Project X ACD and its Upgrades for Neutrino Factory or Muon Collider

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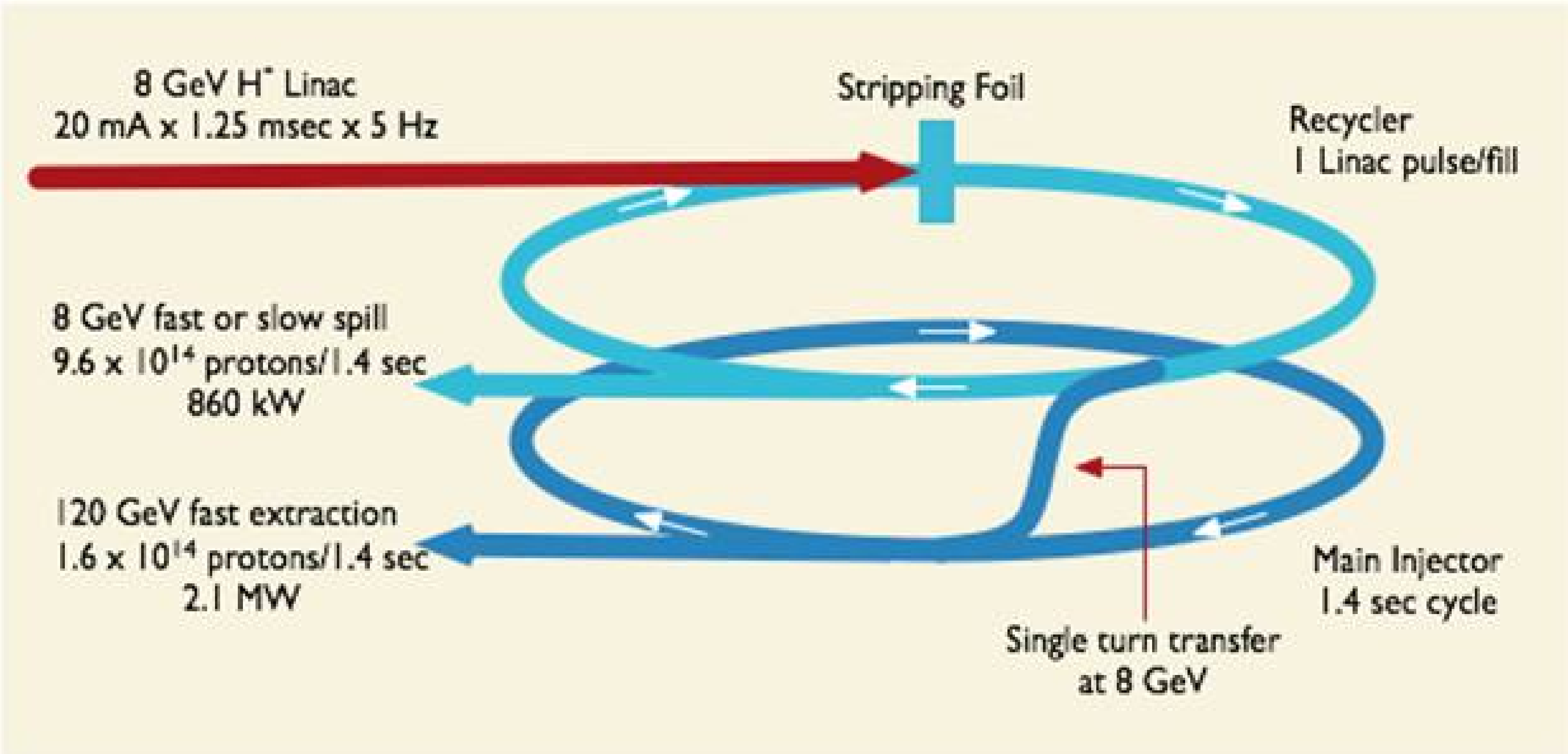
Project X Steps

- Some definitions (project management for a large DoE project)
  - ICD (Initial Configuration Document) is required by DoE for CD0 (mission need statement)
    - ACD (Alternative Configuration Document) is also required by DoE at CD0
  - Other steps: CD1 ⇒ CD4 (critical decisions) lead to the project design, construction and commissioning
- Fermilab is working on the Project X ICD
  - Project X was initiated in the summer of 2007 and has been considered as a next step in the Fermilab program.
    - Tevatron operations will be terminated in 2-3 years.
  - "First" ACD proposal (November 2008) – tried to address problems of Muon collider but did not bring any good for physics program and did not get support
  - Next ACD proposal appeared in April 2009
    - Subject for this presentation
    - Looks as something what we would like to build
    - New committee was created to strengthen the physics program
    - Strong support at PAC (end of June 2009, Aspen, Colorado)

      ⇒ ACD was renamed to ICD-II

What is Project X?



- New proton injector or a replacement for 40 years old Booster
- 8 GeV SC linac +
  - Modifications in Recycler and MI

