

Simulating particle interactions in transit with Impact-T

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2018-05-09

Molecular Hydrogen H_2^+

Particle	Protons	Neutrons	Electrons	Mass	Charge	Charge/Mass ratio
Proton	1	0	0	m_p	$+1 e$	1
Deuteron	1	1	0	$m_p + m_n \sim 2 m_p$	$+1 e$	1/2
H_2^+	2	0	1	$2 m_p + m_e \sim 2 m_p$	$+1 e$	1/2

Molecular Hydrogen H_2^+

- Testing deuteron RFQs
- Multi-ion accelerators
- Stripping to proton beams

Testing deuteron RFQs

- Avoid activation
- Same charge-to-mass ratio
- Same ion source
- Low current for commissioning

FOR EXAMPLE:

Challenges of the high current prototype accelerator of IFMIF/EVEDA

J Knaster, Y Okumura, A Kasugai, M Sugimoto and P Cara
Presented at *IPAC 2016: The 7th International Particle Accelerator Conference*, Busan, Korea, 2016, (MOZB02) pp.52–57.

<http://jacow.org/ipac2016/papers/mozb02.pdf>

Preliminary results of H_2^+ beam generated by a 2.45 GHz permanent magnet ECR ion source at PKU

Xu Y, Peng S X, Ren H T *et al.*
Presented at *IPAC 2013: The 4th International Particle Accelerator Conference*, Shanghai, China, 2013, (MOPFI035) pp.363–365.
<http://jacow.org/ipac2013/papers/mopfi035.pdf>

Status of the SARAF CW 40 MeV proton/deuteron accelerator

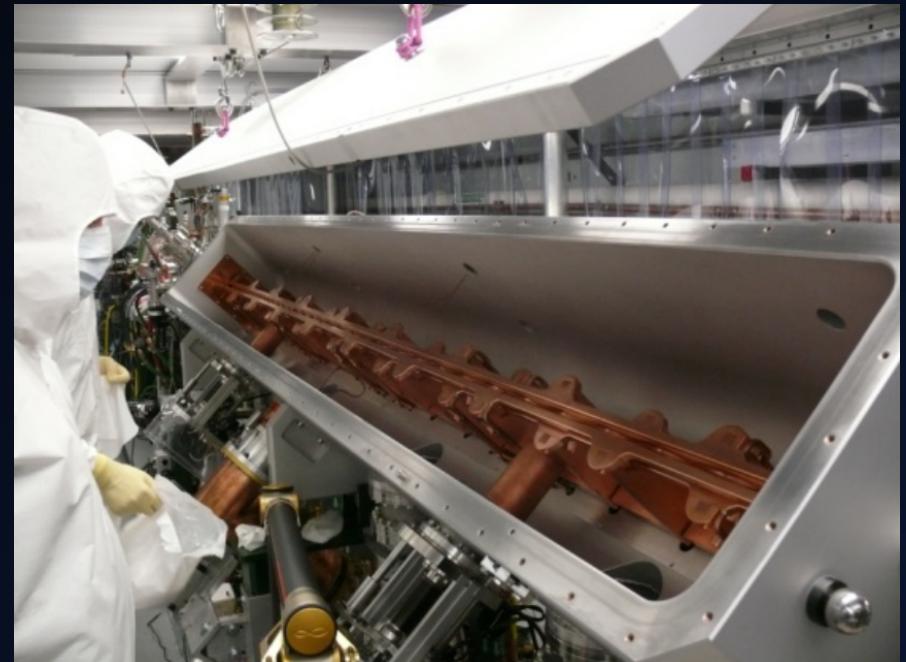
I Mardor, D Berkovits, I Gertz *et al.*
Presented at *PAC 2009: The 23rd Particle Accelerator Conference*, Vancouver, BC, Canada, 2009, (FR5REP087) pp.4981–4983.
<http://jacow.org/pac2009/papers/fr5rep087.pdf>

Low beta CW linacs for intense beams

G E McMichael
Presented at *LINAC 1990: The 15th Linear Accelerator Conference*, Albuquerque, New Mexico, USA, 1990, (WE104) pp.518–521.
<http://jacow.org/l90/papers/we104.pdf>

FRIB ReA

- Facility for Rare Isotope Beams
- ReAccelerator:
rare isotope post-accelerator
- Multi-species RFQ
- Low current: 2 μA H_2^+



Commissioning results of the ReA RFQ at MSU

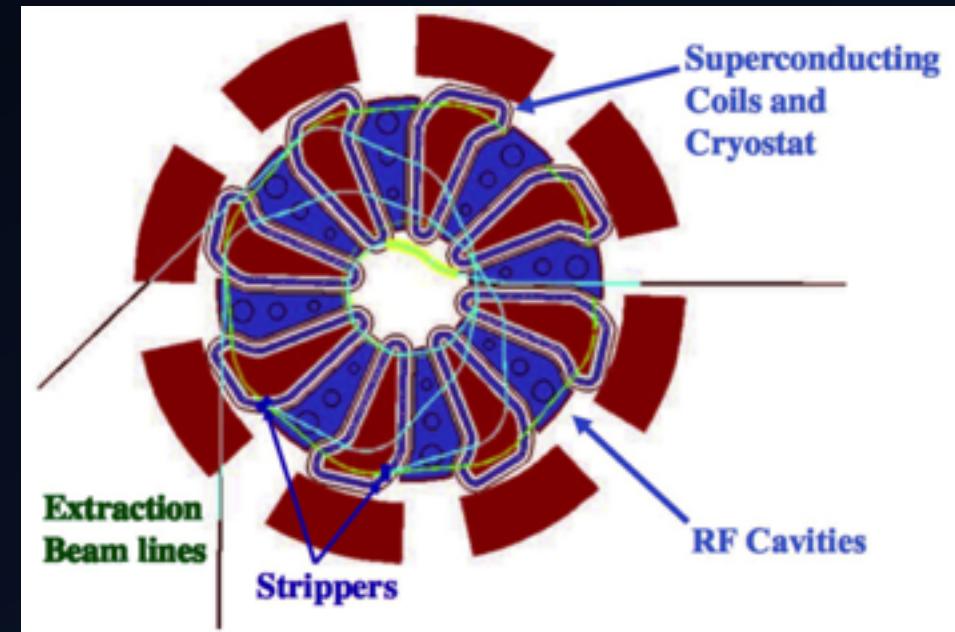
D Leitner, C Benatti, S W Krause *et al.*

Presented at *PAC 2011: The 24th Particle Accelerator Conference*,
New York, USA, 2011, (WEP226) pp.1912–1914.

