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Challenges for High-Intensity Proton Accelerators and Long-Term Experimental R&D

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The 1% Regime

- Very small fractions of particle beams will establish the performance limits of future high-power accelerators.

$$P = L_T / \chi$$

- Where L_T is the tolerable loss power, and χ is the fractional loss

Replaces the conventional power equation:

$$P = E \times I$$

- Approaches to higher energy and current are only acceptable if losses are reduced proportionally (or controlled adequately)
  – Example: Fermilab Main Injector is required to be 95% efficient for 700 kW operation, 1.2 MW under PIP-II will require 97%
- No longer can we focus on conventional instabilities which lead to catastrophic losses
  – Instead, confront the weaker, slower process that lead to small fractional losses, emittance growth, or halo formation

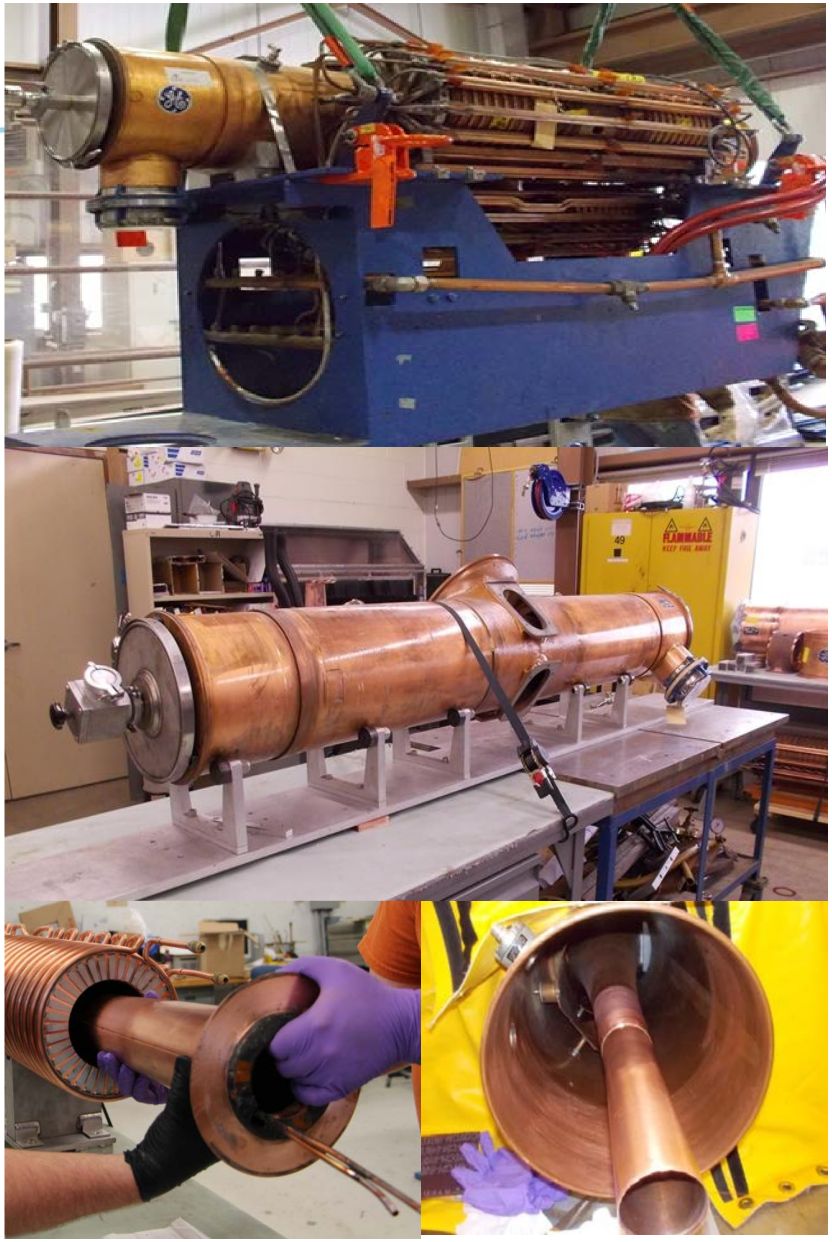
Loss Tolerance – 1 W/m ?

- Need to move beyond 1 W/m as benchmark
  - Leads to ~ 100 mrad/hr. with extended running

- Consider a “hands-on maintenance” job of refurbishing the 19 Booster RF cavities
  - Strip-down and rebuilding requires 100s of hours, many of which are in close contact with cavity
  - 10 mrad/hr. is uncomfortably hot

- **Conclusion:** Many critical devices need to have targets of ≤ 0.1 W/m

- **Note:** 1 W/m has only come out to a reasonable, overall, limit where much of the loss is confined to local, hardened areas such as collimators and absorbers.



Looming Issues (not exhaustive)

- Accumulating and manipulating high-intensity beams
  - Stacking and acceleration schemes
- Collective effects
  - Instabilities such as resistive wall and ECloud
- Loss / radiation control
  - High efficiency and loss mitigation
- Accelerator instrumentation and measurements at high beam intensities
  - Problem of reliably measuring beam properties at high intensity
- Devices and techniques to address loss mechanisms
  - Instability suppression, space charge compensation, injection and extraction schemes.

