# *Construction Status and Issues of the* Spallation Neutron Source Ring

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**for the Spallation Neutron Source Collaboration**

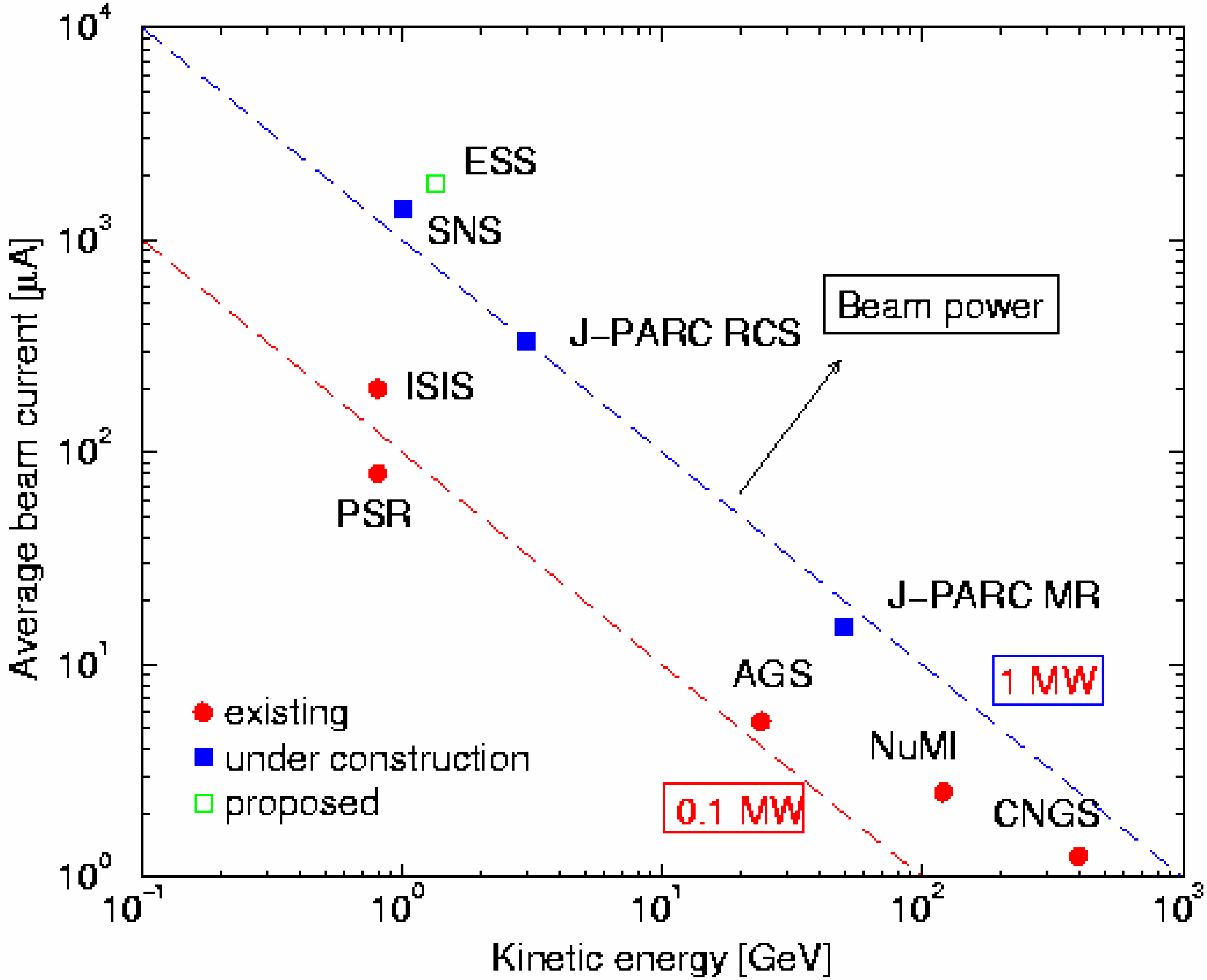
**Talk at EPAC'04, Lucerne, Switzerland**

**July 5 - 9, 2004**

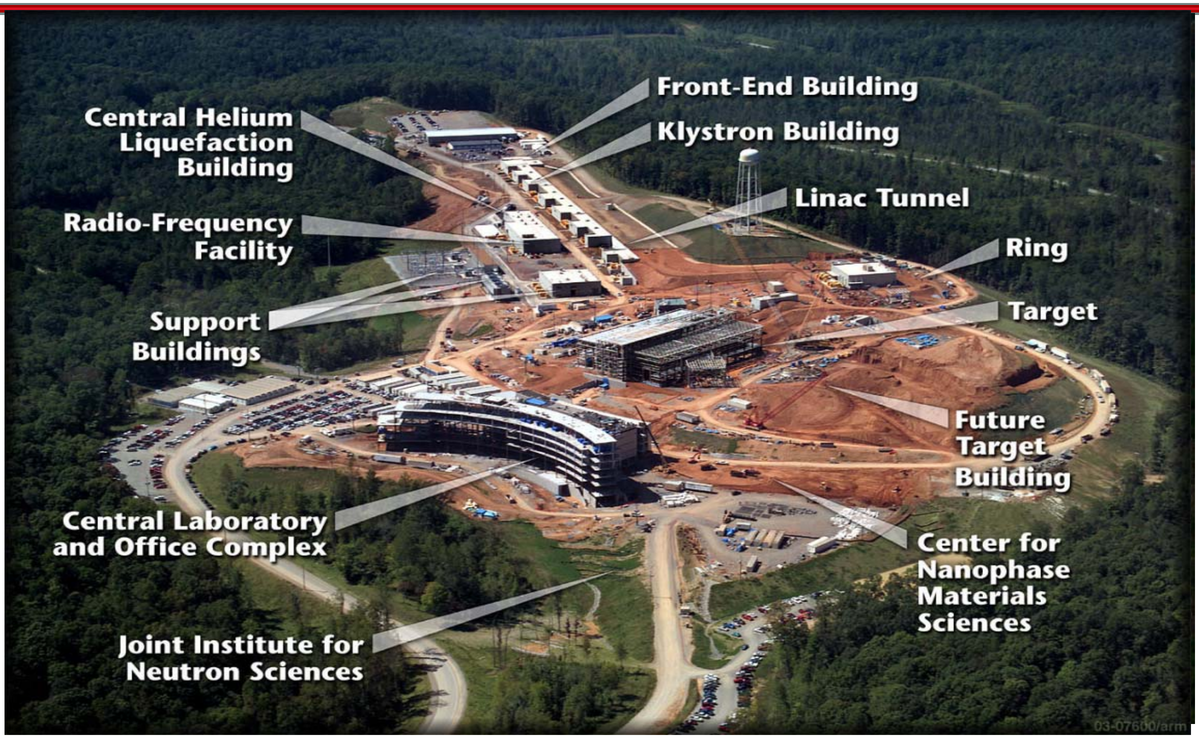
# Outline

- Introduction
- Accumulator ring design summary
  - Favorable design decisions
  - Debatable design decisions
- Engineering status, issues & solutions
  - Magnet post-vendor iterations (shimming, sorting …)
  - Injection trail assembly (mechanical interferences,
  - Collimation and remote handling, target back-shine
  - Extraction, kicker impedance, RF
  - Vacuum, chamber coating, electron cloud mitigation
  - Diagnostics and instrumentation, infra-structure matching
- Summary

# Accelerators at the Power frontier

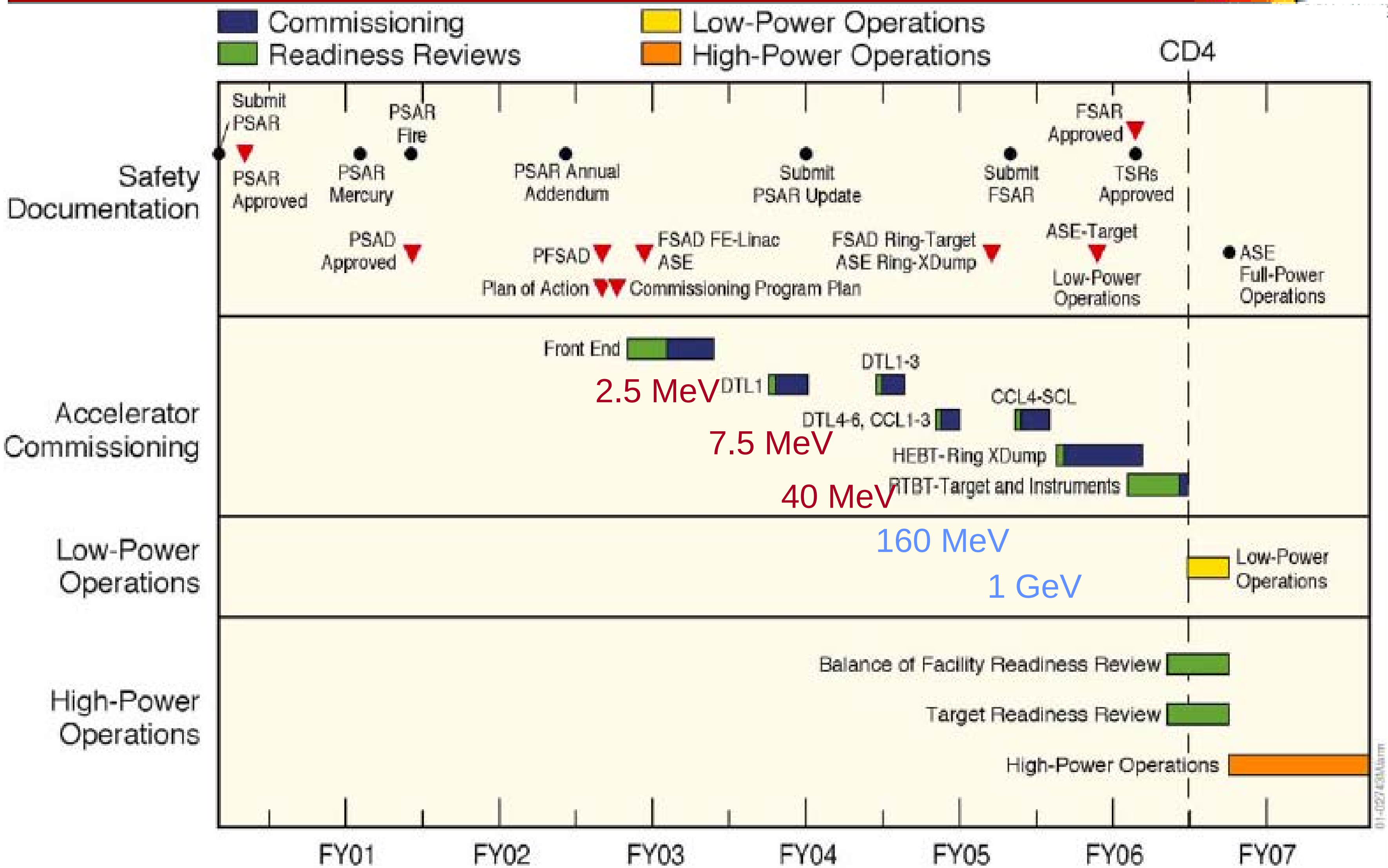


# Spallation Neutron Source complex




- Under construction at Oak Ridge, Tennessee, U.S.
- Collaborated by 6 labs (LBNL, LANL, JLab, BNL, ORNL, ANL)
- Brookhaven National Laboratory is responsible for the design & construction of Ring & Transports

