Production of Particle Beams for Proton and Heavy Ion Therapy: Synchrotrons

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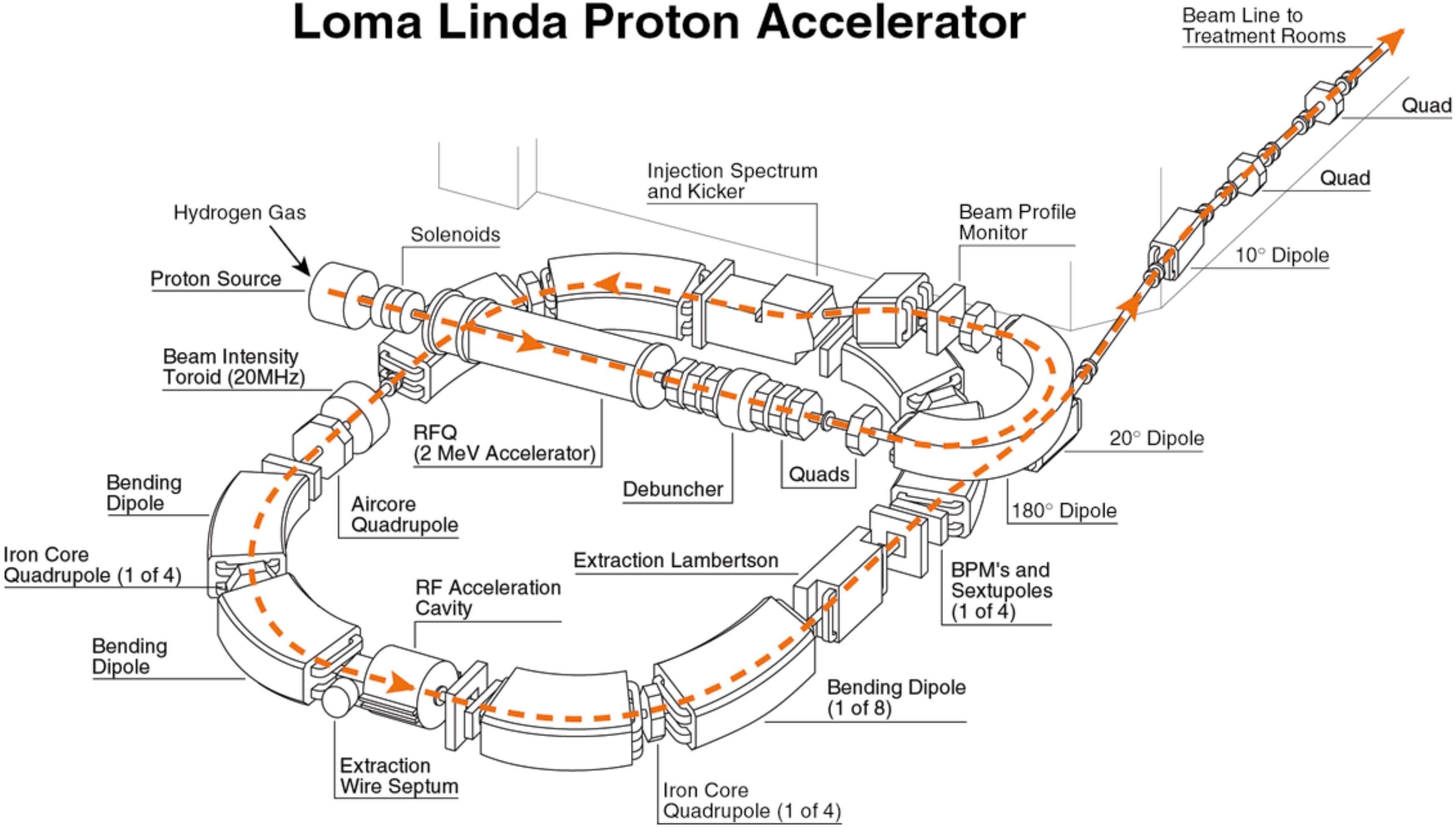
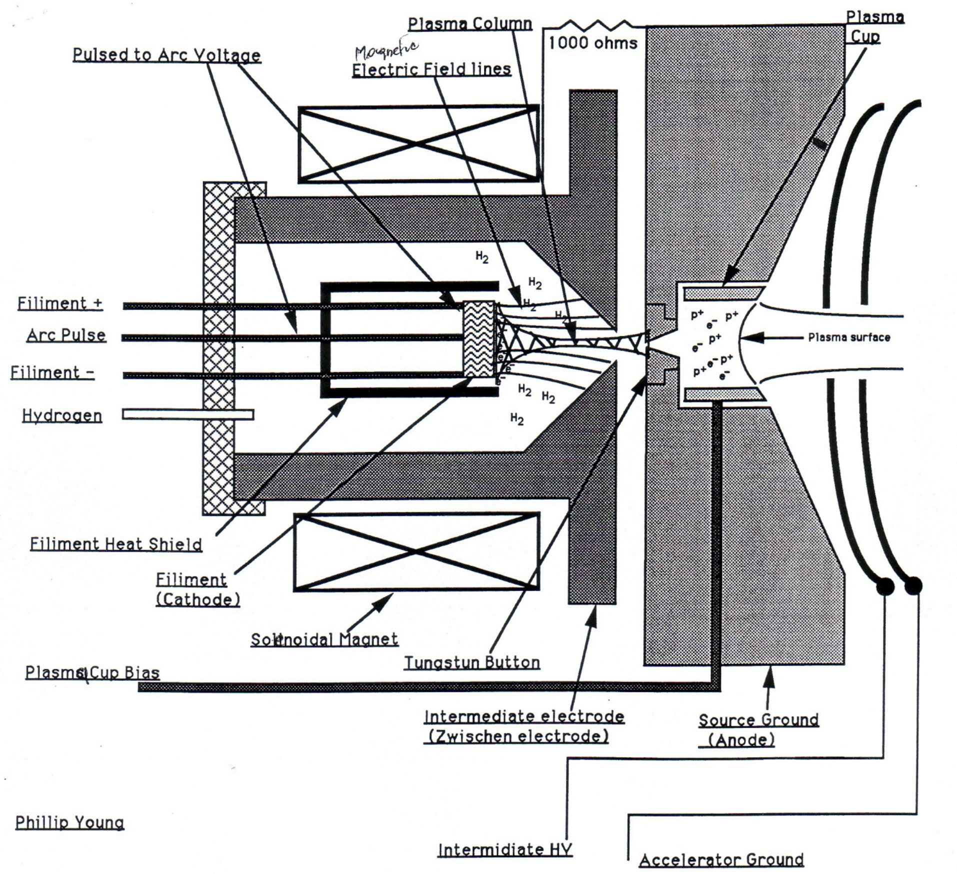
Prepared for PTCOG 47
Jacksonville, FL

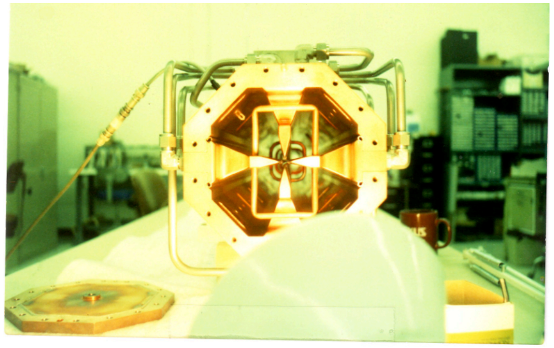
Loma Linda Proton Accelerator

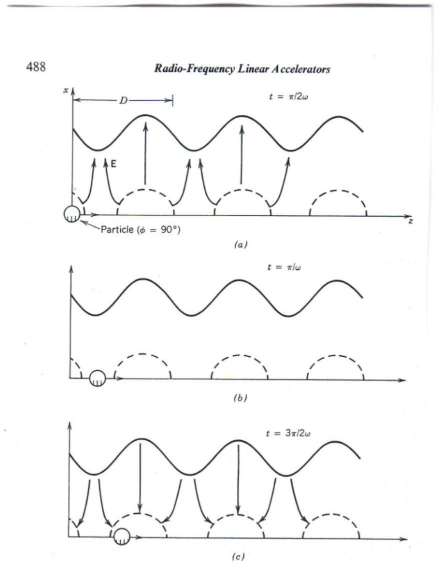


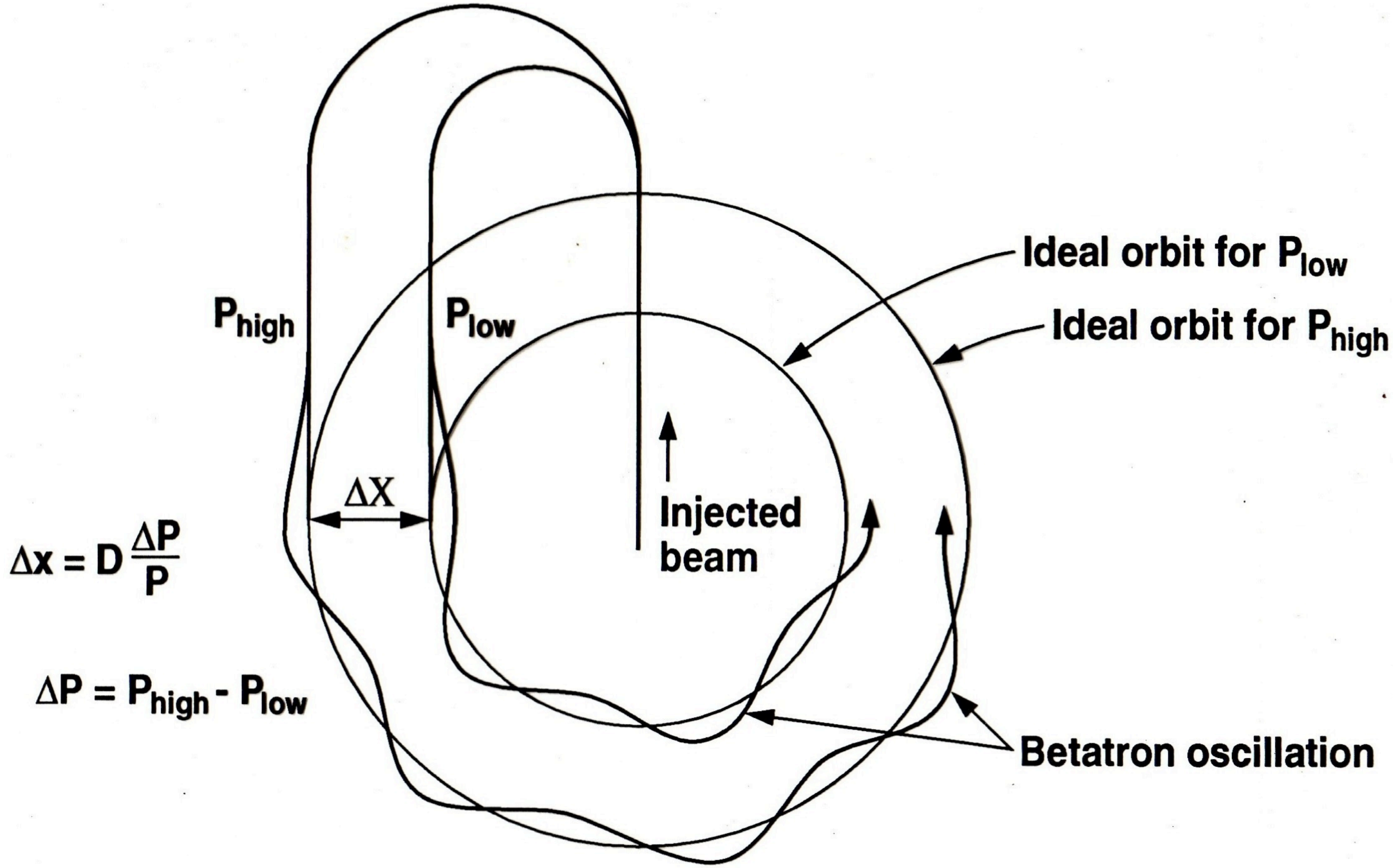
Duo Plasma Hydrogen Ion Source



Radio Frequency Quadrupole Accelerator (35 keV to 2 MeV)

