RCS design

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Outline

- Objectives for RCS design
- Logic behind parameter choices
- Technical description

Project X — Objectives & Challenges

- Objectives
  - Beam acceleration from 2 to 8 GeV
  - Support
    - 2 MW in MI at 60 to 120 GeV (140 – 280 kW)
    - 8 GeV program with fast extracted beam (≥100 kW)
  - Look for a solution being less expensive than pulsed SC linac
  - Look into possible future upgrades
- Challenges
  - Beam current is ~5 times of Booster ⇒ Space charge, instabilities, RF, ep
- Booster problems to be avoided
  - No transition crossing
  - No laminations seen by beam ⇒ smaller $Z_{||}$, $Z_{\perp}$
  - Zero Disp. in cavities ⇒ No SB resonance

RCS Design Choices

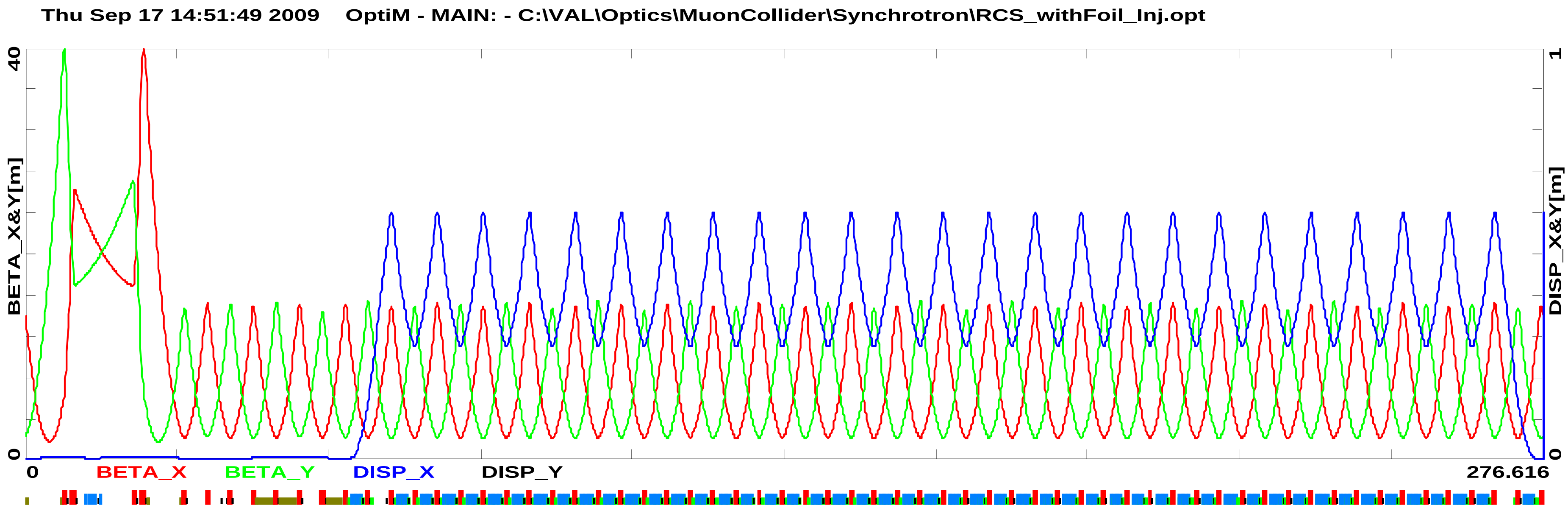
- Circumference, C = $C_{MI}/6$
  - 6 injections to fill MI
- High periodicity FODO
- Racetrack
  - Two long straights
  - Dispersion zeroing with missed dipole
- Acceptance matches MI acceptance
  - 10% allowance for ε growth
- 2 harmonics RF system
  - Space charge mitigation
  - Beam stability
- High injection energy helps with Space Charge and Instabilities
  - Small size of vacuum chamber

Energy, min/max, GeV	2/8
Repetition rate, Hz	10
Circumference, m (MI/6)	553.2
Tunes	18.43
Transition energy, GeV	13.36
Beam current at injection, A	2.2
Harmonic number	98
Max. RF voltage, (V_{98}/V_{196}) MV	1.6/0.7
95% n. emittance, mm mrad	22
Space charge tune shift, inj.	0.07†
Norm. acceptance, mm mrad	40
Injection time for 1 mA, ms	4.3
Linac energy cor. at inject.	1.2%
RF bucket size, eV s	0.38

† KV-like distribution, BF=2.2

Optics

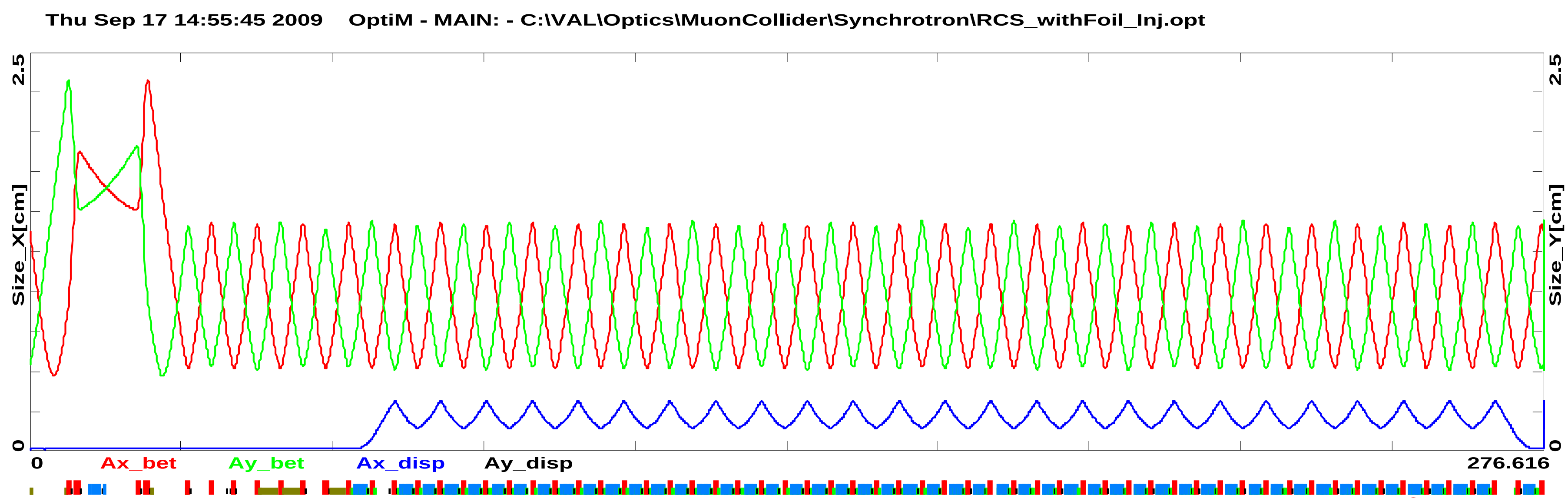
- β-functions are blown-up in injection region – reduction of foil heating
  - 6 half cells are used for injection region
- Two types of quadrupoles with the same integral strength
  - Large aperture quads for injection & extraction



Twiss parameters for the first half of the ring

Optics (continue)

- Straight line assignments
  - Injection, extraction, scraping
  - RF
- Vacuum chamber radius, *a* = 21.3 mm (internal)
  - 7 mm allowance for orbit correction



Beam envelopes; acceptance - ε_n=40 mm mrad, E_k = 2 GeV, $\Delta p/p = 5 \times 10^{-3}$.

