Beam loss & Electron-cloud in the SNS ring: Issues and remedies

Jie Wei

M. Blaskiewicz, P. He, H. Hseuh, D. Raparia, L. Wang, S.Y. Zhang (BNL)

M. Pivi, M. Furman (LBNL)

R. Macek (LANL)

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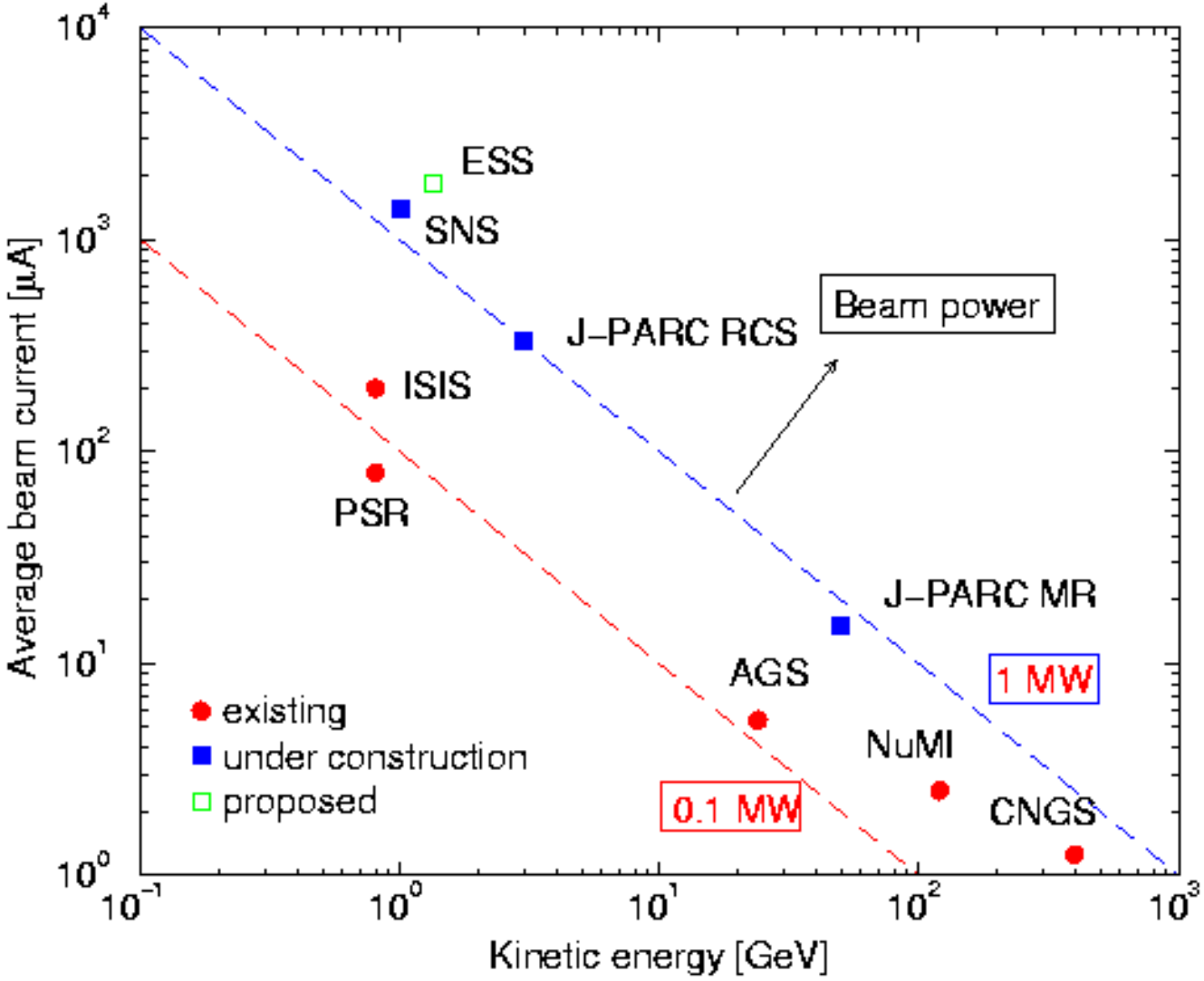
Outline

- SNS Project Overview
- SNS Ring Vacuum Parameters
- Beam Loss and Collimation
- Electron Cloud and Mitigation
- Summary

Spallation Neutron Source complex

- A $1.4 billion, 7-year construction project due June 2006
- Collaborated by six national laboratories, built at Oak Ridge
  - Argonne, Brookhaven, Jefferson, Berkeley, Los Alamos, Oak Ridge
- At 1.4 MW beam power and 1.5×10^{14} particle per pulse, it will a high-power, high-intensity accelerator facility

Evolution of the beam-power front



Vacuum system parameters

Ring 248m in circumference

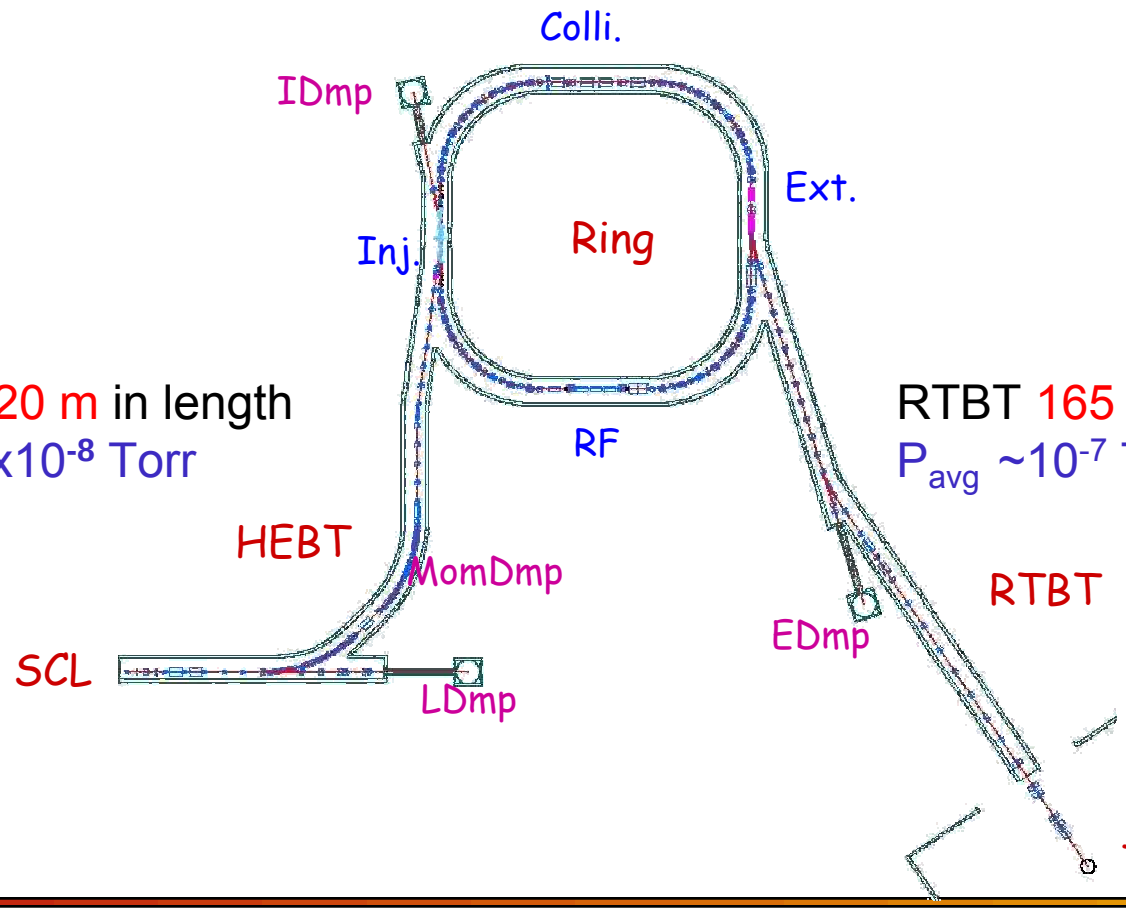
$P_{avg} < 1x10^{-8}$ Torr

HEBT 220 m in length

$P_{avg} < 5x10^{-8}$ Torr

RTBT 165 m in length

$P_{avg} \sim 10^{-7}$ Torr



Vacuum requirements

- Pre-injection transport line (HEBT)
  - $P_{ave} < 5x10^{-8}$ Torr
  - Required by H^- stripping due to residual gas molecules ($\sigma \sim 1/\beta^2$)
  - Beam loss limit: $< 10^{-6}$ per meter
- Accumulator Ring
  - $P_{ave} < 1x10^{-8}$ Torr for design intensity of $1.5x10^{14}$ proton per pulse
  - Required by residual gas ionization due to proton beam, ion desorption & pressure runaway, and ionized electron production
  - Capable of high-pressure operation (10^{-6} Torr) for beam scrubbing
- Ring-to-Target transport (RTBT)
  - Near ring: $P_{ave} \sim 1x10^{-8}$ Torr, to avoid interference with ring operation
  - Near target: $P_{ave} < 1x10^{-6}$ Torr, for reliable operation of Harp profile diagnostics

Pre-injection transport (HEBT)

HEBT (220m, including 3 dump lines)

$P < 5x10^{-8}$ Torr

For H^- stripping:

$\sigma \propto 1/\beta^2 \approx 1x10^{-18}$ cm^2

(40%H_2/40%H_2O/20%CO)

