U.S. DEPARTMENT OF ENERGY

Fermilab

The Project X Accelerator Complex

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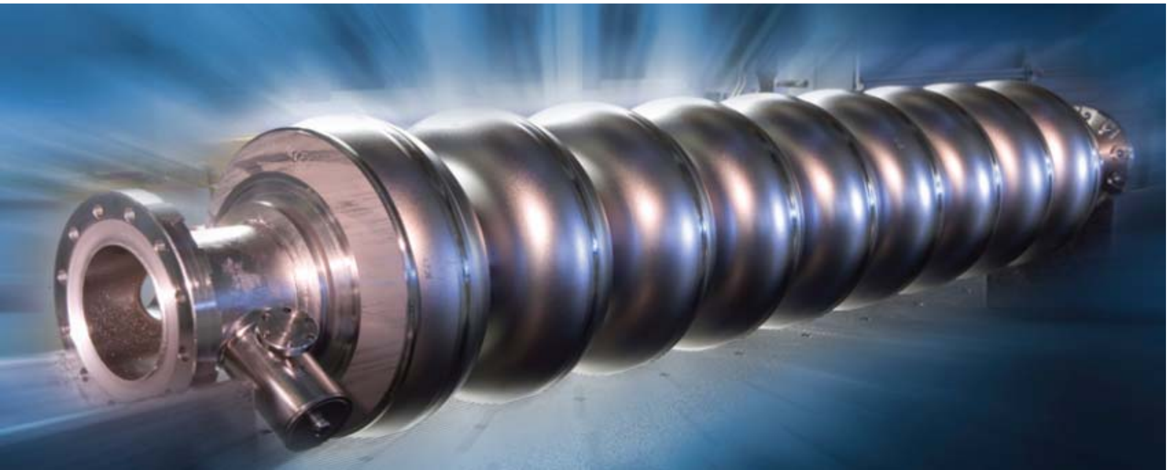


The 4th Workshop on Physics for Project-X
Fermilab
November 9 - 10, 2009

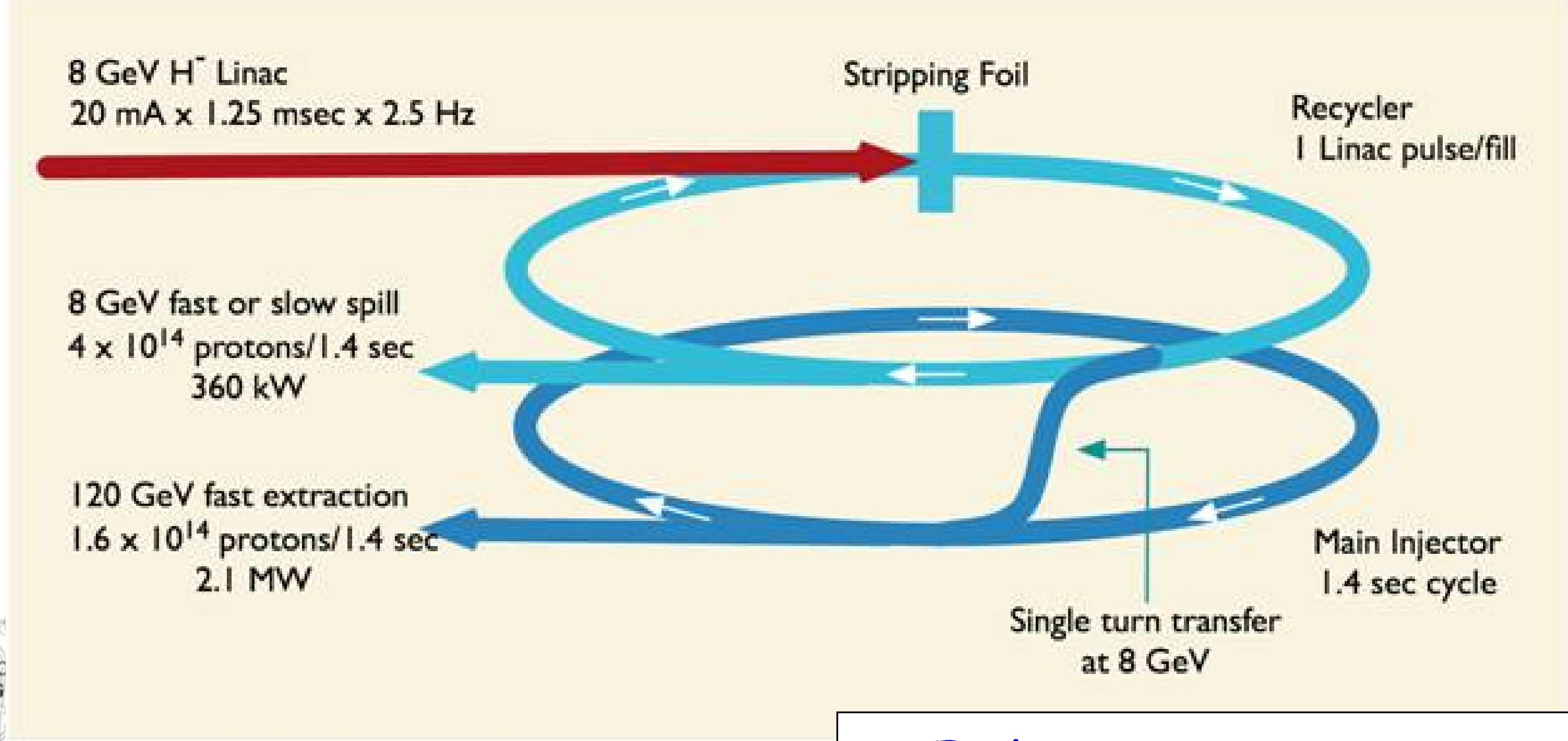
Contents

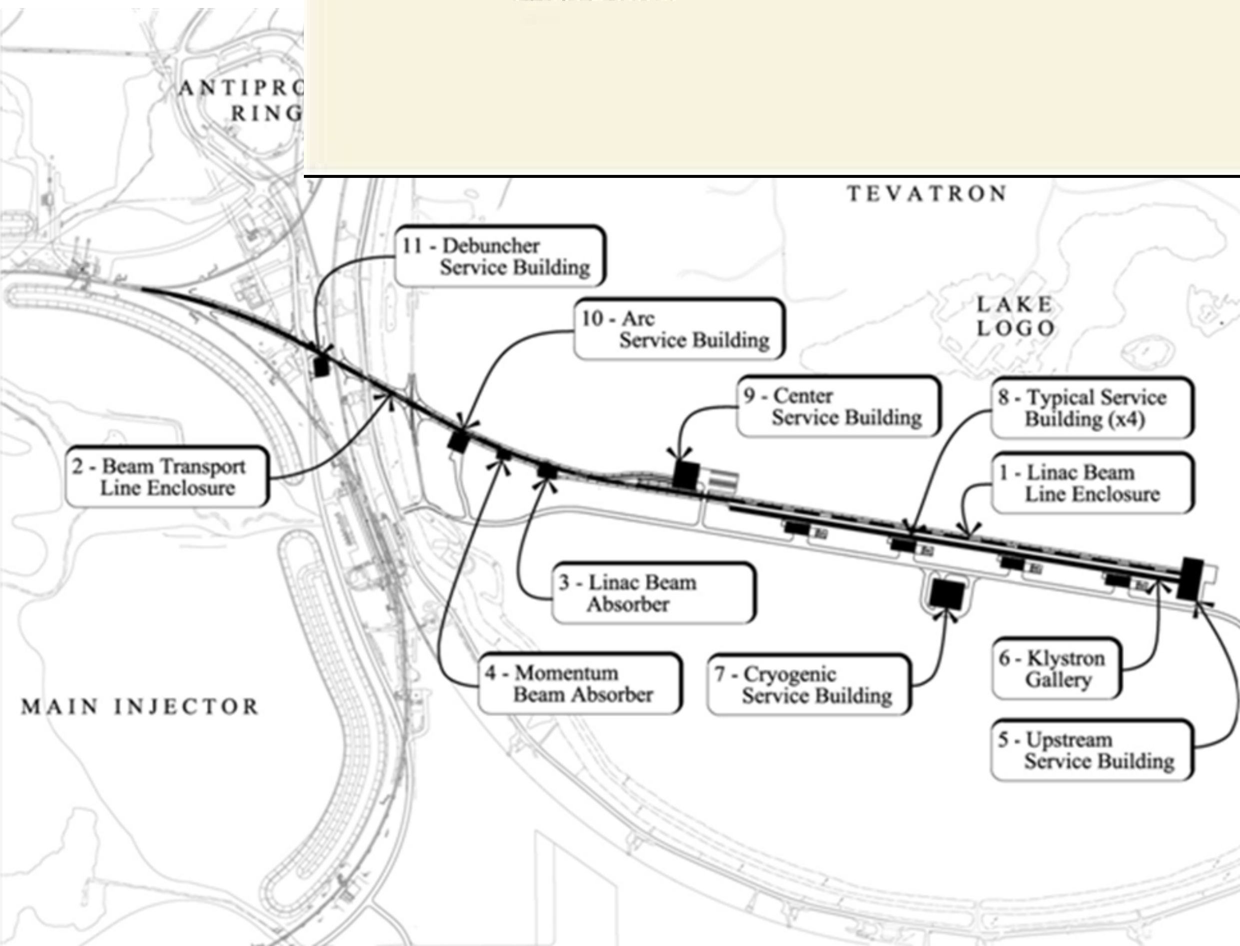
- Issues with Initial Configuration-1 (IC-1)
- Objectives for Initial Configuration-2 (IC-2)
- Description of IC-2
- Conclusions