<http://jacow.org/pac2011/papers/wep226.pdf>

IsoDAR

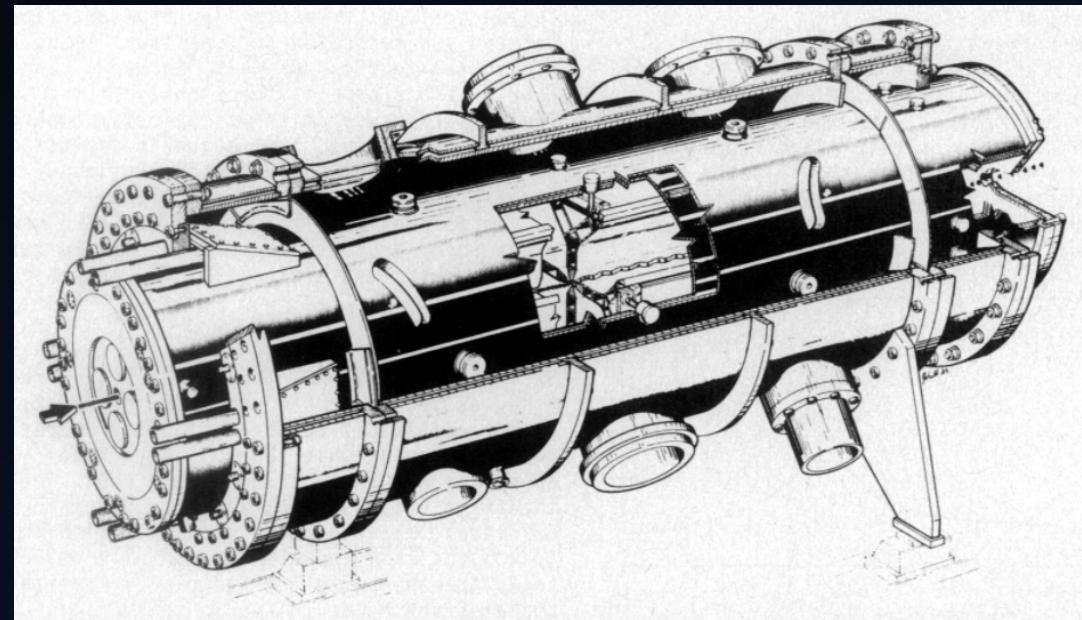
- Isotope Decay-At-Rest
- High-intensity proton beam for neutrino oscillation experiments
- Accelerating H_2^+ and stripping to protons just before extraction
- Small RFQ as injector to driver cyclotron
- Low energy RFQ: 80 keV H_2^+



Preliminary design of a RFQ direct injection scheme for the IsoDAR high intensity H_2^+ cyclotron
D Winklehner, R Hamm, J Alonso, J M Conrad and S Axani
Review of Scientific Instruments **87** (2) 02B929, February 2016.
doi: [10.1063/1.4935753](https://doi.org/10.1063/1.4935753)

FMIT

- Fusion Materials Irradiation Test
- Built in the 1980s at Los Alamos
- Target: 35 MeV, 100 mA CW deuteron beam
- RFQ: 80 MHz, 2 MeV, 4 m
- Achieved 50 mA CW H_2^+ beam at 2 MeV



CW operation of the FMIT RFQ accelerator

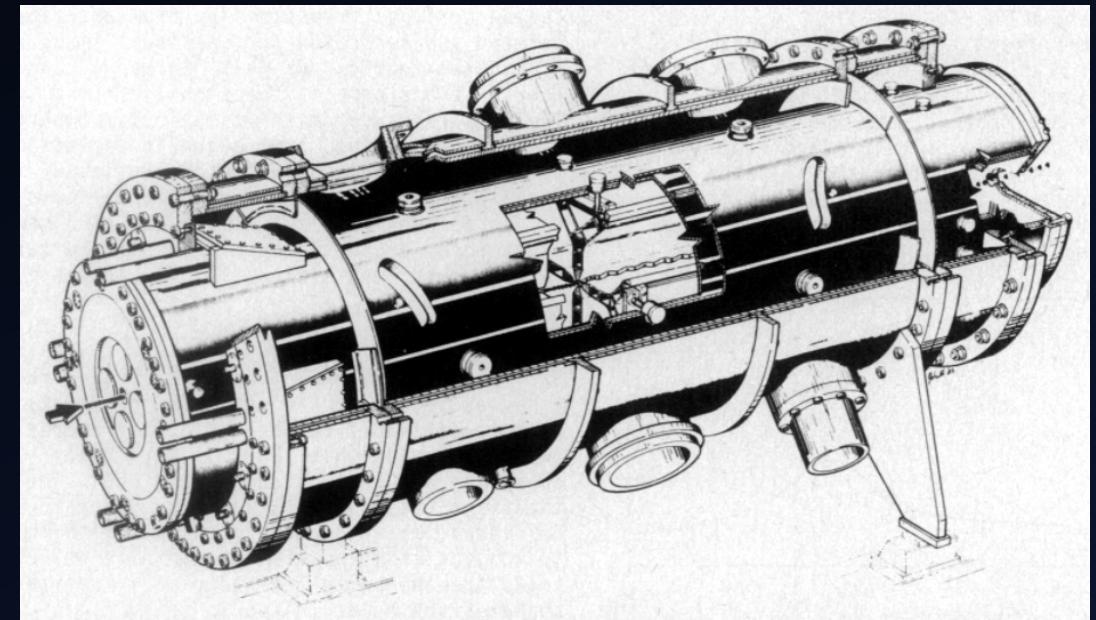
W D Cornelius

Presented at *PAC 1985: The 11th Particle Accelerator Conference*,
Vancouver, BC, Canada, 1985.