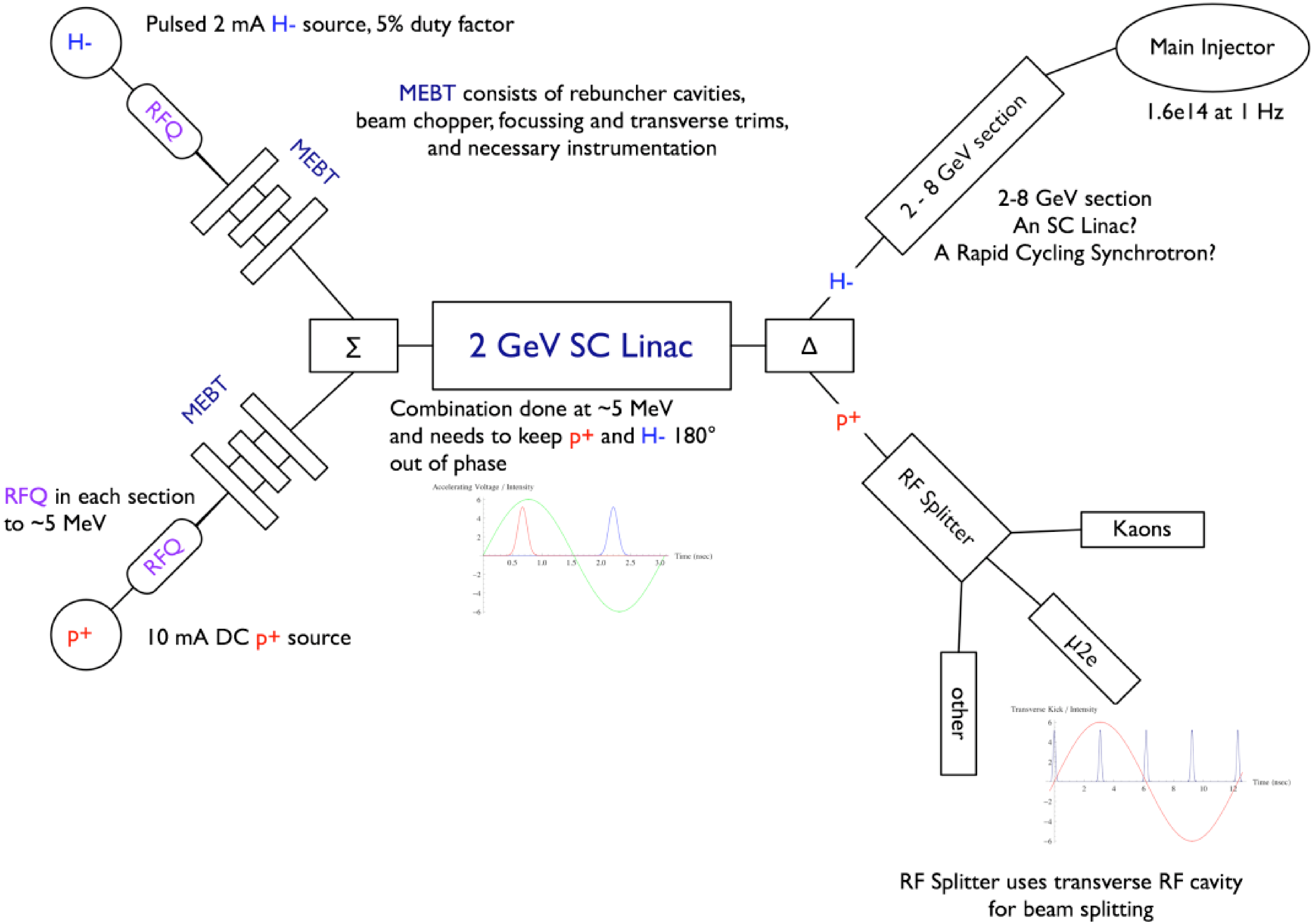
Project X Objectives

- Major Project X objectives (ILC time, stands for now as well)
  - Support of the neutrino program in MI with 2 MW beam power in the energy range of 60 to 120 GeV
  - Development of SCRF technology capabilities at Fermilab for future applications (ILC, neutrino factory, muon collider)
- Is it enough?
  - Present neutrino program (~200-300 people) $\Rightarrow$ Future neutrino program
  - CDF & D0 (1500) $\Rightarrow$ CMS (external) + ??? (internal)
- To succeed we need a strong physics program
  - Transition from the energy frontier to the intensity frontier implies experiments at very high repetition rates from ~30 MHz (kaons) to ~60 Hz (g-2).
- What else we have in plans for intensity frontier
  - Experiments with muons
    - μ-to-e (muon to electron conversion in field of nucleus with lepton number violation) is a front runner
    - g-2 (muon g-2 measurements, inherited from Brookhaven)
  - Rare Kaon decays ($K_L \to \pi^0 \nu\nu$, $K^+ \to \pi^+ \nu\nu$, $K_L \to \pi^0 e^+ e^-$)

Problems with ICD-I

- μ-to-e is considered as the most important experiment
  - It will be using all existing infrastructure (Recycler, Accumulator and Debuncher) leaving no place for other experiments for many years
  - g-2 has time conflict because competes for the same infrastructure (Recycler and Debuncher) and cannot be ran at the same time
    - Lengthening Tevatron Run II worsens the problem
  - Kaon experiments require different time structure of the beam and cannot be ran simultaneously
    - There is another possibility - a usage of Tevatron as a stretcher. We are looking into this as well
- From the High Energy Physics point if view:
  - CDF & D0 $\rightarrow$ μ-to-e + decommissioning of the Antiproton source
- There is also problem with μ-to-e upgrade because of limited power for the beam slow extracted from Debuncher

What is the ICD-II



- Split 8 GeV linac into 2 parts
  - 0-2 GeV, 2-MW (1 mA) CW linac
    - peak current up to 10 mA to have ability to create a desired beam structure for different beam physics experiment without sacrificing average beam power
  - 2-8 GeV acceleration
    - 10 Hz synchrotron looks as a preferred choice for now
      - o Operates below transition energy
    - 2-8 GeV, 0.22-MW pulsed linac

      β = 1 (ILC-like):

      40 ms @ 1Hz or variations for 2.2 MW at 60 GeV (300 kW at 8GeV)
- At least 1 mA of CW linac is required
  - For synchrotron by inj. time (10 Hz, 4 ms of 100 ms cycle, $\Delta p/p=8\cdot 10^{-3}$)
  - 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)
  - Higher current would make pulsed linac easier
- CW linac beam can be split to several experiments by RF separators
  - 3 experiments with independent beam time structures
    - $f = f_{RF} / 3$ (~100 MHz, ~1-3 ps rms bunch length)

ICD II effect on the Physics Program

- Machine Parameters are set by Experiments
- μ-to-e (1 GeV would be enough)
  - much better than the present scheme,
    - some loss in pion yield is compensated by power
    - Smaller background (less neutrons, antiprotons, high energy pions)
    - Negligible intensity variation (serious problem for slow extraction)
    - Easy to control time structure of the beam (~10% duty factor)
    - Extinction
      - ⇒ Proton linac does not accelerate electrons or protons with other momentum. The chopper is the only system determining beam extinction
    - addresses strong competition from JPARC and future upgrade
- Kaons require at least 2 GeV energy
  - Flexible time structure and short bunches are extremely useful
    - Time of flight experiments
- g-2 can be ran with "fast" extraction from Recycler
- Program with antiprotons is discussed
- Additional program is possible
  - Transmutation, medical isotopes production and nuclear physics

CW Linac*

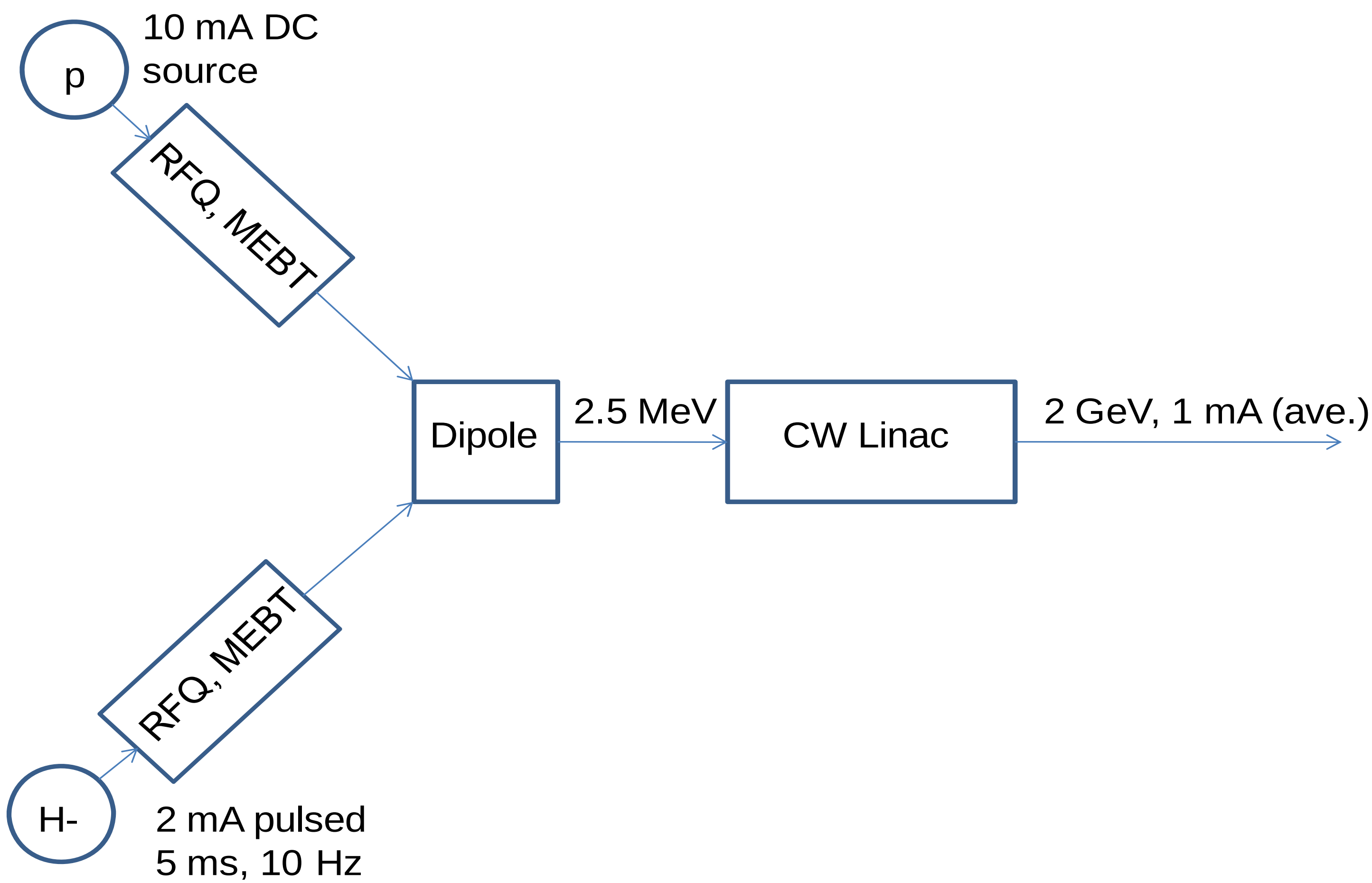
Design criteria

- Linac structure is similar to the ICD-I linac
- Major differences are
  - Reduced accelerating gradient to optimize the cryogenic system (cost optimization results in a wide minimum 15 – 18 MV/m)
    - 25 MV/m $\Rightarrow$ 16 MV/m
  - Reduced peak current
    - 32 mA $\Rightarrow$ 10 mA
    - Less problems with beam space charge
  - SC structures start at 2.5 MeV instead of 10 MeV
    - Reduction of RF power

