HB2012, Beijing, China, September 17-21, 2012

Accelerator System Design, Injection, Extraction and Beam-Material Interaction
Working Group-C Summary

Conveners: D. Li, N.V. Mokhov, H.W. Zhao

Part 1. Nikolai Mokhov

Part 2. Derun Li

WG-C Sessions

- TUO3A: B&C
- TUO1B: A&C
- WEO3A
- WEO3C
- WG-C Discussions
- THO3B

WG-C Talks (1)

1. S. Montesano "Status and results of the UA9 crystal collimation experiment at the CERN SPS"
2. D. Johnson "Injection design for Fermilab Project X"
3. Y. Yuan "Study of intense beam injection and extraction of heavy ion synchrotron"
4. B. Brown "Beam loss control for the Fermilab Main Injector"
5. X. Wu "The design and commissioning of the accelerator system of the Rare Isotope Reaccelerator – ReA3 at Michigan State University"
6. V. Reva "High-energy electron cooling"
7. R. Miyamoto "Beam loss and collimation in the ESS linac"
8. D. Reggiani "Extraction, transport and collimation of the PSI 1.3 MW proton beam"
9. F. Garcia "Current and planned high proton flux operations at the FNAL Booster"

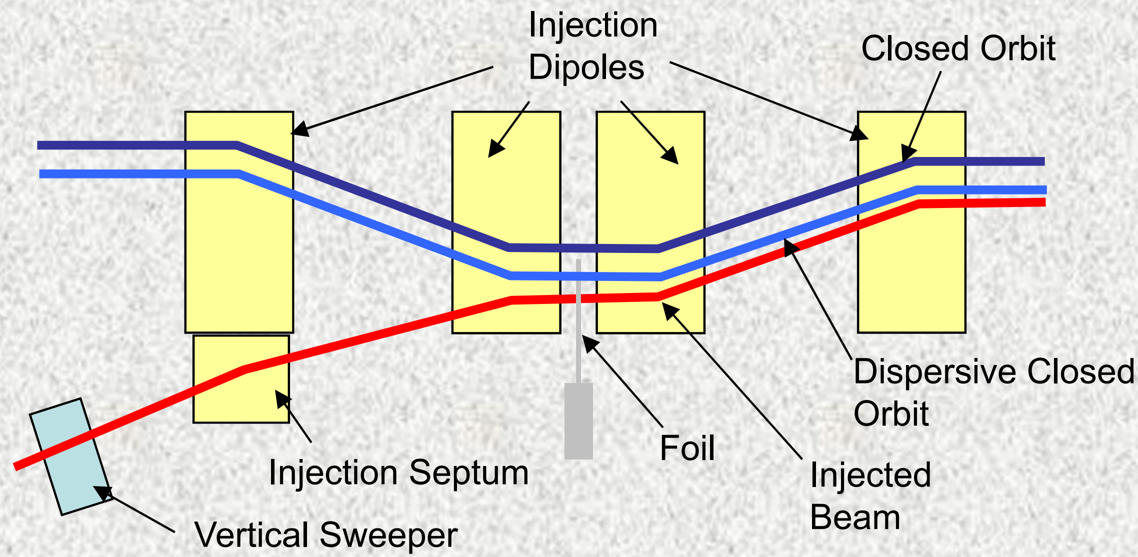
WG-C Talks (2)

10. B. Pine “Injection and stripping foil studies for a 180-MeV injection upgrade at ISIS”
11. I. Strasik “Collimation of ion beams”
12. G. Stancari “Beam halo dynamics and control with hollow electron beams”
13. N. Simos “LBNE target material radiation damage studies using energetic protons of the BLIP facility”
14. N. Mokhov “Radiation effect modeling at intensity frontier: status and uncertainties”
15. M. Tomut “Understanding ion induced radiation damage in target materials”

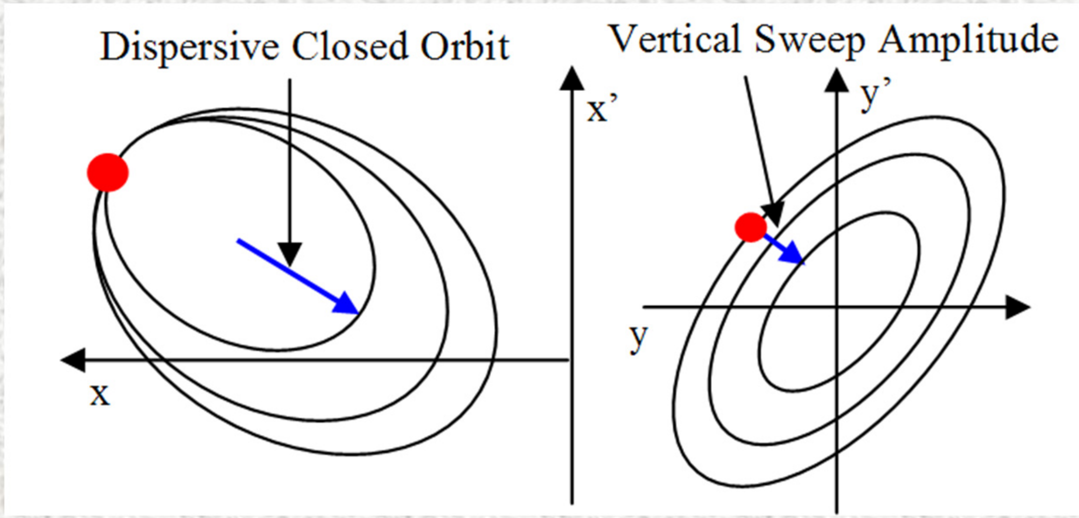
WG-C Talks (3)