Published in *IEEE Transactions on Nuclear Science* **32**, pp. 3139–3143.
doi: [10.1109/TNS.1985.4334300](https://doi.org/10.1109/TNS.1985.4334300)

FMIT

- Major problems with CW RF
 - Thermal expansion
 - Surface outgassing
 - Multipacting
- Major problems with H_2^+ beam
 - Melted vacuum seals
 - Melted beam pipes
 - Incorrectly matched input



CW operation of the FMIT RFQ accelerator

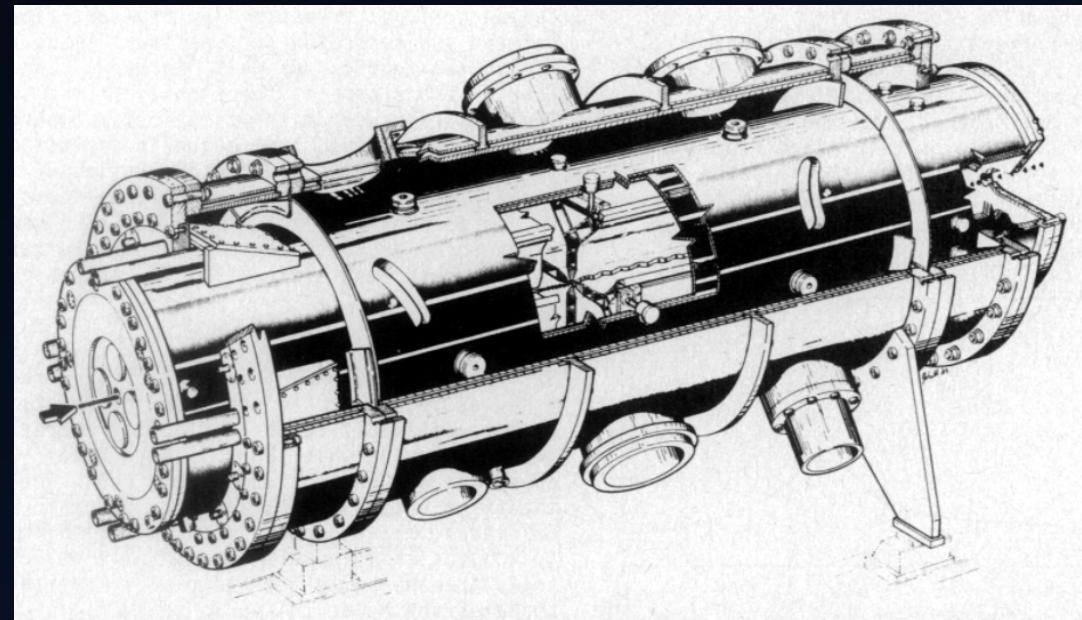
W D Cornelius

Presented at PAC 1985: *The 11th Particle Accelerator Conference*,
Vancouver, BC, Canada, 1985.

Published in *IEEE Transactions on Nuclear Science* **32**, pp. 3139–3143.
doi: [10.1109/TNS.1985.4334300](https://doi.org/10.1109/TNS.1985.4334300)

FMIT

- Beam halo
 - Not just H_2^+
 - Protons, electrons and neutral hydrogen atoms
 - Stripping and dissociation of H_2^+ ions
 - RFQ not matched and equipartitioned
 - Vacuum levels not good



CW operation of the FMIT RFQ accelerator

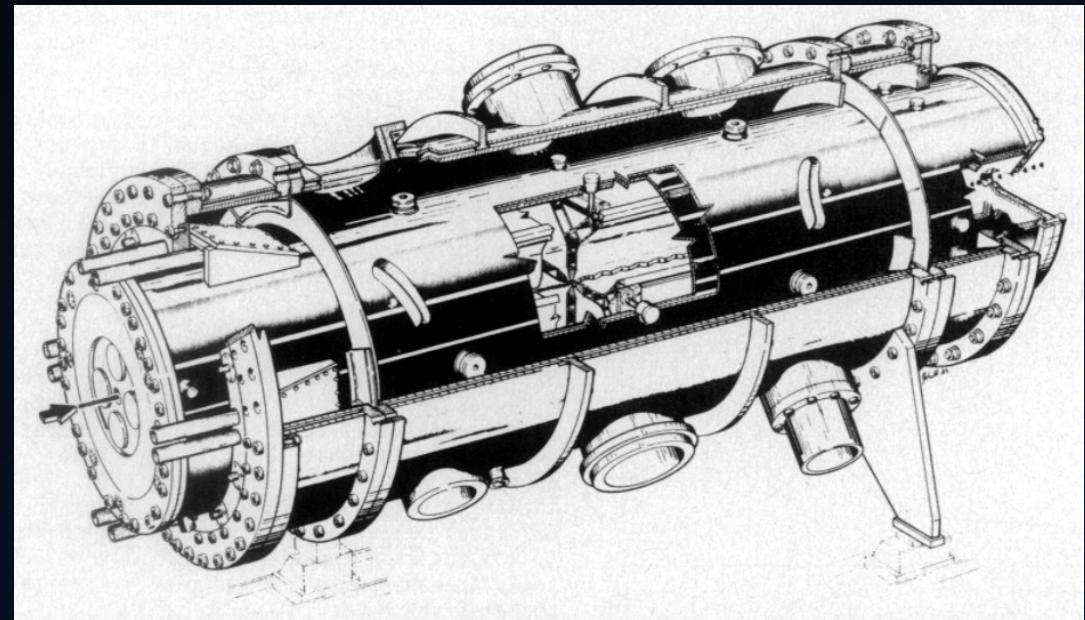
W D Cornelius

Presented at *PAC 1985: The 11th Particle Accelerator Conference*,
Vancouver, BC, Canada, 1985.