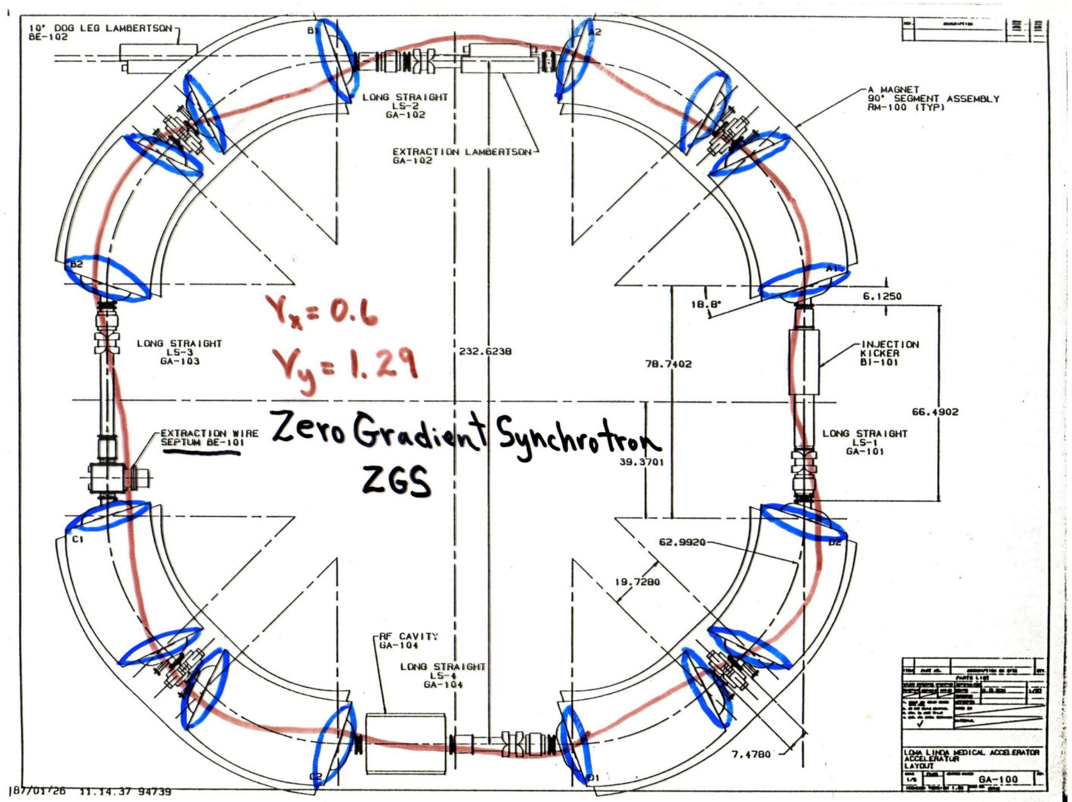






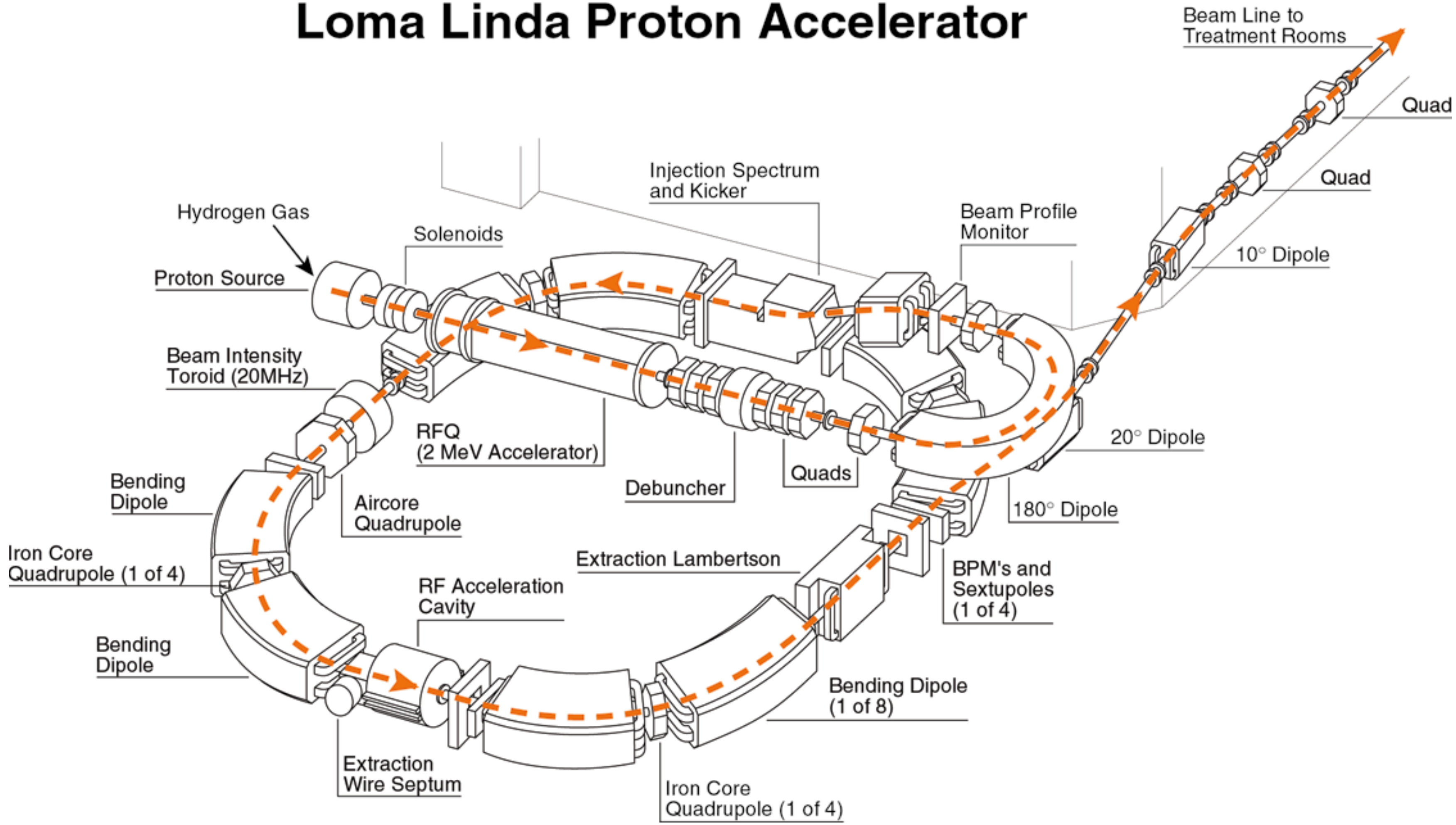
Ideal orbit for P_{low}
Ideal orbit for P_{high}
P_{high}
P_{low}
ΔX
Injected beam
$\Delta x = D \frac{\Delta P}{P}$
$\Delta P = P_{high} - P_{low}$
Betatron oscillation

