Exotica

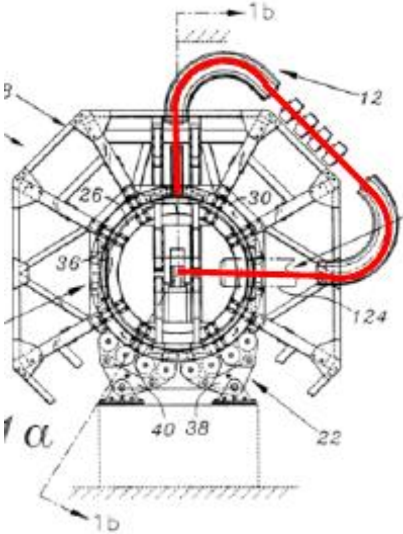
- Exotic (*adj*.): strange, mysterious, unfamiliar, outlandish, exceptional, unusual, new, alien, foreign

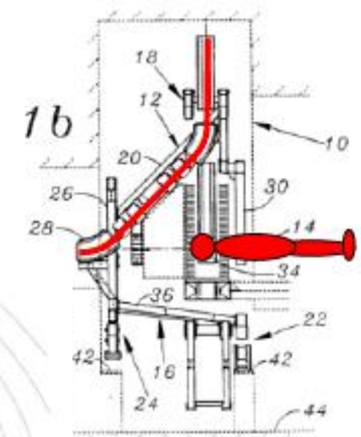
Introduction

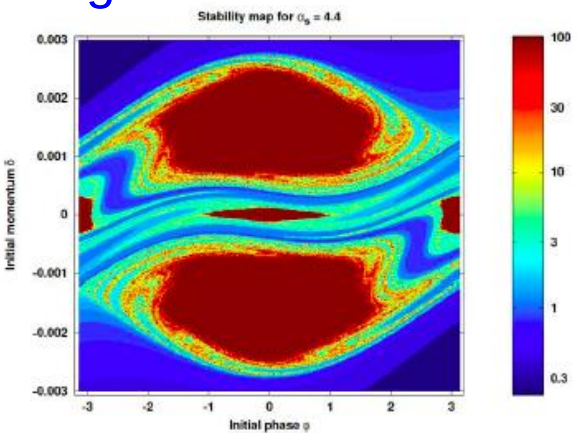
- This lecture was intended to go beyond ‘conventional’, to give a flavor of creativity which can be applied to beam transfer, in terms of :
  - Concepts
  - Systems
  - Challenges
  - Solutions
- But…a dazzling array of techniques and technologies have already been presented this week
  - Difficult to ‘go beyond’ what you’ve already been exposed to: ‘conventional’ here is a very relative term

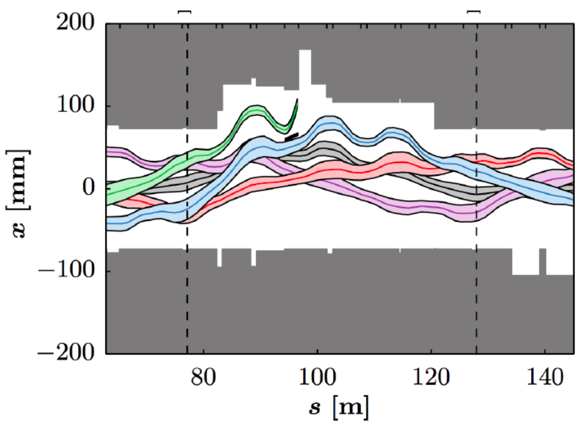
Fantastic beasts already seen in Erice…

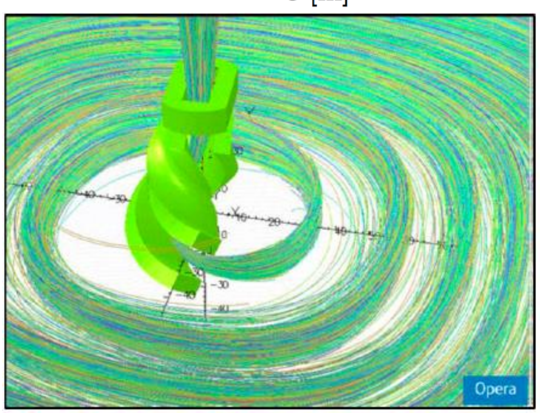
- Electrostatic spiral inflectors for Cyclotrons
- Golf-club long. injection for small aperture storage rings
- Multipole kicker for light source top-up injection
- Corkscrew gantry for medical hadron beam delivery
- Slip-stacking and phase space painting
- Magnetic splitting

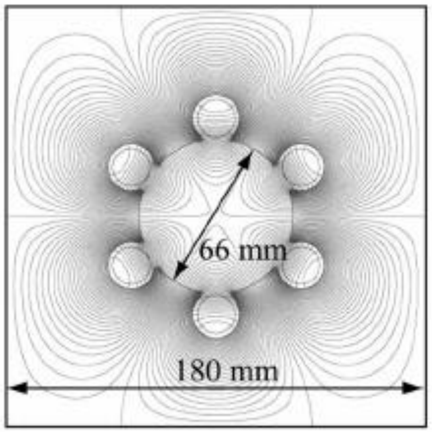


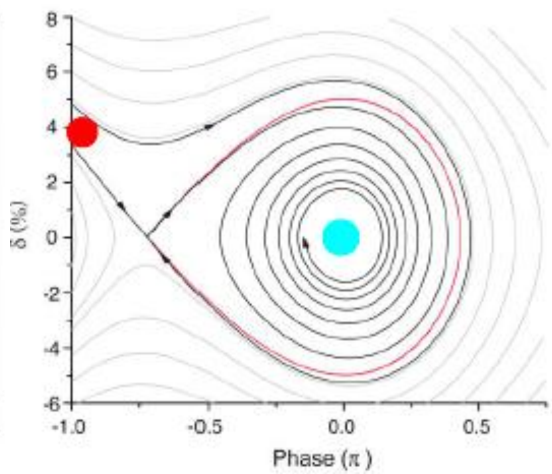












Why are (even more) exotic methods needed/studied?

- Many methods of injection, extraction and beam transfer exist and can be termed “conventional”
  - In regular or widespread use
  - Based on “standard” systems and techniques
- But, in this imperfect world, many limits exist, from laws of physics, engineering, safety, economics, …
  - Beam stability
  - Lifetime of unstable particles
  - Physical space available
  - Maximum electric/magnetic field
  - Beam loss and radiation dose
- And sometimes there is no “conventional” solution
- Difficult to move into new regimes of accelerator performance

“Exotic” methods covered

- Massless septum
  - for extraction
  - for injection failure mitigation
- C core extraction kicker
- Muon decay ring injection
- Extraction with bent crystals
- Laser stripping H- injection

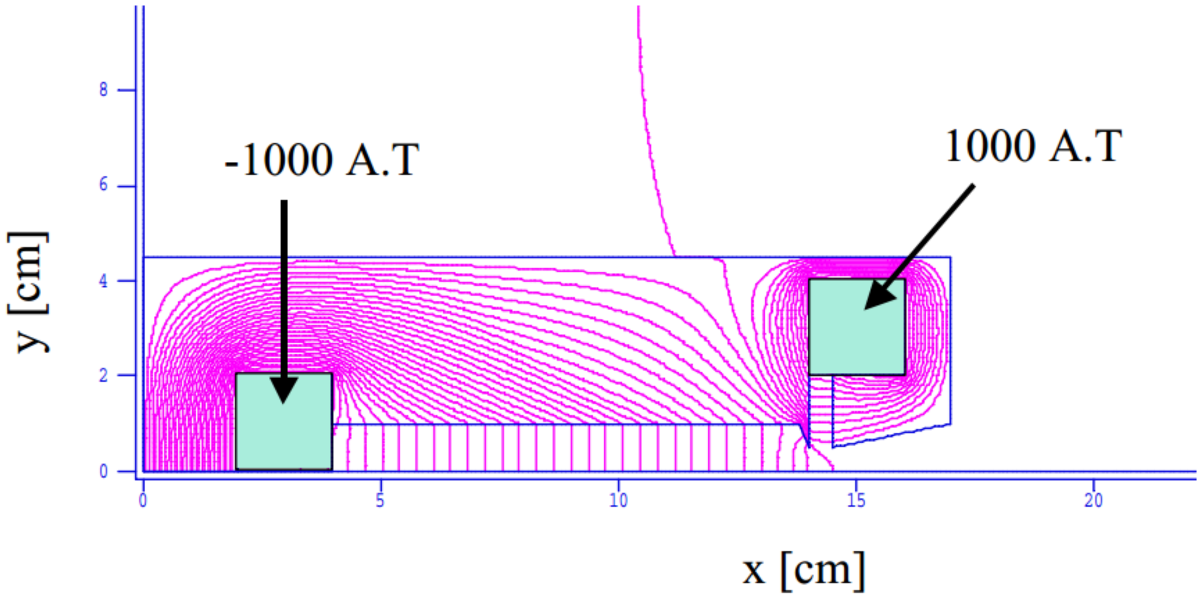
Many, many other fascinating topics are out there…

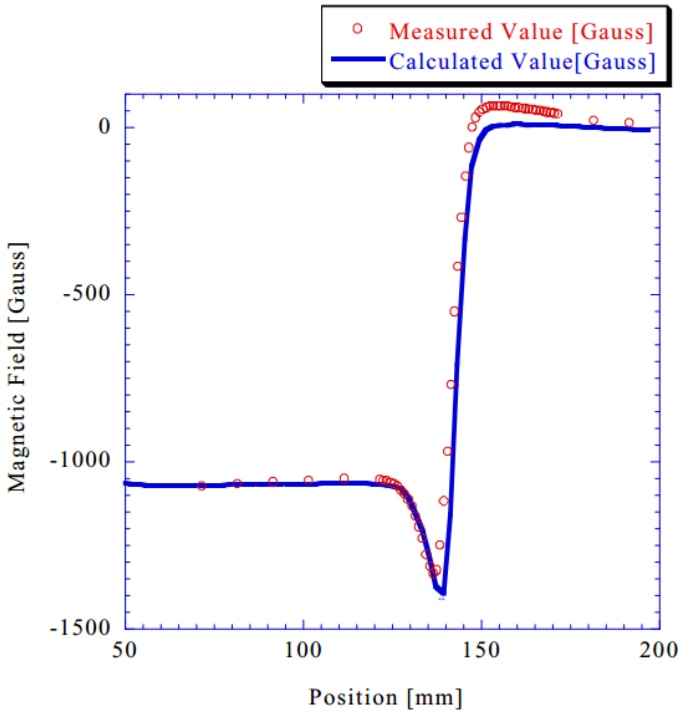
Acknowledgement: thanks are due to all the many colleagues for contributing to the topics described herein, and for their great creativity

Massless septum

Use of a massless septum

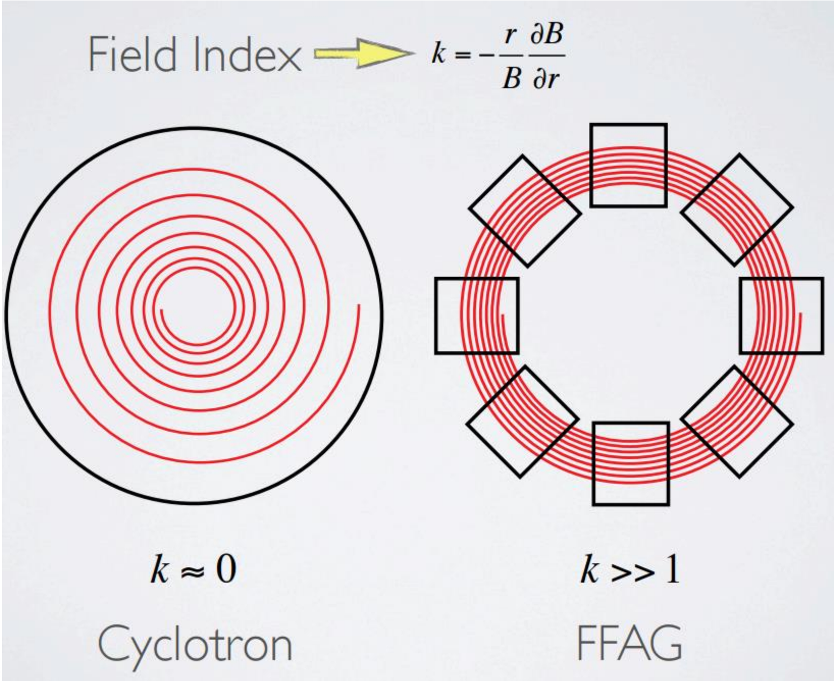
- Massless septum sounds like a dream come true – a fantastic technology idea looking for an application
  - Drawback is relatively thick "septum" (width order of gap height)
- Look at injection and extraction processes where beam intercepting septum blade is problematic
  - Slow/continuous extraction over multiple turns: reduce beamloss
  - High energy injection/extraction: to prevent damage from mis-steered beam

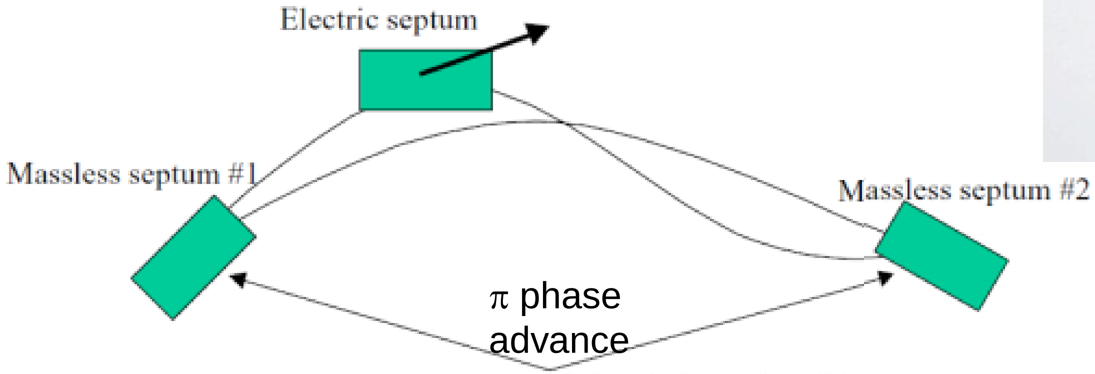


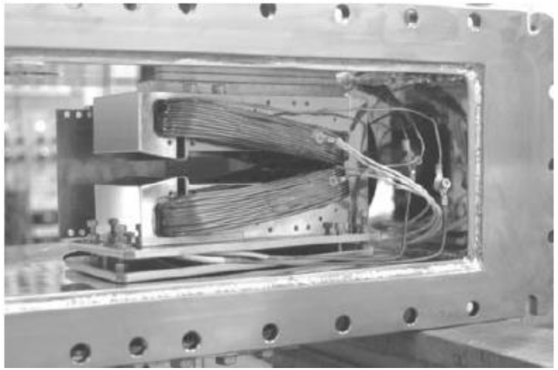


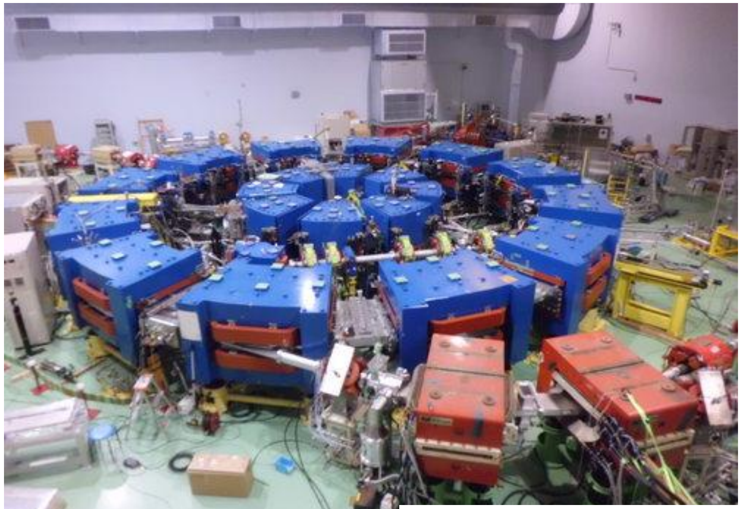
Massless septum: multiturn extraction

- Proposed [3] e.g. for Fixed-Field Alternating-Gradient accelerator FFAG
  - Hybrid of cyclotron and synchrotron
  - Quasi-continuous, high current
  - Adjacent turns close together
  - Thin septum needed to minimize losses







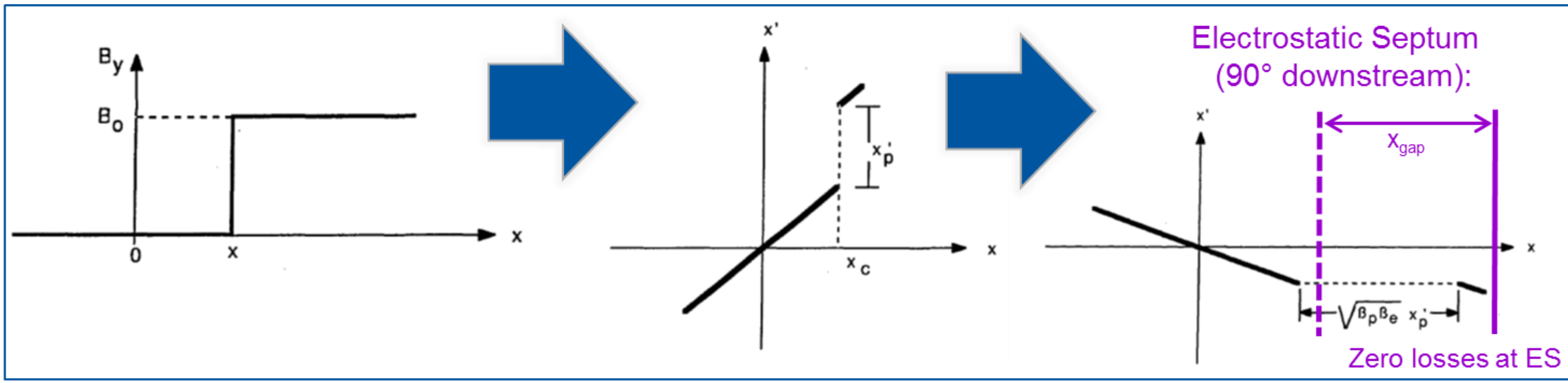


150 MeV Kyoto FFAG

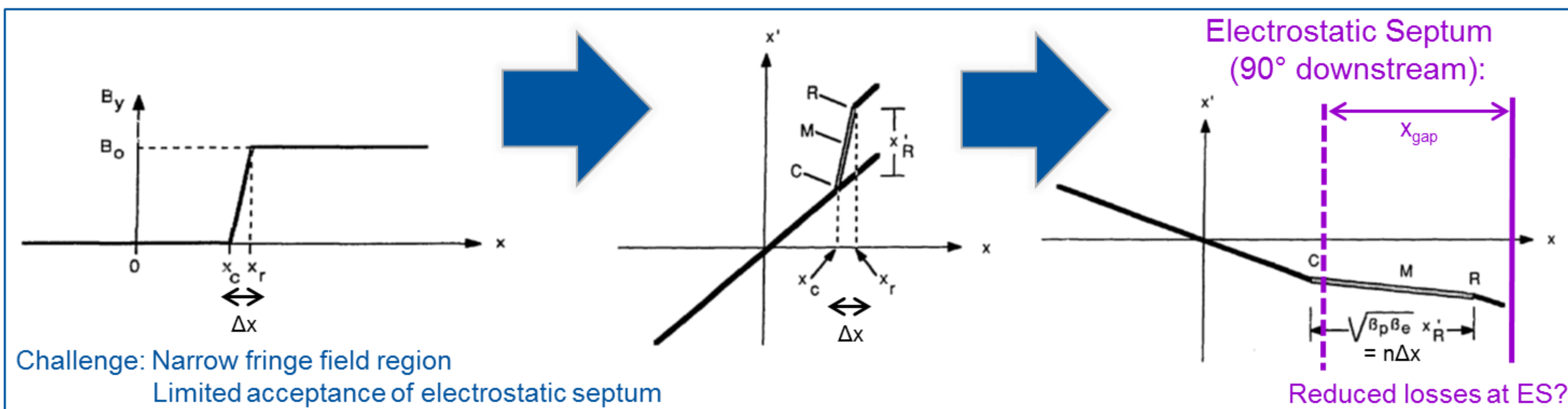
Massless septum: multiturn extraction

- Concept: “stretch” beam distribution at $\pi/2$ ES [4] to reduce density and hence losses: close with second massless septum at π