* Disclaimer: all parameters of the ICD-II are not final. The ICD-2 document is expected to be finished by Sep. 1, 2009

Front end

- Dual beam
  - H- for injection to RCS
  - Proton for 2 GeV experimental program
- Bunch-by-bunch chopping
- 2.5 MeV, normal conducting RFQ



SC linac

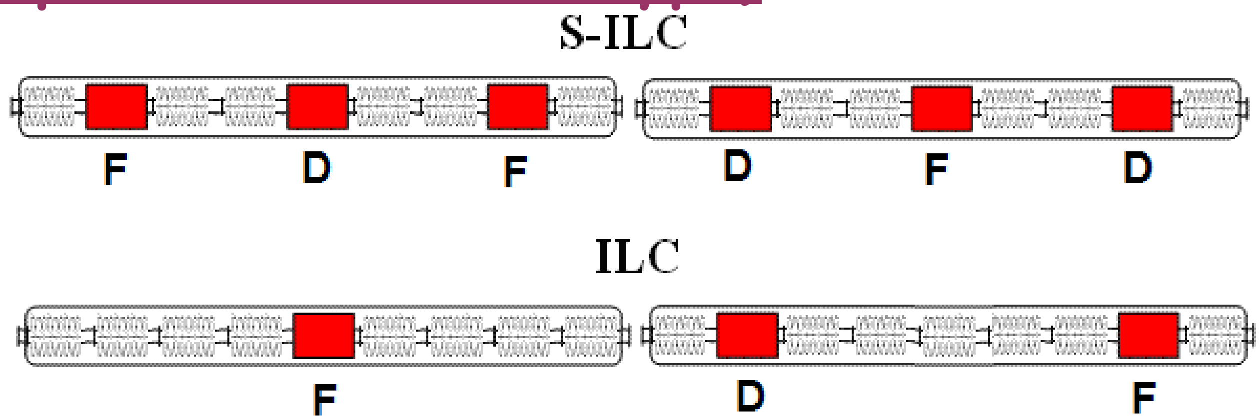
SSR0	SSR1	SSR2	TSR	MS	SILC	ILC

Parameters of 325 MHZ cavities

Section	Energy range MeV	β	Number of cavities/ lenses/CM	Type of cavities and focusing element	Power/cavity, kW (I_{av}=1 mA)
Bunching SSR0 (β_G=0.11)	2.5	0.073	2/3/2	Single spoke cavity, Solenoid	0.5
SSR0 (β_G=0.11)	2.5-10	0.073-0.146	16/16/2	Single spoke cavity, Solenoid	0.5
SSR1 (β_G=0.22)	10-32	0.146-0.261	18/18/2	Single spoke cavity, Solenoid	1.3
SSR2 (β_G=0.4)	32-117	0.261-0.5	33/17/3	Single spoke cavity, Solenoid	4.1
TSR (β_G=0.6)	117-400	0.5-0.713	42/42/7	Triple spoke cavity, quads	8.5

β_G is cavity geometrical phase velocity.

SC linac (Elleptic cevities, ILC type)



Parameters of 1.3 GHZ cavities

Section	Energy range MeV	β	Number of cavities/ quads/CMs	Type	Max Power/cavity (on crest), kW (I_{av}=1 mA)
S-ILC (β_G=0.81)	400-1200	0.71-0.9	84 / 42/ 14	Squeezed elliptical	15
ILC (β_G=1)	1200-2000	0.9-0.95	75 / 15 / 10	9-cell ILC	16

Synchrotron

Design criteria

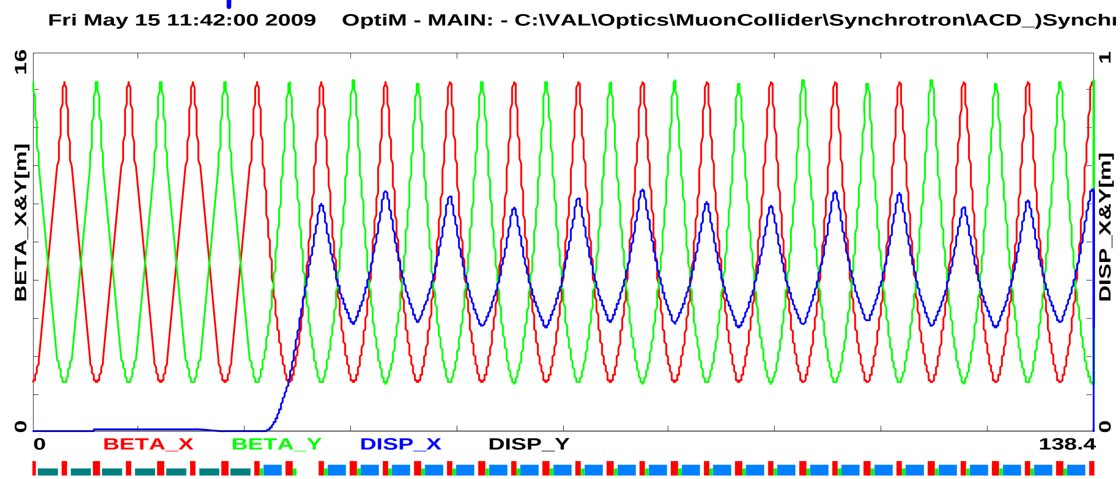
- Repetition rate of 10 Hz is set by 2 MW to MI operating at 60 GeV (6 injections during 0.8 s cycle)
  - Recycler is used for intermediate beam storage
- No transition crossing
- Transverse acceptance (40 mm mrad (norm) + 6 mm orbit distortions) – the same as for MI
- High periodicity FODO structure
  ⇒ Small diameter vacuum chamber
  ⇒ Small and inexpensive magnets
- Stainless still vacuum chamber
  - It shields laminations of magnets resulting in small impedances
    - The impedance value is rather limited by the eddy currents excited by the bending field than by the wall resistivity
  - Ceramic vacuum chamber would be more expensive and would require larger size magnets with limited gain in impedance
- Dual harmonic RF to reduce the beam space charge at injection
  - RF frequency the same as in MI

RCS parameters

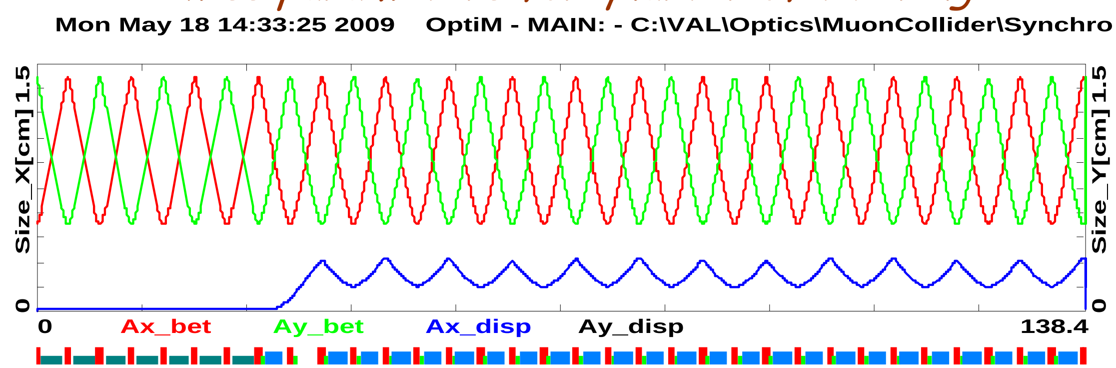
Energy, min/max, GeV	2/8
Repetition rate, Hz	10
Circumference, m (MI/6)	553.2
Tunes	18.44
Transition energy, GeV	13.36
Number of particles	2.67E13
Beam current at injection, A	2.2
Harmonic number	98
RF frequency, MHz	50.33 - 52.81
Maximum RF voltage, MV	1.6
95% n. emittance, mm mrad	25
Space charge tune shift, inj.	0.06†
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	0.4
Number of RF cavities	16
Cavity shunt impedance, kΩ	100

†For the KV-like distribution presented below and bunching factor – 2.2.