Betatron Oscillations

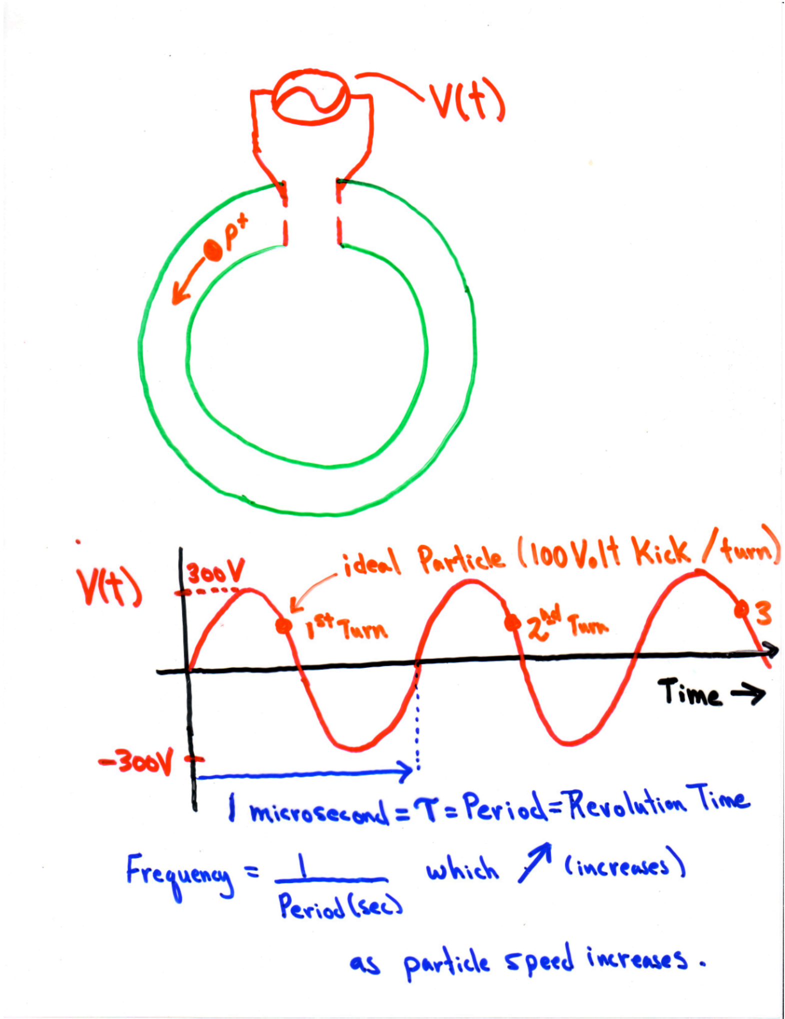


No. of oscillations/turn = Tune = ν: $f_\beta = f_{rev}\,\nu$ ← Tune

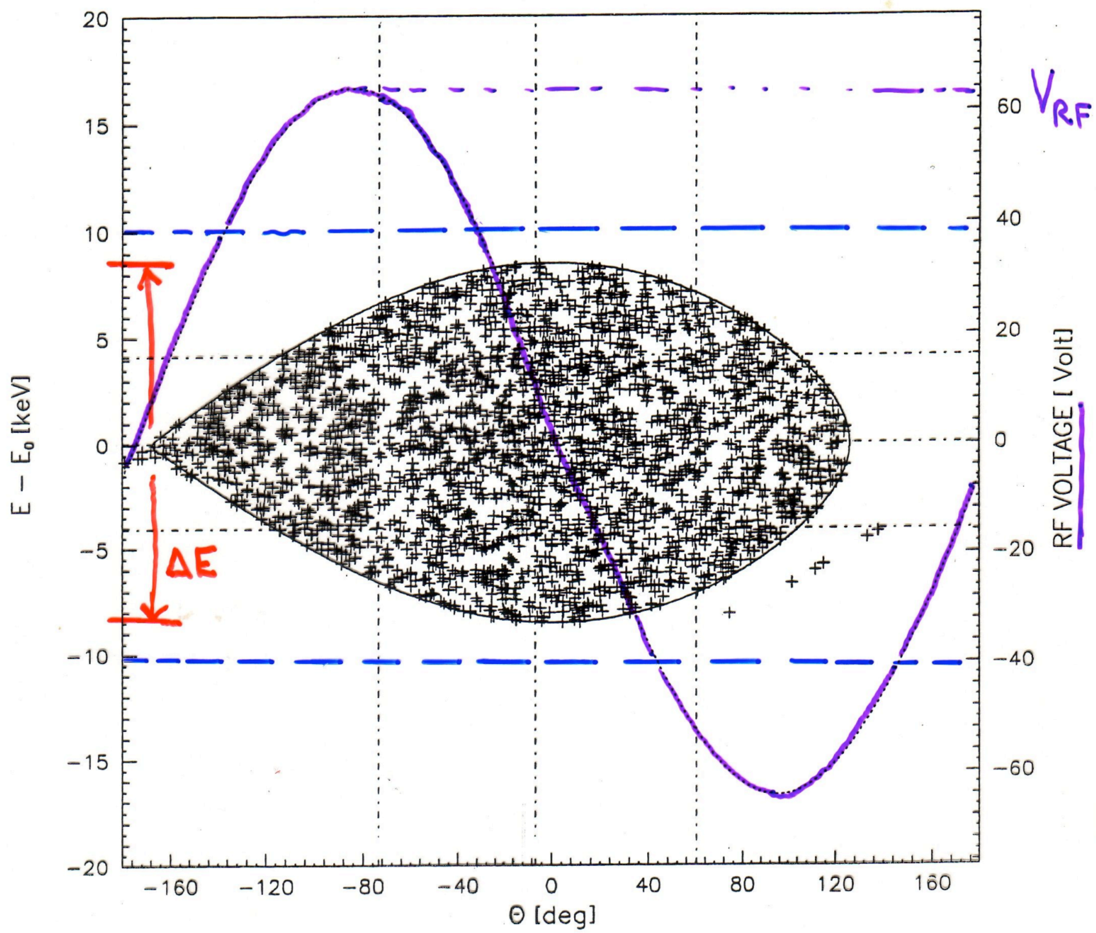
Loma Linda Proton Accelerator



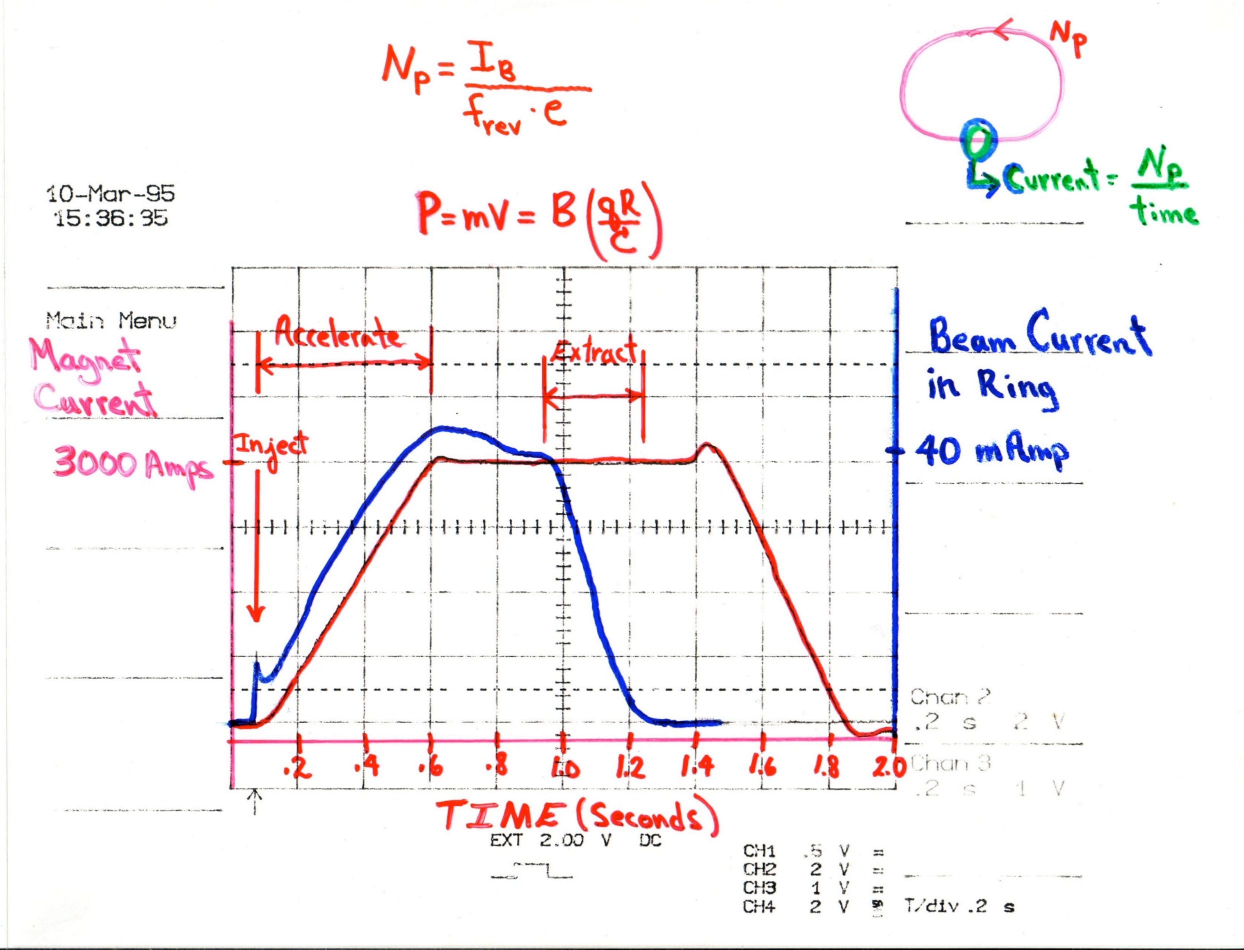
Acceleration: RF voltage sine wave at the proton revolution frequency



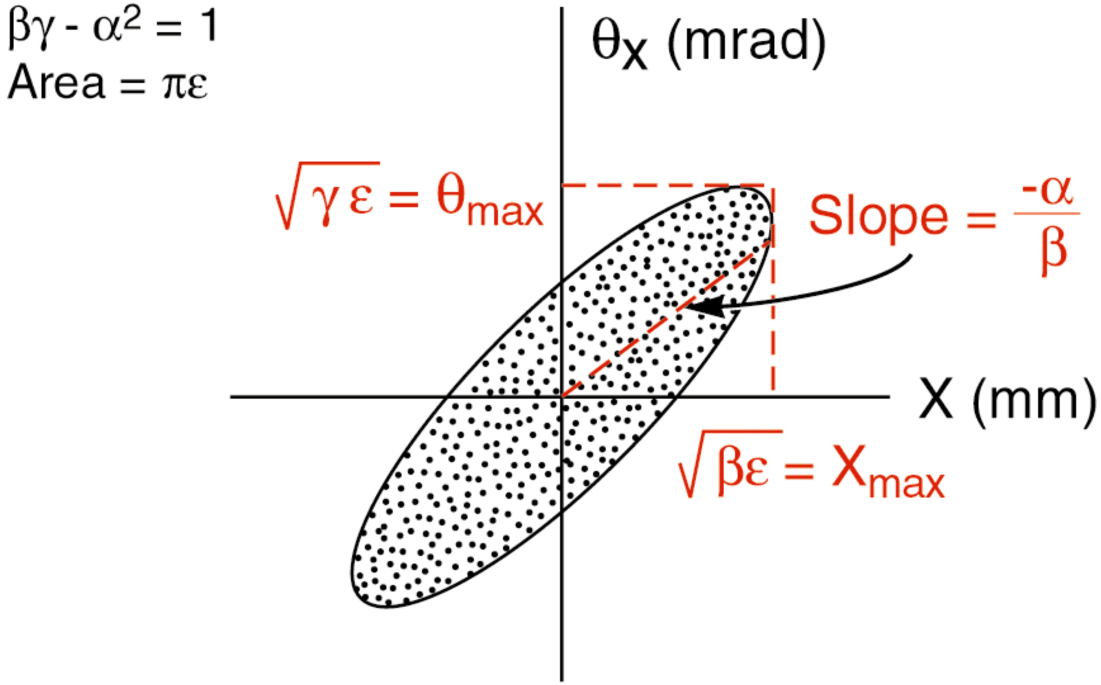
Density of particles around the ring after RF Capture at 2MeV



Dipole Current and Beam Current in the ring during acceleration and extraction



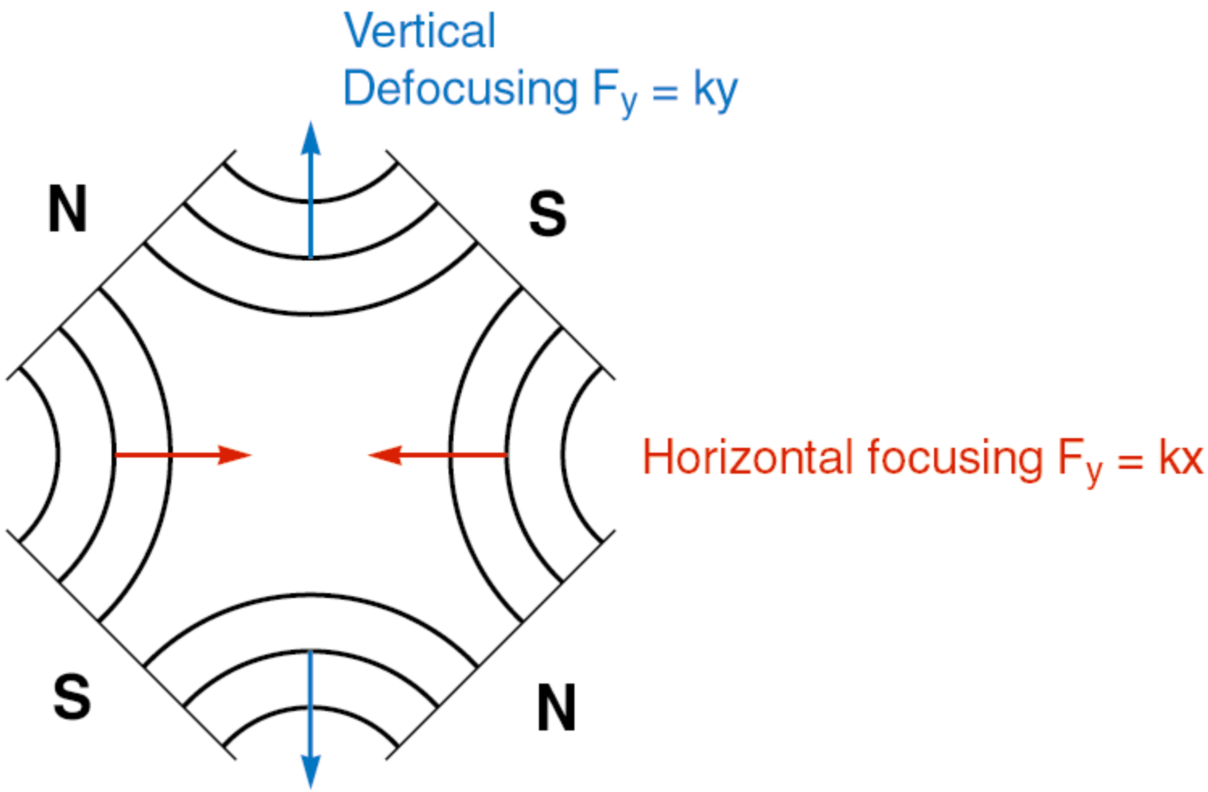
Transverse Beam Emittance



The Beam Ellipse (one for X and one for Y)

