Neutrino Factory R&D

John Back
University of Warwick
1st March 2007

Outline

- Why do we need a Neutrino Factory?
- A sample of UK R&D work
  - Front End Test Stand @ RAL
  - Target Studies
  - Other work
- Summary

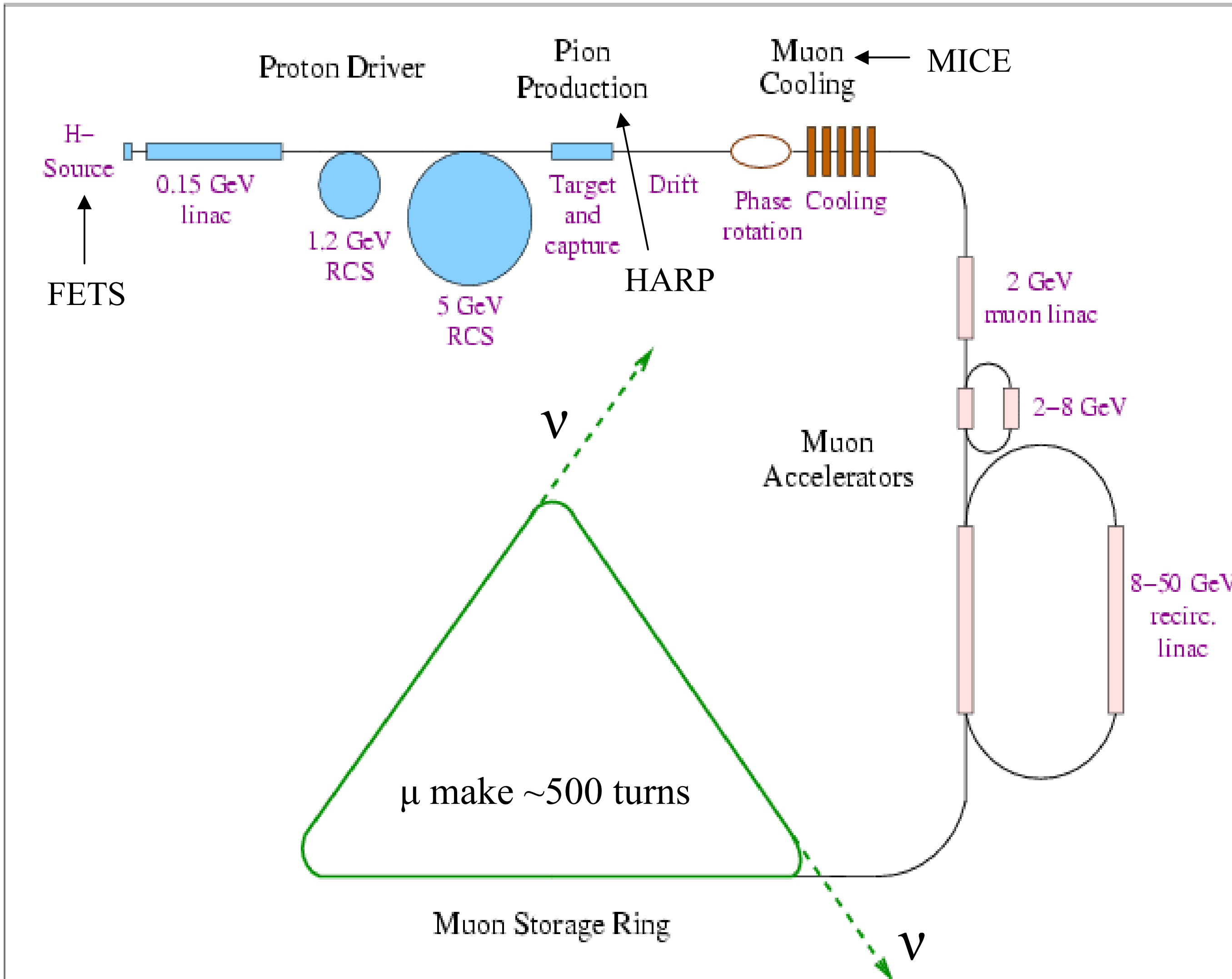
Motivation for ν Factory

- Experimental evidence of ν oscillations
  - Implications for Standard Model: ν's have mass
  - Need more data to explore neutrino physics:
    - $\sin^2 2\theta_{13}$, CP-violation ($\sin\delta$), mass hierarchy
- Neutrino Factory will produce ν's "on demand"
  - Accelerator complex to produce ν's at the required energies in a controlled way.
  - Point ν's from μ decay to detectors around the world (long-baseline method)
  - Extensive international R&D programme underway to address the technological challenges, most of which is beyond current state-of-the art…

ν Factory Requirements

- Need 10^{21} μ/yr for physics programme
  - Very low ν interaction cross-section in detectors
  - Approx. several hundred ν events/yr at a large detector on other side of the Earth (hep-ph/9906487)
- μ from π decays, which are created by smashing protons onto a solid or liquid target
- Proton beam with 4 MW power
  - A challenge to create a target that can withstand this much power and the resulting thermal shock
  - Studies focusing on large solid or liquid target within a very strong B field
- Focus & accelerate μ's to required energies, then allow them to decay to ν's: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ and $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

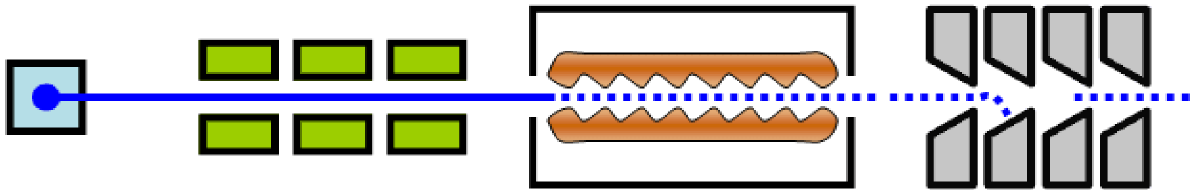
Schematic of Neutrino Factory



Front End Test Stand (FETS) @ RAL

- FETS is part of CCLRC's contribution to accelerator R&D for next generation facilities
  - Spallation sources, ν Factory, waste transmuters, tritium production
- Collaborative effort between
  - CCLRC RAL ISIS/ASTeC Intense Beams group
  - Imperial College
  - Warwick University
  - University of the Basque Country, Spain (new participants)
- Main aim is to demonstrate the technology for a high brightness H^{-} ion source and a very high speed beam chopper.
- New design based on the proton driver system already in operation at ISIS, RAL (neutron production facility).

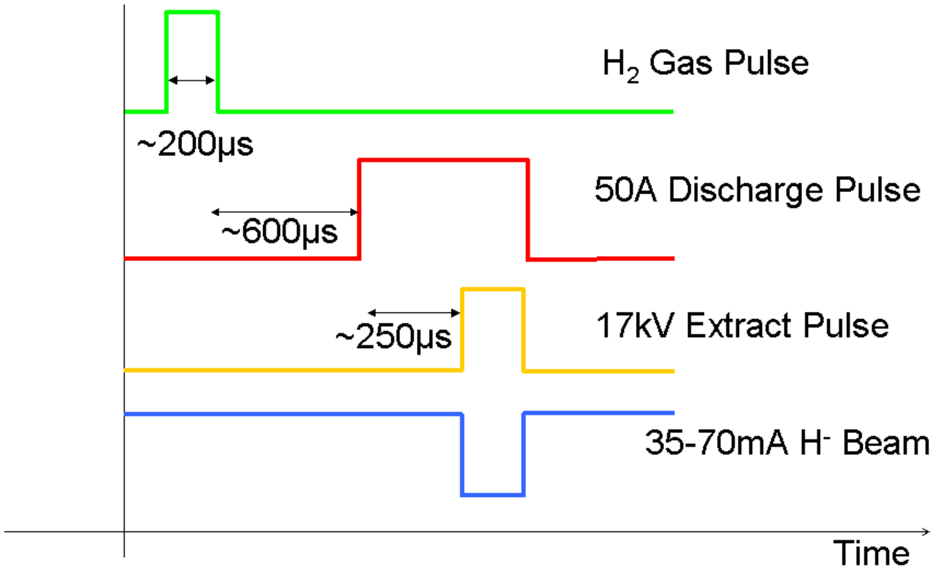
FETS Layout

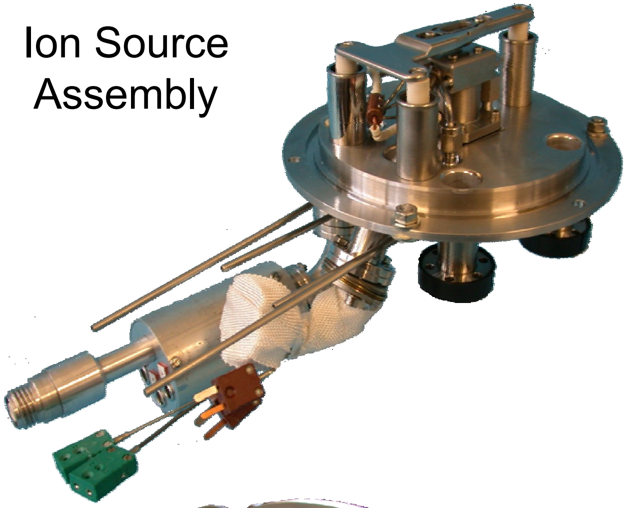


H⁻ ion source LEBT Radio Frequency Quadrupole (RFQ) Beam chopper

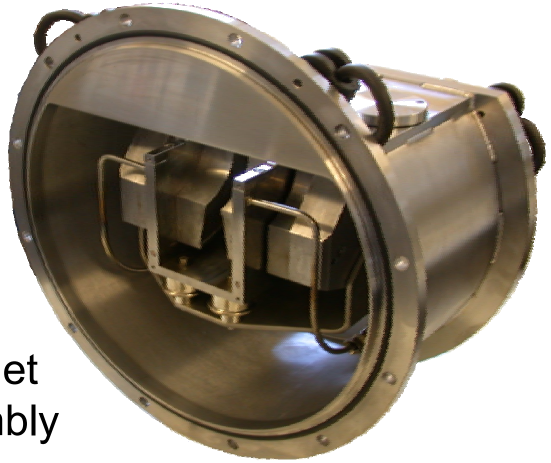
- H^- ion source: I = 60mA, KE = 65keV
- Low Energy Beam Transport: focus H^- beam to RFQ
- RFQ accelerates beam up to 3MeV
- Chopper will divide the beam into bunches
- Diagnostics along the FETS line will measure the beam parameters, and hence the performance of the various accelerator components

H⁻ Ion Source (D. Faircloth, RAL)





Ion Source Assembly



Magnet Assembly

Development goals (done, to do)

Increase pulse length: 200μs to 1.5ms

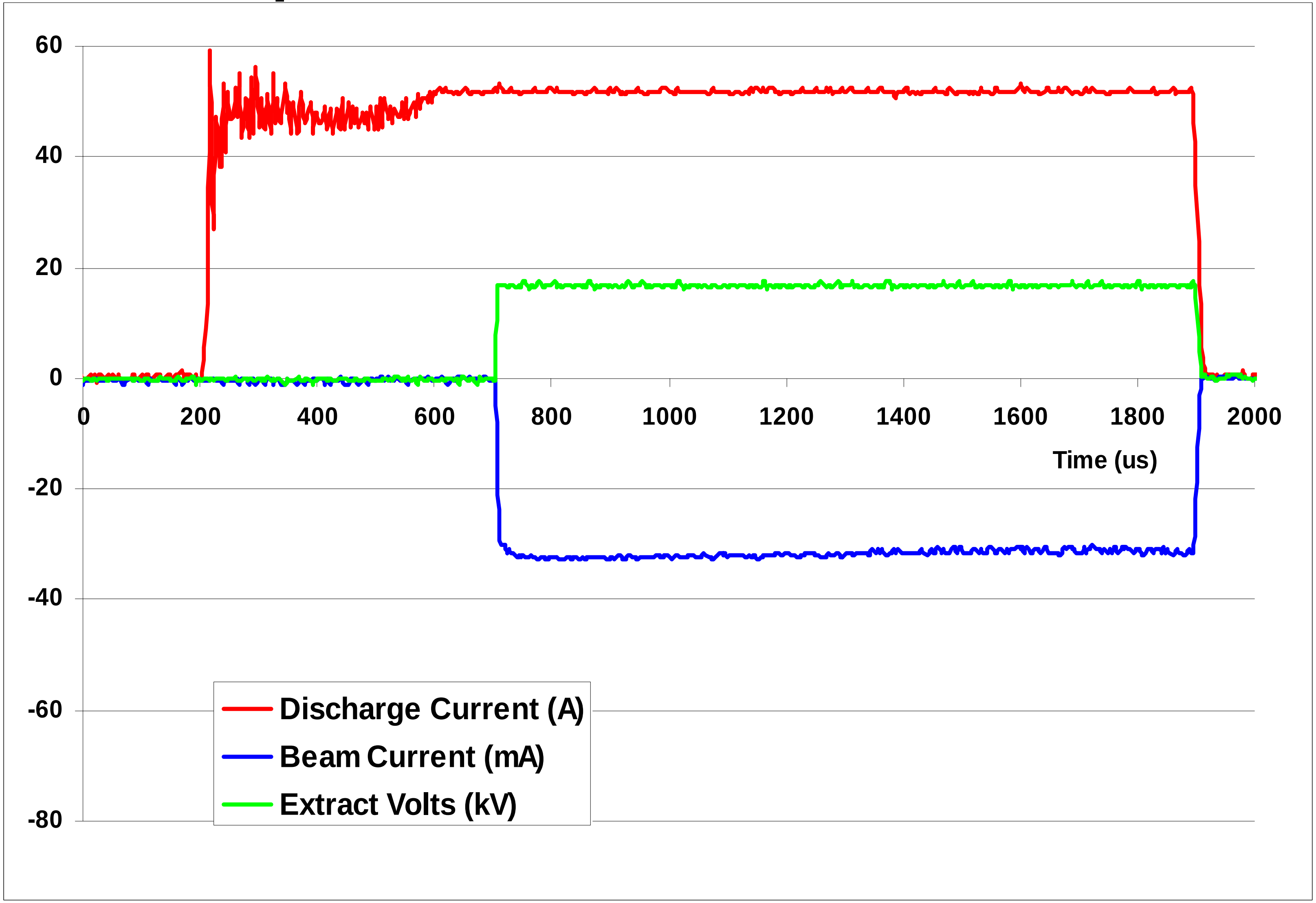
Increase output current: 35mA to 75mA

Reduce emittance ε (size & divergence of beam)