Project X Initial Configuration - 1 (IC-1)

- IC-1 is based on ILC-technology/pulsed, 1.3GHz SC linac
  - Initial proposal, 2007
    - 2 MW at (60 -120 GeV) in MI
    - ILC technology test
    - Replacement for ~40 years old Booster & Linac
  - Final IC-1 (as spring of 2009)
    - 2 MW at (60 -120 GeV) in MI
      - for LBNE
    - ~300 kW for 8 GeV program
      - Mu2e upgrade (slow extraction)
    - Reduced coupling to ILC
    - Improved but still comparatively narrow physics program

IC-1





- Foil strip injection
- Large bending radius
  - Magnetic field stripping
- Cooled transfer line
  - Stripping due to blackbody radiation

IC-1 problems

- Slow extraction
  - ~70 kW demonstrated at Tevatron and AGS (1TeV&25 GeV)
- High efficiency of slow extraction is required
  - Small betatron tune spread
  - Large difference between core emittance and acceptance
- Slow extraction for mu2e
  - Only 8 GeV energy
  - Small duty factor: 50 of ~500 ns (η~0.1)

    $\Rightarrow$ Large tune spread due to beam space charge (γ^2/η~100)
- Mitigation of slow extraction problems
  - 3 ring scheme: Recycler – Accumulator - Debuncher
- Only one experiment can be supported

    Different time structure is required for different experiments
  - Rigid time structure – difficult & expensive to change

Objectives for Initial Configuration – 2 (IC-2)

- 2 MW at 60-120 GeV in MI
  - Same as AC-1

    LBNE, …
- 8 GeV program with single turn extraction (≥100 kW)

    g-2, …
- Diverse program with muons & kaons

    μ-to-e, K→πνν, …
    - Different experiments require different time structures
    - Power on the target has to be rather limited by event rate than by the available beam power
  - CEBAF is an example of such machine with e-beam

Project X IC-2

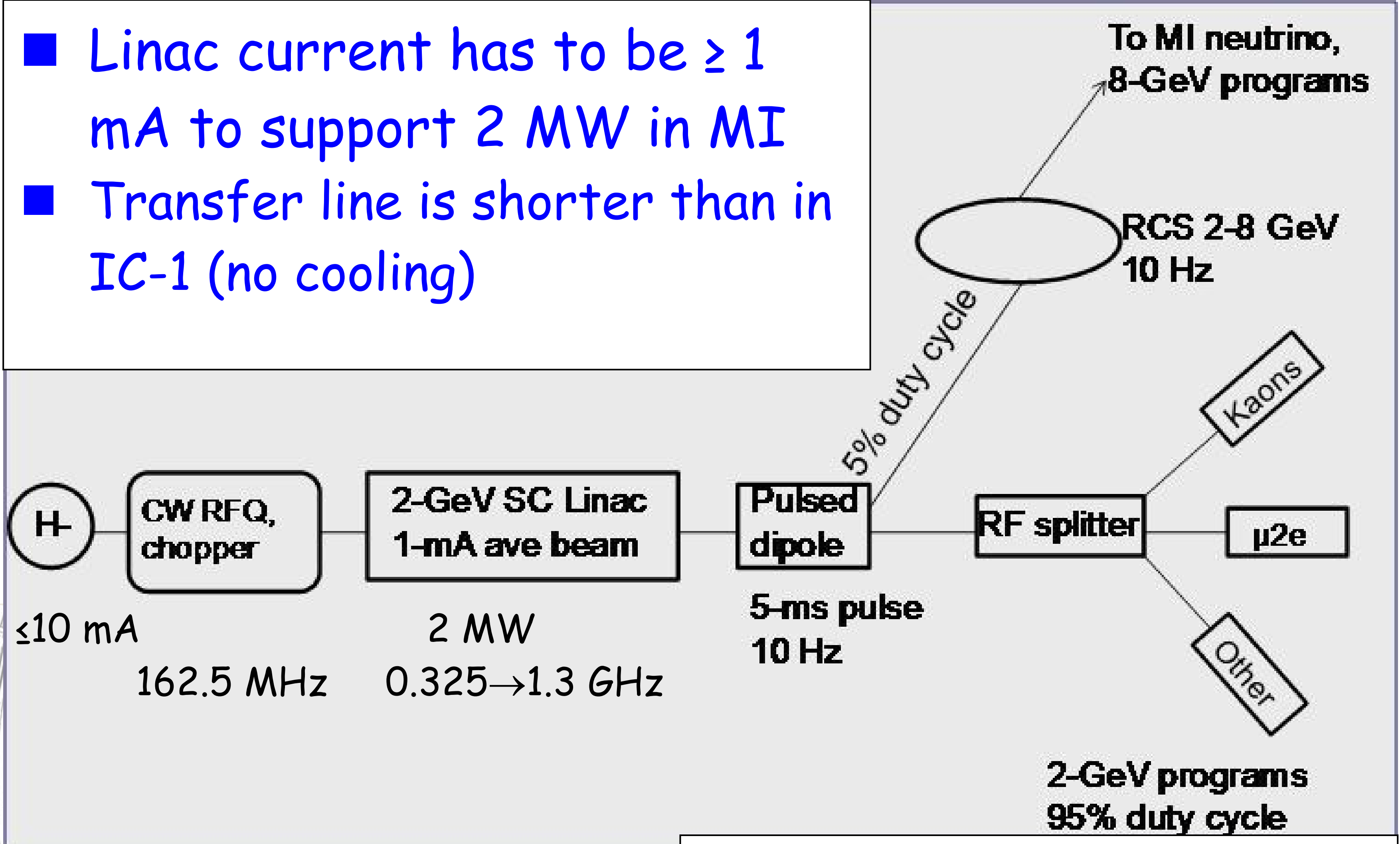
- IC-2 conception
  - 2.0 GeV CW linac (2.X GeV looks as right choice, X=?)
    - potentially "unlimited power"
    - stable beam parameters
  - RF separation + bunch-by-bunch chopping
    - Multiple experiments operating simultaneously
    - Independent bunch structure control
  - "Pulsed" 2-to-8 GeV acceleration (10 Hz, 4.2 ms) to support MI program
    - Both RCS or pulsed SC linac are a good choice