Vacuum Chamber

- Competing effects are
  - Shielding and distortion of dipole bending field by eddy currents excited in the vacuum chamber
  - Vacuum chamber stability under atmospheric pressure
  - Vacuum chamber heating by eddy currents
  - Transverse impedance due to wall resistivity
  - Ring acceptance
- The compromise resulted in
  - Round stainless steel vacuum chamber with radius of a=22 mm and wall thickness of d = 0.7 mm
  - Inside quads of injection and extraction regions: a=43 mm d = 1 mm
  - No limitations on the chamber thickness outside dipoles and quads
- Ring acceptances and beam emittance:
  - 85 mm mrad - limited by vacuum chamber size
  - 40 mm mrad – limited by scrapers
  - 22 mm mrad – 95% norm. beam emittance

Limitations on Vacuum Chamber Design

- Shielding and distortion of the dipole bending field by eddy currents excited in the vacuum chamber
  - Dipoles: $|\Delta B/B|_{max}$=8.5 x 10^{-4} @16 ms
  - Quads – approximately half of the dipole effect
  - Delayed quad wave form by ~70 μs

$$\Delta B_y(0,y) = iB_{AC}\left(1+\frac{\pi^2}{12}+\frac{\pi^4}{240}\frac{y^2}{a^2}+...\right)\frac{ad}{\delta^2},$$

$$\delta = \frac{c}{\sqrt{2\pi\sigma\omega_{ramp}}} << a$$

- Vacuum chamber stability under atmospheric pressure
  - Compression: 3.1 N/mm^2
  - Bend for $\Delta a/a$=0.02: 8.9 N/mm^2
  - Yield stress : 200 N/mm^2

$$\sigma_{cmpr} = P_{atm}\frac{a}{d}$$

$$\sigma_{bend} = \frac{9}{4}P_{atm}\frac{\Delta a}{a}\left(\frac{a}{d}\right)^2$$

- Vacuum chamber heating by eddy currents (~a^3)
  - dP/dz=10 W/m
  - ΔT=15 K for convective air cooling with heat transfer of 10^{-3} W/cm^2/K

$$\frac{dP}{dz} = \frac{\pi\sigma d a^3 \omega_{ramp}{}^2}{c^2}B_{AC}{}^2$$

Vacuum Chamber Impedance

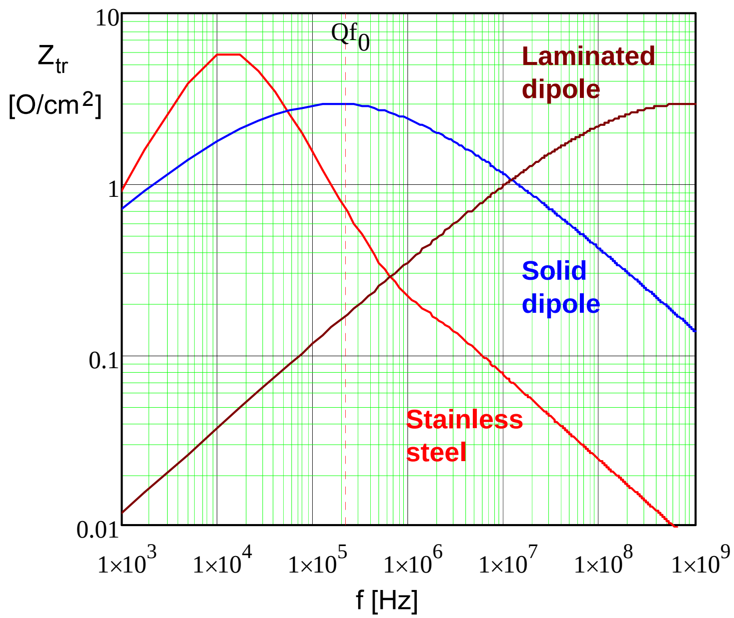
- Transverse impedance due to wall resistivity (~a^{-3})
  - $Z_\perp$ and dP/dz are related inversely proportional
    - No dependence on vacuum chamber parameters

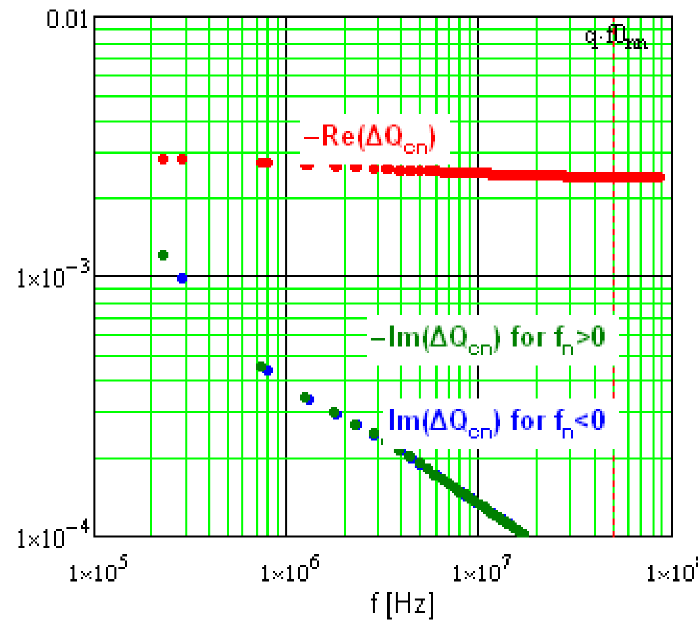
$$Z_\perp(\omega) = Z_0 \frac{c^2}{4\pi^2 \sigma \omega a^3 d}$$

$$\sqrt{ad} \ge \delta \ge d$$

$$Z_\perp(\omega)\frac{dP}{dz} = \frac{Z_0}{4\pi}\frac{\omega_{ramp}{}^2}{\omega} B_{AC}{}^2$$