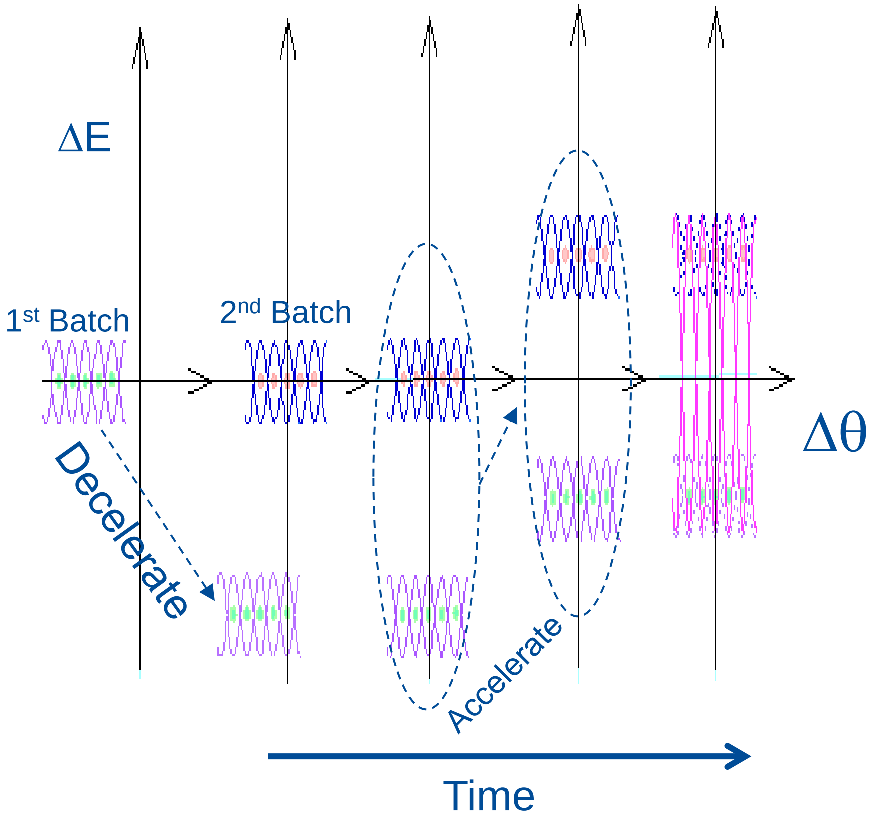
Selected Challenges to Higher Intensity

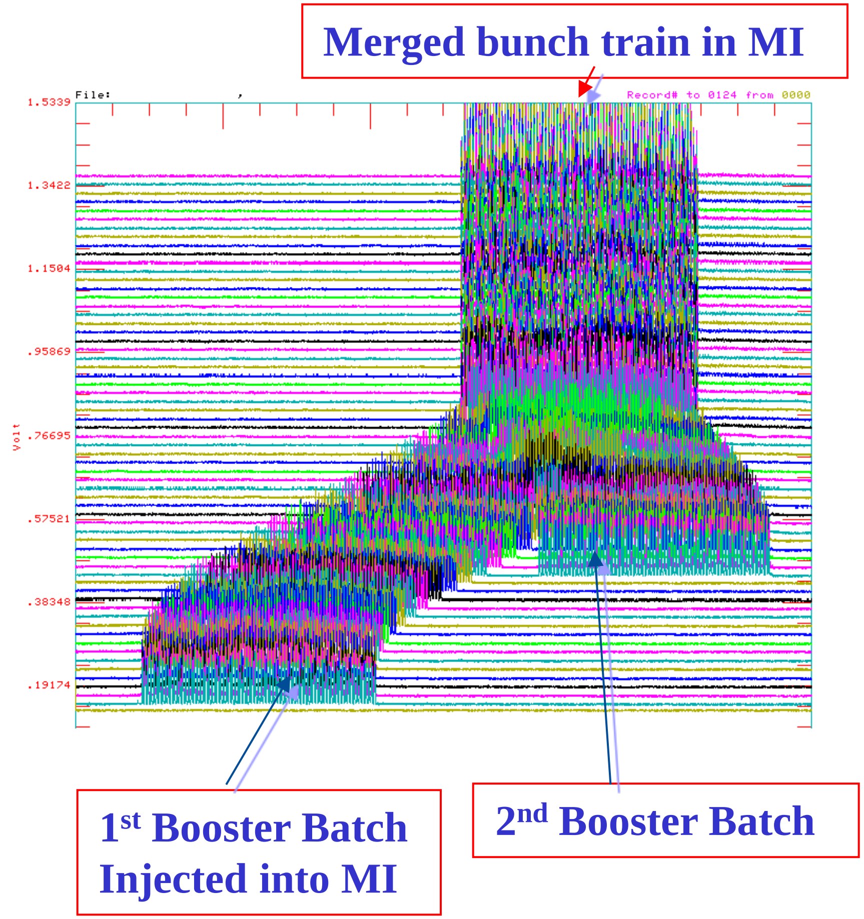
- Slip-Stacking
  - Technique to double beam current
- Electron Cloud
  - Instability and potential loss mechanism
- H^- Notching, Chopping , & Injection
  - Techniques for beam accumulation and patterning, as well as loss reduction

There are numerous others topics throughout the accelerator chains

Slip-Stacking

- **Merge two booster batches through RF manipulations**





➢ **Doubles the azimuthal charge**

Slip-Stacking

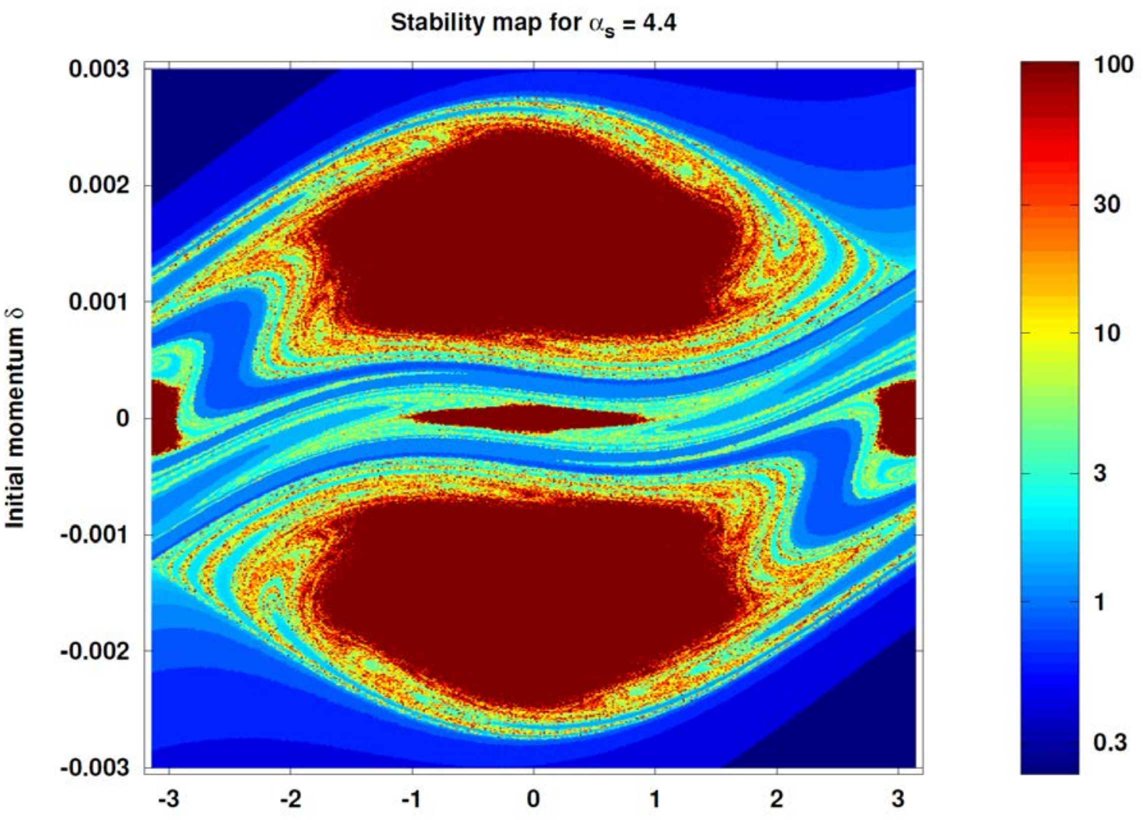
- While the basic idea is straightforward, there are numerous complications
  - Described by a time-dependent Hamiltonian

$$H = \pi f_{rev} h \eta \delta_A^2 + f_{rev} V_\delta \cos(\phi_A) \cos\left(\frac{\omega_\phi t}{2}\right)$$

  - Beam loading in cavities
    - Further distorts buckets
  - Inability to damp overlapping buckets
    - Chromaticity must be held large to avoid coherent instability
  - Large momentum spread of beam while slipping
    - Significant usage of aperture
    - Transverse resonances are encroached upon (via chromaticity)

