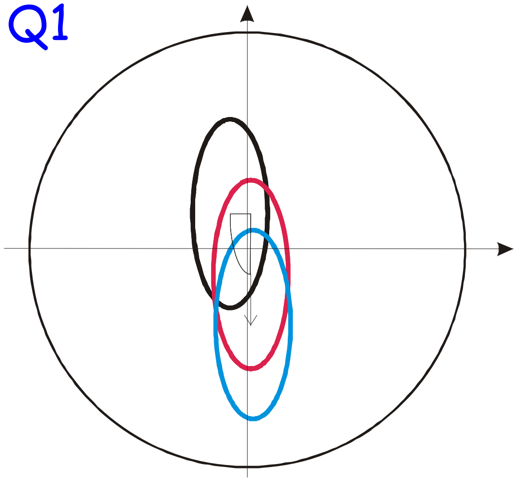
Corrector strength for injection bumps

	Injection bump [kG cm]	Injection bump +Maximum for painting bumps [kG cm]*
C1x	4.50	-1.51
C1y	16.50	-25.93
C2x	0.00	-1.34
C2y	1.56	12.25
C3x	6.00	-1.56
C3y	2.46	-7.78
C4x	2.14	-1.44
C4y	16.10	11.28

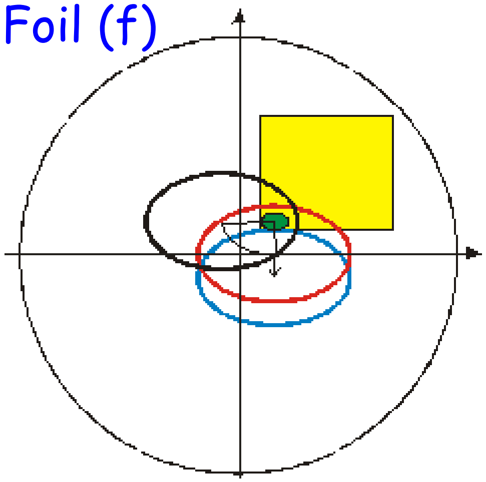
* These values of inj. bump correctors (at the injection end) are sufficient to missteer the beam through the rest of accelerating cycle

- Painting bump starts from the maximum (negative) value in the horizontal plane describes quarter of ellipse in XY plane and then the beam is displaced down to steer the beam off the foil