“Ideal” massless septum field



“Real” massless septum field

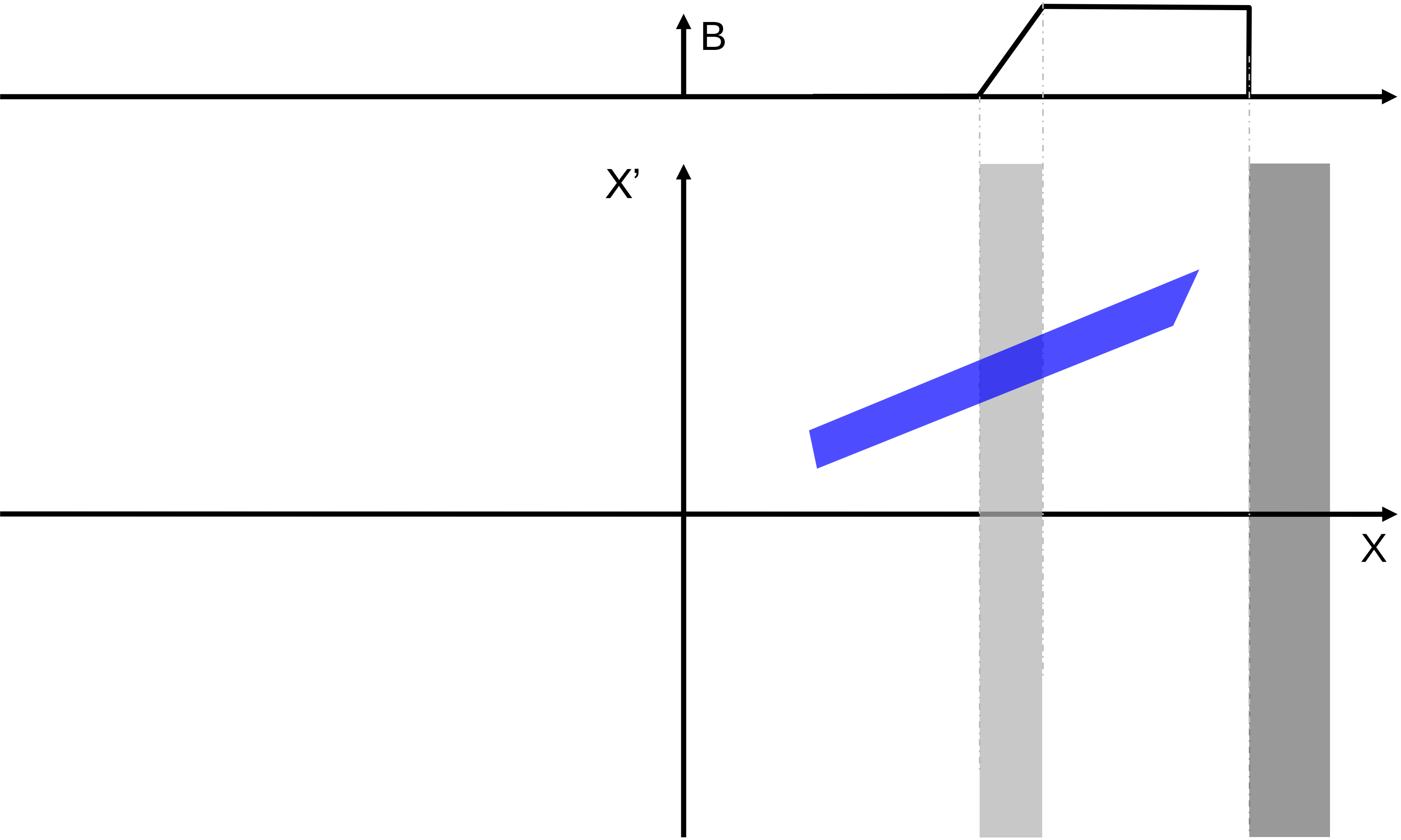


Massless septum: multiturn extraction

- Disadvantage with this arrangement is that large physical anode-cathode gap needed for ES, to accommodate the normal and stretched part of the spiral step – would limit attainable ES field
- Could improve by shifting ES position outward…need larger circulating beam aperture to accommodate "stretch"

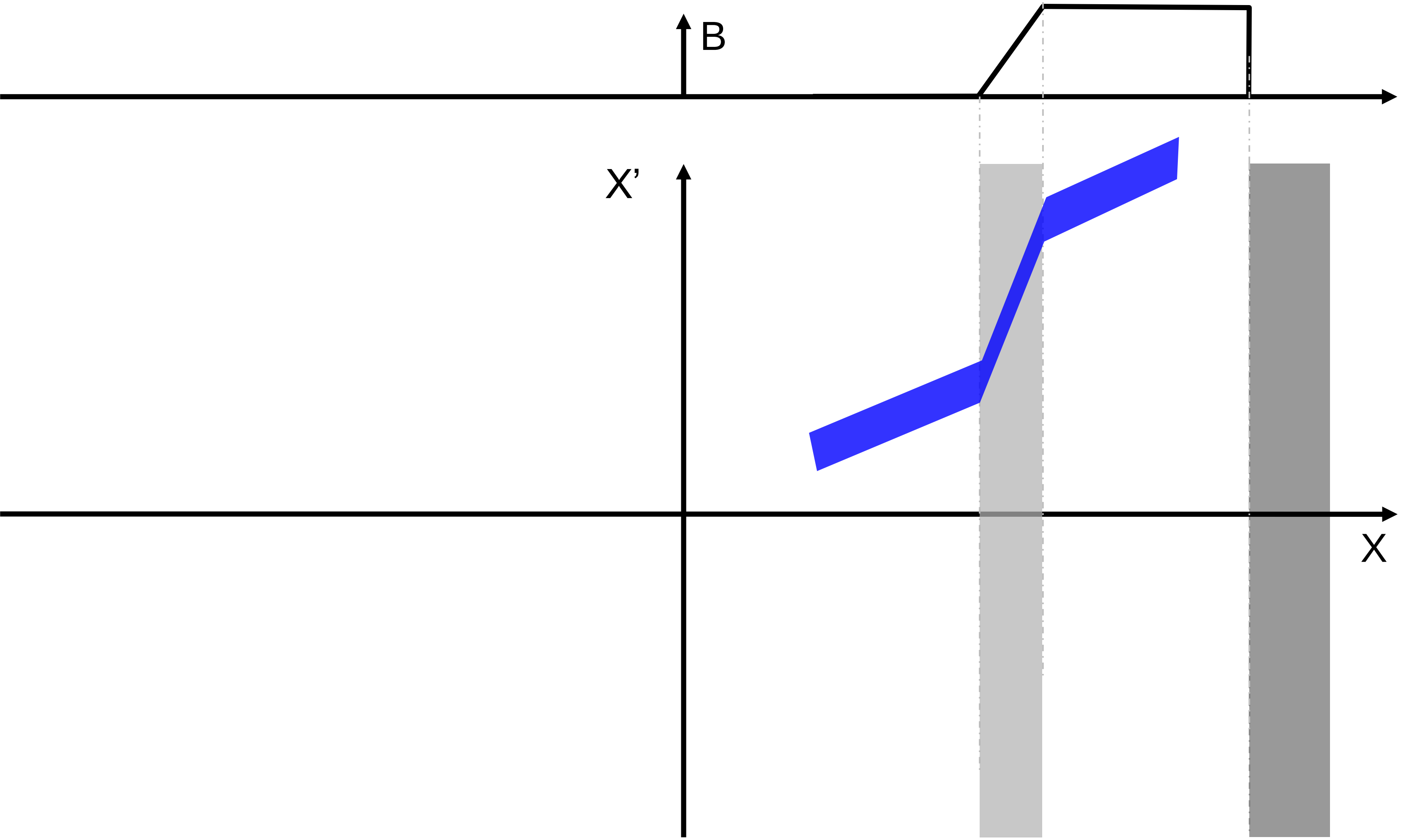
Massless septum: multiturn extraction

- Extracted beam "separatrix" at massless septum



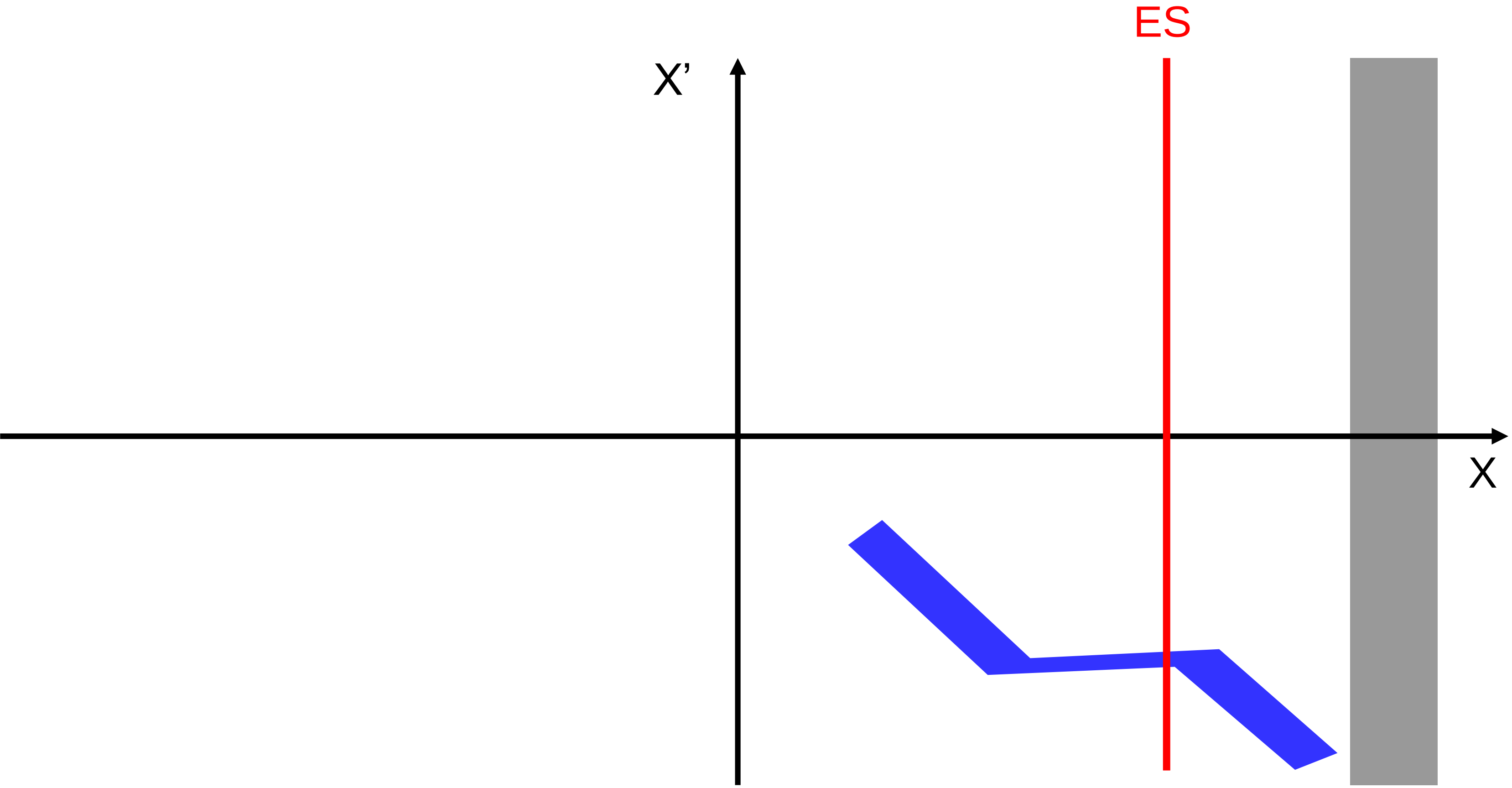
Massless septum: multiturn extraction

- Extracted beam "separatrix" at massless septum



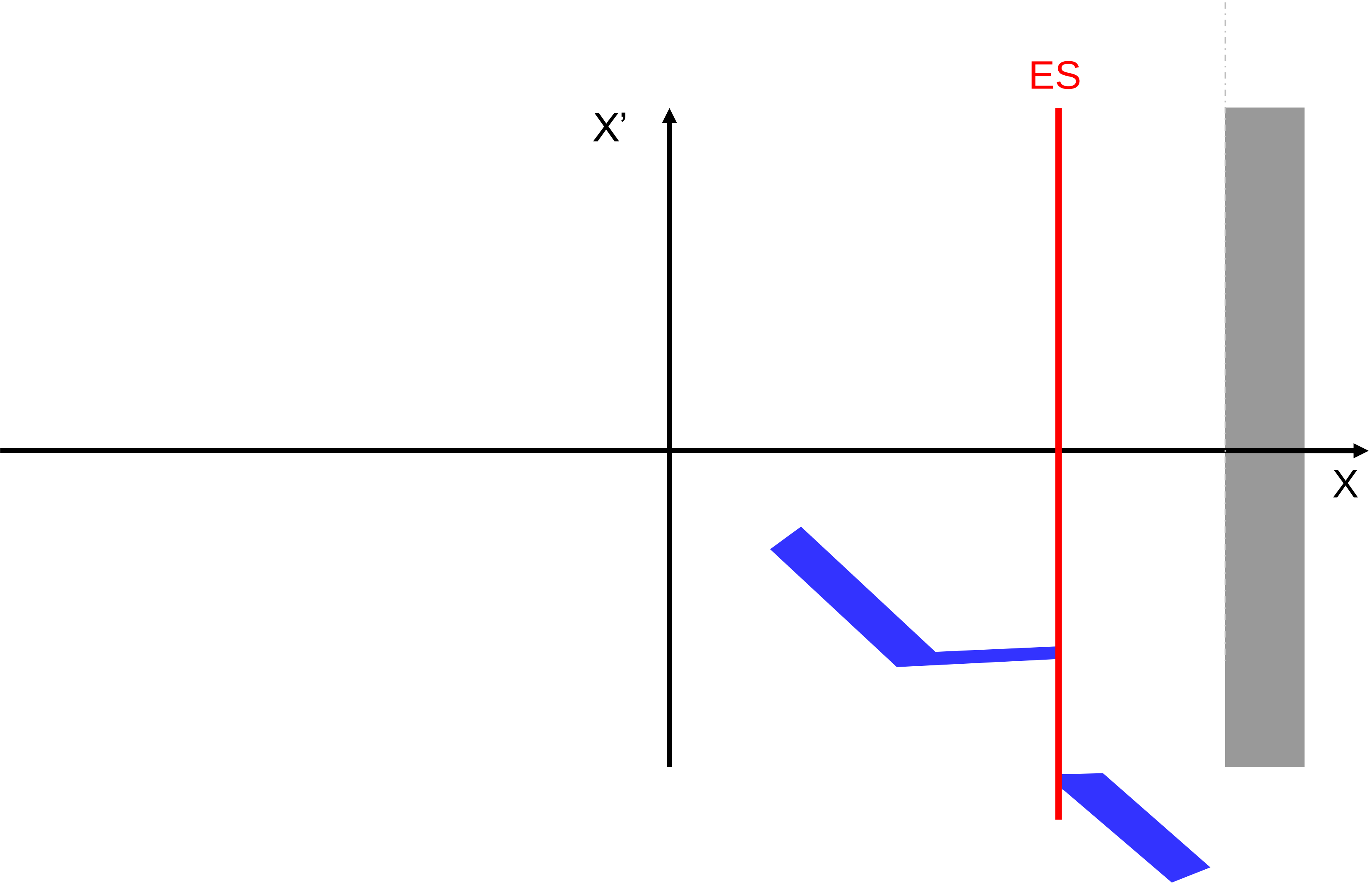
Massless septum: multiturn extraction

- At electrostatic septum ~$\pi/2$ downstream



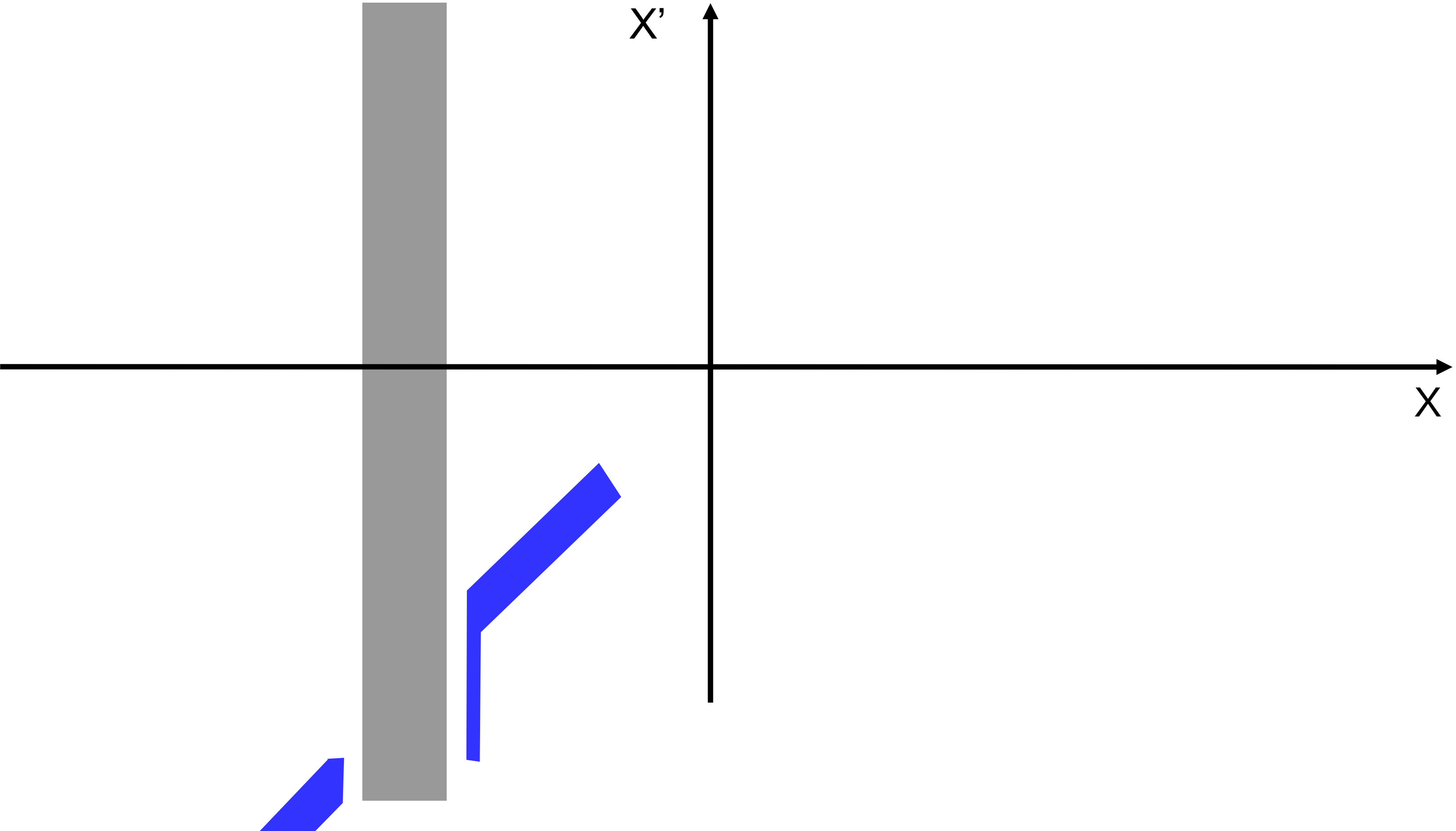
Massless septum: multiturn extraction

- At electrostatic septum ~$\pi/2$ downstream



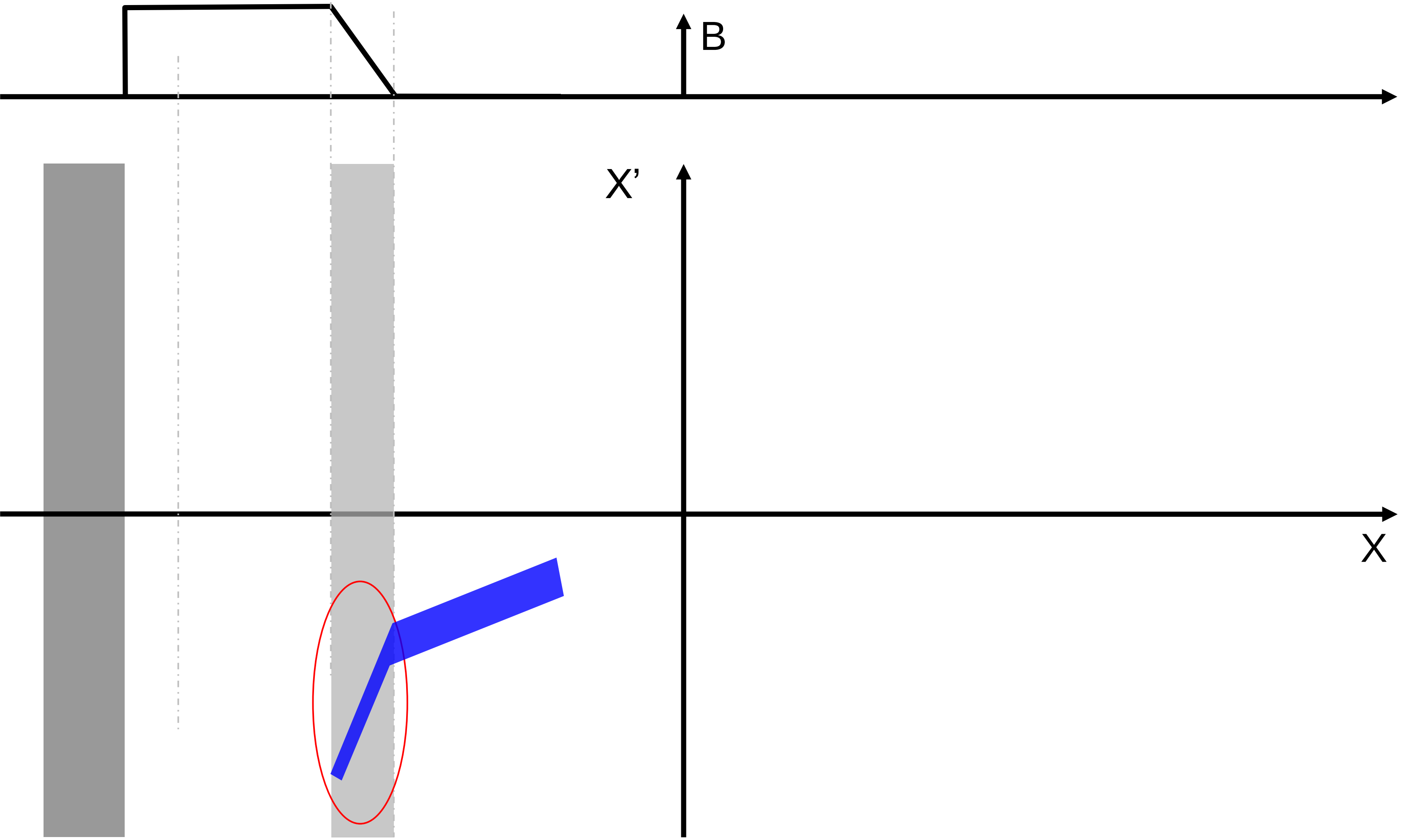
Massless septum: multiturn extraction

- At extraction septum: another ~$\pi/2$ from the ES, large kick to extract wanted part of beam