Slip-Stacking

- RF buckets are strongly deformed by the presence of a second frequency
  - Stable phase space is chaotic
  - Loss can be slow
- Challenges:
  - Maximizing the stable phase space
  - Minimizing the incoming beam emittance
  - Matching the shape of the beam to that of the bucket
- Collaboration with Indiana (PhD student)



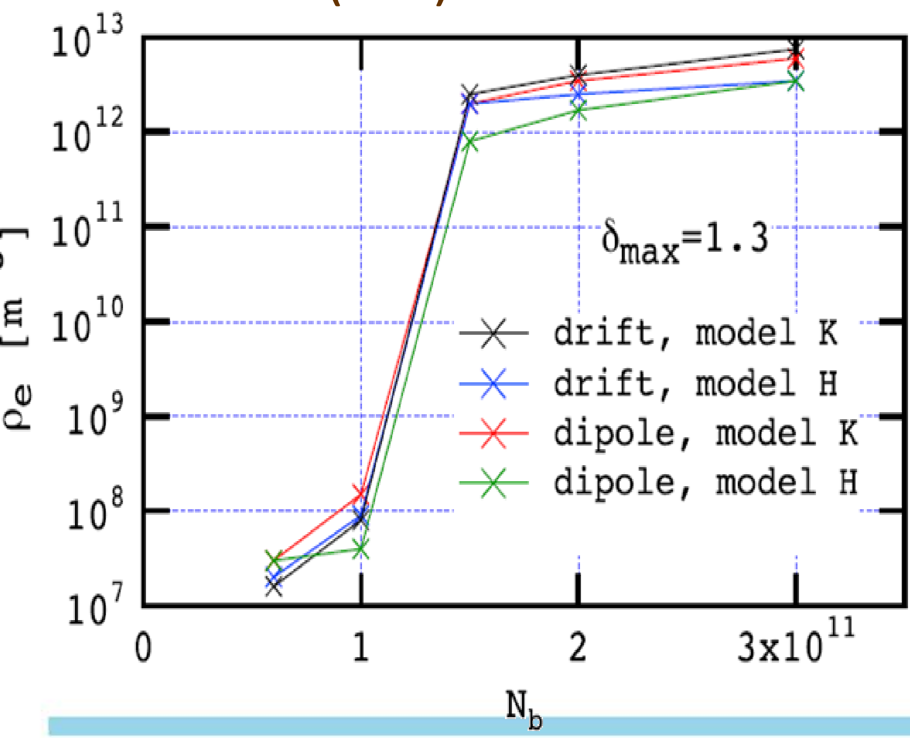
Slip-Stacking

- Slip-Stacking is central to near-term operations
  - Doubles the beam current by exploiting the large longitudinal acceptance of the Recycler and Main Injector
  - Vital to 700 kW for NOvA; also vital for 1.2 MW with PIP-II
- Slip-stacking losses will limit beam power
  - Losses must be kept < 5% for 700 kW in immediate future
  - Kept to < 3% for PIP-II
- Major (expensive) question is whether slip-stacking is acceptable for later upgrades
    - Trade-off of slip-stacking losses vs. doubled beam current in the previous synchrotron
    - R&D now into the process will inform this future decision, and also guide near-term program for upgradeability

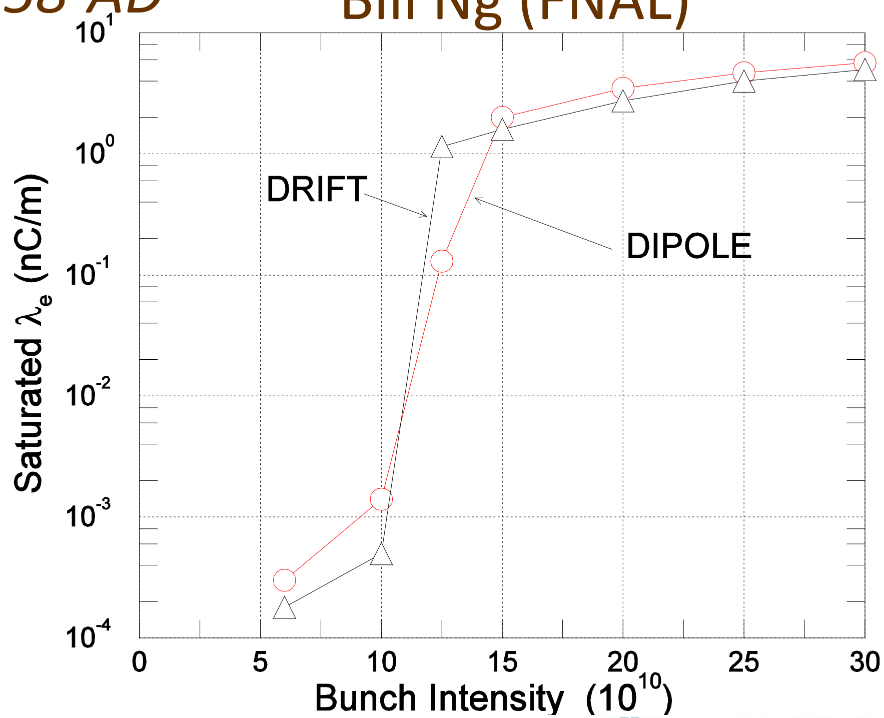
Electron Cloud at Fermilab

- Early simulations suggested that the Main Injector may be near a threshold for electron cloud formation
  - Above a certain intensity level, a catastrophic number of free electrons may be created and distort the beam
- Recent operation with the Recycler has been suggestive of an electron cloud forcing a strong horizontal instability

M. Furman (LBL) *FERMILAB-PUB-05-258-AD*



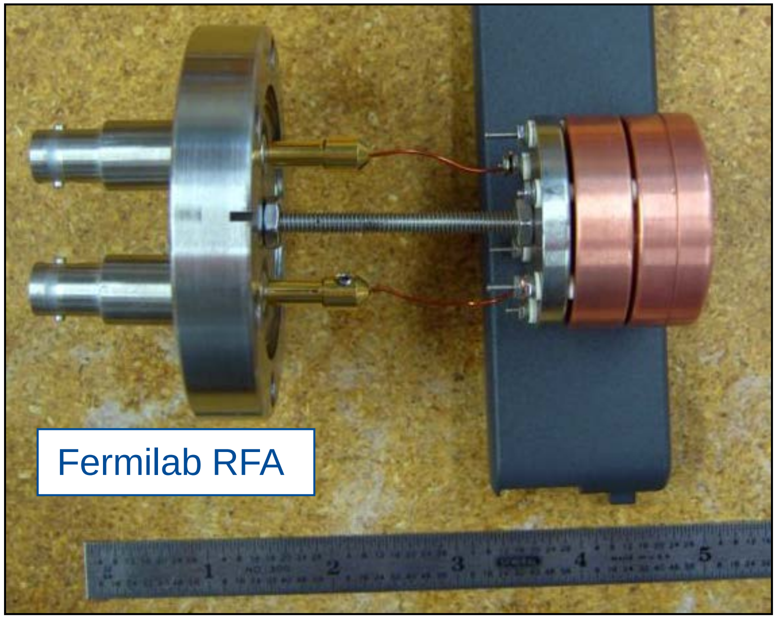
Bill Ng (FNAL)