16. E. Prebys "Proton beam inter-bunch extinction and extinction monitoring for the Mu2e experiment"
17. A. Facco "SRF technology challenge and developments"
18. R. Kephart "SRF cavity research for Project X"
19. Q. Li "Beam dynamics studies of H- beam chopping in a LEBT for Project X"
20. L. Sun "Intense high charge state heavy ion beam production for the advanced accelerators"

Injection: ISIS as an Example

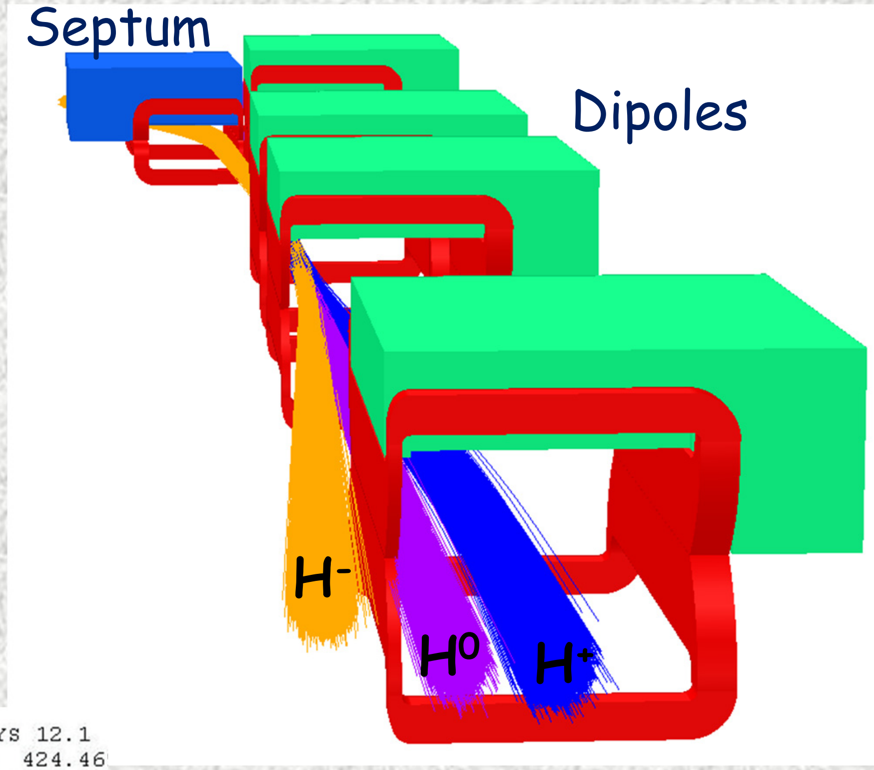


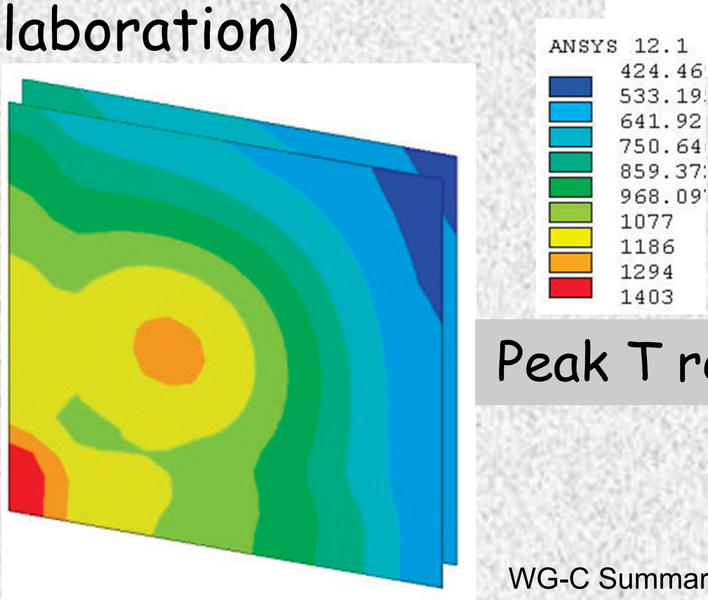
- Serially powered dipoles
- 45 mrad - 65mm bump
- 50 μg/cm^2 Al_2O_3 foil
- Vertical 'sweeper' magnet
- Horizontal painting via closed orbit movement