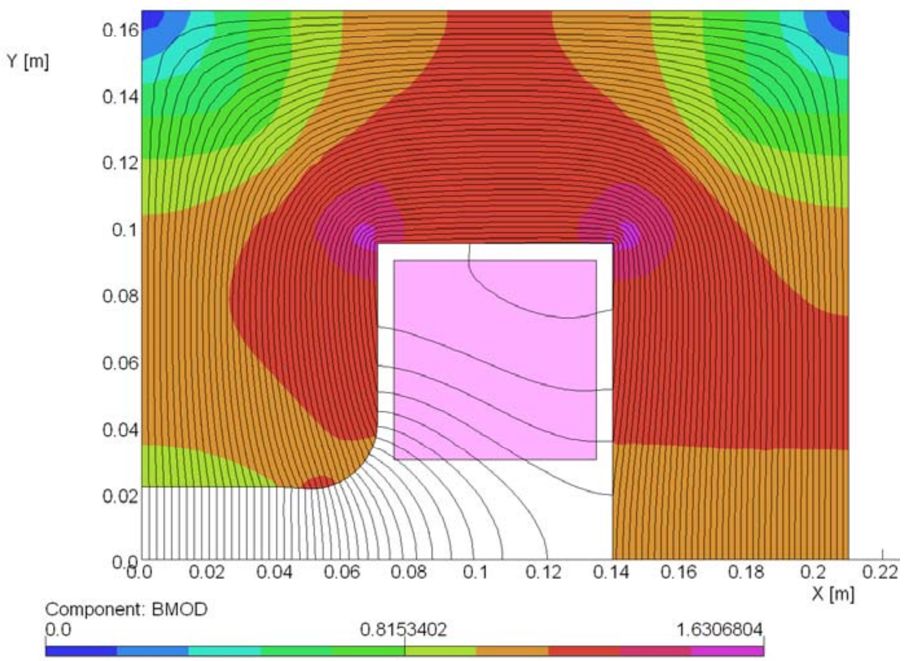
$$\delta = \frac{c}{\sqrt{2\pi\sigma\omega}}$$





Dipoles

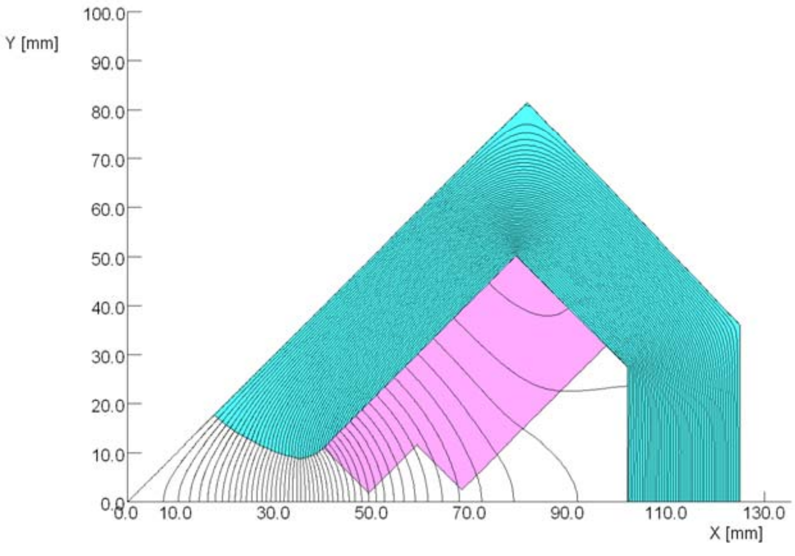
- Small aperture
  ⇒ Compact dipole
- Sagitta – 1.7 cm



Parameter	Unit	Value
Number of magnets		100
Peak field	T	0.87375
Field at injection	T	0.2184
Magnet gap	mm	44
Good field area diameter	mm	40
Field homogeneity		0.02 %
Effective length	m	2.13216
Peak current	A	667 A
Number of turns/pole		24
Copper conductor	mm x mm	12.5 x 12.5
Conductor cooling hole diameter	mm	7
Number of pancake coils/pole		2
Lamination material		M17
Lamination thickness	mm	0.35
Inductance	mH	25
DC resistance	Ohm	0.021
Stored energy	kJ	5.47
Av. Power losses (no eddy current)	kW	4.3
Peak inductive voltage	V	390
Number of cooling circuits/magnet		1
Water pressure drop	MPa	0.5
Water flow	l/min	2.8
Water temperature rise	C°	22

Quadrupoles

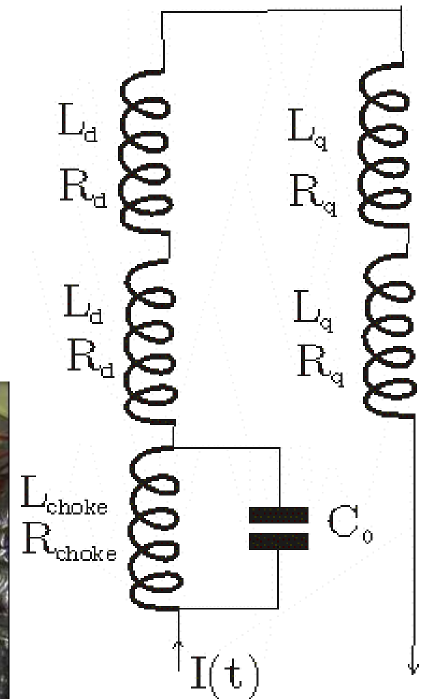
- Large and small quads have the same field integral
- Large quads
  - 4 in injection region
  - 4 in extraction region



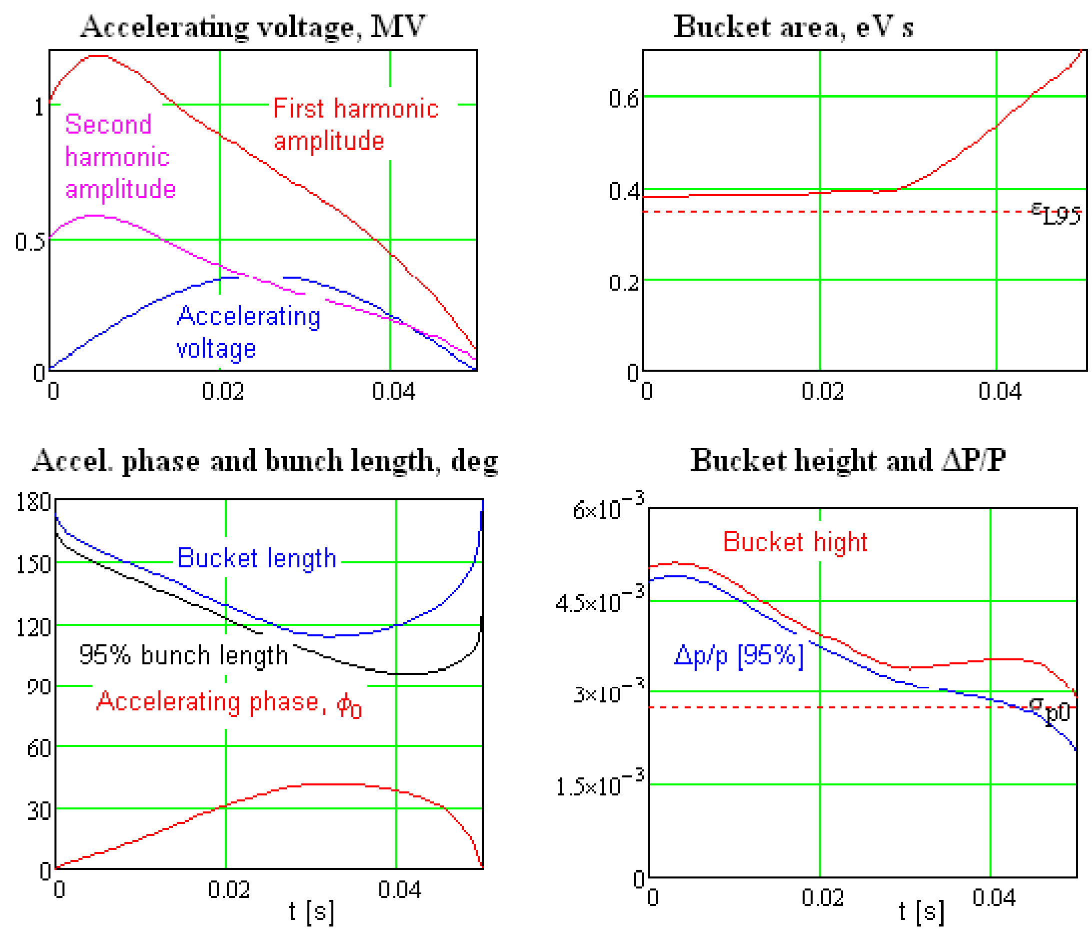
Parameter	Unit	Normal quad	Large quad
Number of magnets		122	8
Peak field gradient	T/m	17.65	14.65
Field gradient at injection	T/m	5.528	4.589
Pole tip radius	mm	25	45
Good field area diameter	mm	40	75
Field nonlinearity (2D)		0.03 %	0.03 %
Effective length	M	0.69	0.794
Peak current	A	672 A	
Number of turns/pole		7	19
Copper conductor	mm x mm	10 x 10	10 x 10
Conductor cooling hole diameter	mm	5	5
Number of coils/pole		1	1
Lamination material		M17	M17
Lamination thickness	mm	0.35	0.35
Inductance	mH	1.15	3.12
DC resistance	mΩ	12	40
Stored energy	J	260	700
Av. power losses (no eddy currents))	kW	2.0	6.7
Peak voltage	V	40	110
Number of cooling circuits/magnet		1	4
Water pressure drop	Mpa	0.5	0.5
Water flow	l/min	1.9	1.6
Water temperature rise	C^o	16	11