A beam is a collection of particles moving in approximately the same direction

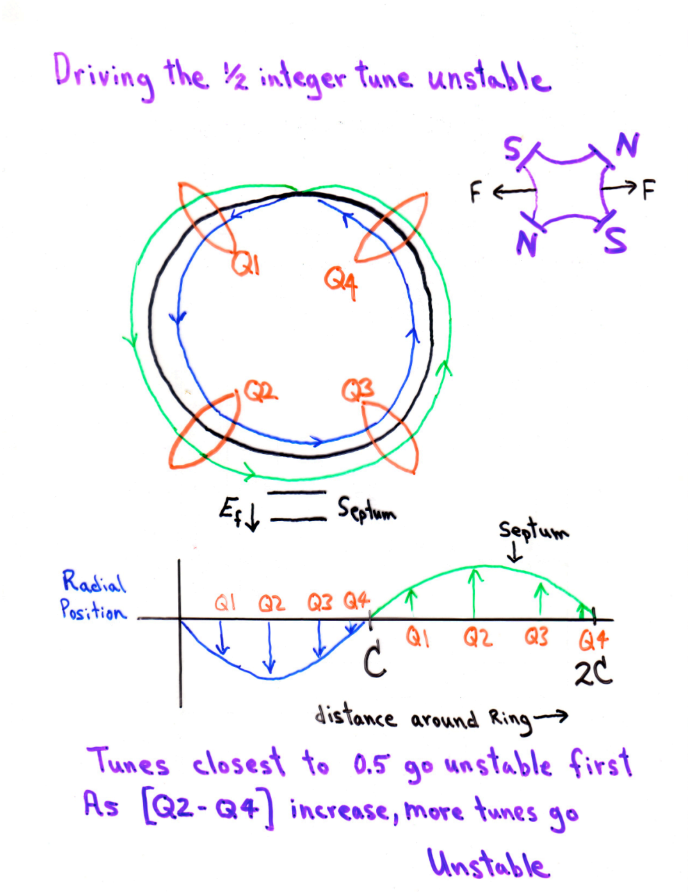
Magnetic Quadrupole Lens



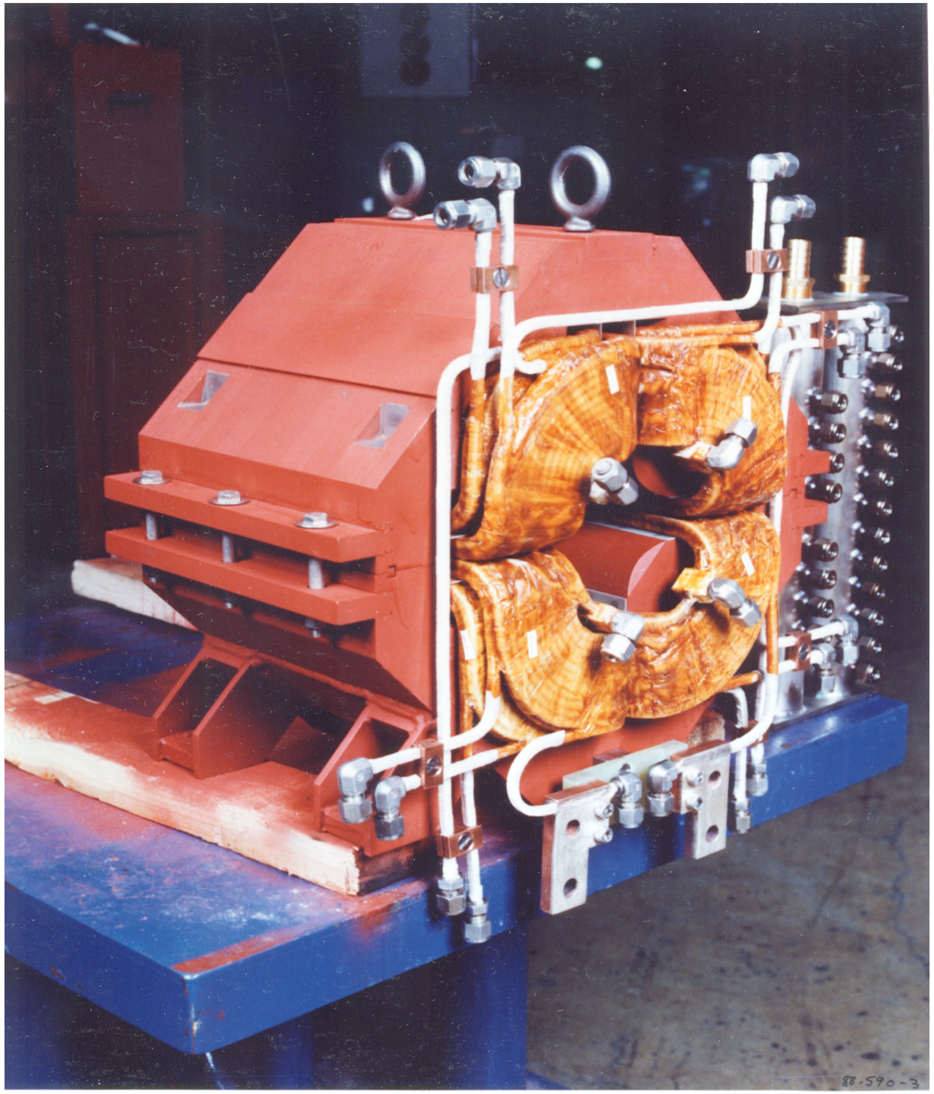
Horizontal Focusing and
Vertically Defocusing Quadrupole

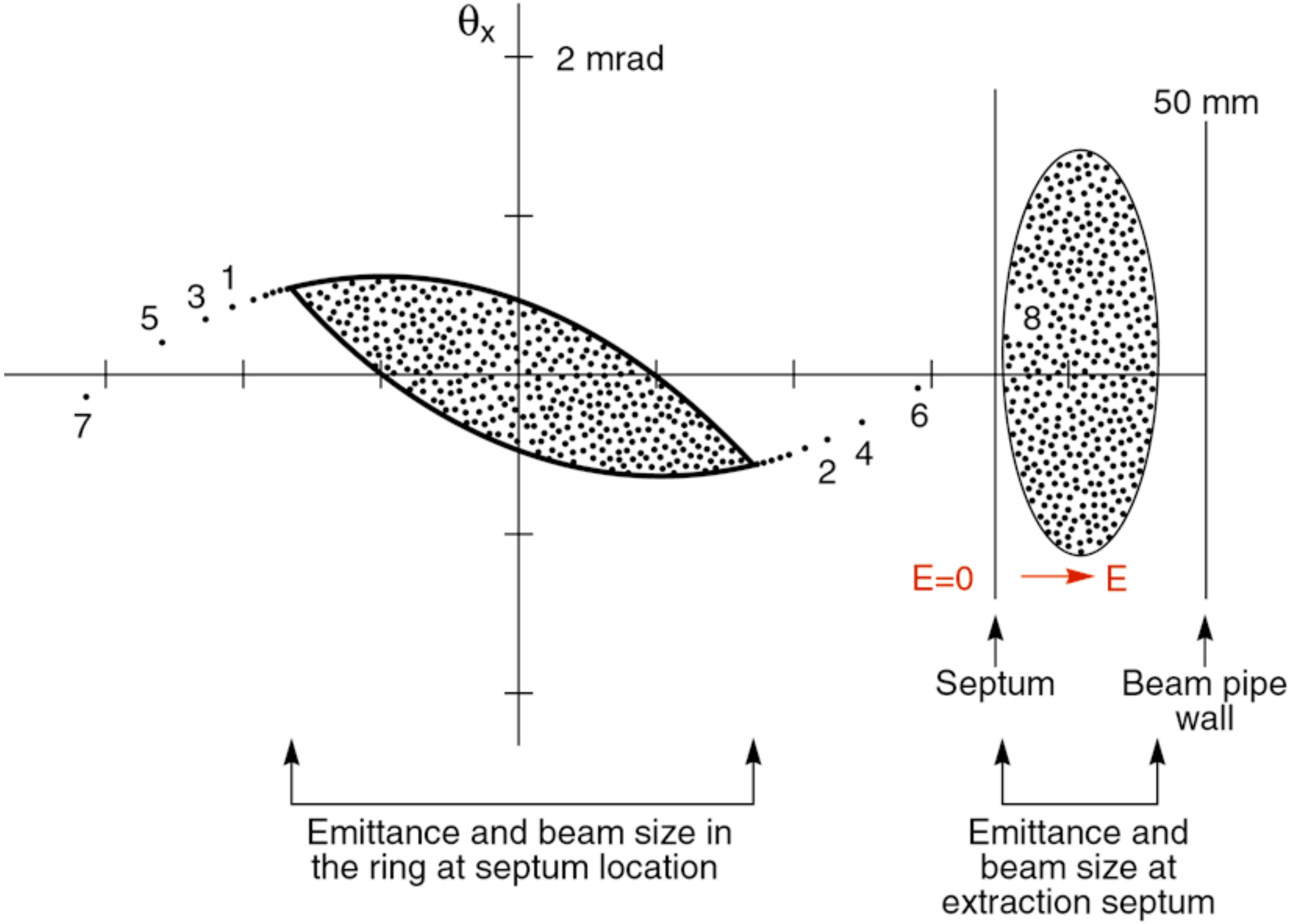
Beam's Eye View of proton beam
entering magnetic quadrupole

Slow Resonant Extraction (0.2 to 5 sec)



Quadrupole for tune adjustments and driving the betatron resonance





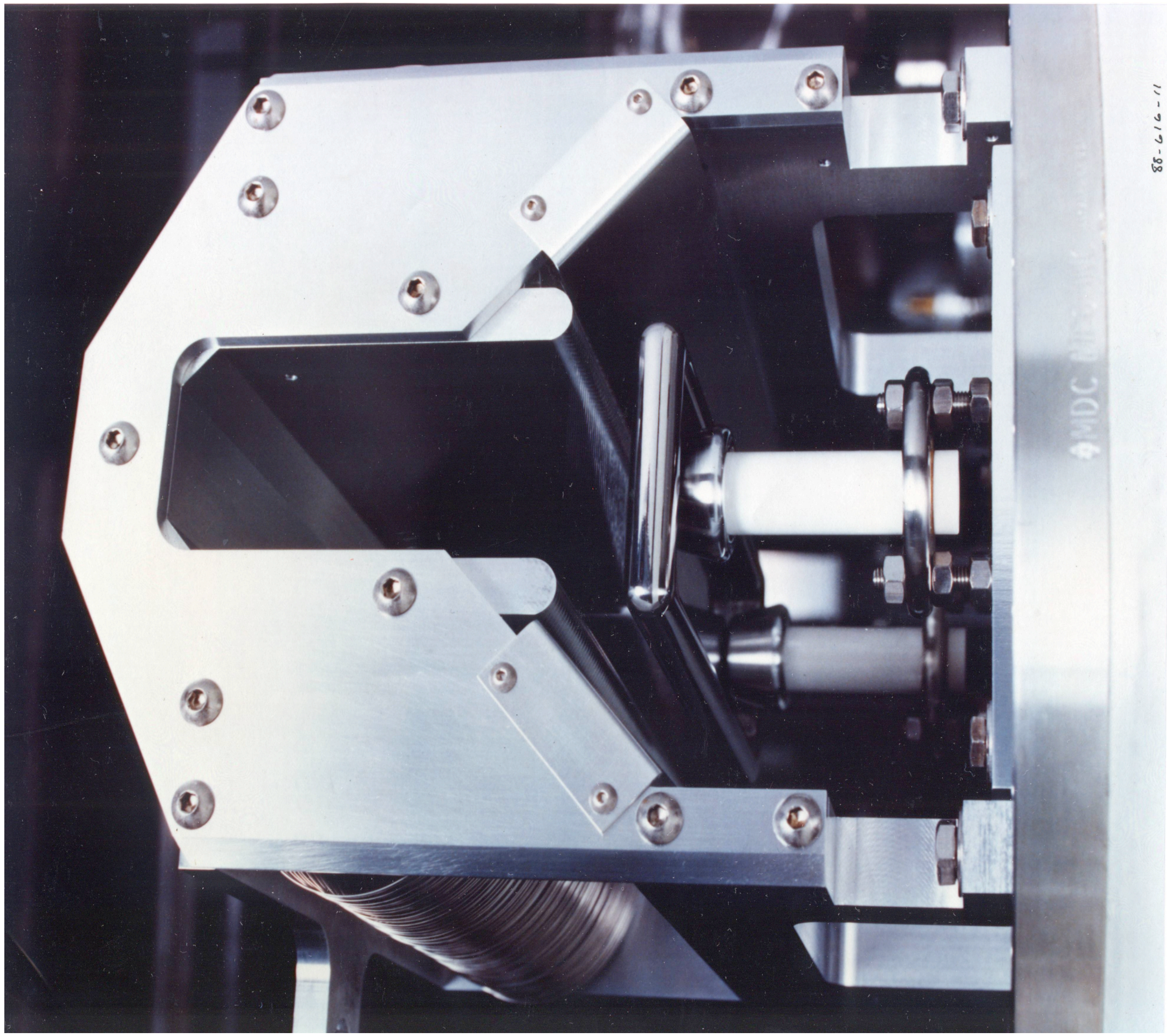
$$\sigma(1) = R\,\sigma(0)R^T \leftarrow \text{2x2 Matrix}$$

Final beam size and angles at the patient

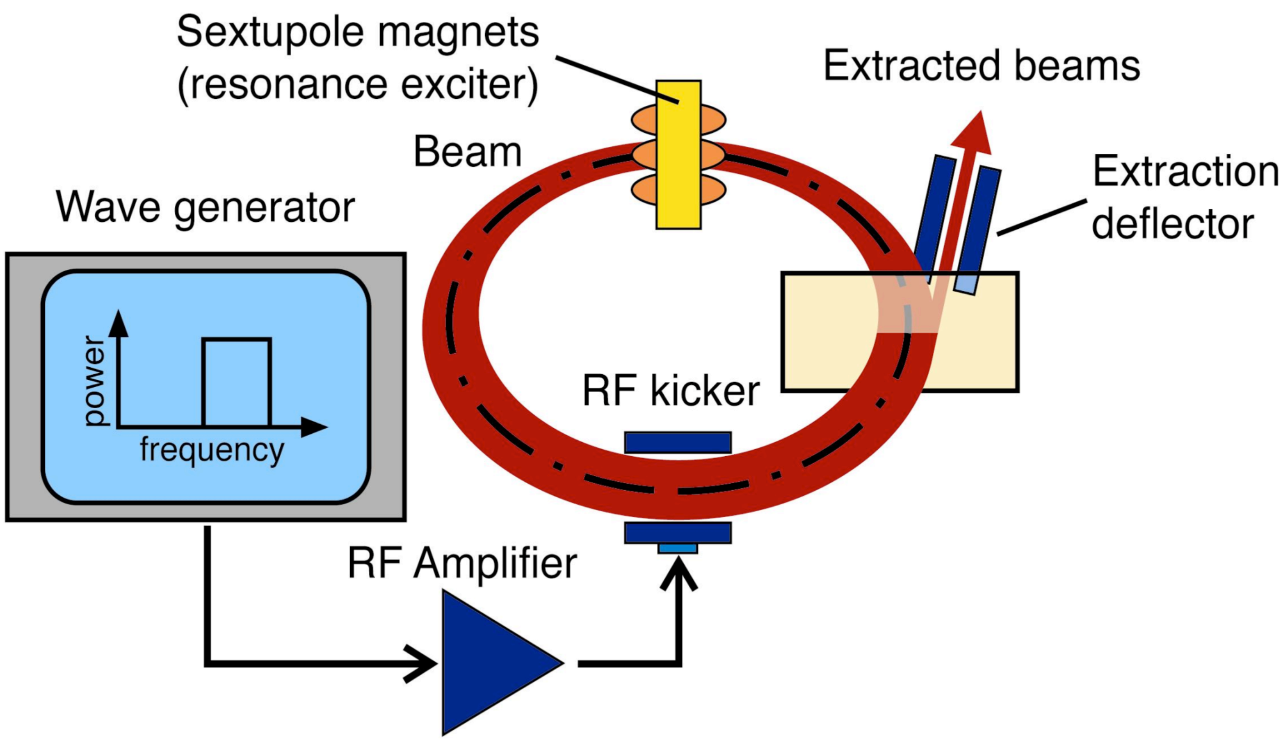
Initial beam size and angles at extraction septum