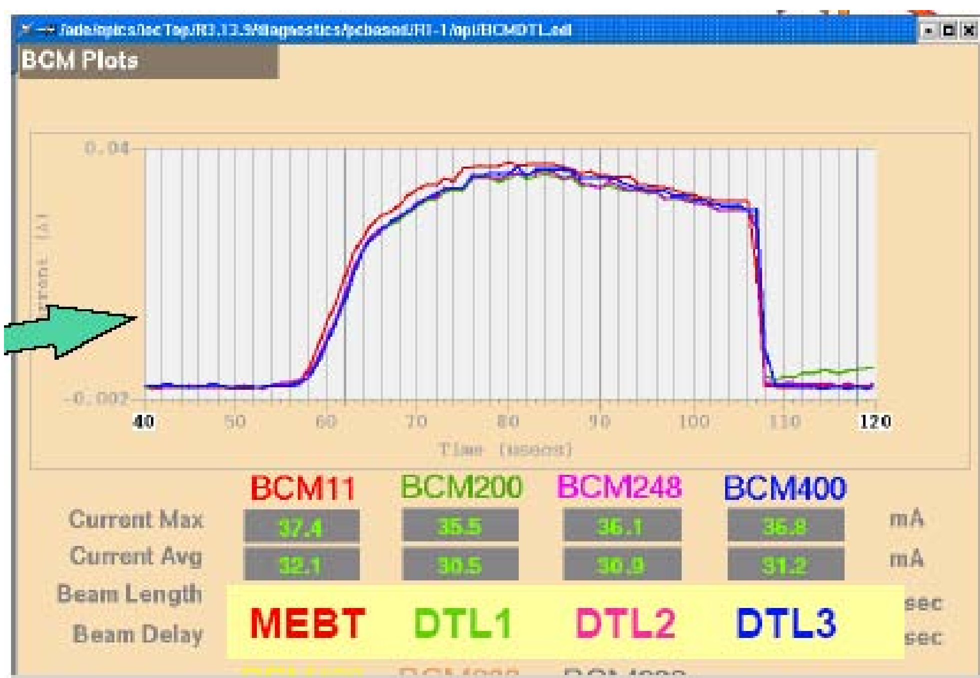
# SNS commissioning at ORNL

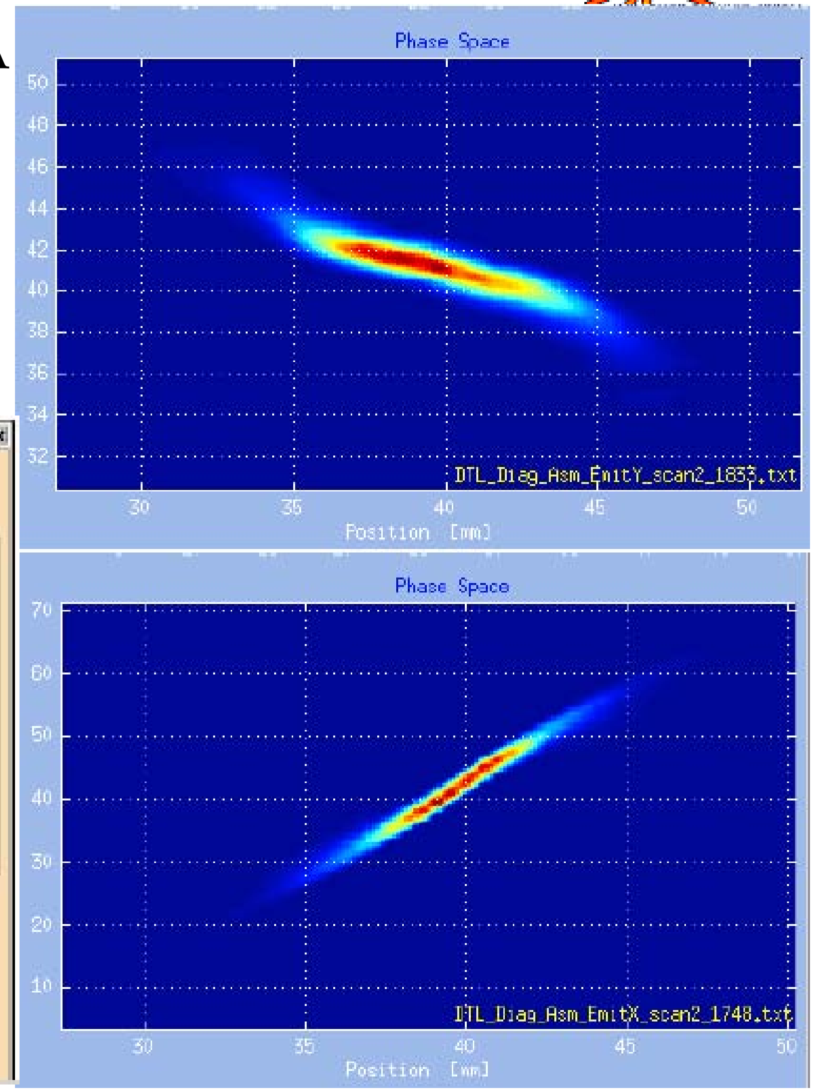


# Drift-tube-linac 1-3 results

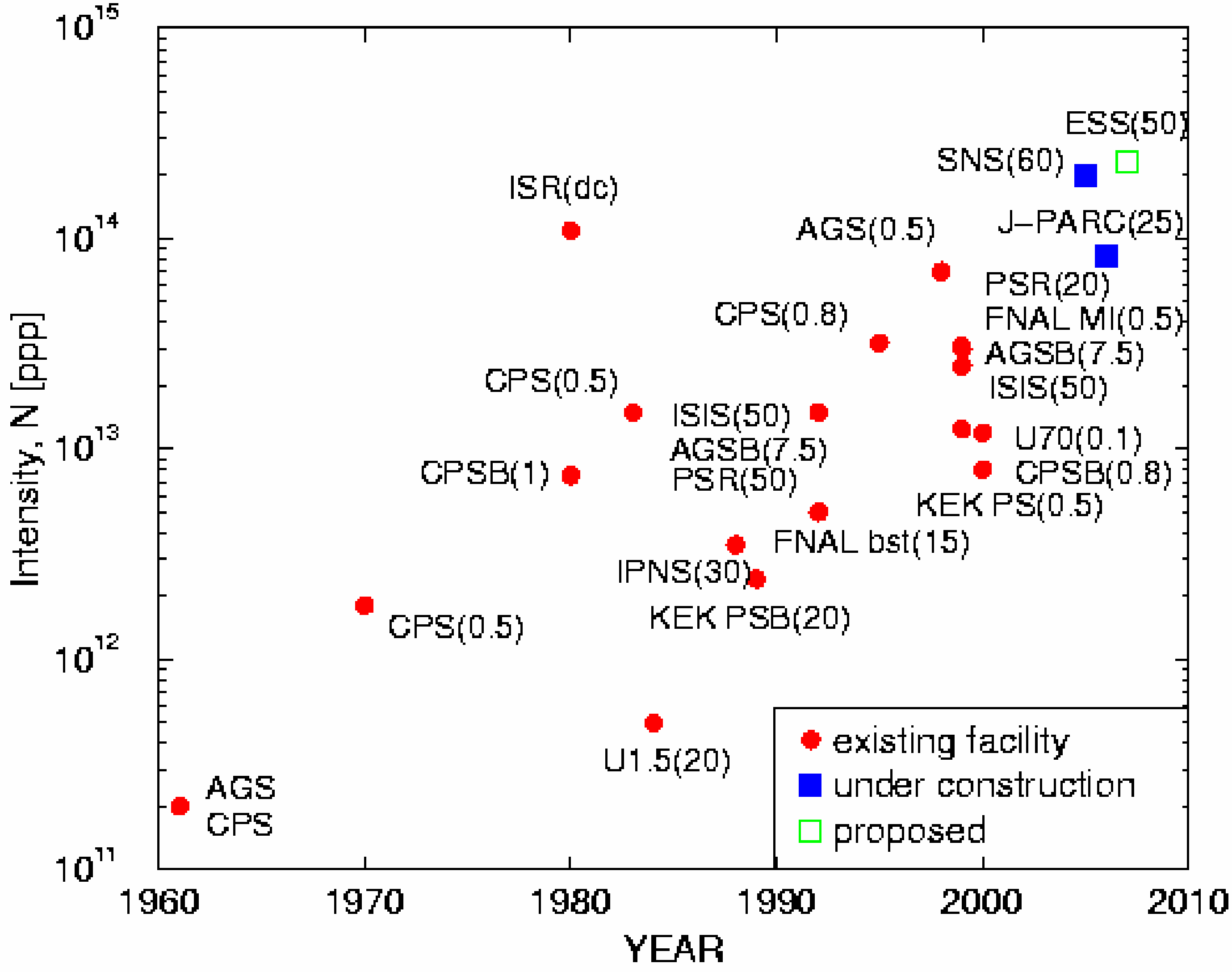
- Reached design peak current 38 mA
- Routinely transported 100% beam
- Emittance at DTL-1 ~ 0.3 πμm

(Aleksandrov, Henderson, Holtkamp …)