Stripping Foils

- Multiple and single Coulomb scattering, energy loss, elastic and inelastic nuclear interactions in foil as a source of beam loss
- Space charge: 2D and 3D ORBIT simulations for ISIS and Project X
- Beam distributions tracked in OPERA
- Foil heating: double layer foils (ISIS-JPARC collaboration)



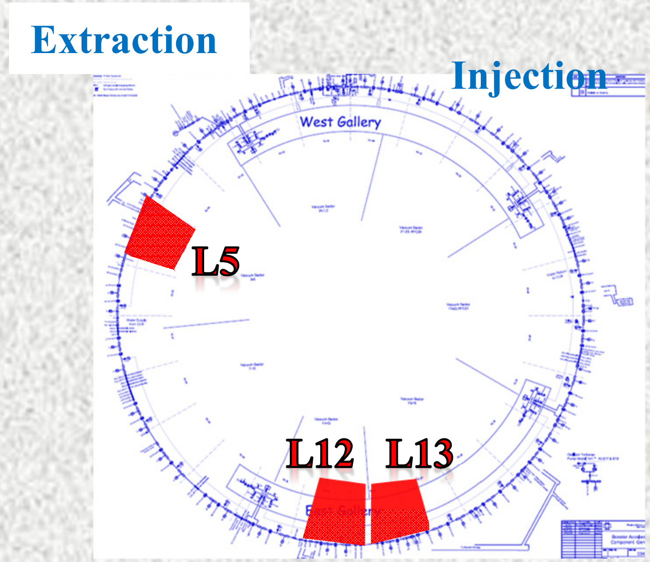


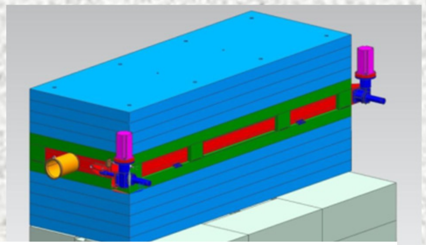
Peak T reduced from 1657 to 1403K

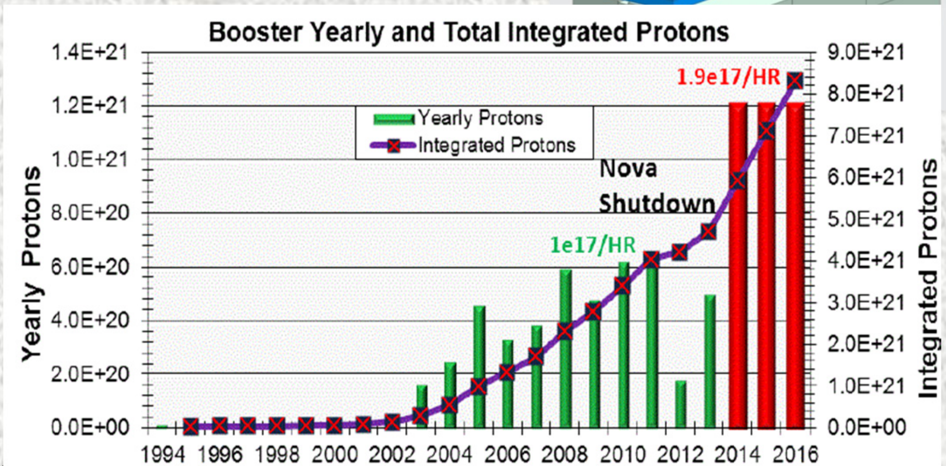
Fermilab Booster Improvement

Proton Improvement Plan (PIP):

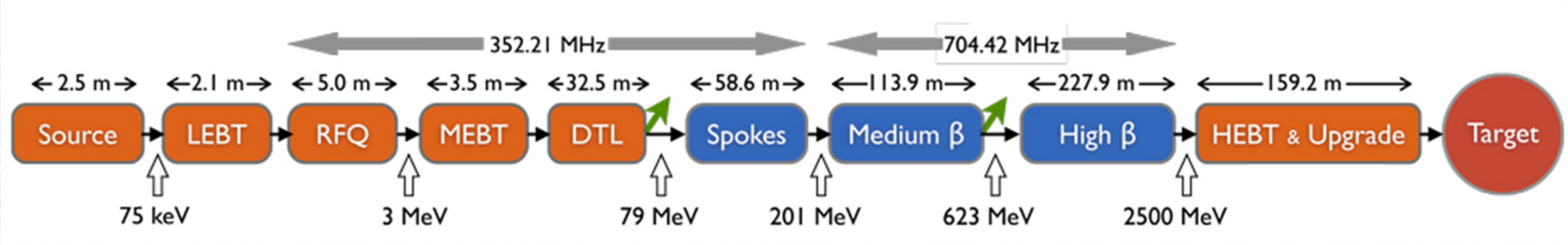
- Aperture improvement
- Better orbit control: Magnet realignement
- Notcher relocation from L5 (V) to L12 (H) with a new absorber at L13
- New strong correctors for magnetic cogging
- Switch to a 2-stage collimation as was designed
- Improved radiation protection scheme