Resonance Driving of Dipoles and Quads

- Dipoles and quads of each cell have a resonance circuit compensating their inductive impedance
  - 50 standard + 2 special cells (one for each straight line)
    - each is tuned to 10 Hz
  - Total power ~1.5 MW
  - Maximum voltage to ground 600 V
- Similar to the Booster



Beam Acceleration



RF System

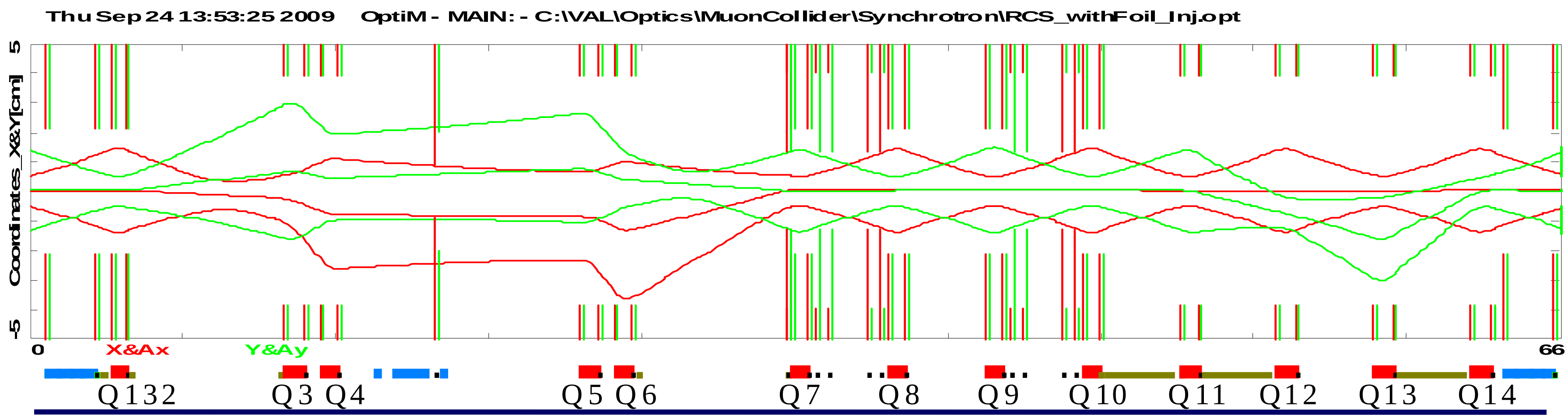
- Dual Harmonic RF system,
  - At injection V_2=0.5 V_1
- 10 Bunches extraction gap
  - Set by required length of MI extraction gap
- Beam loading is serious issue
  - 1.6 MV beam induced voltage (at resonance)
- Longitudinal emittance is blown up to ~0.6 eV s to match to MI RF bucket
  - Can be excited by quadrupole damper (same as in Booster)

	1-st harmonic	2-nd harmonic
Harmonic number	98	196
Maximum voltage, MV	1.6	0.7
Minimum voltage, kV	20	10
Frequency sweep, MHz	50.33-52.81	100.66 – 105.62
Number of cavities	16	10
Shunt impedance, kΩ	100	100

Injection-Extraction Straight

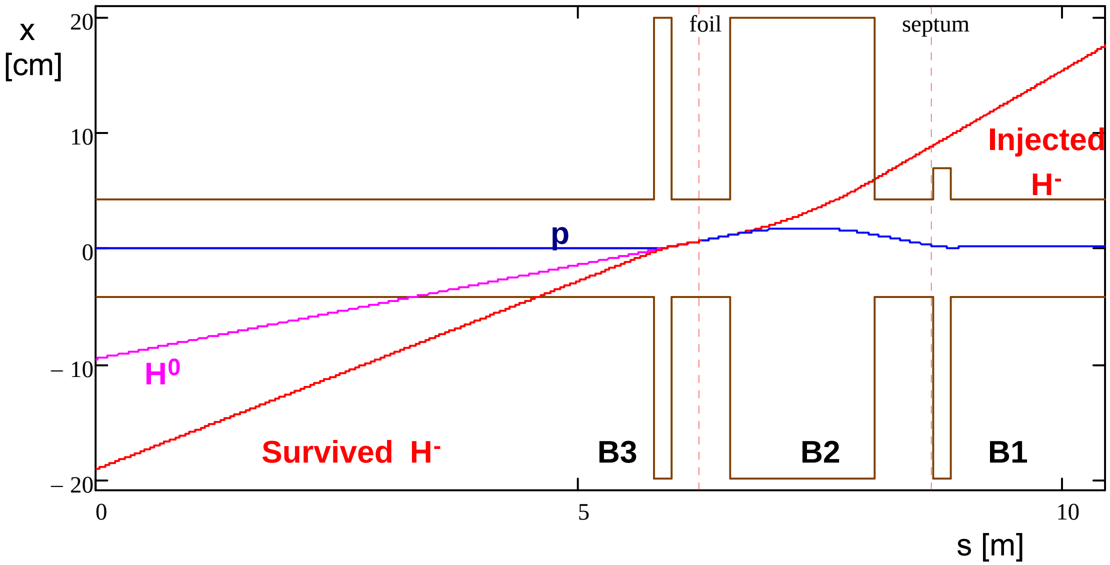
Cell N	Assignment
132	TBD
4	Injection
6	Primary collimators
7	Vertical and Horizontal collimators
8	TBD
9	Vertical and Horizontal collimators
10-11	Extraction kickers
12	TBD
13	Extraction septum