Published in *IEEE Transactions on Nuclear Science* **32**, pp. 3139–3143.
doi: [10.1109/TNS.1985.4334300](https://doi.org/10.1109/TNS.1985.4334300)

FMIT

- Stripping and dissociation of H_2^+
 - Residual gas collisions
 - Electrostatic field component in ion rest frame
 - Beam thermal energy due to mismatch



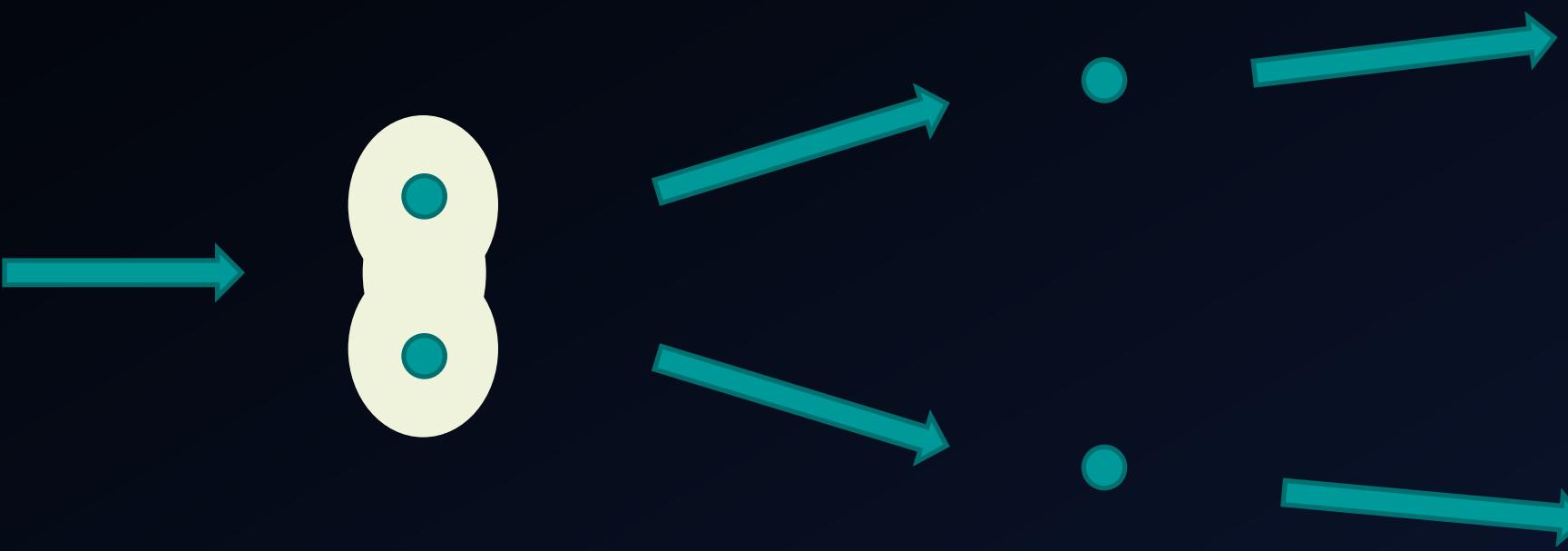
CW operation of the FMIT RFQ accelerator

W D Cornelius

Presented at *PAC 1985: The 11th Particle Accelerator Conference*,
Vancouver, BC, Canada, 1985.

Published in *IEEE Transactions on Nuclear Science* **32**, pp. 3139–3143.
doi: [10.1109/TNS.1985.4334300](https://doi.org/10.1109/TNS.1985.4334300)

Molecular hydrogen ion dissociation



Molecular hydrogen ion dissociation

Molecular hydrogen bunches

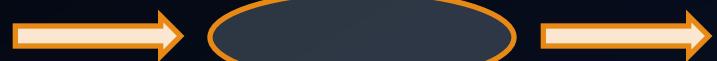


Molecular hydrogen ion dissociation

Molecular hydrogen bunches



Proton bunches



Molecular hydrogen ion dissociation

Molecular hydrogen bunches



Proton bunches



Molecular hydrogen ion dissociation

Molecular hydrogen bunches



Proton bunches



Molecular hydrogen ion dissociation

Molecular hydrogen bunches



Proton bunches



Impact-T code modifications

- InteractionClass

```
12 MODULE InteractionClass
13
14 ! Includes
15 USE BeamBunchClass
16 USE PhysConstClass
17 USE CalculationClass
18 USE InputClass
19 USE QuickSort
20
21 ! Declarations
22 IMPLICIT NONE
23 PRIVATE
24
25 ! Parameters
26 LOGICAL, PARAMETER, PRIVATE :: debug_mode = .FALSE. ! Include debugging output?
27
28 ! Enumeration of interaction types
29 INTEGER, PARAMETER :: IT_DISSOCIATION = 1
30 INTEGER, PARAMETER :: IT_CAPTURE = 2
31 INTEGER, PARAMETER :: IT_CAPTURESPLIT = 3
32
33 ! Types
34 TYPE Interaction
35   INTEGER :: type
36   INTEGER :: source_bunch_id
37   INTEGER :: target_bunch_id
38   DOUBLE PRECISION :: peak_energy
39   DOUBLE PRECISION :: peak_cross
40   DOUBLE PRECISION :: interval
41   DOUBLE PRECISION :: next
42 END TYPE Interaction
43
44 TYPE BeamBunchTemplate
45   DOUBLE PRECISION :: current
46   DOUBLE PRECISION :: energy
47   DOUBLE PRECISION :: mass
```