Magnet lattice

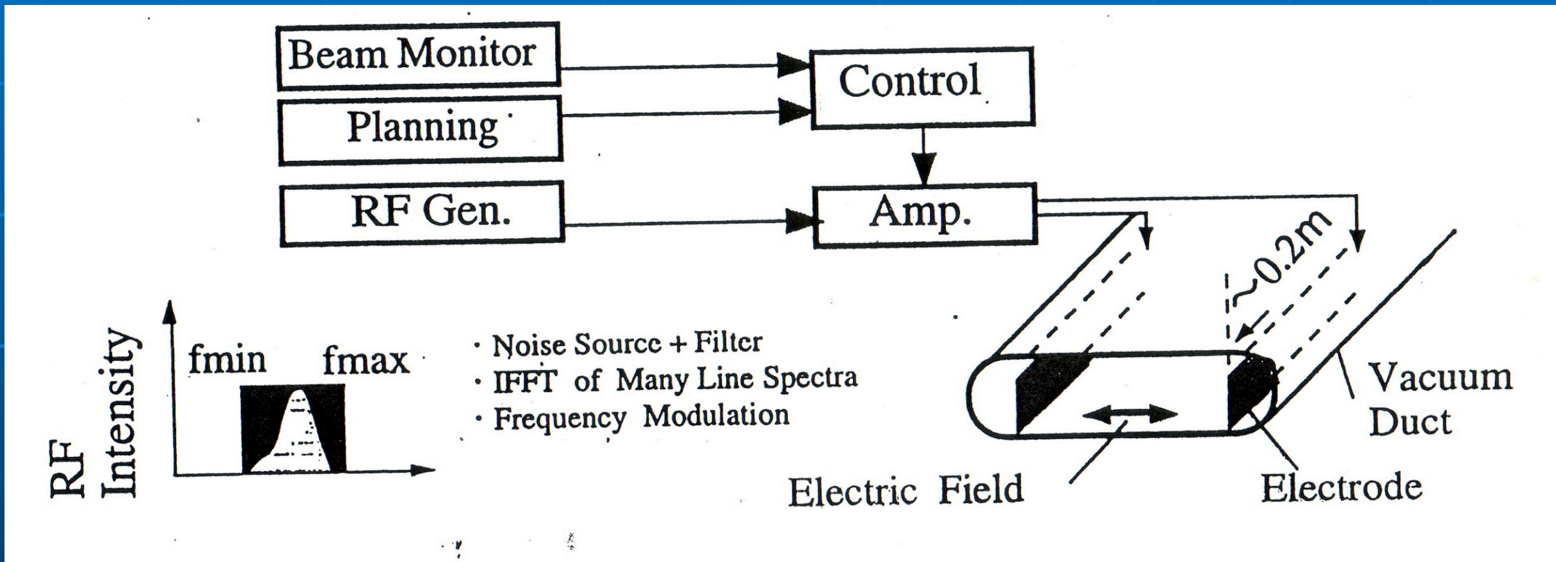
Extraction Septum in the Ring

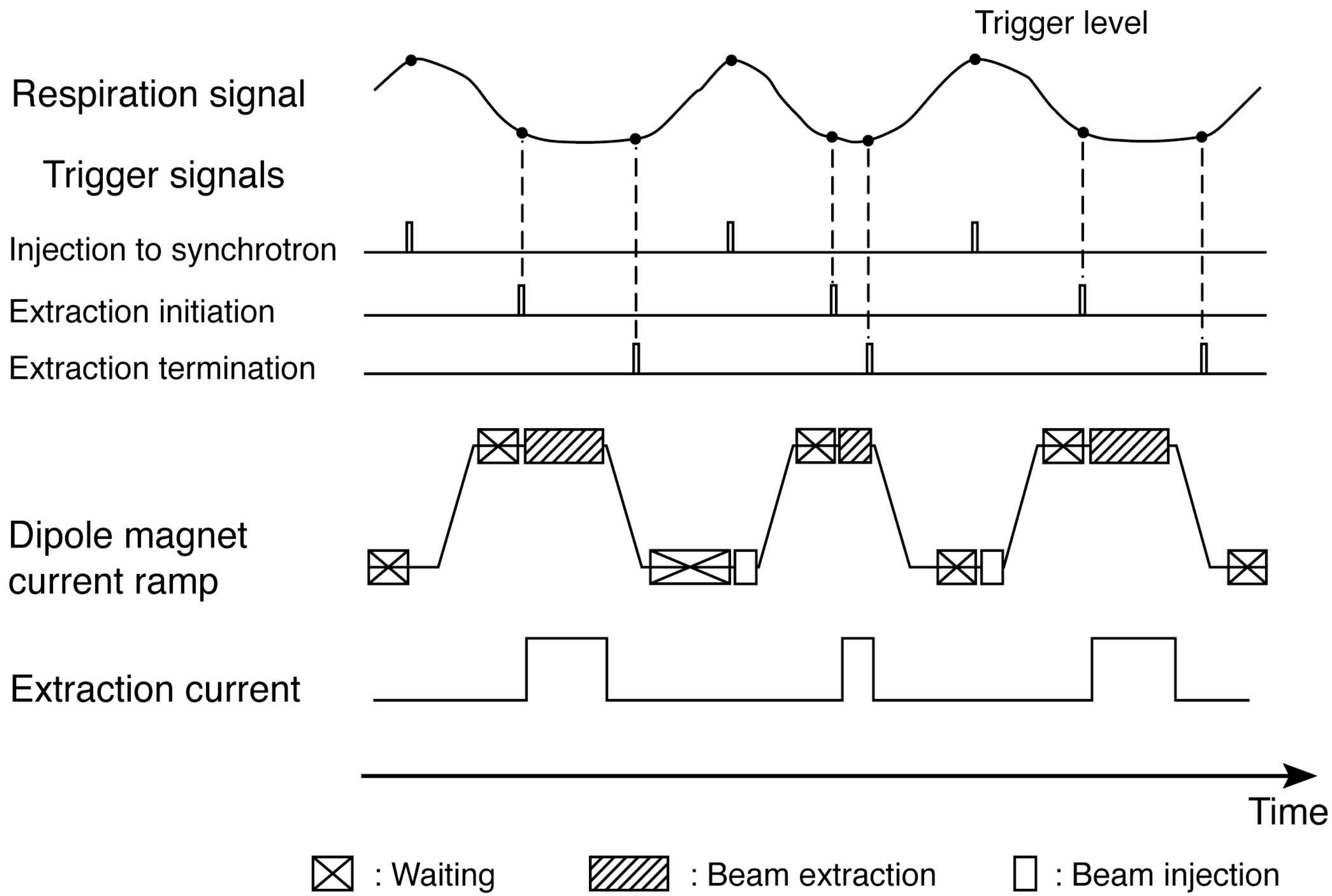


RF driven extraction system (courtesy Hitachi)



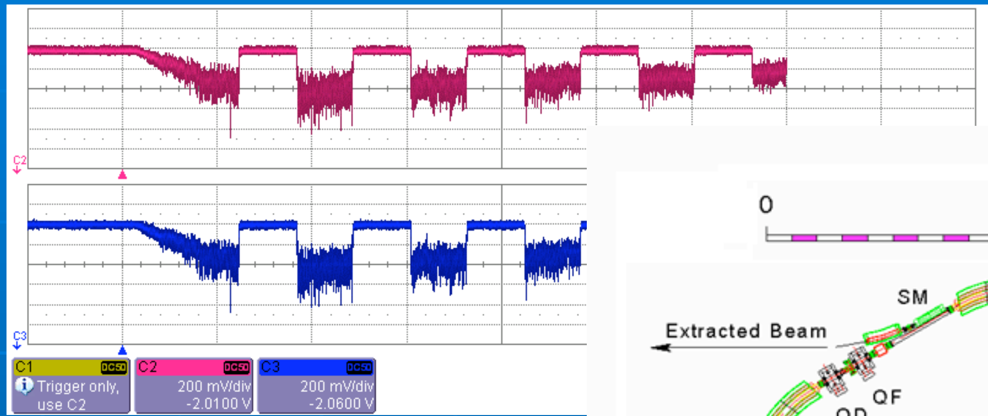
Excite betatron frequencies for slow extraction




Trigger level
Respiration signal
Trigger signals
Injection to synchrotron
Extraction initiation
Extraction termination
Dipole magnet
current ramp
Extraction current
Time
: Waiting
: Beam extraction
: Beam injection

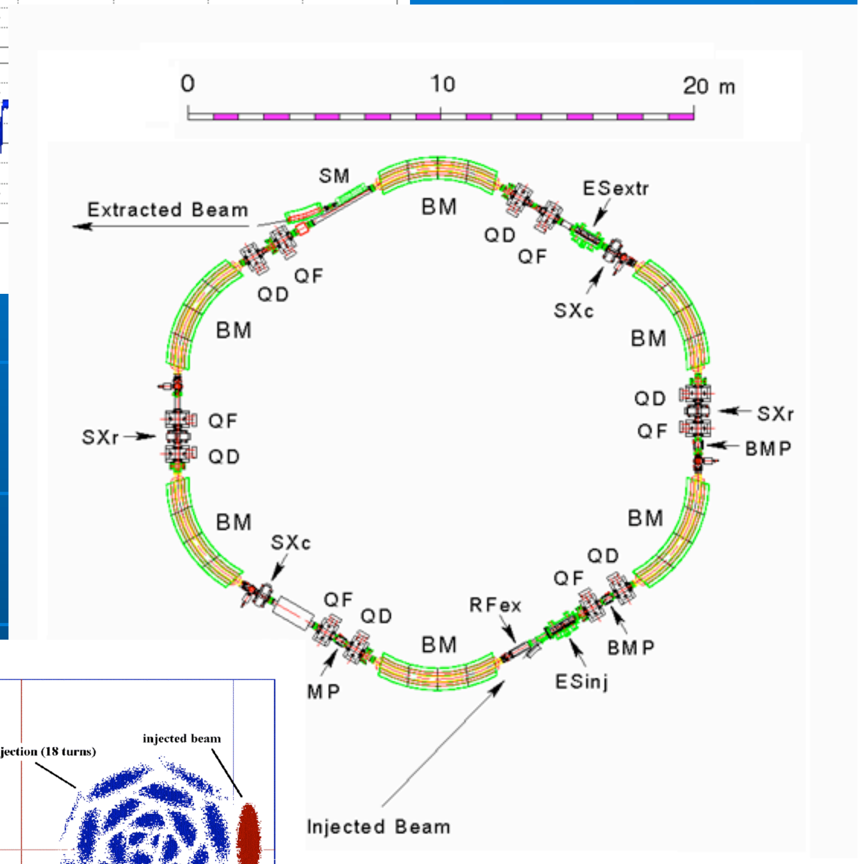
Synchrotron

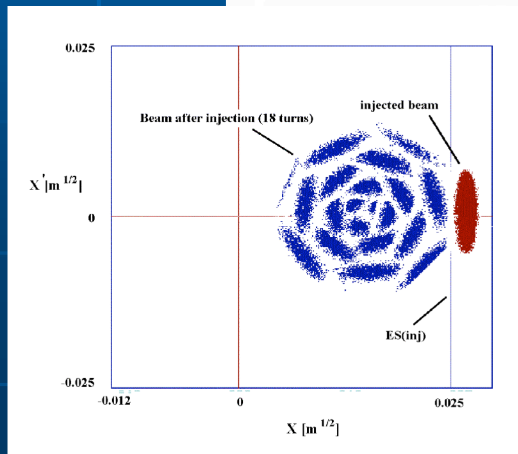
- compact design
- proven technology
- multiturn-injection => high intensities
- rasterscanning optimized, extremely flexible beam extraction
- fast variation of energy (range)