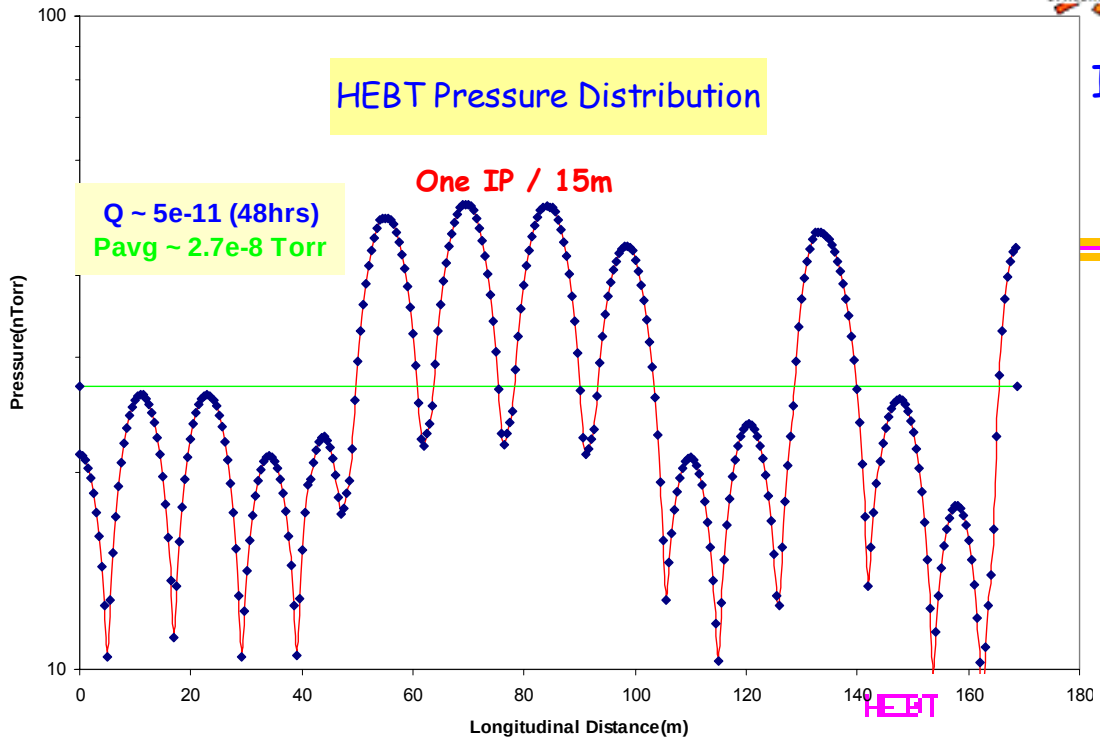
⇒ 0.3 nA/m ≈ 0.3 watts/m

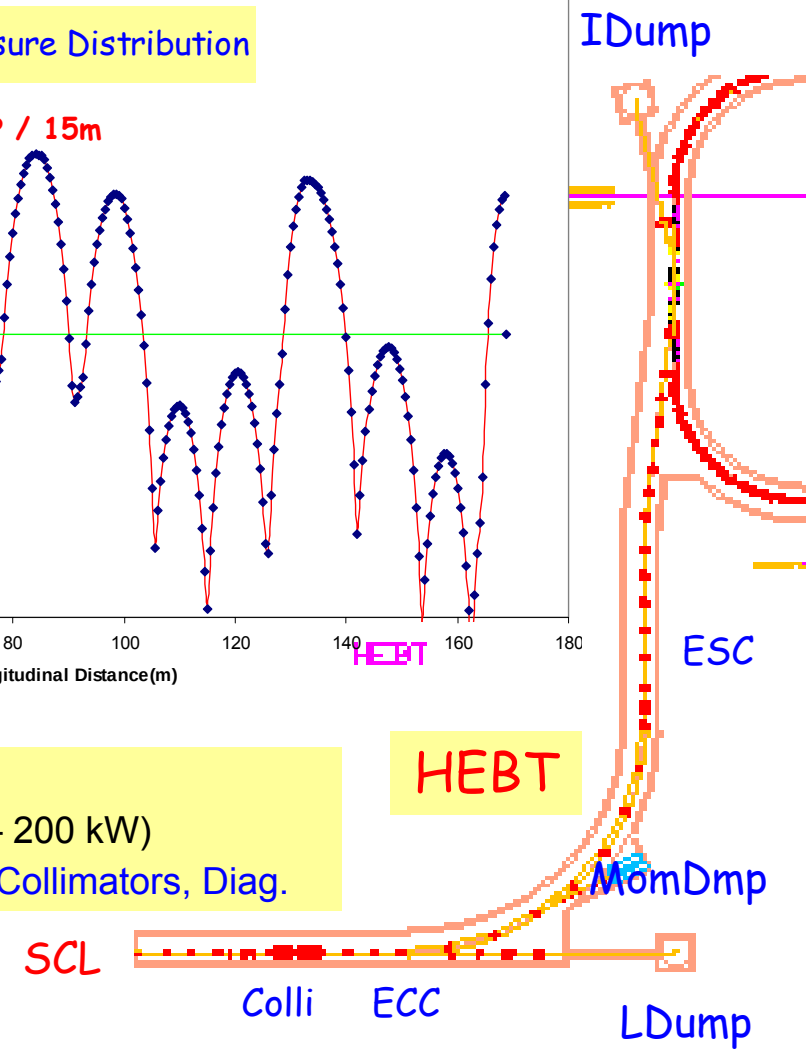
@ 2 mA x 1 GeV (2 MW)

⇒ <30 mR/hr @ 1 ft

(4 hrs after 100 day operation)

Acceptable for hands-on maintenance





Interface to

3 dumps (2 kW – 200 kW)

SCL, ECC/ESC, Collimators, Diag.

(Courtesy H. Hseuh et al)

Accumulator ring

4 Arcs x 34m, 4 SS x 28m

isolatable by all-metal gate valves

P_{avg} <1x10^{-8} Torr

$\sigma_i \approx 6\times10^{-19}$ cm^2 (res. gas ionization)

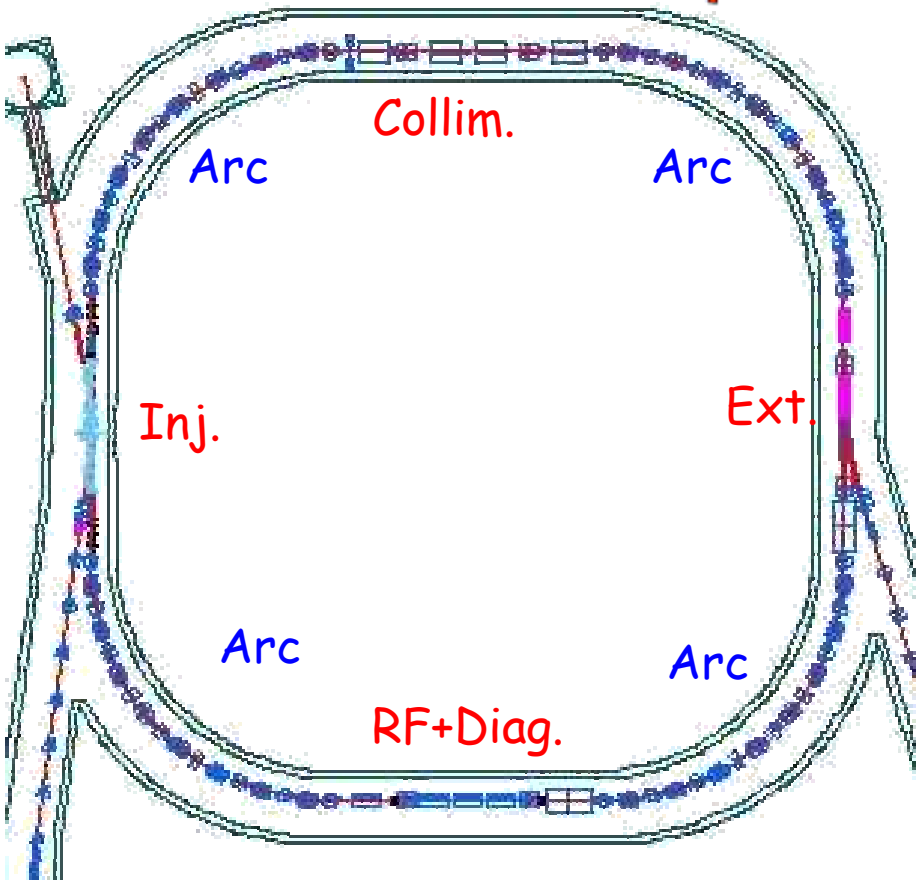
for 40%H_2/40%H_2O/20%CO

⇒ ~3x10^{-3} ionization/p.msec smaller than other source of e$^-$

TiN Coating of all chambers w/ ~100nm to reduce SEY to ≤ 1.9

Conductive coating of inj. kicker ceramic chambers (~0.04 Ω)

TiN coating of ext. kicker ferrites



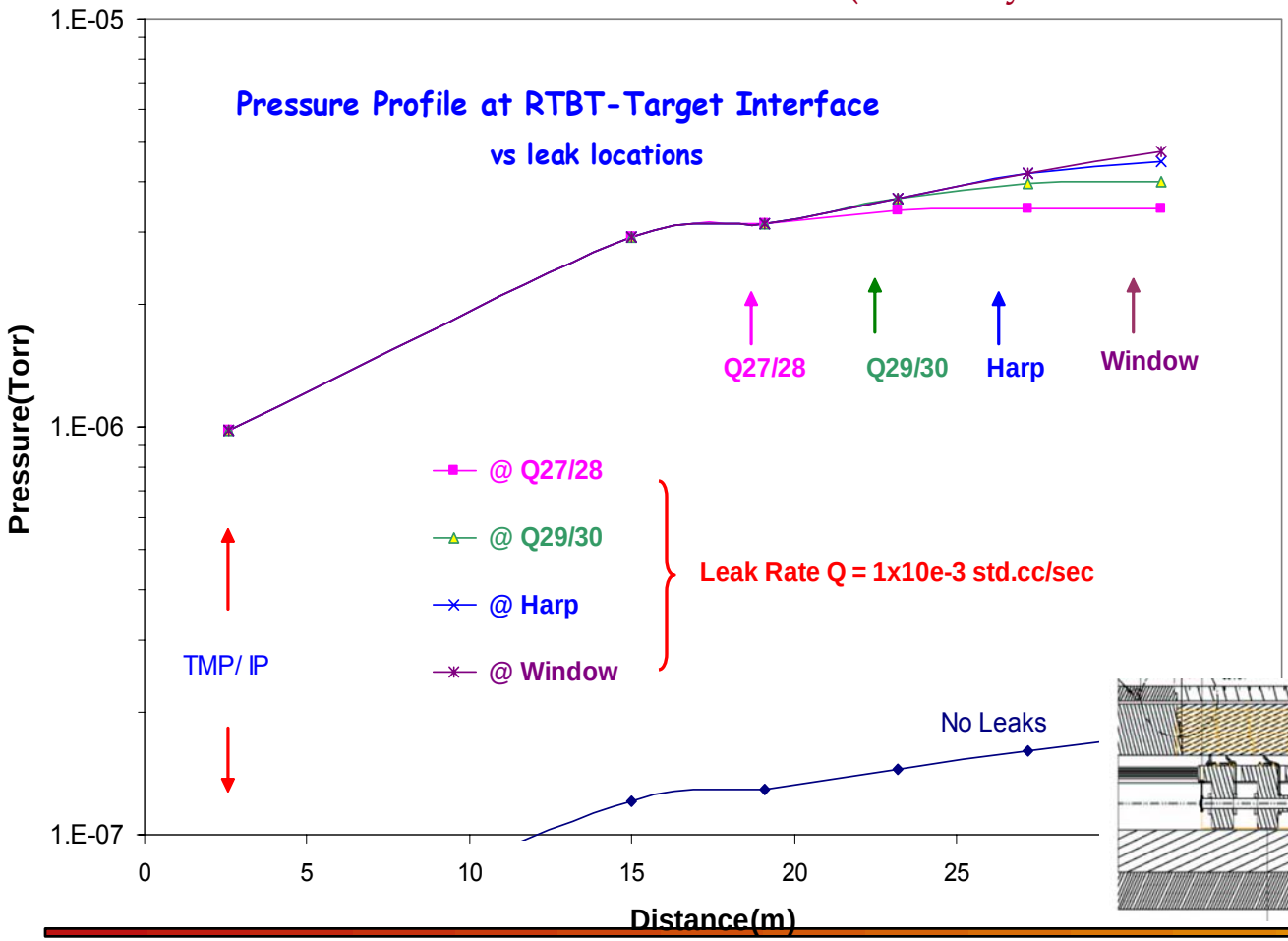
(Courtesy H. Hseuh et al)