Now: ε ~ 1π mm mrad. Need: ε ~ 0.25π mm mrad

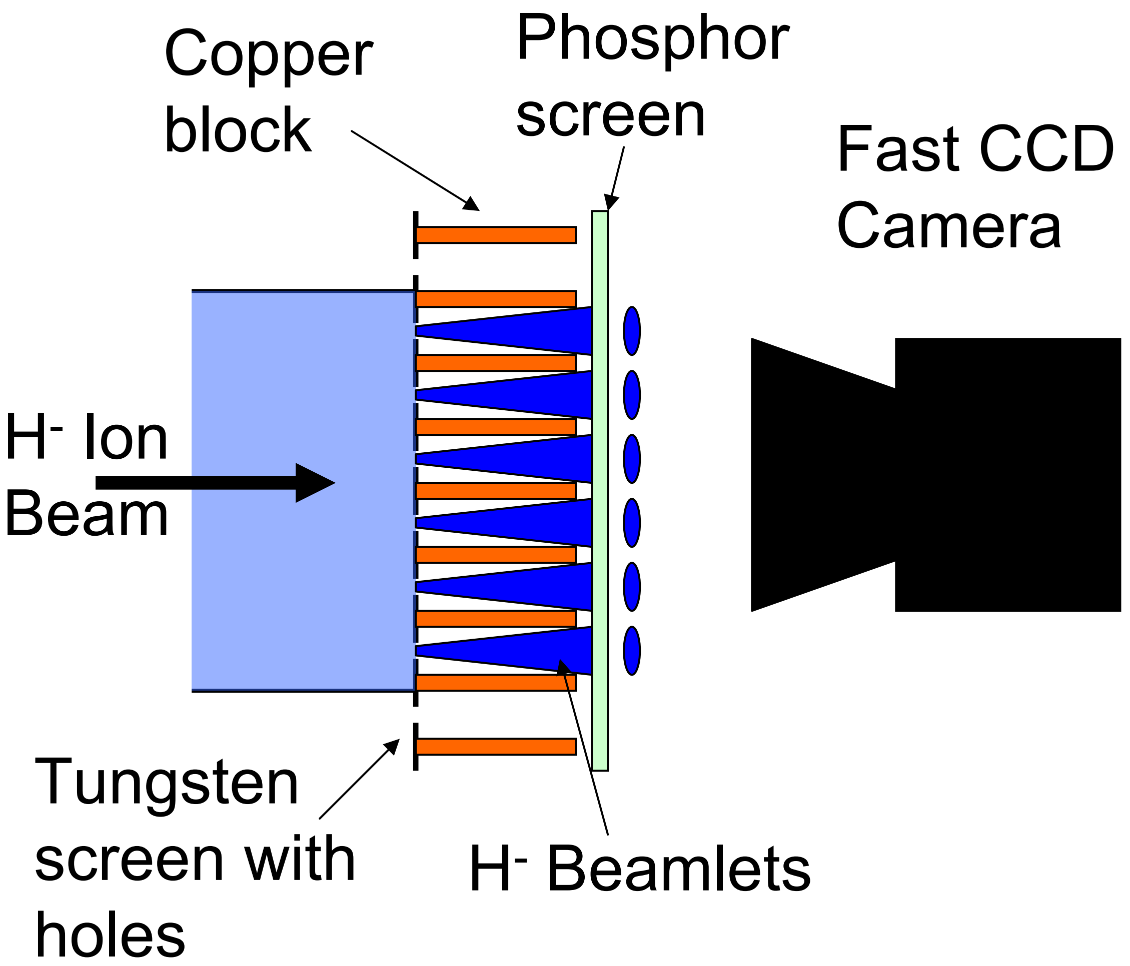
Maximise lifetime

Example Current Distribution

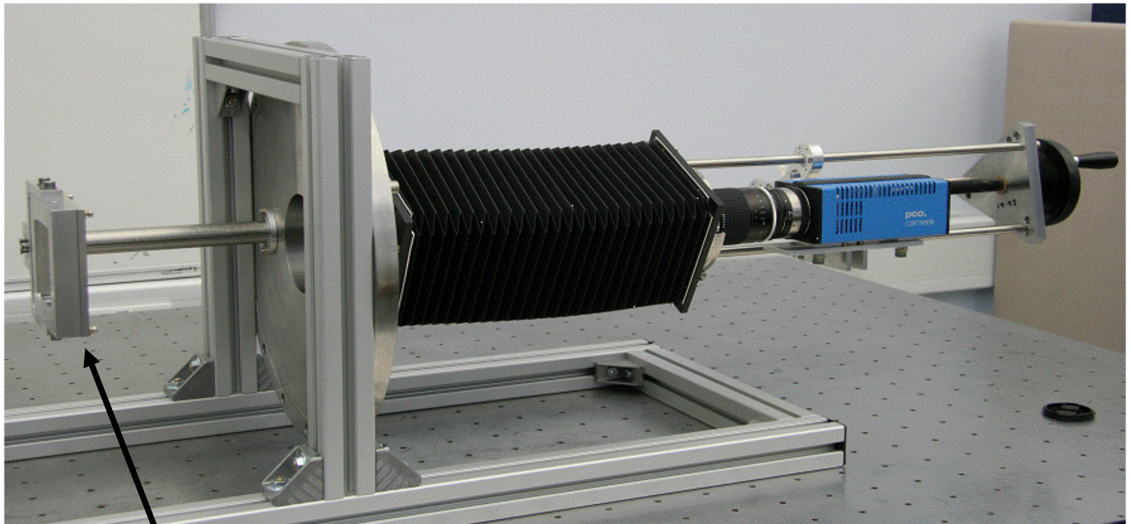


Pepperpot Emittance System (S. Jolly, IC)

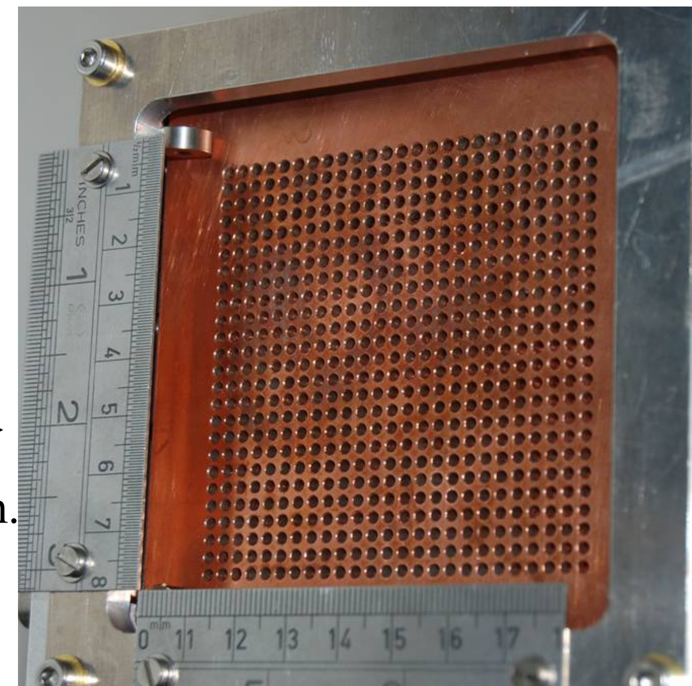
- A way to measure the initial beam size and shape from the ion source; needed to finalise LEBT design
- Beam segmented by tungsten screen.
- Beamlets drift ~10mm before producing an image on a phosphor screen.
- Copper block prevents beamlets from overlapping and provides cooling.
- CCD camera records image of light spots.



Pepperpot Mk1 Equipment



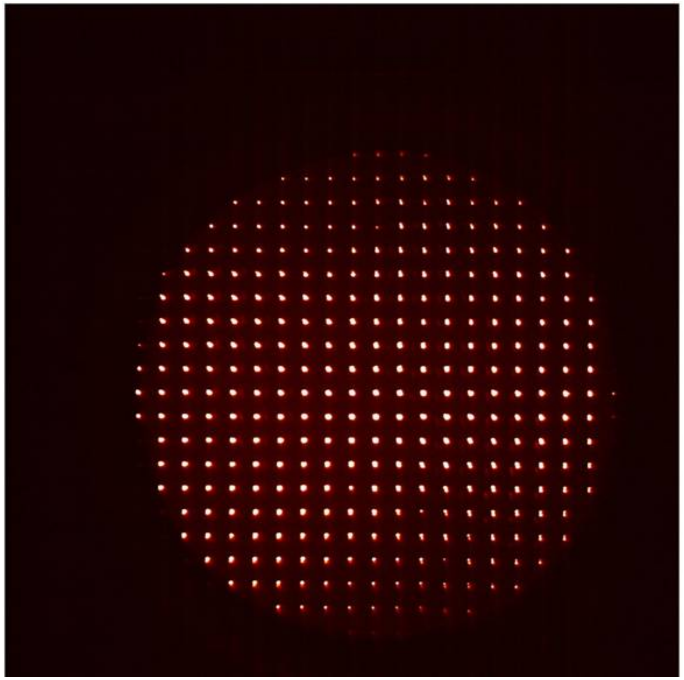
2048 x 2048 pixel, 15.3 x 15.6 mm^2 CCD camera mounted on movable arm. Light-tight bellows connects camera system to vacuum window.



Tungsten screen with 100μm holes in 25x25 array.
Cu mount with 2mm holes to prevent beamlet crossover and help thermal conduction.
Scintillator (e.g. P46) mounted 13mm from tungsten.
Mounted to Al frame: rulers give calibration.

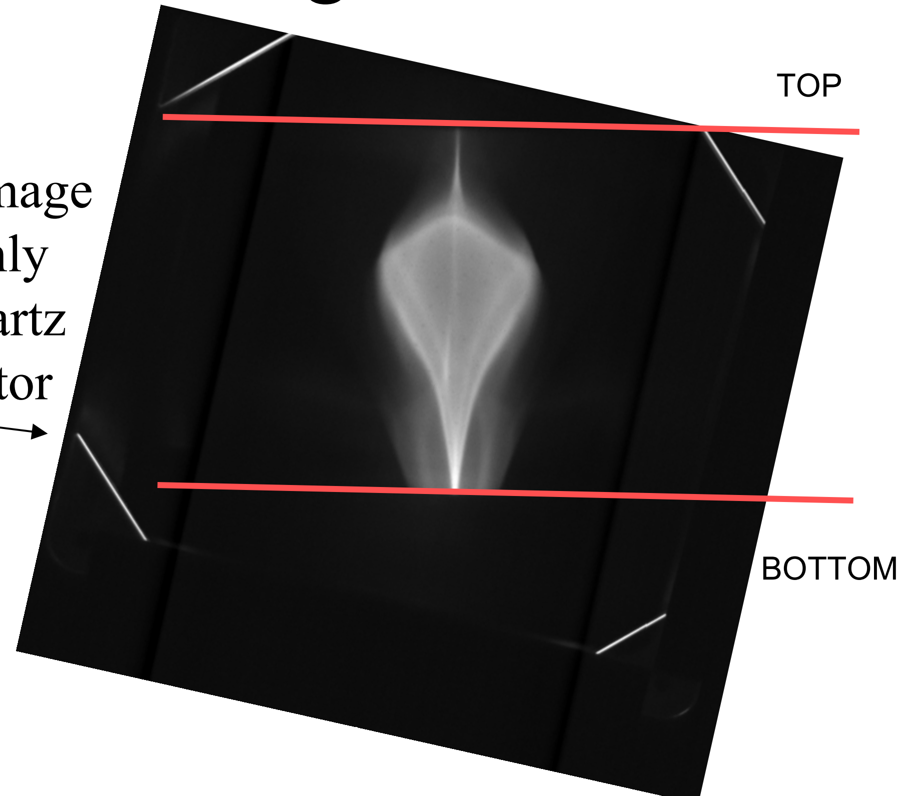
At present, Mk2 is being constructed: larger screen, quartz scintillator (survives beam unlike P46); better cooling, support structure and improved data analysis.