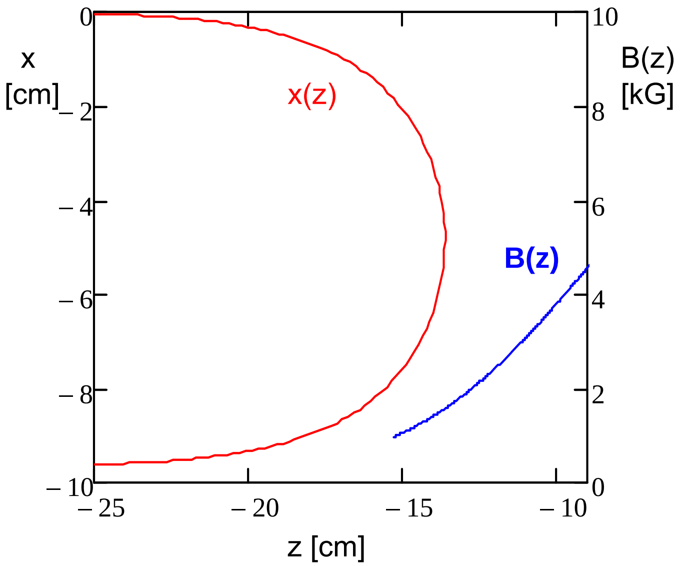
- Doublet focusing for injection straight
  - It takes space of 6 FODO half cells
- Increased aperture for 8 quads
  - 4 in injection
  - 4 in extraction



Injection

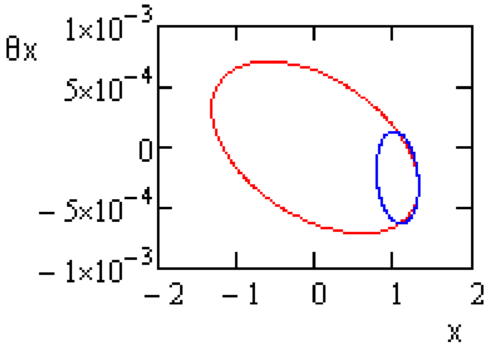
- Strip injection through 600 $\mu g/cm^2$ graphite foil
- Small linac current (1 mA)
  $\Rightarrow$ 2200 turn injection (11 for Booster, 1000 for SNS)
- B2 – small field to avoid H^- stripping (2 kG)
- B3 – Large field to strip H^- to H^0 (-8.3 kG)
- Stripped electrons carry ~100 W beam power and have to be directed to the electron dump

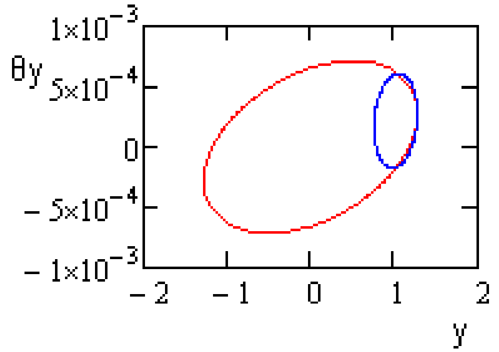


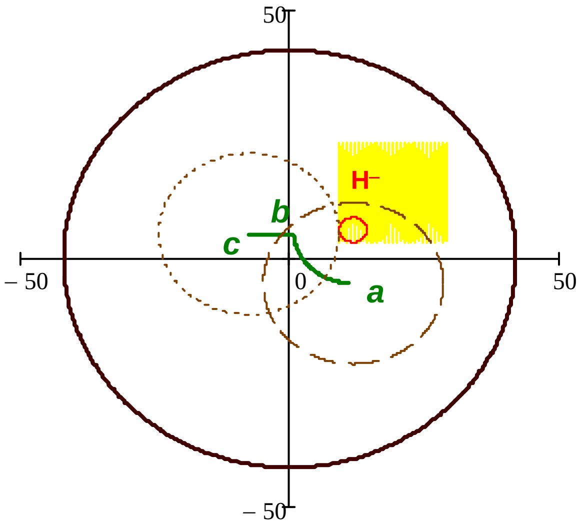


Transverse Painting

- Transverse painting objectives
  - Paint K-V like distribution
  - Minimize number of secondary passages through foil
- Major parameters
  - Linac emittance – 0.5 mm mrad (rms, norm.)
  - RCS beam emittance – 22 mm mrad (95%, norm.)
  - Linac α- and β- functions are 0.345 of RCS ones
- X-Y painting by CO displacement
  - Closed 4 corrector bumps in each plane
    - Independent control for X & θ on foil