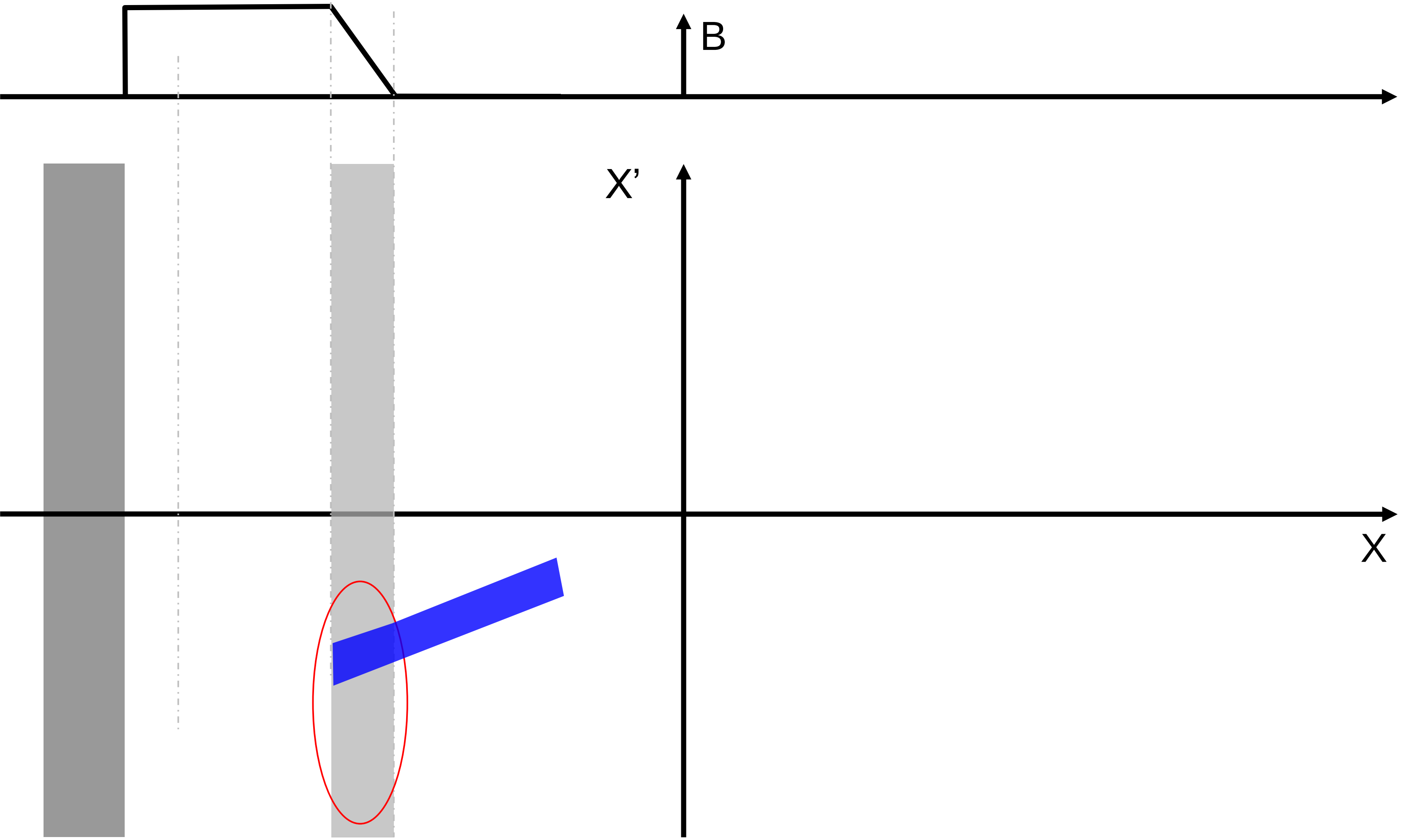
Massless septum: multiturn extraction

- 2nd massless septum corrects residual stretched part of distn.



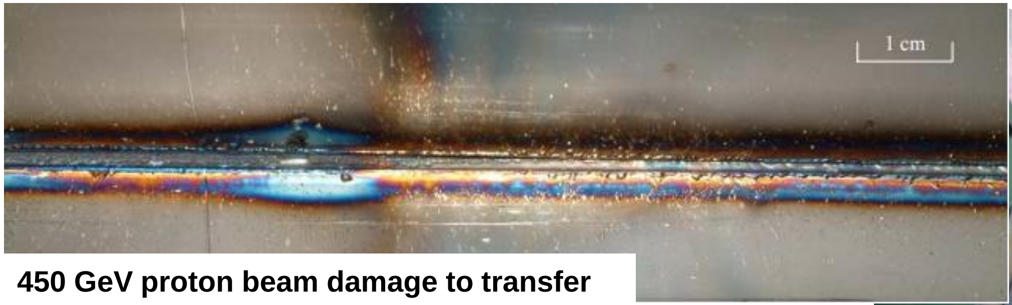
Massless septum: multiturn extraction

- 2nd massless septum corrects residual stretched part of distn.



Massless septum: failure mitigation

- Failures (kicker timing, high voltage breakdown during pulsing, …) could be catastrophic for beams above several MJ of stored energy
  - Beam swept across septum blade, or machine aperture
  - Relevant for conceptual and engineering designs of LHC, and any eventual successor like FCC

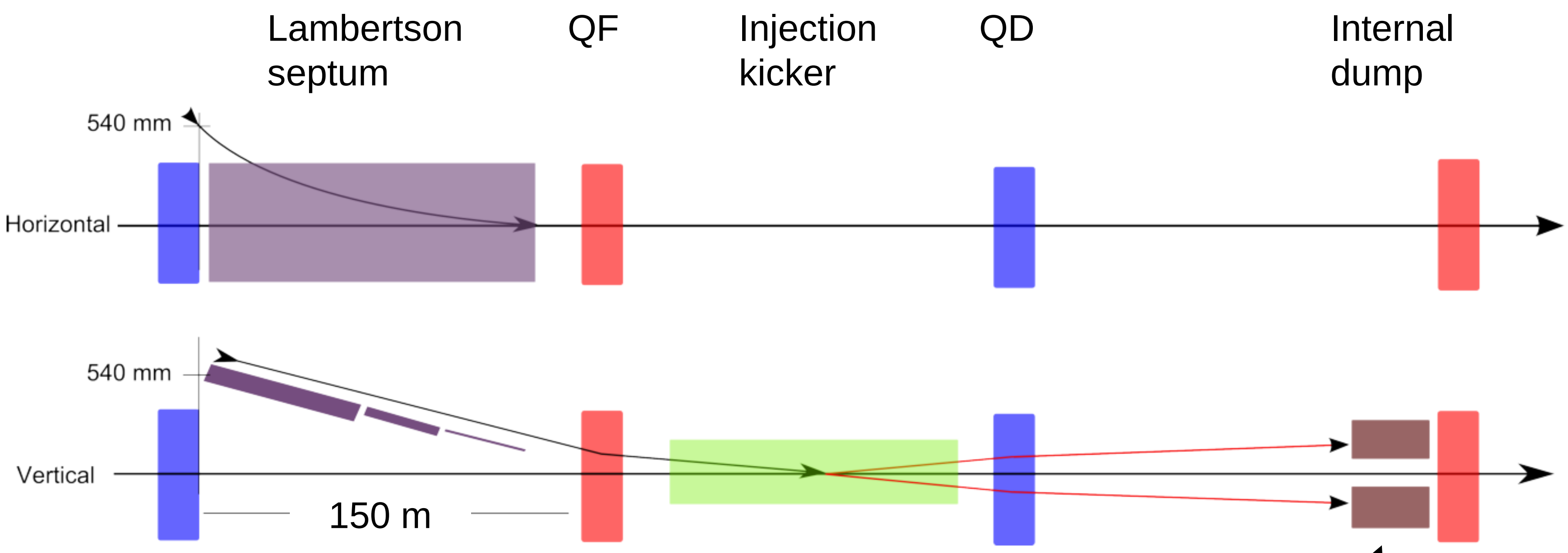


450 GeV proton beam damage to transfer line magnet

450 GeV proton beam damage tests on protection device materials

Massless septum: failure mitigation

- Stored energy in injected beam is a limit for the transfer to FCC (3.3 TeV proton beam)

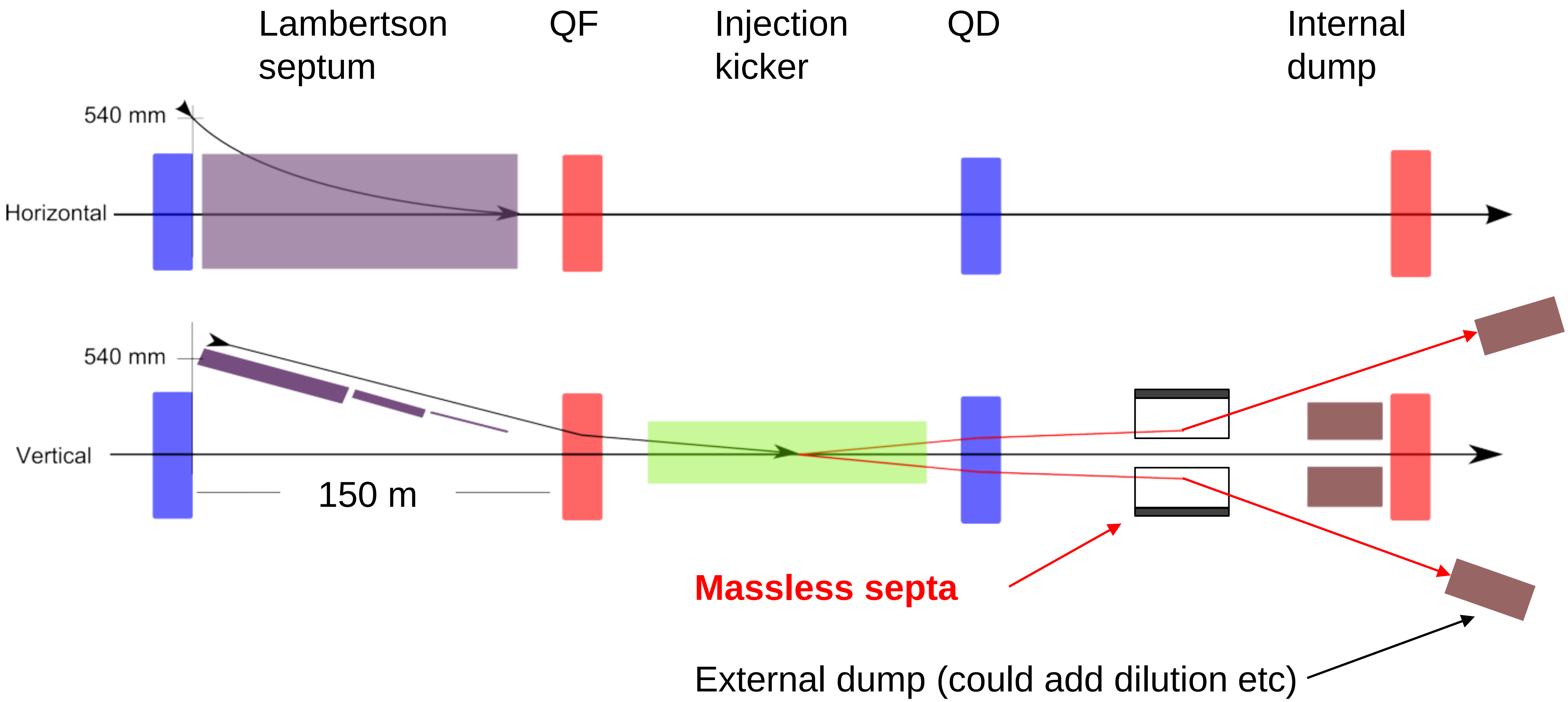


Beam load on this internal dump may limits FCC injected bunches and hence FCC performance

Constrains injection to ~5 MJ (as per case study)

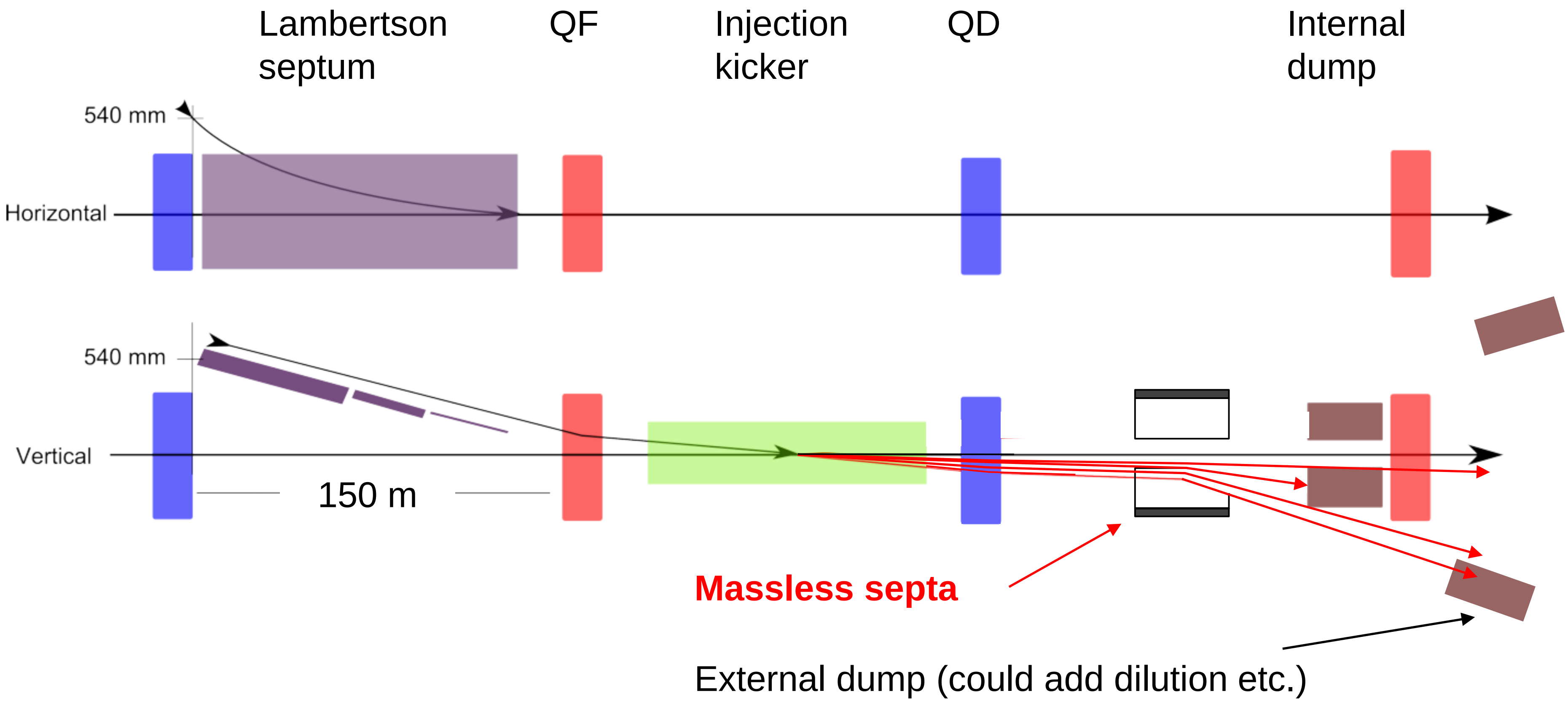
Massless septum: failure mitigation

- Massless septum can allow ‘extraction’ of mis-steered injected beam [5]



Massless septum: failure mitigation

- Can be transparent to a swept beam as resulting from some kicker errors (e.g. wrong timing)



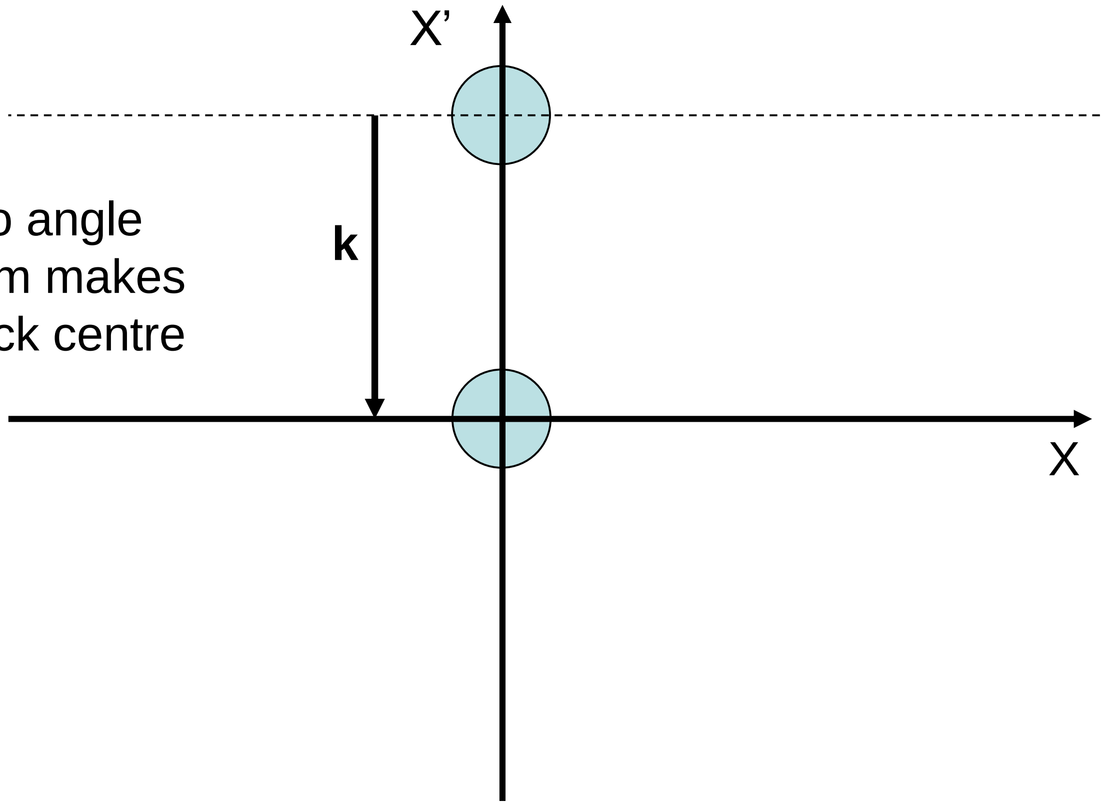
Massless septum: failure mitigation

- Advantage of allowing ‘extraction’ of the highest density part of the beam, while producing spatial sweep on internal dump – reduced energy density, higher intensity/smaller beam size possible
- No protection device needed upstream of the ‘septum’, as no material to interact with

Massless septum: failure mitigation

- Nominally injected beam at kicker location
- Kicker rise time coincides with beam-free gap

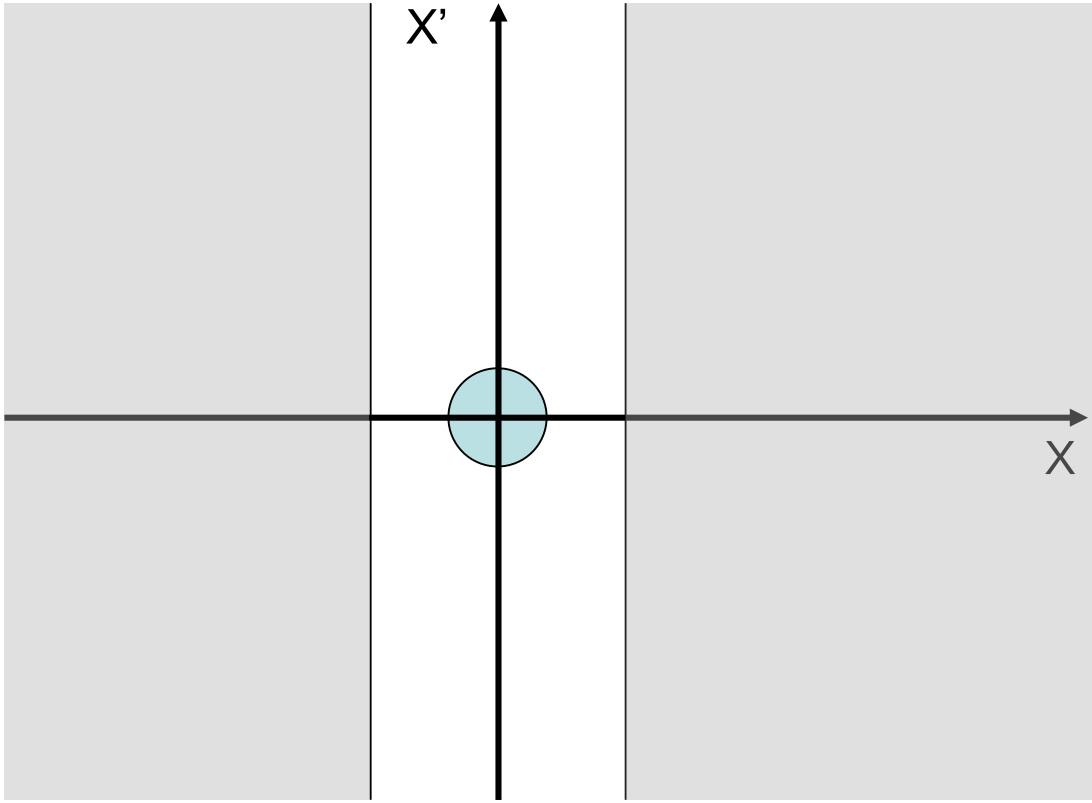
kick **k** equal to angle incoming beam makes with axis at kick centre