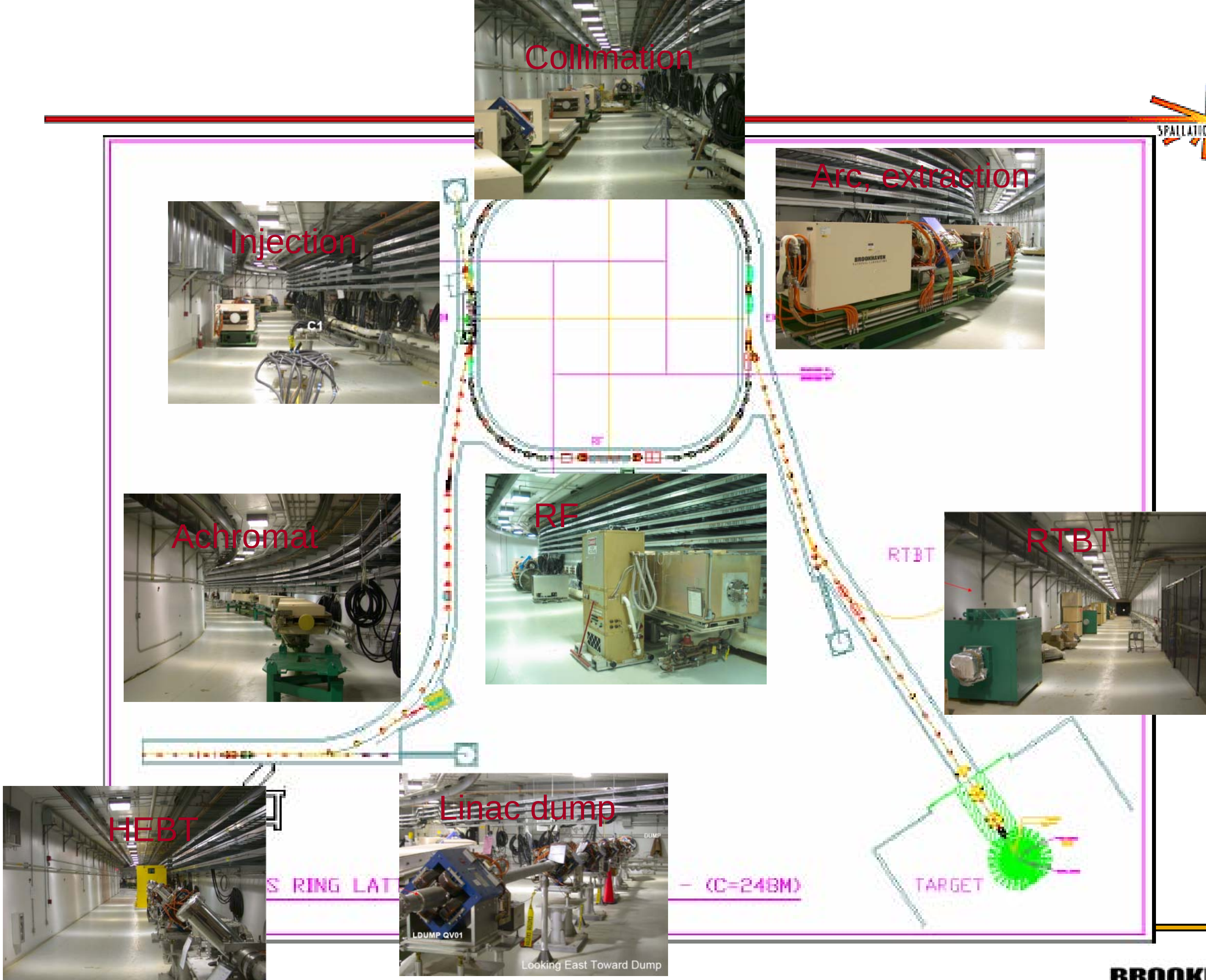


# Ring's intensity goal



SNS
SPALLATION NEUTRON SOURCE

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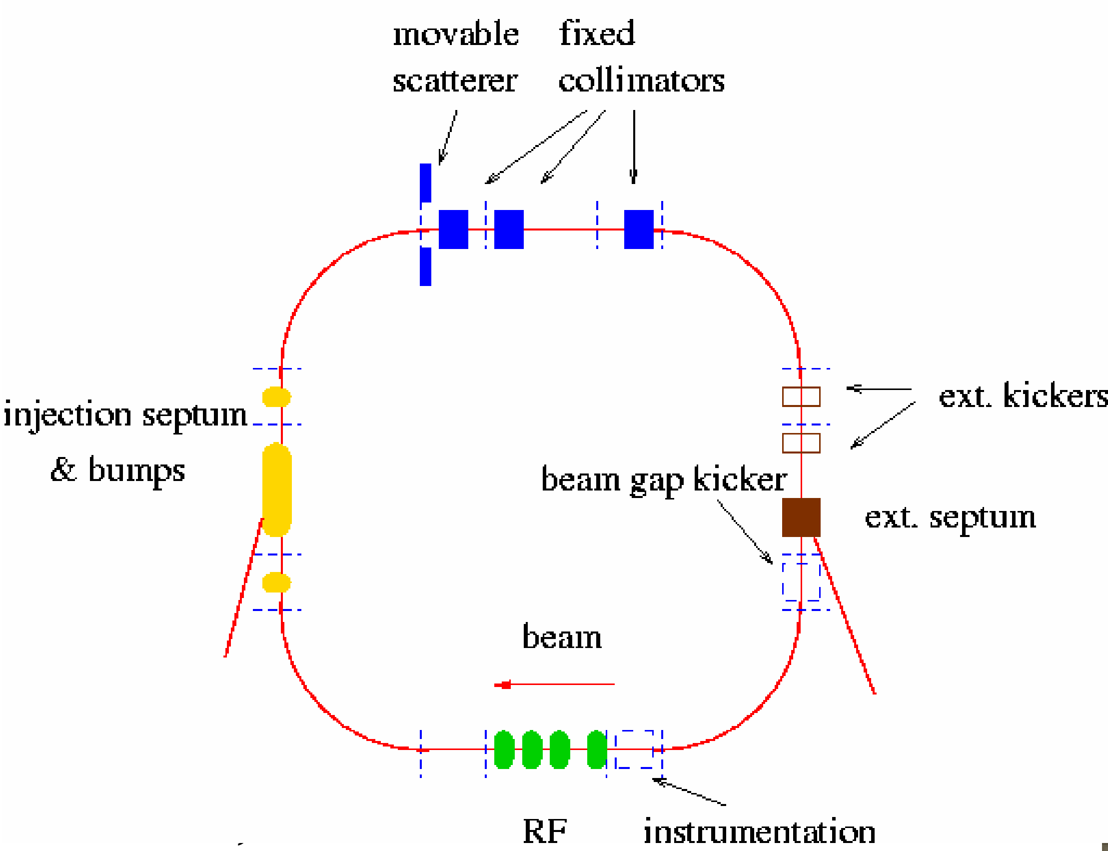
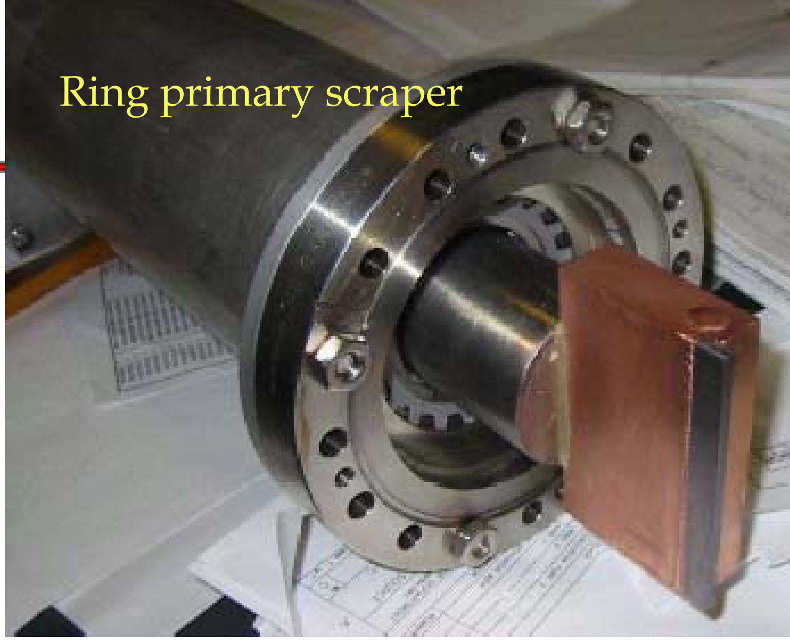
# Low-loss design philosophy

- Localize beam loss to specific area for remote handling
  - 2-stage collimation: HEBT, Ring, (RTBT)
  - 3-step beam-gap chopping/cleaning: LEBT, MEBT, Ring
- A low-loss design
  - 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 in energy (+/- 5%), tunes (H 1 unit, V 3 units), injection painting, collimation; interchange RF cavities
- Accident prevention:
  - Design redundancy: immune to accidental linac & kicker errors

# Beam-loss localization

- "Sacrifice" collimation region for the rest
- Two-stage system, efficiency above 90%
- Utilize large vacuum chamber aperture and long straight sections



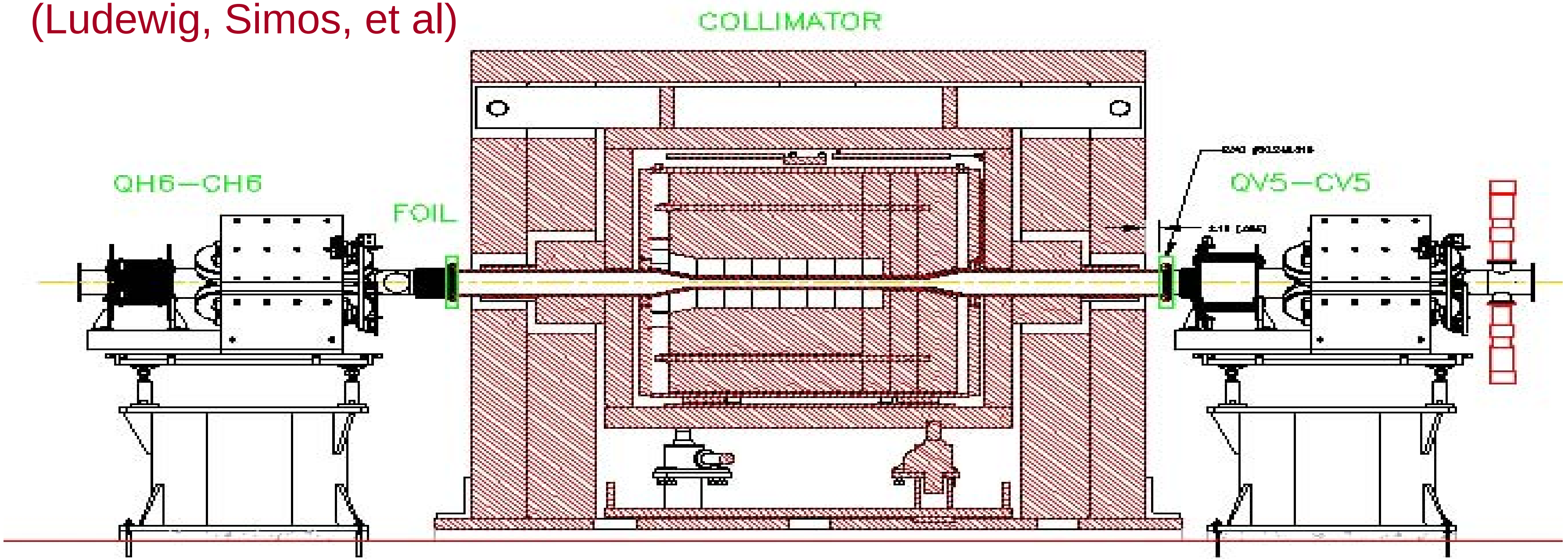




(Catalan-Lasheras, Ludewig, Simos, Tuozzolo, McGahern, Tuozzolo, Cousineau, Davino…)

# Secondary collimator construction

- 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

(Ludewig, Simos, et al)

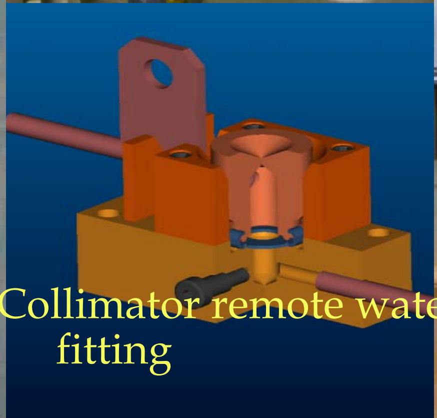


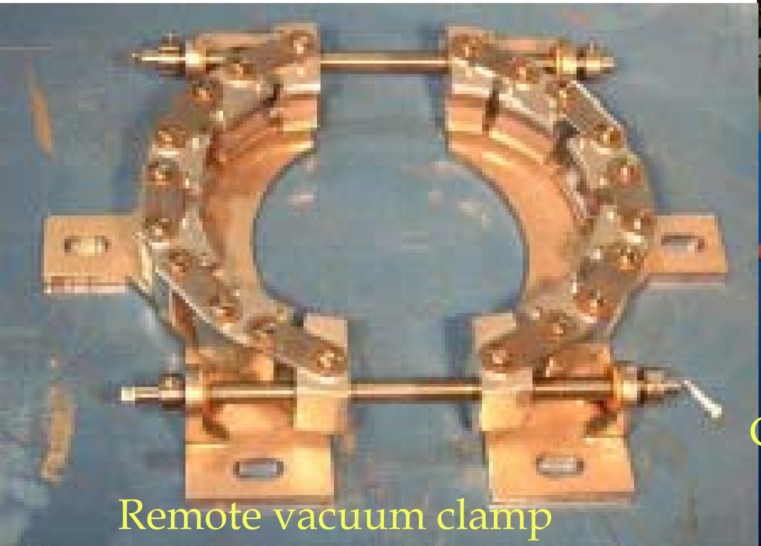
# Remote handling

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

(Murdoch, Pearson, Plum, et al)

Overhead crane


Collimator remote water fitting


Remote vacuum clamp


RTBT radiation hardened quad

# Favorable design decisions

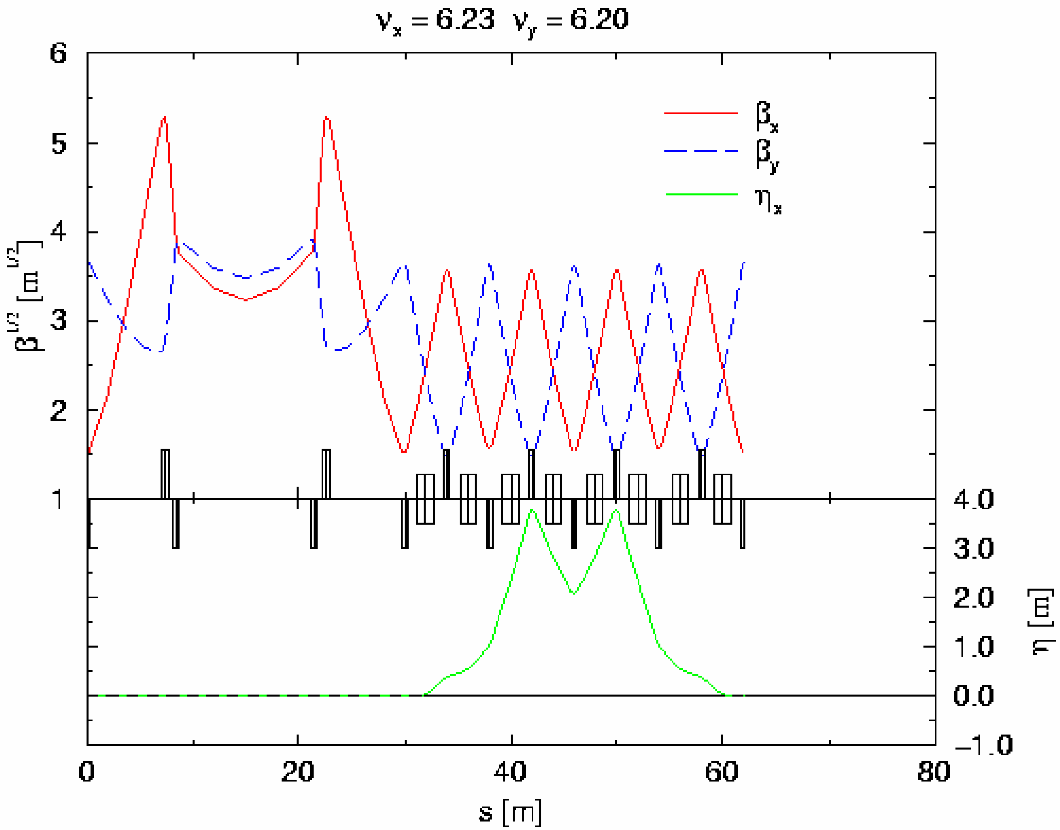
- Choose accumulator, not rapid-cycling synchrotron
  - Years of non-trivial battle to achieve good field with the Ring
  - Avoid potentially costly R&D needed for low-loss design
- Choose 4-fold lattice symmetry, not 3-fold
  - Collimator back-shine along vacuum pipe a serious concern
  - Avoid sharing injection with collimation for maintenance
- Choosing doublet straight/FODO arc lattice, not all FODO
  - Allow a robust, symmetric injection layout
  - Allow ideal collimator placement for high efficiency (>90%)
- Reserve upgrade potential for beam energy and power
  - Most magnet/power supply capable for 30% higher energy, matching future superconducting RF linac potential