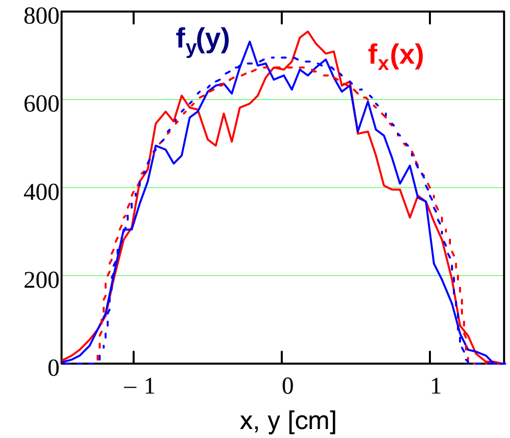


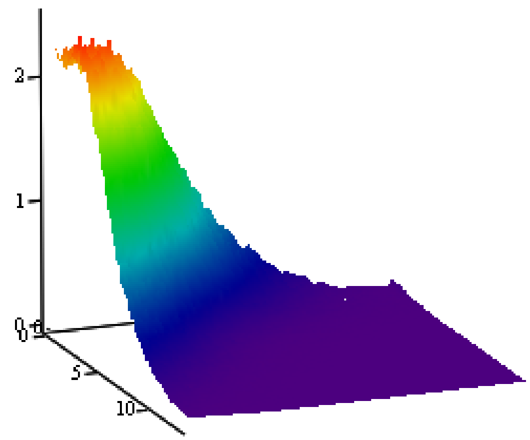


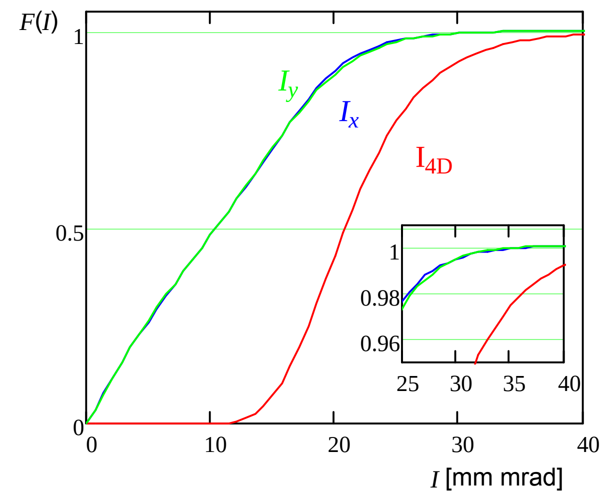


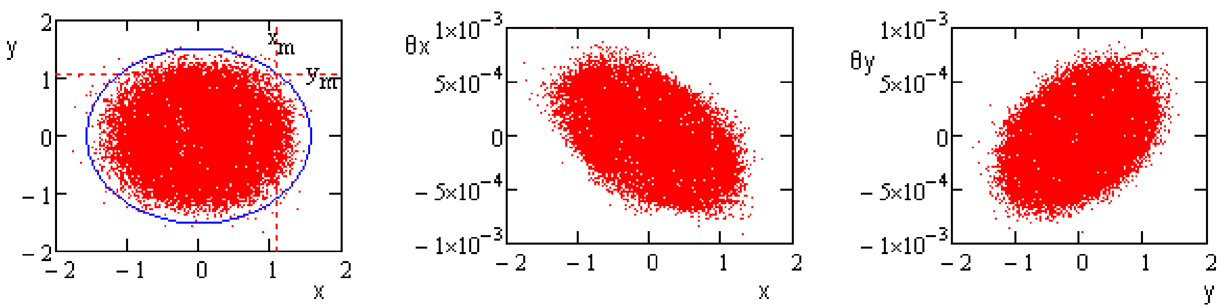
Simulation Results for Transverse Painting

- Final distribution is close to the KV-distribution
- 50 secondary passages per particle
  - 2.2 mm^{-2} per particle
- 420 μg/cm^2 foil is tilted by 45 deg. to increase cooling due to black body radiation
  - T_{max} = 1500 K
  - δ-electrons remove ~25% of heating







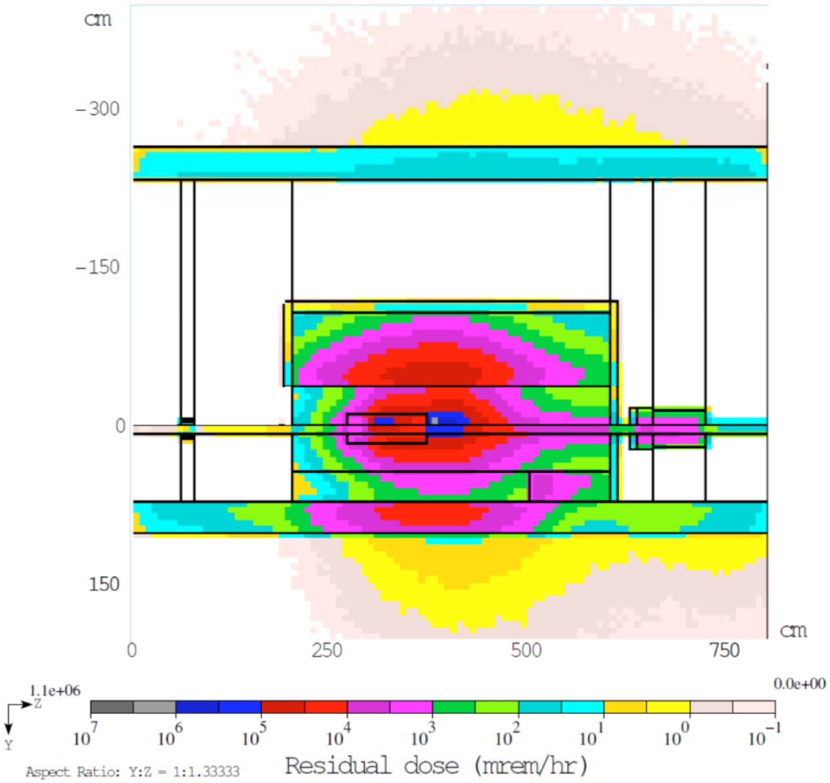


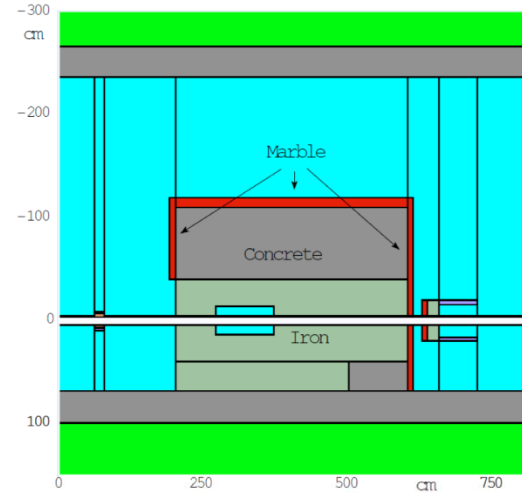
Injection Loss

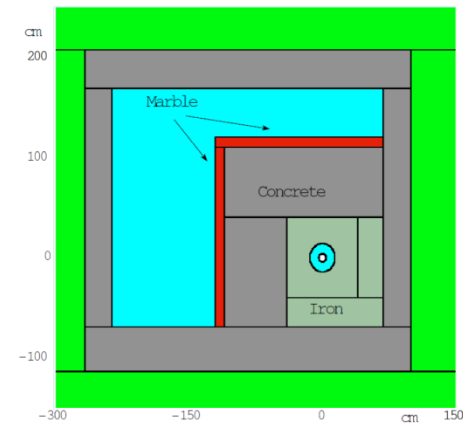
- Total injection loss ~4%
  - ~2% miss the foil
  - ~0.5% are not completely stripped in the foil
  - 0.15% are single scattered in the foil
  - ~1% are outside of 40 mm mrad RCS acceptance
- In normal operating conditions it results in the heat load
  - injection beam dump ~3 kW
  - collimation system ~1.5 kW
- Prudent design (confirmed by SNS experience) would have both the injection waste beam absorber and the collimation system designed to handle 10% or 8.5 kW

Injection Dump

- Injection dump is located in the tunnel
- It requires considerable radiation shielding