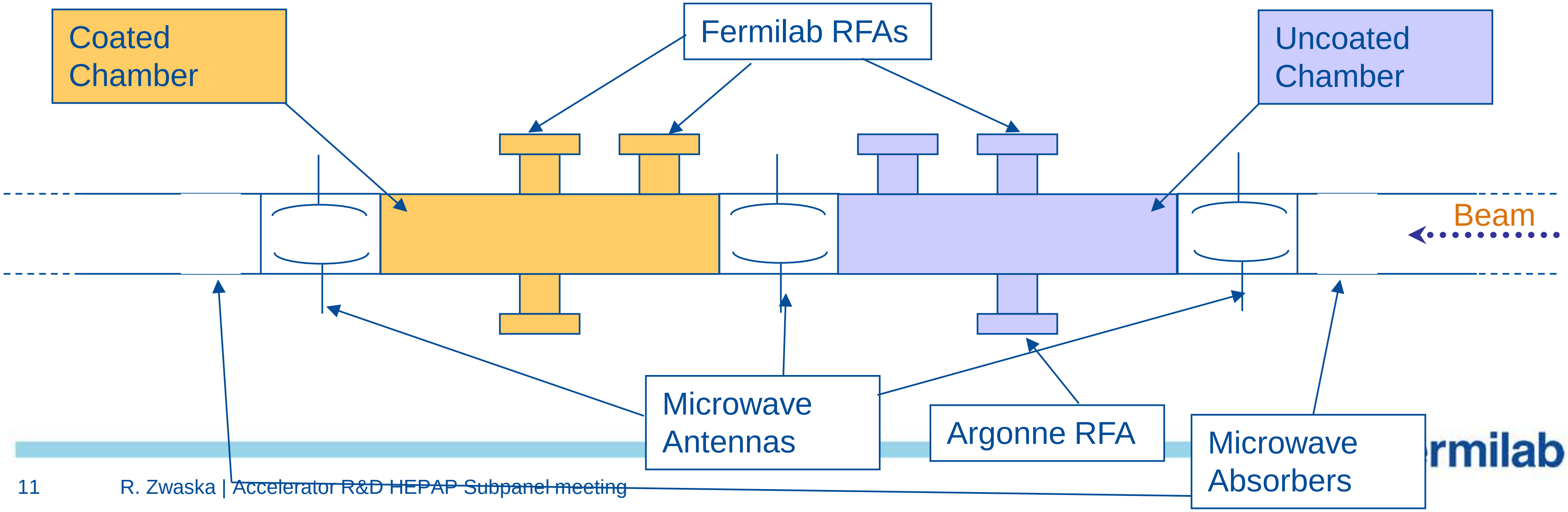


Electron Cloud Experimental Station

Upgraded Station in Main Injector:

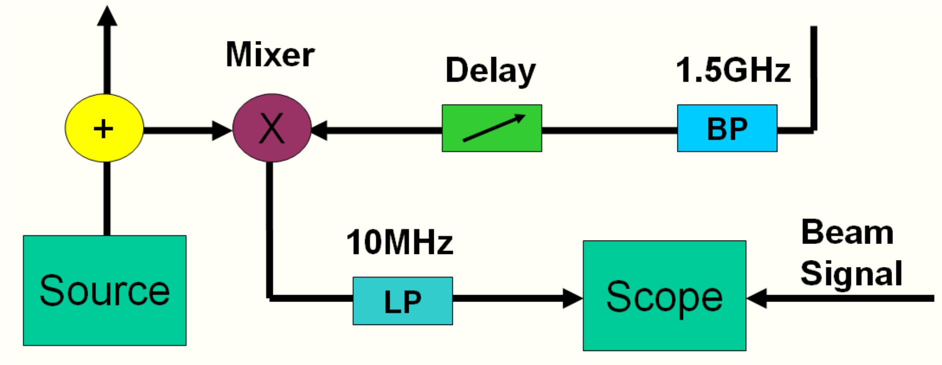
- 2 experimental Chambers (coated and SS)
  - Test coating for ECloud suppression
- 3 Fermilab and 1 Argonne RFA
  - Retarding Field Analyzers
  - Directly measure electron flux
- 3 microwave antennas and 2 absorbers
  - Measure ECloud density by phase delay of microwaves
- Testing multiple chambers:
  - TiN, α-C (CERN): Complete
  - DLC (KEK): Underway
  - Graphite (KEK): Planned

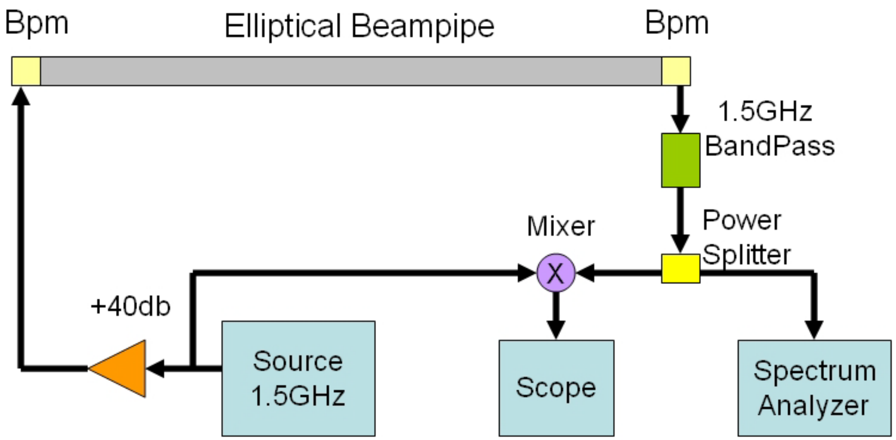


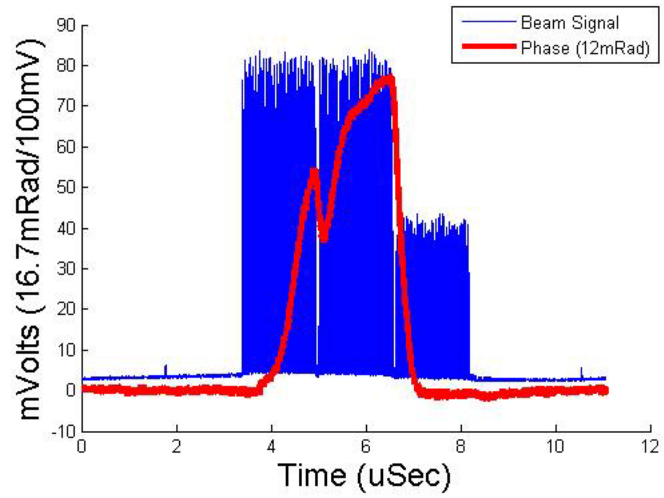


Microwave Measurements

- Electron cloud causes a phase modulation of microwave traversing beam pipe
- Sideband and direct phase measurements
- Allows measurement in dipole sections
- Techniques needed to control measurement region and absolutely calibrate measurement







