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# TeV slow extraction challenges

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# Why TeV extraction?

- Availability of machines in ~2035
  - Large Hadron Collider (up to 6.5-7 TeV)
  - Future Circular Collider (up to 50 TeV design)
  - High Energy Booster (up to ~ 3.3 TeV design)
- Experimental interest
  - Fixed target experiments have much more potential than colliders for some physics cases (dark matter)
  - Higher energies bring possibilities for new experiments

# Experience

- SPS (Resonant)
  - Operational: 400 GeV, $7.3 \cdot 10^{12}$ $p^+$/s, 4.8 s. ($3.5 \cdot 10^{13}$)
  - Proposed: 400 GeV, $3.3 \cdot 10^{13}$ $p^+$/s, 1.2 s. ($4.0 \cdot 10^{13}$)
- Tevatron (Crystal)
  - 1990's E853: 900 GeV, $1.5 \cdot 10^5$ $p^+$/s, luminosity driven without disturbing collider physics ($10^{12}$ $p^+$)
  - Experimental RF driven and fiber driven extractions
  - "Kick mode": $10^8$-$10^9$ $p^+$/kick for $10^{11}$ $p^+$/bunch
- SSC (several design ideas)

# Extraction types

- Amplitude growth mechanism
  - Natural halo re-population
  - Resonance
    - 2nd order with octupoles or anti-symmetric sextupoles
    - 3rd order with sextupoles
  - Noise
  - Damper (used as 'exciter')
  - Combination
  - None (e.g. controlled momentum change)