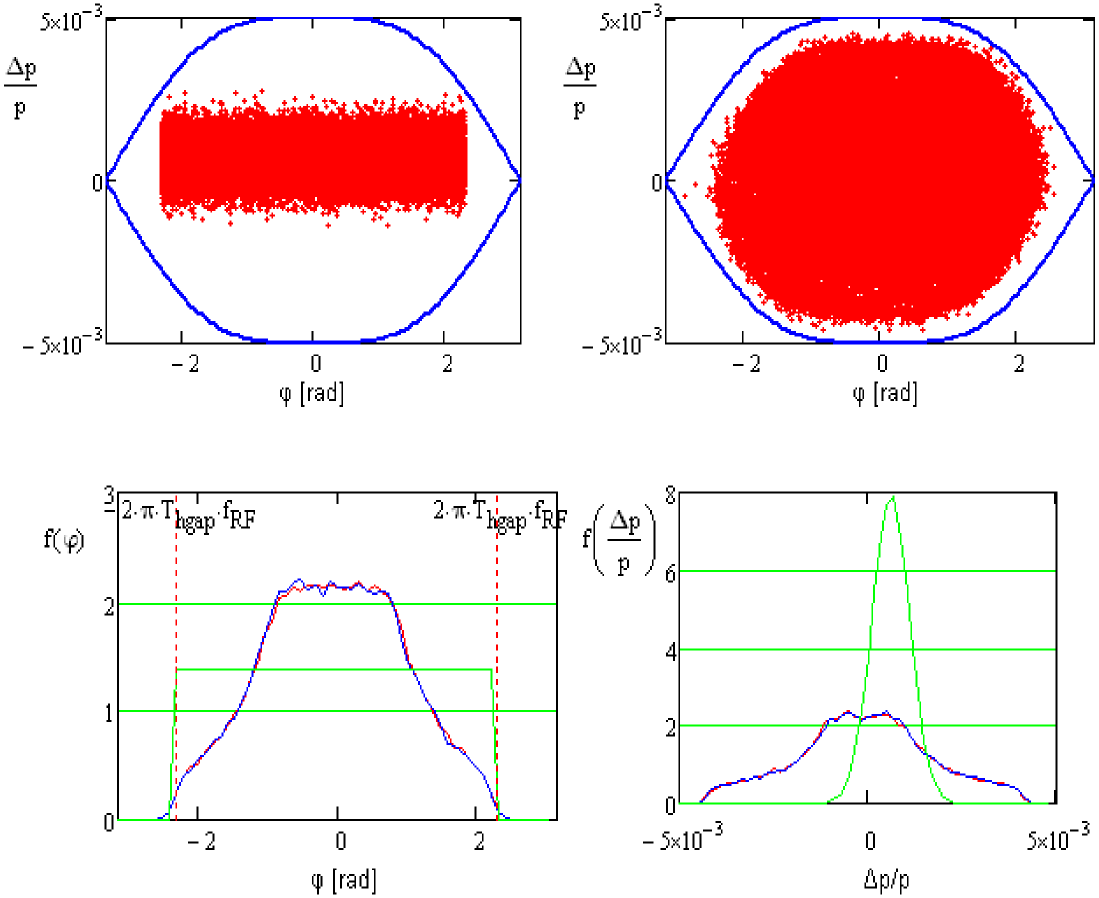




Longitudinal Painting

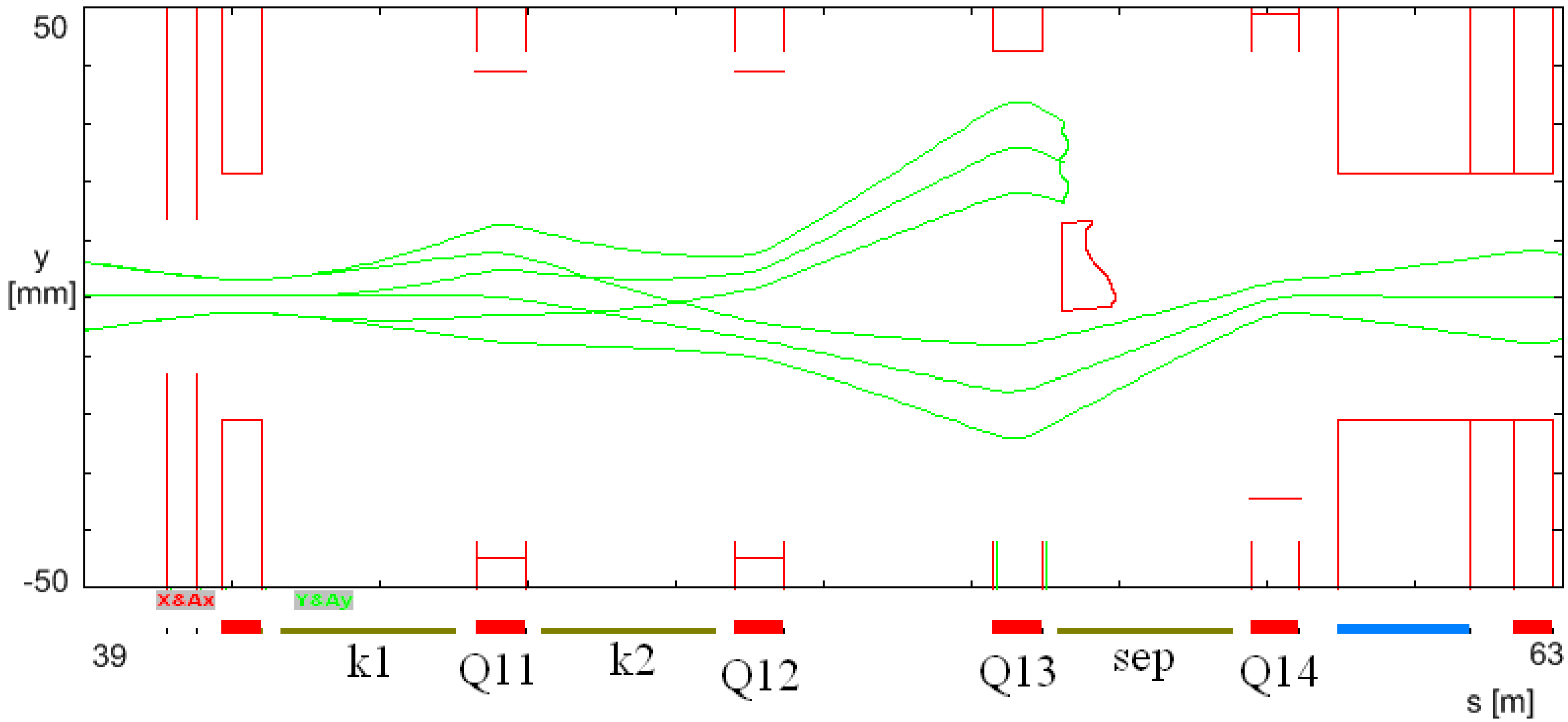
- Longitudinal painting is performed by momentum offset of linac beam
  - $\sigma_p = 5 \cdot 10^{-4}$,
  - $\Delta p/p = 7 \cdot 10^{-4}$,
  - $T_{inj} = 14.6$ ns (73%)
- Additionally, Linac has to compensate the RCS energy variation during injection (4.3 ms)
  - $\Delta E/E = 1.2\%$

$\Rightarrow$ Bunching factor = 2.2



Extraction

- Two kickers of 2.3 mrad each (±25kV, filling time 90 ns)
- Quads displacements make vertical closed bump
  - Q11 = -4.8 mm, Q12 = -6.39 mm, Q14 = 9.84 mm



RCS versus Pulsed Linac

- RCS
  - Less expensive
  - Injection at smaller energy
    ⇒ Easier to manage injection loss
  - Limited upgrade potential
    - Up to ~1 MW @15 Hz & 2-3 ns (MC) feasible with increased acceptance
- Linac
  - Easier to upgrade
    - to 4 MW power proton driver for MC
    - + to ~20 GeV recirculator for neutrino factory
  - Many injections per cycle if foil strip-injection is used (10 Hz)
    - Requires Recycler
      ⇒ 8 GeV final energy
  - An upgrade will require beam current increase: 1 → ≥20 mA
    ⇒2 GeV program discontinue or
    building another 2 GeV frontend!!!