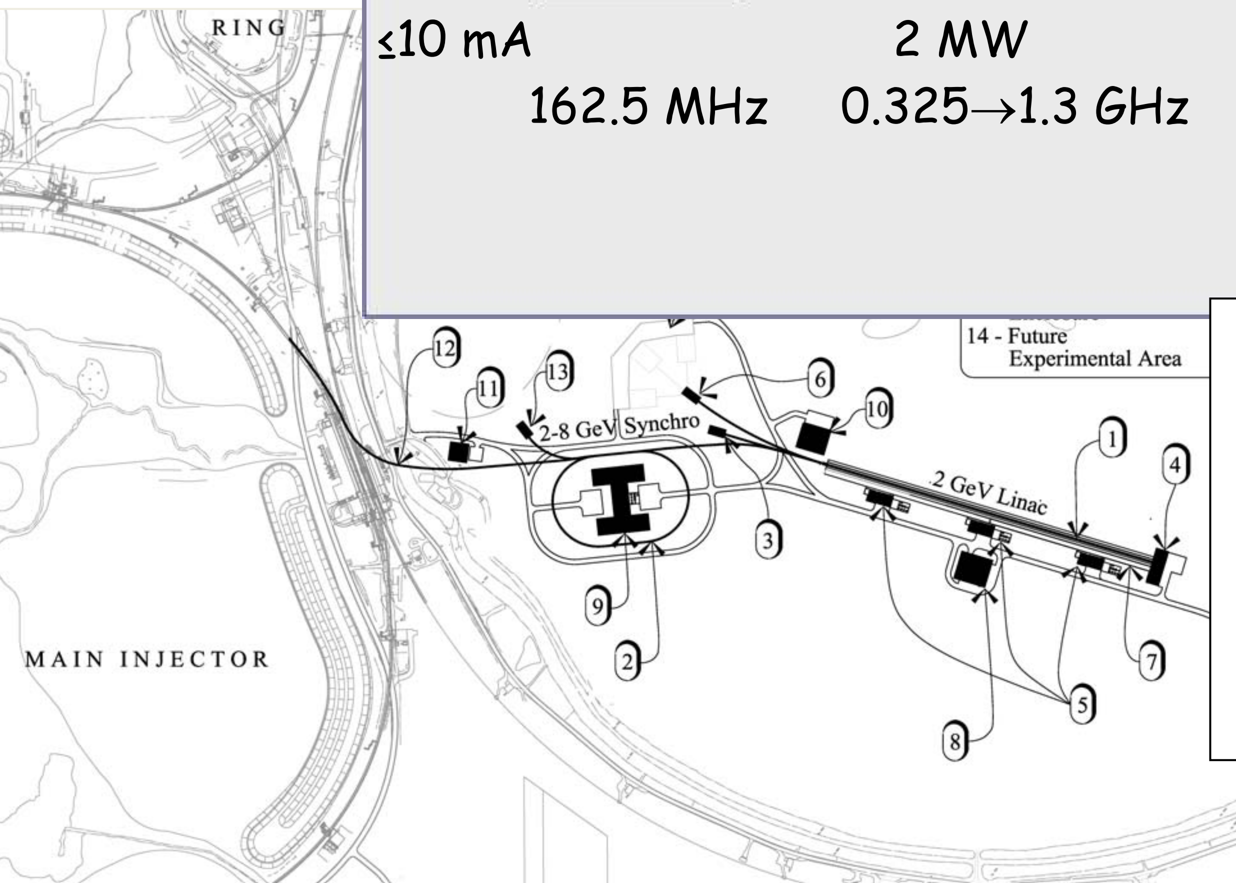
IC-2 developments

- Development of IC-2 concept started in March, 2009
- It was strongly supported by Physics Advisory Committee in June 2009
  - Highest priority since then
- Now we are ready to release
  - Report on physics part
    "Report from the ICD-2 Research Program Task Force"
  - Report on accelerator part
    "Project X Initial Configuration Document – 2"

IC-2

- Linac current has to be ≥ 1 mA to support 2 MW in MI
- Transfer line is shorter than in IC-1 (no cooling)





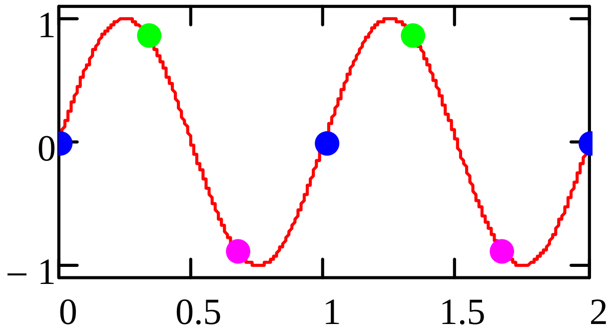
- Bunch length, ≤10 ps(rms)
  - Time of flight
- If required, more than 3 experiments can operate simultaneously

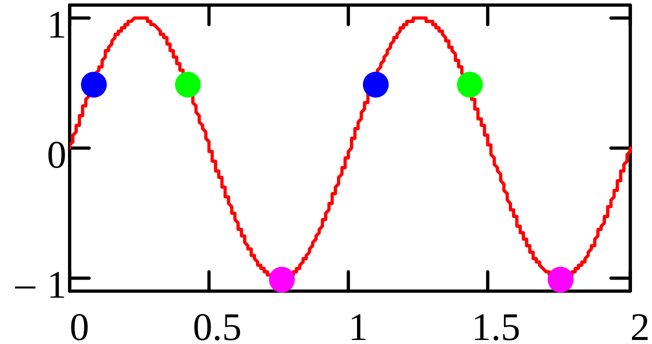
RF separation

- One RF separator can split linac beam into 2 or 3 beams
  - 3-rd sub-harmonic splitter – splits beam in 3 equal beams (CEBAF like)