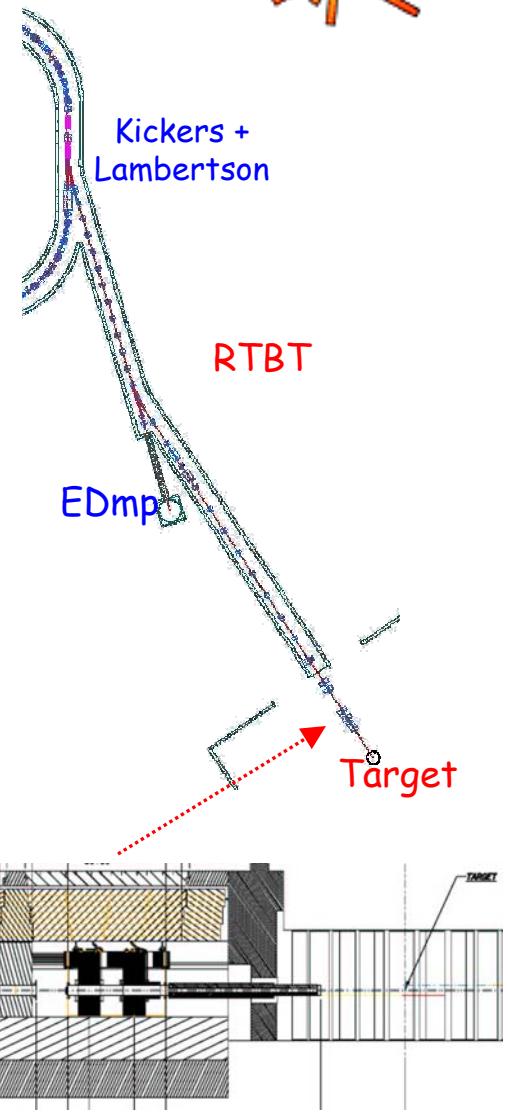
Leak check in RTBT/Target interface

Locating leaks in Target interface (Q26-Q30-target window)

No significant pressure profile due to large conductance (36cm Φ)

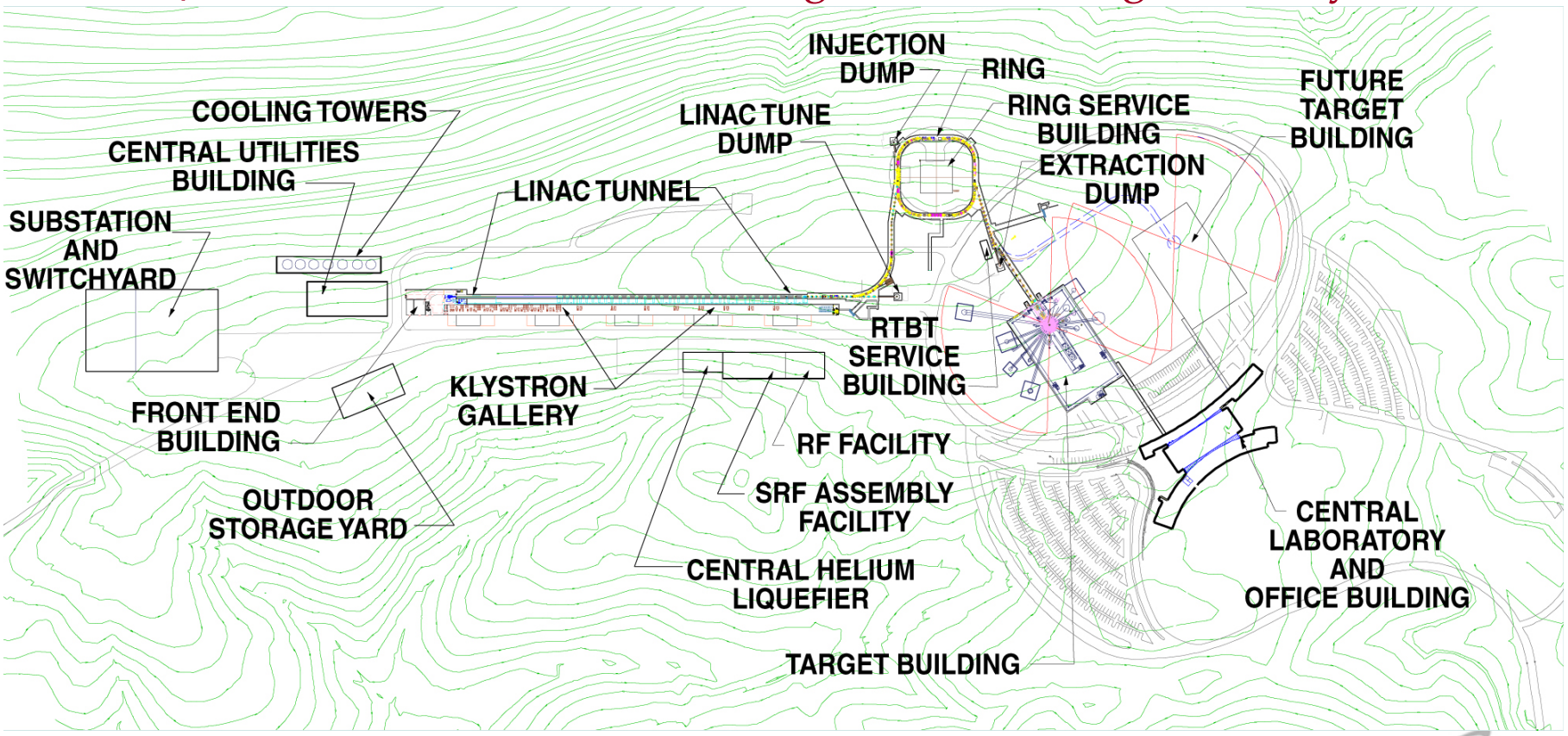
Locate leaks w/ remote He manifolds + RGA? (Courtesy H. Hseuh et al)



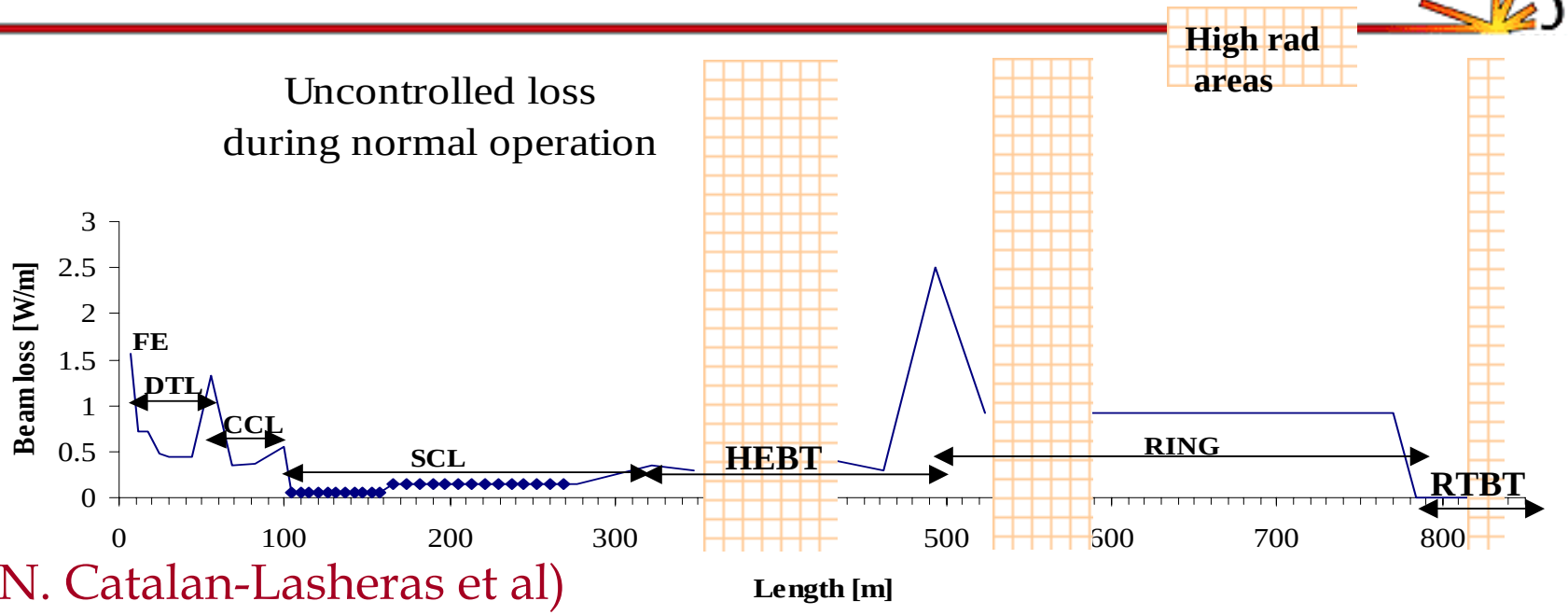


Primary concern: uncontrolled beam loss

- Minimize uncontrolled beam loss for hands-on maintenance
  - 1 Watt / meter loss of beam power
  - 1 mSv / hour (100 mrem/hour) activation level
- 1 W/m loss in linac; 10^{-3} loss in ring; >90% cleaning efficiency



Predicted SNS loss distribution



(N. Catalan-Lasheras et al)

Mechanism	Location	Fraction	Power [W/m]
Ring beam halo	collimator	1.9×10^{-3}	2,000
Excited H^0 at foil	collimator	1.3×10^{-5}	20
Energy straggling at foil	collimator	3×10^{-6}	4.5
H- magnetic stripping	injection dipole	1.3×10^{-7}	0.3
Nuclear scattering at foil	injection foil	3.7×10^{-5}	2.5
Collimator inefficiency	all ring	10^{-4}	0.9

Source of beam loss

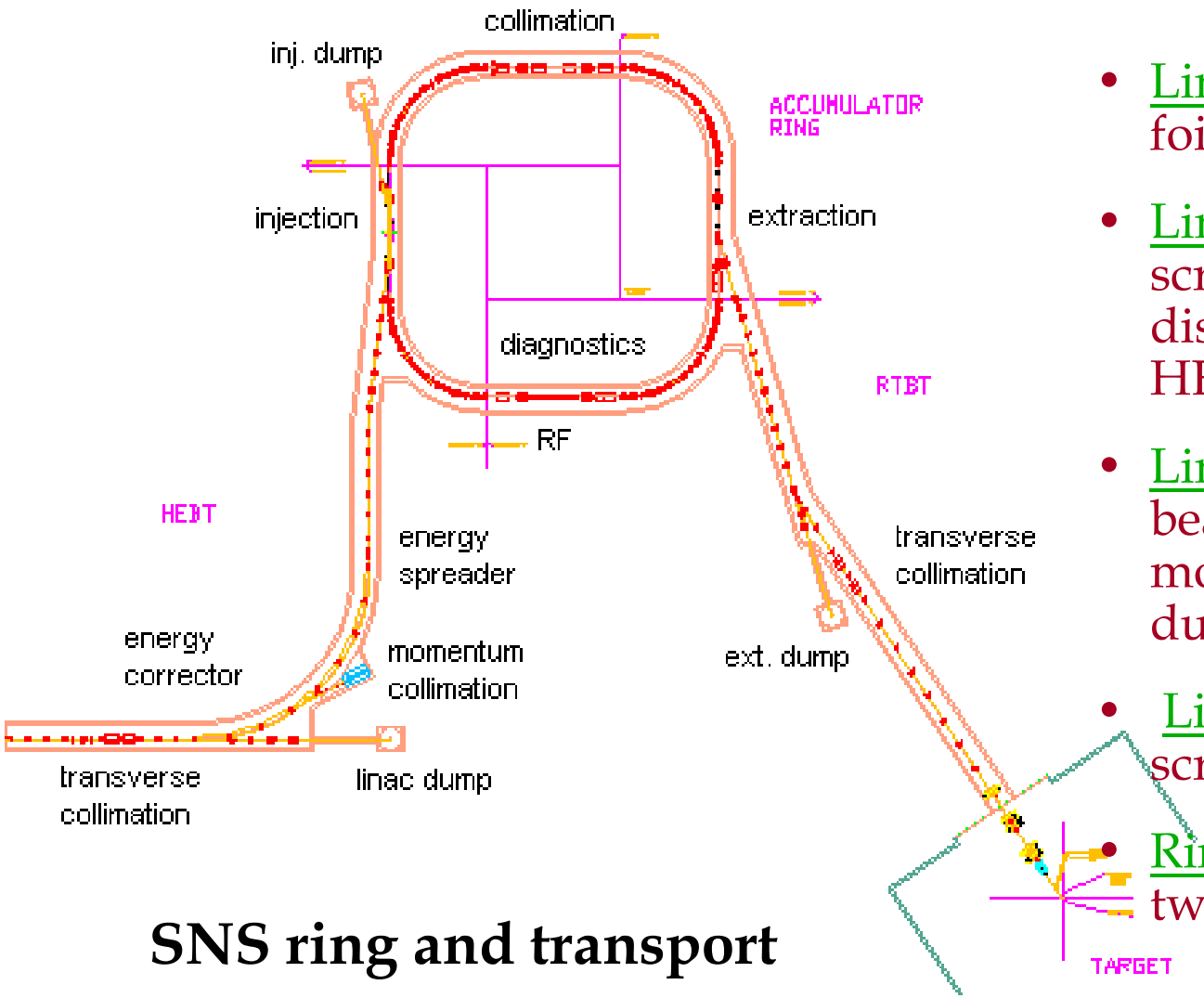
- High radio-activation at injection, extraction,collection
  - AGS: up to 10 rem/hour at localized area
- High beam loss
  - FNAL Booster (30 - 40%): ramp tracking, debunching-recapturing, transition, aperture!
  - AGS/Booster (20 – 30%): pushing record intensity
  - ISIS (~15%): injection capture, initial ramp
  - PSR (0.3% Full energy accumulation): injection loss