Pepperpot Mk1 Images



P46 phosphor scintillator image of H- beamlets

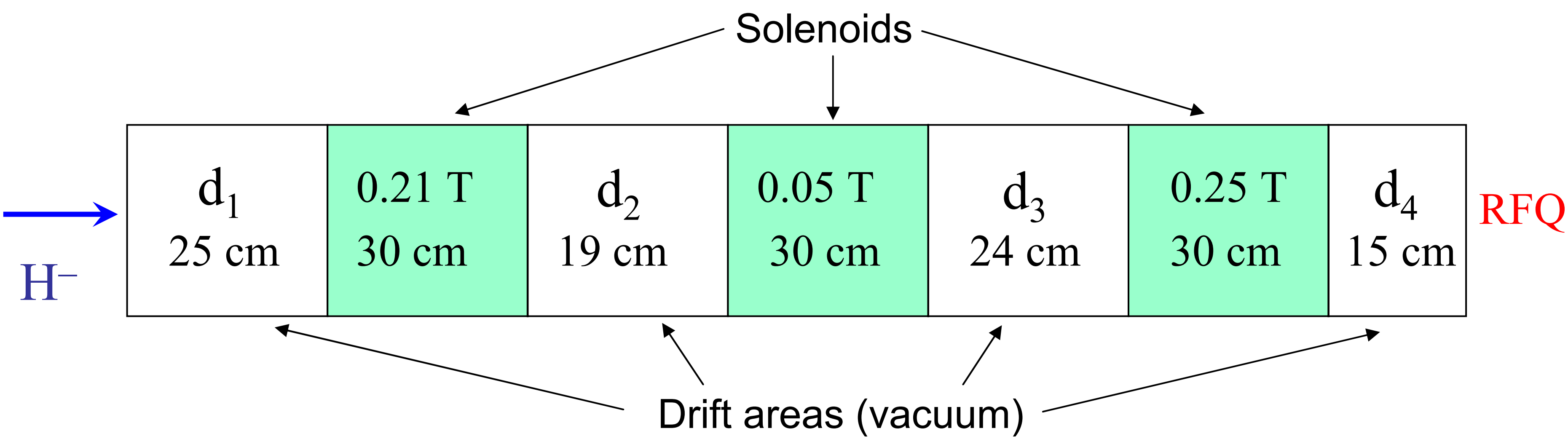
Beam image using only pure quartz scintillator



Burn marks on P46 scintillator

Low Energy Beam Transport (LEBT)

The LEBT will focus the H^- beam from the ion source into the RFQ.



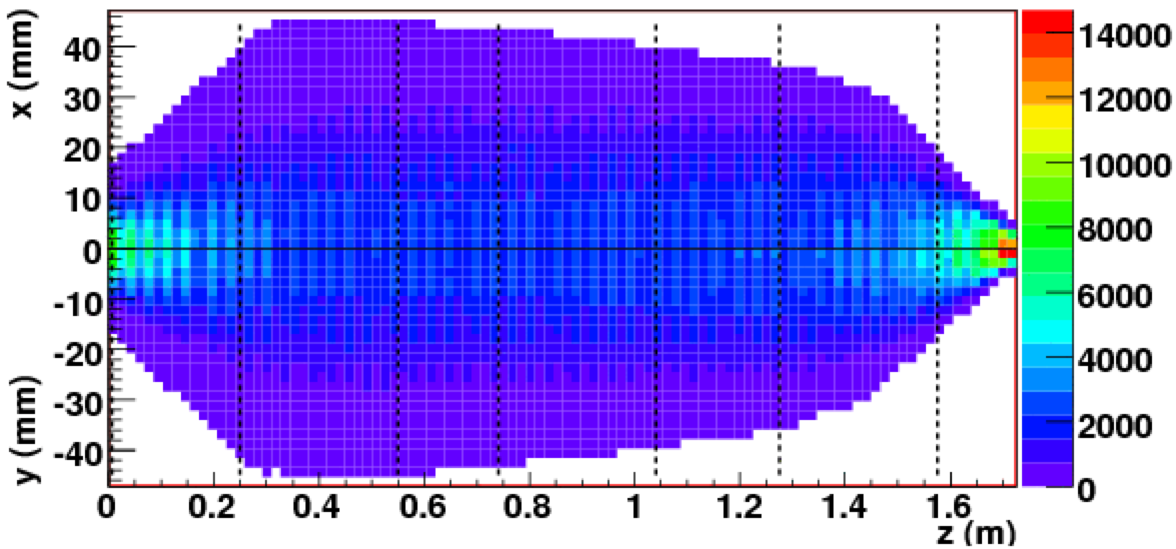
Design optimisation: Vary drift lengths d_2 and d_3 and the solenoid lengths and B fields.

Look for solutions where the beam is focused (converging) into the RFQ.

Constraints:

- $B < 0.6$ T, solenoids long enough to ensure flat axial field ($d \geq 25$cm)
- $d_1 = 25$cm, $d_4 = 15$cm (minimum for vacuum equipment and diagnostics)
- Overall length must not be too long (cost)

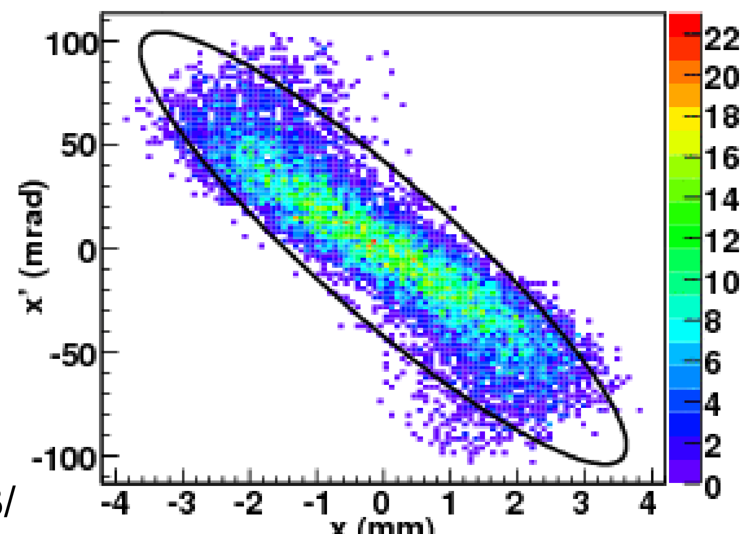
Beam profile for ideal input beam

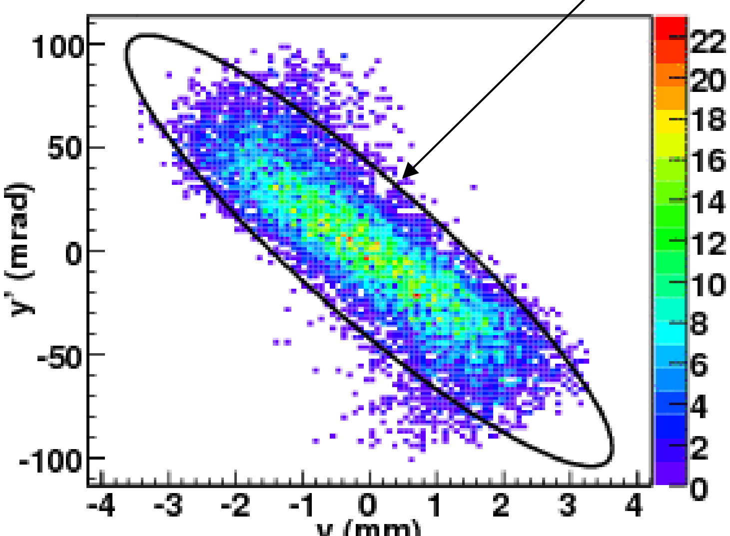


Vertical lines: Drift and solenoid regions

RFQ Acceptance Ellipse

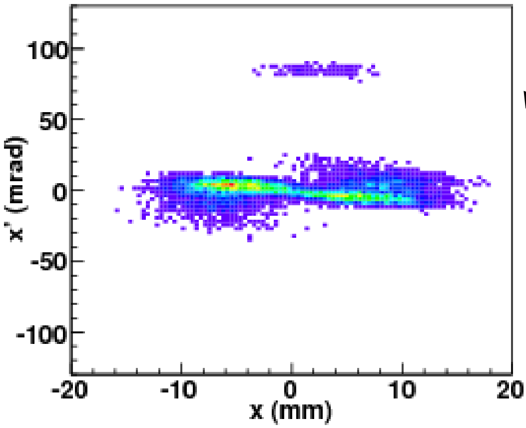
End of LEBT:

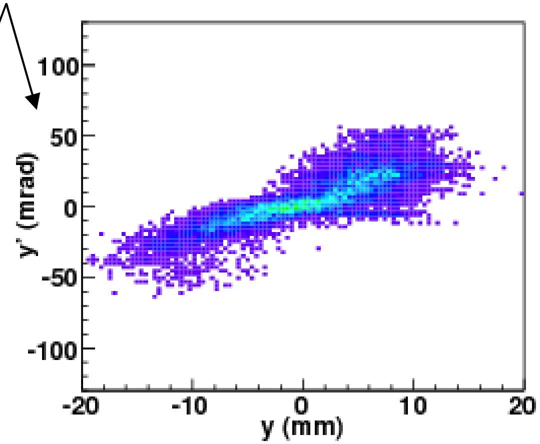




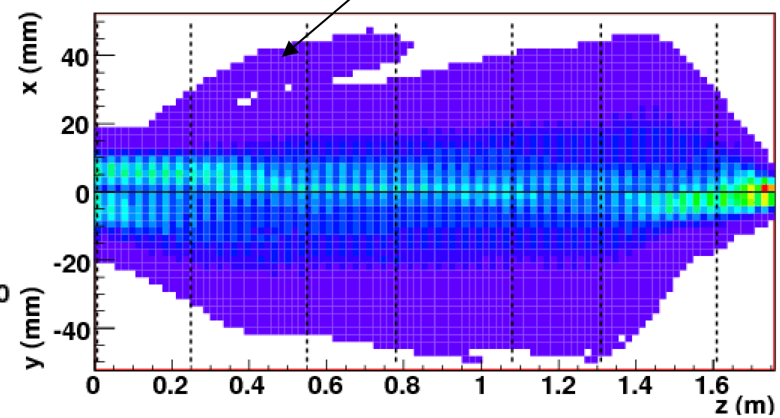
Beam profile using Mk1 pepper-pot data

Initial beam distribution based on pepper-pot data $\varepsilon_{rms\ norm} \sim 0.9\ \pi$ mm mrad

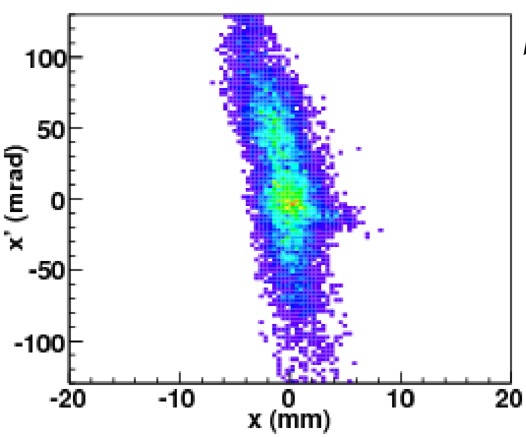


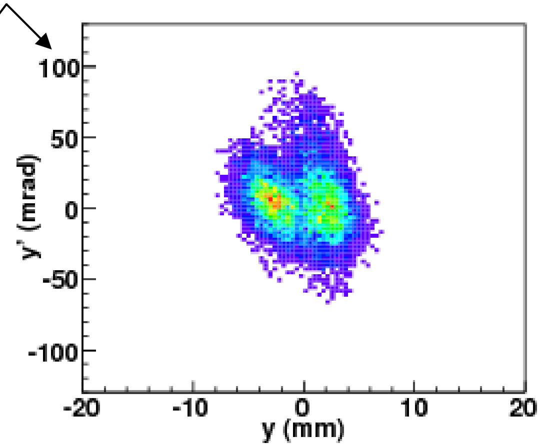


1% beam loss



At end of LEBT

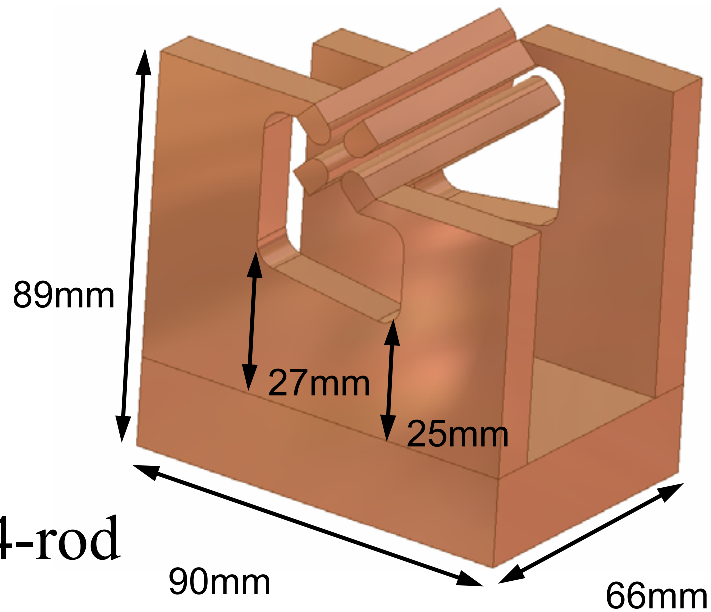




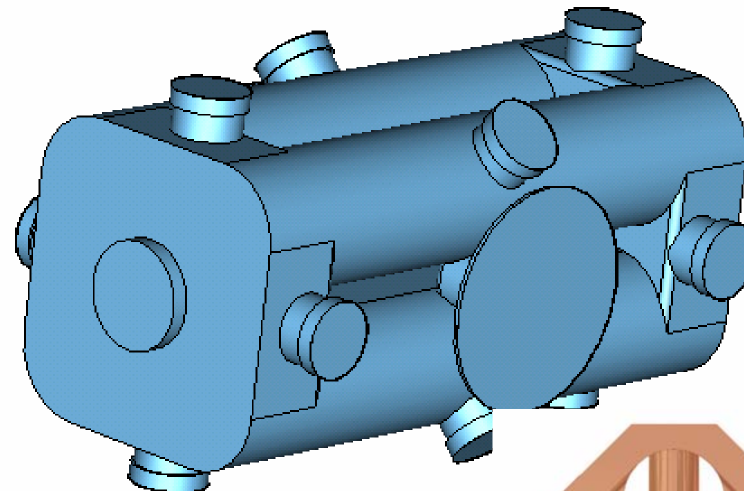
Performance will improve:
- better pepperpot data soon,
- work is starting to reduce emittance of beam from the ion source