    f_b = 162.5 MHz

    $f_{exp} = f_b/3 \approx 54$ MHz



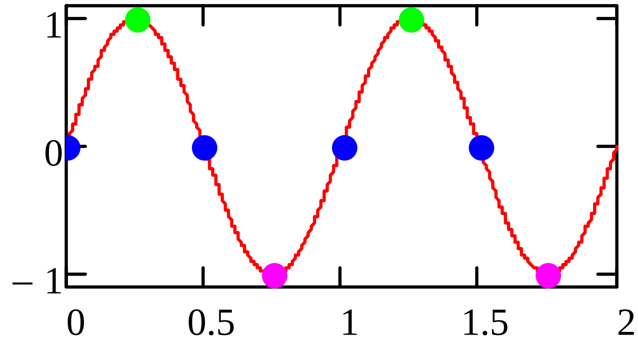


  - 4-th sub-harmonic splitter – one of 3 beams has twice larger intensity

    f_b = 162.5 MHz

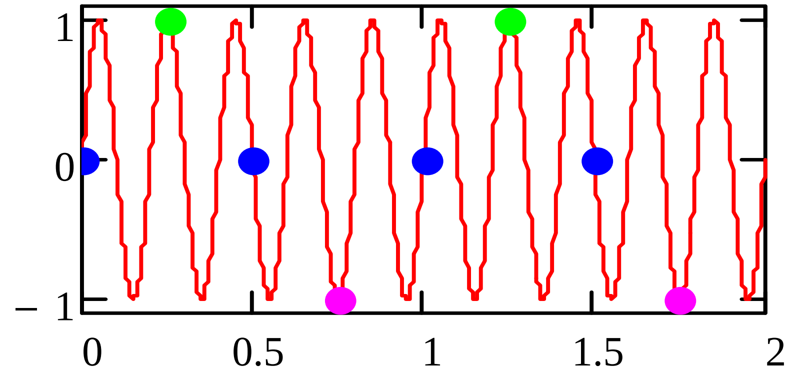
    $f_{exp} = f_b/2 \approx 81$ MHz

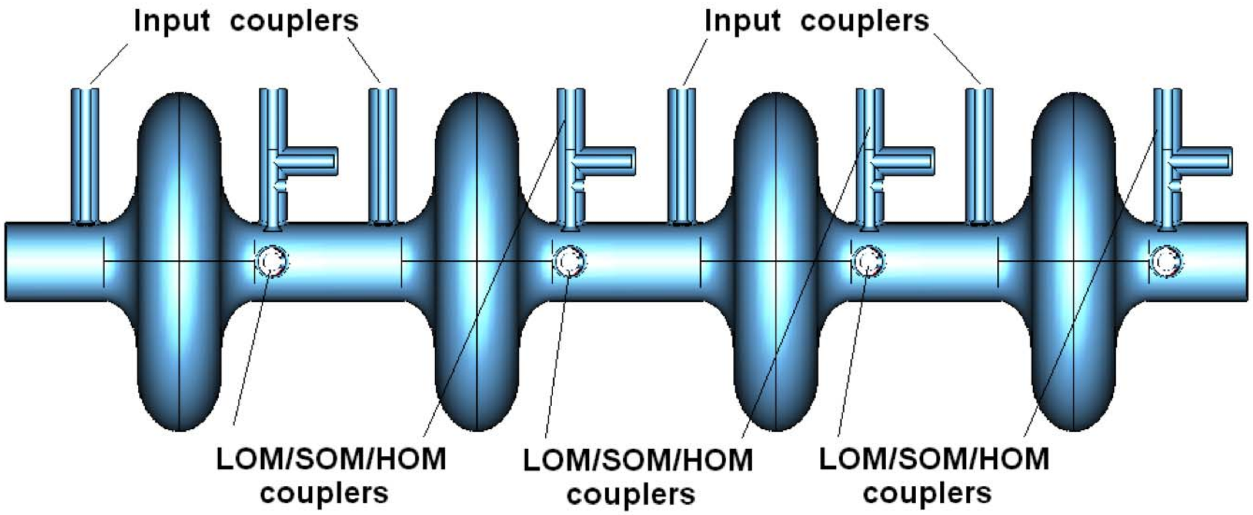
    $= f_b/4 \approx 40.5$ MHz



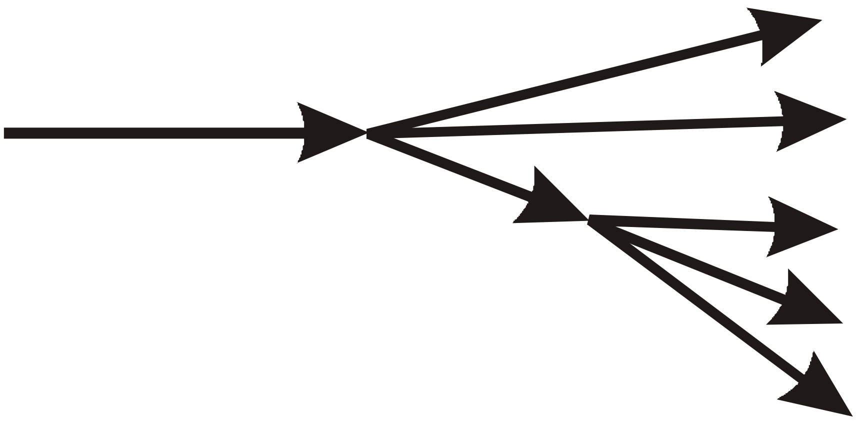
RF separation (continue)

- ICD-2 RF splitter:
  - 4 SC cavities ,
  - $f_{RF} = (2+1/4)f_b$ =365.625 MHz,
  - L=4.5m
  - θ = 5 mrad
  - $E_{\perp}L$=5 MeV



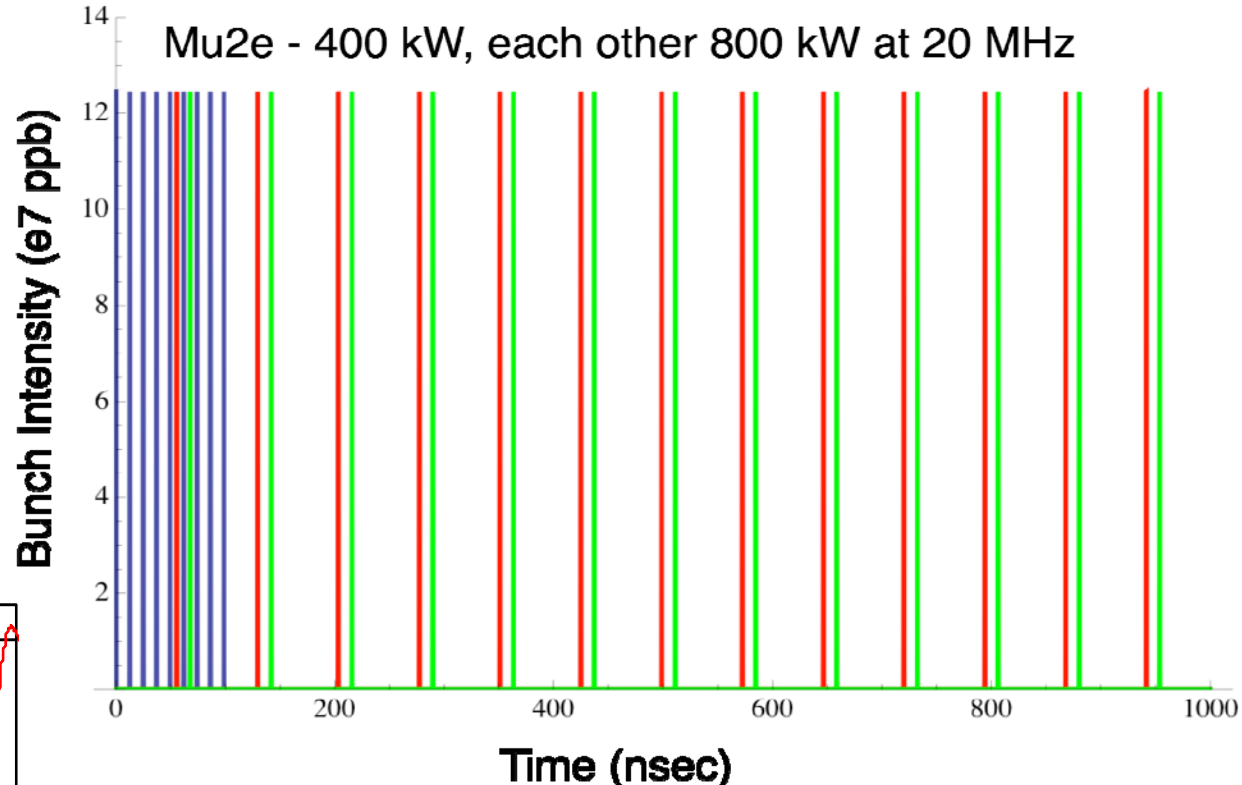


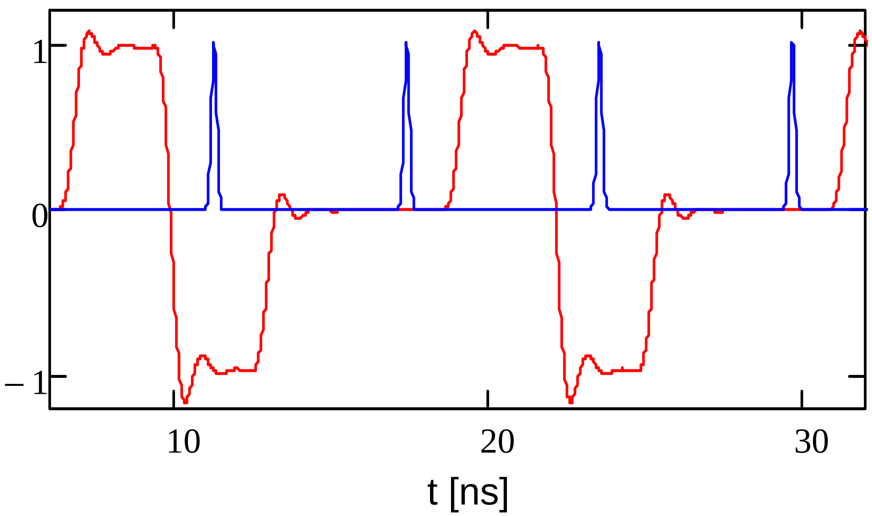
- Additional RF separators allow simultaneous operation for more than 3 users
  - Bunch frequency and power for each experiment will be smaller



Beam chopping

- Bunch-by-bunch chopper supports a bunch structure required for each experiment
  - Setting desired structure on-line
  - Digital control of chopping pulses
  - Wide band amplifier, ~1 GHz