(1) space-charge tune shift (0.25 or larger) & resonance crossing
(2) limited geometric/momentum acceptance
(3) premature H- and H0 stripping and injection-foil scattering
(4) errors in the magnetic field and alignment
(5) instabilities (e.g., electron-cloud instability)
(6) accidental beam loss (e.g., malfunction of the ion source/linac & misfiring of ring extraction kickers)
(7) beam-halo loss during fast extraction.

Low-loss design philosophy

- Localize beam loss to shielded area
  - 2-stage collimation: HEBT, Ring, RTBT
  - 3-step beam-gap chopping/cleaning: LEBT, MEBT, Ring
- A low-loss design
  - Matching between linac structures; space charge effects
  - Resonance minimization; Magnet field compensation & correction
  - Proper lattice design with adequate aperture & acceptance
  - Injection painting; Injection & space-charge optimization
  - Impedance (extraction kicker) & instability control (e-p)
- Flexibility:
  - Adjustable energy (+/- 5%), Variable tunes (H 1 unit, V 3 units), flexible 3-D injection painting; adjustable collimation; foil interchange
- Accident prevention:
  - Design redundancy: immune to front end, linac & kicker errors

Normal & fault condition protection



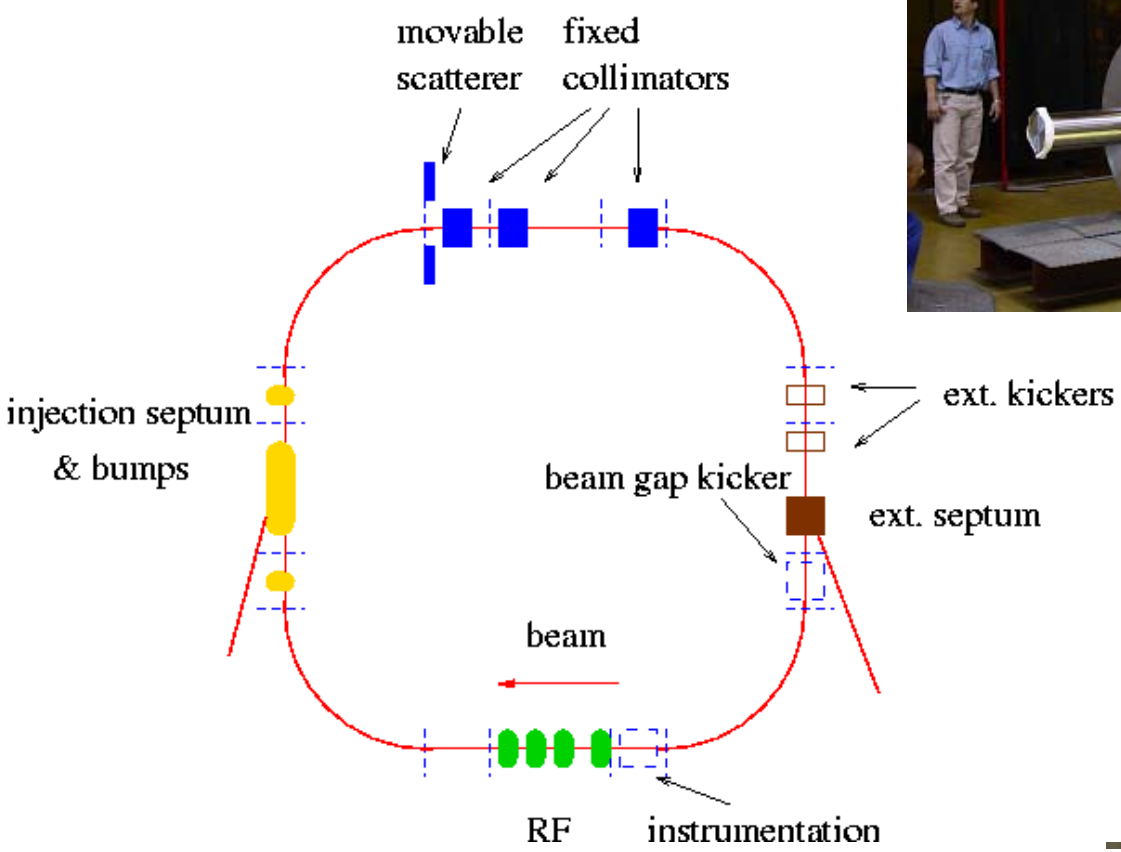
SNS ring and transport

- Linac halo: adjustable foil scraper in HEBT
- Linac energy tail: scraping at high-dispersion location in HEBT
- Linac gap residual: beam-in-gap kicker or momentum collection during initial ramping
- Linac malfunction: scraper in HEBT
- Ring halo: two-stage collimation

Beam-loss localization

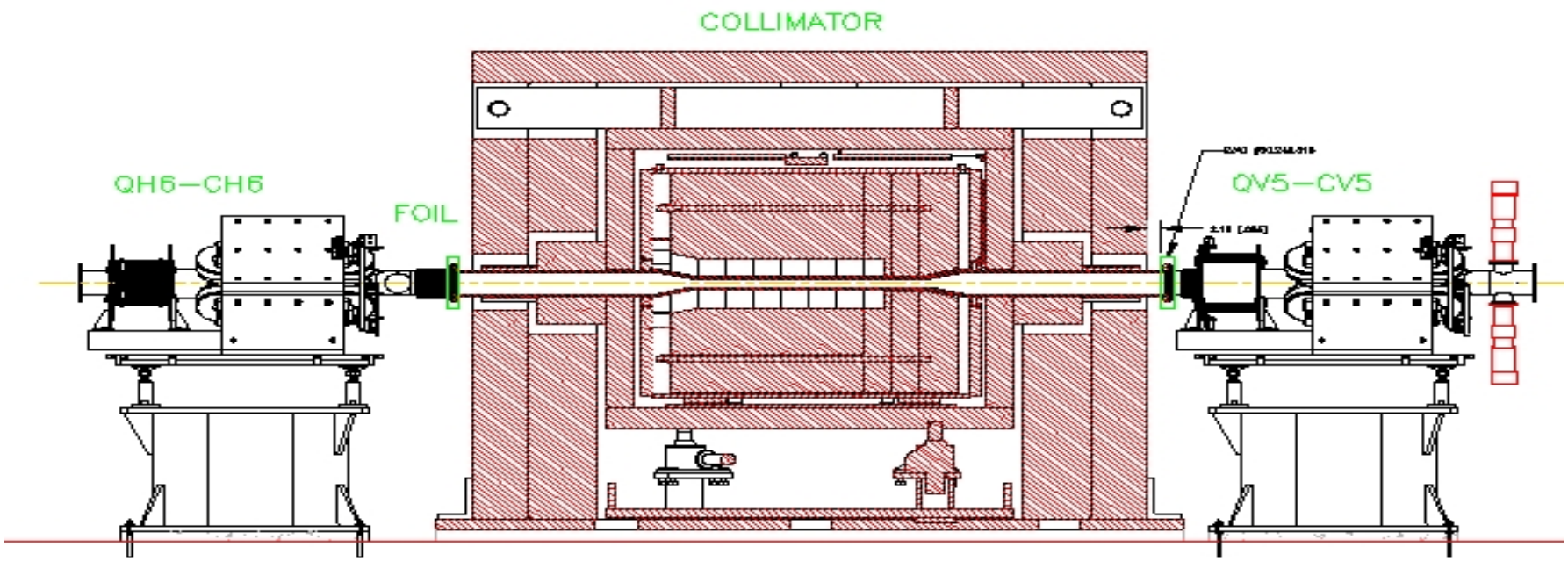
- "Sacrifice" collimation region for the rest
- Two-stage system, efficiency above 90%
- Needs a large vacuum-pipe aperture and a long straight section

(Courtesy H. Ludewig et al)



Secondary collector design

- Length enough to stop primary protons (~ 1 m for 1 GeV beam)
- Layered structure (stainless steel particle bed in borated water, stainless steel blocks) to shield the secondary (neutron, γ)
- Fixed, enclosing elliptical-shaped wall for operational reliability
- Double-wall Inconel filled with He gas for leak detection

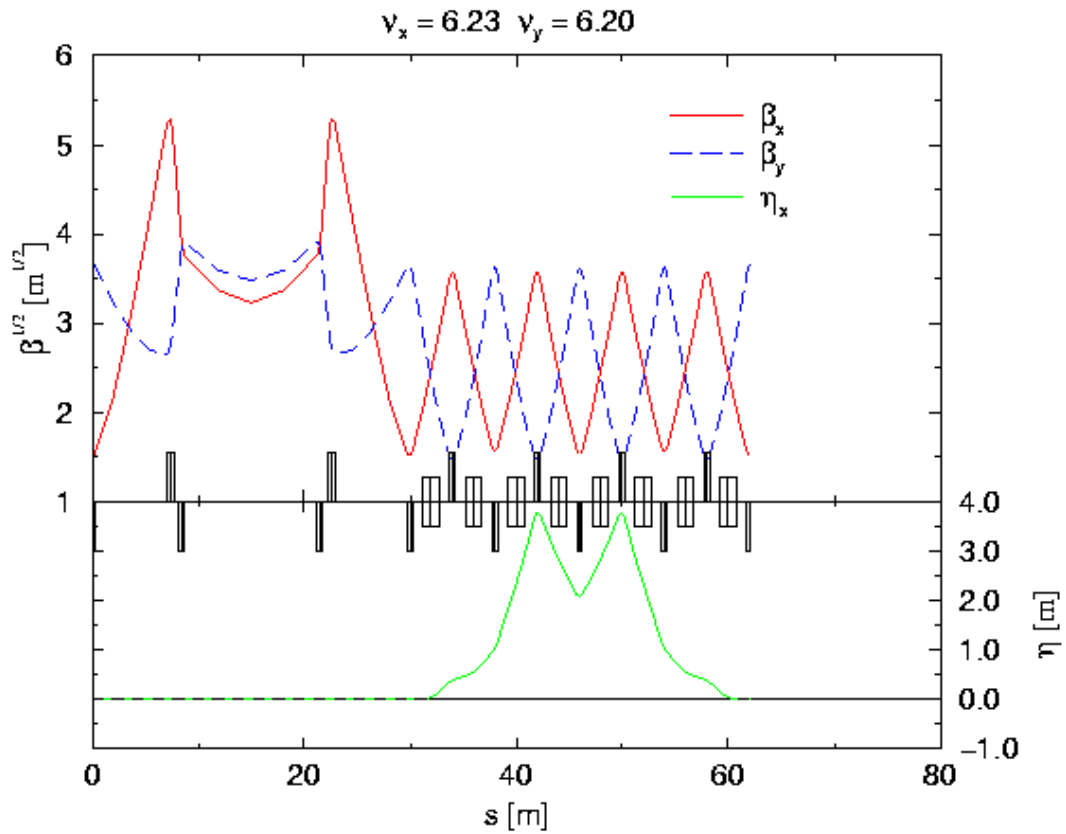


Ring Lattice
FODO arcs & doublet straights

- Matched, hybrid lattice
  - FODO arc:

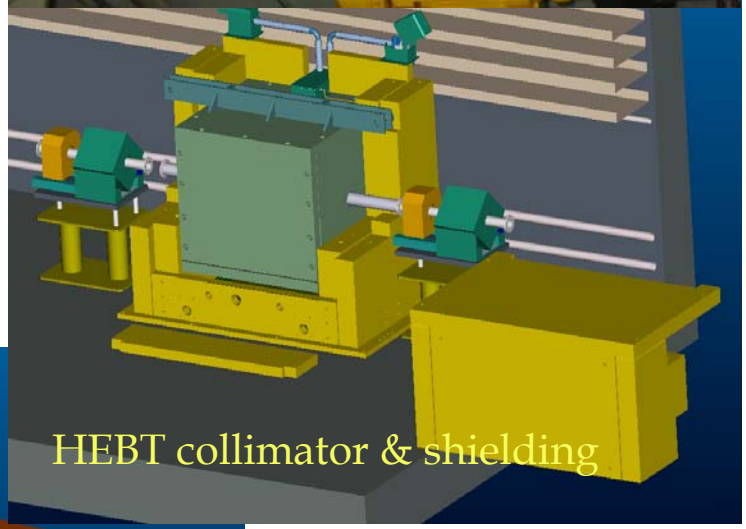
    easy-to-implement correction system, moderate magnet strength
  - Doublet straight:

    long, uninterrupted straight
    - » Improved collimation efficiency
    - » Robust injection
- Zero-dispersion injection
  - Independent painting in the transverse & longitudinal directions

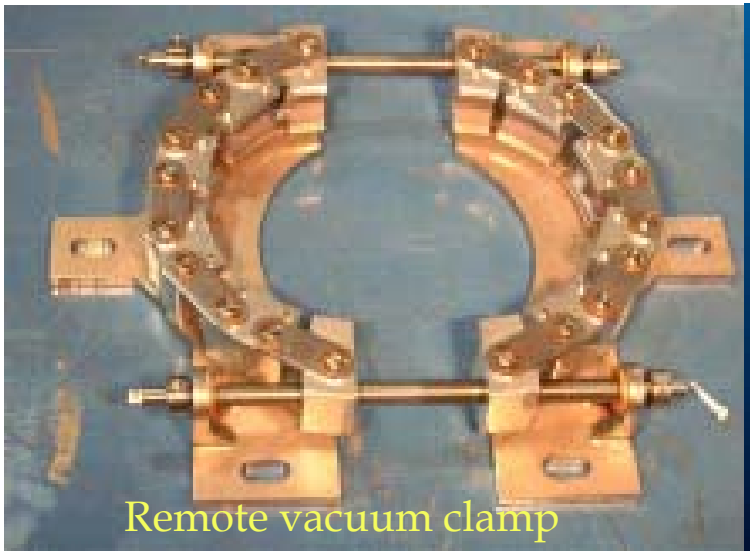


Remote handling

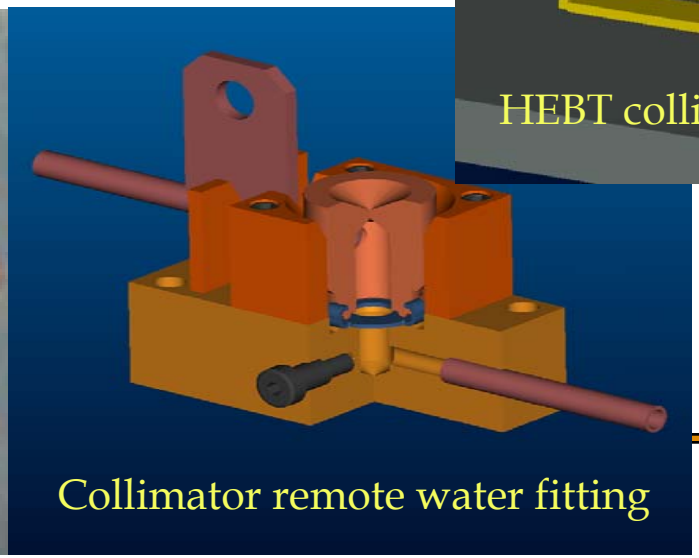
- Overhead, around-the-ring crane
- Quick handling fixtures incorporated into shielding/absorber design
- Remote vacuum clamps; remote water fittings
- Passive dump window & change mechanism



HEBT collimator & shielding



Remote vacuum clamp



Collimator remote water fitting

(Courtesy
G. Murdoch et al)

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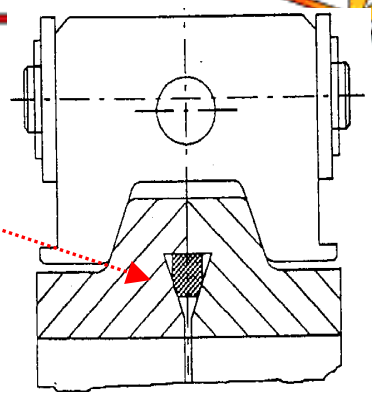
Quick disconnect flanges, clamps & seals

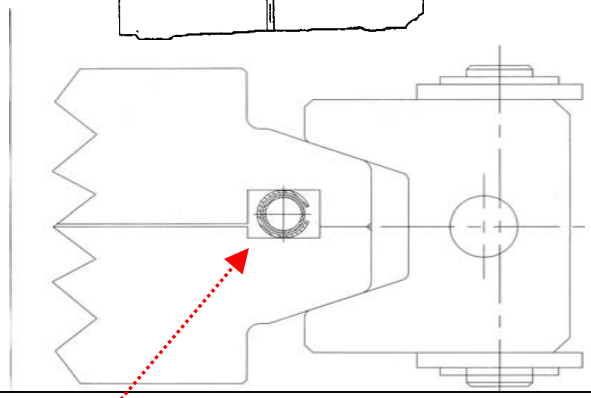
<250mm Φ w/ CFX Flanges/ Chain

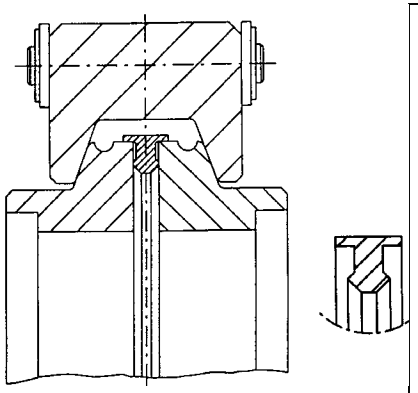
- Durable Cu seal, SS Chain
- No knife edge on seal or flanges
- Medium sealing torque 62 ft-lbs
- ~ 3mm gap for seal insertion
- ~ 5 minute assembly by one person
- Moderately heavy chain ~ 22 lbs



(Courtesy H. Hseuh et al)

Gaols: Reliable, ease of assembly, light weight, low torque, cost





250mm to 360mm Φ w/ Al diamond

- Seal w/ knife edge, Al Chain ~ 8 lbs
- Low sealing torque 22 ft-lbs
- ~ 6mm gap for seal insertion
- Moderately difficult for one person
- ~ 5 minute assembly time
- Flange surface & seal may be damaged

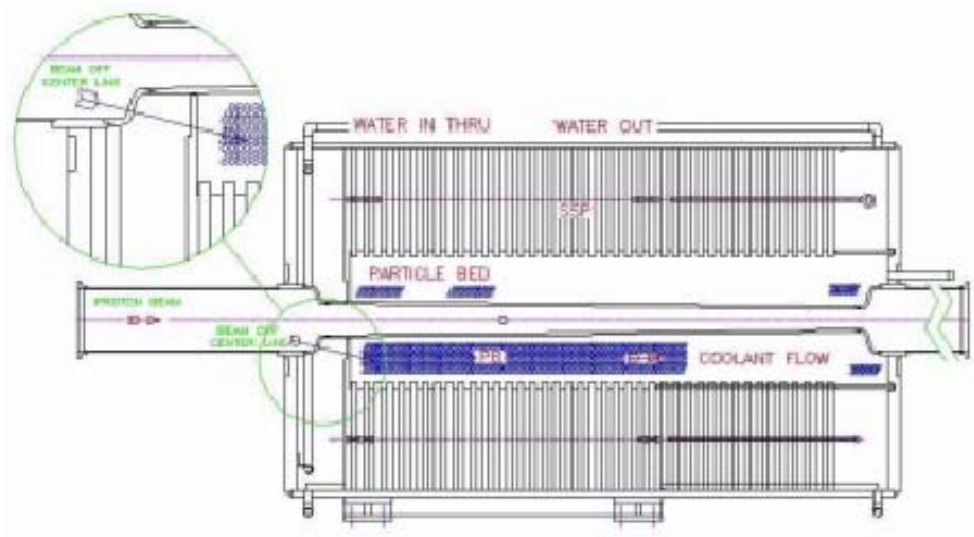
250mm to 360mm Φw/Helicoflex Seal

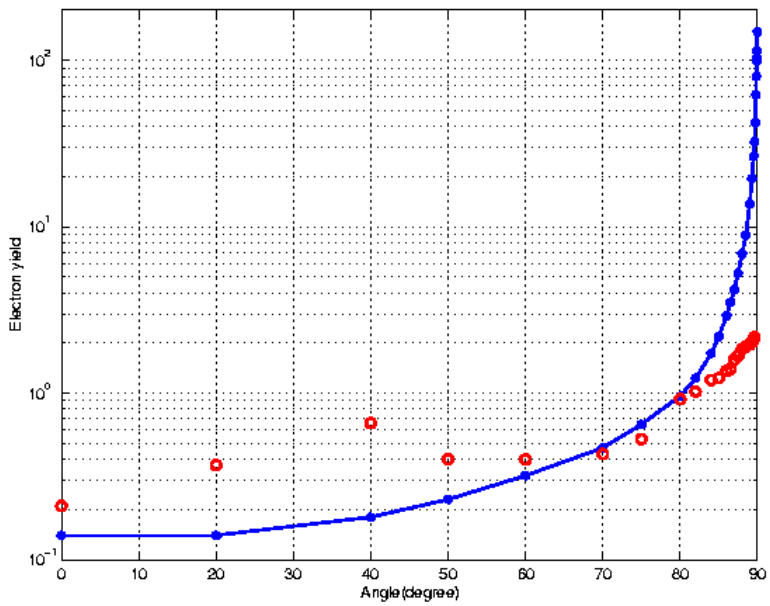
- Diamond gasket w/ internal springs
- Flange has O-ring groove
- Low sealing torque 20 ft-lbs
- ~ 6mm gap for seal insertion
- Easy assembly by one person
- ~ 4 minute assembly time
- Light weight Al chain