# 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

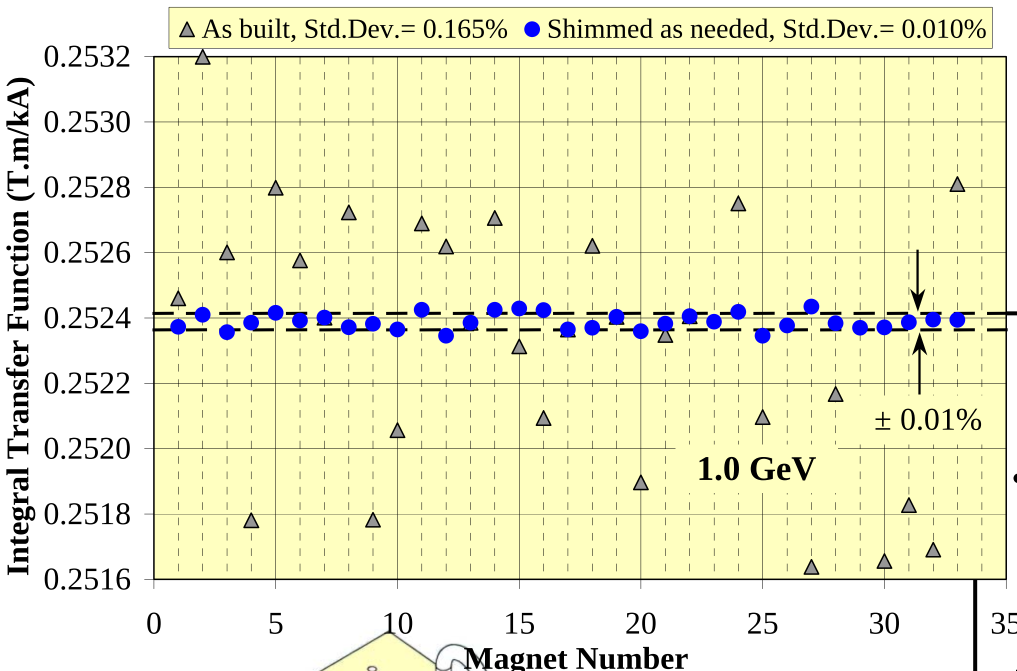


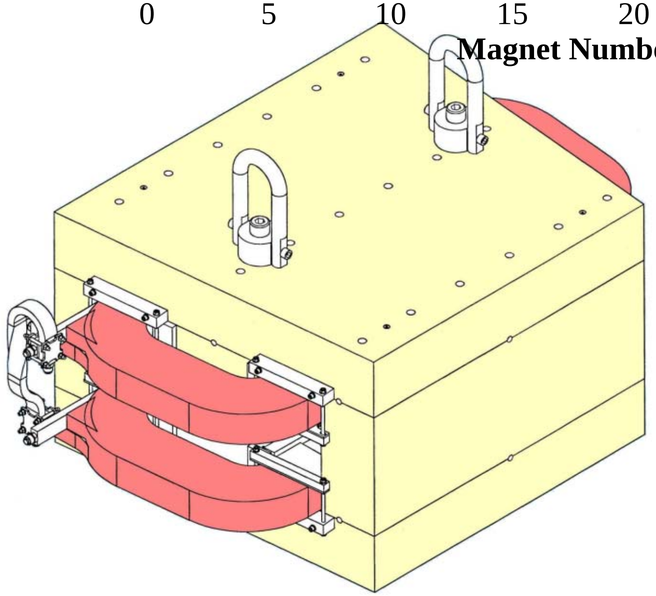
# Debatable design decisions

- Solid-steel core for all ring dc magnets
  - Instead of laminated steel, solid steel was chosen to save cost, leading to large magnet-to-magnet field variations.
  - A big effort in measurement and shimming
- In-situ baking not allowed for vacuum chambers
  - Tight mechanical clearance between magnet pole & chamber
  - Chamber presently coated with TiN; material of lower SEY may be available although maintenance is non-trivial
- Field optimization of narrow-body quads
  - Large 20$^{th}$ pole remains although impact is negligible for a 1 ms accumulation
- Adequacy of spare components
  - Limited by budget availability

# Dipole field variation & shimming (Wanderer, Jain, …)

### Integral Transfer Function at 1.0 GeV in SD17 Dipoles



### Summary of Field Quality in SD17 Dipoles

**Harmonics in "Units" at a reference radius of 80 mm**

**(10 Magnets; Center Position)**

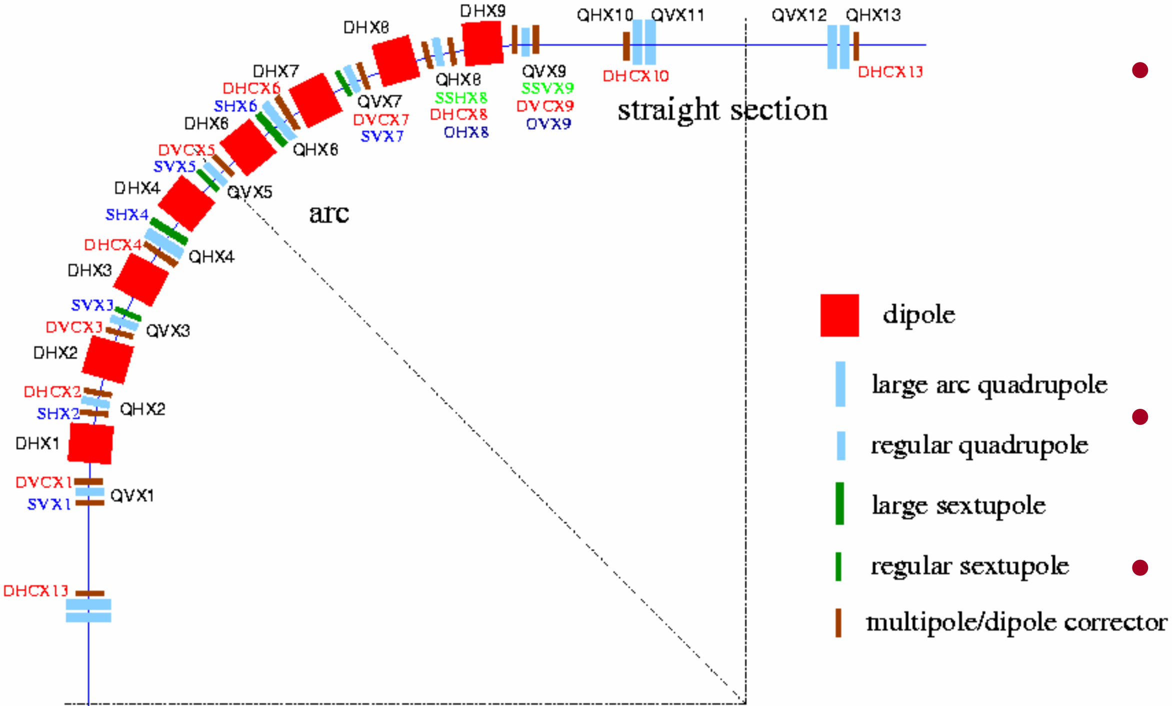
| | | 1.0 GeV | | 1.3 GeV | |
|---|---|---|---|---|---|
| | | Mean | Std.Dev. | Mean | Std.Dev. |
| | I.T.F. (T.m/kA) | 0.25241 | 0.100% | 0.24597 | 0.074% |
| | Fld Angle (mr) | -0.81 | 1.06 | -0.84 | 1.06 |
| Normal Harmonics | $b_0$ | 10000.0 | 0.00 | 10000.0 | 0.0 |
| | $b_1$ | -105.16 | 0.14 | -103.79 | 0.17 |
| | $b_2$ | 0.30 | 0.43 | -6.13 | 0.44 |
| | $b_3$ | 2.11 | 0.16 | 2.54 | 0.17 |
| | $b_4$ | 1.15 | 0.24 | -0.45 | 0.23 |
| | $b_5$ | 0.06 | 0.10 | 0.07 | 0.10 |
| | $b_6$ | -0.32 | 0.17 | -0.51 | 0.17 |
| | $b_7$ | 0.15 | 0.07 | 0.14 | 0.07 |
| | $b_8$ | -0.06 | 0.17 | -0.05 | 0.17 |
| | $b_9$ | -0.05 | 0.07 | -0.05 | 0.07 |
| | $b_{10}$ | -0.19 | 0.20 | -0.19 | 0.20 |
| | $b_{11}$ | 0.01 | 0.08 | 0.01 | 0.08 |
| | $b_{12}$ | 0.12 | 0.22 | 0.12 | 0.22 |
| | $b_{13}$ | 0.01 | 0.06 | 0.01 | 0.06 |
| | $b_{14}$ | -0.09 | 0.23 | -0.09 | 0.23 |

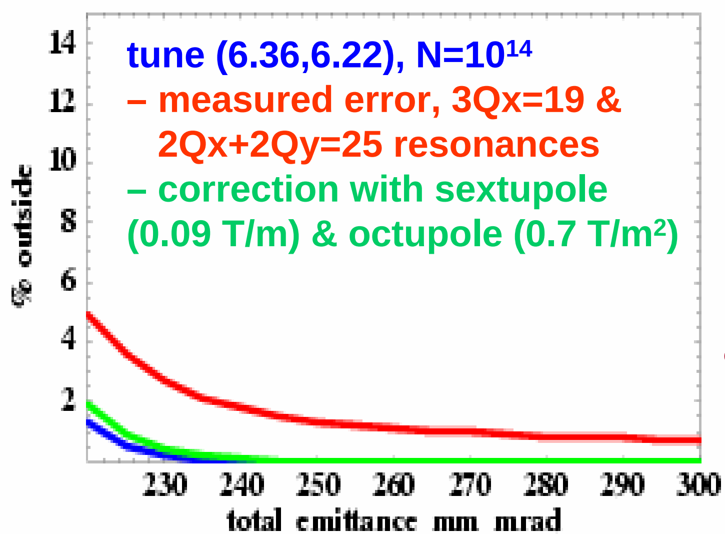
coil angle calibr. drifts

Sector dipole

# Magnetic field iterations

(Jackson, Jain, Lee, Meng, Papaphilippou, Raparia, Tepikian, Tsoupas, Tuozzolo, Wanderer, ..)