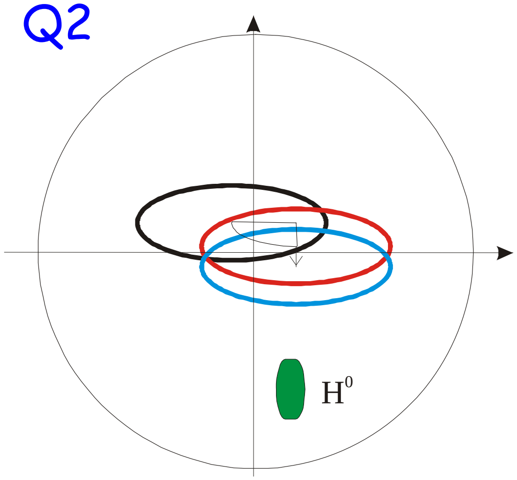
Q1

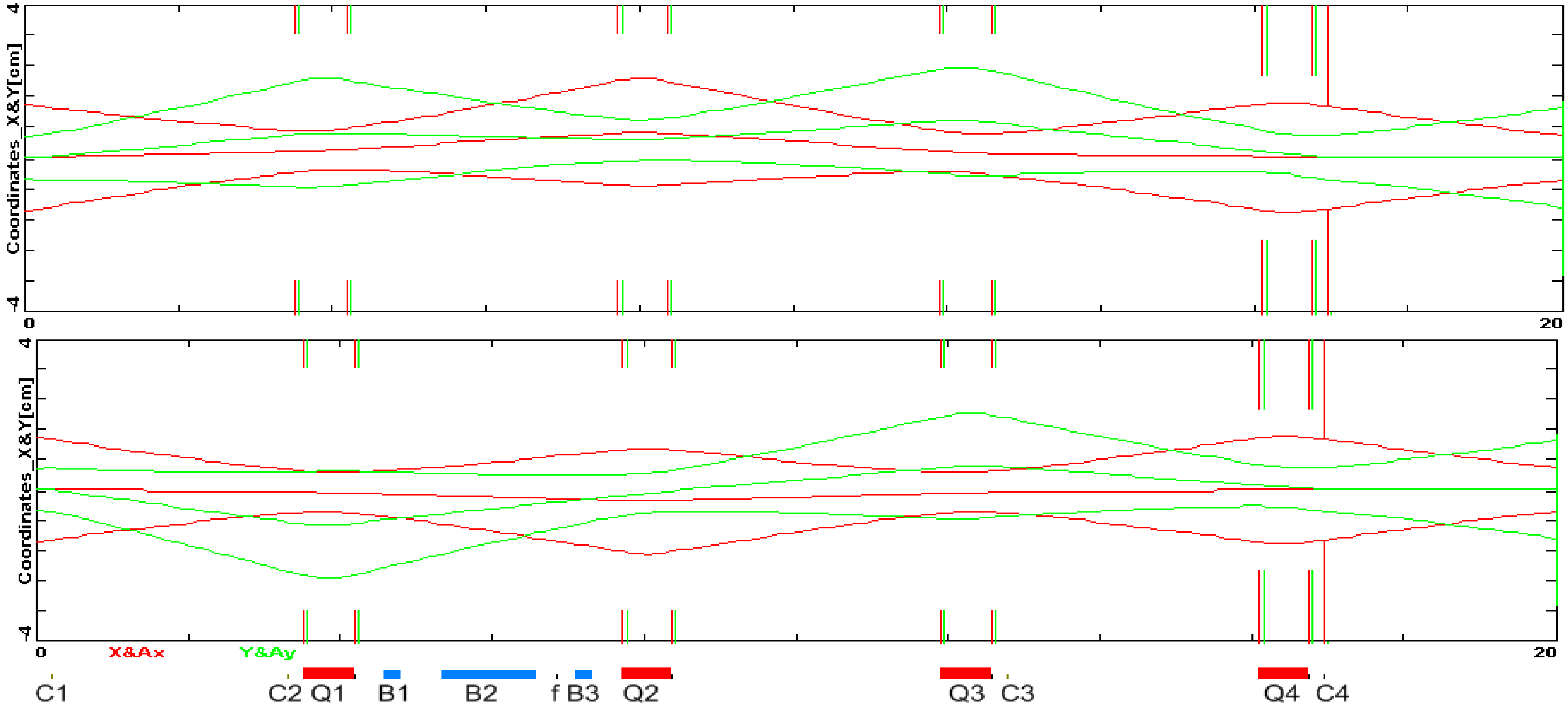


Foil (f)