Beam Loss and Collimation in ESS Linac (1)



Drastic underestimation of activation due to beam loss in RFQ and DTL:

The **<u>1 W/m rule</u>** for beam loss doesn't apply here as we derived it for continuous loss of E_p > 100-200 MeV beam resulting in contact dose (30 day/1 day) of 0.5-1 mSv/hr on an outer surface of a typical (massive) accelerator magnet.

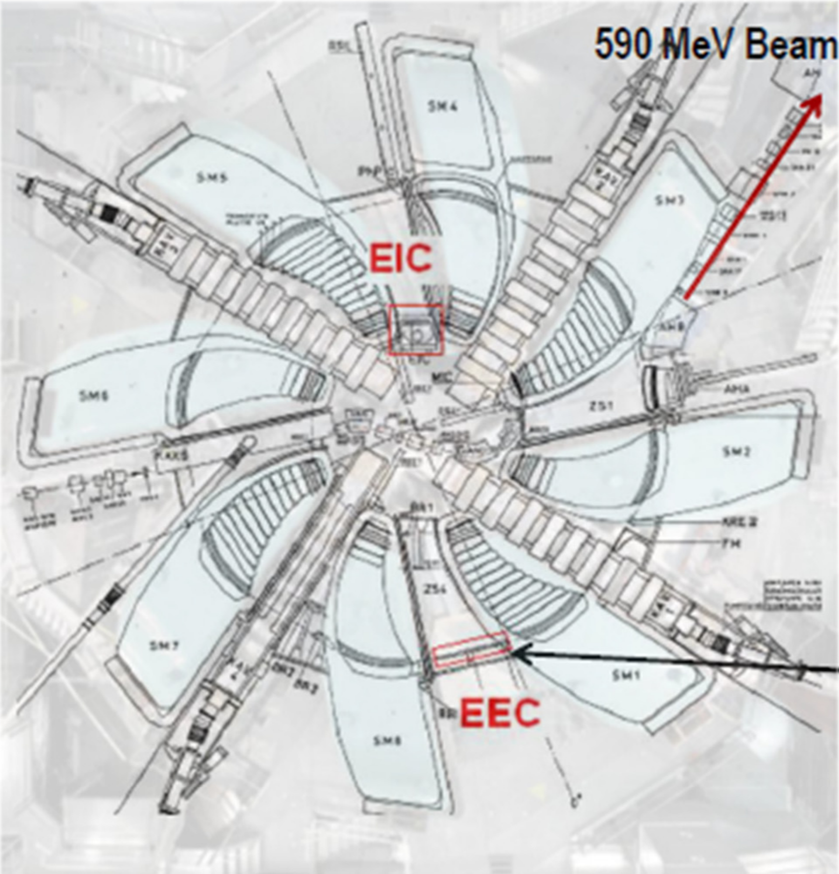
"Beam Halo and Scraping", Ed. N.V. Mokhov, W. Chou, 7^{th} ICFA Workshop on High Intensity High Brightness Hadron Beams, Lake Como, Wisconsin, 13-15 Sep. 1999.

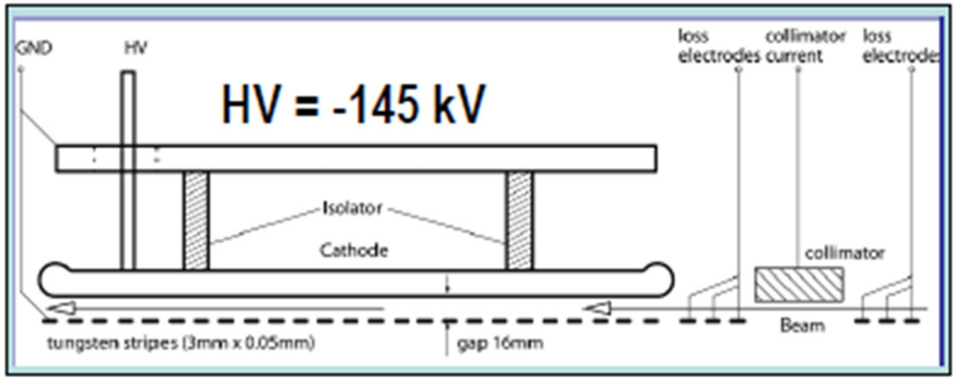
Beam Loss and Collimation in ESS Linac (2)