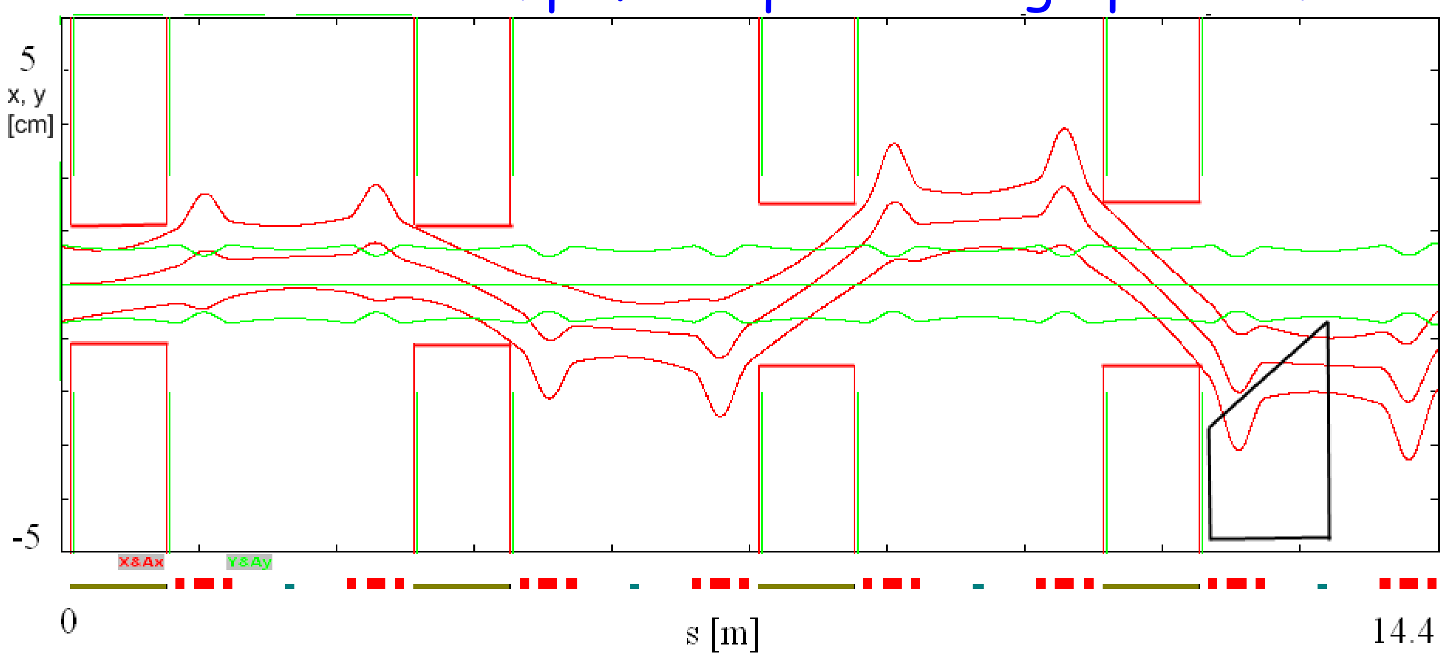




- Set time structure
- Adjust ion source current to get 1mA in linac

Beam chopping (continue)

- Achieving high extinction (~10^{-9} for Mu2e) is not simple
  - ♦ Particle lost from bunch in linac cannot get to another bunch
    - Extinction is determined by chopper
  - ♦ Chopper problems
    - Bunch space charge can create tails
    - CW operation + wide band (50 Ω) → Limited power
      → small kick → Large length of the system
      → amplifies space charge problems

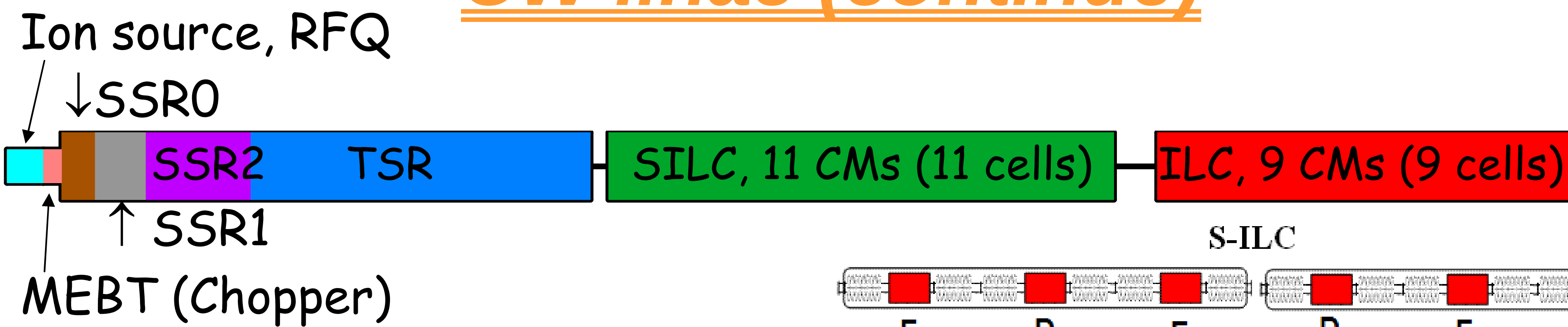


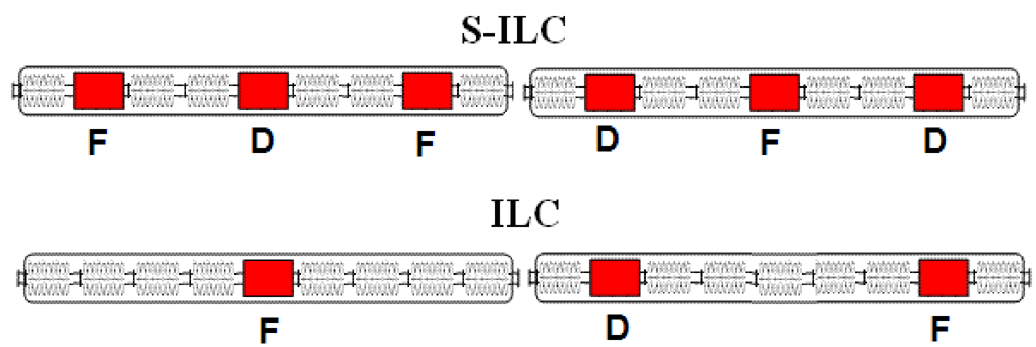
3σ beam envelopes in chopper region:
ε_{rms_n} = 0.3 mm mrad,
Four 1 m choppers
U = ±300 V
Gap: ±11 & ±15 mm
Quad triplets &
Bunching cavities