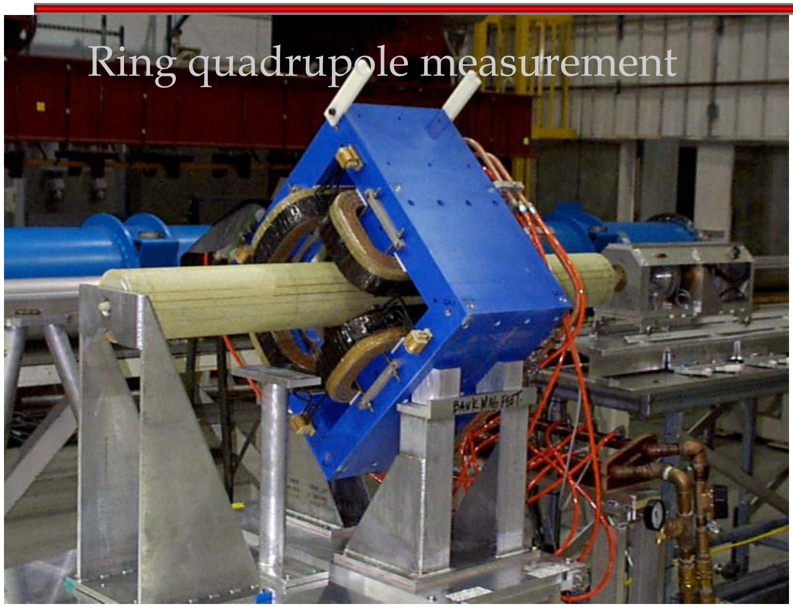



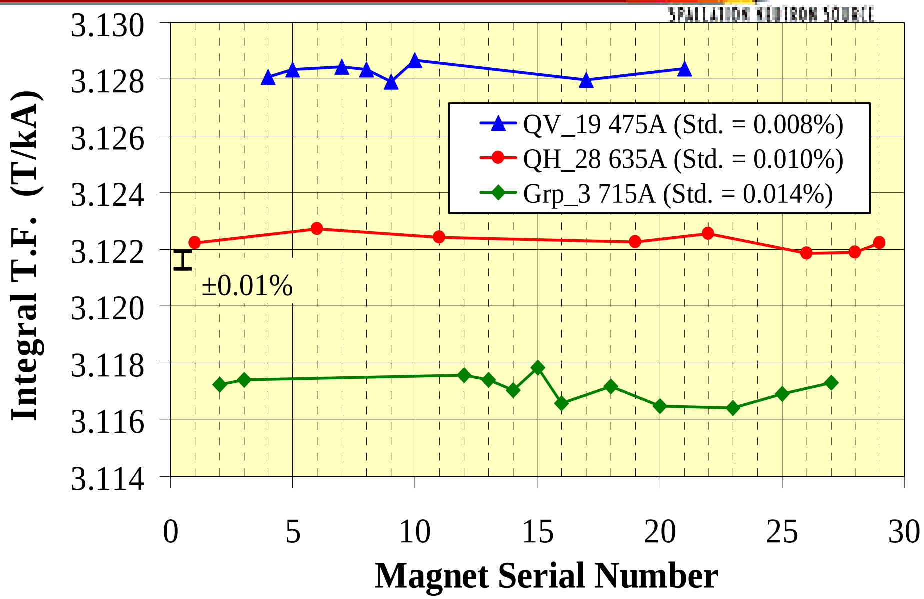

(Fedotov, Parzen, Raparia, et al)

- Field quality goal at full 480πμm acceptance (rms)
  - $10^{-4}$ main magnets
  - $10^{-3}$ sextupole, chicane
  - $10^{-2}$ correctors
- Design iterations
  - chamfer & cross-section
- Post-vendor re-iterations
  - pole alignment, iron shimming, coil shimming, coil flipping
- Sorting
  - ITF and sextupoles
- Resonance correction under space charge
  - Multipoles up to octupole components

# Arc quad

(Jackson, Jain, Lee, Meng, Raparia, Tepikian, Tsoupas, Tuozzolo, Wanderer…)



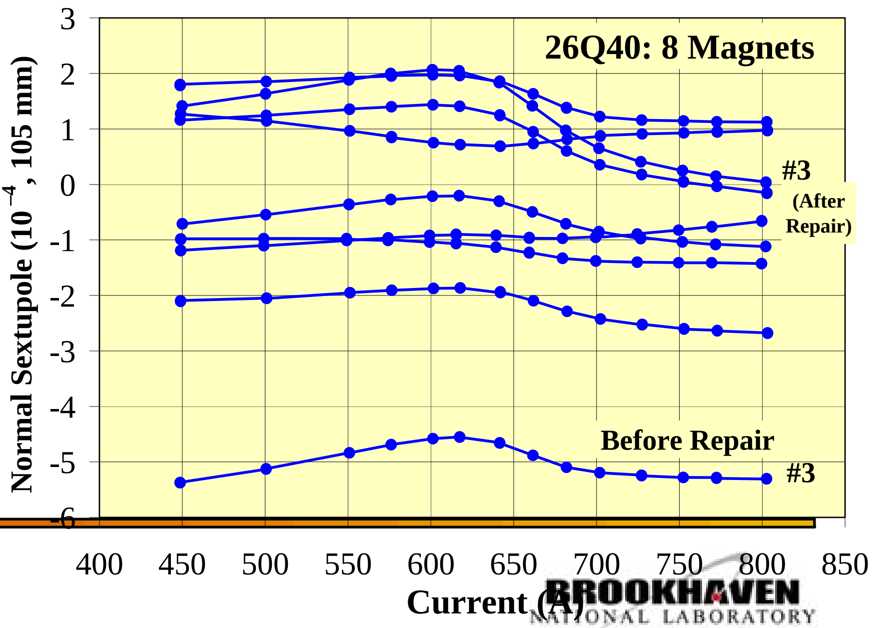




## 21-cm ID quads: iron shimmed, sorted

- Initial field variation rms ~3x10$^{-4}$; final 0.8 ~ 1.4 x 10$^{-4}$ (rms)
- Sorted in 3 power-supply families
- Trim quad coil available for back-up

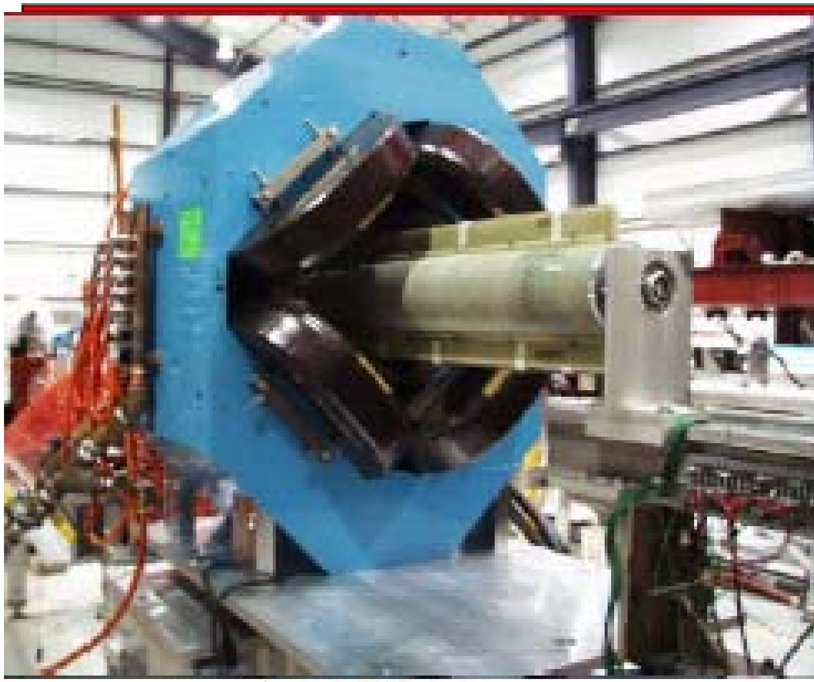
## 26-cm ID quads iron shimmed, re-aligned

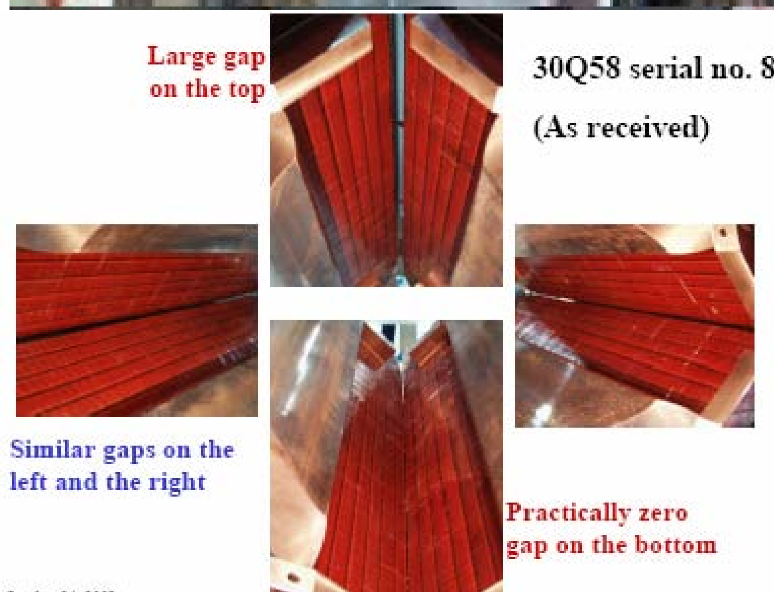
- ~1mm re-alignment to reduce sext. $b_3$



# Narrow-body quad

(Jackson, Jain, Lee, Meng, Raparia, Tepikian, Tsoupas, Tuozzolo, Wanderer…)






- Design
  - Narrow body to clear injection and extraction
  - Pole tip shape iterated for 12-pole
  - Large ($2x10^{-3}$) 20-pole from narrow geometry; no noticeable effect during 1 ms accumulation
  - Correctable with pole shape scalloping if needed
- Post-vendor
  - ~ 10 unit skew sext $a_3$ measured
  - Coil shimming applied

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# Field comparison

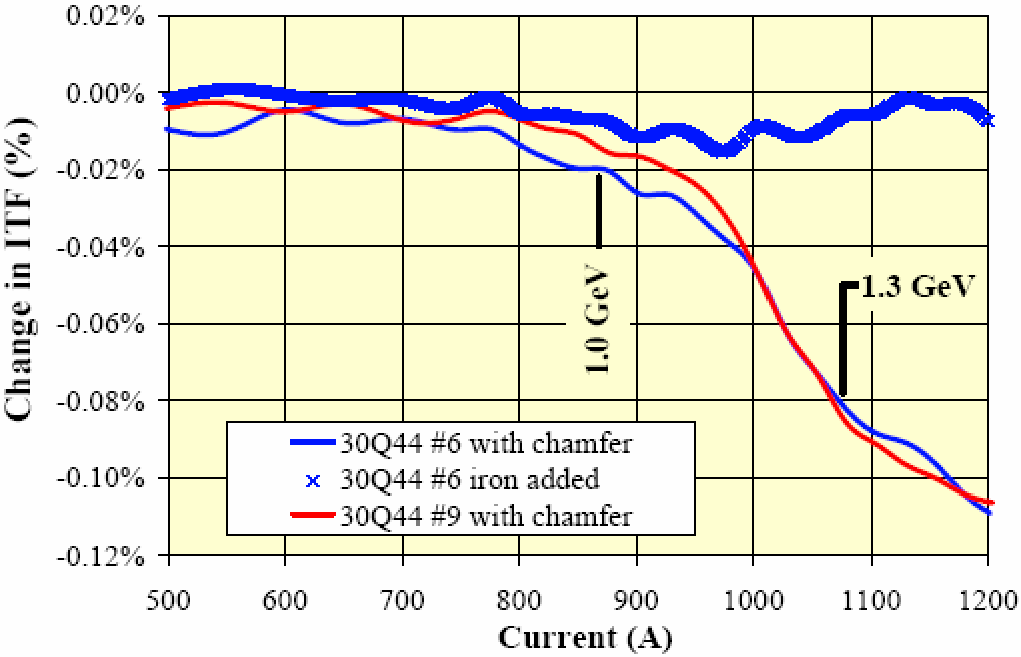
Regular quad
(ring arc)

| $n$ | $b_n$ | | $a_n$ | |
|---|---|---|---|---|
| | mean | S.D. | mean | S.D. |
| 1 | 10000 | 0.00 | – | – |
| 2 | −0.27 | 1.21 | 0.51 | 2.07 |
| 3 | 0.30 | 1.32 | 0.18 | 0.69 |
| 4 | 0.07 | 0.47 | −0.05 | 0.45 |
| 5 | 1.07 | 0.60 | −0.12 | 0.19 |
| 7 | -0.01 | 0.10 | −0.02 | 0.18 |
| 9 | −0.52 | 0.41 | 0.00 | 0.06 |