Impact-T code modifications

- `InteractionClass`
- `BeamBunchClass`

```
2917      ! Copy particles from a source bunch to a target bunch
2918      SUBROUTINE addto_BeamBunch_copy(this, source_bunch, particle_ids)
2919          ! Parameters
2920          TYPE(BeamBunch), INTENT(INOUT) :: this
2921          TYPE(BeamBunch), INTENT(IN)    :: source_bunch
2922          INTEGER,           INTENT(IN)    :: particle_ids(:)
2923          ! Variables
2924          INTEGER :: array_size, number_to_copy
2925          INTEGER :: last_particle, Npt_old
2926
2927          ! Particle counts
2928          number_to_copy = SIZE(particle_ids)
2929          array_size = SIZE(source_bunch%Pts1, 2)
2930          last_particle = this%Nptlocal
2931
2932          ! Copy particles
2933          this%Pts1(:, last_particle+1:last_particle+number_to_copy) &
2934              = source_bunch%Pts1(:, particle_ids)
2935
2936          ! Adjust the number of particles
2937          Npt_old = this%Npt
2938          this%Npt      = this%Npt      + number_to_copy
2939          this%Nptlocal = this%Nptlocal + number_to_copy
2940          this%Nptrans  = this%Nptrans  + number_to_copy
2941
2942          ! Adjust the current
2943          IF(Npt_old == 0) THEN
2944              IF(is_zero(source_bunch%Current)) THEN
2945                  this%Current = 0.0
2946              ELSE
2947                  this%Current = this%Nptlocal * this%Charge
2948              ENDIF
2949          ELSE
2950              this%Current = this%Current * this%Npt / Npt_old
2951          ENDIF
2952
2953      END SUBROUTINE addto_BeamBunch_copy
2954
```

Impact-T code modifications

- InteractionClass
- BeamBunchClass
- AccSimulatorClass
- `init_AccSimulator()`

```
! Set up particle interactions
IF(flag_interact == 1) THEN
    PRINT *, "Initializing particle interactions"
    CALL construct_interactions(Ebunch, Nbunch)
ENDIF
```

- `run_AccSimulator()`

```
! Implement any interactions that may be defined for the simulation
IF(flag_interact == 1) THEN
    CALL interact_all(Ebunch(1:Nbunch), distance, dzz)
ENDIF
```

Impact-T code modifications

- `InteractionClass`
- `BeamBunchClass`
- `AccSimulatorClass`
- Input files

```
! more information needed by the integrator:  
! phase-space dimension, number of particles, a series of flags  
! that set the type of integrator, error study, diagnostics, and  
! image charge, the cutoff distance for the image charge,  
! and a flag whether to include interactions  
!  
! PSdim Nptcl integF errF diagF imchgf imgCutOff (m) interactF  
6 100000 1 0 2 0 0.0 1  
!
```

```
! This file defines any interactions in the simulation.  
! To use interactions, the main input file must have the interact flag ON (1).  
!  
! General settings:  
! - N: Number of interaction types  
! - p: Residual gas pressure (Pa)  
! - T: Residual gas temperature (deg C)  
!  
! N p (Pa) T (deg C)  
1 1.0d-6 22  
!  
!  
! Interaction definitions: one line per interaction type  
! - Type: A code number corresponding to a particular type of interaction:  
! 1: Dissociation
```

Impact-T code modifications

- `InteractionClass`
- `BeamBunchClass`
- `AccSimulatorClass`
- Input files
- `InputClass`

```
635      SUBROUTINE readbonusflags_Input(fileunit, flag_interact)
636          ! Parameters
637          INTEGER, INTENT(IN) :: fileunit
638          INTEGER, INTENT(OUT) :: flag_interact
639          ! Variables
640          INTEGER :: dim_in, np_in, flagmap_in, flagerr_in, &
641                      flagdiag_in, flagimg_in
642          INTEGER :: dim_chk, np_chk, flagmap_chk
643          DOUBLE PRECISION :: zimage_in
644          INTEGER :: ierr
645
646          ! Read the last input line again with the bonus flags included
647          BACKSPACE(fileunit)
648          READ(fileunit, *, IOSTAT=ierr) dim_in, np_in, flagmap_in, flagerr_in, &
649                                      flagdiag_in, flagimg_in, zimage_in, &
650                                      flag_interact
651
652          ! If we hit an error at this point, it's probably because
653          ! there are no bonus flags
654          IF(ierr /= 0) THEN
655              flag_interact = 0
656              BACKSPACE(fileunit)
657              RETURN
658          ENDIF
659
660          ! Read in the first few standard flags again and compare
661          ! - this is to check that we haven't moved to the next line
662          BACKSPACE(fileunit)
663          READ(fileunit, *, IOSTAT=ierr) dim_chk, np_chk, flagmap_chk
664          IF((ierr /= 0).OR.(dim_chk /= dim_in).OR.(np_chk /= np_in) &
665              .OR.(flagmap_chk /= flagmap_in)) THEN
666              flag_interact = 0
667              BACKSPACE(fileunit)
668              RETURN
669          ENDIF
670
671      END SUBROUTINE readbonusflags_Input
672
```

Impact-T code modifications

- `InteractionClass`
- `BeamBunchClass`
- `AccSimulatorClass`
- Input files
- `InputClass`
- `CalculationClass`