Massless septum: failure mitigation

- Nominally injected beam at internal beam dump ~π downstream

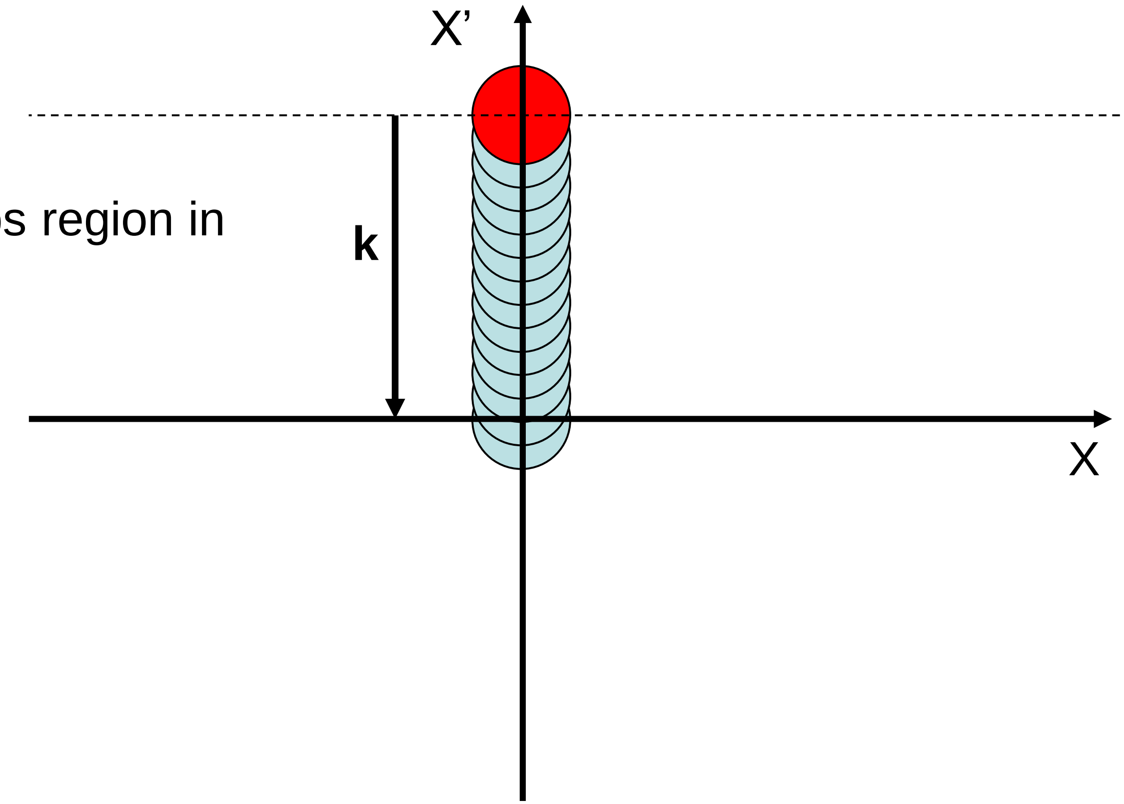
At internal beam dump,
90° downstream of kicker



Massless septum: failure mitigation

- Kicker sweep (timing error) at kicker location
- Can lead to high particle density with wrong/missing kick

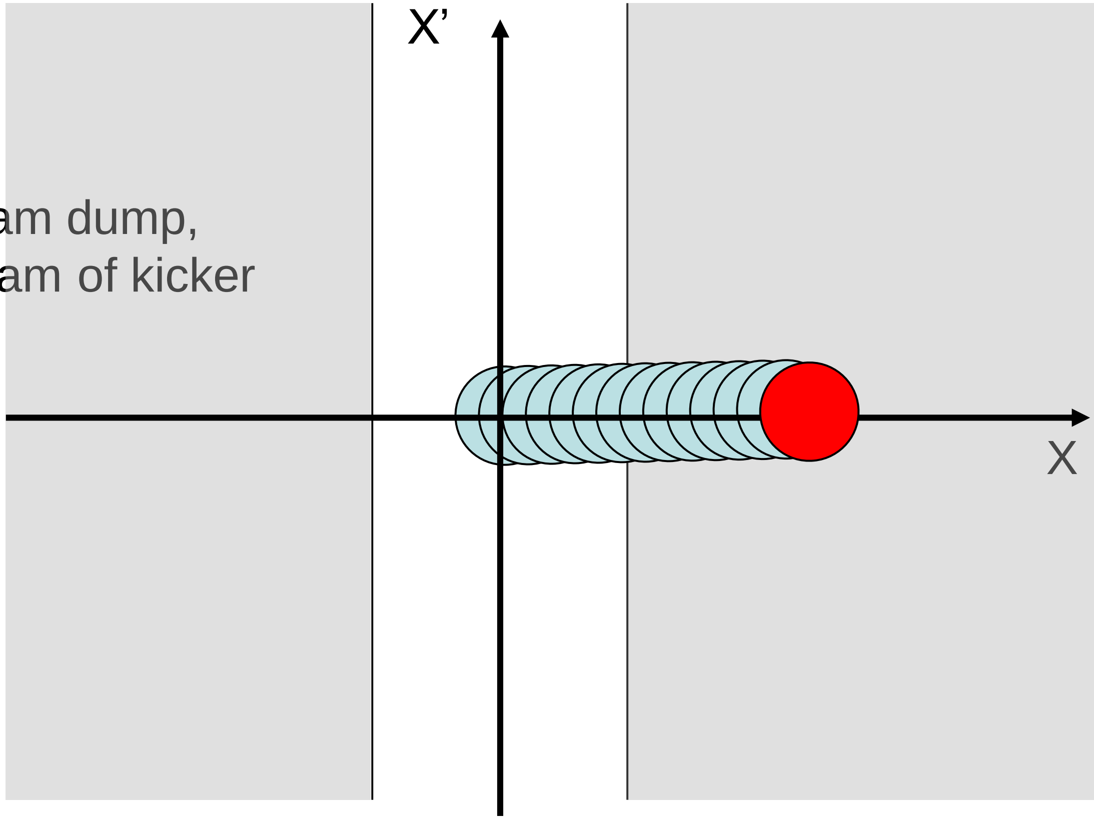
Beam sweeps region in phase space



Massless septum: failure mitigation

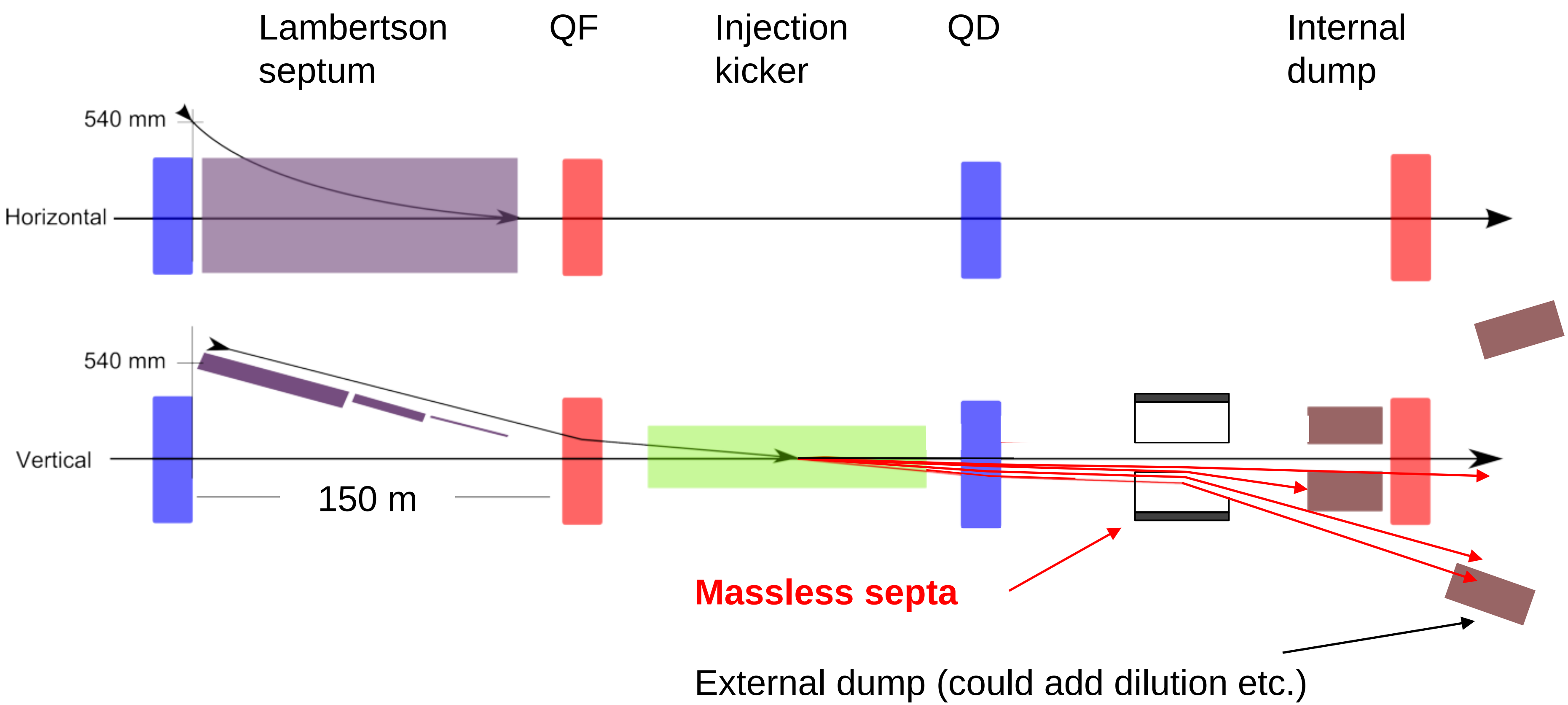
- Swept beam at internal beam dump

At internal beam dump,
90° downstream of kicker



Massless septum: failure mitigation

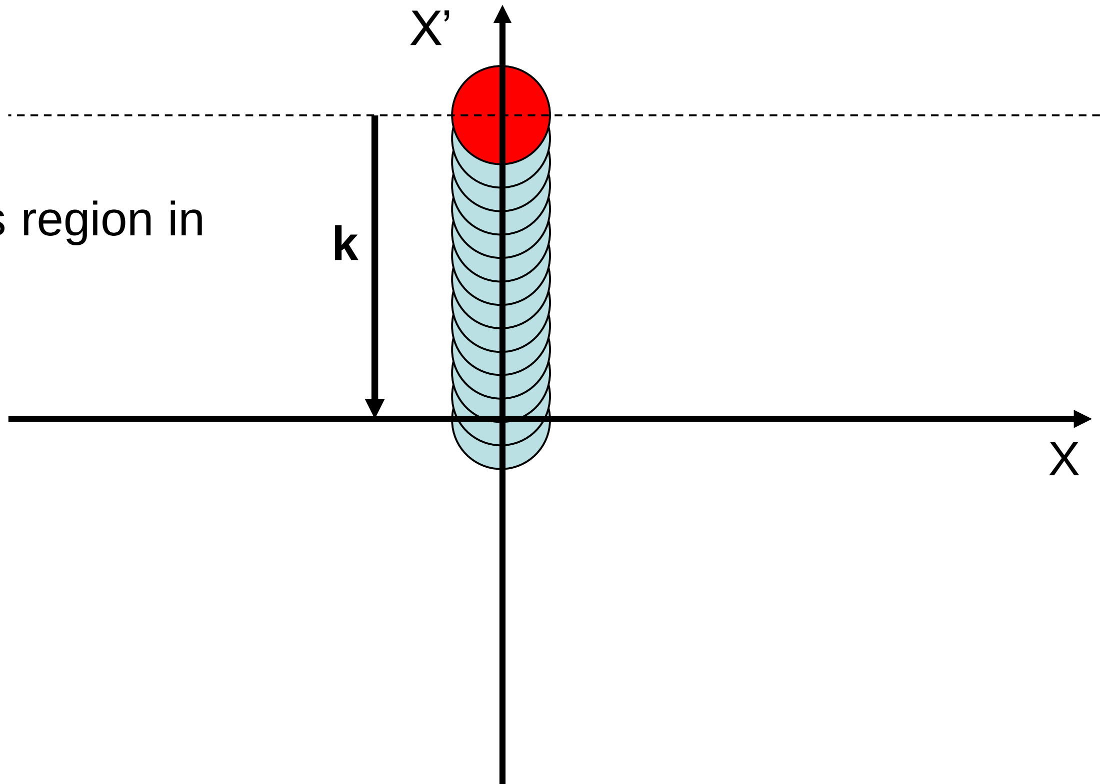
- With massless septum



Massless septum: failure mitigation

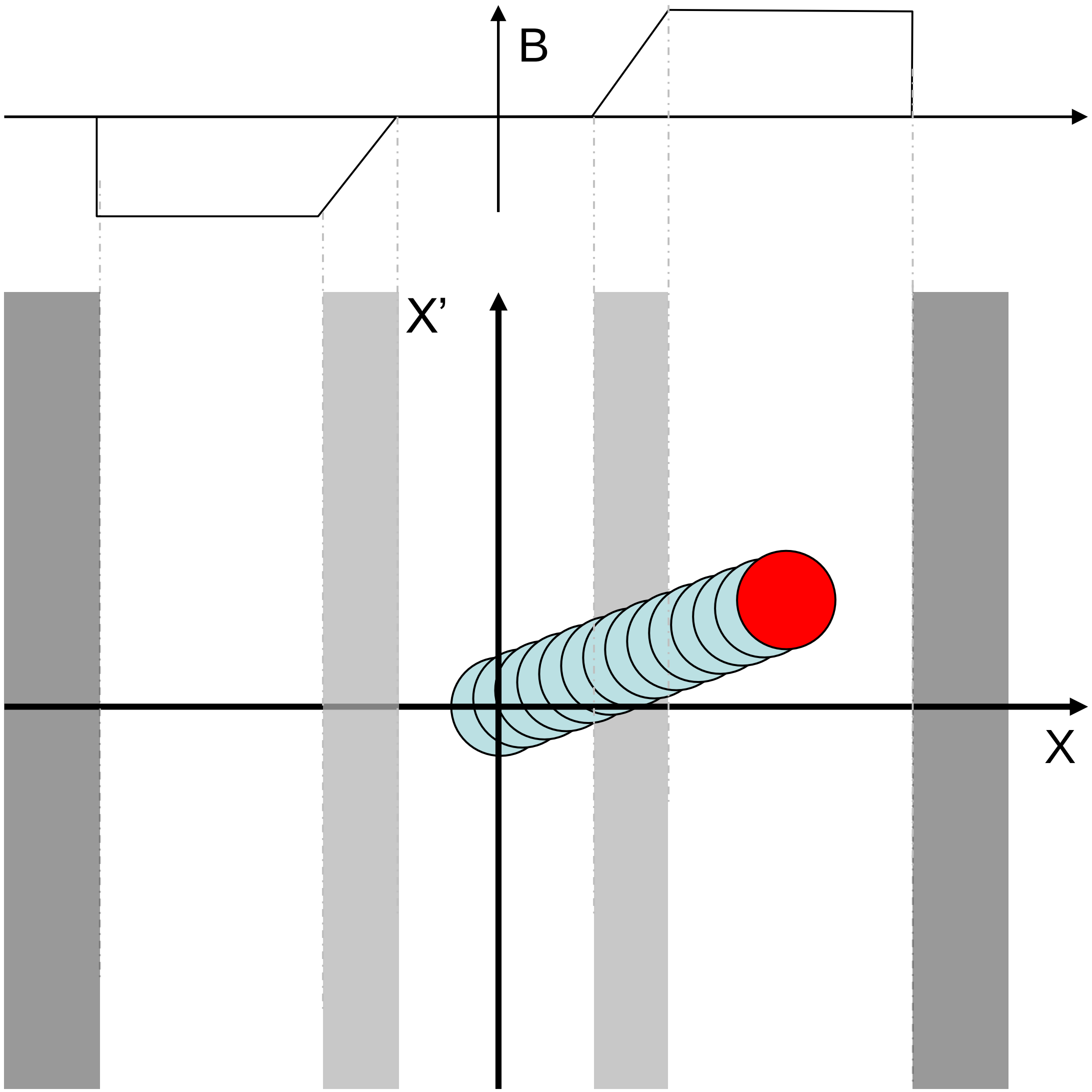
- Picture at the kicker stays the same
- Kicker sweep (timing error) at kicker location

Beam sweeps region in phase space



Massless septum: failure mitigation

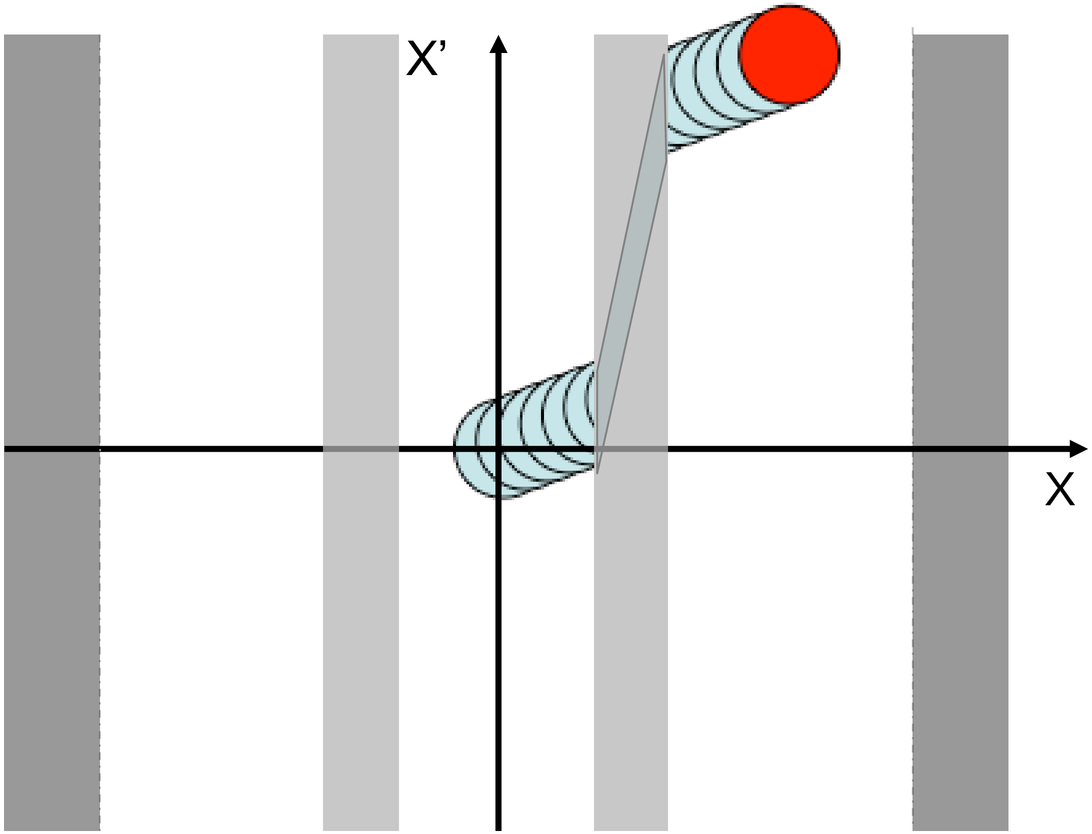
- New intervening element: massless septum (in fact two septa)