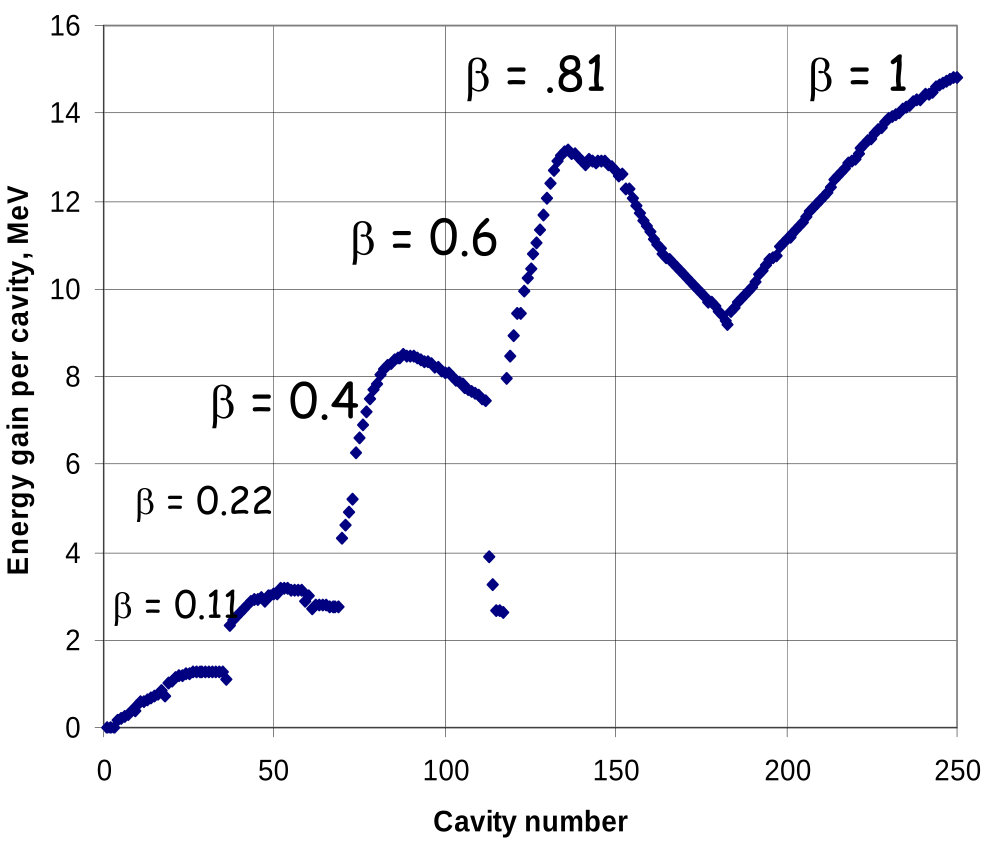
CW linac

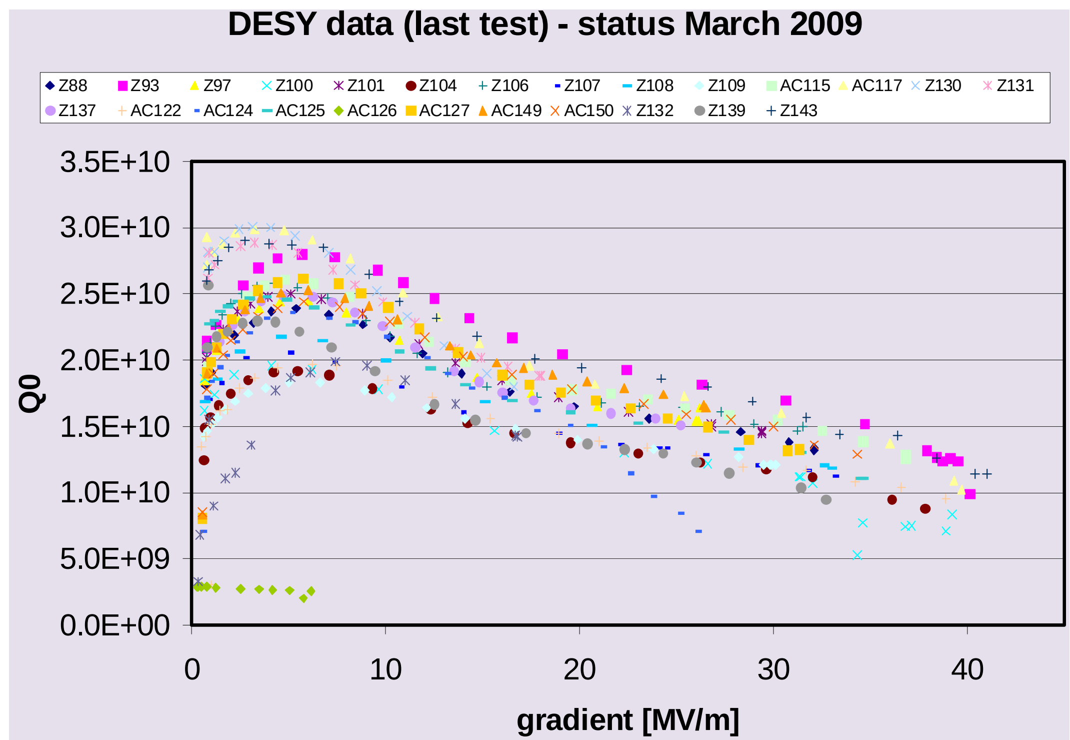
- Same structure as for IC-1
  - ILC like SC cryomodules
  - Accelerating gradient is reduced: 25 $\rightarrow$17 MeV/m
    - Machine cost versus cost of operations
      - Cryogenic power reduction
- Different SC cavities to support wide range of velocities (same as IC-1)
  - Support acceleration from 2.5 MeV to 2 GeV
- NC RFQ: 2.5 MeV, 10 mA, 25 kW (~150 kW RF)

CW linac (continue)



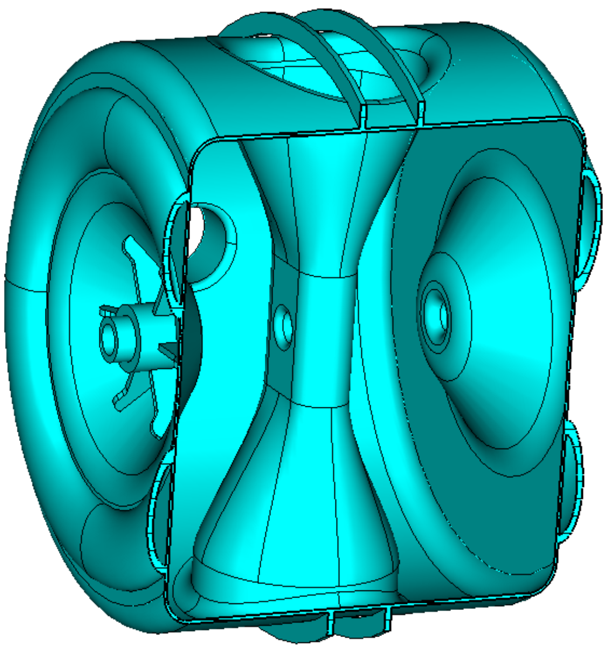




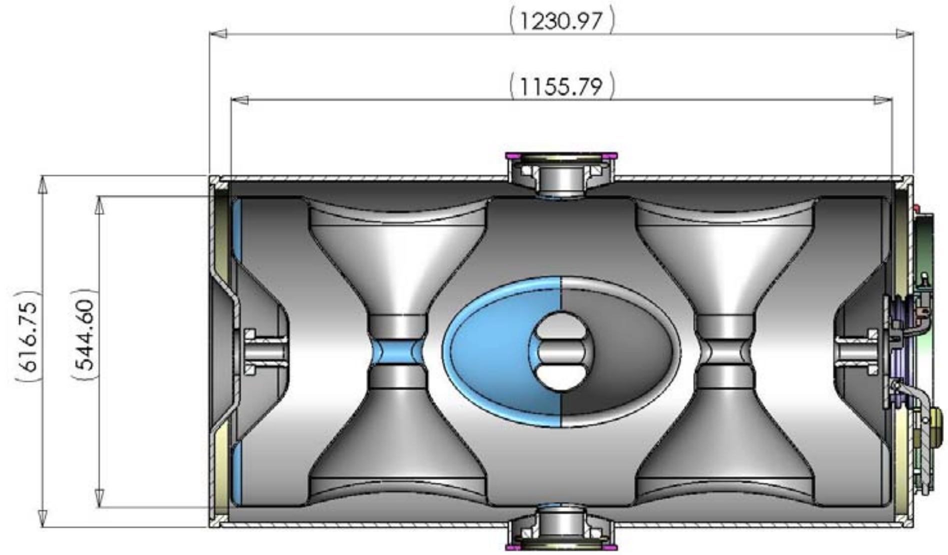


CW linac (continue)