- Quad and cavity error studies with TraceWin tracking simulations
- MEBT collimation studies: optimization of the scheme and loss limit on a graphite collimator; halo growth occurs in the last half of the MEBT (sometimes in the final 10-20 cm); the standard scheme of two collimators separated by 90 deg etc is not optimum for the ESS MEBT; phase advance of an individual particle (angle in the normalized phase space) depends on its initial position due to strong space charge; angular distribution of halo particles is not uniform.
- HEBT collimation:
  - S1: Energy upgrade + movable collimators.
  - S2: Achromatic elevation. Tune-up lines below.
  - S3: Linear + non-linear (octupole) expansion of beam + fixed collimator.

Extraction of 1.3-MW Beam at PSI

590 MeV Beam Exctraction Line

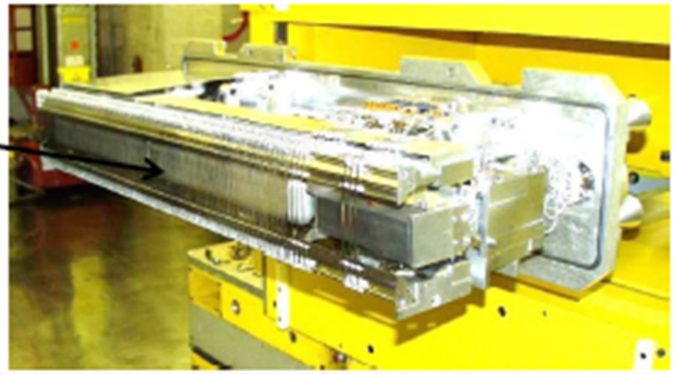




EEC: Electrostatic Extraction Channel

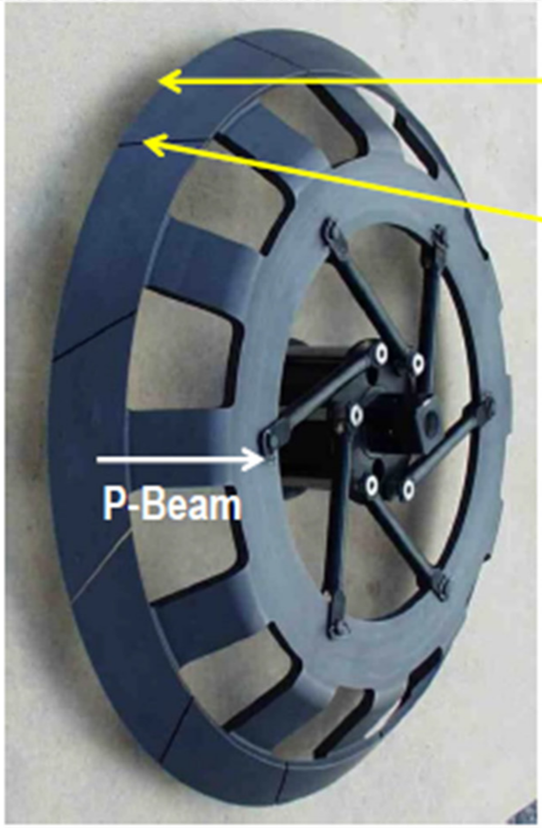
Gap = 16 mm θ_{beam} = 8.2 mrad L_{eff} = 920 mm

50 µm thick tungsten stripes



Extraction Efficency: 99.98 %

PSI Target-E

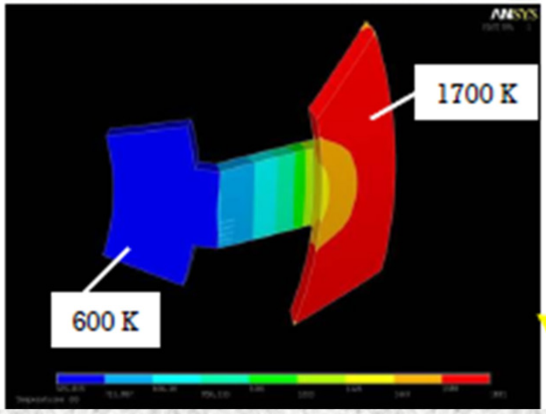


Target width: 6 mm, Beam width (1σ) $\approx$ 1 mm
Beam transverse range $\approx$ 4 mm

New design (2003): **gaps** allow dimensional changes of the irradiated part of the graphite