At massless septum

Massless septum: failure mitigation

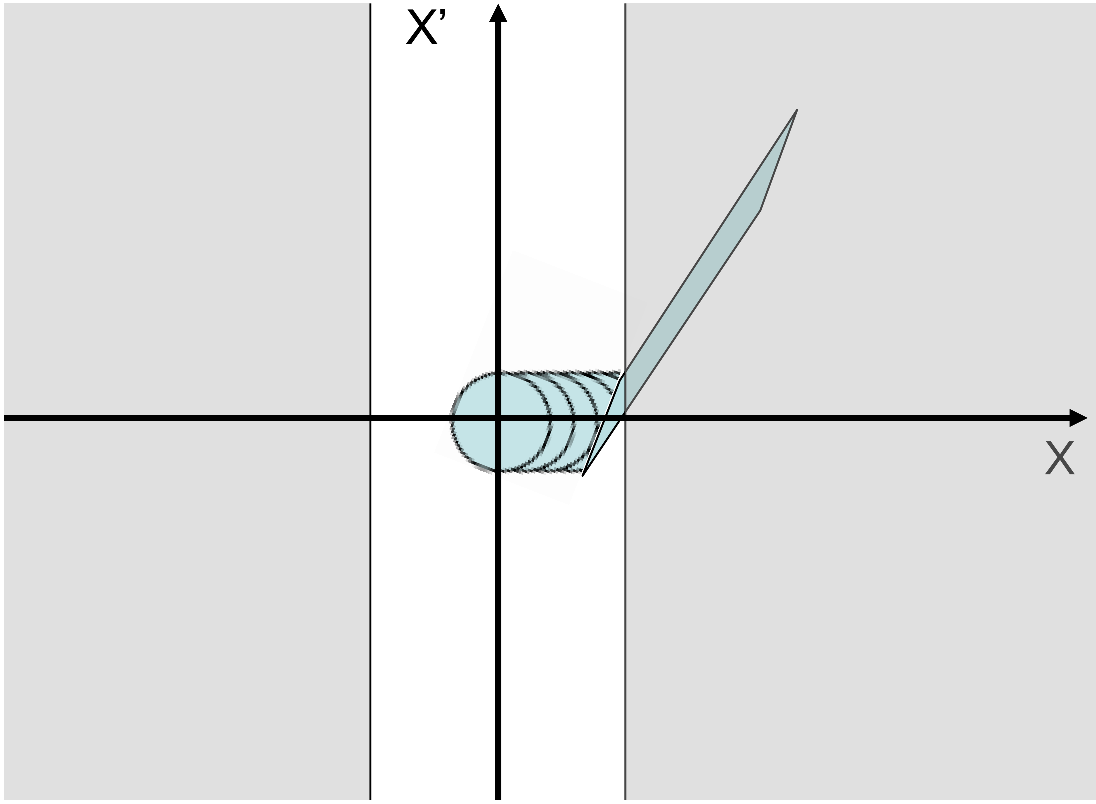
- Swept beam at massless septum
- Part of beam stretched in ‘septum part with increasing field
- Part of beam deflected into ‘extraction’ field for safe disposal



Massless septum: failure mitigation

- Swept beam at internal beam dump – reduced intensity/density

At internal beam dump, π downstream of kicker



Open “C” core extraction kicker

Open "C" core extraction kicker

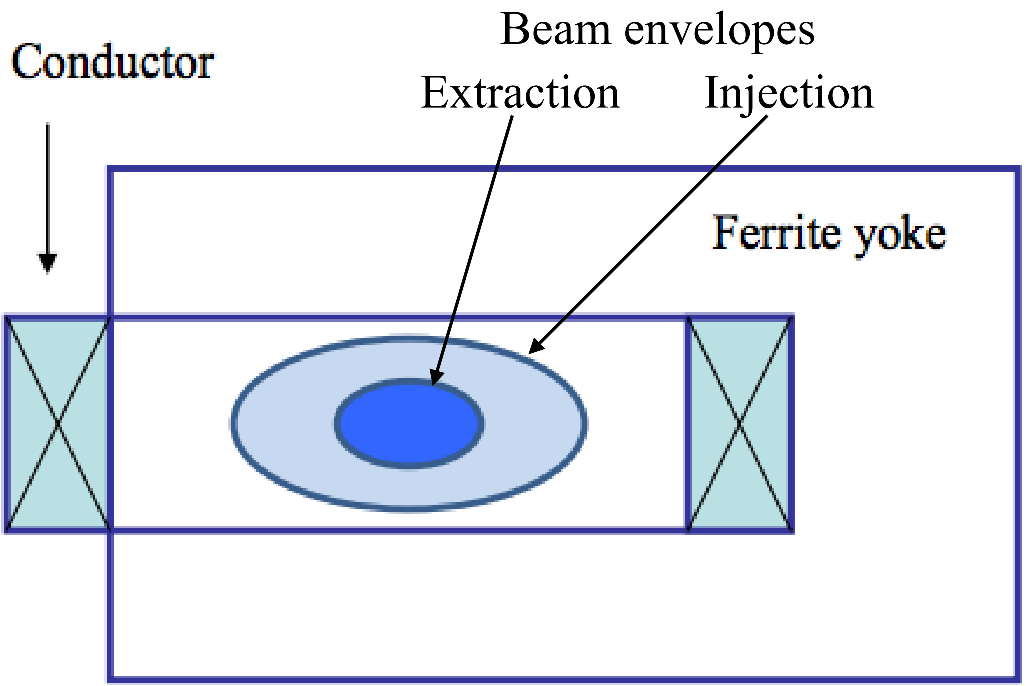
- Extraction kicker magnets can be difficult to design for high energy beams, due to conflicting constraints:

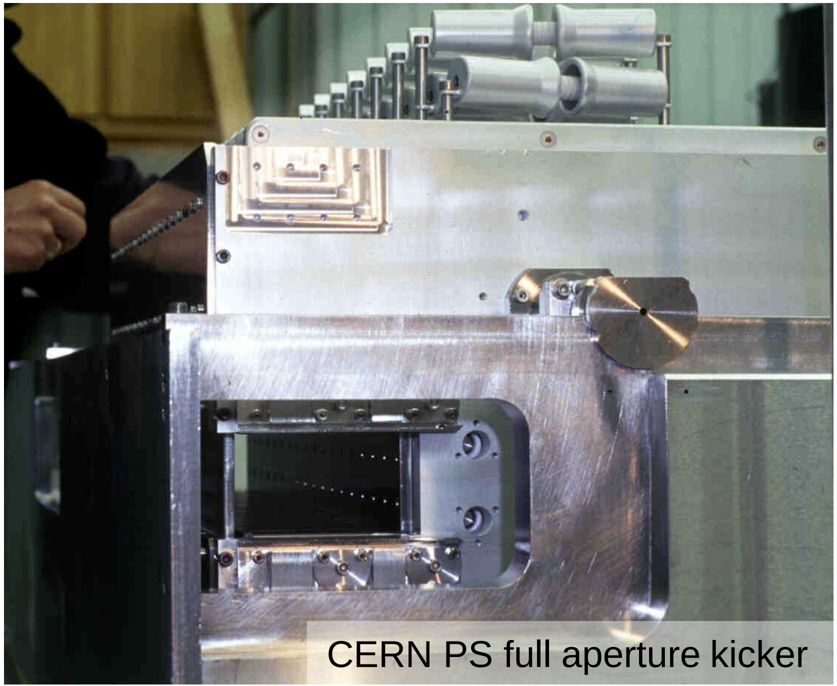
  – Need strong kick angle
    - Small gap in non-kicked plane
    - Long magnetic length

  – Need small beam coupling impedance
    - Large gaps better
    - Short length better
    - Shielding of ferrite required (increases rise time and gap)

Full aperture extraction kicker

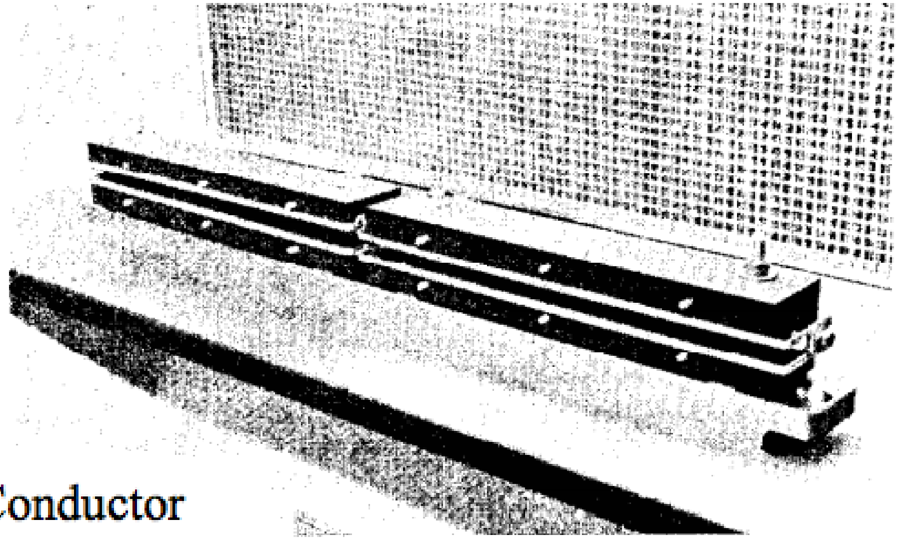
- A conventional full aperture extraction kicker has to be large enough to accept injected beam
- For large energy swings, this can mean a lot of 'wasted' aperture
  - Injected beam physical beam size is larger, as it scales with ratio of $(\beta\gamma)^{1/2}$, plus some extra mm aperture for injection oscillations



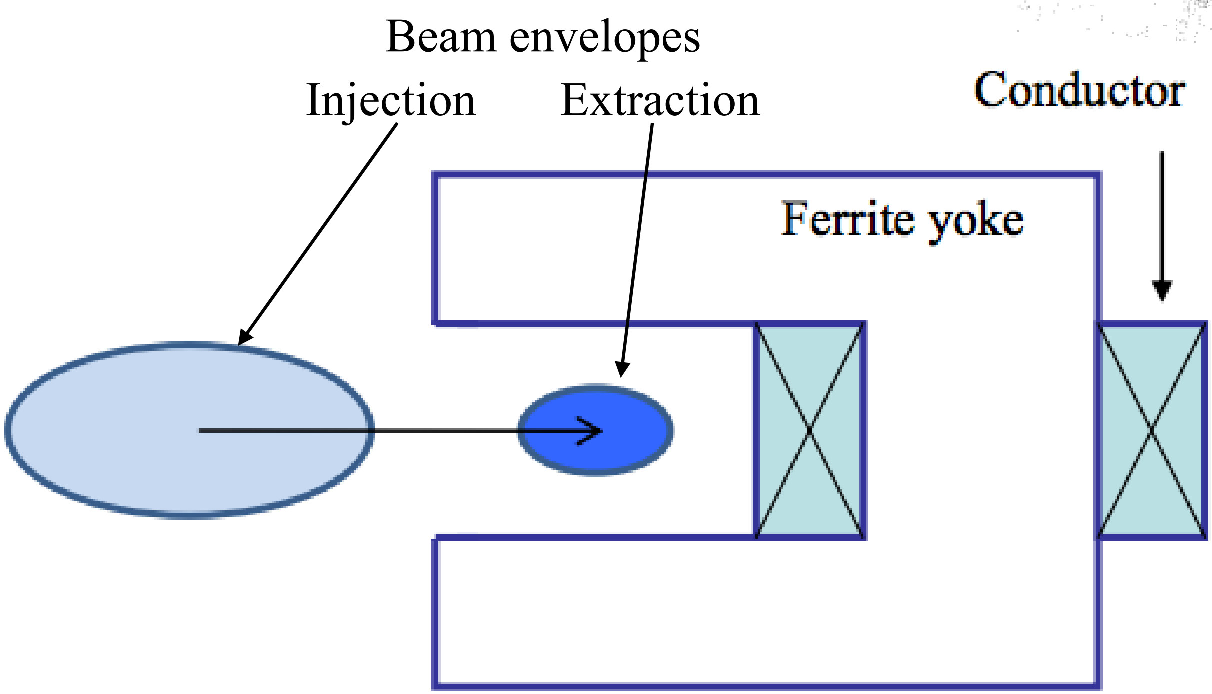


Open "C" core extraction kicker

- Open "C" core kicker can be designed with aperture sufficient only for extracted beam
- Significantly smaller gap (x2)
  - Higher kick for given drive current
  - Less magnetic length

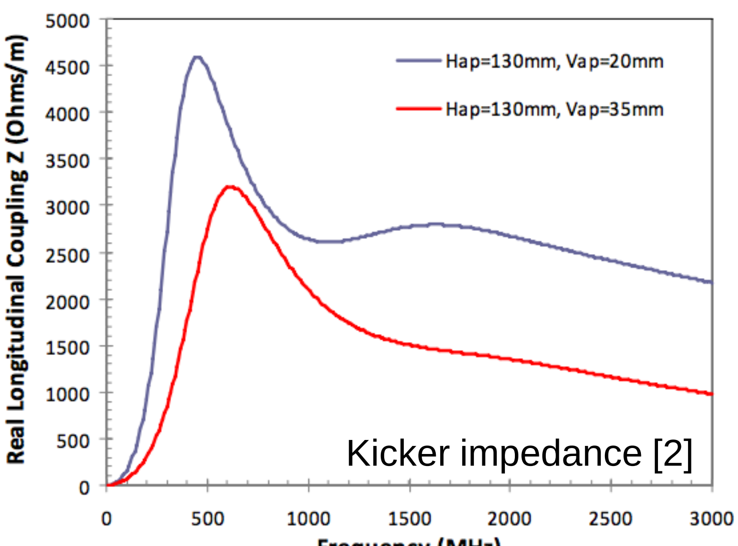


AGS C core kicker (1981) [1]

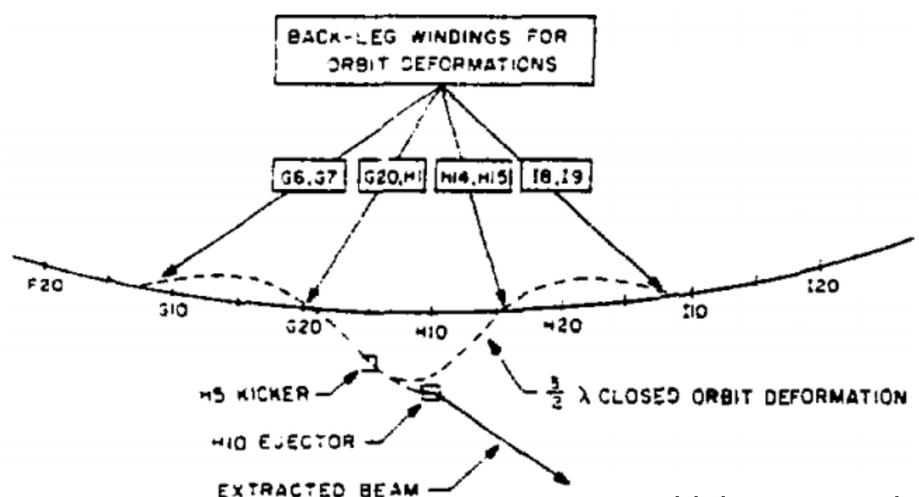


Open "C" core kicker

- Need an extraction bump to move beam into kicker
  - Anyway sometimes used for high energies to reduce required kick strength
- Kicker beam coupling impedance is higher with smaller gap
  - But compensated (to first order) by reduced kicker length
  - Beam only exposed to this impedance for ~100 ms, so power deposition in the kicker is not a major issue
  - Beam only exposed to this impedance at high energy (much less sensitive to instabilities as beam is "stiff")



Kicker impedance [2]



AGS C kicker extraction

Stochastic muon decay ring injection

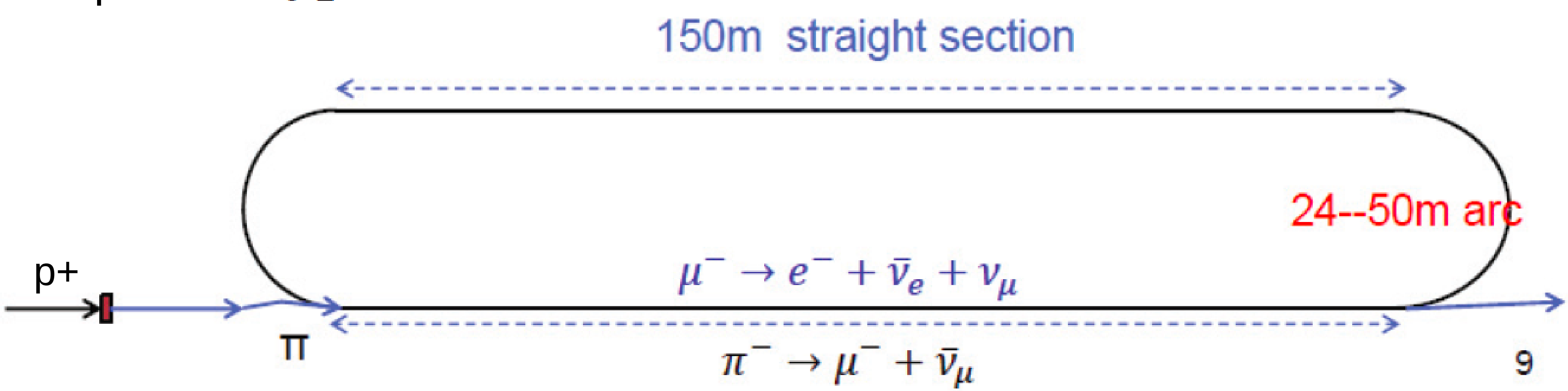
Stochastic injection

- Intense circulating muon beams of great interest as bright, controlled source of neutrinos, e.g. light sterile neutrino search, cross-sections
- -ve muons (200 x m_e, 2.2 μs lifetime at rest) decay into an electron, an electon anti-neutrino and a muon neutrino

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

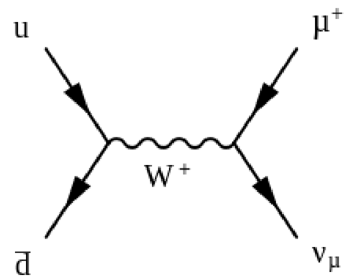
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

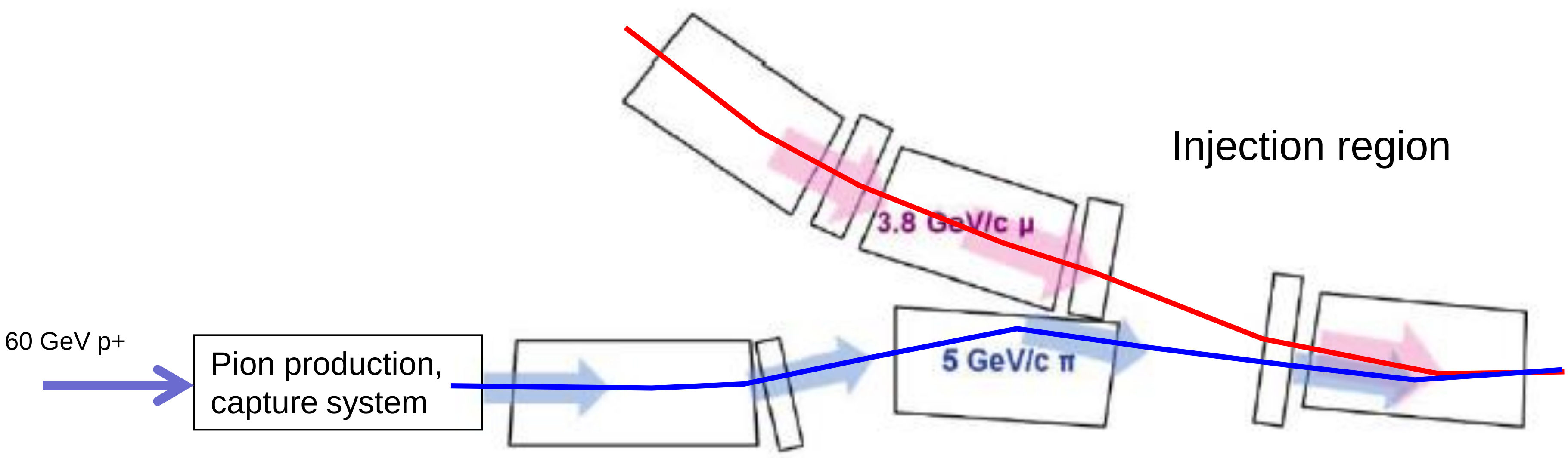
- One concept proposes a racetrack decay ring filled with muons, to produce intense neutrino beams. Muon lifetime is ~60 turns…



Stochastic injection

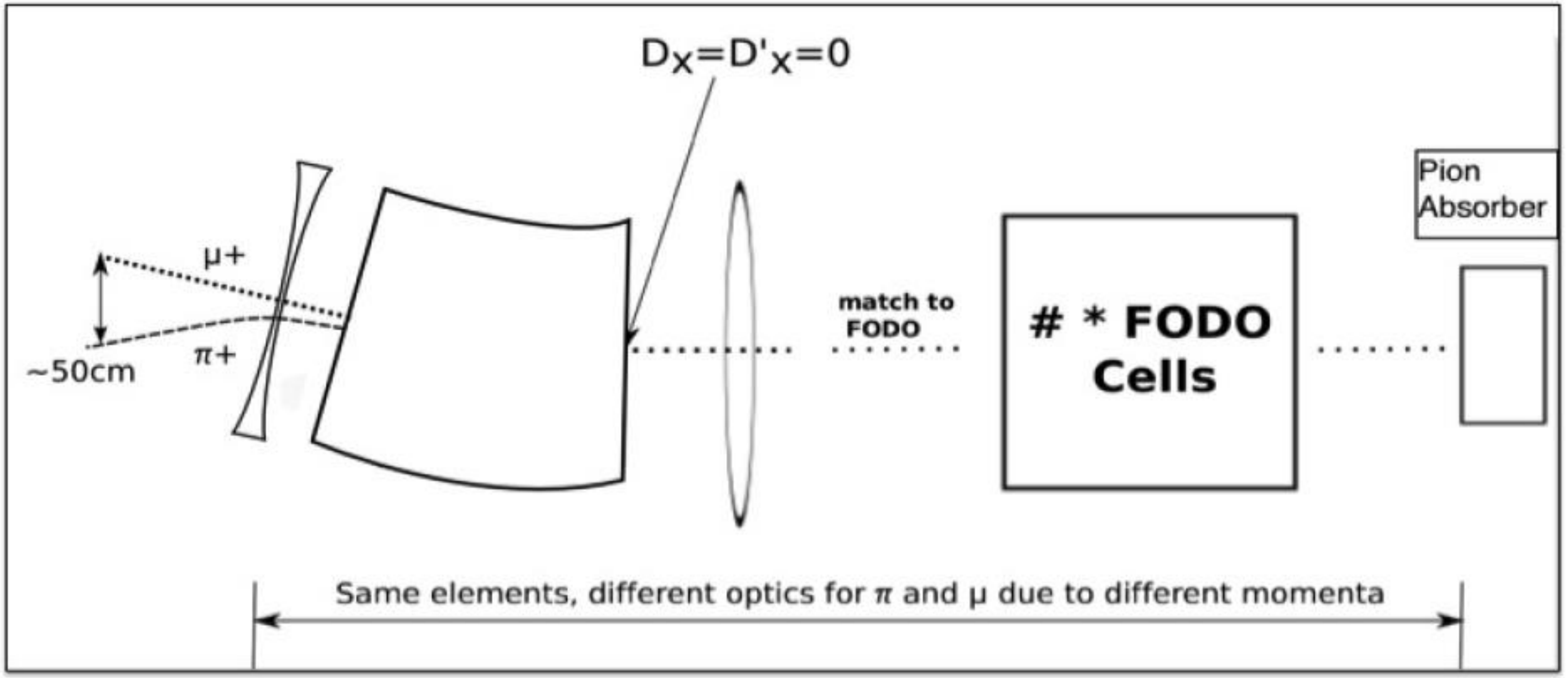
- muons are produced from decay of pions (composed of up- and down-quark-antiquark pair, lifetime of 26 ns)
- 5 geV/c pions produced by 10-100 GeV p+ on a target π^+
- In this injection [6], pion and already-circulating muons have very different momenta. Ring optics and injection layout merges pions and muons in a special dipole, to 'defeat' Liouville (every injection system designer's dream)