Multiple extraction

0,5 bis 10 sec

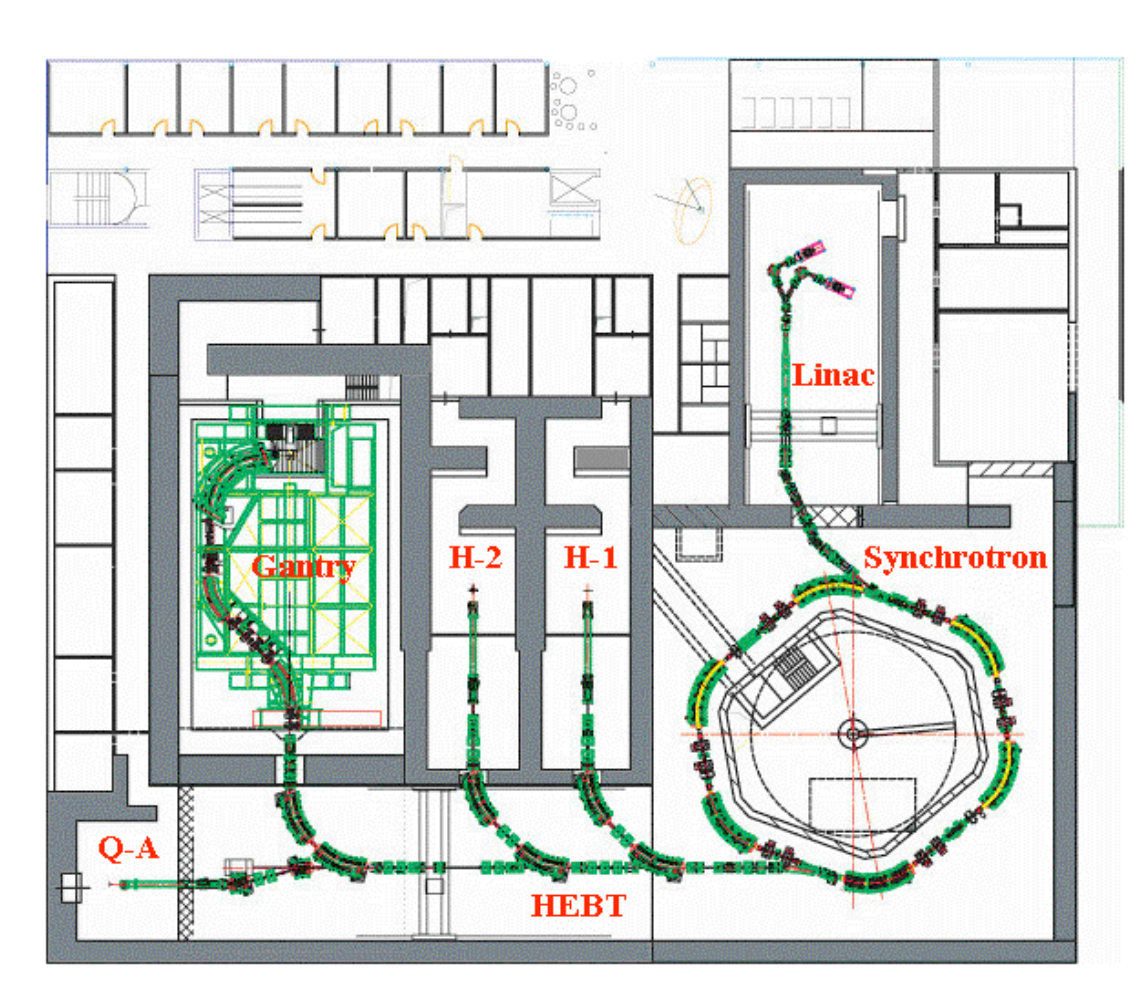




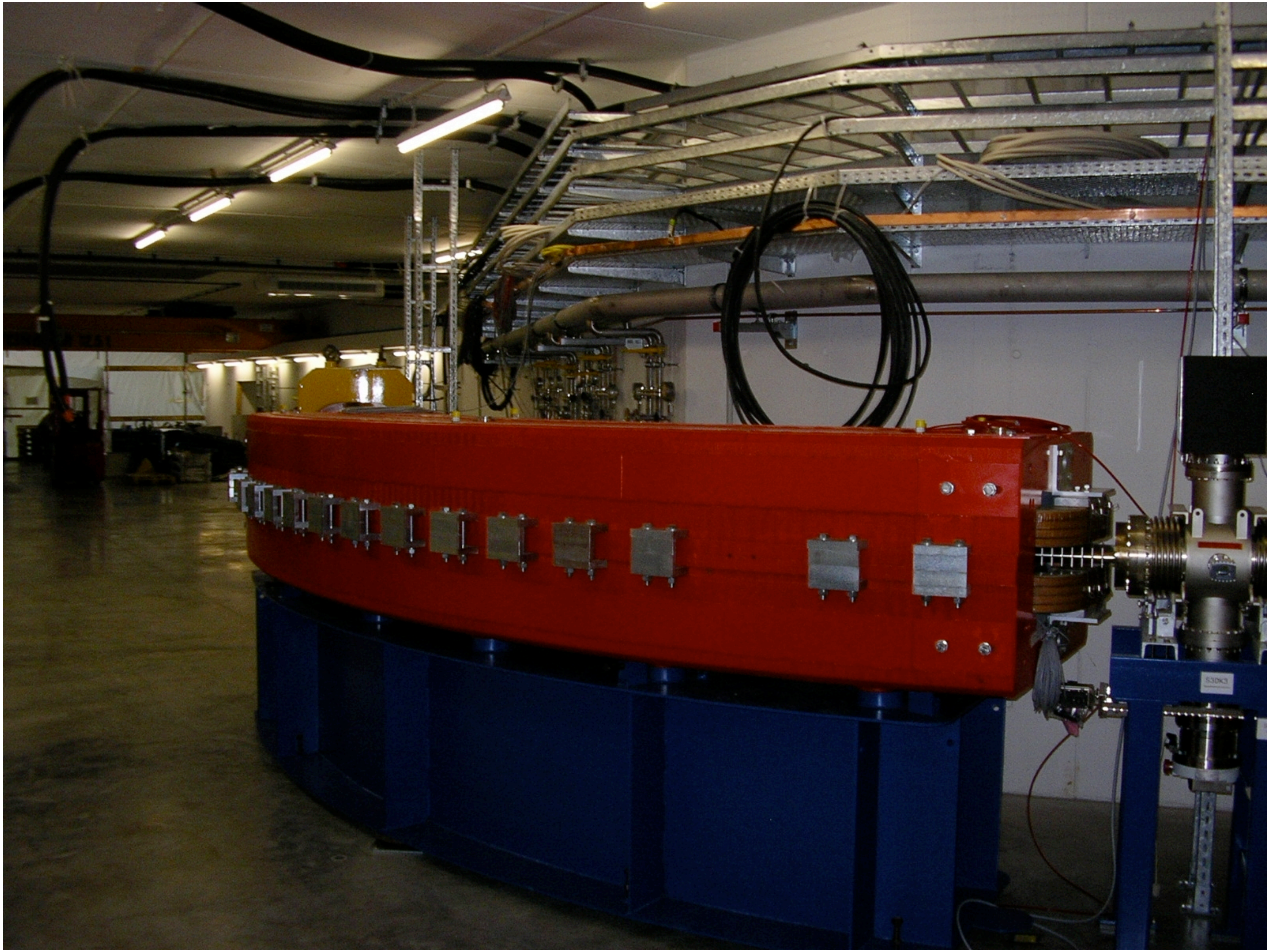
Multiturn injection

General Requirements

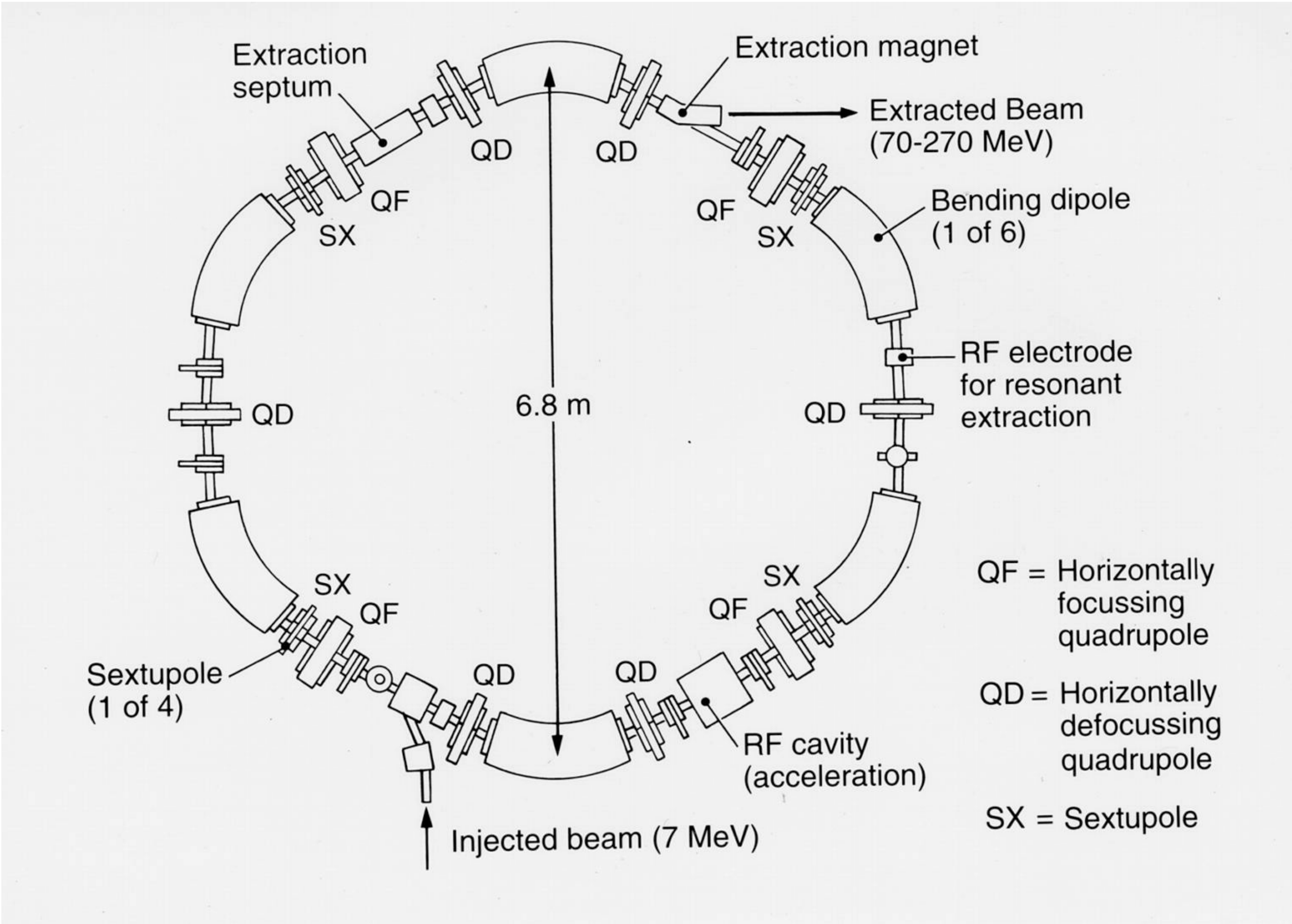
- compact design
  (60m x 70m)
- full clinical integration
- raster scanning only
- treatments with various
  ions: p, He, C, O
  change within minutes
- world-wide first scanning ion gantry
- > 1000 patients per year