TARGET WHEEL

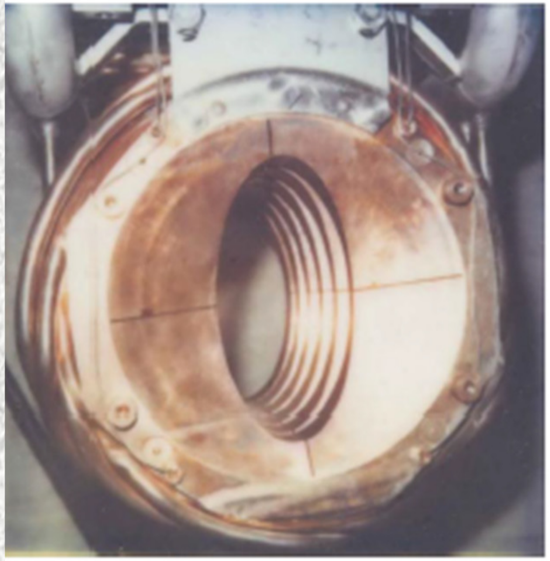
Mean diameter:	450 mm
Graphite density:	1.8 g/cm^3
Operating Temperature:	1700 K
Irradiation damage rate:	0.1 dpa/Ah
Rotational Speed:	1 Turn/s
Target thickness:	40 mm (7g/cm^2)
Beam loss:	12 %
Power deposition:	20 kW/mA
Cooling:	Radiation



Temperature distribution simulation

PSI 150 kW Beam on Collimator: ΔT and Activation

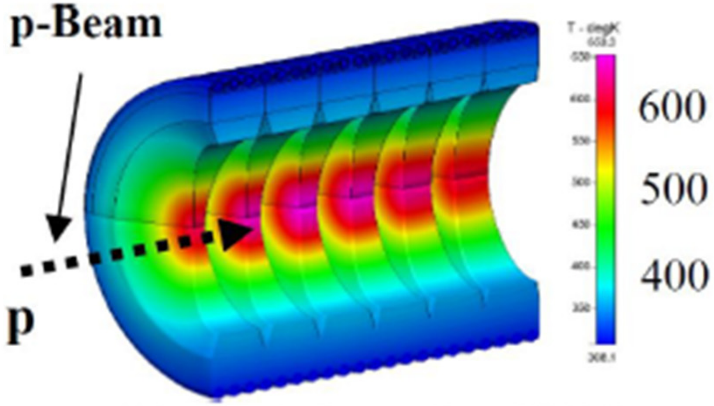
KHE2 Collimator during installation (1990)



500 Sv/h in 2010

...and after 20 years operation (120 Ah total beam charge)

KHE2 Temperature Distr. for 2.0 mA
Proton Beam on Target E
T_{max} = 653 K,   safe till 770 K (~2.6 mA)



Y. Lee et al., Proceedings HB2010

Do we need a new collimator or a new running strategy for 3.0 mA?

Halo Collimation of Ion Beams

Intermediate charge-state ions will be accelerated in SIS 100.

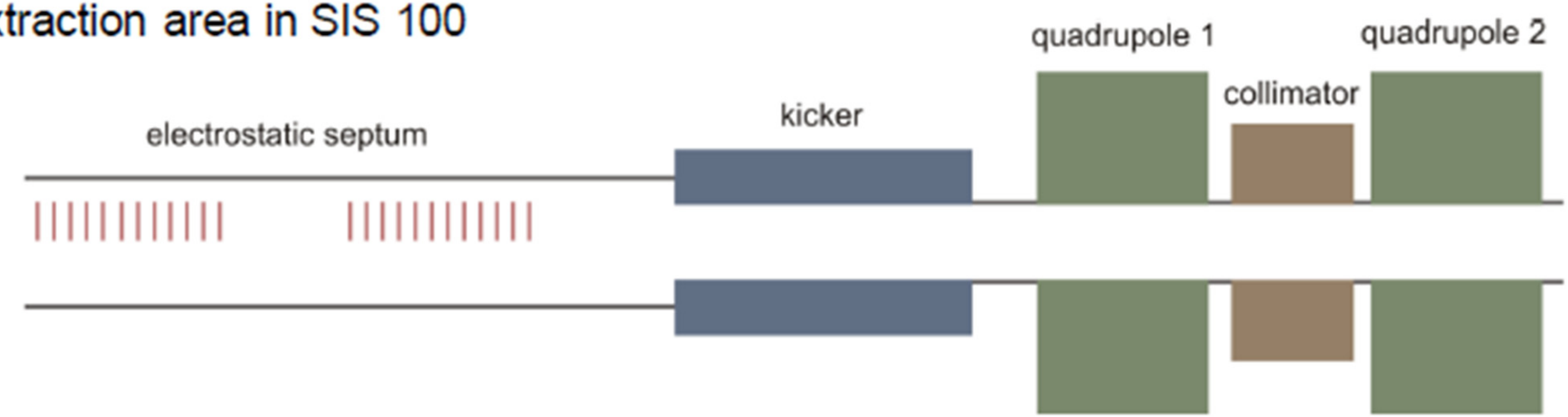
$^{238}_{92}U^{28+}$, $^{197}_{79}Au^{25+}$, $^{181}_{73}Ta^{24+}$, $^{132}_{54}Xe^{22+}$, $^{84}_{36}Kr^{17+}$ Partially-stripped ions

[Ref] FAIR - Baseline Technical Report, GSI Darmstadt, (2006).