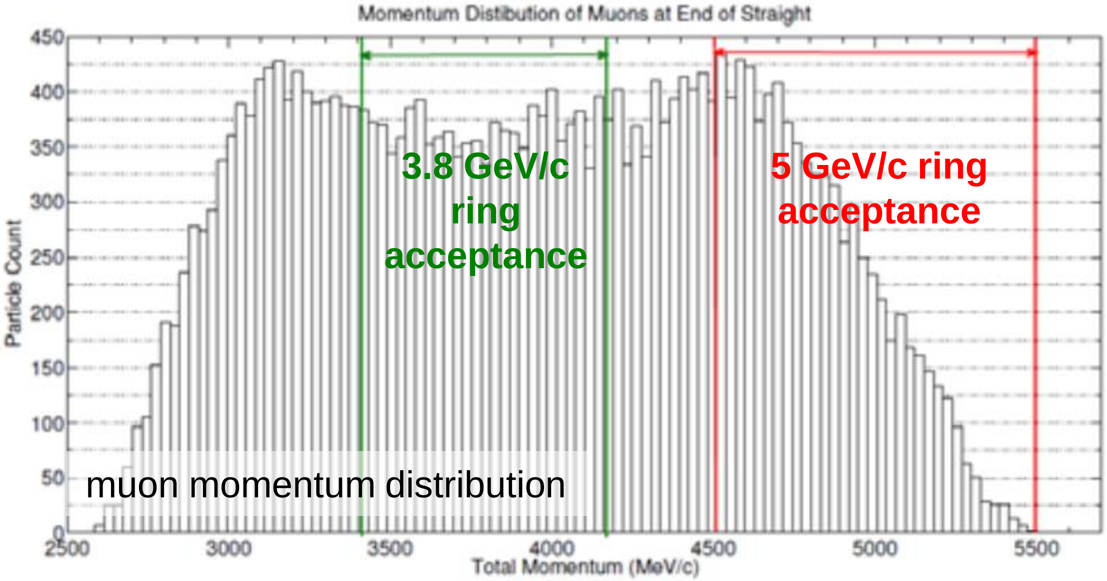
Stochastic injection

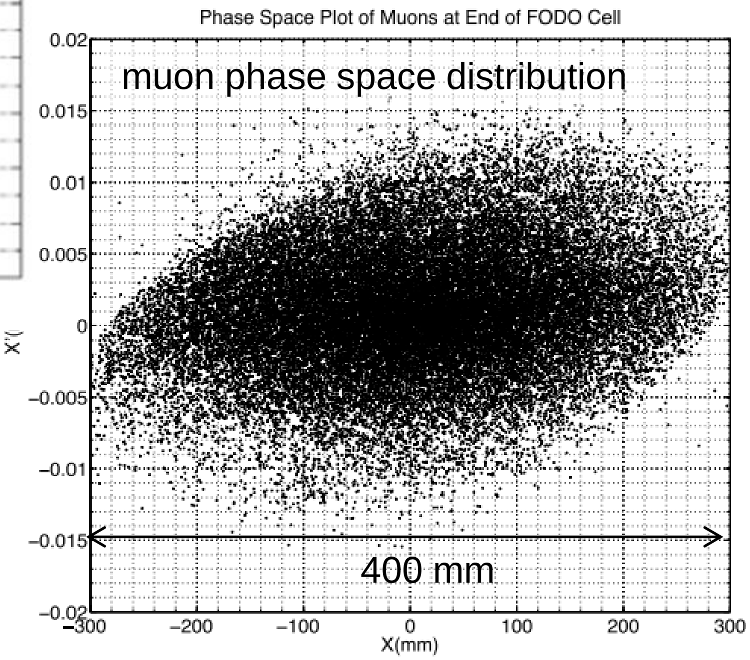
- When pions decay, muon energies are between ≈$0.5E_{\pi}$ and E_{π}: those within ring acceptance (which needs to be as large as possible) will circulate.
- Ring design acceptance: 3.8 GeV/c ±10% (!)
- Also need absorber at end of decay straight for surviving pions



Stochastic injection

- Simulated muon momentum distribution [7] at end of injection straight
- Lots of tricks needed for the ring design (large acceptance, achromatic arcs, optics matched to both beams in decay straight, …)





Extraction with bent crystals

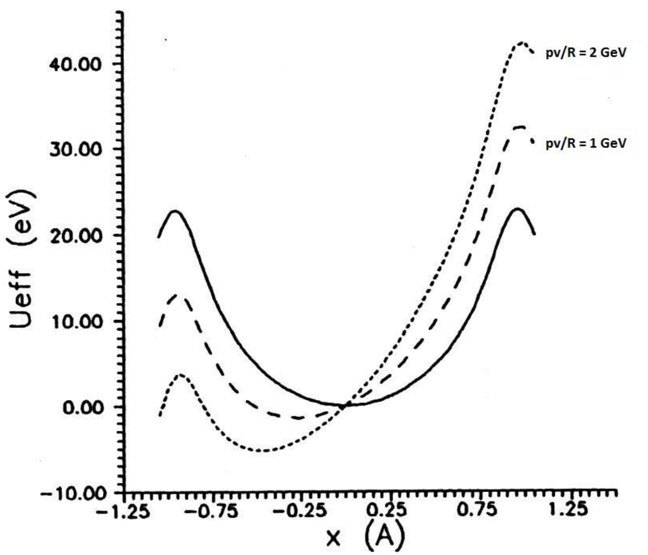
Use of bent crystals

- Slow extraction of multi-TeV p^+
- Active areas of research on providing Fixed-Target physics or test beams, from LHC at 7 TeV or even from FCC at 50 TeV
- Difficult to design slow extraction for TeV energies
  - Large amplitudes and aperture needed for 1/3 integer resonance
  - Superconducting magnets very sensitive to beam losses
  - Technological limit of ~10 MV/m for electrostatic septa: length of extraction systems become unfeasibly large
    - For FCC $B\rho$ at 50 TeV is 166,000 Tm. Stiff. Need ~500 m of electrostatic septum field length (0.1 mm wide…)
    - An issue for mechanical engineers for alignment

Bent crystals

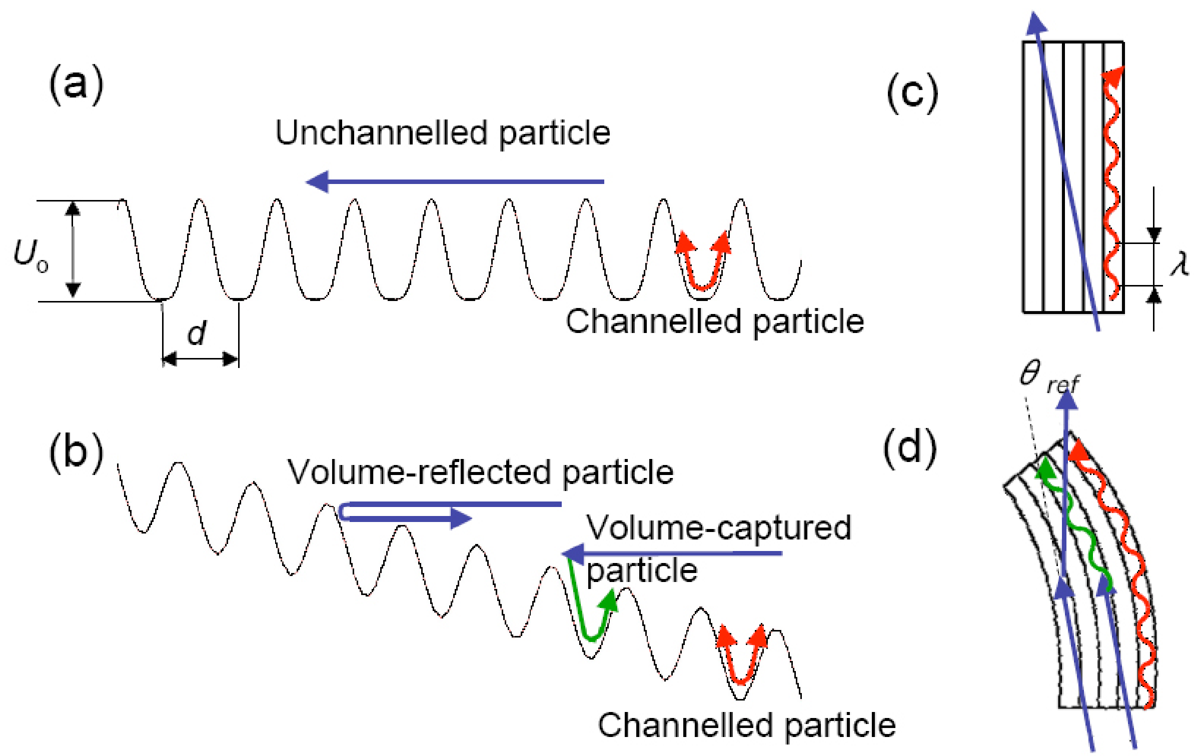
- Charged particles can be deflected by a bent crystal [8]
- Potential well between atomic planes guides particles

Crystal inter-nuclear potential



$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

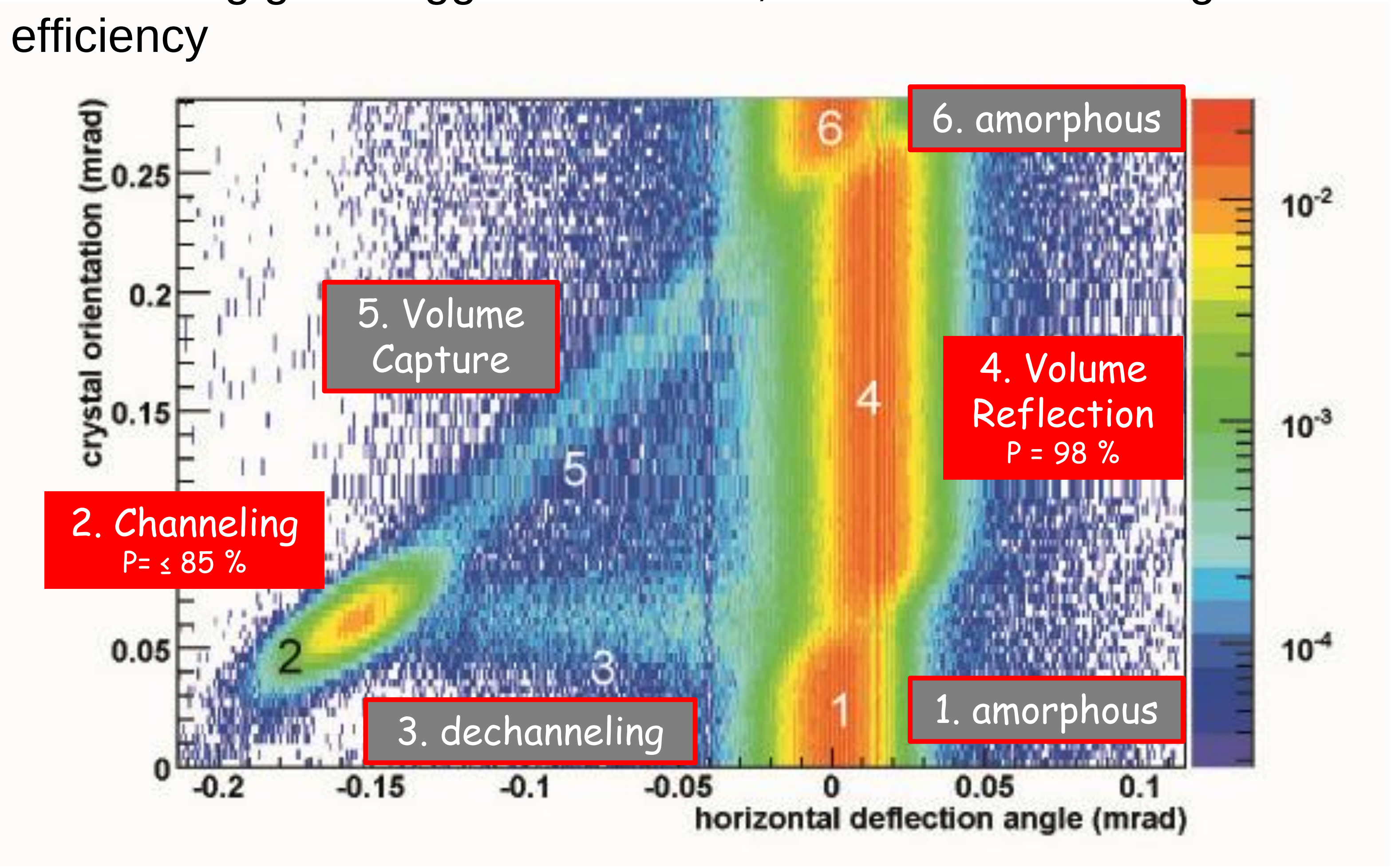
Critical angle for channeling



W.Scandale

Bent Crystals: Processes

- Several distinct effects have been identified in the coherent and incoherent scattering behaviour [9]
- Channeling gives biggest deflection, volume reflection highest efficiency



W.Scandale

Bent crystals: why?

- Bent crystal with radius *R* channels beam of energy *pv* if:

$$pv/R \approx 1\ GeV/cm$$

This is astounding!

- Take 7 TeV protons….then $R \approx 70\ m$

- For comparison, LHC dipoles (≈ 8 T) bend 7 TeV p+ with $R \approx 3000\ m$

- So the bent crystal is as effective as a 330 T magnet…

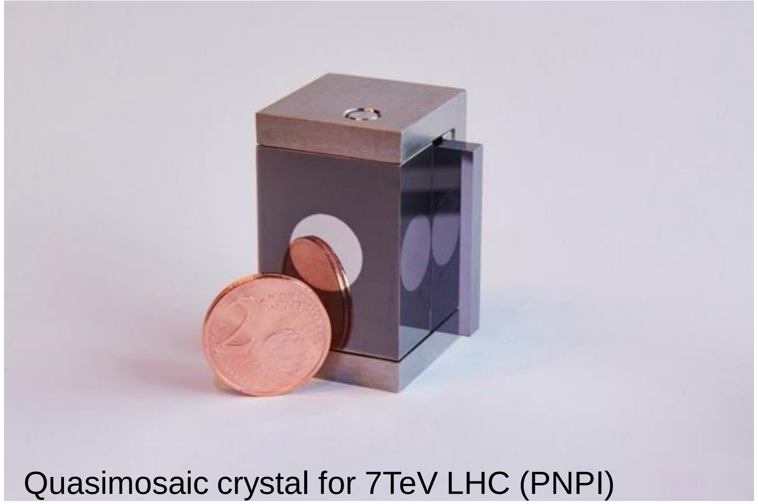
- 2 cm of bent crystal can deflect a 7 TeV p+ by 0.3 mrad

Bent crystals: compact way forward…

- Bent crystals may have potential to replace huge 5-500 m long electrostatic septum devices needed at 100 GeV – 50 TeV energies, with extremely compact mm – cm long devices

25 m long ES for SPS 450 GeV slow extraction

Short crystal for 7 TeV LHC (INFN)



Quasimosaic crystal for 7TeV LHC (PNPI)

Bent crystals: multi-TeV extraction

- Proposed for LHC and higher energy machines [10] since 1990's
- Seems (at present) the most promising way to provide flux of slow extracted beams from very high energy, superconducting synchrotrons

Extraction scenario from LHC

W. Scandale, Proc. LHC Workshop, eds G. Jarlskog and D. Rein, Aachen, 1990, vol. III p. 760.

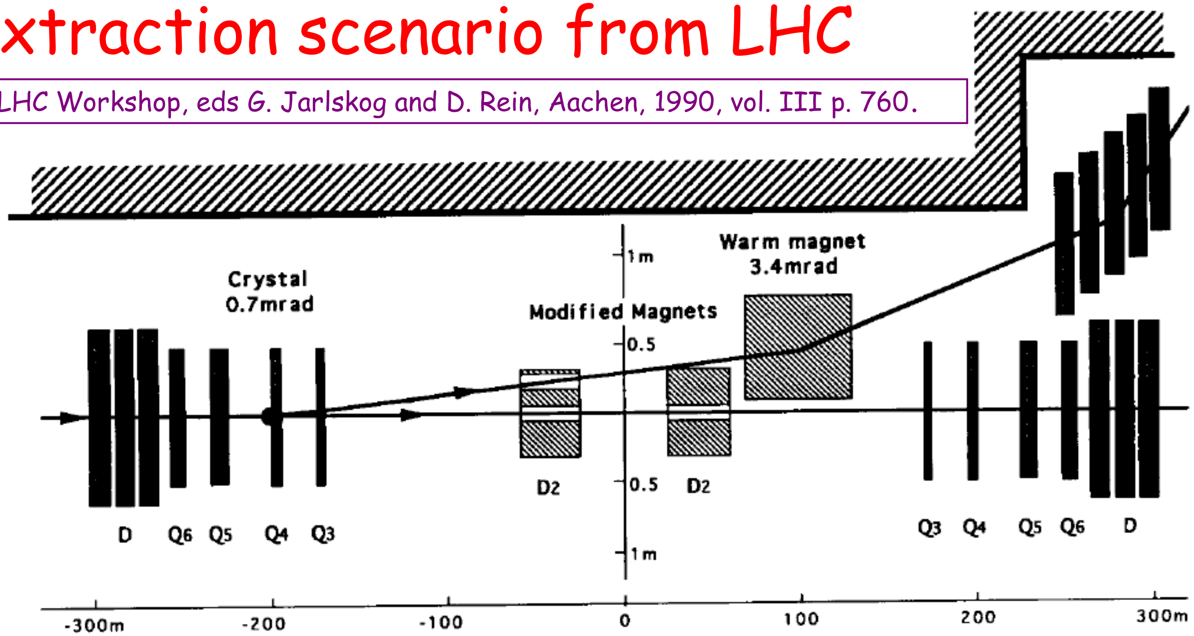
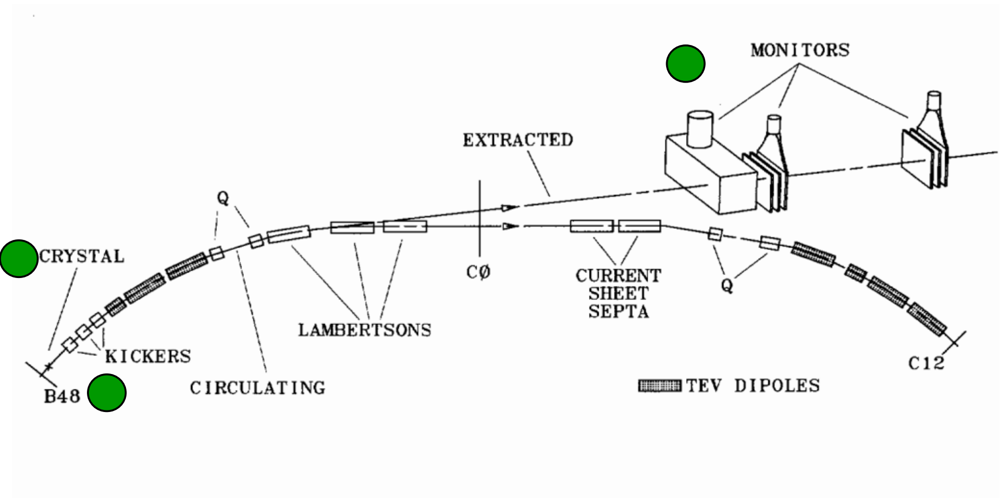


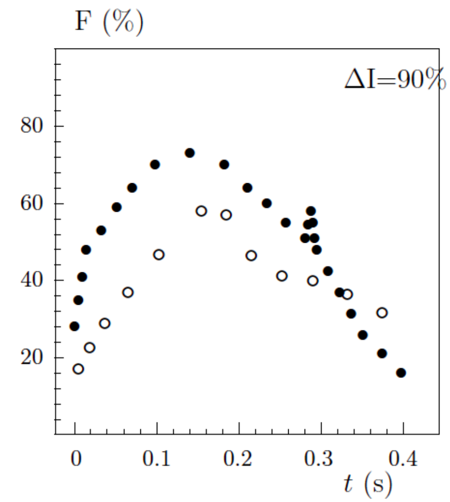
Fig. 2. Schematic layout of vertical halo extraction using channeling in a bent silicon crystal. After the warm septum magnet the extracted beam is bent by a string of five superconducting dipoles of the LHC type [14].