- 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

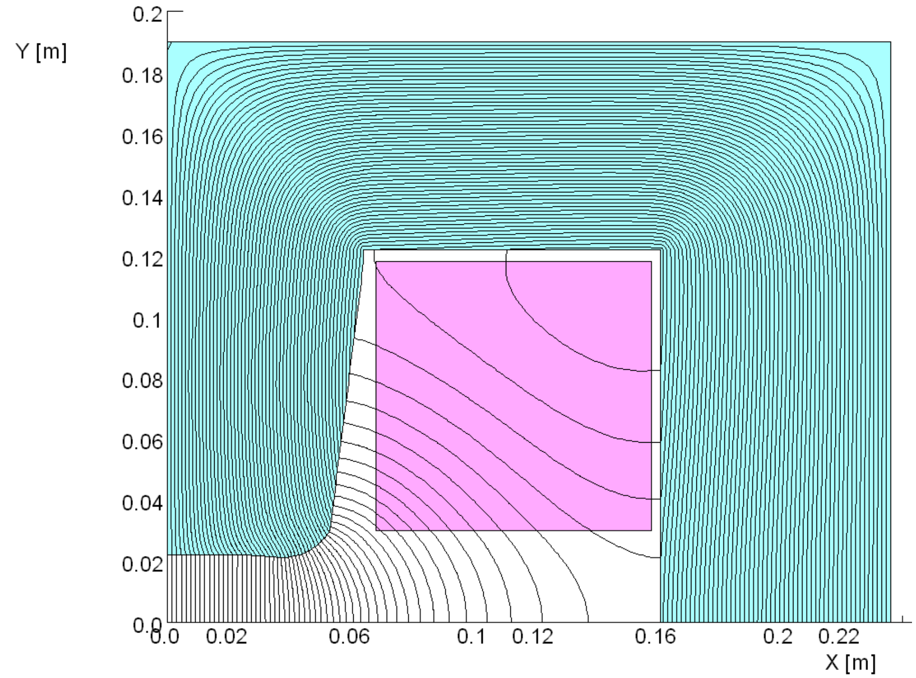


Beam envelopes for quarter of the ring;
ε_n=40 mm mrad (E_k = 2 GeV), $\Delta p/p = 5\cdot 10^{-3}$

Magnets

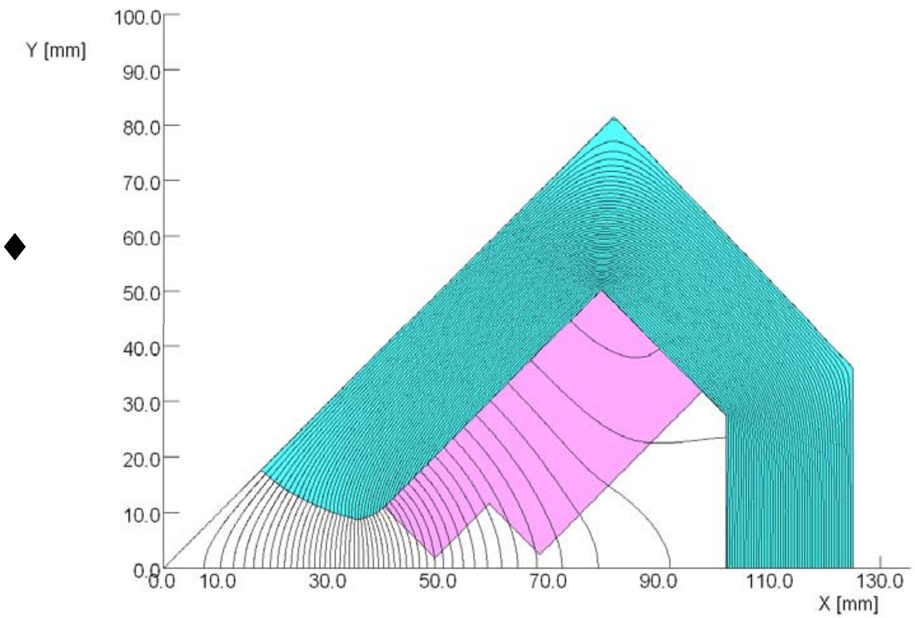
Dipoles

Parameter	Unit	Value
Field at 8 GeV (672 A)	T	0.874
Magnet gap	mm	44
Effective length	m	2.13
Number of turns/pole		24



Quadrupoles

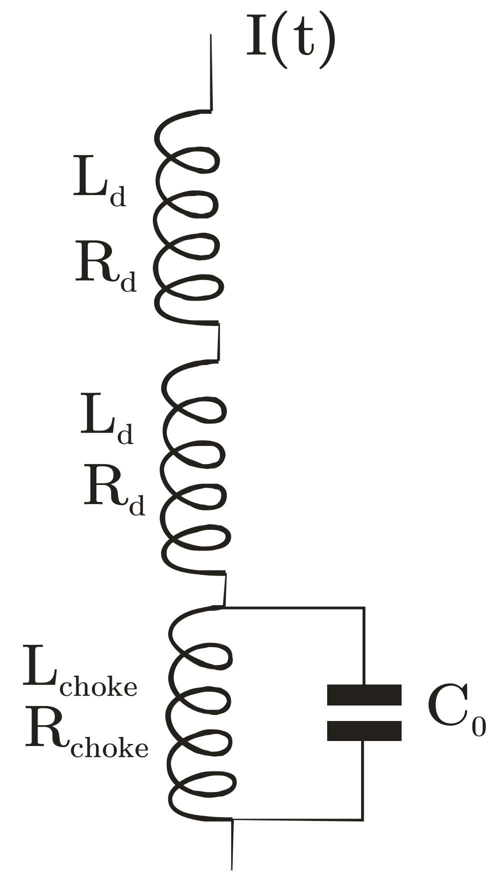
Parameter	Unit	Value
Gradient at 8 GeV (672 A)	T/cm	0.1743
Pole tip radius	mm	25
Effective length	m	0.659
Number of turns/pole		7



100 Rectangular dipoles and 134 quads (6 of them with increased aperture for inj. & extr.)

Vacuum chamber

- Round
  - External diameter - 44mm
  - Stainless steel - 0.7 mm
- Bend in dipoles, R=34 m
  - Sagitta – 1.67 cm
- Eddy currents (dipoles)
  - $\Delta B/B$ - $i \cdot 1.4 \cdot 10^{-3}$
  - Power loss(B_m=8 GeV)-11W/m
- Growth rate of the transverse instability due to wall resistivity at lowest betatron sideband – 0.006 turn^{-1}