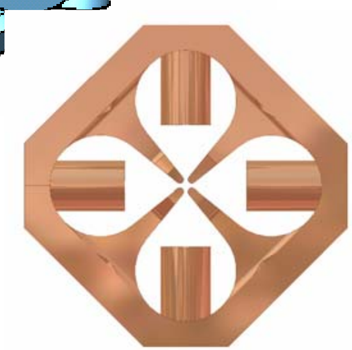
FETS RFQ (A. Kurup, P. Savage, IC)

- Requirements:
  - Accelerate 60mA H^- beam from 65keV to 3MeV. Input emittance is 0.25π mm mrad and transmission efficiency is ~95%.
- Frequency of operation: 324 MHz



4-rod





4-vane design

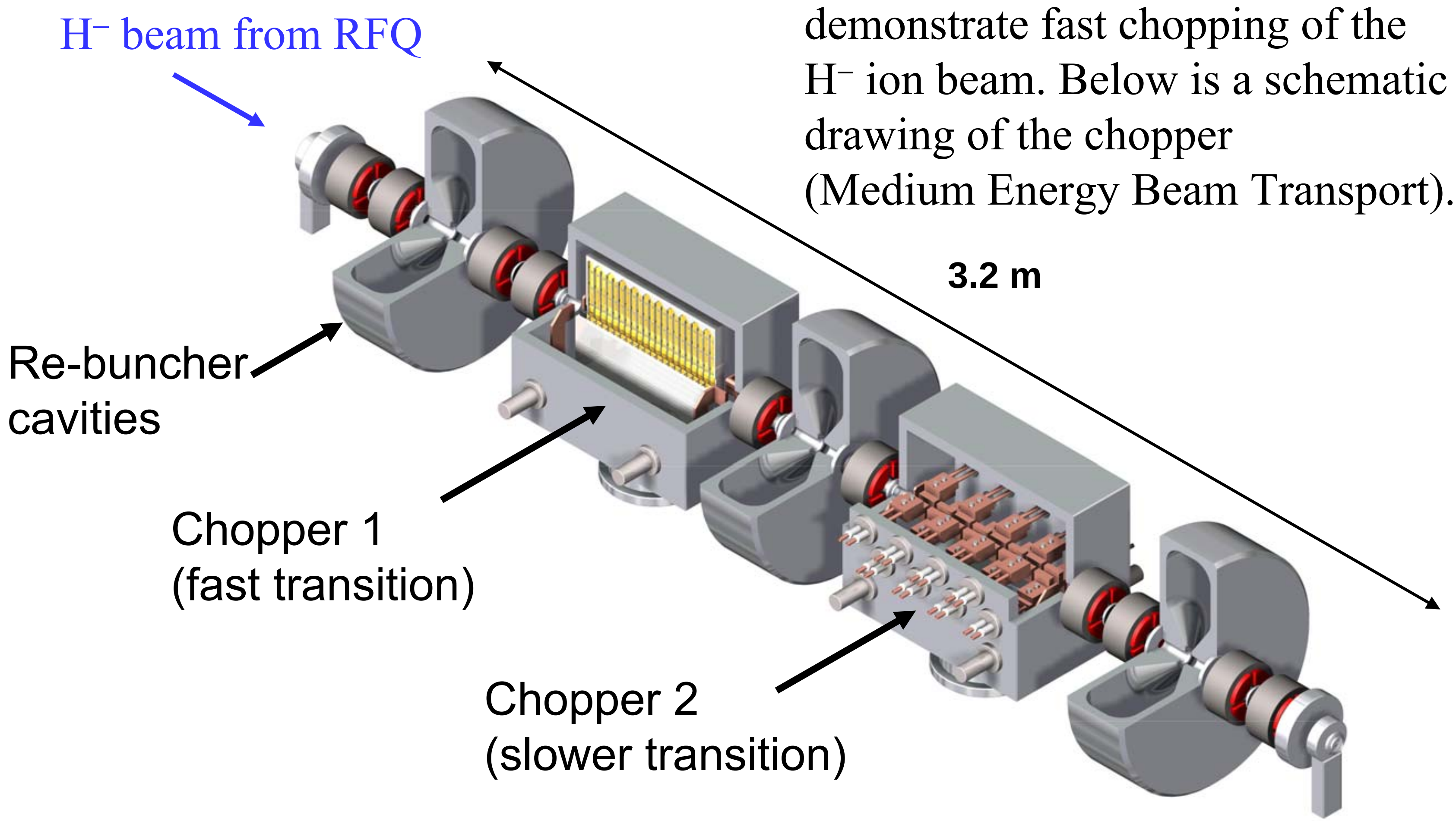
- 4-rod will be difficult to cool adequately; 4-vane is the preferred option
- Simulations are ongoing to get best design. Total length will be 4m.

RFQ Cold Model

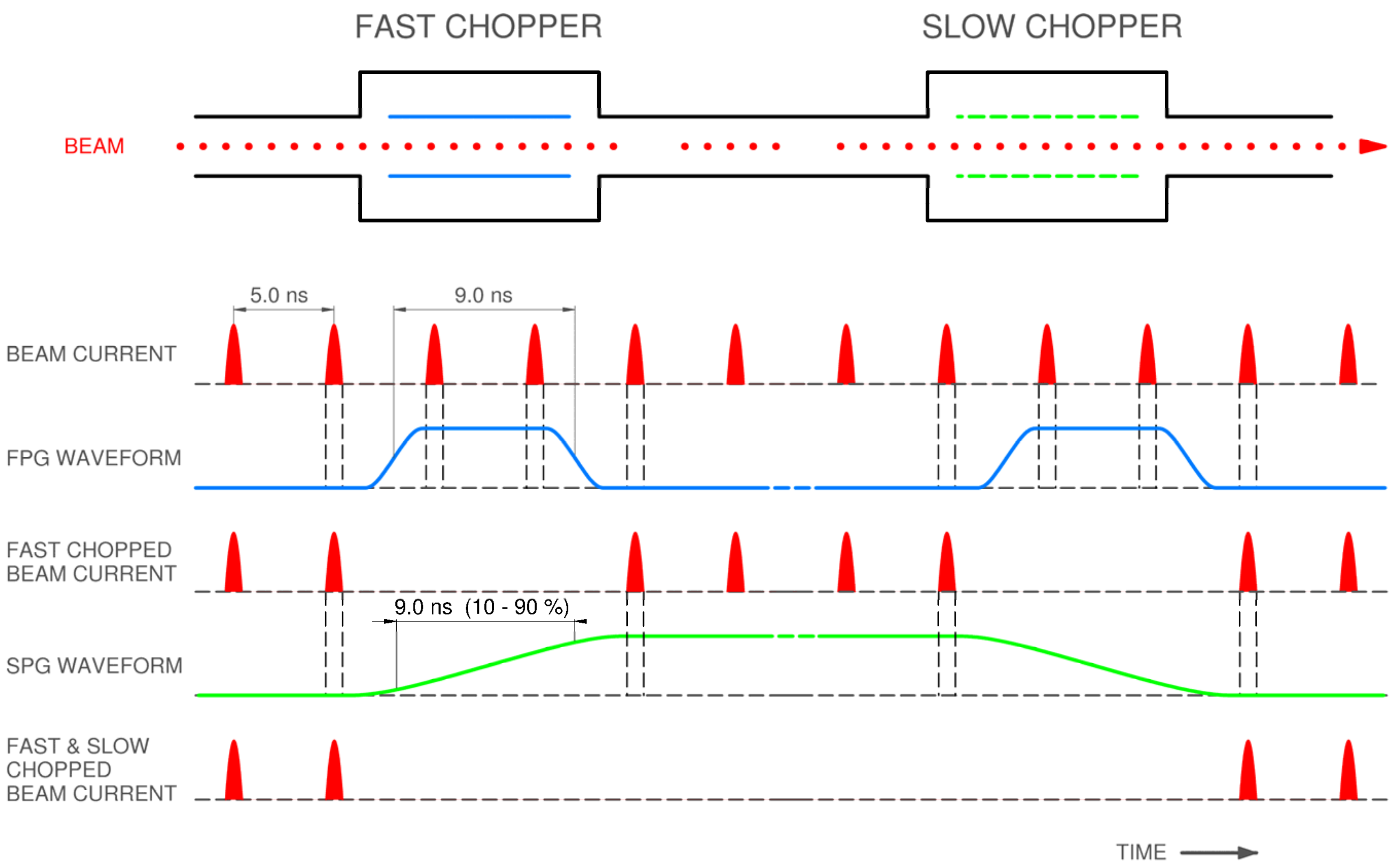
- Cold model components of one section of the RFQ has been constructed at IC (and with some help from Daresbury)
  - Measurements of the frequency and Q value will be compared with simulations used to optimise RFQ design

Beam Chopper (M. Clarke-Gayther, RAL)

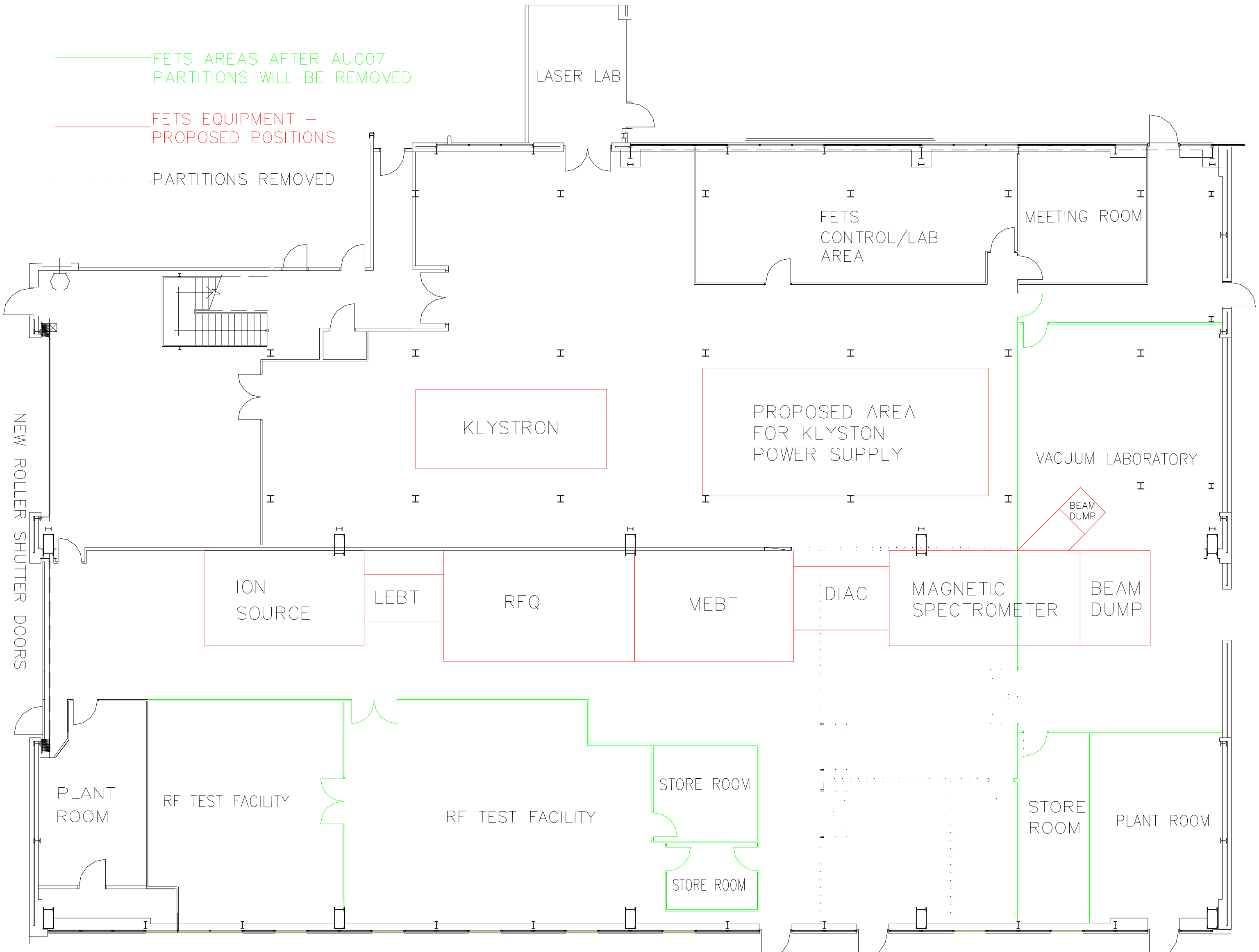
Main aim of FETS program is to demonstrate fast chopping of the H^- ion beam. Below is a schematic drawing of the chopper (Medium Energy Beam Transport).