Colimation concept

Stripping foil $^{238}_{92}U^{28+} \rightarrow {}^{238}_{92}U^{92+}$ ⟶ Deflection by a beam optical element

Slow extraction area in SIS 100



Lost particles during the slow extraction → intercepted by two warm quadrupoles

[Ref] A. Smolyakov at al, EPAC2008, 3602 (2008).

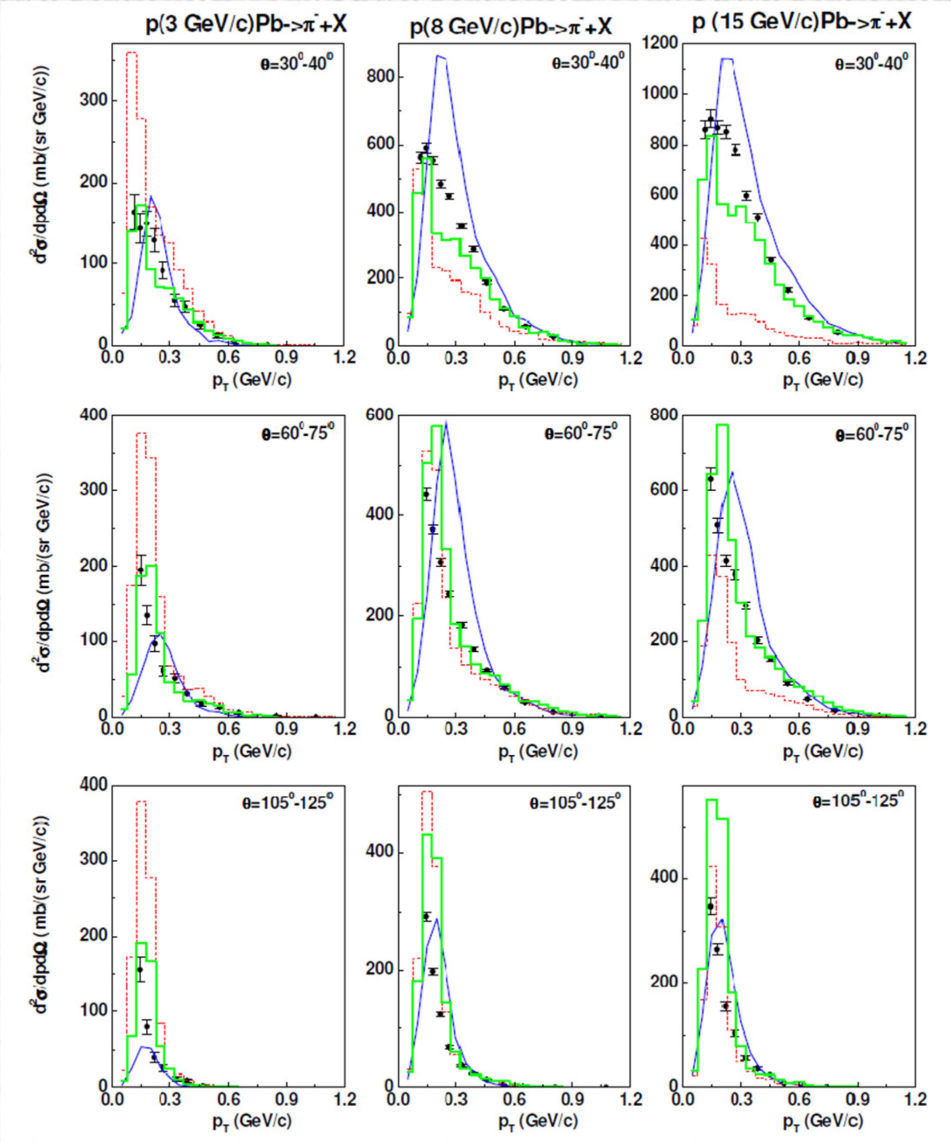
The stripping foil for halo collimation is placed in the slow extraction area in SIS 100

Modeling for Intensity Frontier

MARS

- Particle yields: p,n,π,K,μ,Σ,HI
- Nuclide inventory
- Radiation damage: DPA, dose, H/He, soft errors (SEE)
- Background suppression
- Beamline optimization, beam loss, particle capture and collimation, SC magnet quench
- Prompt and residual radiation, shielding, impact on environment
- Targetry: power dissipation, integrity (shock & buildup), magnetohydrodynamics

Particle Production in Nuclear Interactions



- The key for fixed target and collider experiment planning.
- The origin of the majority of beam-induced deleterious effects in machine/detector components and environment.
- OK at $E_p < 1$ GeV and $E_p > 10$ GeV.
- At intermediate energies, most interesting for the Intensity Frontier: substantial theoretical difficulties; experimental data contradict each other (**outstanding example HARP vs HARP-CDP**); the main problem with low-energy pion production that is crucial, e.g., for all Project X experiments.