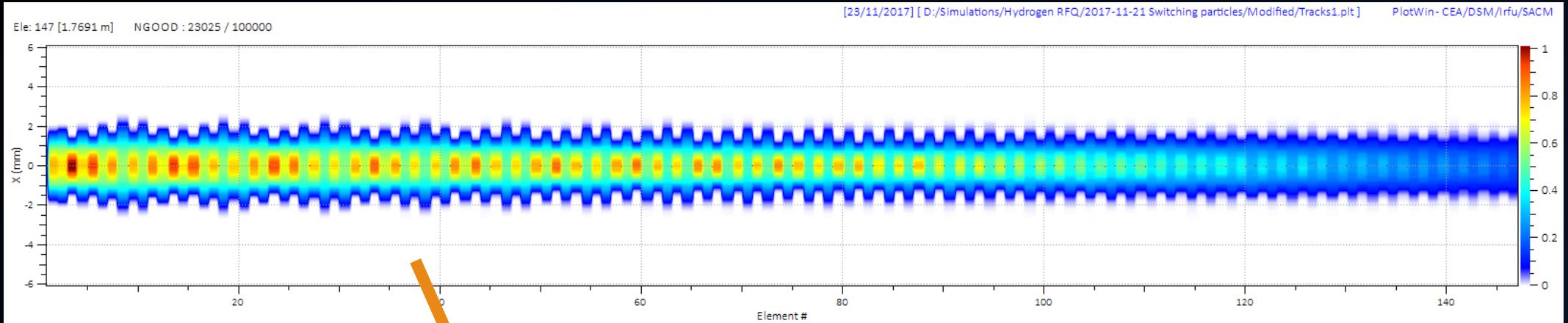
```
12 MODULE CalculationClass
13
14 ! Includes
15
16 ! Declarations
17 IMPLICIT NONE
18 PRIVATE
19
20 ! Parameters
21 LOGICAL,           PARAMETER, PRIVATE :: debug_mode = .FALSE. ! Include debugging output?
22 LOGICAL,           PARAMETER, PRIVATE :: detailed_debug_mode = .FALSE. ! Warning: SLOW!
23 DOUBLE PRECISION, PARAMETER, PRIVATE :: almost_zero = 0.1d-10
24
25 ! Variables
26
27 ! Types
28
29 ! Interfaces
30 INTERFACE is_zero
31     MODULE PROCEDURE is_zero_real
32     MODULE PROCEDURE is_zero_dp
33     MODULE PROCEDURE is_zero_int
34     MODULE PROCEDURE is_zero_log
35     MODULE PROCEDURE is_zero_char
36 END INTERFACE
37
38 INTERFACE remove_duplicates
39     MODULE PROCEDURE remove_duplicates_int
40 END INTERFACE
41
42 ! Public procedures
43 PUBLIC :: is_zero
44 PUBLIC :: remove_duplicates
45
46 CONTAINS
47
```

Impact-T code modifications

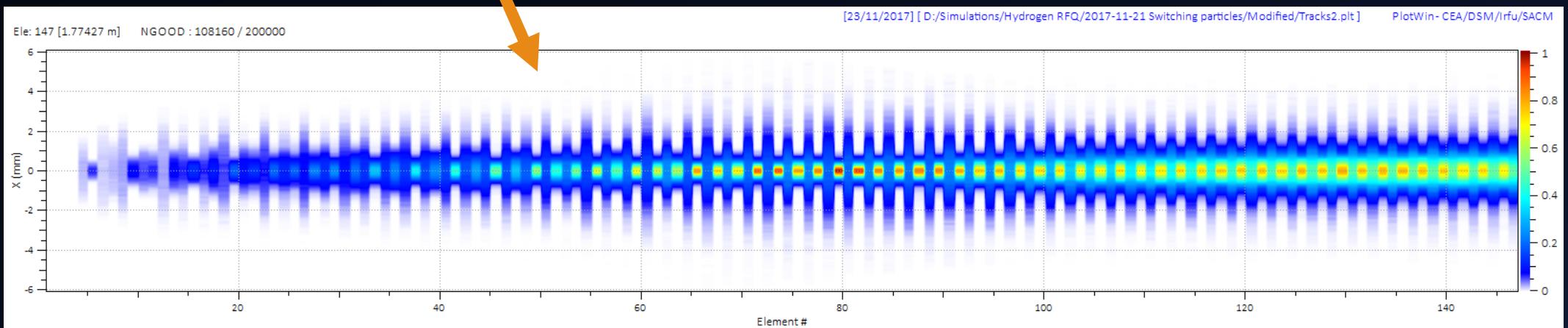
- `InteractionClass`
- `BeamBunchClass`
- `AccSimulatorClass`
- Input files
- `InputClass`
- `CalculationClass`
- `QuickSortClass`