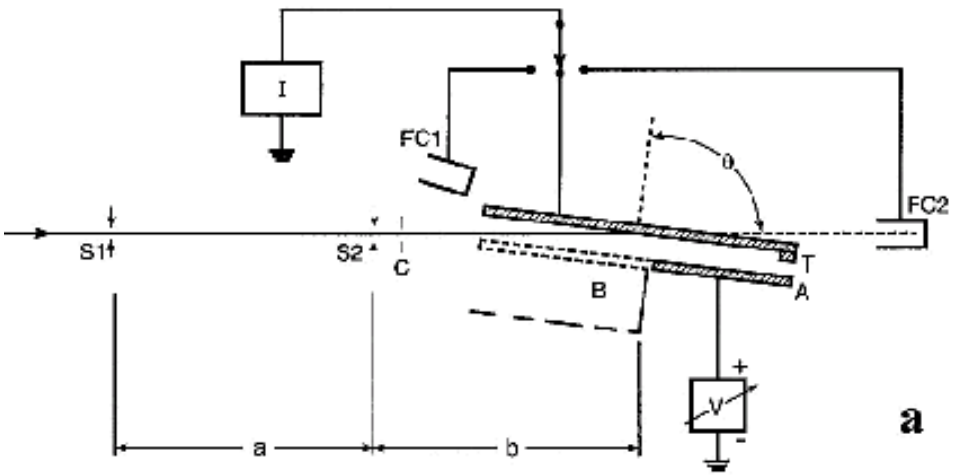
Major sources of electron cloud

- Proton beam loss, especially at a shallow grazing angle
- Stripped & scattered electrons
- Gas ionization
- Beam-driven multipacting

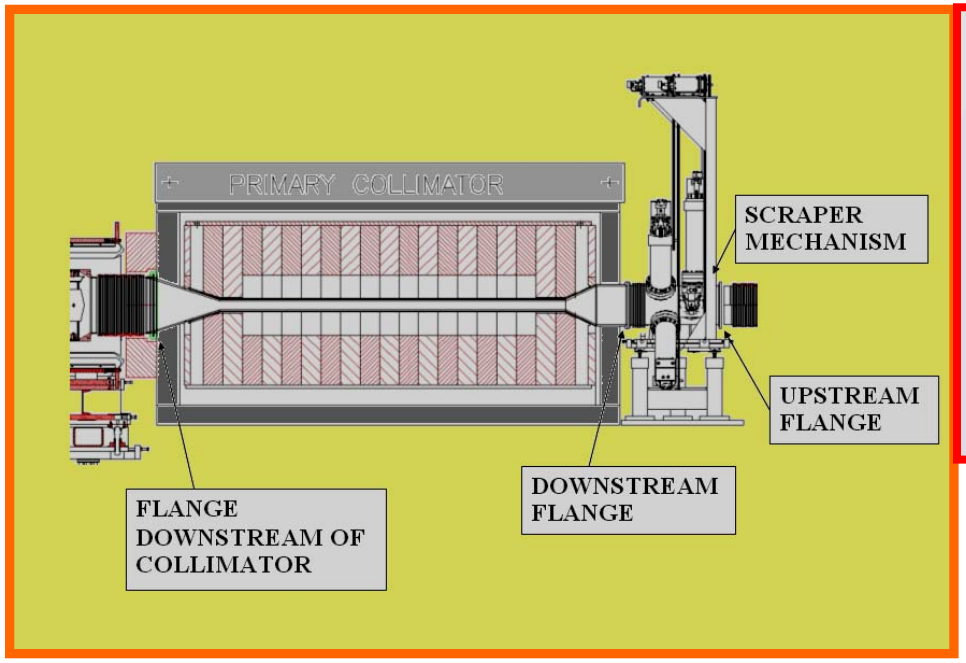
(courtesy P. Thieberger et al)

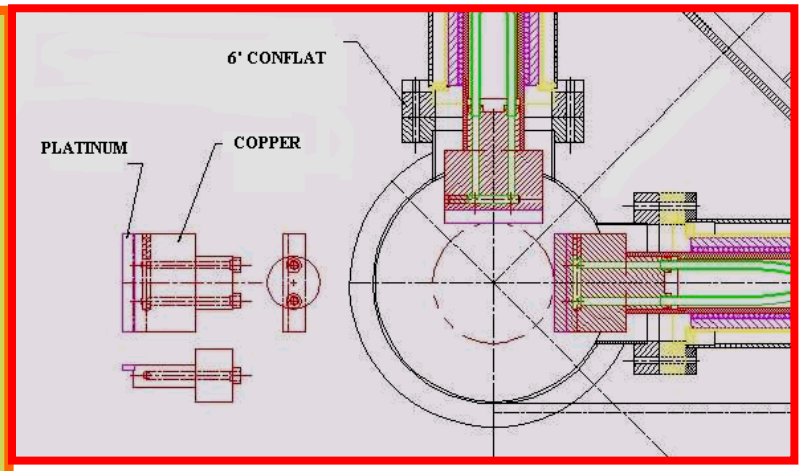






Electrons from collimator surface





(courtesy H. Ludewig, N. Simos)

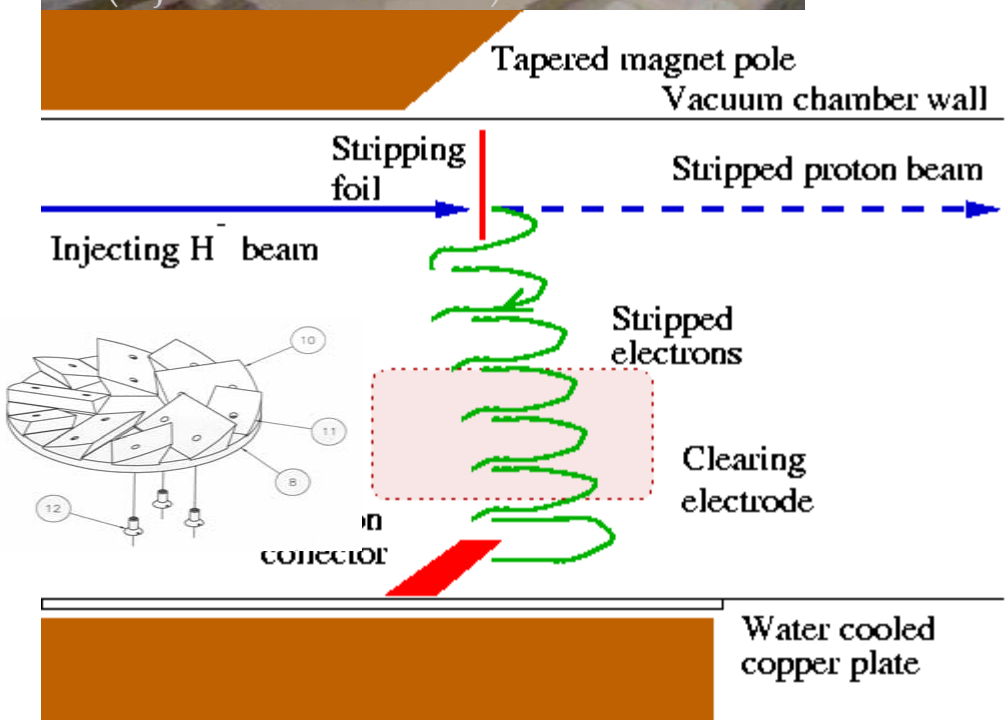
- Designed to absorb 2 – 10 kW (0.1% -- 0.5%) proton beam loss
- Possible saw-tooth surface complicated by proton stopping distance

→ Rely on two-stage collimation for a large impact distance

→ Use clearing solenoids

Stripped electrons

(Meng, Jackson, Brodowski, Lee, Abell …)



- 2 kW of stripped electrons must be properly collected
- Carbon-Carbon block on water-cooled Cu plate; reduced backscattering
- Window/video monitor
- Tapered magnet ends
- Dedicated clearing electrode (10 kV)

Ionization and desorption

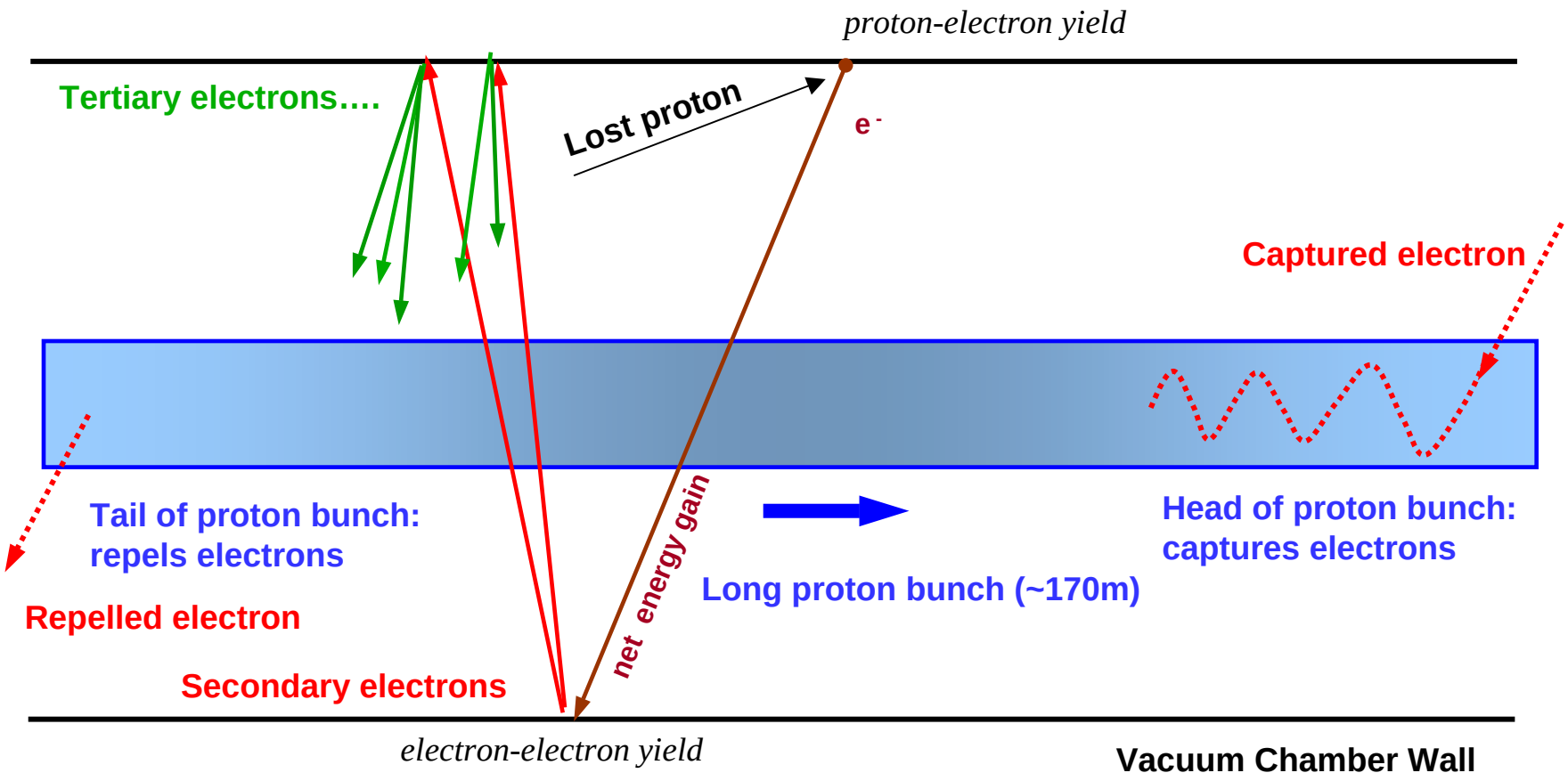
- Electron production due to ionization is proportional to vacuum pressure, average beam current, and ionization cross section

$$\frac{d^2\lambda_e}{dtds} = \frac{\rho_m \beta I \sigma_{ion} P}{e}$$

  - Molecular density ρ_m=3.3x10^{22} m^{-3} at 300 K
  - Ionization cross section σ_{ion}=2 Mbarn = 2x10^{-22} m^2
  - Pressure P [Torr]