Bent crystals: tests in synchrotrons

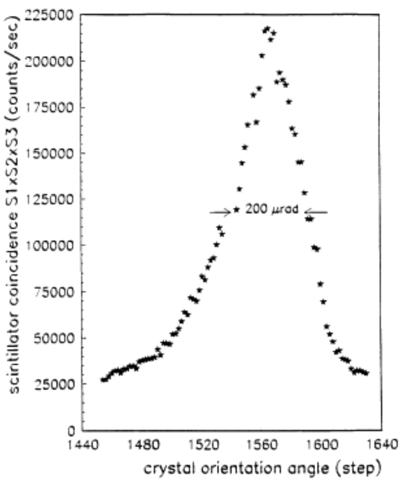
- Extraction tests have been performed in SPS, Tevatron and Serpekov, for p+ energies of 70, 120, 270 and 900 GeV
- Tests also made of crystal channelling at 6.5 TeV for LHC collimation



Tevatron layout for parasitic luminosity-driven extraction with bent crystal of 900 GeV p+



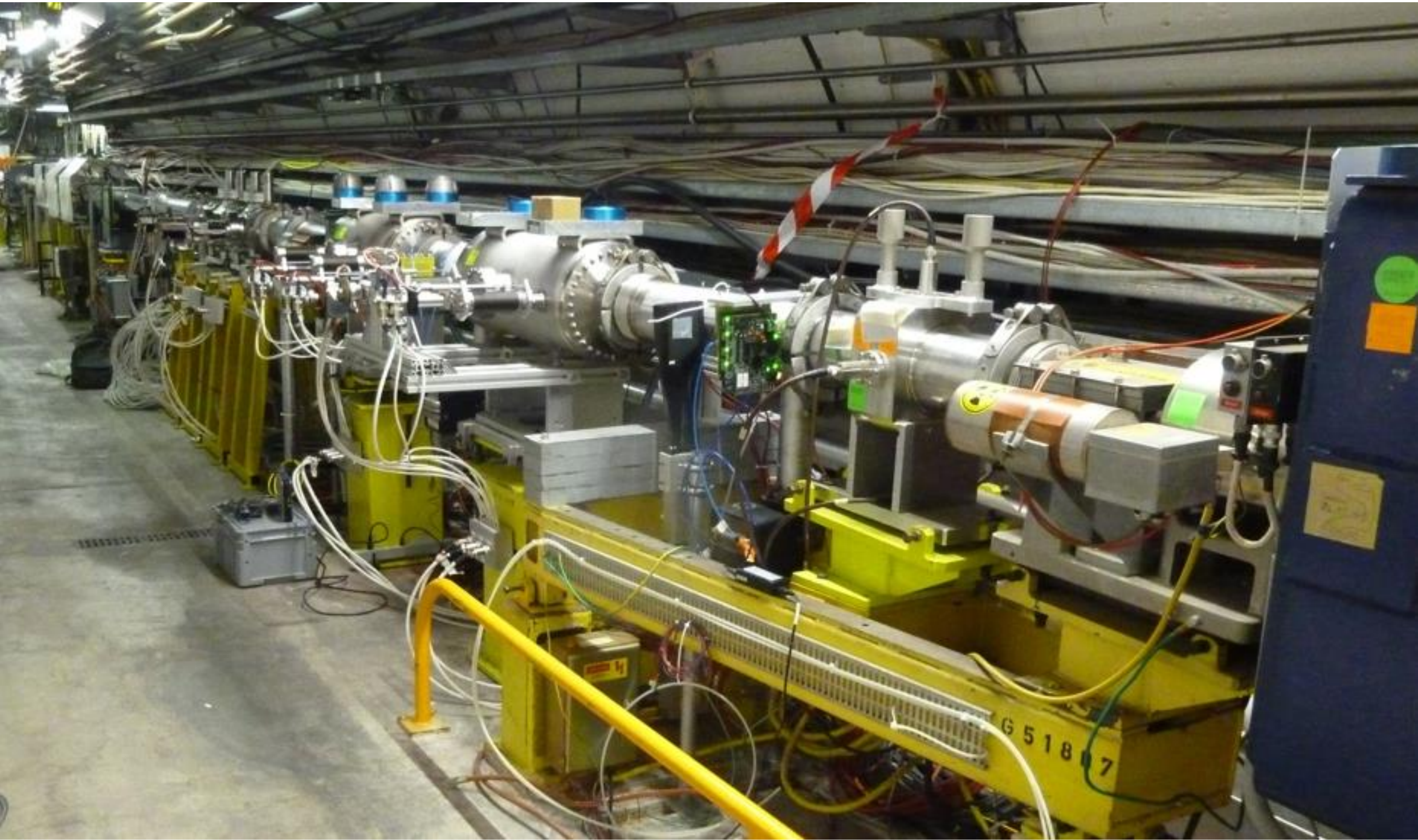
Slow extraction spill of 70 GeV p+ with bent crystal at U70



Extracted SPS 120 GeV p+ intensity as a function of crystal orientation

Bent crystals: active area of research

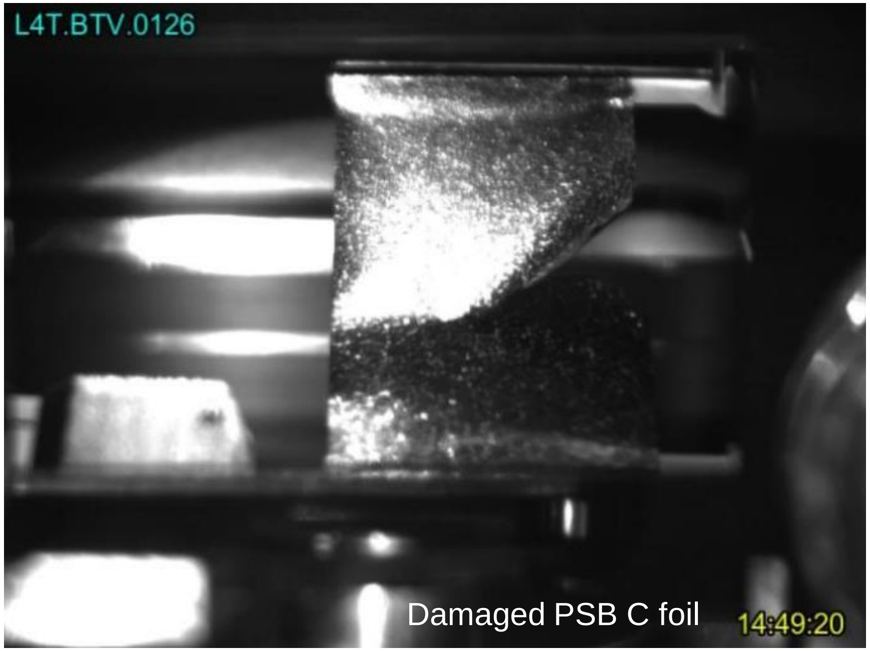
- Part of the UA9 installation presently installed in SPS at CERN



Laser H^- stripping

H^- injection: loss and foil heating

- We've seen this week, H^- is fantastic ion for accelerators:
  - Charged, so we can accelerate and deflect it
  - Easy to produce and stable: e- binding energies are 0.75 eV,13.6 eV
  - Remove e- with thin foil, "defeat Liouville" by injecting on top of existing distribution
- But….physical stripping foil means beam loss, foil heating/damage, ε growth



Damaged PSB C foil


Damaged SNS C foil

H^- Lorentz stripping

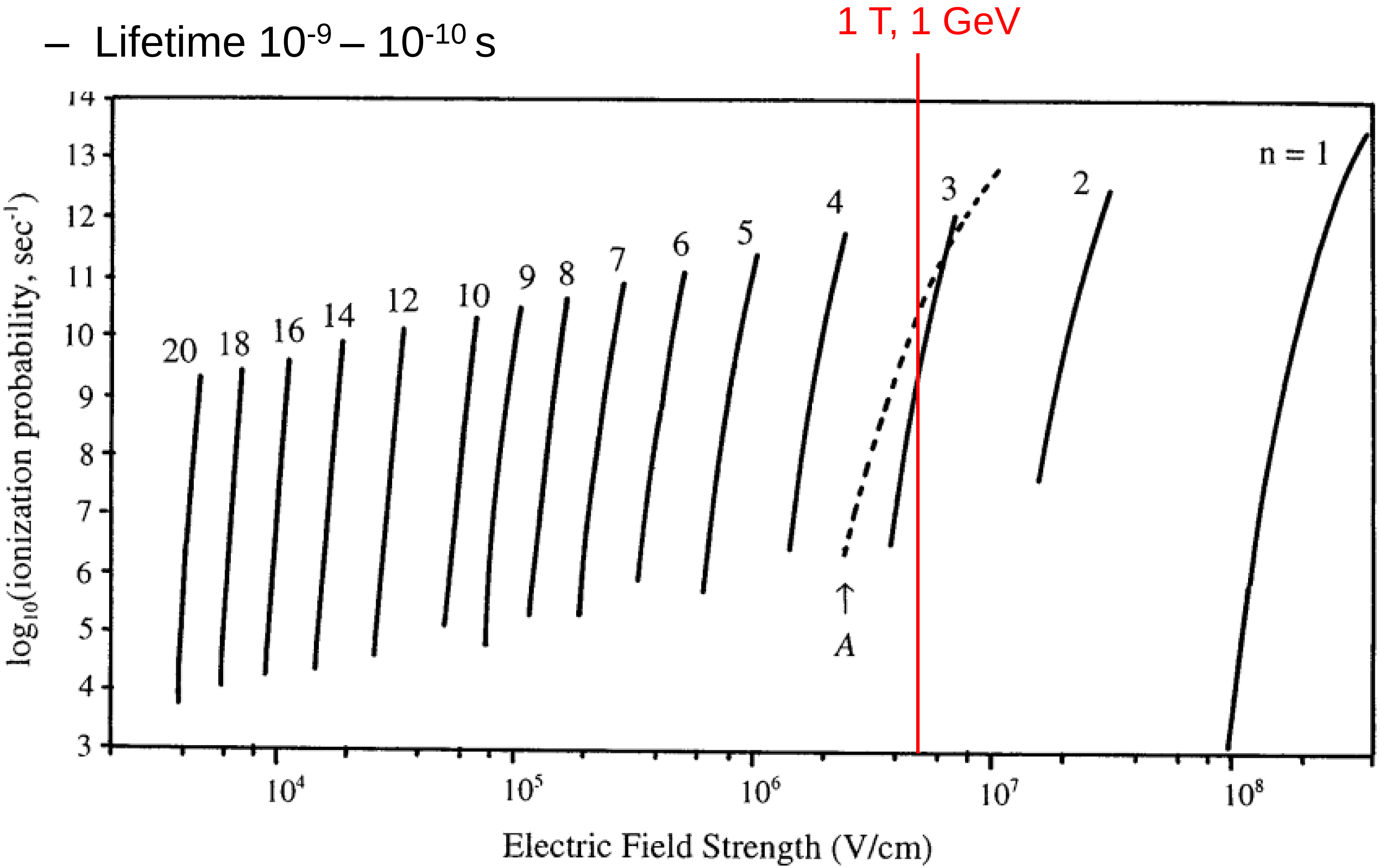
- H^- ion passing through transverse magnetic field B with velocity βc experiences electric field E in its own rest frame of $E = \beta\gamma c \times B$
- This electric field can field-strip (called Lorentz stripping) the loosely-bound outer electron (only 0.75 eV binding energy), giving uncontrolled beam loss
- Fractional loss rate per m is $$\frac{df}{ds} = \frac{B}{A_1}\exp\left(-\frac{A_2}{\beta\gamma c B}\right)$$

where A_1 and A_2 are constants: 2.47×10^{-6} Vs/m and 4.49×10^{9} V/m)

- Can't afford more than 0.1 – 1 W/m of beam loss power (activation)
- Places a practical upper bound on maximum magnetic field, which depends very strongly on beam energy
  - Issue for injection and transfer line (dipoles, quadrupoles, correctors)
  - Also - an opportunity for creative thinking….

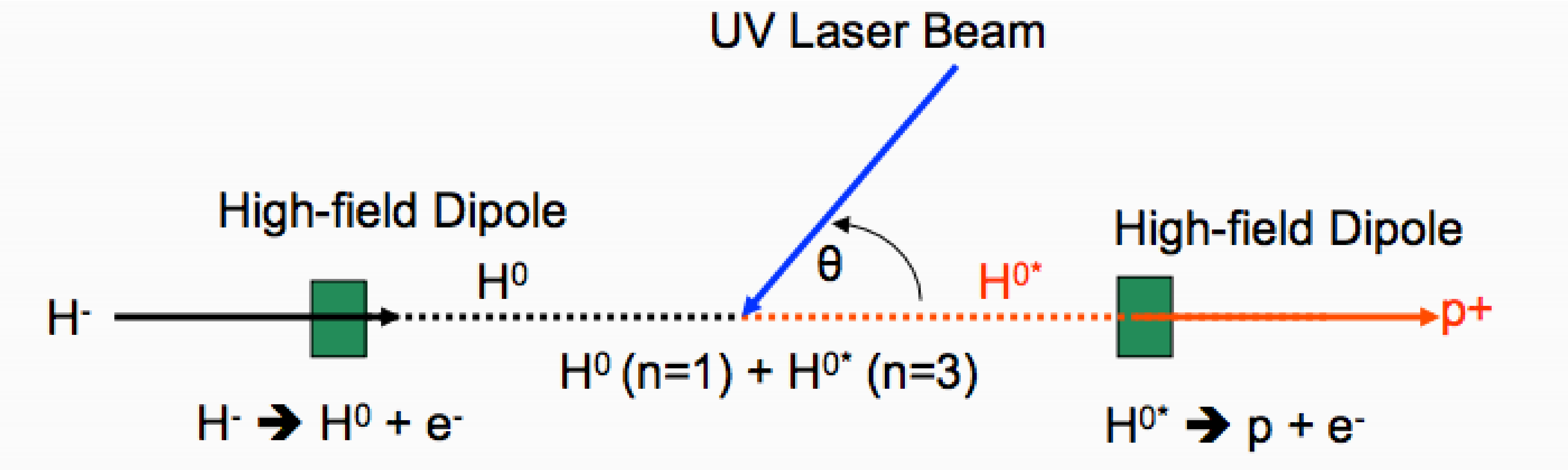
H- field stripping

- At 1 GeV, H^- and H^0 in n=3 excited state are easy to Lorentz strip with a 1-2 T magnetic field
  - Lifetime $10^{-9} – 10^{-10}$ s

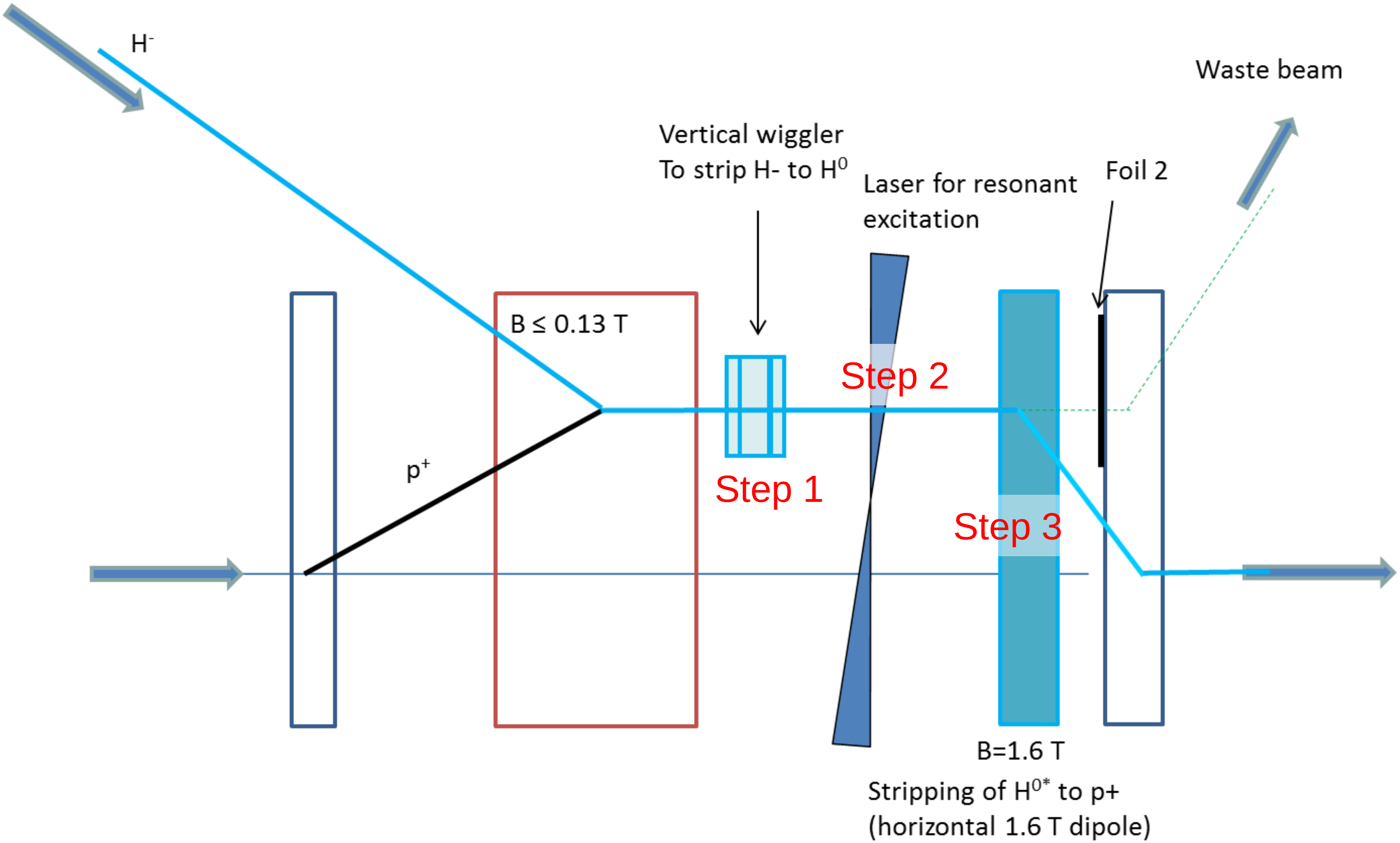


Laser stripping of H-

- Baseline scheme [11] (in fact, laser does NOT strip either electron!):
  - Step 1: remove loosely bound e- from H- with strong magnet (~2T)
    - Do this in vertical plane to avoid increasing spread in x'
  - Step 2: resonant excitation of 2nd e- to high energy level: n=1 to n=3 (or higher) transition, using high-power laser
  - Step 3: remove excited electron with another strong magnet (~2T)

