CRITICAL BEAM-INTENSITY ISSUES IN CYCLOTRONS – OVERVIEW OF THE SANTA FE WORKSHOP

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A Workshop on Critical Beam-Intensity Issues in Cyclotrons was hosted by LANL in Santa Fe, New Mexico, in December 1995, with the primary aim of assessing the feasibility of using cyclotrons to obtain a 10 mA cw proton beam at 1 GeV for an "energy amplifier". Machines considered included separated-orbit, separated-sector and conventional integrated-sector cyclotrons accelerating either protons or H^- ions. Various injectors were also considered - dc devices, RFQs and small cyclotrons - the latter having already produced internal beams of 5 mA cw. With the overall major concern being minimization of beam loss, the detailed concerns discussed included space-charge effects, clean extraction, rf beam loading, beam loss detection and control, and reliability. These matters are reviewed and the conclusions of the Workshop summarized. It appears that cyclotrons offer a feasible, and probably the most economical, route to the desired beams, but that R&D will be needed on rf systems, collimation and high space-charge beam dynamics.

1 Introduction

From 3–6 December 1995, the Accelerator Operations and Technology Division of Los Alamos National Laboratory held a Workshop on Critical Beam-Intensity Issues in Cyclotrons in Santa Fe, New Mexico. The basic purpose of the workshop was to explore the capability of cyclotrons for producing several-MW proton beams for accelerator-driven nuclear waste transmutation, energy production and spallation sources, objectives towards which LANL had already been developing designs based on linacs.

There were 42 participants in all, 30 from LANL and 12 from outside. But as only these 12 were from the cyclotron community (from just 6 laboratories), this review of the workshop may be of interest to the rest of the community. It is based on two talks given during the workshop, and simply records the situation then, without trying to bring it up to date. The full proceedings of the workshop, consisting of copies of the speakers' viewgraphs, are available as a Los Alamos report[1].

Stan Schriber's charge to the Workshop may be summarized in four questions:

- How can 10 mA at 1 GeV be achieved?
- What critical issues limit beam intensity?
- What resources are needed to resolve the issues?
- Can the issues be resolved in the next generation of machines?

Some idea of the topics covered in the talks and discussion periods can be gained from the program, which is listed below. The chairmen of each technical session also acted as rapporteurs, providing summary talks in the final session.

Workshop Program

SESSION I: TUTORIAL

H. Blosser:	Cyclotron fundamentals
W. Joho:	High intensity issues in cyclotrons
T. Stammbach:	The PSI approach to high intensity cyclotrons

SESSION II: OPERATION RELATED ISSUES

G. Dutto:	TRIUMF accelerators
T. Stammbach:	Operational experience with space charge effects in the injector cyclotron
D. Clark:	LBNL 88″ cyclotron experience

SESSIONS III & V: BEAM DYNAMICS ISSUES

F. Marti:	Space charge models for cyclotrons
R. Baartman:	Intensity limitations in H^- cyclotrons
T. Wangler:	RFQ as injector

EVENING SESSION: NEW IDEAS AND DIRECTIONS

U. Trinks:	Separated orbit cyclotrons
M. Craddock:	H^- cyclotrons for 10 MW?

SESSIONS IV & VII: RF ISSUES

P. Sigg:	High power rf systems for cyclotrons
R. Poirier:	TRIUMF rf systems

SESSION VI: CONTROL, SAFETY, RELIABILITY

J. Nolen:	Control, safety and reliability issues

SESSION VII SUMMARY SESSION

H. Blosser:	R&D and future plans
D. Clark:	Beam dynamics issues
H. Blosser:	Operation related issues
E. Heighway:	Control, safety and reliability
J. Nolen:	RF issues
M. Craddock:	Rapporteur's talk.

2 State of the art and critical issues

Some idea of how close proton and H^- cyclotrons are to the 1 GeV × 10 mA goal may be gained from Table 1, which lists the maximum beam currents already achieved. No new technical problems are expected in extending the energy range of isochronous cyclotrons from 590 MeV to 1 GeV. Some development will be needed to increase beam currents by a factor 2 (p) or 4 (H^-), but there was confidence that this could be done.

Table 1: Highest beam currents achieved in cyclotrons (1995).