Narrow-body quad
(ring straight)

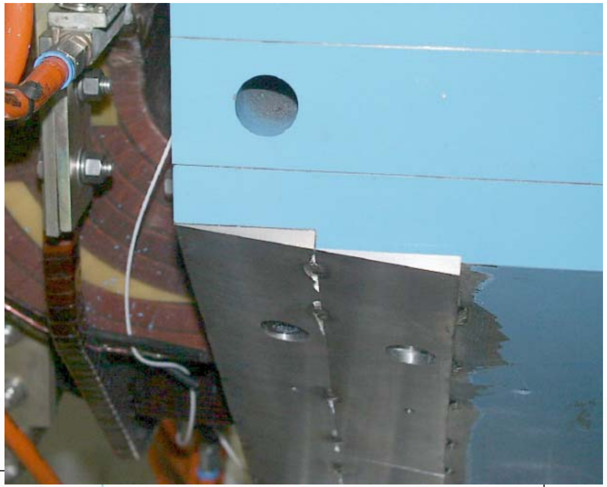
| $n$ | $b_n$ | | $a_n$ | |
|---|---|---|---|---|
| | mean | S.D. | mean | S.D. |
| 1 | 10000 | 0.00 | – | – |
| 2 | 2.97 | 2.86 | −0.87 | 1.45 |
| 3 | 0.04 | 0.70 | 1.31 | 0.37 |
| 4 | 0.38 | 0.63 | −0.08 | 0.43 |
| 5 | 2.58 | 0.38 | 0.16 | 0.56 |
| 7 | −0.01 | 0.08 | 0.06 | 0.08 |
| 9 | $\boxed{-21.7}$ | 0.53 | 0.00 | 0.08 |

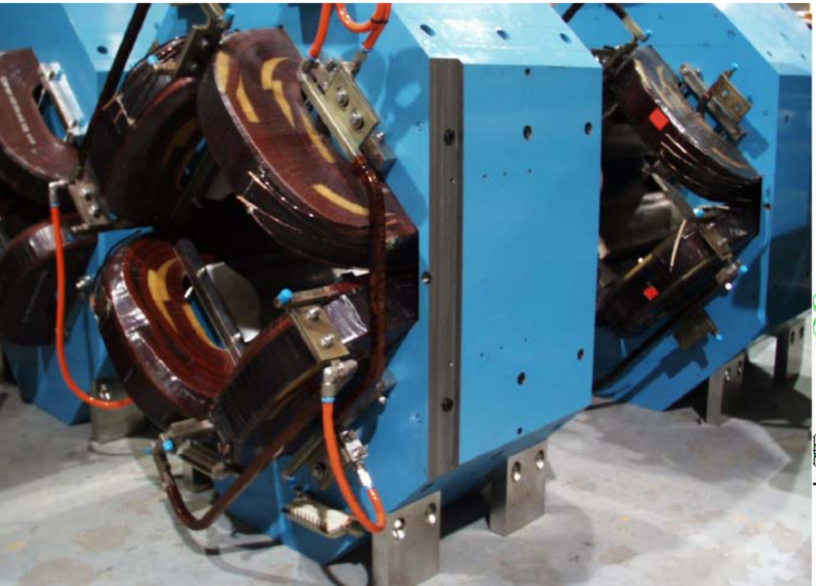
# Injection region mechanical clearance

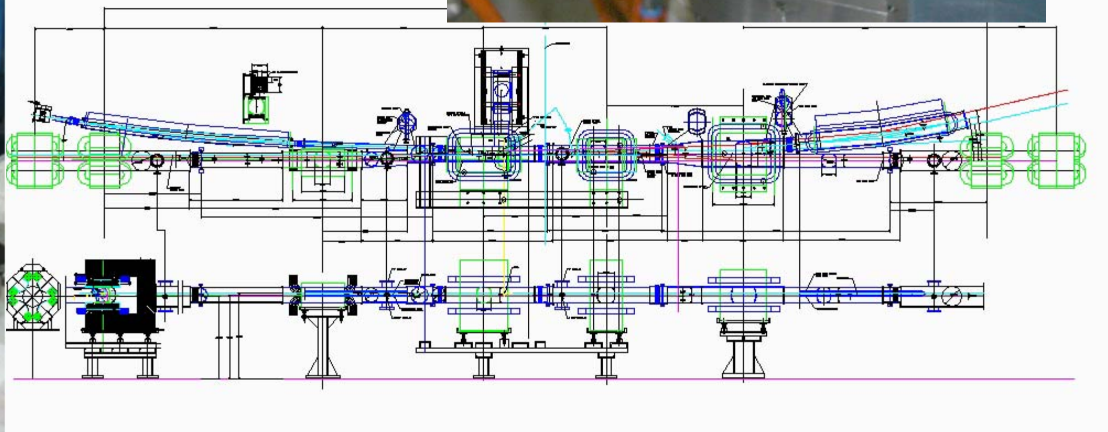



## Injection region trail-assembly

- Mechanical interference found
- Quad edge trimmed & re-welded to minimize ITF variation for all beam energy

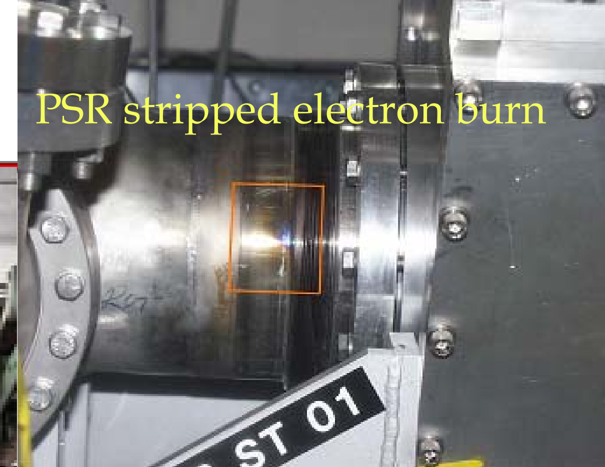




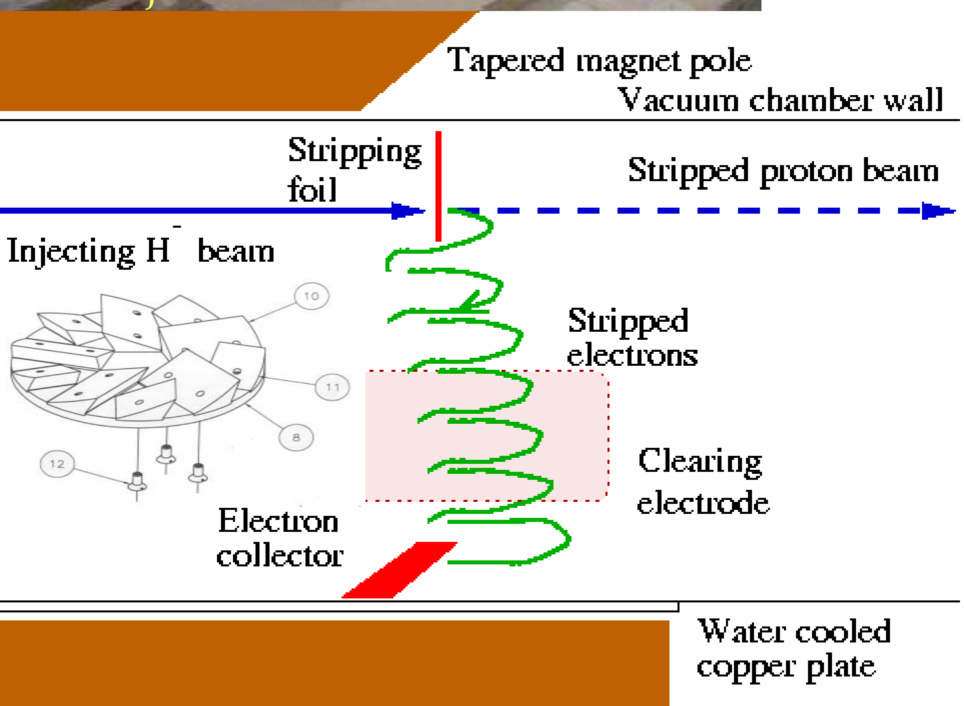


# Stripped electron collection






(Meng, Brodowski, Lee, Abell, Macek et al)




- Tapered magnet to guide stripped electrons (~ 2 kW), compensated for the circulating beam
- Carbon-carbon collector on water-cooled copper plate
- Clearing electrode (~ 10 kV) to reduce scattered electrons
- Video monitors on foil & collector

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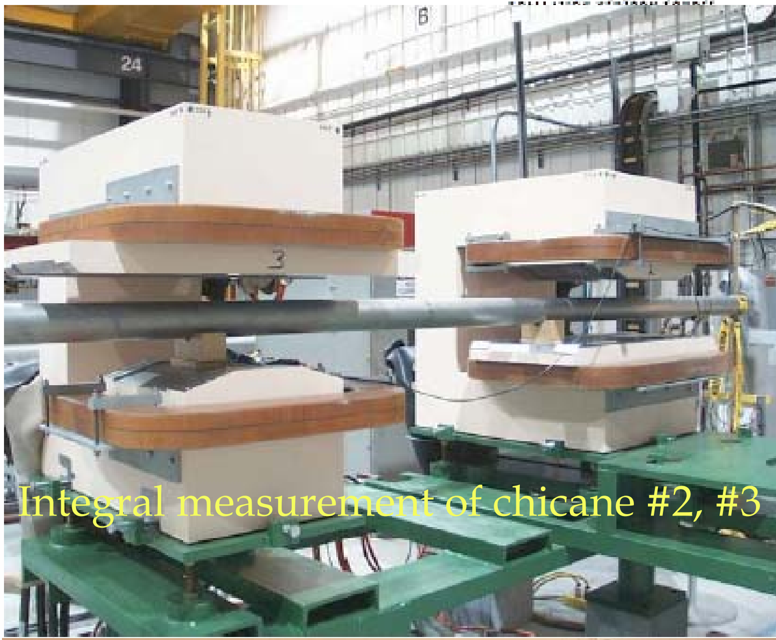
# Injection chicane measurements

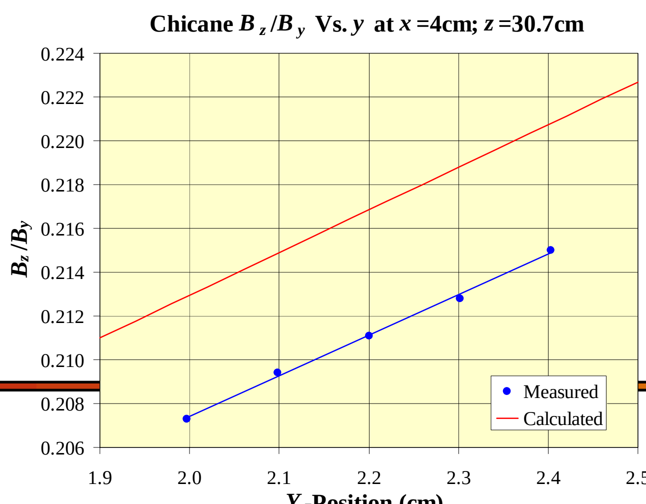
(Meng, Jackson, Jain, Wanderer, Hoey, Lee …)