S3QD32



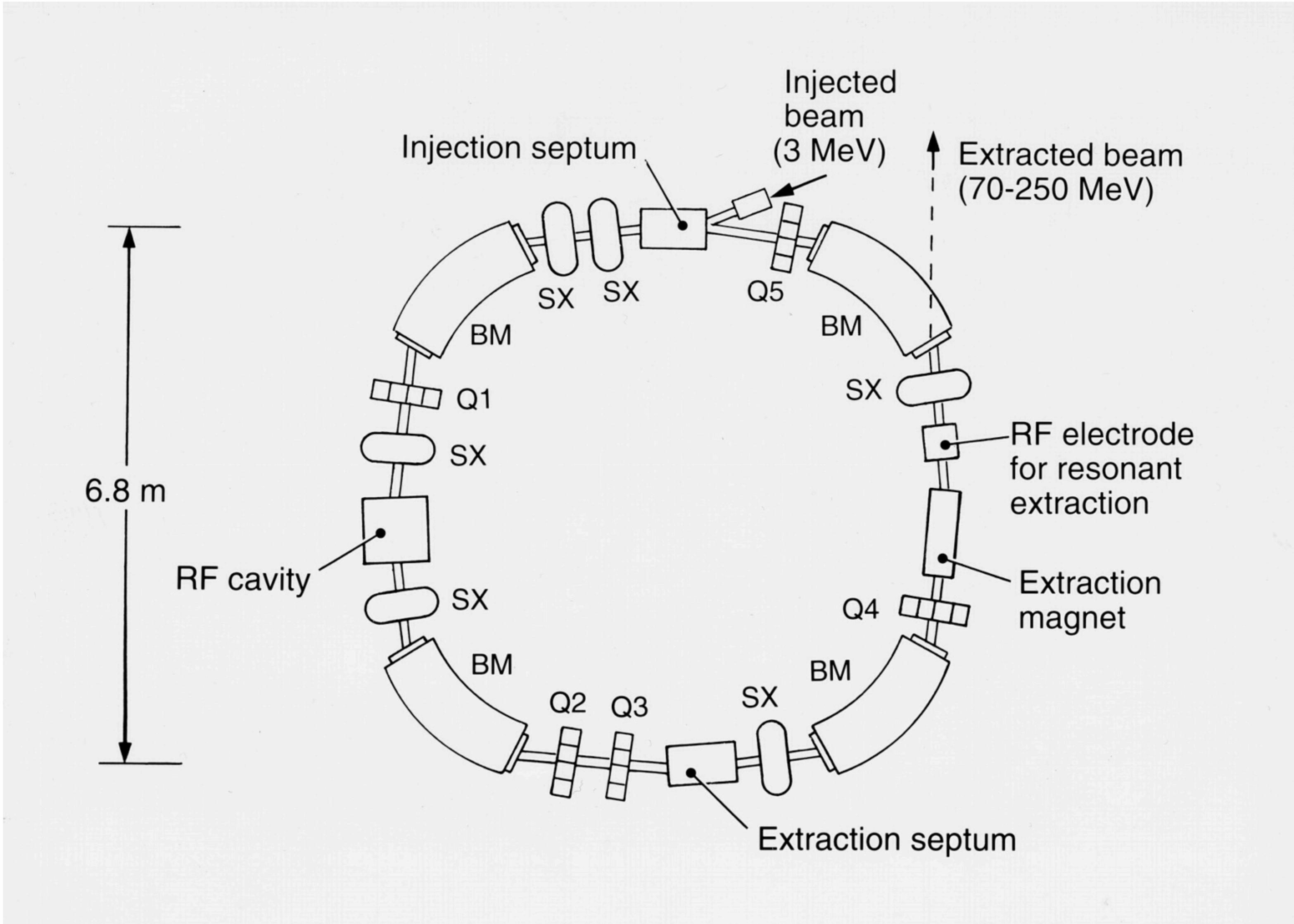
Hitachi Medical Synchrotron



Hitachi and Siemens Synchrotrons

- Both designs use 7 MeV multi-turn injection for higher intensity: 1.2×10^{11} protons per pulse (Hitachi)
- Both use RF driven extraction for turning beam on and off quickly ($< 200\ \mu$sec) and for gated respiration
- Both are strong focusing (tune > 1) with similar magnet layout and beam optical properties (tune, dispersion, beta function, etc)
- However, Siemens' accelerator for heavy ions (430 MeV/nucleon) is 3 times the size (20 m diameter) of the proton only synchrotrons

Mitsubishi Medical Synchrotron



Mitsubishi 250 MeV Synchrotron

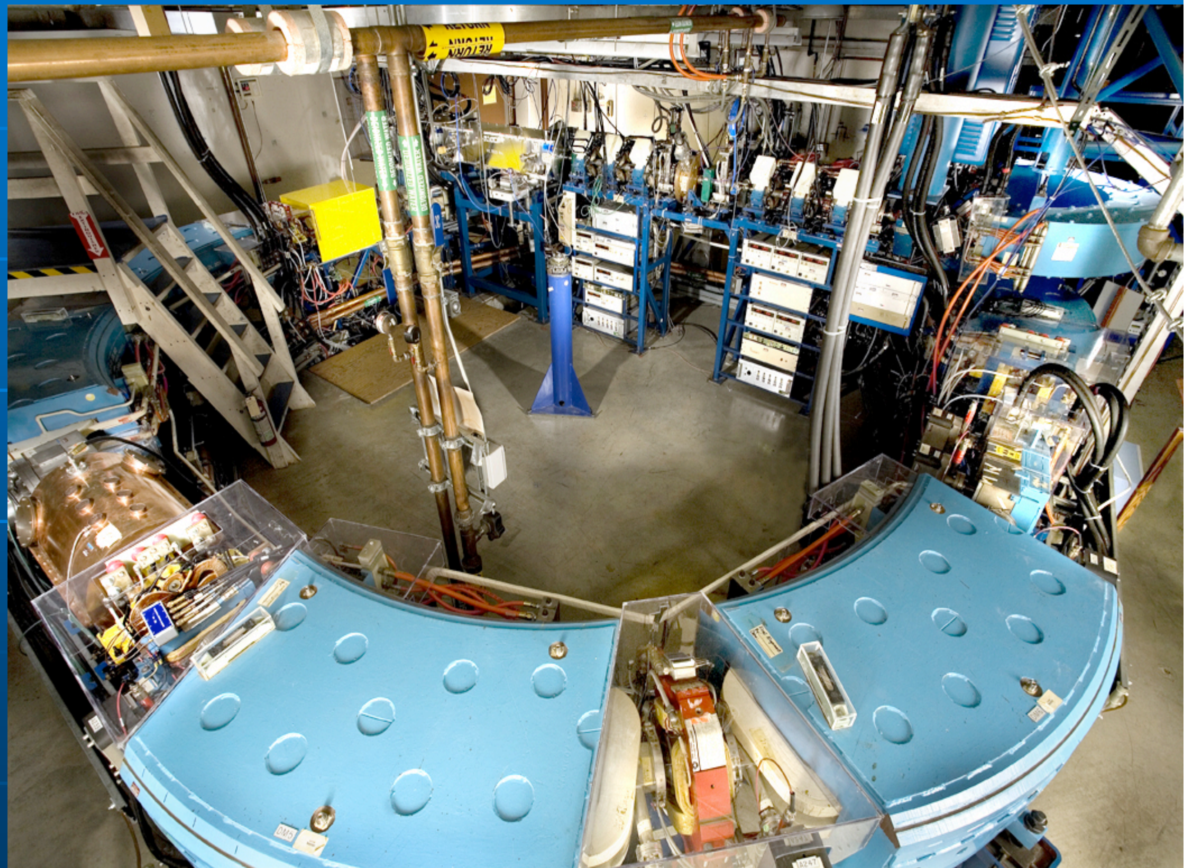
- Accelerator vendor for 7 facilities in Japan
- Also provides beam gating for respiration
- High intensity : 6 x 10^{10} protons per pulse and 30 pulses per minute

Hitachi Proton Therapy Synchrotron

- Accelerator cycle can be synchronized with respiration cycle
- Patented RF driven extraction for fast beam on/off and uniform intensity (+/- 15%) to patient
- Dose rate = 2 Gy/min/liter with FS = 25 x 25 cm
- 2 accelerators built and commissioned
- FDA approved in USA

250 MeV Synchrotron at LLUMC offered by Optivus Tech., Inc.

- Continuous operation since 1990
- FDA approved (also for scanning applications)
- 98% reliability with 24/6 operations
- 2 Gy/min for volume of 1 liter, field size = 13 cm dia.
- Proton range stability 0.1 mm
- New control system in 2002 for beam scanning upgrade
- Uses slow extraction



LLUMC Synchrotron and beam lines control room

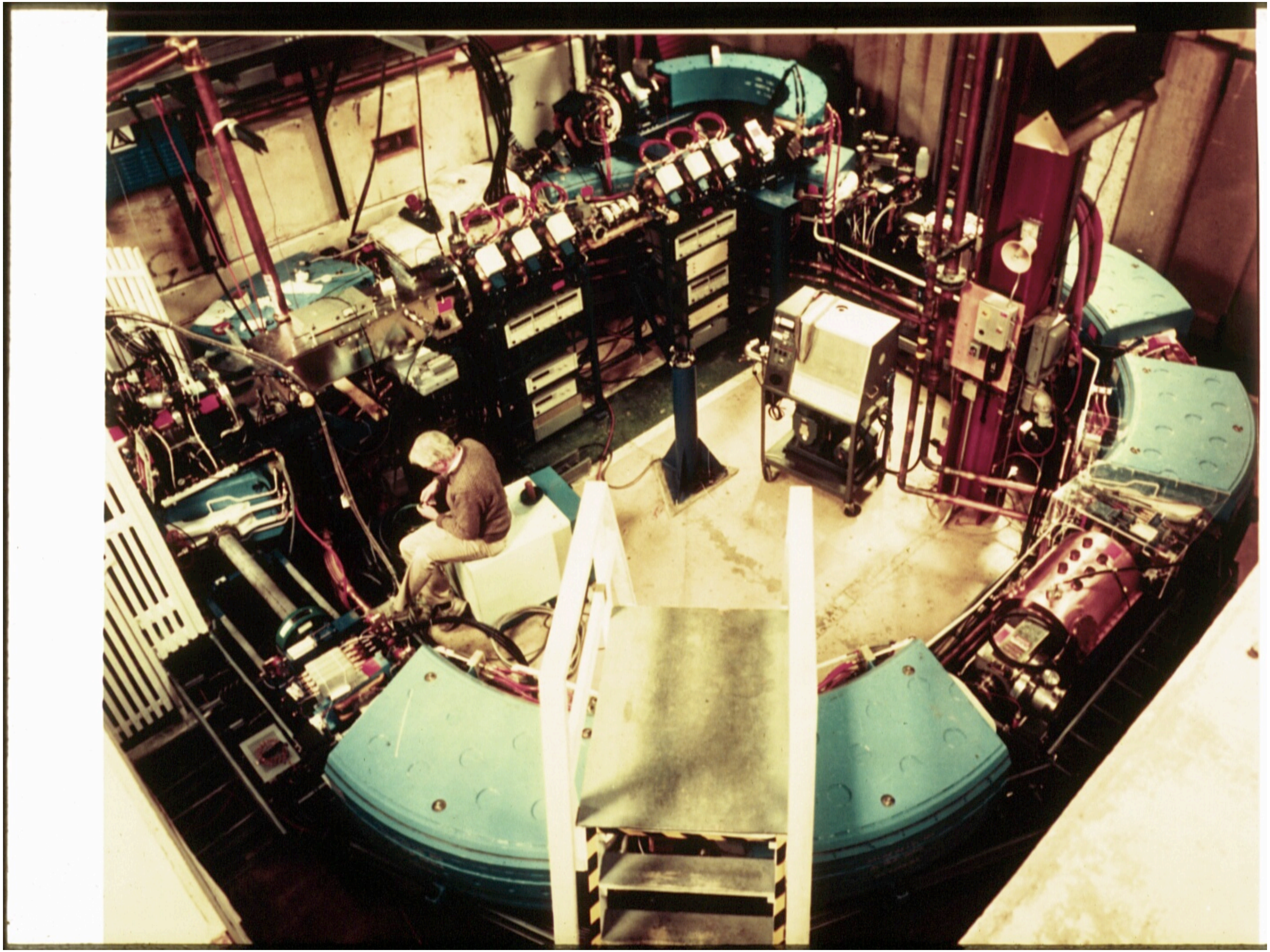
LLUMC Synchrotron and beam lines control room

Summary

- Synchrotrons do not require energy degraders since the beam is only accelerated to the energy being used.
- Synchrotrons can deliver adequate dose rates for all tumor sites : 1.0×10^{11} protons per pulse with 30 pulses per min ➔ allows 2 Gy/min/liter
- Beam energies can be changed in less than 2 sec for scanning
- Energy stability for scanning is < 0.2 MeV
- 0.5 sec spill durations are adequate for scanning

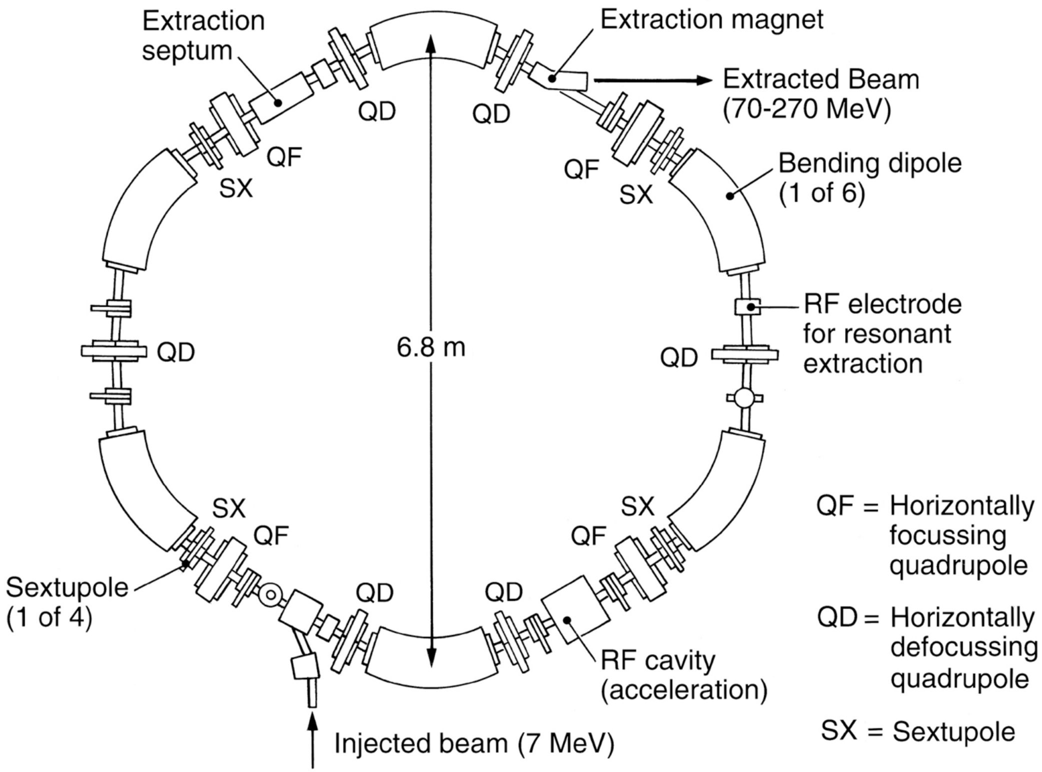
Summary

- Maintenance can be performed immediately after shutdown (no cool down time required).
- Synchrotrons require less shielding and can be operated continuously at 70 MeV without increased shielding or impacting access for maintenance
- Synchrotron intensities are inherently safe and do not require variable intensity depending on energy degrader thickness.