Machine	Ion	Energy	Current
LBL model	p	1 MeV	6 mA*
LBL 88″	p	few MeV	3 mA*
IBA	p	1-2 MeV	5 mA*
ORNL 86″	p	22 MeV	3 mA
PSI Injector II	p	72 MeV	1.8 mA
PSI Ring	p	590 MeV	1.3 (2) mA†
Gachina SC	p	1000 MeV	≤ 0.001 mA
TRIUMF CRM	H^-	1 MeV	2.5 mA*
TR30	H^-	30 MeV	1.2 mA
TRIUMF	H^-	500 MeV	0.4 mA

* internal beam
† beam loss $< 0.2\mu$A

The critical issues were felt to lie in four main areas:

BEAM LOSS AND SAFETY: With a 10 MW beam, *beam loss is the overriding issue and must be strictly limited.* Its detection, control (by collimation and tuning), and shielding must receive the highest priority. Loss levels regarded as acceptable, based on experience at high-current machines, are listed in Table 2.

Table 2: Beam loss acceptability.

Loss	Acceptability
0.01% = 1 kW	Yes
0.1% = 10 kW	If directible to beam dump
1% = 100 kW	If directible to dump and provides major benefit

BEAM DYNAMICS: Here space charge is the major source of problems; while transverse effects are serious only at lower energies, longitudinal ones are of concern throughout, especially for extracting protons and in the transfer lines. Low-loss extraction can be achieved either by stripping H^- ions or by cleanly separating proton turns (with either high rf voltage and flat-topping or a separated-orbit cyclotron).

RF SYSTEMS: Beam power per cavity may be ≈5 times higher than now, giving 70% beam loading and requiring improved control systems; flat-top cavities would be heavily beam-driven. R&D is also needed on couplers to get >1 MW per window, and on cavities to raise the voltages and improve profiles.

RELIABILITY: The reliability goal should be the same as for fission reactors (95%). As this is somewhat higher than the norm for research accelerators, some redundancy needs to be built into the design. There should be multiple low-current first stages, and complete facilities (like reactors) should be built in clusters of say four.

3 Proposed 10 MW cyclotron schemes

A number of possible cyclotron schemes were discussed for achieving 10 MW beams. They are listed in Table 3, along with the parameters of lower energy stages, using the acronyms CC, SSC and SOC for compact, separated-sector and separated-orbit cyclotrons respectively. The star (*) ratings are purely personal assessments.

Table 3: Possible Cyclotron Staging Schemes.

Type	Injector	Mid-stage	1 GeV
EA	2 × 10 MeV H^-	p SSC	p SSC
***	12 MeV SOC	120/200 MeV	$N = 10$
PSI	1 MeV dc p	p SSC	
Dream		120 MeV	p SSC
Mach.	~5 MeV RFQ	$N = 4$	$N = 12$
***	50 keV dc H^-	120 MeV H^-	
p SOC	SOC I	SOC II	SOC III
***	180 MeV	400 MeV	100 MW
H^-	300 keV dc H^-	–	H^- SSC
**	50 keV dc H^-	120 MeV H^-	$N = 6$

*** Prime schemes for evaluation
** Preliminary concept

The first schemes to be proposed were the 'Energy Amplifier' (EA) and the PSI 'Dream Machine' (PSIDM), both with high-energy stages modelled on the 590 MeV PSI SSC, though with more magnet sectors and rf cavities to improve the turn separation and extraction efficiency at 1 GeV. Unfortunately, the EA (Figure 1) was not presented at the workshop, but has been described by Mandrillon *et al.* elsewhere[2]. Details are given of all three stages, and preliminary space-charge studies are included for both cyclotrons and transfer lines. H^- and H^+ beams from the two injectors would be merged to avoid debunching in the 10 MeV line.

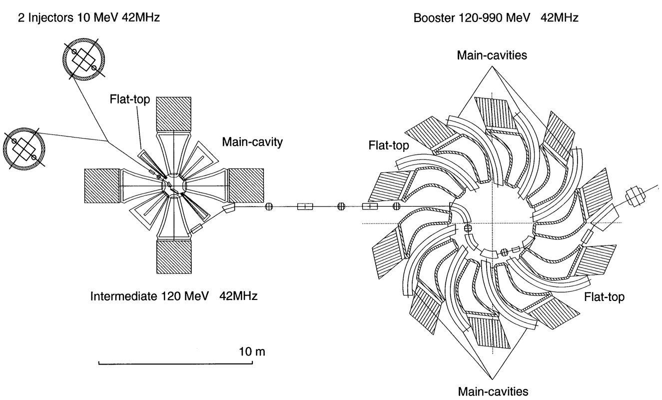

Figure 1: The Energy Amplifier cyclotron complex.