Beam Chopper Scheme

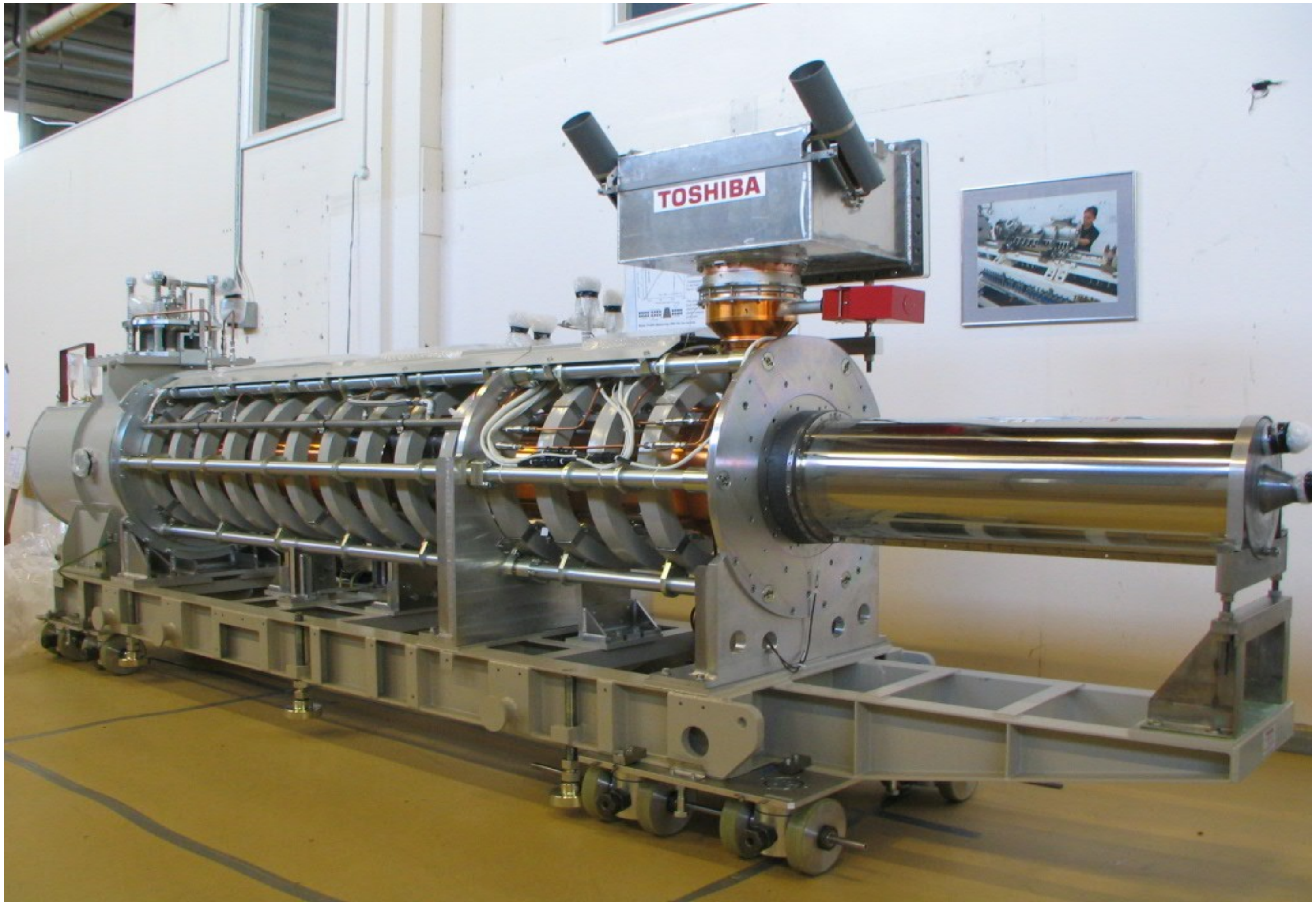


FETS Home: R8 @ RAL

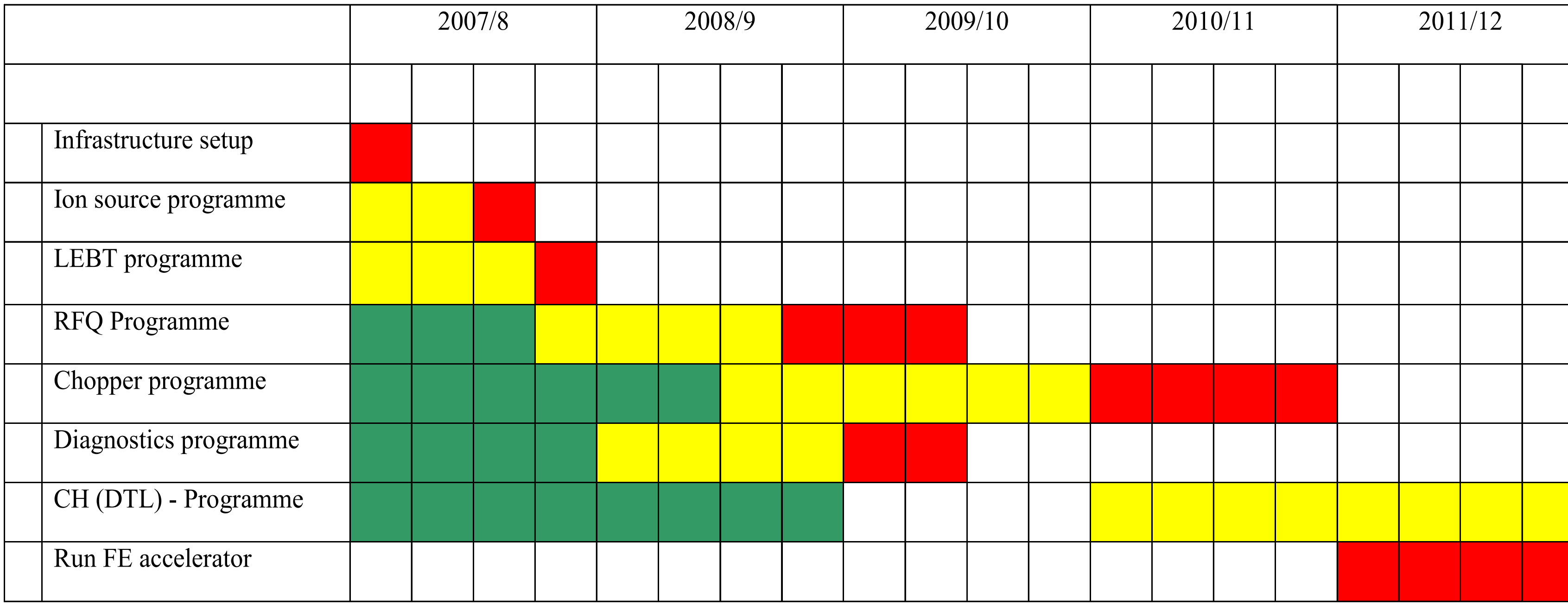


Refurbishment of work areas in R8

3MW 324 MHz Klystron for RFQ now in R8



FETS Schedule

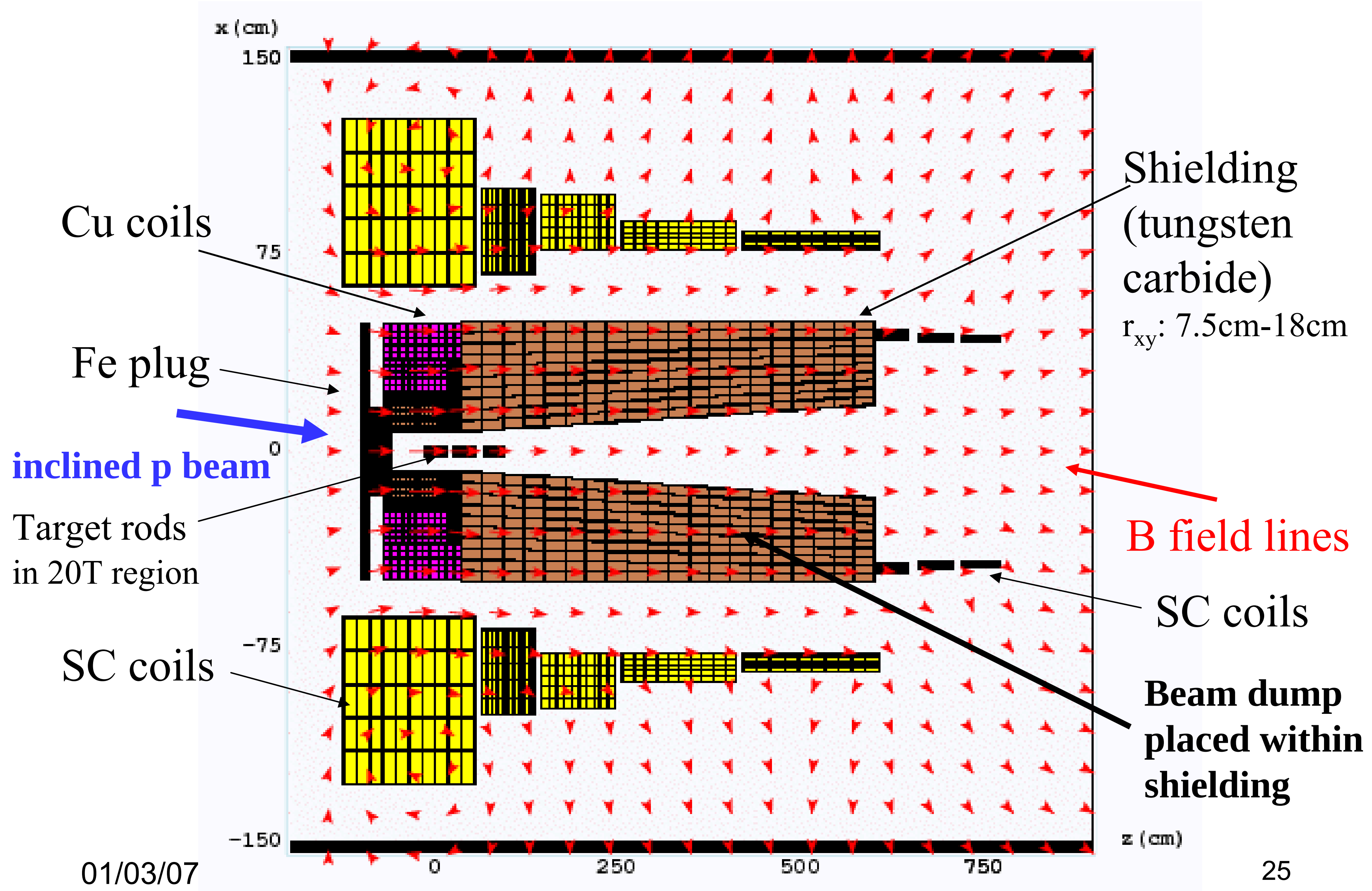


Green :	R&D phase
Yellow :	Design & Construction phase
Red :	Installation and Commissioning phase

Target Studies

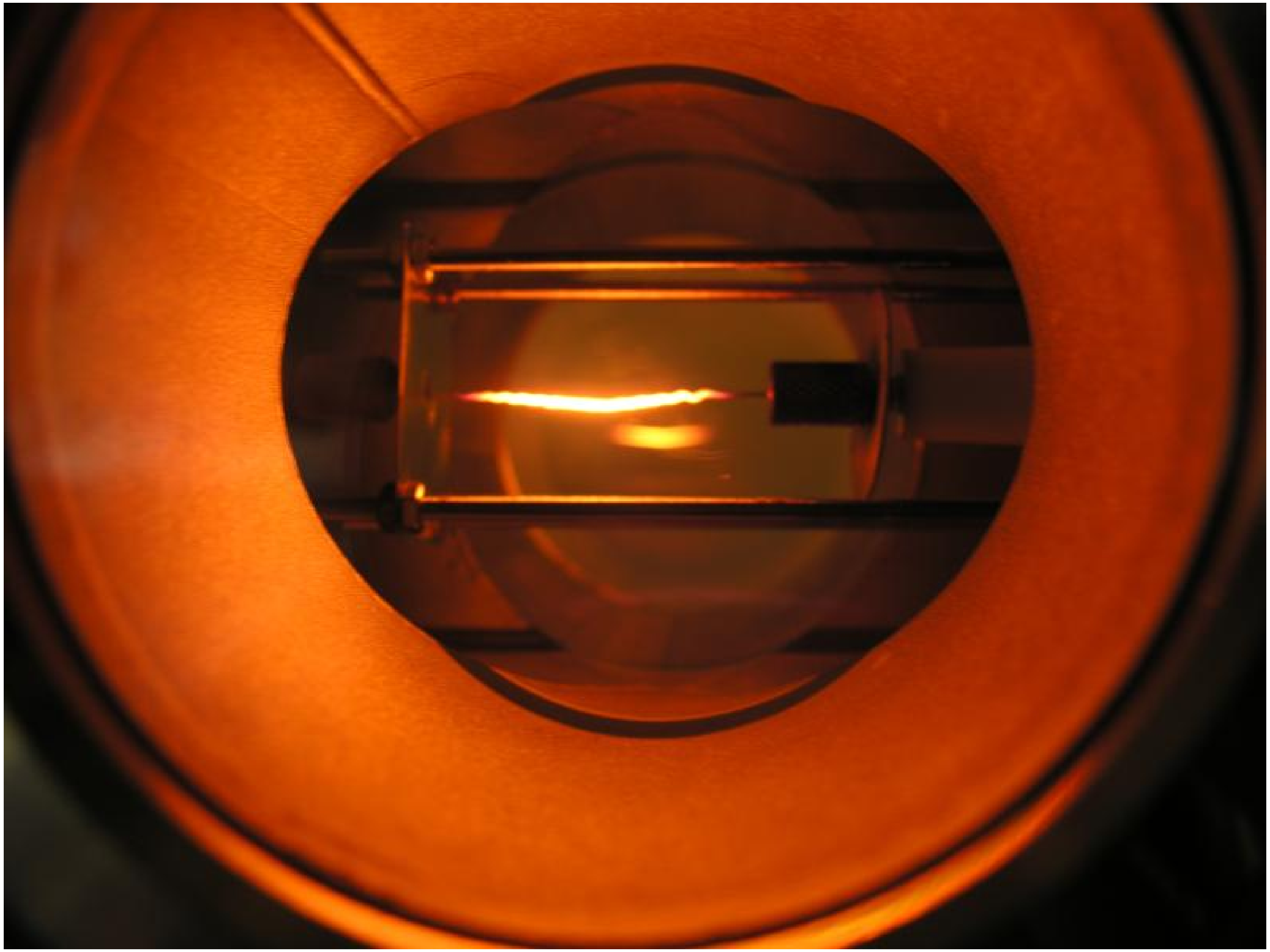
- Create π ($\rightarrow\mu \rightarrow \nu$) by bombarding target with protons.
- Proton beam power of 4 MW required to get 10^{21} μ/yr.
  - Solid targets can generally only cope with ~1.5 MW before breaking/melting…
- Extreme heating, shock and radiation damage suggest:
  - Moving, large, solid target with extensive cooling
  - A liquid metal (Hg) jet target
- UK studies focusing on solid targets (RAL,Sheffield,Warwick)
  - Investigating best material (i.e. survives beam)
  - Optimising target geometry
    - Size/shape/arrangement of solid target (maximise π yield)
    - Amount of cooling and shielding required
    - Solenoid configuration to get 20T field to focus π and μ