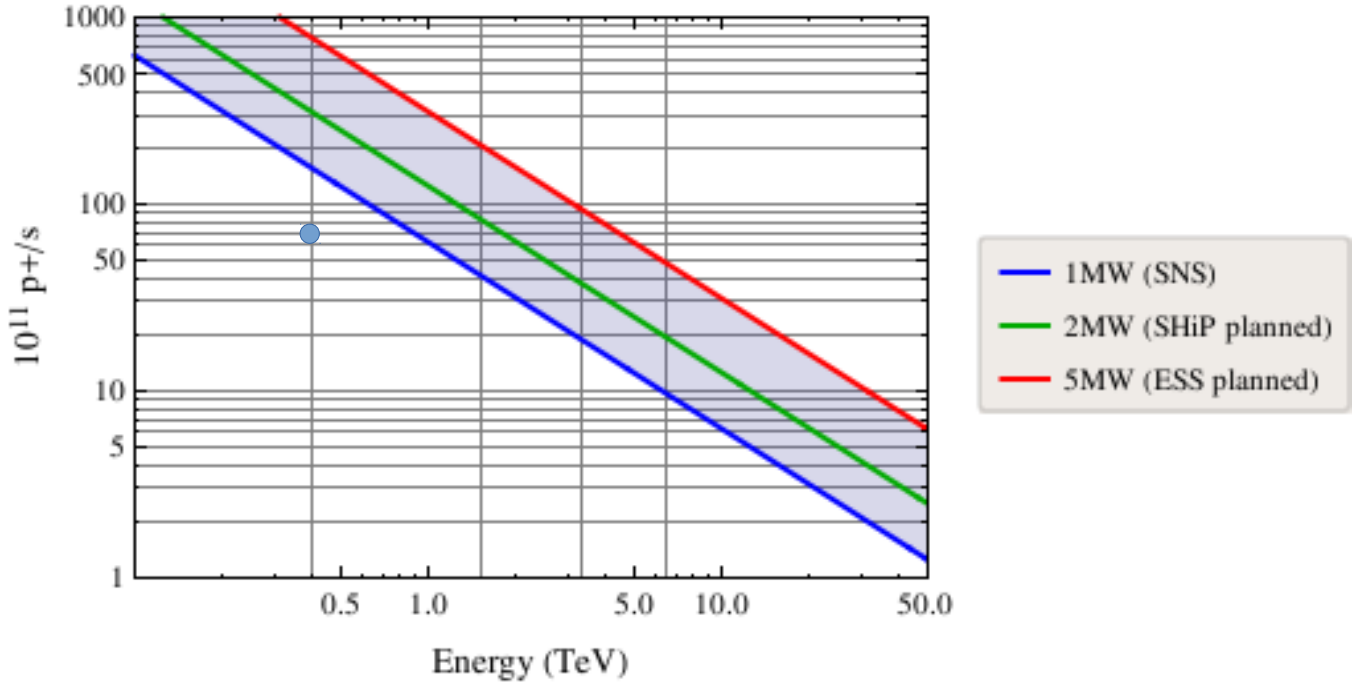
# Extraction types

- Beam intercepting device (start extraction)
  - Electrostatic (thin) septum
  - Crystal
  - Both (crystal shadowing septum)
  - Neither? (Massless septa, ...)
- Spill length
  - Few seconds – few minutes
  - Few minutes – hours (possibly parasitic)

# TeV fixed target experiments

- Likely want a uniform instantaneous spill rate, as high as the electronics permit
- Very little known at the moment
  - Desired intensity per year
  - Desired spill rate
  - Tolerance of momentum change/spread
- Will be very important input for design choice

# TeV fixed target experiments




- Maximal power on target determines maximal extraction rate/minimum spill time

# Spill time

| Machine | Minimal spill time | Ramp up+down time |
|---|---|---|
| FCC | 0.5-3 hours | 40 minutes |
| LHC | 1-6 minutes | 20 minutes |
| “HEB@FCC” | 2-9 minutes | 2 minutes |
| “HEB@LHC” | 0.5-3 minutes | 4 minutes |
| “HEB@SPS” | 3-16 seconds | 30 seconds |

- A relatively fast spill does not make sense when the cycle time is long (duty cycle)
  - Top-up injection?