- Rate of ion or electron desorption is proportional to the number of ion or electron hitting surface – resulting in pressure run-away

Beam-induced multipacting



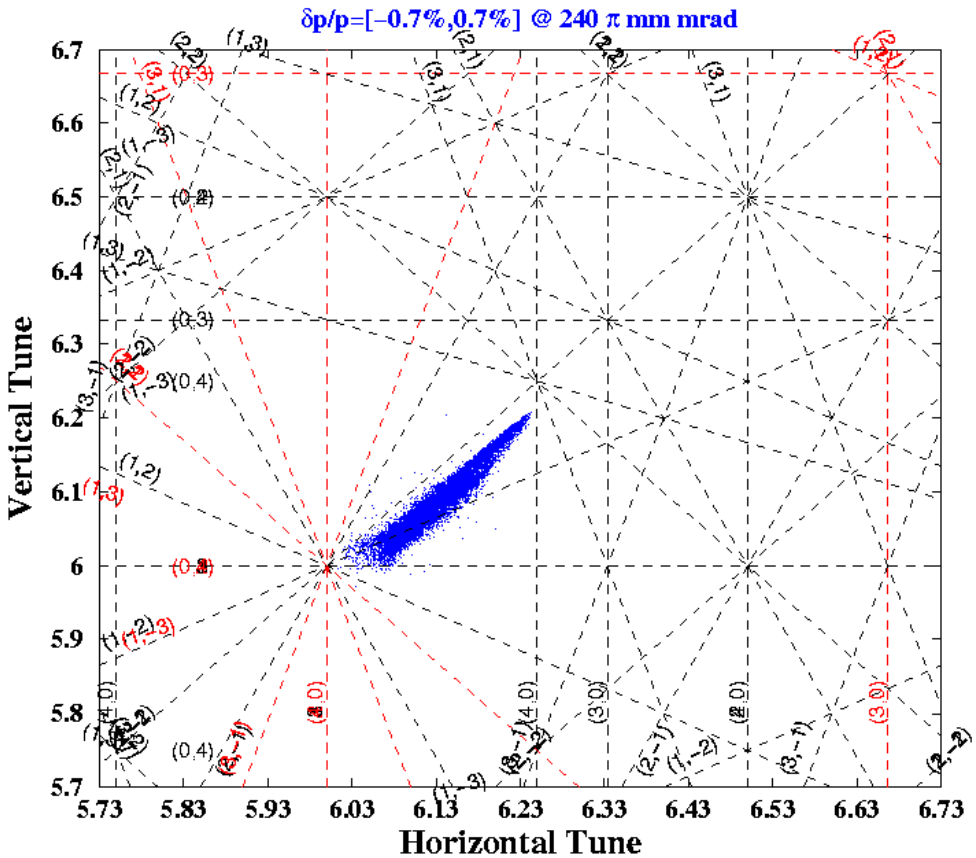
(R. Macek, D. Danilov, M. Furman, M. Pivi …)

Effects of electron clouds in SNS Ring

- Electron neutralization, tune shifts, and resonance crossing
- Transverse (horizontal or vertical) instability
- Associated emittance growth and beam loss
- Vacuum pressure rise
- Heating & damage of vacuum chamber
- Interferences with diagnostics system

Tune-shift & the Pacman effect

$$\Delta\nu_{x,y} = -\frac{f_{sc} N r_p R_0}{2\pi B_f \nu_{x,y} \beta^2 \gamma}\left(\frac{1}{\sigma_{x,y}(\sigma_x+\sigma_y)}\left(\frac{1}{\gamma^2}-\eta_e\right)+A_{image}\right)$$



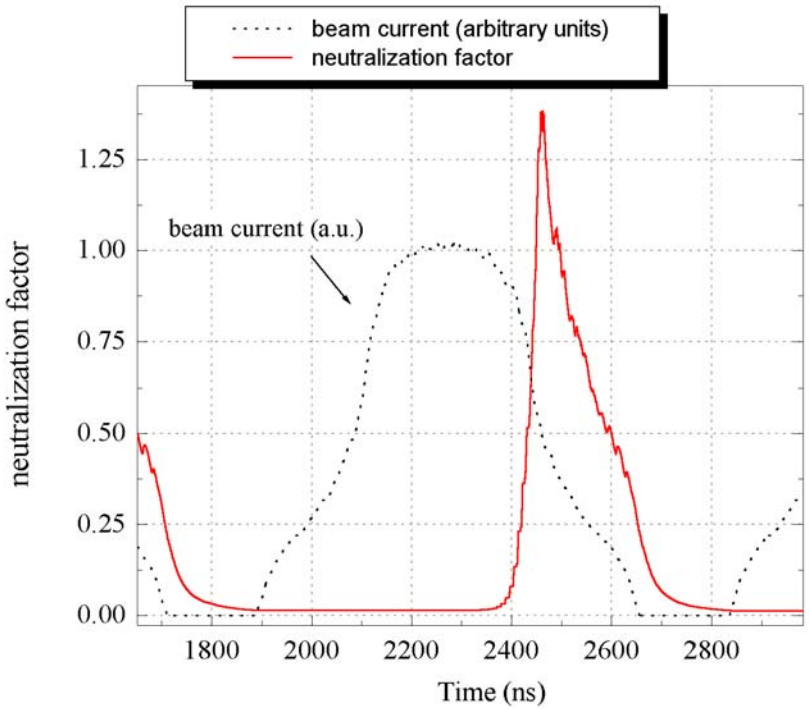
(courtesy A. Fedotov)

- Electron neutralization causes positive tune shifts on trailing-edge particles
- For given space-charge tune spread at injection (typically 0.2), the electron tune-shift if enhanced by factor γ^2 -- may be important at a high injection energy
- May keep on losing trailing-edge particle upon resonance crossing – the Pacman effect
- Require detailed evaluation of neutralization level in proton beam

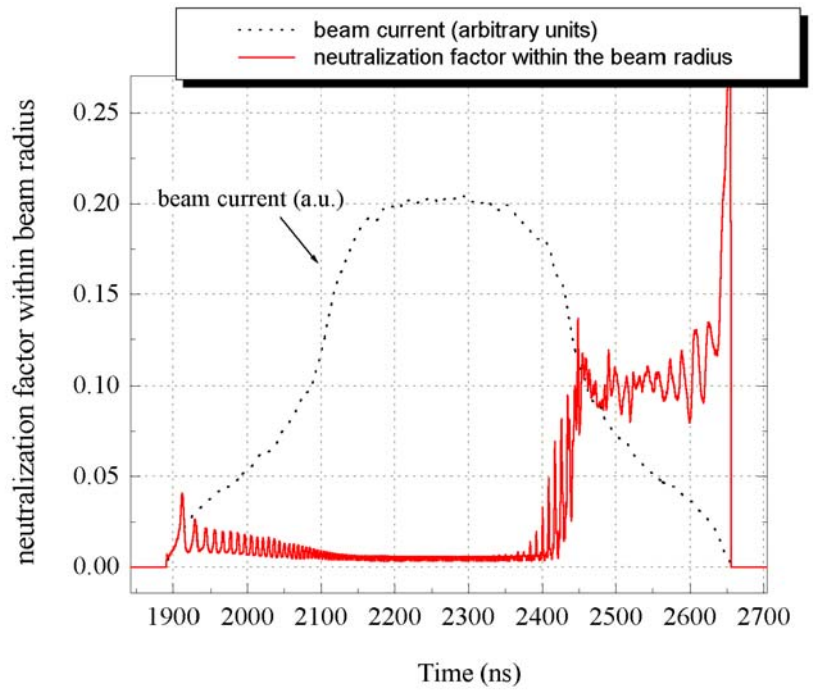
Simulation of electron production

(courtesy M. Pivi, M. Furman)

within vacuum pipe



within beam



- SNS: electron-cloud tune-shift ~ 0.4 $\eta_{e,peak}$: +0.04 (~ 0.4?)

Mitigation measures

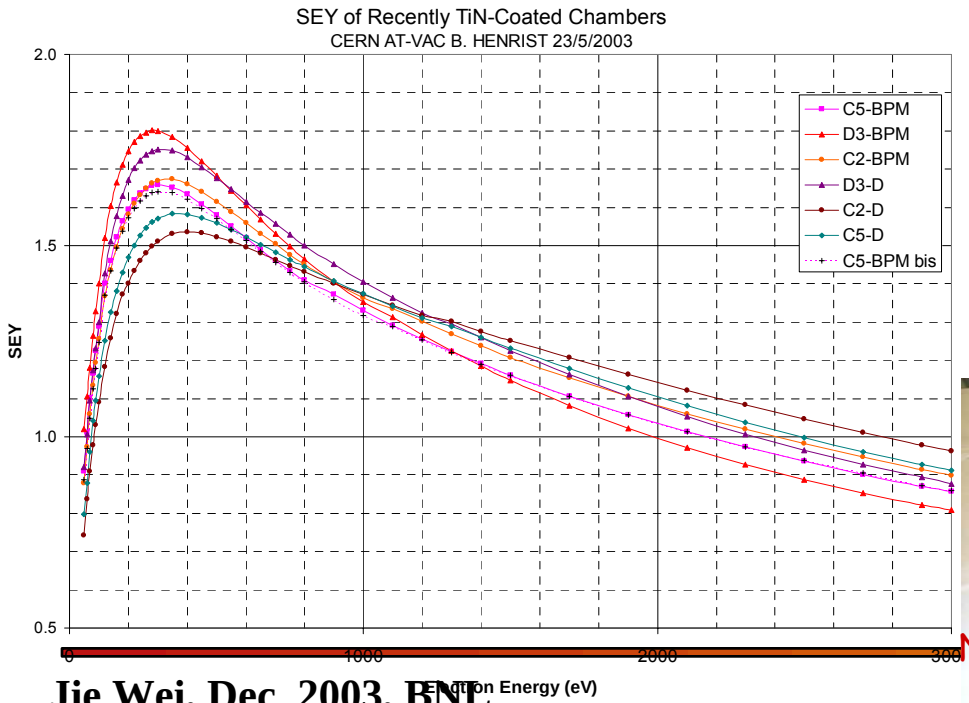
- Suppress electron production
  - Tapered magnets for electron collection near injection foil; back-scattering prevention
  - TiN coated vacuum chamber to reduce multipacting
  - Striped coating of extraction kicker ferrite (TiN)
  - Beam-in-gap kicker to keep a clean beam gap (10^{-4})
  - Good vacuum (5×10^{-9} Torr or better)
  - ports screening, step tapering; BPMs as clearing electrodes
  - Install electron detectors around the ring
  - Two-stage collimation; winding solenoids in the straight section
- Enhance Landau damping
  - Large momentum acceptance with sextupole families; high RF voltage; momentum painting
  - Inductive inserts to compensate space charge
  - Reserve space for possible wide band damper system