Target Geometry & B Field (based on BNL Study-II)



Selection of target material

- Experimental work at RAL (by R. Bennett et al.) investigating material lifetime for a solid target
  - BNL and MERIT @ CERN testing liquid Hg targets
- RAL Wire Test:
  - Induce thermal shocks by passing high current pulses at 50Hz through thin wires of material (Ta, W)
  - Wire is heated to T~2000K, simulating conditions in a ν Factory target
  - Find out how long the wire survives without breaking/melting
- Computer simulations (with LS-DYNA) done in parallel to understand shocks inside the solid target (G. Skoro, Sheffield)
  - Not much data for T > 1000K to compare with theory, hence the experimental work at RAL



Example wire test done at RAL on 16 Dec’05

Wire is fixed at one end and gets white hot as high current passes through it. Photo shows bending/ripples in the wire – stresses inside the material.

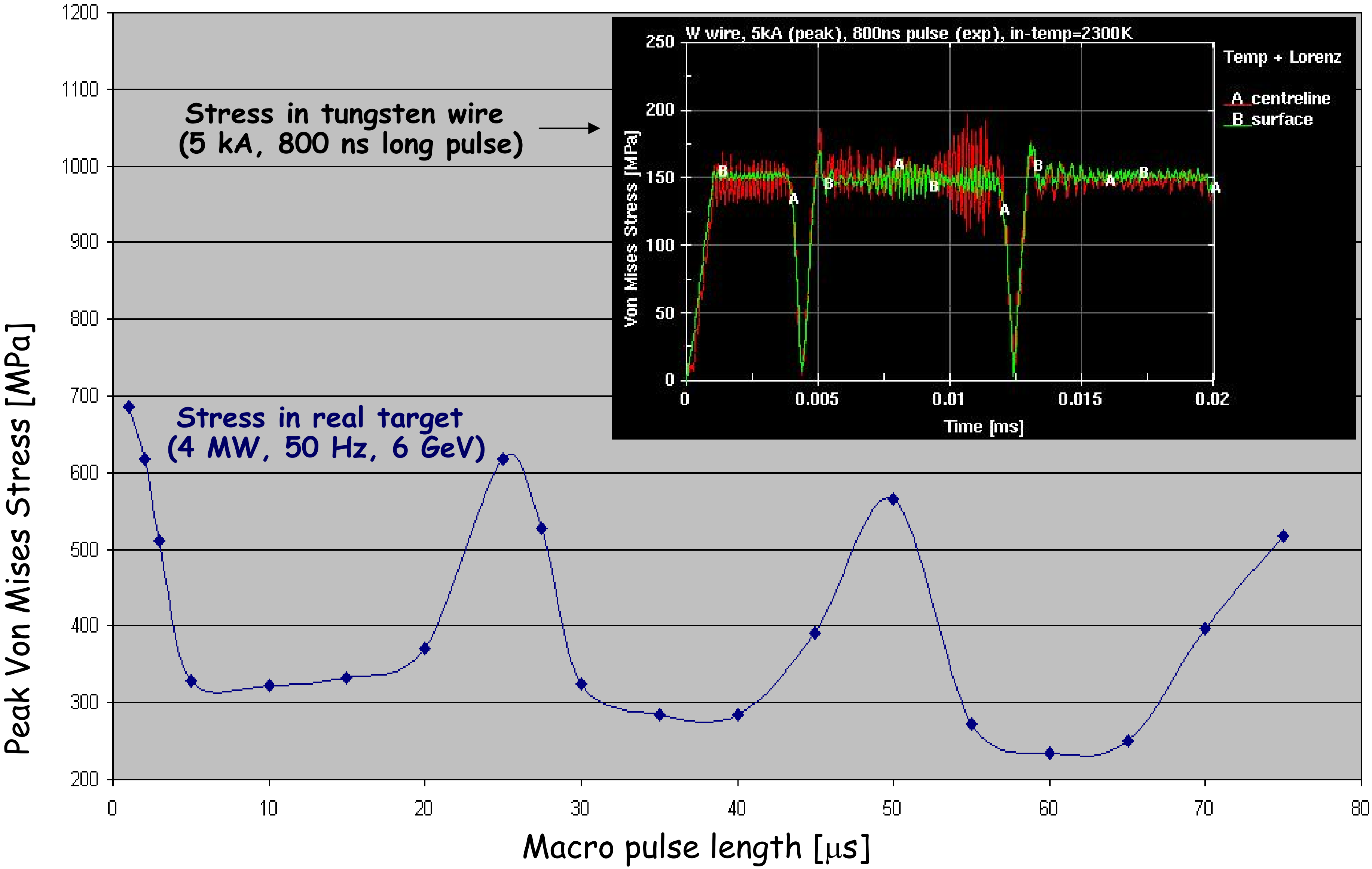
Achieved T_{max} ~2350K for 15 mins

Latest Wire Test Results

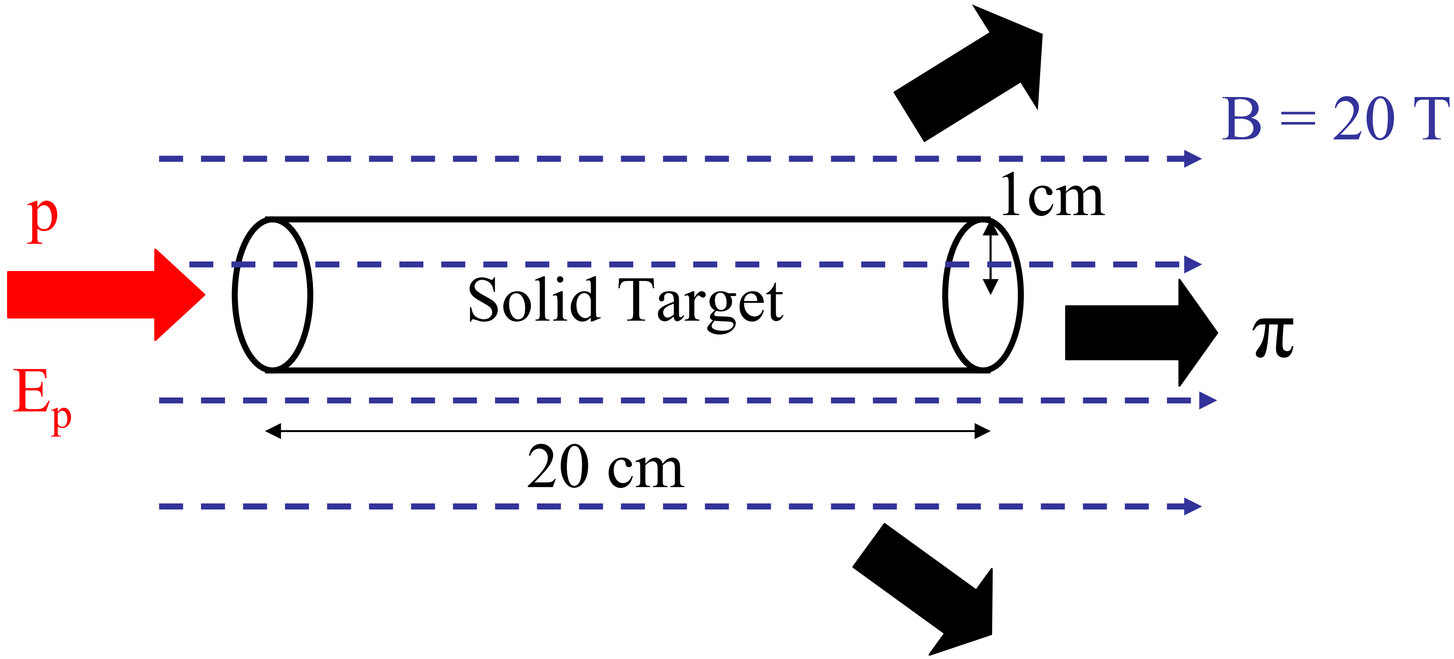
- Ta is not strong enough (T_{max} ~1500K before breaking)
- W looks promising. Able to reach T~2000K.
- W results from Jan 2007:
  - 0.5mm diameter wire ran for 10,075,000 pulses at 6200A. Equivalent to 3.6 or 7.8MW in 2 and 3cm diameter targets, respectively.
  - Wire broke after a further 2,688,000 pulses for 7500A-8000A (~6MW in 2cm diameter target). T_{max} ~ 1900K.

Target Stress Analysis

LS-DYNA computed stress as a function of proton beam pulse length

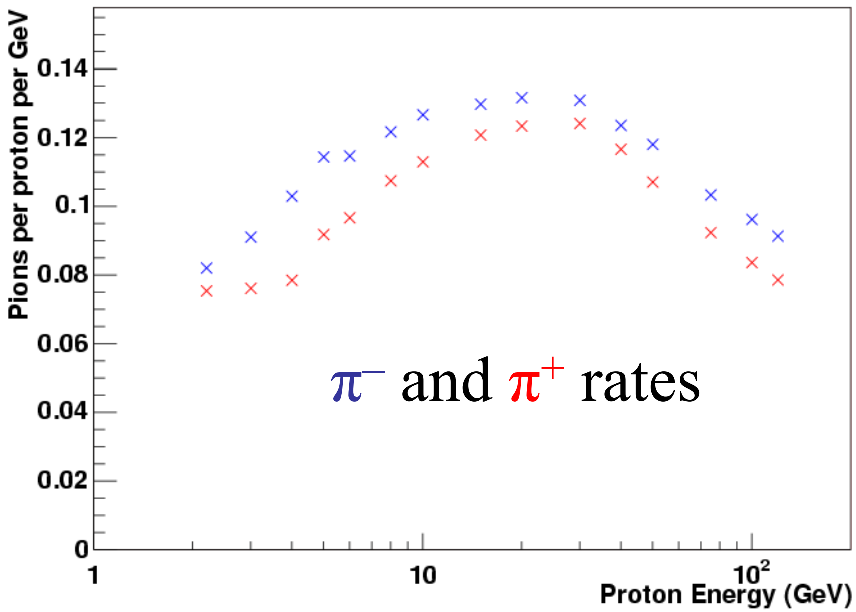


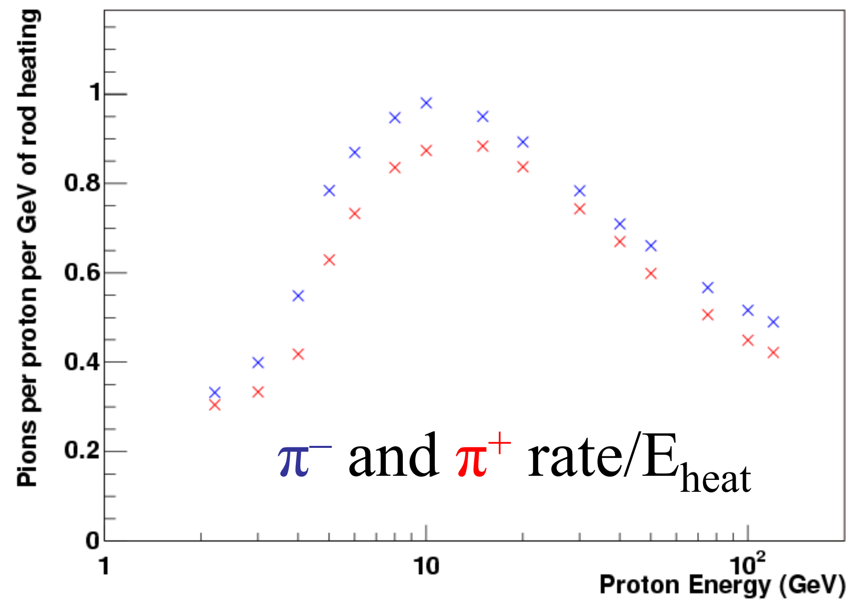
Pion Production Yield

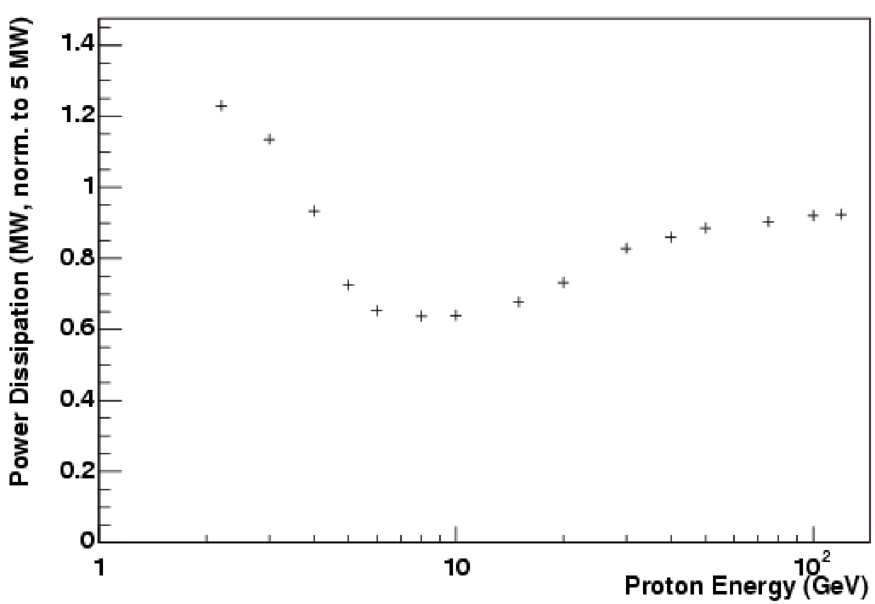


- Optimise target rod size and beam energy to maximise π production
  - Count π's leaving rod surface (cylinder)
  - Total π rate = (n_π at surface)/(E_p x N_p)
  - Total π rate/E_{heat} where E_{heat} = energy in target
  - Assume constant 20T B field along z axis
  - Use MARS simulation code for analysis