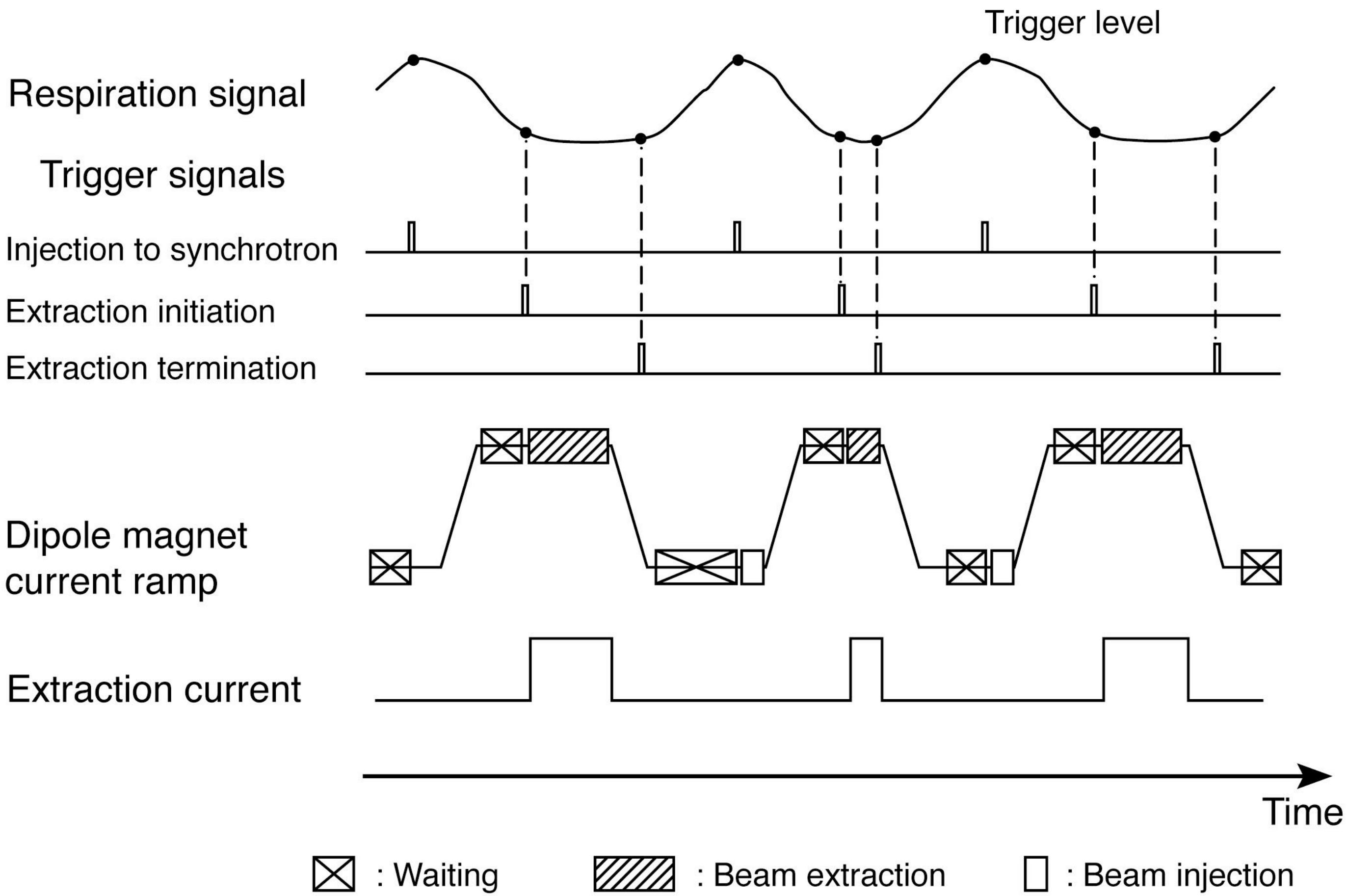


Hitachi 250 MeV Proton Therapy Synchrotron

7 MeV multi-turn injection
RF driven slow extraction
Dynamic beam gating with respiration cycle



Timing Diagram for breath gating technique Synchrotron begins acceleration triggered by phase of breathing cycle (courtesy Hitachi)



Hitachi (Power and Industries)

- Synchronizes accelerator cycle with respiration cycle for chest tumors(typically 4 sec long)
- Capable of 1 x 10^{11} ppp with 2 sec cycle time
- Offers scanning and passive beam spreading
- Presently has delivered one complete system and three subsystems in Japan and one in commissioning phase in Houston, TX
- Patented RF driven extraction system for slow smooth extraction.
- Can build all components "in house"

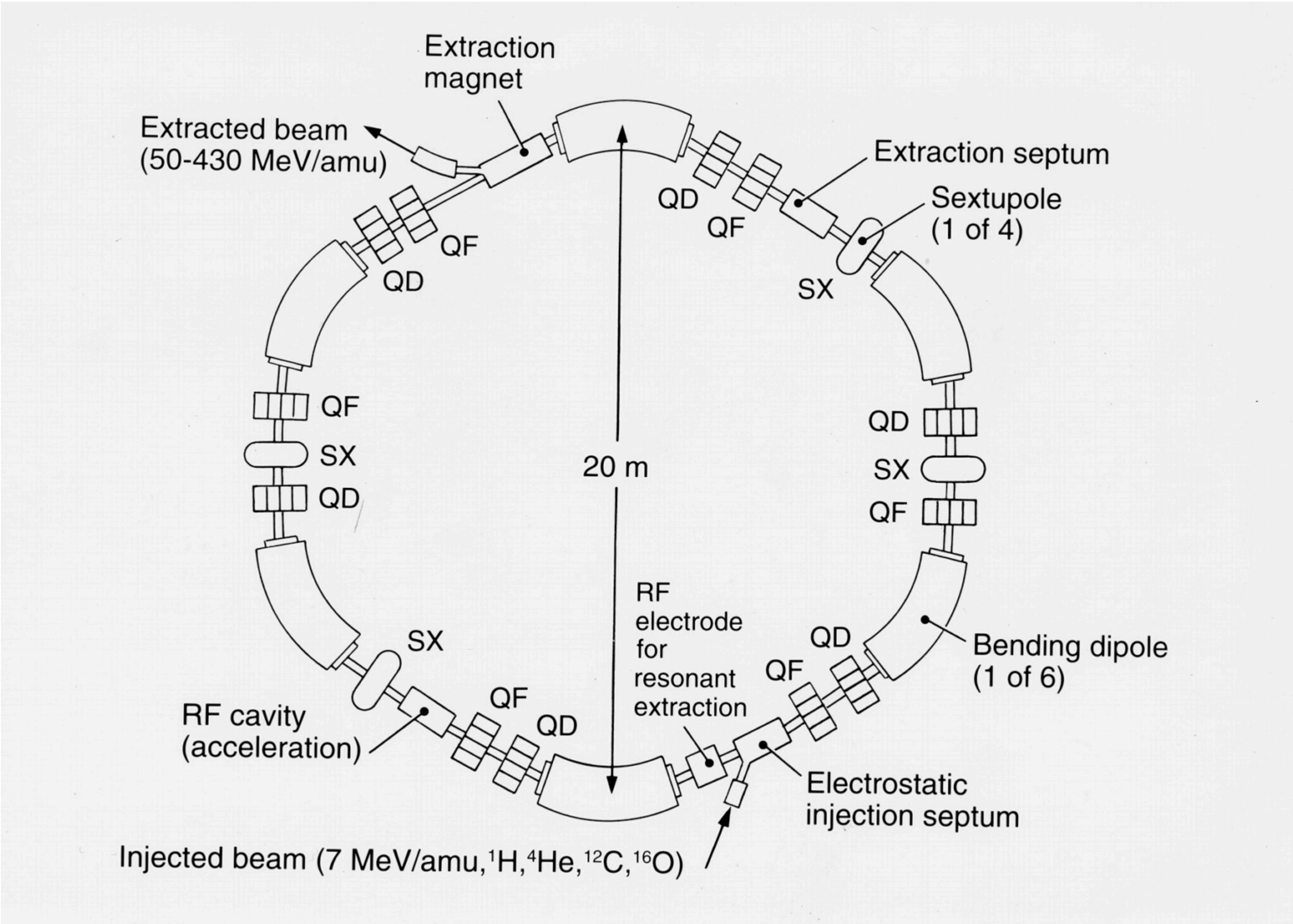
Siemens

- Only commercial vendor of Proton and Carbon beams, partnership with Dan Physik for particle accelerator technology
- Uses a 20 meter diameter synchrotron to accommodate C^{6+} as well as Protons
- Offers proton gantries and horizontal beams for Carbon
- Presently building facility in Heidelberg, GE.
- Lab partner at the GSI nuclear lab (Darmstadt) is building massive 600 ton Carbon gantry (compared to Loma Linda's 90 ton gantry)
- Offers only scanned beam delivery systems

Mitsubishi

- Uses 3 MeV multi turn injection to synchrotron
- Capable of 5×10^{10} ppp with 2 sec cycle time
- Beam deliver system is passive only (no scanning)
- One working facility in Shizouka, Japan with 3 to 4 Treatment rooms
- Built subsystems for other Japanese facilities

Heidelberg Medical Synchrotron



Common Myths about Synchrotrons

- Myth #1 – Synchrotrons do not have enough intensity to treat large fields (>20 x 20 cm^2) in less than 2 min.
- Myth #2 – Because synchrotrons are pulsed machines with low duty cycle (about 25%), treatment times with beam scanning will be too long when 10's of thousands of spots are needed for each field
- Myth#2 – The time profile of the beam intensity is too irregular to use scanning techniques.
- Myth#3 – Maintenance is higher with synchrotrons due to more magnets and power supplies to control and therefore will have higher down times
- Myth#4 – Synchrotrons are more expensive than cyclotrons and therefore reduce profitability of a clinical facility

Why choose a synchrotron accelerator for proton therapy?

1. Synchrotrons are variable energy as required by therapy. I.e. they accelerate protons only to the energy required for a specific treatment.

2. They are capable of achieving >90% extraction efficiency with minimal residual activity of the accelerator or beam lines.

3. Synchrotrons satisfy all intensity and energy requirements without the need for "dirty" degraders.

- 4. Their intensities are inherently limited to avoid accidental overdose conditions
- 5. The beam lines do not need a degrader and the beam lines may transport >90% of the extracted beam.
- 6. Lower costs are possible with reduced shielding requirements.

Optivus Technology (San Bernardino, CA)

- Presently marketing “turn key” system using 250 MeV Fermilab synchrotron with enhancements(in use for 15 years)
- Company was formed as a “spin off” from Loma Linda engineering group in 1995
- Offer scanning beam and passive beam delivery systems
- At the Loma Linda facility they have built
- a) passive beam delivery systems for clinical use
- b) New accelerator control systems
- c) 1st Digital imaging system for patient alignment
- Intensity is 2.4 x 10^{10} ppp with 2.2 sec cycle time, but have plans for upgraded intensity