- Integral measurement confirmed field compensation ($10^{-3}$)

| Harmonic | Chicane #2 (2154.8 A) | Chicane #3 (1732.0 A) | Chicane #2 (2154.7 A) + Chicane #3 (1733.2 A) |
|---|---|---|---|
| $\int B.d\ell$ (T.m) | 0.3006 | 0.2016 | 0.5012 |
| $b_1$ | -1.8 | -4.1 | -1.9 |
| $b_2$ | -8.2 | -9.4 | -9.2 |
| $b_3$ | 1.2 | 0.9 | 1.3 |
| $b_4$ | 0.0 | -0.4 | -0.1 |
| $b_5$ | 0.5 | -0.7 | 0.0 |
| $b_6$ | -0.9 | 0.0 | -0.6 |
| $a_1$ | 116.0 | -158.2 | 6.2 |
| $a_2$ | -8.0 | 9.6 | -0.9 |
| $a_3$ | 8.0 | -11.3 | 0.3 |
| $a_4$ | -0.5 | 0.4 | -0.1 |
| $a_5$ | 1.5 | -1.3 | 0.0 |
| $a_6$ | 0.1 | -0.3 | 0.0 |

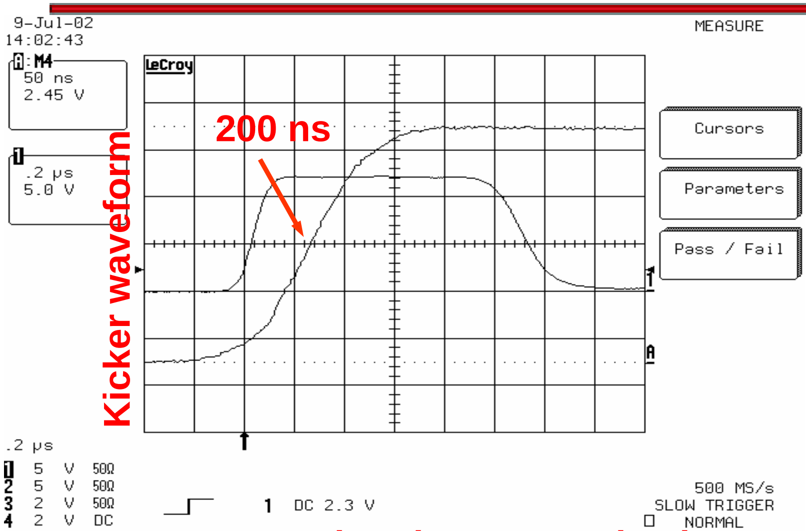



- Point-coil measurement confirmed field angle for electron collection

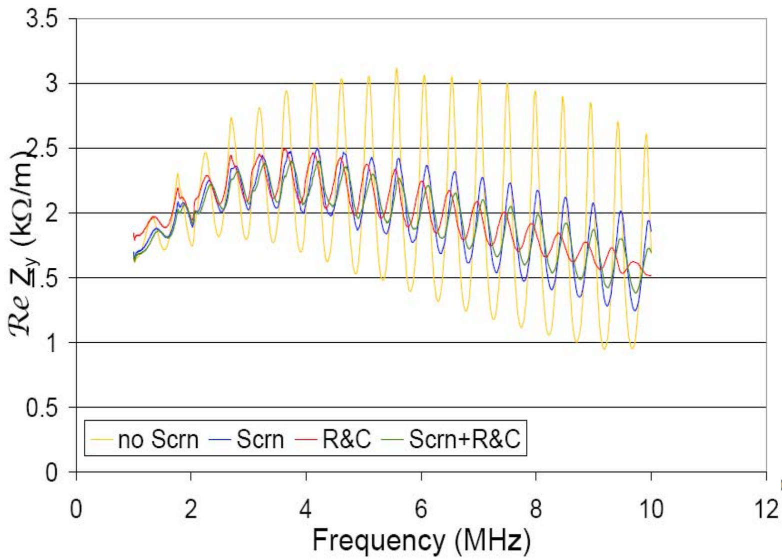


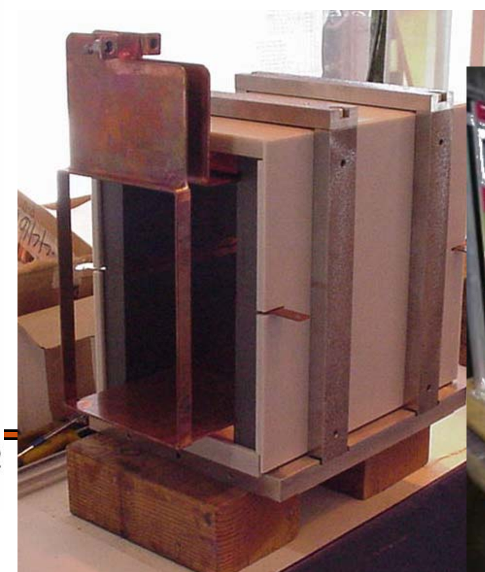

# Extraction kicker

(Hahn, Davino, Danilov, Kurennoy, Danilov, Lambiase, Lee, Mi, Sandberg, Zhang …)




- Ferrite kicker inside vacuum pipe
- Optimize saturable inductor to effectively “shorten” rise time (200ns)
- Improved flat-top flatness (~0.5%)
- PFN termination: lower impedance
- Increase magnet height to halve coupling impedance (same drive)
- Shield the terminating resistance, reducing cable reflection



# Vacuum chamber coating

(Hseuh, He, Blaskiewicz, Mapes, Todd, Aleksandrov, Davino, Henderson, …)

## Injection kicker ceramic chamber double coating

- Cu (~ 0.7 μm) for image current passage
- TiN (~ 0.1 μm) for electron cloud suppression
- Thickness uniformity < ± 30%

## Extraction kicker ferrite patterned TiN coating

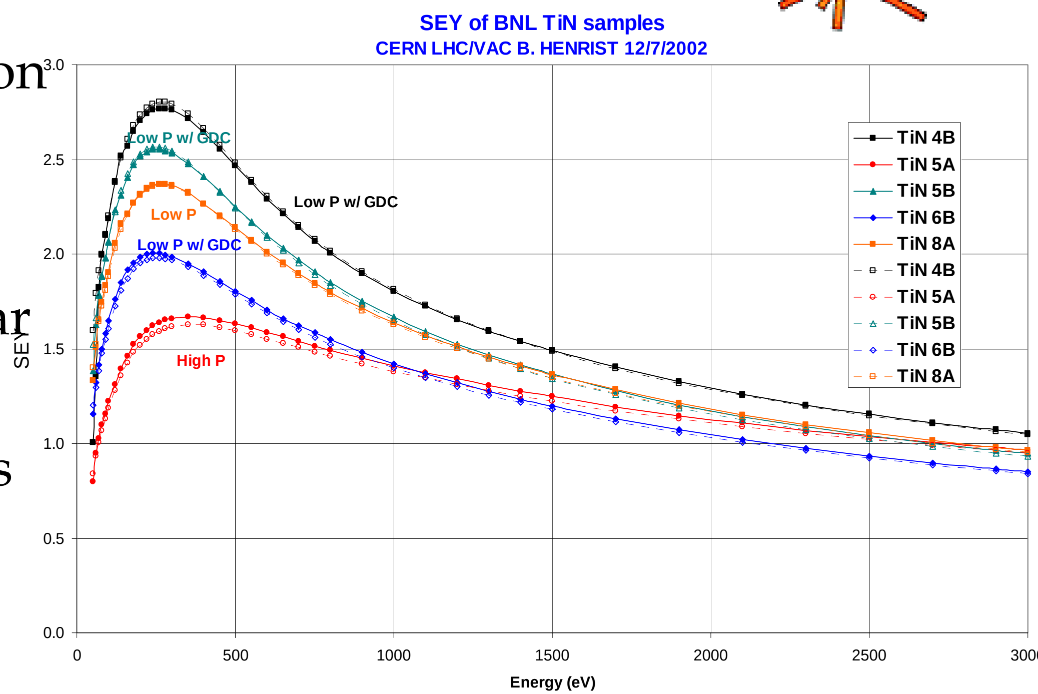
- ~ 0.1 μm TiN on ≥ 90% ferrite inner surface
- Masked for eddy-current heating control
- Masked near HV conductor to prevent circuit shorts

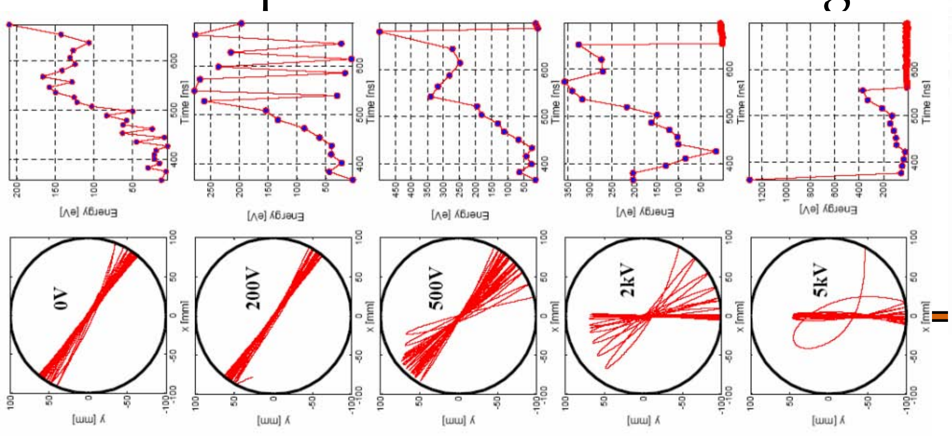


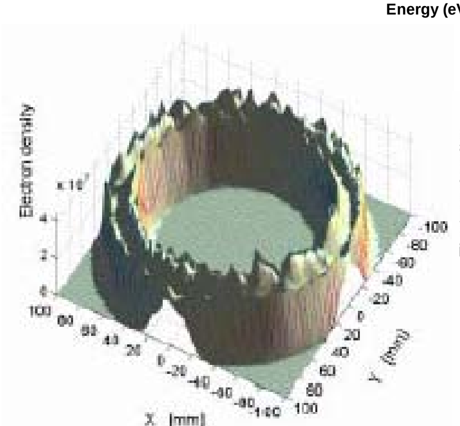
# Electron-cloud mitigation

(Wang, Blaskiewicz, Furman, Macek, Pivi, Zhang, Hseuh, He, et al)

- Inner surface coated with TiN SEY ~ 1.6, no baking/activation
- Solenoids applied in collimation region
- Clearing electrode (10 kV) near injection foil
- Beam-position-monitors act as clearing electrodes (+/- 1 kV)
- Beam-in-gap kicker to clear residuals
- Extra ports for beam scrubbing