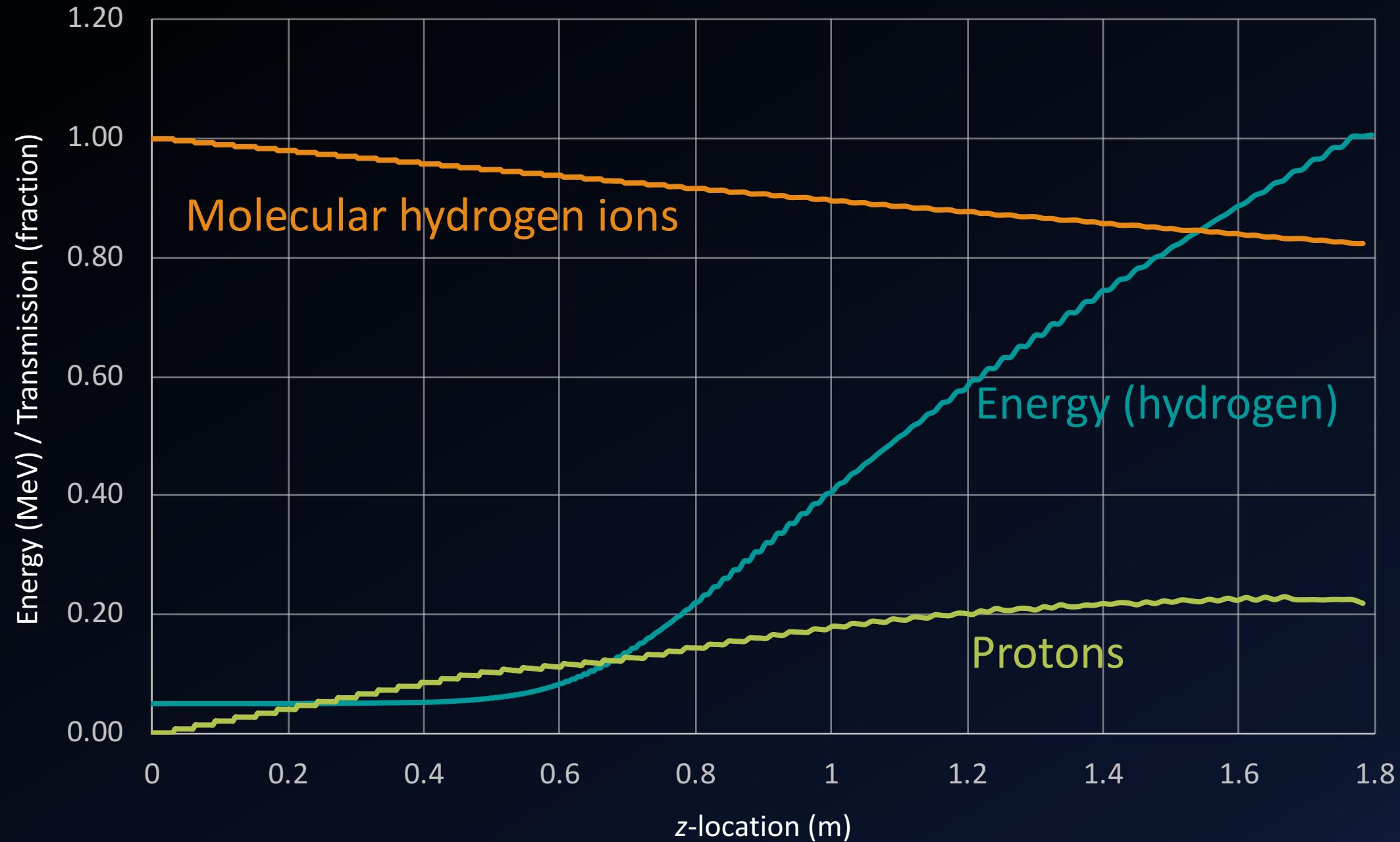
```
42 MODULE QuickSort
43
44 ! Declarations
45 IMPLICIT NONE
46 PRIVATE
47
48 ! Types
49 TYPE QuickSortArray
50     INTEGER :: key
51 END TYPE
52
53 ! Interfaces
54 INTERFACE qsort
55     MODULE PROCEDURE qsort_int
56     ! TODO: other types
57 END INTERFACE qsort
58
59 ! Public procedures
60 PUBLIC :: qsort
61
62 CONTAINS
63
64 ! Handler for integer arrays
65 SUBROUTINE qsort_int(array)
66     ! Parameters
67     INTEGER, INTENT(INOUT) :: array(:)
68     ! Variables
69     TYPE(QuickSortArray), ALLOCATABLE :: internal_array(:)
70
71     ! Allocate memory
72     ALLOCATE(internal_array(SIZE(array)))
73
74     ! Copy array
75     internal_array%key = array
76
77     ! Call the quicksort routine
78     CALL qsort_array(internal_array)
```

Molecular hydrogen bunches



Proton bunches





Status

- Added interaction bunches
 - Specified by the interactions input file
 - Created by the interactions module
 - Uses standard tracking and space charge methods
- Implemented three interaction types
- Probabilistic particle selection
- Interaction rates and trends don't match expectations

Future

- Fix interaction probability calculation
- Investigate full Monte Carlo method
- Implement other types of interaction
- Compare with experiment

References

FMIT

The FMIT accelerator

D D Armstrong

Presented at *PAC 1983: The tenth Particle Accelerator Conference*, Santa Fe, New Mexico, USA, March 1983, published in *IEEE Transactions on Nuclear Science* **30** (4) pp.2965–2969. doi:[10.1109/TNS.1983.4336541](https://doi.org/10.1109/TNS.1983.4336541)

CW RF operation of the FMIT RFQ

M V Fazio

Presented at *PAC 1985: The 11th Particle Accelerator Conference*, Vancouver, BC, Canada, January 1985, published in *IEEE Transactions on Nuclear Science* **32** (5) pp.2840–2842. doi:[10.1109/TNS.1985.4334199](https://doi.org/10.1109/TNS.1985.4334199)

The Fusion Materials Irradiation Test facility at Hanford

E W Pottmeyer

Presented at *FRM 1979: The first topical meeting on Fusion Reactor Materials*, Miami, Florida, January 1979, published in *Journal of Nuclear Materials* **85** (December 1979) pp.463–465. doi:[10.1016/0022-3115\(79\)90531-2](https://doi.org/10.1016/0022-3115(79)90531-2)

High-intensity deuteron linear accelerator (FMIT)

R A Jameson

Presented at *PAC 1979: The eighth Particle Accelerator Conference*, San Francisco, California, USA, March 1979, published in *IEEE Transactions on Nuclear Science* **26** (3) pp.2985–2991. doi:[10.1109/TNS.1979.4329915](https://doi.org/10.1109/TNS.1979.4329915)

CW operation of the FMIT RFQ accelerator

W D Cornelius

Presented at *IEEE Transactions on Nuclear Science*, Vancouver, BC, Canada, May 1985, published in *IEEE Transactions on Nuclear Science* **32** (5) pp.3139–3143. doi:[10.1109/TNS.1985.4334300](https://doi.org/10.1109/TNS.1985.4334300)

The Fusion Materials Irradiation Test (FMIT) facility

J W Hagan, E K Opperman and A L Trego

Presented at *FRM 1983: The third topical meeting on Fusion Reactor Materials*, Albuquerque, New Mexico, USA, September 1983, published in *Journal of Nuclear Materials* **123** (1-3) pp.958–964. doi:[10.1016/0022-3115\(84\)90201-0](https://doi.org/10.1016/0022-3115(84)90201-0)

LEDA

Simulations of the LEDA LEBT with H+, H2+ and e- particles

L M Young

Presented at *PAC 1997: The 17th Particle Accelerator Conference*, Vancouver, BC, Canada, March 1997, (6W023) pp.2749–2751. <http://jacow.org/pac97/papers/pdf/6w023.pdf>

High power operations of LEDA

L M Young, L J Rybarczyk, J D Schneider, M E Schulze and H V Smith

Presented at *LINAC 2000: The 20th International Linear Accelerator conference*, Monterey, California, USA, August 2000, (TU201) pp.336–340. <http://jacow.org/l00/papers/tu201.pdf>

Operations of the LEDA resonantly coupled RFQ

L M Young

Presented at *PAC 2001: The 19th Particle Accelerator Conference*, Chicago, USA, December 2001, (WOAA004) pp.309–313. <http://jacow.org/p01/papers/woaa004.pdf>

IFMIF

Challenges of the high current prototype accelerator of IFMIF/EVEDA

J Knaster, Y Okumura, A Kasugai and M Sugimoto

Presented at *IPAC 2016: The 7th International Particle Accelerator Conference*, Busan, Korea, May 2016, (MOZB02) pp.52–57. <http://jacow.org/ipac2016/papers/mozb02.pdf>

IFMIF: overview of the validation activities

J Knaster, F Arbeiter, P Favuzza, T Furukawa, F Groeschel et al.