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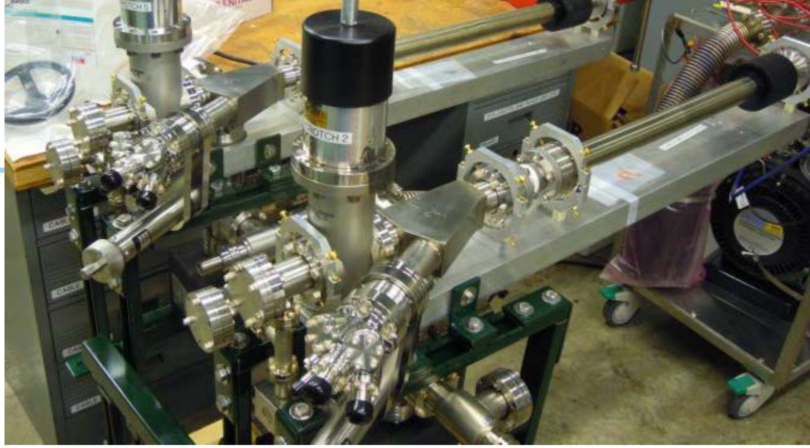
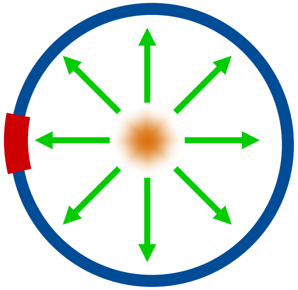
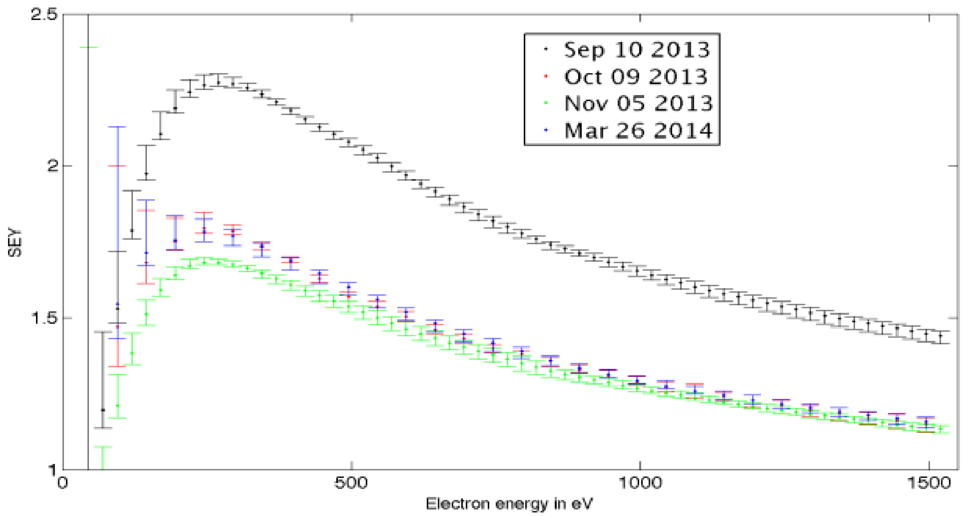
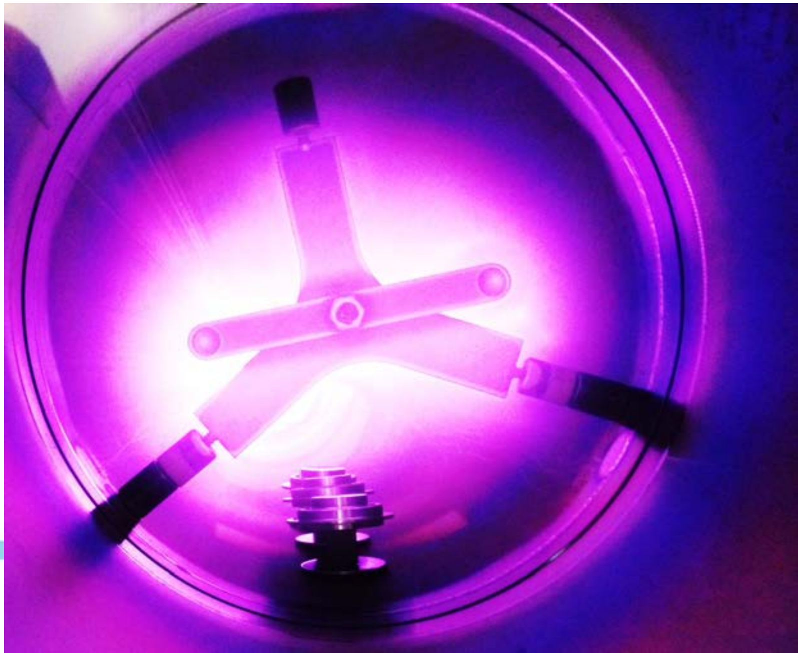
Direct SEY Measurement



- SEY measurement station from Cornell, adapted from SLAC
  - Allows in situ measurement of SEY on samples
- Place sample "buttons" of materials as portion of beampipe circumference
- Directly measure the SEY of the sample
- Comparison between conditioning in electron/positron ring and our proton ring
- Beam irradiation "scrubs" the surfaces
  - Ultimate SEY is an open question
- Newly coated TiN will be installed in FY15
- IIT working on coatings & SEY measurements (Prof, PhD student, NSF)