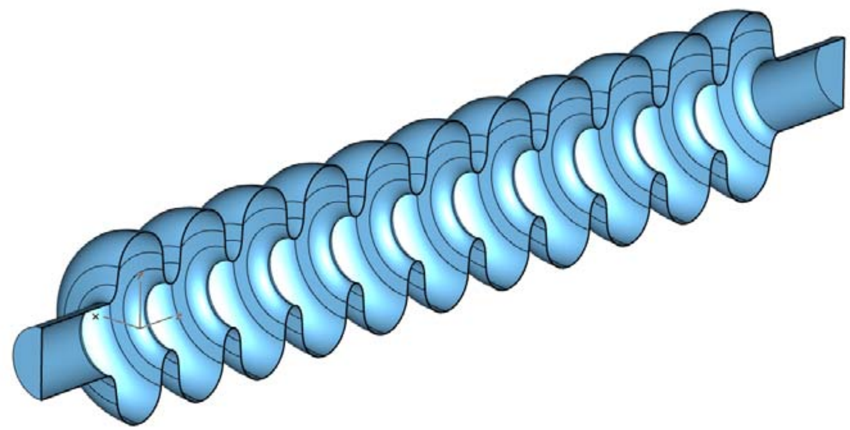
SSR1 cavity



SSR2 cavity



Triple spoke



ILC

Synchrotron

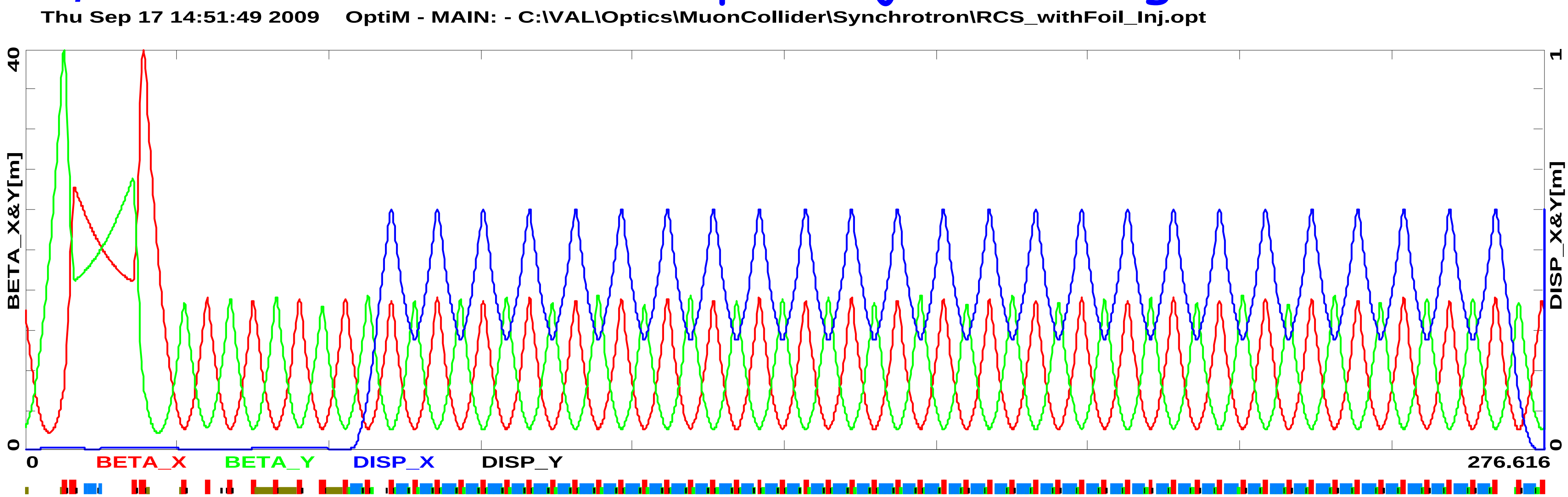
Energy, min/max, GeV	2/8
Repetition rate, Hz	10
Circumference, m (MI/6)	553.2
Tunes	18.44
Transition energy, GeV	13.36
Beam current at injection, A	2.2
Harmonic number	98
Maximum RF voltage, MV	1.9
95% n. emittance, mm mrad	25
Space charge tune shift, inj.	0.07†
Norm. acceptance, mm mrad	40
Injection time for 1 mA, ms	4.3
Linac energy cor. at inject.	0.8%
RF bucket size, eV s	0.4
Number of 1-st harm. RF cav.	16

†For KV-like distribution at injection, longitudinal bunching factor 2.2.

- Acceleration from 2 to 8 GeV
  - Less expensive than SC linac
- I_{Beam}: 5 times of Booster
- Avoid Booster problems
  - No transition crossing
  - No laminations seen by beam; smaller $Z_{||}$, $Z_{\perp}$
  - Zero Disp. in cavities: SB resonance
- Features
  - Circumference, $C = C_{MI}/6$
  - High periodicity FODO
  - Acceptance Matches MI
  - 2 harmonics RF system
  - High injection energy helps with SC and instabilities

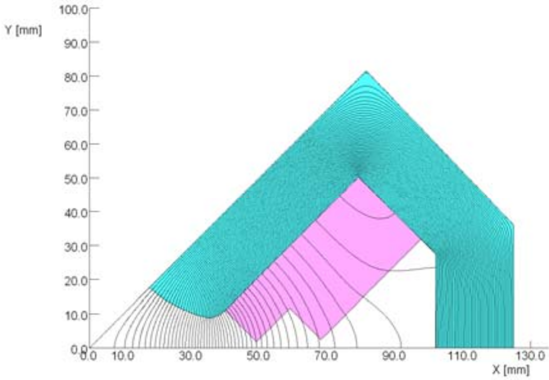
Synchrotron (continue)

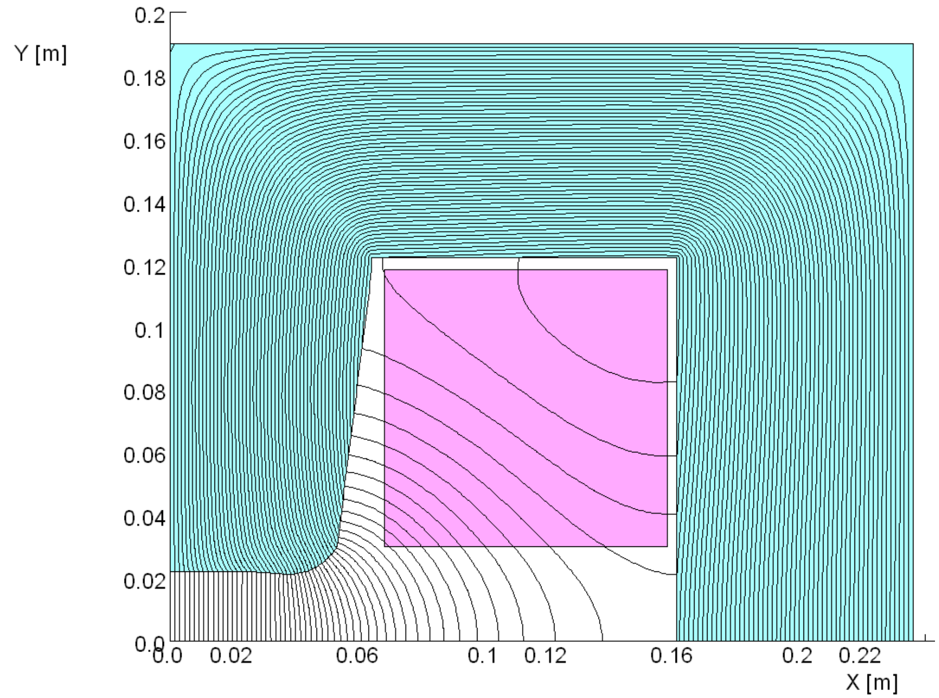
- Racetrack
- Dispersion is zeroed by missed dipole
- Two types of quadrupoles but with the same strength
- All quads and dipoles are on the same bus
  - Resonance circuit to reduce PS voltage
- β-functions are blown-up in injection region



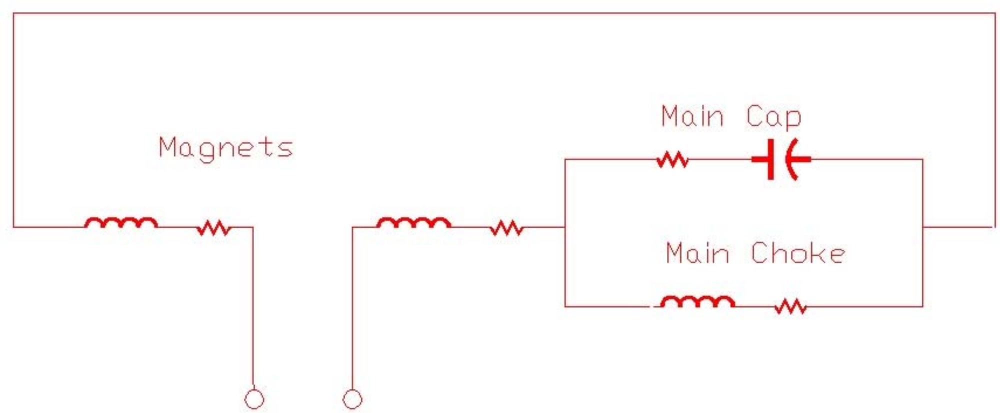
Twiss parameters for the first half of the ring

Synchrotron (continue)