Pion Production vs Energy





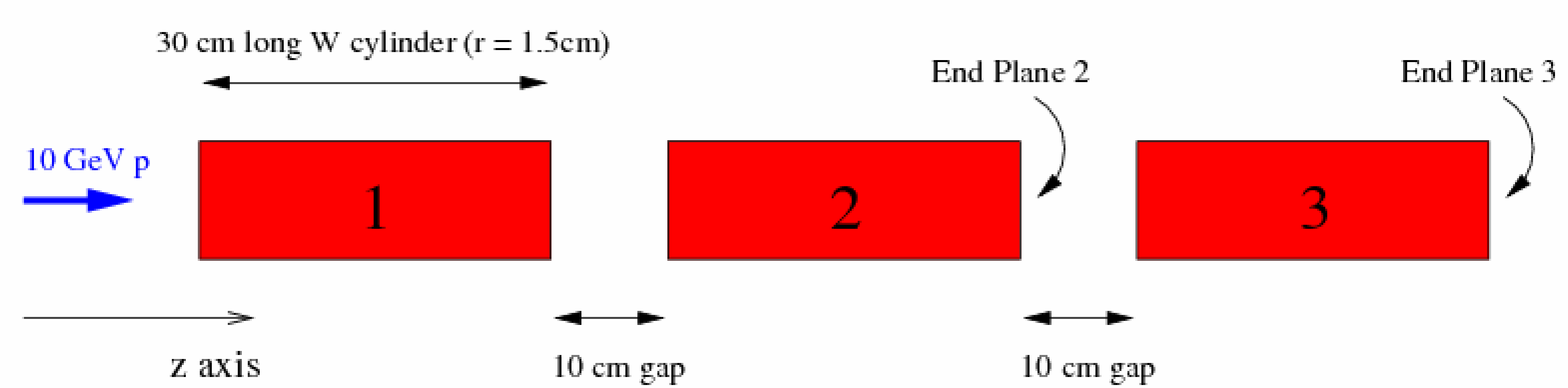


Heat within target w.r.t. 5 MW p beam

$$y = (E_{heat}/E_p) \times 5\text{ MW}$$

Re-absorption of π and μ

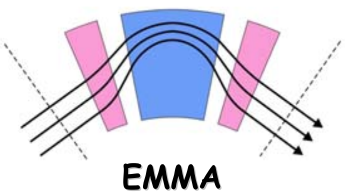
- Solid target geometry could be toroidal ring arrangement (R ≥10m), containing 30cm-long cylindrical rods separated by spaces of ~10cm
- Is there any re-absorption of π and μ (from decaying π) by cylindrical W rods in front of original rod in the 20 T field?
- Assume worst case scenario: rods are along same (z) axis as the beam
  – Measure fraction of π and μ stopped by rods 2 and 3



- Re-absorption fractions (using Study-II solenoid/shielding geometry and B field)
  – ~35% (~20%) at end-plane 3 (2) for rod d = 1cm
  – ~50% (~25%) at end-plane 3 (2) for rod d = 2cm
  – ~60% (~33%) at end-plane 3 (2) for rod d = 3cm

Other R&D Work

- End-to-end simulations of the ν Factory (ASTeC group@RAL)
  - Accelerator schemes for protons and muons
- **M**uon **I**onisation **C**ooling **E**xperiment @ RAL
  - Need to reduce size of muon beam to accelerate it to required energies (10-50GeV) before it decays to ν
  - Pass muon beam through absorber to reduce transverse momentum, accelerate it along the z axis to the next absorber
  - Repeat until the transverse spread of the beam is reduced so that the beam can fit inside accelerator components downstream
- **E**lectron **M**odel for **M**any **A**pplications @ Daresbury to investigate non-scaling Fixed Field Alternating Gradient accelerators
  - B field has gradient which follows increase in particle energy
  - Non-scaling means that the particle orbits do not have the same shape

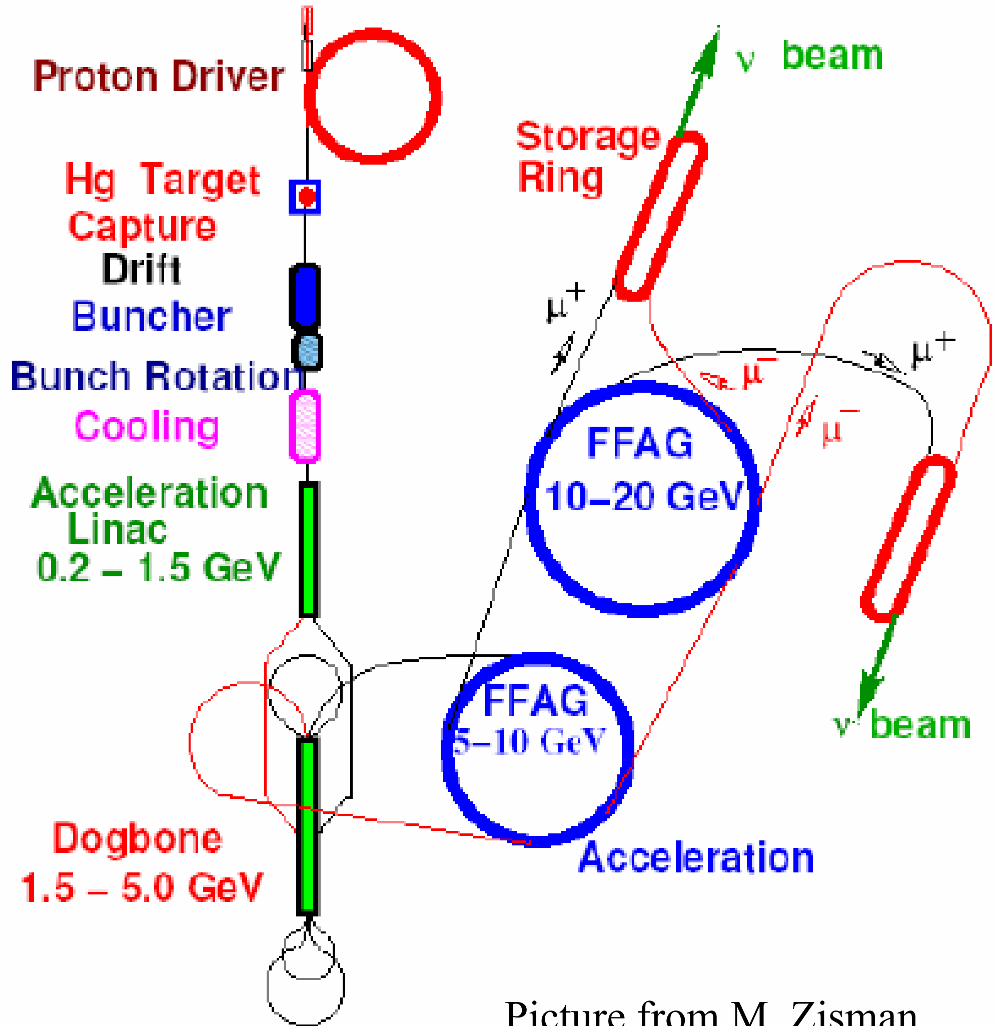


- Improving manufacture and performance of RF cavities for accelerating protons/muons (Lancaster/Cockcroft Institute)
  - Collaborations with UK industry
- Investigating detector technologies
  - Magnetised iron and/or liquid argon calorimetry etc..

International Scoping Study

Two year ('05-'06) international effort to identify baseline options for major components of a Neutrino Factory.

ISS baseline design (Aug. '06)



Target: 4MW, 10GeV, 50Hz, 4 bunches per pulse, 2ns bunch length

Baseline target: liquid Hg
- however, there are issues with radiation activation, cavitation & containment (preventing spillage)

Picture from M. Zisman, ISS/NuFact'06

Summary

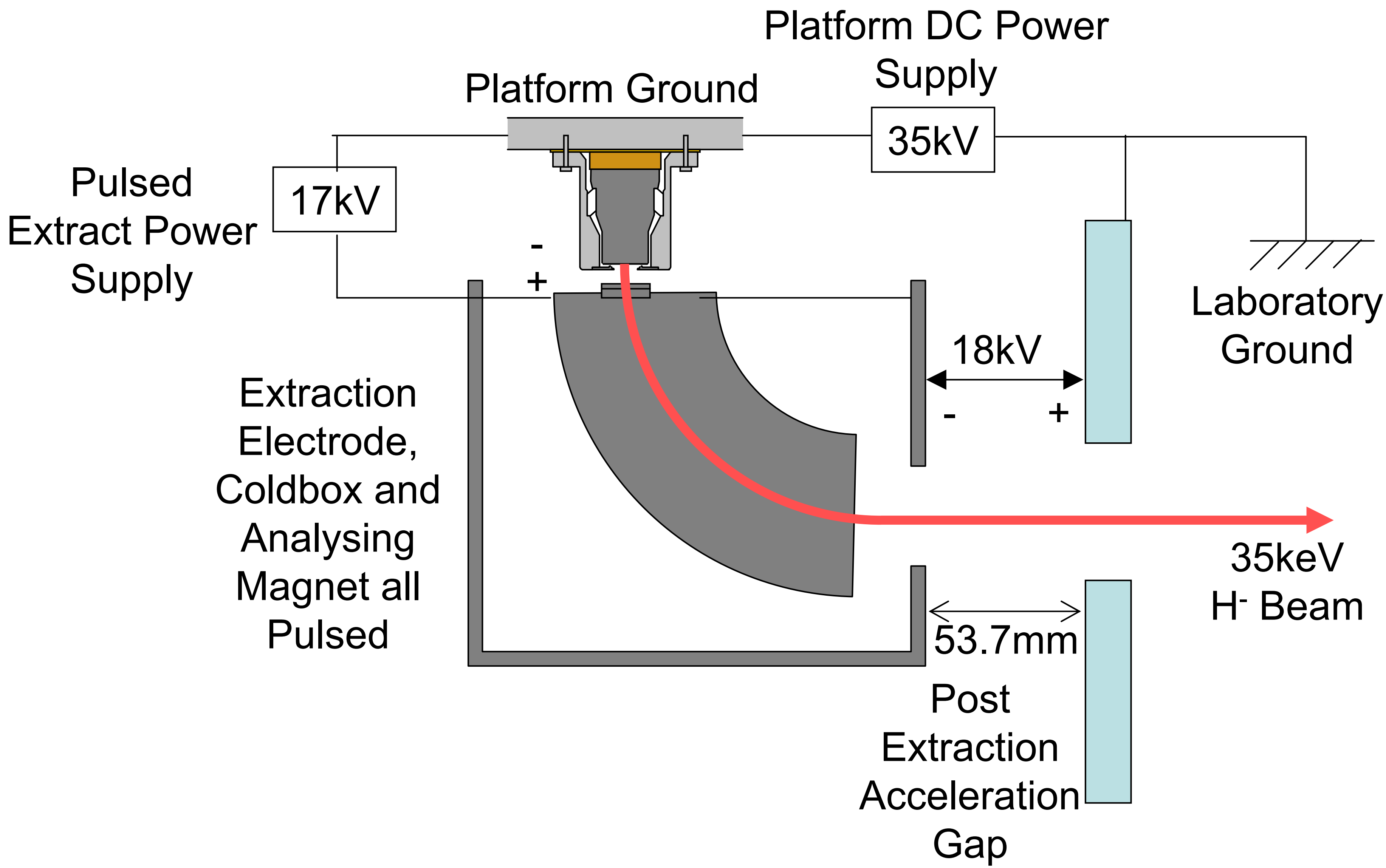
- Neutrino Factory is the best way to measure properties of neutrinos
  - Increase understanding of the flavour sector of the Standard Model
- Shown part of the UK R&D efforts for a future Neutrino Factory
  - All aspects of a Neutrino Factory are being studied in the UK: proton driver, target, end-to-end simulations, muon cooling, accelerator schemes, RF cavity construction and detectors.
  - UK expertise in designing and constructing such a facility
- International Design Study (IDS) is starting, continuing on from the International Scoping Study (ISS)
  - Aim to have design report written by ~2012 (5 yr programme)
  - UK is playing a major role in this effort.