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

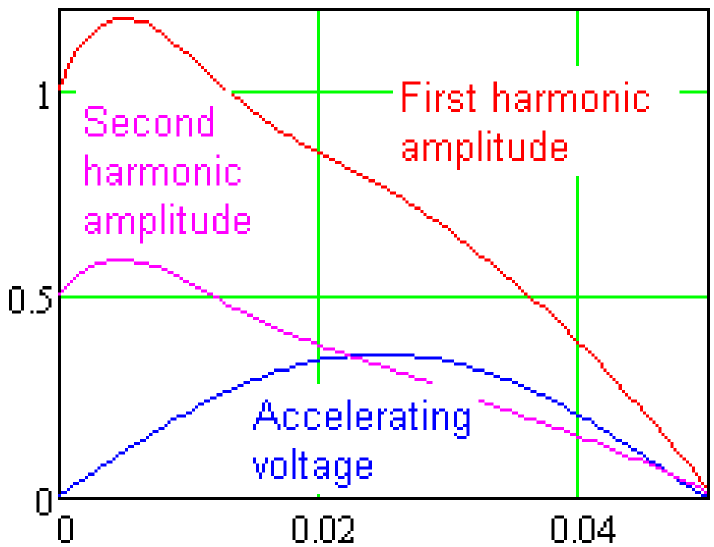
Total AC (ampl) – 1.1 kV

Dipole resonance circuit

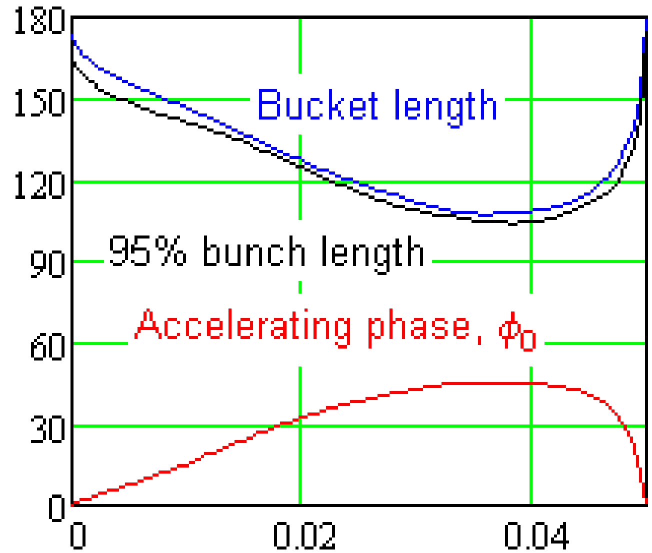
- Resonance circuit is similar to the Booster one
  - One choke and one capacitor per cell (2 dipoles and 2 quads)

Beam acceleration

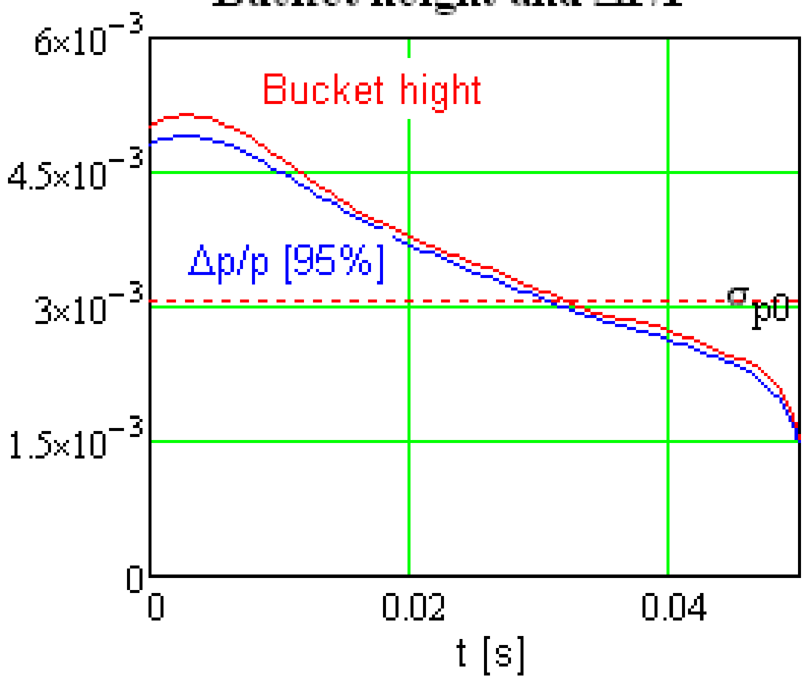
Accelerating voltage, MV



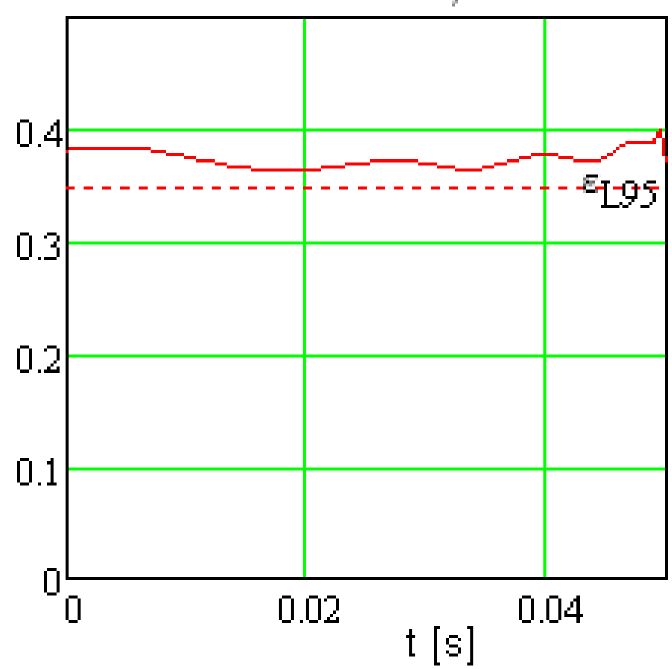
Accel. phase and bunch length, deg



Bucket height and ΔP/P

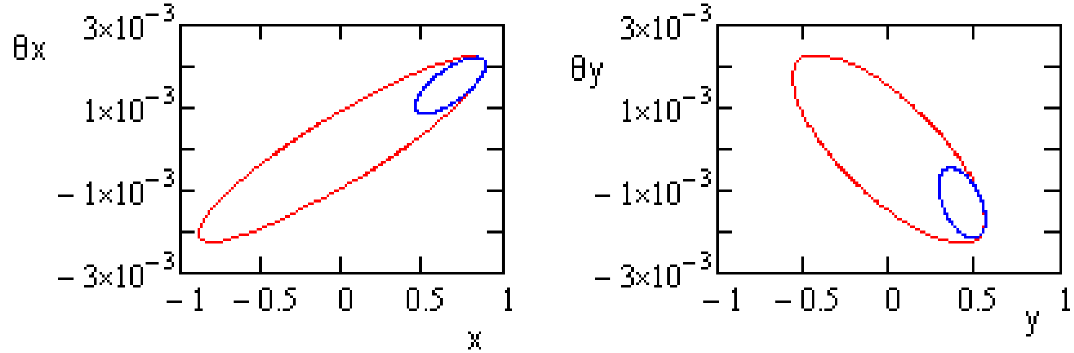


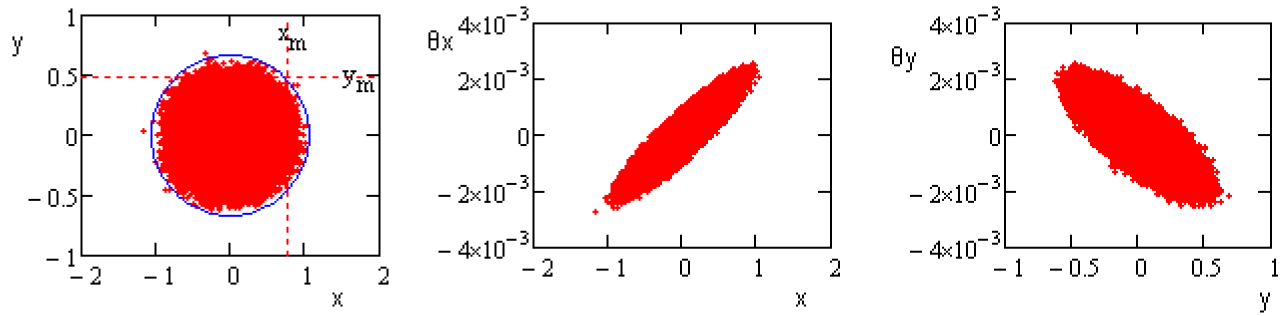
Bucket aria, eV s

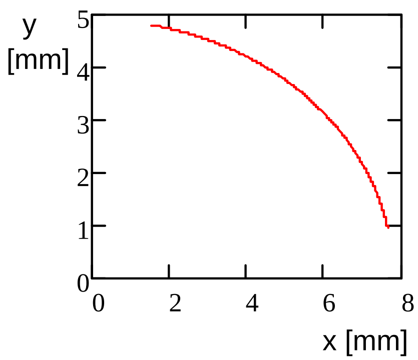


Transverse painting at Injection (rms norm. linac emit. – 0.5 mm mrad)