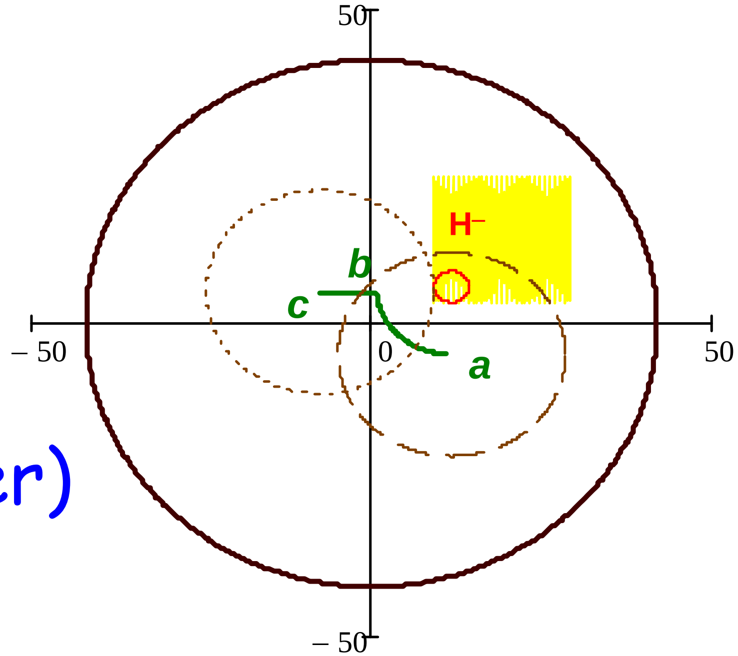
- 100 dipoles and 130 quads
- High injection energy (2 GeV)
  - →small aperture
    - →small magnets
- Round vacuum chamber
  - Stainless steel - 0.7 mm
  - External diameter - 44mm
  - Sagitta – 1.67 cm
  - Eddy currents
    - $\Delta B/B_{max}$ = $i \cdot 1.4 \cdot 10^{-3}$
    - Power loss – 11 W/m
    - Chromaticity correction: $|\Delta\xi|$ ~1

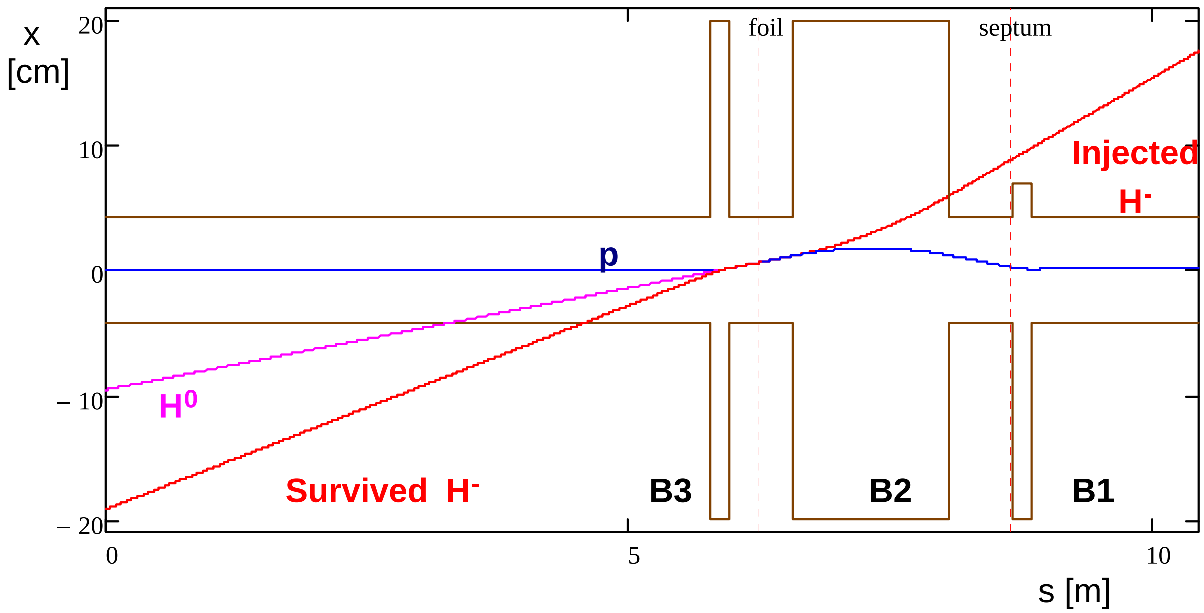


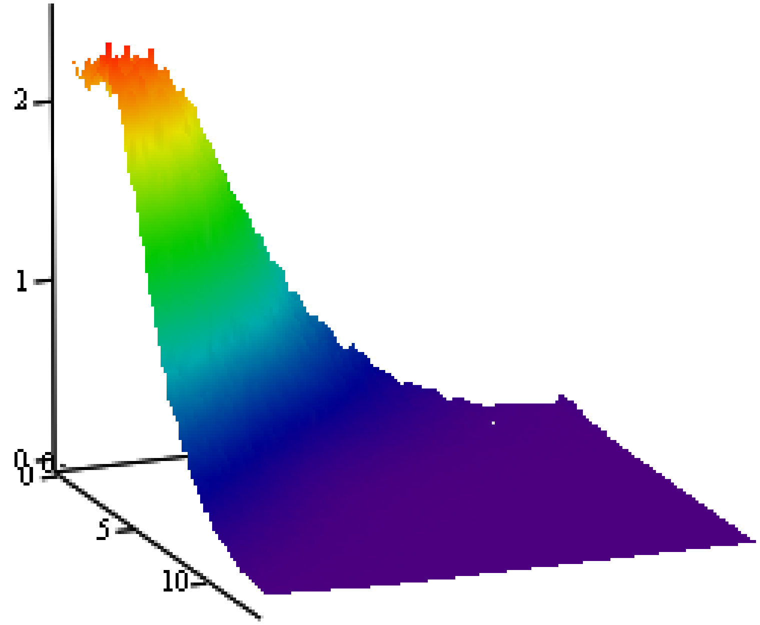
Resonance circuit for 1 lattice cell

Injection to Synchrotron

- Strip injection through 600 μg/cm² graphite foil
- Small linac current
  ⇒ 2200 turn inject. (11 for Booster)
  - X-Y painting by CO displacement
  - ~50 secondary passages per particle
    - Foil T_{max} = 1500 K







RCS versus Pulsed Linac

- RCS
  - Less expensive
  - Injection at smaller energy
    $\Rightarrow$ Easier to manage injection loss
  - Limited upgrade potential
- Linac
  - Easier to upgrade
    - to 4 MW power proton driver
    - + to ~20 GeV recirculator for neutrino factory
  - Many injections per cycle if foil strip-injection is used (10 Hz)
    - Requires Recycler
      $\Rightarrow$ 8 GeV final energy
  - An upgrade will require beam current increase: 1 $\rightarrow$ $\geq$20 mA
    $\Rightarrow$2 GeV program discontinue or
    building another 2 GeV frontend!!!

Ideal Project X Scenario (an accelerator physicist point of view)

- Start "g-2" or antiproton physics experiments in Accumulator after Tevatron shutdown, 2012-2013.
  - In contrast to mu2e the "g-2" experiment does not require complete decommissioning of Antiproton source
- Build 2 GeV linac & first experiment (mu2e?) by 2016
- Finish RCS by 2018
  - 2 MW in MI should follow
  - Booster and linac can be decommissioned
- Build facility for kaon and muon physics at 2.X GeV by ~2020

Conclusions

- ICD-2 creates diverse program at Intensity Frontier
  - Choice between RCS and Pulsed linac need to be done. It will be driven by
    - Cost & Upgradability
- There are no obvious cost reduction schemes without sacrificing machine parameters
  - Staging will work
- We need a prioritized list of experiments for:
  - Continuous beam at 2.X GeV (2 MW)
    - What is X in 2.X GeV?
  - Fast extracted 8 GeV beam (100 - 300 kW)
  - Antiproton physics ($2\cdot10^{11}$ pbars per hour, $E\leq8$ GeV)

Backup viewgraphs

Bunch train requirements for the kaon and muon rare decay programs

	Train Frequency	Pulse Width (nanoseconds)	Inter-Pulse Extinction
Kaon experiments	20-30 MHz	0.1-0.2	10^{-3}
Muon conversion experiment	0.5-1.0 MHz	50	10^{-9}