Extra Material

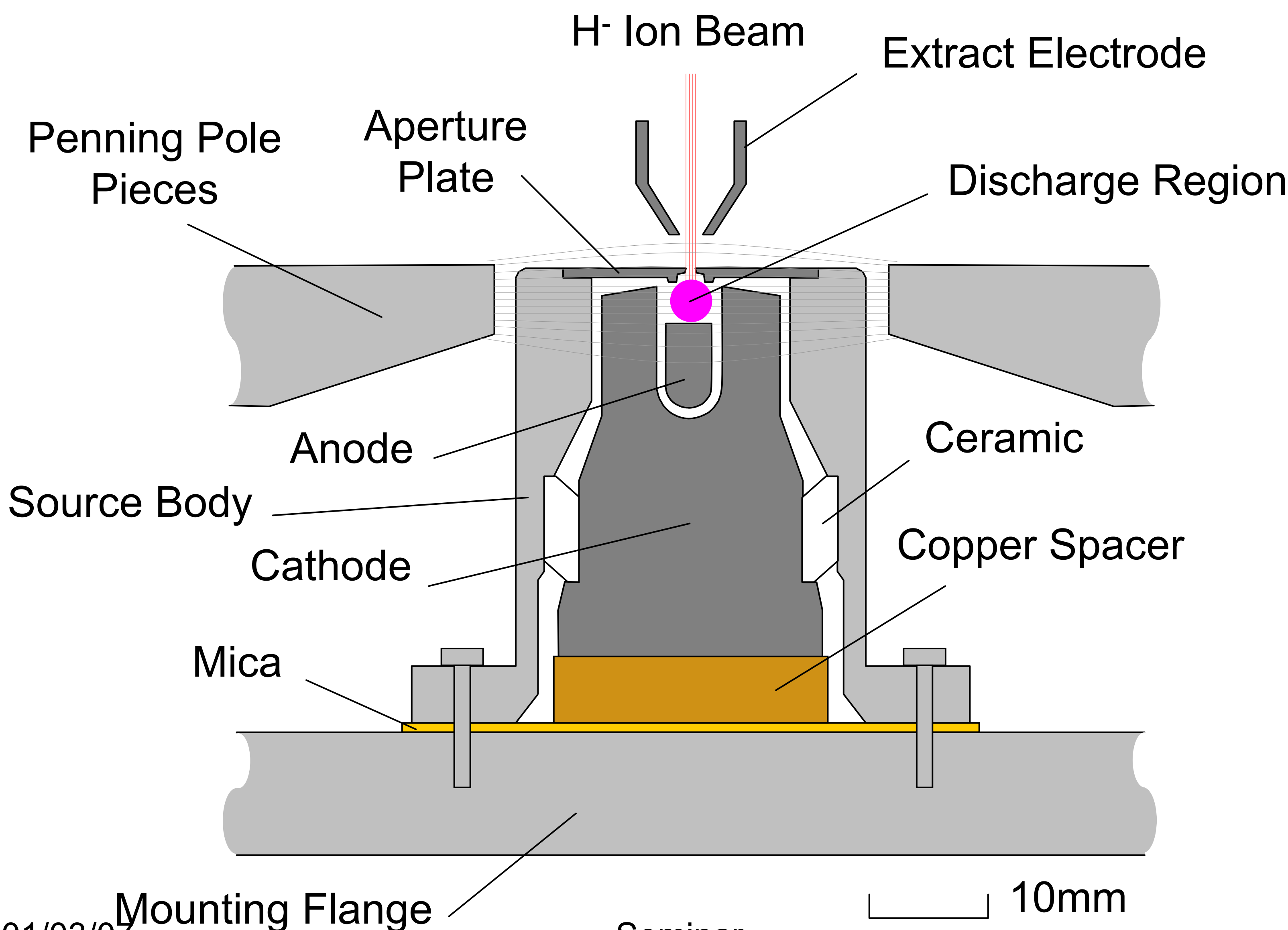
FETS Team

John Back (Warwick) - LEBT
Aaron Cheng (Imperial) – RF Measurements
Mike Clarke-Gayther (ISIS/ASTeC) – MEBT (Chopper)
Adeline Daly (ISIS) – Infrastructure (R8 @ RAL)
Dan Faircloth (ISIS) – Ion Source
Christoph Gabor (ASTeC) – Laser Diagnostics
Simon Jolly (Imperial) – Pepperpot System (LEBT)
Ajit Kurup (Imperial) - RFQ
David Lee (Imperial) – Laser Diagnostics
Alan Letchford (ISIS) – Project Leader/RFQ
Ciprian Plostinar (ASTeC) – MEBT/Drift Tube Linac (DTL)
Jürgen Pozimski (ASTeC/Imperial) – Ion S., LEBT, RFQ, Diag.
Peter Savage (Imperial) – Mechanical Engineer

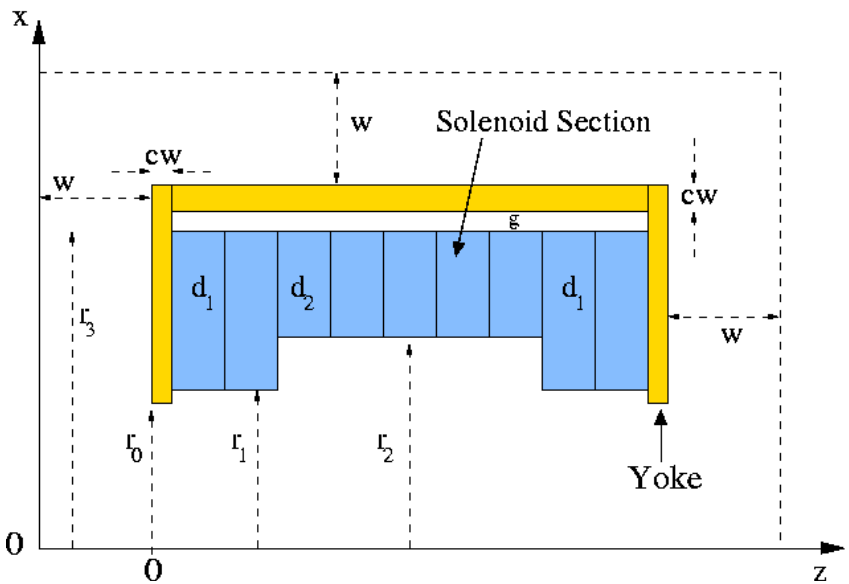
H^- Ion Source Schematic



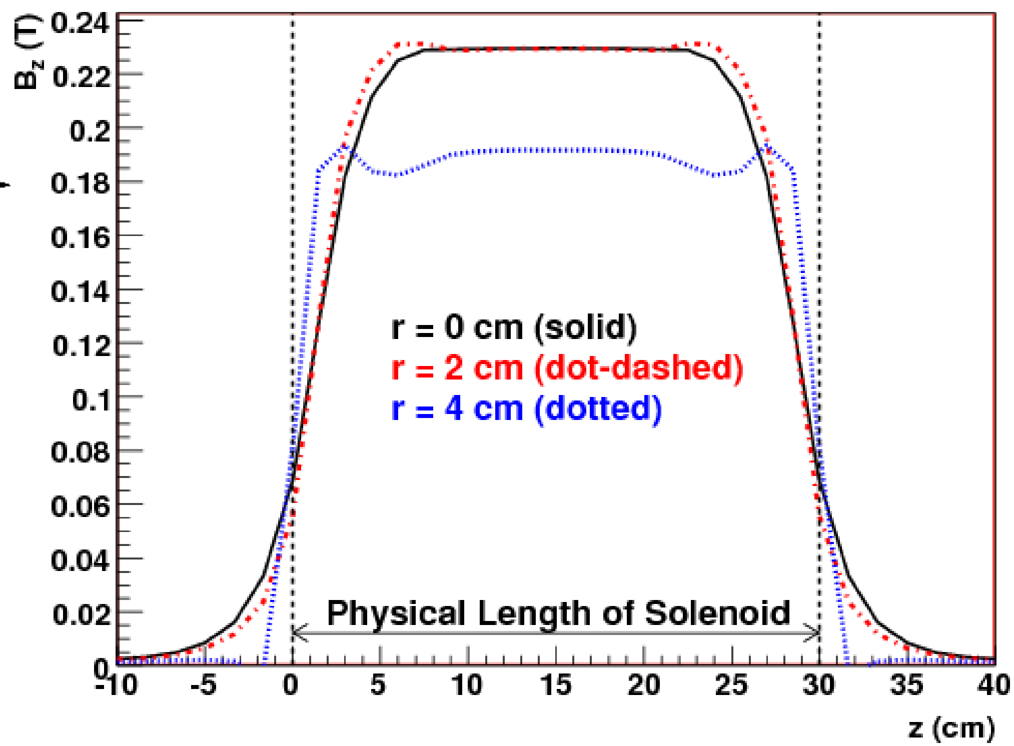
H^- Ion Source


H- Ion Beam
Extract Electrode
Aperture
Plate
Penning Pole
Pieces
Discharge Region
Anode
Ceramic
Source Body
Cathode
Copper Spacer
Mica
Mounting Flange
10mm

LEBT Solenoid Study



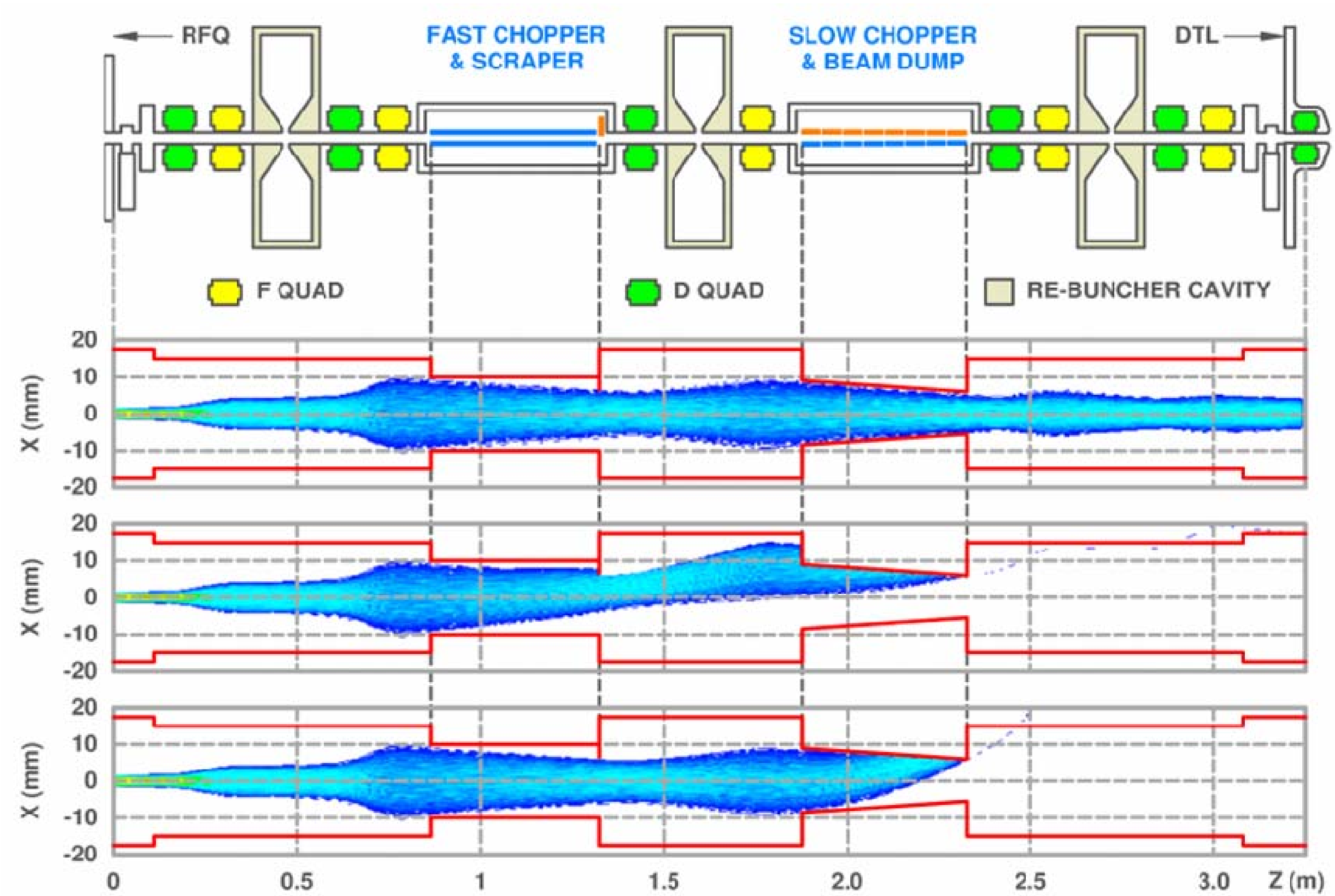
Solenoid design optimised with MAFIA. "2-5-2" coil arrangement produced most uniform axial field



Typical dimensions (± 0.5cm):
$r_0 = r_1$ = 5cm, r_2 = 6cm, r_3 = 12cm,
$d_1 = d_2$ = 3cm, cw = 2cm, g = 1cm
w = 10cm (for calculation volume)

Iron yoke has μ_r = 500

Beam Chopping Simulations



Magnetic field map in target region along z (r=0)