Q2

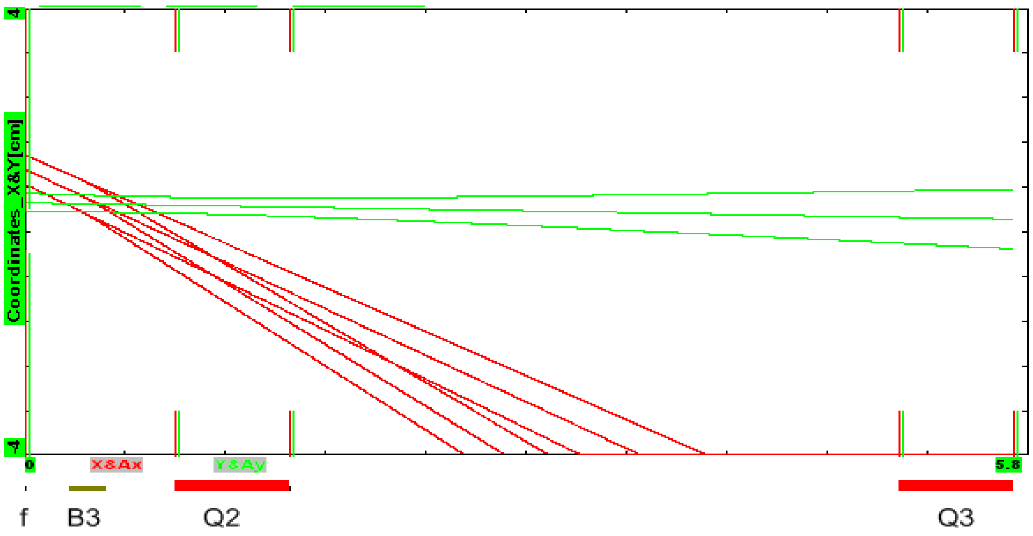




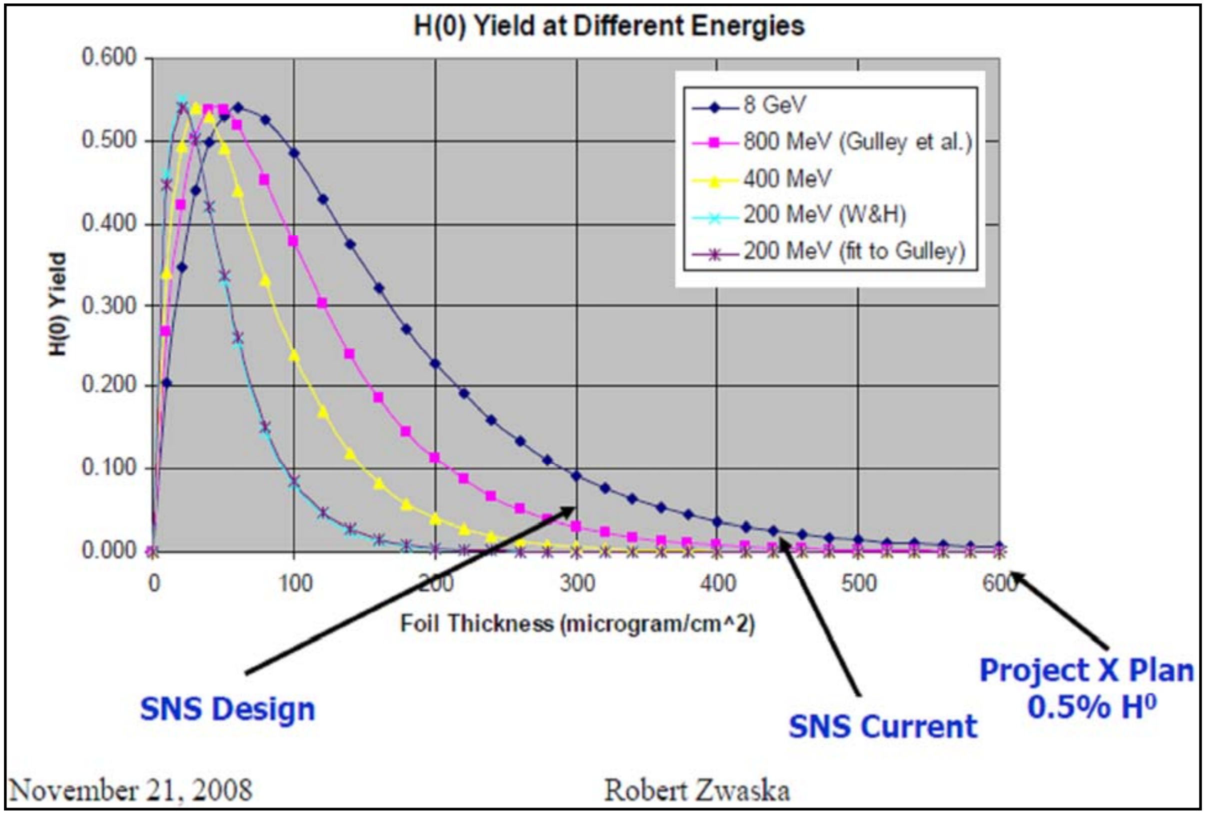
Beam envelopes through injection bump region for the 40 mm mrad boundary emittance;
top – injection bump only, bottom – injection bump + maximum amplitude for X&Y painting bumps

Injection dump

- ~3% of particles are lost at injected stripping
  - 2% - miss stripping foil
    - In each plane 2.32σ H^- beam offset from foil edges
  - 0.5% - did not strip
- In normal operating conditions the beam dump should intercept ~3 kW
  - It has to be rated to ~10 kW to support reliable operation



3σ beam envelops for H^0 which missed the foil or did not strip completely, Angular spread due to stripping is also shown



Injection (continue)

- Single and multiple scattering in the foil (thickness - 600 $\mu g/cm^2$)
  - Emittance increase due to multiple scattering is not a problem
    - Emittance increase per foil crossing:

      $\Delta\varepsilon_{xn95\%} = 8.5 \cdot 10^{-3}$ mm mrad; $\Delta\varepsilon_{yn95\%} = 3.3 \cdot 10^{-3}$ 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 - $1.4 \cdot 10^{-5}$ per foil crossing
    - For 50 crossings per particle the total loss ~0.07% or 200 W for 300 kW operation
- Stripped electrons are reflected from field of B3 dipole and intercepted by electron beam dump (located radially inside)
  - Total power – 90 W for 340 kW operation