Surface coating

(Hseuh, He, Todd, Hilleret, Sato …)

SEY of SNS coating samples measured by CERN & KEK

- SEY of SS > 2.5
- TiN coated at low pressure ~ 1.9 – 2.2
- TiN coated at high pressure ~ 1.5 – 1.8



Goal: low SEY, good adhesion and low outgassing Q

Use Magnetron DC with permanent magnets

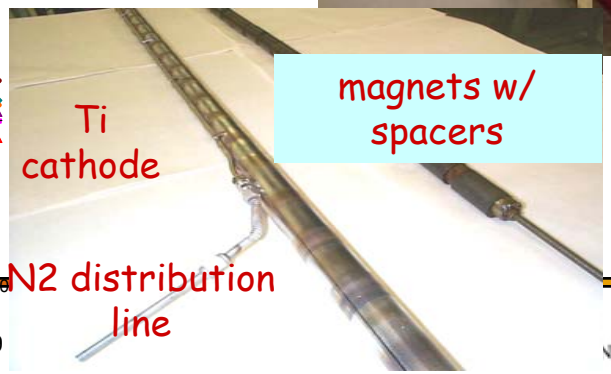
higher sputtering rate due to dense plasma

Bake & coat @ 250 C to ~ 100 nm of TiN

to minimize impurity & improve adhesion

Need uniform gas flow along the length

to get correct stoichiometry (0.95 – 1.03)



Jie Wei, Dec. 2003, BNL

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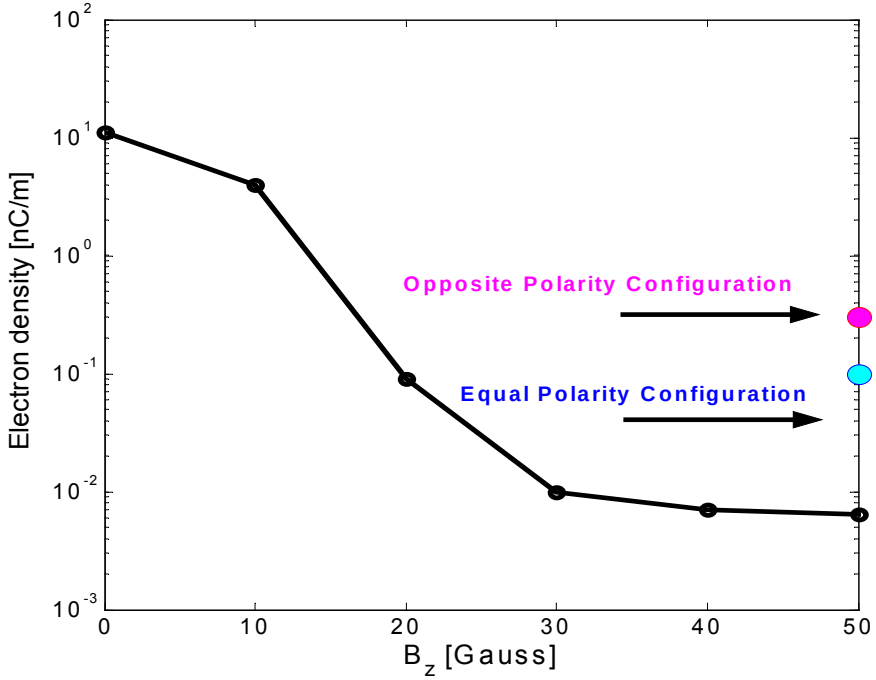
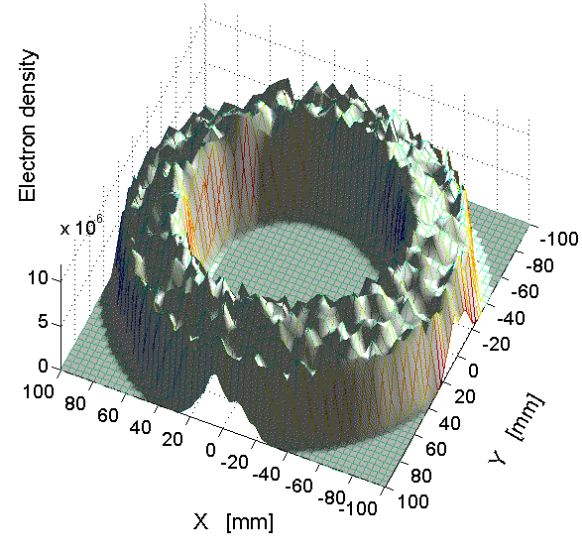
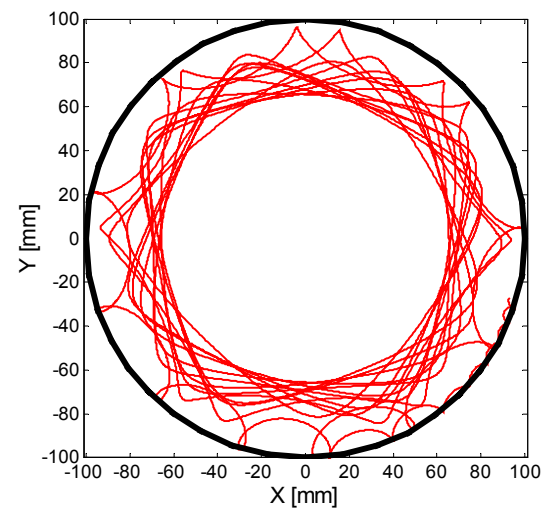
Electron-confining solenoids

- Using solenoids to reduce electron multipacting in straight sections (collimation section)
- Efficiency studied

(courtesy L. Wang)



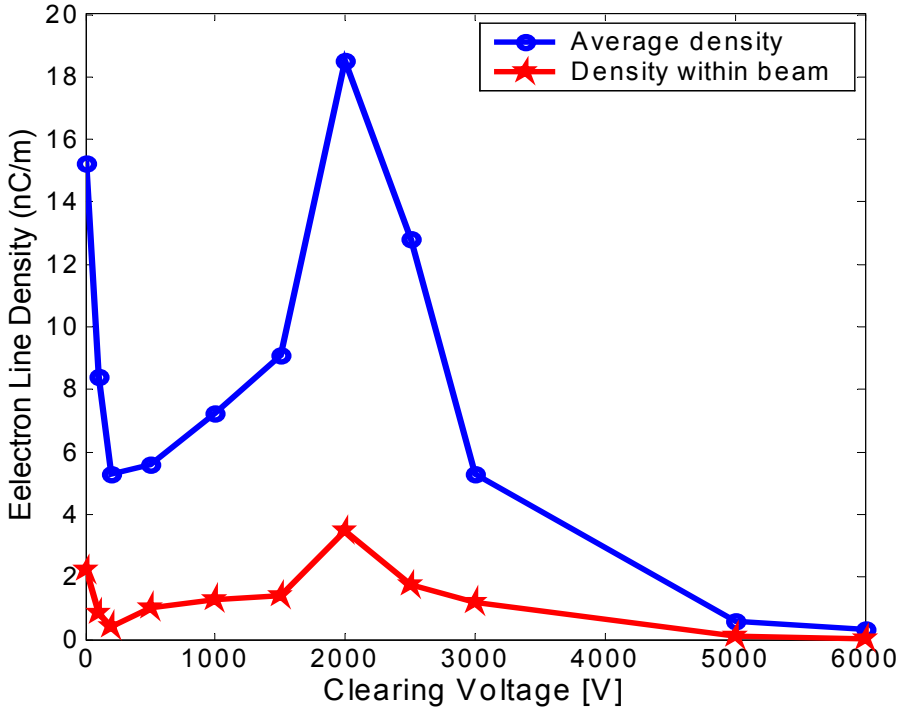


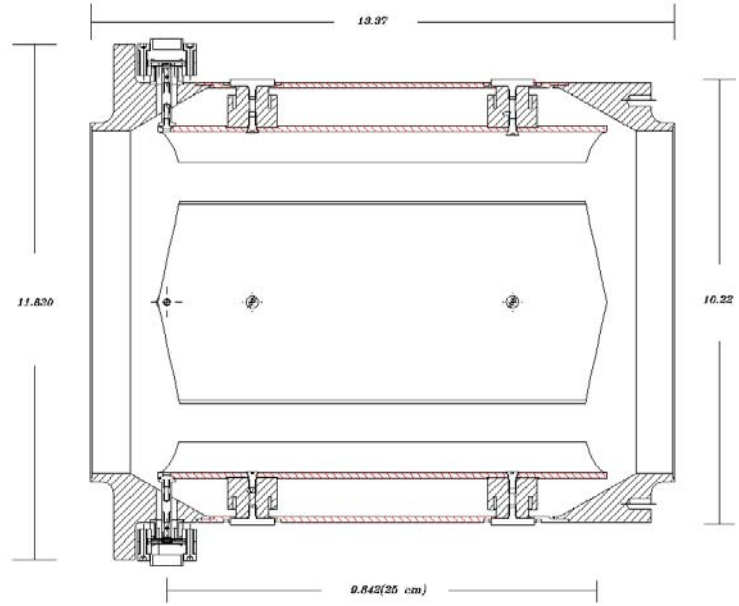


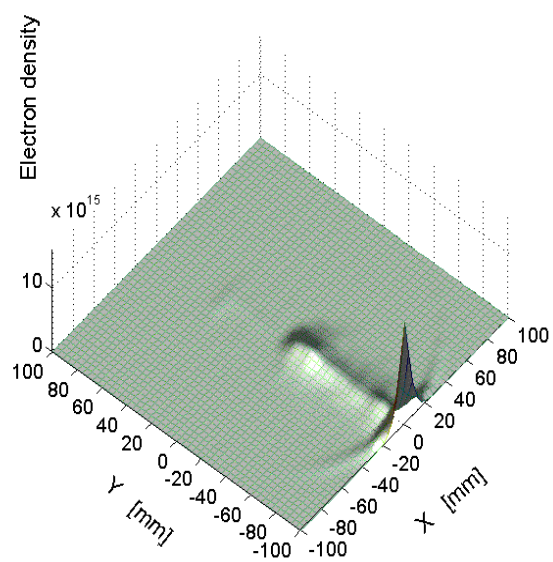
Clearing electrodes

- Under strong beam potential (~10 kV), how does weak clearing field perform?
- Floating-ground BPM serve as clearing electrodes (up to +/- 1 kV)
- Dedicated electrode (10 kV) at injection

(courtesy L. Wang, P. Cameron)







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Summary

- In a high-intensity ring like SNS, beam loss is of primary concern. Multi-location, two-stage beam collimation plays a crucial role
- Electron cloud is one of the intensity limiting mechanisms at the SNS ring. Mitigation measures like surface coating, solenoid confinement, and electrode clearing are expected to be highly effective