Nuclear Fusion **53** (11) p.116001, September 2013. doi:[10.1088/0029-5515/53/11/116001](https://doi.org/10.1088/0029-5515/53/11/116001)

The Linear IFMIF Prototype Accelerator (LIPAc) design development under the European-Japanese collaboration

P Cara, R Heidinger, S O'Hira, K Sakamoto, A Kasugai et al.

Presented at *IPAC 2016: The seventh International Particle Accelerator Conference*, Busan, Korea, May 2016, (MOP0Y057) pp.985–988. doi:[10.18429/JACoW-IPAC2016-MOP0Y057](https://doi.org/10.18429/JACoW-IPAC2016-MOP0Y057)

A 140 mA cw deuteron electron cyclotron resonance source for the IFMIF-EVEDA project

R Gobin, P Y Beauvais, O Delferrière, D De Menezes, O Tuske, G Adroit, Y Gauthier and F Harrault

Review of Scientific Instruments **79** (2) p.02B303, 2008. doi:[10.1063/1.2801976](https://doi.org/10.1063/1.2801976)

Materials R&D for a timely DEMO: Key findings and recommendations of the EU Roadmap Materials Assessment Group

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Presented at *ISFNT11: The 11th International Symposium on Fusion Nuclear Technology*, Barcelona, Spain, September 2013, published in *Fusion Engineering and Design* **89** (October 2014) pp.1586–1594. doi:[10.1016/j.fusengdes.2013.11.007](https://doi.org/10.1016/j.fusengdes.2013.11.007)

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PKUNIFTY

PKUNIFTY: A neutron imaging facility based on an RFQ accelerator

Zou Y-B, Wen W-W, Guo Z-Y, Lu Y-R, Peng S-X et al.

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **651** (1) pp.62–66, September 2011. doi:[10.1016/j.nima.2011.02.011](https://doi.org/10.1016/j.nima.2011.02.011)

Four-rod RFQ beam dynamics design of PKUNIFTY upgrade

Zhu X-W, Lu Y-R, Zhu K, Yan X-Q, Wang H and Gao S-L

Chinese Physics Letters **34** (1) p.012901, January 2017. doi:[10.1088/0256-307X/34/1/012901](https://doi.org/10.1088/0256-307X/34/1/012901)

Neutron radiography with compact accelerator at Peking University: Problems and solutions

Guo Z-Y, Zou Y-B, Lu Y-R, Yan X-Q, Peng S-X, Zhu K and Chen J-E

Presented at *UCANS I: The first meeting of the Union of Compact Accelerator-Driven Neutron Sources*, Beijing, China, August 2010, published in *Physics Procedia* **26** (April 2012) pp.70–78. doi:[10.1016/j.phpro.2012.03.011](https://doi.org/10.1016/j.phpro.2012.03.011)

Progress of PKUNIFTY – a RFQ accelerator based neutron imaging facility at Peking University

Guo Z-Y, Lu Y-R, Zou Y-B, Zhu K et al.

Presented at *ITMNRT7: The seventh International Topical Meeting on Neutron Radiography*, Kingston, Ontario, Canada, June 2012, published in *Physics Procedia* **43** (2013) pp.79–85. doi:[10.1016/j.phpro.2013.03.010](https://doi.org/10.1016/j.phpro.2013.03.010)

Trouble shooting of deuteron RFQ for PKUNIFTY

Lu Y-R, Guo Z-Y, Zhao J, Zhu K, Zeng H-J et al.

Presented at *UCANS IV: The fourth meeting of the Union for Compact Accelerator-Driven Neutron Sources*, Sapporo, Hokkaido, Japan, September 2013, published in *Physics Procedia* **60** (2014) pp.212–219. doi:[10.1016/j.phpro.2014.11.030](https://doi.org/10.1016/j.phpro.2014.11.030)

The Beijing ISOL initial conceptual design report

Cui B-Q, Gao Y, Ge Y-C, Guo Z-Y, Li Z-H et al.

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **317** pp.257–262, December 2013. doi:[10.1016/j.nimb.2013.07.059](https://doi.org/10.1016/j.nimb.2013.07.059)

Beam dynamics design of a 50 mA D+ RFQ

Jia F-J, Zhu K, Lu Y-R, Wang Z, Fu Q and He Y

Chinese Physics Letters **33** (7) p.072901, July 2016. doi:[10.1088/0256-307X/33/7/072901](https://doi.org/10.1088/0256-307X/33/7/072901)

SARAF

Status of the SARAF CW 40 MeV proton/deuteron accelerator

D Berkovits, I Gertz, K Dunkel and P vom Stein

Presented at *PAC 2009: The 23rd Particle Accelerator Conference*, Vancouver, BC, Canada, May 2009, (FR5REP087) pp.4981–4983. <http://jacow.org/pac2009/papers/fr5rep087.pdf>

IsoDAR

Proposal for a high power deuteron cyclotron at RISP

J R Alonso and Kim J W

Presented at *HIAST 2015: The 13th international conference on Heavy Ion Accelerator Technology*, Yokohama, Japan, September 2015, (MOPA06) pp.45–7. <http://jacow.org/hiat2015/papers/mopa06.pdf>

Preliminary design of a RFQ direct injection scheme for the IsoDAR high intensity H₂+ cyclotron

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