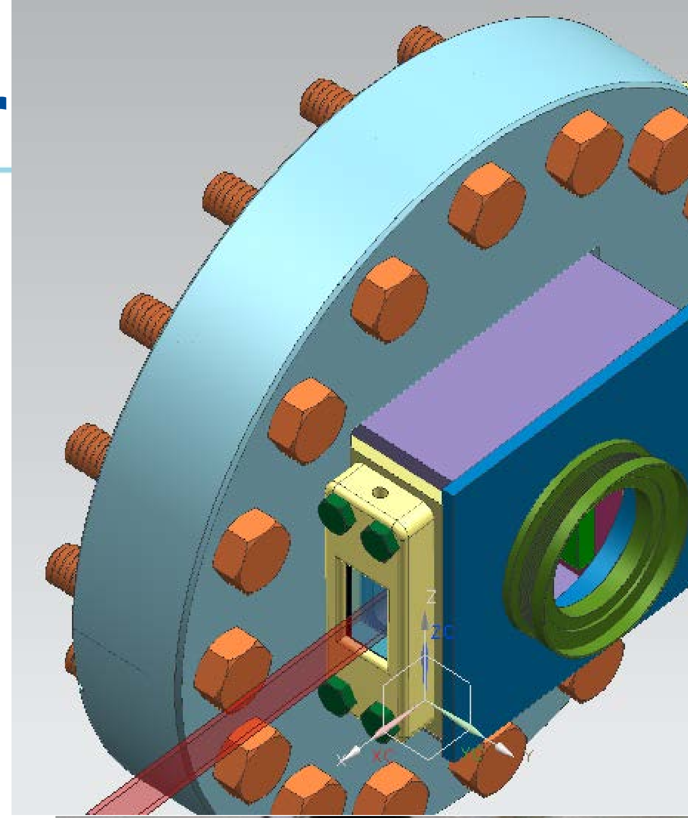


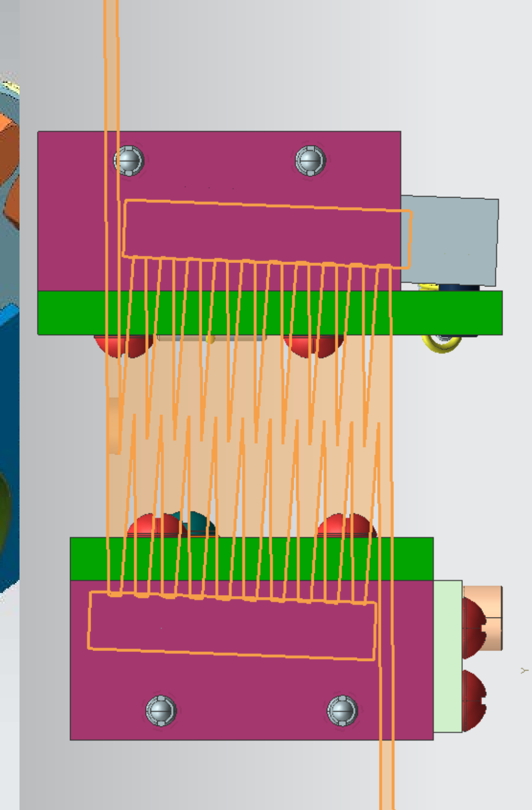
Electron Cloud Program

- Develop tools to understand Electron Cloud for PIP-II and other future accelerators
  - LHC, ILC, future proton machine, light sources
- Measurements in existing machines
  - Understand the cloud as it exists
  - Install experimental sections (specifically within magnets)
- Develop Instrumentation
- Develop Mitigation
- Develop Models of beam instability

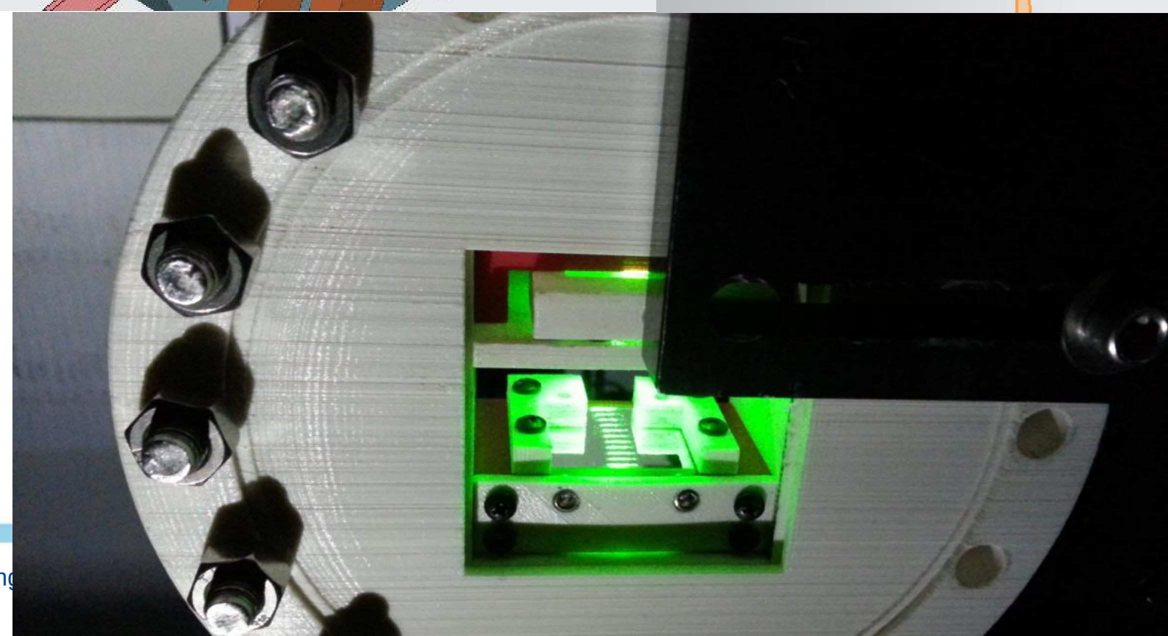
Laser Notcher

- Neutralize a portion of the Linac beam with a pulsed laser
  - Form a “notch” within the Booster without kickers
  - Remove the majority of the loss from the Booster entirely

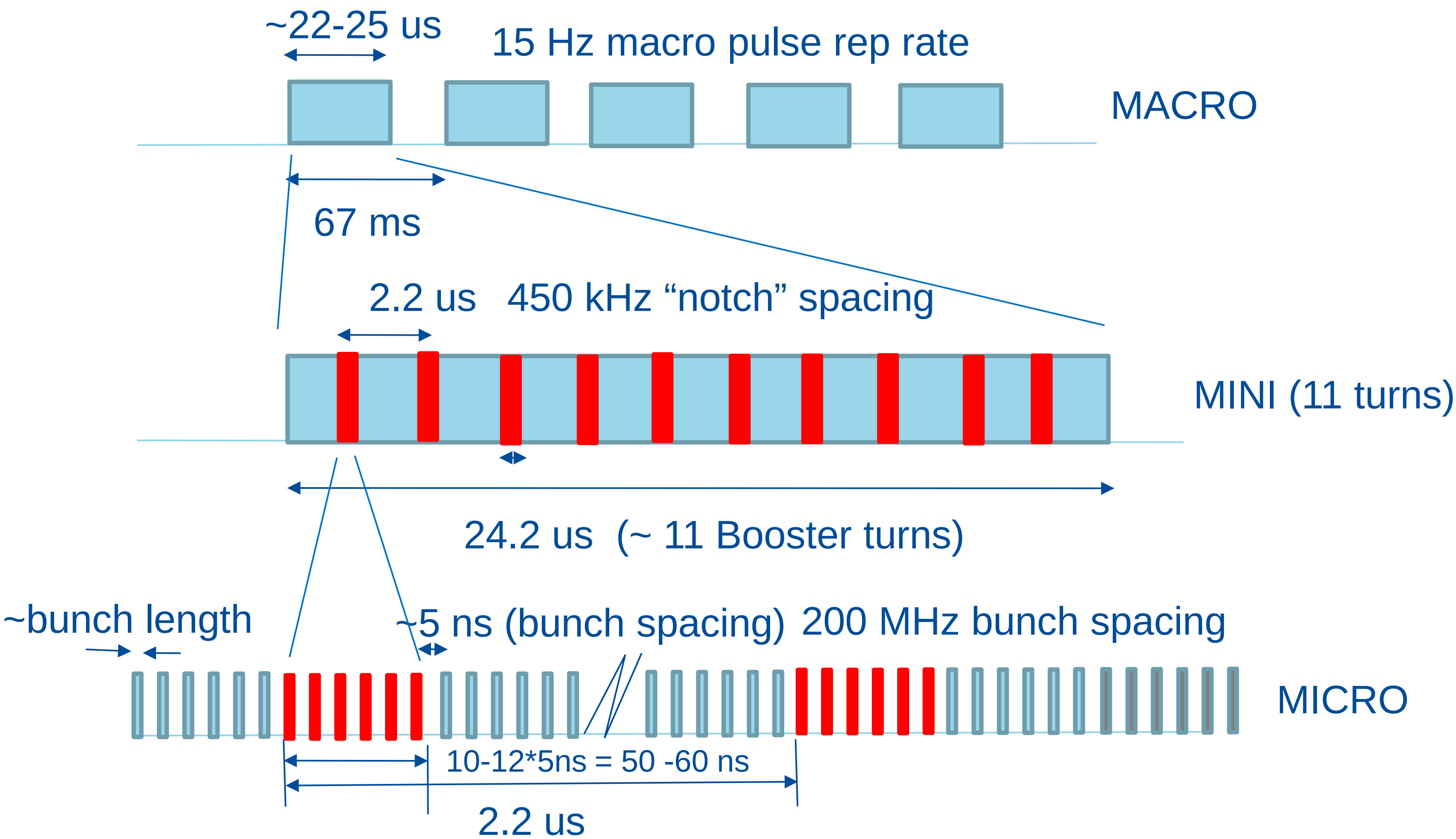




- Atypical laser
  - Multiple timescales
  - High-pulse power
  - Moderate average power (few W)