Project X

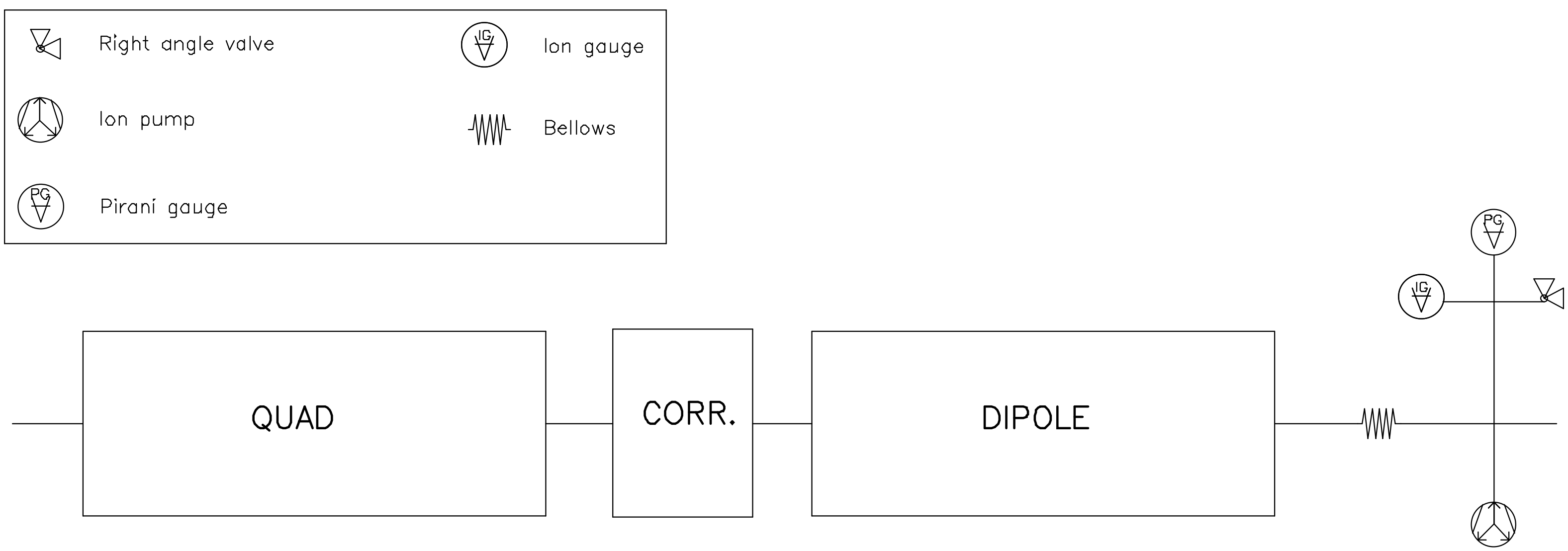
Conclusions

- RCS looks as a good choice to accelerate from 2 to 8 GeV
  - Less expensive than pulsed SC linac
    - ~287 M$ versus ~355 M$ (no escalations)
- It has considerable upgrade potential but cannot meet 4 MW required by Muon Collider
- Choice between RCS and Pulsed linac need to be done. It will be driven by
  - Cost & Upgradability

Backup Viewgraphs

Vacuum

- Vacuum chamber
  - 10^{-7} Torr or better (beam loss, ep instabolity)
    - No baking
  - Secondary emission suppression (TiN or carbon film)



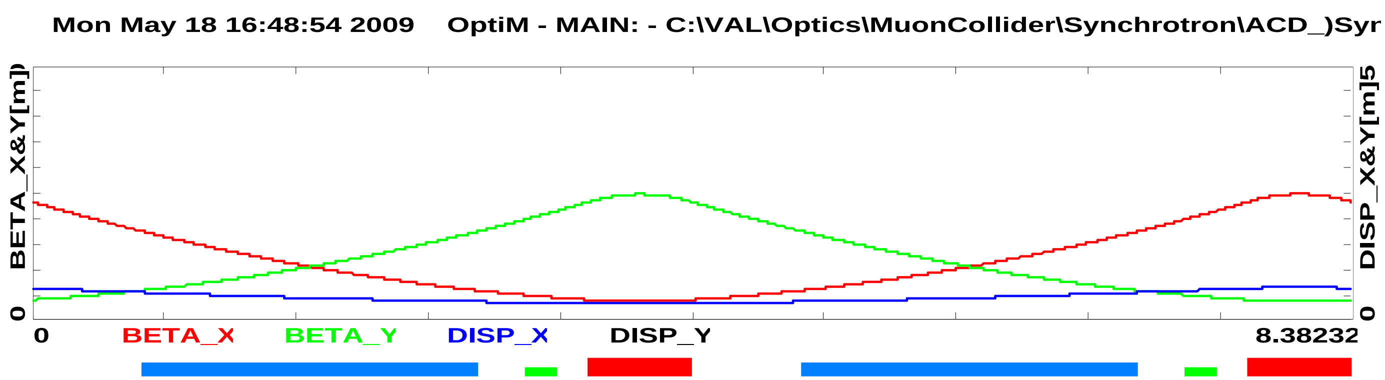
Optics and Orbit Correction

- Corrector pack near each quad: S and D coils
  - Dipole corrector near each quad (h – F, v – D)
    - 4 fast correctors in each plane for injection painting
  - Two families of sextupoles
    - Partial chromaticity correction: from -25 to -(10 ÷ 15)
    - No dynamic aperture limitation
- Optics correction
  - Additional coils in all quads for optics correction
  - F and D families (±0.25 tune correction) (∫GdL=1.1 kG)
    \+ 36 separate optics correction quads (∫GdL=2.2 kG)
  - 12 Skew-quads (coupling & vertical dispersion)

Name	Quantity	L[cm]	B_H[G]	B_V[G]	S[G/cm^2]
Regular H	50	20	550	-	200
Regular V	48	20	-	550	200
Straight line H	12	20	550	-	-
Straight line V	14	20	-	550	-
Injection	4	30	1000	1000	-

Optics Cell

Name	S[cm]	L[cm]	B[kG]	G[kG/cm]	S[kG/cm/cm]
qF	65.9	65.9	0	1.7675	0
o2	85.9	20			
sF	105.9	20	0	0	0.185
o1	135.9	30			
bD	349.116	213.216	8.7375	0	0
o	419.116	70			
qD	485.016	65.9	0	-1.7634	0
o2	505.016	20			
sD	525.016	20	0	0	-0.324
o1	555.016	30			
bD	768.232	213.216	8.7375	0	0
o	838.232	70			



Collimation and Instrumentation

- Collimators
  - Two stage
  - Located in the injection-extraction straight line
    - Positioning in the other line is also discussed
      - Choice is determined by loss scenario
- Instrumentation
  - Standard set of FNAL instrumentation (BPMs, BLMs, …)
  - Instrumentation for the injection region
    - Will be based on SNS experience

Stripping on Carbon Foil