Geant4 models:

Green – UrQMD, red – Binary, blue - Fritiof

Uncertainties in Simulation Codes

- Predictive power, capabilities and reliability of major **particle-matter interaction codes** (FLUKA, MARS, Geant4) used in accelerator applications are quite high.
- On particle yields, accuracy of predictions is at a 20% level in most cases, although the issues (up to a factor of 2) remain in some phase space regions. EM interactions are described at a few % level.
- Accuracy of beam-induced macroscopic effect predictions today:
  - Energy deposition effects (instantaneous and accumulated) < 15%
  - Hydrogen/Helium gas production and DPA: ~20% (with similar DPA models) to a factor of 2; still need better link of DPA to changes in material properties
  - Beam loss generation and collimation: quite good (Tevatron, J-PARC, LHC)
  - Radiological issues (prompt and residual): a factor of 2 for most radiation values, if all details of geometry, materials composition and source term are taken into account.

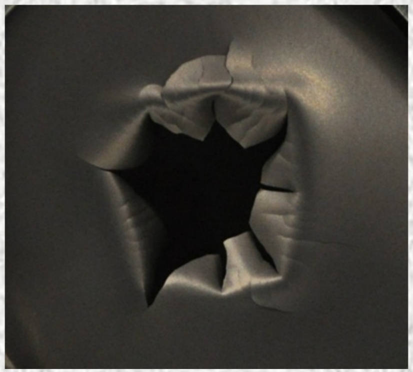
Materials, Materials, Materials…

- New study confirmed that energetic proton fluence thresholds are a reality for carbon-based lattices
- There is significant variability between graphite grades in the way that graphite responds to irradiation
- Non-destructive testing has shown great potential in assessing damage annealing
- Fast neutron exposure to fluences similar to those for protons has just been completed and will provide good correlation between the different irradiating species

4.8 MeV/u ^{197}Au on carbon foil at 10^{14} cm^{-2}

5ms, 48Hz

0.15ms, 0.4Hz



- Ion-induced disordering of graphite different from neutrons ⇨ swelling, stress concentrators, bending, hardening, degradation of thermal conductivity and fatigue resistance
- A steep degradation of properties takes place at doses corresponding to ion track overlapping (given by ion track size – depends on ion mass and energy)
- High temperature (above 1000 °C) operation of graphite extends lifetime due to defect recovery
- Fatigue induced by cyclic thermo-mechanical loading reduces lifetime

New Techniques

- High-energy electron cooling

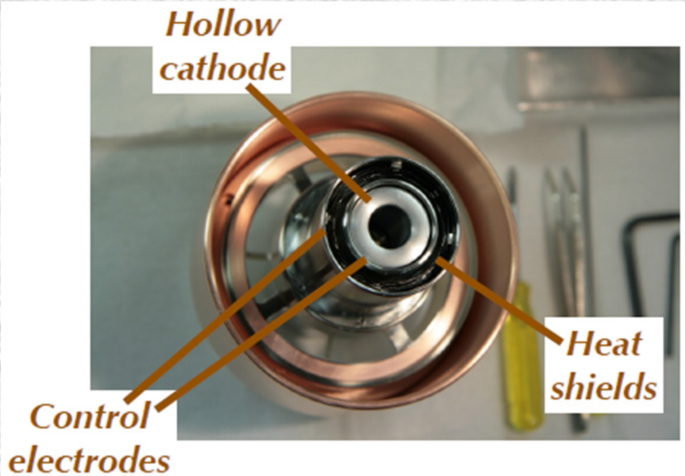
Combination of electron and stochastic cooling at the same high beam energy: key problems of 2-MeV electron cooler experimentally verified in Novosibirsk; the cooler is ready for assembly and commissioning in COSY

- Crystal collimation

Successful beam tests at SPS, plans for tests in LHC

- Hollow electron beams

Magnetically confined hollow electron beams are a safe and flexible technique for halo control in high-power accelerators. Material-less soft complement to a two-stage collimation. Very promising for LHC. Tevatron experiments provided experimental foundation.



Discussions, Action Items, Data Needs

- Full 3D models of the entire machine integrated for beam loss and shower simulations
- Linking CAD and simulation codes; geometry exchange tools
- Low-energy pions. How to resolve HARP vs HARP-CDP?
- Materials beam tests: cryo temperatures, high-energy protons, annealing, atmosphere
- "Dream materials" for foils, targets, collimators and beam dumps; nano-structures
- Moving from calculated dose and DPA to changes in material properties: ready for coupling shower simulation codes (FLUKA, MARS) and "materials" modeling codes