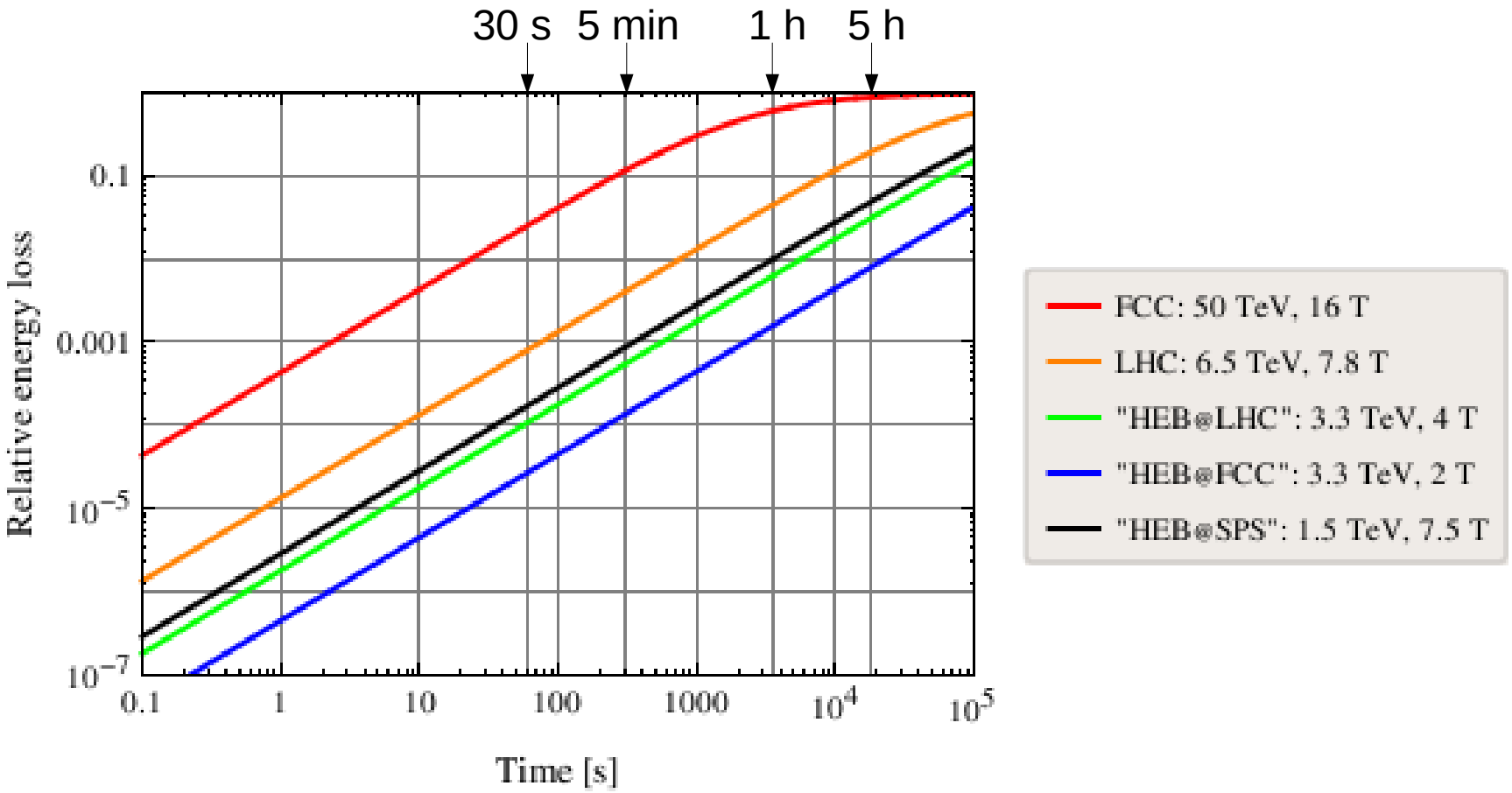
# Aperture/collimation

- High energy (collider) rings tend to be designed with a small aperture
  - Larger apertures increase the cost
- Collimation is necessary at high energies
  - Need to extract particles before they hit collimators
  - Or use the collimation system as part of the extraction (crystals!)

# Synchrotron radiation

- Energy loss due to synchrotron radiation
  - Proportional to $E^2B^2$.
  - In LHC at 3.3 TeV this is 5.8 MeV/s
  - LHC collimator momentum acceptance of $3 \cdot 10^{-3}$ reached in ~ $1.7 \cdot 10^3$ s.
- Can be a constraint, or a driving mechanism for the extraction
  - Keep the beam bunched and at constant energy
  - Beam in coast → ramp down or drift to extraction

# Synchrotron radiation



# Damage and activation

- One of the major concerns in SPS
- Losses on
  - Electrostatic septa
  - Crystal (high radiation hardness, for 450 GeV deterioration coefficient of 6% per $10^{20}$ $p^{+}/cm^{2}$)
  - Beam sharing devices (no splitters!)
  - The ring itself
- Fault scenarios
  - Choice plane/phase advance for dump kickers

# Septum losses

- Fraction lost ≈ effective thickness/spiral step
- Possible spiral step depends on aperture
- Effective thickness is due to wire thickness, alignment of individual wires wrt eachother and alignment of the septum with the beam
  - Not much to gain in the first two
- Angular spread at the septum and septum length are also an influence.

# Abort gap

- Need to be able to safely dump the beam at any time → an abort gap is necessary
  - Will influence the spill structure at $f_{rev}$
- Abort gap cleaning
  - Should be able to cope with the rate of diffusion in to the abort gap
  - Could be part of the extraction

# Spill structure

- Abort gap
- Bunched or coasting (RF off)
- Resonant extraction: power converter ripple
  - Tolerance similar to present day extraction
  - Tolerance dependent on momentum spread
- Parasitic extraction: orbit jitter
  - Try to minimize by design

# Speculative design ideas

- Parasitic crystal extraction from FCC/LHC
- Dedicated slow extraction from HEB
  - Decrease of RF stable bucket size, extraction by momentum loss
  - Resonant slow extraction with a crystal shadowing the septum
- Dedicated slow extraction from LHC
  - Extraction by exiting particles as they populate the abort gap, gradually increasing the abort gap length and injecting into the emptied region at top energy

# Conclusion

- TeV scale machines will (likely) become available for slow extraction
- Main concerns
  - Aperture limitation
  - Synchrotron radiation
  - Activation and damage due to losses
- Many options, but experimental input needed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