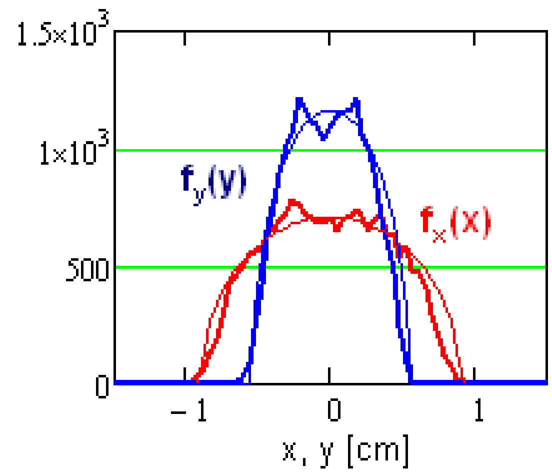
- Optimization of injection beta-functions: $\beta_L \approx \beta_R/2$
- KV-like distribution with 25 mm mrad KV boundary
  - 99% in 35 mm mrad
  - x-y anti-correlated painting
  - angles correlated with positions to minimize betatron amplitudes



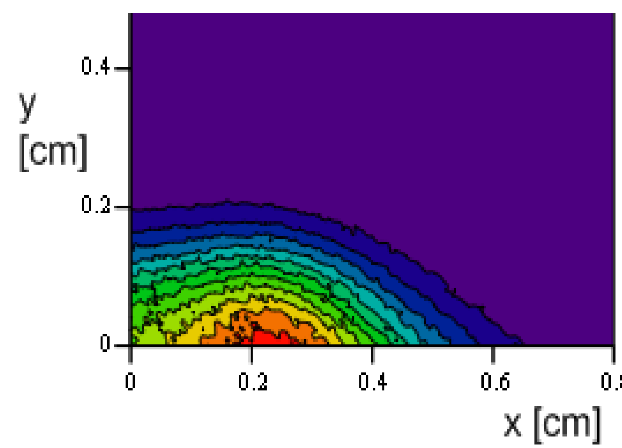




Single dimentional beam density at injection point at the end of painting



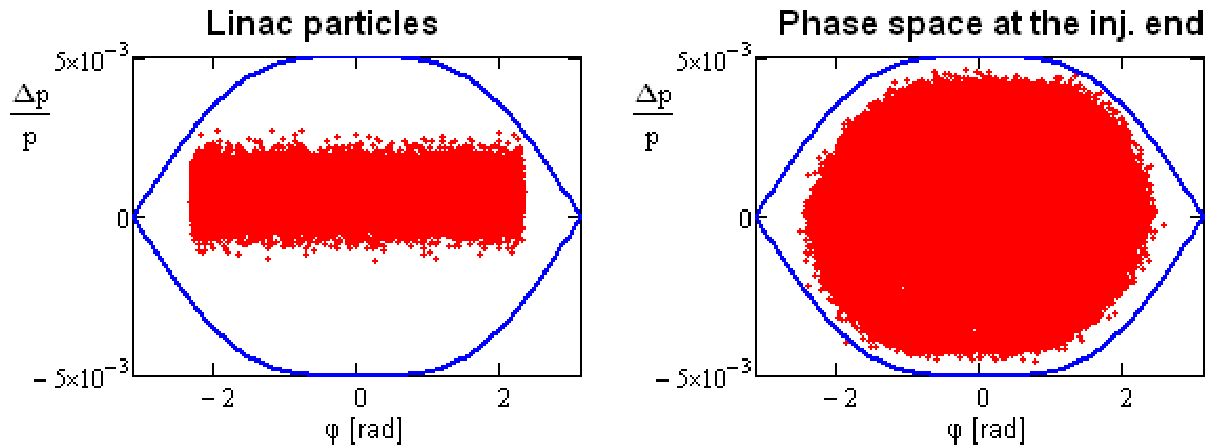
Power density

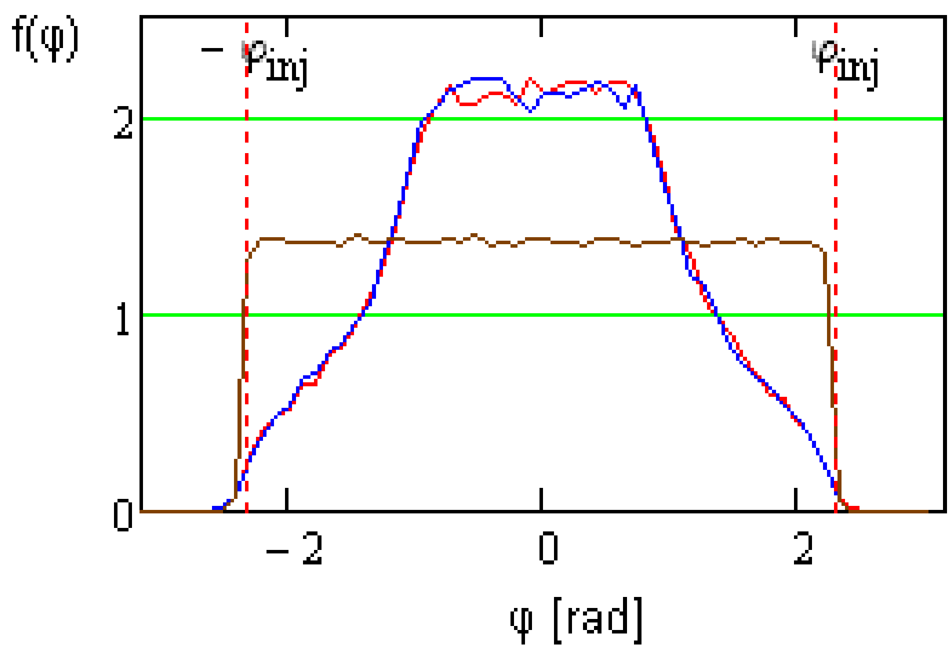


- Secondary foil passages make a major contribution to the foil heating
  - 55 hits per particle or $1.2 \cdot 10^5$ passages per particle per mm^2

Longitudinal painting at injection (rms. long. linac emit. – $5 \cdot 10^{-5}$ eV s)

- Linac energy is changing ±0.5% to match the RCS energy during 4.2 ms injection
  - Constant offset of 0.07% between linac and RSC momenta
  - 73% duty factor
- High synchrotron frequency helps to make uniform distribution
- Debunching and phase rotation of the linac beam is required
- Resulting bunching factor – 2.2





Possible upgrade paths

RCS without any upgrades

- Low longitudinal density is the major limitation of the beam power. To mitigate it:
  - Beam is accelerated in two trains of 24 buckets (50% duty factor)
    - Bucket size is reduced from 0.4 to 0.13 eV s to fit required ε_L
    - Space charge tine shift – 0.12
  - Two turn injection in the compressor ring with consecutive adiabatic bunching and bunch rotation
- **It results in P=340 kW at 10 Hz (single bunch)**
  - σ_s = 60 cm, σ_p = 0.1%, $\varepsilon_{s95} = 6\pi\, \sigma_s\, \sigma_p\, p\, /\, (\beta c)$ ~3.3 eV·s)
- The only additional requirement (upgrade) is doubling the current of H- source (2 mA $\rightarrow$ 4 mA)
  - And, of course, the 8 GeV compressor ring with circumference half of the RCS

Possible Upgrade Paths (2)

New 20 GeV 20 Hz RCS

- Peak power of the SC linac has to be increased by at least 12 times to 12 mA
  - 1.5 times larger energy (3 GeV, pulsed)
  - 2 times shorter injection to RCS (20 Hz)
  - 2 times larger beam current in RCS (larger injection energy)
  - 2 times larger circumference (20 GeV)
- Synchrotron can be built using the same technology as 8 GeV synchrotron
  - 3 trains of bunches, 3 turn injection to the compressor ring
- **It results in P=1.7 MW at 20 Hz (single bunch)**
- Upgrades
  - RF of SC linac
    - it can be converted to the pulsed (preferred and chipper) operation or operation with two RF sources for concurrent pulsed and CW operations
      - 24 MW CW RF is not excluded as well
  - And, 20 GeV compressor ring with circumference one third of the RCS

Possible Upgrade Paths (3)

Linac extension to 8 GeV

- Follows scenario presented in Berkeley (Jan. 2009, NFMCC meeting)
- 1 MW at 15 Hz single bunch
  - Power will grow proportionally to the repetition frequency and number of bunches
  - i.e. four bunches 4 MW at 15 Hz