The PSIDM (Figure 2) is modelled more closely on the present PSI complex (Stammbach[3]), with a 1 MeV dc injector and 120 MeV SSC, following the current successful practice. Two alternative injection options were also discussed and proposed for further study:

- $\approx$5 MeV RFQ and 120 MeV SSC; initial studies suggested the RFQ longitudinal emittance might be too big and that space-charge debunching should be studied.

- 120 MeV H^- CC, a hypothetical TR120 from the Ebco/TRIUMF stable. Baartman[1] described how scaling up the TR30 injection system would yield 10 mA. The beam loading is relatively high and bunch compression might be needed to match PSIDM, but this is potentially the least expensive option (and for the EA also).

The cost estimate of MCHF 222 plus 940 man-years suggests cyclotrons would be much less costly than linacs.

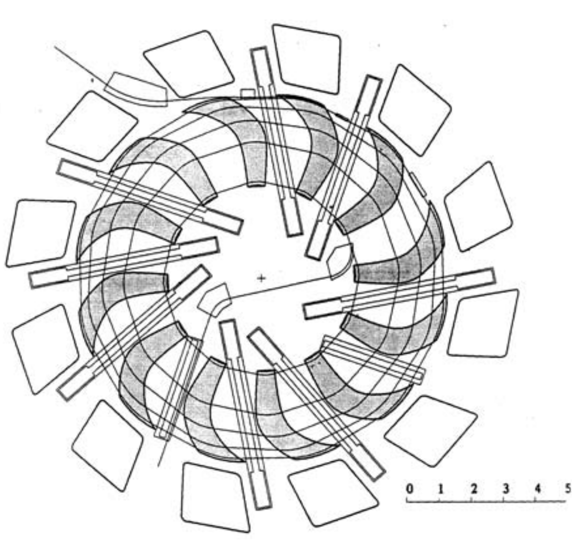

Figure 2: The PSI 'Dream Machine'.

The use of separated-orbit cyclotrons (Trinks[4], Figure 3), where the focusing is locally adjustable and resonant effects are absent, would make it possible to accelerate currents as large as in linacs, say 100 mA. The design is somewhat complicated, but the use of superconducting magnets and rf minimizes the size and the power needs. Full demonstration of TRITRON was eagerly awaited.

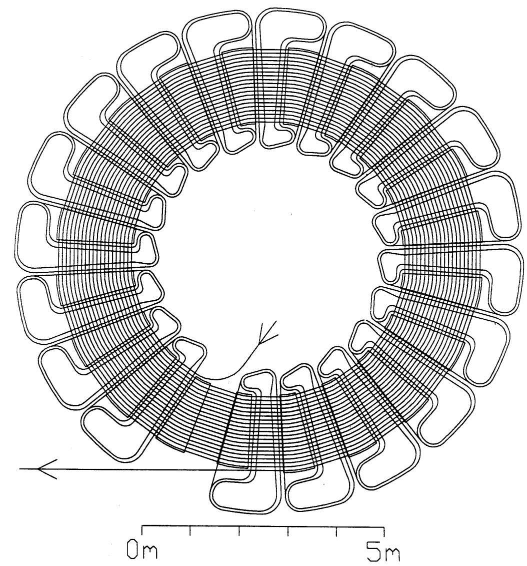

Figure 3: A large separated-orbit cyclotron.

4 H^- cyclotrons for 10 MW?

The author suggested that a single-stage H^- cyclotron should also be considered, as it offered a number of advantages for high-current low-loss applications:

- Stripping by a thin foil provides a simple and reliable low-loss (<0.1%) extraction mechanism, obviating the need for cleanly separated turns, high energy-gain/turn, narrow bunches and flat-topping rf cavities.

- A single-stage scheme simplifies design and operation and eliminates a whole set of loss-prone extraction, transfer and re-injection systems.

- An H^- source and first stage are possibly the best options in the $\approx$10 mA intensity range (Baartman[1]), and have been adopted for the EA.

H^- ions also bring problems, but no showstoppers:

- Foil heating by stripped electrons (0.1% = 10 kW), if the foil is placed in a magnetic field.

- Better vacuum is required ($\sim 10^{-8}$ Torr).

- Electromagnetic stripping limits the magnetic field to 0.3 T, making the orbit radius $R \approx 20$ m at 1000 GeV.