Linac Beam Bunch Structure



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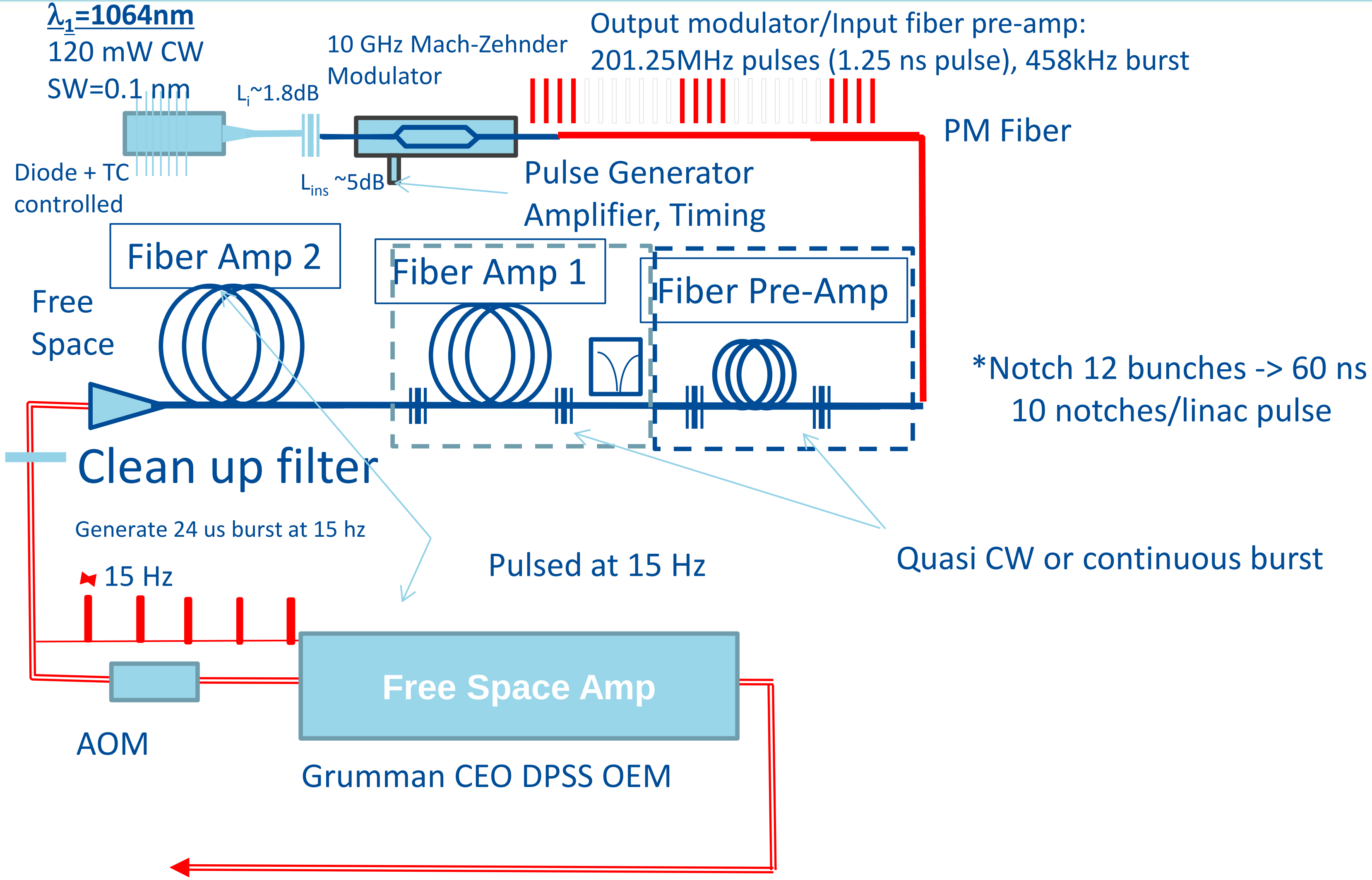
Laser system outline



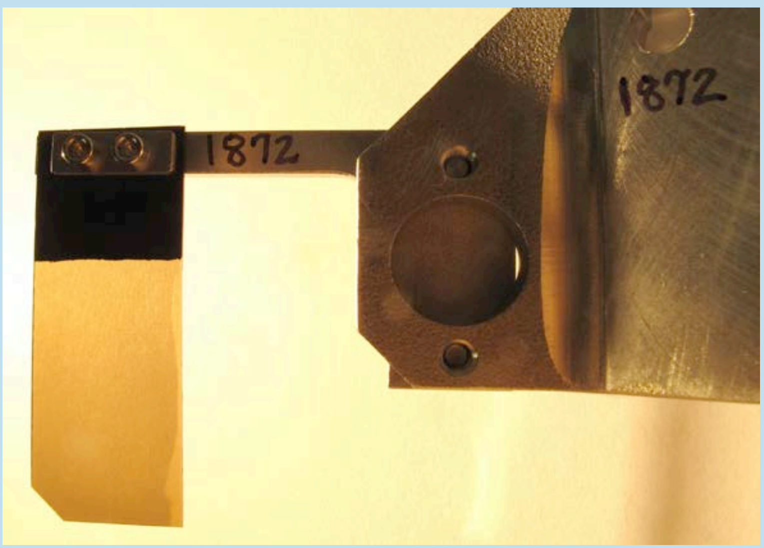
TRANSPORT BEAM SHAPING OPTICS & OPTICAL CAVITY

H⁻ Laser Stripping

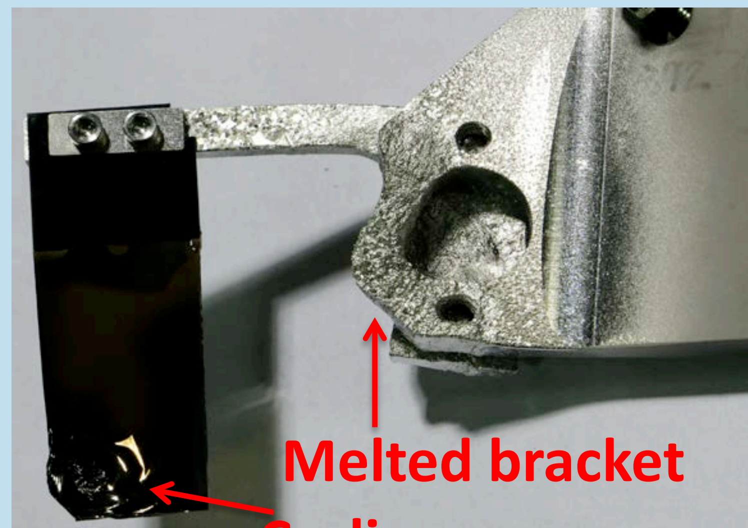
- Injection foils may not survive in beam powers >1.5 MW.
- Seeing *many* cases of foil damage at SNS – curling, tears, melting brackets, etc.
- Damage increasing exponentially with higher beam power.
- Due to injection beam loss, SNS injection region is hottest area in accelerator (~800 mrem @ 30 cm).