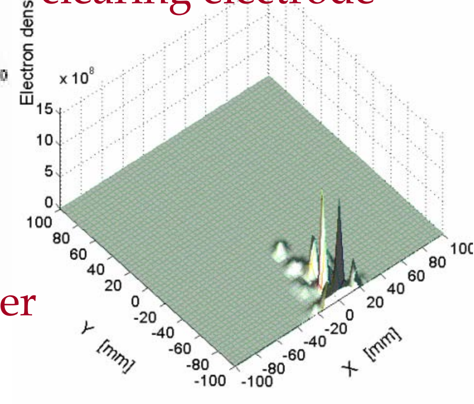


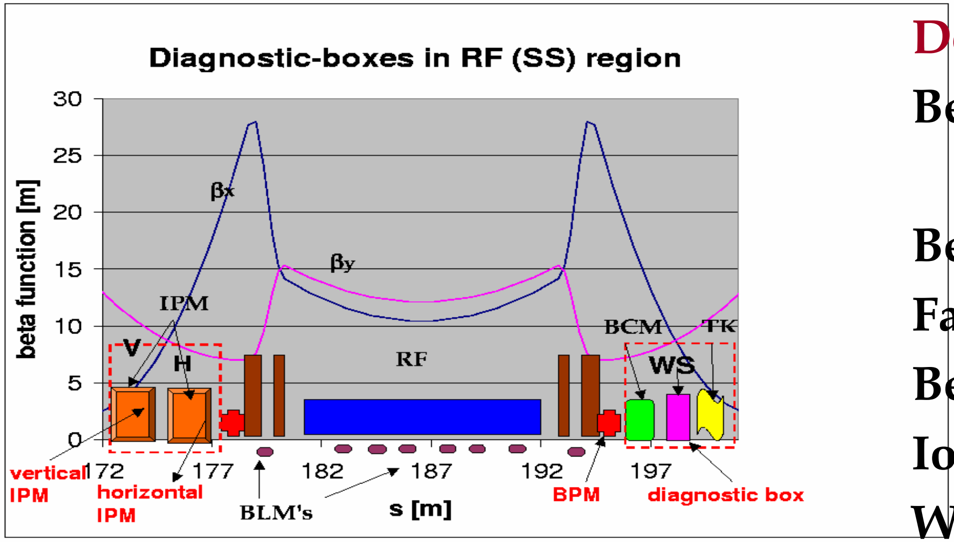




electron cloud under a solenoid

electron cloud under a clearing electrode



# Instrumentation
(Russo, Dawson, Sandberg, Shea …)

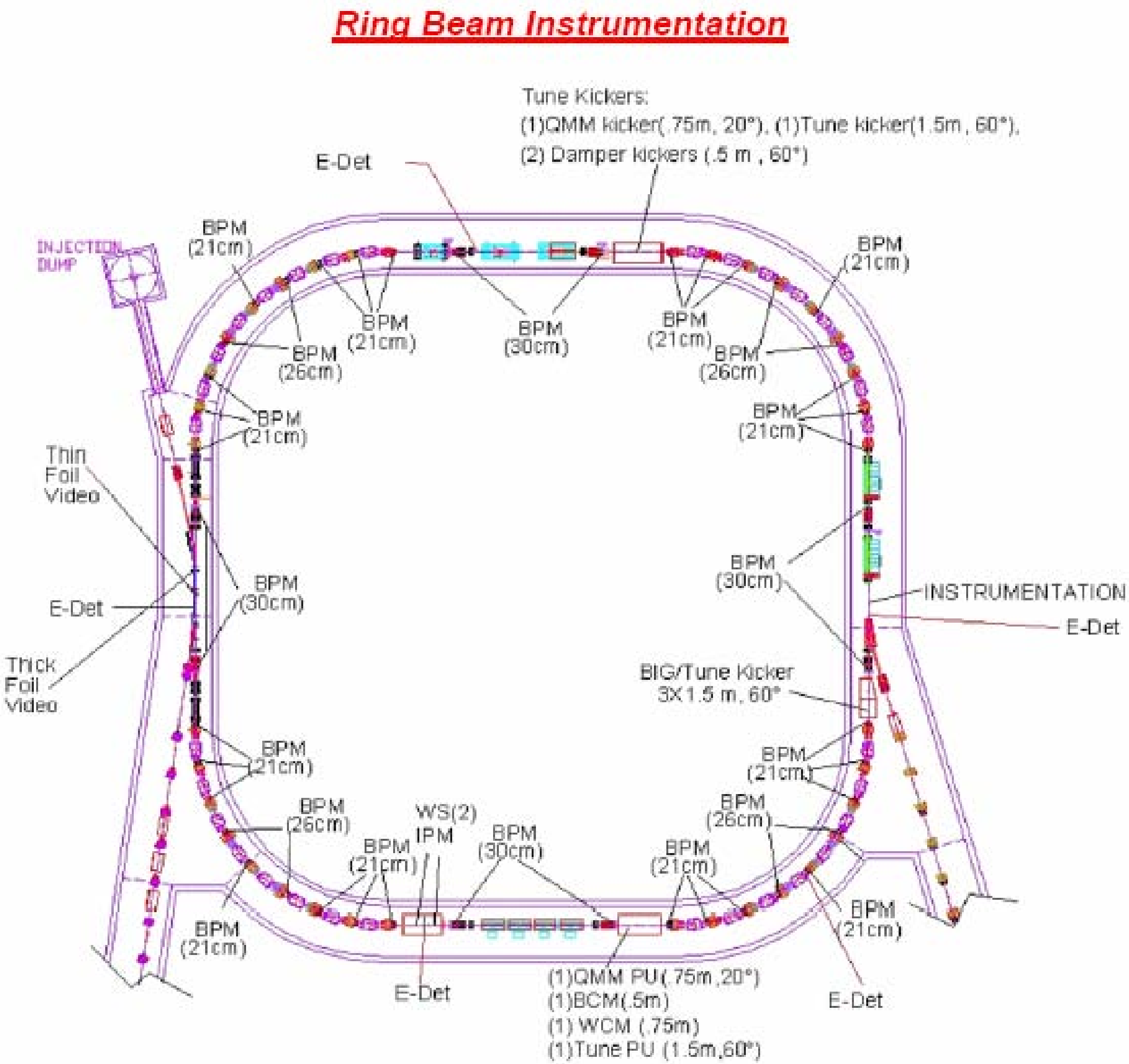



- Part of machine protection; fast response
- Wide dynamic range
  - Intensity three order-of-magnitude; amplitude 30 times
- Turn-by-turn capability
- Presence of electron cloud

| Detectors | Number | Comments |
|---|---|---|
| Beam Position M | 44 | dual plane ( includes 2 RF radial loop) |
| Beam Loss M | 75 | ion chamber |
| Fast BLM | 12 | photomultip. |
| Beam-In-Gap | 1 | kicker+PMT |
| Ion. Profile M | 2 | H+V |
| Wire scanner | 2 | H+V |
| Coherent Tune | 1 | kick/PU |
| Incoherent Tune | 2 | PLL & QMM |
| Beam Current M | 1 | FCT |
| Wall Current M | 2 | including RF |
| e-detector | 5 | |
| Wide-band damper | 2 | |
| High moment | 1 | |
| Luminescence profile study | | |

# Tune diagnostics, halo scraper, dampers

(Cameron, Fedotov, Raparia, Russo, Henderson, Danilov …)




Added new beamline components for full-power & beyond operations

- Dipole / quadrupole mode incoherent tune measurement pick-ups and kickers (4 units)
- Diagnostics halo scraper
  - In addition to collimation scraper
- Wide-band dampers
  - Possible e-p instability damping
  - Possible resistive instability damping

# Infrastructure matching & installation

(McGahern, Tuozzolo, Sandberg, Lambiase, Tepikian, Hemmer … Hechler, Galambos, Murdoch, Error, Cutler, Hunter…)

- Ring crane capacity iteration
  - Increased assembly weight with increased ring capacity to 1.3 GeV and added chromatic sextupoles
  - Minimum crane capacity restored to 20 tons; design modified to match reduced crane height
- Magnet/cable resistance, water capacity, power supply ratings
  - Power supply ratings to match actual magnet/cable resistance, operating temperature, and water volume & pressure
- Global coordinates & database


# Ring hardware

(Zaltsman, Smith, Pai, Pearson, Seaberg, et al)

Ring RF cavities

Extraction kicker chamber

Diagnostics resonance pick-up

Winding of radiation resistant coil on RTBT doublet magnet

# Handling & shipping

Ring injection kicker shipped to ORNL


Ring injection kickers in ORNL tunnel


Ring injection septum at BNL during trial assembly

# Summary

- SNS has been a test bed of multi-laboratory collaboration
- Brookhaven is on its way to deliver promised fine products on time and on budget
- We are looking forward to ring commissioning in 2005

# Acknowledgements

- Thank you, Our friends & collaborators!
- The entire SNS teams (ORNL, LANL, …)
- Review committees' constructive advice (ASAC, DOE, DAC, …
- And …

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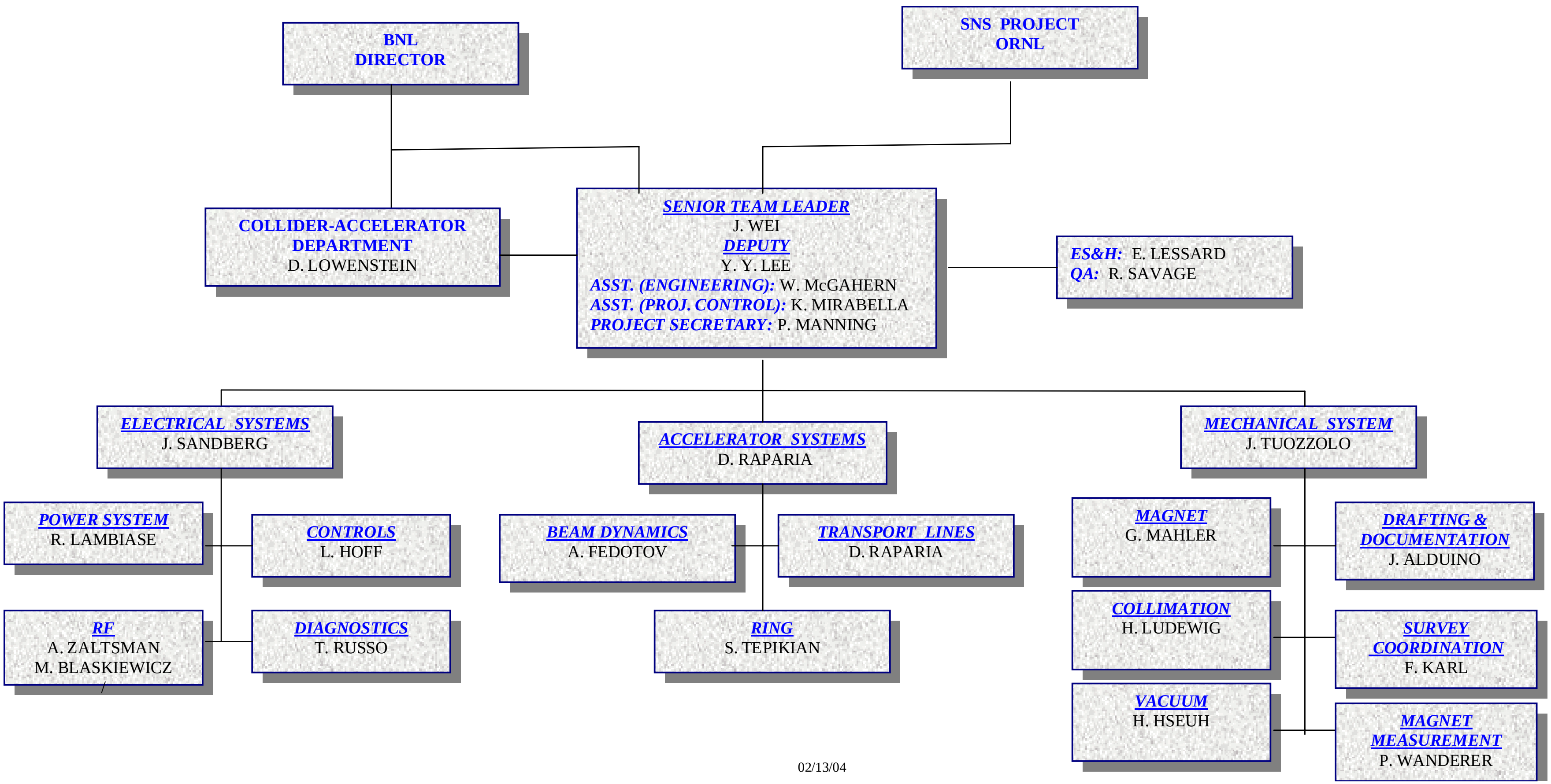
# Thanks to the devoting team




Thank you for your attention!

# SNS Main Parameters

| | |
|---|---|
| Kinetic energy, $E_k$ [MeV] | **1000** |
| Uncertainty, $\Delta E_k$ (95% probability) [MeV] | +/- 15 |
| SRF cryo-module number | 11+**12** |
| SRF cavity number | 33+48 |
| Peak gradient, $E_p$ ($\beta$=0.61 cavity) [MV/m] | 27.5 (+/- 2.5) |
| Peak gradient, $E_p$ ($\beta$=0.81 cavity) [MV/m] | **35 (+2.5/-7.5)** |
| Beam power on target, $P_{max}$ [MW] | **1.4** |
| Pulse length on target [ns] | 695 |
| Chopper beam-on duty factor [%] | 68 |
| Linac beam macro pulse duty factor [%] | 6.0 |
| Average macropulse H- current, [mA] | **26** |
| Linac average beam current [mA] | **1.6** |
| Ring rf frequency [MHz] | 1.058 |
| Ring injection time [ms] / turns | 1.0 / 1060 |
| Ring bunch intensity [$10^{14}$] | 1.6 |
| Ring space-charge tune spread, $\Delta Q_{sc}$ | 0.15 |

assuming 4% injection loss to dump; 4% target window loss; linac max. -20$^o$ phase