Present H^- cyclotrons are of traditional combined-function design, with internal dees and single magnet coils, but a *separated-sector design*, which permits small magnet pole gaps, (5 cm rather than TRIUMF's 50 cm), would offer significant advantages here:

- lower amp-turns, reducing the power requirement;
- a field-free region in the valleys for simpler design, installation and operation of rf cavities, diagnostic probes and stripping foil;
- accurate computation of the magnetic field B;
- because of the sensitivity of the stripping to the maximum field $\hat{B}$, more flutter can be obtained at a given mean $\overline{B}$, and hence less spiral angle ϵ is needed to provide vertical focusing.

Some zero-order estimates for major magnet parameters for 10 MW H^- SSCs are shown in Table 4. As the great size of a 1 GeV machine would present a major challenge, values are also given for lower top energies $\hat{T}$ down to 500 MeV (requiring higher currents I). $\hat{B}$ was chosen to give the same $E = \gamma v \hat{B}$ as TRIUMF at 400 MeV to ensure zero stripping loss, and $\hat{\epsilon}$ was computed in hard-edge approximation for a hill fraction of 0.80. In all cases the spiral is less than for TRIUMF, allowing straight rf cavities to fit between the sectors.

Table 4: H^- cyclotron parameters for various maximum energies, with TRIUMF values (*) for comparison.

$\hat{T}$ (MeV)	$\hat{B}$(kG)	$\hat{R}$ (m)	$\hat{\epsilon}$ (deg)	I (mA)
500*	5.8	7.92	70	0.4
500	5.07	8.96	56.0	20
600	4.53	11.2	59.5	16.7
700	4.12	13.6	62.2	14.3
800	3.78	16.1	64.4	12.5
900	3.50	18.8	66.3	11.1
1000	3.26	21.7	67.8	10

Figure 4 shows the layout of a 6-sector 500 MeV SSC, about 12% larger than TRIUMF. Single-gap $\lambda/4$ rf cavities are assumed, with voltage increasing towards the outside in some cases, but towards the centre in others, to ensure sufficient energy gain at all radii.

The large diameter of these machines makes it tempting to consider two-stage designs. A 100 MeV first stage (TR120 again?) would enable the radial extent of the main ring magnets and vacuum chamber to be halved – but would require development of a highly efficient H^- extraction system. Although a few percent loss at 100 MeV amounts to tens of kilowatts, the lost beam could be stripped on a pre-septum and sent to a dump outside.

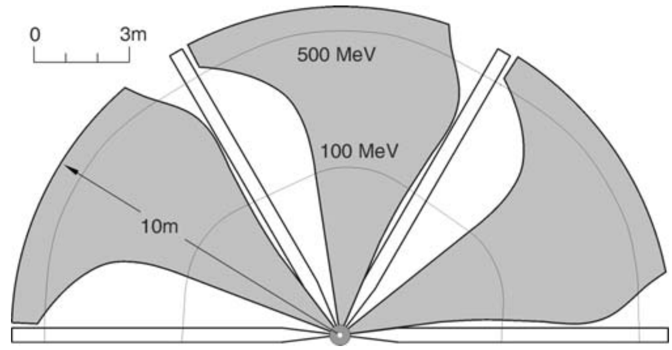

Figure 4: Three sectors of an H^- separated-sector cyclotron.

5 Conclusions

The conclusions were generally very favourable:

- A 1000 MeV × 10 mA cyclotron complex looks feasible, would be less costly than linacs, and should be achieveable in the next generation.
- A proton SSC with 10 or 12 sectors looks very promising for the final stage.
- The injection options need to be brought to a conceptual design stage to assess their feasibility and cost.
- SOCs await experimental demonstration but look cost-competitive and offer 100 MW capability.
- System R&D is needed on
  - demonstrating 10 mA cyclotron beams;
  - rf systems, especially high-voltage cavities, couplers, and control of high beam loading;
  - beam dynamics under high space charge in cyclotrons and transfer lines.

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References

[1] *Proc. Workshop on Critical Beam-Intensity Issues in Cyclotrons* (Santa Fe, 1995), ed. S. Nath, A. Jason and R. Salazar, LAUR-96-1492 (LANL, 1996).

[2] N. Fiétier, P. Mandrillon and C. Rubbia, *Proc. Cyclotrons'95*, Cape Town (World Scientific, 1996) 598; P. Mandrillon, N. Fiétier, these proceedings.

[3] Th. Stammbach, *AIP Conf. Proc.* 346, 229 (1994) and these proceedings.

[4] U. Trinks, *Proc. Cyclotrons'92*, Vancouver (World Scientific, 1993) 693, and these proceedings.