Conclusions

- ICD-II 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 the Recycler
- Benefits
  - ♦ Diverse physics program at low energy
    - expected to bring the price below ICD-I
      ⇒ Pricing should be finished by the end of August
  - ♦ Potential improvements of μ-to-e sensitivity can be more than an order of magnitude – it makes it really competitive
- Drawbacks
  - ♦ More expensive upgrade to MW scale beam power required for neutrino factory or muon collider
- Both Synchrotron and Pulsed linac can coexist with CW linac
  - ♦ Final choice will be compromise between

    Cost - Political implications - Long term plans

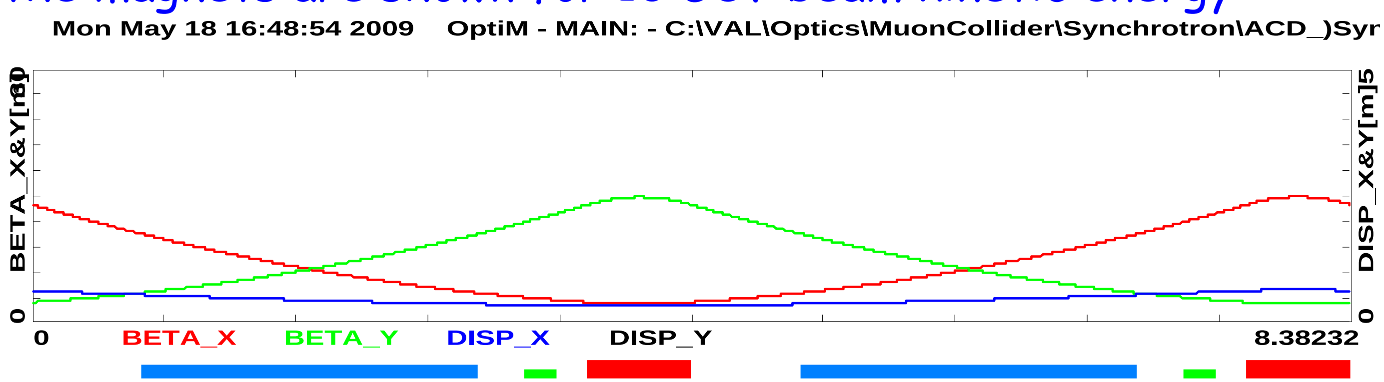
Backup viewgraphs

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

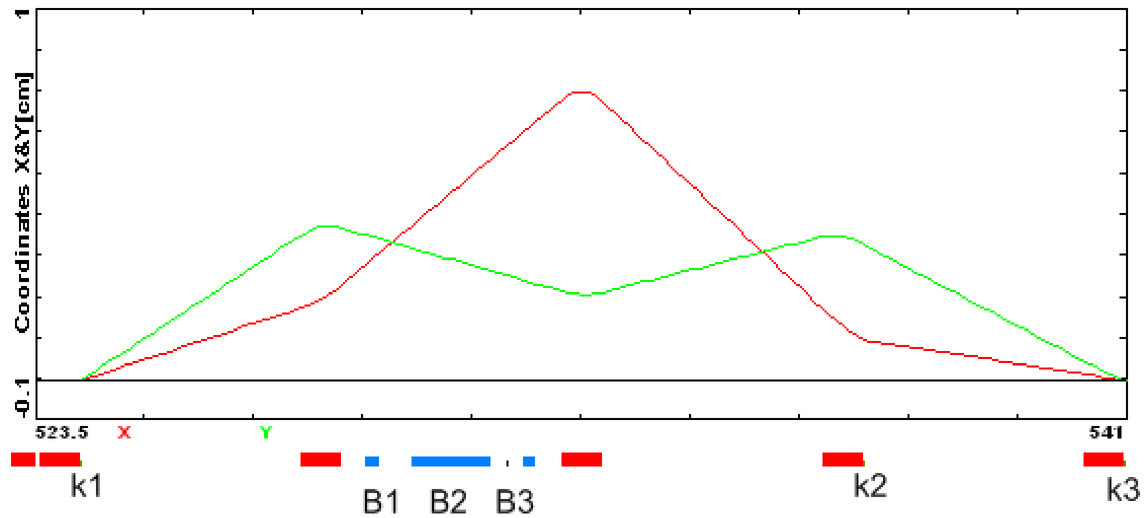


Injection

- 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



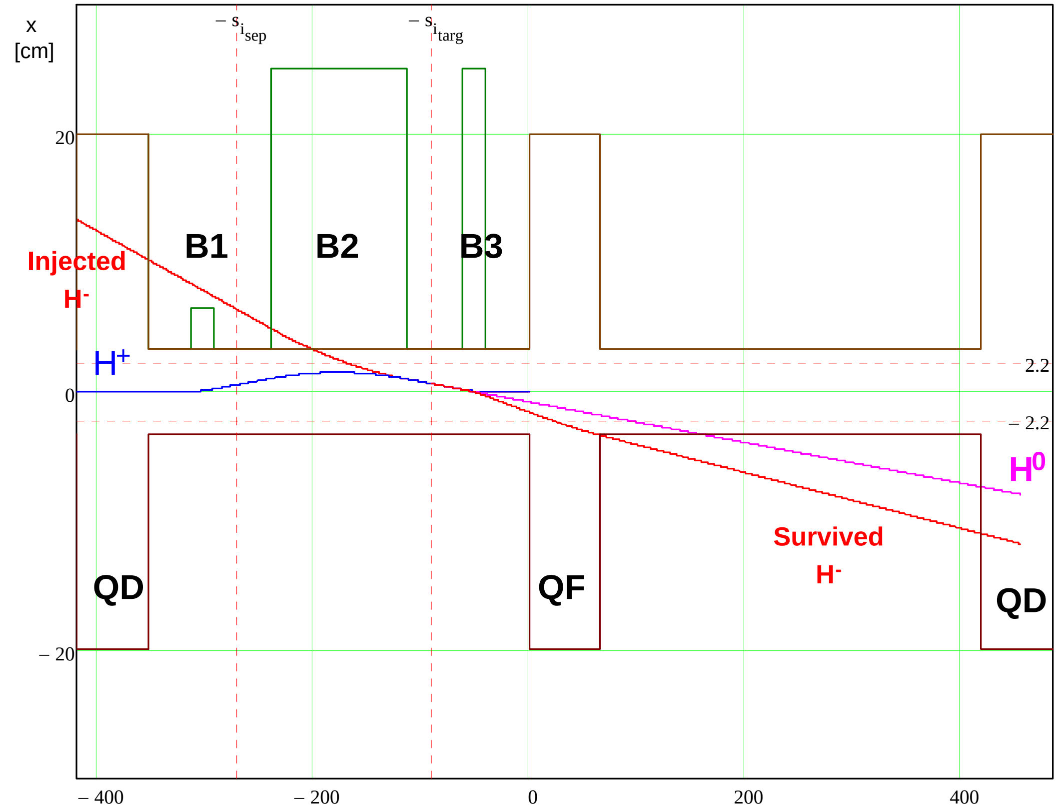
Local orbit bump for painting;