2014 SNS foil: 3 months in 1 – 1.4 MW beam

Before



After

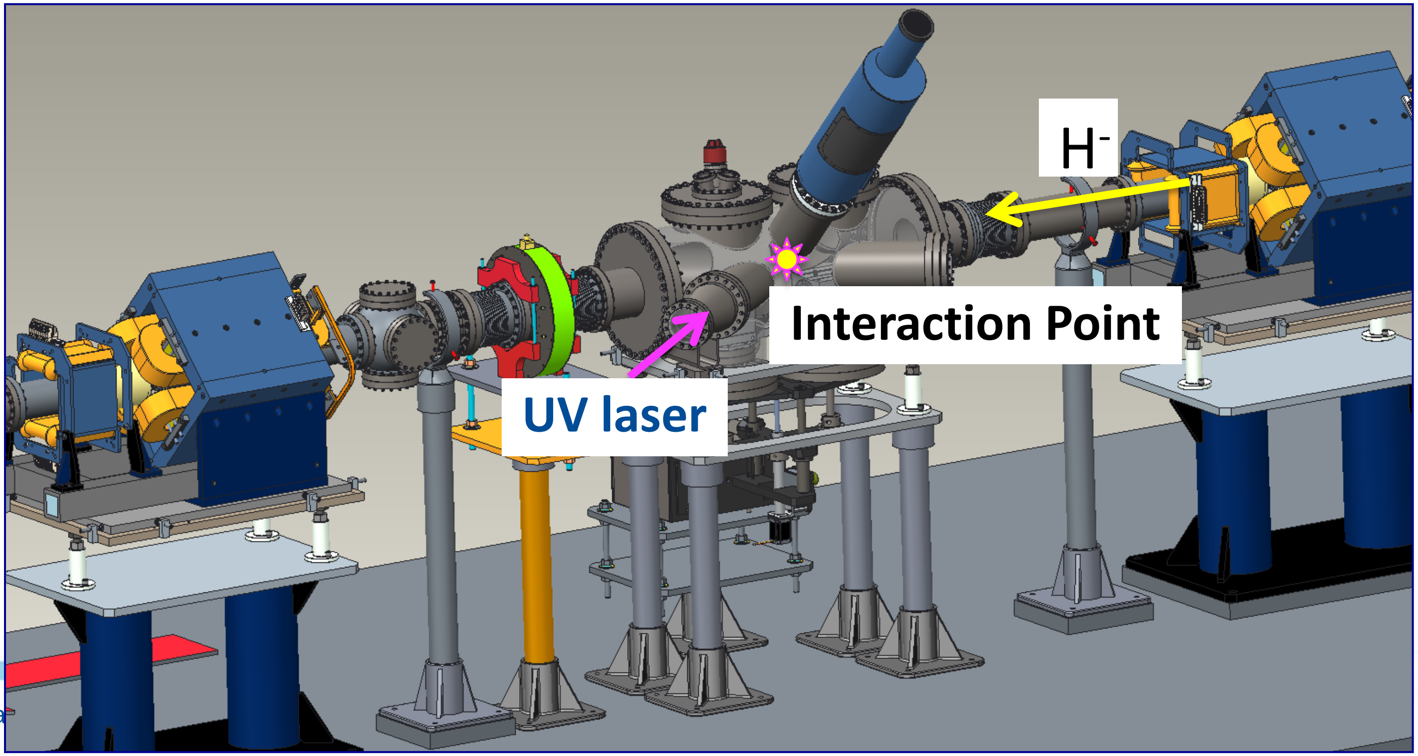


10 us Laser-Assisted H⁻ Stripping Demonstration

THE UNIVERSITY of TENNESSEE KNOXVILLE
OAK RIDGE National Laboratory

- Preparations underway for 2016 demonstration of H^- laser-assisted stripping of a 10 us, 1 GeV H^- beam at SNS (S. Cousineau *et al*.).
- Parallel lab-based effort to develop a laser power recycling cavity for future stripping of ~1 ms pulse.
- Eventual plans to mature system to HEP operational needs – injection painting, etc.

Final Design of Experimental Station



H^- Injection, Chopping, Notching, …

- The **notching** system acts as a prototype for future laser H^- devices
  - We develop and implement laser technology matched to a Linac beam structure
  - Gain long-term operational experience in an accelerator environment
- **Chopping**:
  - A higher duty-factor neutralization scheme for a Linac to produce arbitrary chopping of bunches, including intensity modulation
- **Stripping** Injection:
  - Replacement of foil systems with a laser ionization system. Requires higher energy and power laser.
- Beam "**sculpting**"
  - Selective neutralization and/or ionization of H^- beam to customize the beam parameters
    - E.g. collimation, beam-splitting, selection of the core, space-charge matched distributions

Achieving 99.9% Occupancy

- High-power and low-loss are different sides of the same coin
- Every small fraction of the beam must be watched, cared for, and carefully discarded (if necessary)
- Achieving low-loss requires new instrumentation, devices, techniques, measurement strategies, theories, simulations…
- Existing machines are an ideal place to test and demonstrate these approaches in realistic conditions

Recommended GARD thrusts

1. High-field magnets and materials
2. Multi-MW beams and targets
3. Cost-Effective SRF Technology
4. Advanced Accelerator Concepts
5. Accelerator Science, Modeling & Design
6. Core Accelerator Competencies

GARD Thrusts: Rationale and Goals

1. High-field magnets and materials
   - Far-term; maintain US leadership in SC magnets; Nb_3Sn, HiTc
   - Significant T*m cost reduction, modest support of global design
2. Novel techniques for multi-MW beams and targets

PIP-II | Beyond PIP-II

	1st 10 years	2nd 10 years		
To Achieve :	100 kT-MW-year	500 kT-MW-year		
We combine :		Option 1	Option 2	Option 3
Mass	10 kT	50 kT	20 kT	10 kT
Power	1 MW	1 MW	2.5 MW	5 MW
Time	10 years	10 years	10 years	10 years

   - Mid-term strategy after PIP-II depends on the technical feasibility of each option and the analysis of costs/kiloton versus costs/MW
   - R&D needed on effective control of beam losses in proton rings with significantly higher currents (Q_{SC}) and on multi-MW targets