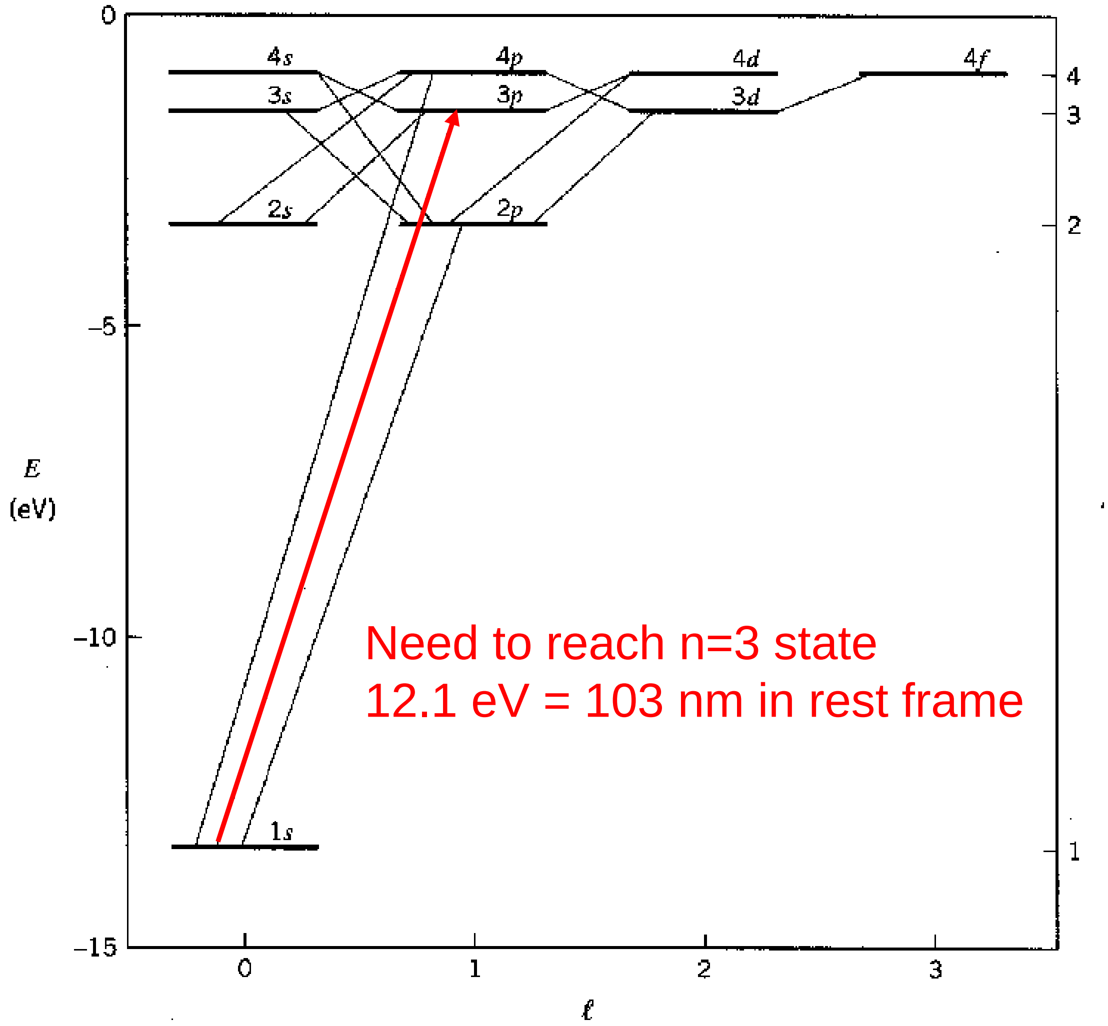


H- laser stripping layout



Laser Stripping: laser frequency

- Hydrogen atomic energy levels and allowed transitions

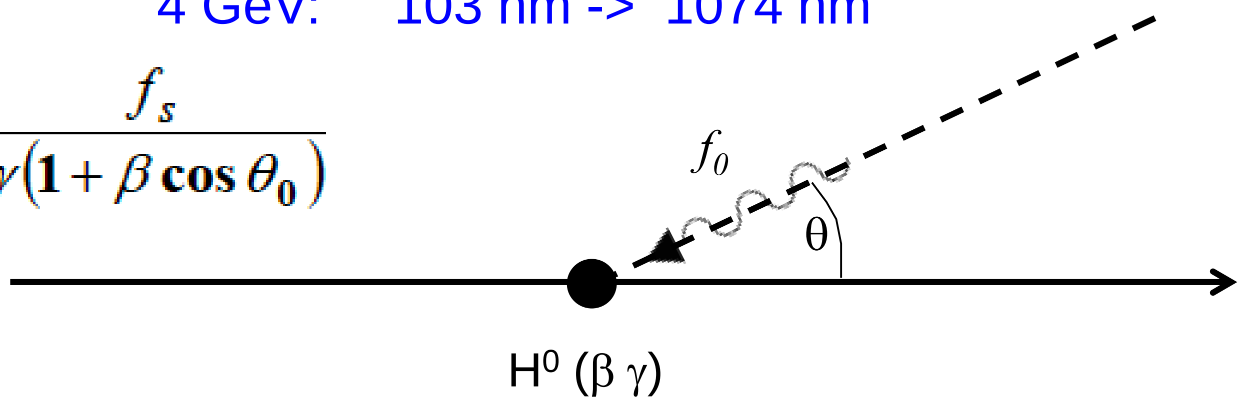


Laser Stripping: laser frequency

- Relativistic Doppler effect is a rare "free lunch"
- Enhancement factor of $\gamma(1 + \beta \cos\theta) \approx 2\gamma$

160 MeV: 103 nm -> 183 nm
1 GeV: 103 nm -> 400 nm
4 GeV: 103 nm -> 1074 nm

$$f_0 = \frac{f_s}{\gamma\left(1 + \beta \cos\theta_0\right)}$$

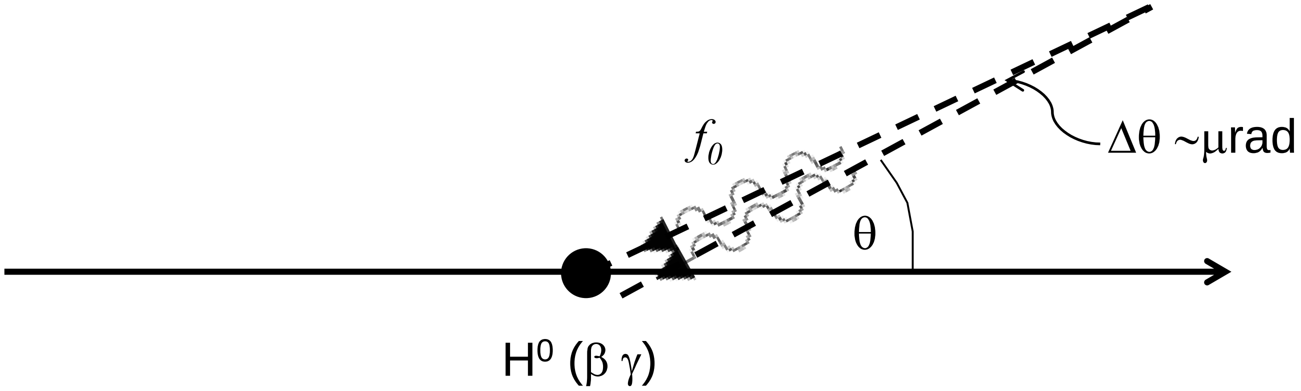


- Use the interaction angle to match frequency to resonance f_s

$$\theta_0 = a\cos\left(\left[\frac{f_s}{\gamma f_0} - 1\right] \Big/ \beta\right)$$

Laser H- stripping

- The devil, as always, is in the detail
- Need to pump all ground state electrons into excited state
- Several possibilities – one is Adiabatic Rapid Passage, where sweep in excitation frequency across transition frequency populates upper state with 100% probability
  - Arrange by making laser beam divergent at interaction region, as change in θ is seen by beam as change in frequency
  - Only a small $\Delta\theta$ needed (μrad), to cover resonance linewidth



Laser H- stripping

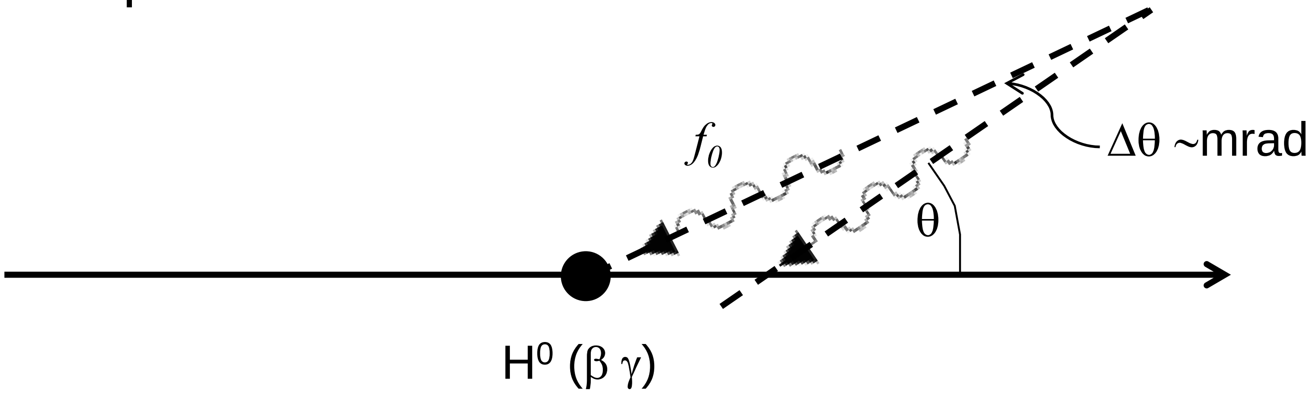
- A big ‘detail’: Doppler broadening and beam angular spread
  - Spread in particle angles from beam emittance and lattice

$$x'_{\max} = \sqrt{\varepsilon}\sqrt{\gamma} = \sqrt{\varepsilon}\sqrt{\frac{1+\alpha^2}{\beta}}$$

    - 10^{-4} – 10^{-5} with small α, large β and ~μm normialized emittance
  - Beam also has a momentum spread $\Delta p/p_0$, typically 10^{-3} - 10^{-4}
    - Changes the resonant frequency by same amount
  - Much larger than laser frequency spread or resonance linewidth
    - Increasing laser frequency spread would require a big increase in overall required laser power, and technically very difficult

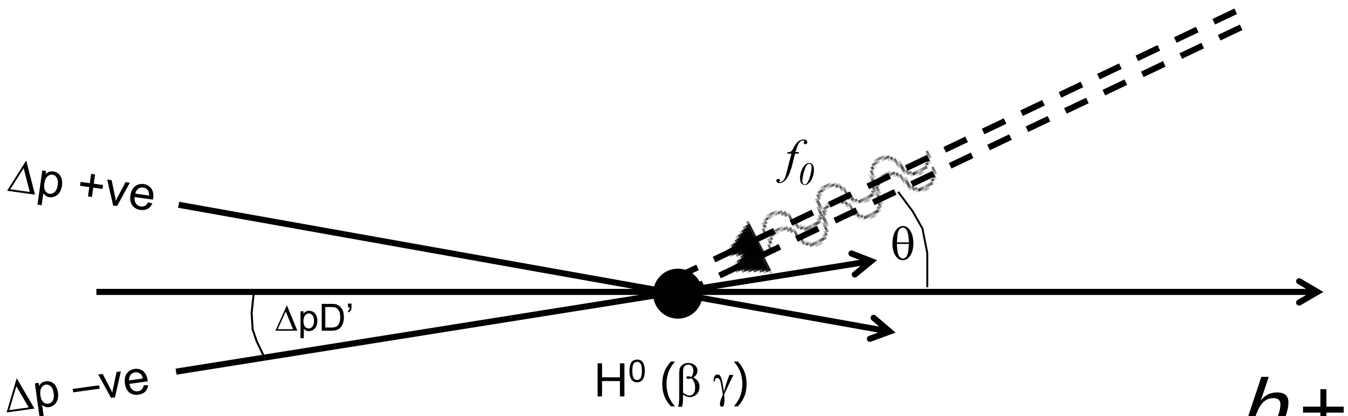
Laser H- stripping

- To overcome Doppler spread, can further increase laser divergence, to ~mrad
  - Resulting frequency spread then covers Doppler spread from Δp
  - Solves the technical issue associated with spreading the laser frequency
  - But only a small fraction of the laser photons are actually in resonance with the transition : need more laser power
  - Also reduces laser power density at interaction region : need more laser power



Laser H- stripping

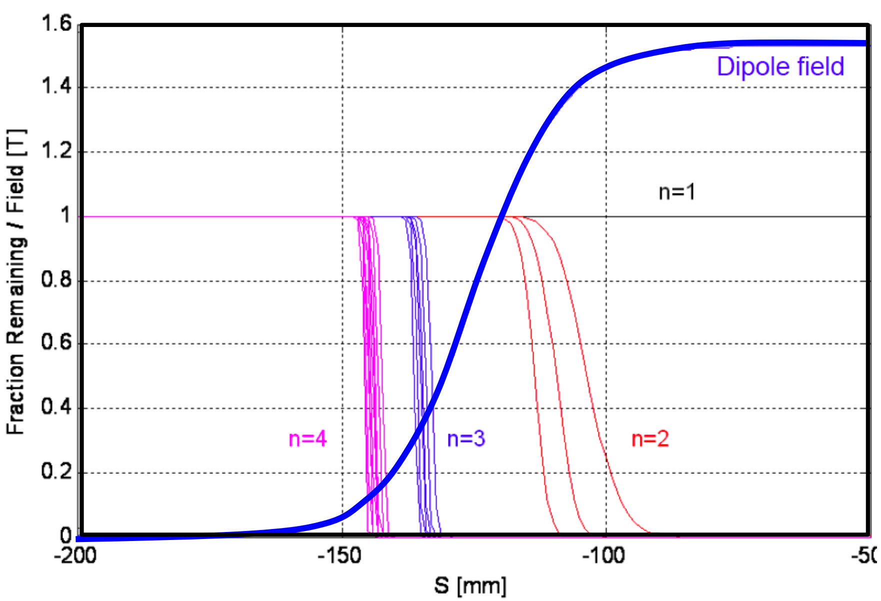
- Overcoming Doppler broadening
  - Use clever idea [12] to arrange correlation between particle momentum offset and angle θ with laser
  - This angle defined by dispersion angle D’ (Twiss parameter)
  - Arrange change in angle to match difference in frequency of resonance: dispersion tailoring



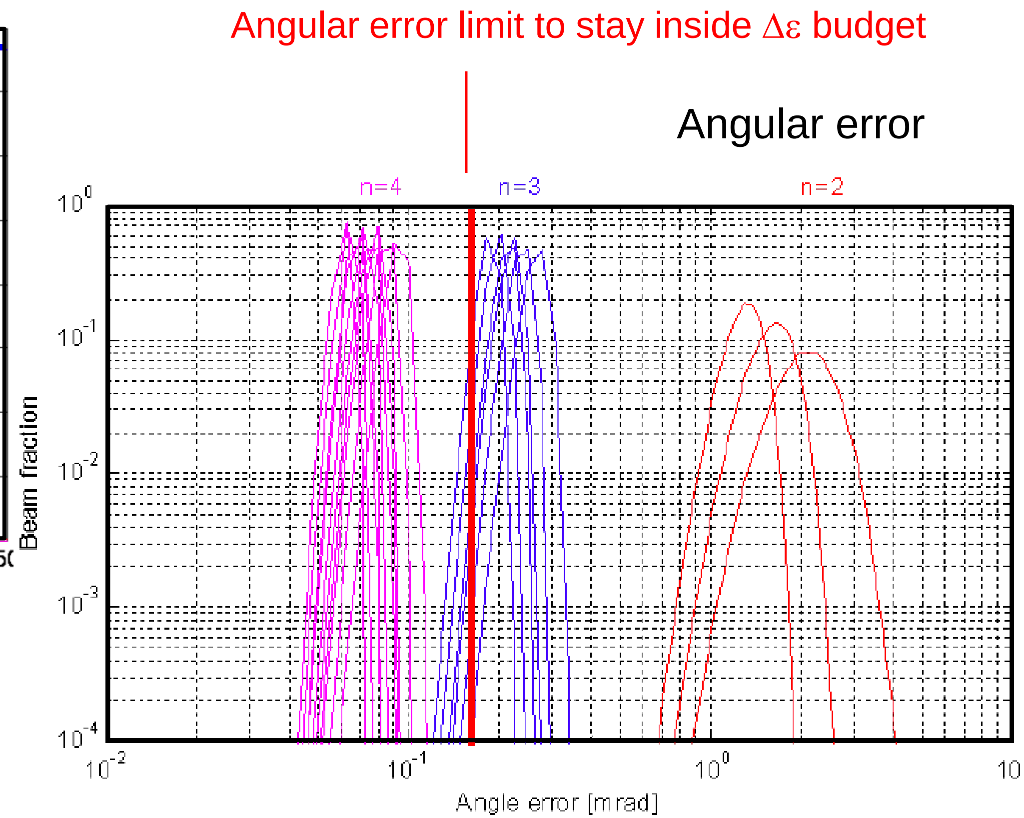
$$D' = -\frac{b + \cos q}{\sin q}$$

Laser stripping: 2^{nd} electron removal

- Stripping in dipole fringe field depends on energy level
- Different S position gives different angle, and ε growth
  - Acceptable for SNS with large emittance beam, was issue for a 4 GeV design study, (interesting magnet design challenge)

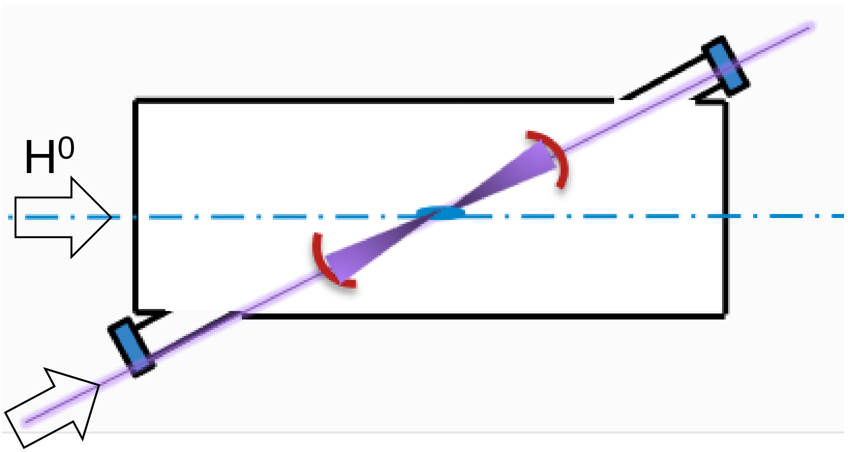


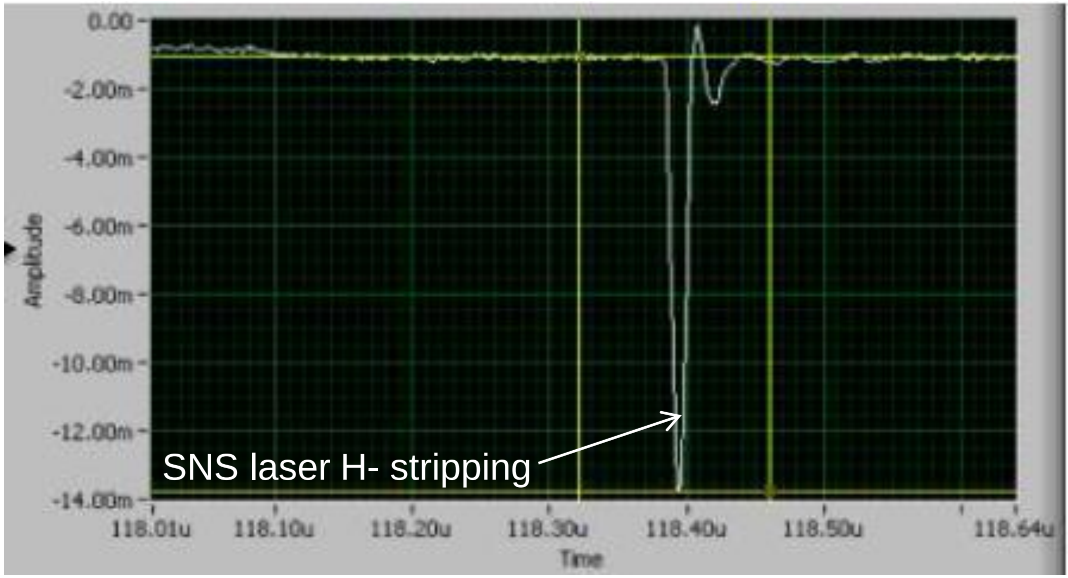
Stripping of 4 GeV H^0 in 1.5 T dipole



Laser stripping: SNS

- SNS have demonstrated efficient laser stripping of 1 GeV H- over short pulse length of 7 ns [12]
- Now working on stripping 10 us pulses with a new 355 nm laser system [13], looking toward 1 ms, then CW
- Research also ongoing into resonant Fabry-Perrot Cavity to sustain high UV laser power at IR over “long” periods





Laser H- stripping: SNS

- Key performance limitation is required laser power to reach required efficiency

$$P_{peak} = \frac{\ln(1/\delta)\hbar^2 \varepsilon_0 c^2 \kappa \omega_0 \sin\theta \; h}{2\mu_{1n}^2 \gamma (1+\beta\cos\theta)^2}$$

- This turns out to be about 10 MW peak power
- Need many tricks to reduce average laser power to
  - Dispersion tailoring to reduce Doppler spread……10 MW -> 3 MW
  - Reduce vertical beam size & α_x……..………………….. 3 MW -> **1 MW**
  - Match laser macro-pulse to H- duty factor……….. 1 MW -> 20 kW
  - Mode-lock laser pulses to 30 ps 402 MHz ………. 20 kW -> 240 W
  - x50 recycling of laser power in FPC……………….240 W -> 5 W

Conclusion

- Beam transfer offers some unique opportunities for merging different domains of physics, engineering and technology
- The next breakthrough may come from a totally different domain
- There is always scope for creativity and elegance: stay in touch with other disciplines, and use imagination

References

[1] W.T.Weng et al., “The AGS Fast Kicker Magnet Systems”, Part. Accel. Coni., Wash. DC, 1981.
[2] M.Barnes et al., “Considerations on a new fast extraction kicker concept for SPS”, sLHC-Project-Note-0018; CERN-sLHC-Project-Note-0018.
[3] Y.Yonemura et al., “Beam Extraction of the PoP FFAG with a Massless Septum”, Proc. PAC’ 2003
[4] C.Wiesner, “Massless Septum for loss reduction at the ZS SPS”, SPS Losses and Activation WG #5, http://indico.cern.ch/event/562757/
[5] W.Bartmann et al., “FCC-hh Injection and Extraction”, Proc. FCC Week 2015 (Washington)
[6] D.Neuffer, “Design Considerations for a Muon Storage Ring”, Proc. Neutrino Mass Miniconference, Telemark, WI, Oct. (1980): 199.
[7] A.Liuy, A.Bross, D.Neuffer, “Decay Ring Design Updates for nuSTORM”, Proc. IPAC2014, Dresden, Germany TUPRI006
[8] E.N.Tsyganov, Preprint TM-682, TM-684, Fermilab, Batavia (1976)
[9] W.Scandale et al., ” High-Efficiency Volume Reflection of an Ultrarelativistic Proton Beam with a Bent Silicon Crystal”, PRL 98, 154801 (2007)
[10] W.Scandale et al., “Bent crystal extraction from a 100 TeV proton collider”, NIM B, Vol. 355, 2015
[11] I.Yamane, “H- charge-exchange injection without hazardous stripping foils”, Phys. Rev. Special Topics Accel. Beams, Vol. 1, 053501 (1998).
[12] V. Danilov et. al., “Three-step H charge exchange injection with a narrow-band laser”, Phys. Rev. Special Topics – Accel. Beams 6, 053501 (2003)
[13] Y.Liu, C.Huang, A.Rakhman, “Laser System for SNS Laser Stripping Experiment”, (2014)