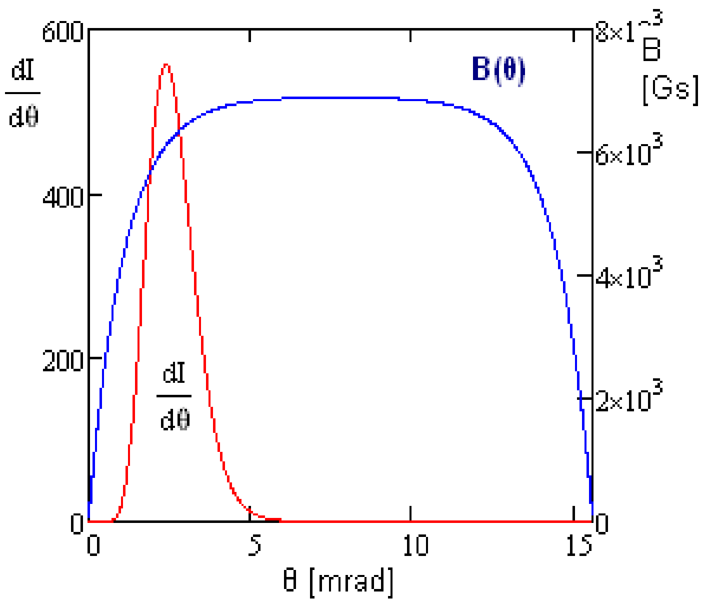
Maximum corrector strength – 15 kG cm

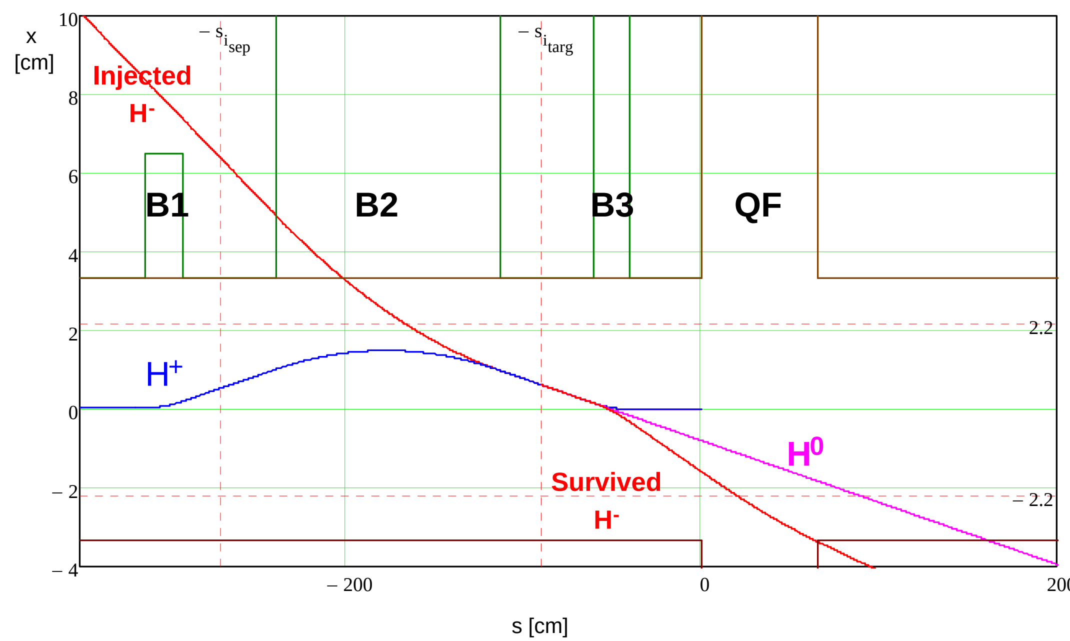
Swiping time – 4 ms

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)

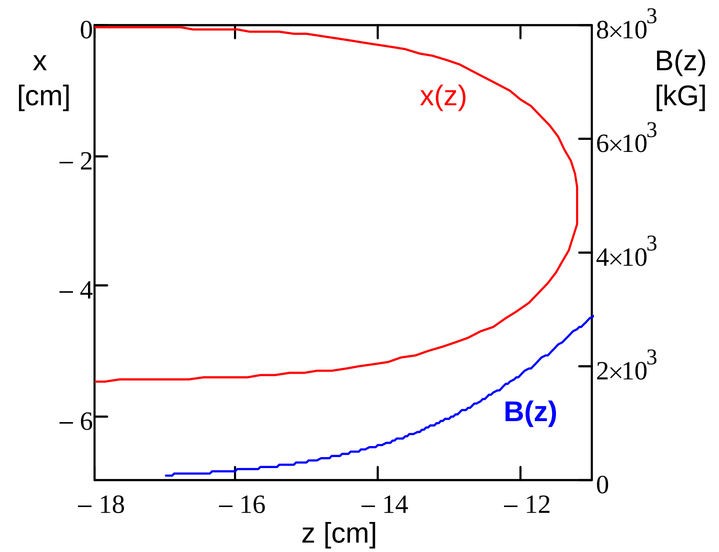
- Single and multiple scattering in the foil (thickness - 450 $\mu g/cm^2$)
  - Emittance increase due to multiple scattering is not a problem
    - Emittance increase per foil crossing:

      $\Delta\varepsilon_{xn95\%} = 8.5 \cdot 10^{-3}$ 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
    - 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



Extraction

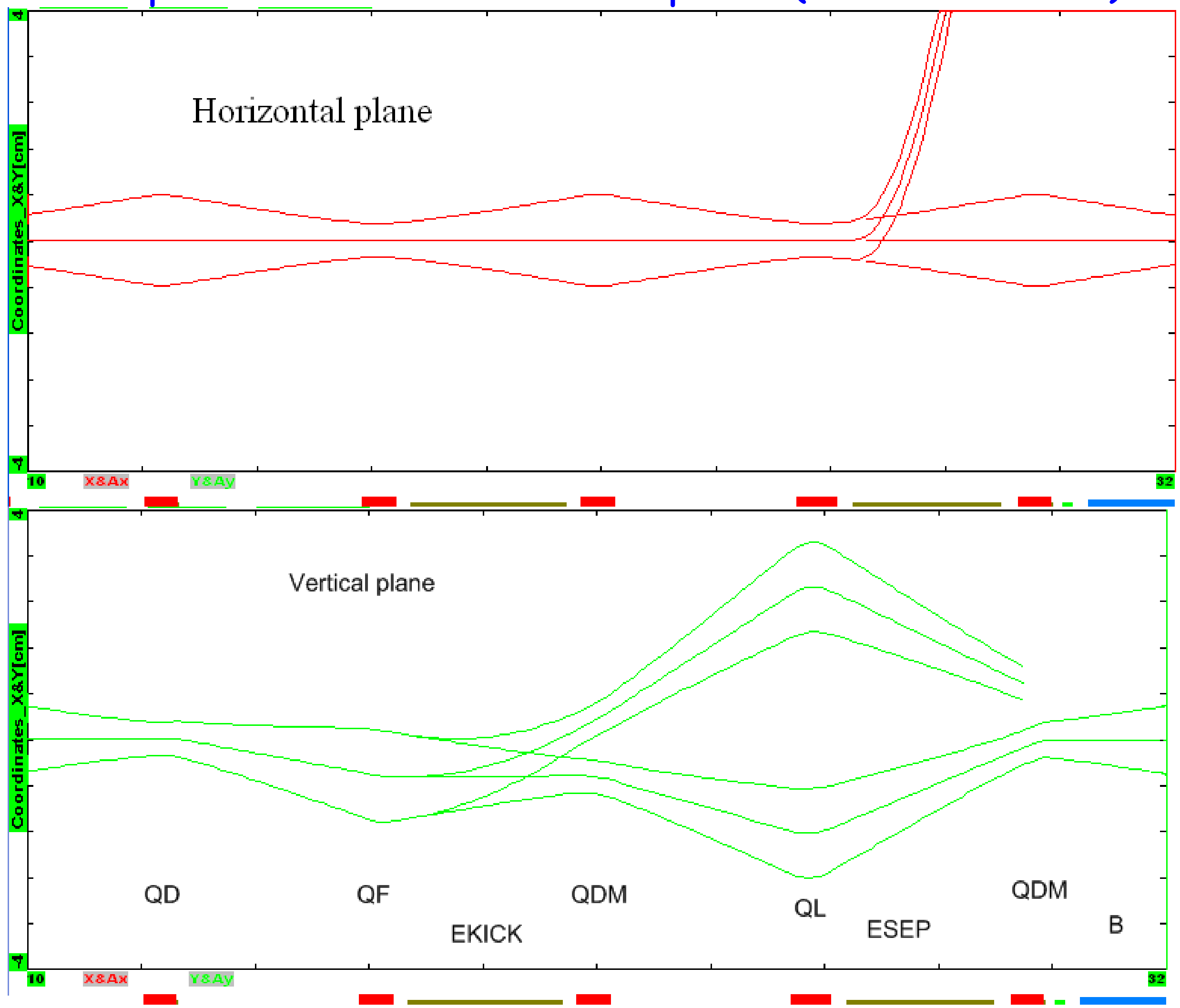
Extraction structure

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)



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 for the round vacuum chamber

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

  - 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)